Light nuclei cumulants and ratios with a first-order phase transition in UrQMD

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Together with

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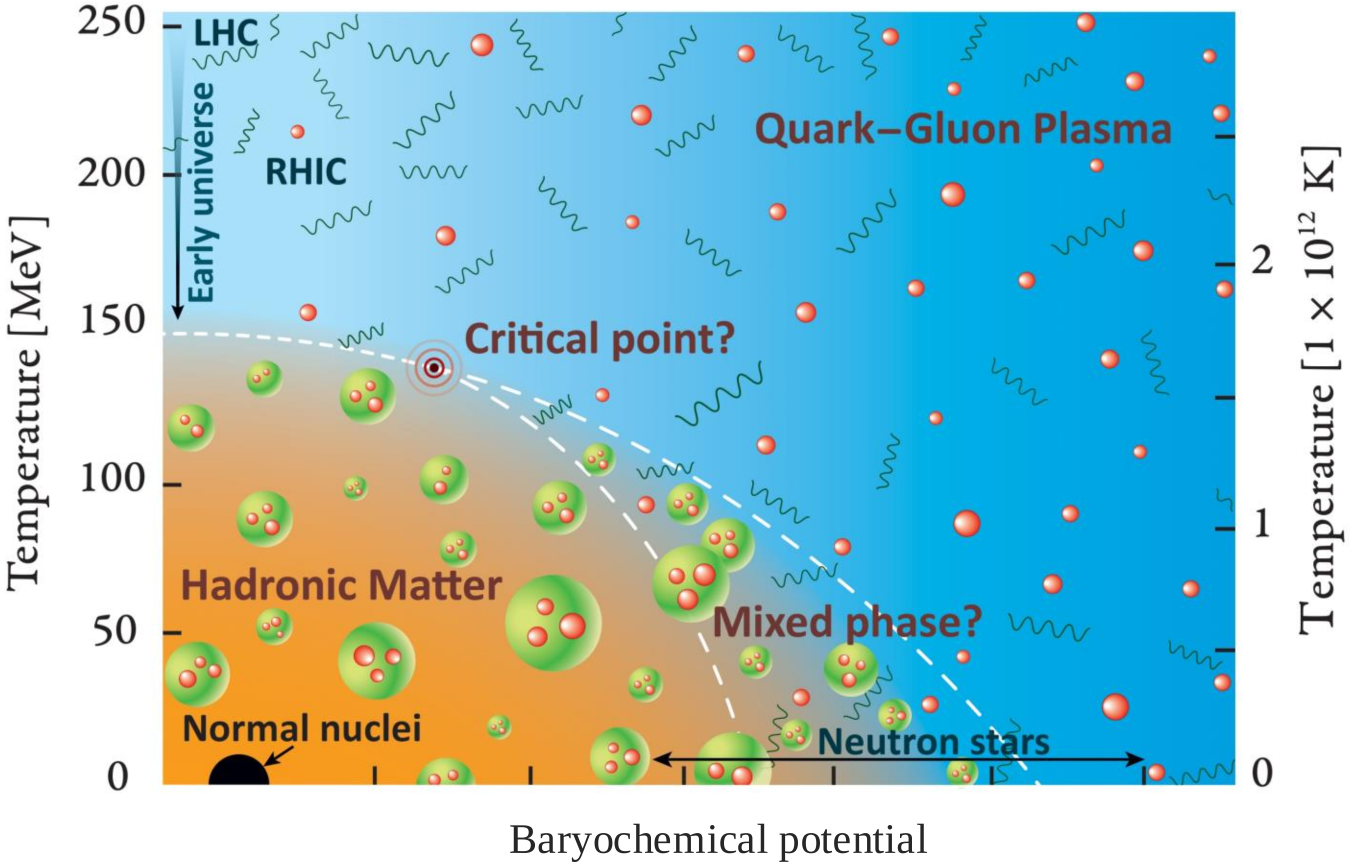
- Marcus Bleicher
- Jan Steinheimer
- Tom Reichert
- Ayut Limphirat

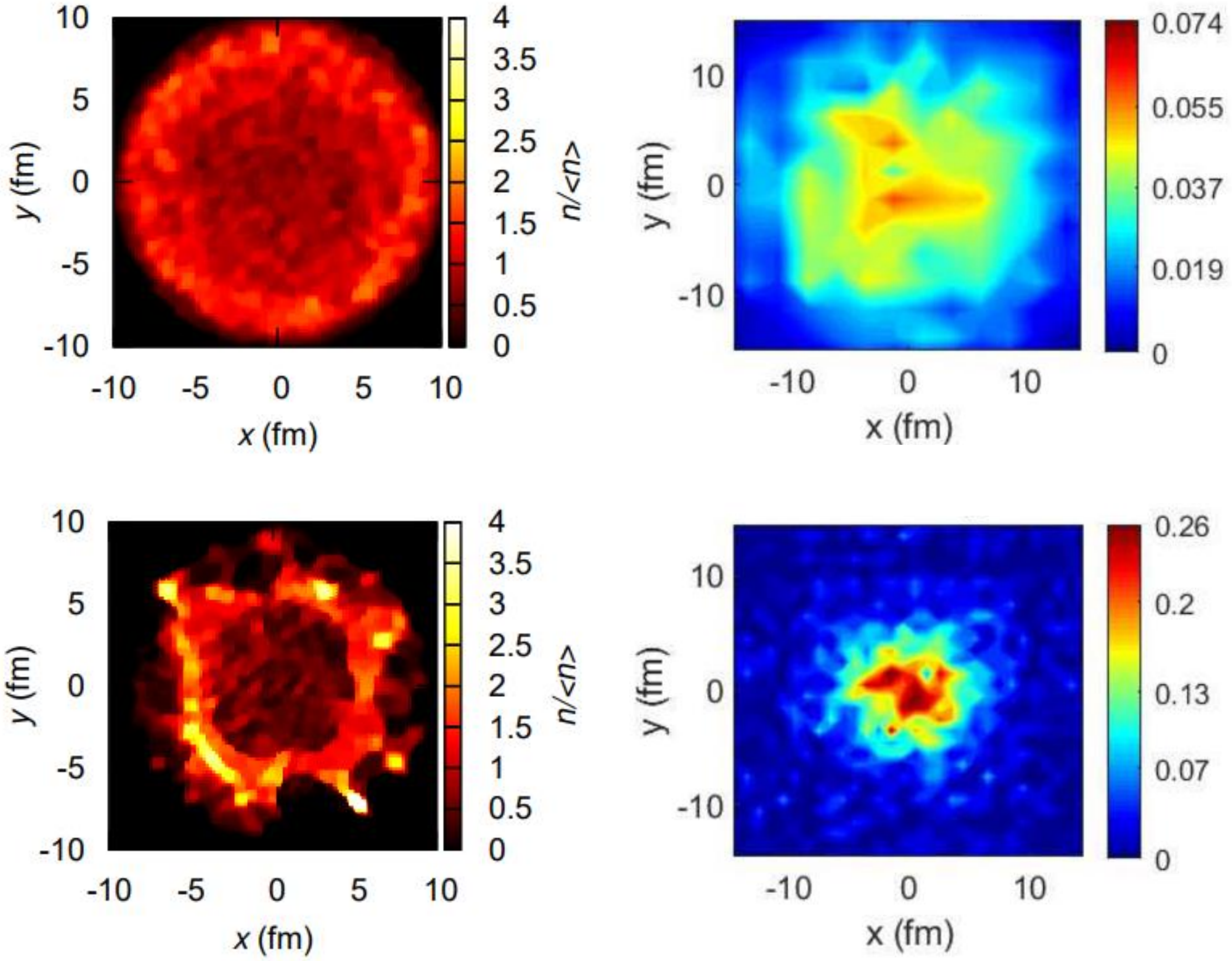
Phase diagram of QCD

- Critical point?
- First-order phase transition?



Spinodal clumping

- Crossover (upper row)
- First order (lower row)
  Enhanced light nuclei yields?



Left: *CH, Nahrgang, Mishustin, Bleicher,* Nucl. Phys. A **925**, (2014)

Right: *Sun, Ko, Li, Xu, Chen*, EPJA **57** (2021)

Central questions

- How are light cluster yields and fluctuations affected by a phase transition?
- How do these observables evolve in coordinate vs. momentum space?

