Study of signals of hot and dense nuclear matter in HICs at NICA energies using micro- and macroscopic models

RFBR grant 18-02-40084

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in collaboration with

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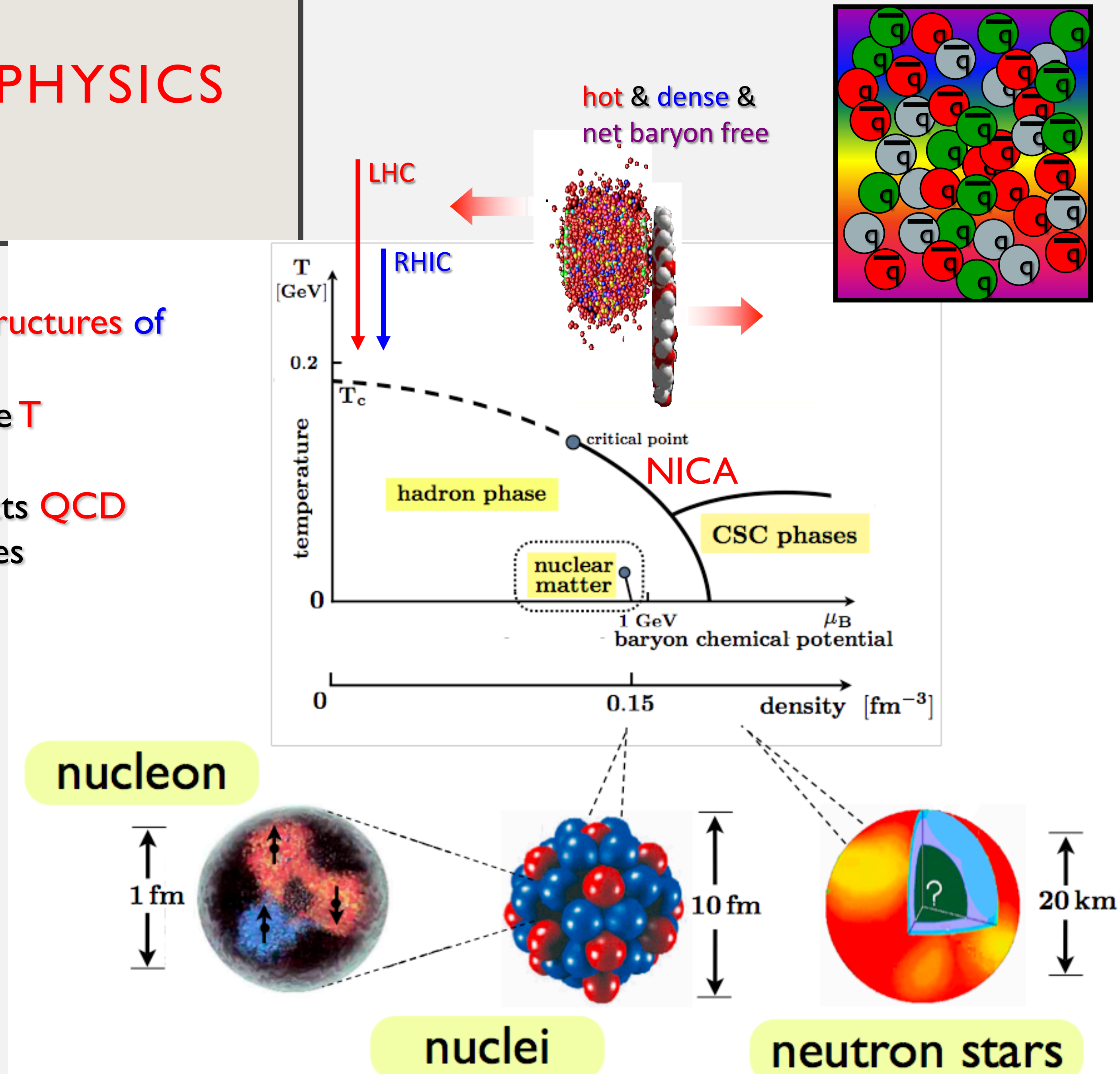
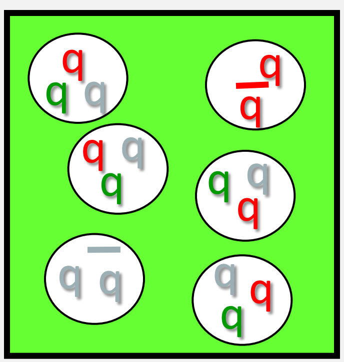
HEAVY ION PHYSICS

Exploring Phases and Structures of QCD phase diagram

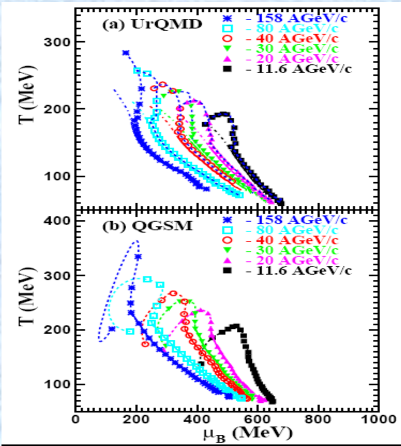
- High temperature T
- High density ε
- Many-body aspects QCD
- Vacuum properties



