Beam energy scan using a 3+1D viscous hydro+cascade model

FIAS Frankfurt Institute for Advanced Studies

Iurii Karpenko[1,2], Pasi Huovinen[1,3], Hannah Petersen[1,3], Marcus Bleicher[1,3]

[1]Frankfurt Institute for Advanced Studies, Ruth-Moufang-Straße 1, Frankfurt am Main, Germany
[2]Bogolyubov Institute for Theoretical Physics, 14-b, Metrolohichna str., Kiev, Ukraine
[3]Institute for Theoretical Physics, Johann Wolfgang Goethe Universität, Max-von-Laue-Str. 1, Frankfurt am Main, Germany

HIC for FAIR Helmholtz International Center

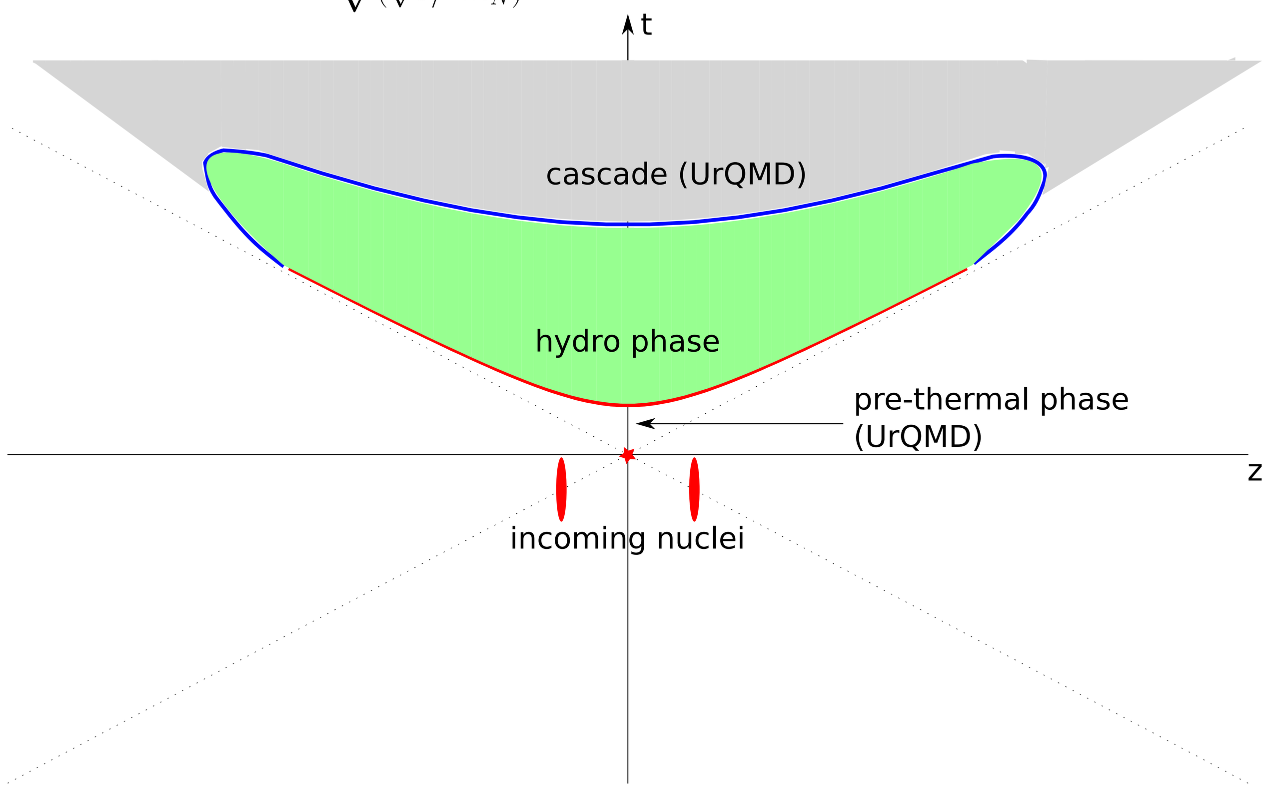
The model

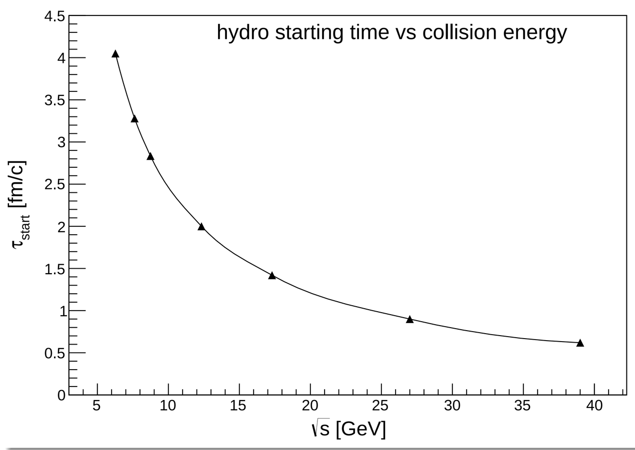
Cascade-hydro-cascade approach:

