Recent results on event-by-event fluctuations from the RHIC Beam Energy Scan program in the STAR experiment

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Abstract. Event-by-event fluctuations of global observables in relativistic heavy-ion collisions are studied as probes for the QCD phase transition and as tools to search for critical phenomena near the phase boundary. Dynamical fluctuations in mean transverse momentum, identified particle ratios and conserved quantities (such as net-charge, net-baryon) are expected to provide signatures of a de-confined state of matter. Non-monotonic behavior in the higher-moments of conserved quantities as a function of beam energy and collision centrality are proposed as signatures of the QCD critical point. To study the QCD phase transition and locate the critical point, the STAR experiment at RHIC has collected a large amount of data for Au+Au collisions from √s_{NN} = 7.7 to 200 GeV in the RHIC Beam Energy Scan (BES) program. We present the recent beam energy scan results on dynamical fluctuations of particle ratios and two-particle transverse momentum correlations at mid-rapidity. Higher-moments of the net-charge and net-proton multiplicity distributions as a function of beam energy will be presented. We give a summary of what has been learnt so far and future prospectives for the BES-II program.

1. Introduction
Importance of the Event-by-Event (E-by-E) fluctuations in heavy-ion collisions has been studied and discussed in a series of papers [1, 2, 3, 4]. The E-by-E fluctuation observables could provide information about the QCD phase transition and a possible signature of QCD critical point. RHIC, at Brookhaven National Laboratory, started the Beam Energy Scan (BES) program since 2010 in order to explore the QCD phase diagram. The STAR experiment, at RHIC, has collected data at √s_{NN} = 39 GeV down to 7.7 GeV for this BES program.

2. RHIC Beam Energy Scan Program
The main goals of the BES program are to (1) locate the existence of the QCD critical point, (2) find evidence of the first order phase transition in the QCD Phase diagram, and (3) understand the properties of the QGP as a function of μ_B. The variation of RHIC colliding energy from √s_{NN} = 7.7 to 39 GeV, along with 62.4 and 200 GeV, covers the baryonic chemical potential from 410 to 20 MeV [5]. The RHIC beam energy scan program started in the year 2010 and the first phase of the beam energy scan has been finished in year 2014 with √s_{NN} = 14.5 GeV data taking. Details about the BES program are listed in Table 1.

The STAR experiment is able to measure various E-by-E observables to study the signatures of QGP-to-Hadron-Gas phase transition. Full 2π azimuthal coverage, enriched particle
identification capabilities and large uniform acceptance of STAR provides a suitable environment for the E-by-E characterizations of heavy-ion-collisions. In order to achieve the goals of the BES program, the STAR collaboration have analyzed various E-by-E fluctuation measures. For the search of QCD critical point, higher-moments of the conserved charge, like net-charge, net-protons (proxy for net-baryon) and net-kaon (proxy for net-strangeness) distributions, particle ratio fluctuation, and transverse momentum fluctuations have been analyzed. Dynamical charge fluctuations for the signature of QGP have been studied as well. An elaborate discussion can be found in the subsequent sections.

Table 1. Beam Energy Scan program details. The $\mu_B$ values are taken from Ref. [5]

| $\sqrt{s_{NN}}$ (GeV) | $\mu_B$ | Year | Events ($\times 10^6$) | Beam times (weeks) |
|-----------------------|---------|------|------------------------|-------------------|
| 39                    | 115     | 2010 | 130                    | 2.0               |
| 27                    | 155     | 2011 | 70                     | 1.0               |
| 19.6                  | 205     | 2011 | 36                     | 1.5               |
| 14.5                  | 206     | 2014 | 20                     | 3.0               |
| 11.5                  | 315     | 2010 | 12                     | 2.0               |
| 7.7                   | 420     | 2010 | 4                      | 4.0               |

3. Search for QCD Critical Point

Lattice QCD calculations reveal that at vanishing $\mu_B$, the transition from QGP to hadron gas is a simple crossover [6], whereas at large $\mu_B$, the phase transition is of first order [6, 7, 8, 9, 10, 11, 12, 13]. Therefore, one expects the existence of a critical point at the end of the first order phase transition. Search for the QCD critical point has been one of the major thrusts of the RHIC BES program.

At the critical point, thermodynamic susceptibilities and the correlation length ($\xi$) of the system are expected to diverge for large samples in equilibrium. The finite volume effect puts a constraint on the divergence of the thermodynamic susceptibilities and $\xi$ of the system. The phenomenon of critical slowing down in the vicinity of the critical point drives the system away from thermodynamic equilibrium, so $\xi$ reaches a maximum value of around $1.5 - 3$ fm [14, 15]. Besides these challenges, in heavy-ion-collision experiments, the signature of critical point could be observed if the critical point is close enough to the freeze-out curve [16]. Various observables such as, higher-moments of the conserved charge, transverse momentum fluctuations, particle ratio fluctuations, have been proposed in order to search for the QCD critical point. Detailed discussions about these analysis and their observables can be found in the following sections.

