Overview and highlights of bulk correlations at STAR

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Abstract. The first phase of the Beam Energy Scan (BES) program at the Relativistic Heavy Ion Collider (RHIC) was completed during the years 2010, 2011 and 2014, with Au+Au collisions at center-of-mass energies ($\sqrt{s}_{NN}$) of 7.7, 11.5, 14.5, 19.6, 27, and 39 GeV. The BES has three distinct goals: search for the turning off of the signatures of the Quark Gluon Plasma (QGP), search for the first-order phase transition, and search for the critical point of nuclear matter. We report several interesting results on each of these fronts. In addition, we report the first bulk correlation results from U+U collisions at STAR from a three week exploratory run in 2012.

1. Introduction

Heavy-ion collisions at top energies at RHIC produce a new phase of nuclear matter known as the Quark Gluon Plasma (QGP), where quarks and gluons are no longer confined within each individual nucleon but are asymptotically free in a region where net-baryon density is vanishing [1]. Little is known about the phase diagram of quark (Quantum Chromodynamics, QCD) matter. The scientific goal of the BES is to explore this phase diagram, significantly increasing the scientific community’s knowledge in a very nascent field of study. Figure 1 shows a schematic of the QCD phase diagram, with temperature on the y-axis and baryochemical potential, $\mu_B$, on the x-axis. In the upper right is the QGP phase, and in the lower left is the Hadronic Gas (HG) phase. Theoretical trajectories at various BES energies are shown in yellow. At very low $\mu_B$, lattice QCD calculations predict a smooth crossover transition [2, 3, 4]. Meanwhile, at higher values of baryochemical potential, QCD-based models predict that there will be a first-order phase transition between the QGP and HG [5, 6]. At the low-$\mu_B$ end of the first-order phase transition line is a posited critical point. The BES has three distinct goals, searching for: 1) the turning off of the signatures of the QGP, 2) the first-order phase transition, and 3) the critical point. Table 1 lists details of the BES data sets. In addition, RHIC successfully collided uranium nuclei in a three week exploratory run in 2012, collecting 360 million minimum bias events, as well as 13 million central top 1 percent events according to the Zero-Degree Calorimeter (ZDC). This 193 GeV U+U dataset aims to utilize uranium’s unique prolate shape to explore the effects of different collision geometries.

2. Search for the turning off of QGP signatures

2.1. Nuclear modification factor, $R_{CP}$

At top RHIC energies, we observed the energy loss of high-energy partons and the associated suppression in the production of mesons with high transverse momentum ($p_T$) in Au+Au collisions [7]. This nuclear modification factor is denoted by $R_{CP}$, which is the ratio of the number of particles in central A+A collisions to the number of particles in peripheral A+A
Figure 1. Schematic of the QCD phase diagram with trajectories (yellow) of the RHIC BES program. Trajectories are for illustrative purposes only.

Table 1. Overview of the Beam Energy Scan data sets

| Energy (GeV) | Events (M) | Time (Weeks) |
|-------------|------------|--------------|
| 200         | 350        | 11           |
| 62.4        | 67         | 1.5          |
| 39          | 130        | 2            |
| 27          | 70         | 1            |
| 19.6        | 36         | 1.5          |
| 14.5        | 20         | 3            |
| 11.5        | 12         | 2            |
| 7.7         | 4          | 4            |

collisions, scaled by the number of binary collisions.

Figure 2 shows $R_{\rm CP}$ versus $p_T$ at seven different beam energies at STAR. Suppression at high $p_T$ is indicative of QGP formation. No suppression is seen below 39 GeV, but further statistics are needed to extend the $p_T$ reach to lower beam energies.

2.2. Elliptic flow

The second-order Fourier coefficient of the azimuthal particle distribution relative to the reaction plane (RP) is given by the elliptic flow $v_2$, where $v_2 = \langle \cos[2(\phi-\Psi_{\rm RP})] \rangle$, and $\Psi_{\rm RP}$ is the azimuth of the reaction plane and $\phi$ is the azimuthal angle.

Figure 3 shows $v_2$ scaled by the number of constituent quarks ($n_Q$) as a function of $n_Q$-scaled $m_T$-$m$ for identified hadrons for 0-80% Au+Au collisions as published by the STAR collaboration at BES energies [8]. Scaling by the number of constituent quarks is thought to be indicative of partonic behavior. In Fig. 3, $n_Q$ scaling holds for most particles to within $\sim 10\%$. The $\phi$ meson may not follow the trend of the other identified hadrons at 7.7 and 11.5 GeV, but more data are needed since the associated errors are quite large.
When one looks at the difference in $v_2$ between particles and their associated antiparticles for 0-80% Au+Au collisions at STAR [9], the particle and antiparticle $v_2$ agree well at 200 GeV, and the difference between the particle and antiparticle $v_2$ increases as the beam energy decreases. This difference is almost linearly proportional to $\mu_B$, implying a correlation between the $v_2$ difference of particles and antiparticles and the net-baryon density.

