Scaling properties of collective flow in Au+Au collisions at 1.23 A GeV

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Abstract

One of most important goals in low temperature heavy-ion collisions is to understand the nuclear equation of state. Being strongly dependent on the initial pressure, the collective flow is a very promising observable to study the nuclear equation of state as well as the role of the formation of small nuclear clusters. The UrQMD model including a hard and non-momentum dependent equation of state and deuteron formation via coalescence was used to study the collective flow of protons and deuterons in semi-peripheral Au+Au collisions at $E_{lab} = 1.23$ A GeV and to compare the results with the HADES collaboration. The simulations agree well with the experimental data. A direct mass number scaling of the even flow harmonics is observable as function of transverse momentum.

Introduction

Heavy-ion collisions in accelerators have since now been a very succesful tool to understand the physics of hot and dense matter how it was present in the early universe and is present in compact stellar objects. At high densities and corresponding low temperatures the dynamics of the particles are very sensitive to the nuclear equation of state. Anisotropic flow is very sensitive to the initial pressure gradients and therefore a promising variable to study the equation of state [1, 2, 3]. The collective flow is given as the Fourier-series of the the momentum distribution:

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

So one calculates the v_n as average over all particles in a given event, accepting all events in the fixed centrality class:

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

Here, Ψ_{RP} denotes the reaction plane angle and φ is the azimuthal angle with respect to the reaction plane.

The HADES experiment at GSI in Darmstadt has performed Au+Au collisions at a beam energy of 1.23 A GeV with a huge amount of data and therefore is able to measure higher order flow components [4, 5]. At this energy range, one expects to find a high formation of small nuclear clusters like deuterons allowing to study the scaling properties of their flow with the flow of free protons.

The UrQMD model with coalescence and equation of state

- For the simulation of the collective flow of free protons and deuterons, we applied the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) transport model [7, 8].
- It is based on a geometrical interpretation of the nuclear cross section. If possible, the cross section is taken from experimental data, otherwise theoretical models like the quark model are used.
- The model includes resonance and string dynamics, as well as strangeness exchange and scattering processes.
- At low energies, an equation of state is of utmost importance to understand the dynamics of the interacting particles and the evolution of collective flow. Therefore a hard, non-momentum dependent Skyrme type equation of state is used. The Skyrme-potential is given by [2]:

$$V_{Sk} = \alpha \cdot \left(\frac{\rho_{int}}{\rho_0}\right) + \beta \cdot \left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma}. \quad (3)$$

- By changing the parameters α, β, and γ the stiffness of the EoS is changed. The current set-up is shown in ref. [1].
- Notice that also momentum-dependent equations of state are succesful to describe data at low energies. But we stay with the non-momentum dependent potential which was used to describe the data at HADES energies in previous studies.
- For the deuteron formation, a phase-space coalescence approach is used. For all possible proton and neutron pairs, the relative space and momentum distances of the kinetic freeze-out coordinates are considered in the two-particle rest-frame. If the relative distance $\Delta r < 3.575$ fm and the relative momentum distance $\Delta p < 0.385$ GeV, then a deuteron is formed with the probability of 3/8 (statistical spin-iso-spin coupling factor).

Results

In the following, the results of elliptic and quardrangular flow for free protons and deuterons in Au+Au collisions at 1.23 A GeV is presented. For the calculations only particles with $n_{coll} \neq 0$ are considered and an impact parameter of $b = 6 - 9$ is used (corresponding to 20-30% centrality).

- The calculations are in good agreement with the experimental data. Due to higher p_x the deuteron flow is more positive.
- A strong dependence on rapidity and transverse momentum is observable.
- A direct mass number scaling is observable which is a direct consequence of the coalescence approach.
- The non vanishing v_4 with respect to the reaction-plane indicates an interplay of initial and expansion stage of the system.

