Collision Energy Dependence of Moments of Net-Kaon Multiplicity Distributions at RHIC

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Fluctuations of conserved quantities such as baryon number, charge, and strangeness are sensitive to the correlation length of the hot and dense matter created in relativistic heavy-ion collisions and can be used to search for the QCD critical point. We report the first measurements of the moments of net-kaon multiplicity distributions in Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, \text{and} \ 200 \text{ GeV}$. The collision centrality and energy dependence of the mean ($M$), variance ($\sigma^2$), skewness ($S$), and kurtosis ($\kappa$) for net-kaon multiplicity distributions as well as the ratio $\sigma^2/M$ and the products $S\sigma$ and $\kappa\sigma^2$ are presented. Comparisons are made with Poisson and negative binomial baseline calculations as well as with UrQMD, a transport model (UrQMD) that does not include effects from the QCD critical point. Within current uncertainties, the net-kaon cumulant ratios appear to be monotonic as a function of collision energy.

PACS numbers: 25.75.Gz,12.38.Mh,21.65.Qr,25.75.-q,25.75.Nq
I. INTRODUCTION

One primary goal of high energy heavy-ion collisions is to explore the phase structure of strongly interacting hot, dense nuclear matter. It can be displayed in the quantum chromodynamics (QCD) phase diagram, which is characterized by the temperature (T) and the baryon chemical potential (μ_B). Lattice QCD calculations suggest that the phase transition between the hadronic phase and the quark-gluon plasma (QGP) phase at large μ_B and low T is of the first order [1, 2], while in the low μ_B and high T region, the phase transition is a smooth crossover [3]. The end point of the first order phase boundary towards the crossover region is the so-called critical point [4, 5]. Experimental search for the critical point is one of the central goals of the beam energy scan (BES) program at the Relativistic Heavy-Ion Collider (RHIC) facility at Brookhaven National Laboratory.

Fluctuations of conserved quantities, such as baryon number (B), charge (Q), and strangeness (S) are sensitive to the QCD phase transition and QCD critical point [6–8]. Experimentally, one can measure the moments (mean (M), variance (σ^2), skewness (S), and kurtosis (κ)) of the event-by-event net-particle distributions (particle multiplicity minus antiparticle multiplicity), such as net-proton, net-kaon and net-charge multiplicity distributions in heavy-ion collisions. These moments are connected to the thermodynamic susceptibilities that can be computed in lattice QCD [5, 9–15] and as in terms of cumulants (UrQMD, version 2.3) model calculations [35].

As a part of the BES, Au+Au collisions were run by RHIC with energies ranging from $\sqrt{s_{NN}} = 200$ GeV down to 7.7 GeV [32–34] corresponding to μ_B from 20 to 420 MeV. In this paper, we report the first measurements for the moments of net-kaon multiplicity distributions in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, 14.5, 19.6, 27, 39, 62.4, and 200 GeV. These results are compared with baseline calculations (Poisson and negative binomial) and the Ultrarelativistic Quantum Molecular Dynamics (UrQMD, version 2.3) model calculations [35].

The manuscript is organized as follows. In section II, we define the observables used in the analysis. In section III, we describe the STAR (Solenoidal Tracker At RHIC) experiment at BNL and the analysis techniques. In section IV, we present the experimental results for the moments of the net-kaon multiplicity distributions in Au+Au collisions at RHIC BES energies. A summary is given in section V.

II. OBSERVABLES

Distributions can be characterized by the moments M, σ^2, S, and κ as well as in terms of cumulants C_1, C_2, C_3, and C_4 [36].

In the present analysis, we use N to represent particle multiplicity in one event and ∆N_K (N_K+ − N_K−) the net-kaon number. The average value over the entire event ensemble is denoted by ⟨N⟩. Then the deviation of N from its mean value can be written as δN = N − ⟨N⟩. The various order cumulants of event-by-event distributions of N are defined as:

\[
C_1 = ⟨N⟩ \quad (1)
\]
\[
C_2 = ⟨(δN)^2⟩ \quad (2)
\]
\[
C_3 = ⟨(δN)^3⟩ \quad (3)
\]
\[
C_4 = ⟨(δN)^4⟩ - 3⟨(δN)^2⟩^2 \quad (4)
\]

The moments can be written in terms of the cumulants as:

\[
M = C_1, \sigma^2 = C_2, S = \frac{C_3}{(C_2)^{3/2}}, \kappa = \frac{C_4}{(C_2)^2} \quad (5)
\]

