ATHIC2023

The 9th Asian Triangle Heavy-Ion Conference

QCD Phase Diagram and Extreme States

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Institute of Modern Physics
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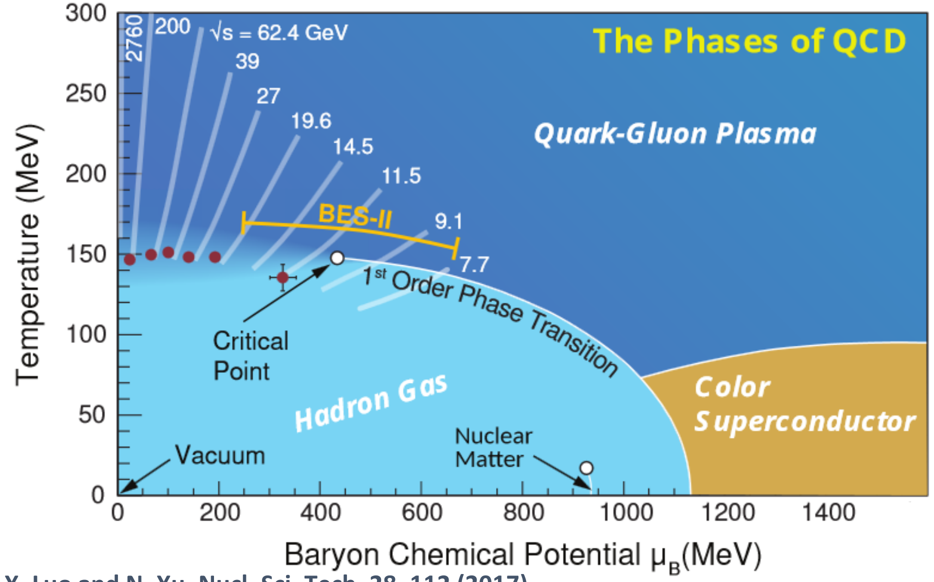
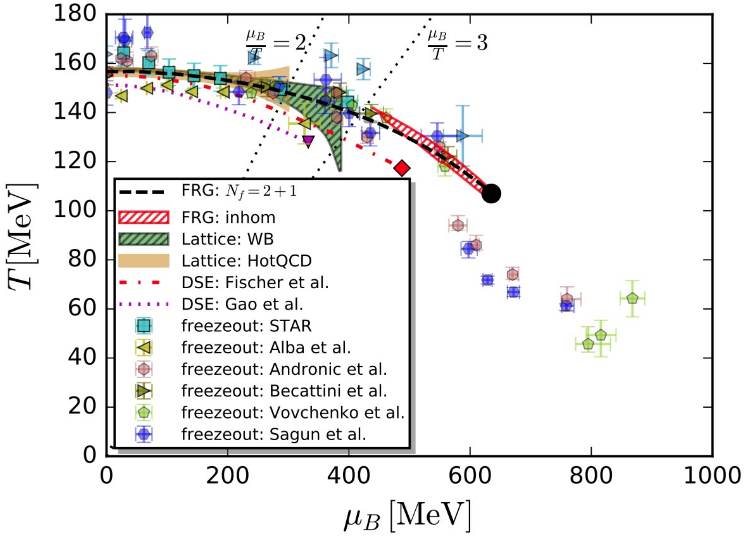
4/25/2023

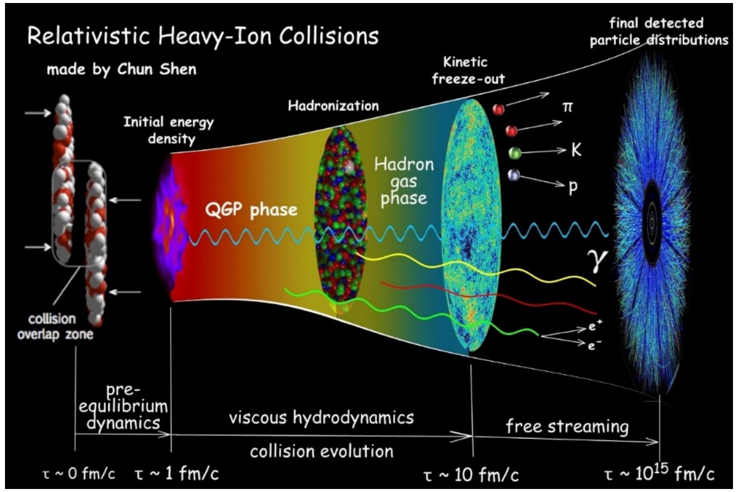
QCD phase diagram and extreme states in HICs (1)



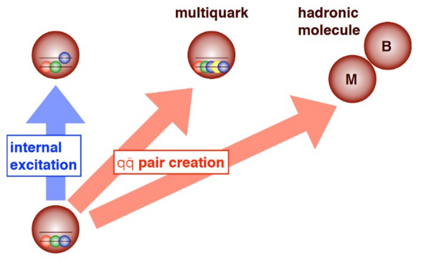
X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017)
A. Bzdak et al., Phys. Rept. 853, 1 (2020)

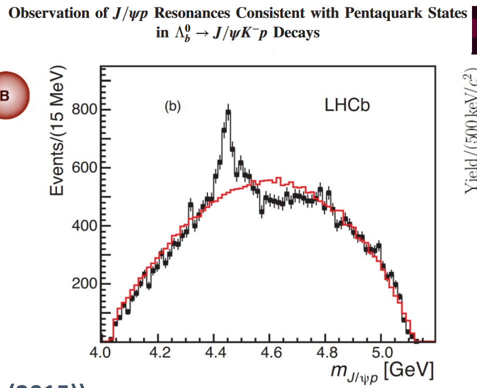


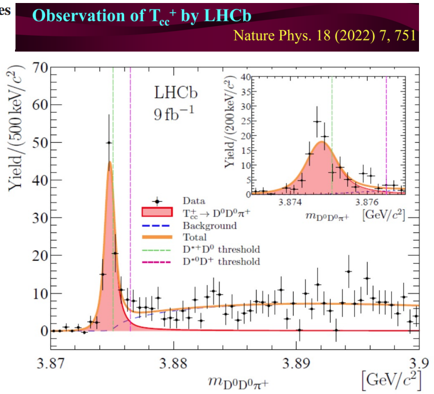
Y. Aoki et al., Nature 443, 675 (2006)
W. J. Fu, J. M. Pawlowski, F. Renneke, Phys. Rev. D101, 054032 (2020)



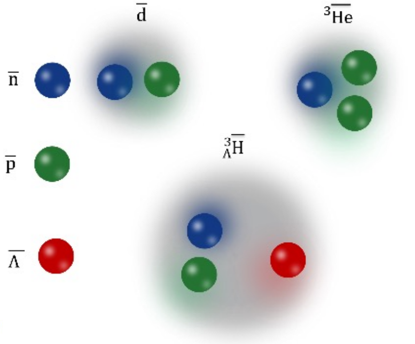
Extreme states







Multi-baryon States



LHCb (Phys. Rev. Lett. 115, 072001 (2015))
ExHIC Collaboration, Prog. Part. Nucl. Phys. 95, 279 (2017)
F. -K. Guo et al., Rev. Mod. Phys. 90, 015004 (2018)

STAR (Science 328, 58(2010); Nature 473,353(2011); Nat. Phys. 16 409(2020))
ALICE (Nat. Phys. 11,811(2015); 19, 61 (2023);Phys. Rev. Lett. 128, 252003 (2022))

Elementary states

p^+ n^0 Σ^- Σ^0 Σ^+ Σ^{++} Δ^- Δ^0 Δ^+ Δ^{++}

Λ^0 e^+ e^-

Ω^- Ω^0 Ω^+ π^+ π^0 π^-

Ξ^- Ξ^0 Ξ^+ Ξ^{++} τ^+ τ^-

ρ^+ ρ^0 ρ^-

μ^+ μ^- ω

η η' γ

ϕ

ν_e ν_μ ν_τ K^+ K^0 K^-

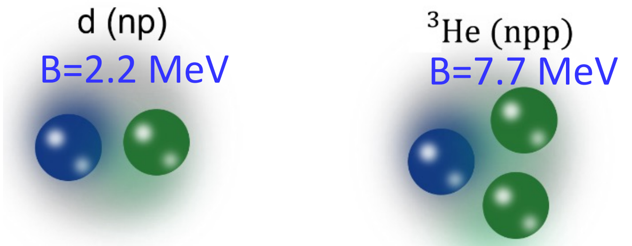
I. Production mechanism of extreme states (mainly on light (hyper)nuclei)

*Quantum corrections due to finite sizes
*Effects of post-hadronization dynamics

II. Probing QCD phase transitions with light nuclei production

*Transport approach to the first-order chiral phase transition
*Spinodal enhancement of light nuclei yield ratio

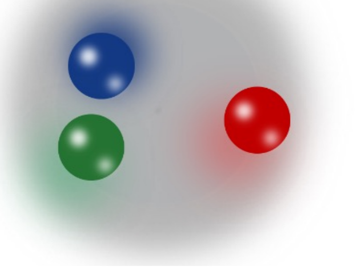
Light (anti)(hyper)nuclei in high-energy nucleus collisions (2)



$^3_\Lambda$H (npΛ)

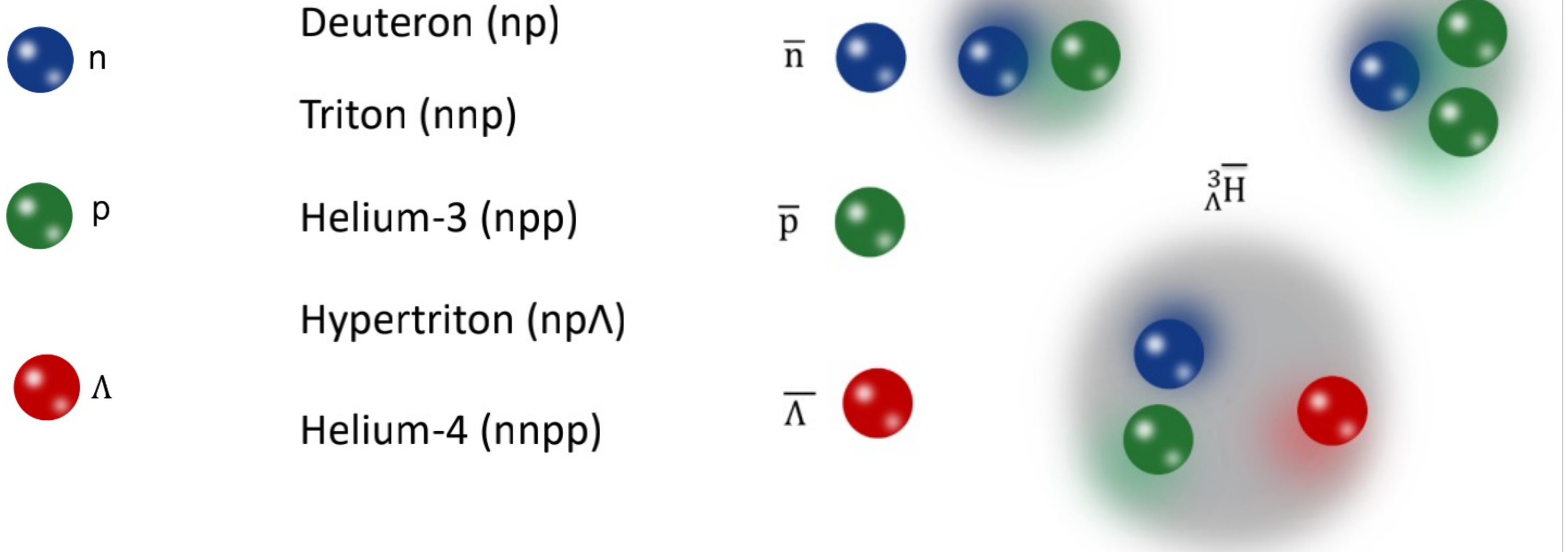
$B_{\Lambda d}$ ≈0.41 MeV **[STAR(Nat. Phys. 16 409(2020))]**

$B_{\Lambda d}$ ≈ 0.072 MeV **[ALICE(2209.07360)]**



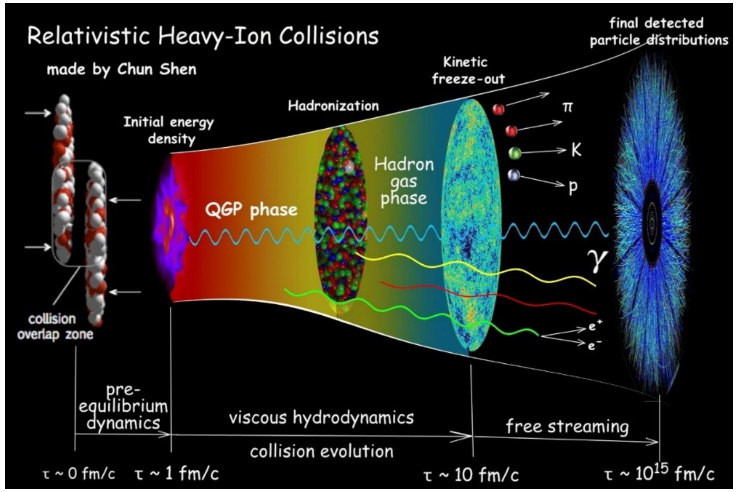
STAR (Science 328, 58(2010)).

