SEARCH FOR THE CRITICAL POINT OF THE NUCLEAR MATTER PHASE DIAGRAM. FIRST RESULTS FROM THE BEAM ENERGY SCAN PROGRAM AT RHIC*

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In 2010, the Relativistic Heavy Ion Collider (RHIC) launched a multi-step experimental program to investigate the QCD Phase Diagram in general, and to search for the QCD Critical Point (CP) and/or 1st order phase transition in particular. The BES (Beam Energy Scan) program involves an "energy scan" of Au+Au collisions from the top RHIC energy ($\sqrt{s}$ = 200 GeV) down to energies as low as 5 GeV in NN center of mass. During the first BES run (2010), data were collected at 7.7, 11.5 and 39 GeV. It was complemented in 2011 by two other data sets at 27 and 19.6 GeV. The preparations for the remaining data taking at $\sqrt{s} = 5$ GeV are in progress. The overview of the BES program and the first experimental results are presented and discussed.

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1. Introduction

All matter, including strongly interacting matter described by QCD, undergoes a phase transition as external conditions change. This is usually illustrated with the phase diagram. The phase diagram of QCD matter is the most important single figure of our field and therefore it has been intensively studied both theoretically and experimentally. It represents the variation of temperature T as a function of chemical potential μ_B. At low temperatures, the relevant degrees of freedom are hadronic, but at higher ones it is expected that the quarks and gluons become the degrees of freedom of the system. Finding the Critical Point of the QCD phase diagram and/or

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the boundary between Quark-Gluon Plasma (QGP) and the hadronic phases would be a major breakthrough 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 at all, and if it does, 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" of the QCD phase diagram are believed to be somewhat understood: the latest lattice QCD calculations [1] predict a cross over phase transition from a hadronic gas to a QGP phase at baryon chemical potential $\mu_B \sim 0$ and critical temperature $T_c \sim 150$–170 MeV (top-left in Fig. 1), while several QCD based calculations [2] show that at lower T and high baryon chemical 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. Considering both arguments, 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, 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).

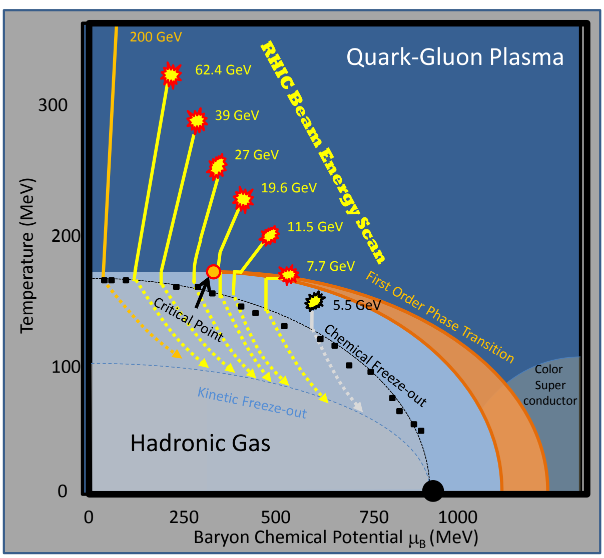

Fig. 1. A cartoon of the RHIC BES program coverage of the QCD Phase Diagram. White (yellow) trajectories represent schematics of the collision evolution at different energies of the BES program. The circle (red) symbolizes the critical point.

Heavy-ion collision experiments at moderate $\sqrt{s}$, achievable presently with *e.g.* RHIC's Beam Energy Scan (BES) Program, would be able to probe the μ_B interval in the range of interest.

2. Beam Energy Scan program at RHIC

The main goal of RHIC BES program is to search for the hypothetical critical point and the phase boundary of the QCD matter phase diagram. But at the same time, this scan will also provide insights on how the various observables, established as signatures of partonic degrees of freedom at the top RHIC energy of $\sqrt{s} = 200$ GeV, behave as the collision energy decreases. This may allow us to identify the energy in the center of mass of the system, where there is no longer evidence of QGP formation. This energy will represent the "turn off" of the QGP signatures and indicate that the system is back in the hadronic phase. Note that this must be observed in several QGP signatures simultaneously.

