Deuteron productions in Au+Au collisions at RHIC Energy

a) The effect of d productions on T_{ch} and μ_B
b) CEP by $\bar{d}/d$ ratios

Ning Yu (喻宁)
Xinyang Normal University

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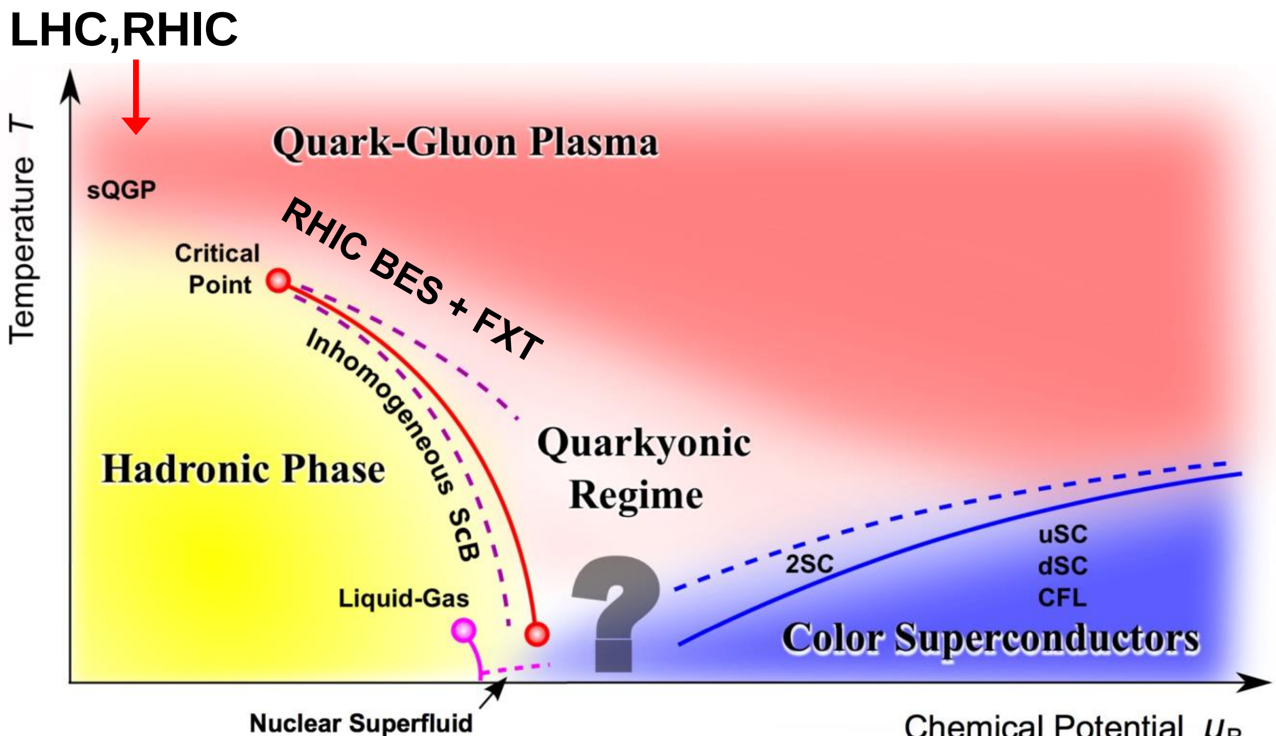
Outline

- ✫ Introduction
- ✫ Chemical freeze-out with deuteron yield at RHIC BES-I
- ✫ QCD Critical point:

  Based on : N. Yu, D. Zhang, and X. Luo arXiv:1812.04291
- ✫ Summary

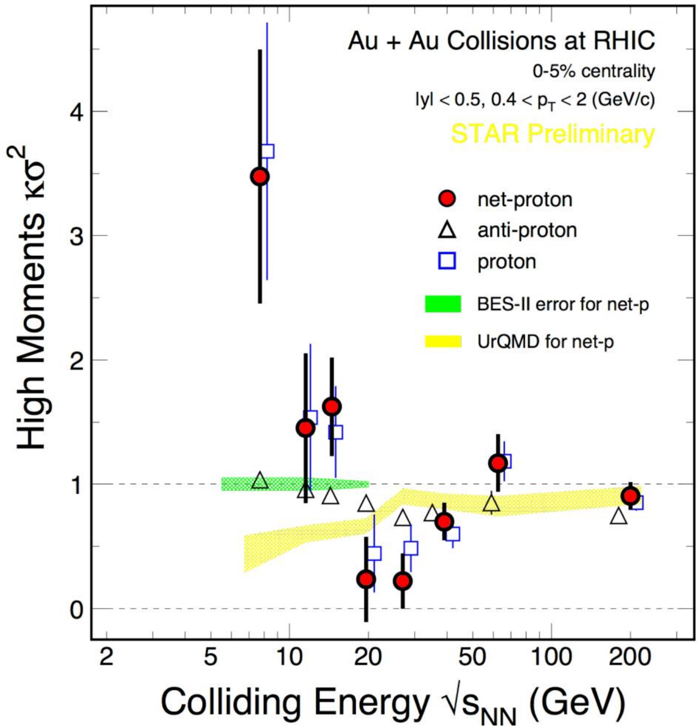
QCD Phase Diagram



K. Fukushima and C. Sasaki
Prog. Part. Nucl. Phys, 72, (2013) 99

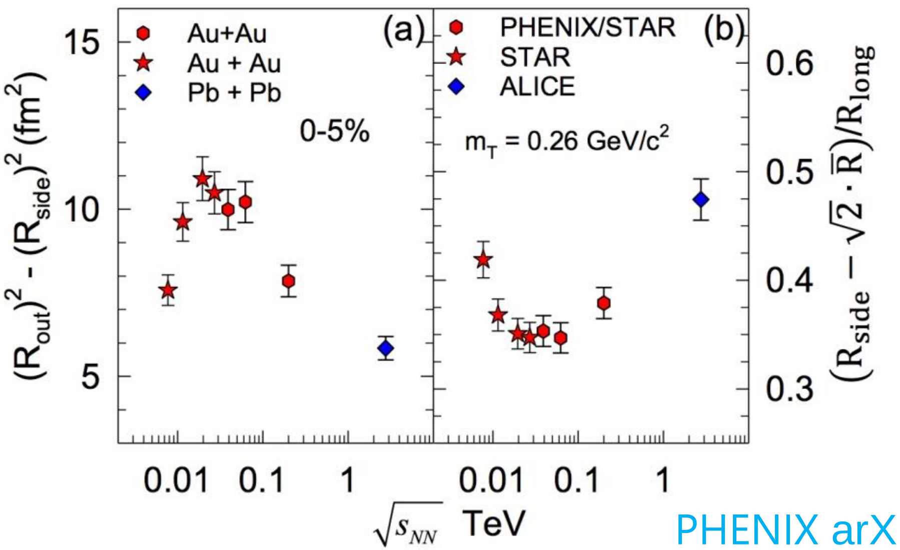
- ✫ High temperature: QGP properties
- ✫ High baryon density:
  - ✓ Critical Point and Phase boundary
  - ✓ Possible New Phase structure : Quarkyonic Matter

fluctuations



X.F.Luo, N.Xu,
Nucl. Sci. and Tech., 2017,28,112

π -π femtoscopic correlations



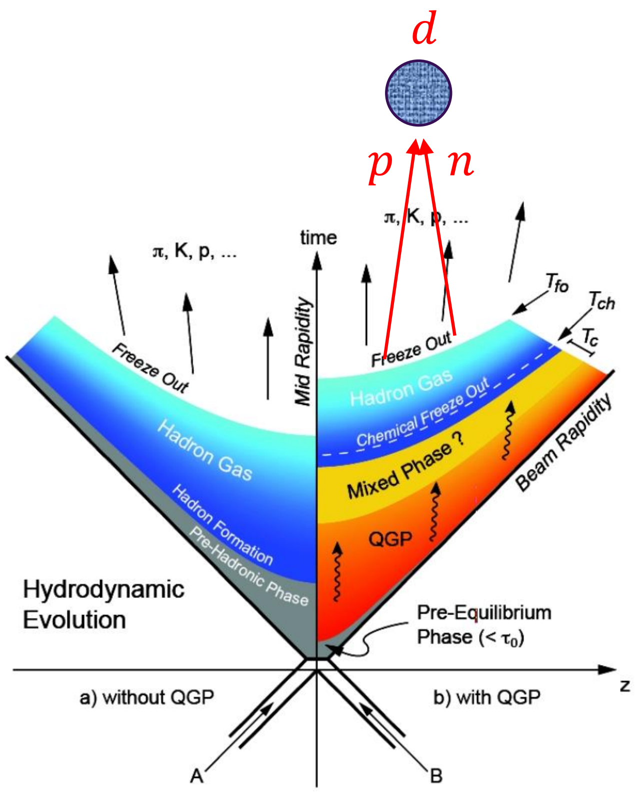
PHENIX arXiv:1410.2559

Phase Transition

Correlations of nucleons
(volume, density)