- Initial state: UrQMD cascade [1]
- Hydrodynamic phase: numerical 3+1D hydro solution via original relativistic viscous hydro code [2]
- Hadronic cascade: UrQMD

Initial conditions for hydrodynamic evolution from UrQMD

Switch from UrQMD to fluid at Bjorken proper time $\tau = \sqrt{t^2 - z^2} = \tau_0$, where $\tau_0 = \frac{2R}{\gamma v_z} = \frac{2R}{\sqrt{(\sqrt{s}/2m_N)^2 - 1}}$. Switching surface is the red curve





Initial $\{T^{0\mu}, N_b^0, N_q^0\}$ of fluid = = averaged or event-by-event $\{T^{0\mu}, N_b^0, N_q^0\}$ of particles

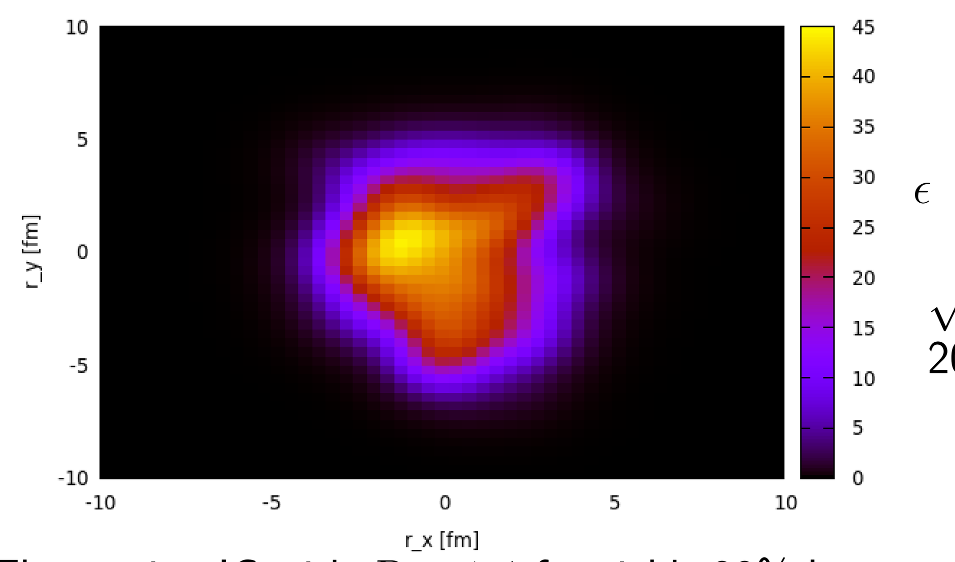
Initial shear stress tensor $\pi^{\mu\nu} = 0$.

