



Production and Polarization of Hypernuclei in Heavy-Ion Collisions

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In collaboration with Dai-Neng Liu, Yun-Peng Zheng, Lie-Wen Chen, Jin-Hui Chen, Che Ming Ko, Jun Xu, Yu-Gang Ma

24-28, October

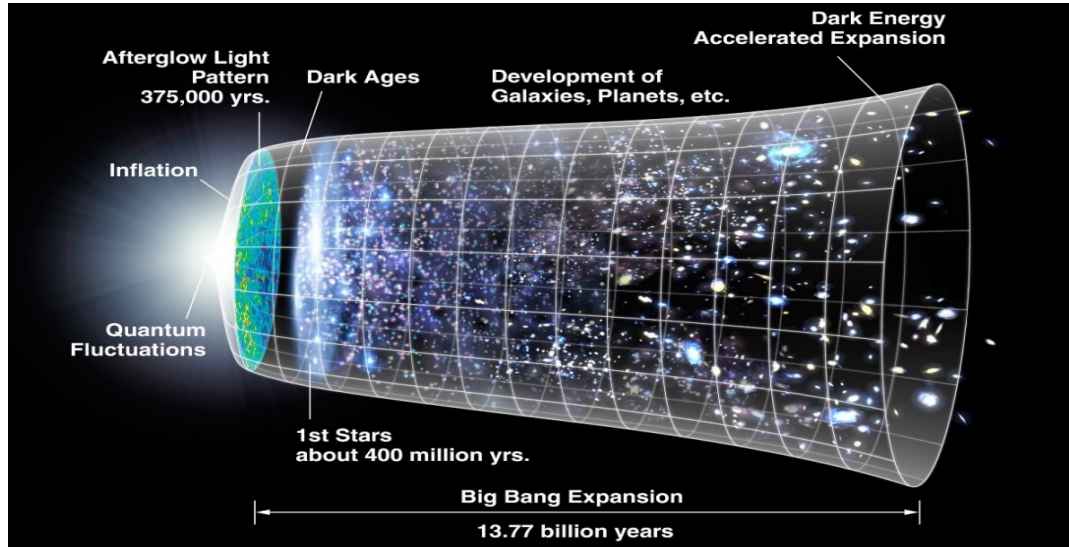
Outline

1. Production of light (anti-)hypernuclei production in heavy-ion collisions
2. Probing the wave function size of (anti-)hypertriton
Kai-Jia Sun *et al.*, Phys. Lett. B 792, 132-137 (2019)
Dai-Neng Liu *et al.*, Phys.Lett.B 855, 138855 (2024)
3. Global spin polarization of unstable light (hyper)nuclei
Kai-Jia Sun *et al.*, Phys. Rev. Lett. 134, 022301 (2025)
Dai-Neng Liu *et al.*, arXiv:2508.12193 (2025)
Yun-Peng Zheng *et al.*, arXiv:2509.15286(2025)
4. Dynamics of light (hyper)nuclei production with pion-nucleus femtoscopy
Kai-Jia Sun, Rui Wang *et al.*, Nature Commun. 15, 1074 (2024)
4. Open questions

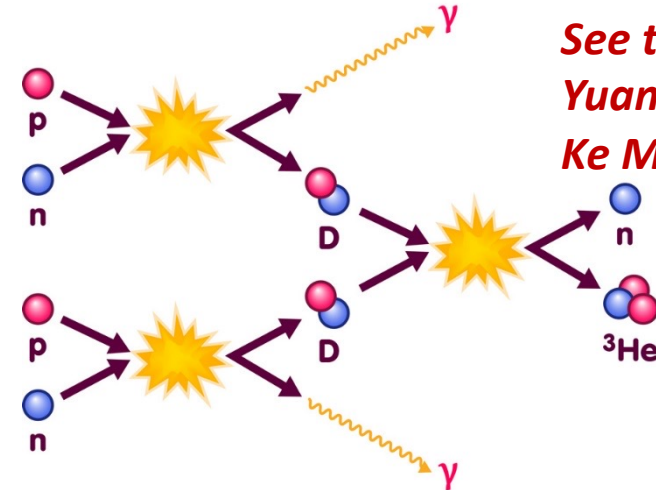
Little-Bang Nucleosynthesis (LBN)

(1)

K. A. Olive et al., Phys. Rept. 333, 389–407 (2000);

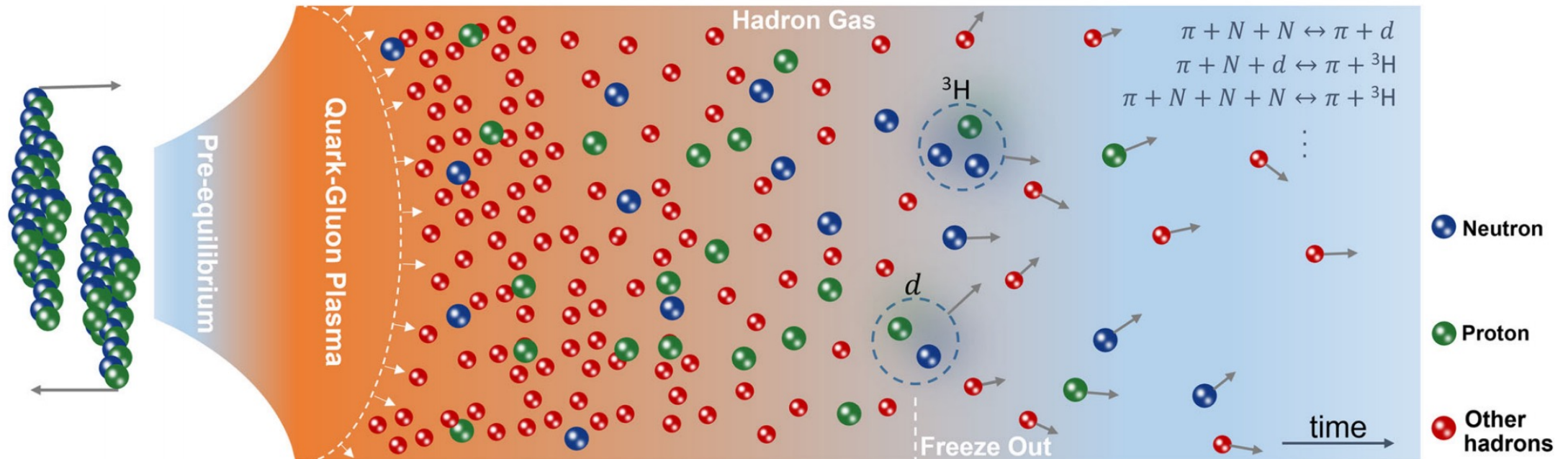


$$t \sim 100 \text{ s}, kT < 1 \text{ MeV}$$



See talks by Rui-Qin Wang,
Yuan-Zhe Wang, Tian-Hao Shao,
Ke Mi, Xiu-Jun Li et al.

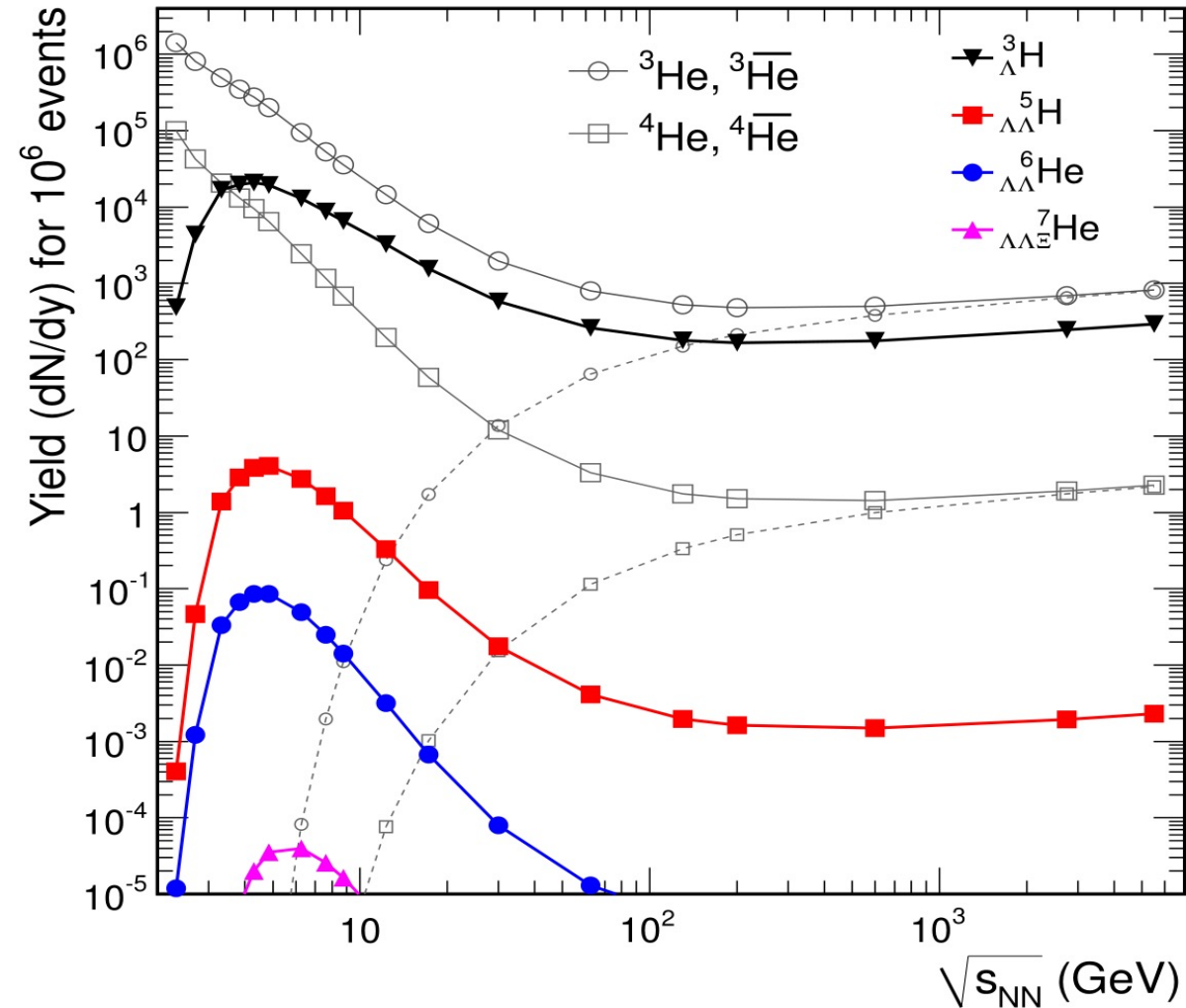
K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024) $t \sim 10^{-23} \text{ s}, T \sim 100 \text{ MeV}$



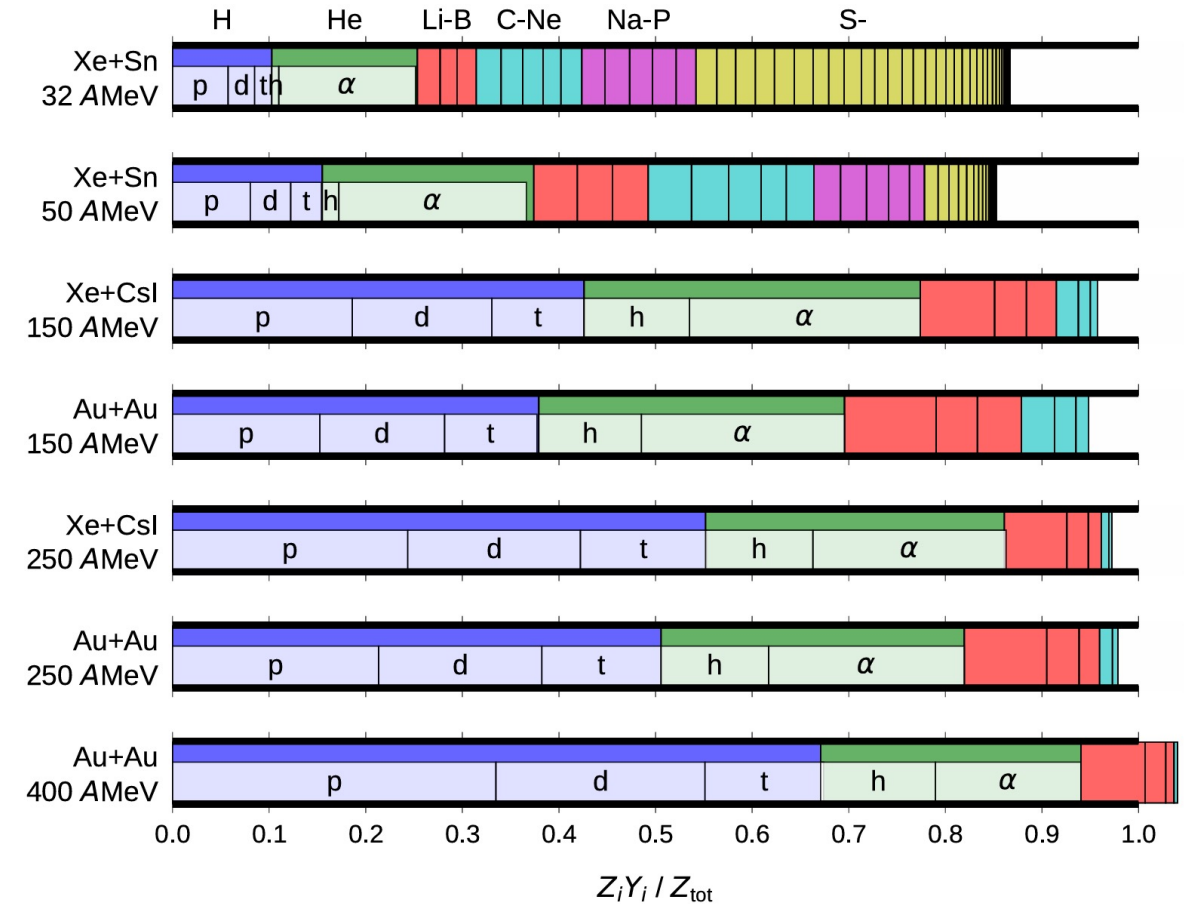
Little-Bang Nucleosynthesis (LBN)

(2)

