COLLECTIVE PROPERTIES OF THE NUCLEAR MATTER AT RHIC*

Sonia Kabana, Vipul Bairathi

Instituto de Alta Investigación, Universidad de Tarapacá
Casilla 7D, Arica 1000000, Chile

Received 14 December 2024, accepted 7 February 2025, published online 6 March 2025

The collective flow of particles produced in heavy-ion collisions offers valuable insights into the dynamics of the Quark–Gluon Plasma (QGP) medium. Flow coefficients can be measured to probe the medium as they are sensitive to its different properties. The directed flow (v_1) slope ($\mathrm{d}v_1/\mathrm{d}y$) of protons at mid-rapidity is expected to be sensitive to the first-order phase transition. The number of constituent quarks (NCQ) scaling of elliptic flow (v_2) can be regarded as a signature of the QGP formation. Triangular flow (v_3) typically arises from fluctuations and can offer constraints on the initial state geometry and fluctuations. The Relativistic Heavy-Ion Collider (RHIC) is a versatile facility to collide a wide range of heavy-ion systems at various beam energies. In this paper, we will discuss selected results on the collective properties of nuclear matter from the STAR and PHENIX experiments at RHIC.

DOI:10.5506/APhysPolBSupp.18.1-A8

1. Introduction

Quantum Chromodynamics (QCD) proposes that at high temperatures and energy densities, there is a transition from confined hadronic matter to a deconfined state of partonic matter known as the Quark–Gluon Plasma [1, 2]. Figure 1 shows a schematic layout of the QCD phase diagram of the temperature (T) as a function of the baryon chemical potential (μ_B) [3]. Lattice QCD calculations indicate that in the low-μ_B region, the phase transition is a smooth crossover at T_c of about 150 MeV [4]. In the high-μ_B region, it is expected to be first order and ends at a critical point as μ_B decreases [4]. Various high-energy heavy-ion collision experiments aim to explore the QGP matter and study its properties through the QCD phase diagram. An experimental way to characterize the QCD phase diagram is by varying beam

* Presented at the Diffraction and Low-x 2024 Workshop, Trabia, Palermo, Italy, 8–14 September, 2024.

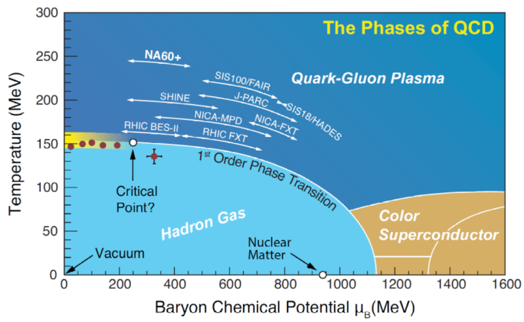

Fig. 1. Schematic layout of the QCD phase diagram [3].

energy. Heavy-ion collisions are currently being conducted by experiments such as NA61/SHINE, SIS18/HADES, and RHIC at the high-μ_B region. New experimental facilities at FAIR, NICA, and J-PARC are planned in the future.

In this paper, we will present selected results of collective flow from the STAR and PHENIX experiments at RHIC for Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV and the beam energy scan program ($\sqrt{s_{NN}}$ = 3.0 to 27 GeV). The results will be compared with model calculations to help elucidate the underlying physics mechanisms in heavy-ion collisions.

2. Relativistic heavy-ion collider

RHIC is a highly versatile collider, capable of colliding various nuclear species (U, Au, Ru, Zr, Cu, Al, O, ^{3}He, and d) and protons, at energies between $\sqrt{s_{NN}} = 7.7$ and 200 GeV in collider mode, and from 3.0 to 7.7 GeV in fixed-target mode. The Solenoidal Tracker at RHIC (STAR) and the Pioneering High Energy Nuclear Interaction eXperiment (PHENIX) are two experiments providing precision particle identification and tracking [5, 6].

The STAR experiment has full azimuthal coverage over a wide range of rapidity and excellent particle identification and tracking capabilities. The main detector upgrades included the inner Time Projection Chamber (iTPC), the end-cap Time-of-Flight (eTOF) system, and the Event Plane Detector (EPD) for the beam energy scan program. These upgrades significantly increased the acceptance and tracking capabilities of the STAR experiment. The PHENIX Collaboration has finished taking data in the year 2016 and they are currently analyzing the collected large statistics data. It has central and muon arms for particle identification and tracking in a wide range of azimuthal and rapidity coverage. The PHENIX experiment is recently upgraded to sPHENIX to precisely quantify properties of the QGP matter created in high-energy collisions at the RHIC. The STAR and the sPHENIX experiments are presently the only active experiments at the RHIC.

3. Collective flow results

Collective flow refers to the azimuthal anisotropy of produced particles in the momentum space. This phenomenon has been observed in relativistic heavy-ion collision experiments. It can be measured using the Fourier decomposition of the azimuthal angle (ϕ) distribution of produced particles with respect to the angle of the reaction plane (Ψ_n). The coefficients obtained from this decomposition, denoted as v_n, are commonly known as flow coefficients. Specifically, the first three coefficients are referred to as directed flow (v_1), elliptic flow (v_2), and triangular flow (v_3). These flow coefficients are extensively studied to gain insights into the properties of the QGP [7, 8].

