PROCEEDINGS OF SCIENCE

Results from the Beam Energy Scan program at STAR

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A significant goal of high-energy nuclear collisions is to determine the Quantum Chromodynamics (QCD) phase diagram for the strongly interacting matter. The most experimentally accessible way to characterize the QCD phase diagram is to scan in temperature (T) and the baryon chemical potential (μ_B). The hadronic matter exists in a state where the fundamental constituents, 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 (QGP). In hot and dense state QCD matter is melted into their constituent quarks, and the strong interaction becomes dominant. In addition, a chiral phase transition is predicted. QCD-based models predict a first-order phase transition and the existence of a critical point (CP) at higher μ_B. However, the exact locations of the first-order phase transition and the CP are still unknown. Experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have provided compelling evidences of the formation of a QGP matter close to $\mu_B = 0$. In order to study the QCD phase structure experimentally as a function of T and μ_B, the Beam Energy Scan (BES) program at RHIC was proposed. Several collision energies are used to create systems described by various initial coordinates of T and μ_B. The experimental goals of the BES program are the following: search for threshold energies for the QGP signatures, search for signatures of a first-order phase transition, search for a CP, and search for possible signatures of chiral symmetry restoration. In these proceedings we present the current status of the BES program at the STAR experiment.

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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, 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).

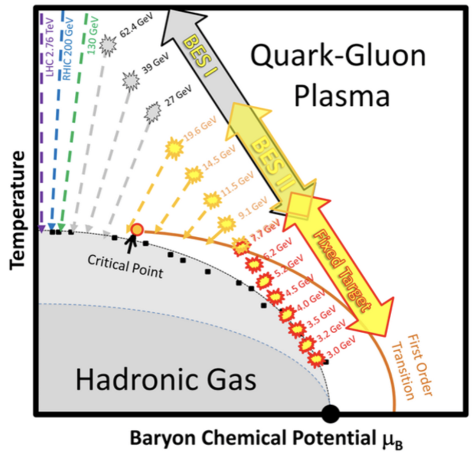

Figure 1: Schematic view of the QCD phase diagram [2]

Figure 1 shows a schematic layout of the QCD 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 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. A transition from HG to QGP is found to be of smooth cross-over type. Many other areas of the QCD phase diagram, for significantly lower T and higher μ_B values currently being explored by the HADES experiment conducted at Heavy Ion Synchrotron SIS18 at GSI, will be studied in the future by CBM experiment at FAIR, currently under construction. Two experiments were conducted at RHIC: STAR and PHENIX also 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. 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 and detector upgrade,
- FXT (fixed-target mode), covers collision energies $\sqrt{s_{NN}} = 3.0 - 7.7$ GeV (as RHIC is unable to operate at the collider mode below $\sqrt{s_{NN}} = 7.7$ GeV), STAR has inserted a gold target into the beam pipe.

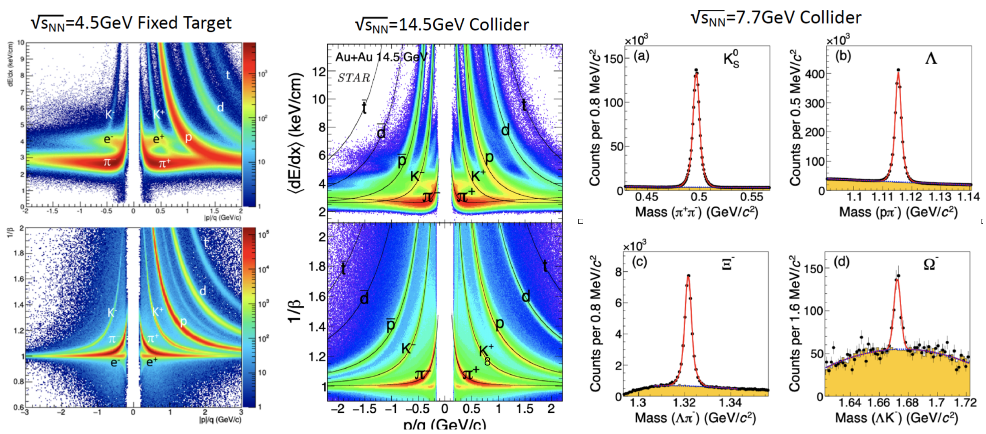

Figure 2: Primary particle identification measured in the fixed-target mode for $\sqrt{s_{NN}} = 4.5$ GeV (left), collider mode for $\sqrt{s_{NN}} = 14.5$ GeV (middle), and the particle identification for weakly decayed particles for $\sqrt{s_{NN}} = 7.7$ GeV.

