Physics Letters B 841 (2023) 137947

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Decoding the flow evolution in Au+Au reactions at 1.23A GeV using hadron flow correlations and dileptons

Tom Reichert [a,b,*], Oleh Savchuk [c,d,e,f], Apiwit Kittiratpattana [a,g], Pengcheng Li [h,i], Jan Steinheimer [d], Mark Gorenstein [d,e], Marcus Bleicher [a,b]

[a] Institut für Theoretische Physik, Goethe Universität Frankfurt, Max-von-Laue-Strasse 1, D-60438 Frankfurt am Main, Germany
[b] Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtz Center for Heavy Ion Physics, Campus Frankfurt, Max-von-Laue-Str. 12, 60438 Frankfurt, Germany
[c] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany
[d] Frankfurt Institute for Advanced Studies (FIAS), Ruth-Moufang-Str. 1, D-60438 Frankfurt am Main, Germany
[e] Bogolyubov Institute for Theoretical Physics, 03680 Kyiv, Ukraine
[f] Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA
[g] Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
[h] School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China
[i] School of Science, Huzhou University, Huzhou 313000, China

ARTICLE INFO

Article history:
Received 8 March 2023
Received in revised form 24 March 2023
Accepted 30 April 2023
Available online 5 May 2023
Editor: B. Balantekin

ABSTRACT

We investigate the development of the directed, v_1, and elliptic flow, v_2, in heavy ion collisions in mid-central Au+Au reactions at $E_{\text{lab}} = 1.23A$ GeV. We demonstrate that the elliptic flow of hot and dense matter is initially positive ($v_2 > 0$) due to the early pressure gradient. This positive v_2 transfers its momentum to the spectators, which leads to the creation of the directed flow v_1. In turn, the spectator shadowing of the in-plane expansion leads to a preferred decoupling of hadrons in the out-of-plane direction and results in a negative v_2 for the observable final state hadrons. We propose a measurement of $v_1 - v_2$ flow correlations and of the elliptic flow of dileptons as methods to pin down this evolution pattern. The elliptic flow of the dileptons allows then to determine the early-state EoS more precisely, because it avoids the strong modifications of the momentum distribution due to shadowing seen in the protons. This opens the unique opportunity for the HADES and CBM collaborations to measure the Equation-of-State directly at 2-3 times nuclear saturation density.

© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP³.

1. Introduction

Heavy-ion collisions provide an excellent opportunity to study nuclear matter in a controlled laboratory setting allowing to recreate conditions which were present in the early universe or are present in neutron stars. One of the main goals of nuclear research is the precise extraction of the nuclear Equation-of-State (EoS) at large baryon densities which are found in the interior of neutron stars. The link between astrophysical observations on a scale of 10^{15} m and collisions of heavy atomic nuclei at nearly the speed of light on a scale of 10^{-15} m comes as a surprise. Remarkable resemblance between binary neutron star mergers (BNS merger) and heavy ion collisions (HICs) has been found in Ref. [1]. Most intriguing is the fact that BNS mergers and HICs are subject to the same microscopic interactions, namely Quantum-Chromo-Dynamics (QCD). In order to better understand astrophysical objects, it is of utmost importance to pin down the nuclear Equation-of-State with high precision, desirably in a neutron rich system.

HICs range from center of mass energies of 2 GeV at GSI's SIS18 accelerator up to several hundred GeV at BNL-RHIC or CERN-SPS or even to 13 TeV at CERN-LHC. However, the density range suited for BNS comparison will be probed in the upcoming FAIR facility which is currently constructed near Darmstadt, Germany. In this energy regime, the density in central heavy ion collisions reaches from 2-6 times nuclear saturation density [2]. Currently, the lower range of this regime can already be probed in the currently running HADES experiment at GSI. Here, information about the Equation-of-State can be extracted via measurements of harmonic flow of hadrons [3–5], investigations of the speed of sound [6–8] or strangeness enhancement or flow [9–13] and many more. Especially the second flow coefficient v_2 (called elliptic flow) is perfectly suited to investigate the EoS at large densities. It is well

* Corresponding author.
E-mail address: treichert@itp.uni-frankfurt.de (T. Reichert).

https://doi.org/10.1016/j.physletb.2023.137947
0370-2693/© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP³.

known from higher beam energies that the measured elliptic flow in the final state is directly connected to the pressure gradients exerted by the EoS. A detailed comparison of flow measurements at BNL's RHIC [14,15] with hydrodynamic simulations [16–19] lead to the renowned finding that the deconfined phase of QCD (a Quark-Gluon-Plasma, QGP) resembles the most perfect liquid.

At low energies the situation is more challenging: here the incoming baryon currents cannot decouple quickly enough to allow free expansion driven solely by the pressure gradients. Instead, the residues of the incoming nuclei (the spectators) are blocking the emission of particles in-plane during the compression phase. This leads to the well known squeeze-out effect of nucleons. Therefore, the final elliptic flow of protons is negative in the range $\sqrt{s_{\mathrm{NN}}} = 2 - 4$ GeV, which is confirmed by measurements at FOPI [20,21], EOS/E895 [22,23], E877 [24], STAR-BES [25–27].

Even though the magnitude of the negative elliptic flow is still sensitive to the EoS [28], a detailed understanding of the dynamics which lead to this dependency and its connection to the directed flow is still missing.

In this article we aim to understand the precise expansion dynamics during the compression stage and how the initial positive elliptic flow is observed as negative elliptic flow in the final state. This will allow to extract information on the Equation-of-State in the most dense stage of the reaction. We analyze the flow of Au-Au collisions at 1.23A GeV kinetic beam energy, in line with recent HADES measurements [29,30], and investigate the contributions to the final observable flow. Finally we propose two distinct measurements (flow correlations and dilepton flow) to test our findings.

