SQM 2024
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

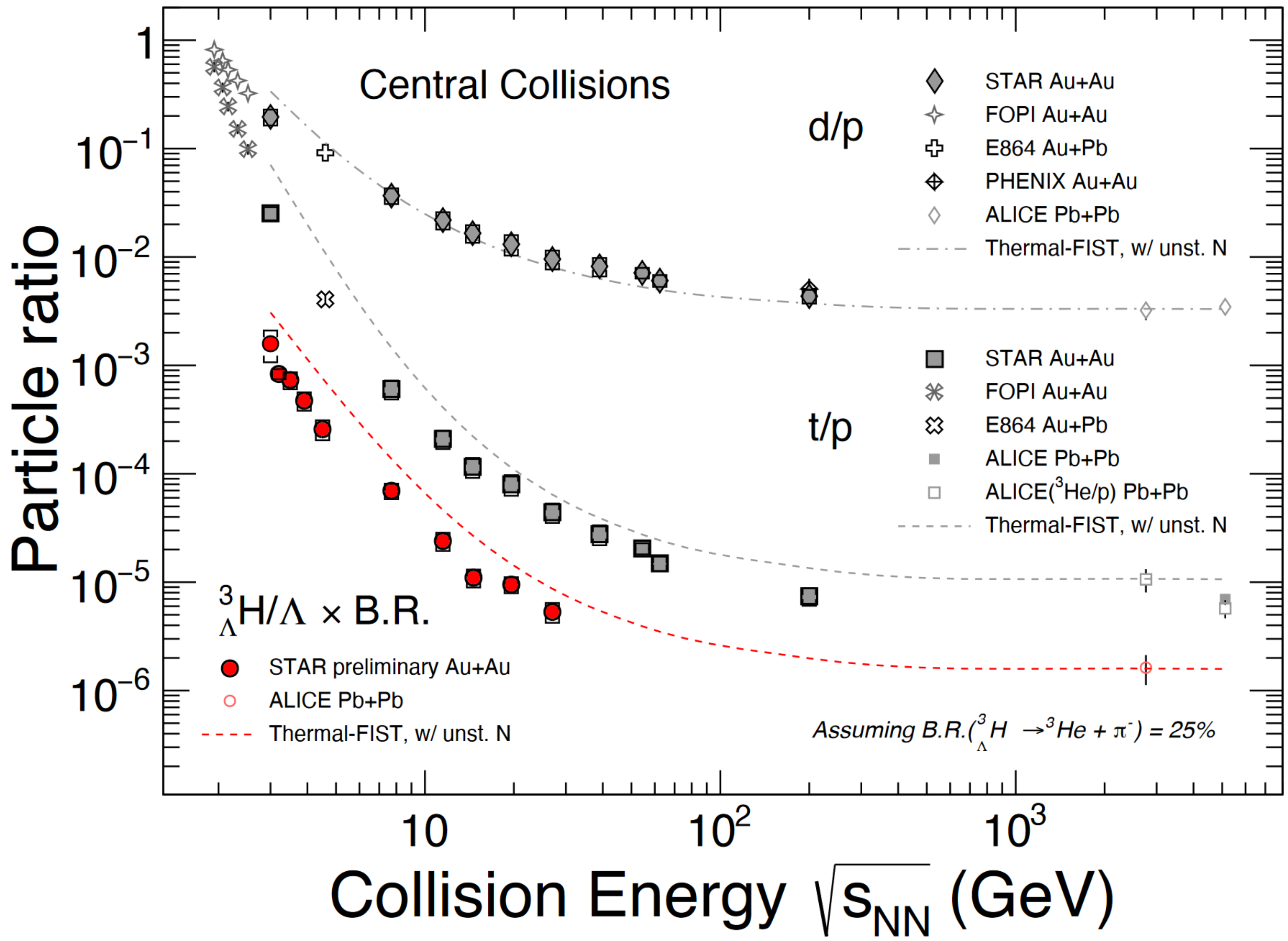
Unveiling the Dynamics of Little-Bang Nucleosynthesis

KaiJia Sun(孙开佳)
kjsun@fudan.edu.cn;
Institute of Modern Physics
Fudan University, China
June 5, 2024

复旦大学 FUDAN UNIVERSITY

Reference: *K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024)*
K. J. Sun, D. N. Liu, Y. P. Zhen, J. H. Chen, C. M. Ko, and Y. G. Ma, arXiv:2405.12015(2024)

Talk by XiuJun Li for STAR Collaboration (June 4)



Thermal model, assuming that light (hyper-)nuclei produced at a common chemical freeze-out with hadrons, overestimates both t/p **and** $^3_\Lambda H/\Lambda$.

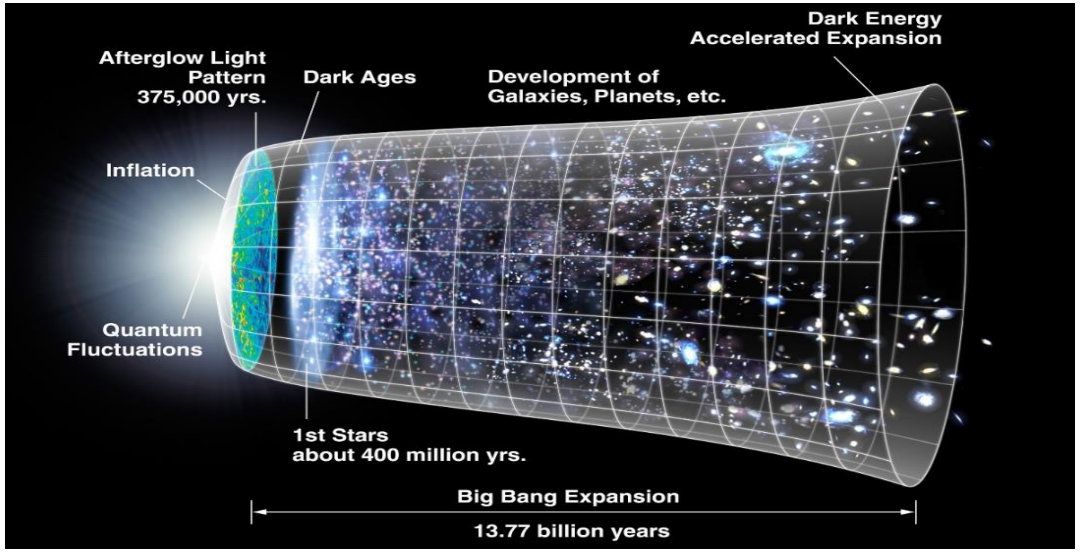
I will try to resolve this discrepancy by including the effect of **regeneration and dissociation** processes of loosely bound states during the hadronic matter expansion.

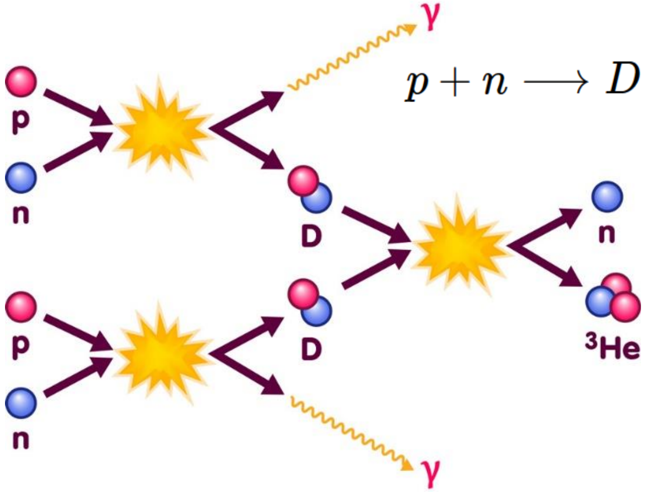
Little-Bang Nucleosynthesis

Big-bang nucleosynthesis is responsible for the formation of light nuclei in our Universe.

