

STAR experiment results from the beam energy scan program at RHIC

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Abstract.

We present the first results using the STAR detector from the Beam Energy Scan (BES) program at the Relativistic Heavy-Ion Collider (RHIC). In this program, Au ion collisions at center of mass energies ($\sqrt{s_{NN}}$) of 7.7, 11.5 and 39 GeV allowed RHIC to extend the study of the QCD phase diagram from baryonic chemical potential values of 20 MeV to about 400 MeV. For the high net-baryon density matter at midrapidity, formed in these collisions, we report several interesting measurements. These include the observation of difference between anti-particle and particle elliptic flow, disappearance of the difference in dynamical azimuthal correlations with respect to event plane between same and opposite signed charged particles, change in slope of eccentricity at freeze-out and directed flow of protons as a function of $\sqrt{s_{NN}}$ and the deviation of higher order fluctuations from hadron resonance gas and Poissonian expectations. Possible interpretations of these observations are also discussed.

1. Introduction

One of the main goals of the heavy-ion collision program at RHIC is to study various aspects of the QCD phase diagram [1]. The results from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV have established the existence of a system with partonic degrees of freedom [2]. Lattice QCD calculations at zero baryon chemical potential (μ_B) show that the quark-hadron transition is a cross over [3]. Some of the remaining goals at RHIC are to search for the signals of phase boundary and critical point (CP) [4]. These form the main motivations for the RHIC BES program. In pursuit of which, it was first established that RHIC (both accelerator and experiments) can operate below injection energies of 19.6 GeV through a test run of Au+Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV [5]. Further, a set of observable for the physics goals were formulated [6]. This allowed for the starting of the first phase of the BES program in the year 2010. The STAR experiment, with full azimuthal coverage, large and uniform acceptance for all midrapidity hadrons across all $\sqrt{s_{NN}}$ is ideally suited for this program. So far we have collected about 5, 11 and 170 million good events for 7.7, 11.5 and 39 GeV Au+Au collisions respectively, in addition to taking data at higher energies of 62.4 and 200 GeV. Here we present results on (a) turn-off of observations related to partonic degrees of freedom, through

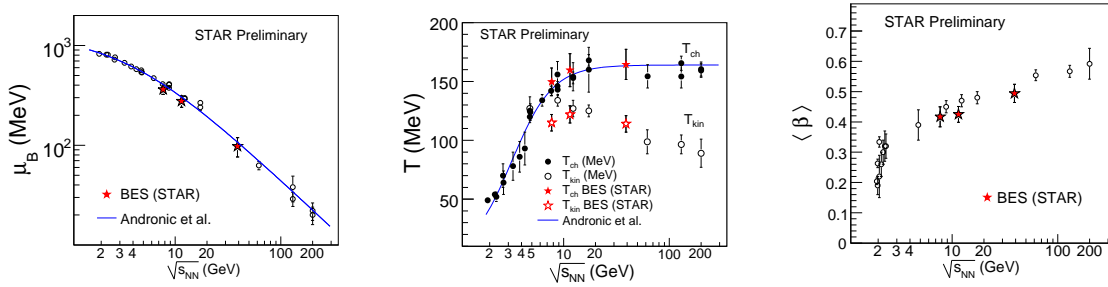


Figure 1. (Color online) Left panel: μ_B vs. $\sqrt{s_{NN}}$. Middle panel: T_{ch} and T_{kin} vs. $\sqrt{s_{NN}}$. Right panel: $\langle\beta\rangle$ vs. $\sqrt{s_{NN}}$. The red stars are new STAR results at midrapidity from 0-5% central Au+Au collisions at BES energies [9] and the solid line are calculations from Ref. [10].

the measurements of v_2 and dynamical charge correlations, (b) search for the signatures of softening of Equation Of State (EOS), through HBT and v_1 measurements and (c) search for signatures of CP through fluctuation measurements.

