Clusters production in heavy io collisions

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- Enhanced cluster yields have been observed.
- How can we interpret them?
- What are the confounding factors?

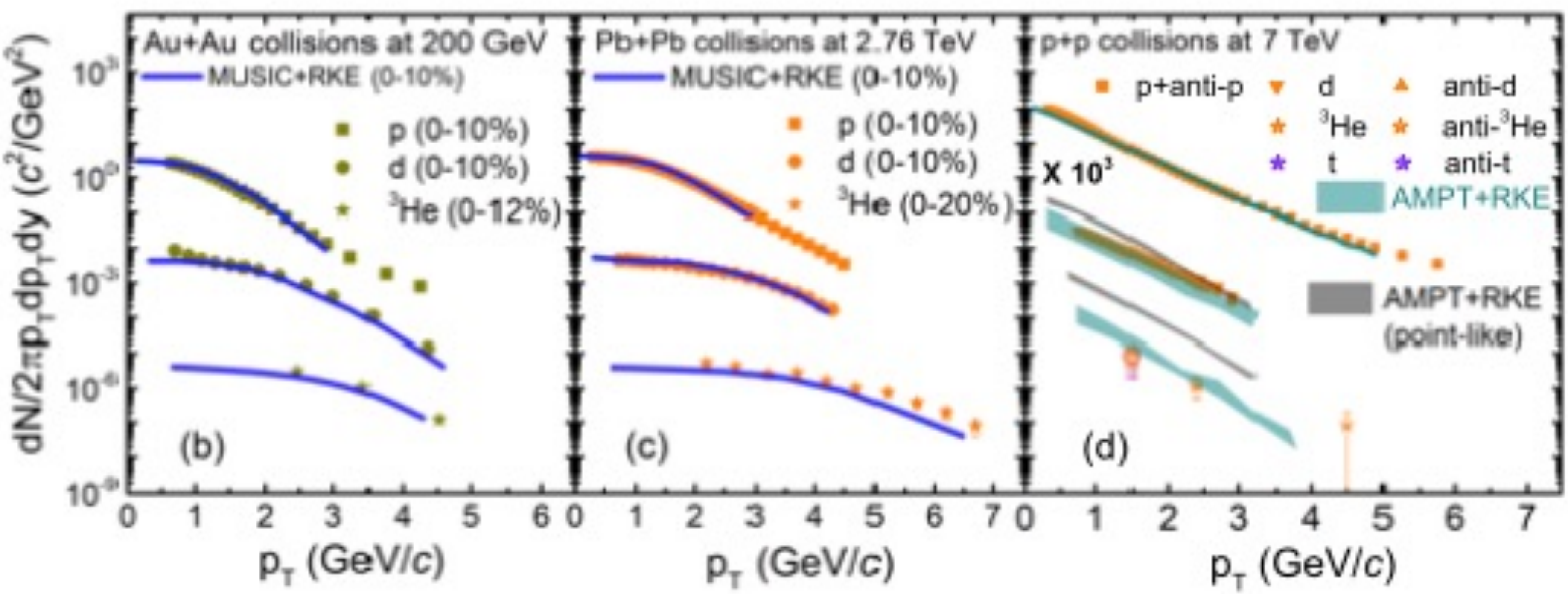
Light nuclei production from non-local many-body scattering

Sun, Wang, Ko, Ma & Shen, Nature Commun. 15, 1074 (2024)

$$\frac{\partial f_d}{\partial t} + \frac{\mathbf{P}}{E_d} \cdot \frac{\partial f_d}{\partial \mathbf{R}} = \frac{1}{2 g_d E_d} \int \prod_{i=1}^{3} \frac{\mathrm{d}^3 \mathbf{p}_i}{(2\pi)^3 2E_i} \frac{\mathrm{d}^3 \mathbf{p}_\pi}{(2\pi)^3 2E_\pi} \frac{E_d \mathrm{d}^3 \mathbf{r}}{m_d} 2 m_d W_d(\tilde{\mathbf{r}}, \tilde{\mathbf{p}})$$

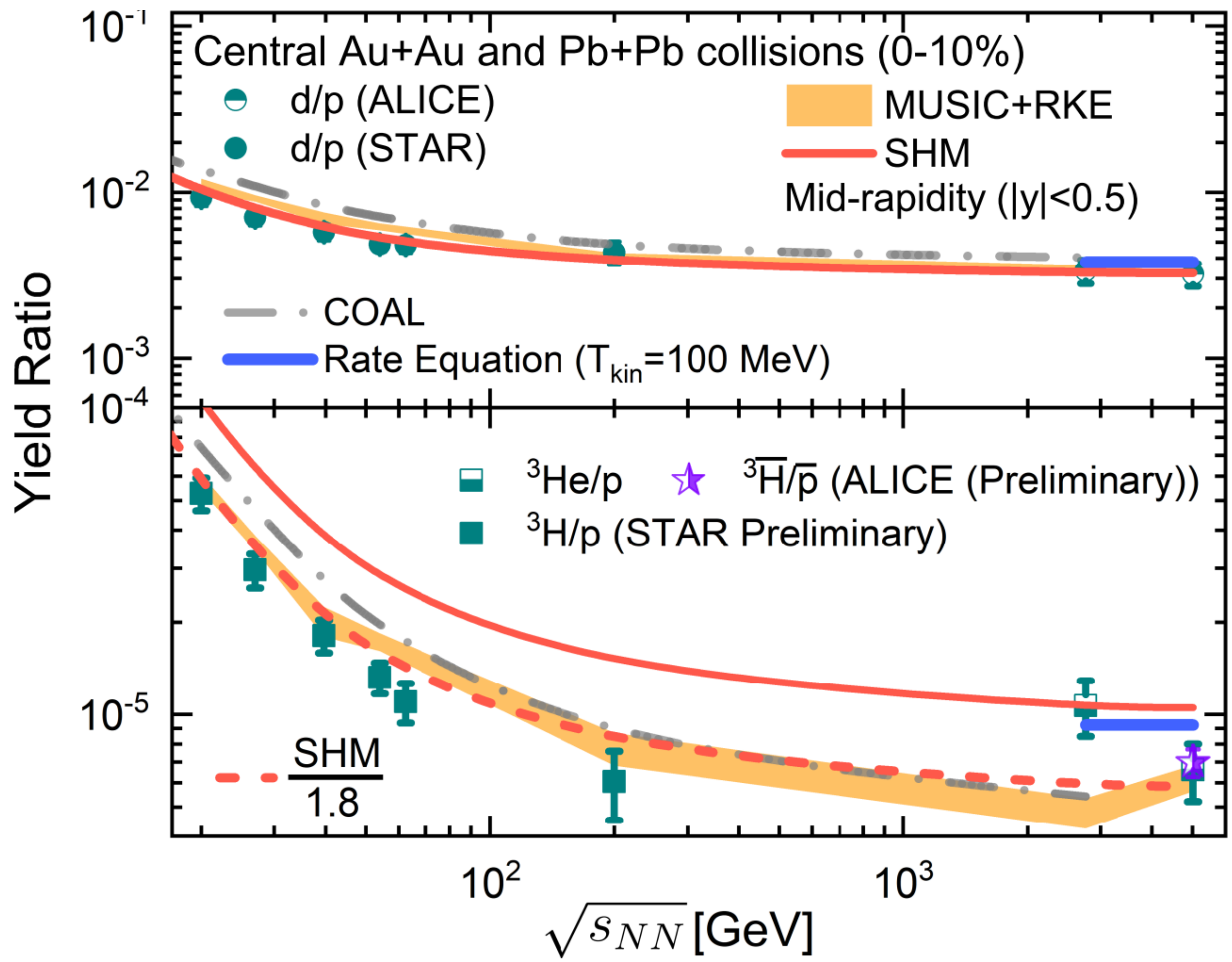
$$\left(\overline{|\mathcal{M}_{\pi^+ n \to \pi^+ n}|^2} + n \leftrightarrow p\right) \left[-g_\pi f_\pi g_d f_d \prod_i^3 (1 \pm f_i) + \frac{3}{4}(1+f_\pi)(1+f_d) \prod_{i=1}^{3} g_i f_i \right]$$