$t \sim 100\ s, kT < 1\ \mathrm{MeV}$

K. A. Olive et al., Phys. Rept. 333, 389–407 (2000);
《The First Three Minutes》 S. Weinberg



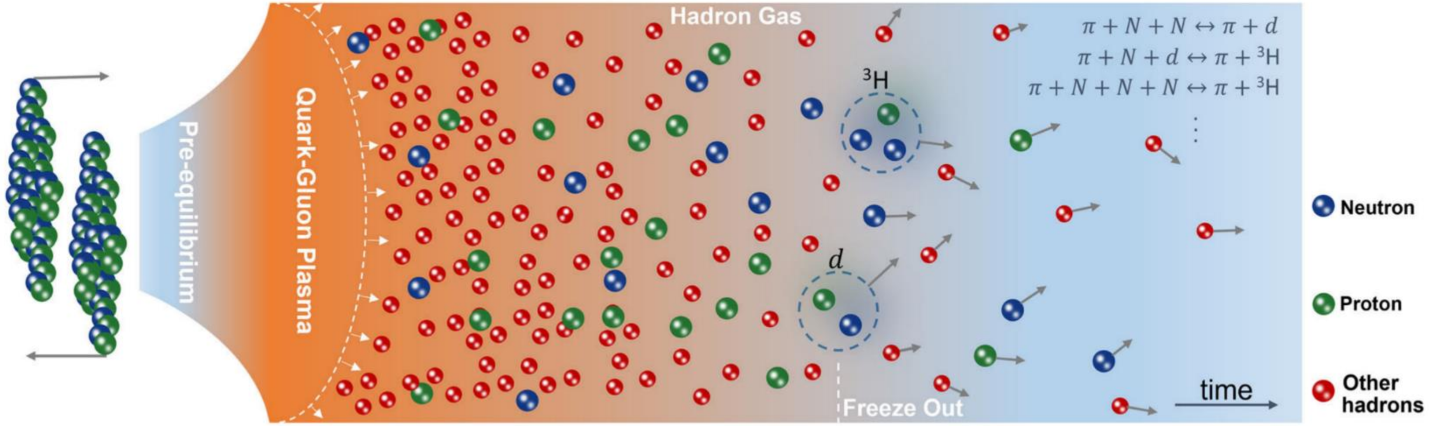


$$p + n \longrightarrow D + \gamma$$

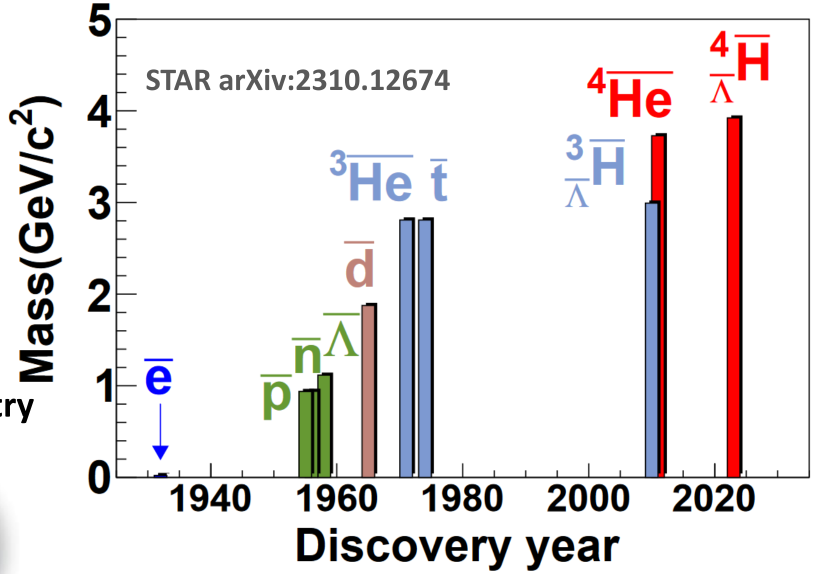
$$D + p \longrightarrow {}^3He + \gamma$$
$$D + D \longrightarrow {}^3He + n$$
$$D + D \longrightarrow {}^3H + p$$
$${}^3He + n \longrightarrow {}^3H + p$$
$$D + D \longrightarrow {}^4He + \gamma$$
$${}^3He + D \longrightarrow {}^4He + p$$
$${}^3H + D \longrightarrow {}^4He + n.$$

Synthesis of antimatter nuclei in little bangs of relativistic heavy-ion collisions $t \sim 10^{-22}\ s, kT \sim 100\ \mathrm{MeV}$

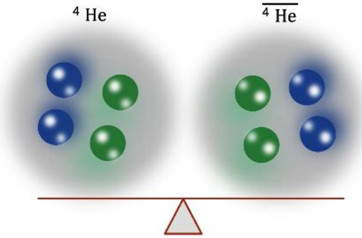
K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024)



Antimatter factory



Matter-antimatter asymmetry



J. Chen et al., Phys. Rep. 760, 1 (2018);
P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)

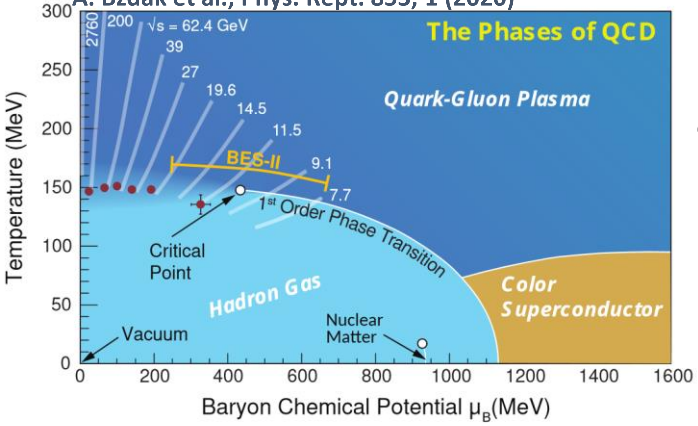
Importance of Little-Bang Nucleosynthesis (2)

Rich Physics:

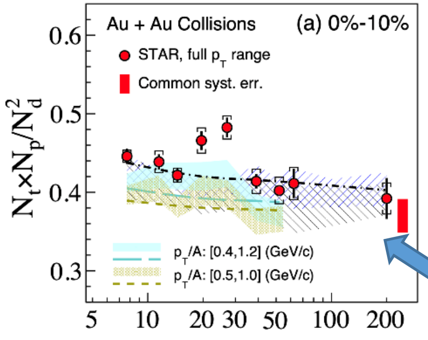
QCD phase structure

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

A. Bzdak et al., Phys. Rept. 853, 1 (2020)



STAR, PRL (2209.08058)

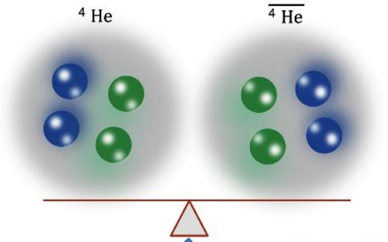


$$\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}\left[1 + \Delta\rho_n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right)\right]$$

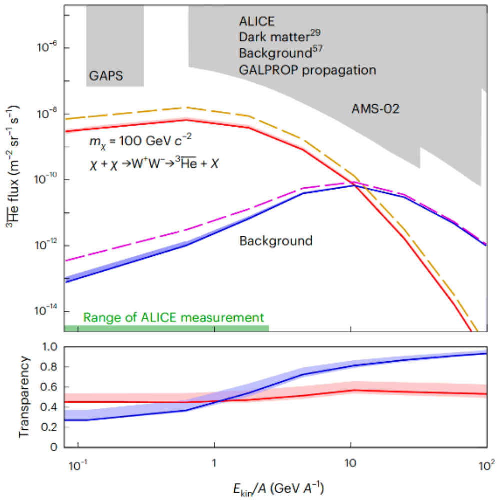
K. J. Sun, L. W. Chen, C. M. Ko, and Z. Xu, Phys. Lett. B 774, 103 (2017);

K. J. Sun, C. M. Ko, and F. Li, PLB 816, 136258 (2021)

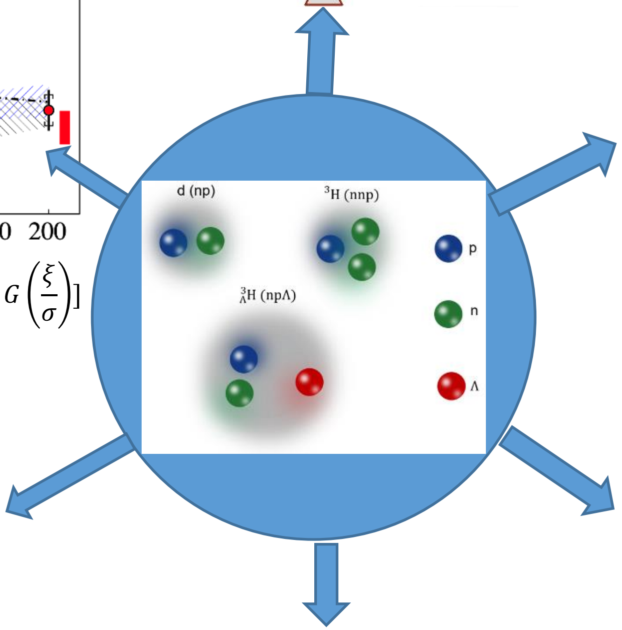
Matter-antimatter asymmetry



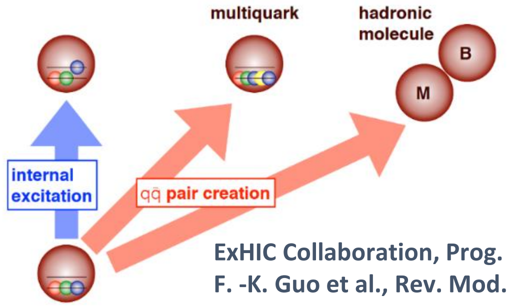
Dark matter searches



ALICE, Nature Phys. 19, 61-71 (2023)



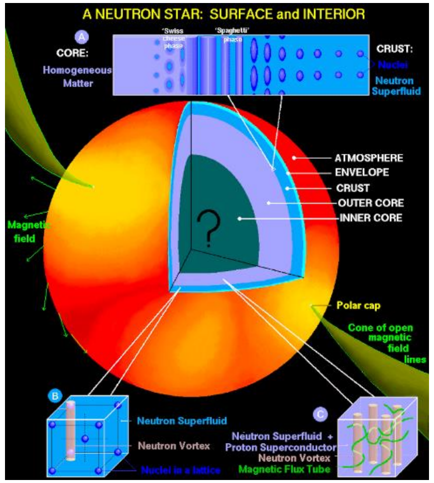
Extreme states



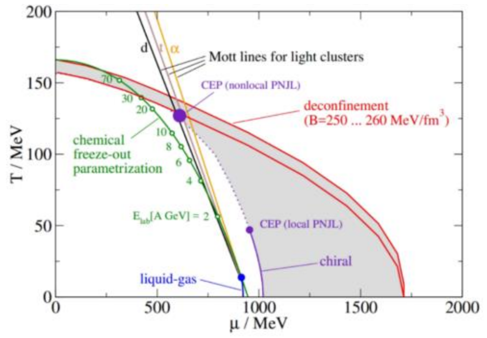
ExHIC Collaboration, Prog. Part. Nucl. Phys. 95, 279 (2017)

