Beam Energy Scan Program in RHIC – Experimental Approach to the QCD Phase Diagram

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The Beam Energy Scan (BES) program at RHIC was launched with the specific aim to explore the QCD (Quantum Chromodynamics) Phase Diagram. Particular emphasis was given to the search for phase boundaries and the location of the Critical Point (CP). The first run with AuAu collisions at 7.7 GeV, 11.5 GeV, and 39 GeV took place in 2010, and the next one, with energies of 18 and 27 GeV, will start in a few months. The results of the first stage of the BES program obtained by the STAR (Solenoidal Tracker at RHIC) experiment are presented and discussed, as well as plans for the future of the program.

1. INTRODUCTION

All matter, including strongly interacting matter described by QCD, undergoes a phase transition as external conditions change. The phase diagram of QCD matter (T vs. μ_B) is generally considered to be the most important single figure of our field and therefore it has been the subject of intense study both theoretically and experimentally. Finding the Critical Point of the QCD phase diagram and/or the boundary between Quark-Gluon Plasma (QGP) and the hadronic phases would be a major break though and it would surely place RHIC results in all text books around the world. The main question of interest is, of course, whether this critical point exists and whether it can be found experimentally. So far theory is not able to provide much detailed information about the QCD phase diagram. Only the "edges" are believed to be somewhat understood: Finite temperature lattice QCD calculations [1] predict a cross over phase transition from hadronic to QGP phase at baryon chemical potential $\mu_B \sim 0$ and critical temperature $T_c \sim$ 170-190 MeV (top-left in Fig. 1), while several QCD based calculations [2] show that at lower T and high baryon chemical

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potential (right in Fig. 1) a first order phase transition may take place. The point in the QCD phase diagram where the first order phase transition ends would be the QCD CP. Summing up both findings, one concludes that there must be a critical point at intermediate T and μ_B.

Even though the position of the critical point as well as the location of the phase boundaries are not yet known precisely, various QCD lattice calculations suggest that the most probable location of CP would be in the μ_B interval between 150 and 500 MeV (a significant uncertainty in these estimates comes from the fact that systematic errors of lattice calculations are neither understood nor constrained).

Lattice QCD calculations also suggest that heavy-ion collision experiments at moderate colliding energies, achievable at, e.g., RHIC, could probe the μ_B interval in the range of interest by changing the energy of colliding beams, which would result in varying temperature T and baryonic chemical potential μ_B. With this in mind, RHIC's Beam Energy Scan (BES) Program was launched.

2. BES PROGRAM

The RHIC machine can address the entire range of μ_B values needed for this study, from $\mu_B \sim 0$ to 500–600 MeV, by lowering the center-of-mass energy of colliding nuclei from the top value of 200 GeV down to a few GeV.

There are two tremendous technical advantages of positioning an experiment for executing the BES program in a collider geometry over a fixed target one. The first is that the occupancy for a detector in a collider geometry is almost independent of the beam energy, while at fixed target it rises substantially with energy. The lower track density results in less problems with charge sharing of hits and track merging, leading to better and cleaner track reconstruction and particle identification. The second is that the midrapidity acceptance for each particle type is independent of the beam energy, which allows for an excellent control of systematics. Moreover, a number of the uncertainties cancel out when comparisons at different $\sqrt{s}$ are made. This is especially important for the energy scan where comparisons of findings at different values of μ_B are expected to play a major role in assessing the CP coordinates in the (μ_B,T) space.

Fig. 1 shows the reach of RHIC's BES in the (T, μ_B) plane. The program was designed to cover the full area of interest. The yellow lines in Fig. 1 represent a cartoon of reaction trajectories at energies $\sqrt{s_{NN}}$ = 5, 7.7, 11.5, 17.3, 27, and 39 GeV, proposed for the first stage of the BES program. This will provide almost uniform coverage of the unknown (T, μ_B) space and will narrow down an area of interest for further study.