3.1. Higher-moments of net-charge and net-proton distributions

Moments of the conserved charge distributions (such as the mean ($M$), standard deviation ($\sigma$), skewness ($S$) and kurtosis ($\kappa$)) have been proposed as important observables for the signature of the QCD critical point in the current wisdom. The higher-moments of conserved charge distributions are related to the respective higher order thermodynamical susceptibilities and also $\xi$ of the system [15, 17]. In order to cancel the undetermined volume term in the higher-moments, ratio (or product) like $\sigma^2/M$, $S\sigma$, and $\kappa\sigma^2$ are used. The signature of non-monotonicity of these observables is expected if there is a nearby critical point in QCD phase transition. Recently, the STAR experiment reported net-charge [18] and net-proton [19] results from the BES program.

In an analysis of higher-moments, various sophisticated techniques, like the finite bin width effect [20], finite efficiency correction [21] for the higher-moments, have been incorporated. In order to get precise statistical uncertainty, different statistical error estimation methods (like
the Delta Theorem, Bootstrap method, etc.) have been thoroughly studied and utilized. On the other hand, new centrality definitions (like uncorrected charge multiplicity within $0.5 < |y| < 1.0$ for net-charge analysis and that of other than identified protons and antiprotons within pseudorapidity $|y| < 1.0$ for net-proton) have also been studied and implemented.

The positive ($N_+$) and negative ($N_-$) charged particle multiplicities are counted within $|y| < 0.5$ and $0.2 < p_T < 2.0 \text{ GeV}/c$ (after removing protons and anti-protons with $p_T < 400 \text{ MeV}/c$) to calculate net-charge ($N_+ - N_-$) in each event. The protons ($N_p$) and anti-protons ($N_{\bar{p}}$) are counted at mid-rapidity ($|y| < 0.5$) in the range $0.4 < p_T < 0.8 \text{ GeV}/c$. In addition to these, various track selection cuts have been used. Details about these cuts can be found elsewhere in Ref [19, 18]. Figure 1 shows the net-charge multiplicity distribution for BES energies along with the Skellam distribution (the difference of two Poisson distributions assuming $N_+$ and $N_-$ are independent Poisson distributions) [22]. The Skellam distribution qualitatively follows the data at all energies implying a weak correlation strength between protons and anti-protons, respectively. The results based on independent particle production (by considering independent particle production of protons and anti-protons in a given ensemble of events) have also been studied by constructing net-proton cumulants using the expression

$$C_n(N_p - N_{\bar{p}}) = C_n(N_p) + (-1)^n C_n(N_{\bar{p}}),$$

where $C_n$ is the independently calculated cumulants of protons and anti-protons, respectively. The results based on independent particle production follow the data at all energies implying a weak correlation strength between protons and anti-protons in this analysis acceptance.

Large statistics and more energy points are needed to pin-point the exact position of the deviation from baseline as a function of beam energy. On the other hand, various final state effects like diffusion of conserved charge fluctuation, the effect of resonance decay within a given rapidity window, the effect of volume fluctuations, finite time and volume effects may play significant role in this observable. Large collection of events is needed, and systematic studies both on the experimental and theoretical sides need to be explored.

Besides being a signature of the critical point, the experimentally measured higher-moments of net-charge and net-proton distributions provide the information to extract freeze-out conditions.
Figure 1. The net-charge distributions, for Au+Au collisions at 7.7 to 200 GeV within $|\eta| < 0.5$ and $0.2 < p_T < 2.0$ GeV/c, drawn with the Skellam distribution for three different centralities (0−5%, 30−40%, 60−70%).

Figure 2. (left panel) Beam-energy dependence of (a) $\sigma^2/M$, (b) $S\sigma$, and (c) $\kappa\sigma^2$, after all corrections, for most central (0-5%) and peripheral (70-80%) bins [18]. The error bars are statistical and the caps represent systematic errors. Results from the Poisson and the NBD baselines are superimposed. The values of $\kappa\sigma^2$ for Poisson baseline are always unity. (Right panel) Collision energy and centrality dependence of the net proton $S\sigma$ and $\kappa\sigma^2$ from Au+Au and p+p collisions at RHIC [19]. Skellam distributions (dash lines in top panel), UrQMD (red shaded band) and independent particle production assumption expectation (shaded solid band) for corresponding collision centralities are shown.
3.2. Transverse momentum fluctuations

Transverse momentum ($p_t$) fluctuations could be envisioned as a source of temperature fluctuations of the bulk properties of the system [3]. Two-particle $p_t$ correlation scaled by the ensemble average of $<p_t>$, $\sqrt{\Delta p_{t,i} \Delta p_{t,j}} / \langle <p_t> \rangle$, is also related to the specific heat, $C_V$, of the system. Hence, $p_t$ fluctuations as a function of $\sqrt{s_{NN}}$ may provide information about the order of QCD phase transition. The beam energy dependence of this observable has been studied for the BES program at mid-rapidity $|\eta|<0.5$ [29].

In Fig. 4, the left panel shows the STAR measurement of this fluctuation observable significantly decreases below $\sqrt{s_{NN}}=19.6$ GeV for Au+Au collisions at 0−5% centrality, whereas it remains flat for higher energies (upto ALICE energy). The effects from jet, resonance decay and finite acceptance effect may contribute to this observable. Further study is required to draw conclusions about the phase transition on it.