The data presented are at midrapidity from the STAR Time Projection chamber (TPC) and Time Of Flight (TOF) detectors [7]. A high level trigger was used in the BES program to reject background events arising from beam and beam-pipe interactions [8]. The centrality selection was carried out using the uncorrected charge particle multiplicity measured in TPC for pseudorapidity, $|\eta| < 0.5$ [5]. The particle identification was done by measuring the specific ionization energy loss in TPC and the particle velocities using TOF as a function of momentum.

Within the framework of a statistical model assuming thermodynamical equilibrium [9] the measured particle ratios (π^-/π^+ , K^-/K^+ , \bar{p}/p , K^-/π^- and \bar{p}/π^-) in central (0-5%) Au+Au collisions are used to extract the chemical freeze-out (vanishing inelastic collisions) conditions. Figure 1 shows that the BES program has extended the μ_B range at RHIC from around 20 MeV to about 400 MeV. The chemical freeze-out temperature (T_{ch}) slightly increases with energy from 150 MeV to around 165 MeV. The invariant yields of π^- , K^- and \bar{p} were fitted using a blast wave model to extract the kinetic freeze-out (vanishing elastic collisions) conditions [9]. The kinetic freeze-out temperature (T_{kin}) is observed to slightly decrease whereas the collective radial flow velocity ($\langle\beta\rangle$) increases as the beam energy increases. The large μ_B values at midrapidity indicates formation of a high net-baryon density matter and which is expected to reach a maximum value around 7.7 GeV [11].

2. Partonic versus hadronic degrees of freedom

2.1. Elliptic flow

The elliptic flow (v_2) is calculated as $\langle\cos 2(\phi - \Psi_2)\rangle$, where ϕ denotes the azimuthal angle of the produced particles and Ψ_2 denotes the orientation of the second order event plane. Figure 2 shows the v_2 of p , \bar{p} , π^+ and π^- as a function of transverse momentum (p_T)