See talk by Xiujun Li (for the STAR collaboration)



STAR (Nature 473,353(2011))

ALICE (PRC93,024917(2015))

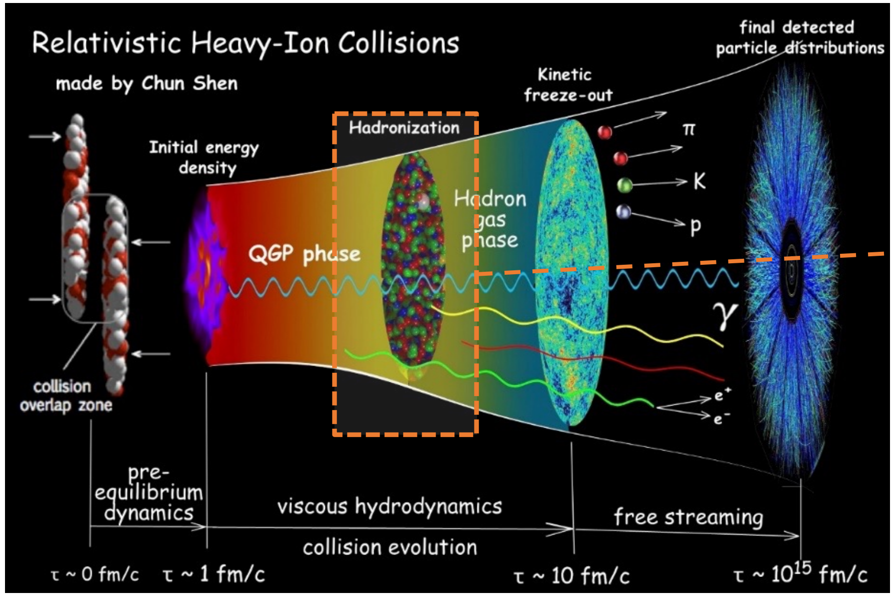


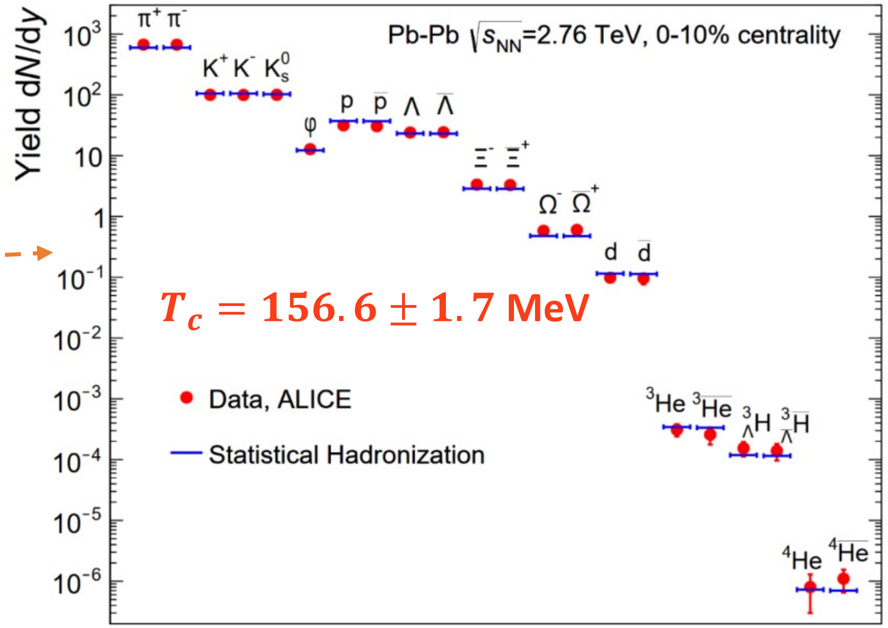
When? Where? How?

1. Statistical hadronization or final-state coalescence?
2. Does finite nuclear size play any role? ✓
3. Does post-hadronization dynamics have visible effects? ✓
4. Any medium effect?

Statistical hadronization (3)

Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561, 321 (2018)





$T_c = 156.6 \pm 1.7$ MeV

$$N_h \approx \frac{\gamma_h g_h V_C}{2\pi^2} m_h^2 T_C K_2\left(\frac{m_h}{T_C}\right)$$

$$\approx \gamma_h g_h V_C \left(\frac{m_h T_C}{2\pi}\right)^{3/2} e^{-m_h/T_C}$$

T_C: Chemical freeze-out temperature, which is close to the chiral transition temperature (LQCD)

γ_h : Fugacity

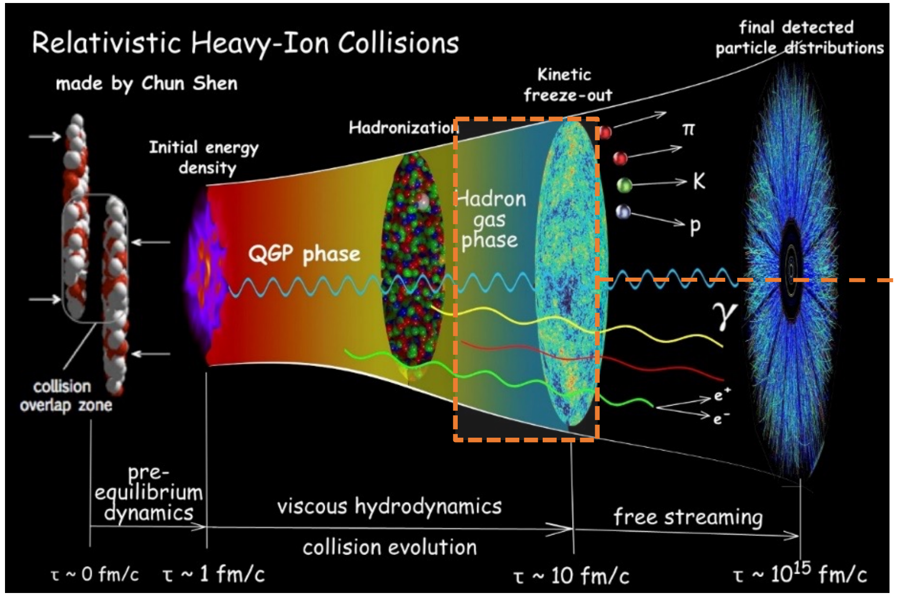
All (stable) particles including light (hyper)nuclei are produced at the QCD phase boundary and share a common chemical freeze-out

1. Rarely produced, suppressed by $e^{-m_A/T}$
2. Binding energies(E_B) << $\boldsymbol{T_c}$ (~150 MeV) << m_N (938MeV)
   The size $r \sim \frac{1}{\sqrt{4\mu E_B}}$, ($r_d$~2 fm, $r_{^3He}$~2 fm, $r_{^3_\Lambda H}$~5 fm)
3. Huge disintegration cross sections

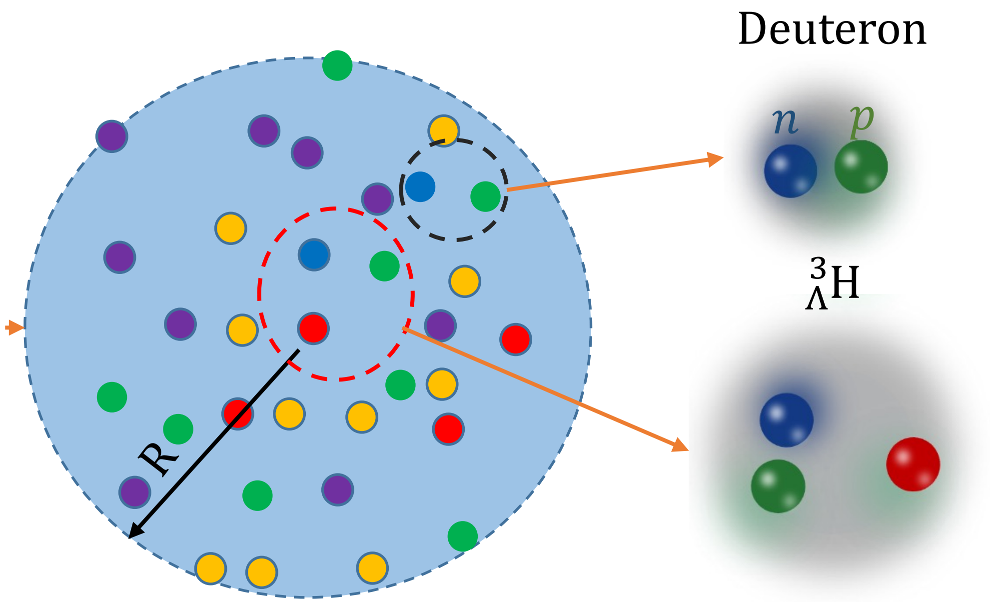
Final-state coalescence (4)

R. Scheibl and U. W. Heinz, PRC59. 1585(1999);

R. Scheibl and U. W. Heinz, PRC59. 1585(1999)



Coalescence Model



Density Matrix Formulation
(sudden approximation)

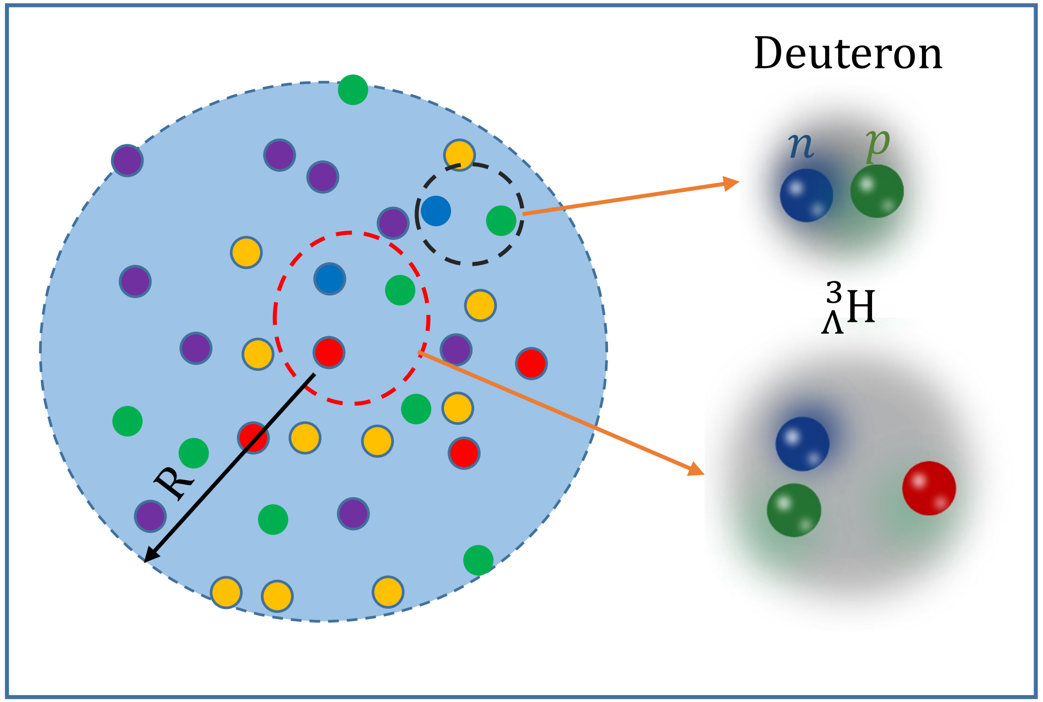
Wigner function of light cluster

$$N_A = Tr(\hat{\rho}_s \hat{\rho}_A)$$
$$= g_c \int d\Gamma\, \rho_s(\{x_i, p_i\}) \times W_A(\{x_i, p_i\})$$

Overlap between source distribution function and Wigner function of light nuclei

Quantum correction in collisions of small system (5)

Coalescence Model



Quantum mechanical correction due to finite nuclear sizes

e.g.

$$C_d \approx \int d^3r\, S(r) |\varphi_d(r)|^2$$

Source function

$$S(r) = e^{-r^2/4R^2}$$

Wavefunction

$$\varphi_d(r) = \frac{e^{-r^2/4\sigma^2}}{(2\pi\sigma^2)^{3/4}}$$

$$C_d \approx \frac{1}{[1 + \frac{\sigma^2}{2R^2}]^{\frac{3}{2}}}$$

$$N_d \propto \frac{1}{\left[1 + \left(\frac{2r_d^2}{3R^2}\right)\right]^{\frac{3}{2}}}$$

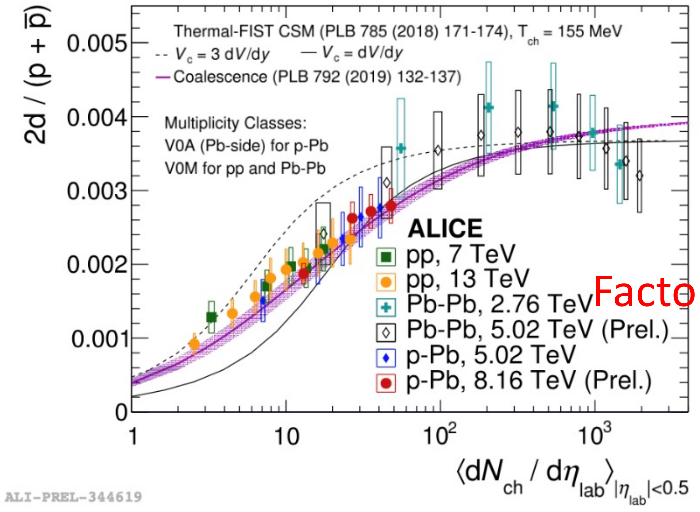
Production

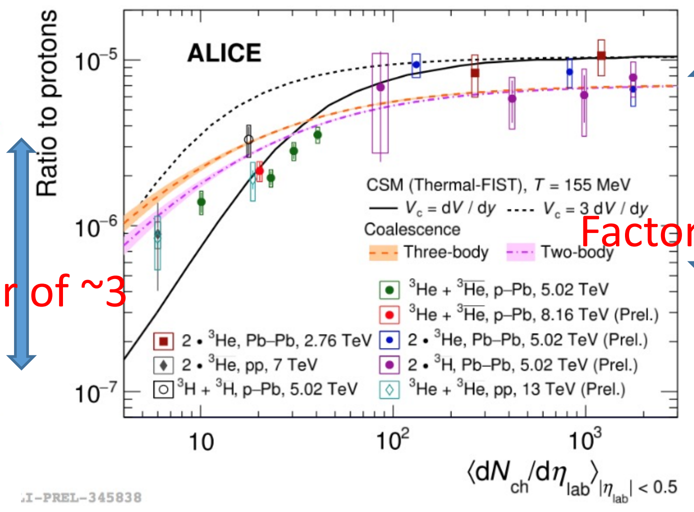
Structure

$$N_{^3_\Lambda\mathrm{H}} \propto \frac{1}{\left[1 + \left(\frac{r^2_{^3_\Lambda\mathrm{H}}}{2R^2}\right)\right]^{3}}$$

K. J. Sun, C. M. Ko, and B. Dönigus, Phys. Lett. B792, 132-137(2019)

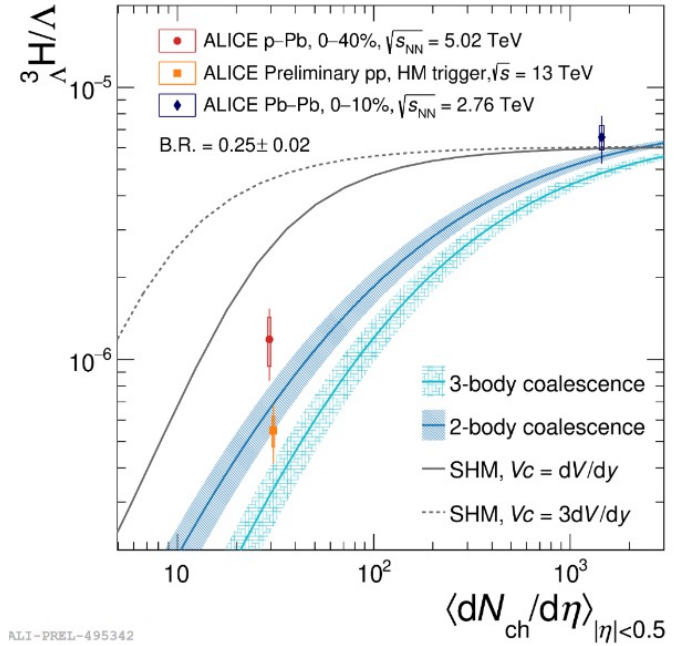
Recent results from ALICE/LHC (6)

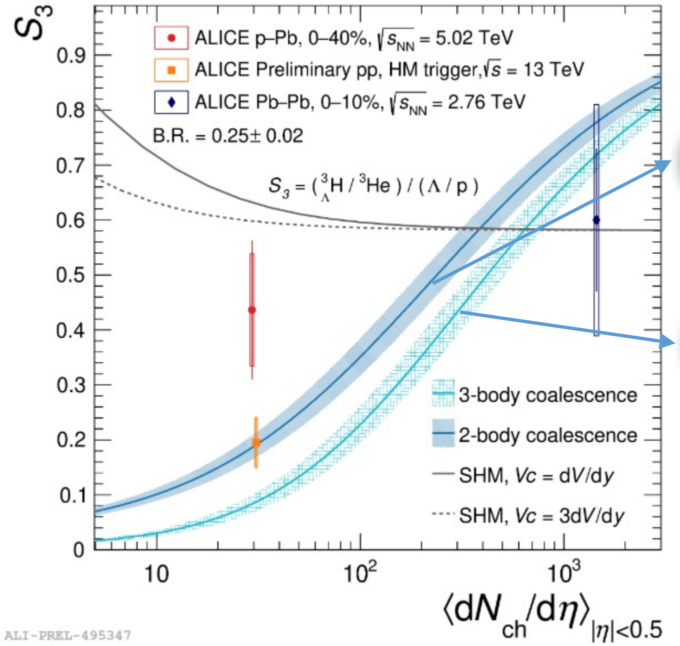




$$\frac{N_d}{N_p} \approx \frac{4.0\times10^{-3}}{\left[1+\frac{2r_d^2}{3R^2}\right]^{3/2}} \qquad \frac{N_{^3He}}{N_p} \approx \frac{7.1\times10^{-6}}{\left[1+\frac{r_{^3He}^2}{2R^2}\right]^{3}}$$

$$\frac{N_{^3_\Lambda H}}{N_\Lambda} \approx \frac{7.1\times10^{-6}}{\left[1+\frac{r_{^3_\Lambda H}^2}{2R^2}\right]^{3}}$$:3-body coal.