2. Model setup and flow extraction

For the present study we use the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [31–33] in its most recent version (v3.5). UrQMD is a microscopic transport simulation based on the explicit propagation of hadrons in phase-space. The imaginary part of the interactions is modeled via binary elastic and inelastic collisions, leading to resonance excitations and decays or color flux-tube formation and their fragmentation. The real part of the interaction potential is implemented via different equations of state, where in the present work a realistic chiral mean field EoS is used, see [2]. In its current version, UrQMD includes a large body of baryonic and mesonic resonances up to masses of 4 GeV. The model is well established in the GSI energy regime. For recent studies of the bulk dynamics, we refer the reader to [34,35]. For the analysis of the integrated harmonic flows at SIS energies see [5,36–38].

The flow coefficients are identified with the Fourier coefficients in the series expansion of the azimuthal angle distribution which can be written as

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_{RP})), \tag{1}$$

in which v_n is n-th order flow coefficient, ϕ is the azimuthal angle and Ψ_{RP} is the angle of the reaction plane. The HADES experiment uses a forward wall to reconstruct the event plane from the spectator nucleons [39]. In the simulation, the spectator event plane is fixed and $\Psi_{RP} = 0$ is used for the present analysis of the simulation. The flow coefficients are then calculated as

$$v_n = \langle \cos(n(\phi - \Psi_{RP})) \rangle, \tag{2}$$

where the average $\langle \cdot \rangle$ is taken over all nucleons in a fixed rapidity or transverse momentum range in a given event.

The reader should be aware that this definition is different than the one usually used at the highest beam energies where the flow components are defined with respect to specific event planes. The methodical difference has its origin in the way that flow develops at low beam energies. Here, the initial squeeze out of nucleons leads to a large negative elliptic flow component with respect to the reaction plane defined by the spectators. The initial compression phase is decisive for the observed flow and therefore the scaling of the initial eccentricity with final state flow known from large collision energies [40] is not as straightforward. Recently, scaling could be established in Refs. [30,41], however with a negative sign. Thus, it can be expected that also the flow correlations will differ significantly from what was observed at high beam energies, which opens up new possibilities to study the equation of state responsible for the formation of flow.

3. Results

All results were obtained by simulating 20-30% peripheral Au+Au collisions at $E_{\mathrm{beam}} = 1.23A$ GeV kinetic beam energy with the UrQMD (v3.5) model. We employ the model with the Chiral Mean Field (CMF) Equation-of-State as it was shown to yield the best description of available data (cf. Ref. [28]). We note that in this energy regime, the results of the CMS-EoS are very similar to the ones obtained by a hard EoS [36,37]. We focus our analysis on participating nucleons and also exclude nucleons that are bound in light clusters. It has been shown [37] that both effects need to be taken into account to reliably describe the measured data on nucleon flow [29,30]. The centrality is selected via impact parameter cuts following previous Monte-Carlo Glauber simulations [42].

3.1. Flow development of the system

In contrast to ultra-relativistic energies probed at RHIC and LHC where the initial baryon-currents decouple quickly allowing the overlap region to propagate its spatial anisotropy to the final state momentum space anisotropy [40], low energy heavy-ion collisions are very different. Here, the baryon-currents of the initial impinging nuclei are present over the whole course of the compression and expansion phase, which results in a space and time dependent interplay between pressure gradients, spectator blocking, compression and expansion phase and corrections due to transport coefficients such as shear viscosity [43] which influence the development of the finally observable flow.

It is thus convenient to start the investigation by discussing how flow develops over the course of the collision in the whole system before we later quantify the different contributions to the final observable flow at freeze-out. For this we simulate semi-peripheral (corresponding to $6.6 \leq b \leq 8.1$ fm, cf. Ref. [42]) Au+Au collisions with UrQMD. In this section we integrate over all baryons present at a specified time t (the time is defined in the computational frame, i.e. the center-of-mass frame of the whole system) to extract the time development of the harmonic flow coefficients v_1^* and v_2. We show the flow coefficients v_1^* in Fig. 1 and v_2 in Fig. 2 calculated from all baryons which are present in the whole phase space at time t as a black solid line with full circles. In addition we also show the directed and elliptic flow only of nucleons being emitted at given time $t + \Delta t$ as a red solid line with full triangles. We show the rapidity weighted averaged directed flow defined as $v_1^* \equiv \langle \mathrm{sign}(y) \cdot v_1 \rangle$ where the average runs over all baryons and y and v_1 correspond to the rapidity and directed flow of each baryon.

First, we observe that the time dependence of the directed flow calculated from all participating baryons present in the system (black line with circles) exerts a strong increase during the collision. During the initial compression stage the curve is consistent with zero until $\approx 5 - 7$ fm/c when the density reaches 2-3 times saturation density and the CMF EoS becomes repulsive [2].

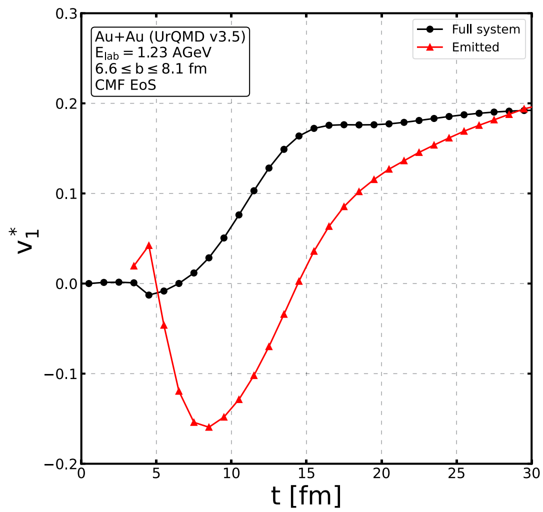

Fig. 1. The directed flow coefficient $v_1^* \equiv \langle \mathrm{sign}(y) \cdot v_1 \rangle$ calculated from all baryons (black circles) which are present in the whole phase space at time t and of the nucleons emitted at time $t + \Delta t$ (red triangles) from 20-30% peripheral Au+Au collisions at a kinetic beam energy of 1.23A GeV from UrQMD.