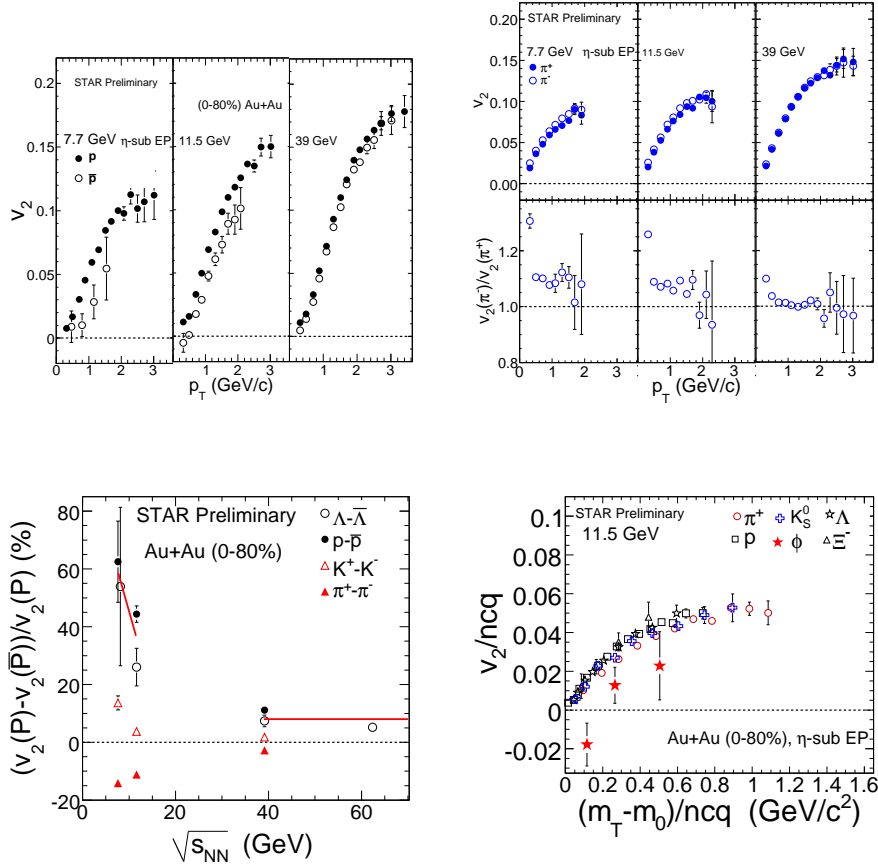


Figure 2. (Color online) Top panel: v_2 of p , \bar{p} and π^\pm vs. p_T in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 39$ GeV. Bottom left panel: Percentage difference between v_2 of particles and anti-particles. Bottom right panel: v_2/ncq vs. $(m_T - m_0)/ncq$ for 0-80% Au+Au collisions at 11.5 GeV [12].

for minimum bias (0-80%) Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV [12]. To avoid autocorrelations we calculated the event plane (EP) in two separated hemispheres with an η -gap of 0.05 on each side. Differences are observed in the v_2 of particles and anti-particles, which increases as the beam energy decreases. The percentage difference relative to v_2 of the particle is also shown in Fig. 2 as a function of $\sqrt{s_{NN}}$. We find that $v_2(\text{anti-baryons}) < v_2(\text{baryons})$, which could be due to high net-baryon density matter at midrapidity. The $v_2(K^-) < v_2(K^+)$ for $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV. This could be due to K^- absorption in the medium, K^- -nucleon potential is attractive, or could be related to dominance of associated production of kaons. The $v_2(\pi^-) > v_2(\pi^+)$, this could be due the coulomb repulsion of π^- by the midrapidity protons or due to contributions from resonance decays or could be due to chiral magnetic effect [13]. The difference in particle and anti-particle v_2 also suggests that the number of constituent quark (ncq) scaling for all particle species (including nuclei) as observed at top RHIC energies [14] are no longer valid at these lower energies. Figure 2 also shows the v_2 for identified particles scaled by ncq as a function of $(m_T - m_0)/ncq$. Where m_T is the transverse mass of a hadron with mass m_0 . We observe that ϕ -meson v_2 drops off the common trend followed by

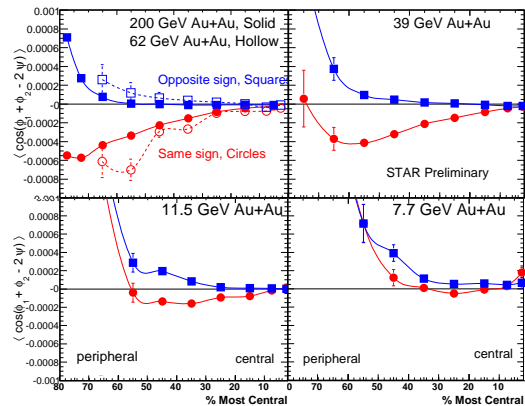


Figure 3. (Color online) Charge hadron azimuthal correlations with respect to reaction plane angle as a function of centrality for Au+Au collisions at midrapidity [17].

other particles. The interaction of ϕ -mesons with nucleons are expected to be smaller compared to other hadrons [15] and at top RHIC energy it was observed that ϕ -mesons freeze-out close to the transition temperature predicted by lattice QCD [2]. All these make ϕ -meson a carrier of early stage information in heavy-ion collisions. ϕ -meson v_2 was found to follow the ncq scaling at top RHIC energy and this was used to conclude that a substantial amount of collectivity at 200 GeV has been developed at the partonic stage [14]. Small ϕ -meson v_2 at 11.5 GeV would then indicate collectivity contribution from partonic interactions to decrease with decrease in beam energy [15].