Option 1) Averaged initial state

Initial particle distribution is taken as an average over $\propto 10^4$ UrQMD simulations of initial state. No smoothening involved.

Option 2) Fluctuating initial state

Fluctuating, but smoothed initial state [6]:
$E \propto \exp(-\frac{(x-x_{part})^2+(y-y_{part})^2+\gamma_z^2(z-z_{part})^2}{R^2})$, where $R = 1.4$ fm



$\sqrt{s_{NN}} = 39$ GeV, 20-30% central

Fluctuating IC with $R = 1.4$ fm yields 23% larger average $dS/dy(y=0)$ than the averaged IC.

Equation of state

The equation of state from Chiral model [3] is used, which agrees qualitatively with lattice QCD results for zero baryon density. However the EoS is also constructed for finite (large) baryon densities.

Hydrodynamic phase

Numerical 3+1D relativistic viscous hydro solution in Israel-Stewart formalism and Milne coordinates is used. The evolutionary equations for shear stress tensor are:

$$< u^\gamma \partial_{;\gamma} \pi^{\mu\nu} > = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_\pi} - \frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^\gamma$$

▷ Bulk viscosity $\zeta = 0$, charge diffusion=0
▷ Shear relaxation time ansatz used: $\tau_\pi = 3\eta/(sT)$

Fluid→particle transition

$\epsilon = \epsilon_{sw} = 0.5$ GeV/fm^3 (blue curve):
$\{T^{0\mu}, N_b^0, N_q^0\}$ of hadron-resonance gas = $\{T^{0\mu}, N_b^0, N_q^0\}$ of fluid
▷ Cooper-Frye prescription for hadron sampling:

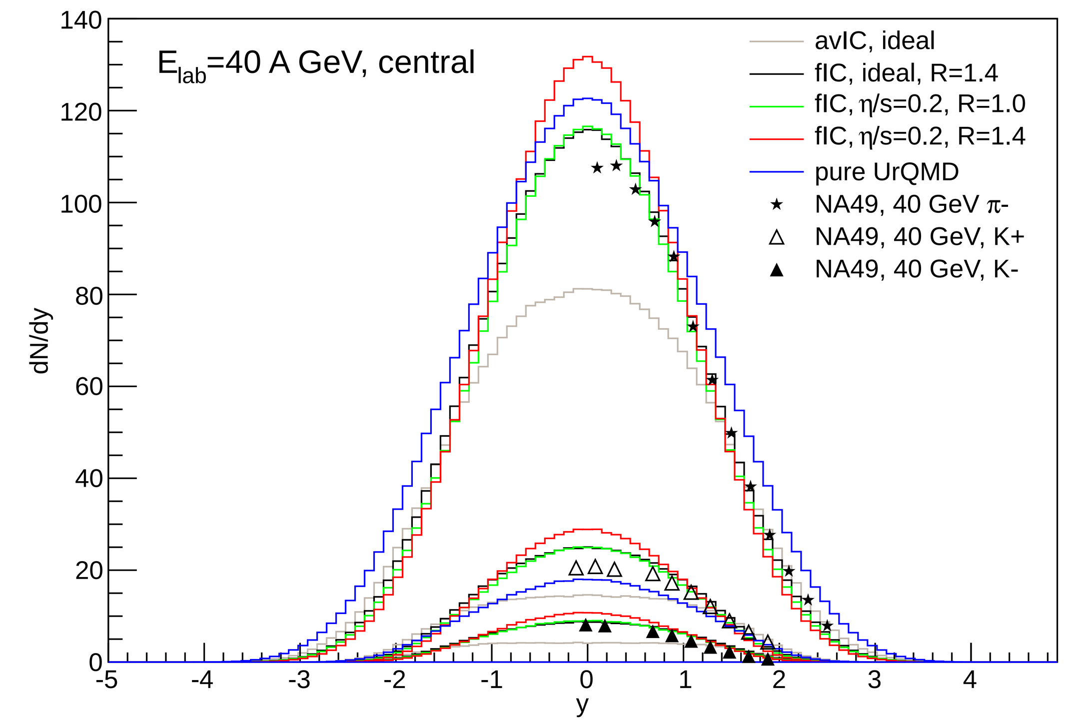
$$p^0 \frac{d^3 n_i}{d^3 p} = \sum f_{\text{l.eq.}}(x,p)\left[1 + (1 \mp f_{\text{eq}})\frac{p_\mu p_\nu \pi^{\mu\nu}}{2T^2(\epsilon+p)}\right] p^\mu \Delta\sigma_\mu$$

