Off-diagonal cumulants of net-charge, net-proton and net-kaon multiplicity distributions in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$-200 GeV from STAR

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Fluctuations of conserved quantities such as net-baryon, net-charge, and net-strangeness numbers have generated considerable interest in the study of the thermodynamic properties of the hot and dense QCD matter. Theoretical calculations suggest that the off-diagonal cumulants of conserved charges along with the diagonal cumulants can help better constrain the freeze-out parameters and, therefore, help to map the QCD phase diagram. In this proceeding, we briefly outline the recent STAR measurements [1] on the second-order off-diagonal cumulants of net-charge, net-proton, and net-kaon multiplicity distributions in Au+Au collisions from the RHIC BES-I program in the energy range of $\sqrt{s_{NN}} = 7.7$-200 GeV. The measured cumulant ratios are compared to the predictions from both thermal (HRG) and non-thermal (UrQMD) models.

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1. Introduction

The major goal of relativistic heavy-ion collision experiment is to study the formation of a new form matter, called the Quark-Gluon Plasma (QGP). Over the last two decades, a number of possible evidences for the QGP phase has been established experimentally. Currently a large community of physicists are exploring the QCD phase structure and trying to find a possible signature of the QCD critical point. One of the most community used method to explore phase diagram is to study the event-by-event fluctuations of conserved charges, such as net electric charge (Q), net baryon number (B) and net strangeness number (S) in the heavy-ion collisions over a wide range of energy \cite{2,3}. It is proposed that the higher-order cumulants of the net-multiplicity distributions are related to the higher order thermodynamic susceptibilities of corresponding conserved charges in QCD and expected to diverge near the critical point \cite{2,4}. Over the past few years, STAR and PHENIX experiments at RHIC published results on the diagonal cumulants (\(c^n_a\)) of net-electric charge \cite{5,6}, net-proton (\(p\), an experimental proxy for net-baryon) \cite{7,8} and net-kaon (\(k\), an experimental proxy for net-strangeness) \cite{9} multiplicity distributions. Similarly, off-diagonal cumulants (\(c^m_n\alpha\beta\)) of Q, p and k are related to the mixed susceptibilities that carry the correlation between different conserved charges \cite{1}. Lattice QCD and hadron resonance gas model (HRG) calculations show that normalized baryon-strange correlations, that can be expressed as off-diagonal to diagonal cumulant \((C_{BS} = c^{1,1}_{BS}/c^2_S)\), are expected to be sensitive to the onset of deconfinement \cite{10}. Another importance of studying off-diagonal cumulants is that it can also be used to constrain the freeze-out parameters in the QCD phase diagram. Different theoretical calculations demonstrate that the 2nd-order off-diagonal cumulants show a significant sensitivity to the difference between HRG and lattice calculations \cite{11,12}.

In this report, we present the measurements of 2nd-order diagonal and off-diagonal cumulants of net charge, net proton and net kaon multiplicity distributions in Au+Au collisions ranging in center of mass energy from \(\sqrt{s_{NN}} = 7.7\) to 200 GeV, with data taken during the first phase of RHIC Beam Energy Scan (BES-I).

2. Observables

The susceptibilities of the conserved charges of a system in thermal and chemical equilibrium (for a grand-canonical ensemble) can be computed from the partial derivatives of the dimensionless pressure with respect to the chemical potentials:

\[
\chi^m_{B,Q,S} = \frac{\partial^{m+n+l}(P/T^4)}{\partial^m(\mu_B/T)\partial^n(\mu_Q/T)\partial^l(\mu_S/T)},
\]

where \(V\) and \(T\) are the system pressure and temperature, respectively, and \(m, n, l = 1, 2, 3, \ldots n\) are the order of derivative. \(\mu_Q\), \(\mu_B\) and \(\mu_S\) are the electric charge, baryon and strangeness chemical potentials, respectively. The \(P\) is obtained from the logarithm of the QCD partition function:

\[
P = \frac{T}{V} \ln[Z(V,T,\mu_B,\mu_Q,\mu_S)].
\]
These susceptibilities can be related to the cumulants ($c$) of the event-by-event distribution of the associated conserved charges by [3, 13, 14]:

$$x_{B,Q,S}^{m,n,l} = \frac{1}{V^3} c_{B,Q,S}^{m,n,l}$$ (2.3)

