BES-II data and critical assessment with respect to QCD critical point search

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Abstract. The beam energy scan (BES) program is being pursued in Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) in several stages, the 1st one BES-I at 2010- and the 2nd one BES-II at 2019-, in order to scan the QCD phase diagram and to possibly find and locate the QCD critical point and/or the 1st order phase transition in the high-density area of the phase diagram. In this presentation, recent results on the higher-order net-proton fluctuation from the STAR experiment at RHIC and a few other related measurements from other experiments and facilities are shown and discussed by comparing with theoretical expectations with and without including the critical point.

1 Introduction

In order to reach the high-density region of the QCD phase diagram, the RHIC accelerator has been providing the heavy-ion collisions from 200 GeV down to a few GeV in center of mass energy. Experimentally, with reducing the colliding beam energy, a fireball with higher baryon chemical potential has been confirmed by measuring the various hadron yields and ratios with chemical freeze-out assumption, and the extracted chemical freeze-out temperature is quite close to the expected phase transition temperature. The "later" kinetic thermal freeze-out temperature, that is extracted from the transverse momentum spectra, is known to be further reduced via strong radial expansion, on the other hand, the temperature measurement with di-leptons mass spectra [1] has been expected to provide "earlier" time information in addition to the later stages, and the extracted temperature is found to be higher than the phase transition temperature as well as chemical and kinetic thermal freeze-out [2]. These various temperature measurements are shown in Fig. 1 as a function of colliding beam energy, that corresponds to the baryon chemical potential.

2 Net-proton higher-order fluctuation measurements

The susceptibility of conserved quantities and/or correlation length of the colliding system are expected to diverge near the QCD critical point in the phase diagram, therefore STAR experiment has been measuring the higher-order cumulants of net-proton distribution as a proxy for the net-baryon fluctuation, before the BES program and in BES-I and BES-II programs

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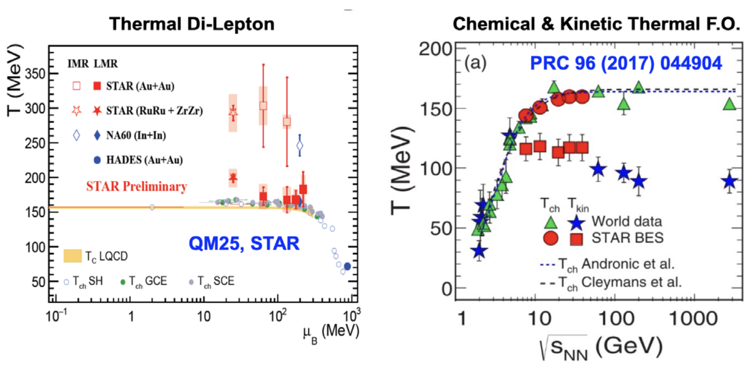

Figure 1. Two different temperature measurements from di-lepton mass spectra in the low (LMR) and intermediate (IMR) mass region are shown on the left panel as a function baryon chemical potential [1], together with chemical freeze-out temperature measurements and expected phase transition temperature from the Lattice QCD calculation. The chemical and kinetic thermal freeze-out temperatures are shown on the right panel as a function of colliding beam energy [2].

as shown in Fig. 2 [3, 4]. For the higher-order cumulant measurements of event-by-event net-proton number distribution, the number of events are the most important factor of this precise shape measurement, that requires a large statistics. As this is a fluctuation measurement of conserved quantity, there will be no fluctuation with full phase space, therefore the choice of the acceptance is also a key, as there will be an optimum acceptance for maximizing the sensitivity to the critical fluctuation. In addition to all other correlation and collectivity measurements, these fluctuation measurements could be one of the most sensitive probes to the critical point.