Light nuclei
(2,3… nucleons)

Light Nuclei Formation in HI Collisions



- Coalescence Model : small binding energy (ε), such as d and $\bar{d}$ with binding energy $\varepsilon = 2.2$ MeV, formed via final-state coalescence

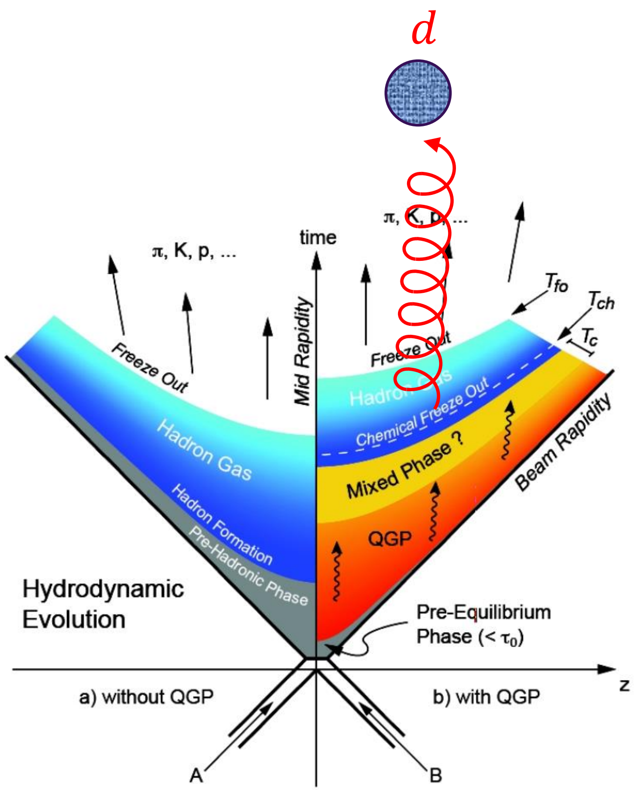
$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3}\right)^Z \left(E_n \frac{d^3 N_n}{dp_n^3}\right)^{A-Z} \approx B_A \left(E_p \frac{d^3 N_p}{dp_p^3}\right)^A, \; p_A = A p_p$$

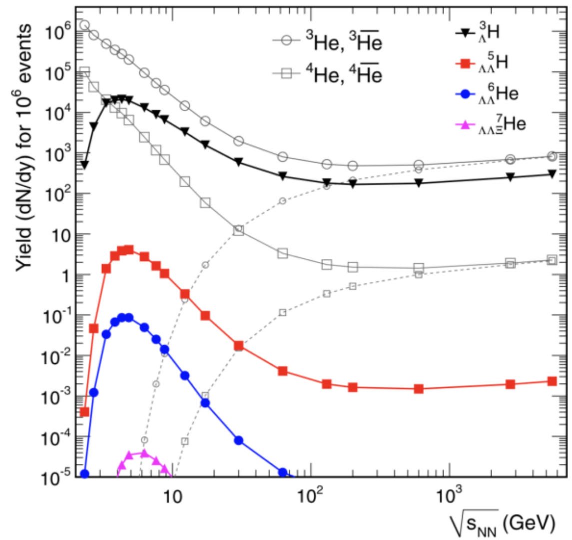
$$B_A \propto V_f^{1-A}$$

Light nuclei produced at the chemical freeze-out might break up and reform between the chemical freeze-out and the kinetic freeze-out.

László P. Csernai, Joseph I. Kapusta Phys. Reps, 131,223(1986)
B. Monreal, *et. al.* PRC60,031901(1999), PRC60,051902(1999)

Light Nuclei Formation in HI Collisions



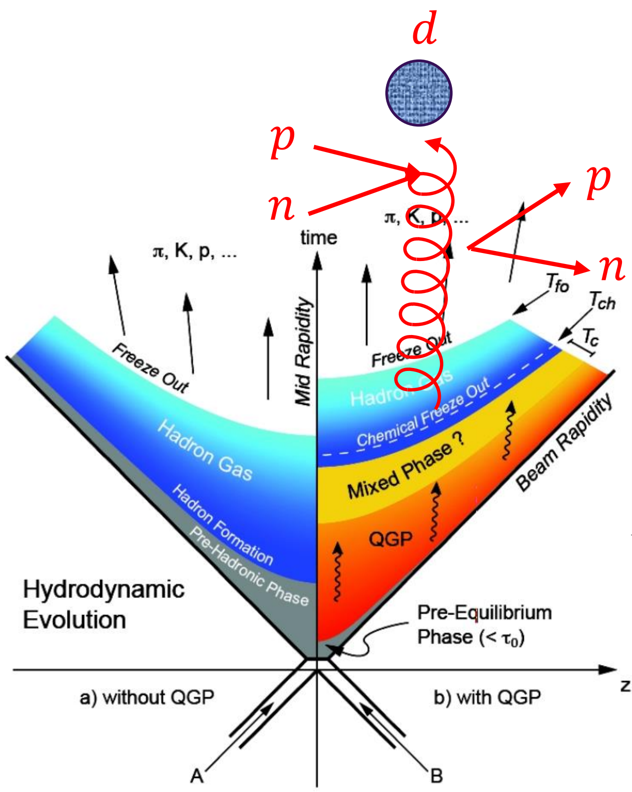


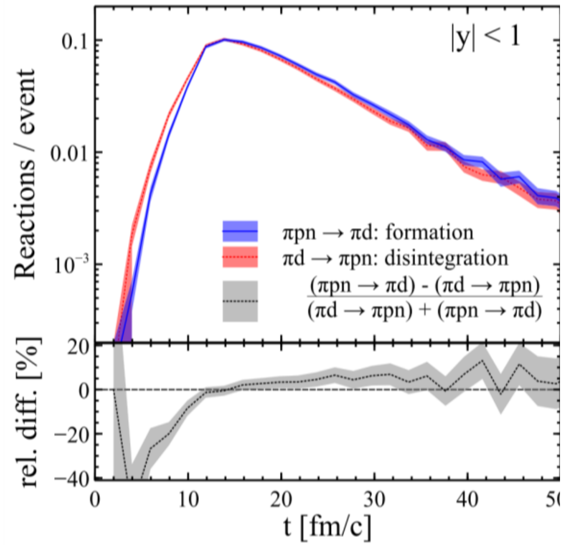
➤ Thermal Model : emitted at chemical equilibrium, yield fixed at chemical freeze-out for all hadrons

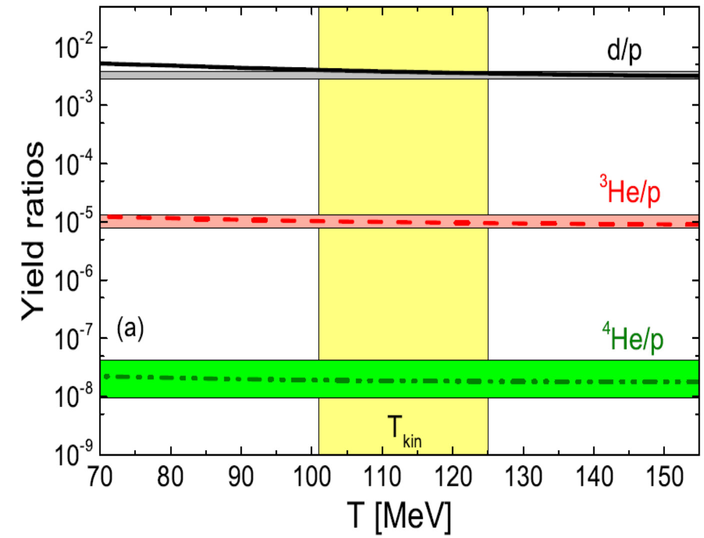
$$N_i = \frac{g_i V}{2\pi^2} m_i^2 T_{ch} K_2\left(\frac{m_i}{T_{ch}}\right) e^{\mu_i/T_{ch}}$$

