The RHIC Beam Energy Scan Phase II: Physics and Upgrades

DAVID Tlustý

Department of Physics and Astronomy
Rice University, Houston, TX, USA

The exploration of the QCD phase diagram has been one of the main drivers of contemporary nuclear physics. The Relativistic Heavy Ion Collider (RHIC) at BNL is uniquely suited for this task through its Beam Energy Scan (BES) program which allowed for a large range in baryon chemical potential $\mu_B$ as was successfully demonstrated after the completion of Phase 1 in 2014. Phase 2 of the BES at RHIC is scheduled to start in 2019 and will explore with precision measurements the intermediate-to-high $\mu_B$ region of the QCD phase diagram, five energies $\sqrt{s_{NN}}$ from 7.7 to 19.6 GeV in collider mode and eight energies $\sqrt{s_{NN}}$ from 3.0 to 7.7 GeV in fixed-target mode. Some of the key measurements are: the net-protons kurtosis that could pinpoint the position of a critical point, the directed flow that might prove a softening of the EOS, and the chiral restoration in the dielectron channel. These measurements will be possible with an order of magnitude better statistics provided by the electron cooling upgrade of RHIC and with the detector upgrades planned to improve STAR’s acceptance. These proceedings review the BES Phase-2 program and the physics opportunities enabled by these upgrades.

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1 Introduction

The first decade of operation of the Relativistic Heavy Ion Collider (RHIC) was dedicated mostly to Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Those measurements accumulated enough evidence in support of a deconfined partonic phase on nuclear matter in the early stages of heavy ion collisions when temperatures are higher than the critical temperature $T_c$ [1, 2, 3, 4]. The deconfined matter, when interactions among quark and gluons are weak enough due to asymptotic freedom, is called the Quark Gluon Plasma (QGP). Finite temperature lattice Quantum Chromodynamics (QCD) calculations predict [5] a cross-over from a hadronic to a QGP phase at a vanishing baryon chemical potential $\mu_B$ and $T_c = 154 \pm 9$ MeV [6]. Several QCD-based calculations [7, 8] show that at lower $T$ and higher $\mu_B$ a first-order phase transition may take place. The point in the QCD phase diagram, where the first-order phase transition ends, is the QCD critical point [9]. Our current understanding of nuclear matter is illustrated by a conceptual phase diagram shown in Fig. 1. It depicts the estimated position of the critical point at $\mu_B = 400$ MeV, but we cannot exclude the possibility that a crossover extends to even higher baryon chemical potentials.

The second decade of RHIC operations included the first phase of the Beam Energy Scan (BES-I) program with the intent to map out the QCD phase diagram, whose goals are [11]

1. to investigate the expected turn-off of QGP signatures that have been established at $\sqrt{s_{NN}} = 200$ GeV.

2. to search for the predicted first-order phase transition [7, 8] between the hadronic and QGP phase. A promising observable for this is the directed flow since it is a proxy for the pressure in a hydrodynamic picture. Some models [10, 12] then predict a dramatic drop in the pressure equivalent to a softening of the Equation of State (EoS) when a first-order phase transition occur.

3. to search for a critical end point, which is expected to exist if the QCD phase diagram includes a first-order phase transition. A macroscopic system at the critical point would show observable effects such as critical opalescence and hence the characteristic length scale (the correlation length) would become infinite. Theory suggests [13] that even in small systems such as in heavy-ion collisions, the local increase in fluctuations near the critical point could be observed experimentally.

4. to search for chiral symmetry restoration which affects mass and width of the $\rho(770), \omega(782)$, and $\phi(1020)$ vector mesons that can be studied via dilepton decays.

The end of the second decade of RHIC operations will be dedicated to a second phase of the BES program (BES-II) program [11]. Its main goal is to revisit the
Figure 1: A conceptual QCD phase diagram, showing the relevant regions in the plane of temperature versus $\mu_B$. Various details, especially the position of the critical point, still remain uncertain. Figure taken from Ref. [14].