$$\times (2\pi)^4 \delta^4 (p_1 + p_2 + p_3 - p_\pi - p_d) \rightarrow \text{Good description of data}$$



Hadronic rescattering effects on light nuclei production

Sun et al., Nature Commun. 15, 1074 (2024)



- *d/p* and *t/p* ratios are similar in kinetic approach and coalescence model.
- Hadronic re-scatterings reduce the triton yields by about a factor of 2 as a result of constant $tp/d^2 = 1/2\sqrt{3}$ and decreasing d/p due to decay of baryon resonances as the hadronic matter expands and cools.

Mechanism of deuteron production at the LHC

ALICE Collaboration, 2504.02393 [nucl-ex]

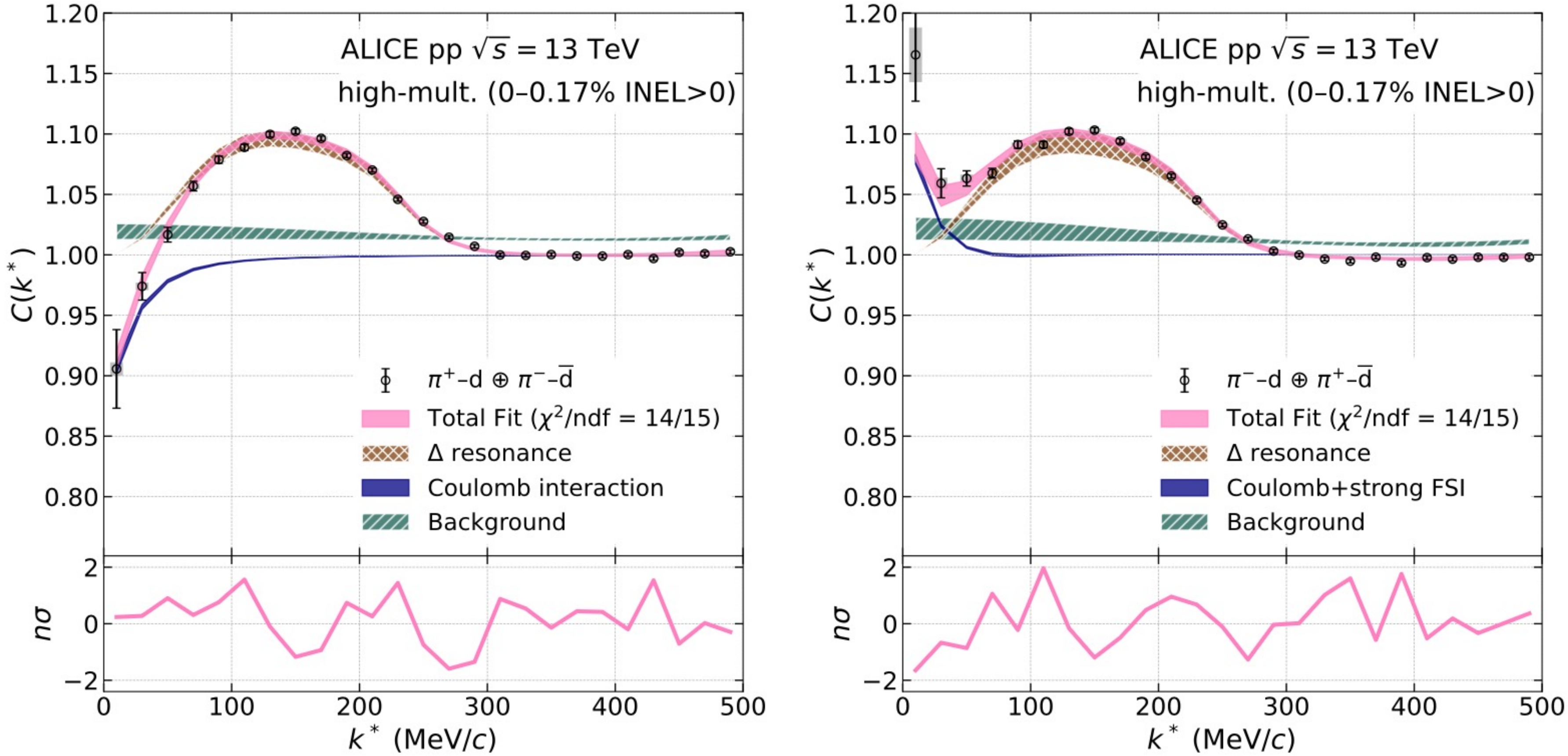
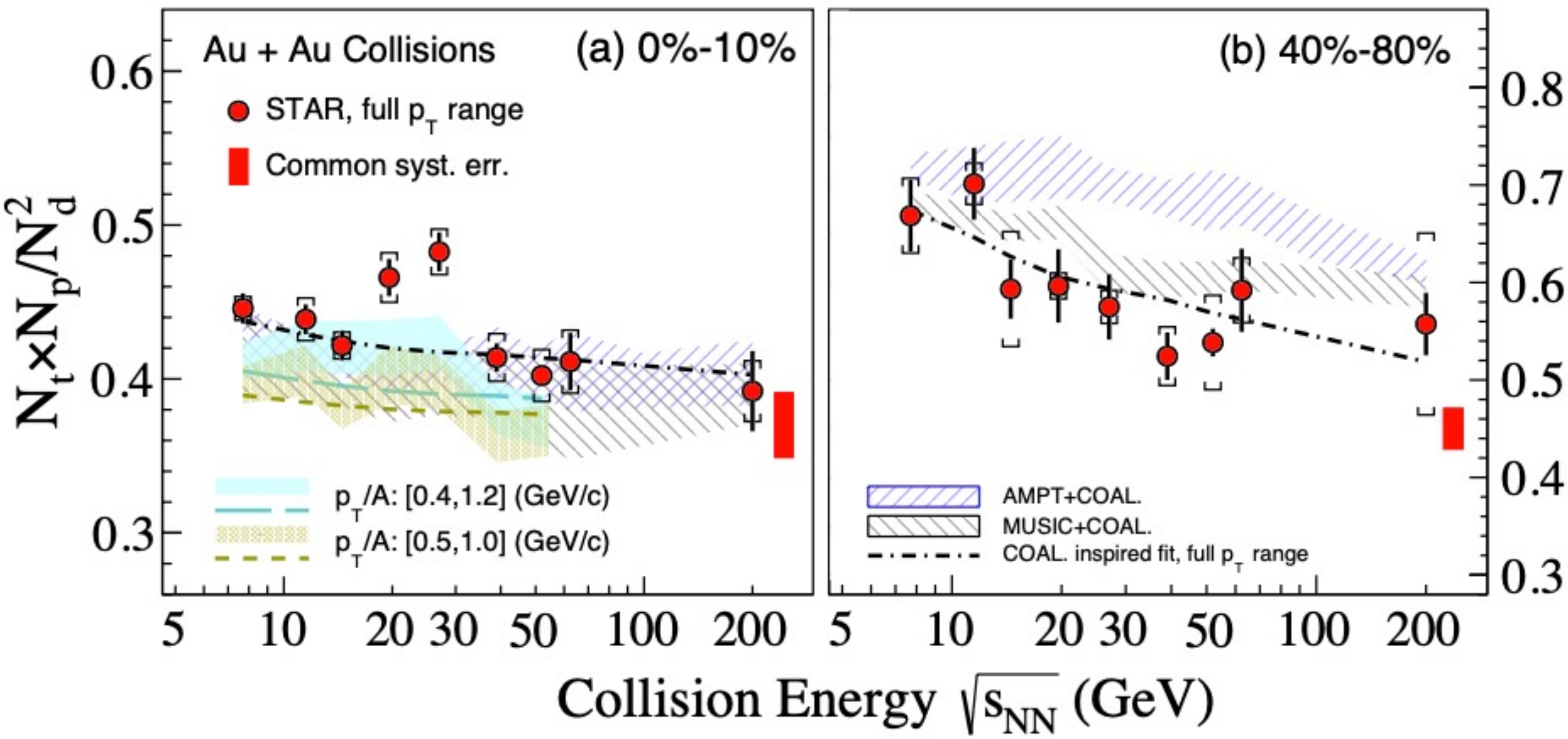