▷ Cornelius subroutine [4] to compute $\Delta\sigma_i$ on transition hypersurface.
▷ UrQMD cascade is employed after particlization surface.

Abstract

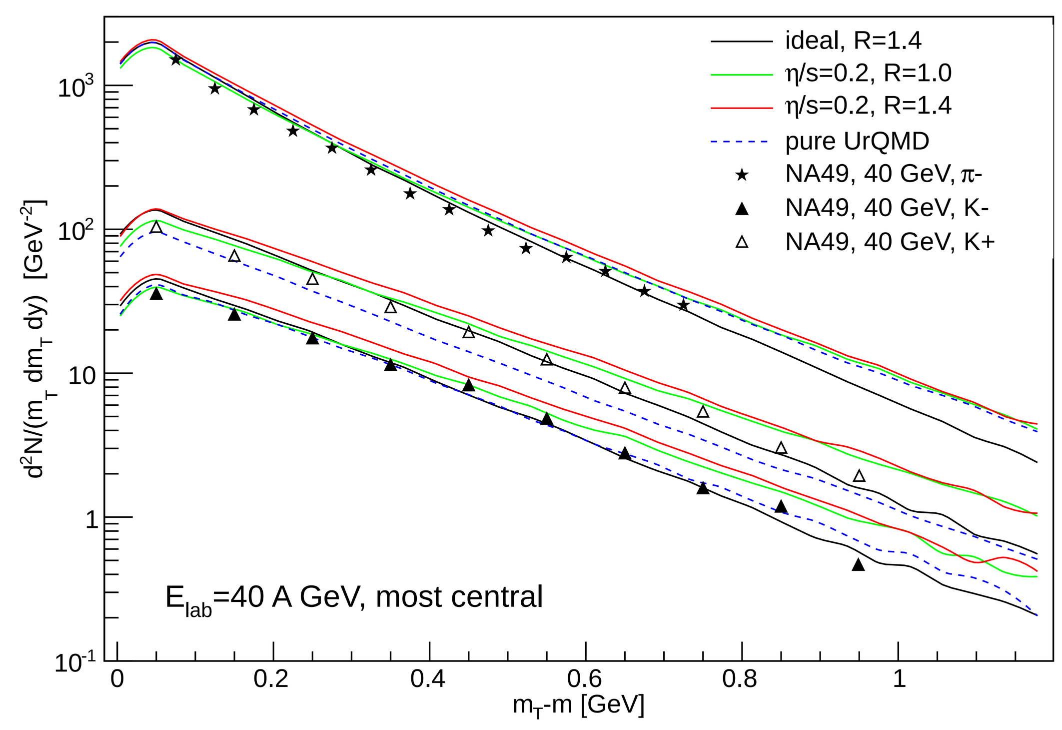
We apply a 3+1D viscous hydro+cascade model for A+A collisions at RHIC Beam Energy Scan energies ($\sqrt{s} = 7.7 - 39$ GeV), as well as for SPS energy points. We show how the results are sensitive to the shear viscosity in hydrodynamic phase and estimate η/s for Au+Au collisions in RHIC BES.