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, PLB697, 203 (2011),

Light Nuclei Formation in HI Collisions







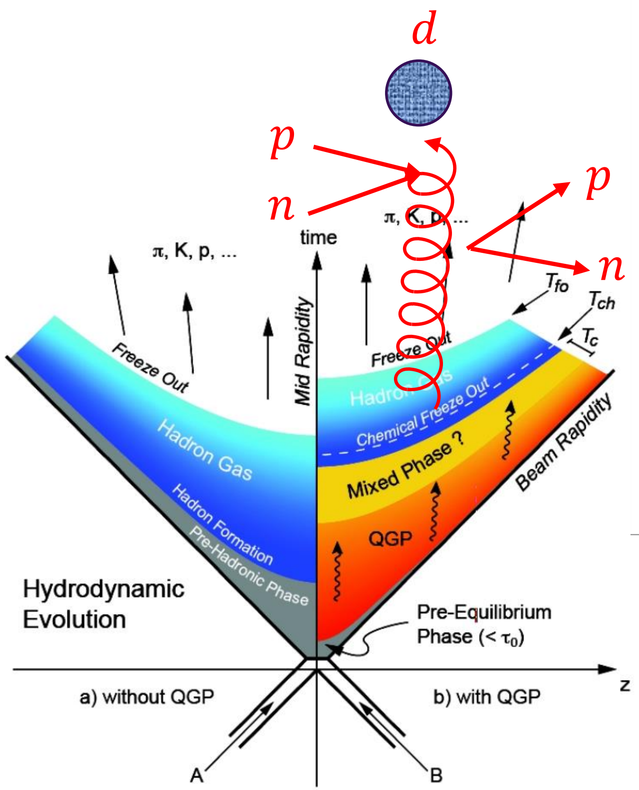
- An interplay of $\pi d \leftrightarrow \pi p n$ reactions and $\bar{B}B$ annihilations.

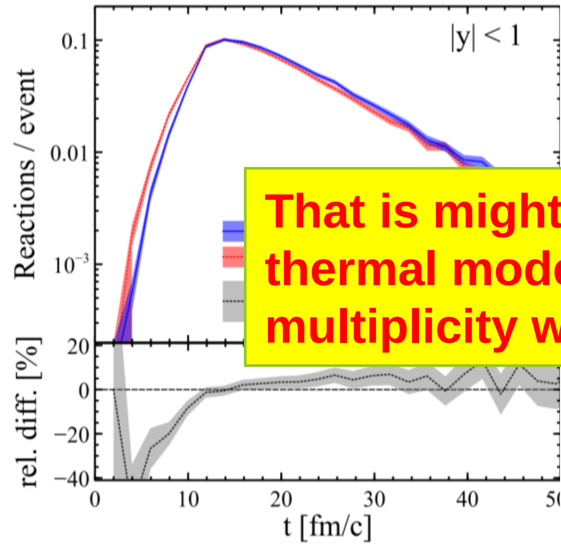
  PRC697, 203 (2011)

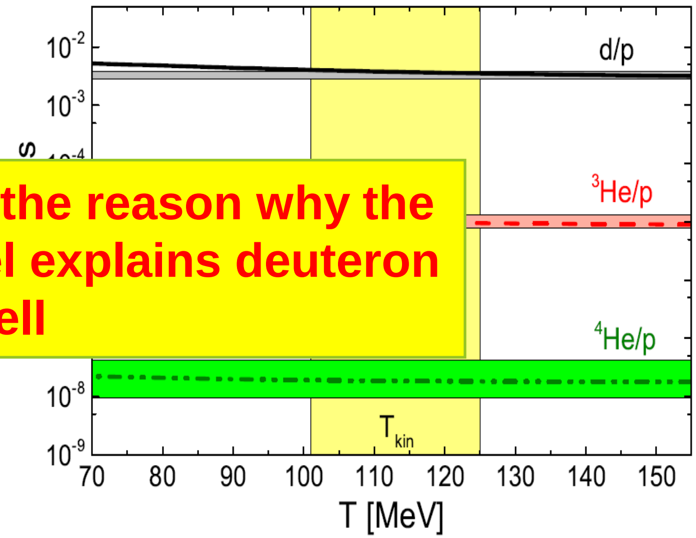
- The deuteron yield does show a notable increase at lower temperatures, indicating that an isentropic expansion after the chemical freeze-out.

  arXiv:1903.10024

Light Nuclei Formation in HI Collisions







That is might the reason why the thermal model explains deuteron multiplicity well

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  PRC697, 203 (2011)

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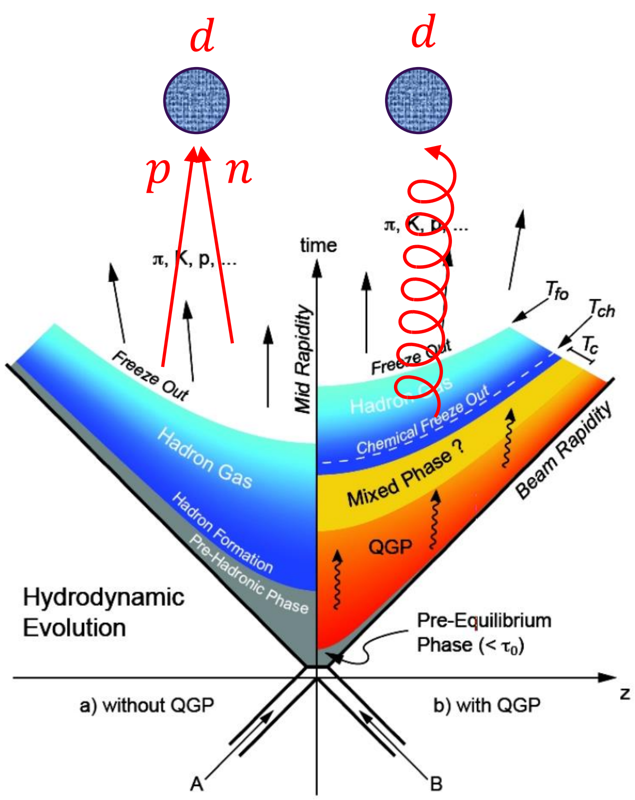
Light Nuclei Formation in HI Collisions



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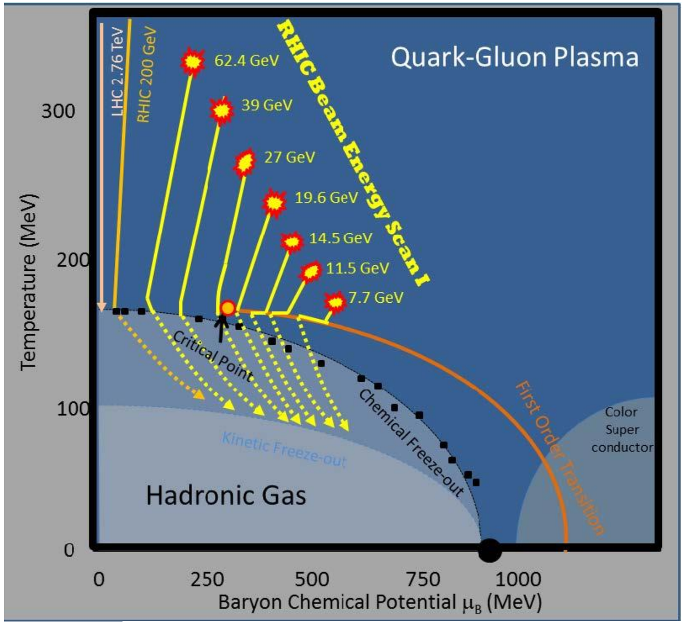
A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, PLB697, 203 (2011)

Light nuclei may serve as probes of space-momentum density and correlation of nucleons at freeze-out.