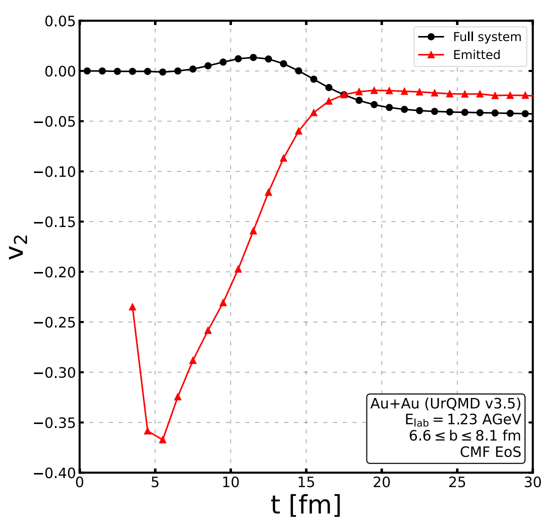

Fig. 2. The elliptic flow coefficient v_2 calculated from all baryons (black circles) which are present in the whole phase space at time t and of the nucleons emitted at time t (red triangles) from 20-30% peripheral Au+Au collisions at a kinetic beam energy of 1.23A GeV from UrQMD.

In Ref. [2], where the authors calculated the density and temperature evolution in UrQMD with the CMF EoS, one can see that at ≈ 5 fm maximum compression is reached saturating at $3\rho_0$ and maintained until ≈ 15 fm. At this time the development of the directed flow component begins due to a large pressure gradient in impact parameter direction. The pressure gradient pushes the nucleons in in-plane direction, which is reflected in a rapid development of large v_1^* over the course of the next 7 fm.

After 15 fm, the directed flow v_1^* of all baryons present in the system reaches a plateau around $v_1^* \approx 0.18$ in line with measured data [29,30]. This tells that the bounce-off is generated in a rather short time frame and thus probes the system at maximal compression, i.e. $\rho_B/\rho_0 \approx 2-3$ [2,43].

The directed flow of the first nucleons that decouple kinetically from the system is strongly negative. This finding can be understood, because the nucleons which propagate in-plane will scatter with the residue of the projectile nucleus still propagating forward and therefore the only direction free for decoupling has a negative v_1^* at initial contact.

Turning to the elliptic flow v_2 (shown in Fig. 2) supports this line of arguments. The elliptic flow of the whole system is zero until maximal compression is achieved at the time of full geometric overlap at 7 fm. This means that the system's momentum space remains isotropic in the transverse plane in momentum space from initial contact until full overlap. At overlap time the compression is maximal with values around $\rho_B/\rho_0 = 2-3$ [2,43]. Although measurements by the HADES collaboration [29] show in agreement with theoretical models [37,44] that the elliptic flow is negative in the final state (i.e. at kinetic freeze-out) at this energy, the elliptic flow of the whole system extracted at different times starts to become positive after full overlap is reached and only turns negative at even later stages of the evolution of the system. This can be interpreted as follows: At the time of maximal compression the overlap zone resembles an almond shape which is known also from high energies. The spatial pressure gradient of this shape exerts a force over a large surface in in-plane direction (i.e. aligned with the impact parameter). The participating baryons in the center of the system thus try to expand in-plane with positive v_2 but they cannot decouple because the spectators are still blocking[1] expansion in this direction. The resulting momentum transfer to the (semi-)spectators next to the central collision zone then generates the observed v_1^* (as discussed above). However, the observed hadrons are emitted out-of-plane, because only in this direction the emission is not blocked and therefore the elliptic flow of the participating nucleons turns negative at a slightly later time around 15 fm which is exactly where the directed flow reaches its plateau.

Contrary to the v_2 of all baryons in the system, the elliptic flow of the emitted nucleons is always strongly negative even though the full systems v_2 is zero or positive over the first 15 fm. In other words even though more nucleons are flowing in in-plane direction than out-of-plane, those in-plane are blocked from emission by the spectators and can not be observed as free hadrons in the detector.

This underlines the importance of shadowing to understand flow at SIS energies: the pressure gradient generated by the Equation-of-State behaves similar to the highest beam energies and tries to generate expansion with positive v_2. However, the momentum flow in x-direction gets absorbed by nucleons close to the central reaction zone and the bypassing spectators generating a strongly positive v_1^* (the bounce-off, or rather a "push-away") and leads to an isotropization of the momentum flow in x-direction. In contrast, the nucleons which can freeze-out dominantly only with momenta in y-direction create a negative v_2. This also explains how a softening of the early EoS, causing less early expansion and smaller early v_2, leads to a smaller final v_1^*.

The tight connection between v_1^* and v_2 should therefore be observable in their correlation. Following our previous study in Ref. [5] we define event classes by triggering on the integrated final state elliptic flow of nucleons $\langle v_2 \rangle_{|y| \leq 0.5}$. As discussed, a smaller v_2 leads to less momentum transfer to the (semi-)spectators and thus the integrated final elliptic flow of protons should have a positive correlation with the mid-rapidity slope of the directed flow. Fig. 3 shows the mid-rapidity slope of the directed flow of nucleons at kinetic freeze-out as a function of event-class selected integrated v_2 values at mid-rapidity from 20-30% peripheral Au+Au collisions at a kinetic beam energy of 1.23A GeV. A clear positive correlation between v_2 and $dv_1/dy|_{y=0}$ is found. This result supports the idea that the initial expansion in x-direction exerts a momentum transfer to the (semi-spectator)

[1] Here the phrase 'blocking' should not be understood as hard wall blocking, but as a deceleration or momentum transfer of the initially expanding system to the (semi-)spectator matter.

