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Collision energy dependence of C_5 and C_6 of net-proton distributions at RHIC-STAR

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Cumulants of net-baryon distributions are predicted to be sensitive observables in the study of the QCD phase diagram. The cumulant ratios are related to the thermodynamic susceptibilities which can be obtained from QCD based models, HRG, and lattice QCD calculations. QCD thermodynamics with a cross-over predicts negative sign of fifth- and sixth-order baryon number fluctuations. Furthermore, higher order proton factorial cumulants are also suggested to carry signals of the first-order phase transition between hadronic phase and the QGP, where the proton multiplicity distributions could develop a two-component structure.

We report the measurements of fifth- and sixth-order cumulants of net-proton distributions in Au+Au collisions from $\sqrt{s_{NN}}$ = 7.7 - 200 GeV, recorded by the STAR detector in the phase I of Beam Energy Scan (BES-I) program at RHIC. In addition, factorial cumulants of proton distributions for Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV are also presented. While C_5/C_1 of net-proton distributions in 0-40% centrality shows a weak collision energy dependece and fluctuates around zero, the C_6/C_2 values are increasingly negative with decreasing energy for the same centrality. Results of the two ratios for peripheral 70-80% collisions are positive at all energies. Within large uncertainties, the proton factorial cumulant κ_5 shows agreement with expectation from first-order transition inspired two-component model calculations while κ_6 remains 1.8σ away from the predictions for 0-5% centrality.

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1. Introduction

Strong interactions, one of the four fundamental interactions in nature, are governed by theory of Quantum Chromodynamics (QCD). The phase diagram of strongly interacting matter, known as the QCD phase diagram, represented on the plane of temperature (T) and baryonic chemical potential (μ_B) is largely conjuctured. It has at least two distinct phases: the Quark-Gluon-Plasma (QGP) [1] and the hadronic phase [2, 3]. While the quarks and gluons are deconfined in the QGP, they are confined in the hadronic phase. QCD calculations on lattice has proven the nature of phase transition between the two phases at vanishing μ_B to be a crossover [4]. Lattice QCD calculations at finite μ_B suffer from the notorious sign-problem. However, QCD-based model calculations at finite μ_B suggest the cross-over changes to be a first-order phase transition accompanied by the QCD critical point [5, 6].

So far there has been no direct experimental evidence of the cross-over and first order phase transition. Study of the QCD phase diagram is facilitated by experimental measurements of cumulants of event-by-event net-particle distributions as proxy for conserved quantum numbers (B,Q,S) in heavy-ion nuclear collisions [7, 8, 9, 10, 11, 12]. The ratios of cumulants are directly related to thermodynamic susceptibilities calculable in lattice-QCD, QCD-based model, and hadron resonance gas (HRG) model [13, 14, 15]. Recently, lattice QCD calculations with cross-over as the nature of phase transition have been extended to finite μ_B ($\mu_B \leq$ 160 MeV) using taylor series expansion about vanishing μ_B, thus avoiding the sign-problem. It predicts negative sign for ratio of fifth-to-first (χ_5^B/χ_1^B) and sixth-to-second (χ_6^B/χ_2^B) order baryon number susceptibilities [16]. It also advocates increasingly negative values of the two susceptibility ratios with increasing μ_B. Calculations from functional renormalisation group (FRG) model also predict the same sign and μ_B dependence for the fifth- and sixth-order net-baryon susceptibility ratios for a wide μ_B range of 20 - 420 MeV corresponding to STAR Au+Au collision energies $\sqrt{s_{NN}}$ = 200 – 7.7 GeV [17]. Furthermore, measurements of proton factorial cumulants have been suggested as sensitive observables to probe first-order phase transition. Near the vicinty of the first-order phase transition, a bimodal or two-component distribution is expected for proton multiplicity which results in a unique trait of factorial cumulants: their magnitude increases with order and flips sign [18, 19].

