RESULTS FROM THE BES PROGRAM AT RHIC*

Hanna Paulina Zbroszczyk

Warsaw University of Technology, Faculty of Physics
Koszykowa 75, 00-662 Warsaw, Poland

Received 31 July 2022, accepted 9 September 2022, published online 14 December 2022

A significant goal of high-energy nuclear collisions is to determine the Quantum Chromodynamics phase diagram for the strongly interacting matter. The most experimentally accessible way to characterize the QCD phase diagram is to scan it in temperature and the baryon chemical potential. The hadronic matter exists in a state where quarks and gluons are confined in composite particles. At high-energy densities, QCD predicts a phase transition from a hadronic gas to a state of deconfined matter — the quark–gluon plasma. In a hot and dense state, QCD matter is melted into quarks, and the strong interaction becomes dominant. The QCD-based models predict a first-order phase transition and the existence of a critical point at a higher μ_B. However, the exact locations of the first-order phase transition and the critical point are still unknown. In order to study the QCD phase structure experimentally, the Beam Energy Scan program at RHIC was proposed. In these proceedings, the current status of the BES program at RHIC is presented.

DOI:10.5506/APhysPolBSupp.16.1-A18

1. Introduction

The hadronic matter is defined as a state in which the fundamental constituents, quarks, and gluons are confined in composite particles: baryons and mesons. At high-energy densities, Quantum Chromodynamics (QCD) predicts a phase transition [1] from a hadron gas (HG) to a state of deconfined, partonic matter called the quark–gluon plasma (QGP). Under extreme conditions, QCD matter, the hadrons are melted into their constituent quarks, and the strong interaction becomes the dominant feature of physics. The most experimentally accessible way to determine the QCD phase diagram is in the plane of temperature (T) and the baryon chemical potential (μ_B).

* Presented at the 29$^{\rm th}$ International Conference on Ultrarelativistic Nucleus–Nucleus Collisions: Quark Matter 2022, Kraków, Poland, 4–10 April, 2022.

Figure 1 shows a schematic layout of the BES phases and hypothesized indications of the areas crossed in the early stages of nuclear collisions at various beam energies. For the last decades, many theoretical and experimental efforts have been devoted to studying the properties of strongly interacting matter described by the QCD phase diagram. At Large Hadron

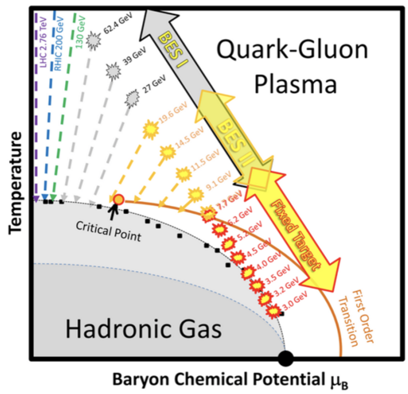

Fig. 1. Schematic view of the QCD phase diagram [2].

Collider (LHC) and top Relativistic Heavy Ion Collider (RHIC) energies, the explored matter is described by high T and low μ_B, and exists in the state of QGP. HG's transition to QGP is found to be of the smooth cross-over type. Many other areas of the QCD phase diagram, for significantly lower T and higher μ_B values are currently being explored by the HADES experiment conducted at Heavy Ion Synchrotron SIS18 at GSI and will be studied in the future by the CBM experiment at FAIR, currently under construction. Two experiments conducted at RHIC are: STAR and PHENIX study areas of the phase diagram for intermediate T and μ_B. In this region, the phase transition from HG to QGP could be the first order and ends at a critical point (CP). However, the CP has not been discovered yet, and its location is still unknown. The Beam Energy Scan (BES) program at RHIC, performed at Brookhaven National Laboratory, was proposed to explore unknown areas of the QCD phase diagram. The main questions regarding the BES program are the following:

— Search for turn-off QGP signatures;
— Search for signals of the first-order phase transition;
— Search for QCD CP;
— Search for signals of chiral symmetry restoration.

The research strategy is to map the QCD phase diagram with the collisions of heavy ions using Au nuclei, changing their collision energy. The STAR experiment participates in the BES program, which consists of phases:

— BES-I (collider mode), covers collision energy $\sqrt{s_{NN}} = 7.7$–62.4 GeV;

— BES-II (collider mode), covers collision energy $\sqrt{s_{NN}} = 7.7$–19.6 GeV with higher collected statistics;

— FXT (fixed-target mode), covers collision energies $\sqrt{s_{NN}} = 3.$–7.7 GeV (as RHIC is unable to operate at the collider mode below $\sqrt{s_{NN}} = 7.7$ GeV).