Coalescence in UrQMD

- – Nucleon
- – Antinucleon
- – Deuteron
- – Antideuteron

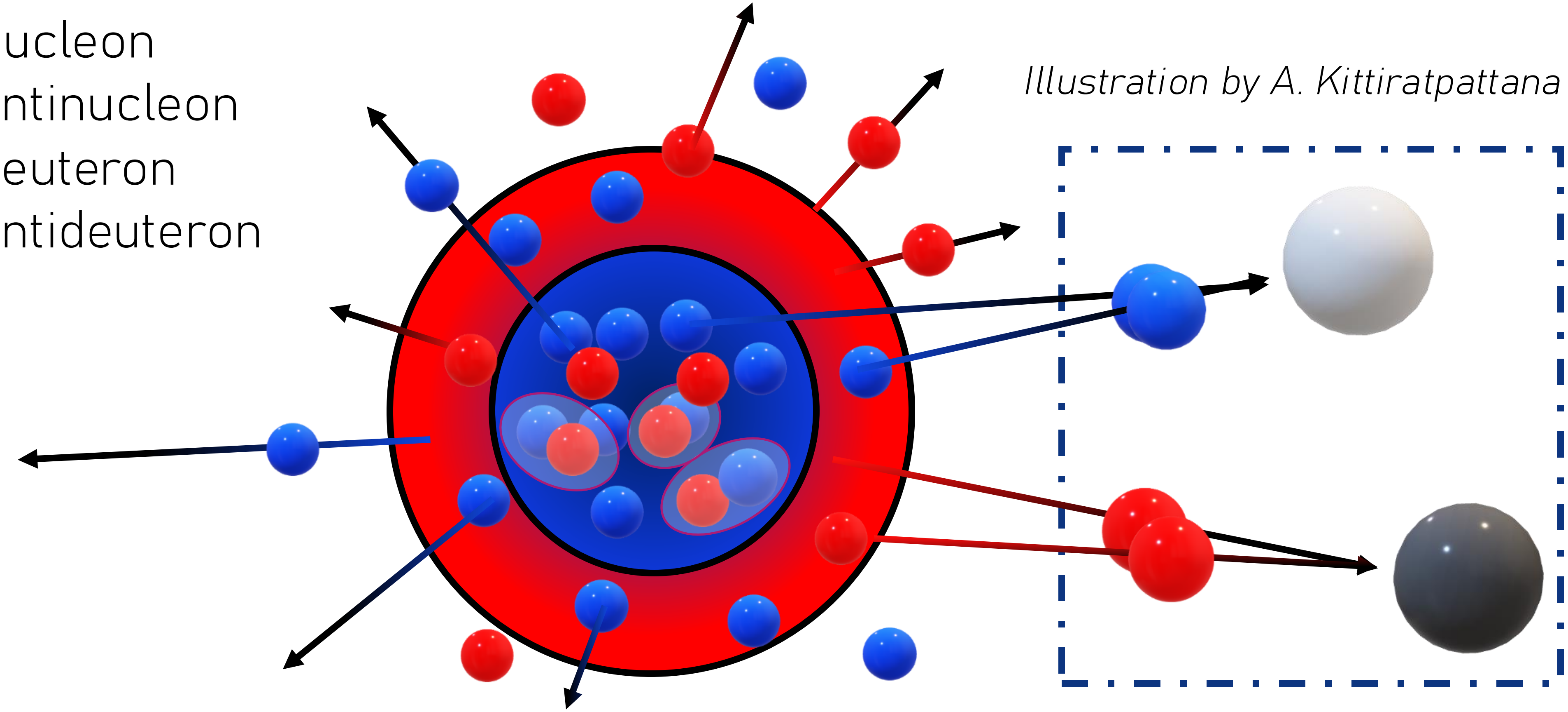
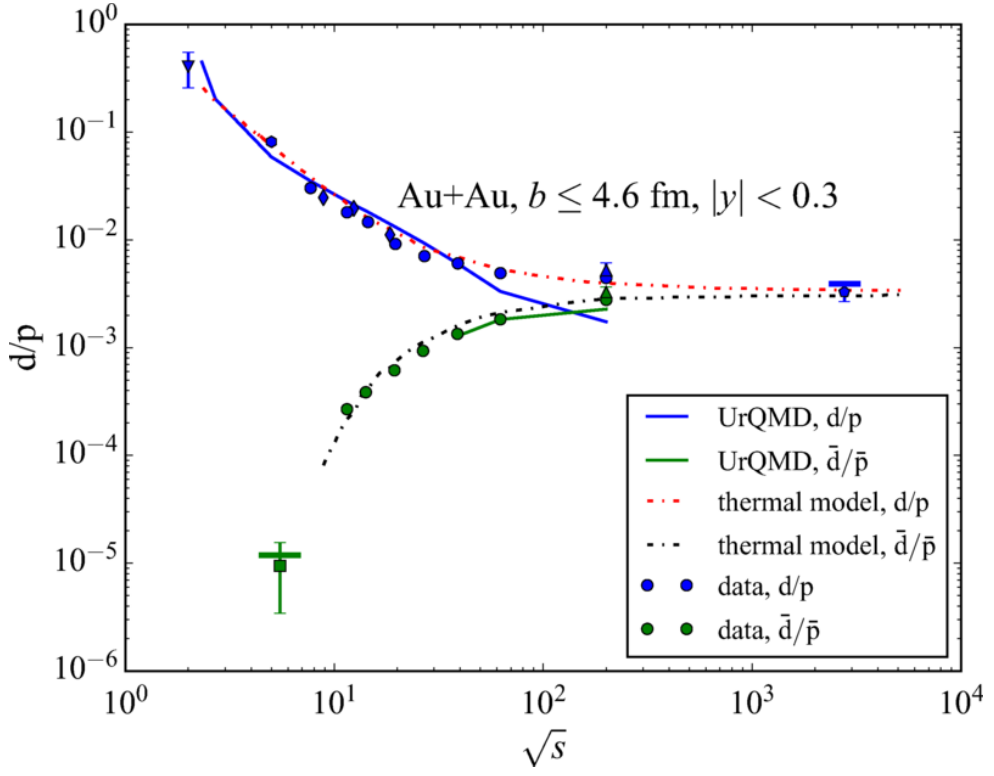


Illustration by A. Kittiratpattana

Coalescence in UrQMD



Sombun, CH et al., Phys. Rev. C **99**, 014901 (2019)

- Cluster formation after end of *kinetic* scattering (cold/dilute system)
- Phase space (PS) coalescence

	d	t	^{3}He	^{4}He
spin-isospin projection	3/8	1/12	1/12	1/96
Δr_{max} [fm]	4.0	3.5	3.5	3.5
Δp_{max} [GeV]	0.3	0.45	0.45	0.55

UrQMD with a phase transition

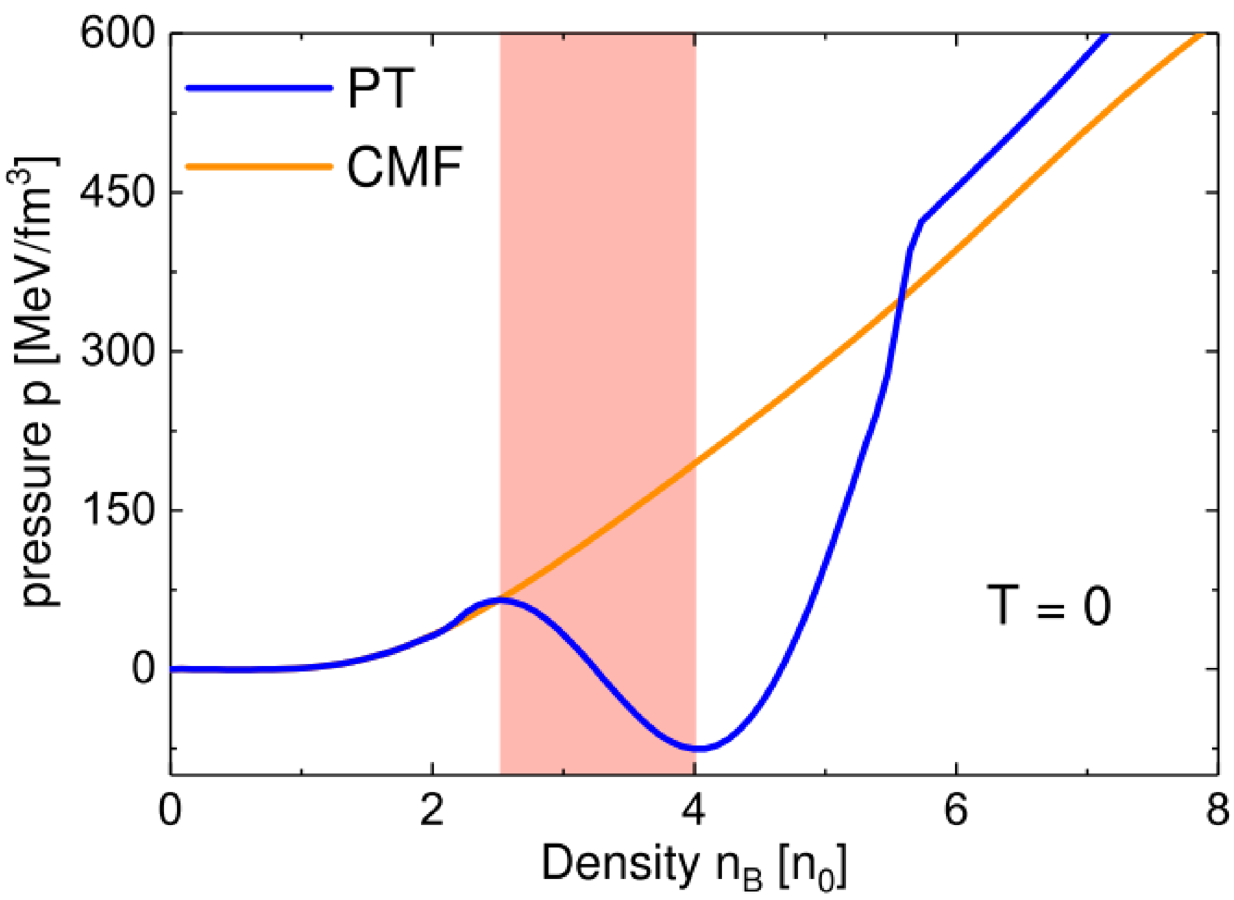
Introduce density-dependent potential to QMD part:

$$\dot{\mathbf{r}}_i = \frac{\partial \mathbf{H}}{\partial \mathbf{p}_i} \qquad \dot{\mathbf{p}}_i = -\frac{\partial \mathbf{H}}{\partial \mathbf{r}_i}$$

$$\mathbf{V} = \sum_i V(n_B(r_i))$$

Chiral mean field (CMF) equation of state

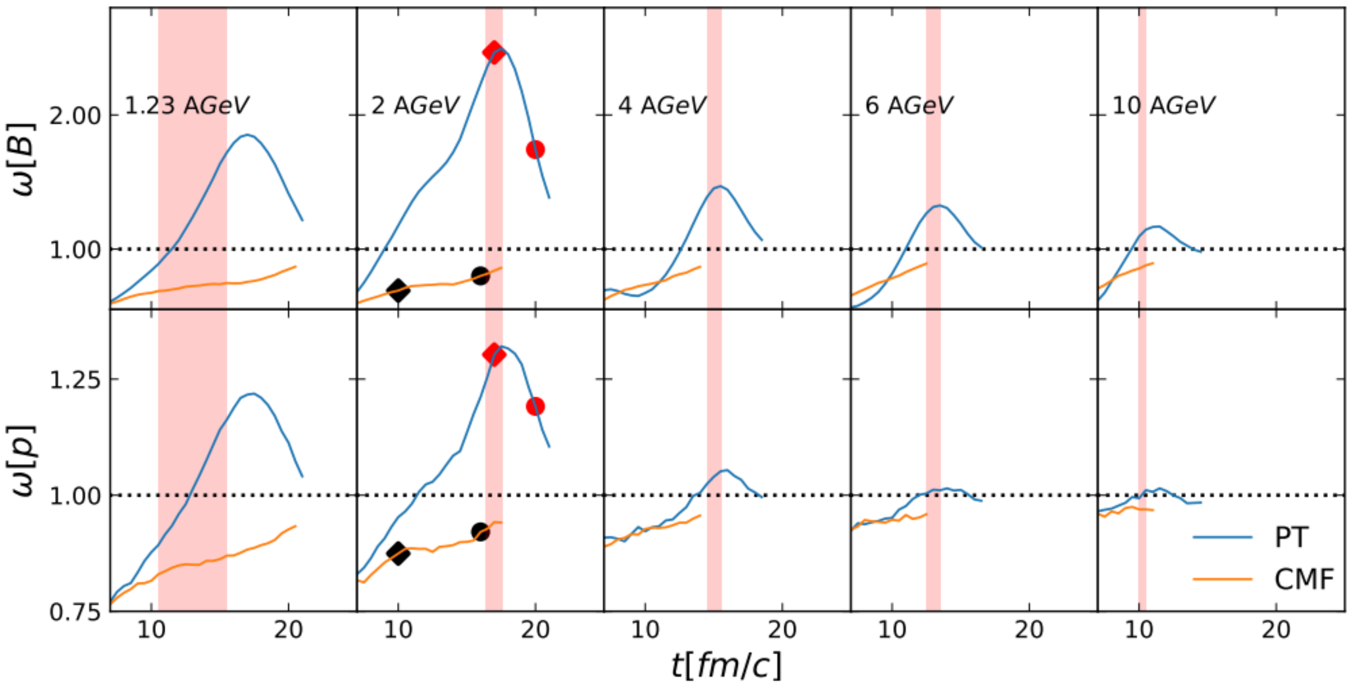
Supplied with smoothly connected polynomial between n_B^{cut} and $n_B^{\mathrm{cut}} + \Delta n_B$ (PT)