3.1. Collectivity at high-μ_B

Figure 2 presents the slope of v_1 at mid-rapidity *versus* collision energy for identified particles (left panel) and light and hyper-nuclei (right panels) in Au+Au collisions from the STAR experiment at RHIC [9–11]. The slope decreases for hadrons and light and hyper-nuclei from $\sqrt{s_{NN}} = 3$ to 4 GeV. The Jet AA Microscopic (JAM) transport model, incorporating a momentum-dependent baryonic mean-field potential and incompressibility $k = 210$ MeV, describes the measured v_1 slope for baryons [12], suggesting a strong mean field at the high-μ_B region. The JAM model with coalescence is also consistent with $\mathrm{d}(v_1/A)/\mathrm{d}y$ for light and hyper-nuclei, indicating coalescence as their particle production mechanism at high-μ_B.

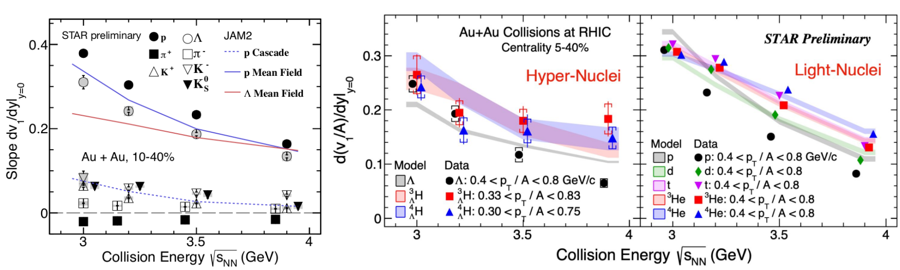

Fig. 2. Left: Slope $\mathrm{d}v_1/\mathrm{d}y$ for identified hadrons. Right: $\mathrm{d}(v_1/A)/\mathrm{d}y$ for light and hyper-nuclei, as a function of collision energy at mid-rapidity in Au+Au collisions from the STAR experiment at RHIC [9–11].

Figure 3 shows v_2 as a function of transverse kinetic energy scaled by NCQ for identified hadrons in 10–40% central Au+Au collisions from the STAR experiment at RHIC. The negative v_2 values and the violation of NCQ scaling below $\sqrt{s_{NN}} \leq 3.2$ GeV indicate a transition from a medium dominated by partonic degrees of freedom to hadronic degrees of freedom [13].

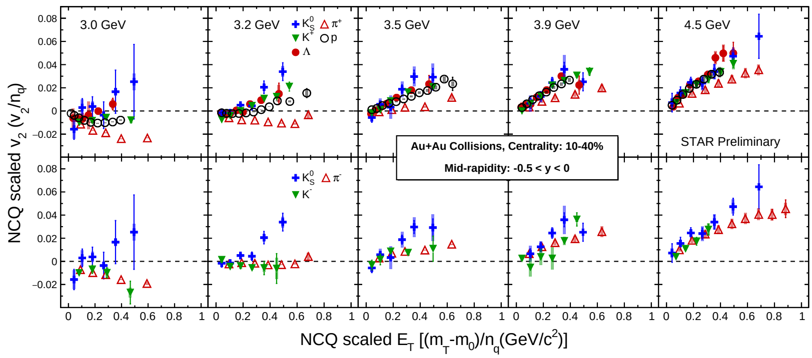

Fig. 3. NCQ scaled elliptic flow (v_2/n_q) as a function of NCQ scaled transverse kinetic energy $(m_\mathrm{T} - m_0)/n_q$ for identified hadrons in 10–40% central Au+Au collisions from the STAR experiment at RHIC.

3.2. *Collectivity in small systems*

Figure 4 shows v_n ($n = 2$ and 3) of charged hadrons and v_2 of π and p as a function of transverse momentum (p_T) within $|\eta| < 0.35$ in 0–5% central collisions at $\sqrt{s_{NN}} = 200$ GeV across three different small systems (p+Au, d+Au, and ^{3}He+Au) from the PHENIX experiment at RHIC [14, 15]. The results are compared with hydrodynamic model predictions with $\eta/s = 0.08$, indicating QGP formation and provide a simultaneous description of the data in all three systems.

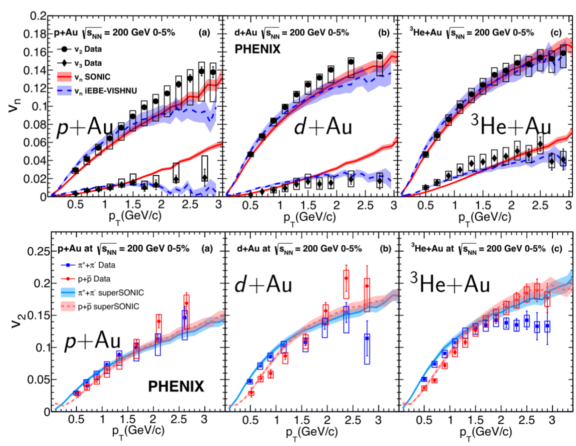

Fig. 4. Elliptic flow of (top) charged hadrons, (bottom) π and p as a function of transverse momentum within $|\eta| < 0.35$ in 0–5% central p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the PHENIX experiment at RHIC [14, 15].