Presently the BES physics program in STAR branches out in two directions:

(1) a search for the signatures of a phase transition and a critical point,

(2) a search for the turn-off of new phenomena observed at higher RHIC energies.

Note that STAR is particularly suited for these studies due to its full azimuthal acceptance and unprecedented particle identification capabilities.

Finding a value of the chemical potential at which the turn-off takes place may point directly to the most relevant range in this study. Note that (2) requires that the effect must be observed in several signatures simultaneously.

3. SEARCH FOR THE CRITICAL POINT AND THE FIRST ORDER PHASE TRANSITION

Theory predicts that an immediate proximity to the critical point or to the phase transition will be signaled by the presence of significant non-monotonic fluctuations in various observables [4]. Lattice QCD shows [5] the divergence of susceptibilities of conserved quantities like baryon number, charge, and strangeness (B, Q, S) at the critical point (a similar critical behavior is known from classic thermodynamics), which translate into fluctuations in the multiplicity distributions [6] which could be studied experimentally. The key observation would be a change of the observable as a function of μ_B. One would need to change the energy in small steps and measure the magnitude of the fluctuations. The highest are expected near the critical point.

The long list of suitable observables is reported in the literature. The ones chosen for the BES program have the best resolving power given the realistic constraints of the experiment and the total available beam time. The first step of this analysis will focus on fluctuation studies of proton and pion multiplicity distributions via their moments. Typically, experimental studies are limited to the second moments, which are expected to be proportional to a square of the correlation length. However, in heavy-ion collisions they are estimated to be rather small around critical point (on the order of 2–3 fm) [7]. Therefore, the higher moments of event-by-event multiplicities are considered as they are significantly more sensitive to the existence of CP. Particularly suitable is the fourth moment, kurtosis, which is expected to be proportional to the 7th power of the correlation length [7]. The measurement of higher moments of event-by-event identified particle multiplicity distributions and their variation with centrality and beam energy is expected to provide the very first direct link between experimental observables and Lattice Gauge Theory calculations [6].

The STAR experiment has already analyzed the first four moments, including the skewness and kurtosis, of the net-proton distributions in AuAu collisions at 200, 62.4, and 19.6 GeV. Both, skewness and kurtosis, were found to be monotonically approaching zero with increasing number of participants at all three energies (first four moments: mean (M), standard deviation(σ), skewness(S), and kurtosis (κ) dependence of centrality for AuAu at 200, 62.4, and 19.6 GeV are shown in Fig. 2), which is expected in the region of a cross-over transition identified at RHIC (μ_B is of the order of a few tenths of an MeV) [8]. These measurements are a baseline for future studies at lower energies.

Fig. 3 shows the energy dependence of $\kappa\sigma^2$ for net proton distributions compared to several models that do not include physics of the critical point. The $\kappa\sigma^2$ as a function of energy is consistent with unity (no non-monotonic fluctuations are observed). The new STAR results at $\sqrt{s_{NN}} = 39$ GeV are consistent with the rest of data points [8]. In particular it is interesting that thermal model predictions (marked by open diamond symbols in Fig. 3) are equal to unity, similar to STAR data. This analysis was discussed, in details, during this meeting by H. G. Ritter [9].

Particle ratio fluctuations from STAR, specifically fluctuations in K/π and p/π, were also already presented and discussed at this meeting (see contribution by T. Tarnowsky [10]). They were studied as a function of energy and system size. The variable used to measure dynamical fluctuations, $\nu_{\rm dyn}$, quantifies deviations in particle ratios from those expected from the pure statistical distribution (Poisson). Fig. 4 of [10] shows the energy dependence of dynamical K/π fluctuations, including a data point from 39 GeV of AuAu collisions from the first BES run. In the same paper, Fig. 5 shows the same dependence but for p/π ratio including two new points from STAR AuAu collisions at 39 and 7.7 GeV. The STAR experiment data have demonstrated dynamical K/π fluctuations to be approximately flat above $\sqrt{s_{NN}} = 19.6$ GeV, and p/π fluctuations to increase with energy through the entire range of measurements.