Promising signals from BES-I with greatly improved statistics and performance of detectors. Using the RHIC beams in a fixed-target mode will extend the $\mu_B$ further to 720 MeV. The improved physics capability will come partly from three detector upgrades, and partly from RHIC beam luminosity increase.

The STAR detector [15] has been designed to study polarized proton heavy-ion collisions at RHIC. STAR offers uniform acceptance in azimuthal angle, larger acceptance in transverse momentum in the mid-rapidity ($-1 < y < 1$) region, and operability in both collider and fixed-target mode. Its large mid-rapidity coverage is very well suited for the BES physics program. In the collider mode, changes in STAR’s acceptance could be considered negligible which is crucial especially in the fluctuations measurements. STAR is further capable of excellent particle identification through $dE/dx$ in its Time Projection Chamber (TPC) [16] and Time-of-Flight (TOF) [17].

These proceedings will discuss some of the remarkable results regarding the QCD phase diagram exploration from BES-I followed by detector upgrades and expected improvements in anticipation of BES-II.
Figure 2: Energy dependence of cumulant ratios $S\sigma$ (left panel), $\kappa\sigma^2$ (right panel) of net-proton, net-charge, and net-kaon multiplicity distributions for the Au+Au collision at $\sqrt{s_{NN}} = 7.7$ to 200 GeV. The solid markers represent the results from the STAR measurement, the open markers represent results from the UrQMD calculation. The dashed lines denote the Poisson expectations for the STAR data. Figure taken from Ref. [18].

2 Selection of BES-I Measurements

2.1 Cumulant Ratios of Net-proton(kaon) Multiplicity

Fluctuations of conserved quantities, such as baryon, electric charge, and strangeness number, are sensitive observables in the study of phase transitions in the QCD matter and critical point [18]. Those fluctuations are studied in limited rapidity window which makes them observable [19]. Statistical moments of multiplicity distributions like skewness, $S \propto \langle (N - \langle N \rangle)^3 \rangle$ and kurtosis, $\kappa \propto \langle (N - \langle N \rangle)^4 \rangle$ are of particular interest since they are sensitive enough to the correlation length ($\kappa$ to the seventh power for example) given the limited statistics. Furthermore, products $\kappa\sigma^2$ and $S\sigma$ are directly related to the ratios of susceptibilities as

$$\kappa\sigma^2 = \frac{\chi_4}{\chi_2}, \quad S\sigma = \frac{\chi_3}{\chi_2}$$

which make them readily calculable by lattice QCD. Since the isospin susceptibility remains finite at the critical point, critical fluctuations in net-baryon number are reflected in the fluctuations of the net-proton number [20]. Net-kaon number is used as a
proxy for net-strangeness in terms of searching for non-monotonic energy dependence of the fluctuation observable near QCD critical point [21].

Figure 2 shows the energy dependence of cumulant ratios $S\sigma, \kappa\sigma^2$ of net-proton, net-charge, and net-kaon multiplicity distributions of the 5% most central Au+$\text{Au}$ collisions in RHIC BES-I energies from the STAR experiment [22, 23] and UrQMD calculations [18]. The non-monotonic energy dependence of the net-proton $\kappa\sigma^2$ and net-kaon $S\sigma$ contrasts with the monotonic behavior of UrQMD predictions which have not the critical physics implemented. In $\kappa\sigma^2$ of net protons, there is a minimum below the unity around $\sqrt{s_{NN}} = 20$ GeV and a steep rise with further decreasing $\sqrt{s_{NN}}$, ending $\sim 2$ standard deviations above unity. If $\kappa\sigma^2$ returns to the unity at $\sqrt{s_{NN}}$ below 7.7 GeV, this could suggest a critical point signature of the kind predicted by Stephanov [13]. This result makes a strong case for more data which STAR will collect in BES-II as well as exploration at $\sqrt{s_{NN}}$ below 7.7 GeV which will be achieved in the fixed-target mode.