Savchuk, Poberezhnyuk, Motornenko, Steinheimer, Gorenstein, Vovchenko, Phys. Rev. C **107** (2023)

UrQMD with a phase transition

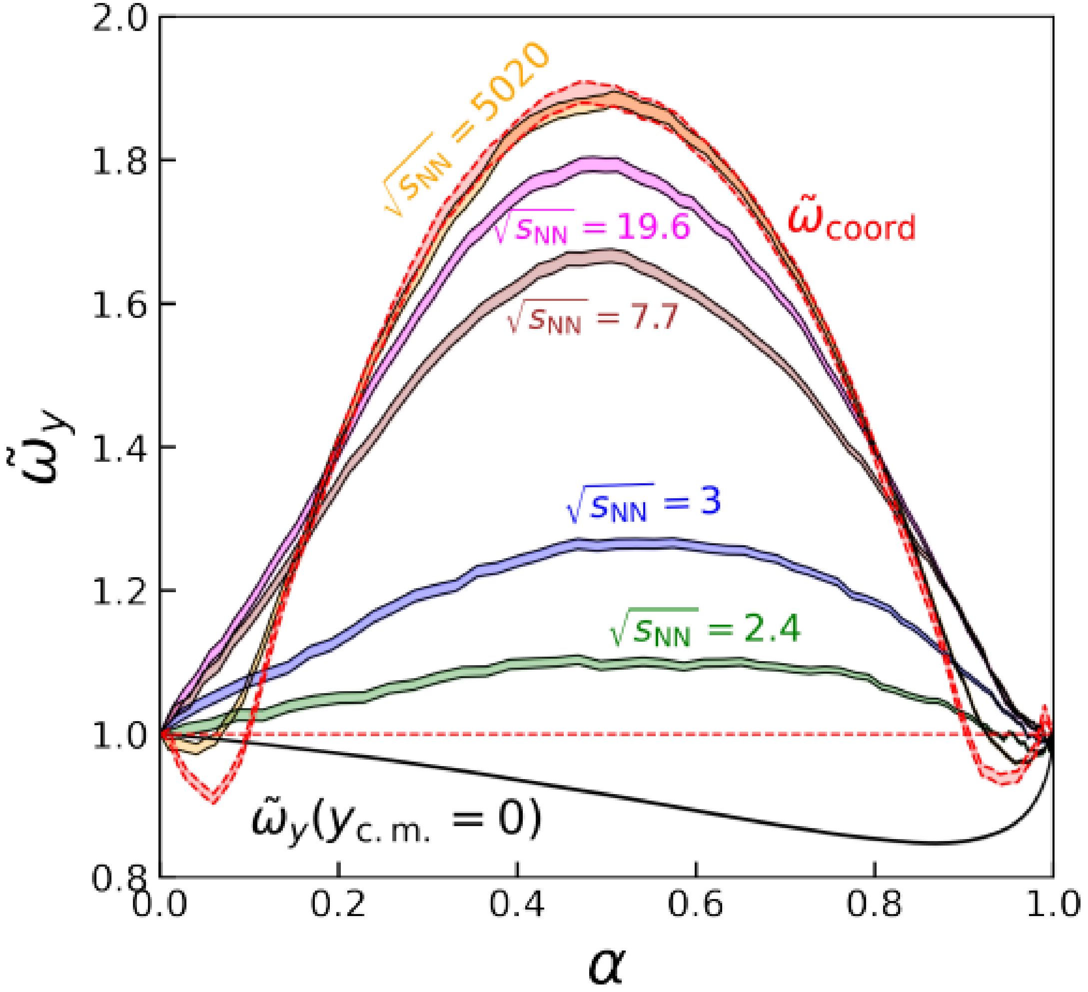
- Scaled variance in spatial volume
- Strong enhancement w/ PT
- Enhancement survives to low *n*
- 50% weaker effect of protons (*p*) compared to baryons (*B*)



Savchuk, Poberezhnyuk, Motornenko, Steinheimer, Gorenstein, Vovchenko, Phys. Rev. C **107** (2023)

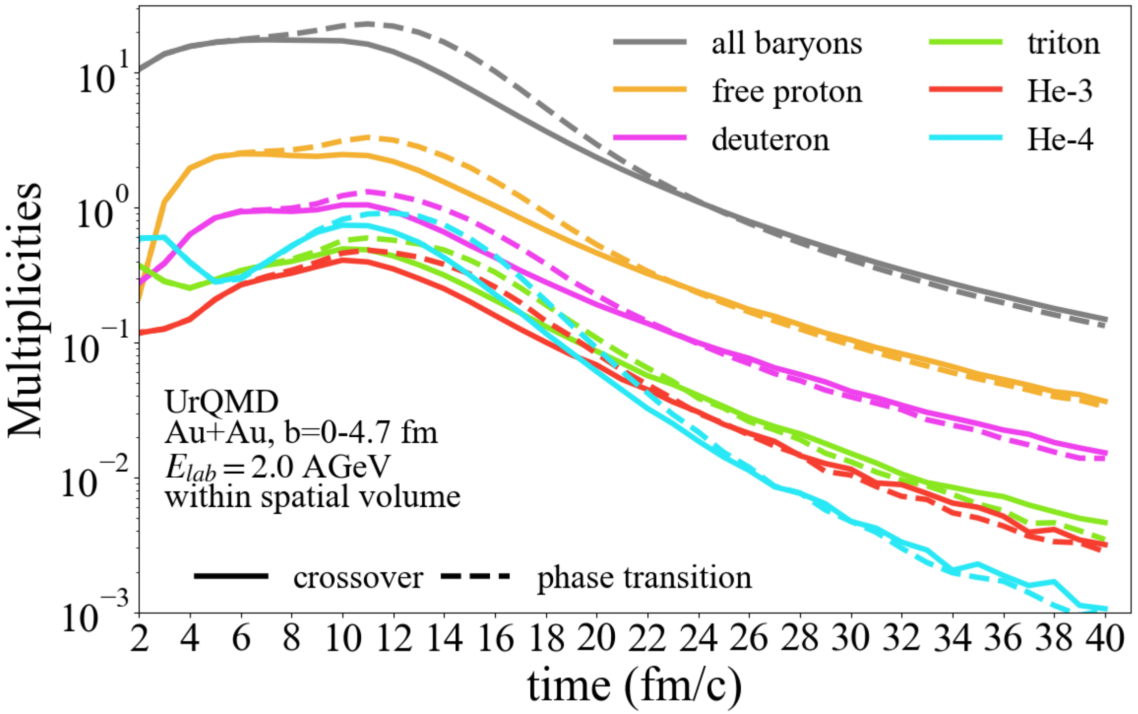
Coordinate vs. momentum space

- Scaled variance vs. acceptance ratio
- Strong enhancement w/ PT
- Approach to coordinate space “limit” with increasing center-of-mass energy
- **Strong collective flow necessary**



Kuznietsov, Gorenstein, Koch, Vovchenko, Phys. Rev. C **110** (2024)

Coordinate vs. momentum space, 2 AGeV



In coordinate space:

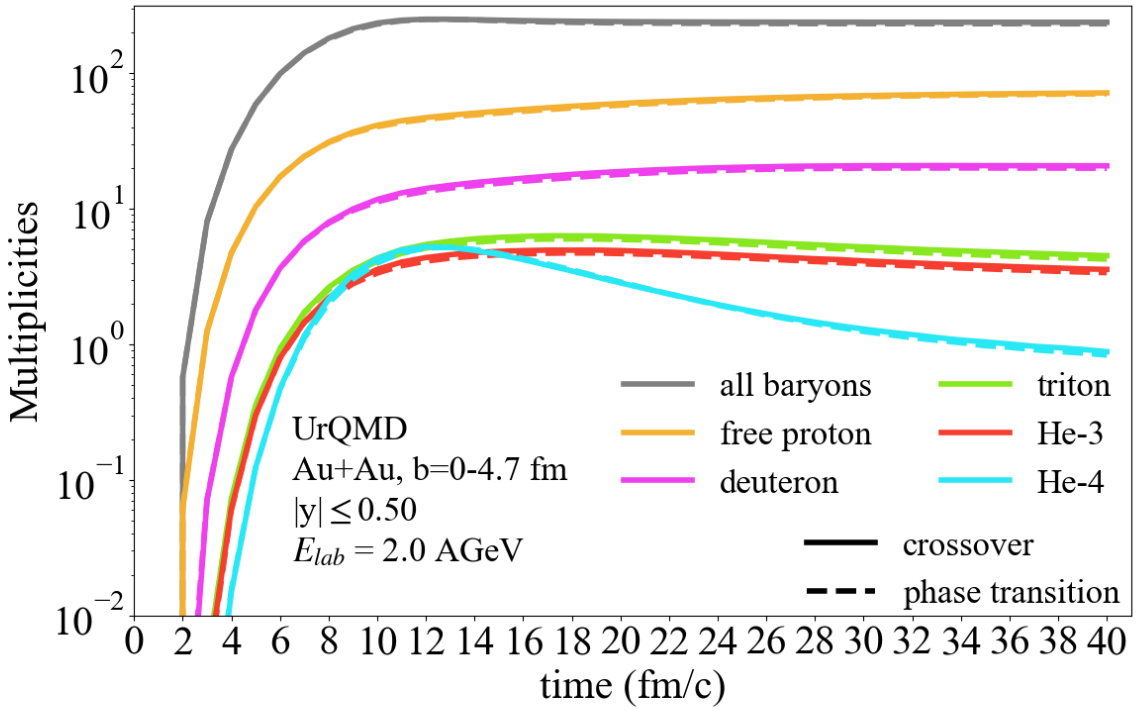
- Fixed spherical volume of radius 2 fm
- Yields CMF/PT similar at early and late times
- Yield decreases as particles leave volume
- He-4 decreases with decreasing density
- **Clear enhancement** w/ PT in coexistence phase around 8– 24 fm/c