The BES data analysis of other proposed signatures of CP/phase transition, such as azimuthally sensitive femtoscopy, elliptic and direct flow, etc., is in progress (the full list of proposed research can be found in [11]).

4. ONSET OF THE QGP

RHIC results at top energies indicate that the passage through the phase transition to the partonic phase took place. It will be very interesting to follow the evolution of the observed partonic signatures with the lowering of $\sqrt{s_{NN}}$, as it is believed that at low enough energies they have to disappear. One of the key results that has been accepted as evidence of partonic behavior at RHIC has been the observation that the elliptic flow (expressed by anisotropy parameter v_2) scales by the number of quarks in a given hadron. This observation supports the conclusion that the flow is established early on, where quarks are the relevant degrees of freedom. If the flow were to have been established during a hadronic phase, then the magnitude of v_2 for a given hadron would scale with its mass. The impact of this signature is most clearly shown in the high transverse kinetic energy, $(m_t - m_0)/n_q$, range from 1–2 GeV/c^2, and for heavier hadrons like ϕ and Ω. Fig. 4 shows the extensive measurements of v_2 for identified particles (data from both STAR and PHENIX). The scaling of flow parameters by constituent quark content n_q (3 for baryons and 2 for mesons) resolved the originally observed meson-baryon separation of final state hadrons. The first measurements of the BES program, see Fig. 5, show v_2 (obtained using the event plane method [12]) plotted as a function of p_t for charged hadrons in 40–50 % AuAu collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV [13]. The results are compared to corresponding results from $\sqrt{s_{NN}} = 62.4$ and 200 GeV [14]. The figure shows that $v_2(p_t)$ at 7.7 GeV is smaller than that at 11.5 GeV, which is smaller than at 39 GeV, suggesting that elliptic flow decreases as BES energies decrease. Analysis of v_2 for identified hadrons, which is currently in progress, would be crucial to evaluate whether scaling still holds at lower energies.

The disappearance of this scaling while lowering the energy, if observed, would suggest that the system is no longer in a partonic phase, and may point towards the transition region.

The crucial question is whether the experimental accuracy would allow for a precision measurement to address this issue. The present estimates of error bars at lower energies show that the statistics accumulated during the first BES run for energies 7.7, 11.5, and 39

GeV are sufficient for this study.

Similarly, the statistics obtained in 2010 are sufficient for all other analyses relevant to the observed partonic signals (for estimates, see[11]).

A special place in this program belongs to the local parity violation in the deconfined medium observed in AuAu collisions at 200 GeV. It was predicted that under a strong magnetic field, when the system is in a state of deconfinement and chiral symmetry restoration is reached, local fluctuations may lead to parity violation [16]. Experimentally, one would observe the separation of the charges with respect to the reaction plane. And, in fact, such a separation, well above the magnitude attributed to the known sources of background, was observed [15]. This phenomenon is very interesting in itself as it provides an experimental test of the QCD aspects. But in the context of the BES program, the energy at which the charge separation disappears will also be suggestive of the phase boundary.

5. CONCLUDING REMARKS

The Beam Energy Scan Program at RHIC with AuAu collisions at $\sqrt{s_{NN}} = 5$–50 GeV, corresponding to μ_B of 600–150 MeV, has just started.

During the first very successful run, the STAR experiment acquired data at three new energies: $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV (STAR already collected earlier data sets at 62, 130, and 200 GeV, and a small data set from technical run at 9.2 GeV [17]). The first results seem to be consistent with the established trends. Further analysis is in progress and results of higher complexity are expected shortly.

The next phase will include $\sqrt{s_{NN}} = 18$ and 27 GeV, and will start in the Spring of 2011.