A. Andronic et al., Phys.Lett.B 697 (2011) 203-207



A. Ono, Prog.Part.Nucl.Phys. 105 (2019) 139-179



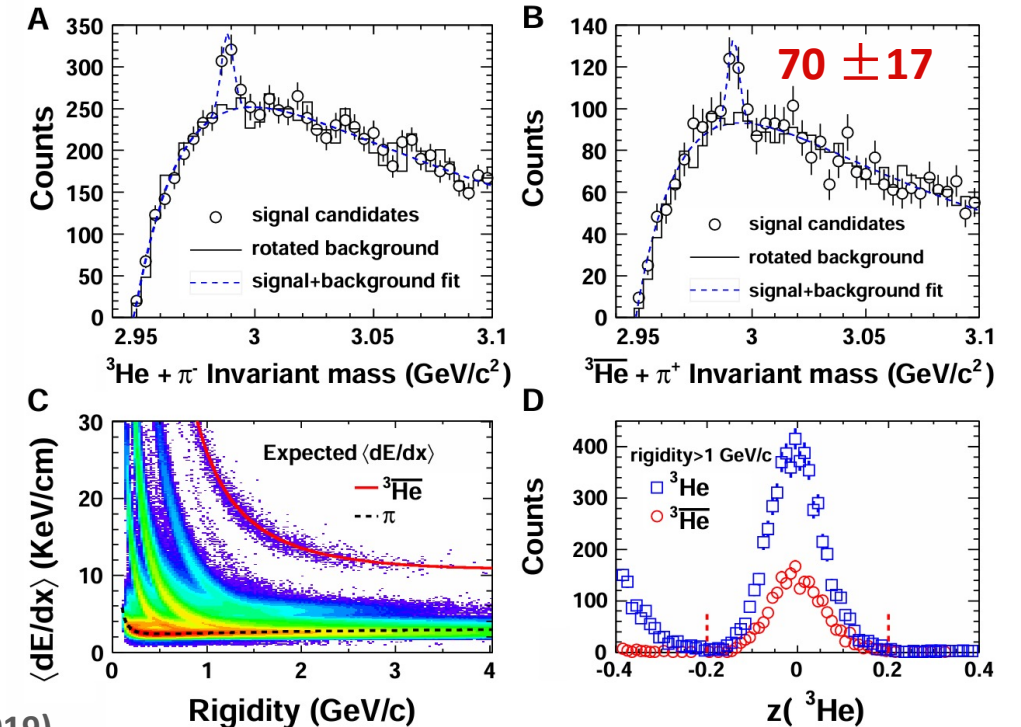
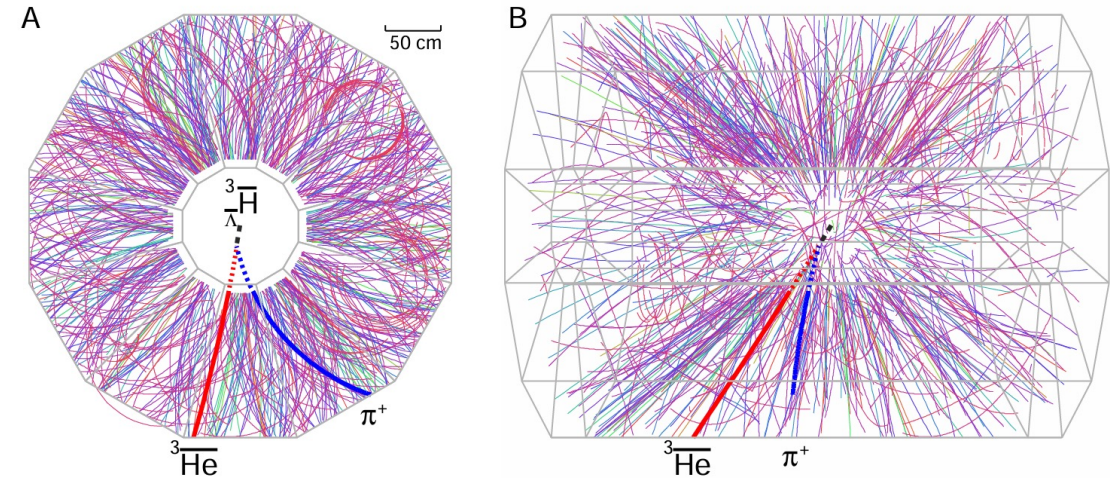
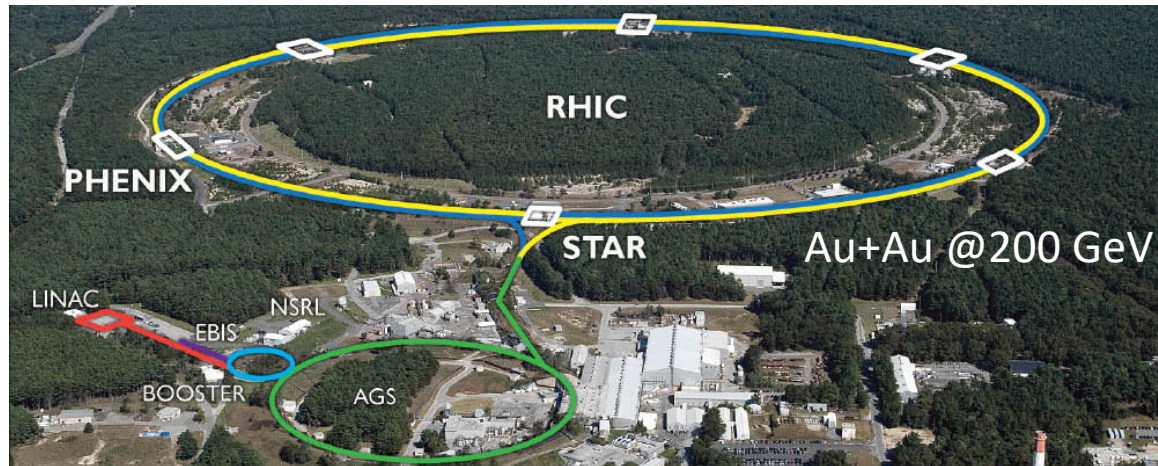
Little-Bang Nucleosynthesis (**anti-hypertriton**) (3)

Synthesis of **antimatter** hypernuclei

Observation of an Antimatter Hypernucleus

The STAR Collaboration*† STAR, Science 328, 58 (2010)

Nuclear collisions recreate conditions in the universe microseconds after the Big Bang. Only a very small fraction of the emitted fragments are light nuclei, but these states are of fundamental interest. We report the observation of antihypertritons—comprising an antiproton, an antineutron, and an antilambda hyperon—produced by colliding gold nuclei at high energy. Our analysis yields 70 ± 17 antihypertritons ($\bar{\Lambda}^3\text{H}$) and 157 ± 30 hypertritons ($\Lambda^3\text{H}$). The measured yields of $\bar{\Lambda}^3\text{H}$ ($\bar{\Lambda}^3\text{H}$) and $\bar{\Lambda}^3\text{He}$ ($\bar{\Lambda}^3\text{He}$) are similar, suggesting an equilibrium in coordinate and momentum space populations of up, down, and strange quarks and antiquarks, unlike the pattern observed at lower collision energies. The production and properties of antinuclei, and of nuclei containing strange quarks, have implications spanning nuclear and particle physics, astrophysics, and cosmology.



Little-Bang Nucleosynthesis (anti-hypernuclei) (4)

nature STAR, Nature 632, 1026 (2024)

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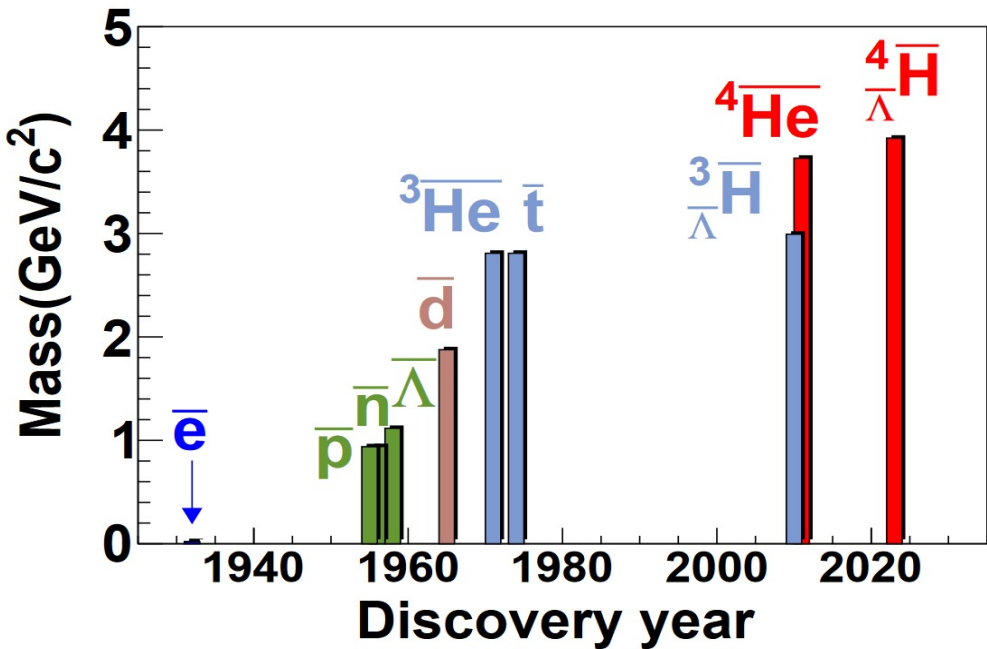
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Article | Published: 21 August 2024

Observation of the antimatter hypernucleus $\bar{\Lambda}^4\bar{H}$

[STAR Collaboration](#)

[Nature](#) 632, 1026–1031 (2024) | [Cite this article](#)



PHYSICAL REVIEW LETTERS 134, 162301 (2025)

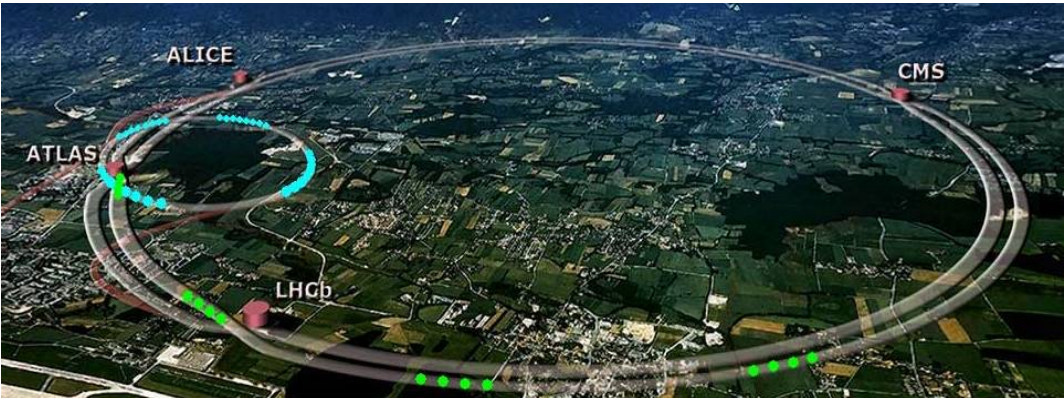
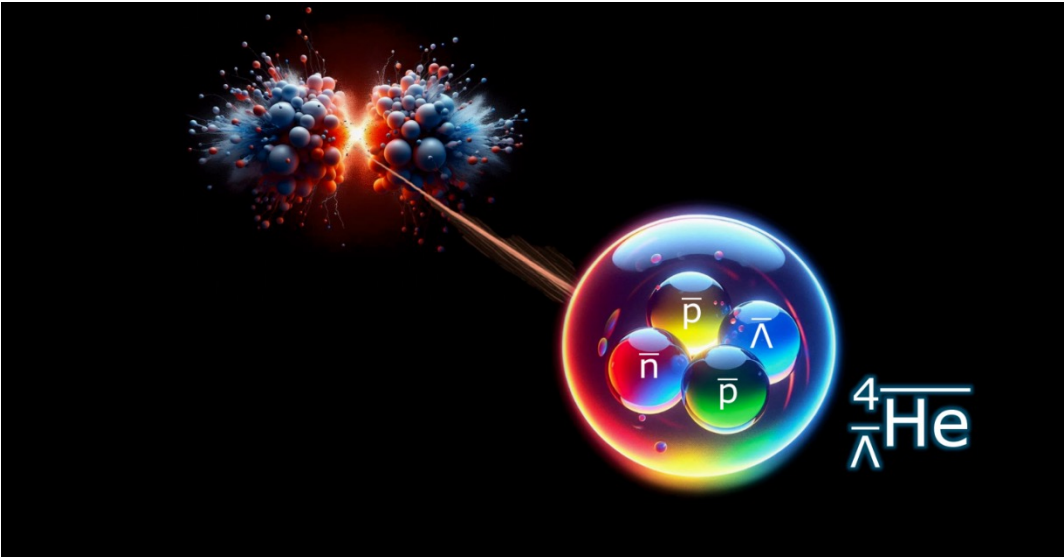
Editors' Suggestion

Featured in Physics

First Measurement of $A=4$ Hypernuclei and Antihypernuclei at the LHC

S. Acharya *et al.**

(ALICE Collaboration)

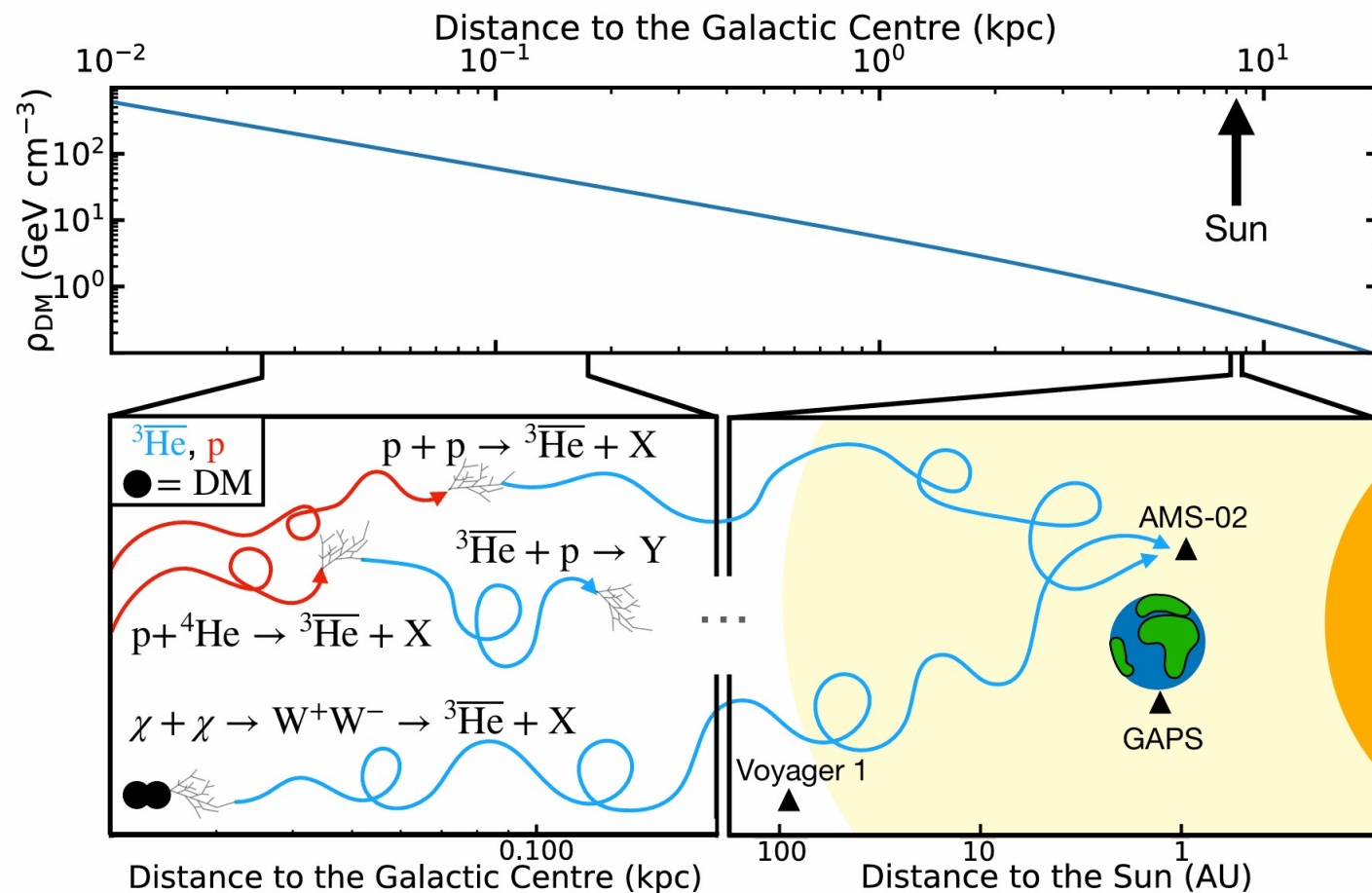


J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)