Therefore, the present BES physics program branches out in two directions:

1. a search for the signatures of a phase transition and a critical point, and
2. a search for the turn-off of new phenomena observed at the top RHIC energies and attributed to the partonic degrees of freedom.

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

Fig. 1 shows the reach of RHIC's BES program in the (T, μ_B) plane. The white (yellow) lines in Fig. 1 represent a cartoon of reaction trajectories at energies $\sqrt{s_{NN}} = 5$, 7.7, 11.5, 19.6, 27 and 39 GeV. All energies, with exception of 5 GeV, were run in 2010 and 2011. This choice of energies provides almost uniform coverage of the unknown (T, μ_B) territory and hopefully will allow us to narrow down an area of interest for further study.

3. First results

3.1. STAR at RHIC

While the RHIC collider is particularly suitable for the BES program, the STAR detector with its large and uniform acceptance, full azimuthal angle coverage and excellent particle identification capabilities, is an ideal device for these studies. All data sets cumulated by the STAR experiment in 2010 and 2011 contain sufficient statistics to allow for all aspects of the analysis outlined in [3, 4]. Each of the considered observables has been modeled in the STAR environment to determine the number of minimum bias events within the STAR acceptance which would be needed to record statistically significant results.

3.2. The "environment" of HI collision at RHIC

At the time of a chemical freeze-out, all inelastic interactions among the debris of nuclei and produced particles stop, and the chemical composition of the final state is "frozen". The system can be described by the thermal equilibrium model [5, 6] with two parameters, $T_{\rm ch}$ (temperature at chemical freeze-out) and μ_B. Both, $T_{\rm ch}$ and μ_B, are extracted from the data by fitting the particle ratios with the thermal model.

Figure 2 shows the variation of the extracted chemical freeze-out parameters for central collisions at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV. While $T_{\rm ch}$ only slightly decreases (from 165 MeV at $\sqrt{s_{NN}} = 200$ GeV to 150 at $\sqrt{s_{NN}} = 7.7$ GeV), there is a significant change in the value of the μ_B. With the lowest energy so far of 7.7 GeV, the RHIC μ_B range was extended to 400 GeV.

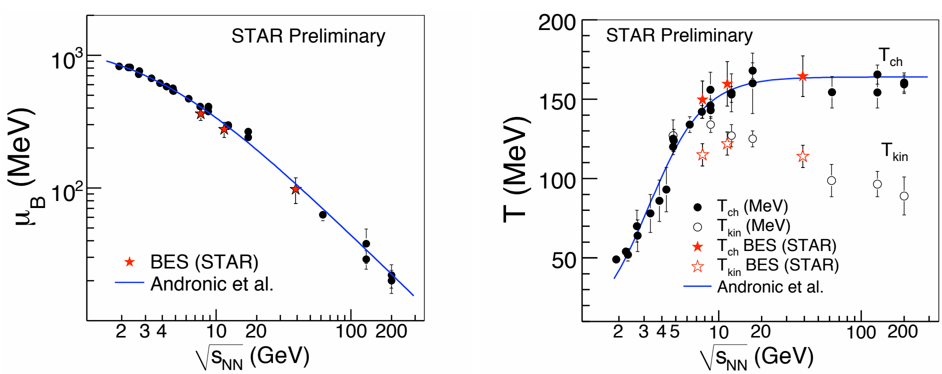

Fig. 2. The energy dependence of baryonic chemical potential (left) and temperature of chemical freeze-out, $T_{\rm ch}$, (right). The open symbols on the right plot show the temperature at kinetic freeze-out, $T_{\rm kin}$ (*i.e.* when all elastic collisions have ceased), obtained from blast-wave model [5, 7] fits to the invariant yields from the data.