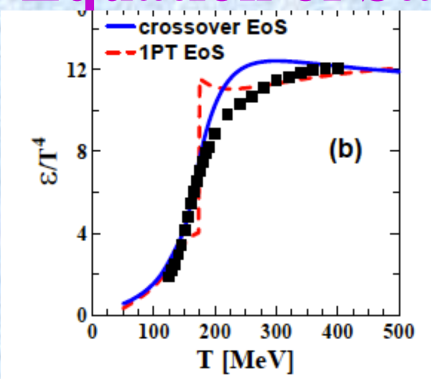


RFBR 18-02-40084
AIMS AND GOALS

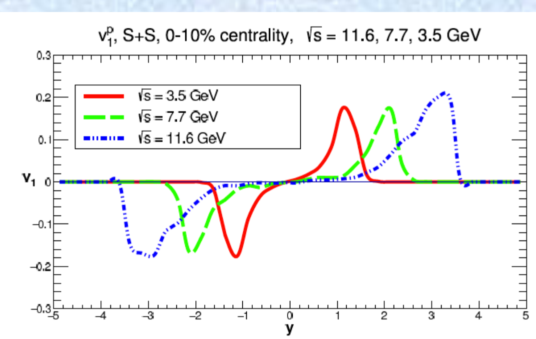
1. Rel. to Equilibrium



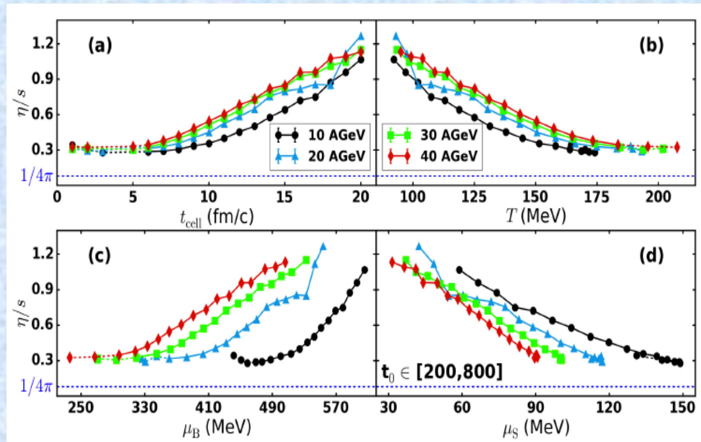
2. Equation of State



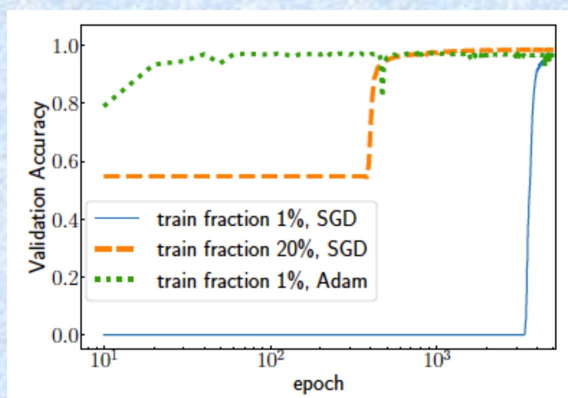
3. Anisotropic flow



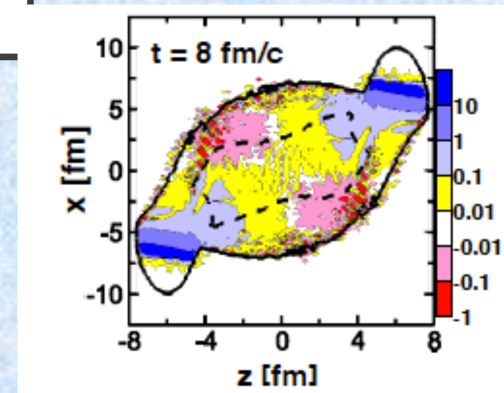
4. Shear viscosity



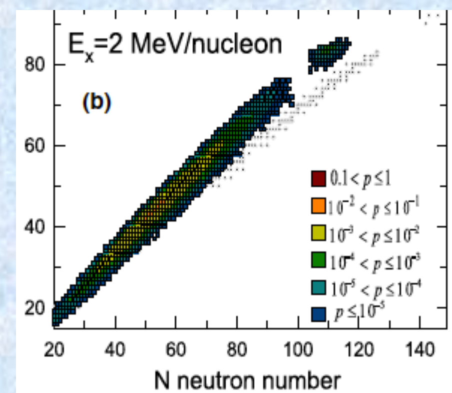
5. Deep Learning



6. Vorticity



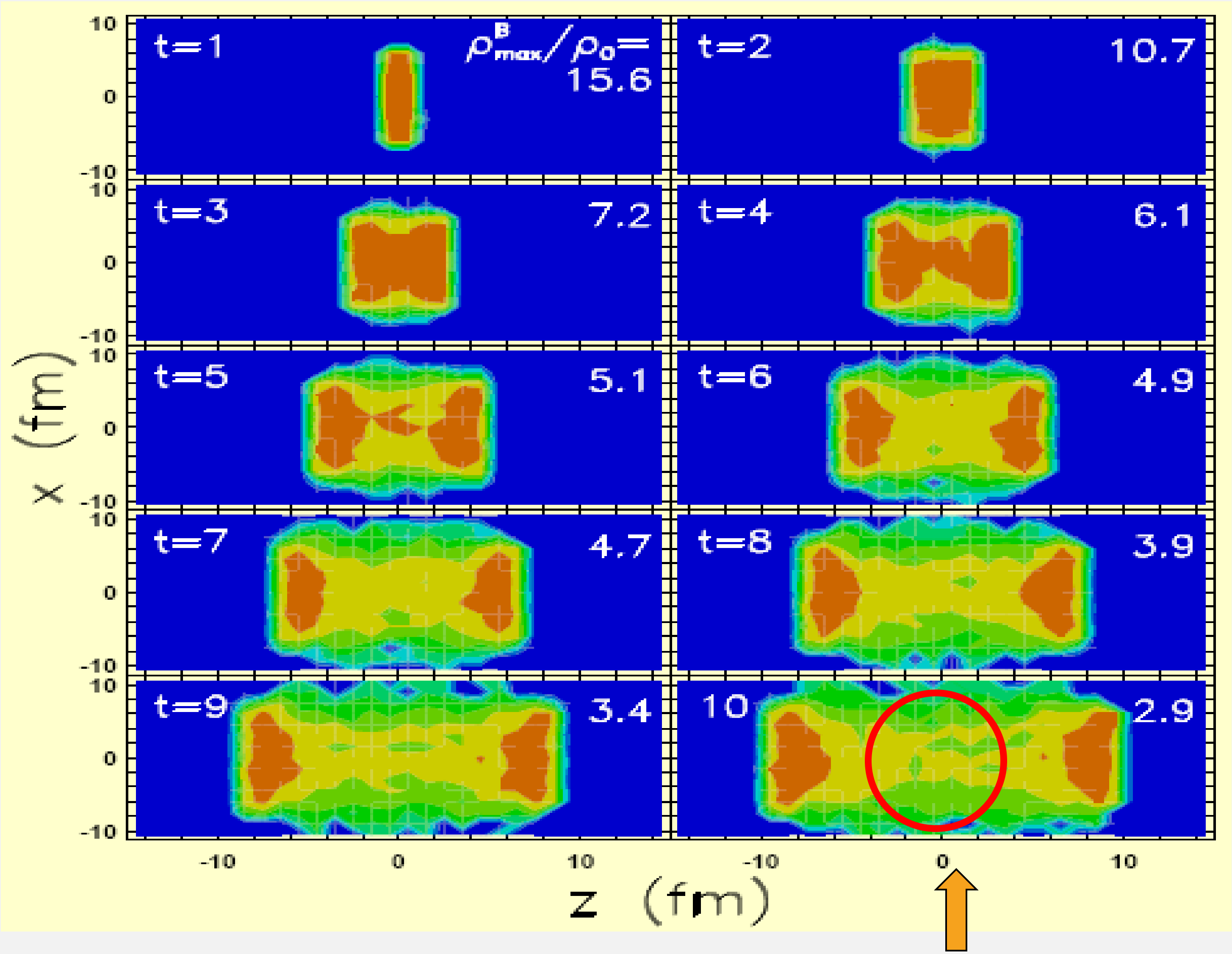
7. Hyperfragments



8. Models: 3FD, UrQMD, DCM, QGSM, SMM

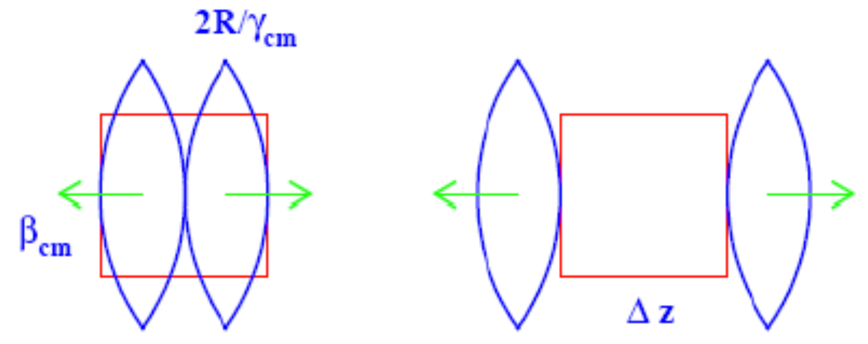
PRE-EQUILIBRIUM: HOMOGENEITY OF BARYON MATTER

L.Bravina et al., PRC 60 (1999) 024904



The local equilibrium in the central zone is quite possible

Equilibration in the Central Cell



$t^{cross} = 2R/(\gamma_{cm}\,\beta_{cm})$

$t^{eq} \geq t^{cross} + \Delta z/(2\beta_{cm})$

Kinetic equilibrium:

Isotropy of velocity distributions

Isotropy of pressure

Thermal equilibrium:

Energy spectra of particles are described by Boltzmann distribution

L.Bravina et al., PLB 434 (1998) 379; JPG 25 (1999) 351

$$\frac{dN_i}{4\pi p E dE} = \frac{V g_i}{(2\pi\hbar)^3} \exp\left(\frac{\mu_i}{T}\right) \exp\left(-\frac{E_i}{T}\right)$$

Chemical equlibrium:

Particle yields are reproduced by SM with the same values of $(T,\ \mu_B,\ \mu_S)$:

$$N_i = \frac{V g_i}{2\pi^2\hbar^3} \int_0^\infty p^2 dp \exp\left(\frac{\mu_i}{T}\right) \exp\left(-\frac{E_i}{T}\right)$$

STATISTICAL MODEL OF IDEAL HADRON GAS

input values → output values

$$\varepsilon^{\rm mic} = \frac{1}{V}\sum_i E_i^{\rm SM}(T,\mu_{\rm B},\mu_{\rm S}),$$

$$\rho_{\rm B}^{\rm mic} = \frac{1}{V}\sum_i B_i \cdot N_i^{\rm SM}(T,\mu_{\rm B},\mu_{\rm S}),$$

$$\rho_{\rm S}^{\rm mic} = \frac{1}{V}\sum_i S_i \cdot N_i^{\rm SM}(T,\mu_{\rm B},\mu_{\rm S}).$$

Multiplicity

$$N_i^{\rm SM} = \frac{V g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 f(p,m_i)dp,$$

Energy

$$E_i^{\rm SM} = \frac{V g_i}{2\pi^2\hbar^3}\int_0^\infty p^2\sqrt{p^2+m_i^2}\, f(p,m_i)dp$$