Deuteron Production at RHIC BES-I



$\sqrt{s_{NN}}$(GeV)	7.7	11.5	14.5	19.6	27	39	62.4	200
N_{eve}(M)	4	11	27	40	71	133	67	480
μ_B(MeV)	420	315	260	205	155	115	72	20

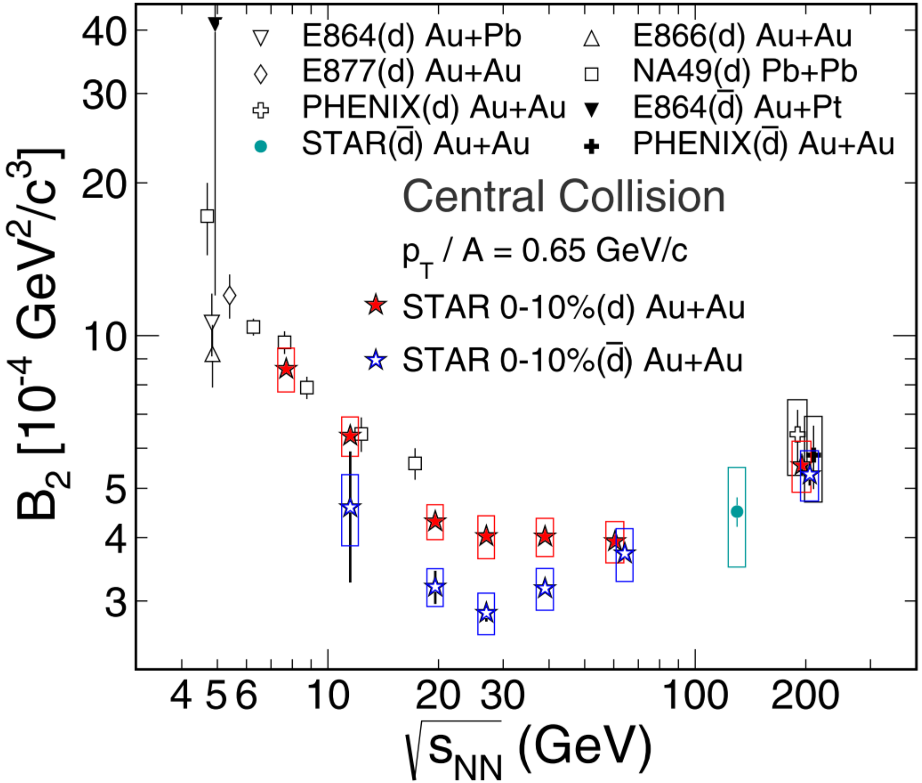
PRC 73,034905 (2006)

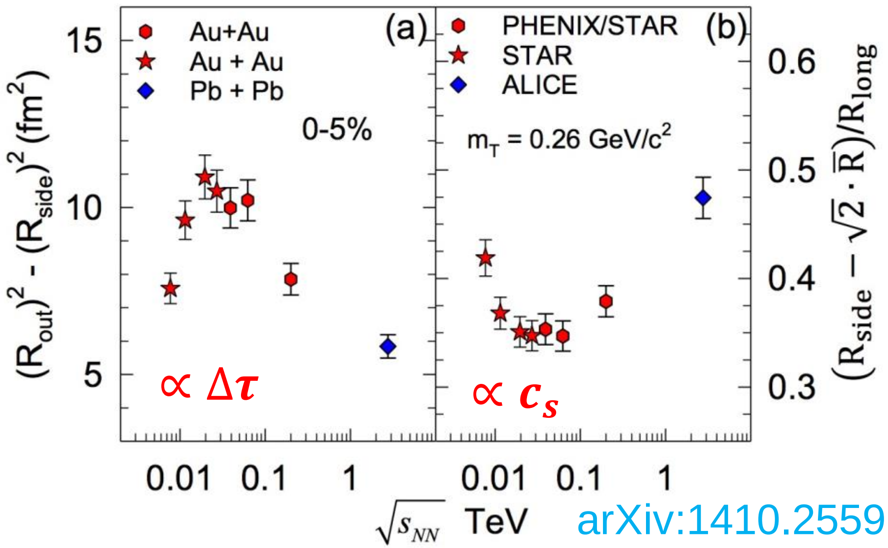
RHIC BES-I Deuteron results have been published

PHYSICAL REVIEW C **99**, 064905 (2019)

Beam energy dependence of (anti-)deuteron production in Au + Au collisions at the BNL Relativistic Heavy Ion Collider

Coalescence Parameters vs. Collision Energy



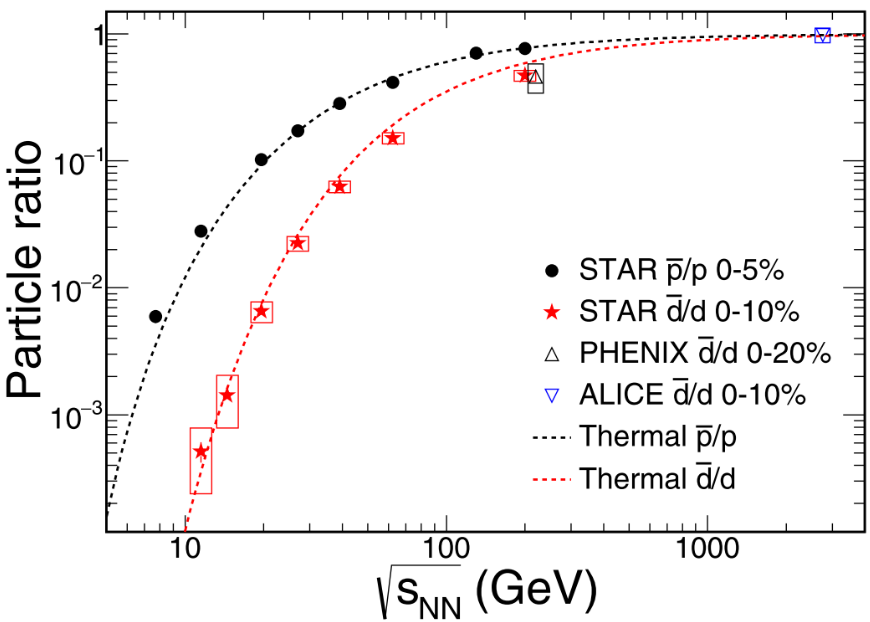


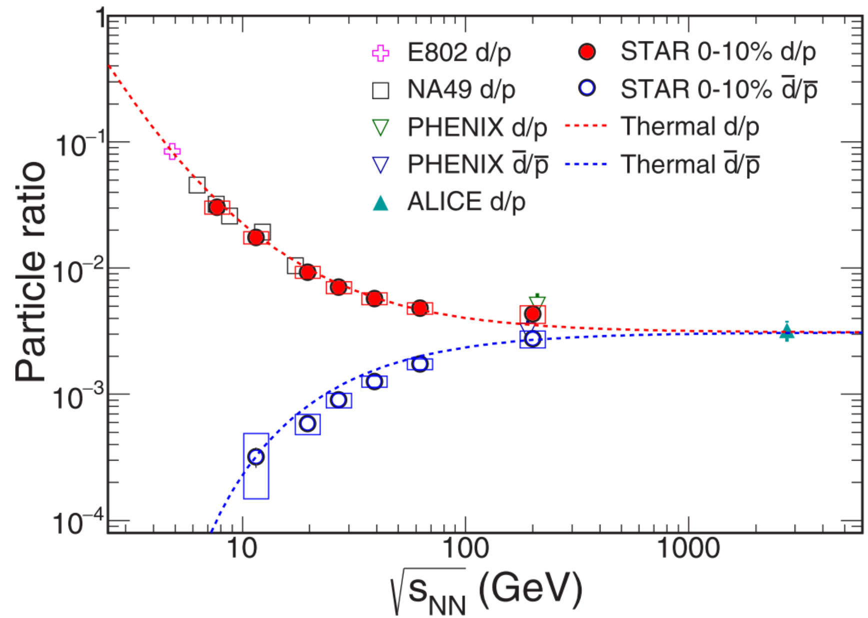
arXiv:1410.2559

☆ $B_2\left(\bar{d}\right)$ values are systematically lower than that of $B_2(d)$ implying emitted source of anti-baryons is larger than those of baryons.