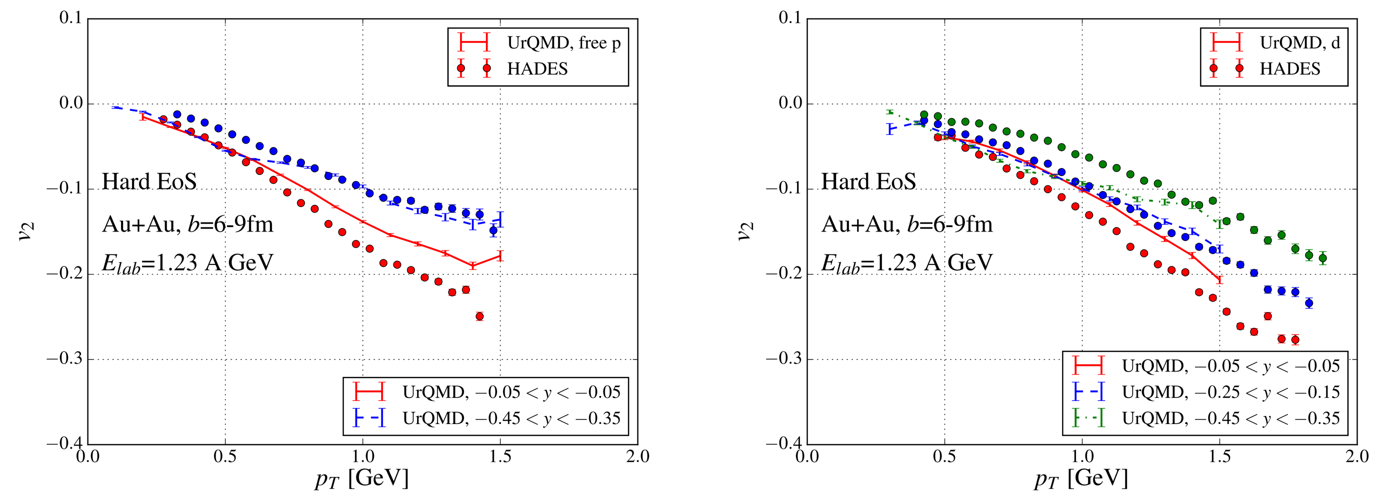

Figure 1: Elliptic flow of protons(left) and deuterons (right) as function of transverse momentum for various rapidity bins in Au+Au collisions at $E_{lab} = 1.23$ A GeV. The lines denote the simulations ($b = 6 - 9$ fm) and the symbols denote the experimental data of the HADES collabroation (20-30% centrality) [4, 5].

