Directed, elliptic, and triangular flow of protons in Au+Au collisions at HADES energy $E_{lab} = 1.23$ A GeV A theoretical analysis of the recent HADES data

Based on: P. Hillmann *et al.*, J. Phys. G **45**, no. 8, 085101 (2018), doi:10.1088/1361-6471/aac96f, arXiv:1802.01951 [nucl-th].

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Matter under Extreme Conditions in Heavy-Ion Collisions and Astrophysics, Dubna, Russia, 2018

Contents

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.

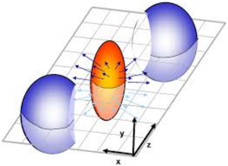
Collective Flow

- 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 ($\Psi_\mathrm{RP} = 0$):

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



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.
- To create two different EoS, potential interactions have to be taken into account.

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:

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

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

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

The equation of state in UrQMD

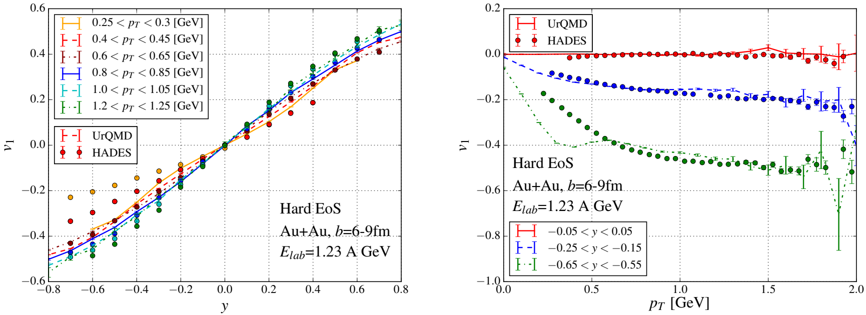
3. The hadronic Skyrme potential V_{Sk} to change the stiffness of the EoS with ρ_{int} the baryon density ρ_0 being the ground state baryon density:

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

Parameters	hard EoS	soft EoS
α [MeV]	-124	-356
β [MeV]	71	303
γ	2.00	1.17

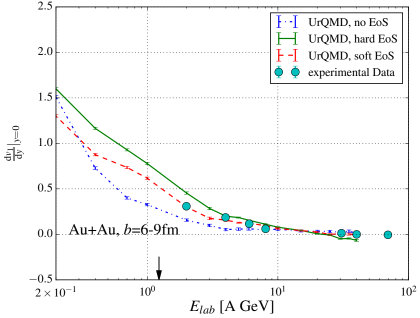
Table: Parameters used in the UrQMD Skyrme potential

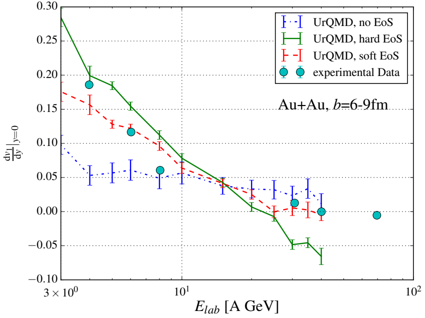
Directed flow



- No strong dependence on transverse momentum.
- Strong dependence on rapidity.
- Deviation at low p_T/higher y values maybe due to a lack of cluster formation.

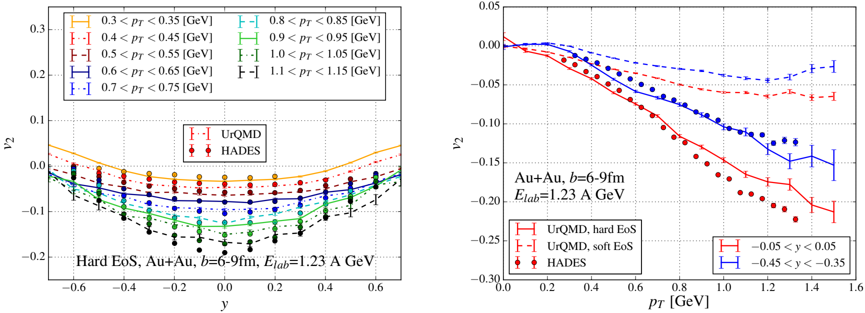
Directed flow





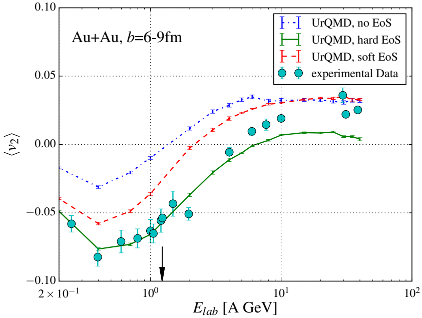
- At low energies hard EoS is preferred and at higher energies soft EoS.

Elliptic flow



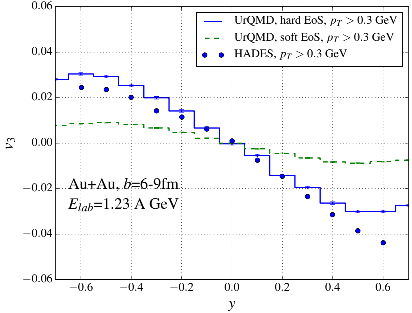
- Strong rapidity dependence.
- Strong transverse momentum dependence, decreasing with growing p_T.