2.2. Dynamical charge correlations

Figure 3 shows the results on charged hadron azimuthal correlations based on 3-particle correlation technique [16]. The results are from Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 39, 64.2$ and 200 GeV at midrapidity between same charged and opposite charged hadrons with respect to reaction plane angle (Ψ) [17]. The observable, $\langle \cos(\phi_1 + \phi_2 - 2\psi) \rangle$ represents the difference between azimuthal correlations projected onto the direction of the angular momentum vector and correlations projected onto the collision event plane. The difference between the same charge and opposite charge correlations at the higher energies seems to be consistent with the predictions for existence of metastable domains in QCD vacuum leading to local *Parity* violation. This phenomena needs deconfinement and chiral phase transitions which are expected to be achieved in heavy-ion collisions (also referred as Chiral Magnetic Effect (CME)) [18]. We observe that the difference in correlations between same and opposite charges seems to decrease as beam energy decreases and almost vanishes at 7.7 GeV. If the differences can be attributed to QCD transitions, absence of it may indicate absence of such transitions at the lower energies. The observable presented is parity-even, making it susceptible to physical processes not related to CME. In this respect STAR has carried out investigations with a new correlator which could be less sensitive to parity-even effects, the results of which suggest that the measurements are consistent with CME [17]. In addition, alternate underlying

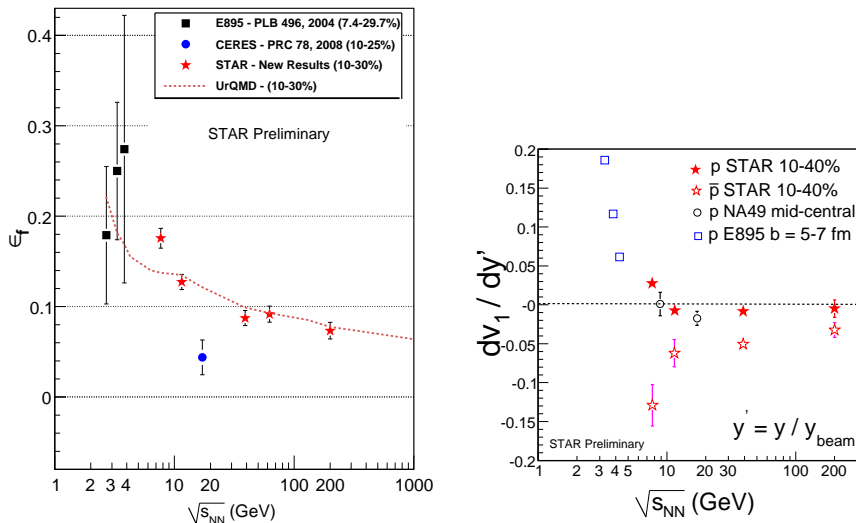


Figure 4. (Color online) Left panel: Eccentricity vs. $\sqrt{s_{NN}}$ for mid-central heavy ion collisions from AGS, SPS and RHIC are shown [21]. The dashed lines are UrQMD model calculations. Right panel: Slope of p and \bar{p} v_1 with respect to rapidity (y) normalized to beam rapidity vs. $\sqrt{s_{NN}}$.

physics mechanisms are also investigated, which includes local charge conservations and flow [19]. In a separate analysis using charge multiplicity asymmetry correlations, it was found that the charge separation is mainly present in the vicinity of the event-plane, and appears proportional to the particle distribution ellipticity [20]. Preliminary results indicate that the observed dynamical correlations could have significant contributions from above sources as well.

3. Search for signatures of softening of EOS

3.1. Freeze-out eccentricity

The eccentricity at the freeze-out (ϵ_f) is defined as the ratio $\frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$, where σ_x and σ_y are the in- and out-of plane length scales of the emitting source. These can be obtained by measuring the HBT radii relative to the reaction plane in an event [21, 22]. The ϵ_f as a function of $\sqrt{s_{NN}}$ is shown in Fig. 4 as measured in AGS, SPS and RHIC experiments at midrapidity for mid-central collisions [21]. Including the SPS result we observe a non-monotonic variation of ϵ_f with $\sqrt{s_{NN}}$. RHIC data at 19.6 and 27 GeV this year may re-confirm this variation. Non-monotonic variations of freeze-out volume (obtained using HBT observables) have been previously reported [23] and interpreted as due to a constant mean free path at freeze-out and transition from a nucleon to a pion dominated freeze-out condition with increase in $\sqrt{s_{NN}}$. However ϵ_f could also be sensitive to the life time of the source and EOS for the system [24]. In such a scenario, a non-monotonic variation of ϵ_f vs. $\sqrt{s_{NN}}$ could be considered as a signature of softening of the EOS [25].

