

Light-nuclei production near the QCD critical point

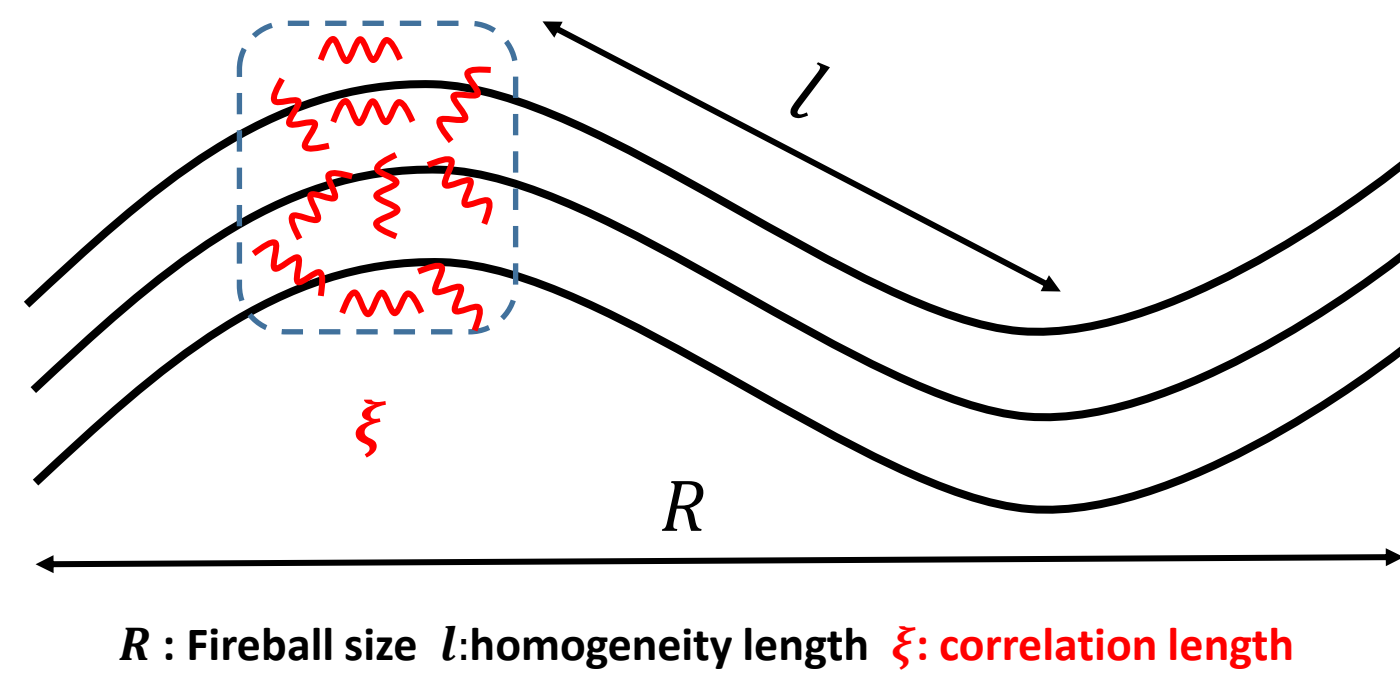


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Introduction

- Searching the QCD critical point is one of the most important goals of the Relativistic Heavy-Ion Collisions. Preliminary non-monotonic behavior of higher order cumulants of net-proton multiplicity has been observed [1] and indicating the possible existence of the QCD critical point.
- Non-monotonic behavior of the light-nuclei yield ratio $N_t N_p / N_d^2$ also been observed [2] and is expected to be the consequence of the critical fluctuations [3].
- Essentially, the relevant scales for the light-nuclei production roughly include the fireball size at freeze-out R , homogeneity length l and freeze-out temperature. These scales are typically much larger than the critical correlation length ξ when the light nuclei is produce not so close to the critical regime. In other word, the background effect is large comparing the critical signal in the light-nuclei production.
- This poster will address the critical fluctuations considering the large background effects in the light-nuclei production.



