Anisotropic Flow Decorrelation in Heavy-Ion Collisions at RHIC-BES Energies with 3D Event-by-Event Viscous Hydrodynamics

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References: Phys. Rev. C 103, 034902 (2021) and arXiv:2104.08022

Motivation

- Longitudinal structure of anisotropic flows brings additional constraints on the initial state and/or transport coefficients of the QGP
- At RHIC-BES energies, flow decorrelation is just starting to be researched
- So far, there are only preliminary results from STAR at $\sqrt{s_{\mathrm{NN}}} = 27$ and 200 GeV [Nucl. Phys. A 982, 403 (2019), Nucl. Phys. A 1005, 121783 (2021)]

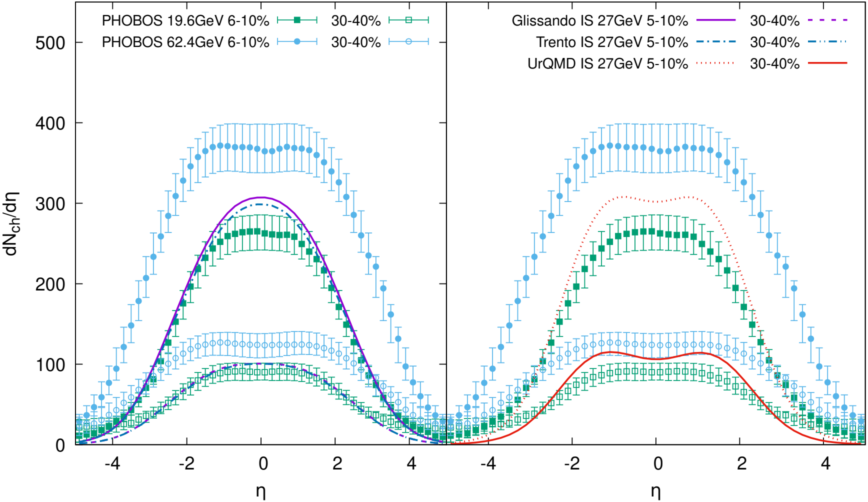
The Model

- We use hybrid model which have four steps
  - 3D initial state - 3 possibilities:
    - UrQMD [Prog. Part. Nucl. Phys. 41, 255 (1998)]
    - GLISSANDO2 [Comput. Phys. Commun. 185, 1759 (2014)] extended to 3D
    - T$_\mathrm{R}$ENTo [Phys. Rev. C 92, 011901 (2015)] extended to 3D, with parameter $p = 0 \Rightarrow T_R = \sqrt{T_A T_B}$
  - vHLLE - (3+1)-dimensional viscous hydrodynamic model for hot and dense stage [Comput. Phys. Commun. 185, 3016 (2014)]
  - Cooper-Frye prescription for particlization
  - Hadronic rescatterings and resonance decays using the UrQMD cascade
  - There is a finite baryon and electric charge density at all stages

The Model

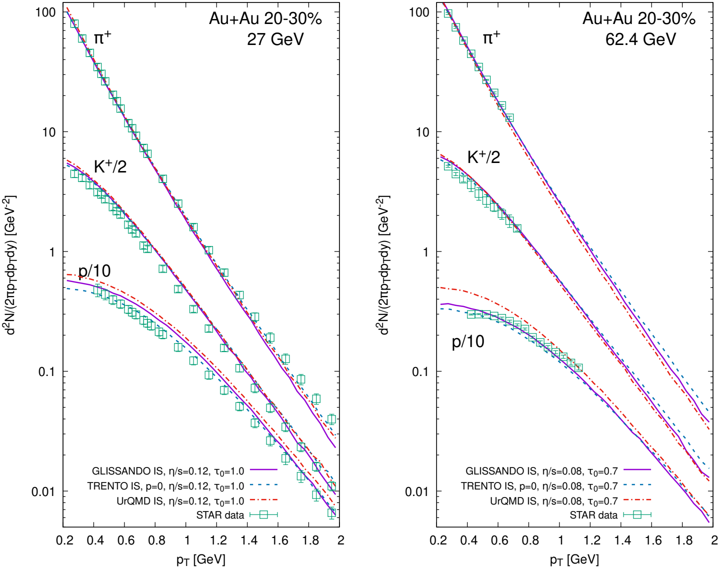
- GLISSANDO2 and T$_\mathrm{R}$ENTo are extended to longitudinal direction following work of Bozek [Phys. Rev. C 85, 044910 (2012)]
  - Parameters of longitudinal expansion were tuned against $\mathrm{d}N/\mathrm{d}\eta$, p_T spectra and $\mathrm{d}N/\mathrm{d}y$ of net protons
  - Total energy and total baryon charge are fixed to those of the participants
  - For baryon number we use superposition of two Gaussian distributions
- We simulated Au+Au collisions at energies $\sqrt{s_{\mathrm{NN}}} = 27$, 62.4 and 200 GeV
- For each run we simulated 3000 hydrodynamic simulations and from each we generated 500 events at the particlization step

