Search for the QCD Critical Point by Higher Moments of Net-proton Multiplicity Distributions at STAR

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Abstract

We present the measurements of the higher moments of the net-proton multiplicity distributions in Au+Au collisions from the first phase of the beam energy scan program at RHIC. The measurements are carried out at midrapidity ($|y| < 0.5$) and within the transverse momentum range $0.4 < p_T < 0.8$ GeV/c by STAR. We report the centrality and energy dependence of the moment products ($\kappa\sigma^2$ and $S\sigma$), with σ^2, S and κ being the variance, skewness and kurtosis, respectively. These moment products are related to the ratios of various order baryon number susceptibilities and sensitive to the correlation length, and hence can be used to search for the QCD critical point. The results are compared to the Poisson expectations, as well as transport model calculations to understand the contributions from effects not related to critical physics.

1. Introduction

In the year 2010, the Relativistic Heavy Ion Collider (RHIC) launched the Beam Energy Scan (BES) program [1] and tuned the Au+Au collision energy from $\sqrt{s_{NN}}$=200 GeV down to 7.7 GeV. The main goal of the BES program is to search for the signature of the first order phase transition and Quantum Chromodynamics (QCD) Critical Point (CP) [2, 3, 4, 5]. By varying the colliding energy, we can access a broad region of the QCD phase diagram. The baryon chemical potential (μ_B) range is between about 20 MeV and 450 MeV [1]. The correlation length (ξ), which diverges near the CP, is related to moments of the multiplicity distributions of conserved quantities, such as net-baryon, net-charge and net-strangeness. Hence a non-monotonic variation of moments of multiplicity distributions with collision energy may serve as the signiture of CP. It was recently proposed that the higher moments such as skewness (S) and kurtosis (κ) of the multiplicity distributions of conserved quantities, are more sensitive to variation of ξ than the variance (σ^2) [6, 7, 8]. The moment products, $\kappa\sigma^2$ and $S\sigma$, are also related to the ratios of various order susceptibilities calculated in Lattice QCD [9, 10, 11, 12], HRG model [13]. Ratios of baryon number susceptibilities can be compared with the experimental data as $\kappa\sigma^2 = \chi_B^{(4)}/\chi_B^{(2)}$ and $S\sigma = \chi_B^{(3)}/\chi_B^{(2)}$. The ratios cancel out the volume effect. Theoretical calculations have shown that the experimentally measurable net-proton number (proton number minus anti-proton number) fluctuations may reflect the fluctuations of the net-baryon number [14]. In this paper, we present measurements for higher moments of event-by-event net-proton multiplicity distributions from the first phase of the BES program at RHIC.

2. Results and Discussion

The results presented here are from the Au+Au collisions data at $\sqrt{s_{NN}}$=7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV collected in the first phase of the BES program and $p + p$ collisions at $\sqrt{s_{NN}}$=62.4 and 200 GeV. The protons and anti-protons are identified using the ionization energy loss (dE/dx) of charged particles as measured by Time Projection Chamber (TPC) at midrapidity ($|y| < 0.5$) and within the transverse momentum range $0.4 < p_T < 0.8$ GeV/c. To suppress autocorrelation effects between measured net-proton fluctuations and centrality defined using charged particles, the following procedure is followed. Collision centrality is determined from the uncorrected charge particle multiplicity ($dN_{\mathrm{ch}}/d\eta$) by excluding the protons and anti-protons within pseudorapdity $|\eta| < 0.5$. This is a new technique employed in the moment analysis since the QM2011 conference [5]. If protons and anti-protons multiplicity follow independent Poissonian distributions, the net-proton multiplicity will follow the skellam distribution, which is expressed as:

$$P(N) = (\frac{M_p}{M_{\overline{p}}})^{N/2} I_N(2\sqrt{M_p M_{\overline{p}}}) \exp[-(M_p + M_{\overline{p}})],$$