Dark Matter Searches with Antimatter

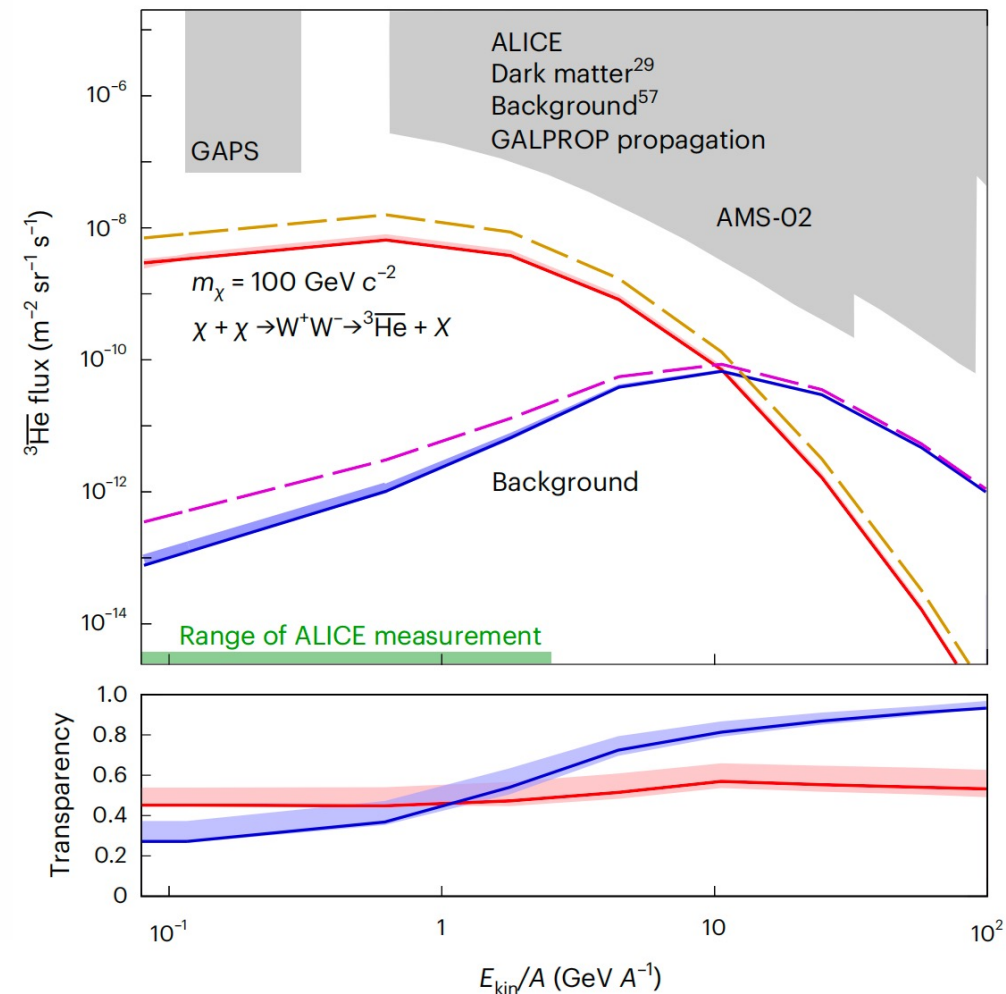
(5)

Dark matter searches in space



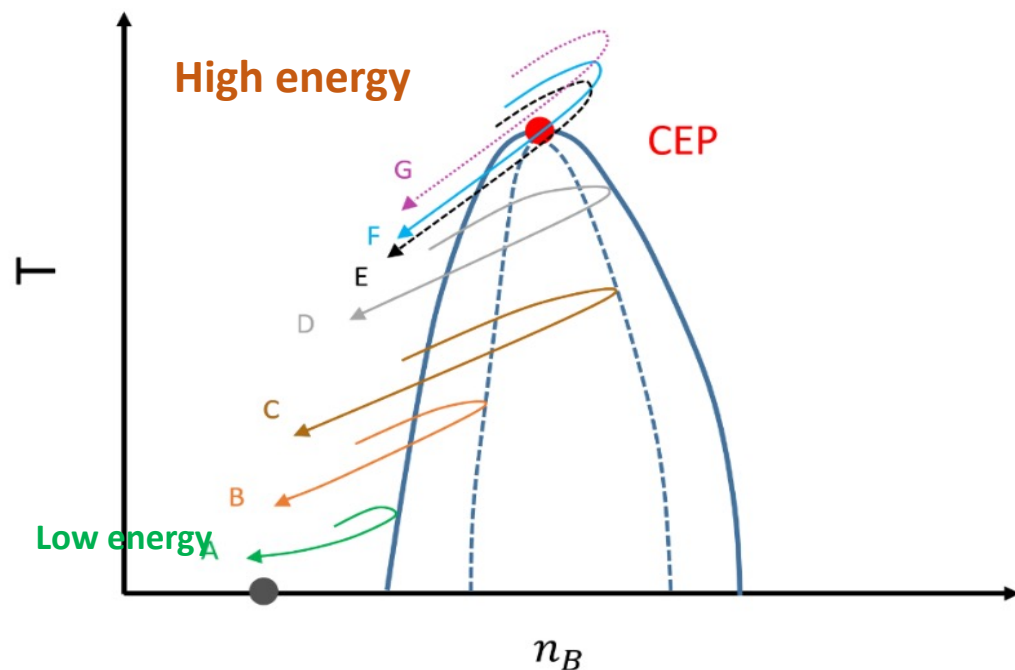
ALICE, Nature Phys. 19, 61-71 (2023)

J. Pu et al., JHEP 08 (2025) 002



C. M. Ko, NST 34, 80 (2023).

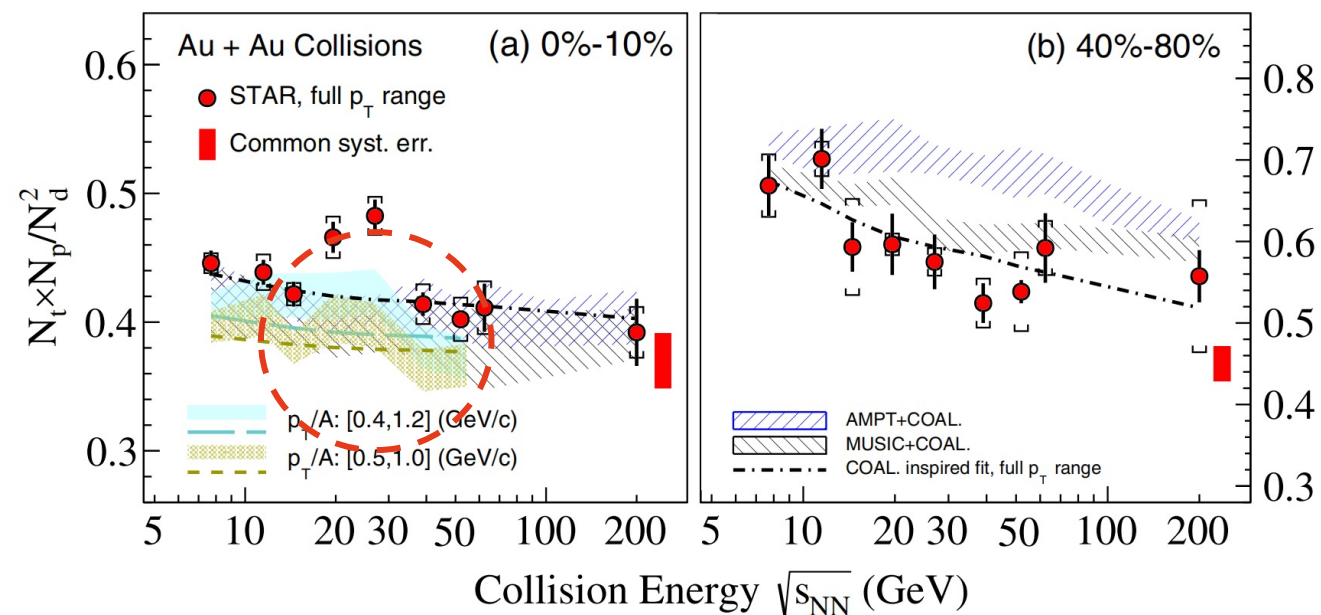
PHYSICAL REVIEW LETTERS **130**, 202301 (2023)



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

$$G(z) = \sqrt{\frac{2}{\pi}} - \frac{1}{z} e^{\frac{1}{2z^2}} \text{erfc}\left(\frac{1}{\sqrt{2}z}\right)$$

Beam Energy Dependence of Triton Production and Yield Ratio ($N_t \times N_p / N_d^2$) in Au + Au Collisions at RHIC

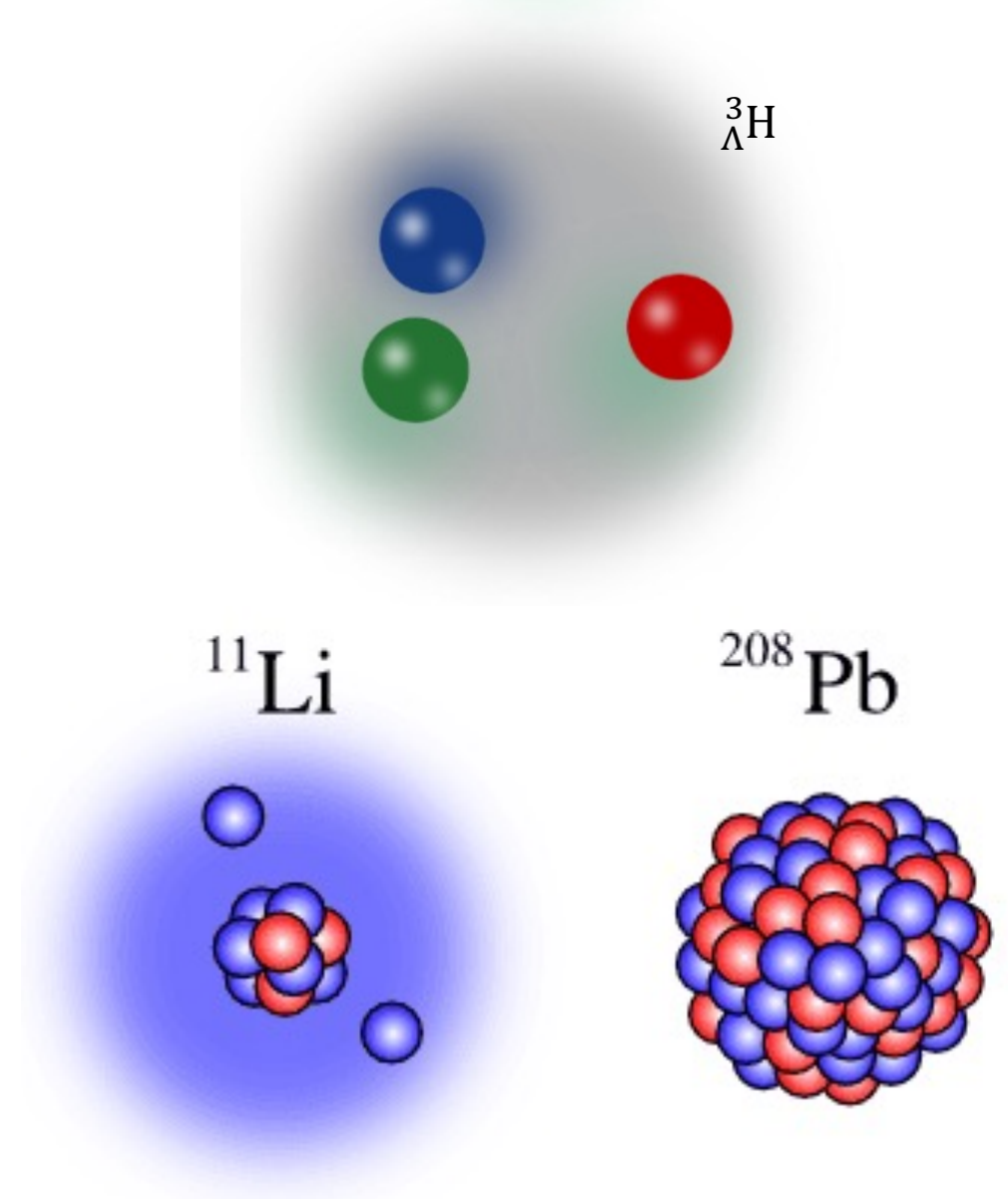
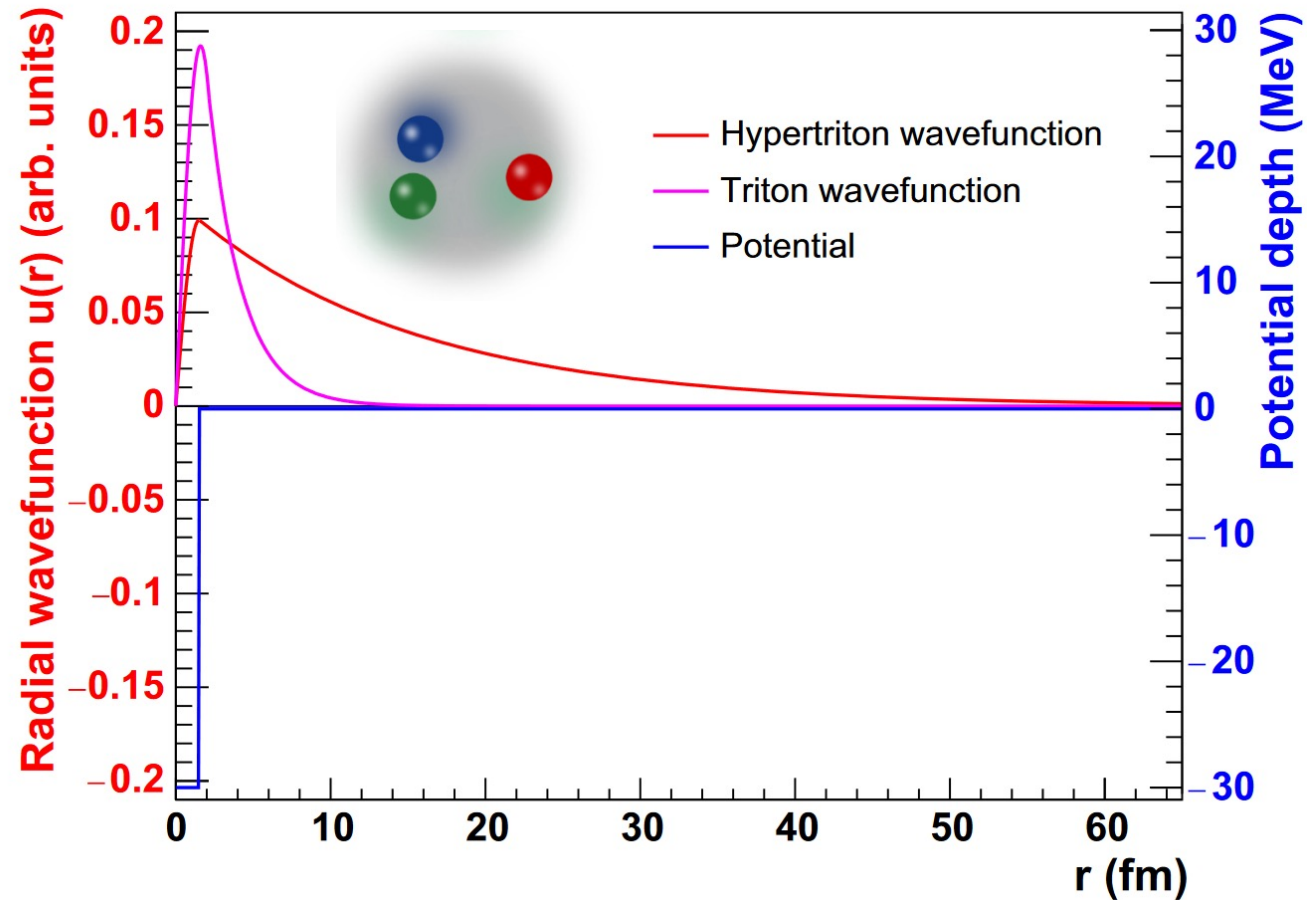