F. -K. Guo et al., Rev. Mod. Phys. 90, 015004 (2018)

YN interaction & Neutron star structure



Warm nuclear matter EOS



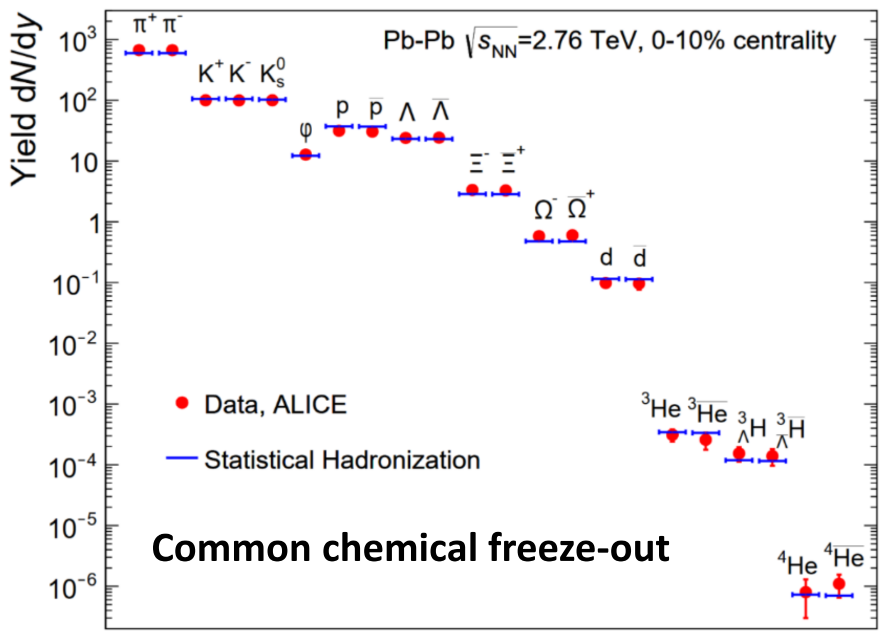
Polarization mechanism

Global Polarization of (Anti-)Hypertriton in Heavy-Ion Collisions

K. J. Sun, D. N. Liu, Y. P. Zhen, J. H. Chen, C. M. Ko, and Y. G. Ma, arXiv:2405. 12015(2024)

Statistical Hadronization of Quark-Gluon Plasma (3)

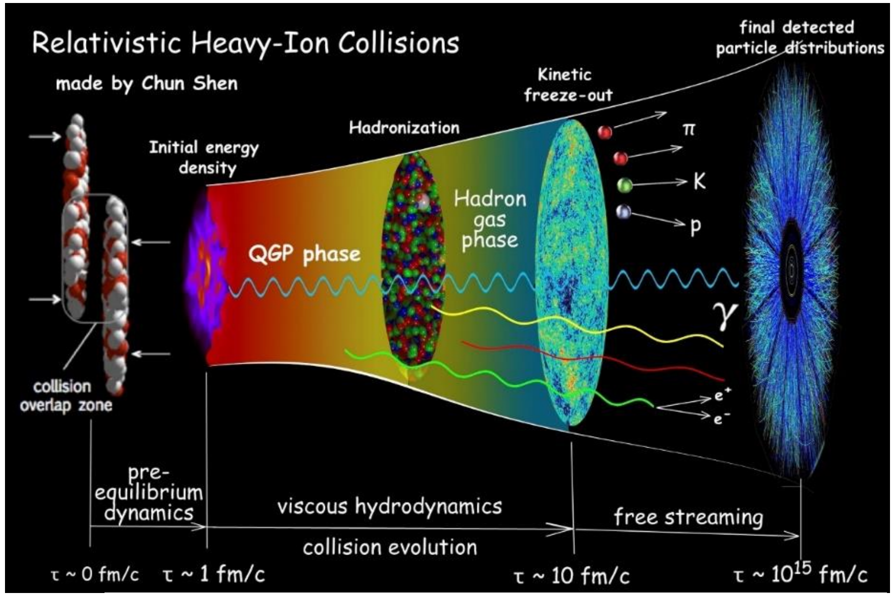
Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561, 321 (2018)