In addition, the products of moments κσ^2 and Sσ can be expressed in terms of cumulant ratios:

\[
κσ^2 = \frac{C_4}{C_2}, Sσ = \frac{C_3}{C_2} \quad (6)
\]

III. DATA ANALYSIS

The results presented in this paper are based on the data taken at STAR [37] for Au+Au collisions at $\sqrt{s_{NN}}$
and mass-squared ($K dE/dx$) of a particle from the primary vertex of the collision. Combined with the path length ($L$) measured in the TPC, one can directly calculate the velocity ($v$) of the particles and their rest mass ($m$) using:

$$\beta = \frac{v}{c} = \frac{L}{ct}$$

(8)

$$m^2c^2 = p^2 \left( \frac{1}{\beta^2} - 1 \right) = p^2 \left( \frac{c^2t^2}{L^2} - 1 \right)$$

(9)

In this analysis, we use mass-squared cut $0.15 < m^2 < 0.4$ GeV$^2$/c$^4$ to select $K^+$ and $K^-$ within the $p_T$ range $0.4 < p_T < 1.6$ GeV/c to get high purity of kaon sample (better than 99%). For the $p_T$ range $0.2 < p_T < 0.4$ GeV/c, we use only the TPC to identify $K^+$ and $K^-$. The collision centrality is determined using the efficiency-uncorrected charged particle multiplicity excluding identified kaons within pseudorapidity $|\eta| < 1.0$ measured with the TPC. This definition maximizes the number of particles used to determine the collision centrality and avoids self-correlations between the kaons used to calculate the moments and kaons in the reference multiplicity [41]. Using the distribution of this reference multiplicity along with the Glauber model [42] simulations, the collision centrality is determined. This reference multiplicity is similar in concept to the reference multiplicity used by STAR to study moments of net-proton distributions [29], where the reference multiplicity was calculated using all charged particles within

= 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV. The 7.7, 11.5, 39, 62.4, and 200 GeV data were collected in the year 2010, the 19.6 and 27 GeV data were collected in the year 2011, and the 14.5 GeV data were collected in the year 2014.

The STAR detector has a large uniform acceptance at midrapidity ($|y| < 1$) with excellent particle identification capabilities, i.e., allowing to identify kaons from other charged particles for $0.2 < p_T < 1.6$ GeV/c. Energy loss ($dE/dx$) in the time projection chamber (TPC) [38] and mass-squared ($m^2$) from the time-of-flight detector (TOF) [39] are used to identify $K^+$ and $K^-$. To utilize the energy loss measured in the TPC, a quantity $n_{\sigma X}$ is defined as:

$$n_{\sigma X} = \frac{\ln[(dE/dx)_{\text{measured}}/(dE/dx)_{\text{theory}}]}{\sigma X}$$

(7)

where $(dE/dx)_{\text{measured}}$ is the ionization energy loss from TPC, and $(dE/dx)_{\text{theory}}$ is the Bethe-Bloch [40] expectation for the given particle type (e.g., $\pi, K, p$). $\sigma X$ is the $dE/dx$ resolution of TPC. We select $K^+$ and $K^-$ particles by using a cut $|n_{\sigma_{K\text{aon}}}| < 2$ within transverse momentum range $0.2 < p_T < 1.6$ GeV/c and rapidity $|y| < 0.5$. The TOF detector measures the time of flight ($t$) of a particle from the primary vertex of the collision. Combined with the path length ($L$) measured in the TPC, one can directly calculate the velocity ($v$) of the particles and their rest mass ($m$) using:

$$\beta = \frac{v}{c} = \frac{L}{ct}$$

(8)

$$m^2c^2 = p^2 \left( \frac{1}{\beta^2} - 1 \right) = p^2 \left( \frac{c^2t^2}{L^2} - 1 \right)$$

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FIG. 1. (Color Online). Raw $\Delta N_K$ distributions in Au+Au collisions from $\sqrt{s_{NN}} = 7.7$ to 200 GeV for 0-5%, 30-40%, and 70-80% collision centralities at midrapidity. The distributions are not corrected for the finite centrality bin width effect nor the reconstruction efficiency.
|η| < 1.0 excluding identified protons and antiprotons. Using this definition, collision centrality bins of 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, and 70-80% of the multiplicity distributions were used with 0-5% representing the most central collisions.