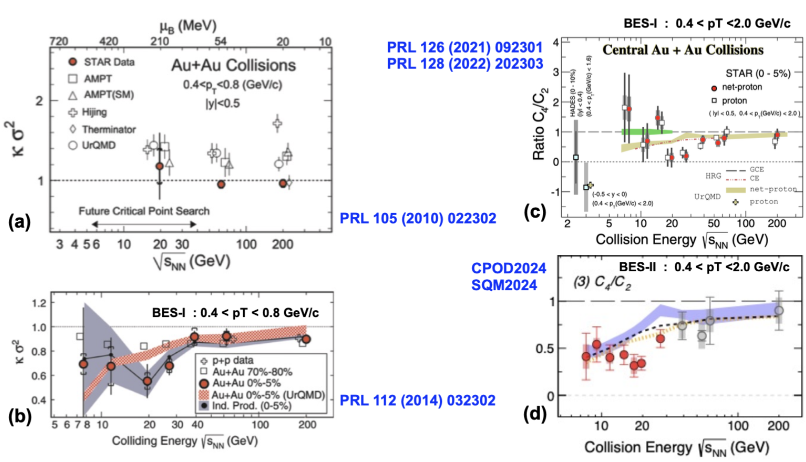

Figure 2. (a) pre-BES measurement, (b) BES-I measurement with limited p_T acceptance with dE/dx particle identification using Time Projection Chamber, (c) BES-I measurements with i ncreased p_T acceptance including velocity information using Time Of Flight, (d) BES-II measurement with increased event statistics and improved centrality resolution [3, 4].

The centrality dependence of net-proton fluctuation for 2^{nd}, 3^{rd} and 4^{th} order cumulant ratios are shown as a function of the number of participants (N_{part}) in Fig. 3 for different colliding beam energies from 7.7 to 27 GeV. Two data sets (open red and solid black symbols) are analyzed with two different centrality selections, characterized by different centrality resolutions, that are given by the Time Projection Chamber upgrade with increasing eta acceptance, where the solid symbols are done with the better resolution, indicating the lower values at peripheral to the mid-central region, while it is less sensitive to the centrality resolution in the central region as expected, because of the upper limit of N_{part} distribution. The corresponding UrQMD calculations, which is a hadronic cascade model without phase transition nor critical point, are shown as color (orange and green) bands to be considered as a hadronic baseline. The experimental data of 4^{th} order cumulant ratios around 17.3 - 19.6 GeV seems to show a significant deviation (suppression) with respect to the hadronic baseline in central collisions.

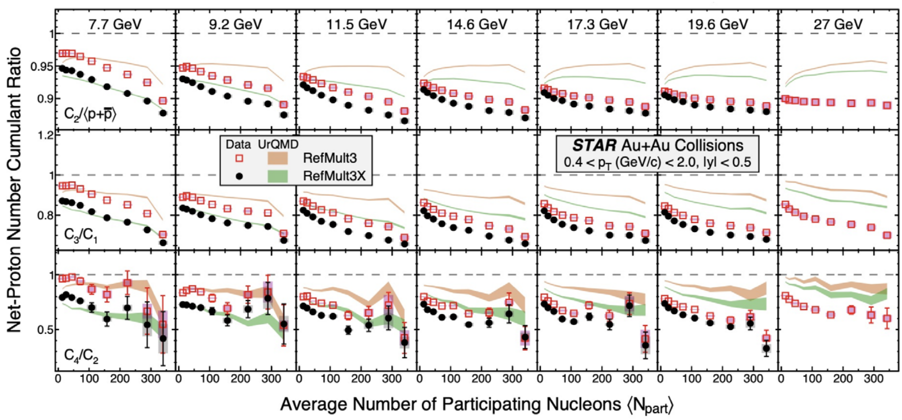

Figure 3. The 2^{nd}, 3^{rd} and 4^{th} order cumulant ratios of net-proton distribution as a function of N_{part} from 7.7 to 27 GeV. RefMult stands for |eta|<1, and RefMult3X for |eta|<1.6, both excluding protons and anti-protons.

The beam energy dependence of the factorial cumulant ratios are compared with a model calculation including critical point in Fig. 4 [4]. Considering the hydrodynamic calculation shown as light blue dashed lines on the right panels as baselines, the experimental data points might show possibly expected behaviors shown on the middle and left panels from the model including the critical point [5], however the accuracy of the experimental data points are not good enough to conclude anything especially for the 4^{th} order measurements, while the 2^{nd} and 3^{rd} orders are clearly deviating from the baseline model to be further investigated.