Charged Hadron Pseudorapidity Distributions



- $\sqrt{s_{NN}} = 27\,\mathrm{GeV}$, centralities 5-10% and 30-40%

Transverse Momentum Spectra



Flow

- Hadron distribution in azimuthal angle can be written as a Fourier series

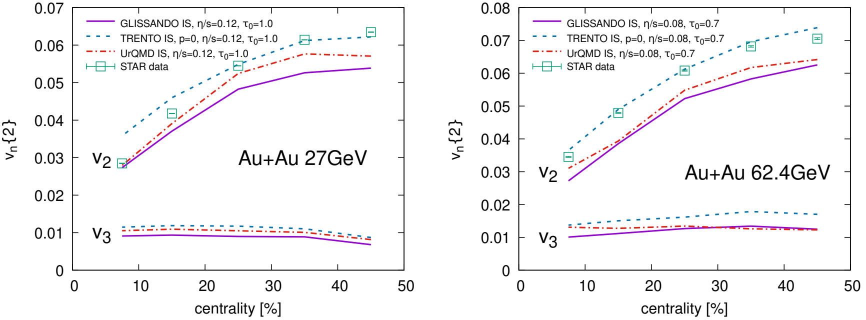
$$\frac{\mathrm{d}^3N}{p_T\mathrm{d}p_T\mathrm{d}y\mathrm{d}\phi} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_T\mathrm{d}p_T\mathrm{d}y}\left(1+\sum_{n=1}^{\infty}2v_n\cos(n(\phi-\Psi_n))\right)$$

- The flow coefficients can then be computed from

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

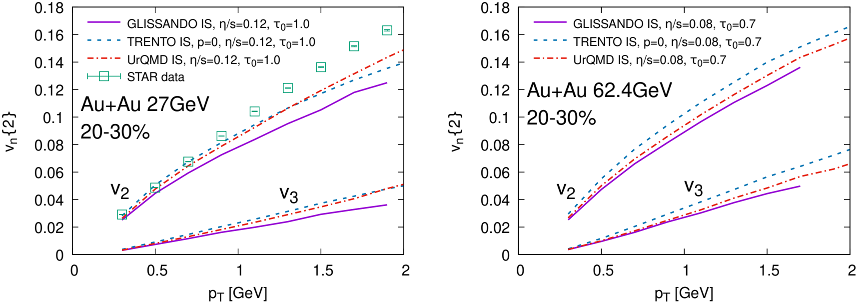
- To calculate flow coefficients we used event plane method [Phys. Rev. C 58, 1671 (1998)] and 2-particle cumulant method [Phys. Rev. C 83, 044913 (2011)]

Elliptic Flow as Function of Centrality



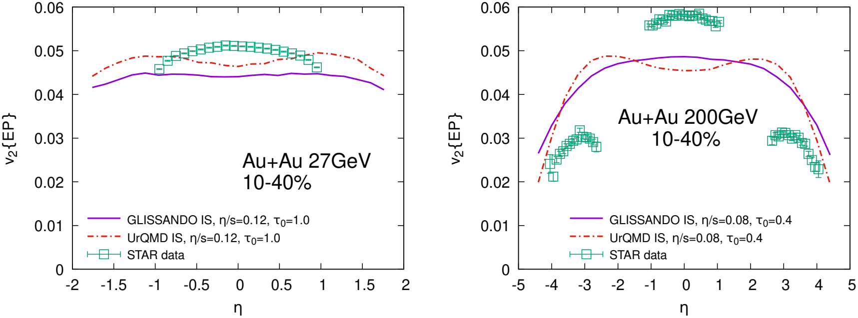
- models with Glissando and UrQMD IC underestimate the p_T-integrated elliptic flow