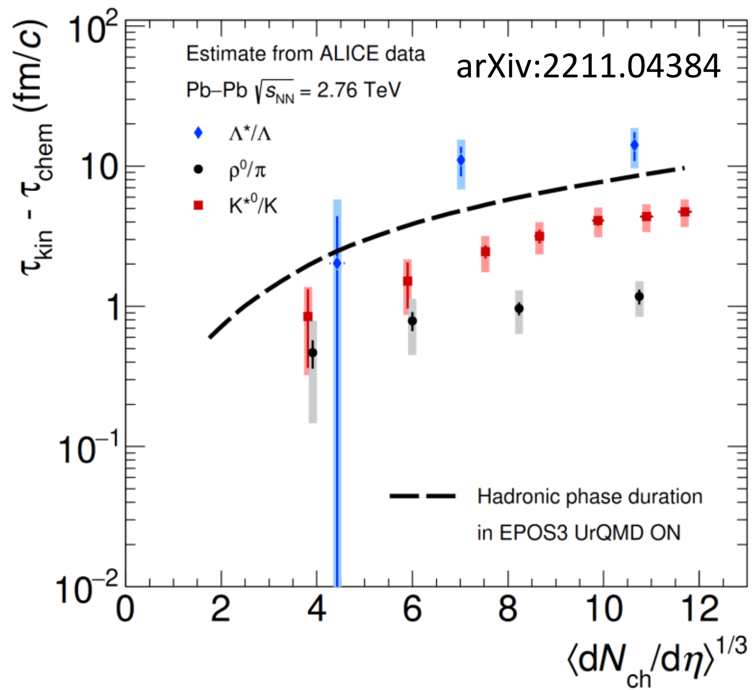


$$N_h \approx \frac{g_h V_C}{2\pi^2} m_h^2 T_C K_2(\frac{m_h}{T_C})$$

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

T_C: Chemical freeze-out temperature

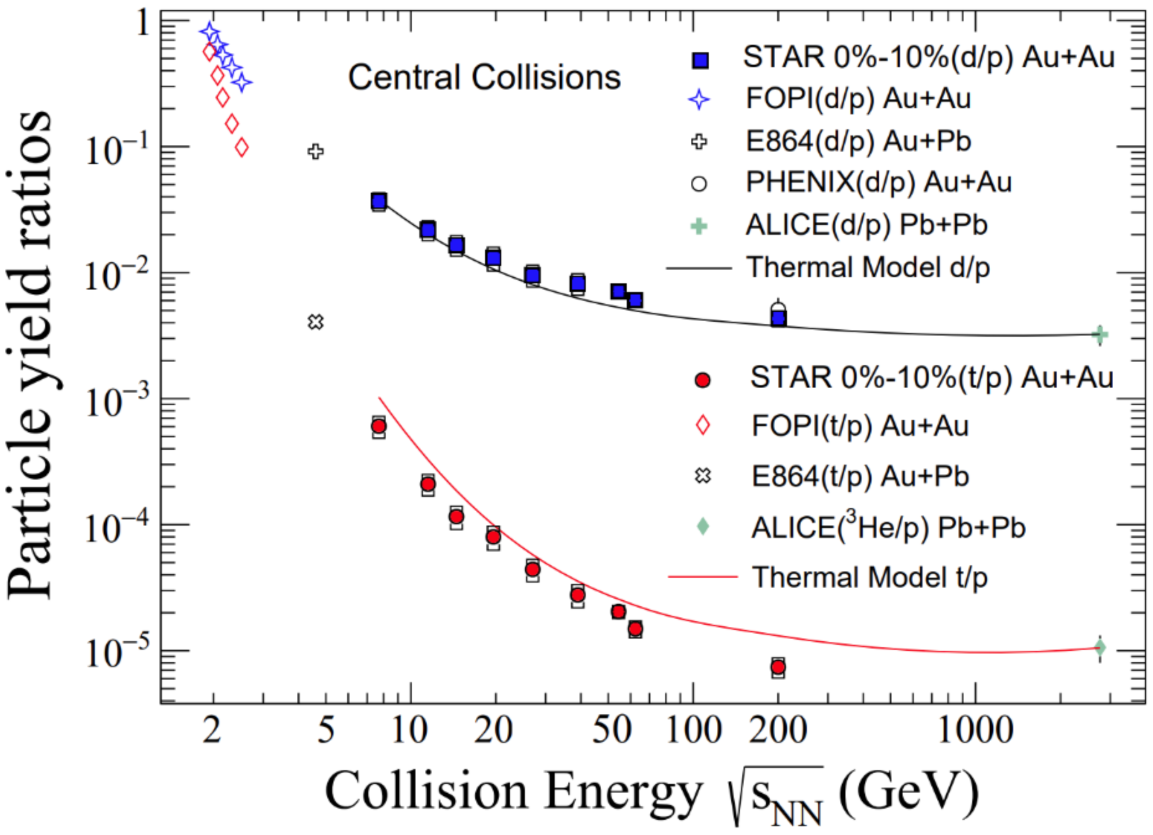


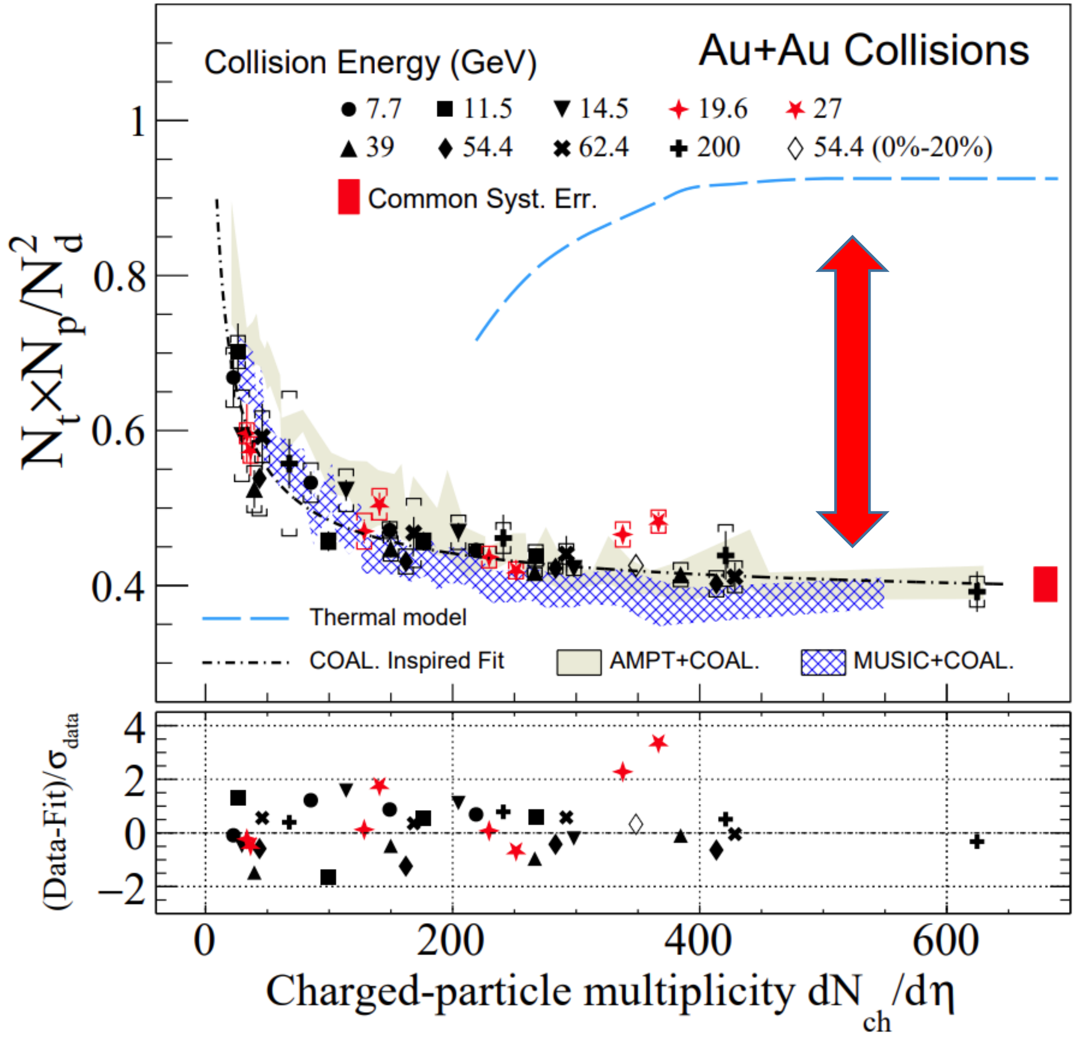


Light (hyper)nuclei and ordinary hadrons share the same high chemical freezeout temperature $T_c = 156.6 \pm 1.7$ MeV, which coincides with the pseudo transition temperature from the QGP phase to the hadron phase.

The Triton ‘Puzzle’ at RHIC (4)

STAR, Phys. Rev. Lett. 130 (2023) 202301

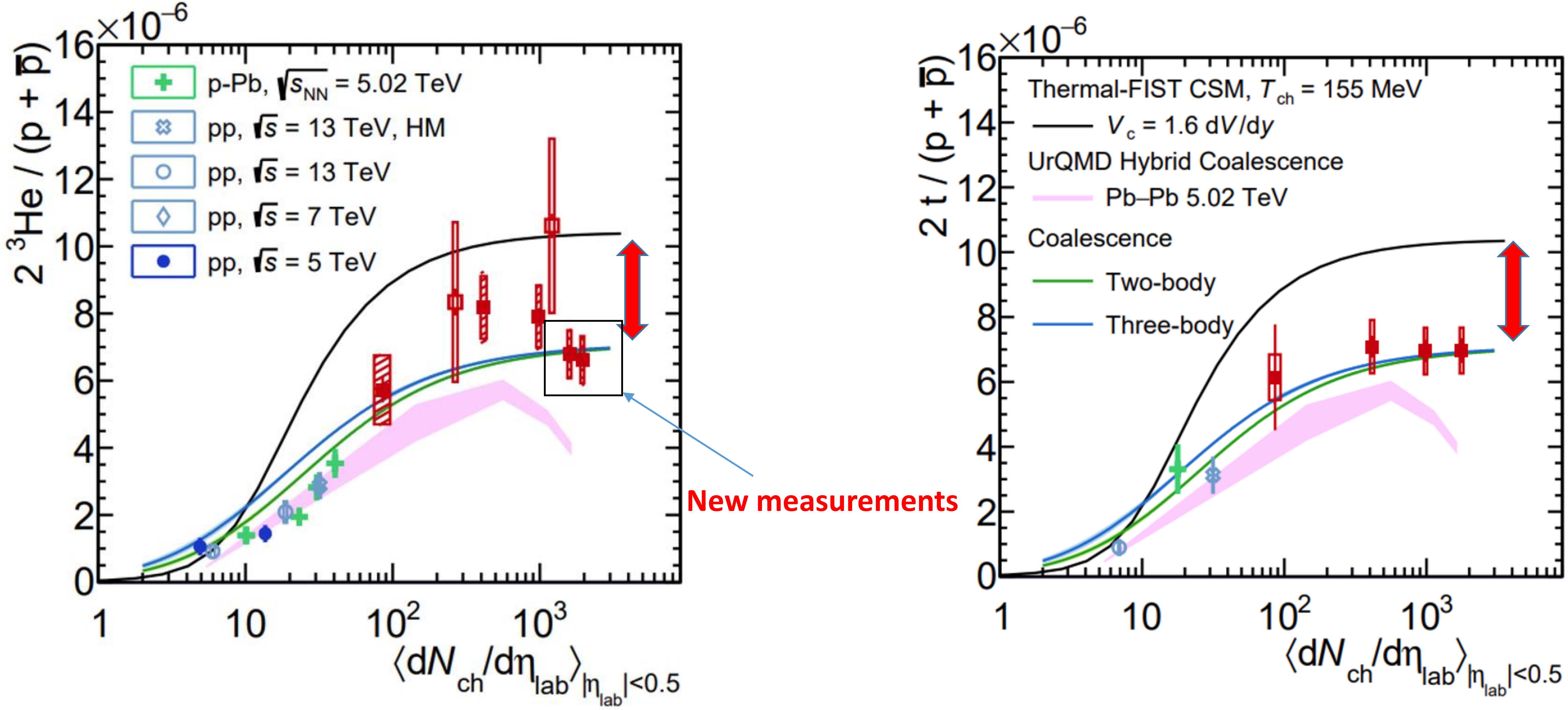




Triton yields at RHIC are overestimated by the statistical hadronization model.

The Triton 'Puzzle' at LHC (5)

ALICE, Phys. Rev. C 107, 064904 (2023)



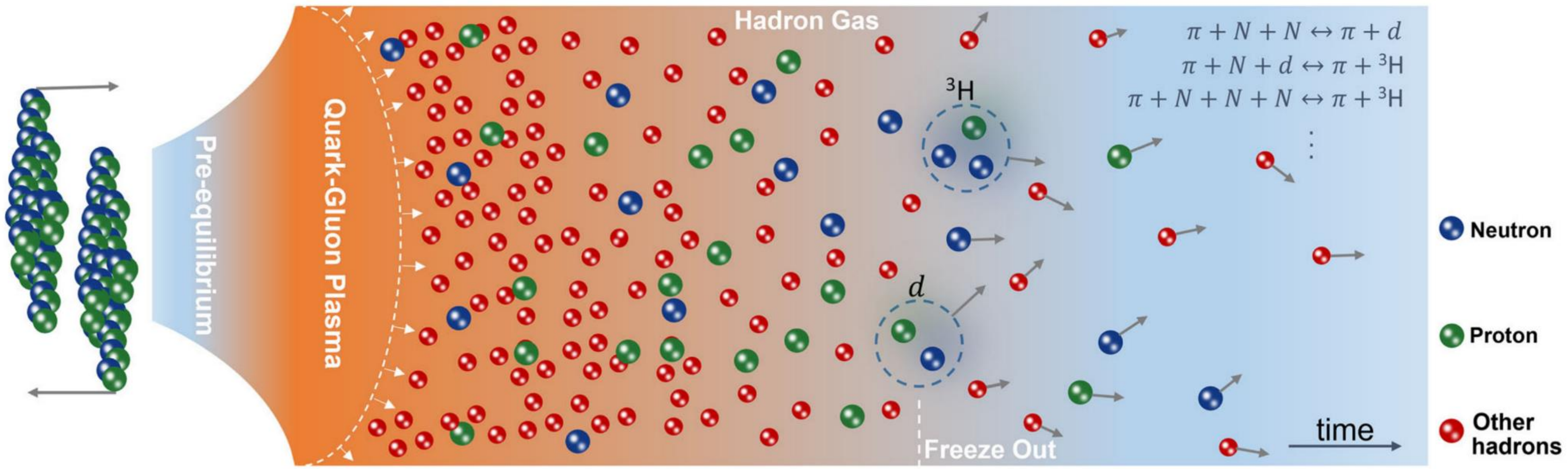
Triton (helium-3) yields at LHC are overestimated by the statistical hadronization model.