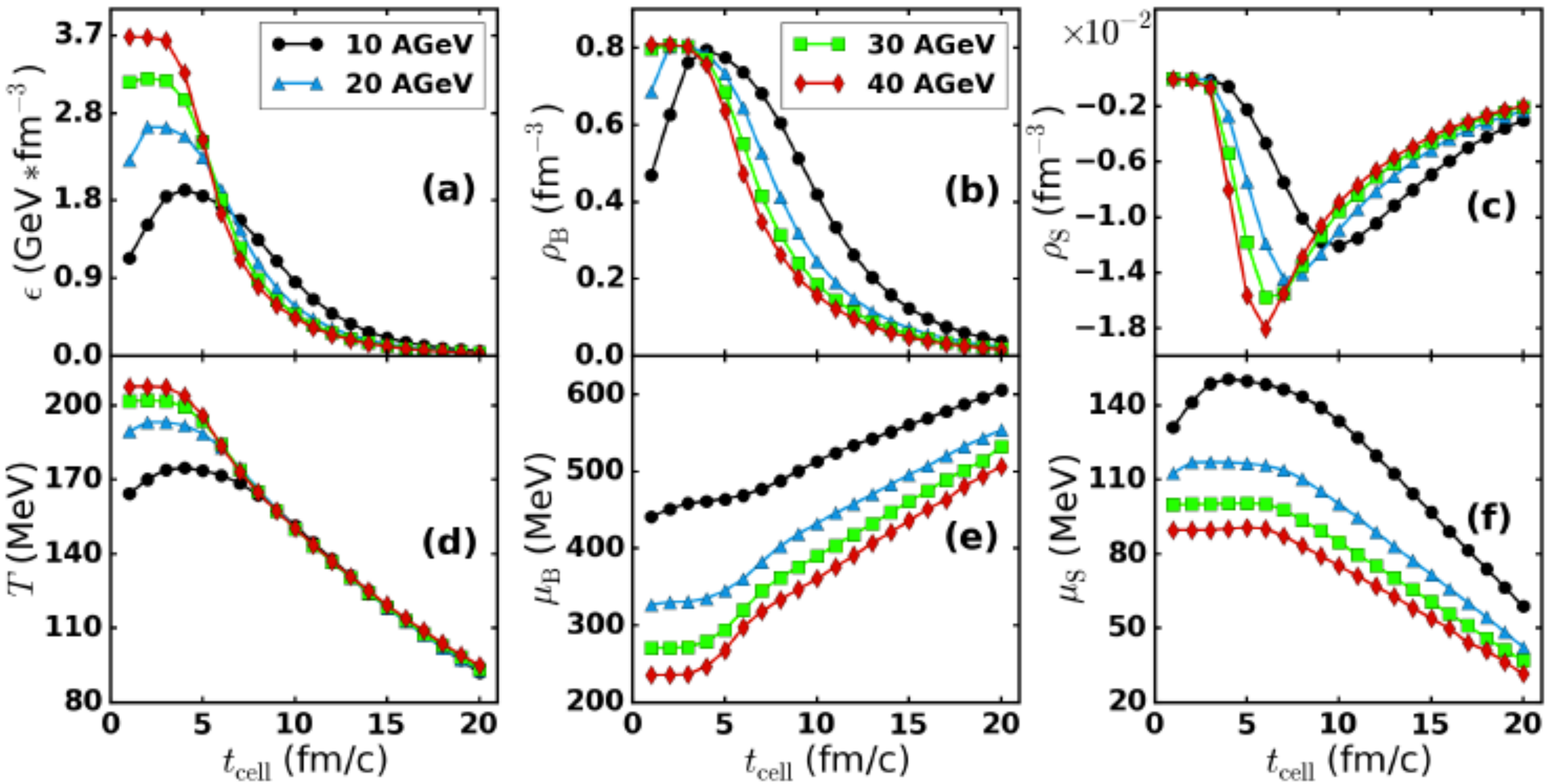
Pressure

$$P^{\rm SM} = \sum_i \frac{g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 \frac{p^2}{3(p^2+m_i^2)^{1/2}}\, f(p,m_i)dp$$

Entropy density

$$s^{\rm SM} = -\sum_i \frac{g_i}{2\pi^2\hbar^3}\int_0^\infty f(p,m_i)\,[\ln f(p,m_i) - 1]\, p^2 dp$$

I. RELAXATION TO EQUILIBRIUM

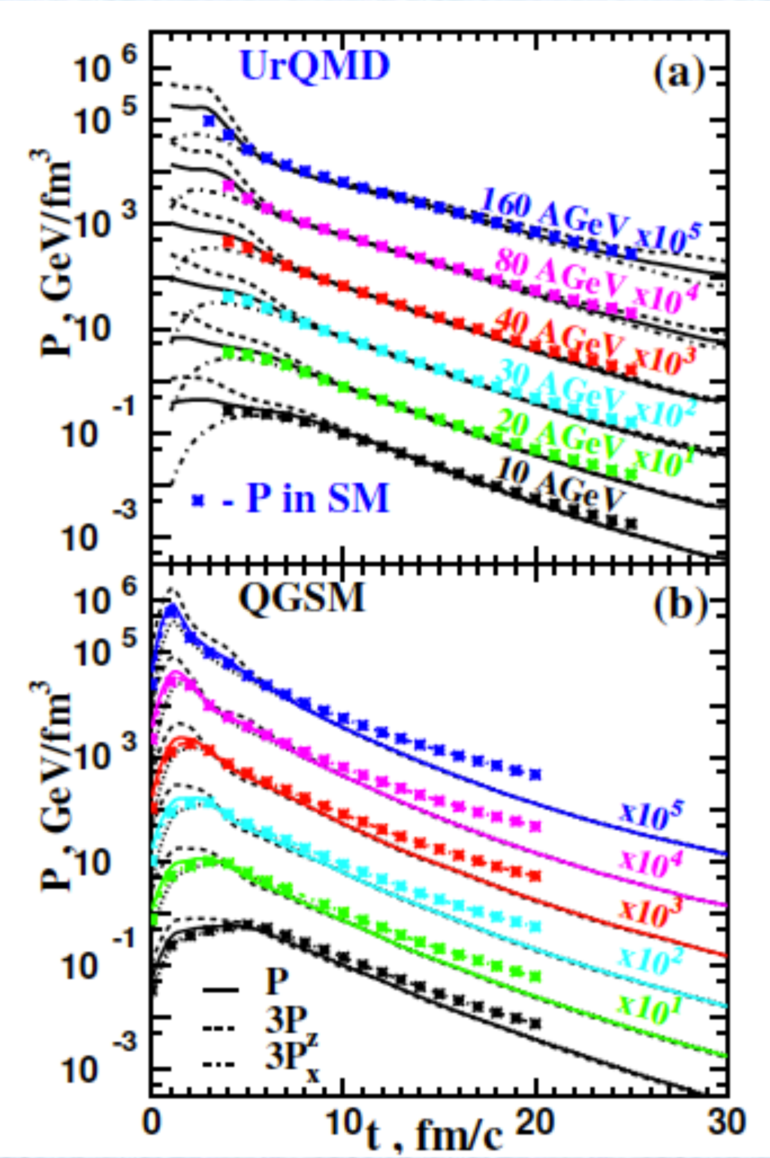


Dependence of $\varepsilon, \rho_{\rm B}, \rho_{\rm S}$ (from cell) and of $T, \mu_{\rm B}, \mu_{\rm S}$ (from SM) on $t_{\rm cell}$

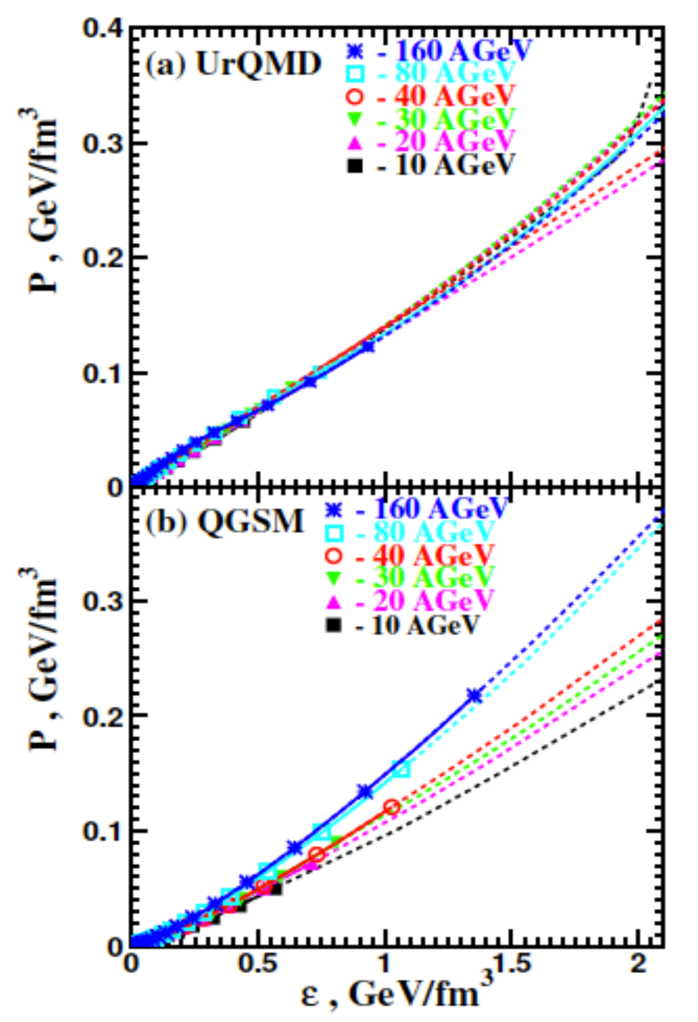
E.Z. et al., arXiv:2002.05181 {nucl-th} (NPA, in press}