Coalescence Model

- In the coalescence model, the production of light nuclei N_A is given by:

$$N_A = g_A \int [\Pi_i^A d^3 \mathbf{r}_i d^3 \mathbf{p}_i f(\mathbf{r}_i, \mathbf{p}_i)] W_A(\{\mathbf{r}_i, \mathbf{p}_i\}_i^A)$$
where g_A is the statistical factor from the spin and $f(\mathbf{r}_i, \mathbf{p}_i)$ is the phase-space distribution function for the constituent nucleons.

- $W_A(\{\mathbf{r}_i, \mathbf{p}_i\}_i^A)$ is the Wigner function corresponding the light-nuclei wave function (Gaussian form of Wigner function is used in this work). One of the most important properties of Wigner function is that it only depends on the relative distance of the constituent nucleons $\mathbf{z}_i - \mathbf{z}_j$, not the $(\mathbf{z}_i + \mathbf{z}_j)/2$.
- One example of the phase-space distribution function is Gaussian distribution:

$$f(\mathbf{r}, \mathbf{p}) = \frac{\rho_0}{(2\pi mT)^{3/2}} \exp\left[-\frac{\mathbf{r}^2}{2R_s^2} - \frac{\mathbf{p}^2}{2mT}\right]$$

leading to the similar expression for N_t and N_d :

$$N_d = g_d N_p^2 \left[\left(R_s^2 + \frac{\sigma_d^2}{2} \right) \left(mT + \frac{1}{2\sigma_d^2} \right) \right]^{-3/2}$$

$$N_t = g_t N_p^3 \left[\left(R_s^2 + \frac{\sigma_t^2}{2} \right) \left(mT + \frac{1}{2\sigma_t^2} \right) \right]^{-3}$$

- If the light-nuclei size difference is negligible ($\sigma_d = 2.26, \sigma_t = 1.59 \text{ fm}$), then the effects from Gaussian profile exactly cancels:

$$\frac{N_t N_p}{N_d^2} = \frac{g_t}{g_d^2} = \frac{4}{9}$$

One can see $N_t N_p / N_d^2$ is a constant v.s. the variance of phase-space distribution $\langle r^2 \rangle^{1/2}$ for Gaussian distribution but decreases in the case of Woods-Saxon distribution.

Conclusions

- N_d, N_t, N_{He} depends on fireball size, homogeneity length, freeze temperature in analogous way when nucleon distribution close to Gaussian and the light-nuclei yield can be expressed in terms of the phase-space cumulants up to second order in similar structure.
- Therefore, we can construct the new ratios to suppress the background effects, such that the ratios are sensitive to the critical signal. We found that long range correlation results a peak, and the square of 2-point correlation induces a double peak in the new ratios.

References

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- [2] STAR Collaboration, Phys. Rev. Lett., 130,202301
- [3] K-J.Sun et al., Phys. Lett. B, 781:499
- [4] S.Wu, K.Murase, S.Tang, H.Song, Phys.Rev.C, 106.034905
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Light-Nuclei Yield in Terms of Phase-Space Cumulants[4]

- To analyze the phase-space effects in the light-nuclei production, we employ the phase-space cumulants with the characteristic function:

$$f(\mathbf{z}_i) = N_p \int \frac{d^6 \mathbf{t}_i}{(2\pi)^6} e^{-i\mathbf{t}_i \cdot \mathbf{z}_i} \exp\left[\sum_{\alpha \in N_0^6} \frac{\mathbf{C}_\alpha}{\alpha!} (i\mathbf{t}_i)^\alpha \right]$$