Rapidity distributions



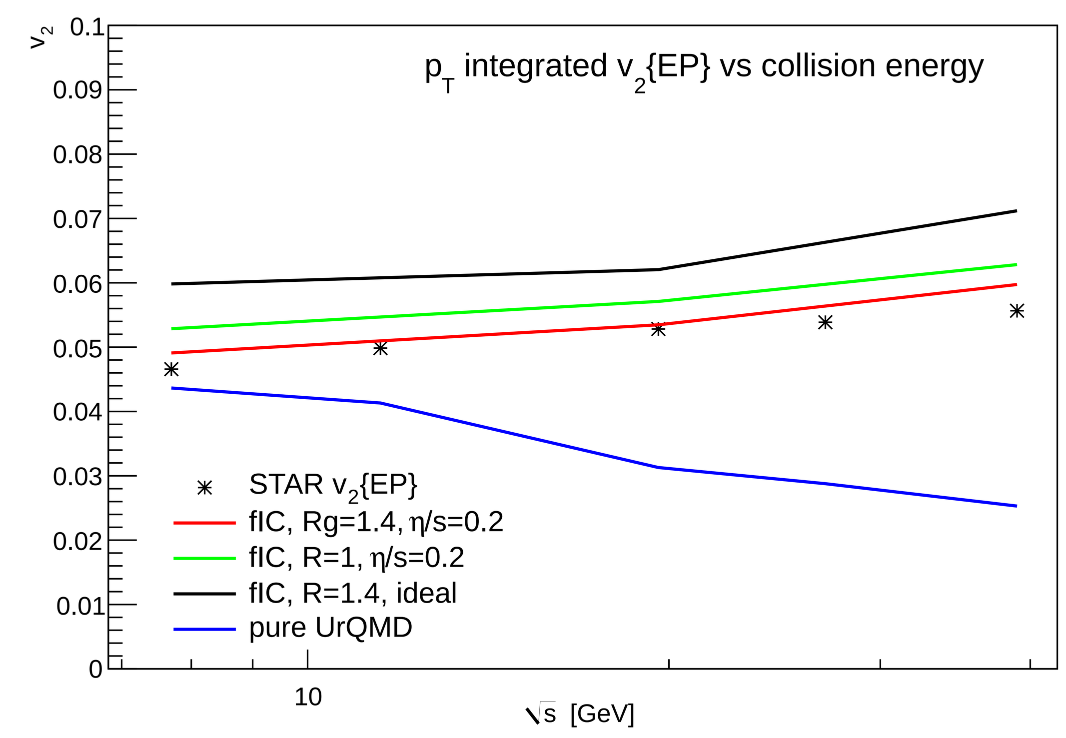
- shear viscosity in hydrodynamic phase makes overall expansion more spherical, bringing extra energy in transverse expansion at midrapidity. This increases both the multiplicity at midrapidity and the effective temperature of p_T spectra

