Measurement of Higher Moments of Net-particle Distributions in STAR

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Abstract Studying fluctuations of conserved quantities, such as baryon number (B), strangeness (S) and electric charge (Q), provides insights into the bulk properties of matter created in high-energy nuclear collisions. The higher moments of multiplicity distributions of net proton, net kaon and net charge are expected to show large fluctuations near the QCD critical point. We present results on energy and centrality dependence of higher moments of net proton, net kaon and net charge multiplicity distribution over all BES-I energies from the STAR experiment. The net proton moments product ($S\sigma$ and $\kappa\sigma^2$) shows deviations from Poisson baseline (unity) in the lower beam energies region (below $\sqrt{s_{\mathrm{NN}}}$ = 27 GeV). In the most central (0-5%) collisions, the $\kappa\sigma^2$ of net proton distribution as a function of collision energy exhibit a non-monotonic behaviour and show deviation in the lower energy region from corresponding predictions from Poisson baseline, a transport model (UrQMD) and a thermal model, all of which do not include any physics of criticality.

1 Introduction

High-energy heavy-ion collision experiments primarily aim to study the properties of nuclear matter subjected to extreme conditions such as temperature and/or pressure and understand the nature of the phase transitions. The phase structure of this matter can be illustrated by the Quantum Chromodynamics (QCD) phase diagram characterized by temperature (T) and baryonic chemical potential (μ_B). Lattice QCD calculations show that quark-hadron phase transition at zero μ_B is a crossover [1, 2], while QCD-based models predict a first order phase transition [3, 4] and the existence of QCD critical point (QCP) at a large value of μ_B. By varying the center of mass energy ($\sqrt{s_{NN}}$) of the colliding nuclei various parts of the QCD phase diagram can

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be accessed in the experiments [5, 6]. Fluctuations of conserved charges such as net charge (Q), net strangeness (S) and net baryon (B) can serve as probes of the QCD phase transition and the critical point [7]. Moments of the conserved charge distributions are related to the correlation lengths of the system, ($\langle(\delta N)^2\rangle \sim \xi^2$, $\langle(\delta N)^3\rangle \sim \xi^{4.5}$ and $\langle(\delta N)^4\rangle \sim \xi^7$) which are expected to diverge near the critical point [8]. Moments are also related to susceptibilities of conserved charges calculated in lattice QCD and thermal models [9, 10]. In heavy-ion collisions, finite time and finite system size effects restrict the growth of the correlation length resulting in finite enhancement of higher moments [11].

In this article, we report the results from phase I of the Beam Energy Scan (BES) program at RHIC, on the ratios of cumulants of net charge ($0.2 < p_T < 2$ GeV/c), net kaon ($0.2 < p_T < 1.6$ GeV/c) and net proton ($0.4 < p_T < 2$ GeV/c) distributions as function of collision energy($\sqrt{s_{NN}}$ = 7.7 - 200 GeV), measured at midrapidity in Au+Au collisions in the STAR experiment [12, 13, 14, 15]. Event-by-event net-particle distribution is found by taking algebraic sum of the quantum numbers of positively charged particles and corresponding antiparticles. Cumulants up to the 4^{th} order of the distribution is calculated using the relations: $C_1 = \langle N\rangle$, $C_2 = \langle(\delta N)^2\rangle$, $C_3 = \langle(\delta N)^3\rangle$ and $C_4 = \langle(\delta N)^4\rangle - 3C_2^2$, where $\delta N = N - \langle N\rangle$ and $\langle N\rangle$ is the mean of the distribution. To avoid the autocorrelation effect, the particles used in cumulant analysis are excluded from the centrality definition. To suppress the background effect such as initial volume fluctuations, the cumulants are calculated in multiplicity bins of unit width and then corrected using a method known as Centrality Bin-Width Correction(CBWC) [16]. Cumulants are corrected for the finite detector efficiency using a Binomial model [17]. Statistical errors are obtained using the Delta theorem [18] and Bootstrap [19] methods.

2 Results and Discussion

Figure 1 shows the raw (uncorrected for CBW and efficiency) multiplicity distributions for $\sqrt{s_{NN}}$ = 14.5 GeV [14]. The mean values of net-particle show an increasing trend from peripheral to central collisions, indicating the production of higher number of positively charged particles than negatively charged particles in central collisions. Similarly the standard deviation (σ) of the distribution also increases from peripheral to central collisions. At a given collision energy and centrality, net charge distribution has larger value of σ compared to net kaon and net proton distributions which results in larger statistical uncertainties on net charge cumulants.

Figure 2 shows the energy dependence of cumulant ratios ($C_2/C_1 = \sigma^2/M$, $C_3/C_2 = S\sigma$, $C_4/C_2 = \kappa\sigma^2$) of net charge, net kaon and net proton distributions at midrapidity in Au+Au collisions measured by the STAR experiment. The $S\sigma$ for net proton and net charge are normalized with the corresponding Skellam expectations [20]. The cumulants used to construct moments product are corrected for CBW effect and detector efficiency. The σ^2/M for all the charges shows a monotonically increasing trend as a function of collision energy, $\sqrt{s_{NN}}$. However, the $\kappa\sigma^2$ of net charge

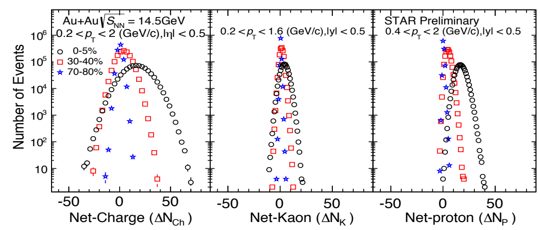

Fig. 1 Event-by-event uncorrected multiplicity distributions of net charge (left), net kaon (middle) and net proton (right) for Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV for 0-5% top-central (black circles), 30-40% mid-central (red squares), and 70-80% peripheral collisions (blue stars).