- where $\mathbf{C}_\alpha = \int d^6 \mathbf{z} f(\mathbf{z}) \mathbf{z}^\alpha$ is the phase-space cumulants with order of $|\alpha|$. Then the yield is expressed as

$$N_A = g_A N_p \left[\frac{8N_p}{\sqrt{\det(\mathbf{C}_2 + \text{const.})}} \right]^{A-1} [1 + O(\{\mathbf{C}_\alpha\}_{|\alpha| \geq 3})]$$

- where \mathbf{C}_2 is the second order phase-space cumulant, corresponding to the Gaussian distribution. $O(\{\mathbf{C}_\alpha\}_{|\alpha| \geq 3})$ denotes the contribution from the higher order phase-space cumulants.
- One can see that the yield N_A for different light nuclei A share analogous expression up to second-order phase-space cumulant \mathbf{C}_2 . In particular, the explicit expression of \mathbf{C}_2 takes the form:

$$\mathbf{C}_2 = 2 \begin{pmatrix} \langle \mathbf{r} \mathbf{r}^T \rangle / \sigma^2 & \langle \mathbf{r} \mathbf{p}^T \rangle \\ \langle \mathbf{p} \mathbf{r}^T \rangle & \sigma^2 \langle \mathbf{p} \mathbf{p}^T \rangle \end{pmatrix}$$

- where the coordinate $\langle \mathbf{r} \mathbf{r}^T \rangle$, momentum $\langle \mathbf{p} \mathbf{p}^T \rangle$ and coordinate-momentum $\langle \mathbf{r} \mathbf{p}^T \rangle$ correlation respectively encode the geometric, thermal and dynamical properties of the profile at freeze-out. The corresponding relevant scales are fireball size R , homogeneity length l and freeze-out temperature T_{fo} , respectively.

Light-nuclei production with critical fluctuations[5,6]

- The light-nuclei production with the critical fluctuations can be evaluated by introducing the correction of phase-space distribution from the order parameter field:

$$f = f_0 + \delta f = f_0 [1 - g_\sigma \sigma / \gamma T]$$

- The yield of light nuclei near QCD critical point can be expressed in terms of the phase-space cumulant

$$\langle N_A \rangle_\sigma = g_A 8^{A-1} N_p^A [\det(\mathbf{C}_2 + \text{const.})]^{-(A-1)/2} [1 - \tilde{\Xi}(A)]$$