☆ B_2 decreases with collision energy. A minimum around $\sqrt{s_{\mathrm{NN}}} = 20$ GeV : **change of EOS?!**

Thermal model predictions





- ✫ Thermal model can describe $N(\bar{p})/N(p)$ and $N(\bar{d})/N(d)$ in a wide energy range.
- ✫ The d/p ratios from thermal model prediction are consistent with the data from SIS up to LHC energies.

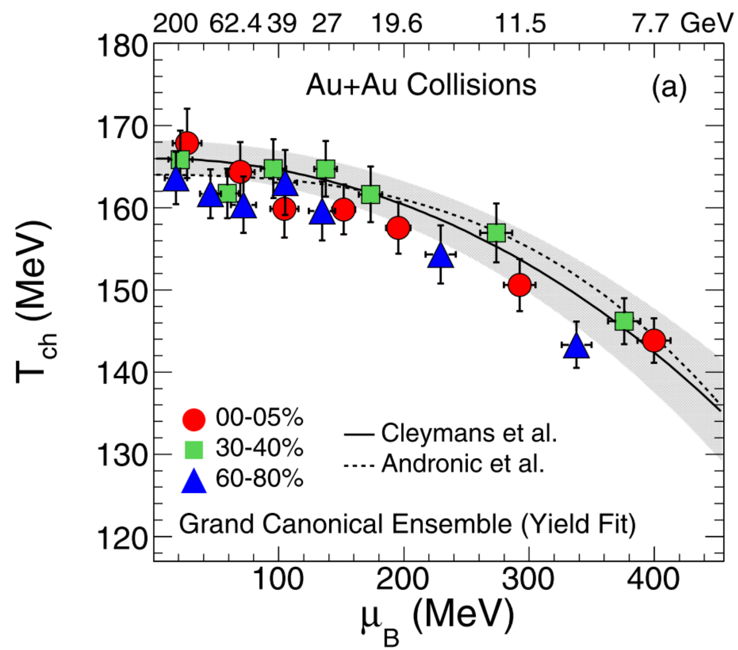
$$T_{\mathrm{ch}} = \frac{T_{\mathrm{ch}}^{\mathrm{lim}}}{1+\exp(2.60-\ln(\sqrt{s_{\mathrm{NN}}})/0.45)}$$

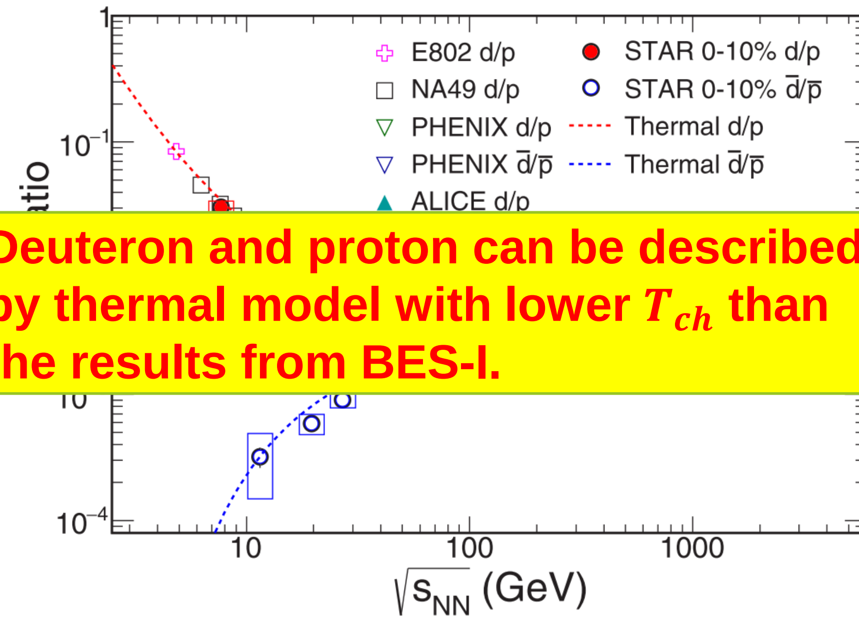
$$\mu_B = \frac{\mu_B^{\mathrm{lim}}}{1+0.288\sqrt{s_{\mathrm{NN}}}},$$

$$T_{\mathrm{ch}}^{\mathrm{lim}} = 158.4 \pm 1.4\,\mathrm{MeV},\ \mu_B^{\mathrm{lim}} = 1307.5\,\mathrm{MeV}$$

PLB697,203 (2011)

Thermal Model Predictions





Deuteron and proton can be described by thermal model with lower T_{ch} than the results from BES-I.

- ☆ Thermal model can describe $N(\bar{p})/N(p)$ and $N(\bar{d})/N(d)$ in a wide energy range.
- ☆ The d/p ratios from thermal model prediction are consistent with the data from SIS up to LHC energies.