Transverse momentum spectra



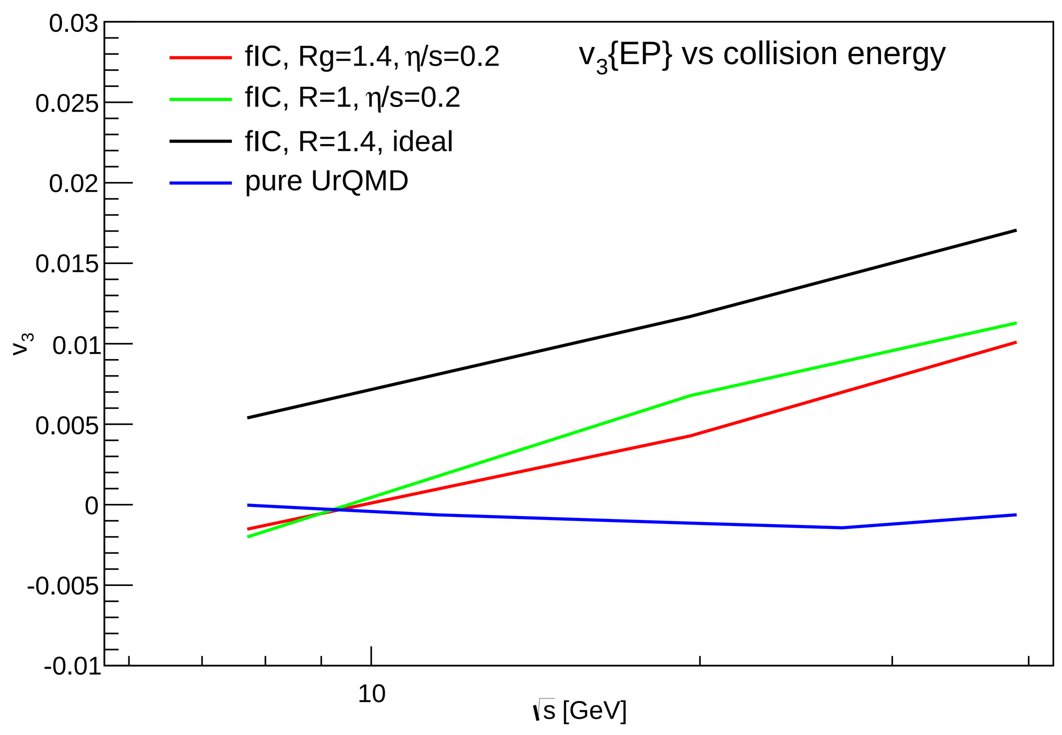
- larger initial entropy for smoothed fluctuating initial state leads to larger final multiplicity
- broader Gaussian smearing of the initial state has an effect on observables, which is qualitatively similar to the increase of shear viscosity in hydrodynamic phase.

p_T integrated elliptic flow at BES energies



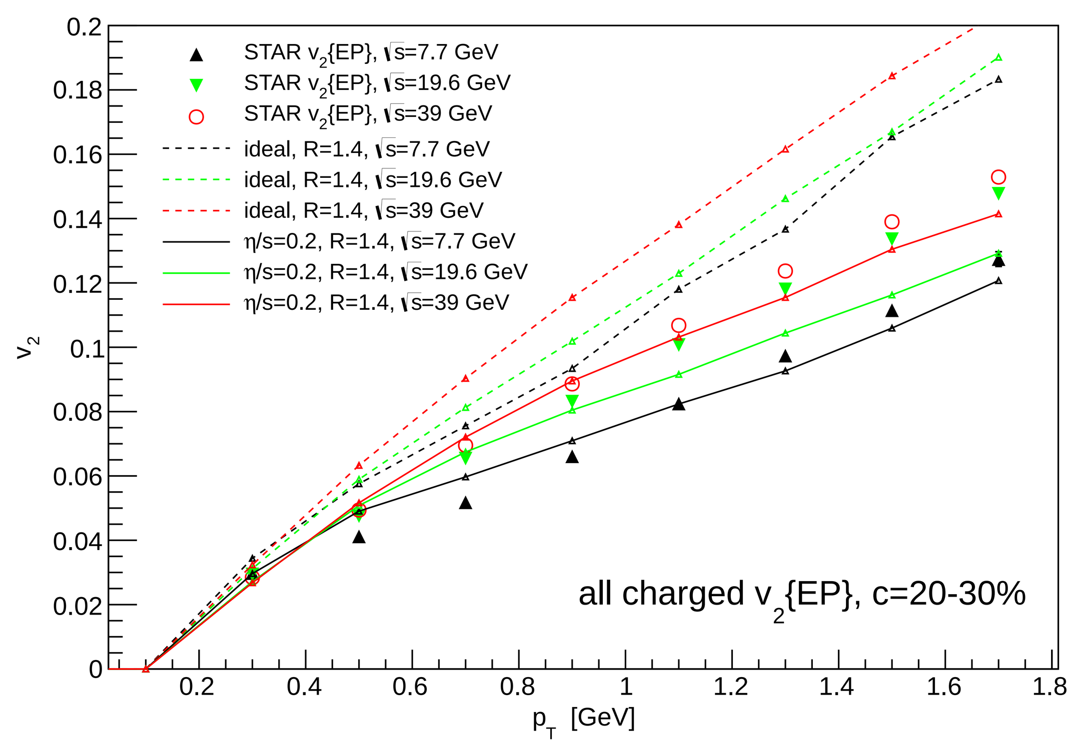
- **Comparison to the experimental v_2 from RHIC BES suggests $\eta/S \geq 0.2$ in hydro phase for BES collision energy range**