Possible signals of non-monotonic behavior is observed at RHIC

Probing the wave function size of (anti-)hypertriton

The strange “halo-like” nucleus: (anti-)hypertriton

(7)



J. Chen et al., Phys. Rep. 760, 1 (2018);

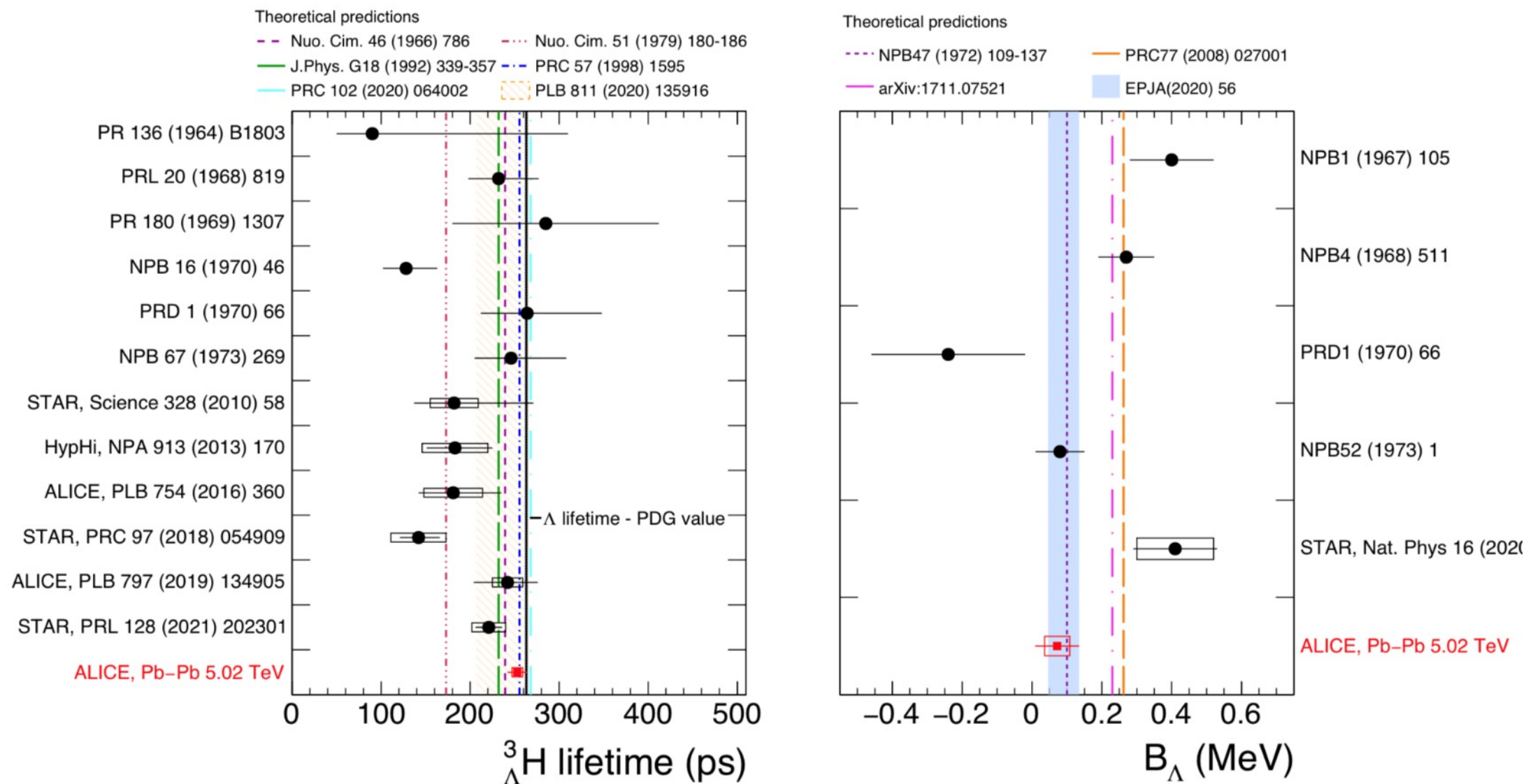
P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)

D. N. Liu et al. Phys. Lett. B 855, 138855 (2024)

ALICE, PRL 131, 102302 (2023)

Lifetime and binding energy

Y. G. Ma, Nucl. Sci. Tech. 3497 (2023)



Final-state coalescence model

(9)

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

Coalescence Model

Deuteron

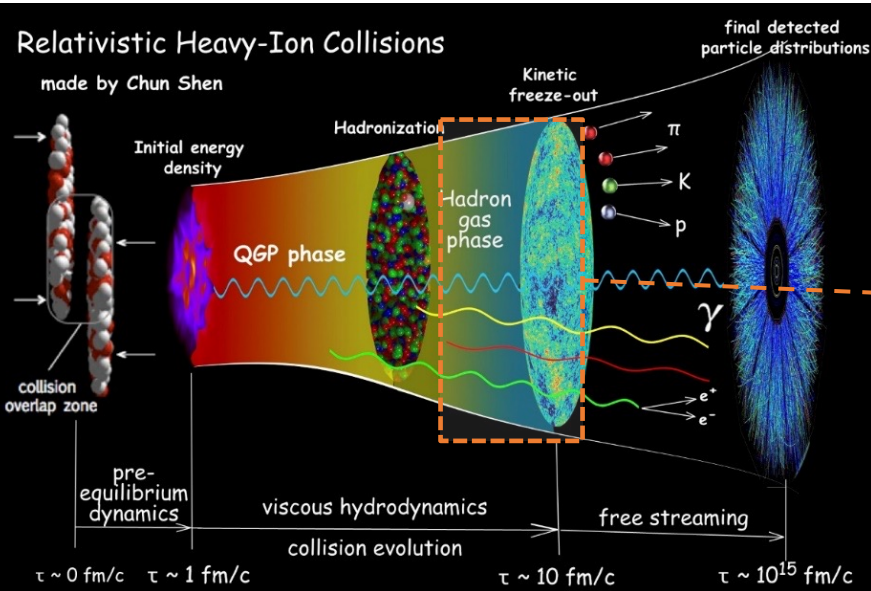
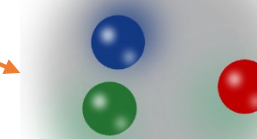
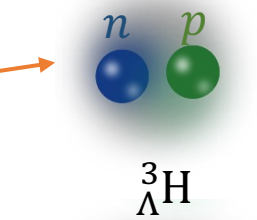
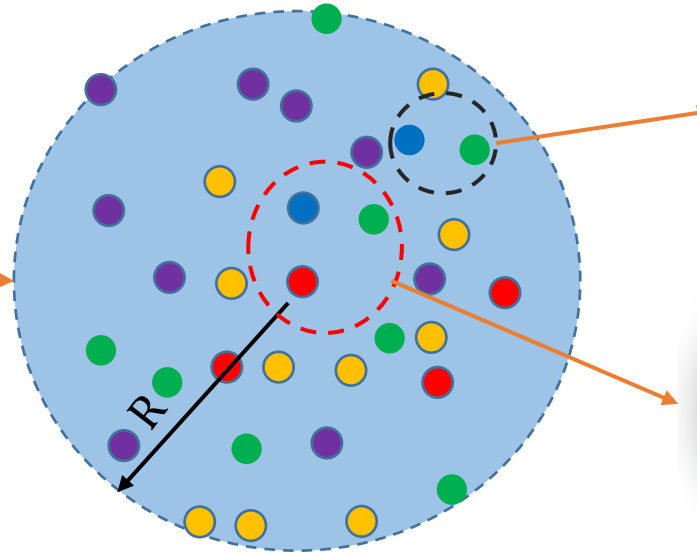
Density Matrix Formulation
(sudden approximation)

$$N_A = \text{Tr}(\hat{\rho}_s \hat{\rho}_A)$$

$$= g_c \int d\Gamma \rho_s(\{x_i, p_i\}) \times W_A(\{x_i, p_i\})$$

Wigner function of light cluster

Overlap between source
distribution function and Wigner
function of light nuclei



Two-body coalescence $a + b \rightarrow c$:

$$N_c = \frac{2J_c + 1}{(2J_a + 1)(2J_b + 1)} \int \frac{dx_a dk_a}{(2\pi)^3} \frac{dx_b dk_b}{(2\pi)^3} f_a(x_a, k_a) f_b(x_b, k_b) W_c(x, k)$$

$$\approx \frac{2J_c + 1}{(2J_a + 1)(2J_b + 1)} \frac{N_a N_b}{\left(\frac{m_a m_b T}{m_a + m_b} (R_a^2 + R_b^2)\right)^{3/2}} \times \boxed{\frac{1}{\left(1 + \frac{\sigma^2}{R_a^2 + R_b^2}\right)^{3/2}}}$$

$$f_a = \frac{N_a}{(m_a T R_a^2)^{3/2}} e^{-\frac{k_a^2}{2m_a T} - \frac{x_a^2}{2R_a^2}} \quad W_c = 8e^{-x^2/\sigma^2 - \sigma^2 k^2}$$

$$N_a = \int \frac{dx_a dk_a}{(2\pi)^3} f_a(x_a, k_a) \quad 1 = \int \frac{dx dk}{(2\pi)^3} W_c(x, k)$$

“Quantum mechanical correction”

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

Production

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

Structure

can be inferred from Femtoscopy

K. J. Sun, C. M. Ko and B. Dönigus, PLB 792, 132 (2019)

Suppression of light nuclei production in collisions of small systems at the Large Hadron Collider

Kai-Jia Sun^{a,b,*}, Che Ming Ko^{a,b}, Benjamin Dönigus^c

K. J. Sun, C. M. Ko and B. Dönigus, Phys. Lett. B 792, 132 (2019)

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

Production

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

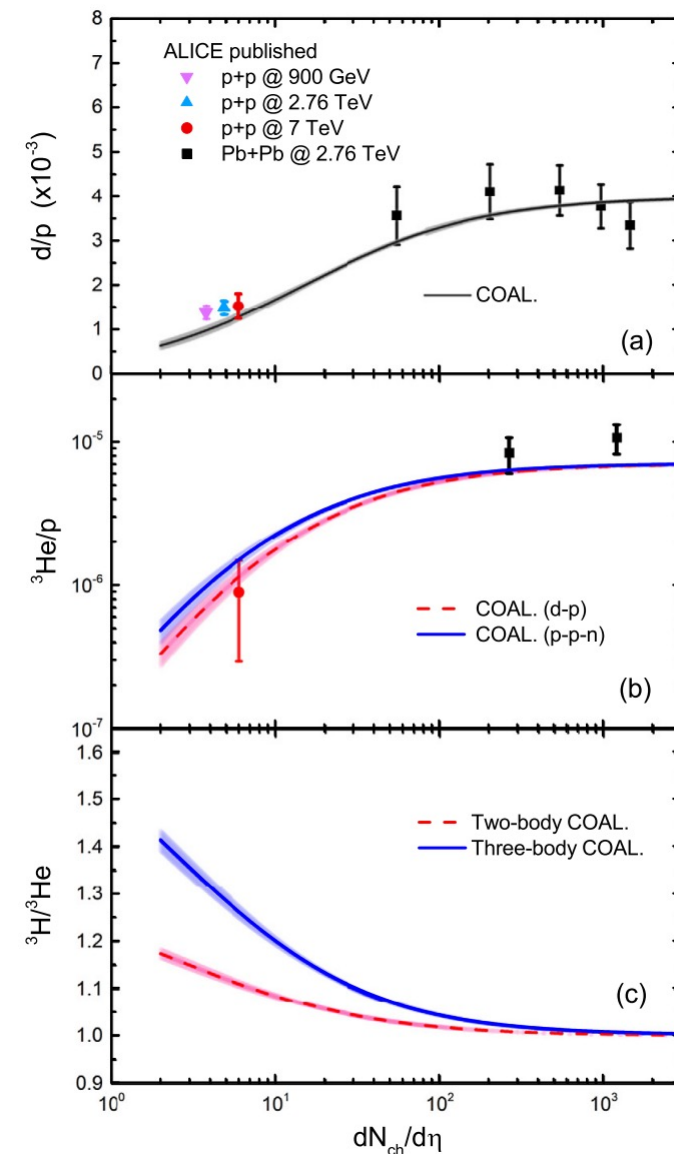
Structure

can be inferred from Femtoscopy

$$\frac{N_d}{N_p} \approx \frac{4.0 \times 10^{-3}}{\left[1 + \frac{2r_d^2}{3R^2}\right]^{3/2}} \quad \frac{N_{^3He}}{N_p} \approx \frac{7.1 \times 10^{-6}}{\left[1 + \frac{r_{^3He}^2}{2R^2}\right]^3}$$

$$\frac{N_{\Lambda^3H}}{N_{\Lambda}} \approx \frac{7.1 \times 10^{-6}}{\left[1 + \frac{r_{\Lambda^3H}^2}{2R^2}\right]^3} \quad : 3\text{-body coal.}$$