**Figure 2.** Nuclear modification factor, $R_{CP}$, as a function of transverse momentum, $p_T$, at different beam energies.

**Figure 3.** $v_2$ scaled by the number of constituent quarks ($n_Q$) for identified hadrons as a function of the $n_Q$-scaled $m_T$ for 0-80% Au+Au collisions from 7.7-62.4 GeV at STAR [8].
2.3. Chiral Magnetic Effect

The Chiral Magnetic Effect (CME) is a phenomenon where charges separate as a result of the large magnetic fields that form in non-central collisions and the intrinsic QCD topological structure [10]. The CME requires the system to be deconfined; therefore, the turnoff at lower beam energies of the CME would be a turn off of a QGP signature. Figure 4 shows the three-point correlator, $\gamma$, versus centrality in Au+Au collisions at STAR from 7.7-62.4 GeV for opposite charge (circles) and same charge (stars) [12]. The value of $\gamma$, a means of experimentally measuring the charge separation, could be sensitive to the CME [13]. One can see that as the energy decreases, the separation decreases and is consistent with zero at 7.7 GeV.

One issue with the CME observables is the potentially large flow-related background. One way to explore the sensitivity of charge separation to the CME is to collide U+U, since the prolate shape of uranium allows one to create systems with finite elliptic flow but a small magnetic field. Figure 5 shows the charge separation signal as a function of $v_2$ in U+U collisions at 193 GeV [14]. The 0-1% most central events are indicated by the blue circle near a y-axis value of 0. As one can see, at a finite value of $v_2$, the value is consistent with zero in the most central events is consistent with the expectation of CME with a small magnetic field and minimal flow-related background in those events.

Figure 4. The three-point correlator ($\gamma$) as a function centrality in Au+Au collisions from 7.7-62.4 GeV [12] for opposite charge (circles) and same charge (stars).

3. Search for the first-order phase transition

3.1. Azimuthal anisotropy, $v_n$

A first-order phase transition would be indicated by a region with the lowest compressibility. According to hydrodynamic calculations that contain a first-order phase transition, the value of $v_1$ of net-baryons can be used as a probe of the phase transition [15]. A non-monotonic variation
of the slope of this directed flow would signal a softening of the equation of state. Figure 6 shows the slope of directed flow \( (dv_1/dy) \) near mid-rapidity of antiprotons (upper), protons (mid), and net protons (lower) for 10-40% centrality versus beam energy in Au+Au collisions from 7.7 to 200 GeV at STAR [16]. The proton values change sign between 7.7 and 11.5 GeV, have a minimum between 11.5 and 19.6 GeV, and then increase but are still negative at 200 GeV. The net-proton result shows a similar local minimum between 11.5 and 19.6 GeV that could be a signal of the softening of the equation of state.

When searching for a softening of the equation of state, one looks for observables that are proportional to pressure, such as the \( v_n \) coefficients. In addition to \( v_1 \), recent work suggests that \( v_3 \) could be more promising. Some model predictions suggest that a hydro phase is not necessary to create \( v_2 \); however, \( v_3 \) is more sensitive to the hydro phase of the fluid created in heavy-ion collisions [17]. Recent STAR results show that while multiplicity increases with energy, \( v_3 \) does not increase until \( \sim 20 \text{ GeV} \), suggesting that this observable warrants further investigation.

3.2. Femtoscopy
The study of two-pion interferometry is typically referred to as the study of HBT (Hanbury Brown and Twiss). HBT has proven to be a precise tool for measuring the pressure anisotropy and lifetime of the system [19]. Since a first-order phase transition involves a mixed-phase regime with pressure gradients of zero, a measurement of the freezeout shape should show non-monotonic behavior near the first-order phase transition [20].

Pion azimuthal HBT allows the study of the coordinate-space almond shape after expansion, given by the kinetic freezeout eccentricity \( \epsilon_F \). Early measurements of \( \epsilon_F \) hinted at possible non-monotonic behavior at CERES [21]. Figure 7 shows \( \epsilon_F \) versus beam energy, where the STAR datapoints are shown as colored stars [19]. Data from CERES are shown as a plus sign and E895 [22] are shown as squares [23]. Even when changing the rapidity range, STAR does not see any non-monotonic behavior and \( \epsilon_F \) agrees well with the trend of the Boltzmann transport model, UrQMD [24].