Recent STAR results on fourth-order net-proton cumulant ratio C_4/C_2 were found to exhibit non-monotonic collision energy dependence which is qualitatively consistent with a QCD-based model calculation that includes a critical point [11]. The study presented in this proceedings extends the net-proton and proton fluctuation measurements to fifth- and sixth-order to study the nature of phase transition by examining the sign-change of the measurements. Collision energy dependence of net-proton C_5/C_1 and C_6/C_2 for central 0-40% and peripheral 70-80% Au+Au collisions from $\sqrt{s_{NN}}$ = 7.7 – 200 GeV is presented where the percentage denotes the fraction of the total cross-section. Proton factorial cumulants as a function of centrality in $\sqrt{s_{NN}}$ = 7.7 GeV gold nucleus collisions are reported. Comparisons of measurements with various theoretical predictions are also shown.

2. Observables

The observables for our study are the nth-order cumulants (C_n) and factorial cumulants (κ_n) of net-proton and proton distributions, respectively. Cumulants can be expressed purely with factorial cumulants and vice versa. The cumulants of a distribution quantify the traits of the distribution. For example, the first and second order cumulant are the well known mean and variance of a distribution. Similarly, the third and fourth order cumulants reflect its skewness and kurtosis. This work extends the order of cumulants to fifth and sixth-order, which are defined as follows:

$$C_5 = \langle(\delta N)^5\rangle - 5\langle(\delta N)^3\rangle\langle(\delta N)^2\rangle, \tag{2.1}$$
$$C_6 = \langle(\delta N)^6\rangle - 15\langle(\delta N)^4\rangle\langle(\delta N)^2\rangle - 10\langle(\delta N)^3\rangle^2 + 30\langle(\delta N)^2\rangle^3, \tag{2.2}$$

Here, N is the observable of our interest, for example net-proton number and $\delta N = N - \langle N\rangle$ where $\langle N\rangle$ is the average of the N across all events. The fifth and sixth order factorial cumulants for a variate can be expressed in terms of its cumulants as follows:

$$\kappa_5 = 24C_1 - 50C_2 + 35C_3 - 10C_4 + C_5, \tag{2.3}$$
$$\kappa_6 = -120C_1 + 274C_2 - 225C_3 + 85C_4 - 15C_5 + C_6, \tag{2.4}$$

3. Analysis Details

Data of Au+Au collisions at nine energies: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4 and 200 GeV were analysed as part of the first phase of beam energy scan (BES-I) program at Relativistic Heavy-ion Collider (RHIC) facility. The number of minimum bias events range from 3 millions at $\sqrt{s_{NN}}$ = 7.7 GeV to about 900 millions at $\sqrt{s_{NN}}$ = 200 GeV. The detectors used for (anti-)proton identification are the Time-Projection-Chamber (TPC) and Time-of-Flight (TOF) [20]. The charged particle multiplicity in the psuedo-rapidity (η) range $|\eta| < 1$ are used to define centrality. As the fluctuations of net-protons are the observables of interest, protons and anti-protons are excluded from centrality definition to avoid self-correlation effects. The (anti-)protons at mid-rapidity ($|y| < 0.5$) within the transverse momentum (p_T) coverage of $0.4 < p_T < 2.0$ GeV/c are used for measurements. In the p_T range of $0.4 < p_T < 0.8$ GeV/c, only the TPC is used to select (anti-)protons whereas one requires both TPC and TOF for (anti-)proton identification in the higher momentum region, $0.8 < p_T < 2.0$ GeV/c. To suppress the background to the cumulant measurements arising due to initial system volume fluctuations, a method called Centrality-Bin-Width-Correction (CBWC) was applied [21]. To correct the cumulants for finite detector efficiency, an analytical correction was performed where the detector response was assumed to follow binomial distribution [22, 23, 24]. For estimation of statistical uncertainties, bootstrap method was used [25, 26, 27]. Systematic uncertainties on the measurements were estimated varying tracking efficiency, track selection and particle identification criteria.