Figure 2: Measured π^+–d (left) and π^-–d (right) correlation functions fitted with model calculations (upper panels) and the number of standard deviations (lower panels). The brown crosshatched bands in both panels correspond to contributions by the Δ resonance, blue bands represent the Coulomb interactions, teal diagonally hatched bands the residual background and the magenta bands the total fit function. The lower panels display comparisons between the data points and the fit in terms of the number of standard deviations $n\sigma$, where statistically 95% of points are expected to lie within $\pm 2\sigma$.

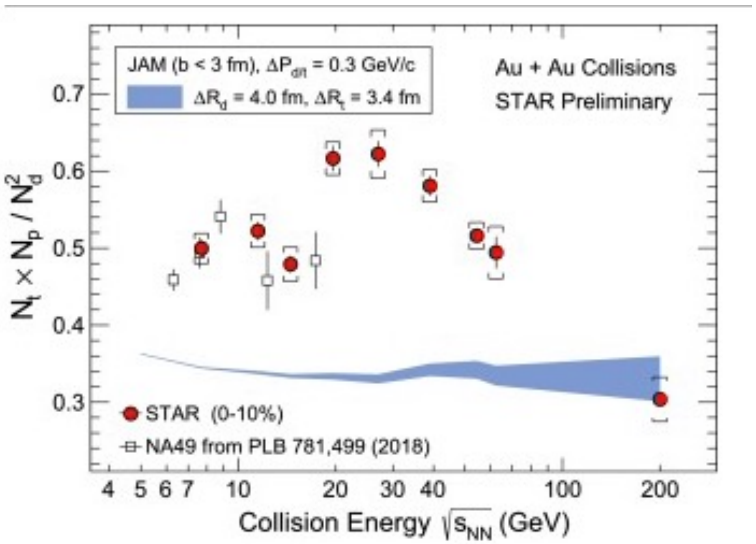
Yield ratio of $N_t N_p / N_d^2$ in Au+Au collisions at RHIC

STAR Collaboration, PRL 130, 202301 (2023)

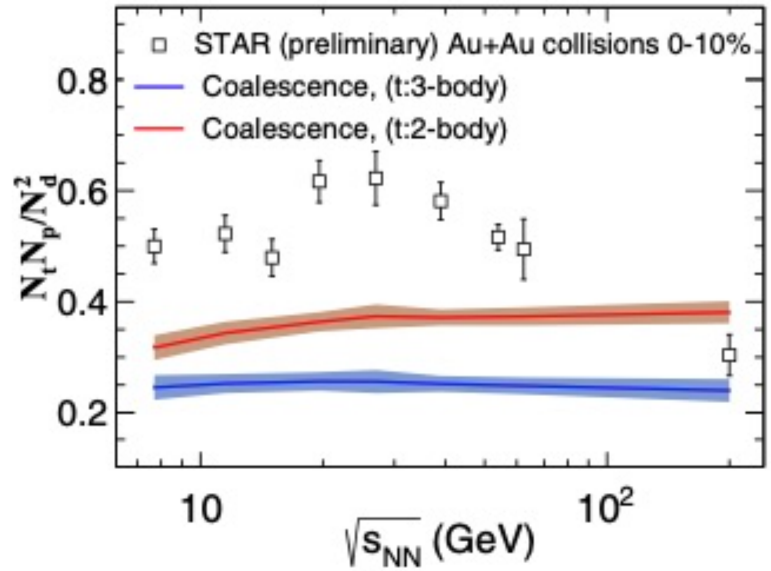


- Enhanced yield ratio of $\mathrm{N_t N_p / N_d^2}$ at $\sqrt{s_{NN}} \approx 25$ GeV in central Au+Au collisions, compared to non-central collisions.

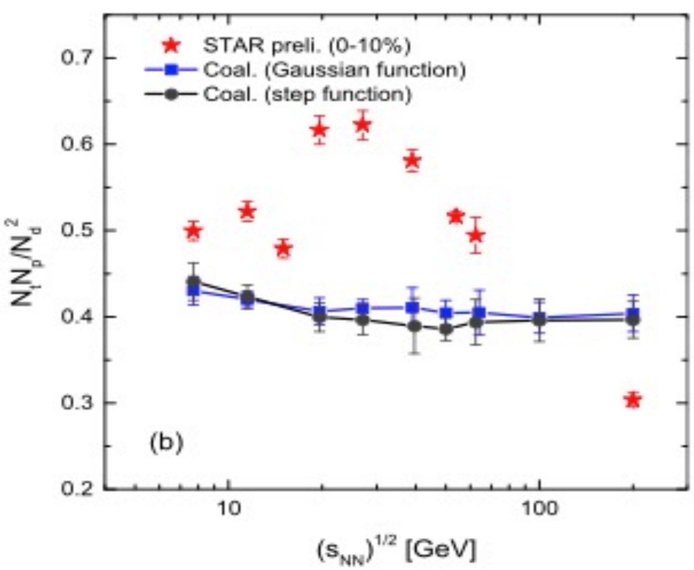
Beam-energy dependence of $N_t N_p / N_d^2$ from theoretical models