where $I_N(x)$ is a modified Bessel function, M_p and $M_{\overline{p}}$ are the measured mean values of protons and anti-protons. The various order cumulants (C_n) are closely connected with the moments, e.g., $C_1 =< N >= M, C_2 =< (\Delta N)^2 >= \sigma^2, C_3 =< (\Delta N)^3 >= S\sigma^3, C_4 =< (\Delta N)^4 > -3 < (\Delta N)^2 >^2 = \kappa\sigma^4$. If the net-proton follows the skellam distribution, then we have, $S\sigma = C_3/C_2 = (M_p - M_{\overline{p}})/(M_p + M_{\overline{p}})$ and $\kappa\sigma^2 = C_4/C_2 = 1$, which then provides the Poisson expectations for the moment products.

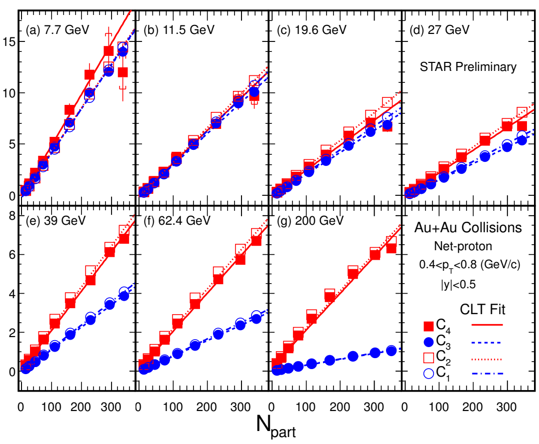

Figure 1: (Color Online) Centrality dependence of the cumulants of net-proton distributions for Au+Au collisions at $\sqrt{s_{NN}}$=7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV. The lines are linear fit to these cumulants. Errors bars are statistical and caps are systematic errors.

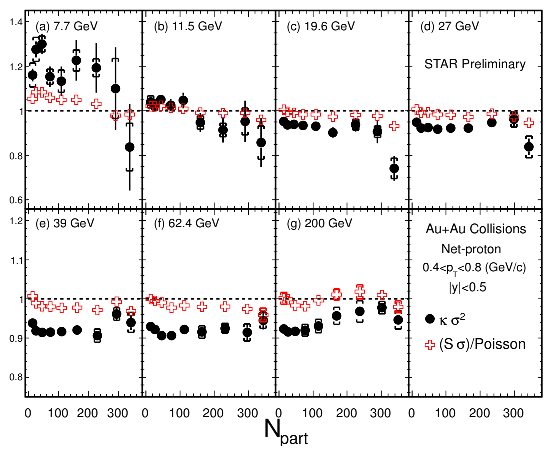

Figure 2: (Color Online) Centrality dependence of $S\sigma$/Poisson and $\kappa\sigma^2$ of net-proton distributions for Au+Au collisions at $\sqrt{s_{NN}}$=7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV. The error bars are statistical and caps are systematic errors.

The various order cumulants ($C_1 - C_4$) shown in Fig. 1 are obtained from the net-proton distributions and corrected for the finite centrality bin width effect [4]. The statistical error estimation in Fig.1 are based on the Delta theorem method [15], which is an updated method compare to the analytical method used in QM2011 results [5]. The systematical errors are estimated by varying the track quality condition and particle identification criteria. $C_1 - C_4$ values in Fig.1 show a linear increase with $N_{\rm part}$ for all beam energies. The lines shown in the Fig.1 represent linear fit to the cumulants vs. $N_{\rm part}$, motivated by the Central Limit Theorem (CLT). We can find that the odd (C_1 and C_3) and even (C_2 and C_4) order cumulants group together. The difference between the two groups are smaller at lower energies. The ratios of the cumulants, which are connected to the moment products as $S\sigma = C_3/C_2$ and $\kappa\sigma^2 = C_4/C_2$, are shown in Fig. 2. It is observed that the $\kappa\sigma^2$ and the $S\sigma$ values normalized to Poisson expectations are below unity for $\sqrt{s_{NN}}$ above 11.5 GeV and above unity for 7.7 GeV in Au+Au collisions. The data presented here may allow us to extract freeze-out conditions in heavy-ion collisions using QCD based approaches [16].