Figure 1 shows the raw event-by-event net-kaon multiplicity ($\Delta N_K = N_{K^+} - N_{K^-}$) distributions in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ to 200 GeV for three collision centralities, i.e. 0-5%, 30-40%, and 70-80%. For the 0-5% central collision, the peaks of the distributions are close to zero at high energies, and shift towards the positive direction as the energy decreases. This is because the pair production of $K^+$ and $K^-$ dominates at high energies while the production of $K^0$ is dominated by the associated production via reaction channel $NN \rightarrow NAK^+$ at lower energy [43]. Those distributions are not corrected for the finite centrality bin width effect and also track reconstruction efficiency. However, all the cumulants and their ratios presented in this paper are calculated for the finite centrality bin width effect [41] and efficiency of $K^+$ and $K^-$. The moments and cumulants can be expressed in terms of factorial moments, which can be easily corrected for efficiency [44, 45]. The efficiency correction is done by assuming the response function of the efficiency is a binomial probability distribution. Figure 2 shows the collision centrality dependence of the $p_T$-averaged efficiencies of tracking and PID combined for two $p_T$ ranges. One can see that at the lower $p_T$ range (0.2 < $p_T$ < 0.4 GeV/c), kaons have a lower efficiency compared with the higher $p_T$ range (0.4 < $p_T$ < 1.6 GeV/c). The efficiencies increase monotonically with the centrality changing from most central (0 ~ 5%) to peripheral (70 ~ 80%). $K^+$ and $K^-$ have similar efficiencies.

By calculating the covariance between the various order factorial moments, one can obtain the statistical uncertainties for the efficiency corrected moments based on the error propagation derived from the Delta theorem [41, 45, 46]. The statistical uncertainties of various order cumulants and cumulant ratios strongly depend on the width ($\sigma$) of the measured multiplicity distributions as well as the efficiencies ($\varepsilon$). One can roughly estimate the statistical uncertainties of $S\sigma$ and $k\sigma^2$ as $error(S\sigma) \propto \frac{S\sigma}{\varepsilon}$ and $error(k\sigma^2) \propto \frac{k\sigma^2}{\varepsilon^2}$. That explains why we observe larger statistical uncertainties for central than peripheral collisions, as well as the width ($\sigma$) of the measured multiplicity distributions. Furthermore, due to the smaller detection efficiency of kaons than the protons, we observe larger statistical uncertainties of cumulants and cumulant ratios than those of the net-proton fluctuations [29]. Systematic uncertainties are estimated by varying the following track quality cuts: distance of closest approach, the number of fit points used in track reconstruction, the $dE/dx$ selection criteria for identification, and additional 5% uncertainties in the reconstruction efficiency. The typical systematic

![Collision centrality dependence of the $p_T$-averaged efficiencies in Au+Au collisions.](image-url)
FIG. 3. (Color Online). Collision centrality dependence of cumulants ($C_1$, $C_2$, $C_3$, and $C_4$) of $\Delta N_K$ distributions for Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV. The error bars are statistical uncertainties and the caps represent systematic uncertainties. The Poisson and NBD expectations are shown as dashed and blue solid lines, respectively.

FIG. 4. (Color Online). Collision centrality dependence of $M/\sigma^2$ for $\Delta N_K$ distributions in Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV. The Poisson expectations are shown as dashed lines.
FIG. 5. (Color Online). Collision centrality dependence of the $S\sigma$ for $\Delta N_K$ distributions from Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV. The error bars are statistical uncertainties and the caps represent systematic uncertainties. The Poisson (dashed line) and NBD (blue solid line) expectations are also shown.

FIG. 6. (Color Online). Collision centrality dependence of the $\kappa\sigma^2$ for $\Delta N_K$ distributions from Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV. The error bars are statistical uncertainties and the caps represent systematic uncertainties. The Poisson (dashed-line) and NBD (blue-solid-line) expectations are also shown.
cumulants are extensive quantities that are proportional to the system volume. The decrease of the $C_1$ and $C_3$ values with increasing collision energy indicates that the ratio $K^+/K^-$ approaches unity for the higher collision energies. Figure 3 also shows the Poisson and negative binomial distribution (NBD) [47, 48] expectations. The Poisson baseline is constructed using the measured mean values of the multiplicity distributions of $K^+$ and $K^-$, while the NBD baseline is constructed using both means and variances. Assuming that the event-by-event multiplicities of $K^+$ and $K^-$ are independent random variables, the Poisson and NBD assumptions provide references for the moments of the net-kaon multiplicity distributions. Within uncertainties, the measured cumulants values of $C_3$ and $C_4$ are consistent with both the Poisson and NBD baselines for most centralities.