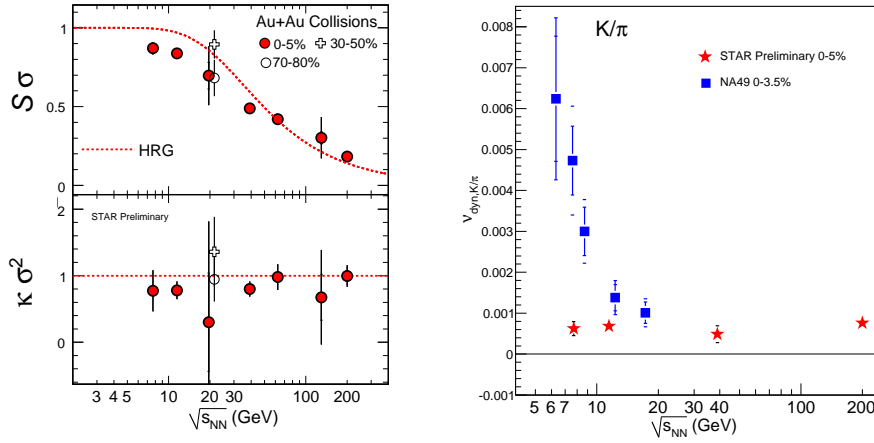


Figure 5. (Color online) Left panel: $S\sigma$ and $\kappa\sigma^2$ vs. $\sqrt{s_{NN}}$ for net-protons [29]. The dashed line are the Hadron Resonance Gas (HRG) model results [30]. Right panel: $v_{dyn}(K/\pi)$ vs. $\sqrt{s_{NN}}$ for Pb+Pb and Au+Au collisions at SPS and RHIC respectively.

3.2. Directed flow

The directed flow (v_1) is calculated by computing the $\langle \cos(\phi - \Psi_1) \rangle$, where Ψ_1 denotes the orientation of the first order reaction plane. The $v_1(y)$ reflects the collective side-ward motion of the particles in the final state. A negative slope of $v_1(y)$ for nucleons are expected to be due to positive space-momentum correlations and baryon stopping. While specific variations of v_1 with y could also be sensitive to the softening of the EOS [26]. Figure 4 right panel shows the slope of v_1 for protons and anti-protons as a function of $\sqrt{s_{NN}}$ for mid-central heavy-ion collisions [27]. The slope which describes the transverse side-ward motion of the particles relative to the beam direction is observed to change sign as the $\sqrt{s_{NN}}$ decreases. The slope for \bar{p} remains negative for $\sqrt{s_{NN}}$ studied. The difference in slope for p and \bar{p} are also observed to decrease with increase in $\sqrt{s_{NN}}$. At a given BES energy, the proton slope also changes sign as a function of collision centrality, being negative for peripheral collisions and positive for central collisions.

4. Search for signatures of critical point

4.1. Higher moments of net-proton distributions

In a static, infinite medium, the correlation length (ξ) diverges at the CP. Finite size and time effects in heavy-ion collisions put constraints on the values of ξ . The higher moments of distributions of conserved quantities (net-baryons, net-charge, and net-strangeness), measuring deviations from a Gaussian, have a sensitivity to CP fluctuations that is better than that of variance (σ^2), due to a stronger dependence on ξ . Recently it has also been shown that a crossing of the phase boundary can manifest itself by a change of sign of skewness (S) as a function of energy density and negative value of kurtosis (κ) could indicate existence of a CP in the vicinity [28]. Further higher moments

are also proposed to be a sensitive probe for chiral phase transition effects [30]. The products $S\sigma \sim \frac{\chi^{(3)}}{\chi^{(2)}}$ and $\kappa\sigma^2 \sim \frac{\chi^{(4)}}{\chi^{(2)}}$ are very useful observables to measure as they cancel the volume effects and have a direct connection to ratios of various order susceptibilities (χ) calculated using lattice QCD [31] and HRG model.