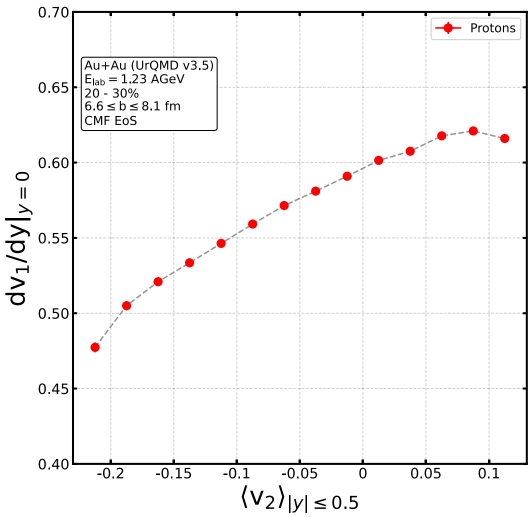

Fig. 3. The mid-rapidity slope of the directed flow of nucleons at kinetic freeze-out as a function of event-class selected integrated v_2 values at mid-rapidity from 20-30% peripheral Au+Au collisions at a kinetic beam energy of 1.23A GeV from UrQMD.

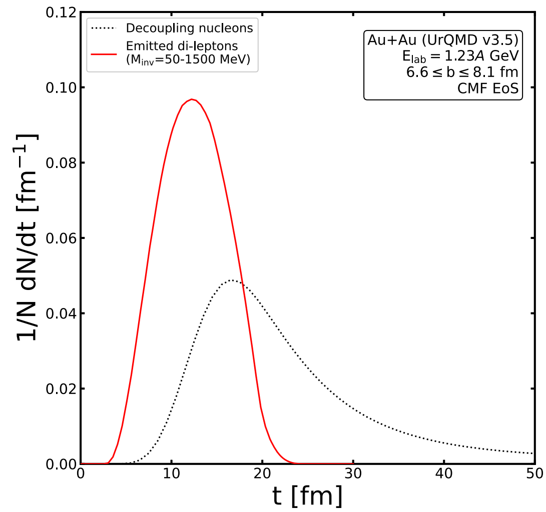

Fig. 4. The time distribution of nucleons at kinetic freeze-out (dotted black line) and of emitted dileptons with invariant masses from 50-1500 MeV (solid red line) from 20-30% peripheral Au+Au collisions at a kinetic beam energy of 1.23 AGeV from UrQMD.

nucleons close to the central reaction zone and thus enforcing a strong correlation between the initial elliptic flow and the final directed flow.

How can such a scenario be tested further? In the following section we suggest dileptons as a second observable to explore the early stage expansion pattern.

3.2. Time of decoupling and measurement via dileptons

In an experimental setup the time dependence of heavy-ion collisions cannot be accessed by hadronic observables. On the other hand, dilepton emission from the hot and dense phase offers time integrated information of the whole evolution history [45–48]. Dileptons are perfect candidates because they only interact electromagnetically and thus very weakly in comparison to the strong interaction [49]. Recent dilepton measurements by the HADES collaboration [50] have shown great potential for future high precision measurements of the properties of the matter produced [51].

To calculate the dilepton emission from our simulated collisions we will employ a well known coarse graining method [43,52–61] where event averaged spatial distributions of the baryon and energy-momentum density are used to calculate the time dependent in-medium dilepton emission using state-of-the-art vector meson spectral functions [62–64]. In particular we run UrQMD-CMF events at a fixed impact parameter of $b = 6.6$ fm and apply the coarse graining method described in [51].

From the coarse grained simulation we can directly extract the time dependence of the dilepton emission rate, at mid-rapidity, and compare it to the time evolution and decoupling rate of the nucleons. In Fig. 4 the normalized freeze-out time distributions of the nucleons are shown as a dotted black line while the emission time distribution of the dileptons with invariant masses from 50-1500 MeV is shown as a solid red line. One can clearly observe that the dilepton emission time distribution is much more narrow and centered at 10-12 fm. In contrast, the nucleon kinetic freeze-out time distribution is very broad, peaks at 18-20 fm and is strongly skewed towards later times. By comparison with the time development of the directed and elliptic flow shown previously in Figs. 1 and 2 one can see that the dileptons are emitted exactly during the most hot and dense phase which is the time when v_1* is just generated and v_2 is positive. The nucleons, on the other hand, mainly

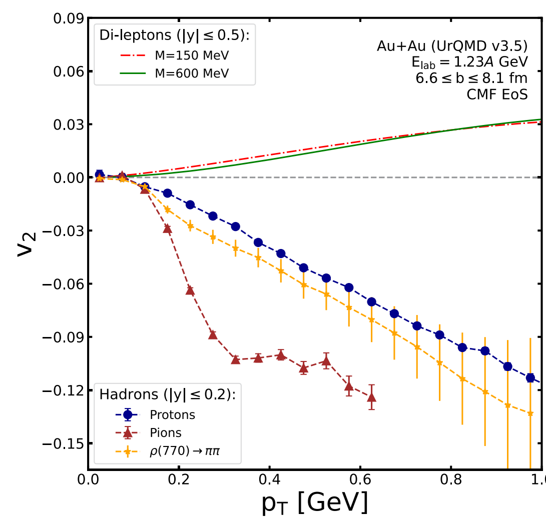

Fig. 5. The transverse momentum dependence of the elliptic flow of π (brown triangles), protons (dark blue circles), final state $\rho(770)$ (orange stars) and dileptons at invariant masses of $M = 0.15$ GeV (red line) and $M = 0.6$ GeV (green line) in peripheral Au+Au collisions at a kinetic beam energy of 1.23A GeV from UrQMD.

decouple when the elliptic flow of the whole system has already turned negative due to immense shadowing and the directed flow has reached its plateau.