I. RELAXATION TO EQUILIBRIUM

Pressure evolution



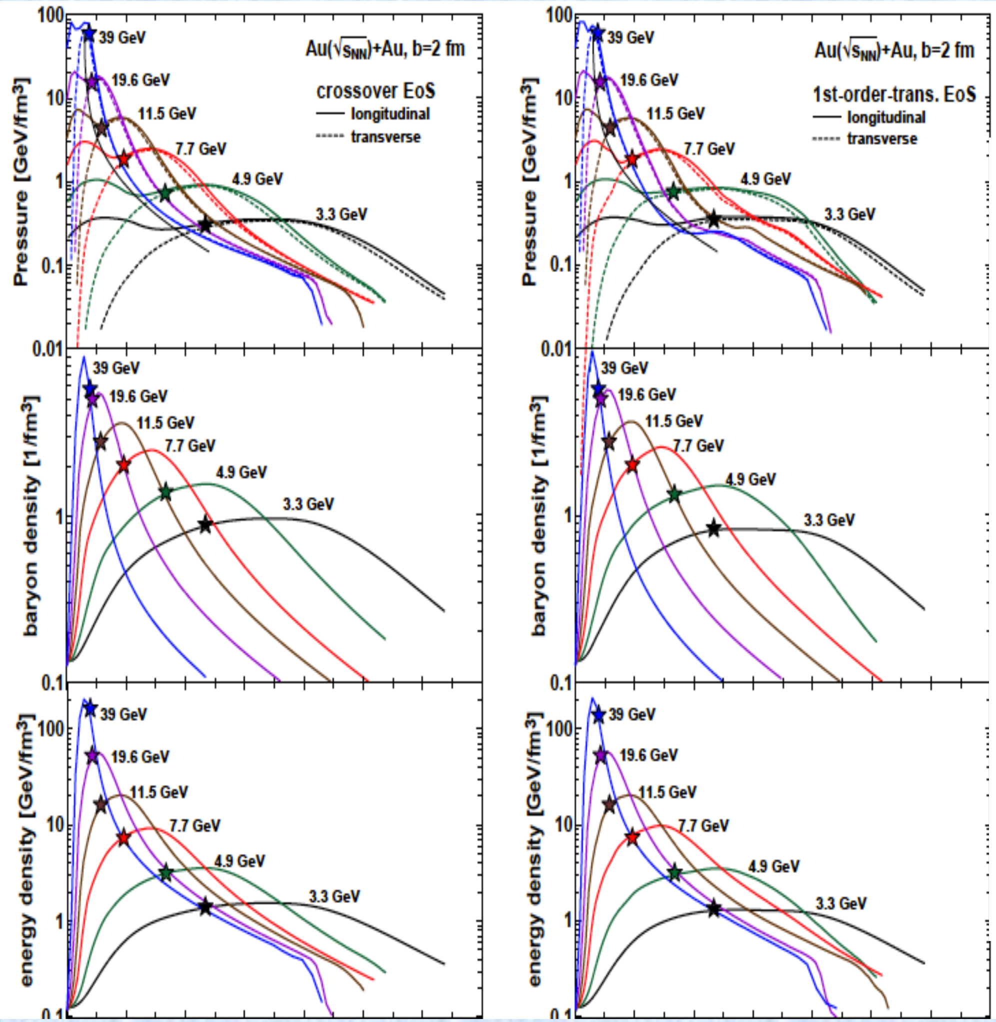
Pressure vs energy density

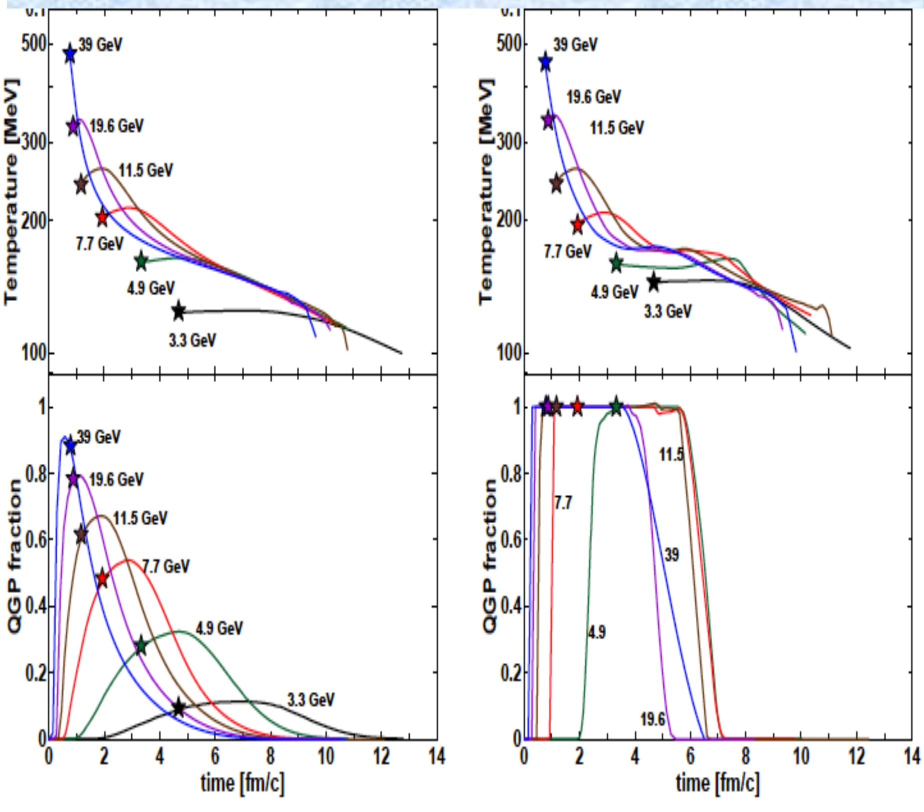


L.Bravina, E.Z., EPJA 56 (2020) 253

2. EQUATION OF STATE

Time evolution of various quantities in central area of Au+Au collisions in 3FD with 2 EOS:
X-over and first-order PT

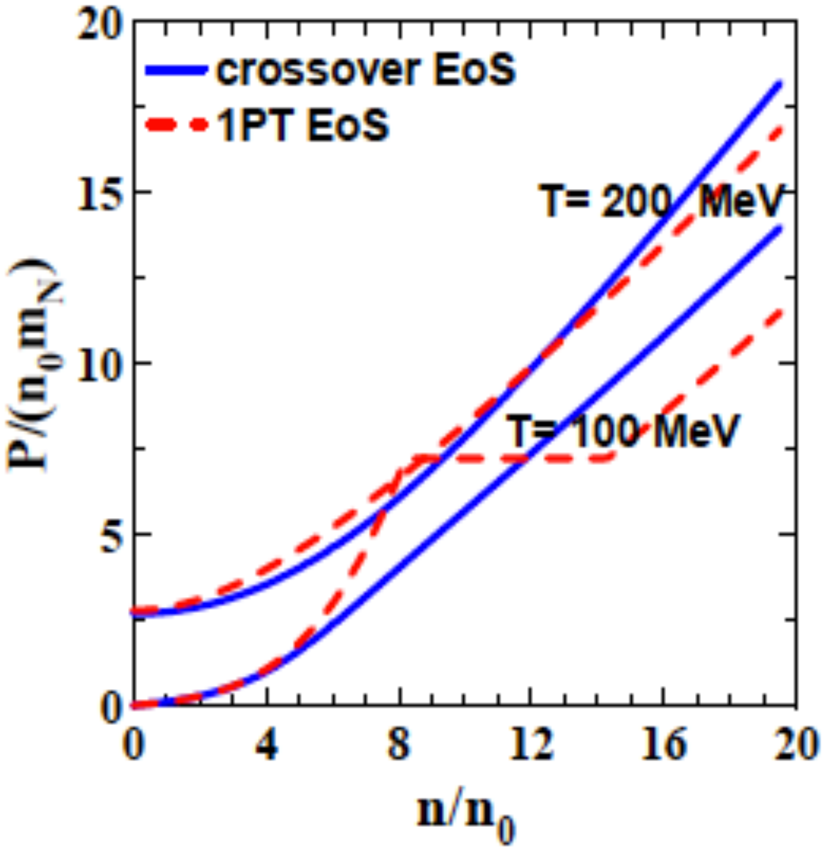




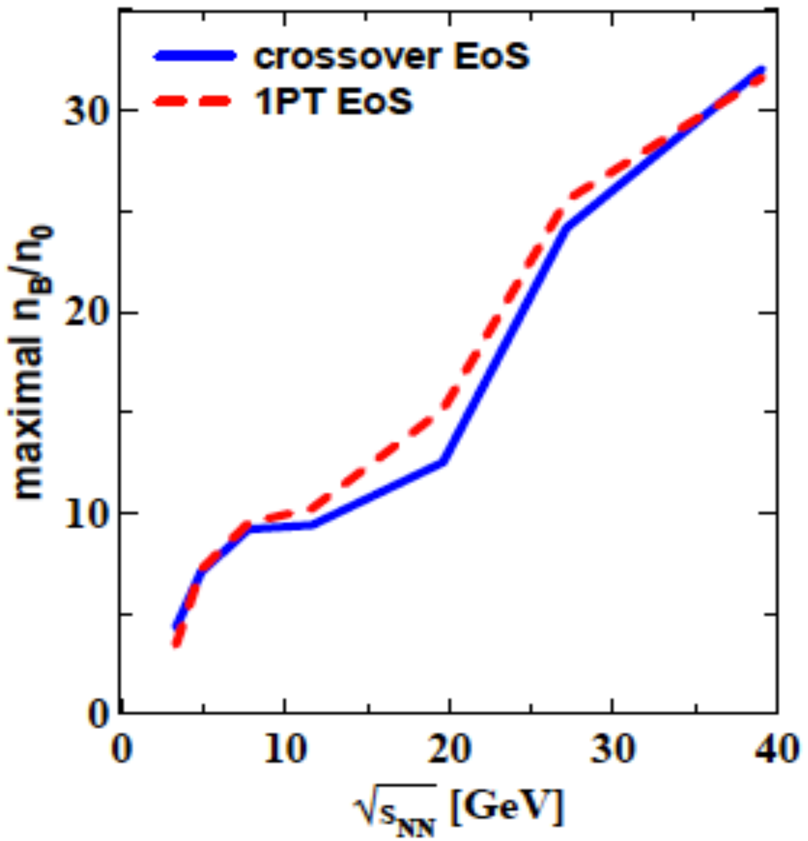
Yu.Ivanov, A.Soldatov, PRC 101 (2020) 024915