4. Results

4.1 Energy dependence of net-proton C_5/C_1 and C_6/C_2

The cumulants ratios C_5/C_1 and C_6/C_2 of net-proton distributions in Au+Au collisions from $\sqrt{s_{NN}}$ = 7.7 – 200 GeV for collision centralities 0-40% and 70-80% centralities are presented in panel (1) and (2) of Fig. 1, respectively. The 0-40% central C_5/C_1 measurements show weak collision centrality dependence and fluctuate around zero in the whole collision energy range at a level of $\leq 2\sigma_{tot}$, where σ_{tot} is the total uncertainties on the data obtained adding statistical and systematic uncertainties in quadrature. The peripheral 70-80% C_5/C_1 ratios at all energies are positive and close to poisson baseline of unity. The C_6/C_2 for 0-40% centrality shows increasingly negative values with decreasing energy. In contrast, the HRG canonical ensemble calculations with no phase transition incorporated are mostly positive and become negative at very low energies. Except at 7.7 GeV, where the transport model UrQMD [29] calculations with impact parameter b <3 fm are positive for both net-proton C_5/C_1 and C_6/C_2, the calculations have too large statistical uncertainties to show a definite sign. The peripheral 70-80% C_6/C_2 data are found to be positive at all energies.

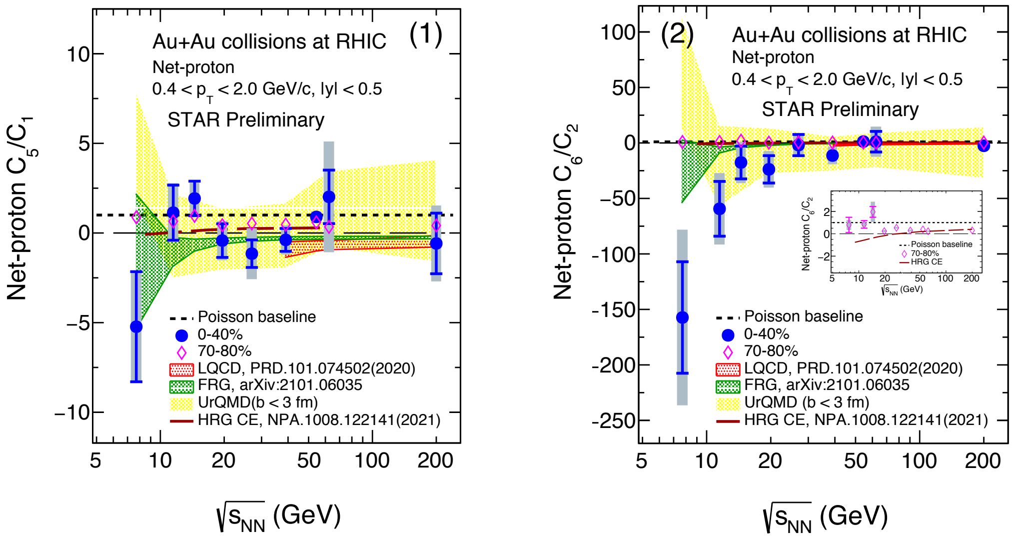

Figure 1: C_5/C_1 (1) and C_6/C_2 (2) of net-proton distributions in Au+Au collisions from $\sqrt{s_{NN}}$ = 7.7 – 200 GeV for central (0-40%, solid blue circles) and peripheral collisions (70-80%, open magenta diamond). The bars and golden shaded bands on the data points represent the statistical and systematic uncertainties, respectively. Calculations from lattice QCD (39 – 200 GeV) [16], FRG (7.7 – 200 GeV) [17], UrQMD model and HRG model with canonical ensemble [28] are shown in red, green, yellow bands and brown dashed line, respectively. The dotted line at unity represents the poisson baseline. The inset in panel (2) contains peripheral 70-80% C_6/C_2 data.

