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EXPERIMENTAL APPROACH TO THE QCD PHASE DIAGRAM — BEAM ENERGY SCAN AT RHIC*

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The QCD phase diagram appears to be the most important single figure of our field. While recent progress in Lattice QCD (LQCD) and model calculations is impressive, the location of phase boundaries and the exact position of the hypothetical critical point (CP) remains unknown. The available theoretical estimates, however, indicate that the critical point might be in the region of the phase diagram probed by current heavy ion experiments. The Beam Energy Scan (BES) program at RHIC, described in this paper, was launched to expand the experimental study where theory cannot yet reach. Both large RHIC experiments, STAR and PHENIX, are in the process of preparing for the first run. Particularly STAR with its large, uniform acceptance and excellent particle identification capabilities, is uniquely positioned to cover this physics in unprecedented depth and detail.

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1. Introduction

The QCD phase diagram (for schematic sketch see Fig. 1) contains information about the location of phase boundaries (phase transition is indicated by solid and dashed lines) and the physics of the phases, hadronic gas (HG) and quark–gluon plasma (QGP), that this boundary separates. So far, our understanding of this diagram is limited to the "edges": LQCD finds a rapid, but smooth crossover transition from HG to QGP at vanishing chemical potential μ_B and large temperature T [1], while various models predict a strong 1-st order phase transition at vanishing T and large μ_B [2]. If this is the case, then a critical point (marked by red dot in Fig. 1) should be located where the transition changes from a smooth cross-over to a first order [3].

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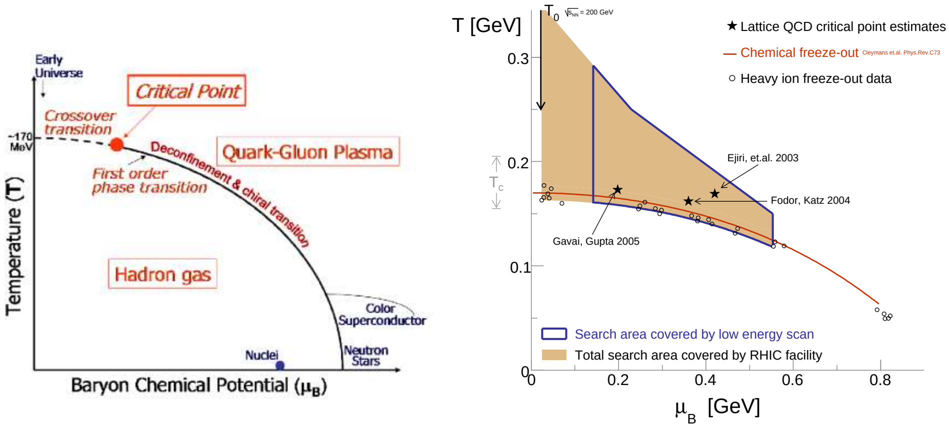

Fig. 1. The QCD Phase Diagram: schematic (left panel), RHIC BES program coverage of the QCD Phase Diagram (right panel).

Exploring the rest of the QCD phase diagram ($T \neq 0$ and $\mu_B \neq 0$) presents a formidable challenge. Several methods were applied to lattice QCD to overcome existing numerical problems at non vanishing μ_B, but there is no agreement in the outcome of the results so far. The most significant difference pertains to the existence of the critical point. Some of these calculations predict it, others do not. An additional complication comes from the fact that systematic errors of lattice calculations are neither understood nor constrained.

Given the very significant theoretical difficulties, it falls upon the experiments to lead the study. The BES experimental program at RHIC with heavy ion collisions at energies in the range of 5–50 GeV$/N$ was designed to provide observational evidence for the existence of the critical point and to address the unknown "territories" of the QCD phase diagram. Heavy ion collisions provide a unique experimental opportunity to study this diagram; by varying the center-of-mass energy of colliding nuclei one can access different values of μ_B (collisions with higher energies probe lower μ_B values).

Establishing the validity of the CP or existence of both a cross-over and a first/second order transition would surely place RHIC results into all text books around the world.

2. The strategy of an experimental search for the CP

The experiments at RHIC have found that a strongly coupled quark–gluon plasma (sQGP) is created in heavy ion collisions at $\sqrt{S_{\rm NN}} \sim$ 62 to 200 GeV$/N$ [4]. The observed v_2 scaling of light and multi-strange hadrons with the number of constituent quarks implies that the hot and dense matter with partonic degrees of freedom has been formed. Particularly strong evidence came from elliptic flow measurements of ϕ mesons [5]. ϕ mesons are formed via coalescence of thermalized strange quarks, and since it is believed that they do not interact in the late hadronic state, their significant elliptic flow v_2 clearly must have been developed in the partonic phase, prior to hadronization.