2. EQUATION OF STATE

Pressure vs baryon density

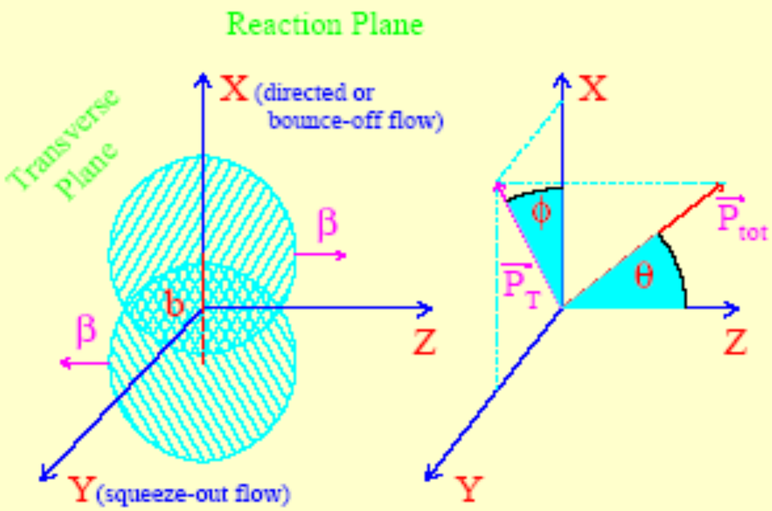


Baryon density vs collision energy



Yu.Ivanov, A.Soldatov, PRC 101 (2020) 024915

3. ANISOTROPIC FLOW IN NON-CENTRAL COLLISIONS



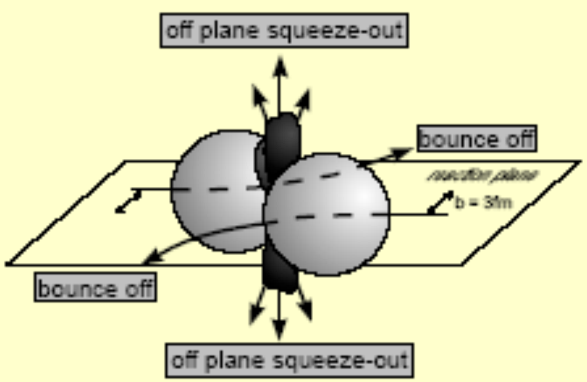
Flow Decomposition:

Transverse flow = Radial + Bounce-off + Squeeze-out

S. Voloshin and Y. Zhang, ZPC 70 (1996) 665

Modern analysis:

Transverse flow =
Radial + Directed + Elliptic + . . .
{isotropic} {anisotropic}



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi')\right)$$

Directed flow:

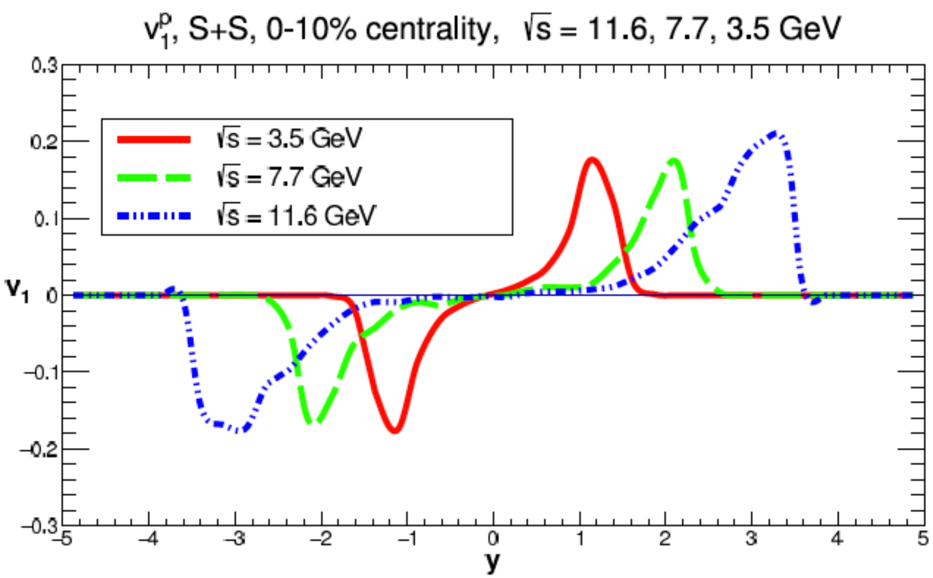
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \equiv \langle \cos(\phi') \rangle$$

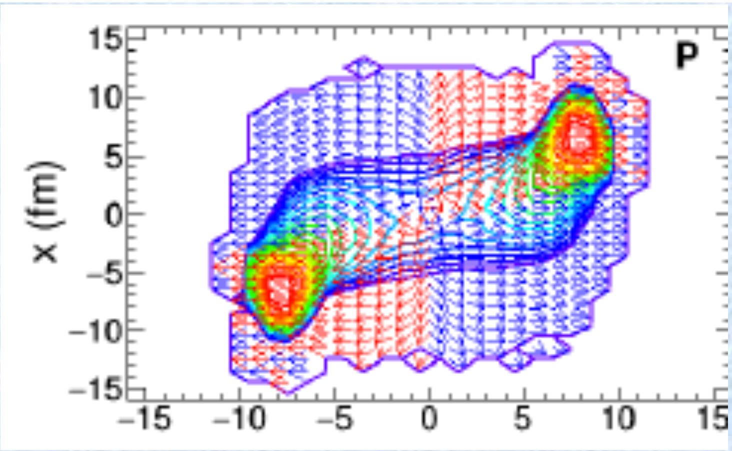
Elliptic flow:

$$v_2 = \left\langle \left(\frac{p_x}{p_T}\right)^2 - \left(\frac{p_y}{p_T}\right)^2 \right\rangle \equiv \langle \cos(2\phi') \rangle$$