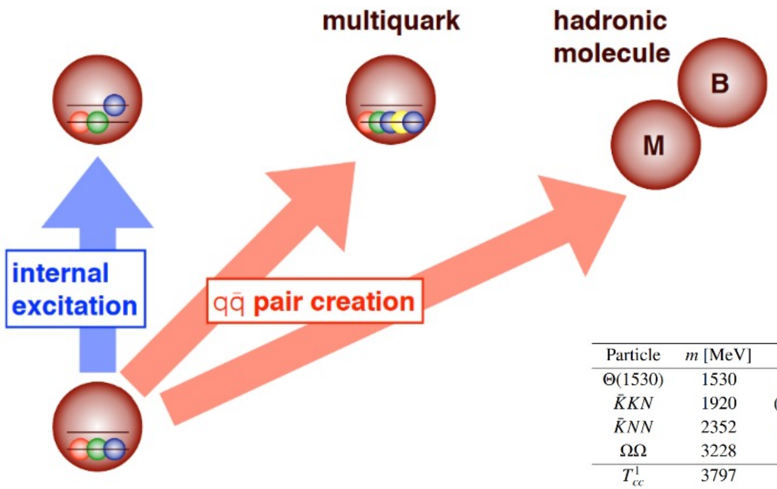
Huge suppression factors in collisions of small systems

Coal: Finite nuclei sizes
(better description on hypertriton production in p+p and p+Pb collisions)

CSM: Baryon number conservation

CSM: V. Vovchenko et al., PLB 785, 171 (2019), PRC 100,054906 (2019)
Coalescence: K. J. Sun, C. M. Ko and B. D ö nigus, Phys. Lett. B 792, 132 (2019)
L. Barioglio for ALICE Collaboration. PoS LHCP2021 (2021) 056;
ALICE, Phys. Rev. Lett. 128 (2022) 25, 252003

Probing internal structure of exotic states

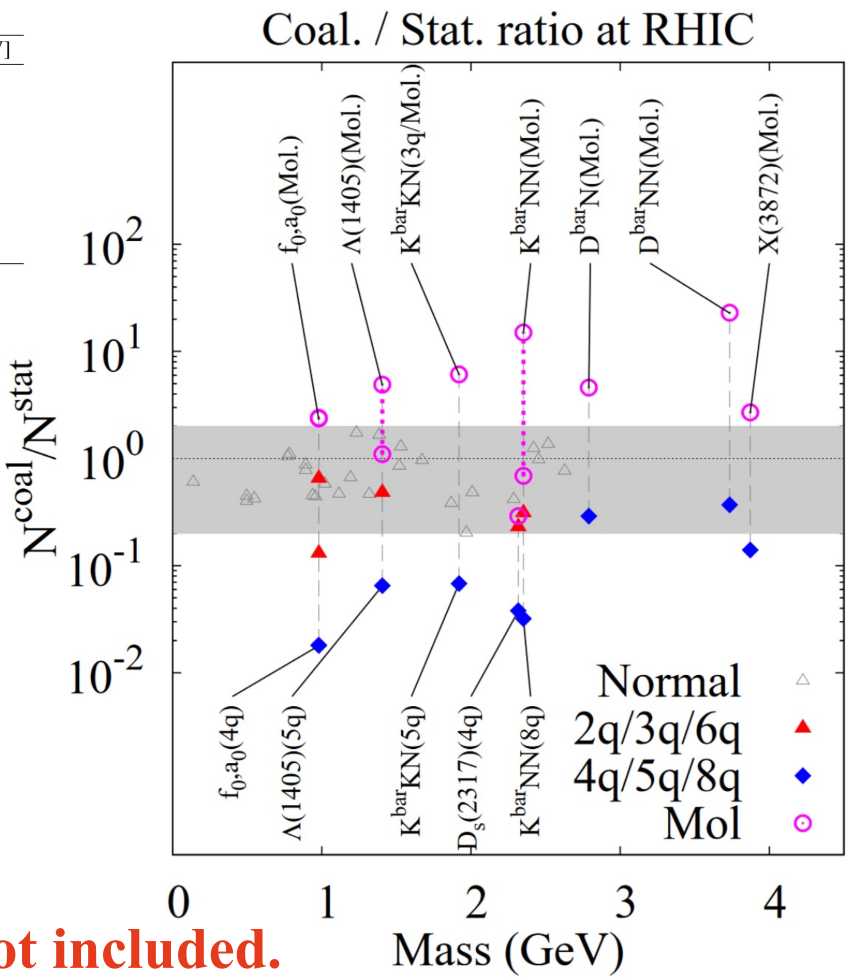


Particle	m [MeV]	(I, J^P)	$q\bar{q}/qqq$ (L)	multiquark	Mol. (L)	$\omega_{\rm Mol}$ [MeV]
$f_0(980)$	980	$(0, 0^+)$	$q\bar{q}$ (P) $(s\bar{s}$ $(P))$	$qs\bar{q}\bar{s}$	$\bar{K}K$ (S)	67.8(B)
$a_0(980)$	980	$(1, 0^+)$	$q\bar{q}$ (P)	$qs\bar{q}\bar{s}$	$\bar{K}K$ (S)	67.8(B)
$K(1460)$	1460	$(1/2, 0^-)$	—	$qq\bar{q}\bar{s}$ (P)	$\bar{K}KK$ (P)	69.0(R)
$\Lambda(1405)$	1405	$(0, 1/2^-)$	uds (P)	$udsq\bar{q}$	$\bar{K}N$ (S)	20.5(R)
$\Delta\Delta$	2380	$(0, 3^+)$	—	q^6	—	—
$\Lambda\Lambda$-$N\Xi$ (H)	2245	$(0, 0^+)$	—	$uuddss$	$N\Xi$ (S)	73.2(B)
$N\Omega$	2592	$(1/2, 2^+)$	—	$uudsss$	—	—

Particle	m [MeV]	(I, J^P)	$q\bar{q}/qqq$	multiquark (L)	Mol. (L)	$\omega_{\rm Mol}$ [MeV]	Ref.
$\Theta(1530)$	1530	$(0, 1/2^+)$	—	$qqqq\bar{s}$ (P)	—	—	[175]
$\bar{K}KN$	1920	$(1/2, 1/2^+)$	—	$qqqs\bar{s}$ (P)	$\bar{K}KN$	42(R)	[176]
$\bar{K}NN$	2352	$(1/2, 0^-)$	q^5s (P)	$q^6s\bar{q}$ (S)	$\bar{K}NN$	20.5(T)	[177]
$\Omega\Omega$	3228	$(0, 0^+)$	—	s^6	—	—	[178]
T^1_{cc}	3797	$(0, 1^+)$	—	$ud\bar{c}\bar{c}$	—	—	[179]
$\bar{D}N$	2790	$(0, 1/2^-)$	—	$qqqq\bar{c}$	$\bar{D}N$	6.48(R)	[180]
$\bar{D}^*N$	2919	$(0, 3/2^-)$	—	$qqqq\bar{c}(D)$	$\bar{D}^*N$	6.48(R)	[181]
Θ_{cs}	2980	$(1/2, 1/2^+)$	—	$qqqs\bar{c}$ (P)	—	—	[182, 183]
H_c^{++}	3377	$(1, 0^+)$	—	$qqqqsc$	—	—	[184]
$\bar{D}NN$	3734	$(1/2, 0^-)$	—	$q^7\bar{c}$	$\bar{D}NN$	6.48(T)	[185]
Λ_cN	3225	$(1/2, 1^+)$	—	$cuduud$	Λ_cN	4.24(R)	[174]
Λ_cNN	4164	$(0, 3/2^+)$	—	$cuduududd$	Λ_cNN	33.16(R)	[174]
T^0_{cb}	7123	$(0, 0^+)$	—	$ud\bar{c}\bar{b}$	—	—	[184]

Particle	m [MeV]	(I, J^P)	$q\bar{q}/qqq$ (L)	multiquark	Mol. (L)	$\omega_{\rm Mol}$ [MeV]
$D_s(2317)$	2317	$(0, 0^+)$	$c\bar{s}$ (P)	$c\bar{s}q\bar{q}$	DK (S)	273(B)
$X(3872)$	3872	$(0, 1^+)$	$c\bar{c}$ (P)	$c\bar{c}q\bar{q}$	$D\bar{D}^*$ (S)	3.6(B)
$Z_c(3900)$	3900	$(1, 1^+)$	—	$c\bar{c}u\bar{d}$	—	—
$Z_c(4430)$	4430	$(1, 1^+)$	—	$c\bar{c}u\bar{d}$	$D_1\bar{D}^*$ (S)	13.5(B)
$Z_b(10610)$	10610	$(1, 1^+)$	—	$b\bar{b}u\bar{d}$	—	—
$Z_b(10650)$	10650	$(1, 1^+)$	—	$b\bar{b}u\bar{d}$	—	—
$X(5568)$	5568	$(1, 0^+)$	—	$s\bar{b}u\bar{d}$	—	—
$P_c(4380)$	4380	$(1/2, 3/2^-)^b$	—	$c\bar{c}uud$ (S)	$\bar{D}\Sigma_c^*$ (S)	60(B)
$P_c(4450)$	4450	$(1/2, 5/2^+)^b$	—	$c\bar{c}uud$ (P)	—	—

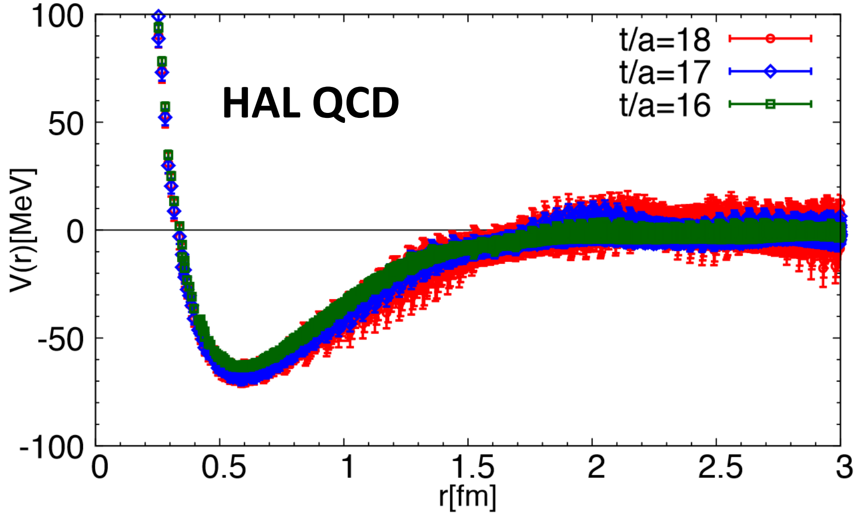
See talk by Hyeongock Yun



But, size effects were not included.

S. Cho et al., (ExHIC Collaboration), Phys. Rev. Lett. 106, 212001 (2011)
Kai-Jia Sun and Lie-Wen Chen, Phys. Rev. C 95, 044905 (2017)
ExHIC Collaboration, Prog. Part. Nucl. Phys. 95, 279 (2017)
F. -K. Guo, C. Hanhart, U. Meibner, Q. Zhao, B. -S. Zhou, Rev. Mod. Phys. 90, 015004 (2018)

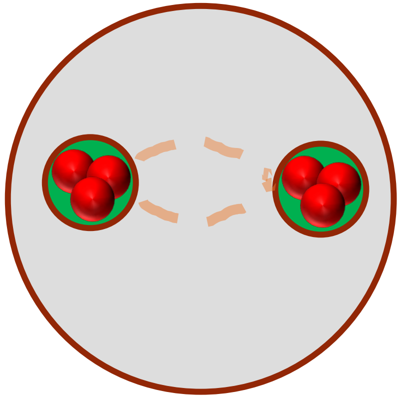
Molecular state or multi-quark state?