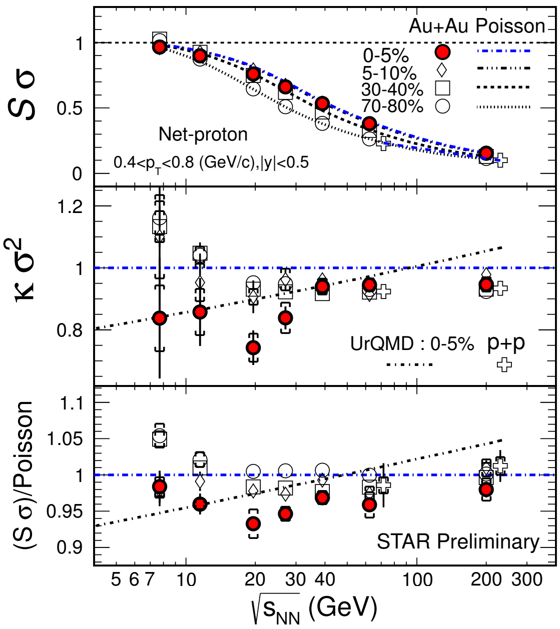

Figure 3: (Color online) Energy dependence of $\kappa\sigma^2$ and $S\sigma$ for net-proton distributions for four collision centralities (0-5%, 5-10%, 30-40% and 70-80%) measured at STAR. The results are compared to UrQMD model calculations and $p+p$ collisions at $\sqrt{s_{NN}}$=62.4 and 200 GeV. The lines in top panel are the Poisson expectations and in the bottom panel shows the $S\sigma$ normalized to the corresponding Poisson expectations.

Fig.3 shows the energy dependence of $\kappa\sigma^2$ and $S\sigma$ of net-proton distributions for four centralities (0-5%, 5-10%, 30-40% and 70-80%) in Au+Au collisions. The Bottom panel of Fig.3 shows $S\sigma$ values normalized to the corresponding Poisson expectations. The $\kappa\sigma^2$ and normalized $S\sigma$ values are close to the Poisson expectation for Au+Au collisions at $\sqrt{s_{NN}}$=39 , 62.4 and 200 GeV. They deviate for the 0-5% central Au+Au collisions and the peripheral collisions below $\sqrt{s_{NN}}$=39 GeV. The UrQMD model [17] results are also shown in the Fig. 3 for 0-5% centrality to understand the non-CP effects, such as baryon number conservation and hadronic scattering. The UrQMD calculations show a monotonic decrease with decreasing beam energy.

3. Summary

We have presented the beam energy ($\sqrt{s_{NN}}$=7.7−200 GeV) and centrality dependence for the higher moments of net-proton distributions in Au+Au collisions from the first phase of the BES program at RHIC. These data provides information towards the experimental search for the QCD critical point. It is observed that the $\kappa\sigma^2$ and $S\sigma$ values are close to the Poisson expectation for Au+Au collisions at $\sqrt{s_{NN}}$=39 , 62.4 and 200 GeV. They deviate from Poisson expectations in the 0-5% central Au+Au collisions and the peripheral collisions below $\sqrt{s_{NN}}$=39 GeV. The experimental data are also compared with the UrQMD model calculation to understand the non-critical physics effects. The UrQMD calculations show a monotonic decrease with decreasing beam energy. Due to the small correlation length and dynamical evolution of the system in the heavy ion collisions, the signature of the CP could be small. Detailed comparison is required between our data and QCD calculations that include dynamical evolution of the heavy-ion collision system. We also need more statistics to get precise measurements below 19.6 GeV and additional data at $\sqrt{s_{NN}}$=15 GeV. These are planned for the second phase of the BES program at RHIC.

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