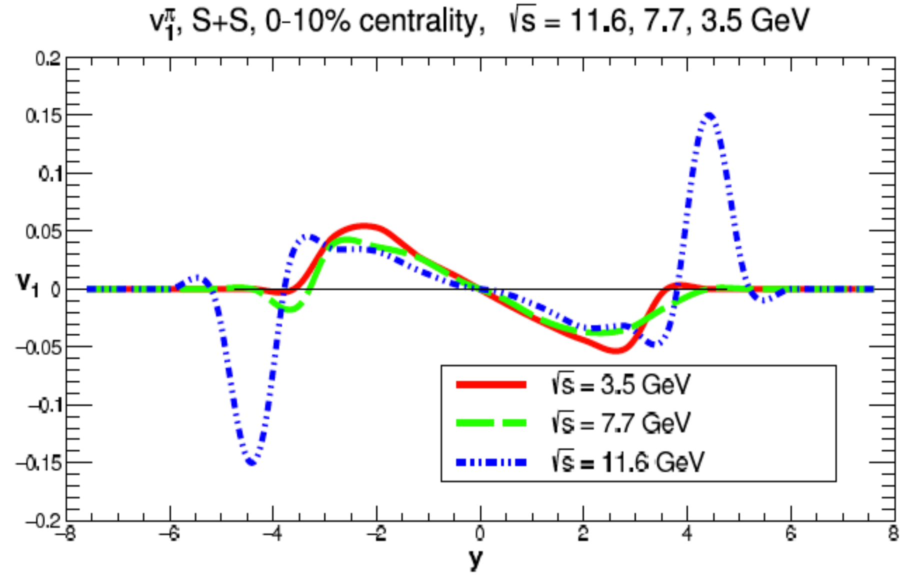
3. ANISOTROPIC FLOW

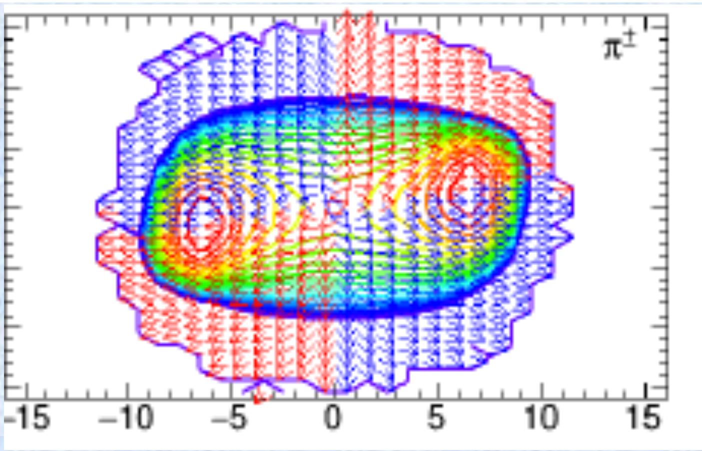
Directed flow of protons





Directed flow of charged pions



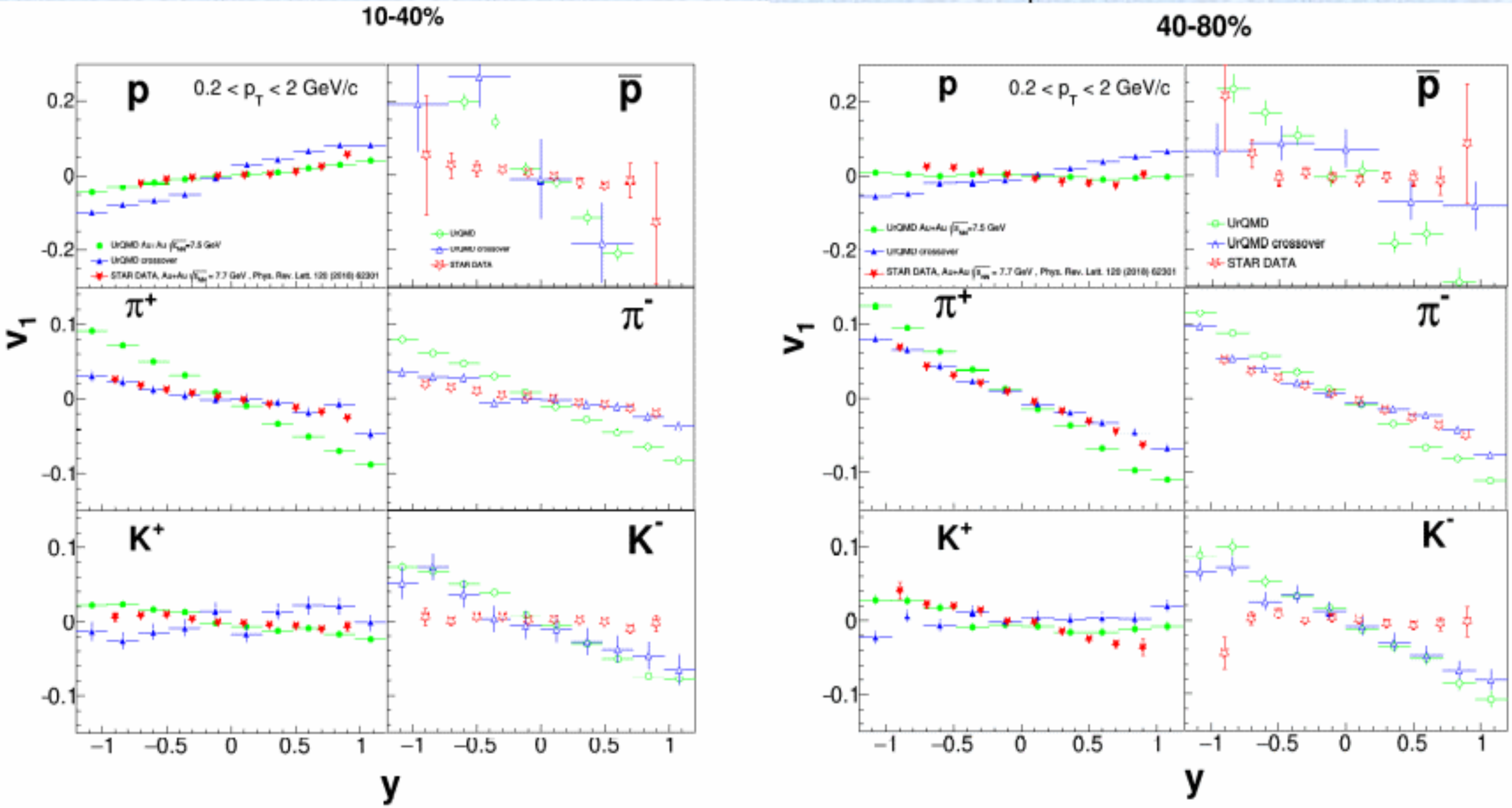


L.Bravina et al., Universe 5 (2019) 69

3. ANISOTROPIC FLOW

UrQMD simulation, collective flow

Mid-central AuAu collisions | Peripheral AuAu collisions



UrQMD hybrid mode with crossover describes STAR data for pions, while UrQMD in hadronic cascade mode describes protons and K^+

G.Eyyubova et al., work in progress

4. SHEAR VISCOSITY

Green-Kubo: shear viscosity η may be defined as:

$$\eta(t_0) = \frac{1}{\hbar}\frac{V}{T}\int_{t_0}^{\infty} \mathrm{d}t \langle \pi(t)\pi(t_0)\rangle_t = \frac{\tau}{\hbar}\frac{V}{T}\langle \pi(t_0)\pi(t_0)\rangle,$$

where

$$\langle \pi(t)\pi(t_0)\rangle_t = \frac{1}{3}\sum_{\substack{i,j=1\\ i\neq j}}^{3} \lim_{t_{\max}\to\infty} \frac{1}{t_{\max}-t_0}\int_{t_0}^{t_{\max}} \mathrm{d}t' \pi^{ij}(t+t')\pi^{ij}(t')$$

$$= \langle \pi(t_0)\pi(t_0)\rangle \exp\left(-\frac{t-t_0}{\tau}\right)$$

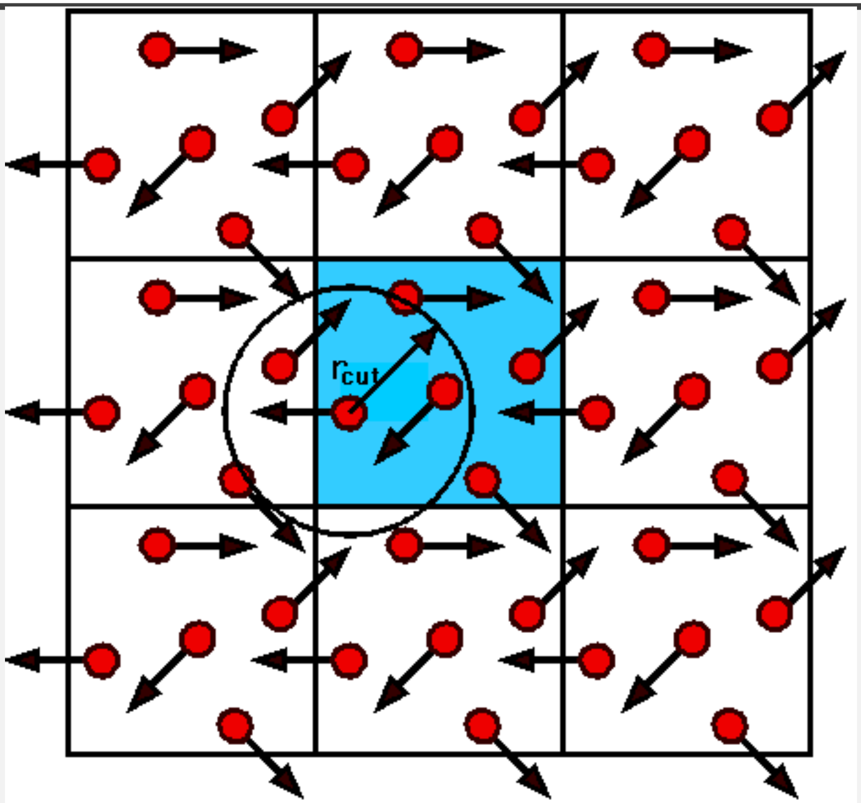
with

$$\pi^{ij}(t) = \frac{1}{V}\sum_{\text{particles}} \frac{p^i(t)\,p^j(t)}{E(t)}$$

t_0: initial cut-off time to start with

M.Teslyk, E.Z. et al., PRC 101 (2020) 014904

BOX WITH PERIODIC BOUNDARY CONDITIONS



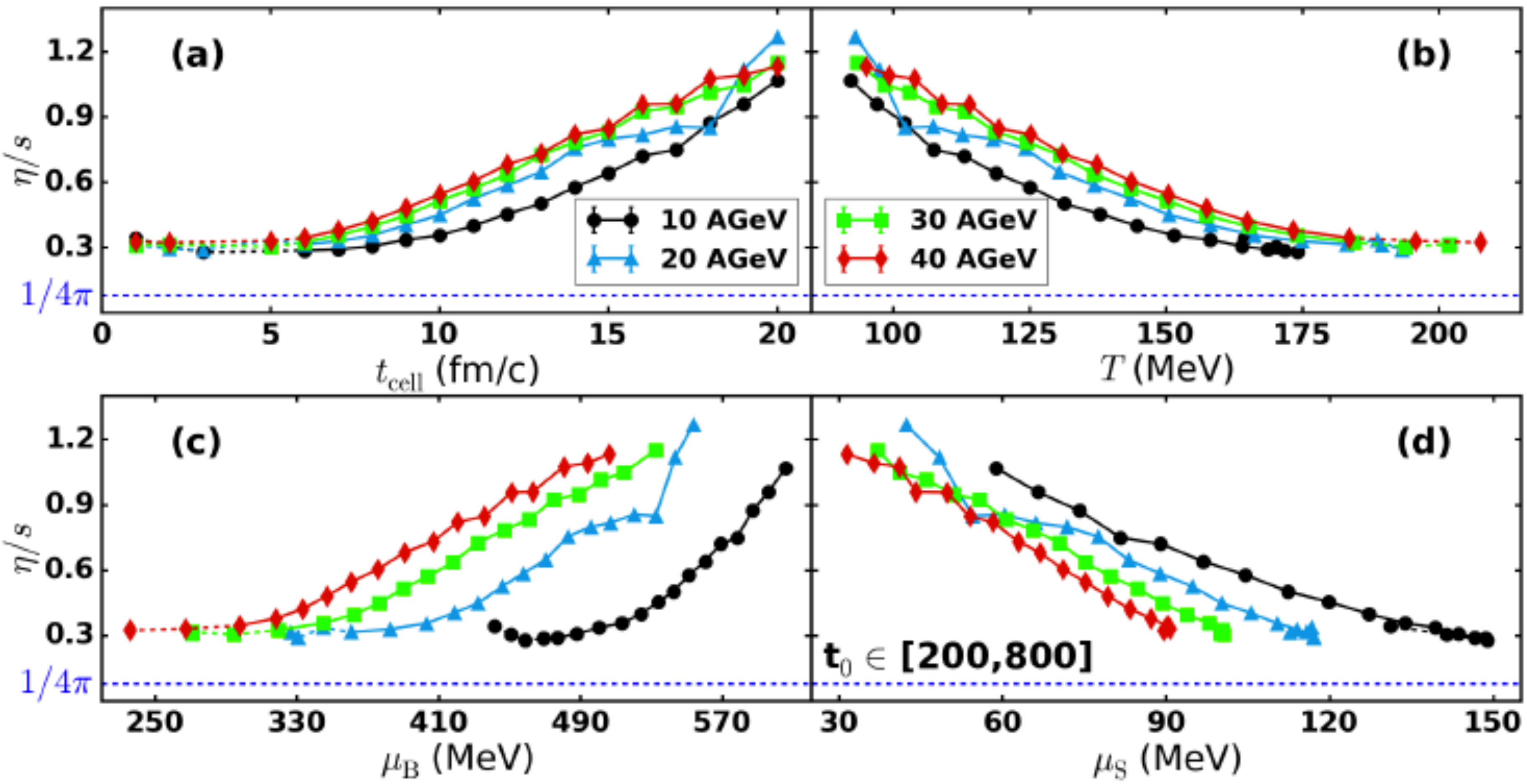
M.Belkacem et al., PRC 58, 1727 (1998)

Initialization: (i) nucleons are uniformly distributed in a configuration space; (ii) Their momenta are uniformly distributed in a sphere with random radius and then rescaled to the desired energy density.

