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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STARS and SMFNS, Cuba, 7th May 2019

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Outline for section 1

Motivation

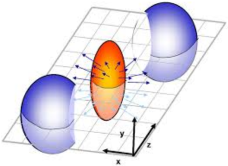
- At low energy Au+Au collisions baryon density is 3-4 times higher than the ground state density can be reached. One expects to find exotic particles or maybe even super conducting matter and a phase transition to the Quark Gluon Plasma.
- The dynamics are sensitive to the initial density and potential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

- Collective flow as Fourier-series of momentum distribution:

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

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

$$v_n(p_T, y) = \langle \cos[n\varphi] \rangle \quad (2)$$



Outline for section 2

The equation of state in UrQMD

- UrQMD is based on a geometrical interpretation of the nuclear cross section and therefore includes string and resonance dynamics, scattering and strangeness exchange[1,2].
- To create a hard EoS, potential interactions have to be taken into account[3].

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:

$$V_C^{ij} = \frac{Z_i Z_j e^2}{\left|\mathbf{r_i} - \mathbf{r_j}\right|} \quad (3)$$

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

$$V_Y^{ij} = V_0^Y \cdot \frac{\exp\left(\left|\mathbf{r_i} - \mathbf{r_j}\right| / \gamma_Y\right)}{\left|\mathbf{r_i} - \mathbf{r_j}\right|} \quad (4)$$

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:

$$V_{Sk} = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma} \quad (5)$$

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

Table: Parameters used in the UrQMD Skyrme potential

[1] S. A. Bass et al., Prog. Part. Nucl. Phys.41,225(1998) , [2] M. Bleicher et al., J. Phys., G25:1859âĂŞ1896, 1999 , [3] P.Hillmann et al., J.Phys G45 (2018)

Deuteron formation via coalescence

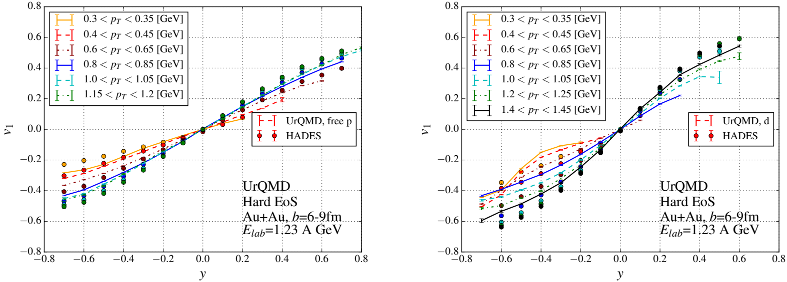
- Deuterons are formed via phase-space coalescence.
- protons and neutrons are boosted into their two-particle restframe.
- If the relative distance $\Delta r \leq 3.575$ fm and the relative momentum $\Delta p \leq 0.285$ GeV a deuteron is formed with the probability of 3/8 (spin-isospin coupling)[4].

[4] S. Sombun et al., Phys. Rev. 99 (2019)

Outline for section 3

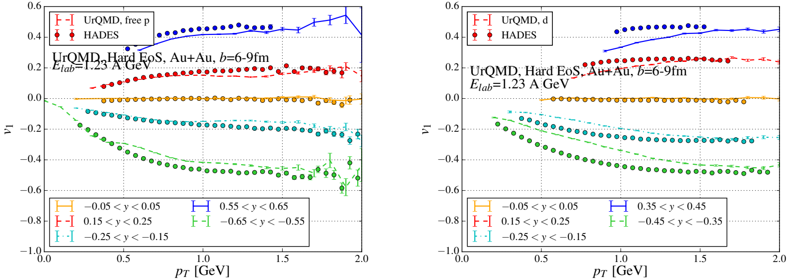
1. Introduction
   - Motivation
   - Collective Flow
2. The equation of state and coalescence in UrQMD
   - The equation of state
   - Deuteron formation via coalescence
3. Results
   - Directed flow
   - Elliptic flow
   - Higher order flow components
4. Summary