K. J. Sun, C. M. Ko, and B. Dönigus, Phys. Lett. B 792, 132-137 (2019)

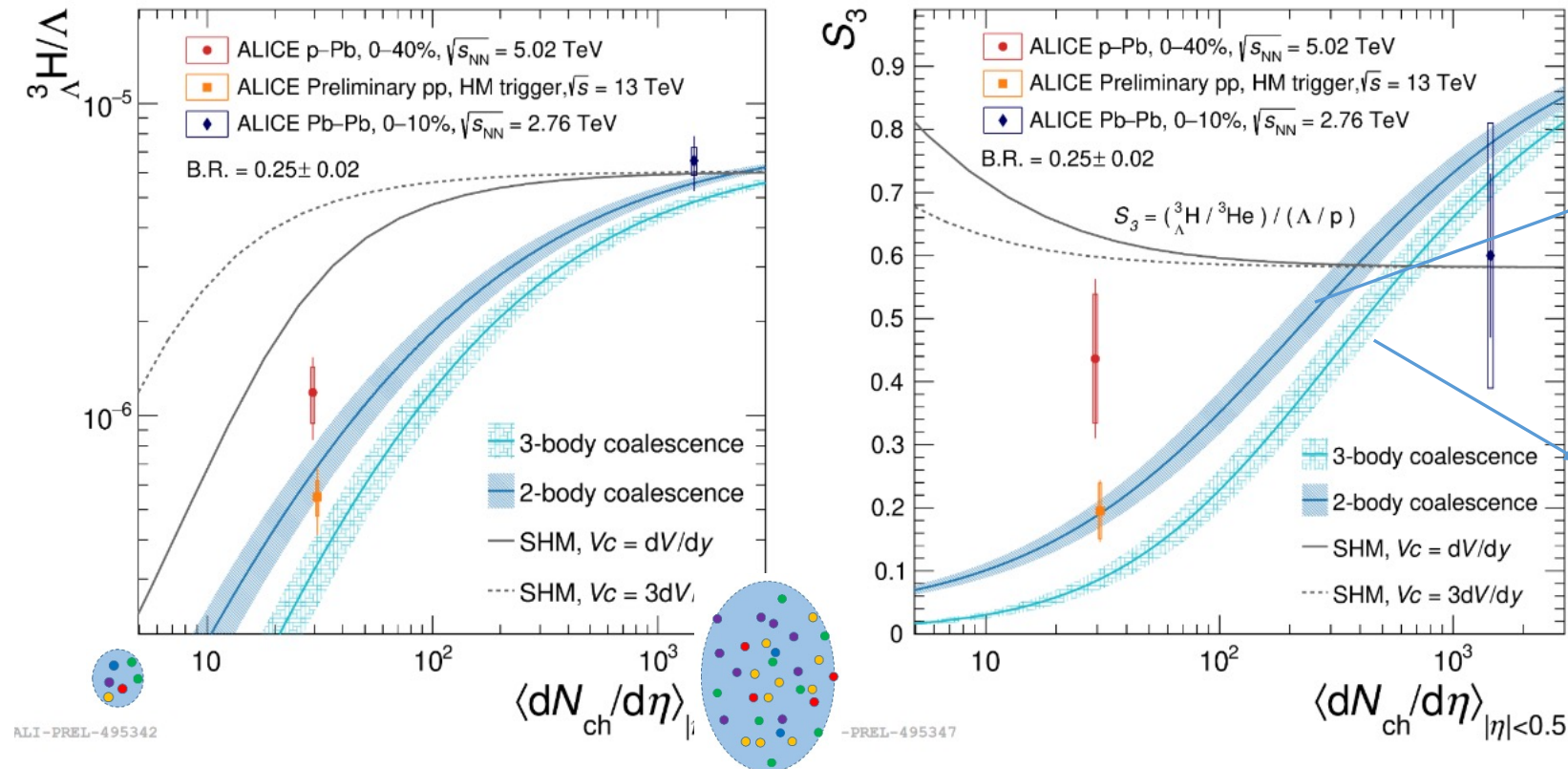


R. Scheibl and U. W. Heinz, PRC59, 1585(1999);

F. Bellini et al., PRC99,054905(2019);

Dai-Neng Liu et al., Phys. Lett. B 855 (2024) 138855

ALICE, Phys. Rev. Lett. 128 (2022) 25, 252003



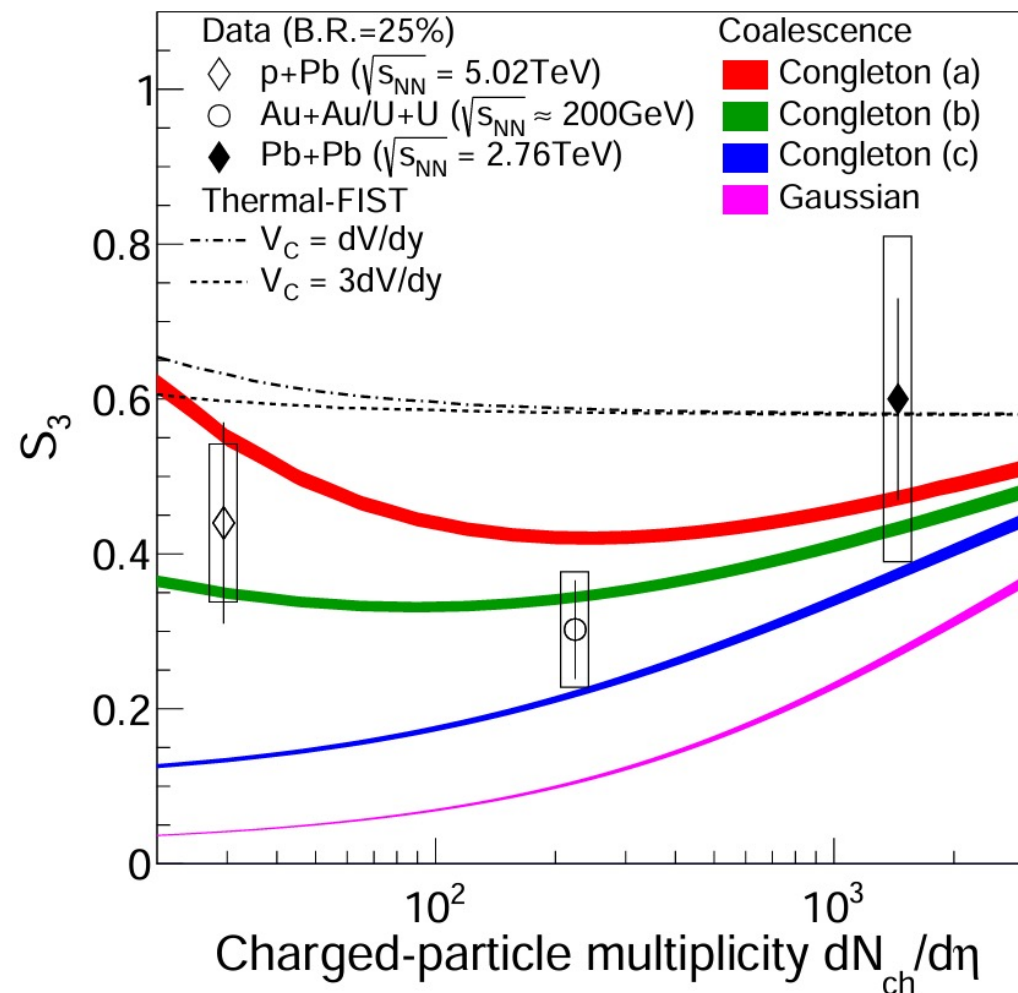
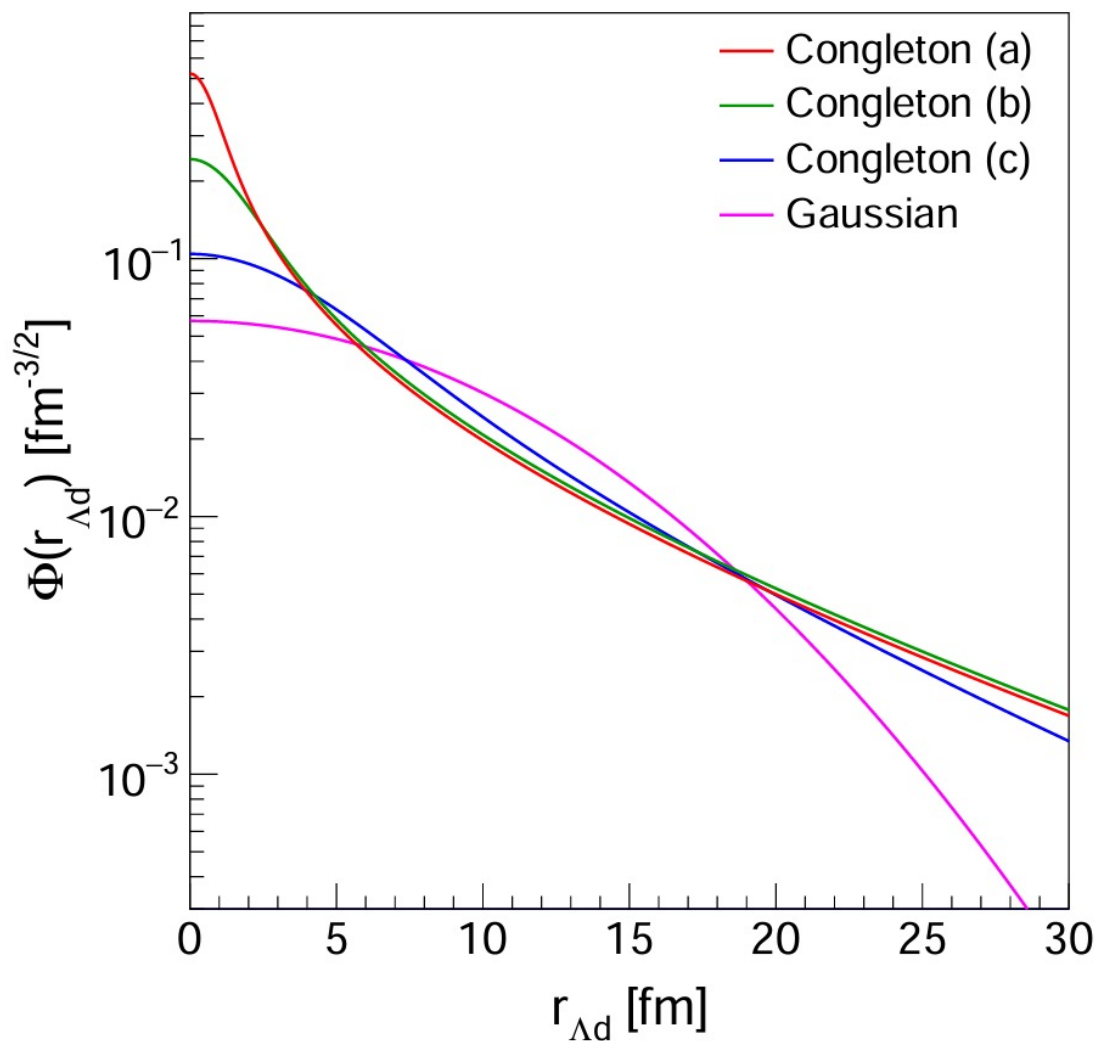
Coal: Finite nuclei sizes (better description on hypertriton production in p+p and p+Pb collisions)

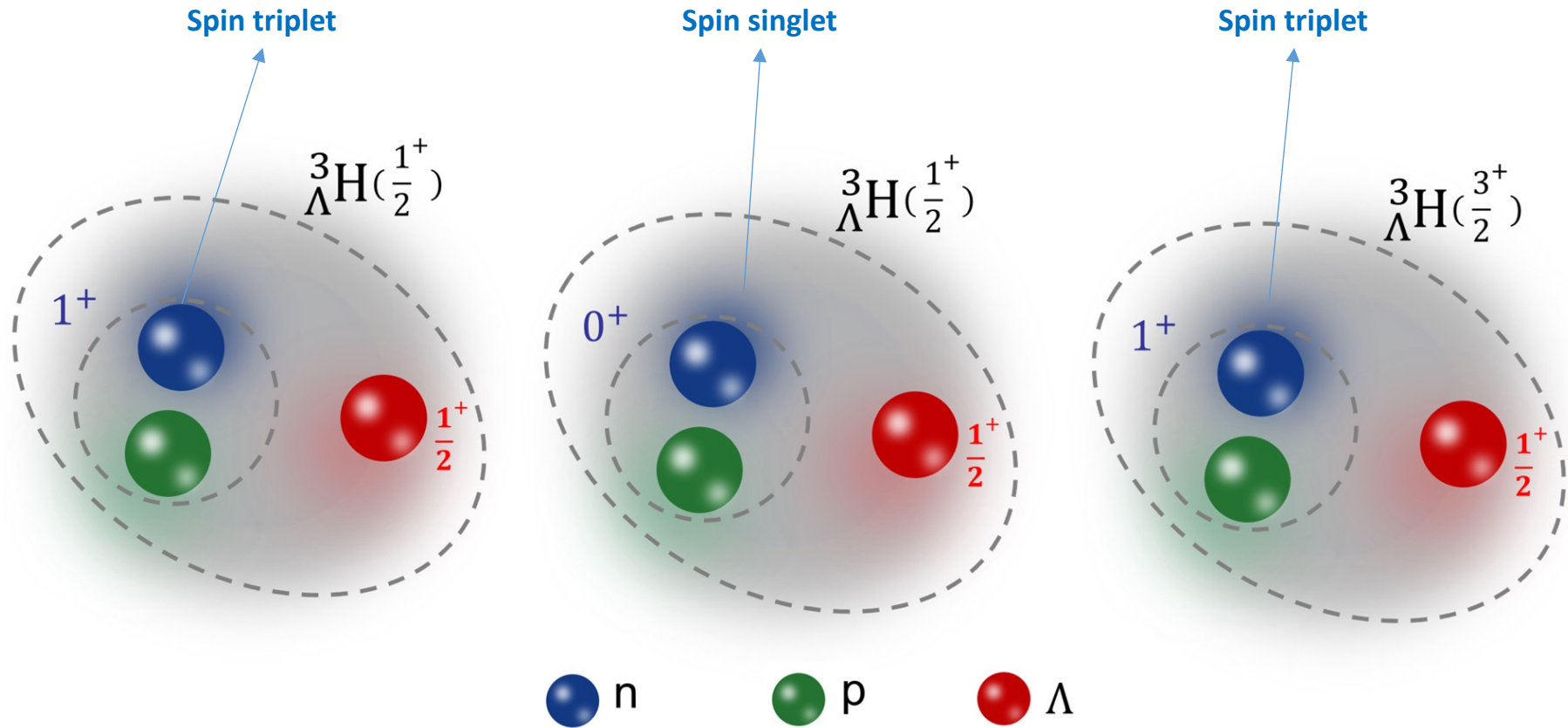
CSM: Baryon number conservation

Shape of wavefunction matters?