In Fig. 2, a perfect particle identification of many particle species for both modes of STAR: collider and fixed-target, can be seen.

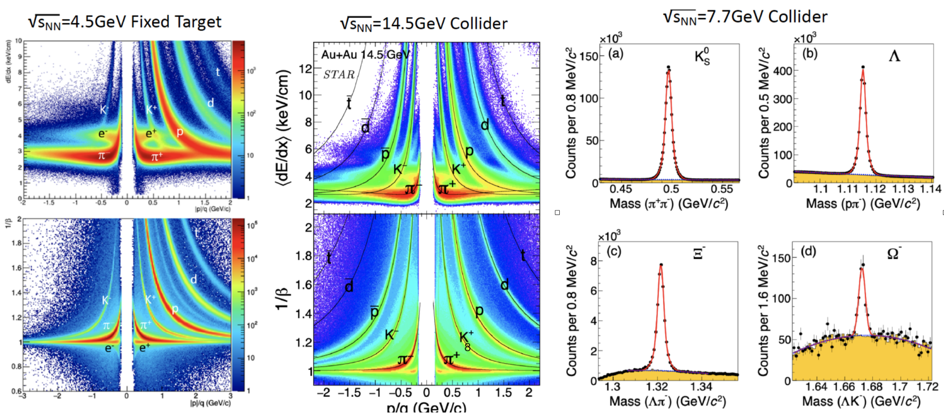

Fig. 2. Primary particle identification measured in the fixed-target mode for $\sqrt{s_{NN}} = 4.5$ GeV (left), collider mode for $\sqrt{s_{NN}} = 14.5$ GeV (middle), and the particle identification for weakly decayed particles for $\sqrt{s_{NN}} = 7.7$ GeV (right).

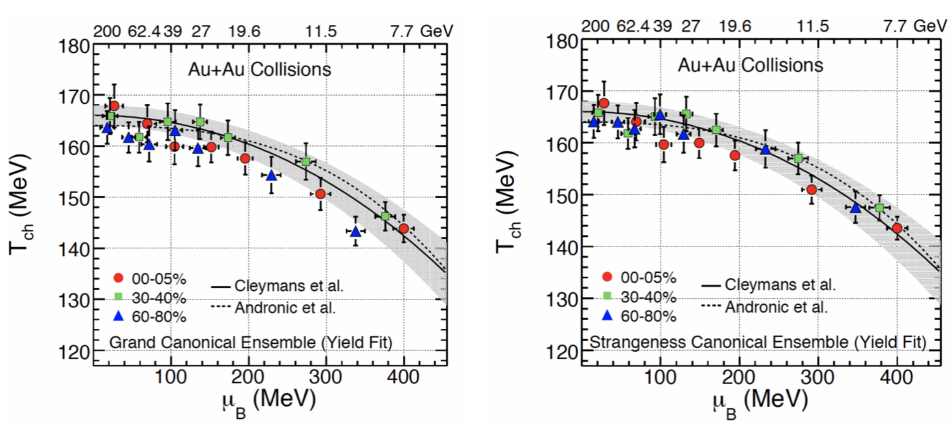

Fig. 3. T_{ch} and μ_B according to Grand Canonical Ensemble (left) and Strangeness Canonical Ensemble (right) [3].

Information about the $T_{\rm ch}$ and μ_B can be considered having extracted particle yields with the THERMUS model assuming Grand or Strangeness Canonical ensemble; they are shown in Fig. 3. From the BES-I phase, the μ_B is between 20 and 420 MeV, and from BES-II (including the FXT program), between 200 and 720 MeV.

2. Results

2.1. Onset of QGP

One of the fascinating BES-I results is the observation of the charge separation. In the presence of a strong magnetic field, when the system is deconfined, the chiral symmetry restoration is reached. Chiral symmetry breaking and the origin of hadrons masses are related to the existence of gluons field. Quarks' interaction with gluon fields can change the quark's chirality and may lead to the Local Parity Violation (LPV) phenomena, seen as the Chiral Magnetic Effect (CME) with separation of the charges along the angular momentum axis. Figure 4 shows the charge separation as a function