ACKNOWLEDGMENTS

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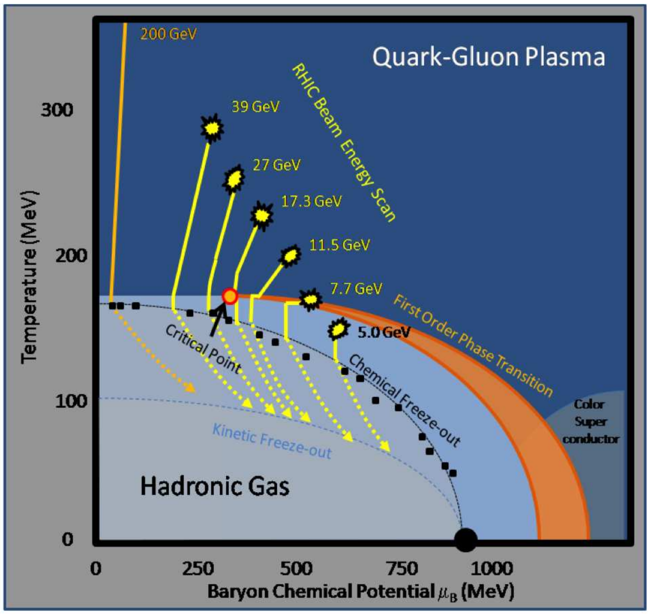

Figure 1. Cartoon of the RHIC BES program coverage of the QCD Phase Diagram. Yellow trajectories represent schematics of the collision evolutions at different energies of BES program. Red circle symbolizes the critical point.

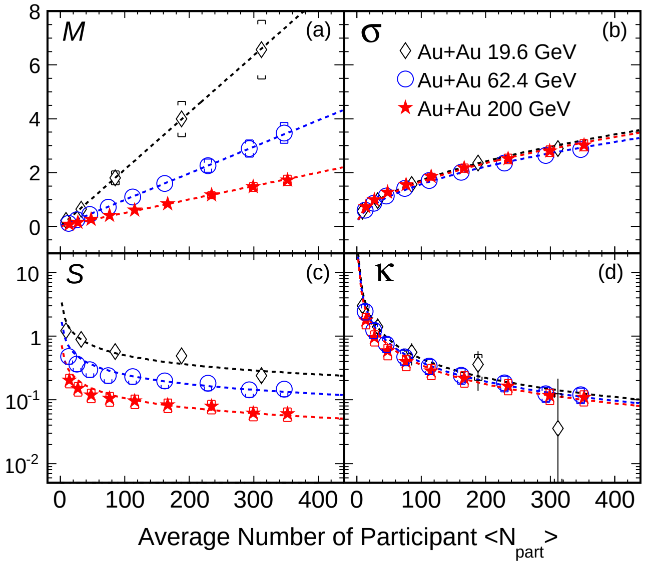

Figure 2. Analysis of the first four moments: mean (M), standard deviation (σ), skewness (S), and kurtosis (κ) of proton distributions as a function of centrality in AuAu collisions at 200, 62.4, and 19.6 GeV. For the detailed description see text.

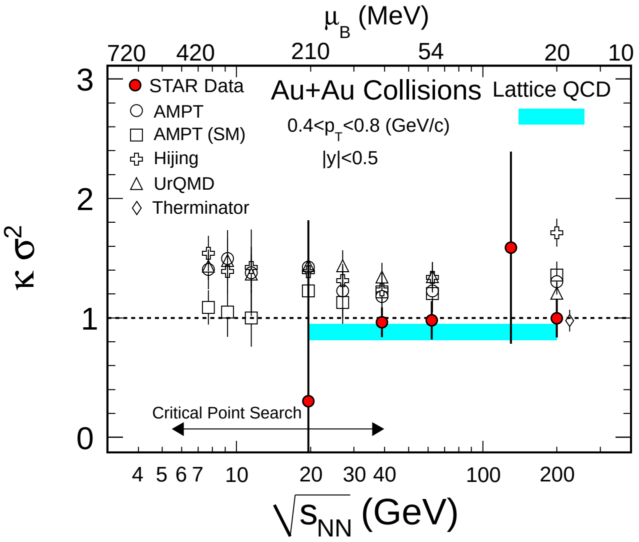

Figure 3. $\sqrt{s_{NN}}$ dependence of $\kappa\sigma^2$ for net-proton distributions measured in AuAu collisions at RHIC. Errors are the quadratic sum of systematic and statistical uncertainties, except for $\sqrt{s_{NN}} = 39$ GeV, which has only statistical errors. A comparison with several models is included. Horizontal arrow represents the range of the BES program