A similar idea has been put forward in Refs. [65–72] considering RHIC and LHC energies where the early v_2 of the partonic phase can be accessed via measurement of the flow of direct photons e.g. at PHENIX [73] or at ALICE [74,75].

We can now compare the elliptic flow of the dileptons with the hadrons at kinetic freeze-out. In particular the proton, π and $\rho(770)$ flows are of special interest. The pions probe the kinetic decoupling stage while the ρ either decays into a dilepton pair within the medium or into a $\pi\pi$ pair at kinetic freeze-out allowing us to study the final state and early flow in a mass range not dominated by pions.

Fig. 5 displays the transverse momentum dependence of the elliptic flow v_2 at mid-rapidity of the emitted dilepton radiation at invariant masses of $M = 0.150$ GeV (dash-dotted red line) and $M = 0.600$ GeV (green line) in comparison to the elliptic flow of protons (dark blue dashed line with circles), pions (brown dashed line with triangles) and final state ρ mesons (dashed orange line with stars).

As expected the elliptic flow of protons, pions and the ρ mesons is negative and decreasing with increasing transverse momentum. (The calculations are also in agreement with the recent HADES measurements for protons, deuterons, tritons and preliminary pions at mid-rapidity [30].) The dilepton v_2 on the other hand shows the opposite behavior: It probes the system during the most hot and dense phase when the pressure gradients generate expansion in in-plane direction and thence their elliptic flow is positive and increases with increasing transverse momentum. The dilepton flow at both invariant masses increases up to 3% at 1 GeV transverse momentum which is in good alignment with the elliptic flow of the whole system (cf. Fig. 2). One can further observe hydrodynamic flow scaling in the dileptons where larger masses are shifted to higher p_T [76].

We conclude that the above discussed effect of a positive elliptic flow experienced by all particles in the central collision zone exerted by the pressure gradients during the most dense phase can be seen in the flow of vector mesons decaying to dileptons throughout the time evolution. In contrast, stable hadrons and resonances that can be reconstructed in their hadronic decay channels are only sensitive to the last generation of particles at kinetic freeze-out and are therefore subject to a negative observable elliptic flow value. This allows to measure the nuclear Equation-of-State directly at 2-3 times saturation density using dileptons in the ρ-mass excess region.

4. Discussion

Before we conclude, we would like to address that similar time evolutions of the elliptic flow where presented in Refs. [77–79] within a QMD model at much lower energies, confirming the general expansion pattern of matter at such collision energies. However, the previous studies did not make any attempts to link the specific anisotropic expansion dynamics of the matter at the highest baryon densities to experimentally accessible observables. Here, we present for the first time two distinct observables that allow to pin down the expansion of the matter during the most dense stages, namely dilepton emission and flow correlations. Therefore, we suggest to scrutinize $v_1 - v_2$ correlations and the positive elliptic flow of dileptons in the region of the ρ mass as distinct signals for an initial expansion in positive x-direction, which is later turned by shadowing into a negative elliptic flow with an expansion predominantly along the y-direction.

5. Conclusion

We presented a detailed study of the time evolution of flow in Au-Au collisions at a beam energy of 1.23A GeV employing the Ultra-relativistic Quantum-Molecular-Dynamics model (UrQMD v3.5). The investigations revealed that, similar to known flow patterns at ultra-relativistic beam energies, the initial overlap geometry does lead to a positive elliptic flow during the early evolution of the system. This positive initial v_2 acts as the source of the directed flow, v_1. The negative v_2, observed in the final state hadrons, is mainly due to shadowing effect. We suggest to use $v_1 - v_2$ correlations to probe the described connection between the different flow components and to confirm the predicted initial state expansion geometry. We further suggest to use dileptons as another independent probe to observe the early expansion of the matter in x-direction, which will be signaled by a positive v_2 for dileptons in contrast to a negative v_2 (already observed) for protons.

As the early flow is a direct reaction of the system to the initial pressure gradient, and thus the Equation-of-State at the highest densities, the measurement of the dilepton elliptic flow may provide direct access to the high density EoS of QCD matter in a clearer way than possible before.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank Tetyana Galatyuk for inspiring discussions on the role of dilepton flow, Behruz Kardan and Christoph Blume as well as Arnaud Le Fèvre and Jörg Aichelin for fruitful discussion about their previous work. This article is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement STRONG – 2020 - No 824093. OS thanks the GSI for funding. Computational resources were provided by the Center for Scientific Computing (CSC) of the Goethe University and the "Green Cube" at GSI, Darmstadt. This project was supported by the DAAD (PPP Thailand). This research has received funding support from the NSRF via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation [grant number B16F640076].