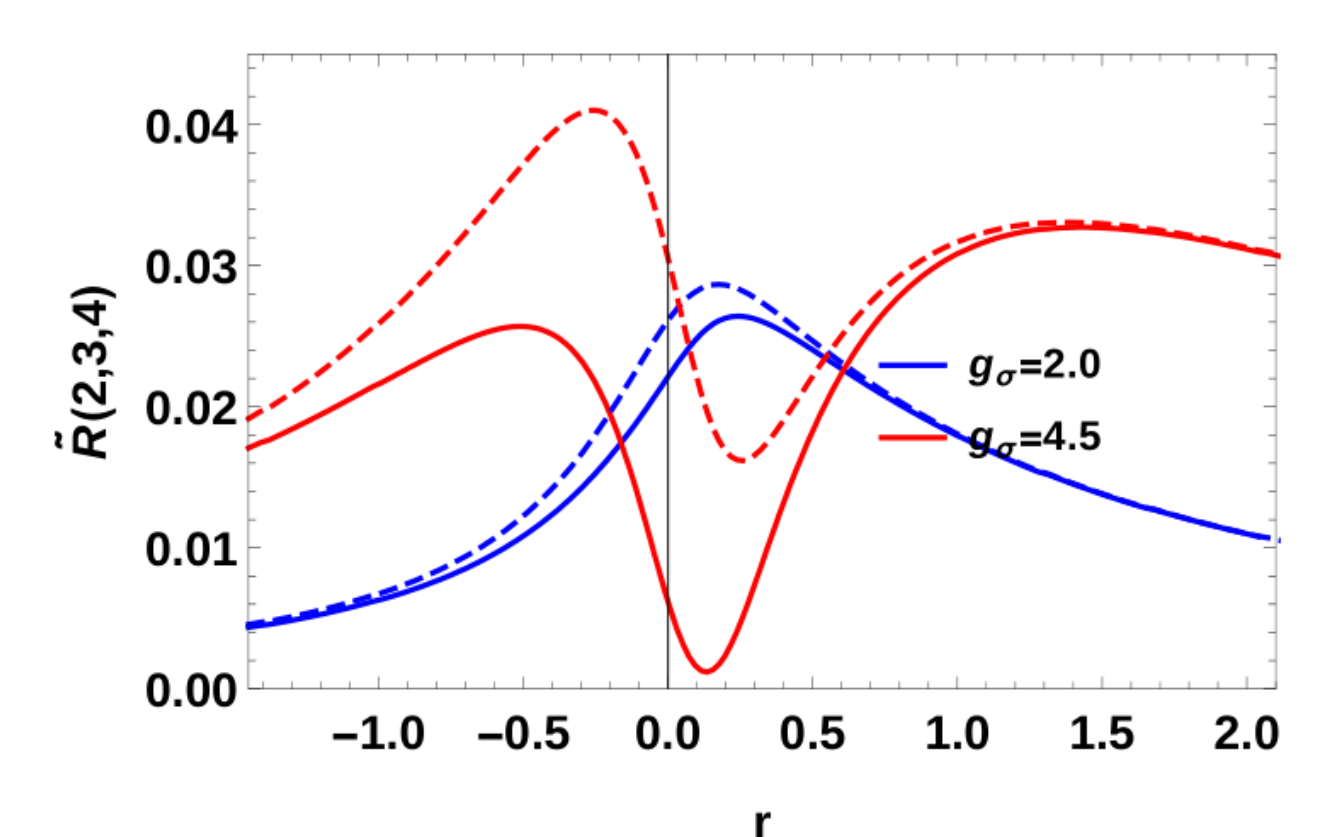
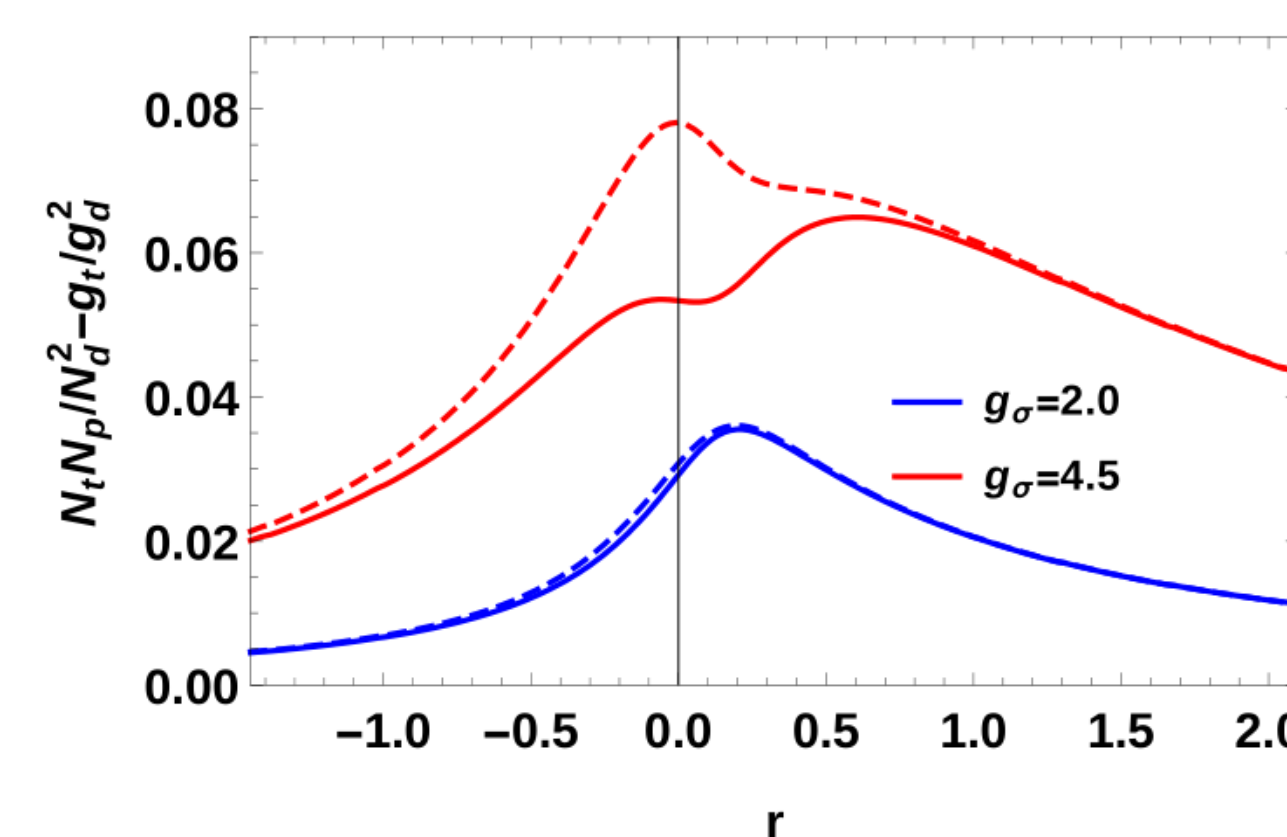
- where the critical contribution $\tilde{\Xi}(A) = \sum_{b=2}^A (-1)^b \binom{b}{A} g_\sigma^b \langle \Pi_{j=1}^b \sigma(\mathbf{r}_j) \rangle_\sigma$. Due to the similar structure related to the second-order phase-space cumulants \mathbf{C}_2 , the combinations such as