2.2 Directed Flow of Net Protons

Directed flow is defined as the first harmonic coefficient in the Fourier expansion of the azimuthal angle distribution $\phi$ of final-state particles relative to the reaction plane azimuth $\Psi_R$, i.e. $v_1 = \langle \cos(\phi - \Psi_R) \rangle$ [24, 25, 26]. It can be interpreted as a collective sideward motion of the participant nucleons in heavy-ion collisions. It is built at early stages of a collision which makes it a very good proxy of the pressure in a colliding system, as suggested by nuclear transport [27, 28] and hydrodynamic [29] models. The excitation function of the directed flow slope with respect to rapidity $dv_1/dy$ is predicted to exhibit a minimum at a certain collision energy in hydrodynamical calculations using an EoS with a first-order QCD phase transition [30].

STAR’s BES-I measurement of the $dv_1/dy$ of net protons [31], shown in Fig. 3, reveals a non-monotonic behavior of $dv_1/dy$ near mid-rapidity with a minimum between 10 and 20 GeV and double-sign change. Qualitatively, this minimum was predicted by three-fluid hydrodynamic calculations [10, 12] only when the EoS has a first-order phase transition. However, other theoretical predictions such as Ref. [32] are ambiguous on the issue of whether a crossover or first-order phase transition reproduces STAR’s measurements better. The hadronic transport model JAM [30] reports a minimum in the case of a first-order phase transition, but the minimum is about an order of magnitude more pronounced and lies about a factor 3 lower in $\sqrt{s_{NN}}$. Hence the models need further development and experimental constrains from new directed flow measurements in finer centrality bins possible in BES-II.
Figure 3: Directed flow slope $dv_1/dy$ near midrapidity as a function of $\sqrt{s_{NN}}$ for net protons, net $\Lambda$, and net kaons in 10-40% centrality Au+Au collisions from STAR. Figure taken from Ref. [31].

3 Plans and Upgrades for BES-II

Three major STAR detector upgrades have been prepared in anticipation of RHIC BES-II. They are aimed at the reduction of systematic uncertainties and increase of STAR acceptance. At the same time, RHIC will improve its luminosity for low energy beams to increase statistics at low $\sqrt{s_{NN}}$ and reduce statistical uncertainties. The following paragraphs list and discuss those upgrades. Figure 4 shows the impact of those upgrades on $dv_1/dy$ (left plot) and net-proton $\kappa\sigma^2$ (right plot).

The Inner TPC (iTPC) upgrade [33] improves the spatial resolution of the TPC anodes which leads to better particle identification from $dE/dx$ ($\sim 25\%$ improvement), and better momentum resolution ($\sim 15\%$ improvement at larger momenta). Furthermore, it extends the pseudorapidity $\eta$ coverage from $(-1, 1)$ to $(-1.5, 1.5)$, which also extends acceptance at low transverse momenta, from $\sim 125$ MeV/$c$ to as low as 60 MeV/$c$. In addition, the tracking at higher $\eta$ is crucial for the endcap TOF (eTOF) (discussed below).

The Event Plane Detector (EPD) [34] is an entirely new subdetector that will improve the event plane resolution by about a factor of 2 in Au+Au collision at $\sqrt{s_{NN}} = 19.6$ GeV and about a factor of 3 at $\sqrt{s_{NN}} = 7.7$ GeV. It consists of two azimuthally symmetric scintillator telescopes with high radial and azimuthal segmentation and with a pseudorapidity coverage $2.1 < |\eta| < 5$. The EPD will allow the centrality and the event plane to be measured in the forward region, reducing systematics due to autocorrelations from mid-rapidity analyses. The left plot in Fig. 4 shows the improvement of net-proton directed flow measurements in BES-II with, and without EPD.
The eTOF [35] is a joint project of STAR and CBM collaborations for the BES-II program. It will cover the pseudorapidity region of $1.1 < \eta < 1.6$ and will improve particle identification in the $\eta$ acceptance region added by the iTPC. This will particularly benefit data from fixed-target collisions.