The ratios between different order cumulants are taken to cancel the volume dependence. Figures 4, 5, and 6 show the $\langle N_{\text{part}} \rangle$ dependence of $\Delta N_K$ multiplicity distributions for cumulant ratios $C_1/C_2 (=M/\sigma^2)$, $C_3/C_2 (=S\sigma)$, and $C_4/C_2 (=k\sigma^2)$, respectively. The values of $C_1/C_2$, shown in Fig. 4, systematically decrease with increasing collision energy for all centralities. The Poisson baseline for $C_1/C_2$ slightly underestimates the data, indicating possible correlations between $K^+$ and $K^-$ production. For $C_3/C_2 (=S\sigma)$ in Fig. 5, the Poisson and NBD expectations are observed to be lower than the measured $S\sigma$ values at low collision energies. The measured values for $C_4/C_2 (=k\sigma^2)$ in Fig. 6 are consistent with both the Poisson and NBD baselines within uncertainties.

The collision energy dependence of the cumulant ratios for $\Delta N_K$ distributions in Au+Au collisions are presented in Fig. 7. The results are shown in two collision centrality bins, one corresponding to most central (0-5%) and the other to peripheral (70-80%) collisions. Expectations from the Poisson and NBD baselines are derived for central (0-5%) collisions. The values of $M/\sigma^2$ decrease as the collision energy increases, and are larger for central collisions compared with the peripheral collisions. For most central collisions, the Poisson baseline for $C_1/C_2$ slightly underestimates the data. Within uncertainties, the values of $S\sigma$ and $k\sigma^2$ are consistent with both the Poisson and NBD baselines in central collisions. The blue bands give the results from the UrQMD model calculations for central (0-5%) Au+Au collisions. The width of the bands represents the statistical uncertainties. The UrQMD calculations for $S\sigma$ and $k\sigma^2$ are consistent with the measured values within uncertainties [49]. A QCD based model calculation suggests that, due to heavy mass of the strange-quark, the sensitivity of the net-kaon $\langle \Delta N_K \rangle$ fluctuations is less than that of the net-proton $\langle \Delta N_p \rangle$ [50]. A much high statistics dataset is needed for the search of the QCD critical point with strangeness.
V. SUMMARY

In heavy-ion collisions, fluctuations of conserved quantities, such as net-baryon, net-charge and net-strangeness numbers, are sensitive observables to search for the QCD critical point. Near the QCD critical point, those fluctuations are expected to have similar energy dependence behavior. Experimentally, the STAR experiment has published the energy dependence of the net-proton (proxy for net-baryon) and net-charge fluctuations in Au+Au collisions from the first phase of the beam energy scan at RHIC. In this paper, we present the first measurements of the moments of net-kaon (proxy for net-strangeness) multiplicity distributions in Au+Au collisions from \( \sqrt{s_{NN}} = 7.7 \) to 200 GeV. The measured \( M/\sigma^2 \) values decrease monotonically with increasing collision energy. The Poisson baseline for \( C_1/C_2 \) slightly underestimated the data. No significant collision centrality dependence is observed for both \( 5\sigma \) and \( \kappa \sigma^2 \) at all energies. For \( C_1/C_2 (=5\sigma) \), the Poisson and NBD expectations are lower than the measured \( 5\sigma \) values at low collision energies. The measured values for \( C_4/C_2 (=\kappa \sigma^2) \) are consistent with both the Poisson and NBD baselines within uncertainties. UrQMD calculations for \( 5\sigma \) and \( \kappa \sigma^2 \) are consistent with data for the most central 0-5\% Au+Au collisions. Within current uncertainties, the net-kaon cumulant ratios appear to be monotonic as a function of collision energy. The moments of net-kaon multiplicity distributions presented here can be used to extract freeze-out conditions in heavy-ion collisions by comparing to Lattice QCD calculations. Future high precision measurements will be made for the net-kaon fluctuations in the second phase of the RHIC Beam Energy Scan during 2019-2020.

ACKNOWLEDGMENTS

We thank the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL, and the Open Science Grid consortium for providing resources and support. This work was supported in part by the Office of Nuclear Physics within the U.S. DOE Office of Science, the U.S. National Science Foundation, the Ministry of Education and Science of the Russian Federation, National Natural Science Foundation of China, Chinese Academy of Science, the Ministry of Science and Technology of China and the Chinese Ministry of Education, the National Research Foundation of Korea, GA and MSMT of the Czech Republic, Department of Atomic Energy and Department of Science and Technology of the Government of India; the National Science Centre of Poland, National Research Foundation, the Ministry of Science, Education and Sports of the Republic of Croatia, RosAtom of Russia and German Bundesministerium fur Bildung, Wissenschaft, Forschung and Technologie (BMBF) and the Helmholtz Association.

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