3.3. Onset of the QGP

RHIC results at top energies indicate that the passage through the phase transition to the partonic phase took place. One of the key results that has been accepted as evidence of partonic degrees of freedom at RHIC has been the observation that the elliptic flow (expressed by anisotropy parameter v_2) scales with the number of constituent quarks in a given hadron.

This indicates 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). Figure 3 shows the v_2 of protons and anti-protons in minimum bias collisions as a function of $p_{\rm t}$ for the five energies: 7.7, 11.5, 19.6, 27 and 39 GeV. The 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. The v_2 gradually increases with energy. At 39 GeV the proton v_2 is only slightly higher than the anti-proton v_2, but this difference increases significantly with decreasing energy. The difference in particle and anti-particle v_2 suggests that the number of constituent quark (NCQ) scaling observed at $\sqrt{s_{NN}} = 200$ GeV [8] is no longer valid at these lower energies.

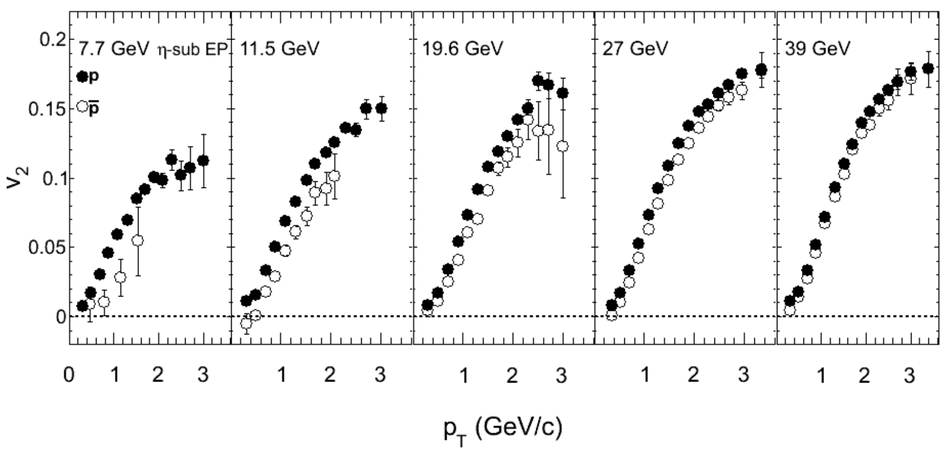

Fig. 3. The v_2 of protons and anti-protons in minimum bias Au+Au collisions as a function of $p_{\rm t}$ for the five energies: 7.7, 11.5, 19.6, 27 and 39 GeV.

A similarly intriguing behavior was observed in the case of ϕ mesons. The ϕ mesons freeze-out close to the transition temperature predicted by lattice QCD [10]. Moreover, their cross section for interactions with other particles is estimated to be very small. Therefore, ϕ mesons are perceived as messengers of the early stages of the collision. At RHIC top energies, ϕ meson v_2 follows the NCQ scaling, which strongly supports the argument that collectivity is developed in the partonic stage. At lower energies, the v_2 of ϕ mesons is smaller than other particles (figure 4), which suggests the decrease of partonic collectivity with decreasing collision energy. For a detailed discussion of ϕ meson studies, see [9, 11] in this proceedings.

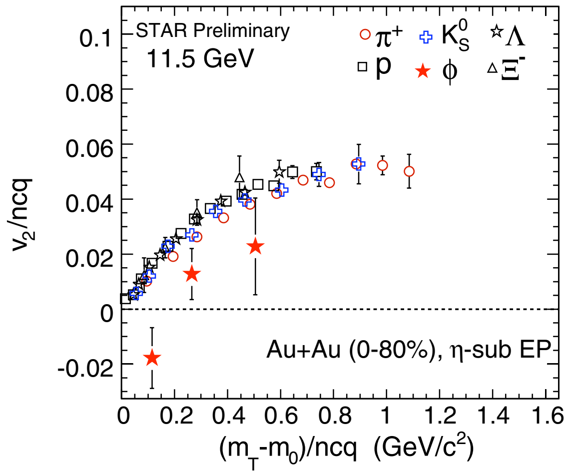

Fig. 4. The v_2/NCQ *versus* $(m_{\rm T} - m_0)$/NCQ in Au+Au collisions at 11.5 GeV [9]. The v_2 of ϕ mesons is lower than the v_2 of the rest of the observed particles.