References

[1] E.R. Most, A. Motornenko, J. Steinheimer, V. Dexheimer, M. Hanauske, L. Rezzolla, H. Stoecker, arXiv:2201.13150 [nucl-th].
[2] M. Omana Kuttan, A. Motornenko, J. Steinheimer, H. Stoecker, Y. Nara, M. Bleicher, Eur. Phys. J. C 82 (5) (2022) 427, https://doi.org/10.1140/epjc/s10052-022-10400-2, arXiv:2201.01622 [nucl-th].
[3] P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592–1596, https://doi.org/10.1126/science.1078070, arXiv:nucl-th/0208016 [nucl-th].
[4] A. Le Fèvre, Y. Leifels, W. Reisdorf, J. Aichelin, C. Hartnack, Nucl. Phys. A 945 (2016) 112–133, https://doi.org/10.1016/j.nuclphysa.2015.09.015, arXiv:1501.05246 [nucl-ex].
[5] T. Reichert, J. Steinheimer, C. Herold, A. Limphirat, M. Bleicher, Eur. Phys. J. C 82 (6) (2022) 510, https://doi.org/10.1140/epjc/s10052-022-10480-0, arXiv:2203.15550 [nucl-th].
[6] P. Bedaque, A.W. Steiner, Phys. Rev. Lett. 114 (3) (2015) 031103, https://doi.org/10.1103/PhysRevLett.114.031103, arXiv:1408.5116 [nucl-th].
[7] I. Tews, J. Carlson, S. Gandolfi, S. Reddy, Astrophys. J. 860 (2) (2018) 149, https://doi.org/10.3847/1538-4357/aac267, arXiv:1801.01923 [nucl-th].
[8] J. Steinheimer, M. Bleicher, Eur. Phys. J. A 48 (2012) 100, https://doi.org/10.1140/epja/i2012-12100-0, arXiv:1207.2792 [nucl-th].
[9] C.T. Sturm, et al., KAOS, Phys. Rev. Lett. 86 (2001) 39–42, https://doi.org/10.1103/PhysRevLett.86.39, arXiv:nucl-ex/0011001 [nucl-ex].
[10] C. Fuchs, A. Faessler, E. Zabrodin, Y.M. Zheng, Phys. Rev. Lett. 86 (2001) 1974–1977, https://doi.org/10.1103/PhysRevLett.86.1974, arXiv:nucl-th/0011102 [nucl-th].
[11] C. Hartnack, H. Oeschler, J. Aichelin, Phys. Rev. Lett. 96 (2006) 012302, https://doi.org/10.1103/PhysRevLett.96.012302, arXiv:nucl-th/0506087 [nucl-th].
[12] J. Adamczewski-Musch, et al., HADES, Phys. Lett. B 793 (2019) 457–463, https://doi.org/10.1016/j.physletb.2019.03.065, arXiv:1812.07304 [nucl-ex].
[13] L. Chlad, HADES, Springer Proc. Phys. 250 (2020) 221–224, https://doi.org/10.1007/978-3-030-53448-6_33.
[14] K.H. Ackermann, et al., STAR, Phys. Rev. Lett. 86 (2001) 402–407, https://doi.org/10.1103/PhysRevLett.86.402, arXiv:nucl-ex/0009011 [nucl-ex].
[15] S.S. Adler, et al., PHENIX, Phys. Rev. C 69 (2004) 034909, https://doi.org/10.1103/PhysRevC.69.034909, arXiv:nucl-ex/0307022 [nucl-ex].
[16] P. Huovinen, P.F. Kolb, U.W. Heinz, P.V. Ruuskanen, S.A. Voloshin, Phys. Lett. B 503 (2001) 58–64, https://doi.org/10.1016/S0370-2693(01)00219-2, arXiv:hep-ph/0101136 [hep-ph].
[17] H. Song, U.W. Heinz, Phys. Lett. B 658 (2008) 279–283, https://doi.org/10.1016/j.physletb.2007.11.019, arXiv:0709.0742 [nucl-th].
[18] M. Luzum, P. Romatschke, Phys. Rev. C 78 (2008) 034915, https://doi.org/10.1103/PhysRevC.78.034915, arXiv:0804.4015 [nucl-th];
M. Luzum, P. Romatschke, Erratum, Phys. Rev. C 79 (2009) 039903.