Figure 5 shows $S\sigma$ and $\kappa\sigma^2$ versus $\sqrt{s_{\text{NN}}}$ for net-protons (number of protons - number of anti-protons) distribution measured at midrapidity for the $0.4 < p_{\text{T}} < 0.8$ GeV/ c in central Au+Au collisions. The results are compared to expectations from HRG model (similar values from Poissonian statistics). The results can test the predictions of non-perturbative QCD calculations at high temperature [31]. The measurements show deviation from HRG for $\sqrt{s_{\text{NN}}} < 39$ GeV. A non-monotonic variation of $\kappa\sigma^2$ with $\sqrt{s_{\text{NN}}}$ could indicate presence of CP. The new data at $\sqrt{s_{\text{NN}}} = 19.6$ and 27 GeV will provide a more complete picture on the presence of CP over a μ_B range of 20 - 400 MeV.

4.2. Particle ratio fluctuations

Particle ratio fluctuations are sensitive to particle numbers at chemical freeze-out and may be insensitive to volume effects. A non-monotonic variation of these fluctuations with $\sqrt{s_{\text{NN}}}$ is expected in presence of a CP. Figure 5 right panel shows the dynamical fluctuations in K/π (ν_{dyn} , which is zero for statistical fluctuations) [32] measured by NA49 and STAR experiment as a function of $\sqrt{s_{\text{NN}}}$. The STAR results shows that the $\nu_{\text{dyn}}(K/\pi)$ are constant as a function of the $\sqrt{s_{\text{NN}}}$ studied. Similar measurements have been carried out in STAR for fluctuations in K/p and p/π ratios. These exhibit a negative value of ν_{dyn} indicating correlated emission of particles and have a monotonic variations with $\sqrt{s_{\text{NN}}}$ [32]. Differences are observed between results from NA49 and STAR experiment in the common $\sqrt{s_{\text{NN}}}$ region and for ratios involving kaons. This could be due to difference in the experimental acceptances and the particle identification techniques used. STAR has a uniform y vs. p_{T} acceptance for different particle species at midrapidity and uses TPC and TOF, to event-by-event identify the charged hadrons.

5. Summary

The BES program has extended the μ_B range at RHIC from 20 MeV to about 400 MeV, thereby covering a large part of the conjectured QCD phase diagram. Several new observations are reported. The identified hadron production and freeze-out parameters revealed a high net-baryon density at midrapidity is achieved. First observations of significant differences in particle and anti-particle v_2 could be attributed to such an effect. Hadronic interactions start to dominate over partonic interactions around 11.5 GeV. This is indicated by the measurement of small v_2 for the ϕ -mesons relative to other hadrons at 11.5 GeV and a reduction in the difference in dynamical charge correlations between same and opposite charges with respect to reaction plane. Interesting $\sqrt{s_{\text{NN}}}$ dependence trends are observed in observables which could be related to search for softening of the EOS. The freeze-out eccentricity shows a possible change in slope

around the BES energies. In addition the slope of proton $v_1(y)$ changes sign at these energies. STAR detector provides a large and uniform acceptance around midrapidity with excellent event-by-event particle identification capabilities to measure multiplicity fluctuations for CP search. Deviations of higher order fluctuations for the net-proton distributions from HRG expectations are observed at 7.7, 11.5 and 39 GeV. These measurements are being used to study the structure of the QCD phase diagram. We expect to complete the first phase of BES program before 2012.

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