3.3. Particle ratio fluctuations

The non-monotonic behavior of the $K/\pi$ yield ratio at $\sqrt{s_{NN}}\sim7.6$ GeV, in SPS energy range for central Pb+Pb collisions, appears to be a unique characteristic of heavy-ion-collisions [25]. This observation is speculated to be a signature of the phase transition from hadronic to QGP state. To understand this behavior as a function of collision energy, dynamical fluctuations of $K/\pi$ ratio and other particle’s yield ratios (like $K/p$, $p/\pi$) have been proposed [26, 27]. STAR collaboration performed similar analyses in the BES program [29].

In Fig 4, the right panel shows the measure of dynamical fluctuation $K/\pi$ yield ratio at BES energies at mid-rapidity. This results shows monotonic behavior as a function of $\sqrt{s_{NN}}$ at 0−5% centrality for Au+Au collisions. Similarly, no non-monotonic behavior is observed in case of $K/p$ fluctuations. It is important to understand the sensitivity of these observables towards critical fluctuations. A further understanding of the various mechanisms of particle production,
Figure 4. (Left) $\sqrt{<\Delta p_t, i, j>/ <p_t>>}$ as a function of $\sqrt{s_{NN}}$ at $0 - 5\%$ centrality. (Right) Dynamical fluctuation of kaon to pion ratio, $\nu_{dyn,k/\pi}$, as a function of $\sqrt{s_{NN}}$ at $0 - 5\%$ centrality [29].

Figure 5. Dynamical Charge fluctuation as a function of centralities at mid-rapidity (left panel) and Forward rapidity (right panel) [29].

charge dependence of different particles species, resonance decays and re-scattering effects on these observables is necessary.

4. Dynamical charge fluctuations
The significant net-charge fluctuations may occur when the QGP phase (state comprises fractional charge carriers) transits to the Hadron Gas phase (state where the charges are integral) [28]. Such charge fluctuations can be detected by dynamical charge fluctuations if it could survive the process of evolution of the system in heavy-ion-collisions. In order to probe such a signature, $\nu_{dyn}$ for positively and negatively charged particles at mid-rapidity ($|\eta| < 0.5$) and forward-rapidity ($-3.7 < \eta < -2.8$) have been measured [29], as shown in Fig 5. It is observed that, both at mid and forward-rapidity, $\nu_{dyn}$ decreases from central to peripheral collisions. This observable increases with increasing collision energies. This observation may imply the correlation between positively and negatively charged particles increases with decreasing beam energy or multiplicity. A further study as a function of different rapidity-windows may help to understand the diffusion of charge fluctuation in heavy-ion-collisions [30]. Detailed study is ongoing to understand more about this observable.
5. Future perspective for the BES-II program and Upgrades

One of the main goals of the BES-I program is to search for the QCD critical point from event-by-event fluctuation. In order to draw a definite conclusion for the location of the QCD critical point, observables like $\kappa \sigma^2$ and $S \sigma$ of net-charge and net-proton distributions need a large collection of data. Besides, limited acceptance in pseudo-rapidity and the centrality determination in STAR experiment constrain further study of these event-by-event observables.

The results from BES-I program corroborate for high statistics and additional beam energies along with detector upgrades for final conclusion for the QCD critical point. Phase-II of BES program has been proposed for the years 2018-2019 from $\sqrt{s_{NN}} = 7.7$-20 GeV. For better particle momentum resolution, dE/dx resolution and improved pseudo-rapidity acceptance ($|\eta| < 1.7$), the upgrade of inner sectors of the current STAR TPC (iTPC) is proposed. An Event Plane and centrality Detector (EPD) is proposed for the dedicated measurement of event-plane and centrality determination at forward region $2 < |\eta| < 4$. To achieve large statistics at low energy, a significant increase of the current luminosity is planned through the electron cooling.

6. Summary

The STAR experiment has successfully collected and analyzed large collection of data from $\sqrt{s_{NN}} = 7.7$ to 39 GeV for its first phase of the BES program. The $\kappa \sigma^2$ and $S \sigma$ values of net-proton distribution show significant deviation from Poisson expectation and Hadron Resonance Gas model prediction at $\sqrt{s_{NN}} = 19.6$ and 27 GeV, with large statistical uncertainty at low beam energies. On the other hand, those of net-charge distribution show no non-monotonic behavior within large statistical uncertainty. Besides, dynamical fluctuation of $K/p, K/\pi$ and $p/\pi$ show monotonicity as a function of beam energy. The two-particle $p_t$ correlation scaled with average $<p_t>$ fluctuation significantly decreases below $\sqrt{s_{NN}} = 19.6$ GeV for Au+Au collisions at $0-5\%$ centrality, whereas it remains flat for higher energies. Limited statistics and detector acceptance in BES-I program constrain the ability to draw final conclusion for the exact location and/or existence of the QCD critical point. The proposed BES-II program with STAR detector upgrades, like iTPC and EPD, is necessary for further understanding and drawing final conclusion on the QCD critical point and phase diagram.

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