At RHIC energies, the baryon chemical potential μ_B extracted from the thermal model is very small ($\sim$ 0.025 GeV, [6]), so these collions are from "above" the cross-over transition line in the phase diagram (dashed line in Fig.1). The lowering of the collision energy will allow one to move the freeze-out point to larger μ_B (to the right in Fig. 1). While stepping in μ_B, one needs to pay close attention to many observables, in particular the signatures predicted for ordered phase transition and the CP. A non-monotonic dependence of variables on $\sqrt{S}$ and an increase of long wavelength Gaussian fluctuations should become apparent only near the critical point. The onset of the non-equilibrium "lumpy" final state is expected after cooling through a first order phase transition. Those fluctuations will have non-Gaussian character. The rise and then fall of the signal as μ_B increases should allow one to ascertain the (T, μ_B) coordinates of the critical point (... if it exists).

However, the magnitude of these oscillations as well as the probability that they will survive the final state interactions is hard to predict. Fortunately for the experiments, there is no need for a trajectory to "pass" precisely through the CP in the (T, μ_B) plane to see the signatures. The hydrodynamical calculations show that the critical point "attracts" trajectories, so if the trajectory is missing the CP by 100–150 MeV along the μ_B axis, the signature will be just as strong as if it would pass directly through it. Therefore, there is no need to take very small steps in μ_B; collecting data at a few values of $\sqrt{S_{\rm NN}}$ should be enough [7].

3. BES at RHIC

The low energy runs at CERN SPS ($\sqrt{S} = 6.3$–17.3 GeV) reported some interesting phenomena, possibly related to phase transition, but the evidence remains inconclusive [8].

Using the collider experiment for the energy scan studies, instead of a fixed target experiment, possesses two tremendous advantages:

(1) The phase space covered by the detectors in collider experiments changes very little with beam energy, which allows for direct comparison. At fixed target experiments, the detector acceptance changes significantly with energy and comparisons require extrapolation to a common phase space. This process is based on assumptions and therefore introduces additional systematic uncertainties.

(2) Track density at mid-rapidity varies very slowly with energy for collider geometry, while it increases dramatically with energy in fixed target experiments. This results in increased technical difficulties in tracking (*e.g.* changes in hit sharing and track merging, changes in dE/dx and momentum resolution).

The energy range of the BES program at RHIC (gray (blue) contour in Fig. 1 right panel) has been chosen to cover the entire span of currently available LQCD estimates. The experiments must be capable of making comprehensive measurements of all the signals related to the critical phenomena [9, 10].

Moreover, with the access to higher baryon density and lower freeze-out temperature systems, RHIC experiments will be able to study the evolution with beam energy (how it varies and, eventually, disappears) of unusual medium properties attributed to the new state of matter found at the top RHIC energies; do any of these properties change or turn off?

And, of course, all experiments hope for new surprises in unexplored regions ...

4. BES at STAR

The STAR detector, due to its large uniform acceptance and (with the completed Time of Flight barrel by 2010) excellent particle identification capabilities, is uniquely positioned to carry on this program in unprecedented depth and detail. Data analysis will focus predominantly on the search for evidence of the CP and 1-st order phase transition (critical fluctuations) and an onset of the phase boundary and opacity (the disappearance of partonic degrees of freedom, collapse of flow, *etc.*).

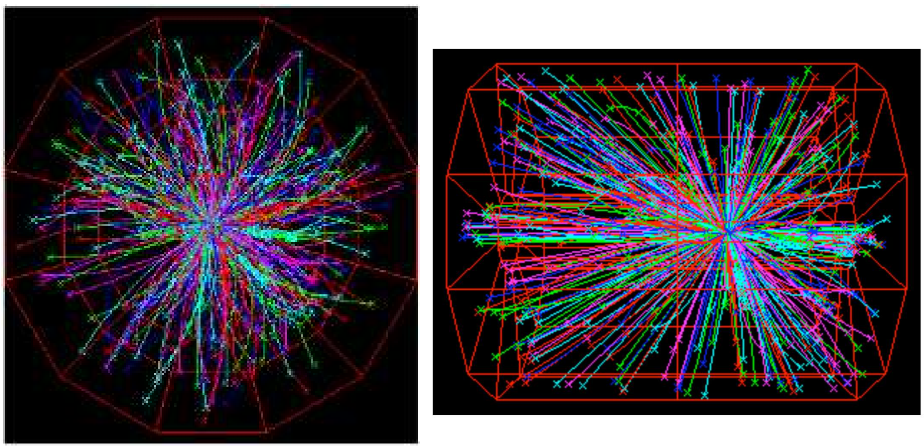

Fig. 2. Central Au+Au collision at $\sqrt{S_{\rm NN}} = 9.2\,{\rm GeV}$: end-view (left panel) and side-view (right panel) recorded by the STAR TPC detector.

