Light nuclei production with/without critical fluctuations

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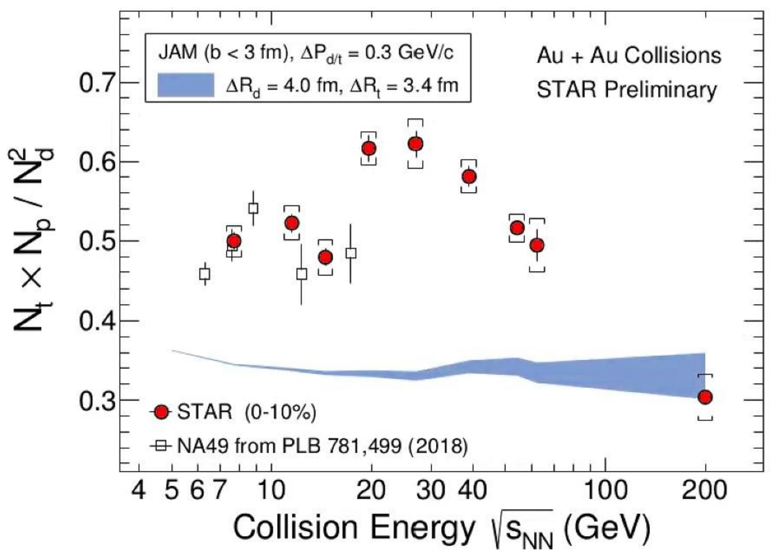
Introduction

- Light nuclei are loosely bounded objects (~MeV), with binding energy much smaller than freezeout temperature T_{kf}
  - $\Rightarrow$ Form at late stages of collisions
  - $\Rightarrow$ Detecting the phase-space distribution at freeze-out
- Experimental measurements show non-monotonicity as a function of collision energy $\sqrt{s_{NN}}$ [1] => critical point?



- The widely description models: Thermal model and Coalescence model

$$N_A = g_A \int \left[\prod_i^A d^3 r_i d^3 p_i f(\boldsymbol{r}_i, \boldsymbol{p}_i)\right] W_A(\{\boldsymbol{r}_i, \boldsymbol{p}_i\}_{i=1}^A)$$

$$= g_A \int \langle \prod_{i=1}^A \left[d^3 r_i d^3 p_i (f_0(\boldsymbol{r}_i;\boldsymbol{p}_i) + \delta f(\boldsymbol{r}_i;\boldsymbol{p}_i))\right] \rangle_\sigma W_A(\{\boldsymbol{r}_i, \boldsymbol{p}_i\}_{i=1}^A)$$

Background — Critical

$f(\boldsymbol{r},\boldsymbol{p})$: phase-space distribution
$W_A(\{\boldsymbol{r}_i,\boldsymbol{p}_i\}_i^A)$: Wigner function

- The critical contribution δf in phase space : nucleons interact with the order parameter field $\delta f = -f_0 \frac{g_\sigma \sigma}{\gamma T}$, which strongly fluctuates event-by-event.
- But we have little knowledge on the coupling constants g_σ => proper treatment of background f_0 is important.

Decompose light-nuclei yield in terms of phase-space cumulants[2]

Characteristic function

- Fourier transform of probability distribution function:

$$\varphi_X(t) = E[e^{itX}] = 1 + \frac{it\, E[X]}{1} - \frac{t^2 E[X^2]}{2!} + \cdots + \frac{(it)^n E[X^n]}{n!})$$

Decompose light-nuclei yield into Gaussian and non-Gaussian contribution

1. The production of light-nuclei with A-constituent nucleons N_A based on the Coalescence model
   $$N_A = g_A \int \left[\prod_i^A d^3\boldsymbol{r}_i d^3\boldsymbol{p}_i f(\boldsymbol{r}_i,\boldsymbol{p}_i)\right] W_A(\{\boldsymbol{r}_i,\boldsymbol{p}_i\}_{i=1}^A)$$
2. Use characteristic function to decompose the $f(\boldsymbol{r},\boldsymbol{p})$ in terms of phase-space cumulants: $C_\alpha := \langle(\boldsymbol{r},\boldsymbol{p})^\alpha\rangle_c$
   $f(\boldsymbol{r},\boldsymbol{p})$ = Gaussian + Non-Gaussian
3. N_A share a common structure $N_A \propto [\ldots]^{A-1}$ for Gaussian distribution
   $$N_A = g_A N_p \left[\frac{8N_p}{\sqrt{\det(\mathcal{C}_2 + \mathcal{I}_6)}}\right]^{A-1} \cdot [1 + \mathcal{O}(\{\mathcal{C}_\alpha\}_{|\alpha|\geq 3})]$$
   Gaussian contribution — Non-Gaussian contribution
4. Combinations of N_A to eliminate the background effect of the Gaussian distribution
   $$\frac{N_p^{B-A} N_B^{A-1}}{N_A^{B-1}} = \frac{g_B^{A-1}}{g_A^{B-1}}[1 + \mathcal{O}(\{\mathcal{C}_\alpha\}_{|\alpha|\geq 3})].$$

