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Recent Results and Methods on Higher Order and Off-diagonal Cumulants of Identified Net-particle Multiplicity Distributions in Au+Au Collisions at STAR

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Abstract

We present recent results on the cumulants of net-particle distributions in Au+Au collisions at the STAR experiment. Beam energy dependence of net-Λ cumulants and off-diagonal cumulants are measured. These measurements provide additional constraints on the chemical freeze-out conditions. The sixth-order cumulant of net-charge and net-proton distributions is measured at $\sqrt{s_{\rm NN}}$ =200 GeV to search for the signal of the crossover phase transition. Finally, an unfolding technique is developed and applied to the net-proton distributions at 19.6 GeV to account for the non-binomial effects of the detector.

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1. Introduction

The ratios of the cumulants of identified net-particle multiplicity distributions have been suggested to be sensitive to the onset of Quantum Chromodynamics (QCD) phase transition and to the additional fluctuations expected from the close proximity to the critical point [1, 2]. The STAR Collaboration has measured the cumulants up to the 4th-order of net-p (proton), net-Q (charge) and net-K (kaon) multiplicity distributions at the Beam Energy Scan program, searching for the QCD critical end point [3–6].

Cumulants are mathematical measures which characterize the shape of a distribution. The rth-order cumulant is expressed as:

$$C_r = \mu_n - \sum_{m=1}^{r-1} \binom{r-1}{m-1} C_m \mu_{r-m}, \quad \mu_r = \langle N^r \rangle,$$

where N is the number of particles in one event, and the bracket represents the average over event samples. Experimentally, the centrality bin width averaging is performed in order to suppress the initial volume fluctuations [2]. The detector efficiency losses have been corrected under the assumption that efficiencies follow a binomial distribution [7–9].

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In this report, we present the results on net-Λ cumulants, results on off-diagonal cumulants, results on net-Q 6th-order cumulant, and the results of an unfolding technique applied to net-p distribution and used to account for the non-binomial effects of the detector.

2. Net-Λ cumulants

Generally, higher-order cumulants are more sensitive to the chemical freeze-out conditions than particle yields. In Ref. [10], by comparing the experimental results [4, 5] with HRG calculations, it has been observed that strange hadrons freeze-out earlier than light flavor hadrons. Since Λ contains both strange and light quarks, measuring net-Λ cumulants could provide hints on the flavor dependence of the freeze-out parameters. Figure 1 shows the cumulants up to the 3rd-order of net-Λ multiplicity distributions as a function of centrality at different beam energies for Λ with $0.9 < p_T < 2.0$ GeV/c and $|y| < 0.5$. The measurement is compared to different models. The statistical baselines of the Poisson and Negative Binomial Distribution (NBD) and the results of UrQMD model are shown as lines. Results are consistent with the statistical baselines within uncertainties. C_1 and C_2 are above UrQMD results, while C_3 shows better agreement with UrQMD.

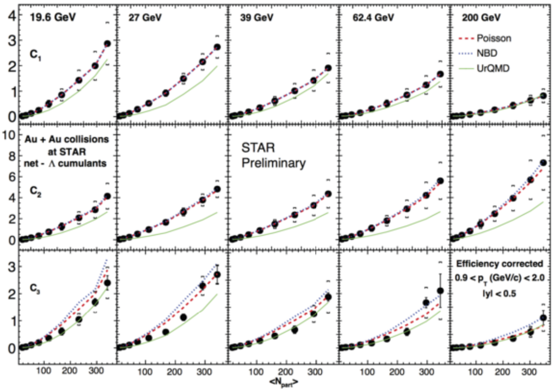

Fig. 1: Centrality dependence of net-Λ cumulants up to the 3rd order at $\sqrt{s_{\rm NN}}$ =19.6, 27, 39, 62.4 and 200 GeV in Au+Au collisions. The dotted lines represent the Poisson baseline, and the dashed lines are the expectation of the Negative Binomial Distribution (NBD). The solid lines are the results of UrQMD.