In Fig. 2, an excellent particle identification of many particle species for both modes of STAR: collider and fixed-target, can be seen. Information about the T_{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 Search for the first order phase transition and CP

In non-central collisions, the initial spatial anisotropy leads to the final momentum anisotropy. It can be measured as v_n coefficients extracted from 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 n_q (Fig. 4). In contrast, for lower collision energy ($\sqrt{s_{NN}} = 3$ GeV - hadronic dominated), v_2 becomes negative and the

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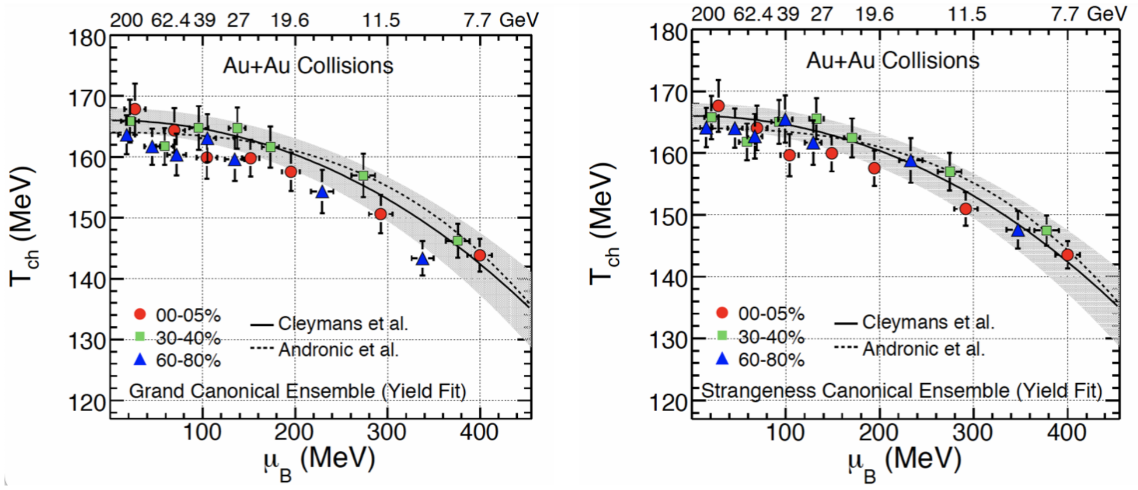

Figure 3: T_{ch} and μ_B according to Grand Canonical Ensemble (left) and Strangeness Canonical Ensemble (right) [3]

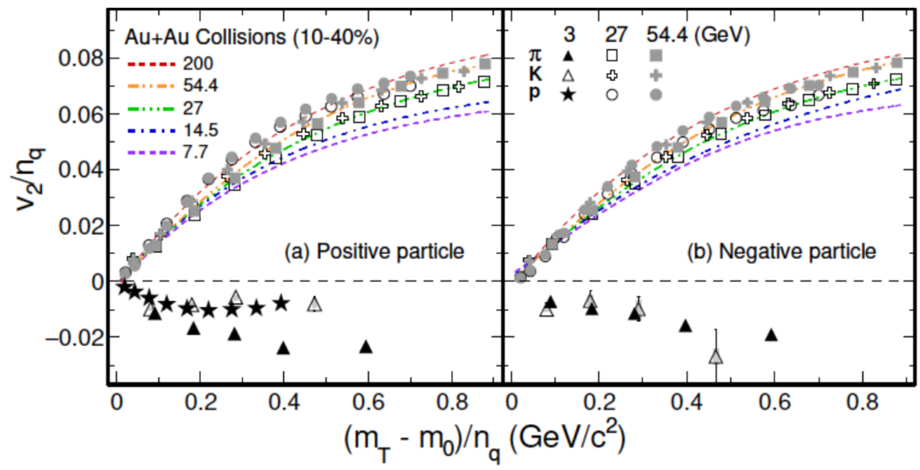

Figure 4: v_2/n_q as a function of transverse kinetic energy shows clear dependence of scaling at high energy domain and the lack of scaling for $\sqrt{s_{NN}}$ = 3 GeV indicating the entrance to the hadronic interaction domain [4].

universal scaling is broken. $v_2 > 0$ is interpreted as the pressure-gradient driven expansion, while $v_2 < 0$ indicates squeeze-out emission due to spectator shadowing.

Identical 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 $R^2_{out} - R^2_{side}(\sqrt{s_{NN}})$ are sensitive to the emission duration (R_{out} is the source's radius directed along the transverse pair direction, R_{side} is the source's radius in the direction perpendicular to the beam axis and to the *out* component). There is a visible peak around $\sqrt{s_{NN}}$ = 20 GeV (Fig. 5) indicating the first order phase transition.