Bumnedpan, Steinheimer, Reicher, CH, Limphirat, Bleicher, arXiv:2411.08444 (2024)

Coordinate vs. momentum space, 2 AGeV

In momentum space:

- Rapidity window |y| < 0.5
- Yield initially increases
- Yields saturate (except for ^{4}He)
- **No enhancement** w/ PT



Bumnedpan, Steinheimer, Reicher, CH, Limphirat, Bleicher, arXiv:2411.08444 (2024)

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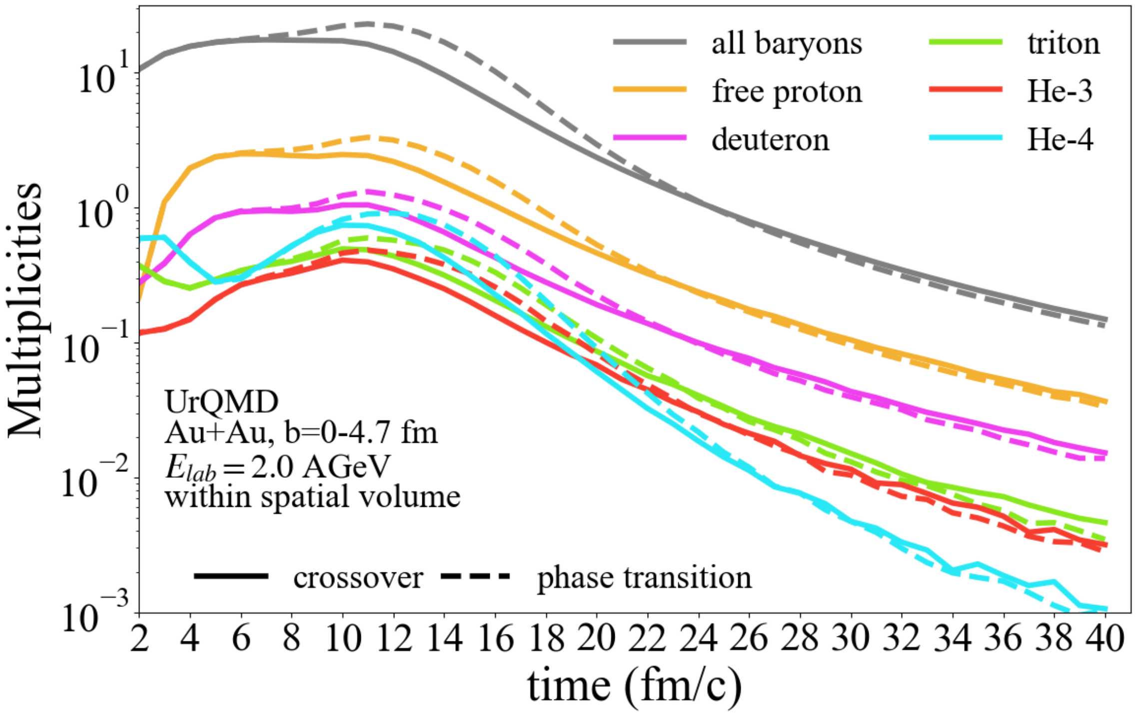
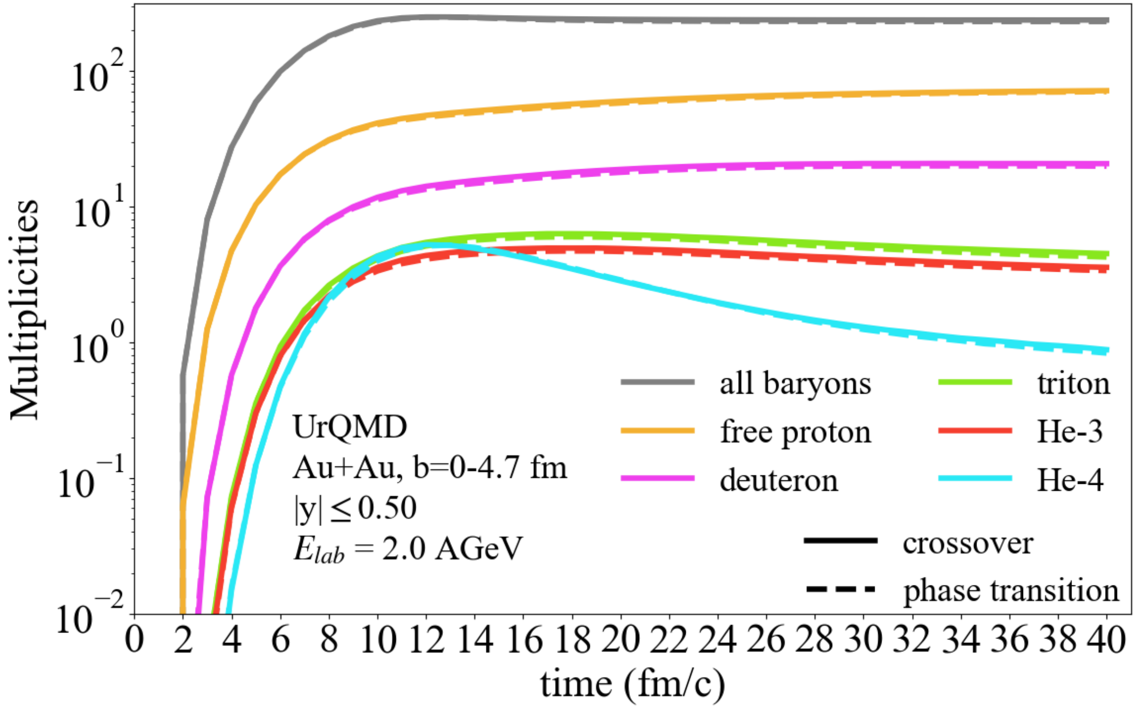
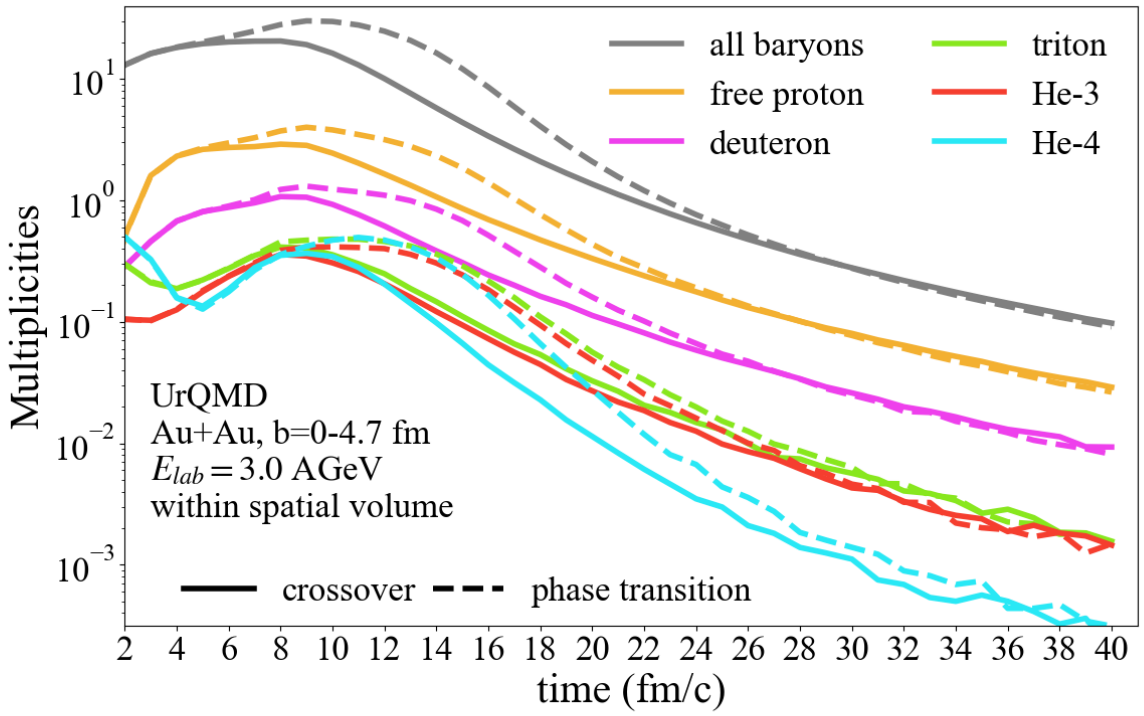
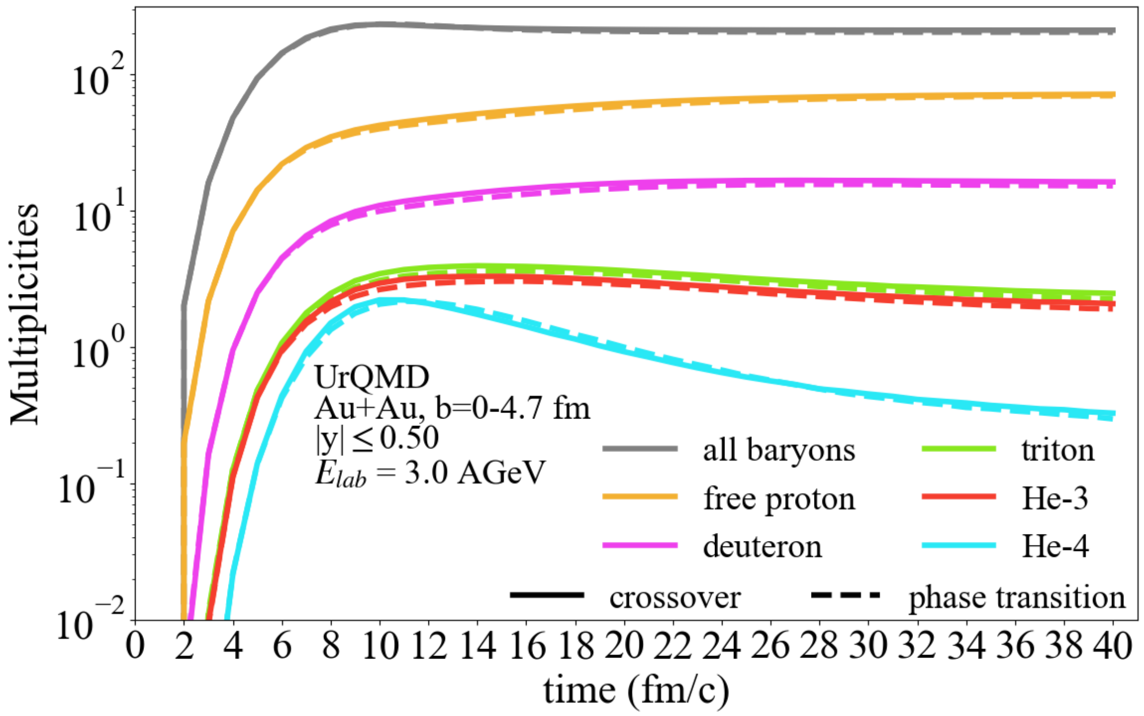