3. Off-diagonal cumulants

In the past, STAR only measured the diagonal cumulants that probes the self-correlation of the conserved charge. In this section, we report the first measurement of the off-diagonal cumulants up to the 2nd-order between net-p, net-K and net-Q, which would provide additional constraints on the chemical freeze-out conditions [11, 12]. The 2nd-order off-diagonal cumulant is defined as:

$$C_{x,y} = \frac{\sigma_{x,y}}{\sigma_y^2}, \quad \sigma_{x,y}^2 = \langle xy\rangle - \langle x\rangle\langle y\rangle, \tag{1}$$

where x and y represent the different conserved charges. Figure 2 shows the normalized off-diagonal cumulants which probe the correlations between net-proton and net-kaon ($C_{\rm p,k}$), net-charge and net-kaon ($C_{\rm Q,k}$), net-charge and net-proton ($C_{\rm Q,p}$), as a function of beam energy for 0-5% and 70-80% centralities. The Poisson baseline and UrQMD results are shown as dotted lines and shaded bands, respectively. $C_{\rm p,k}$ is found to be described well by UrQMD, while significant excess of $C_{\rm Q,k}$ and $C_{\rm Q,p}$ is observed with respect to the Poisson baseline and UrQMD expectations.

4. The 6th-order cumulant of the net-Q distribution

The phase transition at $\mu_B = 0$ (MeV) is predicted by the lattice QCD calculation [13] to be a smooth crossover. However, there is no experimental evidence for this crossover. The lattice QCD calculation and $O(4)$ scaling function [14] predict a negative value of C_6 for net-charge and net-baryon distributions if the chemical freeze-out is close enough to the chiral phase transition [15, 16]. Figure 3 shows the 6th-order cumulant of the net-charge distribution as a function of centrality at $\sqrt{s_{\rm NN}}$ =200 GeV at midrapidity. The values are negative in the most central collision with large statistical errors. The statistical errors of cumulants are given by $error(C_r) \propto \sigma^r/\sqrt{N_{\rm eve}}$ with σ and $N_{\rm eve}$ being the standard deviation of the net-particle distribution and the number of events, respectively [17]. Since σ is much larger for net-charge than for net-proton, the results of net-charge distribution has much larger errors than those of net-proton distribution.

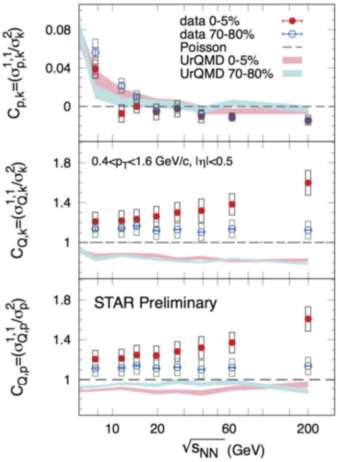

Fig. 2: Beam energy dependence of $C_{\rm p,k}$, $C_{\rm Q,k}$ and $C_{\rm Q,p}$ in 0-5 and 70-80% centralities with $0.4 < p_T < 1.6$ GeV/c and $|\eta| < 0.5$. The dotted lines represent the Poisson baseline, while the shaded bands represent the UrQMD expectations.

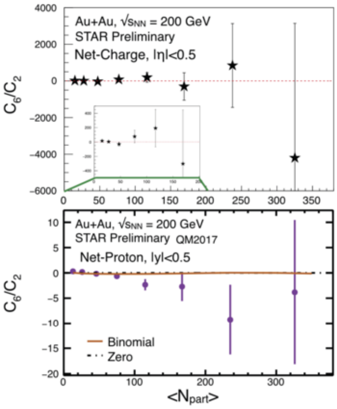

Fig. 3: Centrality dependence of the 6th order cumulant of the net-charge (top) and net-proton (bottom) multiplicity distributions at $\sqrt{s_{\rm NN}}$ =200 GeV. Statistical baselines are shown as continuous lines. The plot focusing on 20-80% centralities are shown inside the upper panel for the net-charge distribution.