Fluctuations of conserved quantities (B, Q, S) and higher-order cumulants have been proposed as a useful tool to search for the CP. Near the QCD CP, the divergence of the correlation length is expected. Non-monotonic correlations and fluctuations related to conserving quantities can indicate

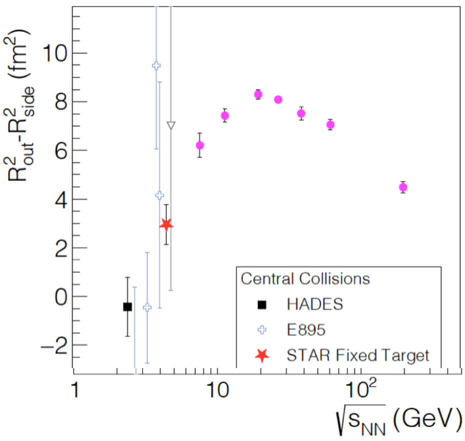

Figure 5: $R^2_{out} - R^2_{side}(\sqrt{s_{NN}})$ shows a peak at $\sqrt{s_{NN}} \simeq 20$ GeV indicating the critical behavior [5]

the CP. Fig. 6 shows (net-)proton cumulant ratio and its non-monotonic tendency as a function of $\sqrt{s_{NN}}$ for the most central collisions. The suppression of $C_4/C_2 = \kappa\sigma^2$ (κ - kurtosis, σ^2 - variance of the multiplicity distributions for proton) is consistent with fluctuations driven by baryon number conservations indicating a hadronic interaction dominated in the region of $\sqrt{s_{NN}} = 3$ GeV (Fig. 6). In conclusion, if the QCD CP exists, it could be located at $\sqrt{s_{NN}} > 3$ GeV.

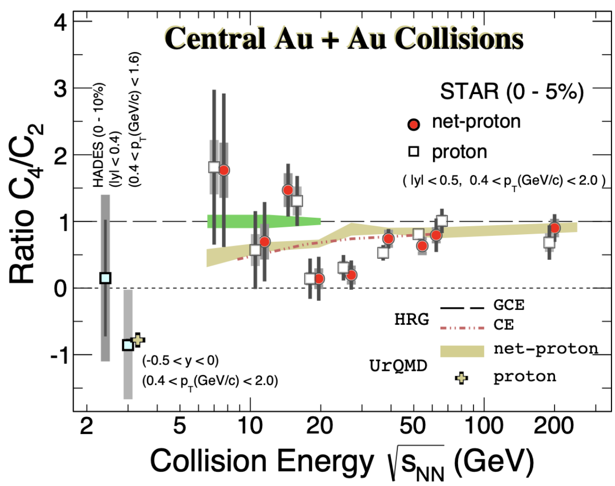

Figure 6: C_4/C_2 as a function of $\sqrt{s_{NN}}$ showing the critical fluctuations of net-protons for the most 5% Au-Au collisions [6]

2.2 Electromagnetic probes

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. Mass spectrum of thermal dileptons reveals the temperature of the hot medium at both QGP and hadronic phases. The temperature of the hadronic medium can be extracted from the Low Mass Region (LMR: $M_{ee} < 1.1$ GeV/c^2) and the temperature of QGP from the Intermediate Mass Region (IMR: $M_{ee} > 1.1$ GeV/c^2). $T^{IMR} \simeq 300$ MeV shows the first measurement of the QGP temperature based on measurements from $Au - Au$ colilsions at $\sqrt{s_{NN}} = 27$ and 54.4 GeV (Fig. 7). These parameters are compared to temperature extracted based on Grand Canonical Ensemble (GCE), Strangeness Canonical Ensemble (SCE), and the Statistical Hadronization (SH).

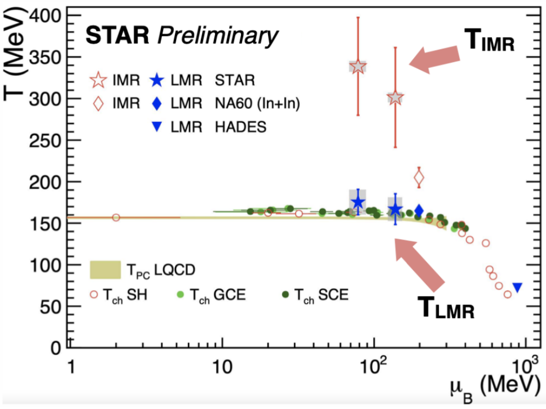

Figure 7: T and μ_B from STAR, HADES and NA60 experiments, indicating the first measurement of the QGP temperature performed by STAR [4]

3. Summary

The measurements of the BES program cover a significant area of the QCD phase diagram. Among the main goals: search for 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.

4. Acknowledgments

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