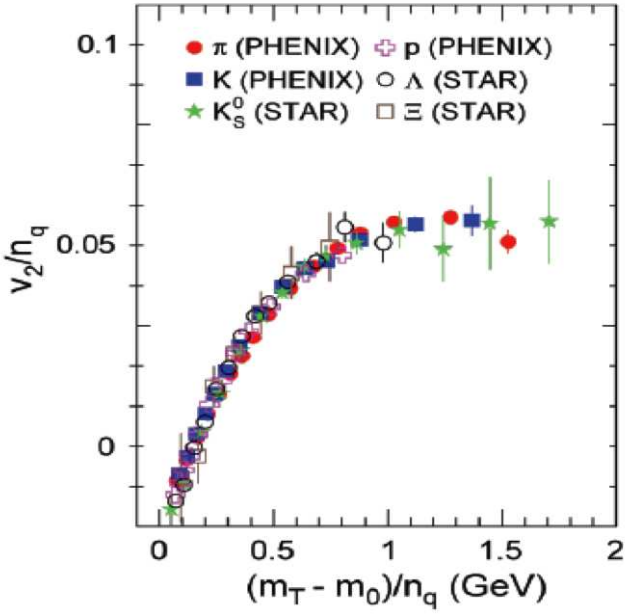

Figure 4. Identified particle v_2 as a function of transverse kinetic energy for AuAu collisions at $\sqrt{s_{NN}} =$ 200 GeV. Figure from [18]

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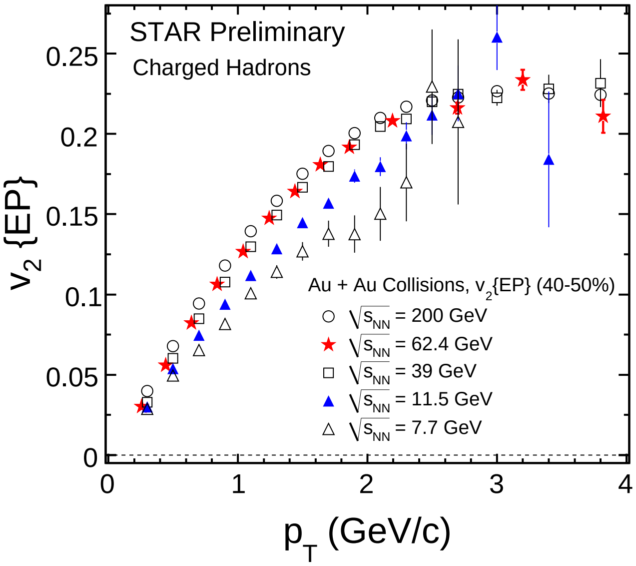

Figure 5. v_2 of charged hadrons as a function of transverse momentum (obtained from the event plane method) for AuAu collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, 39, 62.4, and 200 GeV.

FIGURE CAPTIONS

Fig.1: Cartoon of the RHIC BES program coverage of the QCD Phase Diagram. Yellow trajectories represent schematics of the collision evolutions at different energies of BES program. Red circle symbolizes the critical point.

Fig.2: Analysis of the first four moments: mean (M), standard deviation (σ), skewness (S), and kurtosis (κ) of proton distributions as a function of centrality in AuAu collisions at 200, 62.4, and 19.6 GeV. For the detailed description see text.

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Fig.5: v_2 of charged hadrons as a function of transverse momentum (obtained from the event plane method) for AuAu collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 39, 62.4$, and 200 GeV