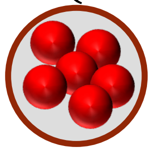
$$a_0^{(\Omega\Omega)} = 4.6(6)\left(^{+1.2}_{-0.5}\right) \quad \text{fm},$$
$$r_{\text{eff}}^{(\Omega\Omega)} = 1.27(3)\left(^{+0.06}_{-0.03}\right) \quad \text{fm}.$$

$$B_{\Omega\Omega}^{(\text{QCD})} = 1.6(6)\left(^{+0.7}_{-0.6}\right) \quad \text{MeV}$$

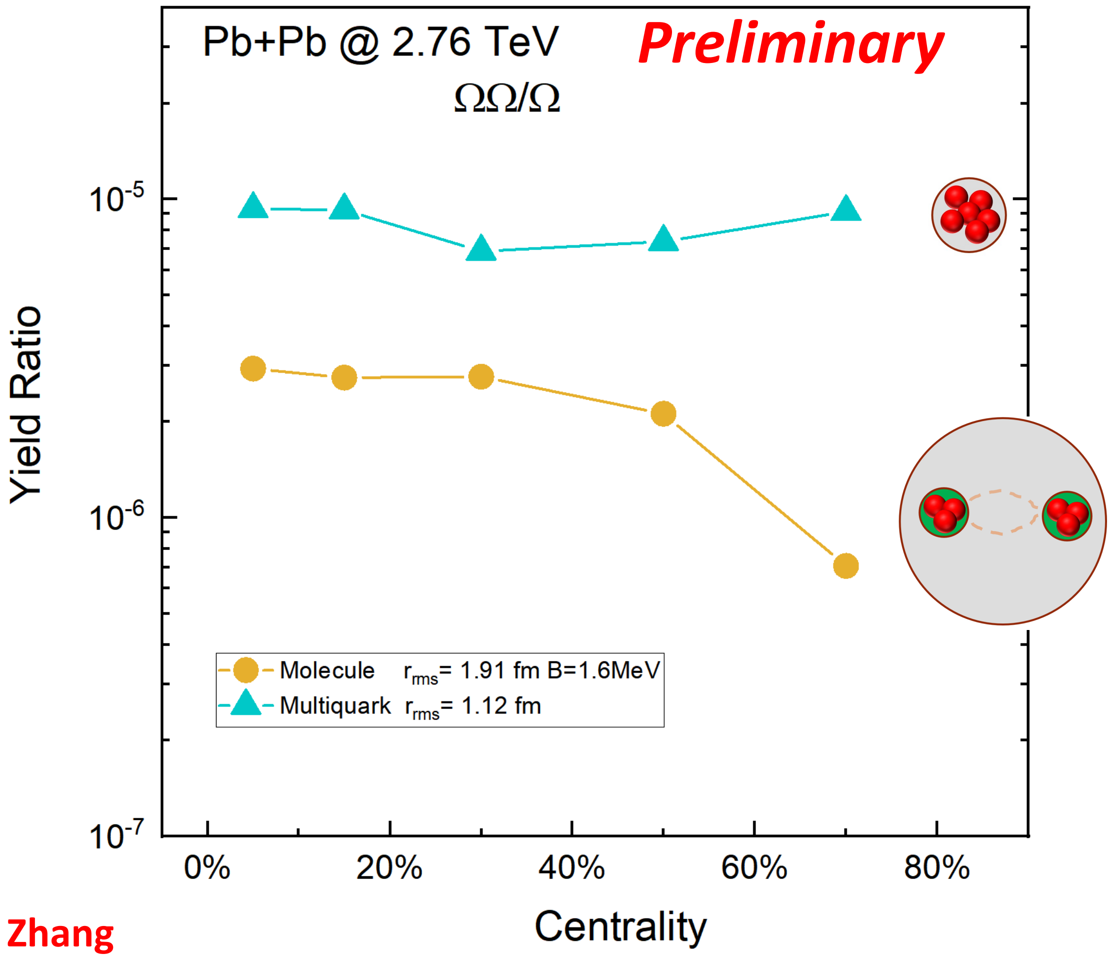
$\Omega - \Omega$



$\Omega\Omega(ssssss)$



See talk by Liang Zhang (NΩΩ)

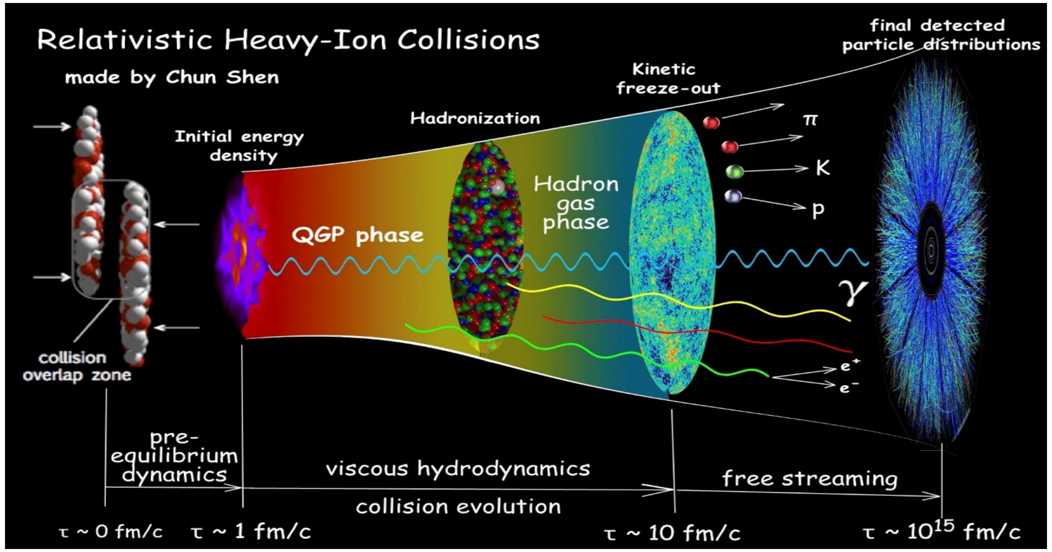


Different centrality dependence for the loosely-bound molecular state and the compact multi-quark state

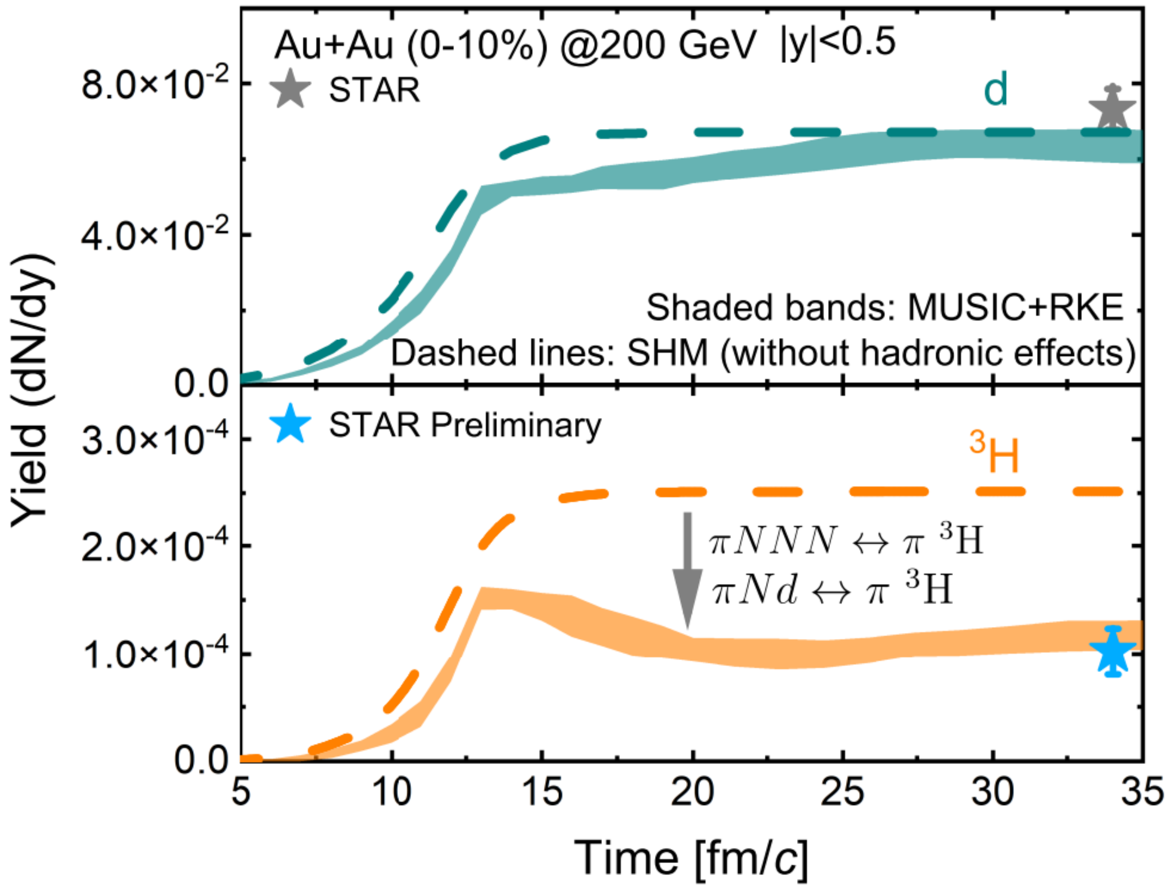
S. Gongyo et al., (HAL QCD Collaboration), Phys. Rev. Lett. 120, 212001 (2018)
S. Zhang and Y. G. Ma, Phy. Lett. B 811,135867 (2020)

Jie Pu, Kai-Jia Sun, Lie-Wen Chen, in preparation

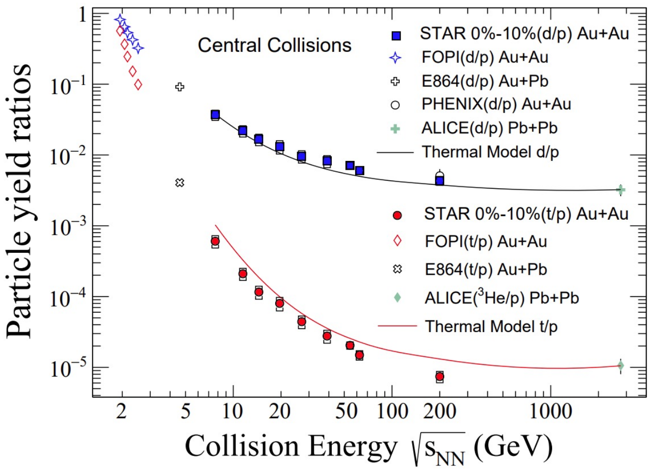
Effects of post-hadronization dynamics

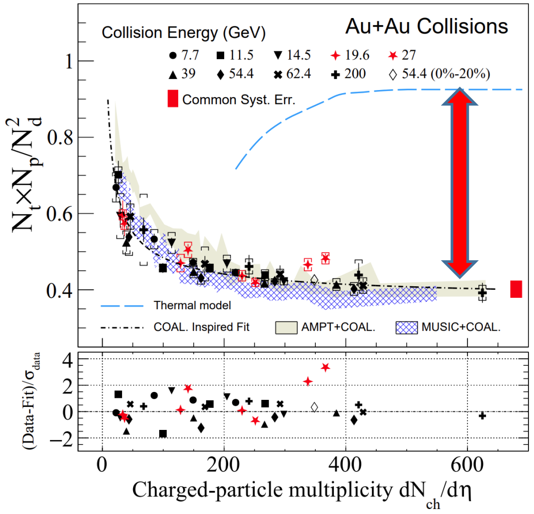


K. J. Sun et al., arXiv:2207.12532(2022)



STAR: arXiv:2209.08058(2022)





Triton yields are reduced by about a factor of 2 due to hadronic re-scatterings.

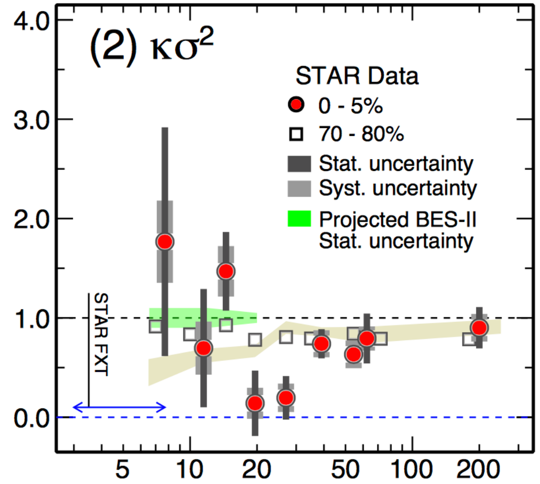
Post-hadronization dynamics have visible effects!

II. Probing QCD Phase Transitions with Light Nuclei Production

*Effects of a first-order chiral phase transition
*Spinodal enhancement of light nuclei yield ratio

Observables

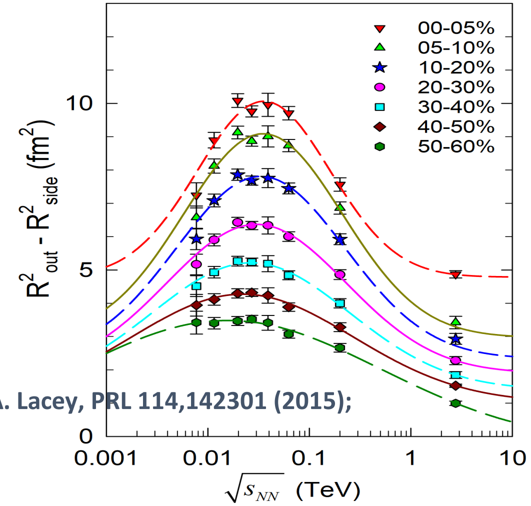
1. Event-by-event fluctuations



$$\frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \sim \xi^5$$

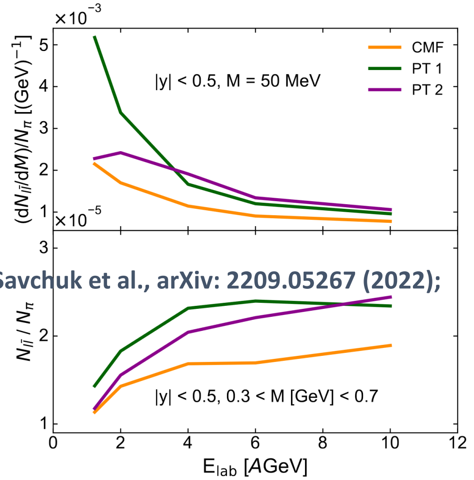
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
X. F. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017)
STAR, arXiv:2001.02852(2020)

2. HBT correlations



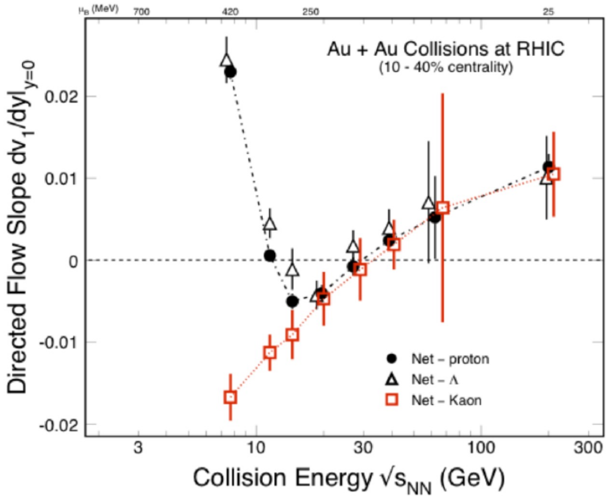
R. A. Lacey, PRL 114,142301 (2015);