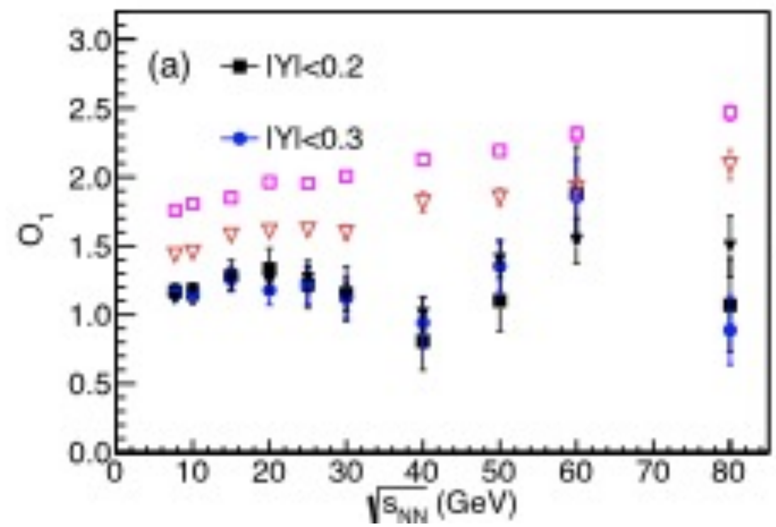
Liu, Zhang, He, Sun, Yu, Luo, PLB 805, 135452 (2020): JAM



Zhao, Shen, Ko, Liu & Song, PRC 102, 044912 (2020). IEBE+MUSIC+UrQMD



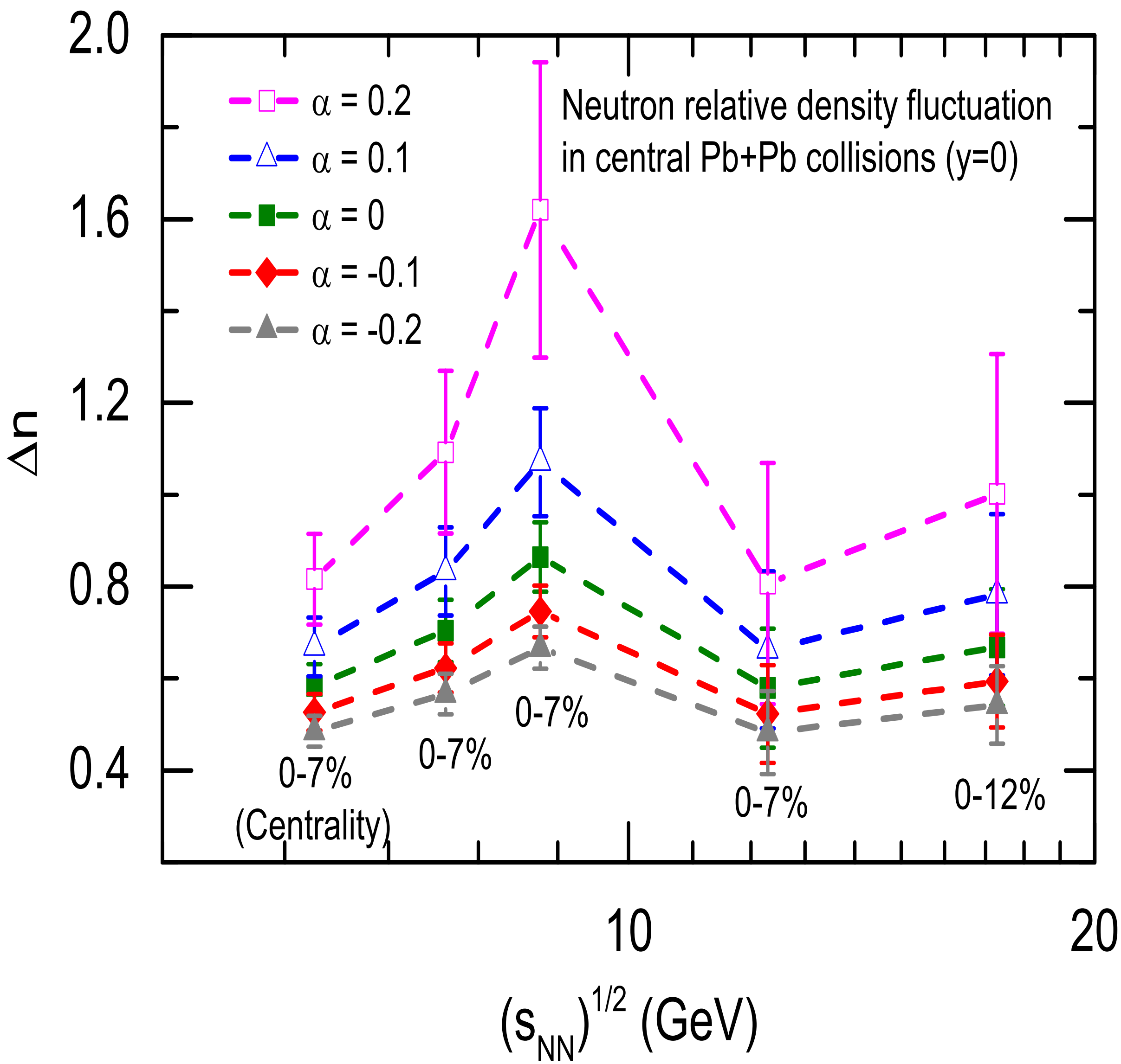
Sun, Ko & Lin, PRC 103, 064909 (2021); AMPT



Deng & Ma, PLB 808, 135668 (2020): UrQMD

Neutron relative density fluctuation from yield ratio of light nuclei

Sun, Chen, Ko & Xu, PLB 774, 103 (2017)



$$\mathcal{O}_{\text{p-d-t}} = \frac{N_{^3\mathrm{H}} N_p}{N_{\mathrm{d}}^2} = g\frac{1+(1+2\alpha)\Delta n}{(1+\alpha\Delta n)^2}$$

$$\Delta n = \frac{\langle(\delta n)^2\rangle}{\langle n\rangle^2}$$

$$\langle \delta n \delta n_p\rangle = \alpha\frac{\langle n_p\rangle}{\langle n\rangle}\langle(\delta n)^2\rangle$$