4.2 Proton factorial cumulants κ_5 and κ_6 in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV

Fifth and sixth-order factorial cumulants of proton multiplicity distributions as a function of collision-centrality (given by average number of participant nucleons, $\langle N_{part}\rangle$) is shown in panel (1) and (2) of Fig. 2, respectively. The κ_5 measurements are increasingly negative as a function of $\langle N_{part}\rangle$ while the κ_6 shows little collision-centrality dependence. Calculation from two-component model, which assumes a two-component distribution for proton multiplicity with the measured factorial cumulants up to fourth-order as inputs in its construction [12], predicts negative κ_5 and positive κ_6 for 0-5% centrality. While the result of κ_5 for 0-5% centrality is consistent with the two-component model expectation within uncertainties, the result of κ_6 remains 1.8 σ_{tot} away

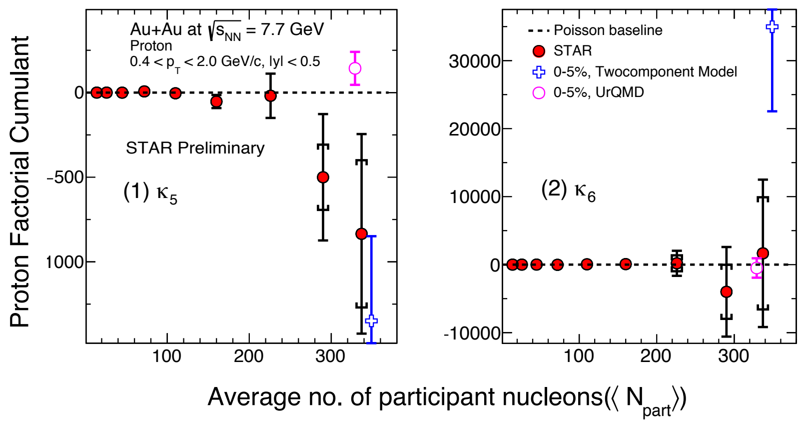

Figure 2: κ_5 (1) and κ_6 (2) of proton distributions in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV as a function of average number of participant nucleons. The STAR measurements are shown in red solid markers. The bars and caps on the data points represent the statistical and systematic uncertainties, respectively. The poisson baseline is shown as the dotted line. The two-component model and UrQMD model expectations for the 0-5% centrality are shown as blue cross and open magenta markers, respectively.

from the prediction for the same centrality and is consistent with the poisson baseline albeit with large uncertainties. The UrQMD calculations for both the order of factorial cumulants are close to poisson baseline of zero.

5. Summary

In summary, we presented measurements on collision energy dependence of net-proton cumulant ratios C_5/C_1 and C_6/C_2 for 0-40% and 70-80% collision centrality for a wide range of collision energies from $\sqrt{s_{NN}}$ = 7.7 to 200 GeV, which corrèponds to μ_B range of 420 - 20 MeV, respectively. The net-proton C_5/C_1 for 0-40% centrality shows weak collision energy dependence. The net-proton C_6/C_2 for the same centrality shows increasingly negative values with decreasing collision energy at a level of $\leq 2\sigma_{tot}$. In contrast, the peripheral 70-80% data for both ratios are found to be positive at all energies. It is noteworthy to mention here that lattice-QCD and FRG calculations predict negative fifth and sixth-order baryon-number susceptibilitiy ratios which become more negative with increasing μ_B, or in other words, decreasing collision energy. Here, when comparing the experimental data to theoretical calculations from lattice-QCD and FRG model one should keep in mind that in contrast to the latter which predict on fluctuations of conserved quantity net-baryon, the experimental measurements are made instead for net-protons. Also, as opposed to the theoretical calculation, the experimental measurements are done within a finite phase-space acceptance determined by experimental limitations of the detectors. These caveats should be accounted in future to facilitate a quantitative comparison between the theory and data. Furthermore, comparison of fifth and sixth order proton factorial cumulants with expectation from a first-order transition inspired two-component model for 0-5% centrality shows agreement within uncertainties for κ_5, while the result of κ_6 remains 1.8σ away from the model prediction. The current measurements suffer from large uncertainties, and thus precision measurements in BES-II will be necessary in order to confirm the reported dependence of fifth- and sixth-order fluctuations.

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