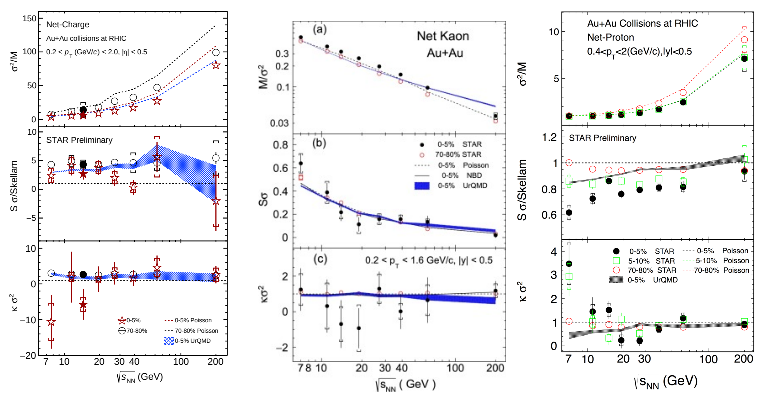

Fig. 2 Energy dependence of cumulant ratios of net charge, net kaon and net proton multiplicity distributions for 0-5% , 5-10% (green squares), and 70-80% centralities. The Poisson expectations are denoted as dotted lines and UrQMD calculations are shown as bands. The statistical and systematical error are shown in bars and brackets, respectively [12, 13, 14].

and net kaon show a weak collision energy dependence. Similarly the $S\sigma$ of net kaon and $S\sigma$/Skellam of net charge weakly vary with energy. Within the large uncertainties, both $S\sigma$/Skellam and $\kappa\sigma^2$ of net kaon and net charge agree with the non-critical baselines such as Poisson expectations and UrQMD model calculations. In 0-5% centrality, the $\kappa\sigma^2$ of net proton shows a non-monotonic behaviour as a function of collision energy. Net proton $\kappa\sigma^2$ measured in 0-5% central collisions, is close to the Poisson expectation, unity, for $\sqrt{s_{NN}} \geq$ 39 GeV, shows a dip at 27 and 19.6 GeV and then at 7.7 GeV shows a large (16 times the value of that measured at 27 GeV) rise above the baselines. The trend of net proton $\kappa\sigma^2$ in 0-5% central collisions is similar to the predictions from QCD-based model calculations if the system traverses in the vicinity of critical point [21]. Also $S\sigma$/Skellam of net proton for central collisions shows a non-monotonic behaviour with collision energy and deviates from non-critical baselines in the low energy region. The results for peripheral collisions at 70-80% centrality agree with the baselines. Figure 3 shows the net proton $\kappa\sigma^2$ in 0-5% centrality compared to the Hadron Resonance Gas (HRG) model calculations. With proper kinematic cuts as used in the experiments, the HRG model [22] calculations are performed using two sets of variables (T and μ_B) obtained

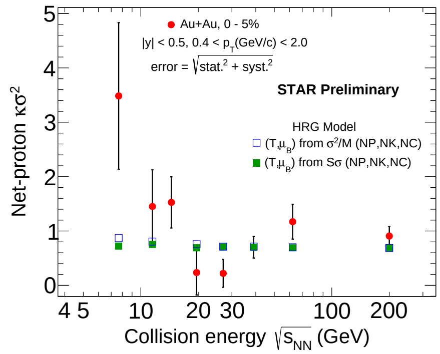

Fig. 3 Net proton $\kappa\sigma^2$ in 0-5% central Au+Au collisions measured by STAR experiment shown in red solid markers. The HRG model predictions with freeze-out conditions from σ^2/M (blue markers) and from $S\sigma$ (green markers) are also shown. Uncertainties on experimental data points are statistical and systematic errors added in quadrature.

from freeze-out of σ^2/M and $S\sigma$. Experimental data points on net proton $\kappa\sigma^2$ show deviations from the HRG model predictions in the low energy region starting from 27 GeV. The HRG model, which successfully explains the various particle yields fails to explain the trend for $\kappa\sigma^2$ of net proton which could indicate possible non-thermal contributions. In the phase II of BES program, the STAR experiment with detector upgrades is currently taking data with high statistics which would enable us to make more precise measurement of higher order cumulants.

3 Summary

The $\kappa\sigma^2$ for central net-proton distribution in Au+Au collisions at midrapidity shows a non-monotonic variation with collision energy. The $\kappa\sigma^2$ values deviate from the Poisson baseline and UrQMD model calculations. The HRG model, with the assumption of thermal equilibrium, can not explain the 4^{th}-order moments of net proton. Within the large statistical and systematic uncertainties, both $S\sigma$/Skellam and $\kappa\sigma^2$ of net kaon and net charge agree with Poisson baseline and UrQMD model [23] results.

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