(12)

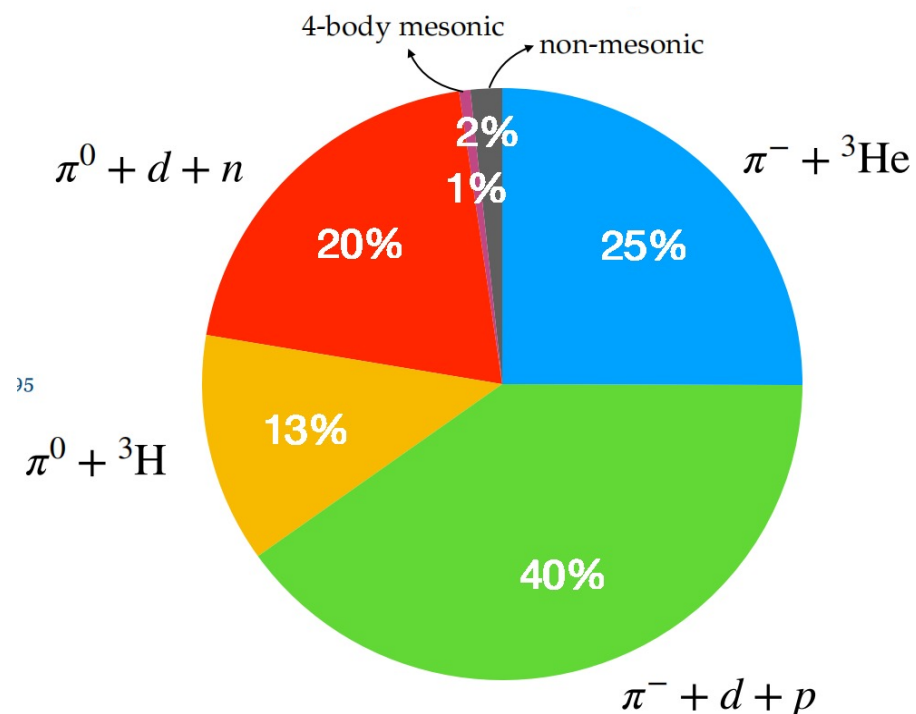
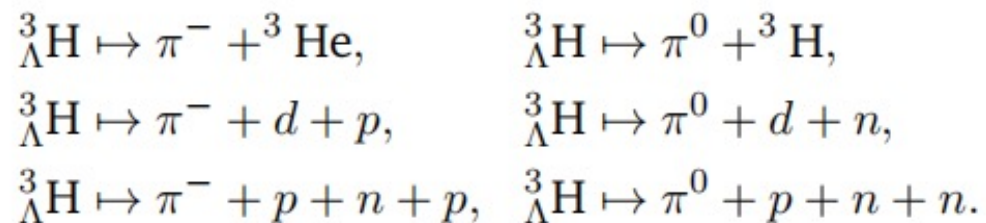
Y. H. Leung, Y. Zhou, N. Herrmann, arXiv:2510.06758 (2025)





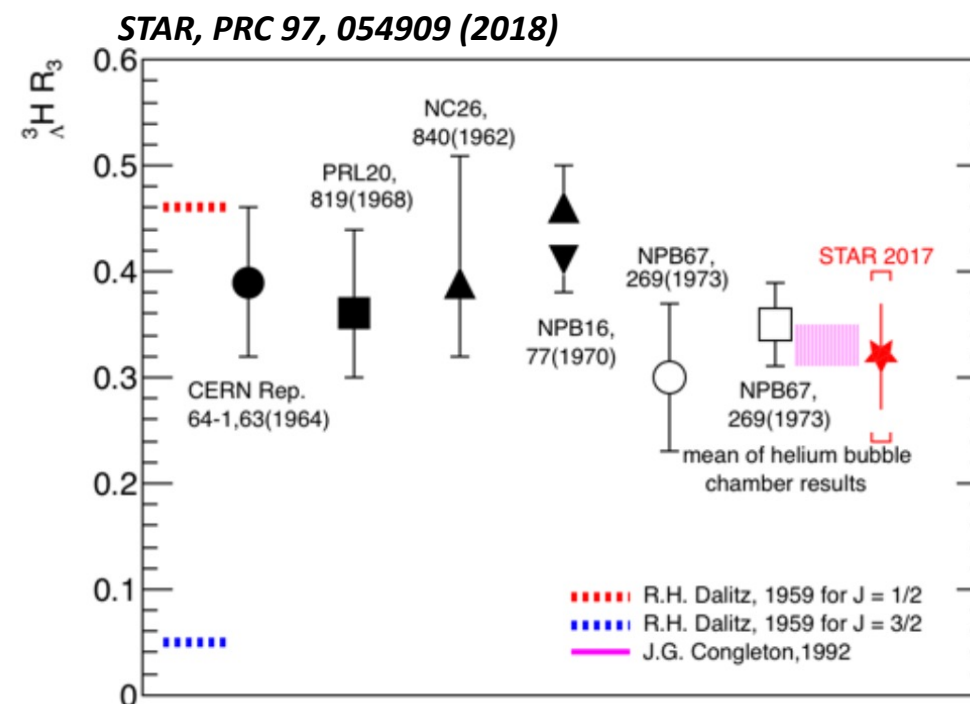
Spin of (anti-)hypertriton ?

(14)



Relative branching ratio:

$$R_3 = \frac{\text{B.R.}({}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He}\pi^-)}{\text{B.R.}({}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He}\pi^-) + \text{B.R.}({}^3_{\Lambda}\text{H} \rightarrow dp\pi^-)}$$



Favors spin 1/2

Global spin polarization of unstable light (hyper)nuclei

Polarization of hadrons in relativistic heavy-ion collisions

(15)

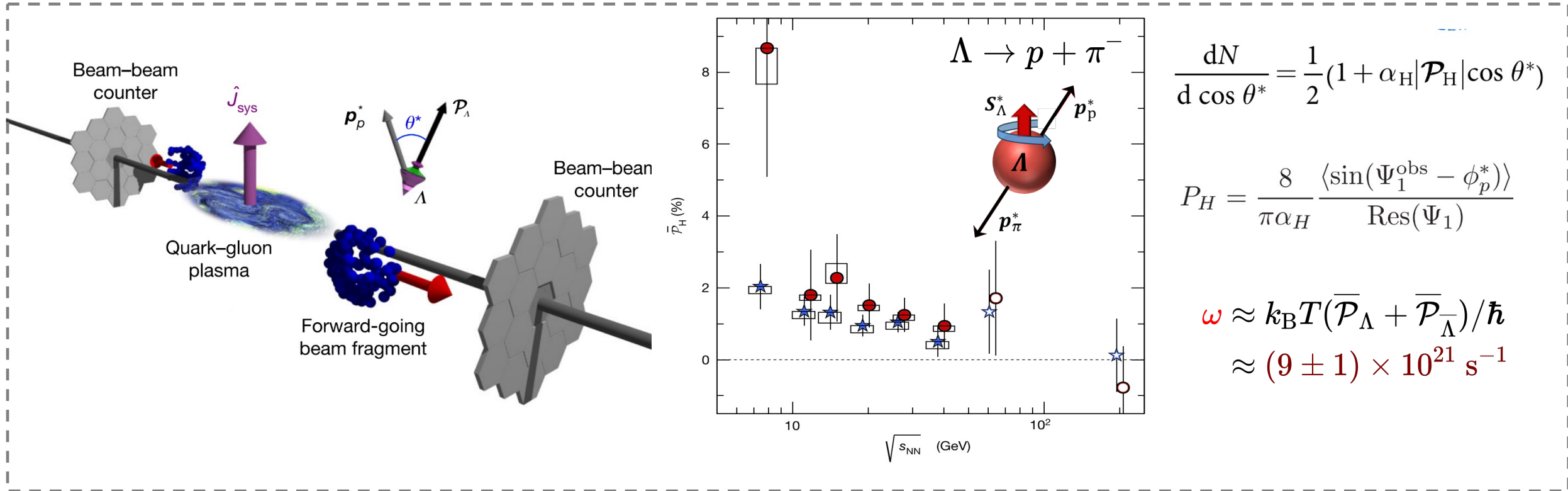
STAR, Nature 548, 62 (2017)

Z. T. Liang and X. N. Wang PRL 94, 102301 (2005)

F. Becattini, F. Piccinini, and J. Rizzo, PRC 77, 024906 (2008)

F. Becattini, M. Buzzegoli, T. Niida, S. Pu, and A. Tang, Int.J.Mod.Phys.E 33 (2024) 06, 2430006

See talks by Shi Pu, Shu Lin, Jun Xu et al.



Spin polarization of Lambda hyperon



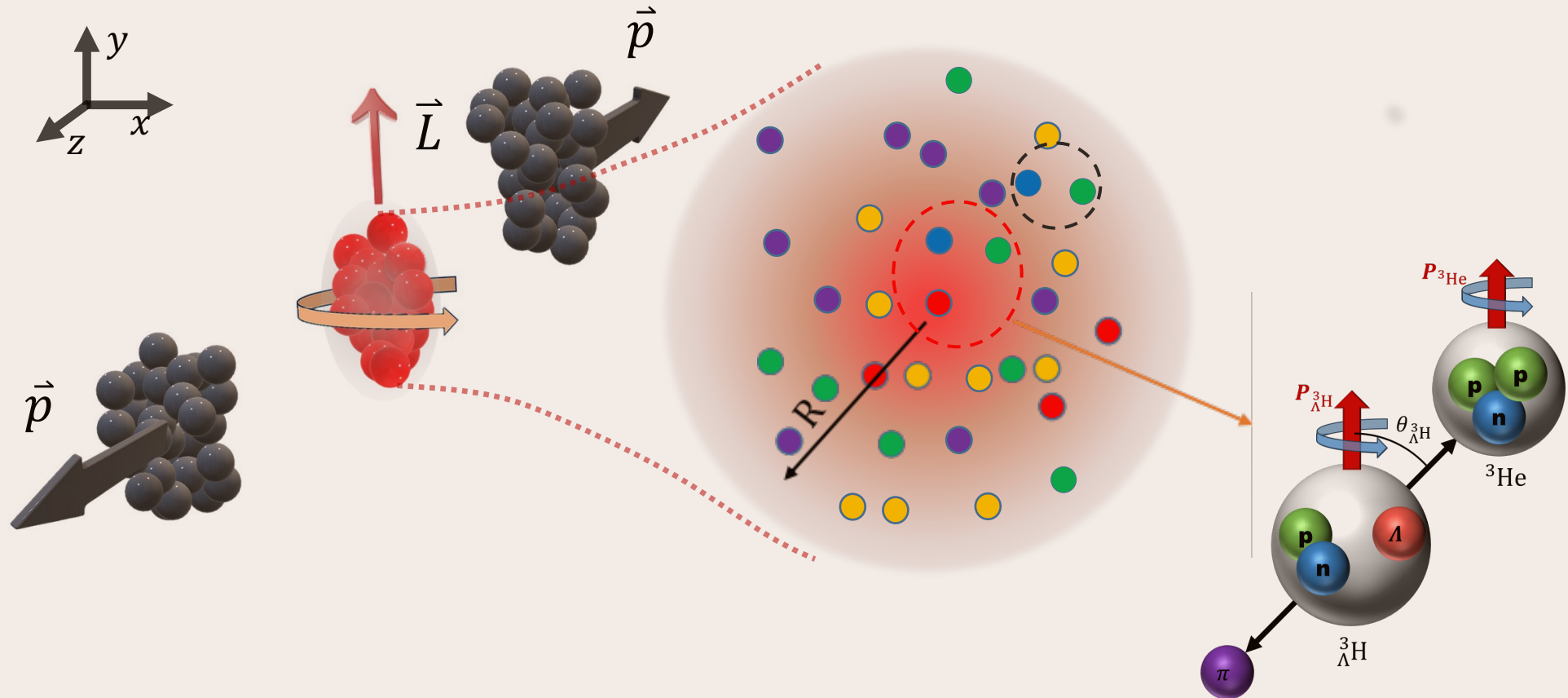
Vorticity of QGP

Global spin polarization of (anti-)hypertriton

(16)

Zuo-Tang Liang and Xin-Nian Wang Phys. Rev. Lett. 94, 102301 (2005)

Kai-Jia Sun et al., Phys. Rev. Lett. 134, 022301 (2025)



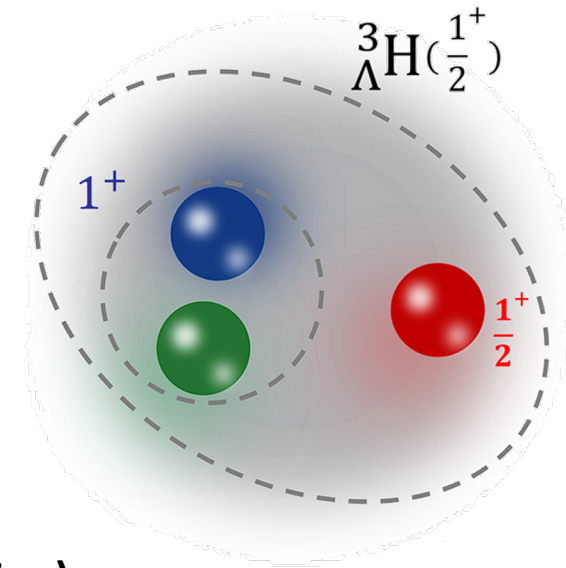
Spin-dependent coalescence model

(17)

Kai-Jia Sun et al., Phys. Rev. Lett. 134, 022301 (2025)

➤ Spin wavefunction

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



➤ Coalescence model for hypertriton production (without baryon spin correlation)

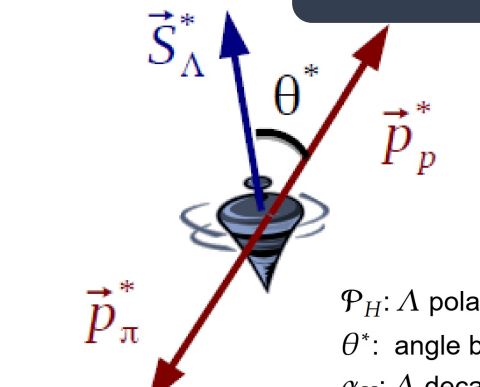
$$\begin{aligned}
 \hat{\rho}_{np\Lambda} &= \hat{\rho}_n \otimes \hat{\rho}_p \otimes \hat{\rho}_{\Lambda} \\
 E \frac{d^3 N_{\Lambda^3\text{H}, \pm \frac{1}{2}}}{d\mathbf{P}^3} &= E \int \prod_{i=n,p,\Lambda} p_i^\mu d^3 \sigma_\mu \frac{d^3 p_i}{E_i} \bar{f}_i(\mathbf{x}_i, \mathbf{p}_i) \\
 &\quad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

$$\begin{aligned}
 \mathcal{P}_{\Lambda^3\text{H}} &\approx \frac{\frac{2}{3} \mathcal{P}_n + \frac{2}{3} \mathcal{P}_p - \frac{1}{3} \mathcal{P}_{\Lambda} - \mathcal{P}_n \mathcal{P}_p \mathcal{P}_{\Lambda}}{1 - \frac{2}{3} (\mathcal{P}_n + \mathcal{P}_p) \mathcal{P}_{\Lambda} + \frac{1}{3} \mathcal{P}_n \mathcal{P}_p} \\
 &\approx \frac{2}{3} \mathcal{P}_n + \frac{2}{3} \mathcal{P}_p - \frac{1}{3} \mathcal{P}_{\Lambda} \\
 &\approx \mathcal{P}_{\Lambda} \quad \mathcal{P}_p \approx \mathcal{P}_n \approx \mathcal{P}_{\Lambda}
 \end{aligned}$$