Net-proton $\kappa \sigma^2$ strongly depends on $p_T$ and rapidity cuts of protons [35]. A new approach has been proposed [35], where $\kappa \sigma^2$ is analysed as a function of the sum of the number of measured protons and anti-protons, as is shown in Fig. [35]. The STAR BES-I $\kappa \sigma^2$ for 7.7 GeV trend upward with total protons while for 19.6 GeV, the trend is downward. It is expected that the $\kappa \sigma^2$ signal will be large for energies that create systems near the critical point, while for systems with a baryon chemical potential below the critical point, the $\kappa \sigma^2$ will drop below unity. The added coverage of the eTOF will extend the measurement further in the sum of protons and anti-protons so the fluctuation signal will provide a clearer and more significant indication of critical behavior.

![Figure 4: Left plot: net-proton directed flow measured by STAR in BES-I [31] (red circles) and systematic error estimation done at two centre-of-mass energies (7.7 and 19.6 GeV) for BES-I, BES-II and BES-II with EPD upgrade. Plot taken from Ref [34]. Right plot: The net-proton $\kappa \sigma^2$ as a function of the proton and anti-proton multiplicity. Plot taken from Ref [35].](image)

At $\sqrt{s_{NN}} = 11.5$ GeV and below, RHIC will use its newly developed Low-energy RHIC Electron Cooler (LEReC) [36] which will increase the luminosity about a factor of 4. At $\sqrt{s_{NN}} = 14.5$ GeV and above, accelerator improvements involving bunch structure and $\beta^*$ which will increase the luminosity about a factor of 3.

RHIC luminosity in normal collider mode decreases like relativistic $\gamma^3$ at energies below AGS energies ($\sqrt{s_{NN}} = 27$ GeV), because the RHIC ring is used as a decelerator, thus $\sqrt{s_{NN}} = 7.7$ was set to be minimum in collider mode. Hence one of the RHIC beams was set to impact a gold fixed target inside the beam pipe at
the z-position of one end of the TPC. In 2015, STAR successfully collected more than 1M good Au+Au events during a 30 min fixed-target test run and demonstrated that with little beam time it can reproduce measurements from previous fixed-target experiment, such as E895, E877, and E892 [37].

During BES-I running, STAR has collected dielectron data for minimum-bias Au+Au collisions at $\sqrt{s} = 19.6, 27, 39, \text{ and } 62.4$ GeV. Below 19.6 GeV, the event size of the data sets have been too small to allow for meaningful measurements in the low-mass range of the dielectron spectrum. Estimated 10x higher statistics in BES-II (at $\sqrt{s} = 19.6$) will allow first measurements at energies below 19.6 [11].

4 Summary

We present two of the BES-I goals, namely, the search for a first-order phase transition through directed flow measurement and critical point through high-moments of net particle multiplicities. Directed flow of net-protons shows non-monotonic behavior and double sign change. It will be interesting to study the directed flow of other hadrons ($\Lambda, \bar{\Lambda}, K^0_S, K^\pm, \phi$) to disentangle the role of produced and transported quarks in heavy-ion collisions. High-moment fluctuations hint at a critical behavior, but need better statistics and extended $\sqrt{s_{NN}}$ coverage on the low side, possibly different analysis approach which was referred to in these proceedings.

BES-II provides a well defined plan for a focused study of the type of a phase transition and localization of the critical point. Presented detector upgrades will reduce systematic uncertainties and extend kinematical and PID range. RHIC facility upgrades will increase luminosity and fixed-target program will extend $\mu_B$ and $\sqrt{s_{NN}}$.

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