![Figure 5](image-url)  
**Figure 5.** \( \gamma_{OS} - \gamma_{SS} \times N_{part} \) versus \( v_2 \) for Au+Au collisions at 200 GeV (red stars) and U+U collisions at 193 GeV (blue circles) [14].


Figure 6. The slope of directed flow \( \left( \frac{d\varepsilon}{dy} \right) \) near mid-rapidity versus beam energy for mid-central (10-40\%) Au+Au collisions at STAR, as well as UrQMD calculations \[16\].

Figure 7. The beam-energy dependence of the kinetic freezeout eccentricity \( \epsilon_F \) for Au+Au collisions at STAR, E895 and Pb+Au collisions at CERES. Three different rapidity ranges (forward, mid, backward) are shown for the STAR energies as colored stars (green, red, blue, respectively) \[19\].

4. Search for the critical point

4.1. Higher-order net-particle moments

Section 3 discusses efforts to locate the first-order phase transition of QCD matter. If there is a first-order phase transition, then there should be a critical point at the end of the first-order phase transition line before the transition becomes a crossover \[25\]. The susceptibilities of conserved...
quantities (electric charge, strangeness, and baryon-number), which are directly related to the experimentally measurable cumulants of the multiplicity distributions, should have distinctly different values in the QGP and hadronic phases [26]. In addition, phenomenological models predict that the moments of multiplicity distributions sensitive to the correlation length will diverge near the CP, and the magnitude of the non-monotonic behavior should increase as the order of the cumulant is increased [27].

Net-proton was used as a proxy of baryon number [28], and net-charge was used as a proxy of electric charge. Figure 8 shows the moment products $S\sigma$ (upper) and $\kappa\sigma^2$ (middle) for net-protons in 0-5% (circles) and 70-80% (squares) collisions at STAR [29]. The lower frame shows the values of the moment product $S\sigma$ scaled by the expectation of a Skellam distribution. The Skellam expectations are shown as solid lines. A possible non-monotonic variation of $\kappa\sigma^2$ relative to unity is not excluded by the existing STAR data. The STAR data does agree well with the expectation from independent production, which breaks intra-event correlations between the numbers of protons and antiprotons. Higher statistics will be necessary to further elucidate results, yielding exciting possibilities for a second phase of the Beam Energy Scan.

The moment products $\sigma^2/M$ (top), $S\sigma$ (middle), and $\kappa\sigma^2$ (bottom) for net-charge show no evidence of non-monotonic behavior within statistical uncertainties [30].

**Figure 8.** The beam-energy dependence of the net-proton moment products $S\sigma$ (top) and $\kappa\sigma^2$ (middle) at two different centralities. The hatched band shows the expectation from UrQMD and the shaded band shows the expectation assuming independent proton and antiproton production. The bottom frame shows the value of $S\sigma$ scaled by the Skellam expectation shown in the upper frame (lines).

5. Dileptons and the chiral transition

Dileptons are ideal probes of heavy-ion collisions since they are emitted throughout the evolution of the system and are inert to the strong force [31]. In the low invariant mass region
(LMR), where $M_{ee} < 1.1 \text{ GeV}/c^2$, the spectral shape of the $\rho$ meson is sensitive to in-medium modifications, so it could be sensitive to the chiral phase transition [32]. One could also potentially study QGP thermal radiation via the dilepton measurements in the intermediate invariant mass region (IMR) of $1.1 < M_{ee} < 3.1 \text{ GeV}/c^2$ [33].

In recent STAR results, there is no strong beam-energy dependence of the LMR excess. Further comparison with SPS would be possible with energies below $19.6 \text{ GeV}$. The excess could spike near the CP because of anomalous increases in the lifetime of the system [34]. Statistics are insufficient for meaningful interpretation of the results in the IMR region, but this observable should be pursued in a second phase of the Beam Energy Scan.

6. Summary and Outlook

We have shown a wide array of interesting results from the first phase of the BES at RHIC. When looking for the turning off of QGP signatures, signs of deconfinement remain down to at least $\sim 27 \text{ GeV}$. Some observables, such as $v_1$, point to the potential softening of the equation of state/first-order phase transition in the region of $\sim 20$ to $40 \text{ GeV}$. Further statistics at the lowest BES beam energies are needed before reaching conclusions about the critical point. While there may be some tantalizing hints of interesting phenomena in the RHIC BES, firmer conclusions could be reached with a second phase of the BES [18]. Early results of U+U collisions at STAR already hint at some interesting physics. For example, in 0-1% central collisions the charge separation signal disappears while $v_2$ remains finite, consistent with a picture of the CME.

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