p_T integrated triangular flow

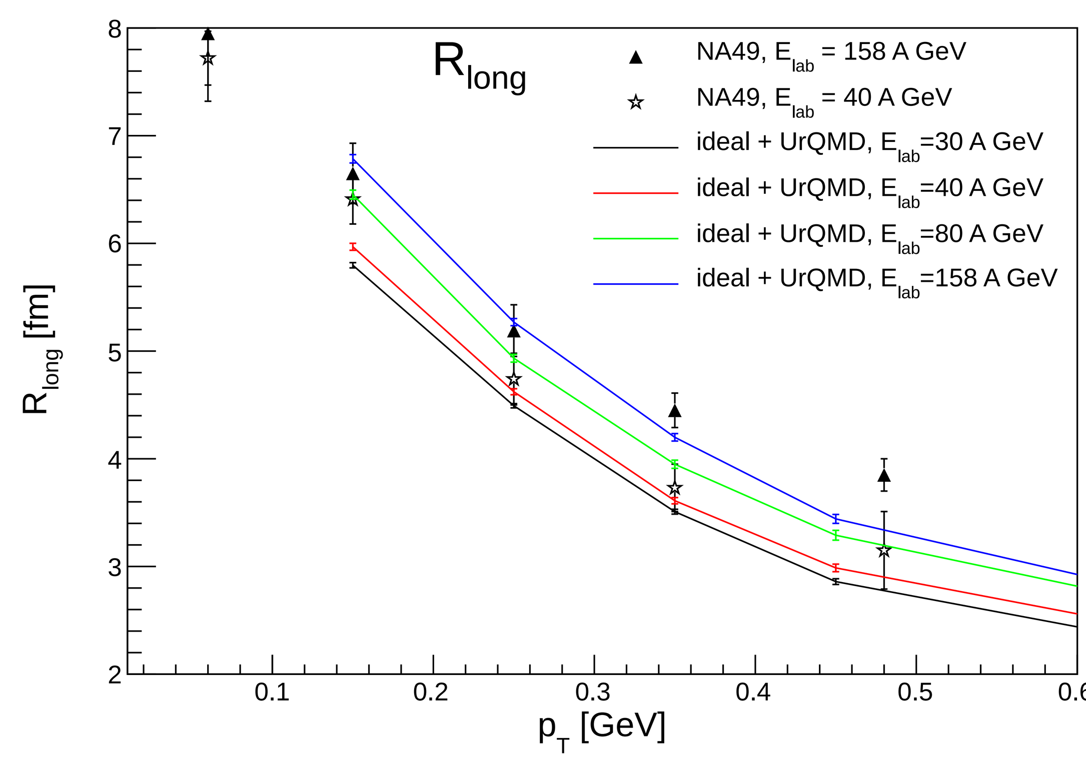


- v_3 is strongly sensitive to the shear viscosity in hydro phase
- pure cascade (UrQMD) shows $v_3 \approx 0$