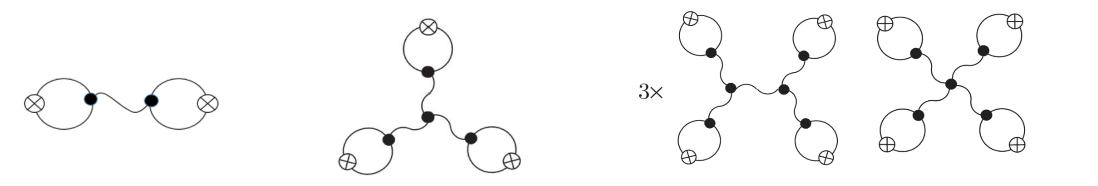
Conclusions

- Light nuclei production shows non-monotonic behavior as a function of collision energy in heavy-ion collisions.
- Based on Coalescence model, we decomposed the phase-space distribution into the Gaussian and non-Gaussian contribution. We found that the light-nuclei yield with different number of constituent nucleons has common contribution from the Gaussian distribution, and can cancelled out by constructing the yield ratio.
- With the consideration of the critical contribution, we construct the new light-nuclei yield ratio which is directly proportional to critical contribution.
- We found that the ratio with triton and deuteron shows non-monotonic behavior and a dip structure inside because of the square term of two-point correlation. The ratio with ^4He and deuteron has similar behavior but with more obvious dip.

Light-nuclei yield with critical fluctuations[3]

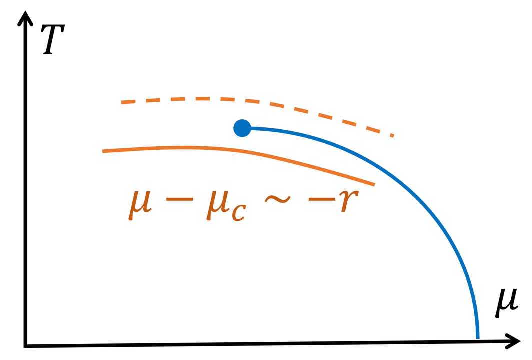
1. Introduce the critical fluctuation δf in $f(\boldsymbol{r},\boldsymbol{p})$
   $$N_A = g_A \int \langle \prod_{i=1}^A \left[d^3 r_i d^3 p_i (f_0(\boldsymbol{r}_i;\boldsymbol{p}_i) + \delta f(\boldsymbol{r}_i;\boldsymbol{p}_i))\right] \rangle_\sigma W_A(\{\boldsymbol{r}_i, \boldsymbol{p}_i\}_{i=1}^A)$$
2. Use characteristic function to decompose the $f(\boldsymbol{r},\boldsymbol{p})$ in terms of phase-space cumulants: $C_\alpha := \langle(\boldsymbol{r},\boldsymbol{p})^\alpha\rangle_c$
   $f(\boldsymbol{r},\boldsymbol{p})$ = Gaussian + Non-Gaussian
3. N_A share a common structure $N_A \propto [\ldots]^{A-1}[Bkg + Cri]$ at low order $|\boldsymbol{\alpha}| < 3$
   $$N_A = g_A N_p \left[\frac{8N_p}{\sqrt{\det(\mathcal{C}_2 + \mathcal{I}_6)}}\right]^{A-1} \cdot [1 + \sum_{i=2}^A \Xi(A,i)]$$
   Bkg — Cri
4. At low order $|\boldsymbol{\alpha}| < 3$, combinations of N_A and the const g_A are directly proportional to critical contribution Ξ
   $$\frac{N_p^{B-A} N_B^{A-1}}{N_A^{B-1}} - \frac{g_B^{A-1}}{g_A^{B-1}} \propto \left\{\sum_{n=1}^{A-1} C^n_{(A-1)}\left[\sum_{i=2}^{B}(-1)^i C_B^i \Xi(B,i)\right]^n - \sum_{m=1}^{B-1} C^m_{(B-1)}\left[\sum_{i=2}^{A}(-1)^i C_A^i \Xi(A,i)\right]^m\right\}$$