Bumnedpan, Steinheimer, Reicher, CH, Limphirat, Bleicher, arXiv:2411.08444 (2024)

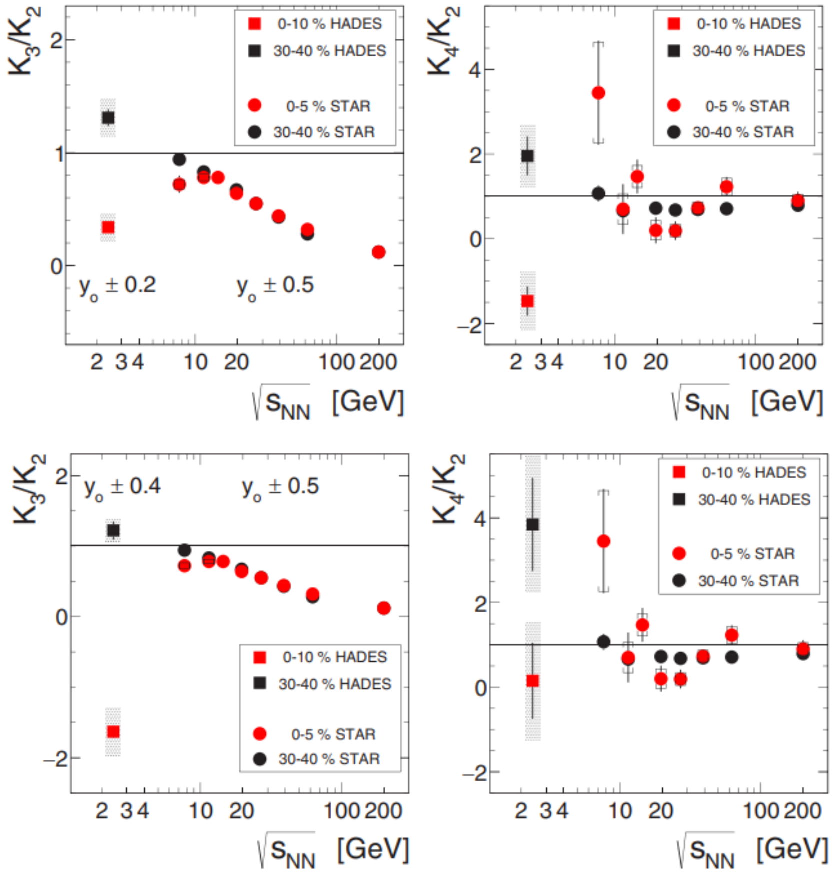
Coordinate vs. momentum space, 3 AGeV





Bumnedpan, Steinheimer, Reicher, CH, Limphirat, Bleicher, arXiv:2411.08444 (2024)

Observable II: Cumulants



Cumulant ratios expected to be sensitive to PT

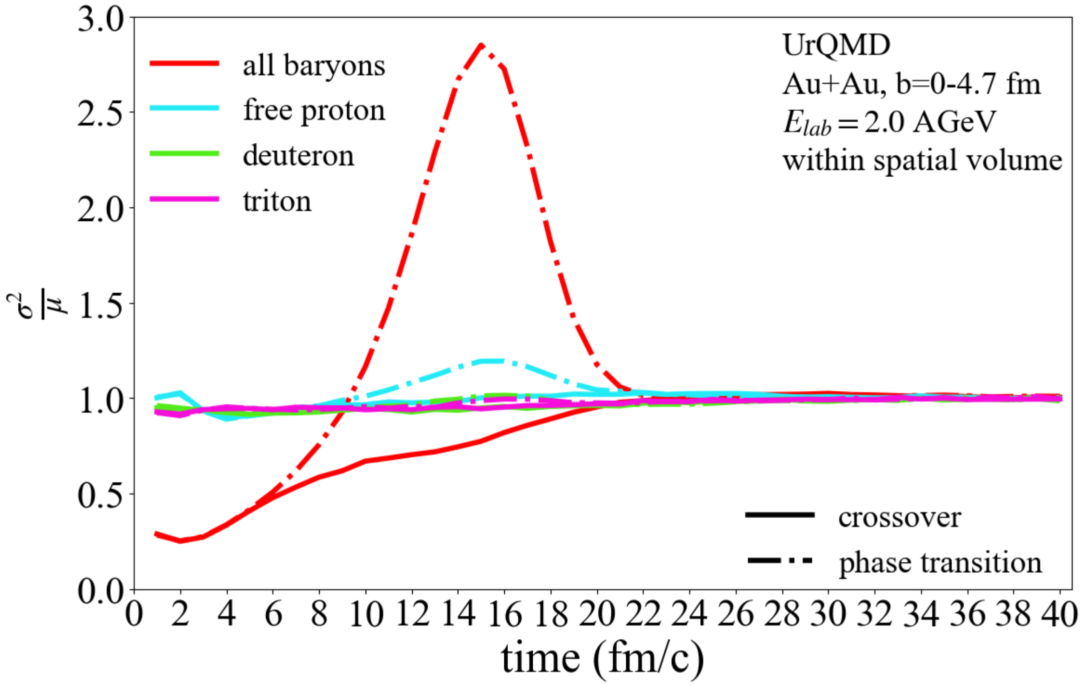
$$\frac{\sigma^2}{\mu} = \frac{\langle(\Delta N_i)^2\rangle}{\langle N_i\rangle} = \frac{K_2}{K_1} \qquad S\sigma = \frac{\langle(\Delta N_i)^3\rangle}{\langle(\Delta N_i)^2\rangle} = \frac{K_3}{K_2}$$

Data at low energy:

- Impact of phase transition?
- Role of spectator fluctuations?
- Role of nuclear clusters?

HADES collaboration, Phys. Rev. C **102** (2020)

Coordinate vs. momentum space, 2 AGeV



In coordinate space:

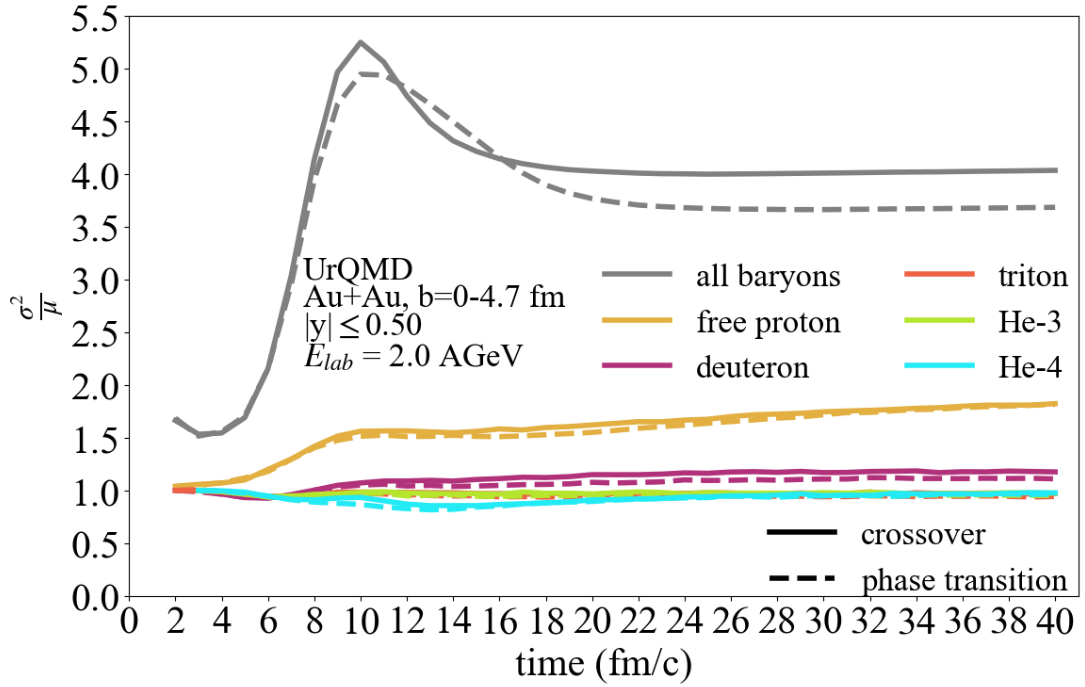
- Fixed spherical volume of radius 2 fm
- *B* starts below 1 due to conservation law
- **Clear enhancement for all baryons** w/ PT, peaks at highest compression
- Weaker enhancement for free protons and clusters

Bumnedpan, Steinheimer, Reicher, CH, Limphirat, Bleicher, arXiv:2411.08444 (2024)

Coordinate vs. momentum space, 2 AGeV

In momentum space:

- Rapidity window |y| < 0.5
- Weak modification w/ PT
- CMF, PT curves separate after 8 fm/c
- (Slight) suppression for baryons, less clearly for clusters