Due to the limitation in detecting all baryons and strange hadrons experimentally, net proton ($p$) and net kaon ($k$) are considered as proxies for the net baryon and net strangeness, respectively. In this report, we present the measurement of second-order ($m+n+l = 2$) diagonal and off-diagonal cumulants of net charge, net proton and net kaon multiplicity distributions, can be expressed as:

$$c^{2}_\alpha = \sigma^{2}_\alpha = \langle (\delta N_\alpha)^2 \rangle \quad \text{and} \quad c^{1,1}_{\alpha,\beta} = \sigma^{1,1}_{\alpha,\beta} = \langle (\delta N_\alpha)(\delta N_\beta) \rangle,$$ (2.4)

where $\alpha$ and $\beta$ can be $Q, p \text{ or } k$, and $\delta N_\alpha = (N_{\alpha^+} - N_{\alpha^-}) - \langle (N_{\alpha^+} - N_{\alpha^-}) \rangle$. Finally, we construct the off-diagonal to diagonal cumulant ratios ($C_{p,k} = c^{1,1}_{p,k}/c^{2}_k$, $C_{Q,p} = c^{1,1}_{Q,p}/c^{2}_p$ and $C_{Q,k} = c^{1,1}_{Q,k}/c^{2}_k$) motivated by Ref. [10], which also cancel the volume dependence.

3. Experimental details

Second-order cumulants of net charge, net proton and net kaon multiplicity distributions for Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 \text{ and } 200 \text{ GeV}$ have been studied in the STAR experiment. The minimum-bias (MB) events are analyzed with the requirement that the position of the primary vertex along $z$-direction ($V_z$) was reconstructed within $\pm 30 \text{ cm}$ of the center of the STAR detector and within $2 \text{ cm}$ on the transverse plane of the beam axis. The number of events analyzed at each energy after applying all event selections criteria is listed in Table 1.

| $\sqrt{s_{NN}}$ (GeV) | Year | Events ($\times 10^6$) |
|----------------------|------|---------------------|
| 7.7                  | 2010 | 1.5                 |
| 11.5                 | 2010 | 2.5                 |
| 14.5                 | 2014 | 12.7                |
| 19.6                 | 2011 | 15.6                |
| 27                   | 2011 | 25.2                |
| 39                   | 2010 | 62.3                |
| 62.4                 | 2010 | 31                  |
| 200                  | 2011 | 74                  |

Table 1: Summary of the number of events analyzed.

All charged tracks used in this analysis are required to be within the pseudorapidity range $|\eta| < 0.5$, and the transverse momentum range $0.4 < p_T < 1.6 \text{ GeV/c}$. To reduce the contamination from the secondary charged particles, only primary tracks are selected within a distance of closest approach (DCA) to the primary vertex of less than 1 cm. The main detectors used in this analysis are the Time Projection Chamber (TPC) and the Time of Flight (TOF). The particle identification (PID) is done with a common acceptance: $0.4 < p_T < 1.6 \text{ GeV/c}$ and $|\eta| < 0.5$. Within
this range, the purities of $K^\pm$ and $p(\bar{p})$ identification is estimated to be 98-99%. The collision centrality for this analysis is defined using uncorrected charged particle multiplicity measured within a pseudorapidity range of $0.5 < |\eta| < 1.0$ in the TPC detector. This way we exclude the particles from the analysis region to determine the centrality in order to suppress autocorrelation effects [15]. We present the results for nine centrality bins, 0-5% (most central), 10-20%, ... , 70-80% (most peripheral) as a function of average number of participating nucleons ($\langle N_{\text{part}} \rangle$) estimated using a Monte Carlo Glauber model [16]. The cumulants and their ratios were calculated as a function of the reference multiplicity and then averaged over the centrality bins to suppress the volume fluctuations over wide centrality bins [17, 18]. We use embedding Monte Carlo simulation techniques to obtain the efficiencies and an algebra based on binomial detector response to efficiency correction [19, 20, 21]. The statistical uncertainty estimation is based on the numerical error propagation method of multivariate cumulants [22]. The systematic uncertainties are estimated by varying different track quality cuts, tracking efficiency and conditions for particle identification.