Model employed: UrQMD
55 different baryon species (N, Δ, hyperons and their resonances with $m \leq$ 2.25 GeV/c^2)
32 different meson species (including resonances with $m \leq$ 2 GeV/c^2) and their respective antistates.
For higher mass excitations a string mechanism is invoked.

Test for equilibrium: particle yields and energy spectra

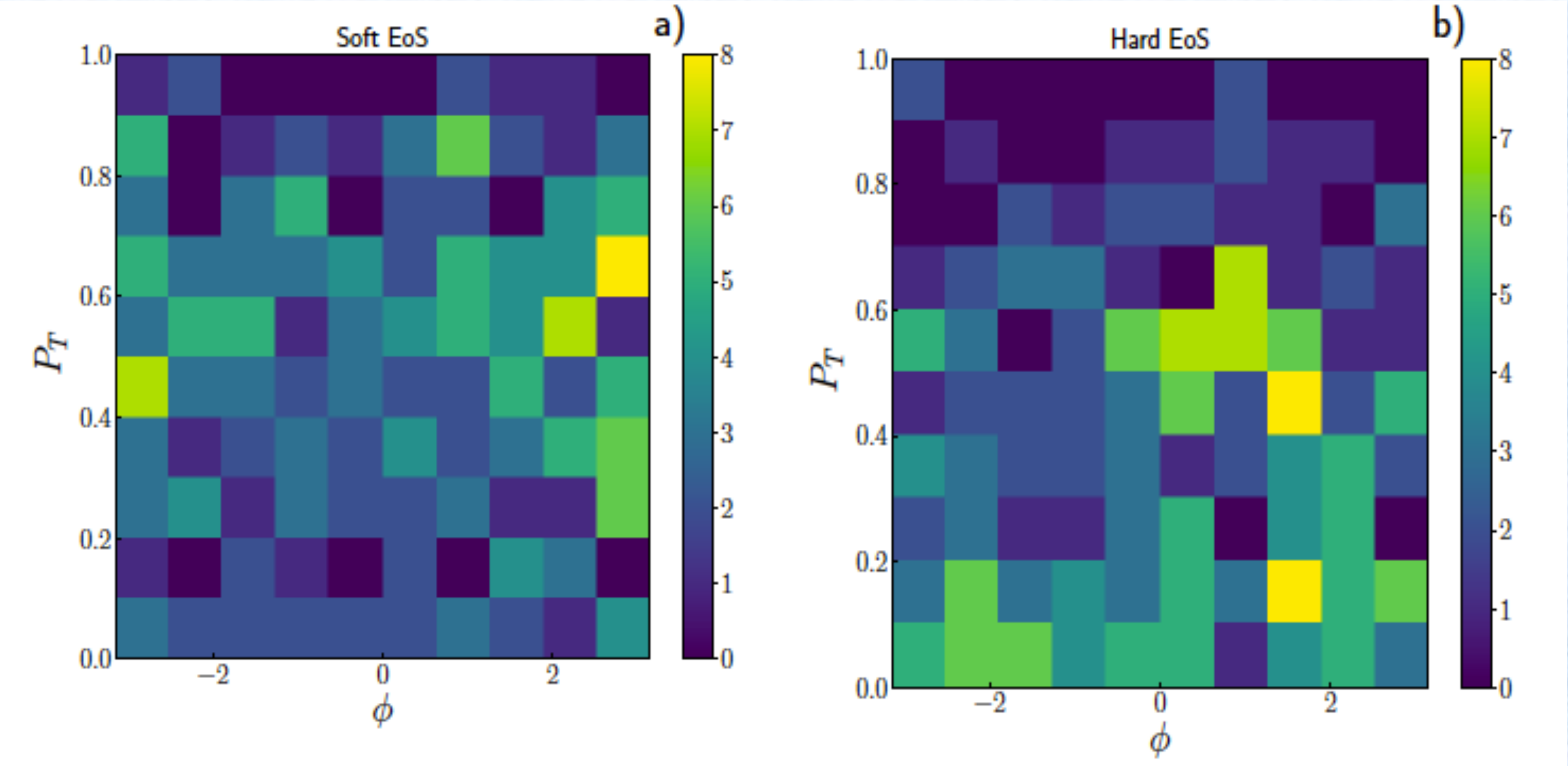
4. SHEAR VISCOSITY



Dynamics of η/s_{SM} in cell
as function of time, T, $\mu_{\rm B}$, $\mu_{\rm S}$

M.Teslyk, E.Z. et al., PRC 101 (2020) 014904

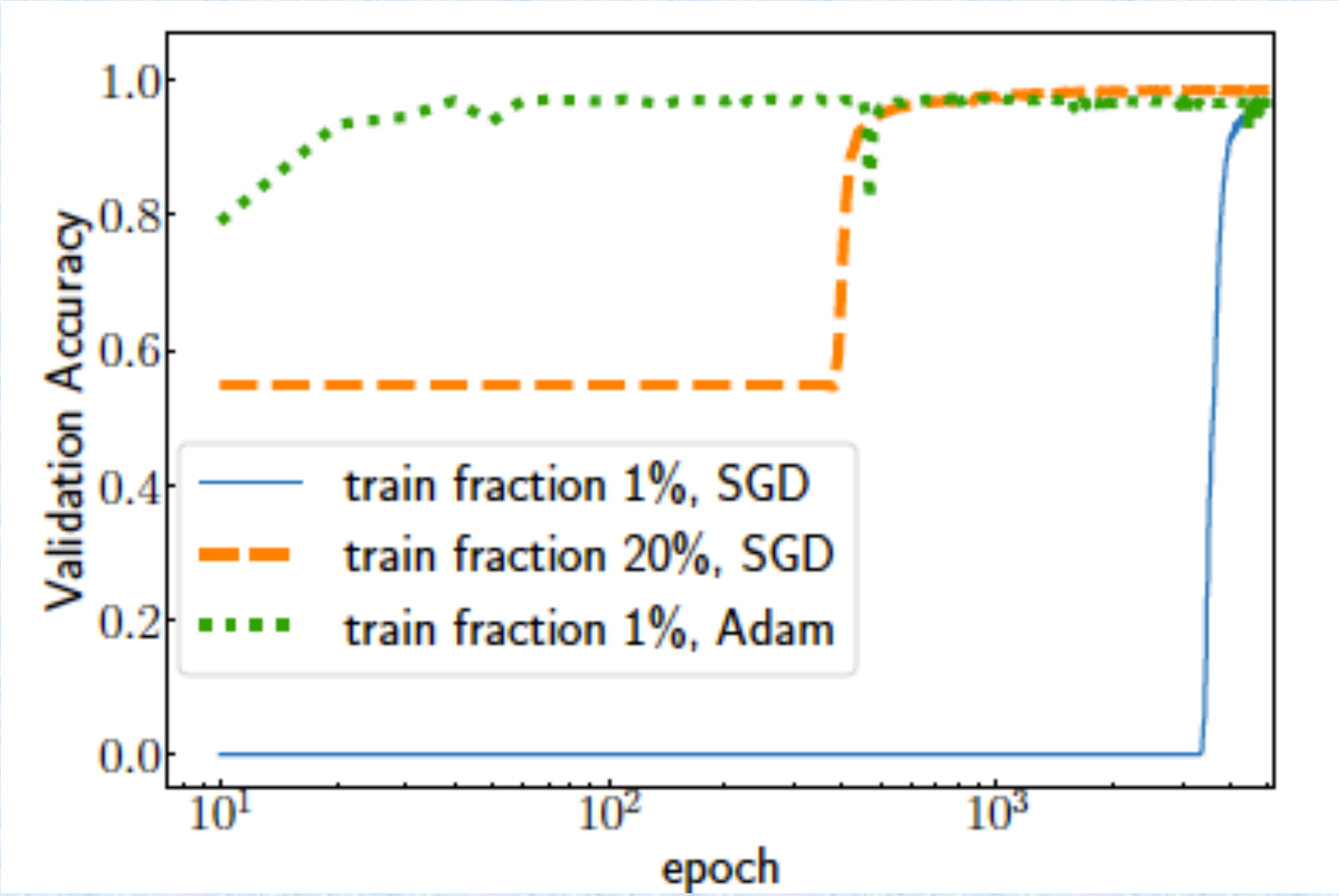
5. DEEP LEARNING



Proton densities for (a) soft and (b) hard potentials from a single UrQMD generated Au+Au collision at 11 GeV