Bumnedpan, Steinheimer, Reicher, CH, Limphirat, Bleicher, arXiv:2411.08444 (2024)

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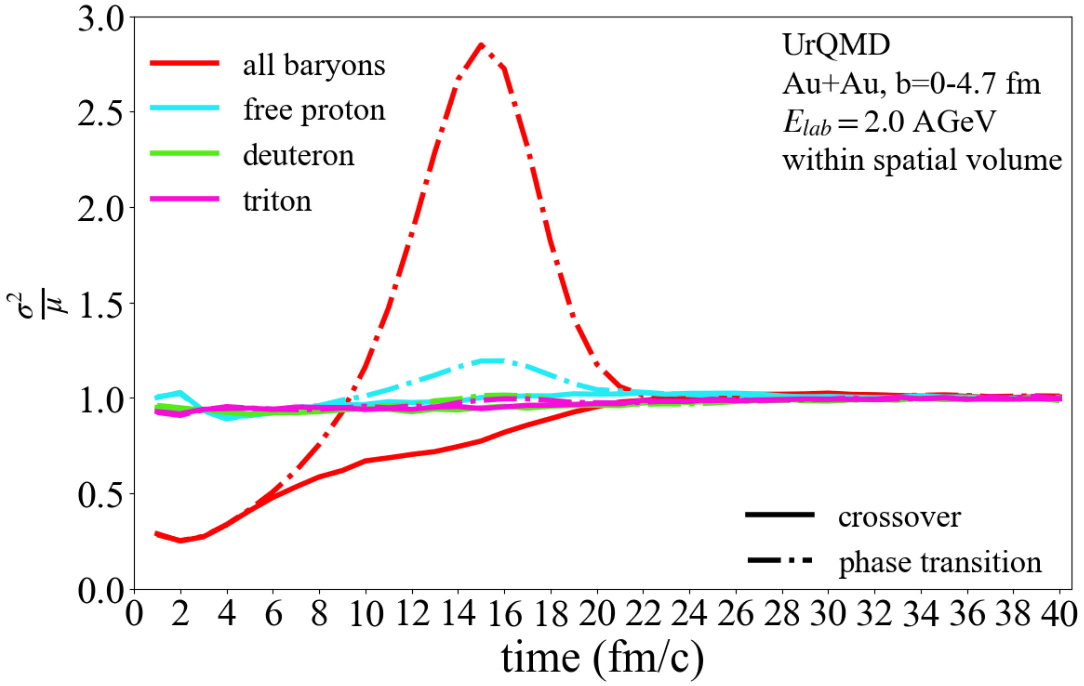

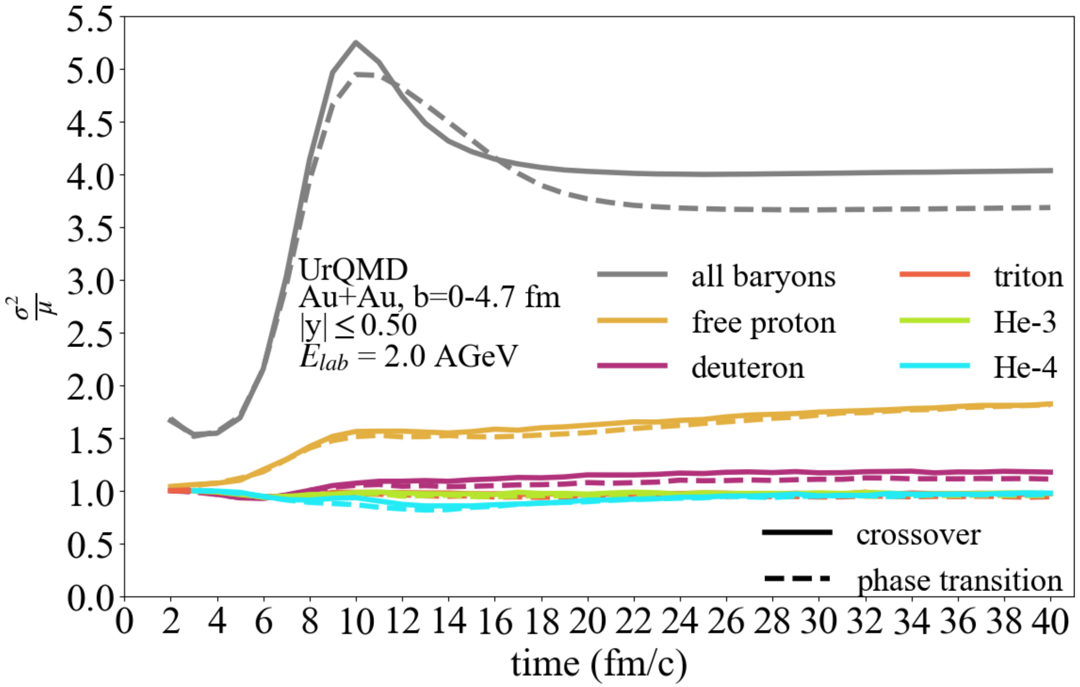

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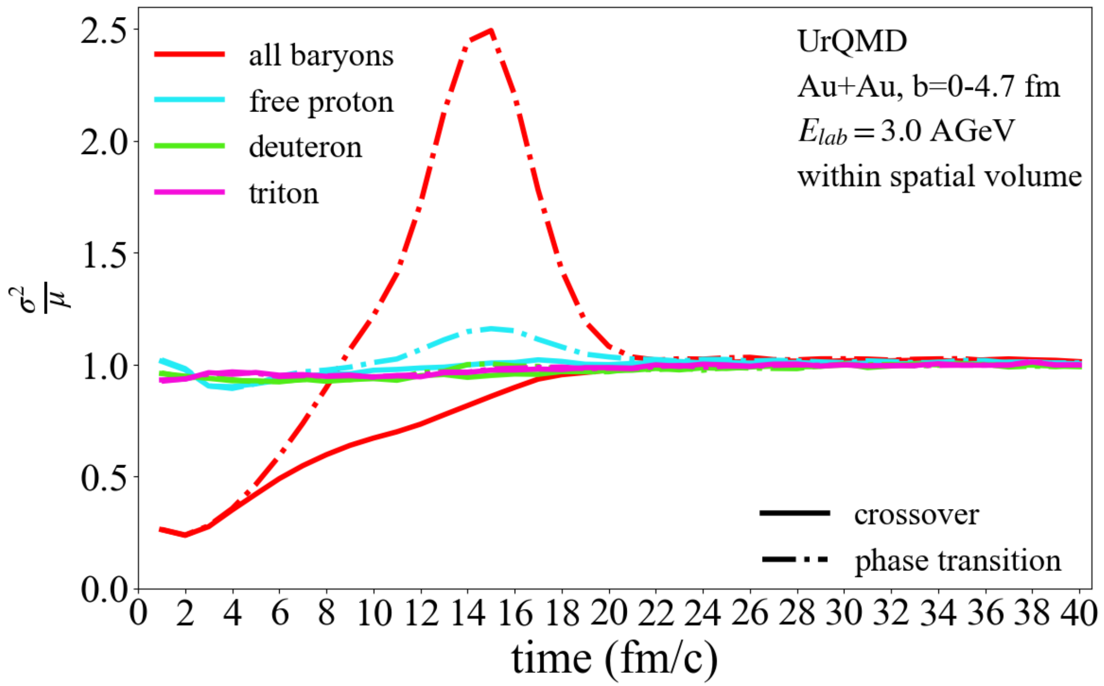

