Directed, elliptic, and triangular flow of free protons and deuterons in Au+Au collisions at HADES energy $E_{lab} = 1.23$ A GeV

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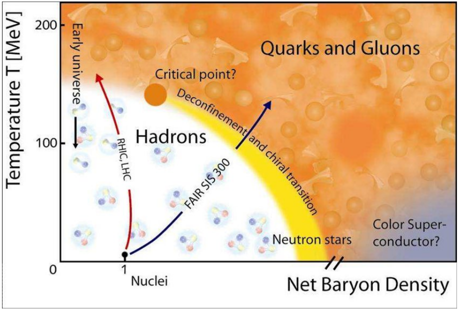
Motivation



- At low energy Au+Au collisions baryon density is 3-4 times higher than the ground state density can be reached. One expects to find exotic particles or maybe even super conducting matter and a phase transition to the Quark Gluon Plasma.

picture: https://www.researchgate.net/figure/A-possible-sketch-of-the-QCD-phase-diagram_ fig3_
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Motivation

- The dynamics of this dense matter are sensitive to the initial density and potential interactions and therefore the nuclear equation of state (EoS).
- Being sensitive to initial pressure gradients the collective flow is a promising variable to study the EoS.
- The HADES experiment performed Au+Au collisions at $E_{lab} = 1.23$ A GeV with a huge amount of data and is able to measure even higher order flow components.
- At these low energies and dense matter phase cluster formation plays an important role to the happening physics and also the collective flow.

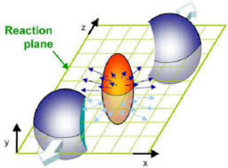
Collective Flow

- Collective flow as Fourier-series of momentum distribution:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_\mathrm{RP})]\right) \quad (1)$$

- Calculation of the flow components as average over events in a given centrality class ($\Psi_\mathrm{RP} = 0$):

$$v_n(p_\mathrm{T}, y) = \langle\cos[n\varphi]\rangle \quad (2)$$



picture: Heinz, Ulrich W. J.Phys. A42 (2009) 214003

Outline for section 2

The UrQMD model

- UrQMD is based on a geometrical interpretation of the nuclear cross section σ and therefore includes string and resonance dynamics, scattering and strangeness exchange.
- It simulates the space-time evolution of each particle including x meson and y baryon species.
- Reaction criterion for the relative distance of two particles d:

$$d < \sqrt{\frac{\sigma}{\pi}} \tag{3}$$

S. A. Bass et al. Prog. Part. Nucl. Phys. 41 (1998) 225-370, M.Bleicher et al. J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859-1896

The equation of state in UrQMD

- To describe the dynamics of particles at low energies and high densities, potential interactions have to be taken into account.
- For the simualtions we used a hard non-momentum dependent Skyrme-type equation of state with the following potentials.

1. The electromagnetic Coulomb potential V_C^{ij} with Z being the charge number of the particles, e the elementary charge and $\left|\mathbf{r_i} - \mathbf{r_j}\right|$ their relative distance:

$$V_C^{ij} = \frac{Z_i Z_j e^2}{\left|\mathbf{r_i} - \mathbf{r_j}\right|} \tag{4}$$

2. The strong force Yukawa potential V_Y^{ij} with $V_0^Y = -0.498$ MeV and $\gamma_Y = 1.4$ fm:

$$V_Y^{ij} = V_0^Y \cdot \frac{\exp\left(\left|\mathbf{r_i} - \mathbf{r_j}\right| / \gamma_Y\right)}{\left|\mathbf{r_i} - \mathbf{r_j}\right|} \tag{5}$$

The equation of state in UrQMD

3. The hadronic Skyrme potential V_{Sk} to change the stiffness of the EoS with ρ_{int} the baryon density ρ_0 being the ground state baryon density:

$$V_{Sk} = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma} \tag{6}$$

Parameters	hard EoS
α [MeV]	-124
β [MeV]	71
γ	2.00

Table: Parameters used in the UrQMD Skyrme potential

P.Hillmann et al., J.Phys. G45 (2018) no.8, 085101 (2018-06-25)

Deuteron formation via coalescence

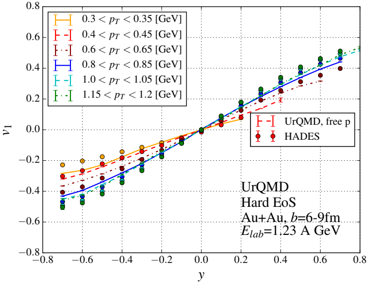
- Deuterons are formed via phase-space coalescence.
- protons and neutrons are boosted into their two-particle resframe.
- If the relative distance $\Delta r \leq 3.575$ fm and the relative momentum $\Delta p \leq 0.285$ GeV a deuteron is formed with the probability of 3/8 (spin-isospin coupling).

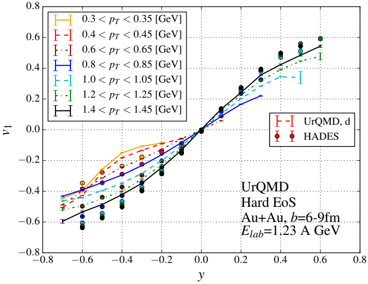
S.Sombun et al., Phys.Rev. C99 (2019) no.1, 014901 (2019-01-10)

Outline for section 3

Directed flow

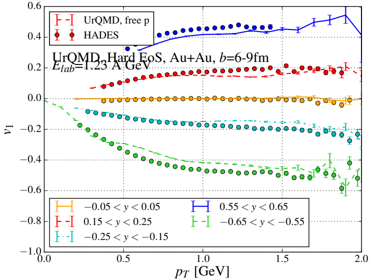
HADES Data:B. Kardan et al., PoS CPOD2017 (2018) 049 and Nucl.Phys. A982 (2019) 431-434

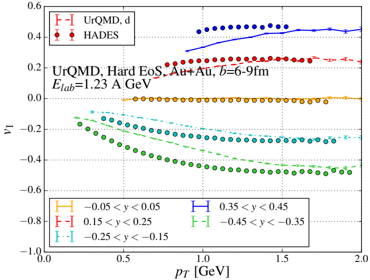




- Strong dependence on rapidity.
- d flow slope is more positive.
- Good agreement with experimental data.