[19] P. Romatschke, U. Romatschke, Phys. Rev. Lett. 99 (2007) 172301, https://doi.org/10.1103/PhysRevLett.99.172301, arXiv:0706.1522 [nucl-th].
[20] A. Andronic, et al., FOPI, Phys. Lett. B 612 (2005) 173–180, https://doi.org/10.1016/j.physletb.2005.02.060, arXiv:nucl-ex/0411024 [nucl-ex].
[21] W. Reisdorf, et al., FOPI, Nucl. Phys. A 876 (2012) 1–60, https://doi.org/10.1016/j.nuclphysa.2011.12.006, arXiv:1112.3180 [nucl-ex].
[22] C. Pinkenburg, et al., E895, Phys. Rev. Lett. 83 (1999) 1295–1298, https://doi.org/10.1103/PhysRevLett.83.1295, arXiv:nucl-ex/9903010 [nucl-ex].
[23] H. Liu, et al., E895, Phys. Rev. Lett. 84 (2000) 5488–5492, https://doi.org/10.1103/PhysRevLett.84.5488, arXiv:nucl-ex/0005005 [nucl-ex].
[24] J. Barrette, et al., E877, Phys. Rev. C 56 (1997) 3254–3264, https://doi.org/10.1103/PhysRevC.56.3254, arXiv:nucl-ex/9707002 [nucl-ex].
[25] L. Adamczyk, et al., STAR, Phys. Rev. Lett. 112 (16) (2014) 162301, https://doi.org/10.1103/PhysRevLett.112.162301, arXiv:1401.3043 [nucl-ex].
[26] J. Adam, et al., STAR, Phys. Rev. C 103 (3) (2021) 034908, https://doi.org/10.1103/PhysRevC.103.034908, arXiv:2007.14005 [nucl-ex].
[27] M.S. Abdallah, et al., STAR, Phys. Lett. B 827 (2022) 136941, https://doi.org/10.1016/j.physletb.2022.136941, arXiv:2112.04066 [nucl-ex].
[28] J. Steinheimer, A. Motornenko, A. Sorensen, Y. Nara, V. Koch, M. Bleicher, Eur. Phys. J. C 82 (10) (2022) 911, https://doi.org/10.1140/epjc/s10052-022-10894-w, arXiv:2208.12091 [nucl-th].
[29] J. Adamczewski-Musch, et al., HADES, Phys. Rev. Lett. 125 (2020) 262301, https://doi.org/10.1103/PhysRevLett.125.262301, arXiv:2005.12217 [nucl-ex].
[30] J. Adamczewski-Musch, et al., HADES, arXiv:2208.02740 [nucl-ex].
[31] S.A. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, L. Bravina, C. Ernst, L. Gerland, M. Hofmann, S. Hofmann, J. Konopka, et al., Prog. Part. Nucl. Phys. 41 (1998) 255–369, https://doi.org/10.1016/S0146-6410(98)00058-1, arXiv:nucl-th/9803035 [nucl-th].
[32] M. Bleicher, E. Zabrodin, C. Spieles, S.A. Bass, C. Ernst, S. Soff, L. Bravina, M. Belkacem, H. Weber, H. Stoecker, et al., J. Phys. G 25 (1999) 1859–1896, https://doi.org/10.1088/0954-3899/25/9/308, arXiv:hep-ph/9909407 [hep-ph].
[33] M. Bleicher, E. Bratkovskaya, Prog. Part. Nucl. Phys. 122 (2022) 103920, https://doi.org/10.1016/j.ppnp.2021.103920.
[34] T. Reichert, P. Hillmann, M. Bleicher, Nucl. Phys. A 1007 (2021) 122058, https://doi.org/10.1016/j.nuclphysa.2020.122058, arXiv:2004.10539 [nucl-th].
[35] T. Reichert, A. Elz, T. Song, G. Coci, M. Winn, E. Bratkovskaya, J. Aichelin, J. Steinheimer, M. Bleicher, J. Phys. G 49 (5) (2022) 055108, https://doi.org/10.1088/1361-6471/ac5dfe, arXiv:2111.07652 [nucl-th].
[36] P. Hillmann, J. Steinheimer, M. Bleicher, J. Phys. G 45 (8) (2018) 085101, https://doi.org/10.1088/1361-6471/aac96f, arXiv:1802.01951 [nucl-th].
[37] P. Hillmann, J. Steinheimer, T. Reichert, V. Gaebel, M. Bleicher, S. Sombun, C. Herold, A. Limphirat, J. Phys. G 47 (5) (2020) 055101, https://doi.org/10.1088/1361-6471/ab6fcf, arXiv:1907.04571 [nucl-th].
[38] T. Reichert, J. Steinheimer, M. Bleicher, arXiv:2207.02594 [nucl-th].
[39] B. Kardan, HADES, Nucl. Phys. A 967 (2017) 812–815, https://doi.org/10.1016/j.nuclphysa.2017.05.026.
[40] C. Loizides, et al., PHOBOS, Braz. J. Phys. 37 (2007) 770–772, arXiv:nucl-ex/0611017 [nucl-ex].
[41] T. Reichert, A. Kittiratpattana, P. Li, J. Steinheimer, M. Bleicher, J. Phys. G 50 (2) (2023) 025104, https://doi.org/10.1088/1361-6471/acaffa, arXiv:2208.10871 [nucl-th].
[42] J. Adamczewski-Musch, et al., HADES, Eur. Phys. J. A 54 (5) (2018) 85, https://doi.org/10.1140/epja/i2018-12513-7, arXiv:1712.07993 [nucl-ex].
[43] T. Reichert, G. Inghirami, M. Bleicher, Phys. Lett. B 817 (2021) 136285, https://doi.org/10.1016/j.physletb.2021.136285, arXiv:2011.04546 [nucl-th].
[44] J. Mohs, M. Ege, H. Elfner, M. Mayer, Phys. Rev. C 105 (3) (2022) 034906, https://doi.org/10.1103/PhysRevC.105.034906, arXiv:2012.11454 [nucl-th].
[45] E.V. Shuryak, Phys. Lett. B 78 (1978) 150, https://doi.org/10.1016/0370-2693(78)90370-2.
[46] L.D. McLerran, T. Toimela, Phys. Rev. D 31 (1985) 545, https://doi.org/10.1103/PhysRevD.31.545.
[47] E.L. Bratkovskaya, W. Cassing, Nucl. Phys. A 619 (1997) 413–446, https://doi.org/10.1016/S0375-9474(97)00140-1, arXiv:nucl-th/9611042 [nucl-th].
[48] R. Rapp, J. Wambach, Adv. Nucl. Phys. 25 (2000) 1, https://doi.org/10.1007/0-306-47101-9_1, arXiv:hep-ph/9909229 [hep-ph].
[49] R. Rapp, H. van Hees, Phys. Lett. B 753 (2016) 586–590, https://doi.org/10.1016/j.physletb.2015.12.065, arXiv:1411.4612 [hep-ph].
[50] J. Adamczewski-Musch, et al., HADES, Nat. Phys. 15 (10) (2019) 1040–1045, https://doi.org/10.1038/s41567-019-0583-8.