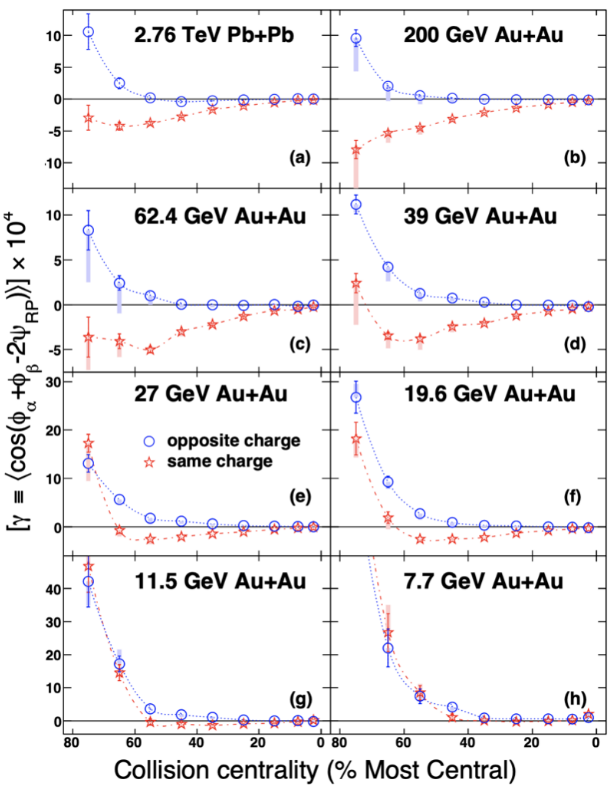

Fig. 4. Two-particle correlator as a function of collision centrality for various $\sqrt{s_{NN}}$ between 7.7 and 2760 GeV [4].

of the collision centrality for collision energies $\sqrt{s_{NN}} = 7.7$–2760 GeV. The splitting between the same- and the opposite-sign charges decreases with decreasing the collision energy and disappears below $\sqrt{s_{NN}} = 11.5$ GeV indicating the exiting of the partonic world.

In non-central collisions, the initial spatial anisotropy leads to the final momentum anisotropy. It can be measured as v_n coefficients extracted from the single-particle distributions of their momentum. v_2/n_q plotted as a function of the transverse kinetic energy of the particle for higher collision energies shows characteristic scaling with the number of constituent quarks (Fig. 5). In contrast, for lower collision energy ($\sqrt{s_{NN}} = 3$ GeV), v_2 becomes negative and the universal scaling is broken. $v_2 > 0$ is interpreted as the formation of the QGP, while $v_2 < 0$ shows hadronic interactions to be dominant.

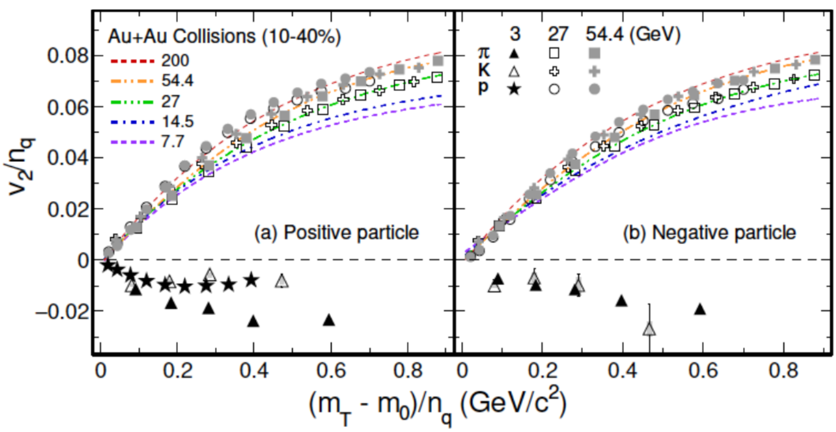

Fig. 5. v_2/n_q as a function of transverse kinetic energy shows clear dependence of scaling at high-energy domain and the lack of scaling for $\sqrt{s_{NN}} = 3$ GeV indicating the entrance to the hadronic interaction domain [5].

2.2. First-order phase transition

Two-particle correlations are sensitive to the geometry and dynamic properties of the system. Radii extracted from the analysis of pairs of identical charged pions seen as $R^2_{\rm out} - R^2_{\rm side}(\sqrt{s_{NN}})$ are sensitive to the emission duration. There is a visible peak around $\sqrt{s_{NN}} = 20$ GeV (Fig. 6) indicating the existence of the critical behavior.