The STAR experiment already has a proven performance record and significant experience with low energy running. Two first low energy runs were taken with 19.6 GeV Au+Au collisions in 2001 and 22.4 GeV Cu+Cu in 2004. For the first time in 2007, 9 GeV Au+Au collisions were investigated, and already during the very next year the first data sample for physics analysis was recorded. The STAR trigger system and DAQ performed well. Fig. 2 shows a central Au+Au event at 9.2 GeV taken by STAR TPC.

5. Preliminary analysis of 9.2 GeV Au+Au test run

While this run was rather short, the collected data sample allowed for a physics analysis and for a number of critical checks to be performed.

Fig. 3 shows a comparison of 9.2 GeV data (marked with the (red) star) with data from other experiments at different energies. The K/π ratio *versus* $\sqrt{S_{\rm NN}}$ (left panel) and HBT pion interferometery (π^+) (right panel) measurements are in very good agreement with the rest of world data. These particular results are in line with the theme of this conference, and therefore were chosen to be included in the proceedings.

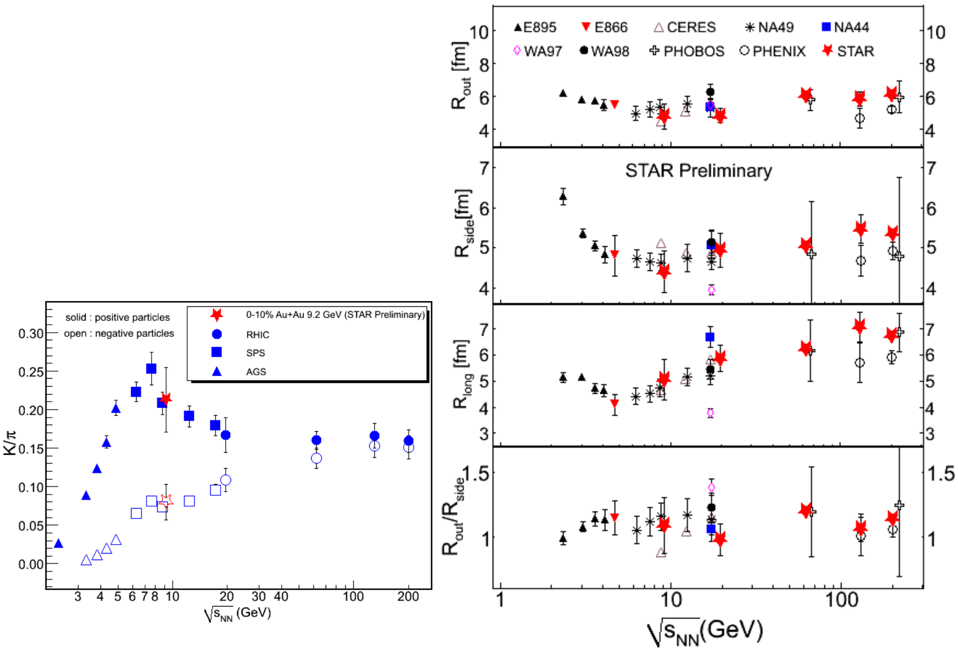

Fig. 3. The K/π ratio *versus* $\sqrt{S_{\rm NN}}$ (left panel) and HBT pion interferometery (π^+) (right panel) measurements.

All other measurements are also [11] consistent with those reported by earlier experiments, indicating that STAR is ready for a full length data taking period.

6. Summary

The Beam Energy Scan Program at RHIC provides a great discovery potential. The most exciting would be, of course, to locate the critical point or to prove that the transition is consistent with features of the 1-st order phase transition (which would naturally imply existence of the CP).

However, this program will also deliver a set of "guaranteed" results on the onset of the phase transition and disappearance of partonic activities reported at top RHIC energies, which is very interesting in itself.

The STAR detector is ideally suited and technically ready for the challenge of this exploratory program. The first run is expected in 2009.

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