Elliptic Flow as Function of Transverse Momentum



- All three IS underestimate the elliptic flow at large p_T

Elliptic Flow as Function of Pseudorapidity

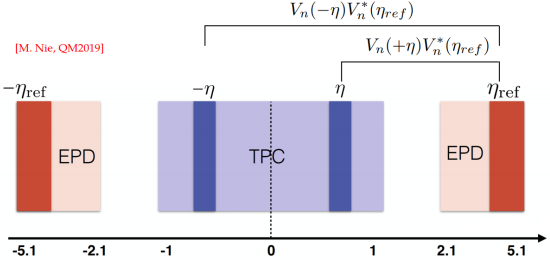


- Ballpark value is reproduced, but not the shape

Decorrelation

- Longitudinal fluctuations can lead to decorrelations of anisotropic flows along the pseudorapidity direction
- We use flow vector $\mathbf{V}_n = v_n e^{in\Psi_n}$ to calculate factorisation ratio
- The factorisation ratio is the defined

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



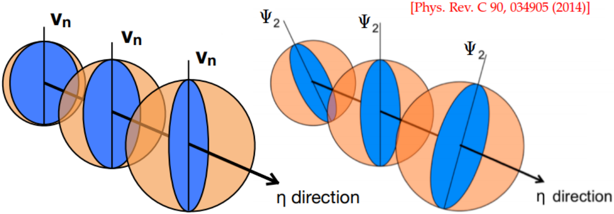
[M. Nie, QM2019]

- $r_n(\eta) = 1 \Rightarrow$ no decorrelation
- $r_n(\eta) < 1 \Rightarrow$ decorrelation

Magnitude and Angle Decorrelation

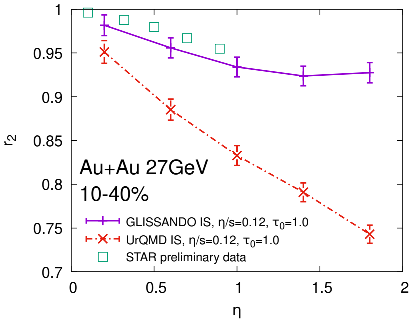
- The factorisation ratio can be split to magnitude and angle decorrelation

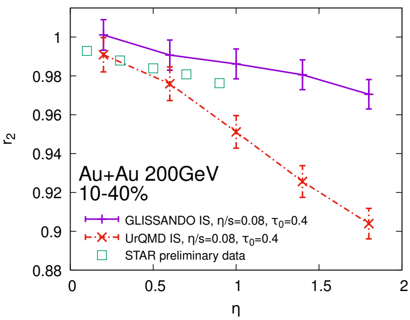
$$r_n^v(\eta) = \frac{\langle v_n(-\eta) v_n(\eta_{ref}) \rangle}{\langle v_n(+\eta) v_n(\eta_{ref}) \rangle} \qquad r_n^{\Psi}(\eta) = \frac{\langle \cos n(\Psi_n(-\eta) - \Psi_n(\eta_{ref})) \rangle}{\langle \cos n(\Psi_n(+\eta) - \Psi_n(\eta_{ref})) \rangle}$$



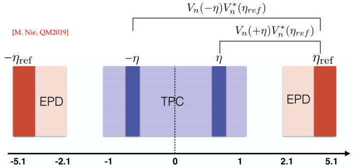
[Phys. Rev. C 90, 034905 (2014)]