Dynamics of Little-Bang Nucleosynthesis

Relativistic Kinetic Approach

P. Danielewicz et al., NPA533, 712 (1991); PLB274, 268 (1992); Oliinychekov, Pang, Elfner & Koch, PRC 99, 044907 (2019)

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)



Relativistic kinetic equation for $\pi NN \leftrightarrow \pi d$

$$\frac{\partial f_d}{\partial t} + \frac{\mathbf{P}}{E_d} \cdot \frac{\partial f_d}{\partial \mathbf{R}} = -\mathcal{K}^{>} f_d + \mathcal{K}^{<}(1 + f_d)$$

Loss term **Gain term**

Relativistic Kinetic Approach

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)

R. Wang, Y. G. Ma, L. W. Chen, C. M. Ko, K. J. Sun, and Z. Zhang, PRC 108, L031601 (2023)

Relativistic kinetic equation for $\pi NN \leftrightarrow \pi d$

$$\frac{\partial f_d}{\partial t} + \frac{\mathbf{P}}{E_d} \cdot \frac{\partial f_d}{\partial \mathbf{R}} = -\mathcal{K}^{>} f_d + \mathcal{K}^{<}(1 + f_d)$$

with collision integral:

$$\text{R.H.S.} = \frac{1}{2g_d E_d} \int \prod_{i=1'}^{3'} \frac{\mathrm{d}^3\mathbf{p}_i}{(2\pi)^3 2E_i} \frac{\mathrm{d}^3\mathbf{p}_\pi}{(2\pi)^3 2E_\pi} \frac{E_d \mathrm{d}^3\mathbf{r}}{m_d}$$
$$\times 2m_d W_d(\tilde{\mathbf{r}}, \tilde{\mathbf{p}}) \left(\overline{|\mathcal{M}_{\pi^+ n \to \pi^+ n}|^2} + n \leftrightarrow p\right)$$
$$\times \Big[-\Big(\prod_{i=1'}^{3'} (1 \pm f_i) \Big) g_\pi f_\pi g_d f_d + \frac{3}{4} \Big(\prod_{i=1'}^{3'} g_i f_i \Big)$$
$$\times (1 + f_\pi)(1 + f_d) \Big] \times (2\pi)^4 \delta^4(p_{\text{in}} - p_{\text{out}})$$

Nonlocal collision integral to take into account the effects of finite nuclei sizes. W_d denotes deuteron Wigner function.

Impulse approximation (IA):

Length/energy scale:

$\lambda_{thermal} \sim 0.5\ fm \ll r_{np} \sim 4\ fm$

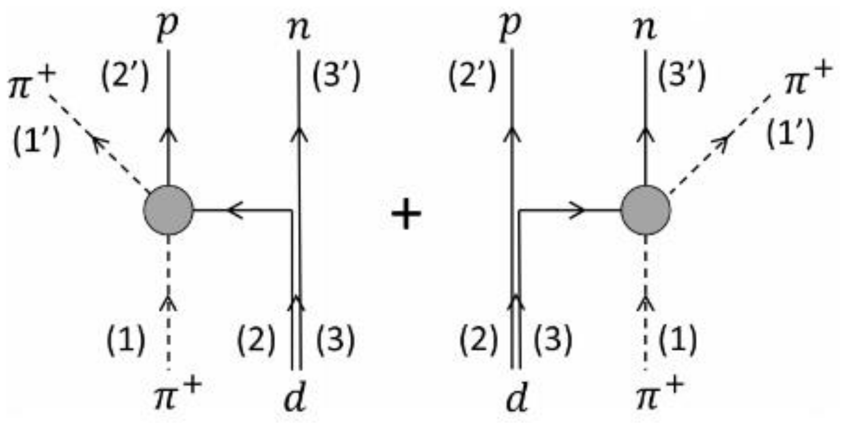


FIG. 1. Diagrams for the reaction $\pi^+ d \leftrightarrow \pi^+ np$ in the impulse approximation. The filled bubble indicates the intermediate states such as a Δ resonance.

Relativistic Kinetic Approach (8)

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)

Solving kinetic equations with the stochastic method using test particles

Probability for reaction $\pi d \leftrightarrow \pi NN$ to take place in volume ΔV and time interval Δt are given by

$$P_{23}\big|_{\mathrm{IA}} \approx F_d v_{\pi^+p}\sigma_{\pi^+p\to\pi^+p}\frac{\Delta t}{N_{\mathrm{test}}\Delta V} + (p \leftrightarrow n).$$

$$P_{32}\big|_{\mathrm{IA}} \approx \frac{3}{4}F_d v_{\pi^+p}\sigma_{\pi^+p\to\pi^+p}\frac{\Delta t W_d}{N_{\mathrm{test}}^2\Delta V} + (p \leftrightarrow n)$$

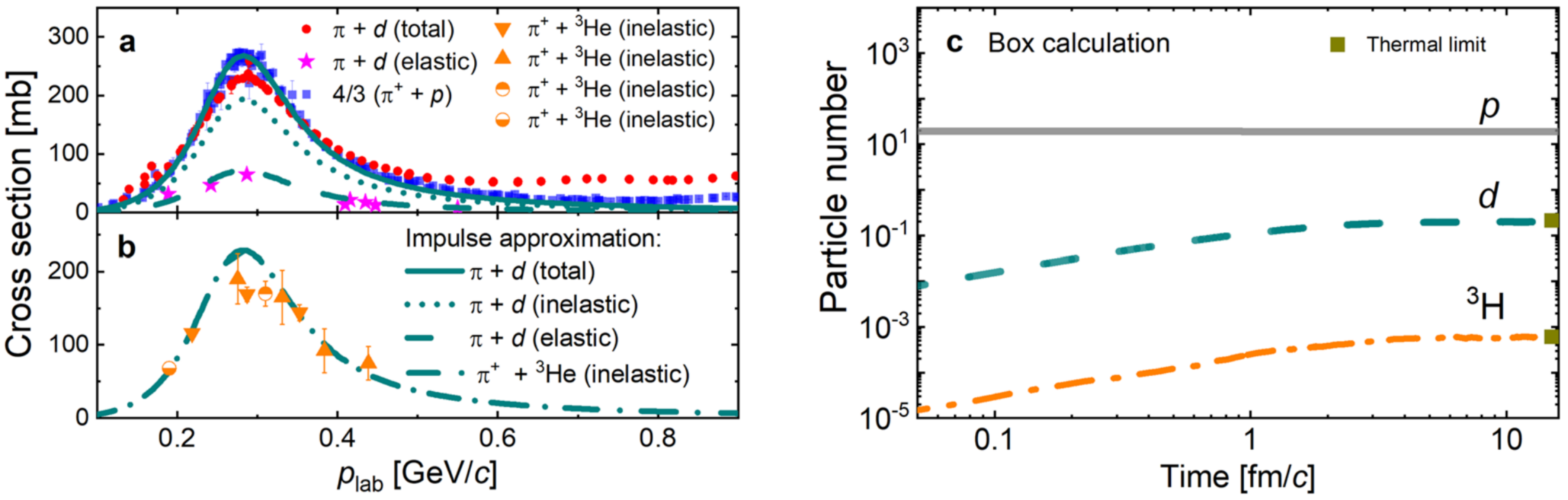
For triton or helium-3:

$$P_{42}\big|_{\mathrm{IA}} \approx \frac{1}{4}F_t\frac{v_{\pi N}\sigma_{\pi N\to\pi N}\Delta t}{N_{\mathrm{test}}^3\Delta V}W_t$$

'renormalization' factor F_d, F_t which can be fixed by πd and πt cross sections.

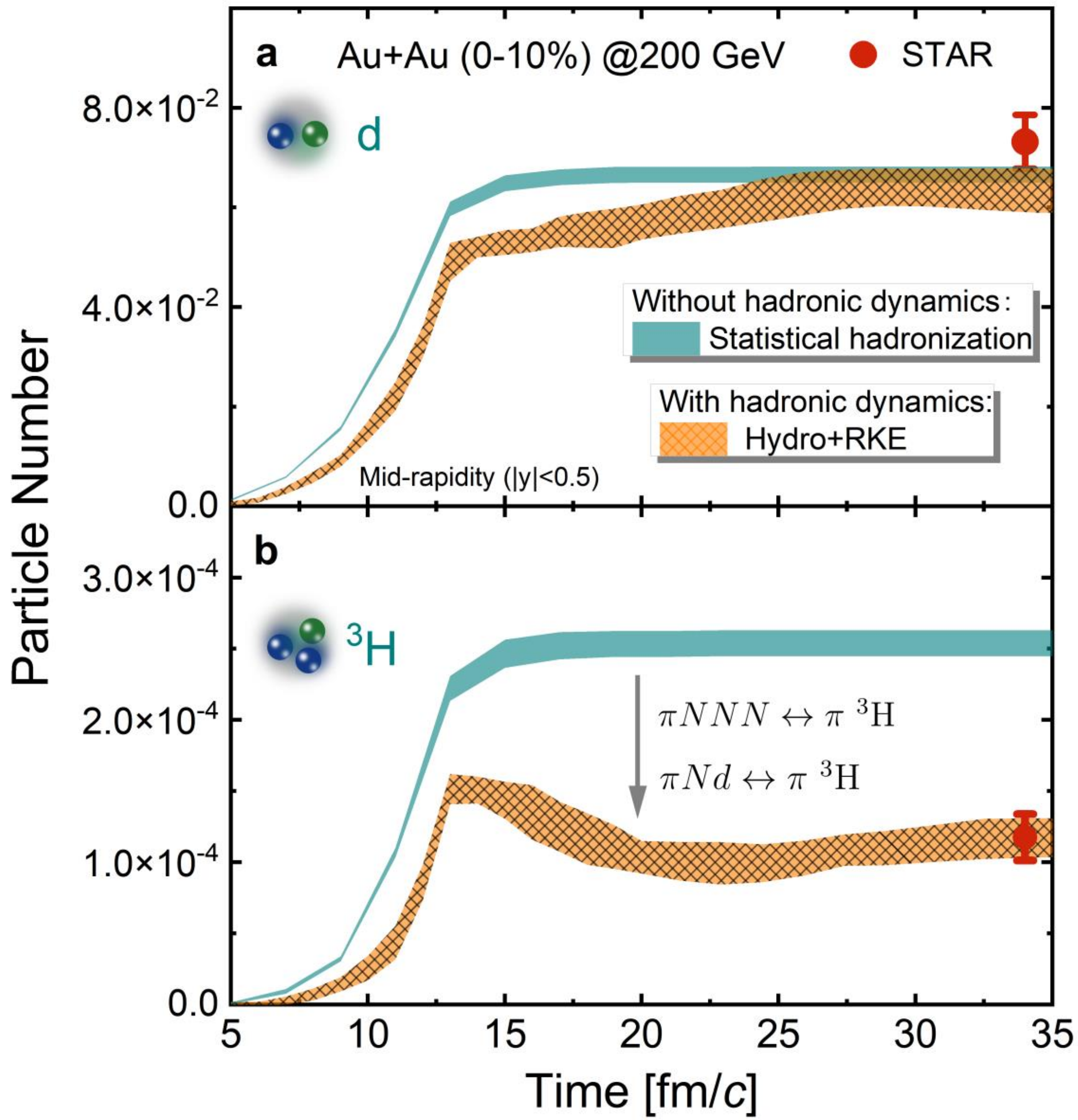
Validation: Box Calculation

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)