Assuming spin polarizations and correlations are small

Parity-violating weak decay

Λ hyperons



$$\frac{dN}{d\cos\theta^*} = \text{Tr}[T^+ \hat{\rho} T]$$

$$\rho_\Lambda = \begin{pmatrix} \frac{1+\mathcal{P}_\Lambda}{2} & \\ & \frac{1-\mathcal{P}_\Lambda}{2} \end{pmatrix}$$

$\mathcal{P}_H$: Λ polarization
 θ^* : angle between proton momentum in Λ rest frame
 α_H : Λ decay parameter
 $\alpha_\Lambda = 2\text{Re}(T_s^* T_p) = 0.732 \pm 0.014$
 BESIII, Phys. Rev. Lett. 129, 131801 (2022).

$$\Lambda \rightarrow p + \pi^-$$

The transition matrix

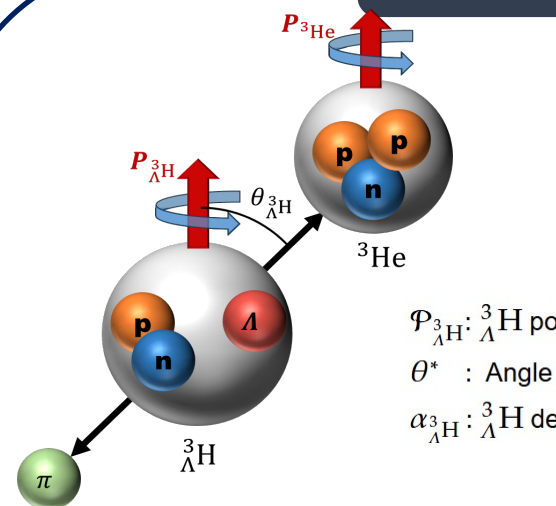
$$T(\Lambda \rightarrow \pi^- + p) = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} T_s + T_p \cos\theta_p^* & T_p \sin\theta_p^* e^{i\phi_p^*} \\ T_p \sin\theta_p^* e^{-i\phi_p^*} & T_s - T_p \cos\theta_p^* \end{pmatrix}$$

The angular distribution

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

H denotes Λ and $\bar{\Lambda}$

Hypertriton



$$\rho_{\Lambda^3\text{H}} = \begin{pmatrix} \frac{1+\mathcal{P}_{\Lambda^3\text{H}}}{2} & \\ & \frac{1-\mathcal{P}_{\Lambda^3\text{H}}}{2} \end{pmatrix}$$

$\mathcal{P}_{\Lambda^3\text{H}}$: $\Lambda^3\text{H}$ polarization
 θ^* : Angle between ${}^3\text{He}$ momentum in $\Lambda^3\text{H}$ rest frame
 $\alpha_{\Lambda^3\text{H}}$: $\Lambda^3\text{H}$ decay parameter

$$T({}^3_\Lambda\text{H} \rightarrow \pi^- + {}^3\text{He})$$

$$= \frac{F}{6\sqrt{\pi}} \begin{pmatrix} 3T_s - T_p \cos\theta^* & -T_p \sin\theta^* e^{i\phi^*} \\ -T_p \sin\theta^* e^{-i\phi^*} & 3T_s + T_p \cos\theta^* \end{pmatrix}$$

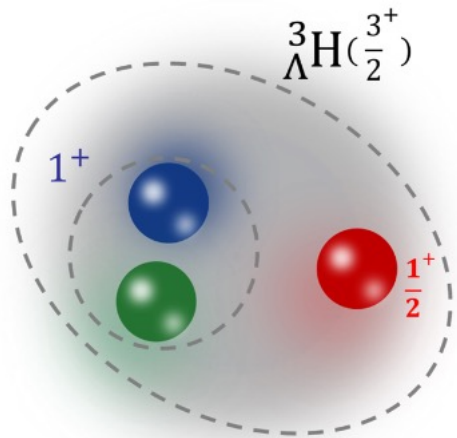
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2} (1 + \alpha_{\Lambda^3\text{H}} \mathcal{P}_{\Lambda^3\text{H}} \cos\theta^*)$$

$$\alpha_{\Lambda^3\text{H}} \approx -\frac{1}{3T_s^2 + \frac{1}{3}T_p^2} \alpha_\Lambda \approx -\frac{1}{2.58} \alpha_\Lambda$$

Sign flip !

2. (Anti-)hypertriton polarization and its spin structure

(19)

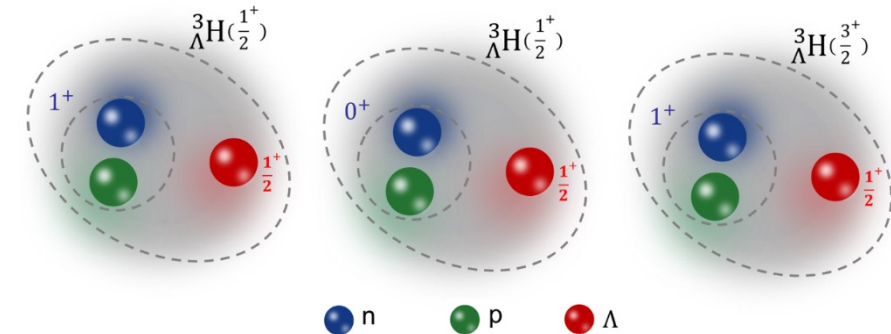


$$\hat{\rho}_{\Lambda}^3 \approx \text{diag} \left[\frac{(1 + \mathcal{P}_{\Lambda})^3}{4(1 + \mathcal{P}_{\Lambda}^2)}, \frac{(1 - \mathcal{P}_{\Lambda})(1 + \mathcal{P}_{\Lambda})^2}{4(1 + \mathcal{P}_{\Lambda}^2)}, \right. \\ \left. \frac{(1 - \mathcal{P}_{\Lambda})^2(1 + \mathcal{P}_{\Lambda})}{4(1 + \mathcal{P}_{\Lambda}^2)}, \frac{(1 - \mathcal{P}_{\Lambda})^3}{4(1 + \mathcal{P}_{\Lambda}^2)} \right]$$

$$T({}^3_{\Lambda}\text{H} \rightarrow \pi^- + {}^3\text{He}) = \frac{FT_p}{\sqrt{6\pi}} \begin{pmatrix} e^{i\phi^*} \sin \theta^* & 0 \\ -\frac{2}{\sqrt{3}} \cos \theta^* & \frac{e^{i\phi^*} \sin \theta^*}{\sqrt{3}} \\ -\frac{e^{-i\phi^*} \sin \theta^*}{\sqrt{3}} & -\frac{2}{\sqrt{3}} \cos \theta^* \\ 0 & -e^{-i\phi^*} \sin \theta^* \end{pmatrix}$$

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2} \left[1 + \left(\hat{\rho}_{\frac{1}{2}, \frac{1}{2}} + \hat{\rho}_{-\frac{1}{2}, -\frac{1}{2}} - \frac{1}{2} \right) (3\cos^2\theta^* - 1) \right]$$

$$\hat{\rho}_{\frac{1}{2}, \frac{1}{2}} + \hat{\rho}_{-\frac{1}{2}, -\frac{1}{2}} - \frac{1}{2} \approx -\frac{\mathcal{P}_{\Lambda}^2}{1 + \mathcal{P}_{\Lambda}^2} \approx -\mathcal{P}_{\Lambda}^2$$



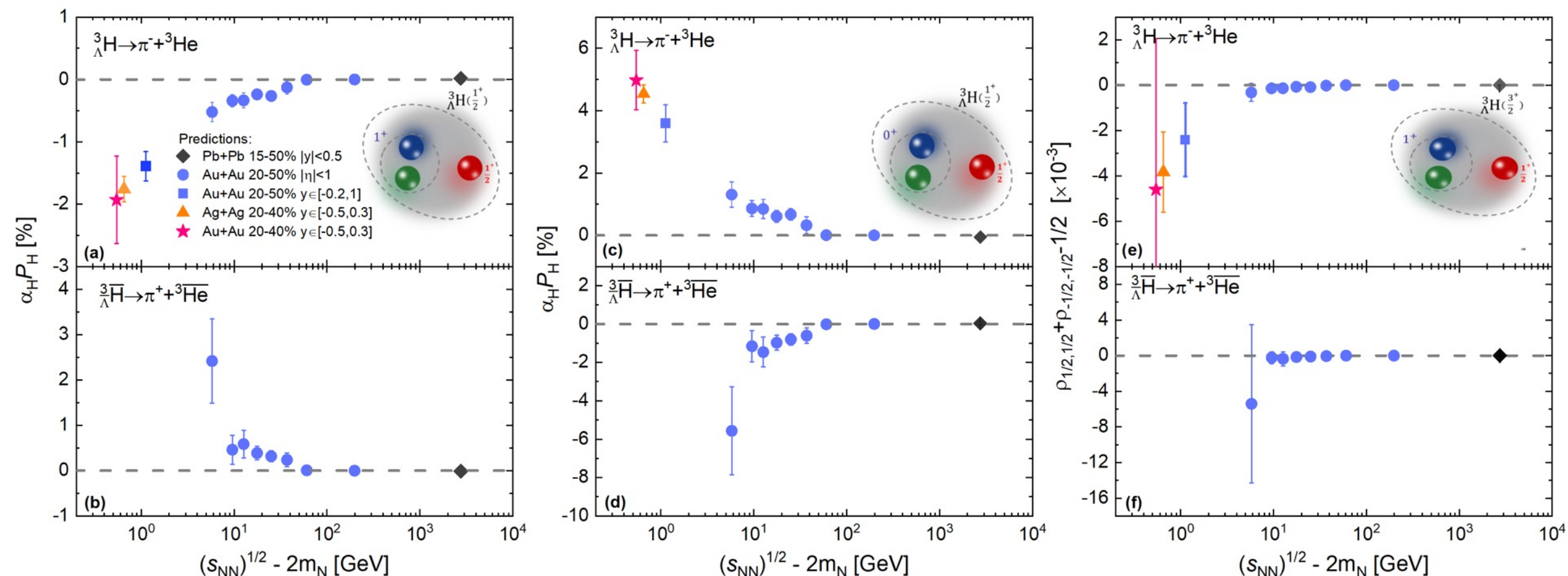
J^{π}	Structure	Decay mode	$dN/(\sin\theta^* d\theta^*)$
$\frac{1}{2}^{+}$	$\Lambda(\frac{1}{2}^{+}) - np(1^{+})$	${}^3_{\Lambda}\text{H} \rightarrow \pi^{-} + {}^3\text{He}$	$\frac{1}{2} [1 - (1/2.58)\alpha_{\Lambda}\mathcal{P}_{\Lambda} \cos\theta^*]$
$\frac{1}{2}^{+}$	$\Lambda(\frac{1}{2}^{+}) - np(0^{+})$	${}^3_{\Lambda}\text{H} \rightarrow \pi^{-} + {}^3\text{He}$	$\frac{1}{2} (1 + \alpha_{\Lambda}\mathcal{P}_{\Lambda} \cos\theta^*)$
$\frac{3}{2}^{+}$	$\Lambda(\frac{1}{2}^{+}) - np(1^{+})$	${}^3_{\Lambda}\text{H} \rightarrow \pi^{-} + {}^3\text{He}$	$\frac{1}{2} \left(1 - \mathcal{P}_{\Lambda}^2 (3\cos^2\theta^* - 1) \right)$
$\frac{1}{2}^{-}$	$\bar{\Lambda}(\frac{1}{2}^{-}) - \bar{n}\bar{p}(1^{+})$	${}^3_{\bar{\Lambda}}\bar{\text{H}} \rightarrow \pi^{+} + {}^3\bar{\text{He}}$	$\frac{1}{2} [1 - (1/2.58)\alpha_{\bar{\Lambda}}\mathcal{P}_{\bar{\Lambda}} \cos\theta^*]$
$\frac{1}{2}^{-}$	$\bar{\Lambda}(\frac{1}{2}^{-}) - \bar{n}\bar{p}(0^{+})$	${}^3_{\bar{\Lambda}}\bar{\text{H}} \rightarrow \pi^{+} + {}^3\bar{\text{He}}$	$\frac{1}{2} (1 + \alpha_{\bar{\Lambda}}\mathcal{P}_{\bar{\Lambda}} \cos\theta^*)$
$\frac{3}{2}^{-}$	$\bar{\Lambda}(\frac{1}{2}^{-}) - \bar{n}\bar{p}(1^{+})$	${}^3_{\bar{\Lambda}}\bar{\text{H}} \rightarrow \pi^{+} + {}^3\bar{\text{He}}$	$\frac{1}{2} \left(1 - \mathcal{P}_{\bar{\Lambda}}^2 (3\cos^2\theta^* - 1) \right)$

Different polarization and decay patterns!