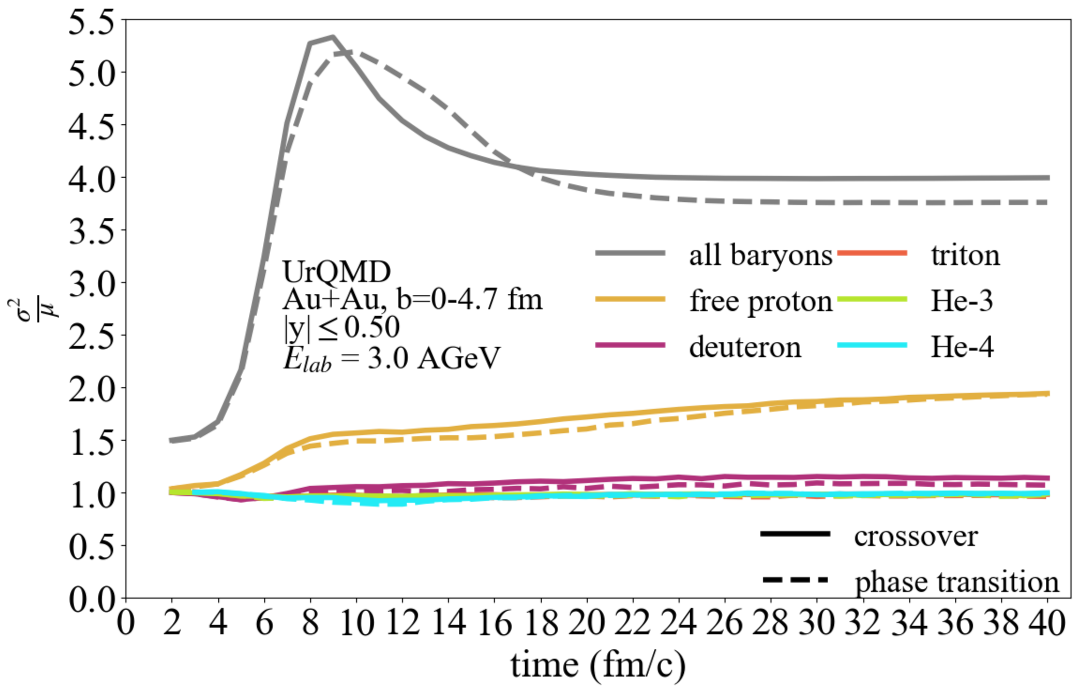

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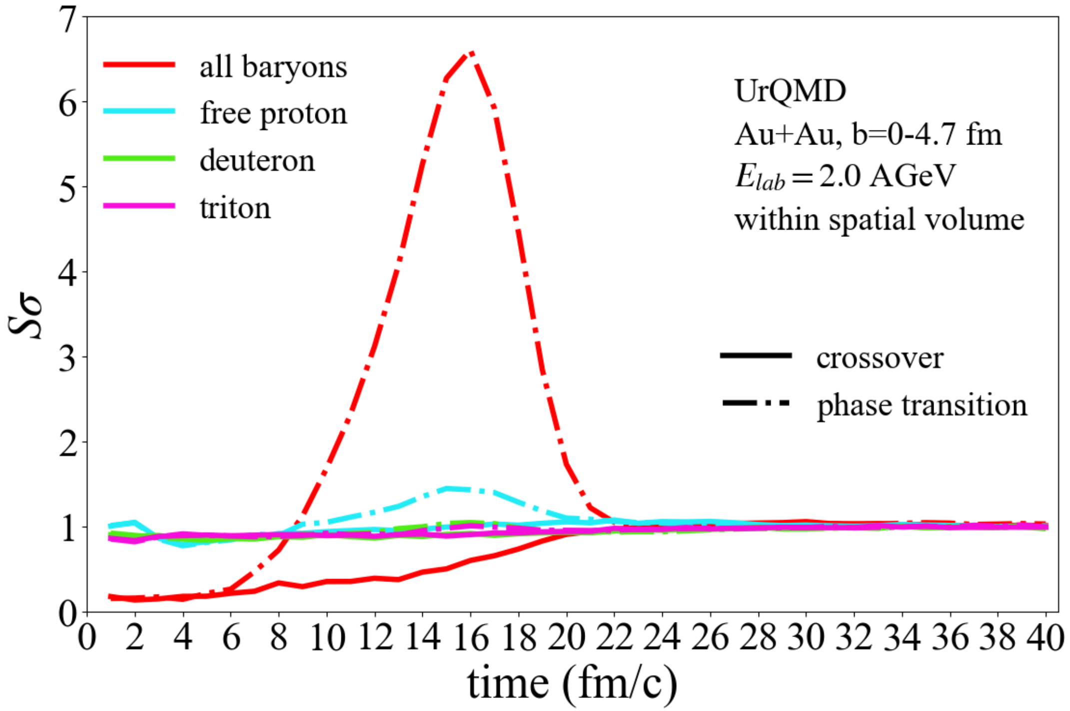

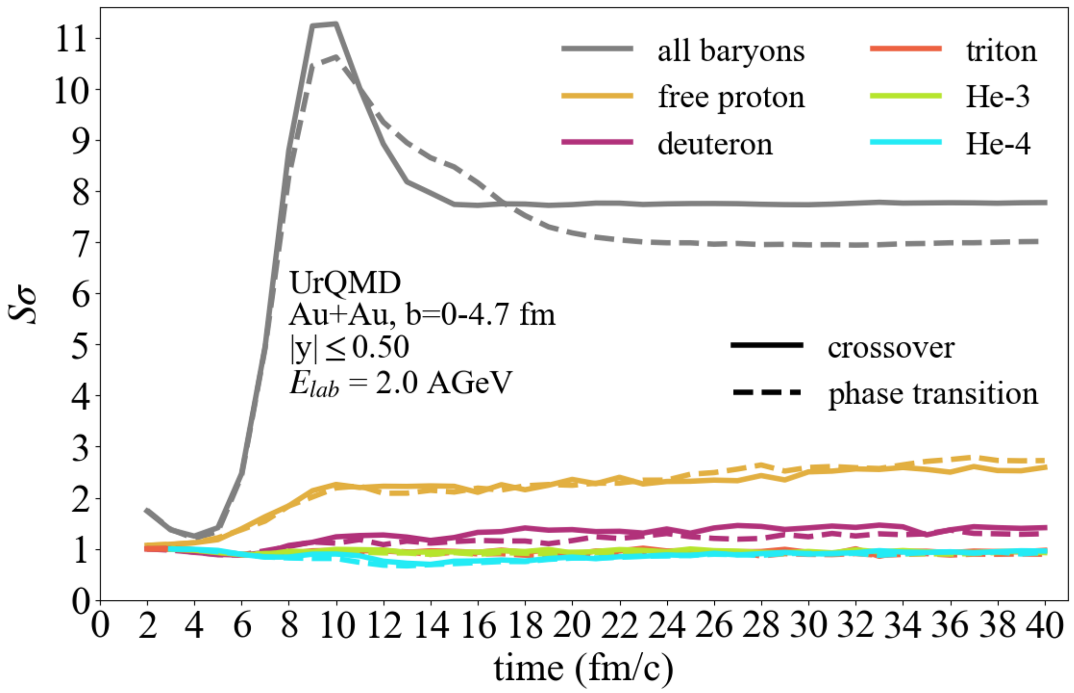

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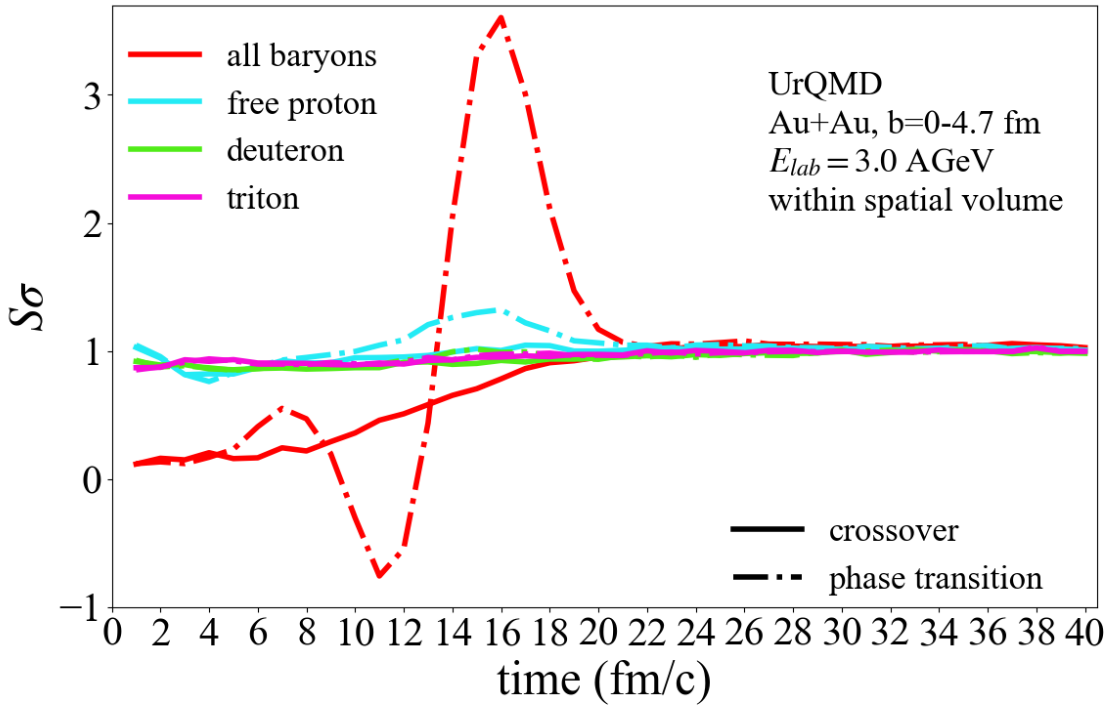
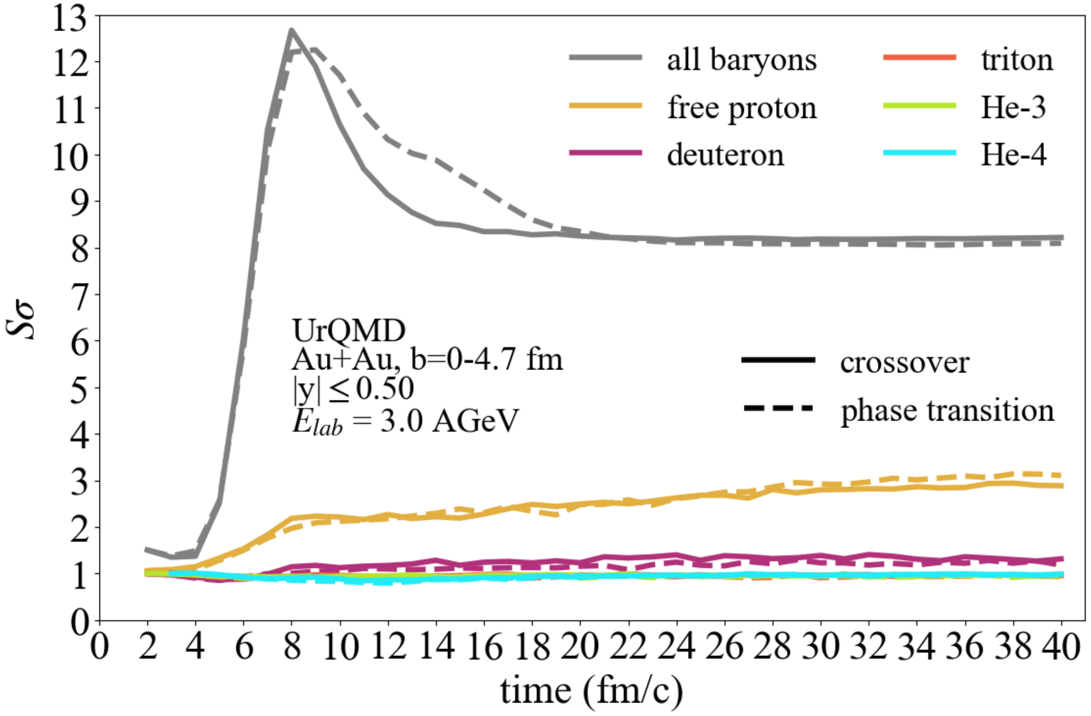
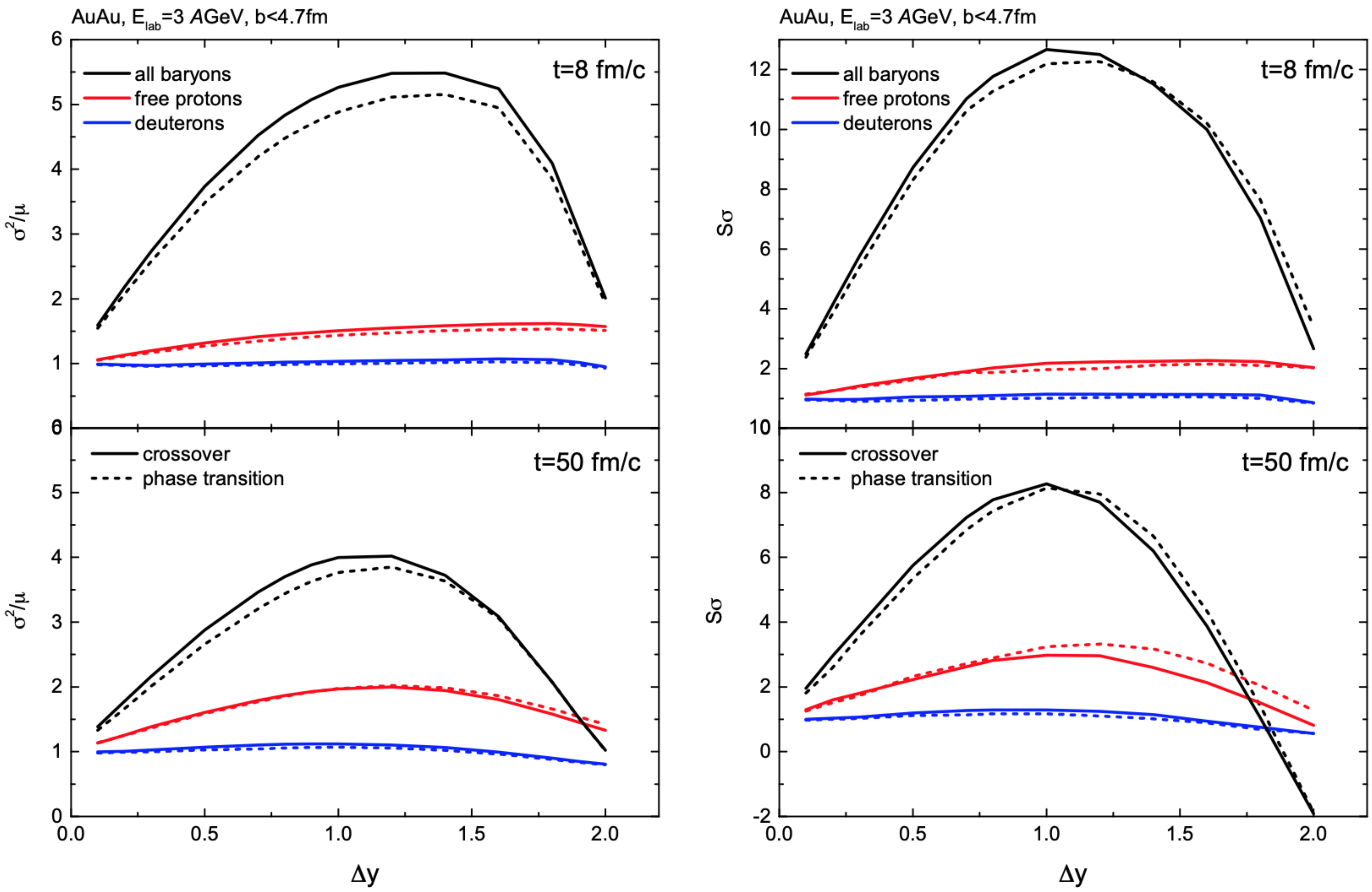