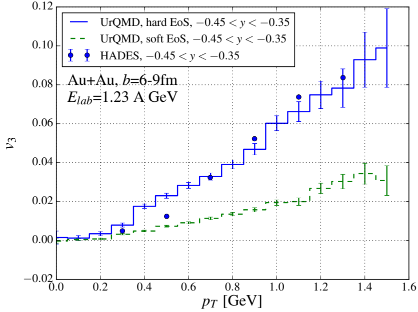
Elliptic flow



- At low energies a hard EoS is preferred, the flow is a consequence of the squeeze-out effect.
- With growing energy in-plane emission becomes more preferable and the flow turns positive. Also here the soft EoS becomes more preferable.

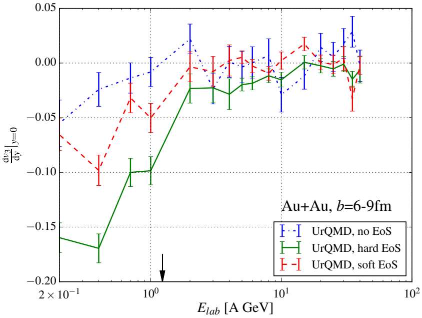
Triangular flow





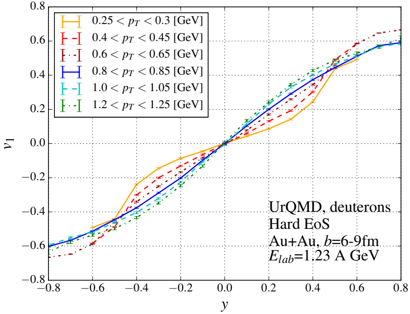
- Soft EoS underestimates the data.
- Measured $v_3 \neq 0$ with respect to the reaction plane makes separation of initial stage and expansion stage impossible at low energies.

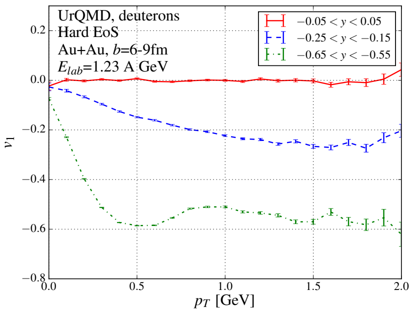
Triangular flow



- Strong EoS dependence is observable.
- At higher energies v_3 vanishes.

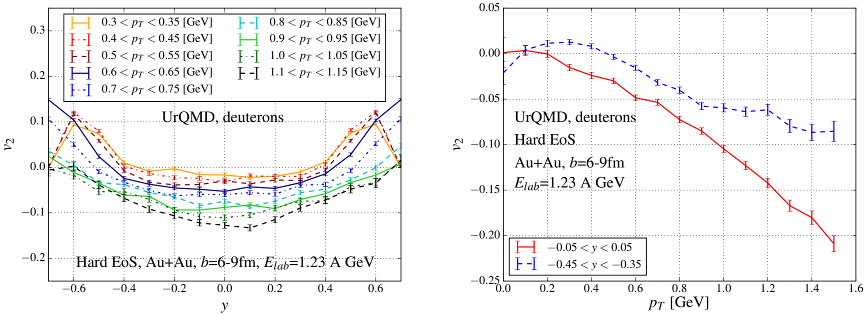
Outlook: Preliminary directed flow of deuterons





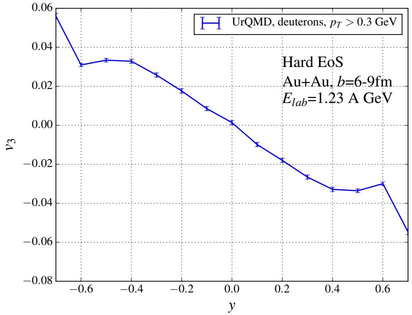
- Stronger dependence on transverse momentum.
- More negative flow as function of p_T.

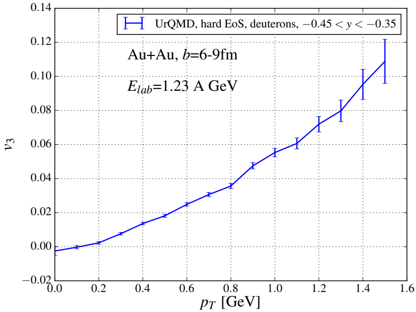
Outlook: Preliminary elliptic flow of deuterons



- More negative elliptic flow as function of p_T due to higher p_y-component.

Outlook: Preliminary triangular flow of deuterons





Summary and Outlook

- UrQMD including two different equations of state was used to measure the collective flow of protons in Au+Au collisions at low and intermediate beam energies.
- The calculations agree with the data of different experiments. For low energies a hard EoS is preferred, for higher energies the soft EoS.
- The $v_3 \neq 0$ with respect to the reaction-plane indicates an interplay of initial stage and expansion stage.
- Cluster forming nucleons have a large effect to the collective proton flow. Therefore deuteron flow is now under investigation. Heavier nucleons will be included in near future.