α: correlation factor

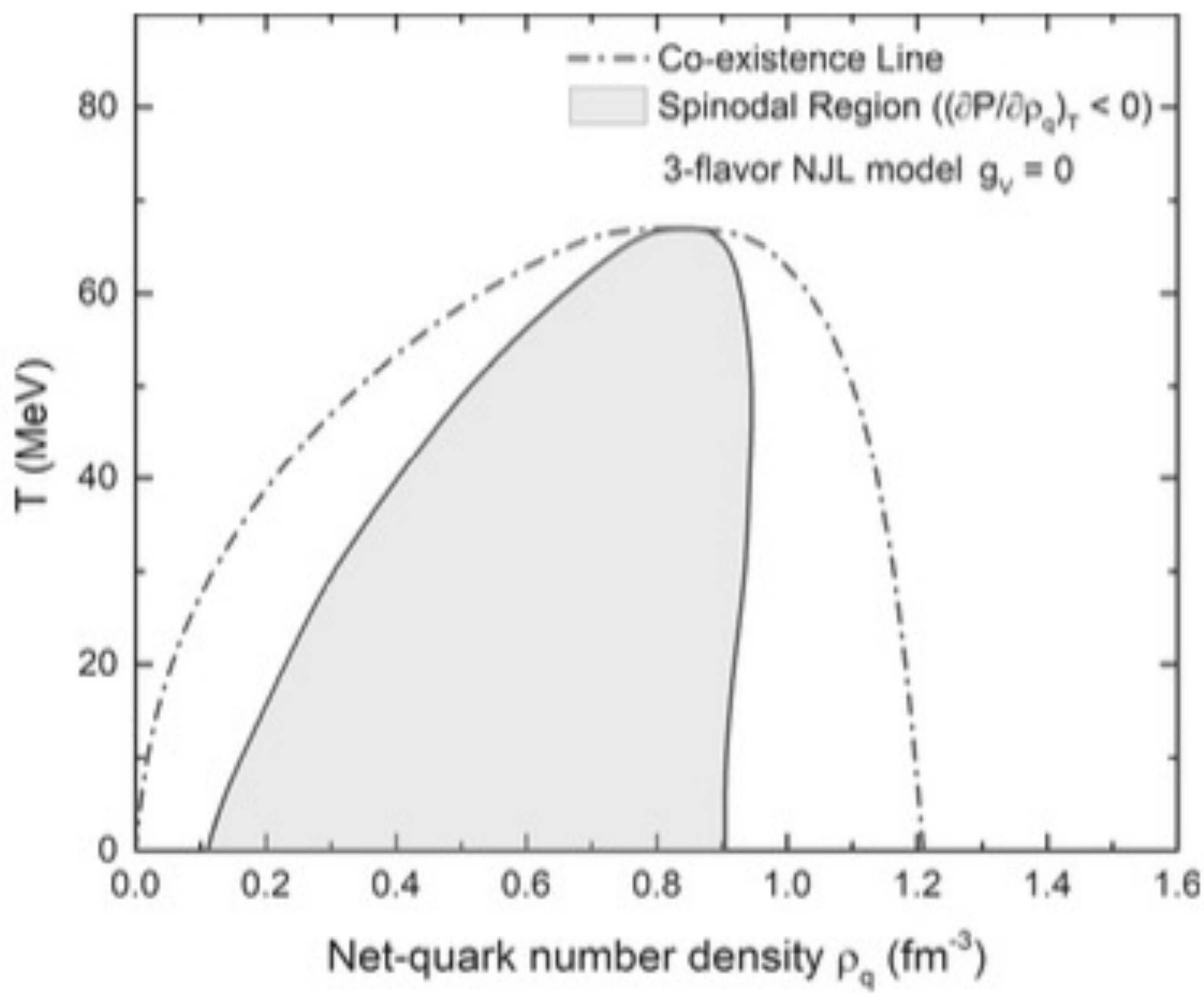
$T_C \approx 144$ MeV

$\mu_C \approx 385$ MeV

- Expect a similar behavior for $\frac{pK_0}{\pi^+\Lambda}$ from u-quark density fluctuation.

Quark matter phase diagram in the NJL model

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - \hat{m})\psi + G_S\sum_{a=0}^{8}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2]$$
$$-g_V(\bar{\psi}\gamma^\mu\psi)^2 - K[\det\bar{\psi}(1+\gamma_5)\psi + \det\bar{\psi}(1-\gamma_5)\psi]$$

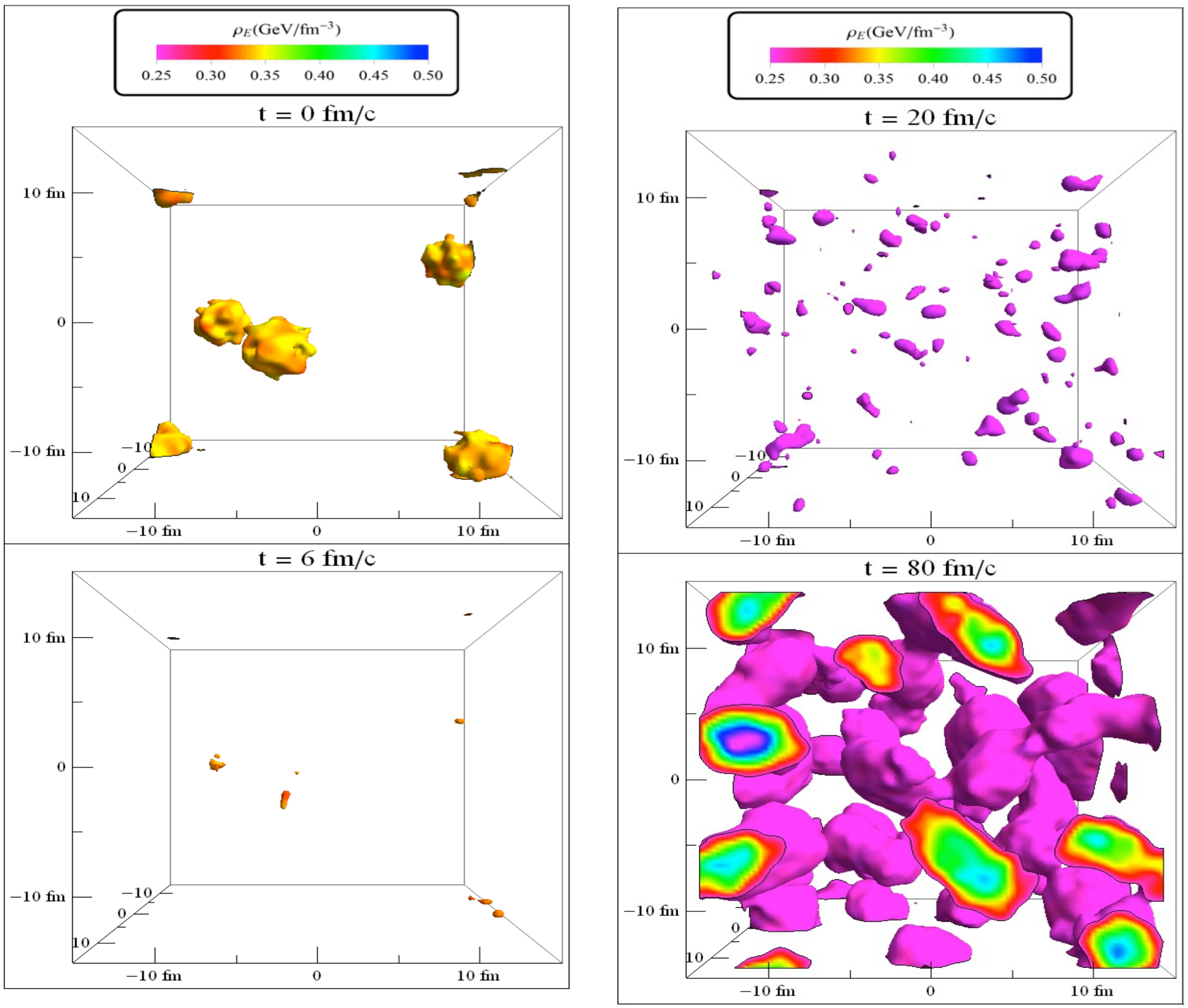


Transport description of quark matter in a box based on NJL

$$\partial_t f + \mathbf{p}/E \cdot \nabla f - \nabla H \cdot \nabla_p f = \mathcal{C}[f]$$