3.3. Open heavy flavor flow

Figure 5 shows $v_2(p_\mathrm{T})$ of muons from heavy flavor decays at forward rapidities in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the PHENIX experiment at RHIC [16]. This is the first-ever measurement of open heavy-flavor elliptic flow at forward rapidities by the PHENIX experiment at RHIC. The results are consistent with $v_2(p_\mathrm{T})$ of electrons from heavy-flavor decays within $|\eta| < 0.35$ (shown with open circles). These new measurements of azimuthal anisotropies of open heavy flavor can provide quantitative constraints on the properties of the medium created in heavy-ion collisions.

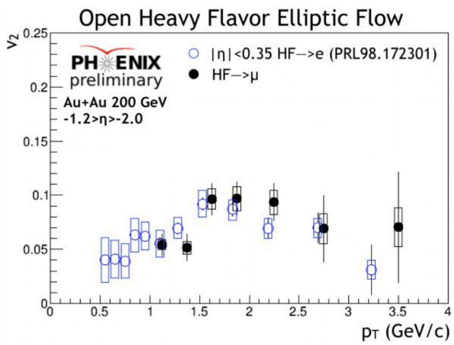

Fig. 5. Elliptic flow $v_2(p_\mathrm{T})$ of muons at forward rapidities and electrons at $|\eta| < 0.35$ from heavy flavor decays in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the PHENIX experiment at RHIC [16].

4. Summary

In summary, a few selected measurements on collective flow in Au+Au collisions from the STAR and PHENIX experiments at RHIC are presented. The results encompass azimuthal anisotropy coefficients of charged and identified hadrons, light and hyper-nuclei, and open heavy flavor. We discuss the potential implications of these findings for the formation of the QGP medium and the parton–hadron phase transition in the QCD phase diagram. Additionally, various model expectations are explored to gain insight into the underlying physics mechanisms. Finally, these measurements offer valuable quantitative constraints on the collective properties of the medium formed in heavy-ion collisions.

S.K. acknowledges partial support from the Agencia Nacional de Investigación y Desarrollo de Chile (ANID), Chile, with the grants ANID PIA/APOYO AFB230003, Chile, and ANID FONDECYT regular No. 1230987, Chile.

REFERENCES

[1] D.J. Gross, R.D. Pisarski, L.G. Yaffe, *Rev. Mod. Phys.* **53**, 43 (1981).

[2] E.V. Shuryak, J.J.M. Verbaarschot, *Nucl. Phys. B* **364**, 255 (1991).

[3] NA60+ Collaboration (A. De Falco), *EPJ Web Conf.* **259**, 09003 (2022), arXiv:2108.11300 [nucl-ex].

[4] HotQCD Collaboration (A. Bazavov *et al.*), *Phys. Lett. B* **795**, 15 (2019), arXiv:1812.08235 [hep-lat].

[5] STAR Collaboration (K.H. Ackermann *et al.*), *Nucl. Instrum. Methods Phys. Res. A* **499**, 624 (2003).

[6] PHENIX Collaboration (K. Adcox *et al.*), *Nucl. Instrum. Methods Phys. Res. A* **499**, 469 (2003).

[7] S.A. Voloshin, A.M. Poskanzer, R. Snellings, *Landolt-Bornstein* **23**, 293 (2010), arXiv:0809.2949 [nucl-ex].

[8] A.M. Poskanzer, S.A. Voloshin, *Phys. Rev. C* **58**, 1671 (1998), arXiv:nucl-ex/9805001.

[9] STAR Collaboration (M.S. Abdallah *et al.*), *Phys. Lett. B* **827**, 137003 (2022), arXiv:2108.00908 [nucl-ex].

[10] STAR Collaboration (B. Aboona *et al.*), *Phys. Rev. Lett.* **130**, 21 (2023), arXiv:2211.16981 [nucl-ex].

[11] STAR Collaboration (M.S. Abdallah *et al.*), *Phys. Lett. B* **827**, 136941 (2022), arXiv:2112.04066 [nucl-ex].

[12] Y. Nara, A. Ohnishi, *Phys. Rev. C* **105**, 014911 (2022), arXiv:2109.07594 [nucl-th].

[13] STAR Collaboration (J. Adam *et al.*), *Phys. Rev. C* **103**, 034908 (2021), arXiv:2007.14005 [nucl-ex].

[14] PHENIX Collaboration (A. Adare *et al.*), *Phys. Rev. C* **97**, 064904 (2018), arXiv:1710.09736 [nucl-ex].

[15] PHENIX Collaboration (C. Aidala *et al.*), *Nature Phys.* **15**, 214 (2019), arXiv:1805.02973 [nucl-ex].

[16] C. Nattrass, *EPJ Web Conf.* **296**, 01006 (2024).