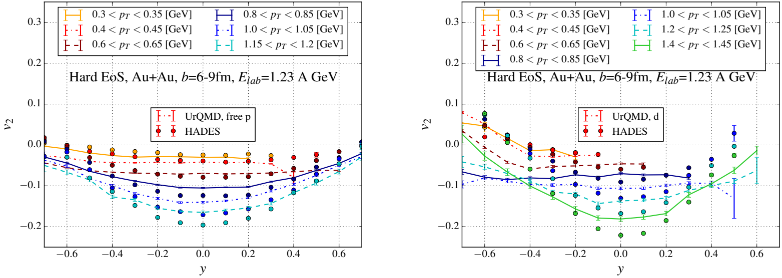
Directed flow





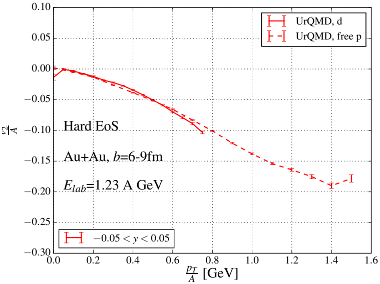
- Strong transverse momentum dependence.
- More positive flow for deuterons due to higher momentum of deuterons.
- Good agreement with experimental data.

Elliptic flow



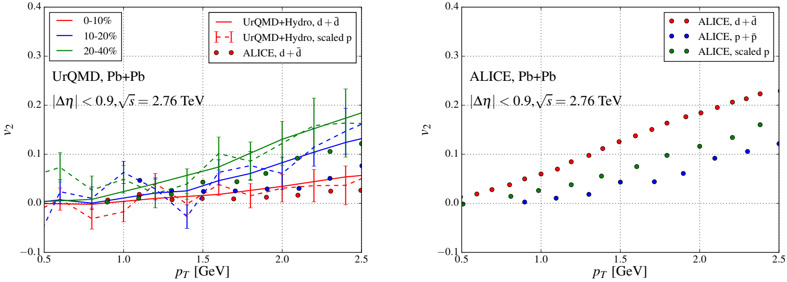
- Strong rapidity dependence.
- More positive flow of d due to higher momentum.
- Good agreement with experimental data.

Elliptic flow



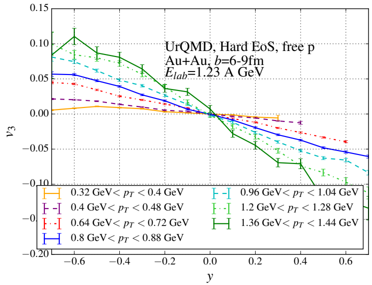
- Strong transverse momentum dependence.
- Mass number scaling observable.

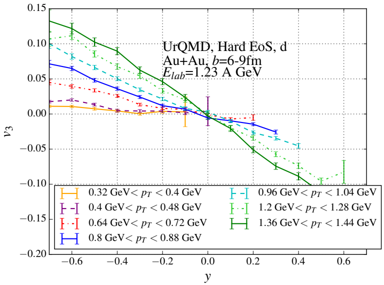
The case of high energies



- Scaling of deuteron and proton flow as function of transverse momentum is observable for UrQMD.
- ALICE data (s. Achaya, Eur.Phys.J. C77 (2017) no.10, 658) does not scale.
- Different flow expansion times.

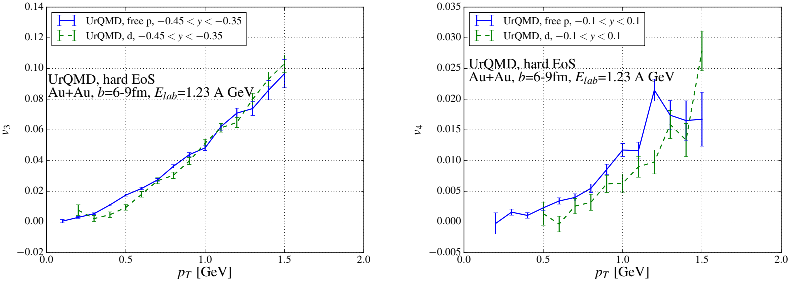
Triangular flow





- Strong rapidity dependence.
- Flow of protons and deuterons behave similar.

Triangular flow



- Strong transverse momentum dependence.
- Non-zero higher order flow components with respect to reaction plane for p and d indicate interplay of initial and expansion stage of the system.

Outline for section 4

Summary and Outlook

- UrQMD including a hard equation of state was used to measure the collective flow of protons and deuterons in Au+Au collisions at 1.23 A GeV.
- The calculations agree with the data of the HADES experiment for both protons and deuterons.
- The v_3 and $v_4 \neq 0$ with respect to the reaction-plane indicates an interplay of initial stage and expansion stage of the fireball.
- Cluster forming nucleons have a large effect to the collective proton flow which also results in a direct mass number scaling of $v_2(p_T)$ for the simulation. This scaling is not given for LHC data.