Feng & Ko, PRC 93, 035205 (16); 95, 055203 (17)

C[f] includes quark elastic scattering with cross section of 3 mb

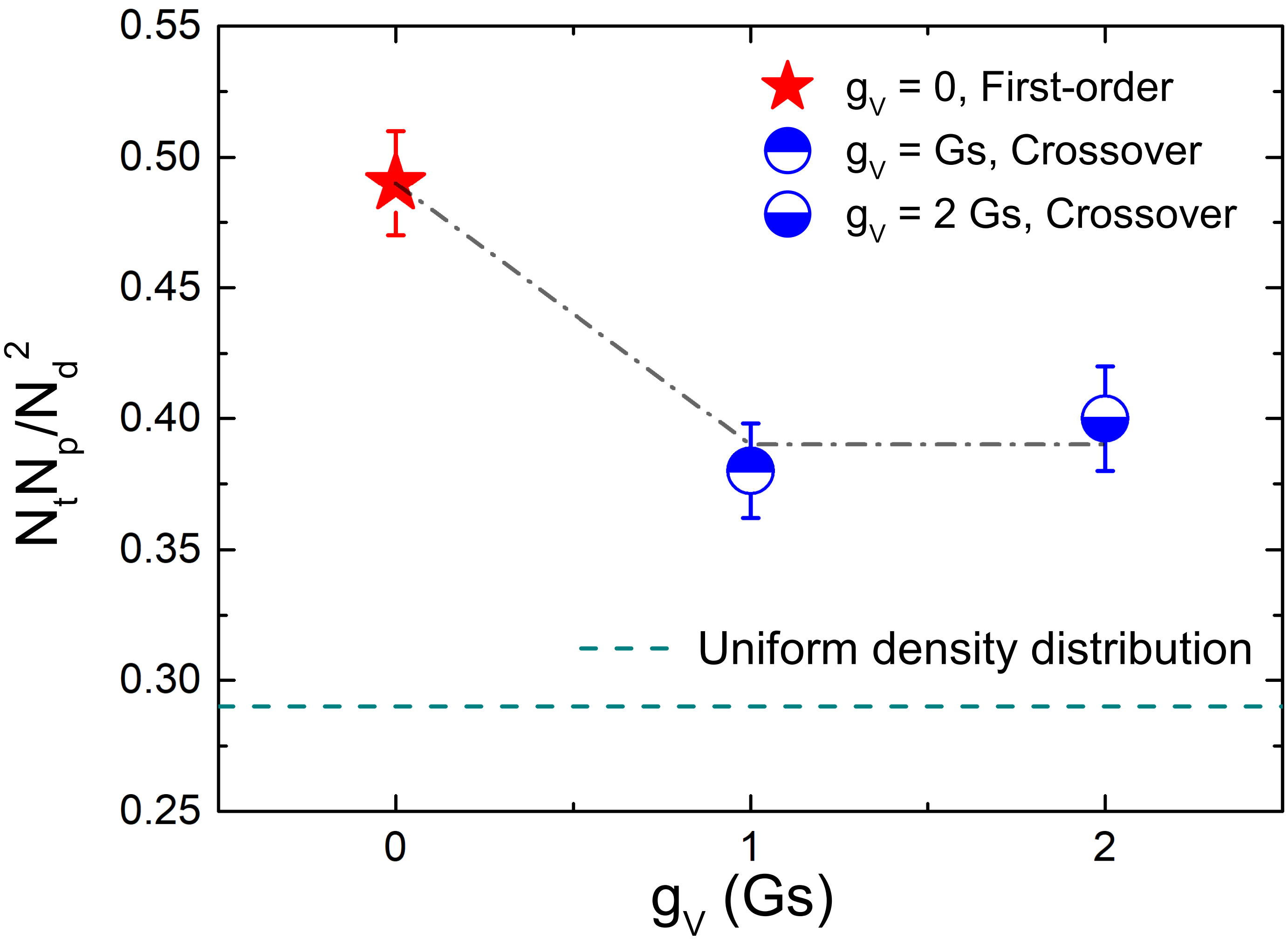


- Left: $n_q = 0.4/fm^3$, T = 100 MeV; outside spinodal region
- Right: $n_q = 0.4/fm^3$, T = 20 Mev, inside spinodal region; large density fluctuations appear due to growth of unstable modes
- Colored regions correspond to $N_q > 0.6/fm^3$

$N_t N_p / N_d^2$ Enhancement due to chiral first-order trasnsition

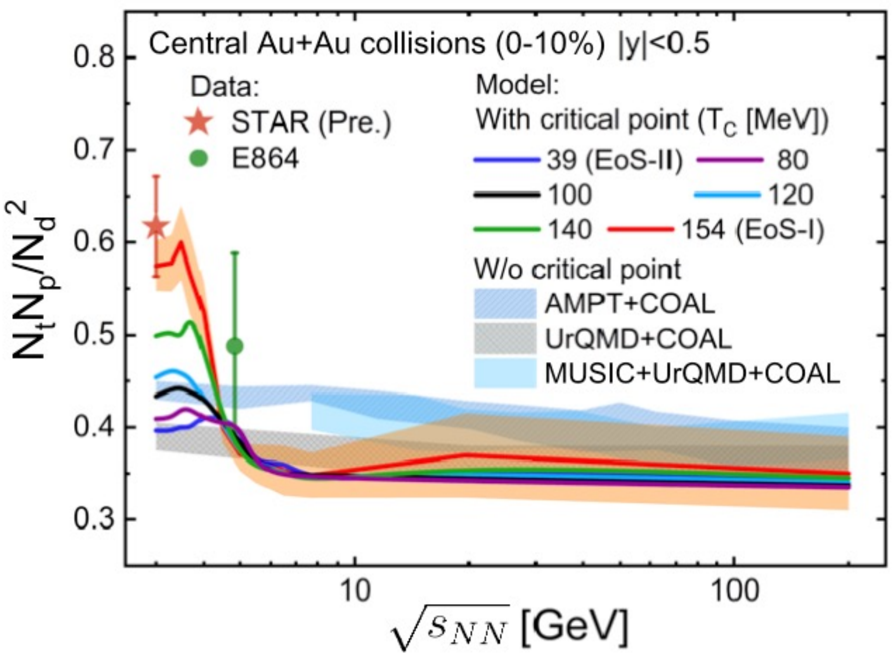
Sun, Ko, Li, Xu & Chen, EPJA 57, 31 (2021)

AMPT with blast-wave initial conditions with T= 70 MeV and net quark density 1.5/fm^3 and NJL based parton transport model