3. Di-lepton yields



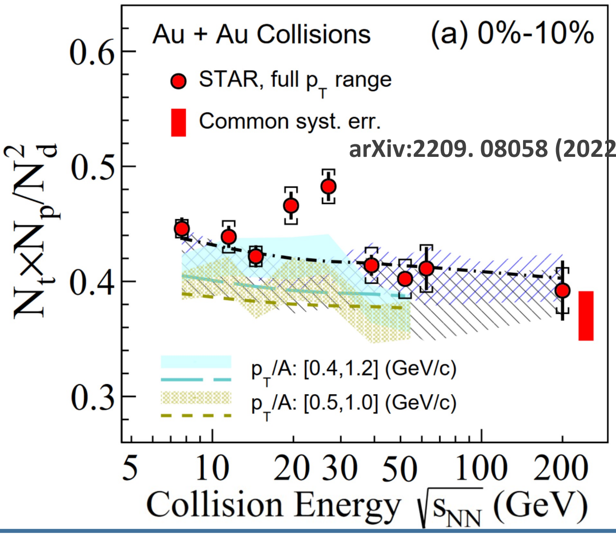
O. Savchuk et al., arXiv: 2209.05267 (2022);

4. Direct flow



STAR, PRL 112, 162301 (2014); PRL120, 062301(2018)
Y. Nara et al., Phys.Rev.C 94 (2016) 3, 034906

5. Light nuclei production



arXiv:2209. 08058 (2022)

$$\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}\left[1 + \Delta\rho_n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right)\right]$$

K. J. Sun, L. W. Chen, C. M. Ko, and Z. Xu, Phys. Lett. B 774, 103 (2017);
K. J. Sun, F. Li, and C. M. Ko, Phys. Lett. B 816, 136258 (2021);
E. Shuryak, J.M.Torres-Rincon et al., PRC 100, 024903(2019)

Intermittency

Z. Li, Mod. Phys. Lett. A 37 (2022) 13, 2230009

Jet Quenching

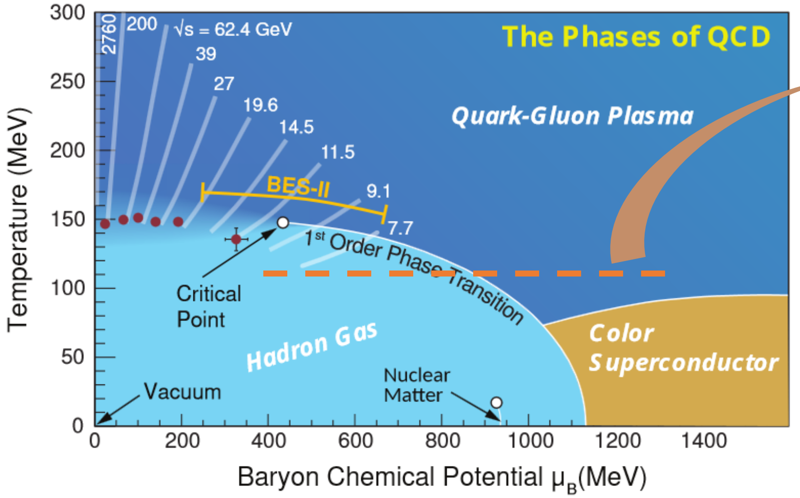
J. Wu, S. Cao, and F. Li, arXiv:2208.14297(2022)

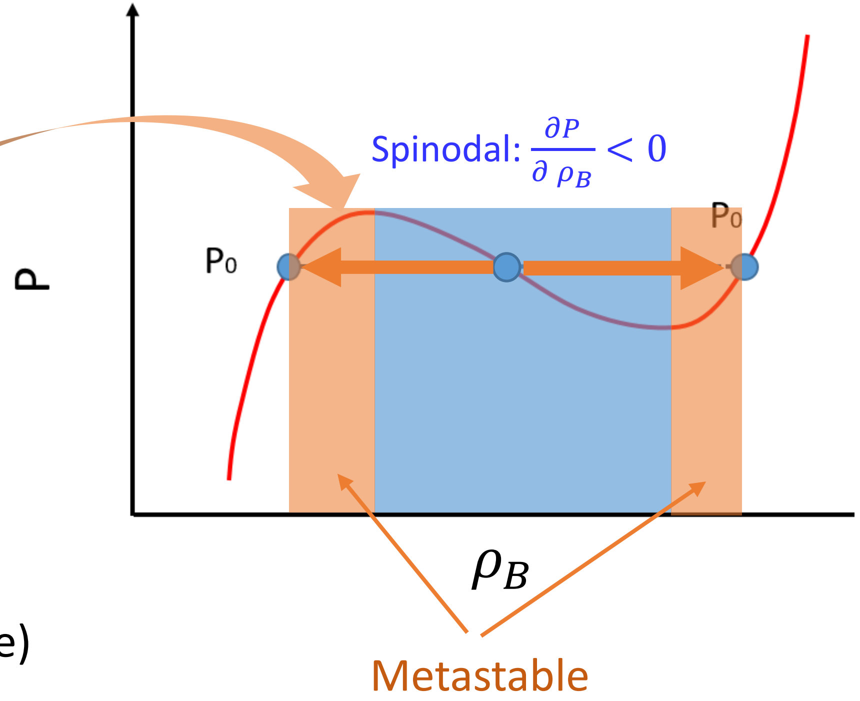
And many more…

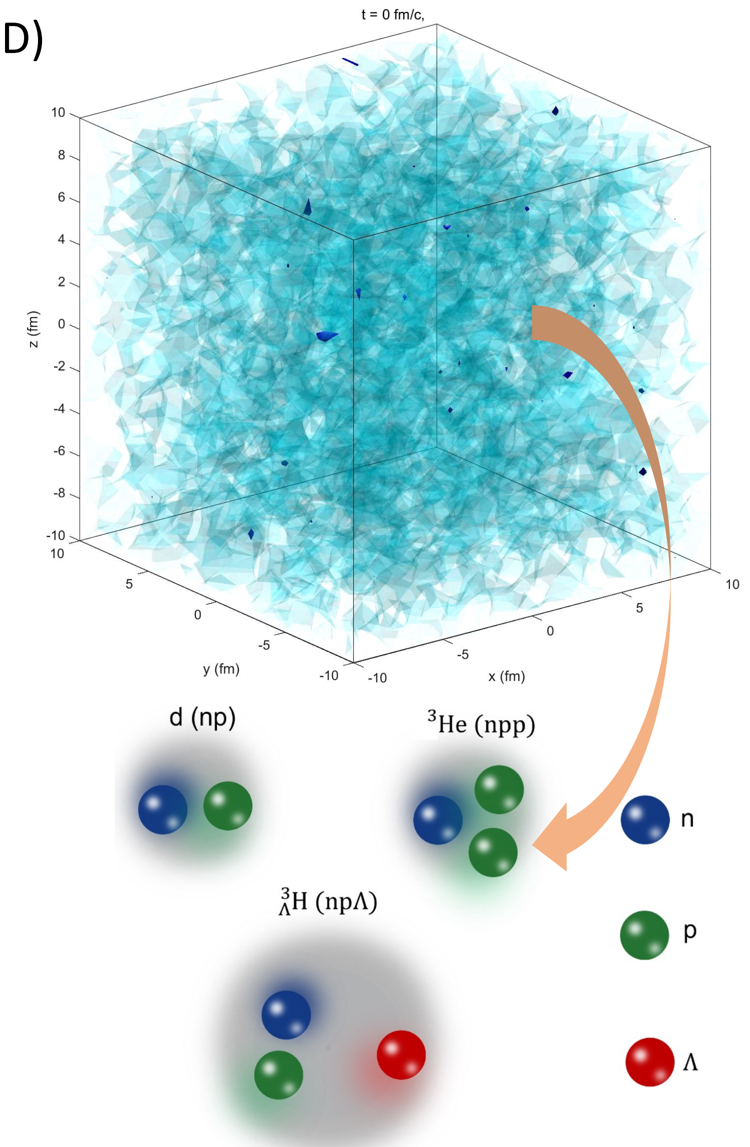
Light Nuclei Production & QCD Phase Transition (11)

P. Chomaz, M. Clonna, and J. Randrup, Phys. Rep. 389, 263 (2004)

Phase separation, spinodal decomposition(SD)







Density matrix formulation (coalescence)

$N_d \propto < d|\hat{\rho}_s|d > \quad N_t \propto < t|\hat{\rho}_s|t >$

$$\Rightarrow \quad \frac{N_t N_p}{N_d^2} \propto \Delta\rho_n \qquad \Delta\rho_n = \frac{\int d\mathbf{x}(\delta\rho(\mathbf{x}))^2}{\int d\mathbf{x}\rho_0^2}$$

characterizes density inhomogeneity

Long-range Corr. $\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}[1 + \Delta\rho_n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right)]$ $\quad G(z) = \sqrt{\frac{2}{\pi}} - \frac{1}{z} e^{\frac{1}{2z^2}} \mathrm{erfc}(\frac{1}{\sqrt{2}z})$

K. J. Sun, L. W. Chen, C. M. Ko, and Z. Xu, Phys. Lett. B 774, 103 (2017); K. J. Sun, C. M. Ko, and F. Li, PLB 816, 136258 (2021)

QCD phase transition & light nuclei production

light nuclei production & QCD phase transition

2012 2014 2015 2016 2017 2018 2019 2020 2021 2022

Other works

First-order phase transition & composite particle production

- J. Steinheimer et al. PRC 87, 054903 (2013)
- PRL 109, 212301 (2012)(Hydrodynamics)
- JHEP 12, 122(2019)(Machine learning)

Baryon clustering near the critical point

- E. Shuryak, J.M.Torres-Rincon et al., PRC 100, 024903(2019)
- PRC 101,034914(2020)
- EPJA 56, 241(2020)
- PRC 104,024908(2021)

Background effects

- S. Wu et al.,PRC 106,034905(2022)

See talk by Koichi Murase

Our works

Probing QCD phase transition with light nuclei production

- PLB 774, 103 (2017)

K. J. Sun, L. W. Chen, C. M. Ko, and Z. Xu

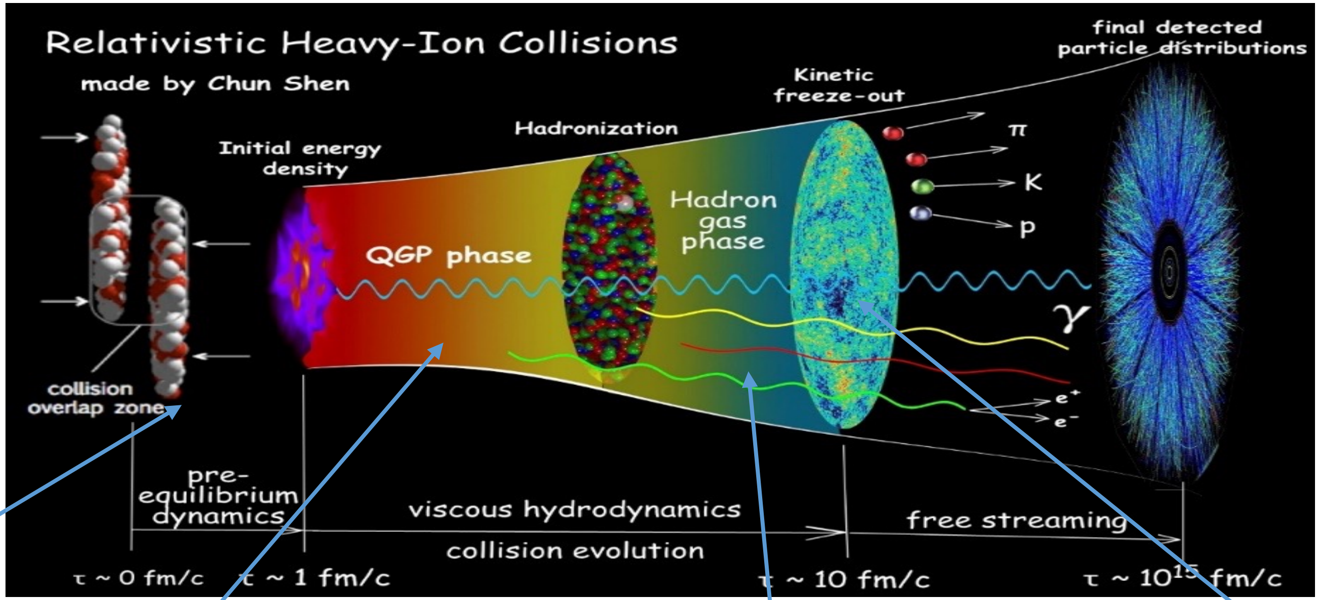
$$\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}[1 + \Delta\rho_n]$$

- PLB 781, 499 (2018)
- PLB 816, 136258 (2021)(criticality)

1st-order QCD phase transition

- PRD 103, 014006 (2021)
- EPJA 57, 313 (2021)(Transport)
- arxiv:2205.11010 (Transport) (First-order PT in BES)

Framework



Hadronization:
Quark coalescence

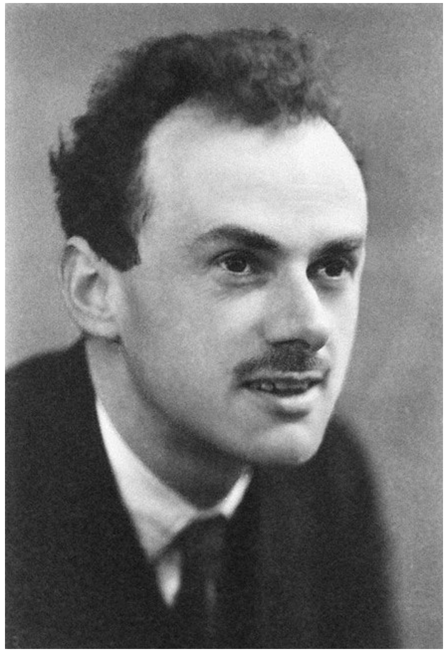
Initialization → Partonic evolution → Relativistic hadronic transport → Light nuclei

Mean field + scattering

Exhibits dynamical chiral phase transition

Nucleon coalescence

Chiral Symmetry



P. Dirac, 1928

$$(i\partial\!\!\!/ - m)\psi(x) = 0$$

H. Weyl, 1929

$$\sigma^\mu \partial_\mu \psi = 0$$
$$\bar{\sigma}^\mu \partial_\mu \psi = 0$$

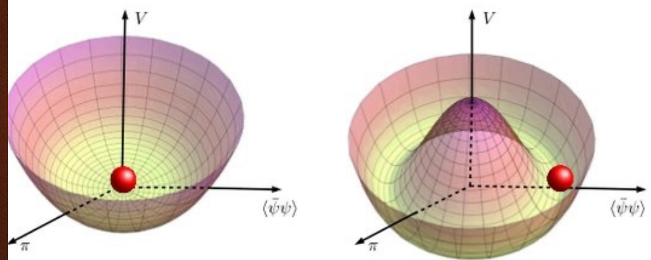
E. Majorana, 1937

$$i\,\partial\!\!\!/\,\psi_c - m\,\psi = 0$$

Y. Nambu, 1961

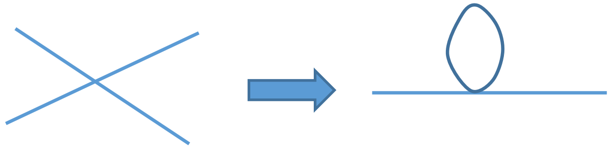
$$\langle \bar{q}^a_{\mathrm{R}}\, q^b_{\mathrm{L}} \rangle = v\,\delta^{ab}$$
$$M \propto -< \bar{q}q >$$