Yu.Kvasiuk, E.Z. et al., JHEP 7 (2020) 133

5. DEEP LEARNING

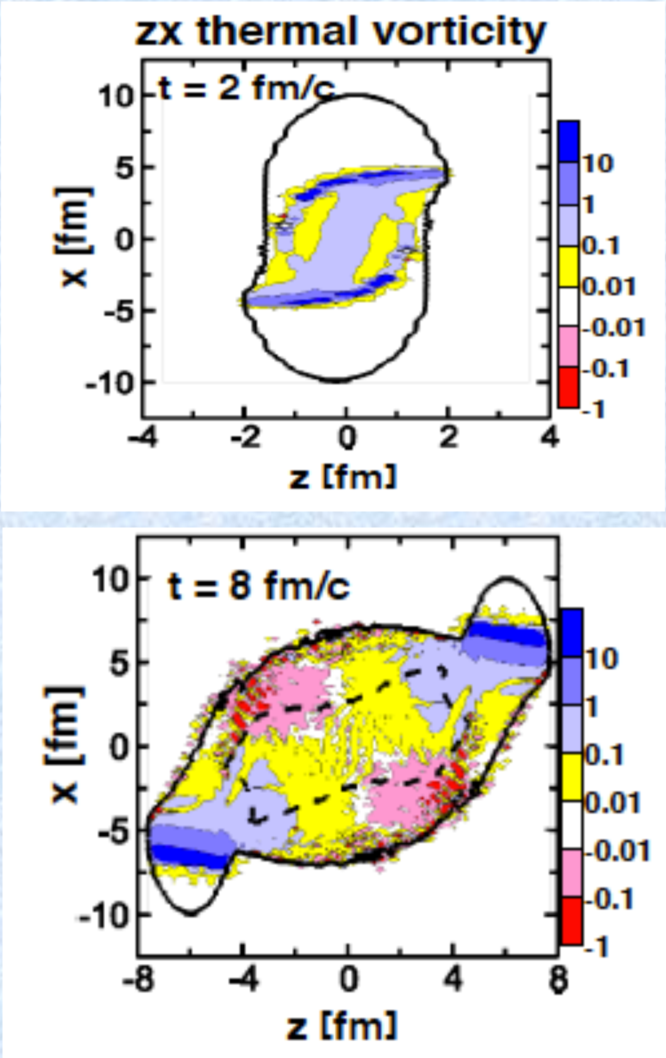


Validation accuracy during 5000 epochs of training for different training data fractions and optimisers in UrQMD generated Au+Au central collisions at 11 GeV

Yu.Kvasiuk, E.Z. et al., JHEP 7 (2020) 133

6. VORTICITY AND HYPERON POLARIZATION

(see talk by Yu. Ivanov)



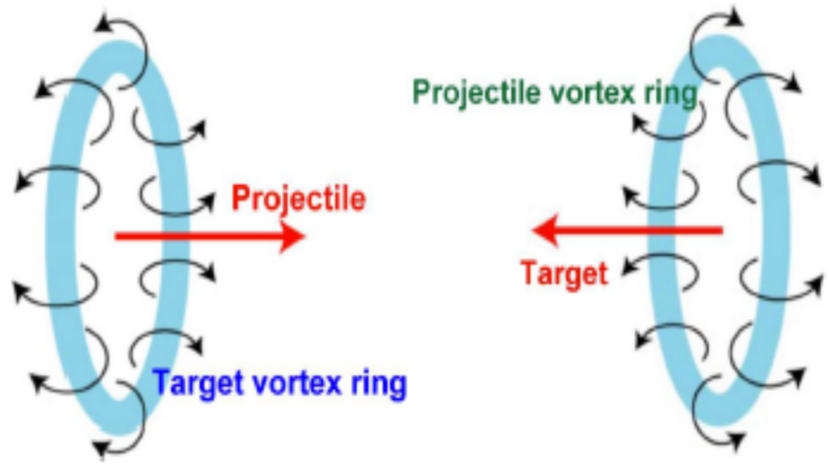


FIG. 4: Schematic picture of the vortex rings in the fragmentation regions. Curled arrows indicate direction of the circulation of the target matter.

Yu. Ivanov, V. Toneev, A. Soldatov, PRC 100 (2019) 014908

7. DCM-QGSM-SMM AND HYPERFRAGMENTS

(see talk by G. Musulmanbekov)

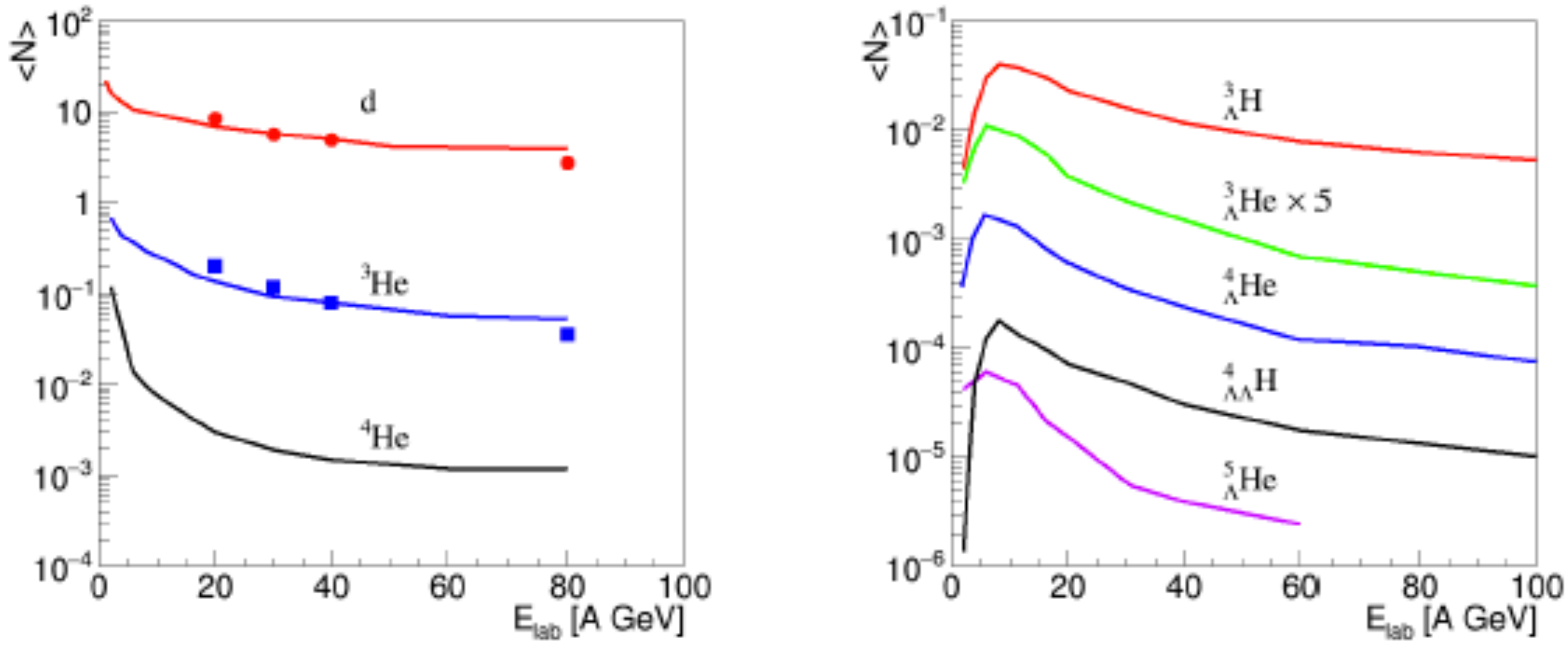


Fig. 1. Mean multiplicities of light fragments and hyperfragments formed due to the coalescence mechanism at the AGS and NA49 energy range compared with NA49 data [16] on deuteron and ^{3}He.

M. Baznat, A. Botvina, G. Musulmanbekov et al., PEPAN Letters 17 (2020) 303

MAIN PUBLICATIONS AND TALKS:

- L. Bravina et al., Universe 5, 69 (2019).
- L. Bravina et al., PoS 347, 171 (2019).
- L. Bravina and E. Zabrodin, Eur. Phys. J. A 56, 253 (2020).
- E. Zabrodin et al., 2002.05181 [nucl-th] (Nucl. Phys. A, in press).
- M. Teslyk et al., Phys. Rev. C 101, 014904 (2020).
- E. Zabrodin et al., Phys. Scripta 95, 7, 074009 (2020).
- Yu.B. Ivanov and A.A. Soldatov, Phys. Rev. C101, 024915 (2020).
- Yu. Kvasiuk, E. Zabrodin et al., JHEP 07, 133 (2020).
- Yu.B. Ivanov, V. D. Toneev, and A.A. Soldatov, Phys. Rev. C 100, 014908 (2019).
- Yu.B. Ivanov, V. D. Toneev, and A.A. Soldatov, preprint 1910.01332 [hep-ph].
- M. Baznat, A. Botvina, G. Musulmanbekov et al., PEPAN Letters, 17, 303 (2020).
- Research results were reported at domestic and international conferences, including Quark Matter 2019, Strangeness in Quark Matter 2019, ICNFP 2019 and 2020, QFTHEP 2019, 26th Nordic Particle Physics Meeting-2020, ICPPA 2020, NUCLEUS-2020, as well as many conferences and meetings at JINR.