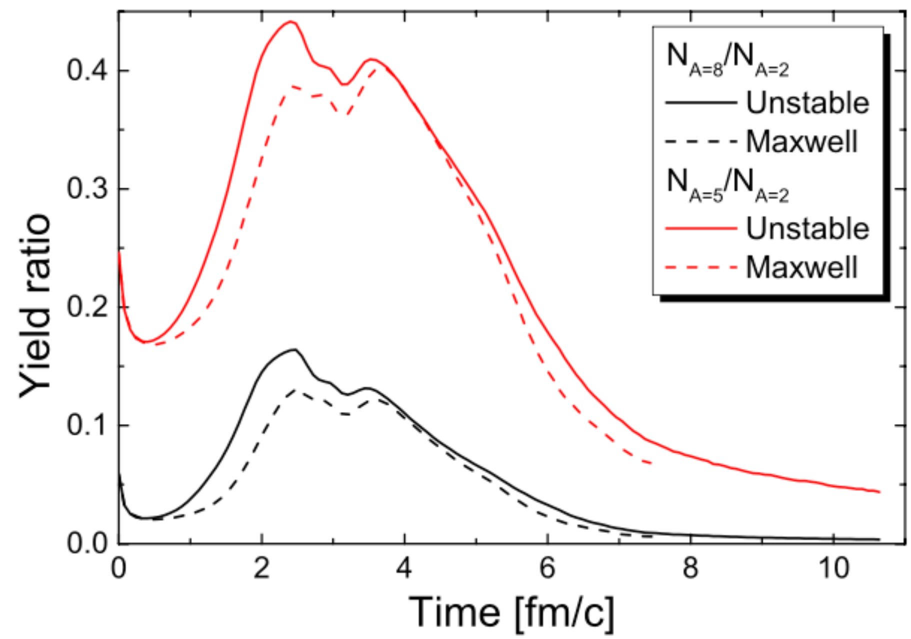


Conflicting results on light clusters due to spinodal instability

Sun et al., Nuclear Techniques 46, 040012 (2023)



Steinheimer et al., PRC 89, 034901 (2014)



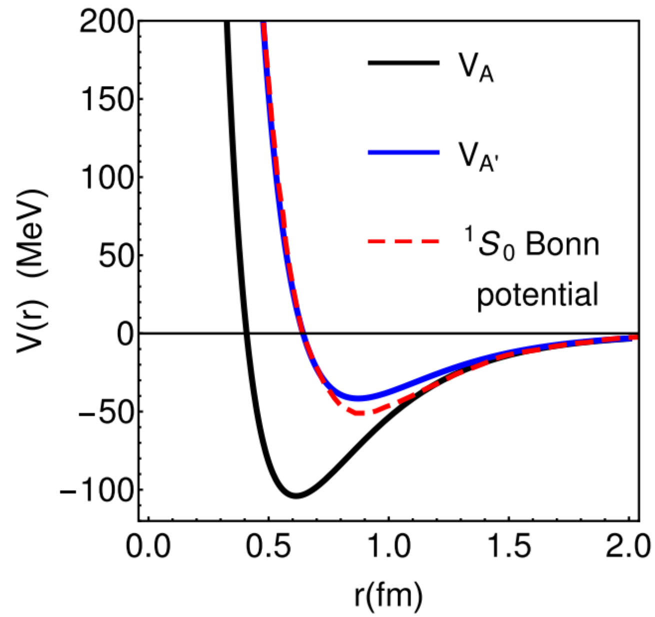
Clustering in the ^{4}He system and light nuclei production

Feed-down should be largest from ^{4}He.

6 NN interactions + small Fermi repulsion

~50 known excited states and resonances that decay to light nuclei

$$V(r) = -\alpha_\sigma \frac{e^{-m_\sigma r}}{r} + \alpha_\omega \frac{e^{-m_\omega r}}{r}$$



Shuryak and Torres-Rincon, *PRC* **100** (2019)

Binding energies are small but $|V| \gtrsim T_{kin}$ for t, ^{3}He, ^{4}He…

E (MeV)	J^P	Γ (MeV)	decay modes, in %
20.21	0^+	0.50	$p = 100$
21.01	0^-	0.84	$n = 24, p = 76$
21.84	2^-	2.01	$n = 37, p = 63$
23.33	2^-	5.01	$n = 47, p = 53$
23.64	1^-	6.20	$n = 45, p = 55$
24.25	1^-	6.10	$n = 47, p = 50, d = 3$
25.28	0^-	7.97	$n = 48, p = 52$
25.95	1^-	12.66	$n = 48, p = 52$
27.42	2^+	8.69	$n = 3, p = 3, d = 94$
28.31	1^+	9.89	$n = 47, p = 48, d = 5$
28.37	1^-	3.92	$n = 2, p = 2, d = 96$
28.39	2^-	8.75	$n = 0.2, p = 0.2, d = 99.6$
28.64	0^-	4.89	$d = 100$
28.67	2^+	3.78	$d = 100$
29.89	2^+	9.72	$n = 0.4, p = 0.4, d = 99.2$

Moderate spatial correlations should remain even at kinetic freezeout conditions → 4N preclusters.

Clustering is sensitive to modifications of the nuclear force, thus should be sensitive to effects of critical point.

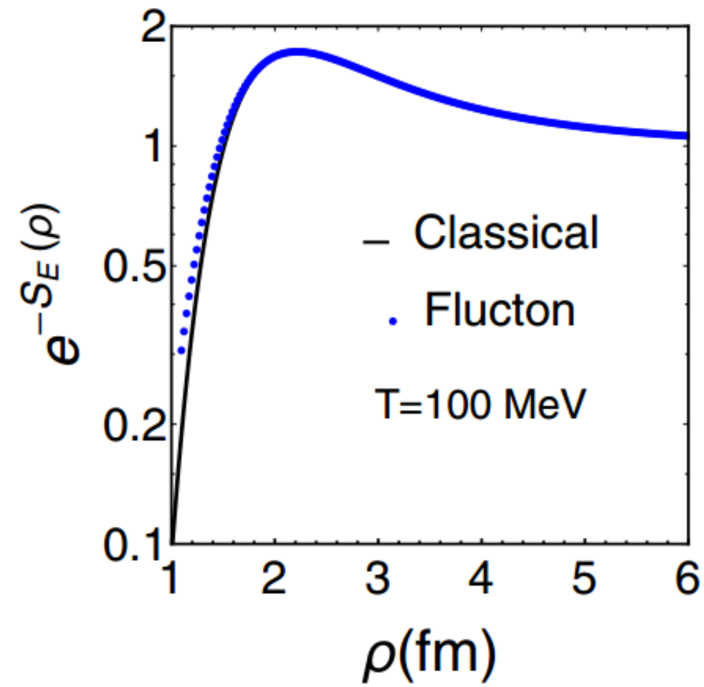
Correlations *do* remain at T ~ 100 MeV.