Spontaneous symmetry breaking:

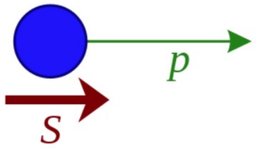


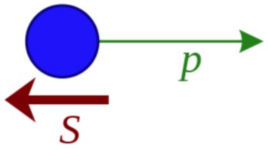
$$U(1)_V \times SU(N_f)_L \times SU(N_f)_R$$
$$\rightarrow U(1)_V \times SU(N_f)_V$$

Mass generation:



In analogy with BCS theory for superconductivity





Chiral anomaly (when coupled to gauge fields): $\partial^\mu J_{\mu 5} = 2m_f i\bar{\psi}_f \gamma_5 \psi_f - \frac{N_f g^2}{16\pi^2} G^{\mu\nu}_\alpha \tilde{G}_{\alpha\mu\nu}$

Strong CP violation: $\mathcal{L}_\theta = -\frac{\theta}{32\pi^2} g^2 G^{\mu\nu}_\alpha \tilde{G}_{\alpha\mu\nu}$

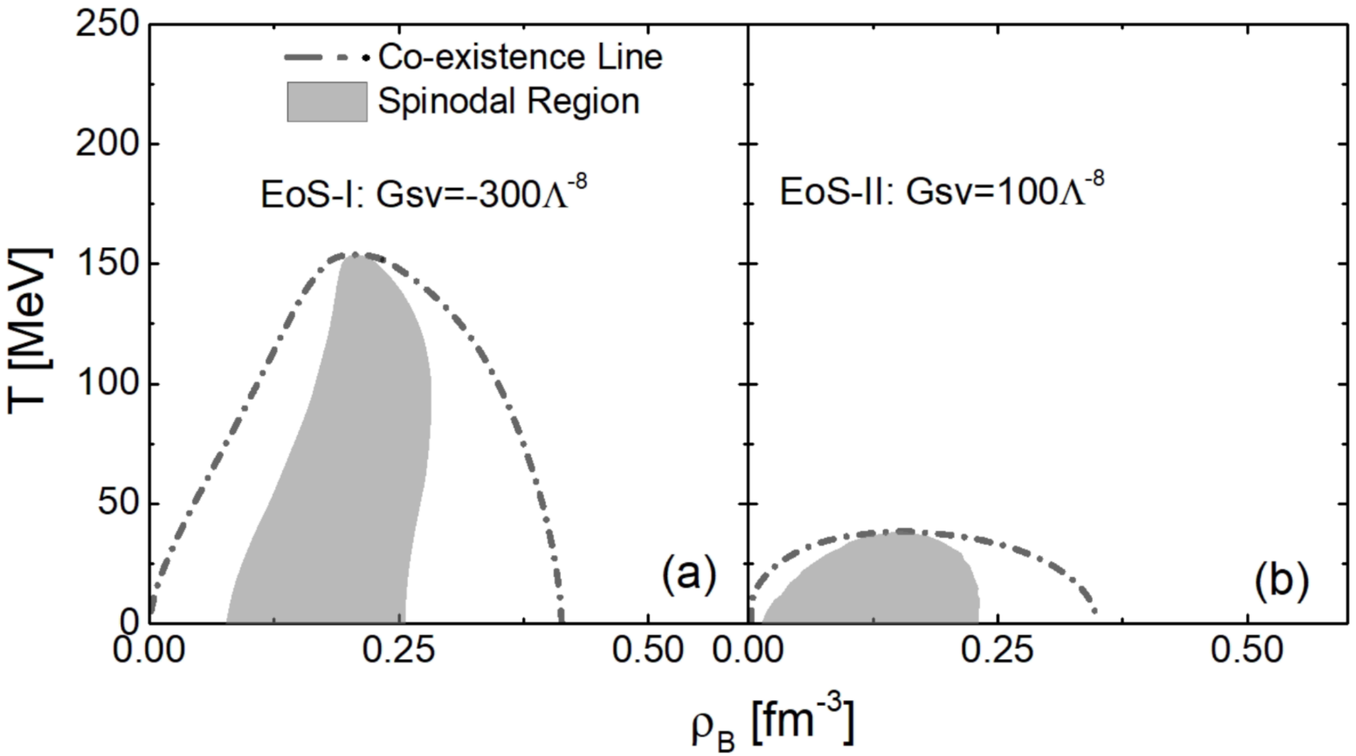
Equation of State (extended NJL model) (15)

The eNJL provides a flexible equation of state (EoS) . The critical temperature can be easily changed by varying the strength of the scalar-vector interaction without affecting the vacuum properties.

Lagrangian density for an extended Nambu-Jona-Lasinio (eNJL) model

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - \hat{m})\psi + G_S \sum_{a=0}^{8}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2]$$
$$- K\{[\det[\bar{\psi}(1+\gamma_5)\psi] + \det[\bar{\psi}(1-\gamma_5)\psi]\}$$
$$+ G_{SV}\left\{\sum_{a=1}^{3}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2]\right\}$$
$$\times\left\{\sum_{a=1}^{3}[(\bar{\psi}\gamma^\mu\lambda^a\psi)^2 + (\bar{\psi}\gamma_5\gamma^\mu\lambda^a\psi)^2]\right\},$$

Λ [MeV]	602.3	$M_{u,d}$ [MeV]	367.7
$G\Lambda^2$	1.835	M_s [MeV]	549.5
$K\Lambda^5$	12.36	$(\langle\bar{u}u\rangle)^{1/3}$ [MeV]	-241.9
$m_{u,d}$ [MeV]	5.5	$(\langle\bar{s}s\rangle)^{1/3}$ [MeV]	-257.7
m_s [MeV]	140.7		



M. Buballa, Phys. Rept. 407, 205 (2005)

K. J. Sun, C. M. Ko, S. Cao, and F. Li., Phys. Rev. D 103, 014006 (2021)

Box Simulation

Effective mass:

$$M_u = m_u - 4G_S\phi_u + 2K\phi_d\phi_s$$
$$-2G_{SV}(\rho_u+\rho_d)^2(\phi_u+\phi_d),$$
$$M_d = m_d - 4G_S\phi_d + 2K\phi_u\phi_s$$
$$-2G_{SV}(\rho_u+\rho_d)^2(\phi_u+\phi_d),$$
$$M_s = m_s - 4G_S\phi_s + 2K\phi_u\phi_d$$

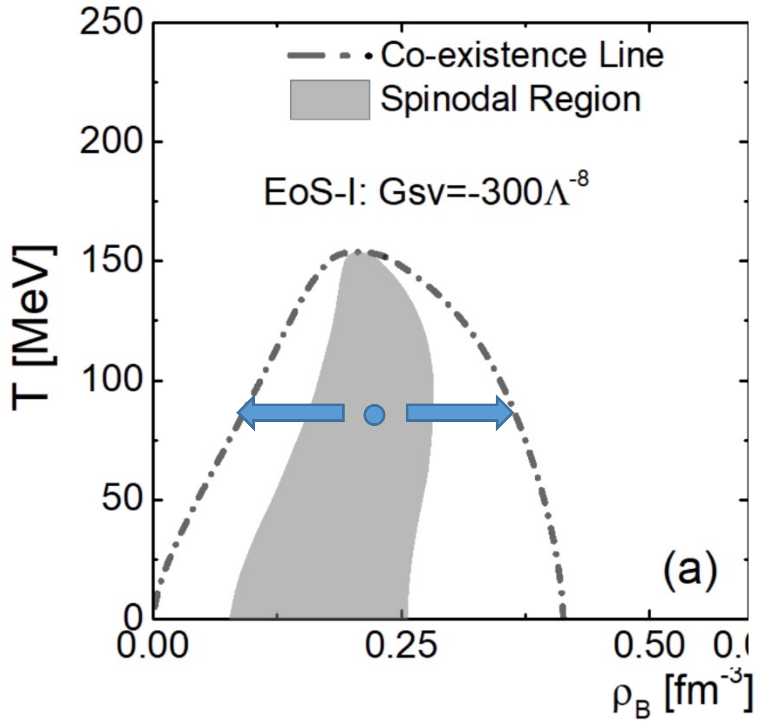
$$\phi_i = -2N_c\int_0^{\Lambda}\frac{\mathrm{d}^3p}{(2\pi\hbar)^3}\frac{M_i}{E_i}\left(1-f_i-\bar{f}_i\right)$$

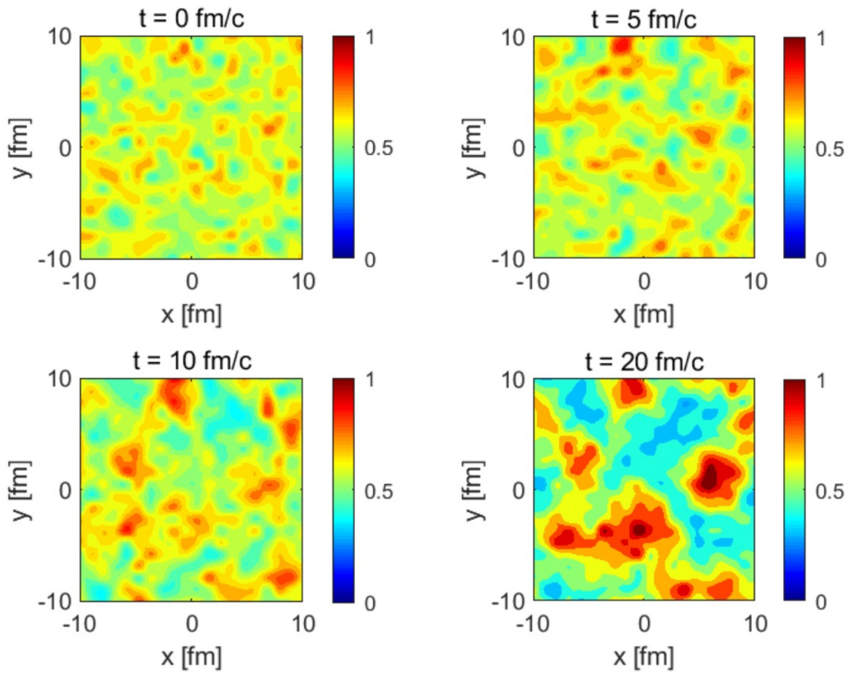
$$\rho_i = 2N_c\int_0^{\Lambda}\frac{\mathrm{d}^3p}{(2\pi\hbar)^3}\left(f_i-\bar{f}_i\right)$$

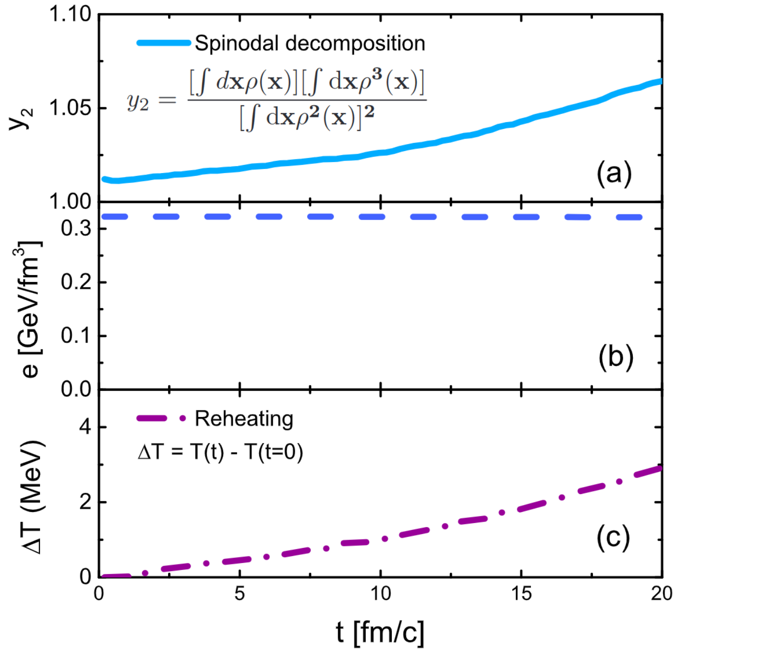
Test –particle method: J. Xu, arXiv:1904.00131 (2019)

$$\frac{d\mathbf{r}}{dt} = \mathbf{v},$$
$$\frac{d\mathbf{p}}{dt} = -\frac{M}{E^*}\boldsymbol{\nabla}_r M \pm \mathbf{E} \pm \mathbf{v}\times\mathbf{B}$$

Strong EM fields







Small irregularities will grow exponentially and soon the evolution becomes 'chaotic'.

