Measurement of higher moments of net-proton distributions in Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV at RHIC

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Abstract. We report the measurement of cumulants (C_n) of event-by-event net-proton distributions up to the sixth order in Au+Au collisions for center-of-mass energy $\sqrt{s_{NN}} = 54.4$ GeV using the STAR detector at RHIC. Measurements are performed as a function of collision centrality. Protons and antiprotons are selected within the rapidity range $|y| < 0.5$ and within transverse momentum range $0.4 < p_T < 2.0$ GeV/c. We observe a strong dependence of cumulants ($C_n, n \leq 4$) on collision centrality whereas the cumulant ratios C_2/C_1, C_3/C_2 and C_4/C_2 exhibit a weak collision-centrality dependence. The cumulant ratio (C_6/C_2) of net-proton distributions for most central gold nuclei collisions at $\sqrt{s_{NN}}$ = 54.4 GeV shows positive value while at $\sqrt{s_{NN}} = 200$ GeV it is negative for the same collision system. The expectation from the UrQMD and HIJING models calculated in the STAR acceptance are compared to the measured cumulant ratios and found not to describe the measurements.

Keywords: quark-gluon plasma, phase transition, cumulants

1 Introduction

Cumulants of conserved charges in high-energy heavy-ion collisions are excellent probes for the study of phase structure in the QCD phase diagram, nature of quark-hadron phase transition and freeze-out dynamics. The cumulants and their ratios are related to the correlation length of the system and the thermodynamic number susceptibilities that are calculable in the lattice QCD and various QCD-based models [1–3]. Cumulants up to the 4^{th} order ($C_n, n \leq 4$) of event-by-event distributions of net charge, net proton (proxy for net baryon) and net kaon (proxy for net strangeness) was measured by the STAR experiment in the phase I of Beam Energy Scan (BES) program at RHIC [4]. The cumulant ratios C_3/C_2 and C_4/C_2 of net-proton distribution in the most central (0-5%) gold nuclei collisions show non-monotonic dependence as a function of beam energy [5] which has important implication vis-a-vis the critical point search. Furthermore, the ratio of sixth- to second-order cumulants (C_6/C_2) can also provide insights into the nature of phase transition. The QCD-based model calculations predict a negative value of C_6/C_2 of net-baryon distributions for cross over phase transitions if the chemical freeze-out is close to the chiral phase transition [6].

2 Analysis details

In order to obtain the cumulants of net-proton distributions, protons and antiprotons are selected within the rapidity coverage $|y| < 0.5$ and within p_T range $0.4 - 2.0$ GeV/c. The collision centrality is determined from the charged particle multiplicity within pseudorapidity range $|\eta| < 1$, excluding the protons and antiprotons to avoid autocorrelation effect. The centrality bin width correction is applied to the measurement of the cumulants and their ratios in order to suppress the volume fluctuation effects [7]. Cumulants are corrected for the efficiency and acceptance effects of the detector assuming the detector response to be binomial. For estimation of statistical uncertainties of cumulants and their ratios, a resampling method called the bootstrap was used [8]. Systematic uncertainties of the C_n's are estimated varying track selection and particle identification criteria.

3 Results and discussions

In this section, new results on the measurement of cumulants up to the 6^{th} order of the event-by-event net-proton distributions for Au+Au collisions at $\sqrt{s_{NN}} =$ 54.4 GeV are presented as a function of collision centrality. Figure 1 shows the event-by-event net-proton multiplicity distributions from Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV for 0-5%, 5-10%, 30-40%, 60-70% and 70-80% most central collisions where protons and antiprotons are selected within the $y - p_T$ acceptance as taken in the calculation of cumulants. The distributions are uncorrected for the efficiency and acceptance effects. The shape of the net-proton distribution broadens and its mean increases as one approaches central collsions from peripheral collisions. Cumulants are obtained for these distributions. They are corrected for finite centrality bin width, the detector efficiency and acceptance effects [9, 10]. Figure 2 shows the cumulants (up to the 4^{th} order) of net-proton distribution as a function of collision centrality (given by the average number of participant nucleons, <Npart>) for Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV. The cumulants increase with number of participant nucleons.

Collision-centrality dependence of cumulant ratios C_2/C_1, C_3/C_2 and C_4/C_2 is shown in Fig. 3. The C_2/C_1 decreases with collision centrality. The ratios C_3/C_2 and C_4/C_2 exhibit a weak dependence on collision centrality. The cumulant ratios obtained from the UrQMD [11] and HIJING [12] models are also compared and found to qualitatively reproduce the measured centrality dependence, whereas quantitative differences exist. The Skellam baseline for C_4/C_2, which is the expected value if protons and antiprotons follow Poisson distribution, fails to describe the measured values. The non-monotonic beam-energy dependence of C_4/C_2 of net-proton distribution is shown in Fig. 4 for peripheral (70-80%) and most central (0-5%) collisions with inclusion of the results from the current measurement (open and solid red markers respectively). The new measurement with high statistics ($\sim$ 550 million minimum-bias events) gives a precise baseline for the possible critical fluctuations studies which is expected to be observed at lower beam energies.