Bumnedpan, Steinheimer, Reicher, CH, Limphirat, Bleicher, arXiv:2411.08444 (2024)

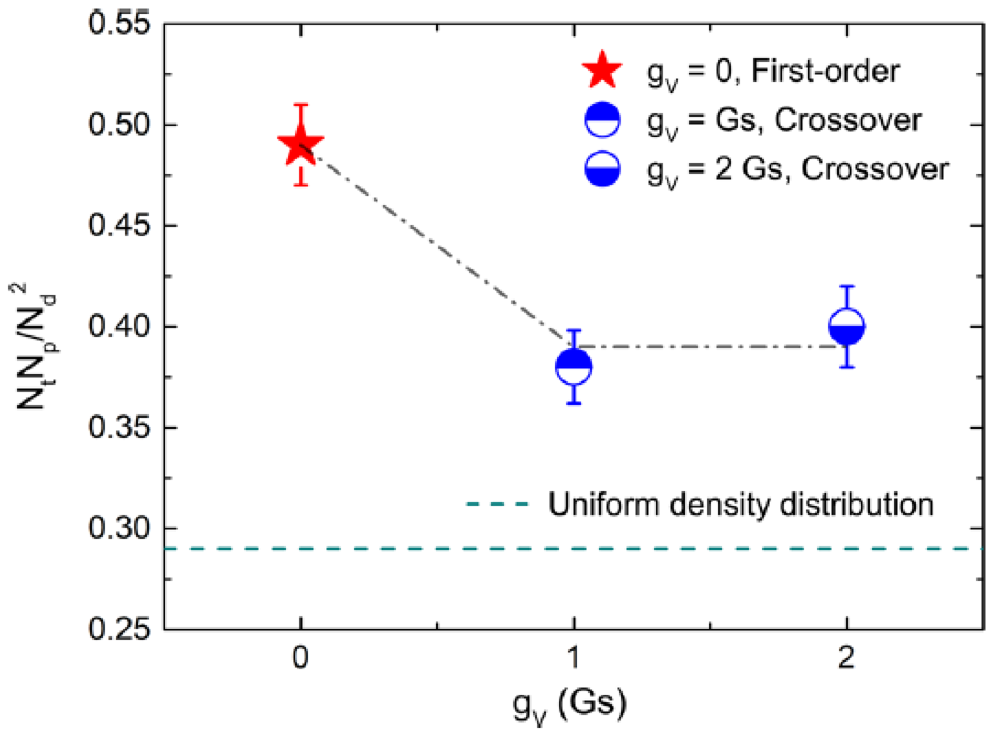


Intermediate stage

Late stage

arXiv:2411.08444

Observable III: Light nuclei ratios

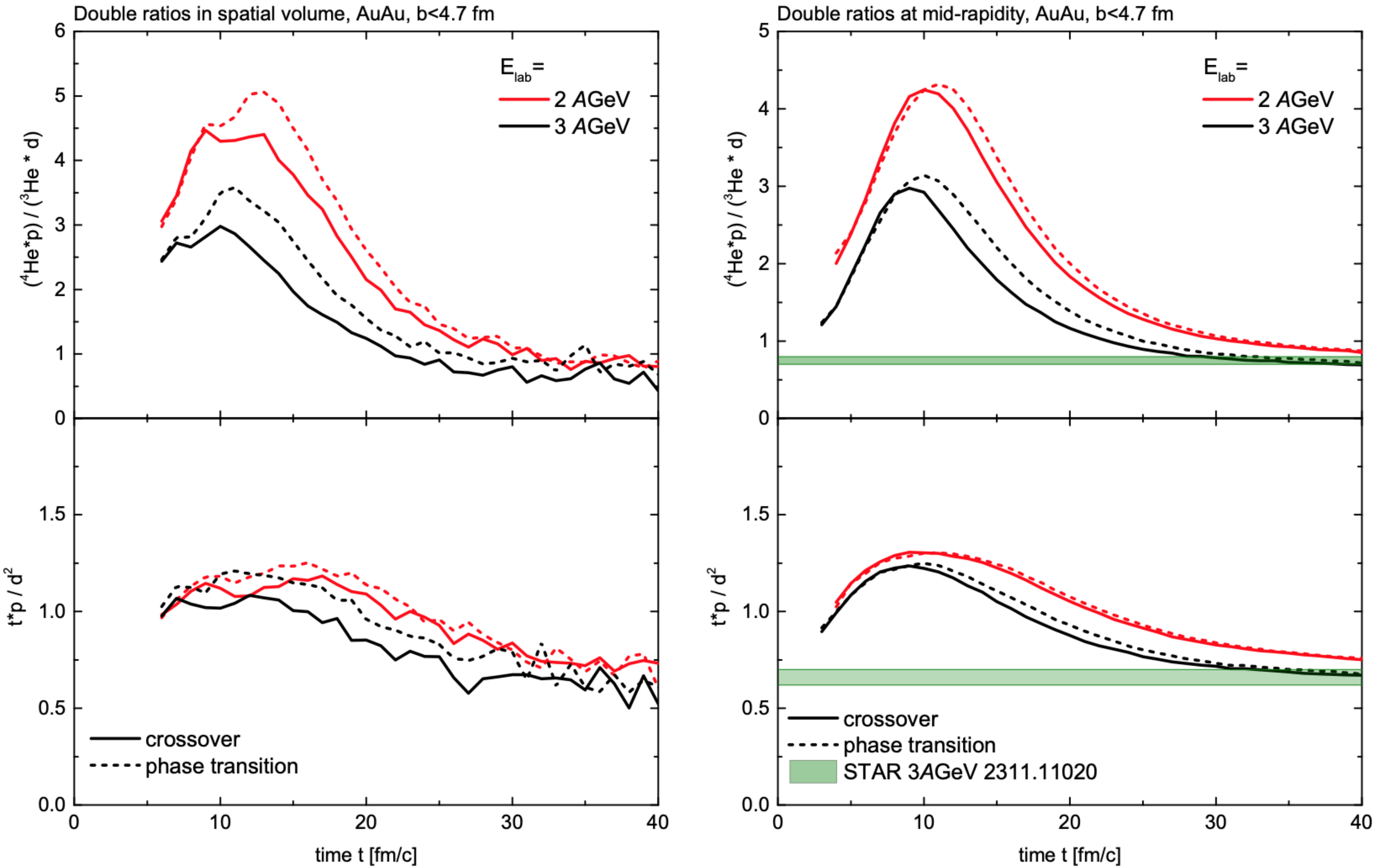


Ratio triton times proton to deuteron squared

- Enhancement w/ first-order PT
- Peak structure in energy dependence
- Survive hadronic scatterings?

Do the large fluctuations in *B* in coord. space translate to measurable cluster production?

Sun, Ko, Li, Xu, Chen, Eur. Phys. J. A **57** (2021)



arXiv:2411.08444

Summary

- Time evolution of light nuclei yields and fluctuations in UrQMD with CMF/PT equation of state
- Coordinate space: Overall enhancement w/ PT, strongest for baryon cumulant ratios
- Momentum space: For proton number: higher-order cumulants in Δy > 1 most promising
- For Δy = 1 , ratio of (^{4}He*p) / (^{3}He*d) w/ PT enhanced by around 10% in intermediate times, Signal disappears at late times, unlikely to be measurable

Bumnedpan, Steinheimer, Reicher, CH, Limphirat, Bleicher, arXiv:2411.08444 (2024)

THANK YOU