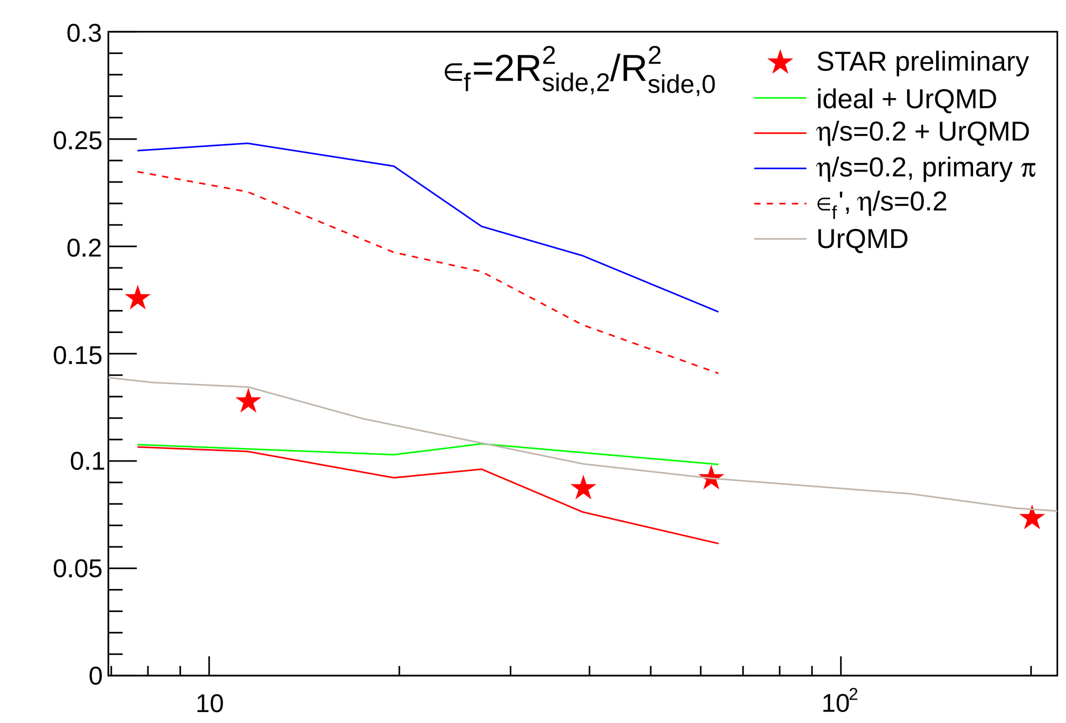
p_T differential elliptic flow



Femtoscopic radius R_{long} (averaged IC only)



- $\eta/s = 0.2$ in hydro phase systematically increases R_{long} by 5-10%, does not affect $R_{\text{out}}/R_{\text{side}}$.



⇐ Freezeout eccentricity from azHBT (averaged IC only) for 10-30% central Au+Au, $p_T = 0.15 \ldots 0.6$ GeV
Dashed curve: $\epsilon' = \frac{\int (y^2 - x^2) u^\mu d\sigma_\mu}{\int (y^2 + x^2) u^\mu d\sigma_\mu}$ (directly from the freezeout geometry)

References

[1] S.A. Bass et al., *Prog. Part. Nucl. Phys.* **41** 255-369, 1998
[2] Iu. Karpenko, P. Huovinen, M. Bleicher, arXiv:1312.4160
[3] J. Steinheimer, S. Schramm and H. Stocker, *J. Phys. G* **38** 35001, 2011
[4] P. Huovinen and H. Petersen, *Eur.Phys.J.* A **48** 171, 2012
[5] N.S. Amelin et al, Phys.Rev.C74:064901, 2006
[6] H. Petersen et al., Phys.Rev. C78 044901, 2008

Acknowledgements: The authors acknowledge the financial support by the ExtreMe Matter Institute EMMI, Hessian LOEWE initiative, Helmholtz International Center for FAIR, BMBF (contract no. 06FY9092) and Helmholtz Young Investigator Group (grant no. VH-NG-822). Computational resources have been provided by the Center for Scientific Computing (CSC) at the Goethe-University of Frankfurt.