Hadronic Re-Scattering Effects at RHIC

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)
Data from STAR, PRL 130, 202301 (2023)

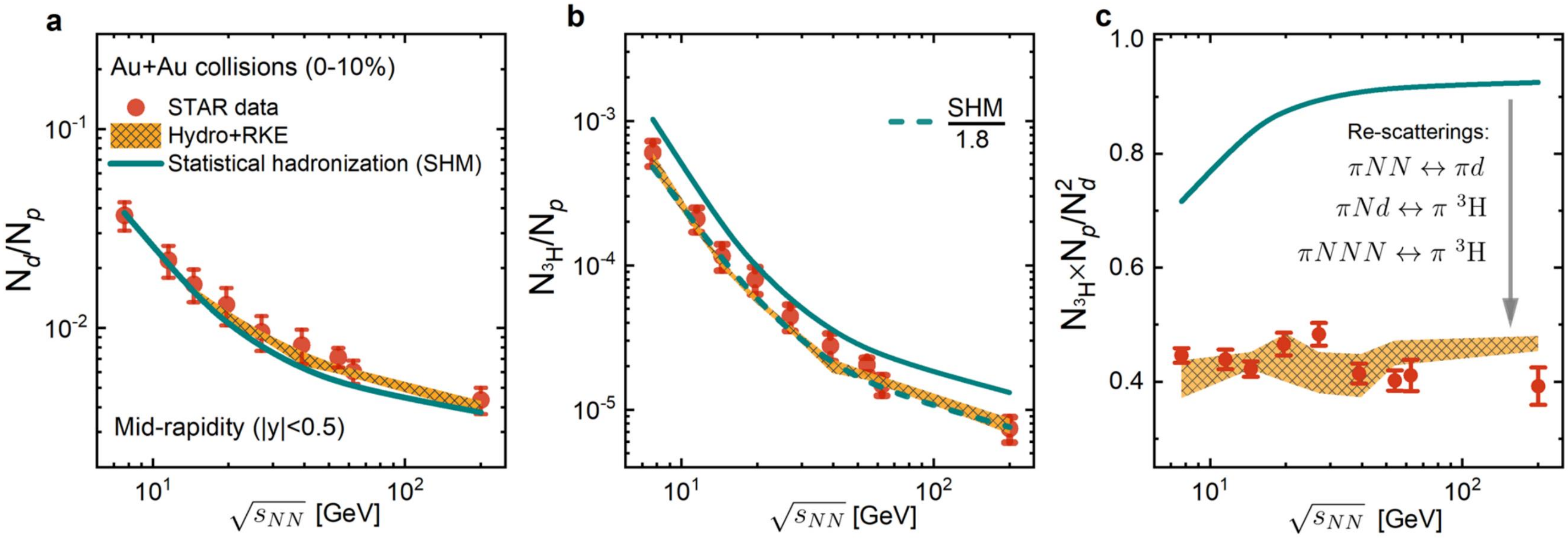


3+1 viscous hydrodynamics coupled with relativistic kinetic equations.

- A = 2 $\pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd$
- A = 3 $\pi NNN \leftrightarrow \pi t(h), \pi Nd \leftrightarrow \pi t(h),$ and etc.

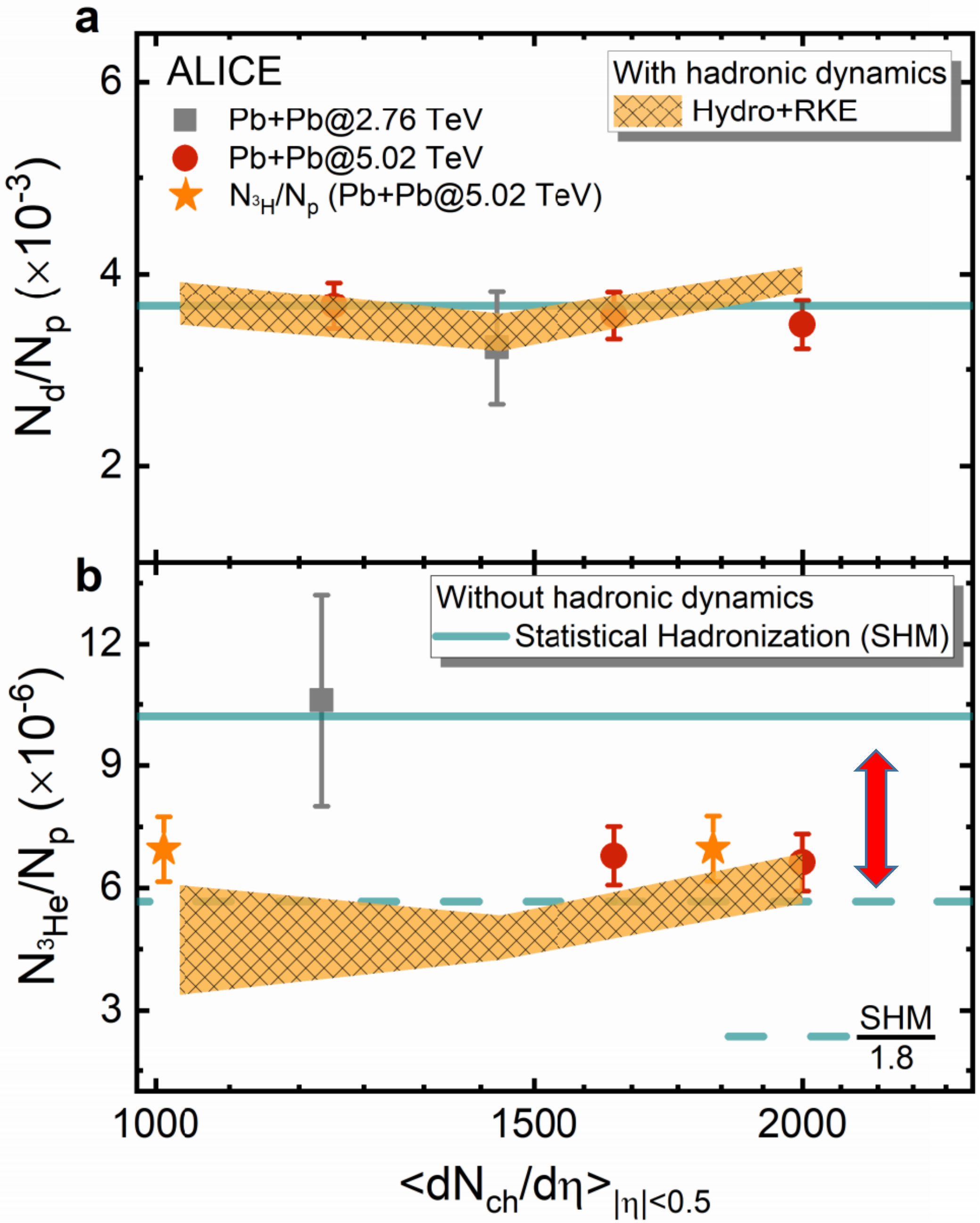
Hadronic Re-Scattering Effects at RHIC

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)
Data from STAR, PRL 130, 202301 (2023)



Hadronic re-scatterings have small effects on the final deuteron yields (see also D. Oliinychenko et al. PRC 99, 044907 (2019)), but they reduce the triton yields by about a factor of 1.8.

Hadronic Re-Scattering Effects at LHC

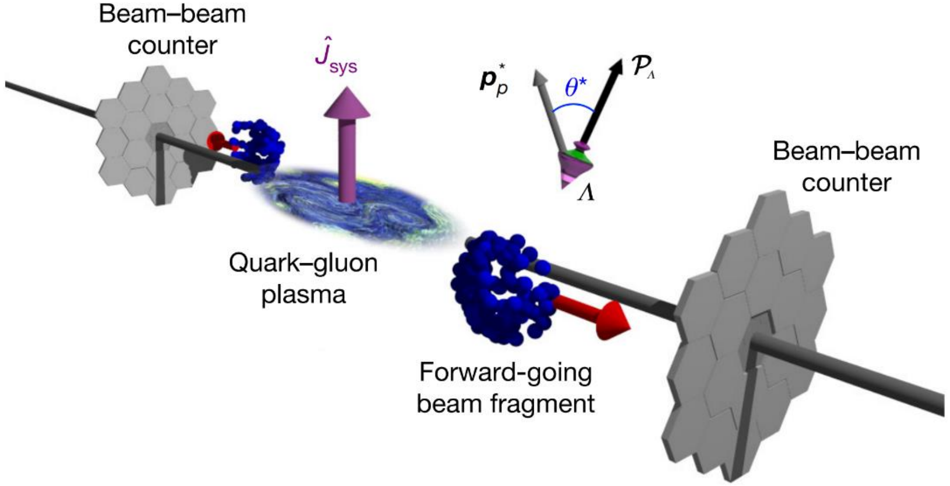


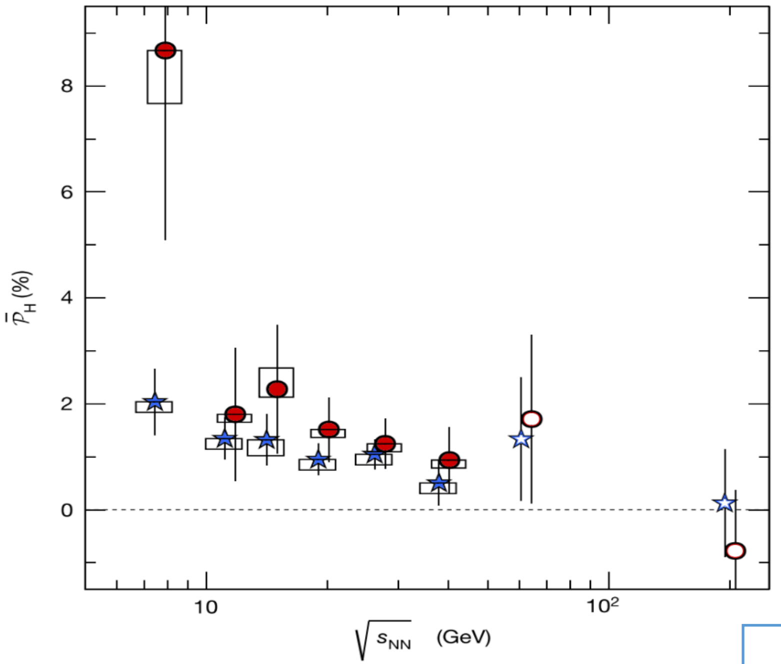
Data from ALICE, Phys. Rev. C 107, 064904 (2023)

Similar strong hadronic effects occur at the LHC energies!