Results of Flow Decorrelation

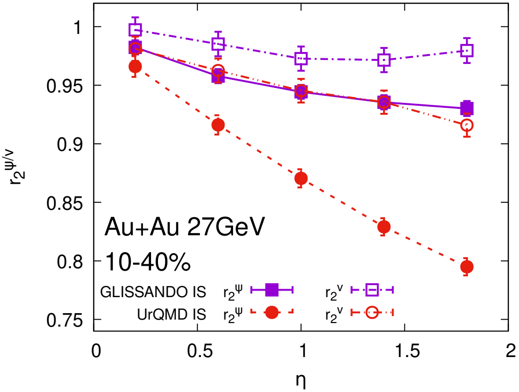




- UrQMD IS results in significantly stronger decorrelation


[M. Nie, QM2019]

Angle and Magnitude Decorrelation



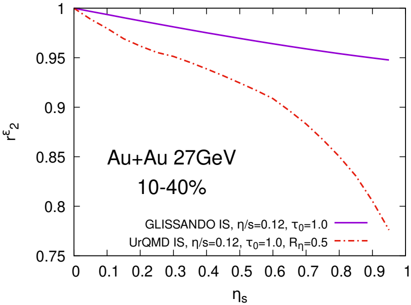
- The flow decorrelation is mainly caused by flow angle decorrelation

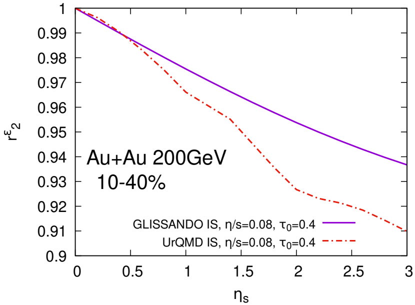
Initial State Eccentricity Decorrelation

- Analogously, we can define decorrelation of initial state spatial eccentricity

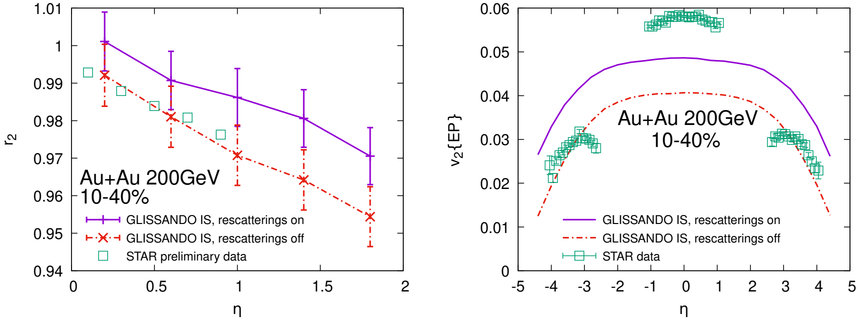
$$r_n^{\epsilon}(\eta_s) = \frac{\langle \epsilon_n(-\eta_s)\epsilon_n(\eta_{s,\mathrm{ref}})\cos[n\,(\Psi_n(-\eta_s) - \Psi_n(\eta_{s,\mathrm{ref}}))]\rangle}{\langle \epsilon_n(\eta_s)\epsilon_n(\eta_{s,\mathrm{ref}})\cos[n\,(\Psi_n(\eta_s) - \Psi_n(\eta_{s,\mathrm{ref}}))]\rangle}$$

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





Impact of Final-State Rescatterings



- Final-state rescatterings can bring the factorisation ratio closer to the experimental data, however it also reduces the already underestimated elliptic flow

Summary

- We presented the elliptic flow and flow decorrelation in Au-Au collisions at $\sqrt{s_{\mathrm{NN}}} = 27$, 62.4 and 200 GeV in 3-dimensional viscous hydrodynamic model with UrQMD, 3D GLISSANDO and 3D T$_{\mathrm{R}}$ENTo initial states
- Flow decorrelation at $\sqrt{s_{\mathrm{NN}}}$ =27 GeV is a first calculation of a kind in a hydrodynamic model
- At midrapidity, model with T$_{\mathrm{R}}$ENTo IS ($p = 0$) best describes the data
- We observe that the flow decorrelation is mainly caused by flow angle decorrelation, which is in agreement with other studies [Phys. Rev. C 98, 024913 (2018), Phys. Rev. C 97, 034913 (2018)]
- The model with UrQMD IS overestimates the decorrelation, which is rooted in much stronger decorrelation of initial state eccentricity
- References: Phys. Rev. C 103, 034902 (2021) and arXiv:2104.08022
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