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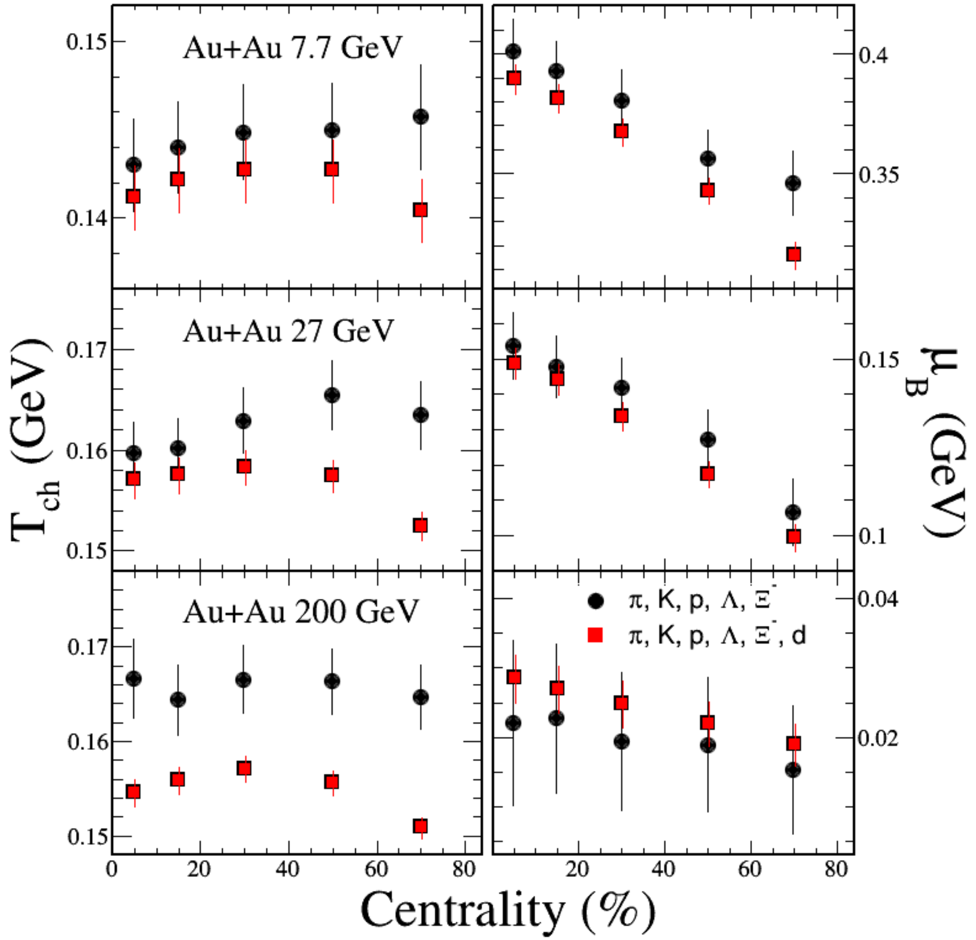
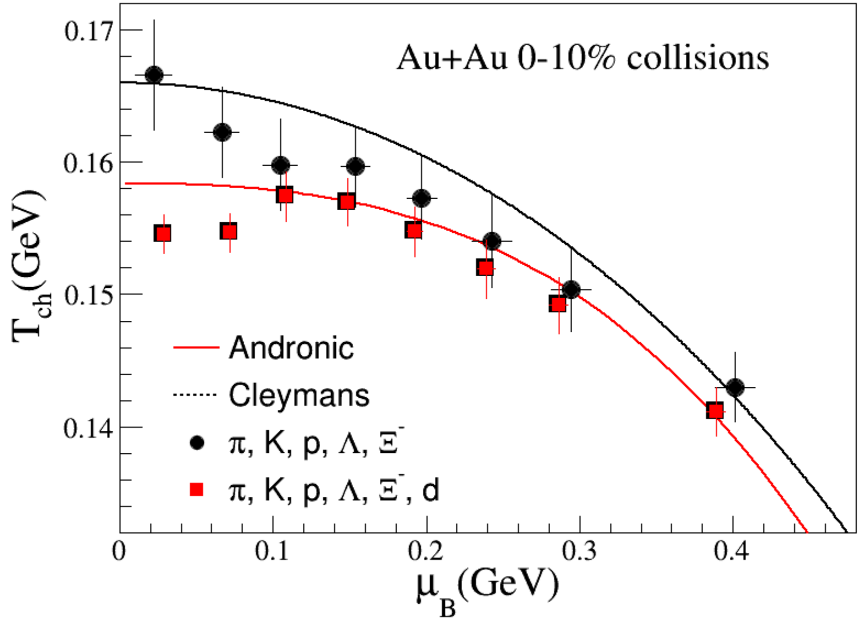
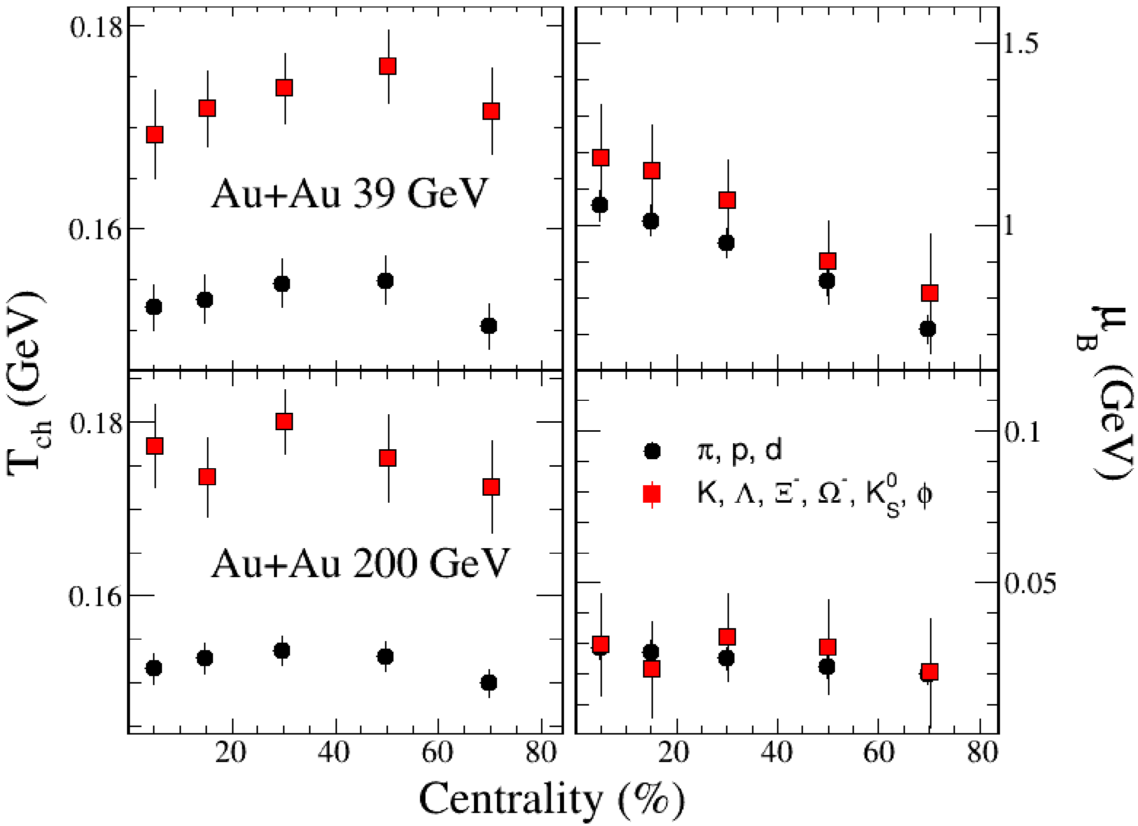
Thermal Fit with Deuteron Production





- ☆ T_{ch} became smaller when deuterons are include in the thermal fit.
- ☆ The $\pi d \leftrightarrow \pi p n$ is not balance at higher temperature? More deuterons break-up at higher temperature?

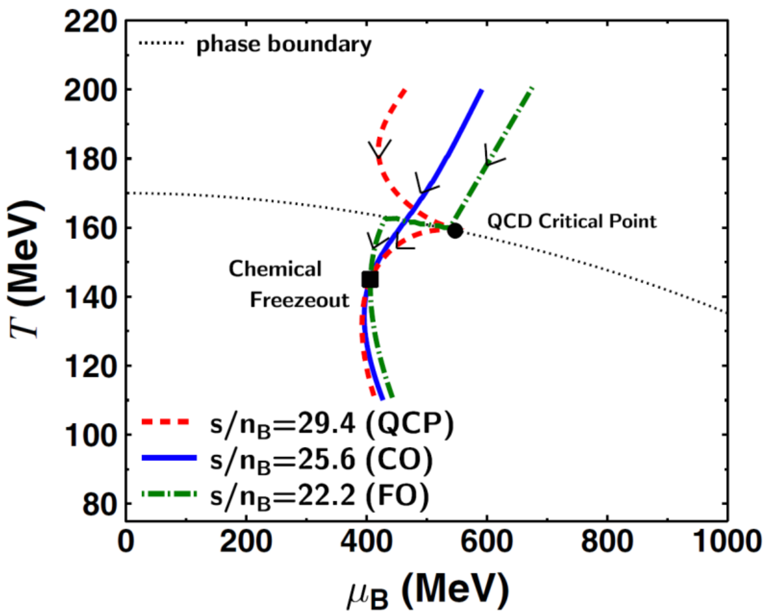
$T_{ch}(u, d)$ and $T_{ch}(s)$



- ☆ T_{ch} of π, p, d is around 150 MeV
- ☆ T_{ch} of strangeness particles is around 175 MeV
- ☆ Light particles freeze-out early than strangeness particles from the analysis of experiment data.
- ☆ Deuteron might freeze-out at the similar temperature as proton and then reach balance by $\pi d \leftrightarrow \pi p n$ reactions

QCD Focusing Effect

☆ QCD critical point focusing effect : critical point will serve as an attractor of the trajectory evolution in the $T - \mu_B$ plane.



M. Asakawa, S. A. Bass B. Muller, C. Nonaka
PRL 101, 122302 (2008)

focusing effect → experimental observable?