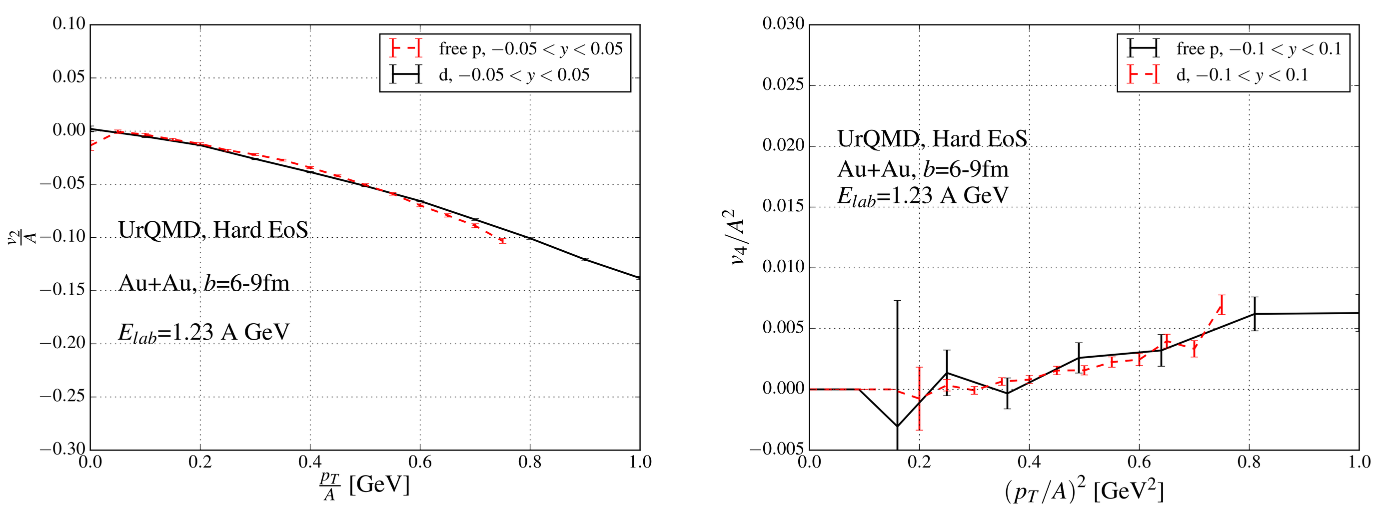

Figure 2: Elliptic flow (left) and quadrangular flow (right) of protons and deuterons as function of transverse momentum scaled by the mass number A in Au+Au collisions at $E_{lab} = 1.23$ A GeV. The lines denote the simulations ($b = 6 - 9$ fm).

Conclusions

- UrQMD including a hard EoS and deuteron formation via coalescence successfully describes the collective flow of deuterons and protons in midperipheral Au+Au collisions at 1.23 A GeV.
- A direct mass number scaling of the even flow harmonics is observable and a strong indicator of coalescence.
- In the future the flow of tritons and helium will be observed and compared to the flow of protons and deuterons.

Acknowledgements

The authors thank Behruz Kardan, Manuel Lorenz, and Christoph Blume for helpful and inspiring discussions. The computational resources were provided by the LOEWE Frankfurt Center for Scientific Computing (LOEWE-CSC) and the FUCHS-CSC. This work was supported by HIC for FAIR and in the framework of COST Action CA15213 THOR and the DAAD-TRF collaboration.

References

[1] P. Hillmann, J. Steinheimer, T. Reichert, V. Gaebel, M. Bleicher, S. Sombun, C. Herold and A. Limphirat, arXiv:1907.04571 [nucl-th].

[2] P. Hillmann, J. Steinheimer and M. Bleicher, J. Phys. G **45**, no. 8, 085101 (2018) doi:10.1088/1361-6471/aac96f [arXiv:1802.01951 [nucl-th]].

[3] H. Petersen, Q. Li, X. Zhu and M. Bleicher, Phys. Rev. C **74**, 064908 (2006) doi:10.1103/PhysRevC.74.064908 [hep-ph/0608189].

[4] B. Kardan [HADES Collaboration], PoS CPOD **2017**, 049 (2018). doi:10.22323/1.311.0049

[5] B. Kardan [HADES Collaboration], Nucl. Phys. A **982**, 431 (2019) doi:10.1016/j.nuclphysa.2018.09.061 [arXiv:1809.07821 [nucl-ex]].

[6] C. Hartnack, R. K. Puri, J. Aichelin, J. Konopka, S. A. Bass, H. Stoecker and W. Greiner, Eur. Phys. J. A **1**, 151 (1998) doi:10.1007/s100500050045 [nucl-th/9811015].

[7] S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255 (1998) [Prog. Part. Nucl. Phys. **41**, 225 (1998)].

[8] M. Bleicher *et al.*, J. Phys. **G25**, 1859 (1999).

[9] S. Sombun, K. Tomuang, A. Limphirat, P. Hillmann, C. Herold, J. Steinheimer, Y. Yan and M. Bleicher, Phys. Rev. C **99**, no. 1, 014901 (2019) doi:10.1103/PhysRevC.99.014901 [arXiv:1805.11509 [nucl-th]].