For small k, $\Gamma_k = -i\, vk,$
$v^2 = \frac{n}{\varepsilon+p}\left(\frac{\partial p}{\partial n}\right)_S$ or $v^2 = \frac{n}{\varepsilon+p}\left(\frac{\partial p}{\partial n}\right)_T < 0$

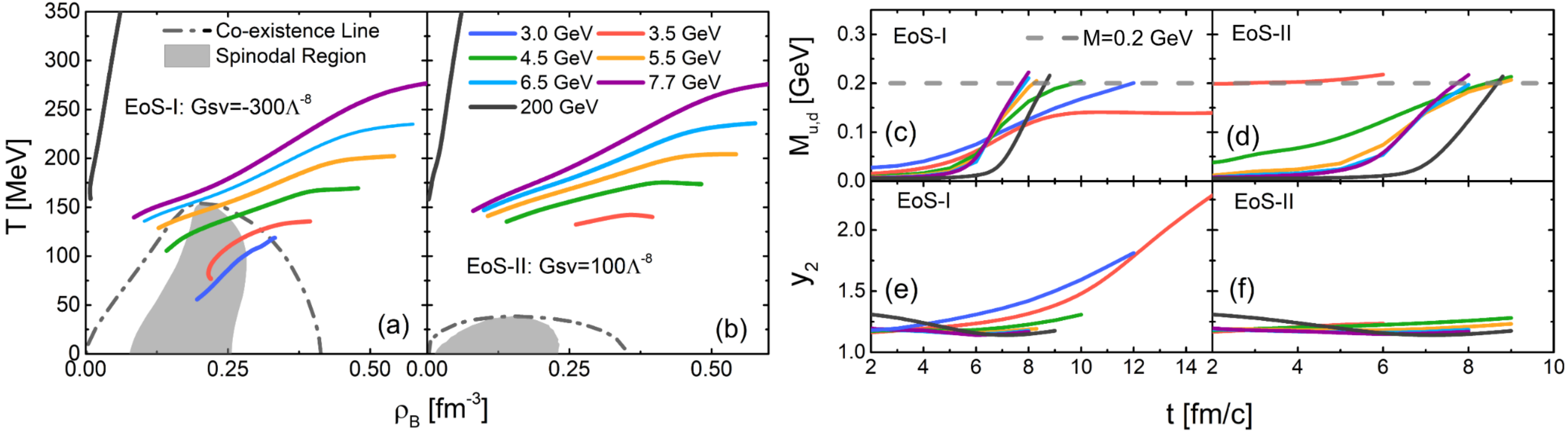
M. Buballa, Phys. Rept. 407, 205 (2005)
K. J. Sun, C. M. Ko, S. Cao, and F. Li., Phys. Rev. D 103, 014006 (2021)

Trajectories in the phase diagram (17)

Phase trajectories of central cells in the phase diagram

$$\overline{\rho^N} = \frac{\int d\mathbf{x}\rho^{(N+1)}(\mathbf{x})}{\int d\mathbf{x}\rho(\mathbf{x})}$$

$$y_2 = \frac{[\int d\mathbf{x}\rho(\mathbf{x})][\int d\mathbf{x}\rho^{\mathbf{3}}(\mathbf{x})]}{[\int d\mathbf{x}\rho^{\mathbf{2}}(\mathbf{x})]^{\mathbf{2}}}$$



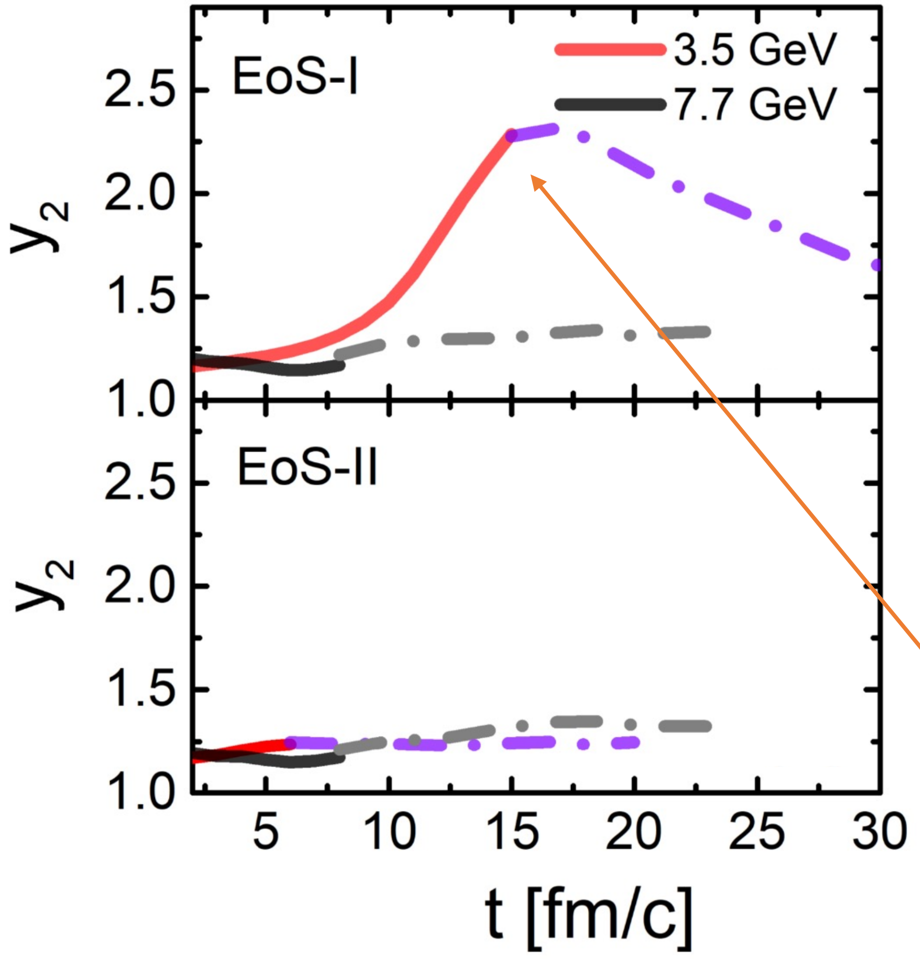
K. J. Sun, et al., arxiv:2205.11010 (2022)

Memory Effects

Survival of density fluctuation in an expanding fireball

Off-equilibrium effects

K. J. Sun et al., Eur.Phys.J.A 57 (2021) 11, 313
K. J. Sun, et al., arxiv:2205.11010 (2022)



Density moment:

$$\overline{\rho^N} = \frac{\int d\mathbf{x}\rho^{(N+1)}(\mathbf{x})}{\int d\mathbf{x}\rho(\mathbf{x})}$$

$$y_2 = \frac{[\int d\mathbf{x}\rho(\mathbf{x})][\int d\mathbf{x}\rho^3(\mathbf{x})]}{[\int d\mathbf{x}\rho^2(\mathbf{x})]^2}$$

$$\approx 1 + \frac{\int d\mathbf{x}(\delta\rho(\mathbf{x}))^2}{\int d\mathbf{x}\rho_0^2} \equiv 1 + \Delta\rho.$$

If the expansion is self-similar or scale invariant

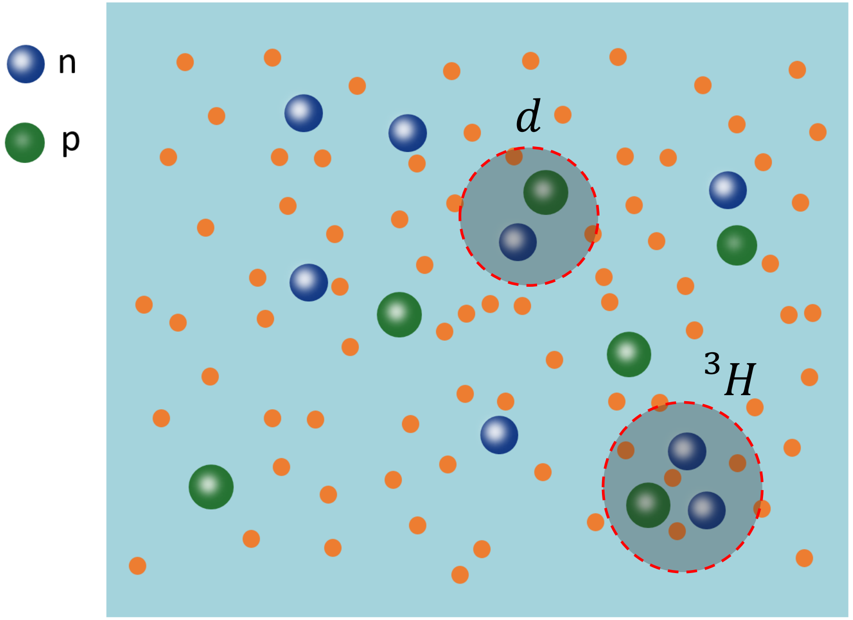
$$\rho(\lambda(t)x, t) = \alpha(t)\rho(x, t_h)$$

then $y_2(t) = y_2(t_h)$, i.e., remains a constant

'Memory effects' in the talk by Lijia Jiang
"Dynamical effects on the phase transition signal"

'Memory effects': Large density inhomogeneity survives to kinetic freezeout

Light Nuclei Production



$$N_d \propto W_d\left(\frac{x_1 - x_2}{\sqrt{2}}, \frac{p_1 - p_2}{\sqrt{2}}\right)$$

$$N_t \propto W_t\left(\frac{x_1 - x_2}{\sqrt{2}}, \frac{p_1 - p_2}{\sqrt{2}}, \frac{x_1 + x_2 - 2x_3}{\sqrt{6}}, \frac{p_1 + p_2 - 2p_3}{\sqrt{6}}\right)$$

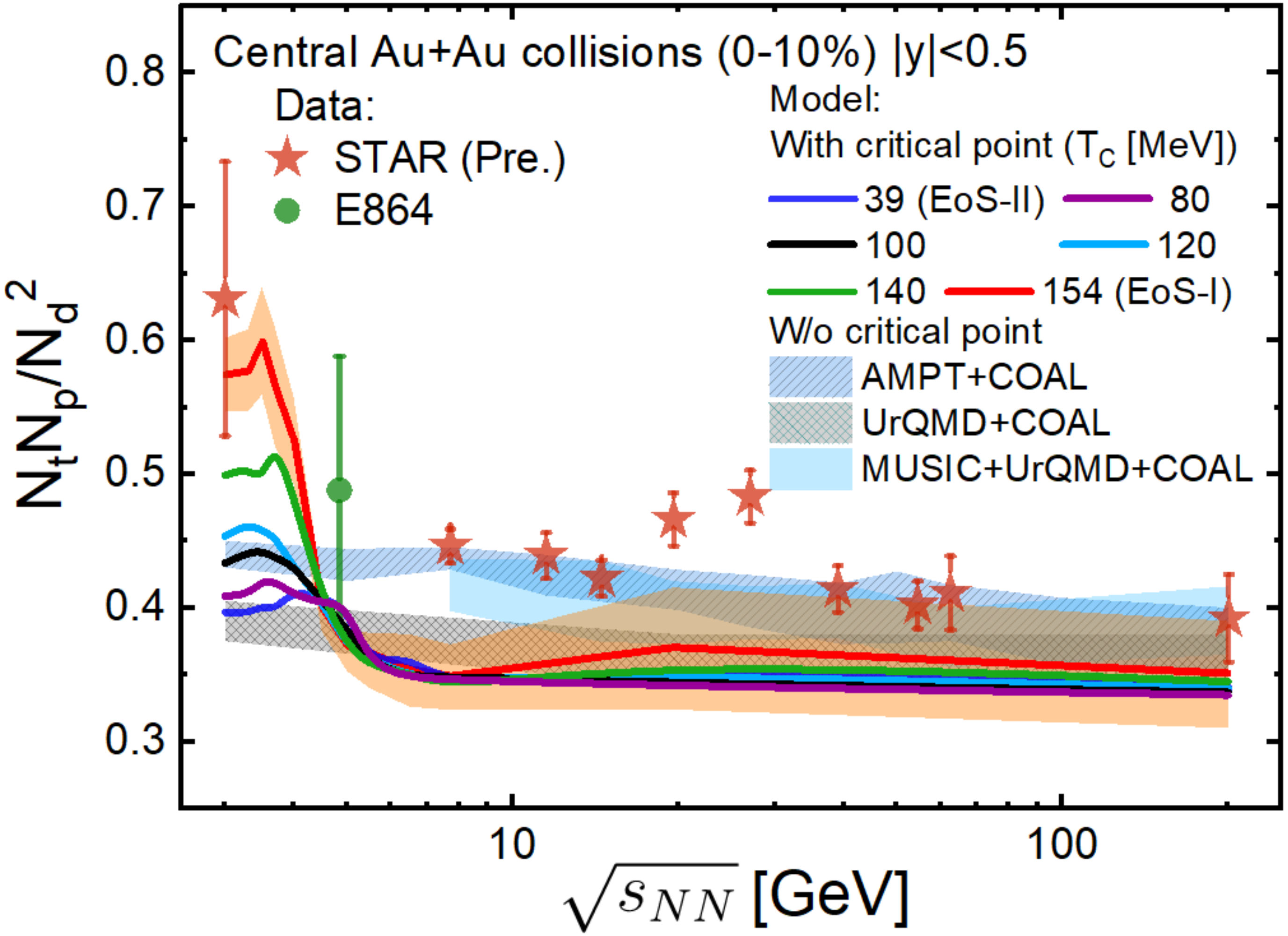
Wigner function: $W_d(r,k) = 8\exp\left(-\frac{r^2}{\sigma_d^2} - \sigma_d^2 k^2\right)$ $\quad \sigma_d \approx 2.26$ fm

$$W_t(\rho, \lambda, k_\rho, k_\lambda) = 8^2 \exp\left(-\frac{\rho^2}{\sigma_t^2} - \frac{\lambda^2}{\sigma_t^2} - \sigma_t^2 k_\rho^2 - \sigma_t^2 k_\lambda^2\right) \quad \sigma_t \approx 1.59 \text{ fm}$$

R. Scheibl and U. W. Heinz, Phys. Rev. C59. 1585(1999)

Collision Energy Dependence

K. J. Sun, et al., arxiv:2205.11010 (2022)

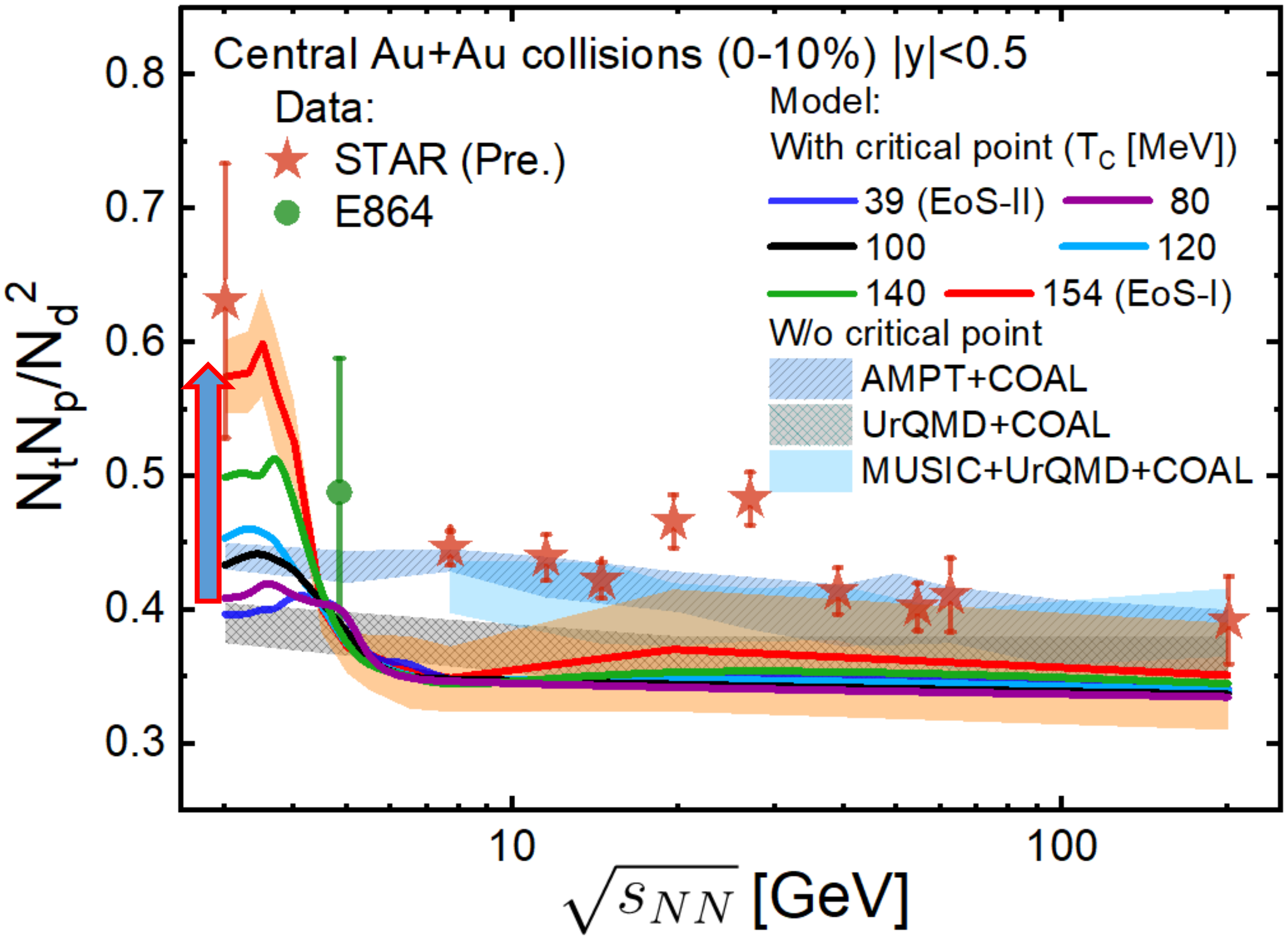


1. Without a critical point:
   The energy dependence of tp/d^2 is almost flat.

2. With a first-order phase transition:
   The spinodal-instability-induced enhancement of tp/d^2 increases as increasing the critical temperature.