There is no clear "QGP turn-off signature" reported yet, however some modifications to partonic phase observables are reported. In this section, the NCQ scaling was discussed as an example of ongoing analysis, however there are also other observables presently under investigation.

3.4. Search for the critical point and the 1st order phase transition

Presently, there is a number of accepted specific signatures to address the presence and location of the critical point and/or the phase space boundary. 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 [12]. Lattice QCD [13] shows the divergence of susceptibilities of conserved quantities such as 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 [14] that can be studied experimentally. The key observation is a change of the observable as a function of μ_B. Therefore, the experimental strategy amounts to small changes in energy with careful measurement of all aspects of the fluctuations. The STAR experiment focuses on fluctuation studies of proton and pion multiplicity distributions. The measurements of event-by-event fluctuations on hadron multiplicity ratios (K/π, p/π and K/p) in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 39 and 200 GeV were presented at this conference [15, 16]. The magnitudes of dynamical fluctuations $\sigma_{\rm dyn}$ for p/π and K/p ratios was shown to change smoothly from a larger negative value at $\sqrt{s_{NN}}$ = 7.7 GeV to a smaller negative value at 200 GeV, while that for

K/π ratios exhibits no significant beam energy dependence. More promising seems to be the moments analysis. Typically, experimental studies are limited to the second moments, which are proportional to a square of the correlation length. However, in heavy-ion collisions, they are estimated to be rather small around the critical point (of the order of 2–3 fm) [17]. Therefore, the higher moments of event-by-event multiplicity distribution are used as they are significantly more sensitive. Particularly suitable is the fourth moment, *kurtosis*, which is proportional to the 7th power of the correlation length [17]. The measurement of higher moments of event-by-event identified particle multiplicity distributions and their variation with centrality and beam energy provide the very first direct link between experimental observables and Lattice QCD calculations [14]. The measurements of higher moments of the net-proton distribution were carried out by the STAR collaboration and presented at this conference [18]. The analyses showed that the moment product $kurtosis * \sigma^2$ and $skewness * \sigma$ of the net-proton distribution in central Au+Au collisions are consistent with Lattice QCD and HRG model calculations at higher energies (62.4 and 200 GeV), while the results are smaller than HRG model calculations at lower energies (7.7, 11.5, 39 GeV).The analysis of $\sqrt{s_{NN}} = 19.6$ and 27 GeV data is still ongoing. So far, the analysis of fluctuations seems to be slightly disappointing. All $\sqrt{s_{NN}}$ dependences are smooth and monotonic, with no "prescribed" anomalous behavior observed.

4. Summary

The Beam Energy Scan program has expanded the range of chemical potential μ_B at RHIC from 20 MeV to $\sim$ 400 MeV, allowing for the first time a direct study of the anticipated CP signatures in the most "suspected" area of the QCD phase diagram.

The first results did not confirm any of the suggested CP signals, however a number of interesting observations was made. For example, the measurement of the increasing discrepancy of v_2 between particles and anti-particles with the lowering of $\sqrt{s_{NN}}$ suggests an increasing role of hadronic degrees of freedom at the lower energies. The reduction of v_2 of ϕ mesons compared to other hadrons at 11.5 GeV (a similar behavior was also noticed at 7.7 GeV, but with large statistical errors) also seems to indicate that at these energies, hadronic interactions play a more visible role. Moreover, there were also observations reported that suggest a softening of the EOS [19,20] in the BES energy region, but they were not discussed here.

The analysis of BES data is in progress, a new results will be available soon. The upcoming run at $\sqrt{s_{NN}} = 5$ GeV will complete the data taking part of the program, and technical aspects of this run are presently under investigations.

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