Directed flow



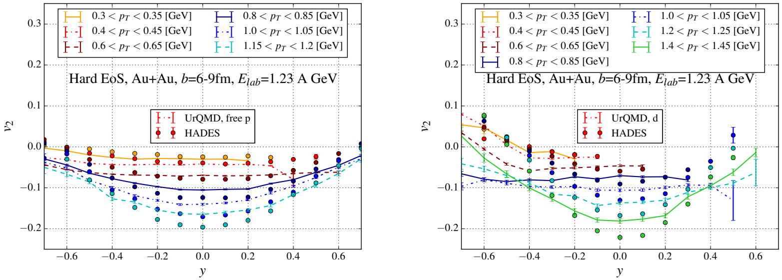
- Strong dependence on rapidity.
- d flow slope is more positive.
  data: Kardan et al., PoS CPOD 2017 (2018) 49

Directed flow



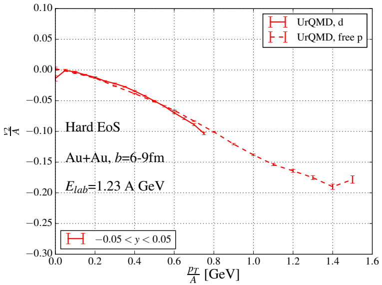
- Strong transverse momentum dependence.
- More positive flow for deuterons due to higher p_x values.

Elliptic flow



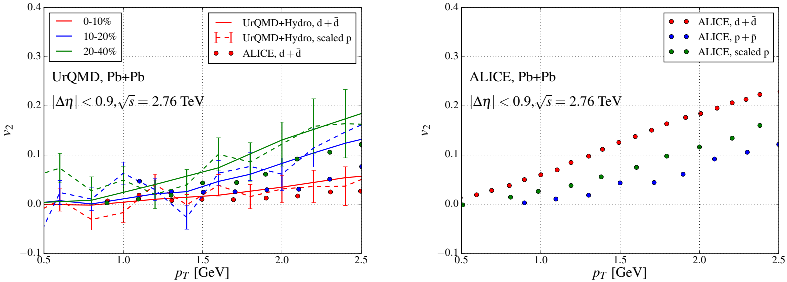
- Strong rapidity dependence.
- More positive flow of d due to higher momentum.

Elliptic flow



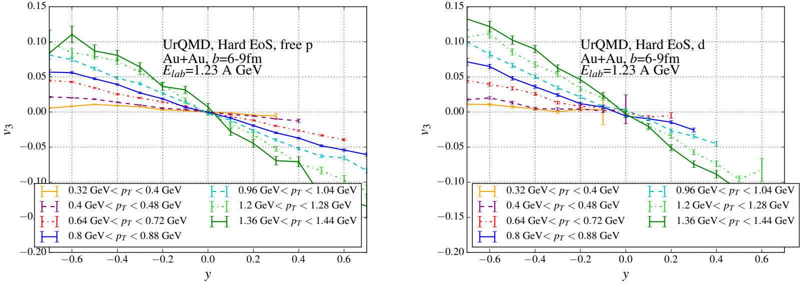
- Strong transverse momentum dependence.
- Mass number scaling observable

The case of high energies



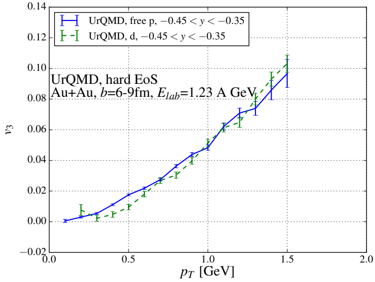
- Scaling of deuteron and proton flow as function of transverse momentum is observable for UrQMD.
- ALICE data does not scale.
- Different flow expansion times. data: ALICE collab., Nucl. Phys. A 956, 2016

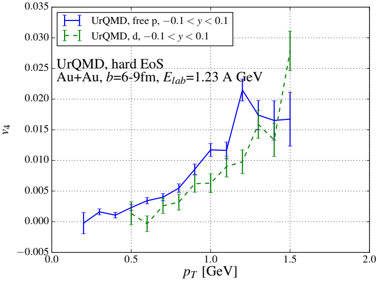
Triangular flow



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

Triangular flow and v_4





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

Outline for section 4

Summary

- 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.
- Non-vanishing higher-order flow components with respect to the reaction plane indicate an interplay of initial and expansion stage of the system.
- For the UrQMD simulations the flow of protons and deuterons scale with mass number, for the data this is not given anymore at LHC energies.