$\Xi(A,2)$ $\Xi(A,3)$ $\Xi(A,4)$

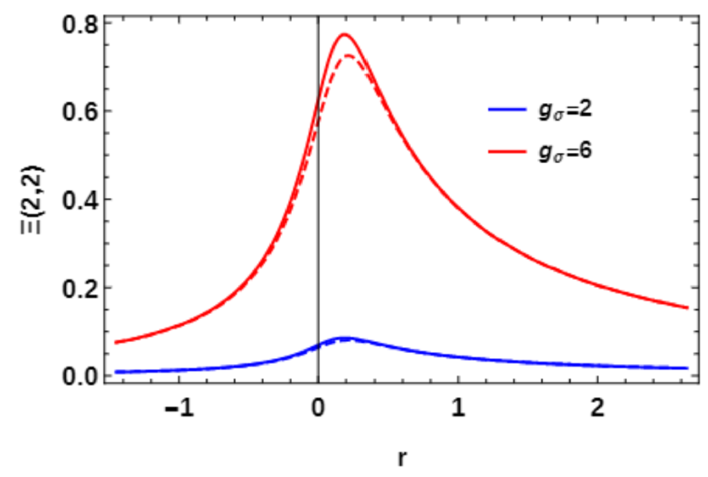


New light-nuclei yield ratio: Example

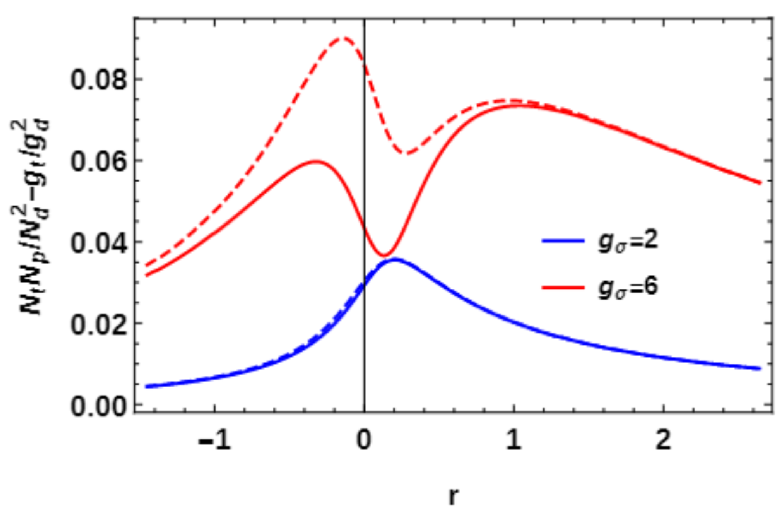
1. Phase-space distribution in non-relativistic form:
   $$f_{p,n}(\boldsymbol{r},\boldsymbol{p}) = \frac{N_{p,n}}{(2\pi)^3 (MTR_s^2)^{3/2}} e^{-\frac{p^2}{2MT} - \frac{r^2}{2R_s^2}}$$



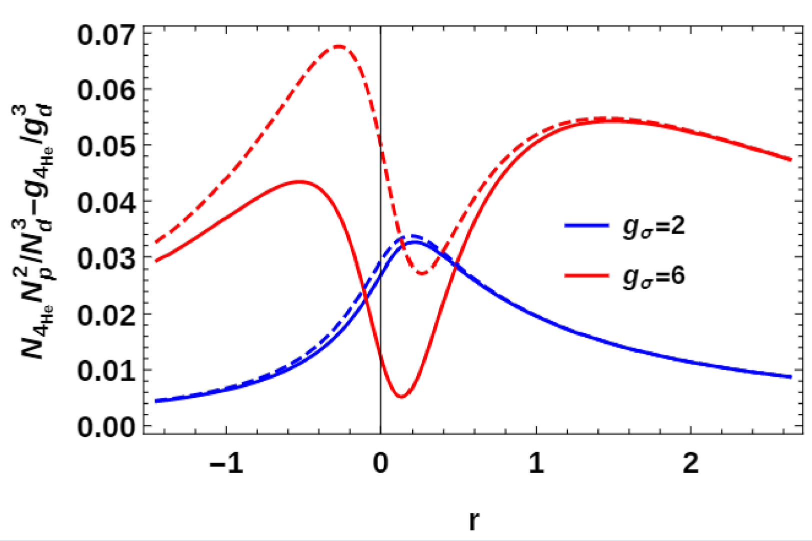
2. Critical correlator $\Xi(A,B)$ from Ising model



3. $\frac{N_t N_p}{N_d^2} - \frac{g_t}{g_d^2}$ ~2pt.-3pt.- 2pt.^{2}:
   - 2pt.>3pt. because of $f_0 > \delta f$
   - 2pt. ~ $(g_\sigma \xi)^2$
   - larger g_σ larger 2pt.^{2} contribution
   - dip when g_σ is large



4. $\frac{N_{4He} N_p^2}{N_d^3} - \frac{g_{4He}}{g_d^3}$ ~ 3 × 2pt. −4 × 3pt. −4pt. −3 × 2pt.^{2} −2pt.^{3}
   - 2pt.>3pt.>4pt. because $f_0 > \delta f$
   - R(4,2)~ 3 × 2pt. −3 × 2pt.^{2} −2pt.^{3} cubic term introduces more obvious dip
   - Indicates the dip structure



References

[1] H. Liu et al., Phys. Lett. B805, 135452 (2020).
[2] S.Wu, K.Murase, S.Tang and H.Song, to appear.
[3] S.Wu, K.Murase,S.Zhao and H.Song, to appear.

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