✓ The system is assumed to be thermodynamically equilibrium and is continuing to emit particles.

$$Y(T,\mu_B) \propto \frac{g_i}{2\pi^2} m_i^2 T K_2\left(\frac{m_i}{T}\right) e^{\mu_i/T}$$

$$\int_{QCP\to CFP} Y(T,\mu_B) dl = \frac{g_i V}{2\pi^2} m_i^2 T_{CF} K_2\left(\frac{m_i}{T_{CF}}\right) e^{\mu_{i(CF)}/T_{CF}}$$

✓ $\beta_T \sim f(t)$

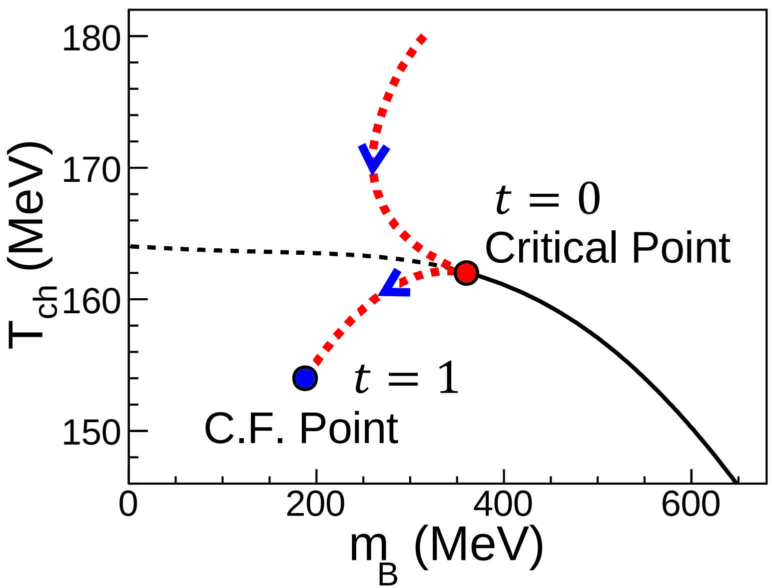
Focusing Effect trajectory

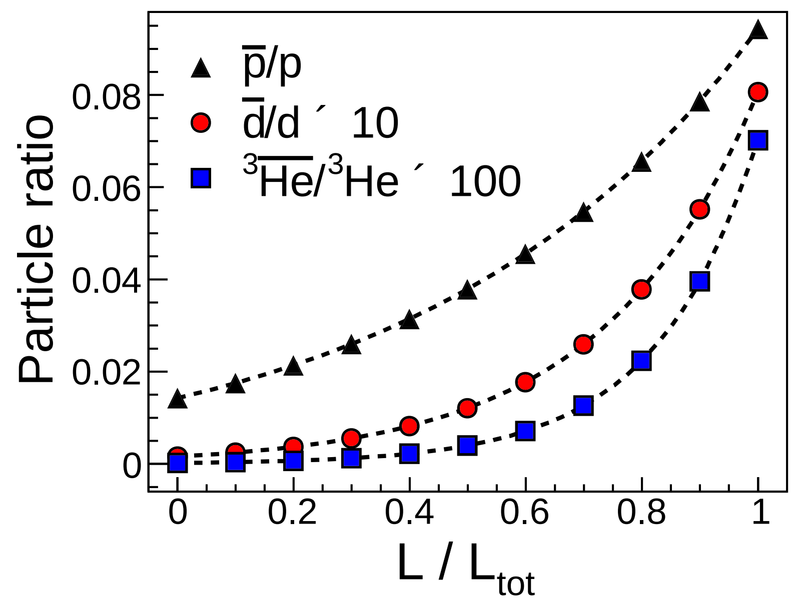
- ✯ C.F. point $(T_{CF}, \mu_B) = (152,188)$ MeV in central Au+Au $\sqrt{s_{NN}} = 19.6$ GeV

  STAR, Phys. Rev. C96, 044904 (2017).

- ✯ Critical point $(T, \mu_B) = (162,360)$ MeV Z. Fodor and S. D. Katz, JHEP2004, 050 (2004).

$$t = L/L_{tot}$$

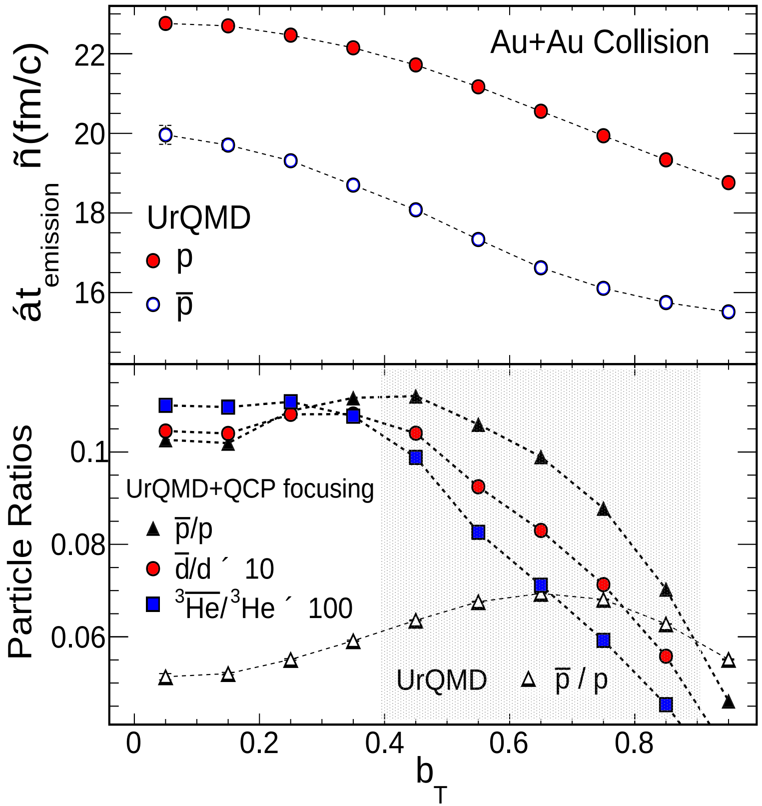




N. Yu, D. Zhang, and X. Luo arXiv:1812.04291

Anomalous β_T dependence of $\bar{d}/d$

✭ $\beta_T - t$ distribution is from UrQMD central Au+Au collision at $\sqrt{s_{NN}} = 19.6$ GeV.

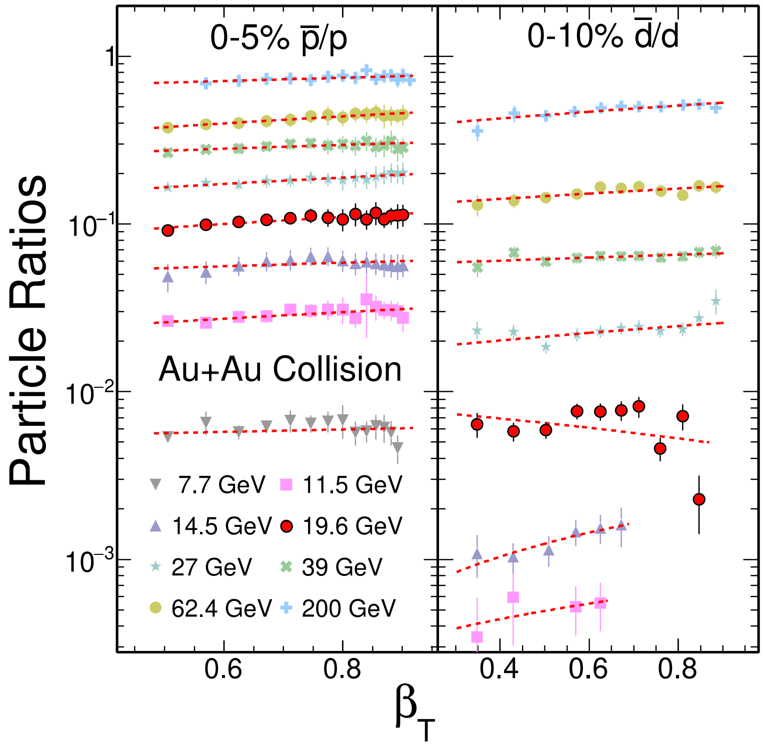


N. Yu, D. Zhang, and X. Luo arXiv:1812.04291

- The $\bar{p}/p$, $\bar{d}/d$, and $^3\overline{\mathrm{He}}/\mathrm{He}$ **decrease with increasing $\boldsymbol{\beta_T}$** with QCP focusing effect.
- The ratios fall faster for heavier particles.
- This behavior is more easier to be observed in $\bar{d}/d$ than $\bar{p}/p$.

Could this anomalous behavior be observed in experiment?