The net-proton higher-order fluctuation measurements have been performed in HADES experiment at SIS-GSI, where rapidity acceptance (Δy) dependence at Ag+Ag 2.55 GeV and centrality (N_{part}) dependence at Au+Au 2.4 GeV of cumulant and factorial cumulant ratios are shown in the left panels of Fig. 5 [6]. STAR experiment has also been taking data with fixed target mode setup in order to go further lower beam energy region below 7.7 GeV limit of the collider mode setup, the net-proton higher-order fluctuation measurements at 3 and 3.2 GeV as a function of rapidity acceptance are shown in the right panels of Fig. 5. As mentioned earlier, the choice of the acceptance is a key for the fluctuation measurement of conserved quantity, and the rapidity acceptance would also reflect the participant-spectator transition region, that can not clearly be separated especially in these colliding beam energy of a few GeV, therefore the observed acceptance dependence having minimum structure in

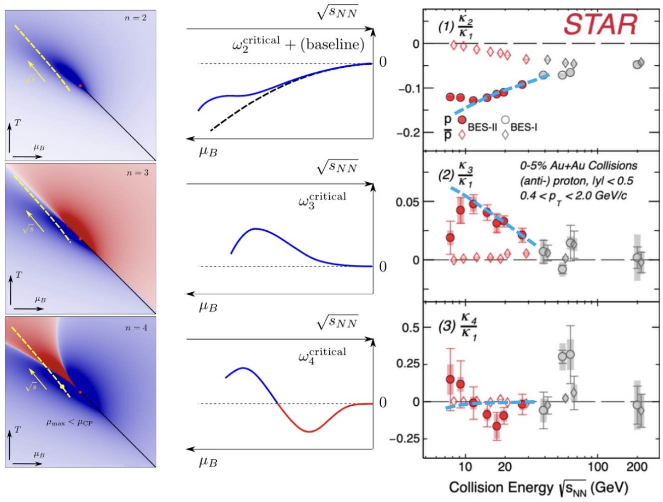

Figure 4. The factorial cumulant ratios with respect to the baseline model are compared with a model calculation including critical point [5].

central collisions would need further investigations. Regarding on the centrality dependence, one also needs to properly take into account the initial volume (N_{part}) fluctuation, that can not directly be accessible in the experiment.

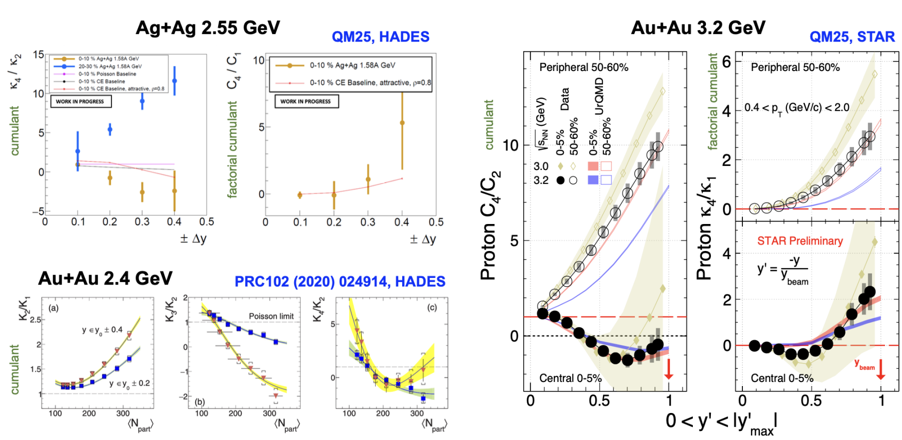

Figure 5. The rapidity acceptance dependence and centrality dependence of cumulant and factorial cumulant ratios are shown at low beam energy regions (around a few GeV) in HADES experiment [6] and STAR experiment with fixed target (FXT) mode setup.

3 Other related measurements

There are few other observations in terms of collective flow, correlation and fluctuation measurements, that might be related with the critical point and/or 1st order phase transition. The mean p_T fluctuation is one of them and is expected to be sensitive to the specific heat of the system, the recent measurements from STAR experiment is shown in Fig. 6. The measurements in fixed target mode setup (3 - 7 GeV) are new results that have confirmed the earlier measurements in collider mode setup (7 - 200 GeV) showing the minimum structure around 7 GeV especially in central Au+Au collisions. This is yet another non-monotonic feature of beam energy dependence in addition to the higher-order fluctuation and directed flow slope of net-proton, as well as the emission source size and duration time via two particle HBT correlation of pion pairs.