5. Unfolding on the net-p distribution

So far, the cumulant have been corrected for the detector efficiency using the analytical formulas with the assumption of the binomial efficiencies [7–9]. This binomial assumption may be broken mainly due to two reasons. One reason is the two-particle correlated detector effects like track-splitting or track-merging effects, which make the detector response matrix non-binomial. The other reason is the fact that the efficiency depends on the local multiplicity in the detector [18]. The multiplicity-dependent efficiency, that is used for the centrality definition, has been already taken into account by centrality bin width averaging. But there could be residual dependence on the number of net-particles within one multiplicity bin. In order to take these effects into account, we performed embedding simulation to determine the response matrices. The response matrices are directly used for unfolding to reconstruct the distribution, from which cumulants are calculated. Figure 4 shows cumulants up to the 4th-order of net-proton multiplicity distribution as a function of centrality at $\sqrt{s_{\rm NN}}$ =19.6 GeV. Black points are calculated with the efficiency correction assuming binomial efficiencies, while red points are calculated using the unfolding technique. The systematic suppression is observed in C_2 and C_3, although C_4, C_3/C_2 and C_4/C_2 are consistent within large systematic uncertainties. More statistics in embedding simulation is needed to achieve precision.

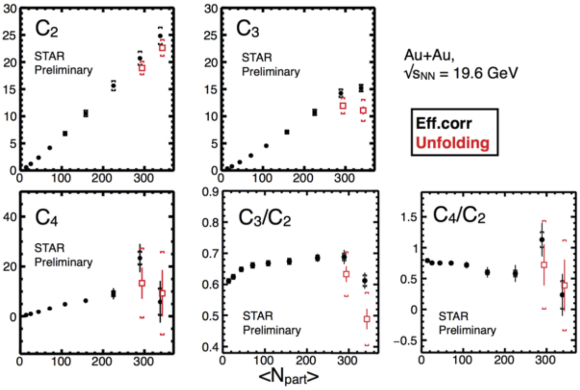

Fig. 4: Centrality dependence of cumulants up to 4th order of net-proton multiplicity distribution at $\sqrt{s_{\rm NN}}$ =19.6 GeV. Cumulants have been calculated with the efficiency correction assuming the binomial efficiencies, and also measured with the unfolding approach.

6. Summary

We present recent results on the cumulants of net-particle distributions in Au+Au collisions at the STAR experiment. Net-Λ cumulants up to the 3rd-order are consistent with the baselines of Poisson and negative binomial distributions within uncertainties. Significant excesses are observed in the 2nd-order off-diagonal cumulants for $C_{Q,k}$ and $C_{Q,p}$ with respect to the UrQMD calculation. Negative values are observed in the net-Q 6th-order cumulant in the most central collision with large uncertainties, which is in agreement with theoretical expectations. Unfolding technique is applied to the net-p distribution at $\sqrt{s_{\rm NN}}$ =19.6 GeV to correct for the non-binomial detector efficiencies. The results show a systematic suppression of C_2 and C_3 evaluated with the unfolding technique at large $\langle {\rm N_{part}} \rangle$ with respect to the results obtained with the standard methods based on the binomial assumption, while C_4, C_3/C_2 and C_4/C_2 obtained with the two methods are consistent within the large uncertainties.

7. Acknowledgement

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References

[1] M. Asakawa and M. Kitazawa, Prog. Part. Nucl. Phys. 90, 299 (2016)
[2] X. Luo and N. Xu, Nucl. Sci. Tech. 28 (2017) 112.
[3] M. M. Aggarwal, et al., Phys. Rev. Lett. 105 (2010) 022302.
[4] L. Adamczyk, et al., Phys. Rev. Lett. 112 (2014) 032302.
[5] L. Adamczyk, et al., Phys. Rev. Lett. 113 (2014) 092301.
[6] L. Adamczyk, et al., arXiv:1709.00773.
[7] A. Bzdak and V. Koch, Phys. Rev. C86 (2012) 044904.
[8] X. Luo, Phys. Rev. C91 (2015) 034970.
[9] T. Nonaka, M. Kitazawa, S. Esumi, Phys. Rev. C95 (2017) 064912.
[10] R. Bellwied, et al., arXiv:1805.00088.
[11] A. Majumder and B. Muller, Phys. Rev. C74 (2006) 054901.
[12] A. Chatterjee, et al., J. Phys. G43 (2016) 125103.
[13] Y. Aoki, et al., Nature 443 (2006) 675–678.
[14] J.Engels, et al., Nucl. Phys. B675, 533 (2003)
[15] M. Cheng, et al., Phys. Rev. D79 (2009) 074505.
[16] B. Friman, et al., Eur. Phys. J. C71 (2011) 1694.
[17] X. Luo, J. Phys. G 39, 025008 (2012)
[18] A. Bzdak, R. Holzmann and V. Koch, Phys. Rev. C94 (2016) 064907.