Experimental Results



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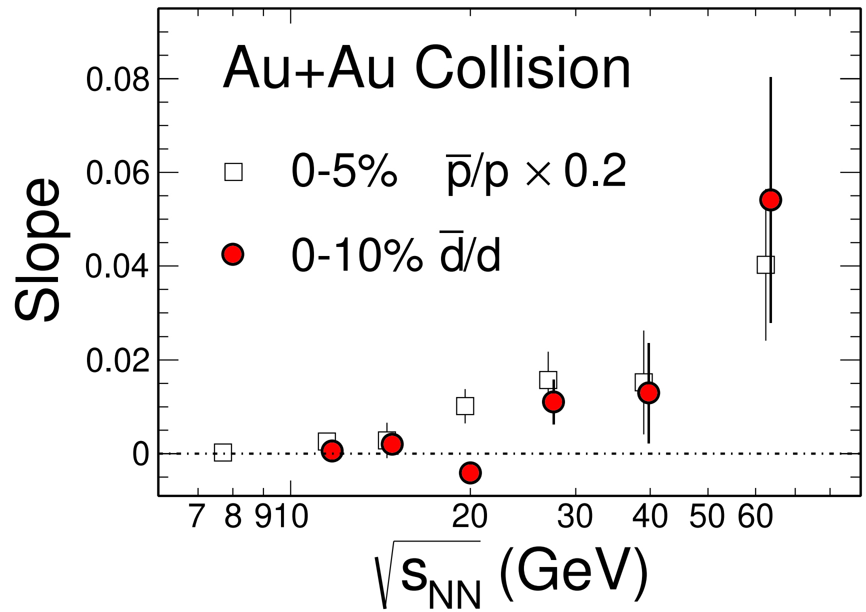


- The decreasing anti-particle to particle ratio only occurs at 19.6 GeV for **deuteron.**
- System evolution trajectory has passed through the critical region at $\sqrt{s_{NN}}$ =19.6 GeV

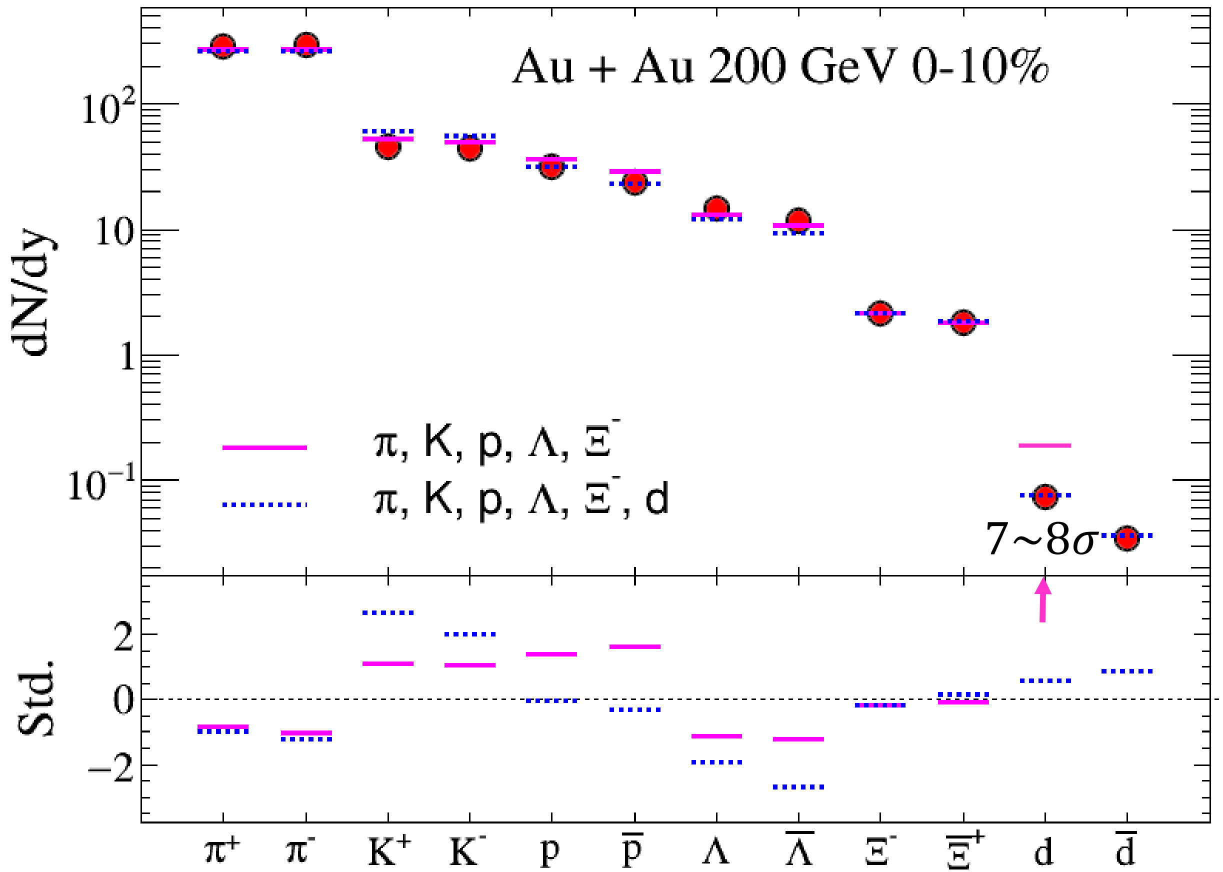
$\mu_B(\textbf{Critical point}) > 188$ MeV.

Summary

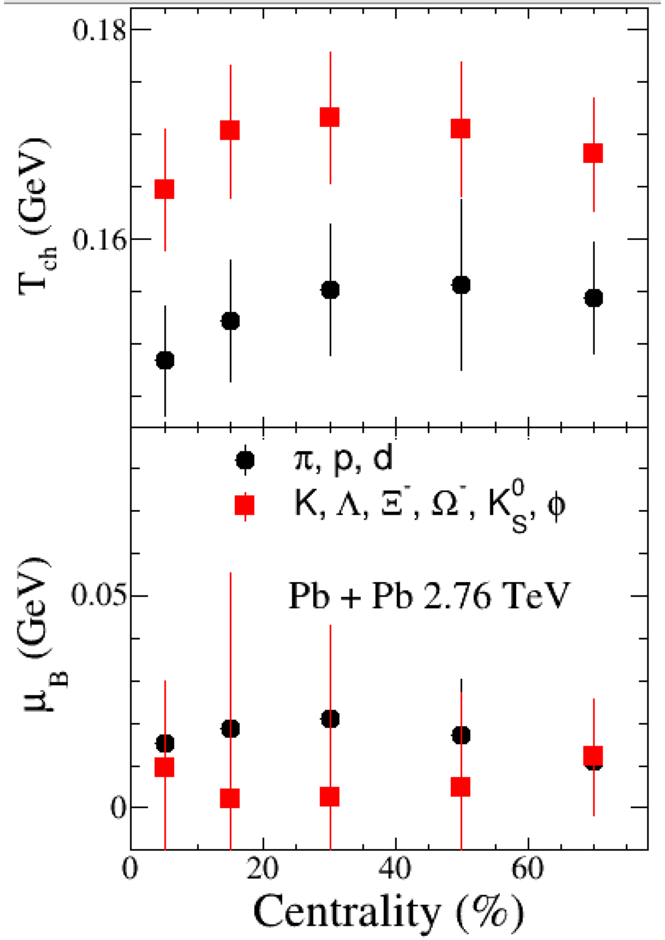
- ✯ $B_2(d)$ and $B_2(\bar{d})$ are found to be different in the most central collisions for the first time.
- ✯ B_2 reaches a minimum around $\sqrt{s_{\mathrm{NN}}} = 20$ GeV, suggesting the change of EOS.
- ✯ Deuteron and proton can be well described by thermal model at RHIC BES energy.
- ✯ T_{ch} is lower when deuterons are included in thermal fit at RHIC BES energy, especially at RHIC top energy.
- ✯ QCD Critical point: Anomalous β_T dependence of $\bar{d}/d$ ratio has been observed at $\sqrt{s_{\mathrm{NN}}} = 19.6$ GeV, implying the system evolution trajectory has passed through the critical region.

Thank you

Backup



LHC Results



0.18
0.16
T_{ch} (GeV)
π, p, d
K, Λ, Ξ⁻, Ω⁻, K_S^0, φ
Pb + Pb 2.76 TeV
0.05
0
μ_B (GeV)
0
20
40
60
Centrality (%)