STAR, arXiv:2209.08058(2022)
Hui Liu (STAR), QM2022
T. A. Armstrong et al. (E864), Phys. Rev. C 61, 064908 (2000).

Collision Energy Dependence

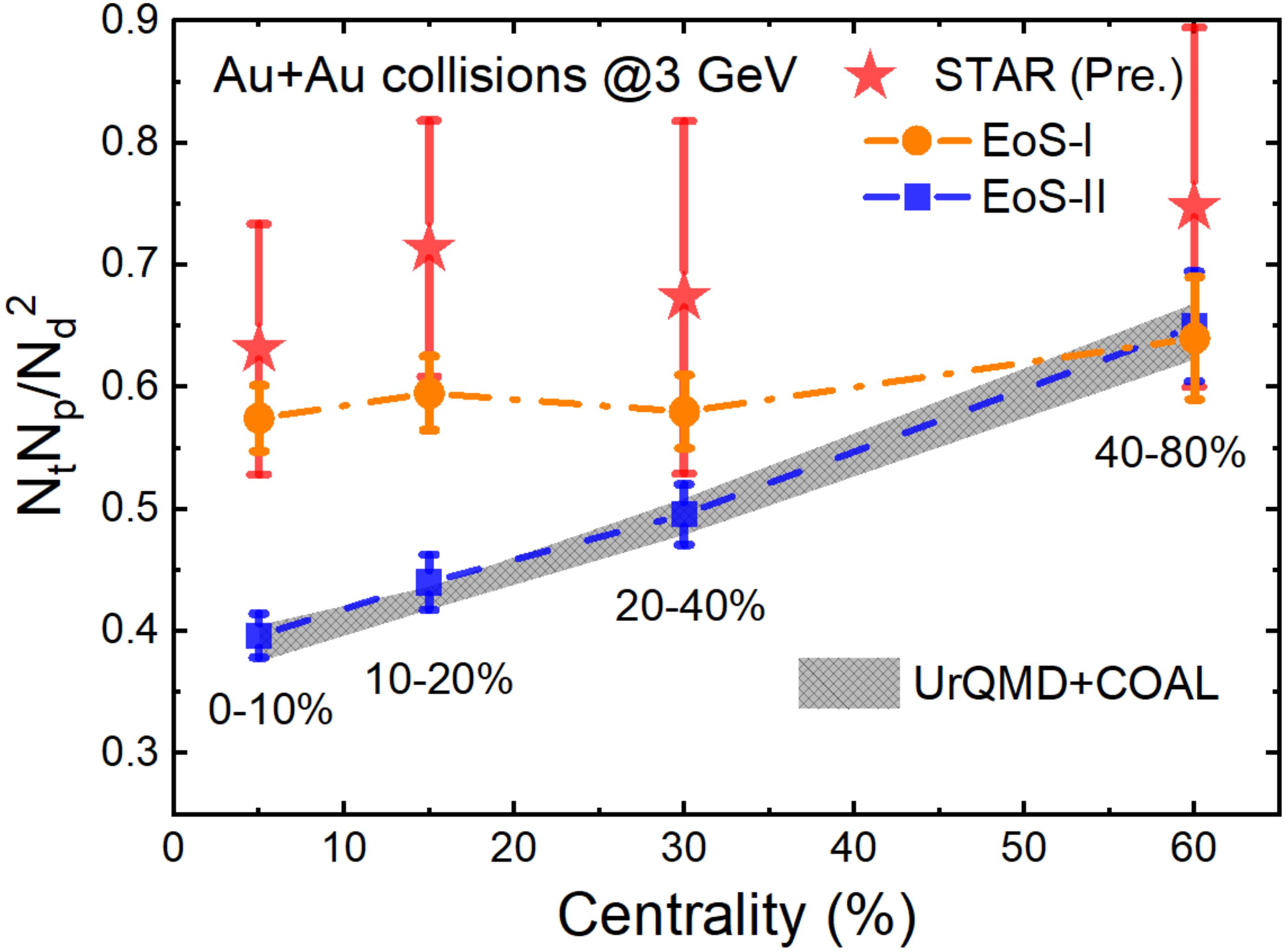


1. Without a critical point:
   The energy dependence of tp/d^2 is almost flat.

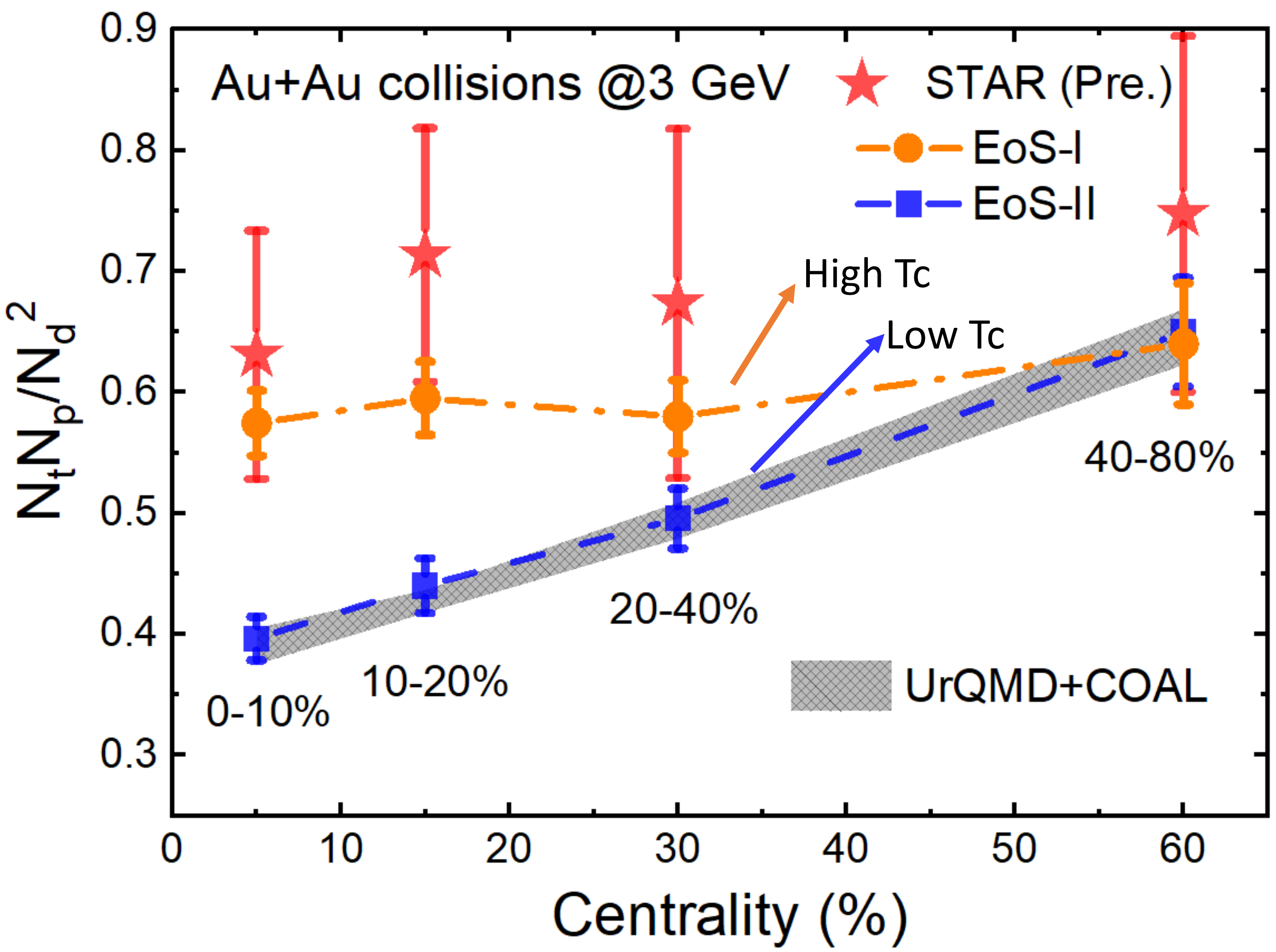
2. With a first-order phase transition:
   The spinodal instability induced enhancement of tp/d^2 during the first-order phase transition increases as increasing the critical temperature.

STAR, arXiv:2209.08058(2022)
Hui Liu (STAR), QM2022
T. A. Armstrong et al. (E864), Phys. Rev. C 61, 064908 (2000).

Centrality Dependence



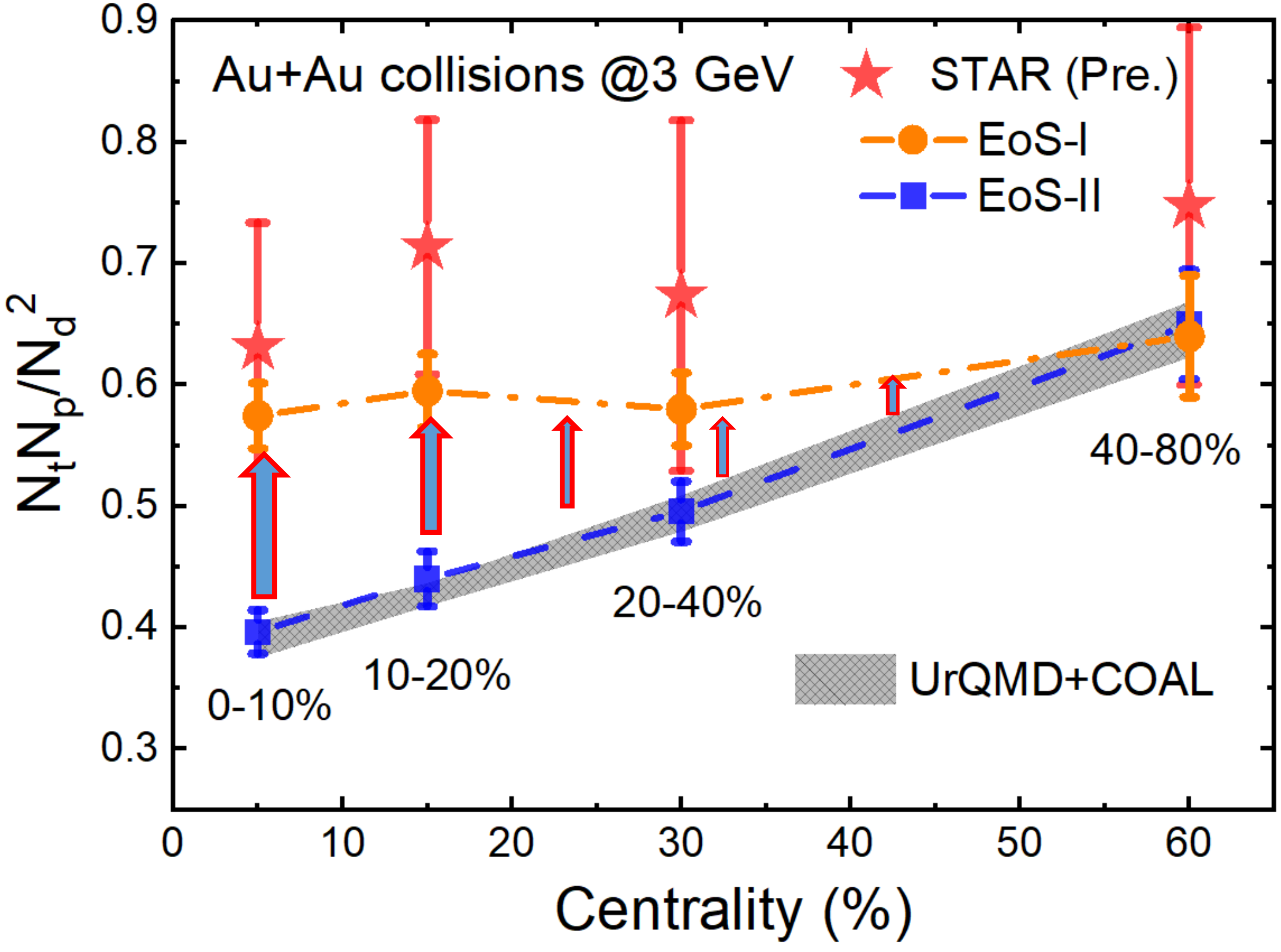
Centrality Dependence



The spinodal enhancement of tp/d^2 subsides with increasing collision centrality because of smaller fireball lifetime in more peripheral collisions.

Centrality Dependence

K. J. Sun, et al., arxiv:2205.11010 (2022)



The spinodal enhancement of tp/d^2 subsides with increasing collision centrality because of smaller fireball lifetime in more peripheral collisions.

The slope with EoS-I is 5 times smaller

Summary and Outlook

I. Production mechanism of light (hyper)nuclei

*Finite sizes of light (hyper)nuclei lead to suppression of their production in collisions of small system. Such quantum effects could be applied to identify the internal structure of more exotic hadrons.

*Post-hadronization dynamics suppresses triton yields by about a factor of two.

II. Probing QCD phase transitions with light nuclei production

*Light nuclei production provides a promising probe to non-smooth QCD phase transition.

*Spinodal instability during the first-order QCD phase transition could induce an enhancement of tp/d^2 in central Au+Au collisions at $\sqrt{s_{NN}}$ =3 – 5 GeV ($T_c \geq 80$ MeV).

***Precise measurements on light (hyper)nuclei production at LHC, RHIC, and lower energies would allow us to explore lots of interesting physics, like YN interaction, QCD phase transition, hadronic dynamics, nucleosynthesis in Jets, indirect dark matter detection, and etc.**

***With joint efforts from both theorists and experimentalists, many more exciting results are in the pipeline.**