Importance of spin degrees of freedom

STAR, Nature 548, 62 (2017)
Z. T. Liang and X. N. Wang PRL 94, 102301 (2005)
F. Becattini, F. Piccinini, and J. Rizzo, PRC 77, 024906 (2008)





$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H |\mathcal{P}_H| \cos\theta^*)$$

$$P_H = \frac{8}{\pi\alpha_H} \frac{\langle \sin(\Psi_1^{obs} - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

Unstable hadrons

$\Lambda(uds)$ $\Xi(uss)$ $\Omega(sss)$
$\phi(s\bar{s})$ $K^{*0}(d\bar{s})$ $\rho^+(u\bar{d})$
$J/\psi(c\bar{c})$ …

Unstable (anti-)(hyper-)nuclei

${}^3_\Lambda\mathrm{H}(np\Lambda)$ ${}^4\mathrm{Li}(\mathrm{nppp})$
${}^3_{\bar{\Lambda}}\overline{\mathrm{H}}(\bar{n}\bar{p}\bar{\Lambda})$ ${}^4\overline{\mathrm{Li}}(\bar{n}\bar{p}\bar{p}\bar{p})$
…

Stable (anti-)(hyper-)nuclei

$d(np)$ ${}^3\mathrm{He}(npp)$
$\bar{d}(\bar{n}\bar{p})$ ${}^3\overline{\mathrm{He}}(\bar{n}\bar{p}\bar{p})$
…

K. J. Sun, D. N. Liu, Y. P. Zhen, J. H. Chen, C. M. Ko, and Y. G. Ma, arXiv:2405. 12015(2024)

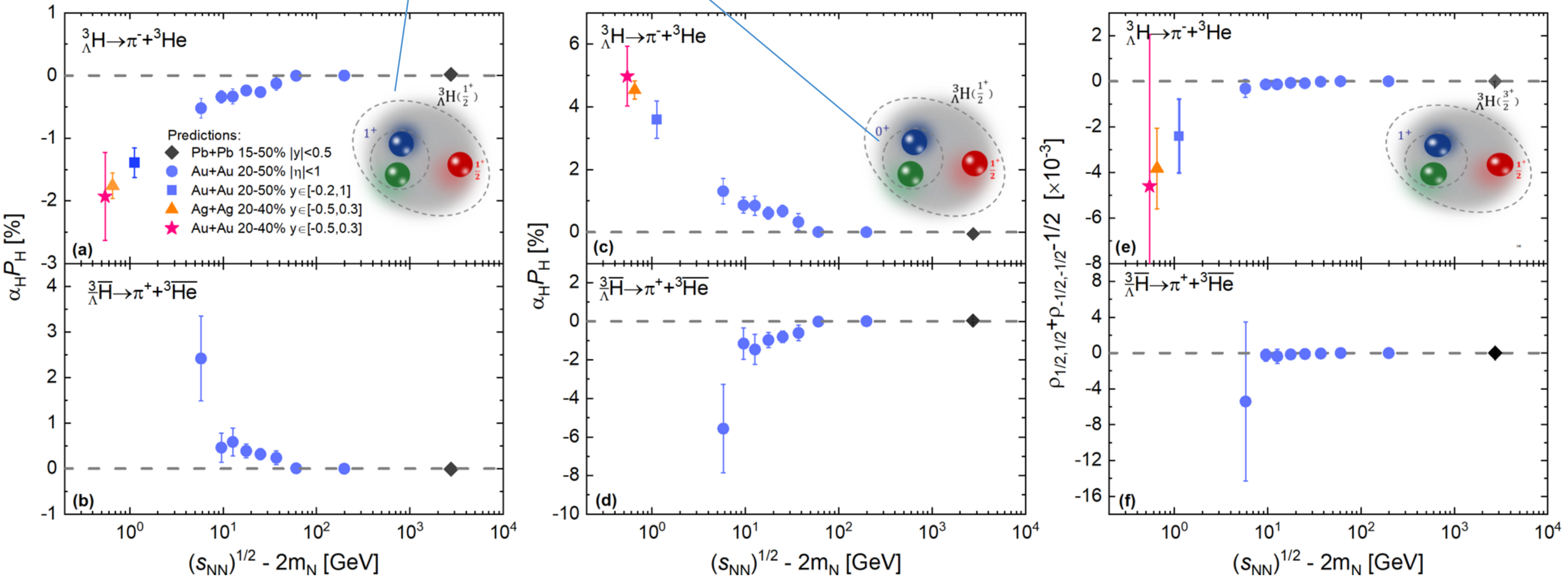
Spin polarization of (anti)hypertriton

K. J. Sun, D. N. Liu, Y. P. Zhen, J. H. Chen, C. M. Ko, and Y. G. Ma, arXiv:2405. 12015(2024)

Hypertriton spin structure versus its global polarization

$\alpha_{^3_\Lambda H} \approx -\frac{1}{2.58}\alpha_\Lambda$ Spin triplet

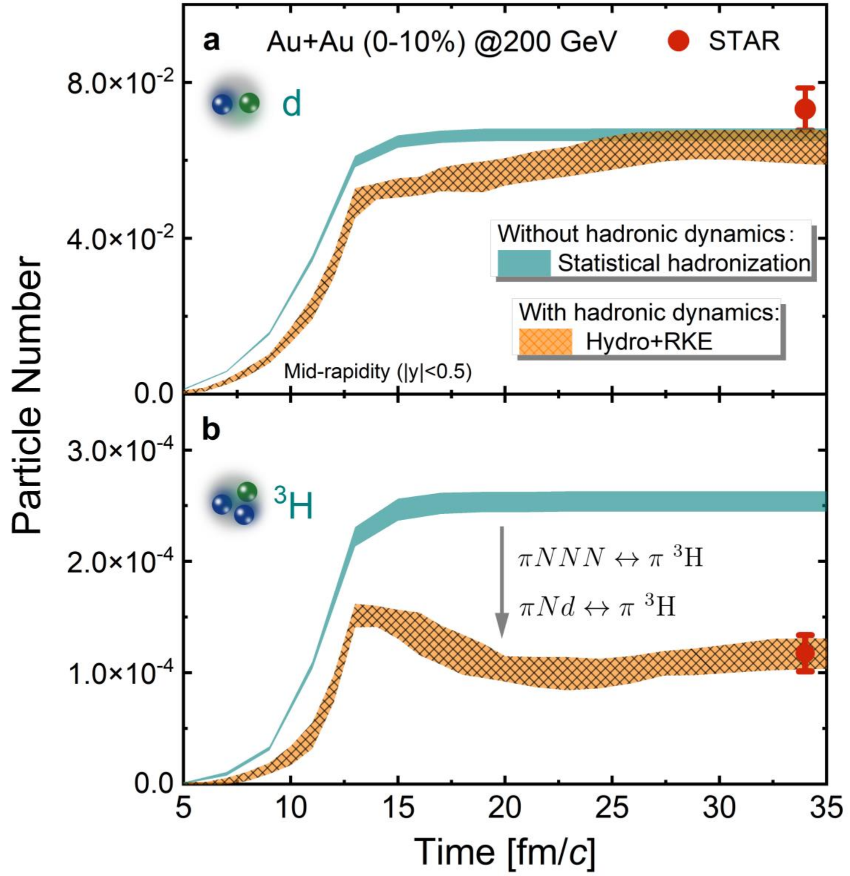
Spin singlet $\alpha_{^3_\Lambda H} \approx \alpha_\Lambda$



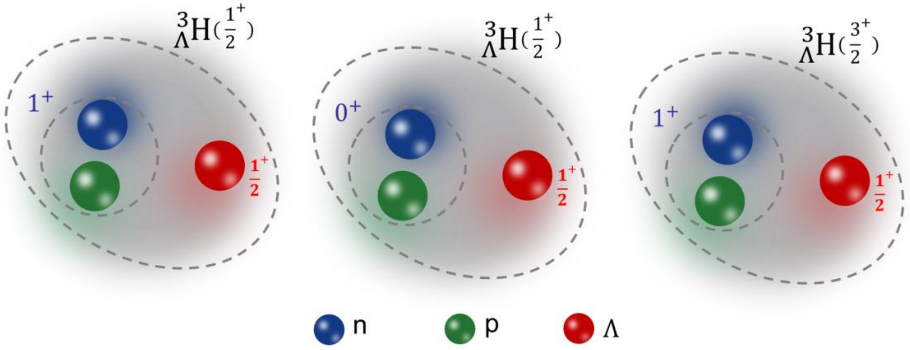
Summary

1. The little-bang nucleosynthesis is relevant to many fundamental physics.

2. Hadronic re-scattering effects: Post-hadronization dynamics plays a vital role in the little-bang nucleosynthesis. It suppresses triton yields by about a factor of two at RHIC and LHC energies. Chemical freeze-out of light nuclei are much later than that of pions, kaons, and protons (consistent with coal.).