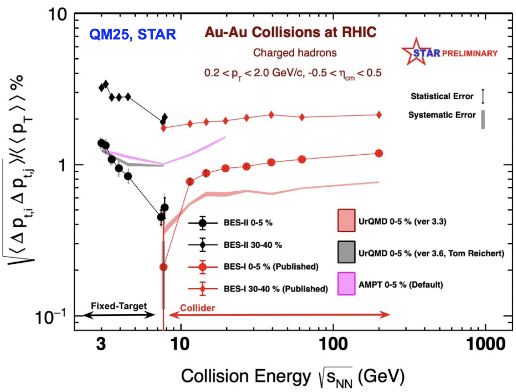

Figure 6. The mean p_T fluctuation is shown as a function of beam energy from STAR experiment, where black points are taken with fixed target mode setup, while red points are taken with collider mode setup.

Recent results on directed and elliptic event anisotropy (anisotropic flow) measurements are shown in Fig. 7. The left panel shows the directed flow slope (dv_1/dy) as a function of beam energy for various different hadrons. There have been clear differences among baryon, anti-baryon and meson in various earlier flow measurements including the sign changes depending on the particle species, while this new v_1 measurements on phi-meson seem to follow baryon v_1, which would need further differential studies. The right panels show the number of constituent quark (NCQ) scaled elliptic flow v_2 of various hadrons (anti-baryon and mesons) as a function of scaled kinetic energy for different colliding beam energies from 3 to 19.6 GeV [7], where panels in green box are taken with fixed target mode setup, while ones in yellow box are taken with collider mode setup in STAR experiment. The breaking of the NCQ scaling is found to be appeared around 4 - 7 GeV, which might also be related with the change of the phase boundary structure including the difference between partonic and hadronic phases.

4 Summary

Recent results from the beam energy scan program at RHIC-STAR experiment with other related experimental results including other facilities and theoretical expectations are shown and discussed. Two detector setups (collider mode, fixed target mode) of the STAR experiment are providing various insights of phase structure of the QCD phase diagram in addition to the results from other facilities such as LHC, SPS at CERN and SIS at GSI. A part of data from the fixed target mode setup especially on the net-proton kurtosis measurement has been shown in this QM25 conference, the full analysis seems to show quite interesting and striking

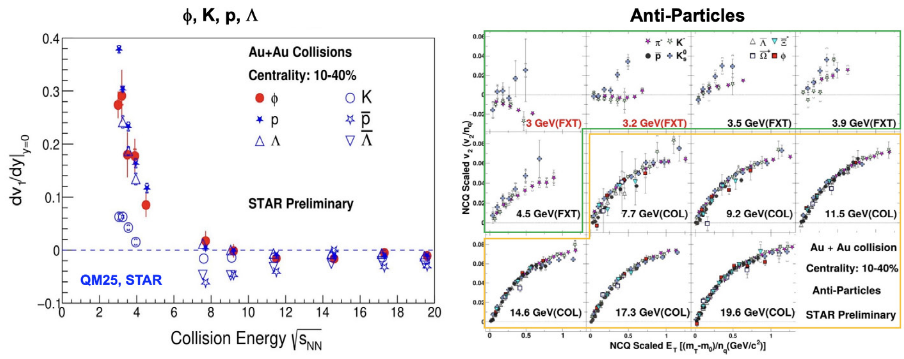

Figure 7. Left: The directed flow slopes of baryon, anti-baryon and mesons are shown as a function of beam energy. Right: The NCQ scaled elliptic flow of anti-baryon and mesons are shows as a function of scaled kinetic energy for different colliding beam energies from 3 to 19.6 GeV [7].

trends and features, which are being finalized at the moment. Because of this, it is also being considered to take some more experimental data around this fixed target energy region before the complete shutdown of the RHIC accelerator. The new projects are also being prepared for taking data soon in FAIR, HIAF, SPS, NICA and J-PARC in order to scan the QCD phase diagram especially towards the high-density area of the diagram. Finding and locating the QCD critical point and/or the 1st order phase transition in the QCD phase diagram is expected to be approaching.

References

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