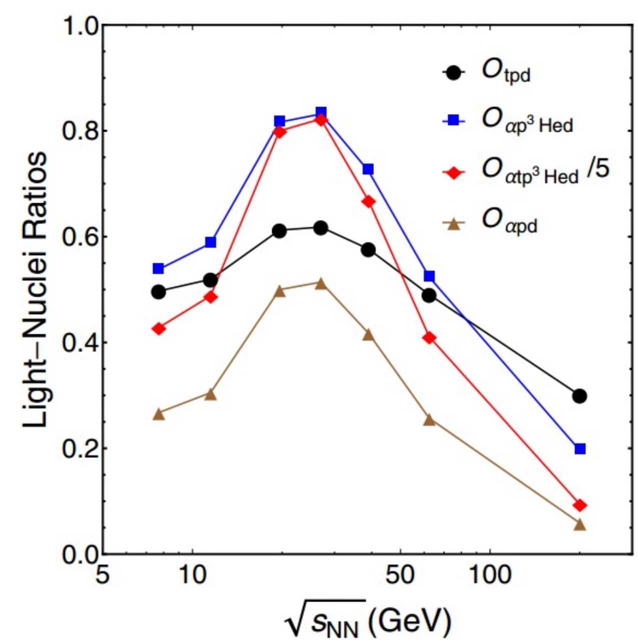
Subtract out the ground state contribution and long-range tail. The remaining "precluster" is assumed to statistically populate excited states and then decay.

Preclustering and feed-down more important at low $\sqrt{s_{NN}}$.

We see this in thermal models of light nuclei ratios at HADES. (See talk of Vovchenko at 3rd EMMI conference (2019))

Non-monotonic behavior of clustering requires a modification of the interaction.





Shuryak and Torres-Rincon, *PRC* **101** (2020)

Many-body forces and the critical σ mode

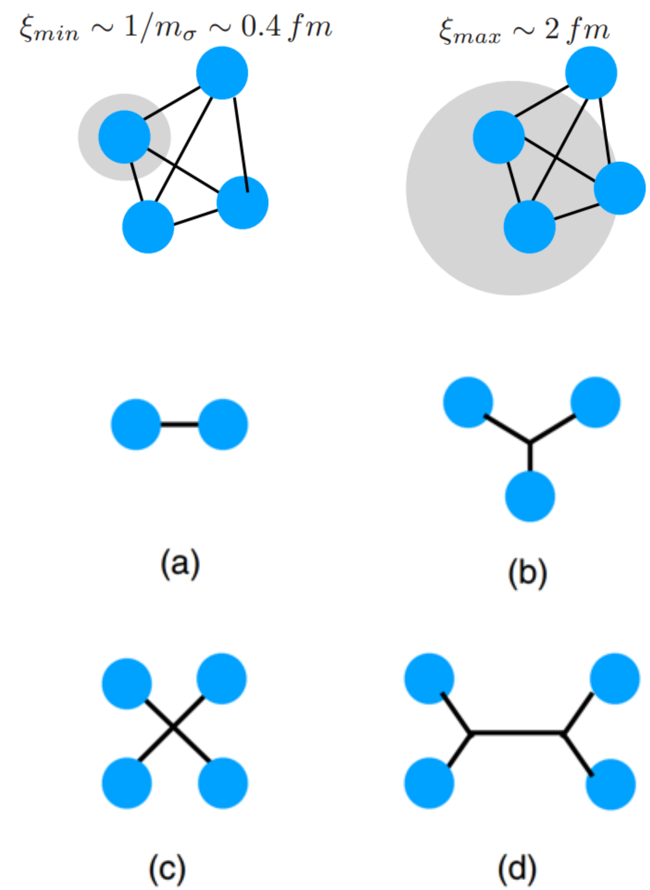
DD and Shuryak, *PRC* **104** (2021)

Quark-meson model predicts σ mass decreases to 285 MeV (Tripolt, Strodthoff, von Smekal, and Wambach, *PRD* **89** (2014))

For simple NN interaction, this leads to unrealistic results.

As ξ increases, critical fluctuations in the σ field induce 3-body and higher-order interactions.

These many-body forces are mostly repulsive and will prevent the 4N system from collapsing in on itself.



Consider a deformed effective potential in the 3D Ising model

$$m = \frac{1}{\xi} = Mt^{\nu}$$

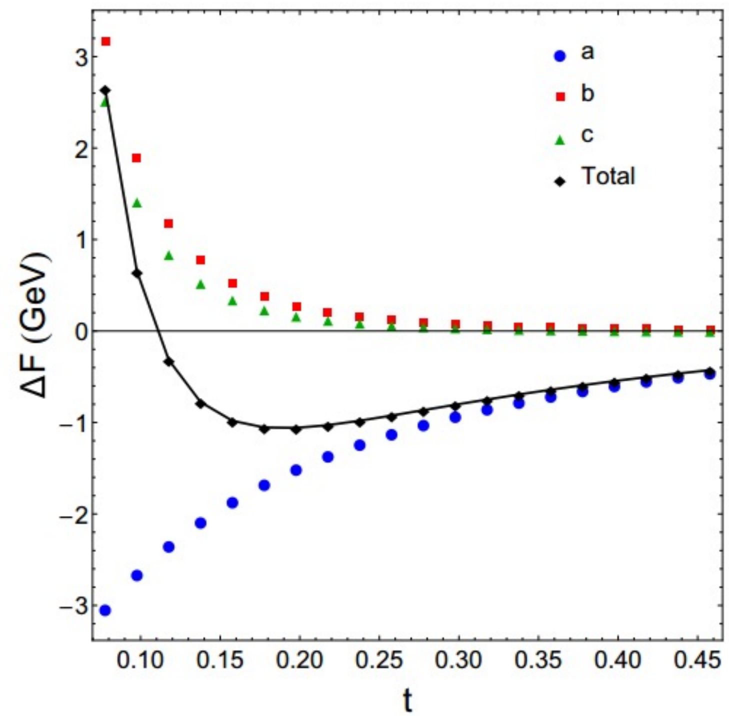
Start from the effective potential on the critical line and add a linear shift to some finite magnetization, calculate new deformed potential.

This gives us the correlation length and many-body coupling strengths.

Repulsive 3- and 4-body forces grow quickly near the critical point (t→0).

Very close to the critical point the forces become repulsive and could *suppress* clustering.

This is a qualitative sketch – The results are dependent on the mapping of the Ising variables onto the QCD phase diagram.



DD and Shuryak, *PRC* **104** (2021)

Summary

- More data, such as that from BES II with a larger statistics, are needed to confirm or disapprove the enhanced yield ratio $N_p N_t / N_d^2$ observed from BES I data at 19.6 and 27 GeV, which has a combined significance of 4.1 σ.
- Further theoretical studies are required to understand the conflicting conclusions from the studies by Sun et al. and Steinheimer et al. about the effects of hadronic scatterings on density fluctuations induced by the instability associated to a first-order phase transition.
- Can CP effects and modified forces be included in transport or hydrodynamic models? Do the effects persist until kinetic freezeout?
- Can we directly identify feed-down from excited ^{4}He states by looking for d+d or t+p resonances? Can we measure other light nuclei ratios that may be sensitive to the same effects?
- Only with both improved experimental data on light nuclei production in heavy ion collisions and theoretical modeling of these collisions can it be possible to see if the yield ratios of light nuclei can be used as a probe to the QCD phase diagram.