[51] O. Savchuk, A. Motornenko, J. Steinheimer, V. Vovchenko, M. Bleicher, M. Gorenstein, T. Galatyuk, arXiv:2209.05267 [nucl-th].
[52] L.V. Bravina, M.I. Gorenstein, M. Belkacem, S.A. Bass, M. Bleicher, M. Brandstetter, M. Hofmann, S. Soff, C. Spieles, H. Weber, et al., Phys. Lett. B 434 (1998) 379–387, https://doi.org/10.1016/S0370-2693(98)00624-8, arXiv:nucl-th/9804008 [nucl-th].
[53] L.V. Bravina, E.E. Zabrodin, M.I. Gorenstein, S.A. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, C. Ernst, M. Hofmann, L. Neise, et al., Phys. Rev. C 60 (1999) 024904, https://doi.org/10.1103/PhysRevC.60.024904, arXiv:hep-ph/9906548 [hep-ph].
[54] P. Huovinen, M. Belkacem, P.J. Ellis, J.I. Kapusta, Phys. Rev. C 66 (2002) 014903, https://doi.org/10.1103/PhysRevC.66.014903, arXiv:nucl-th/0203023 [nucl-th].
[55] S. Endres, H. van Hees, M. Bleicher, PoS CPOD2013 052 (2013), https://doi.org/10.22323/1.185.0052.
[56] S. Endres, H. van Hees, J. Weil, M. Bleicher, Phys. Rev. C 91 (5) (2015) 054911, https://doi.org/10.1103/PhysRevC.91.054911, arXiv:1412.1965 [nucl-th].
[57] S. Endres, H. van Hees, J. Weil, M. Bleicher, Phys. Rev. C 92 (1) (2015) 014911, https://doi.org/10.1103/PhysRevC.92.014911, arXiv:1505.06131 [nucl-th].
[58] S. Endres, H. van Hees, M. Bleicher, Phys. Rev. C 93 (5) (2016) 054901, https://doi.org/10.1103/PhysRevC.93.054901, arXiv:1512.06549 [nucl-th].
[59] T. Galatyuk, P.M. Hohler, R. Rapp, F. Seck, J. Stroth, Eur. Phys. J. A 52 (5) (2016) 131, https://doi.org/10.1140/epja/i2016-16131-1, arXiv:1512.08688 [nucl-th].
[60] S. Endres, H. van Hees, M. Bleicher, Phys. Rev. C 94 (2) (2016) 024912, https://doi.org/10.1103/PhysRevC.94.024912, arXiv:1604.06415 [nucl-th].
[61] T. Reichert, G. Inghirami, M. Bleicher, Eur. Phys. J. A 56 (10) (2020) 267, https://doi.org/10.1140/epja/s10050-020-00273-y, arXiv:2007.06440 [nucl-th].
[62] R. Rapp, J. Wambach, Eur. Phys. J. A 6 (1999) 415–420, https://doi.org/10.1007/s100500050364, arXiv:hep-ph/9907502 [hep-ph].
[63] H. van Hees, R. Rapp, Nucl. Phys. A 806 (2008) 339–387, https://doi.org/10.1016/j.nuclphysa.2008.03.009, arXiv:0711.3444 [hep-ph].
[64] R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253, https://doi.org/10.1155/2013/148253, arXiv:1304.2309 [hep-ph].
[65] R. Chatterjee, E.S. Frodermann, U.W. Heinz, D.K. Srivastava, Phys. Rev. Lett. 96 (2006) 202302, https://doi.org/10.1103/PhysRevLett.96.202302, arXiv:nucl-th/0511079 [nucl-th].
[66] R. Chatterjee, D.K. Srivastava, U.W. Heinz, C. Gale, Phys. Rev. C 75 (2007) 054909, https://doi.org/10.1103/PhysRevC.75.054909, arXiv:nucl-th/0702039 [nucl-th].
[67] R. Chatterjee, D.K. Srivastava, Phys. Rev. C 79 (2009) 021901, https://doi.org/10.1103/PhysRevC.79.021901, arXiv:0809.0548 [nucl-th].
[68] J. Deng, Q. Wang, N. Xu, P. Zhuang, Phys. Lett. B 701 (2011) 581–586, https://doi.org/10.1016/j.physletb.2011.06.027, arXiv:1009.3091 [nucl-th].
[69] H. van Hees, C. Gale, R. Rapp, Phys. Rev. C 84 (2011) 054906, https://doi.org/10.1103/PhysRevC.84.054906, arXiv:1108.2131 [hep-ph].
[70] P. Mohanty, V. Roy, S. Ghosh, S.K. Das, B. Mohanty, S. Sarkar, J.e. Alam, A.K. Chaudhuri, Phys. Rev. C 85 (2012) 031903, https://doi.org/10.1103/PhysRevC.85.031903, arXiv:1111.2159 [nucl-th].
[71] G. Vujanovic, C. Young, B. Schenke, R. Rapp, S. Jeon, C. Gale, Phys. Rev. C 89 (3) (2014) 034904, https://doi.org/10.1103/PhysRevC.89.034904, arXiv:1312.0676 [nucl-th].
[72] V. Vovchenko, I.A. Karpenko, M.I. Gorenstein, L.M. Satarov, I.N. Mishustin, B. Kämpfer, H. Stoecker, Phys. Rev. C 94 (2) (2016) 024906, https://doi.org/10.1103/PhysRevC.94.024906, arXiv:1604.06346 [nucl-th].
[73] A. Adare, et al., PHENIX, Phys. Rev. Lett. 109 (2012) 122302, https://doi.org/10.1103/PhysRevLett.109.122302, arXiv:1105.4126 [nucl-ex].
[74] D. Lohner, ALICE, J. Phys. Conf. Ser. 446 (2013) 012028, https://doi.org/10.1088/1742-6596/446/1/012028, arXiv:1212.3995 [hep-ex].
[75] S. Acharya, et al., ALICE, Phys. Lett. B 789 (2019) 308–322, https://doi.org/10.1016/j.physletb.2018.11.039, arXiv:1805.04403 [nucl-ex].
[76] R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, Phys. Rev. C 68 (2003) 044902, https://doi.org/10.1103/PhysRevC.68.044902, arXiv:nucl-th/0306027 [nucl-th].
[77] A. Le Fèvre, Y. Leifels, C. Hartnack, J. Aichelin, Phys. Rev. C 98 (3) (2018) 034901, https://doi.org/10.1103/PhysRevC.98.034901, arXiv:1611.07500 [nucl-th].
[78] A.L. Fèvre, Y. Leifels, J. Aichelin, C. Hartnack, Nuovo Cimento C 41 (5) (2019) 180, https://doi.org/10.1393/ncc/i2018-18180-x.
[79] B. Gao, Y. Wang, Z. Gao, Q. Li, Phys. Lett. B 838 (2023) 137685, https://doi.org/10.1016/j.physletb.2023.137685, arXiv:2210.08213 [nucl-th].