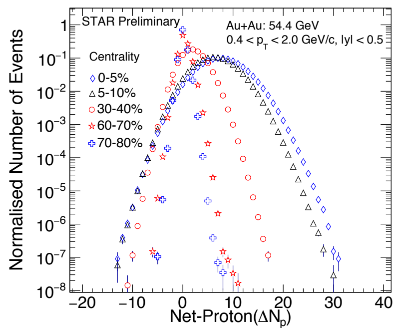

Fig. 1. Event-by-event net-proton multiplicity distributions in Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV for 0-5%, 5-10%, 30-40%, 60-70% and 70-80% collision centralities at mid-rapidity. The distributions are uncorrected for the efficiency and acceptance effects.

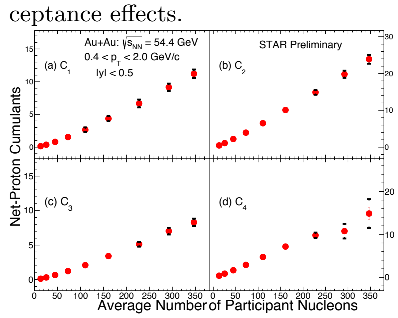

Fig. 2. Cumulants of net-proton distribution up to the 4^{th} order as a function of average number of participant nucleons for Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV.

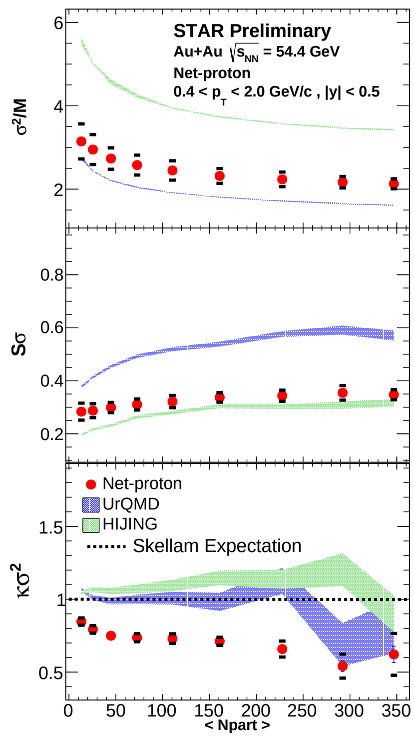

Fig. 3. Ratio of cumulants C_2/C_1, C_3/C_2 and C_4/C_2 of net-proton distribution as a function of average number of participant nucleons (<Npart>) for Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV. Blue and green band are the UrQMD and HIJING expectations, respectively.

Figure 5 shows the ratio of the sixth- to second-order cumulants (C_6/C_2) of net-proton distribution as a function of collision centrality for Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV and $\sqrt{s_{NN}} = 200$ GeV [13]. The value of C_6/C_2 for central collisions (0-40%) at $\sqrt{s_{NN}} = 54.4$ GeV is positive. This is in contrast to the value of C_6/C_2 measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, which is negative for central (0-40%) collisions. A negative value of C_6/C_2 is predicted to occur for a cross over transtion between hadronic matter and quark-gluon plasma in QCD-based calculations [6]. The UrQMD model expectation for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are found to be positive and consistent with the Skellam baseline for (0-40%) collision centrality.

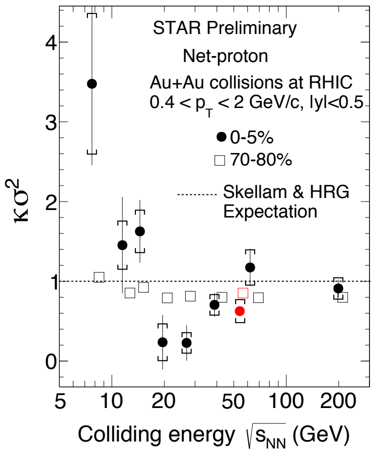

Fig. 4. Collision-energy dependence of C_4/C_2 for net-proton distributions for 0-5% and 70-80% most central collisions for Au+Au collisions with inclusion of the results from the C_4/C_2 measurement at $\sqrt{s_{NN}}$ = 54.4 GeV .

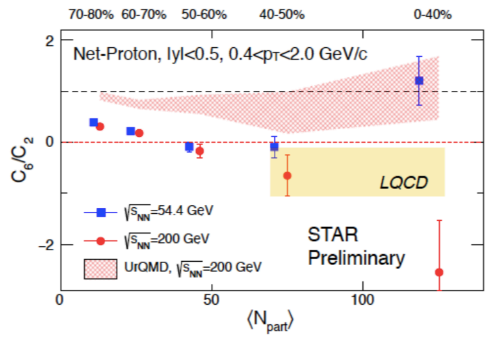

Fig. 5. Cumulant ratio C_6/C_2 of net-proton distribution for Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV (blue) and 200 GeV (red) as a function of collision centrality. Red band is the UrQMD expectation for Au+Au: 200 GeV and yellow band is the Lattice QCD prediction [14].

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