$$\tilde{R}(A, B) = R_{A,B}^{1-B, A-1} - g_B^{A-1} g_A^{-(B-1)},$$

$$\tilde{R}(A, B, D) = R_{A,B}^{1-B, A-1} - g_B^{A-1} g_D^{\frac{(A-1)(B-1)}{D-1}} [R_{A,D}^{1-D, A-1}]^{(B-1)/(D-1)},$$

- (here $R_{A,B}^{1-B, A-1} = \langle N_B \rangle_\sigma^{A-1} \langle N_A \rangle_\sigma^{1-B} N_p^{B-A}$) greatly suppress the contribution from the background scales in \mathbf{C}_2 which helps to isolate the effects related to the correlation signal.

- As an example, the critical correlators $\langle \Pi_{j=1}^b \sigma(\mathbf{r}_j) \rangle$ can be obtained by mapping from the three-dimensional Ising model, and we takes the Gaussian phase-space distribution f_0 . The new light-nuclei combinations in the critical regime behaves as :



- where $r \sim -(\mu - \mu_c)$ is the Ising variable and mapping to the chemical potential. The blue and red curves correspond to the small and large critical effects, respectively. The left plot corresponds to $\tilde{R}(2,3) \sim \langle \sigma(r_1) \sigma(r_2) \rangle - \langle \sigma(r_1) \sigma(r_2) \rangle^2$ and $\tilde{R}(2,3)$ reaches a peak near μ_c because the contribution from $\langle \sigma(r_1) \sigma(r_2) \rangle$. $\tilde{R}(2,3)$ also has a small dip arising from the negative contribution of $\langle \sigma(r_1) \sigma(r_2) \rangle^2$ when critical signal is sufficiently large. The dip is more obvious in the right plot of the ratio $\tilde{R}(2,3,4) \sim \langle \sigma(r_1) \sigma(r_2) \rangle - 4 \langle \sigma(r_1) \sigma(r_2) \rangle^2$ because of the larger negative contribution from $\langle \sigma(r_1) \sigma(r_2) \rangle^2$.