4. Results

The centrality dependence of efficiency corrected second-order diagonal cumulants of net proton, net kaon and net charge (top to bottom) for 0-5% most central Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4$ and 200 GeV are shown as a function of $\langle N_{\text{part}} \rangle$ in Fig. 1 . We find a linearly increasing trend as expected from a scaling, predicted by the central limit theorem. In a given centrality, the width of net-proton distribution decreases as a function of beam energy in the range $\sqrt{s_{NN}} = 7.7-39$ GeV and then increases at top RHIC energies [8]. This is because of baryon transport that has a strong beam energy dependence.

![Figure 1](image-url)  
**Figure 1:** Centrality dependence of the second-order diagonal cumulants (variances) of net proton, net kaon and net charge (top to bottom) multiplicity distributions for Au+Au collisions at $\sqrt{s_{NN}} = 7.7-200$ GeV (left to right) within kinematic range $|\eta| < 0.5$ and $0.4 < p_T < 1.6$ GeV/c. Boxes represent systematic uncertainties. The statistical error bars are within the marker size. The red dashed lines represent a scaling predicted by central limit theorem.
Figure 2 shows the efficiency corrected second-order off-diagonal cumulants of net-charge, net-proton, net-kaon multiplicity distributions for Au+Au collisions at eight colliding energies. The off-diagonal cumulants between net-charge—net-kaon ($\sigma^{1,1}_{Q,k}$) and that of net-charge—net-proton ($\sigma^{1,1}_{Q,p}$) increase with centrality. On the contrary, there is a growing anti-correlation behaviour observed between net-proton and net-kaon ($\sigma^{1,1}_{p,k}$) with centrality at $\sqrt{s_{NN}} > 19.6$ GeV.

Figure 3 shows the off-diagonal to diagonal cumulant ratios $C_{p,k} = \sigma^{1,1}_{p,k}/\sigma^2_k$, $C_{Q,k} = \sigma^{1,1}_{Q,k}/\sigma^2_k$ and $C_{Q,p} = \sigma^{1,1}_{Q,p}/\sigma^2_p$ (top to bottom) as a function of beam energy for most central (0-5%) and peripheral (70-80%) collisions. These cumulant ratios are designed to eliminate the effect of system volume. An excess correlation is observed in $C_{Q,p}$ and $C_{Q,k}$ in 0-5% most central in comparison to the peripheral collisions. The values of $C_{Q,p}$ and $C_{Q,k}$ are observed to increase with beam energy, and this increasing trend cannot be explained by the HRG and UrQMD model calculations. It is observed that the normalized $p$-$k$ correlation ($C_{p,k}$) is positive at the lowest BES energy and negative at higher energies. For 0-5% top central bins, $C_{p,k}$ changes sign around 19.6 GeV.

5. Summary

The second-order diagonal and off-diagonal cumulants of net proton, net kaon, and net charge multiplicity distributions in Au+Au collisions from the RHIC BES-I program in the energy range of $\sqrt{s_{NN}} = 7.7$-200 GeV are presented. Significant excess correlation is observed in $C_{Q,p}$ and $C_{Q,k}$ in central in comparison with peripheral events. Both HRG and UrQMD model underpredict the data and cannot describe the increasing with beam energy trends of $C_{Q,p}$ and $C_{Q,k}$. The value of $C_{p,k}$ in 0-5% central collision is found to be negative at $\sqrt{s_{NN}} = 200$ GeV and positive at $\sqrt{s_{NN}} = 7.7$ GeV. The measurements of the full second-order cumulant matrix elements of net-$p/k/Q$ multiplicity distributions as a function of centrality and beam energy will improve the estimation of freeze-out parameters by theoretical calculations and that help to map the QCD phase diagram. For more details of this analysis we refer the readers to Ref. [1].
Figure 3: Beam energy dependence of cumulants ratios \( C_{p,k}, C_{Q,k} \) and \( C_{Q,p} \) (top to bottom) for Au+Au collisions at \( \sqrt{s_{NN}} = 7.7-200 \) GeV (left to right). The bands denote the UrQMD data for 0-5% and 70-80% central collisions and Poisson baseline is denoted by dotted lines. Error bars and boxes represent statistical and systematic uncertainties, respectively.

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Off-diagonal cumulants

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