3. Polarization of unstable (hyper-)nuclei provides a new probe to their spin structure and production mechanisms.



Outlook

This field is boosting.

1. **Quantum correction:** **In collisions of small systems, light (hyper)nuclei production are suppressed due to their appreciable sizes.**

K. J. Sun et al., Phys. Lett. B792, 132-137(2019)
D. N. Liu et al., 2404. 02701.
ALICE, Phys. Rev. Lett. 128, 055203(2022)

2. **Mott effects:** **Light nuclei yields are reduced in the baryon-rich medium due to Pauli blocking.** *R. Wang et al., PRC 108, L031601 (2023)*

3. **Nucleosynthesis in jets:** **Loosely-bound light nuclei in energetic jets!**

ALICE, PRL 131.042301 (2023)

4. **Correlations and fluctuations:** **EVE fluct. and HBT corr. provide more info.**

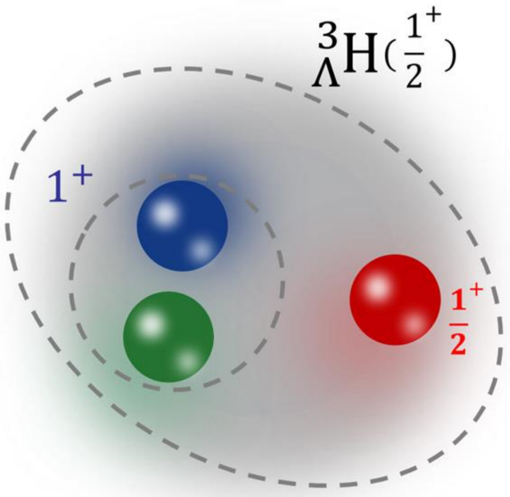
K. J. Sun et al., PLB 840, 137864 (2023) *ALICE, PRL 131. 041901 (2023)*

5. **Polarization of hypernucleus:** *K. J. Sun et al., arXiv:2405.12015 (2024)*

and much more…

Backup

(Anti-)hypertriton polarization and its spin structure



K. J. Sun et al., arXiv:2405.12015 (2024)

$$
\begin{aligned}
|\tfrac{1}{2},\uparrow\rangle_{^3_\Lambda\mathrm{H}} &= \frac{\sqrt{6}}{3}|\tfrac{1}{2},\tfrac{1}{2}\rangle_n|\tfrac{1}{2},\tfrac{1}{2}\rangle_p|\tfrac{1}{2},-\tfrac{1}{2}\rangle_\Lambda \\
&- \frac{\sqrt{6}}{6}\big(|\tfrac{1}{2},\tfrac{1}{2}\rangle_n|\tfrac{1}{2},-\tfrac{1}{2}\rangle_p|\tfrac{1}{2},\tfrac{1}{2}\rangle_\Lambda \\
&+ |\tfrac{1}{2},-\tfrac{1}{2}\rangle_n|\tfrac{1}{2},\tfrac{1}{2}\rangle_p|\tfrac{1}{2},\tfrac{1}{2}\rangle_\Lambda\big), \\
|\tfrac{1}{2},\downarrow\rangle_{^3_\Lambda\mathrm{H}} &= -\frac{\sqrt{6}}{3}|\tfrac{1}{2},-\tfrac{1}{2}\rangle_n|\tfrac{1}{2},-\tfrac{1}{2}\rangle_p|\tfrac{1}{2},\tfrac{1}{2}\rangle_\Lambda \\
&+ \frac{\sqrt{6}}{6}\big(|\tfrac{1}{2},\tfrac{1}{2}\rangle_n|\tfrac{1}{2},-\tfrac{1}{2}\rangle_p|\tfrac{1}{2},-\tfrac{1}{2}\rangle_\Lambda \\
&+ |\tfrac{1}{2},-\tfrac{1}{2}\rangle_n|\tfrac{1}{2},\tfrac{1}{2}\rangle_p|\tfrac{1}{2},-\tfrac{1}{2}\rangle_\Lambda\big).
\end{aligned}
$$

Coalescence model for hypertriton production (without baryon spin correlation)

$$E_i\frac{d^3N_{i,\pm\frac{1}{2}}}{d\mathbf{p}_i^3} = \int_{\Sigma^\mu} d^3\sigma_\mu p_i^\mu w_{i,\pm\frac{1}{2}}(\mathbf{x}_i,\mathbf{p}_i)\bar{f}_i(\mathbf{x}_i,\mathbf{p}_i)$$

$$w_{i,\pm\frac{1}{2}} = \frac{1}{2}[1\pm\mathcal{P}_i(\mathbf{x}_i,\mathbf{p}_i)]$$

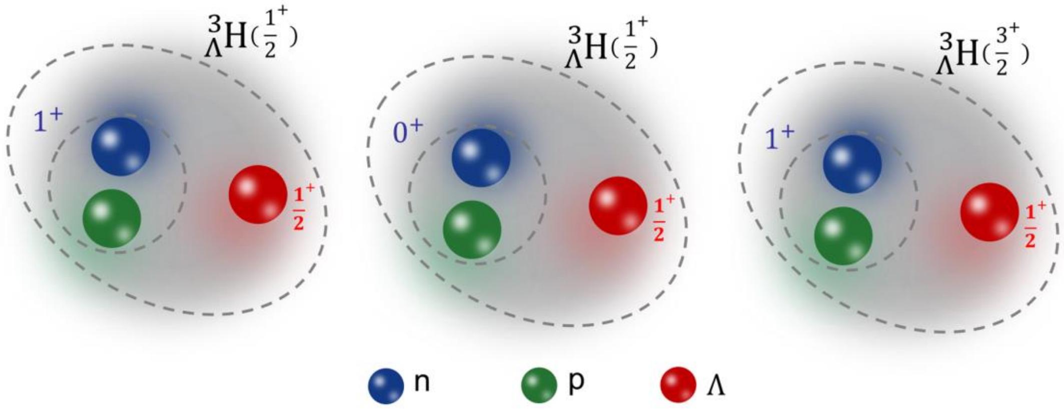
$$\hat{\rho}_i = \mathrm{diag}\left(\frac{1+\mathcal{P}_i}{2},\frac{1-\mathcal{P}_i}{2}\right)$$

$$\bar{f}_i = \frac{g_i}{(2\pi)^3}\left[\exp(p_i^\mu u_\mu/T)/\xi_i+1\right]^{-1}$$

$$\hat{\rho}_{np\Lambda} = \hat{\rho}_n\otimes\hat{\rho}_p\otimes\hat{\rho}_\Lambda$$

$$
\begin{aligned}
E\frac{d^3N_{^3_\Lambda\mathrm{H},\pm\frac{1}{2}}}{d\mathbf{P}^3} &= E\int\prod_{i=n,p,\Lambda}p_i^\mu d^3\sigma_\mu\frac{d^3p_i}{E_i}\bar{f}_i(\mathbf{x}_i,\mathbf{p}_i) \\
&\times\left(\frac{2}{3}w_{n,\pm\frac{1}{2}}w_{p,\pm\frac{1}{2}}w_{\Lambda,\mp\frac{1}{2}}+\frac{1}{6}w_{n,\pm\frac{1}{2}}w_{p,\mp\frac{1}{2}}w_{\Lambda,\pm\frac{1}{2}}\right. \\
&\left.+\frac{1}{6}w_{n,\mp\frac{1}{2}}w_{p,\pm\frac{1}{2}}w_{\Lambda,\pm\frac{1}{2}}\right) \\
&\times W_{^3_\Lambda\mathrm{H}}(\mathbf{x}_n,\mathbf{x}_p,\mathbf{x}_\Lambda;\mathbf{p}_n,\mathbf{p}_p,\mathbf{p}_\Lambda)\delta(\mathbf{P}-\sum_i\mathbf{p}_i)
\end{aligned}
$$

(Anti-)hypertriton polarization and its spin structure



J^P	structure	decay mode	$\frac{dN}{d\cos\theta^*}$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda\mathrm{H} \to \pi^- + ^3\mathrm{He}$	$\frac{1}{2}(1 - \frac{1}{2.58}\alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(0^+)$	$^3_\Lambda\mathrm{H} \to \pi^- + ^3\mathrm{He}$	$\frac{1}{2}(1 + \alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*)$
$\frac{3}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda\mathrm{H} \to \pi^- + ^3\mathrm{He}$	$\frac{1}{2}\left(1 - \mathcal{P}_\Lambda^2(3\cos^2\theta^* - 1)\right)$
$\frac{1}{2}^-$	$\bar{\Lambda}(\frac{1}{2}^-) - \overline{np}(1^-)$	$^3_{\bar{\Lambda}}\overline{\mathrm{H}} \to \pi^+ + ^3\overline{\mathrm{He}}$	$\frac{1}{2}(1 - \frac{1}{2.58}\alpha_{\bar{\Lambda}} \mathcal{P}_{\bar{\Lambda}} \cos\theta^*)$
$\frac{1}{2}^-$	$\bar{\Lambda}(\frac{1}{2}^-) - \overline{np}(0^-)$	$^3_{\bar{\Lambda}}\overline{\mathrm{H}} \to \pi^+ + ^3\overline{\mathrm{He}}$	$\frac{1}{2}(1 + \alpha_{\bar{\Lambda}} \mathcal{P}_{\bar{\Lambda}} \cos\theta^*)$
$\frac{3}{2}^-$	$\bar{\Lambda}(\frac{1}{2}^-) - \overline{np}(1^-)$	$^3_{\bar{\Lambda}}\overline{\mathrm{H}} \to \pi^+ + ^3\overline{\mathrm{He}}$	$\frac{1}{2}\left(1 - \mathcal{P}_{\bar{\Lambda}}^2(3\cos^2\theta^* - 1)\right)$

K. J. Sun et al., arXiv:2405.12015 (2024)