2.3. Search for the CP

Fluctuations of conserved quantities (B, Q, S) and higher-order cumulants have been proposed as a signature of the CP. Near the QCD CP, the

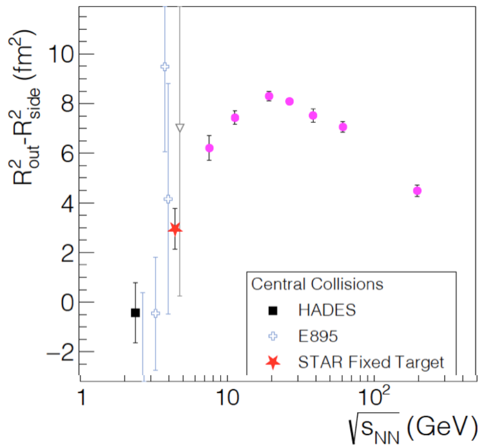

Fig. 6. $R^2_{\mathrm{out}} - R^2_{\mathrm{side}}(\sqrt{s_{NN}})$ shows a peak at $\sqrt{s_{NN}} \simeq 20$ GeV indicating the critical behavior [6].

divergence of the correlation length is expected. Non-monotonic correlations and fluctuations related to conserving quantities can indicate the CP. Figure 7 shows non-monotonic tendency as the function of $\sqrt{s_{NN}}$ for the most central and peripheral collisions separately. The suppression of $C_4/C_2 = \kappa\sigma^2$ (κ — kurtosis, σ^2 — variance of the multiplicity distributions for net-proton) is consistent with fluctuations driven by baryon number conservations indicating a hadronic interaction dominated in the region of $\sqrt{s_{NN}} = 3$ GeV. In conclusion, if the QCD CP exists, it could be located at $\sqrt{s_{NN}} > 3$ GeV.

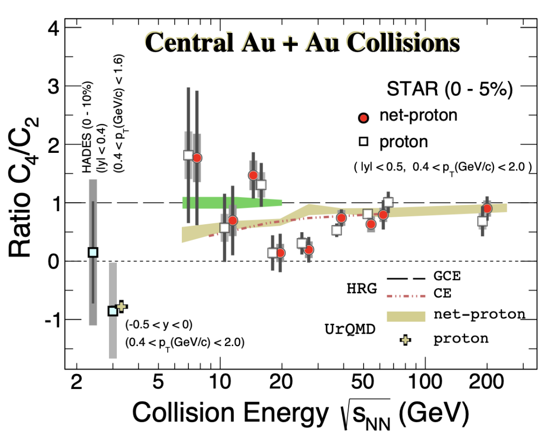

Fig. 7. C_4/C_2 as a function of $\sqrt{s_{NN}}$ showing the critical fluctuations of net-protons for the most 5% Au–Au collisions [7].

2.4. Chiral symmetry restoration

The properties of chemical and thermal freeze-out can be determined with yields and transverse momentum distributions of hadrons. Electro-Magnetic (EM) probes (photons, leptons) are emitted from the early to the final stages of the heavy-ion collision; they carry original information of the emission source and probe earlier and hotter phases of the medium. The mass spectrum of thermal dileptons reveals the temperature of the hot medium at both QGP and hadronic phase. The temperature of the hadronic medium can be extracted from the low mass region (LMR: $M_{ee} < 1.1~\mathrm{GeV}/c^2$) and the temperature of QGP from the intermediate mass region (IMR: $M_{ee} > 1.1~\mathrm{GeV}/c^2$. It is shown in Fig. 8 that $T^{\mathrm{LMR}} \simeq 170$ MeV is the first experimental evidence that in-medium ρ (hadronic matter) is dominantly produced about the temperature higher than the phase transition is predicted. $T^{\mathrm{IMR}} \simeq 300$ MeV shows the first measurement of the QGP temperature.

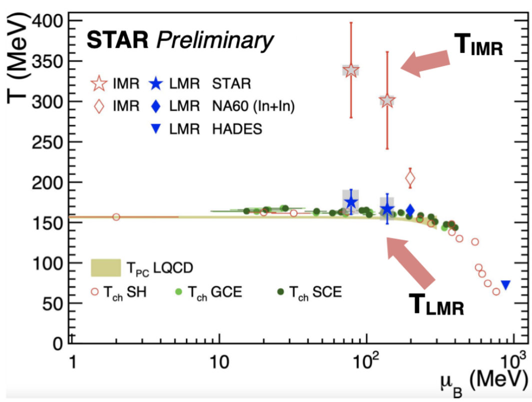

Fig. 8. T and μ_B for the STAR, HADES and NA60 experiments, indicating the first measurement of the QGP temperature performed by STAR [5].

3. Summary

The measurements of the BES program cover a significant area of the QCD phase diagram. Among the main goals there are: search for the onset of QGP, the signatures of the first-order phase transition, the CP, and signals of chiral symmetry restoration; it is clear that just a partial answer has been obtained so far. The BES-II is expected to provide definitive answers to the remaining questions.

This work was supported by the National Science Centre, (NCN) Poland grants No. 2021/41/B/ST2/02409 and No. 2020/38/E/ST2/00019. Studies were funded by IDUB-POB-FWEiTE-3, a project granted by the Warsaw University of Technology under the program Excellence Initiative: Research University (ID-UB).

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