The measurement of hypertriton polarization provides a novel method to uniquely determine its internal spin structure

$$\alpha_{\Lambda^3\text{H}} \approx -\frac{1}{2.58}\alpha_{\Lambda}$$

$$\alpha_{\Lambda^3\text{H}} \approx \alpha_{\Lambda}$$

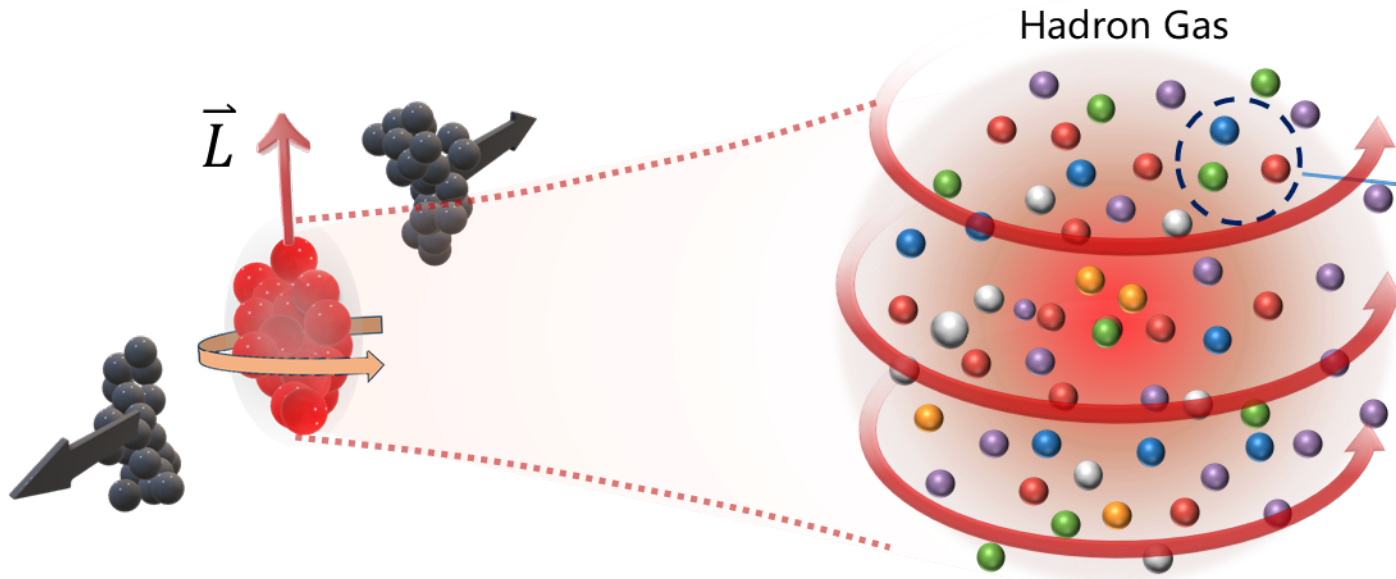


Decoding proton spin polarization from hypertriton production (21)

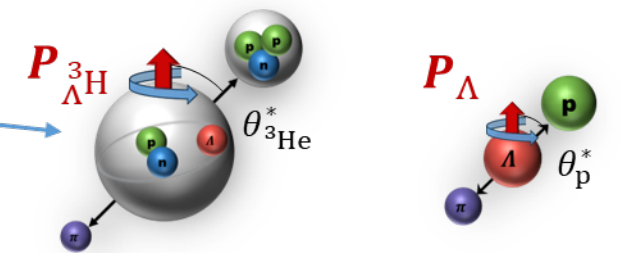
See talk by Dai-Neng Liu (刘代能), Oct. 26 9:45-10:05

Dai-Neng Liu *et al.*, arXiv:2508.12193 (2025)

a



b



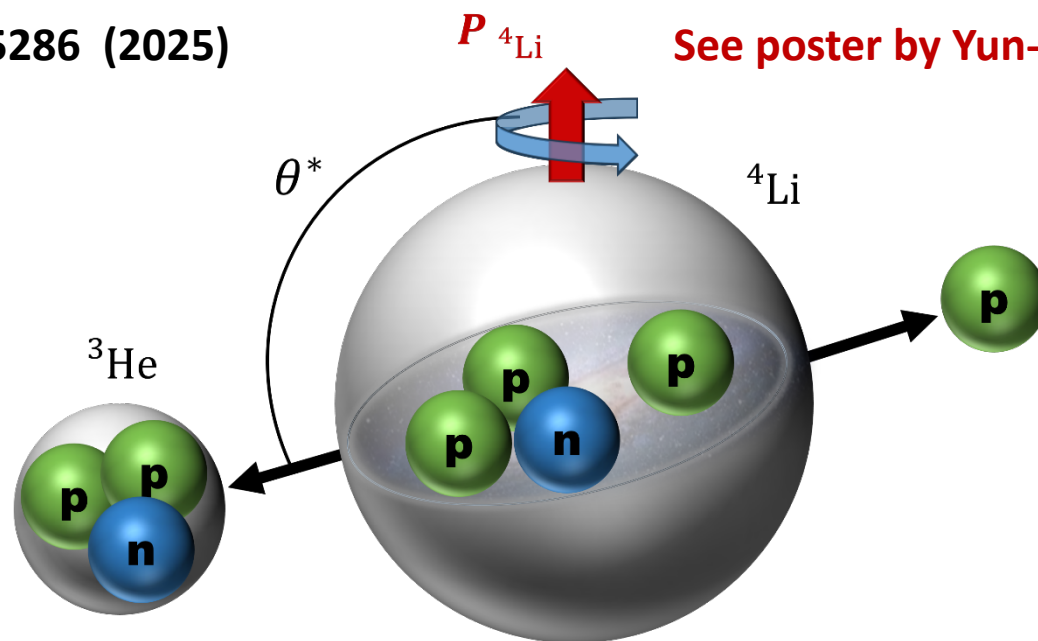
$$\frac{dN}{\sin\theta^* d\theta^*} = \frac{1}{2} (1 + \alpha_H P_H \cos\theta^*)$$

c

$$P(\mathbf{p}) \approx \frac{1}{4} \left[3P(\text{hypertriton}) + P(\text{hypernucleus}) \right]$$

Yun-Peng Zheng *et al.*, arXiv:2509.15286 (2025)

See poster by Yun-Peng Zheng(郑云鹏), Oct. 27



State	E (MeV)	Structure	L	Decay mode	Γ (MeV)	$\frac{dN}{\sin\theta^* d\theta^*}$
${}^4\text{Li}({}^3P_2)$	g.s.	${}^3\text{He}(\frac{1}{2}^+) - p(\frac{1}{2}^+)$	1	${}^4\text{Li} \rightarrow {}^3\text{He} + p$	6.03	$\frac{1}{2} \left(1 - \frac{7}{30} (\mathcal{P}_N^2 + 4\mathcal{P}_N\mathcal{P}_L + \mathcal{P}_L^2) (3\cos^2\theta^* - 1) \right)$
${}^4\text{Li}({}^3P_1)$	0.32	${}^3\text{He}(\frac{1}{2}^+) - p(\frac{1}{2}^+)$	1	${}^4\text{Li} \rightarrow {}^3\text{He} + p$	7.35	$\frac{1}{2} \left(1 - \frac{1}{6} (\mathcal{P}_N^2 - 4\mathcal{P}_N\mathcal{P}_L + \mathcal{P}_L^2) (3\cos^2\theta^* - 1) \right)$
${}^4\text{Li}({}^3P_0)$	2.08	${}^3\text{He}(\frac{1}{2}^+) - p(\frac{1}{2}^+)$	1	${}^4\text{Li} \rightarrow {}^3\text{He} + p$	9.35	$\frac{1}{2}$
${}^4\text{Li}({}^1P_1)$	2.85	${}^3\text{He}(\frac{1}{2}^+) - p(\frac{1}{2}^+)$	1	${}^4\text{Li} \rightarrow {}^3\text{He} + p$	13.51	$\frac{1}{2} \left(1 - \frac{2}{3} \mathcal{P}_L^2 (3\cos^2\theta^* - 1) \right)$

$$\mathcal{P}_N = \frac{w}{2T}$$

$$\mathcal{P}_L = \frac{w}{2T}$$

Dynamics of light (hyper)nuclei production with pion-nucleus femtoscopy

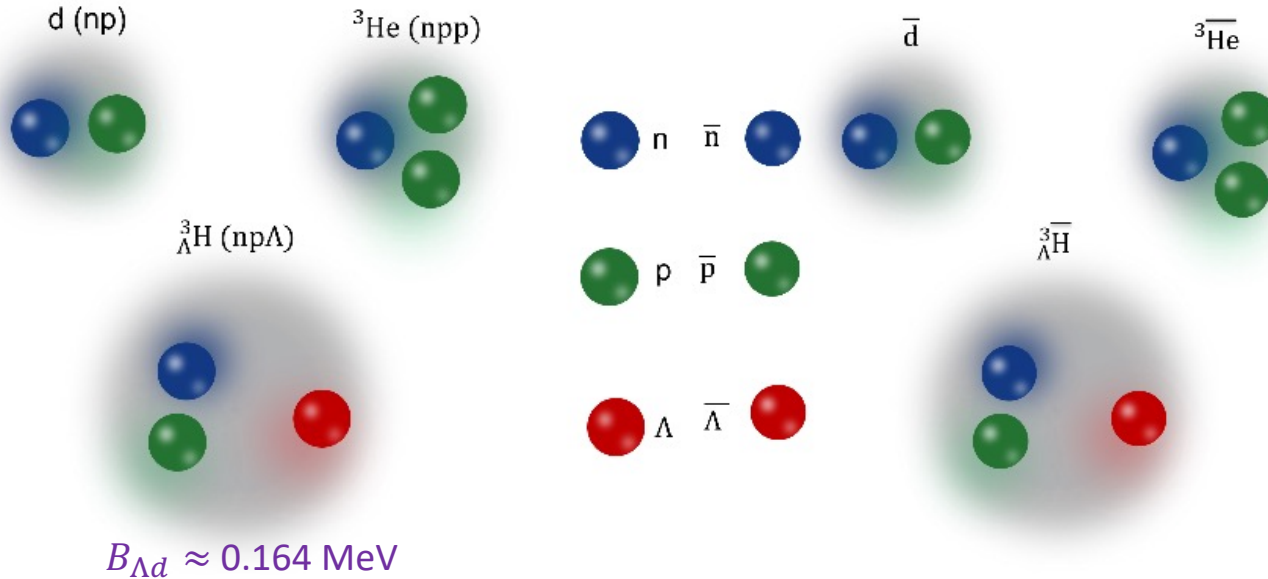
ALICE investigates ‘snowballs in hell’

26 August 2015

Peter Braun-Munzinger, Benjamin Dönigus,

How is it that loosely bound objects are observed in high-energy nuclear collisions?

$B=2.2$ MeV $B=7.7$ MeV



1. Formation of light (anti-)nuclei occurs at $t \sim 10^{-22}$ s and $T \sim 100$ MeV
2. Rarely produced (suppressed by $e^{-m_A/T}$)
3. Binding energies(E_B) $\ll T$
4. The size $r \sim \frac{1}{\sqrt{4\mu E_B}}$, ($r_d \sim 2$ fm, $r_{3He} \sim 2$ fm, $r_{3H} \sim 5$ fm)

PHYSICAL REVIEW LETTERS **134**, 252301 (2025)

Explaining Snowball-in-Hell Phenomena in Heavy-Ion Collisions Using a Novel Thermodynamic Variable

Eric Braaten,^{1,*} Kevin Ingles^{1,2,†} and Justin Pickett^{1,‡}

A loosely bound hadronic molecule produced by a relativistic heavy-ion collision has been described as a “snowball in hell” since it emerges from a hadron resonance gas whose temperature is orders of magnitude larger than the binding energy of the molecule. This remarkable phenomenon can be explained in terms of a novel thermodynamic variable called the “contact” that is conjugate to the binding momentum of the molecule. The production rate of the molecule can be expressed in terms of the contact density at the kinetic freeze-out of the hadron resonance gas. It approaches a nonzero limit as the binding energy goes to 0.

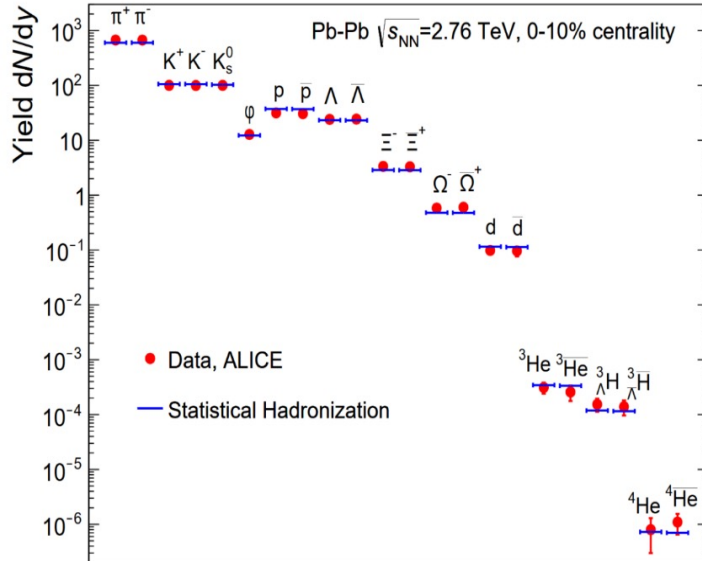


“Contact” density from cold atom physics

$$\mathcal{C} = 8\pi\gamma n_X$$

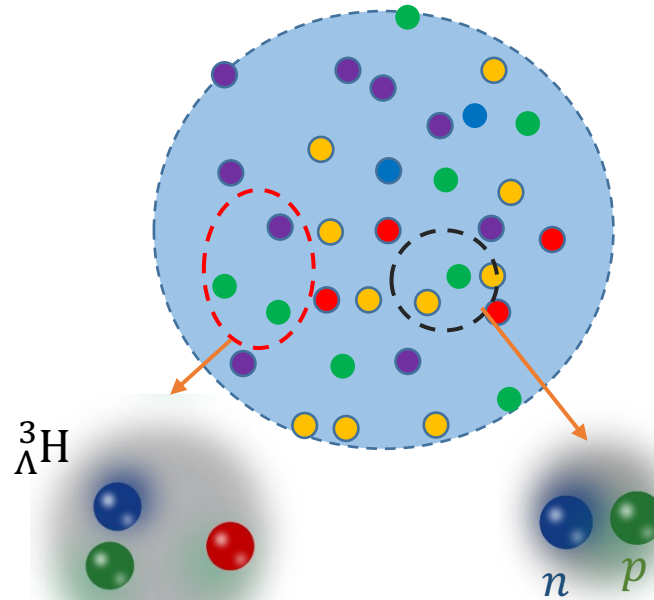
$$dN_X/dy = \frac{\kappa}{4\pi} \left(C_{Xkf} / n_{\pi kf}^{4/3} \right) dN_\pi/dy,$$

热力学统计模型



A. Andronic *et al.*, Nature 561, 321 (2018)

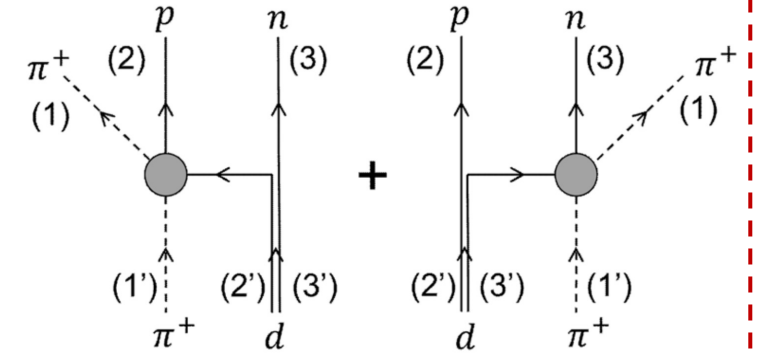
粒子并合模型



R. Scheibl *et al.*, PRC59, 1585(1999)

F. Bellini *et al.*, PRC99, 044913 (2019)

微观运输模型



$$\pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd$$

$$\pi NNN \leftrightarrow \pi t, \pi Nd \leftrightarrow \pi t$$

D. Oliinychenko *et al.*, PRC99, 044907 (2019)

K. J. Sun *et al.*, Nat. Commun. 15, 1074

(2024)

Hadronic re-scattering effects at RHIC

(25)

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)

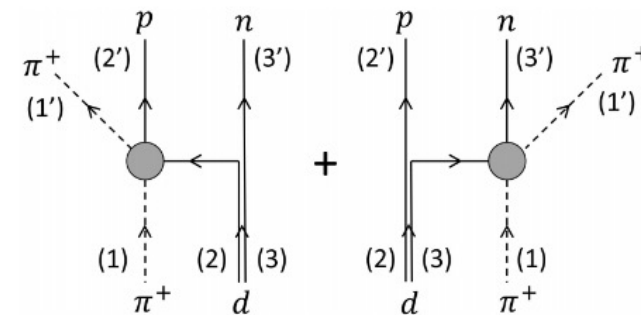
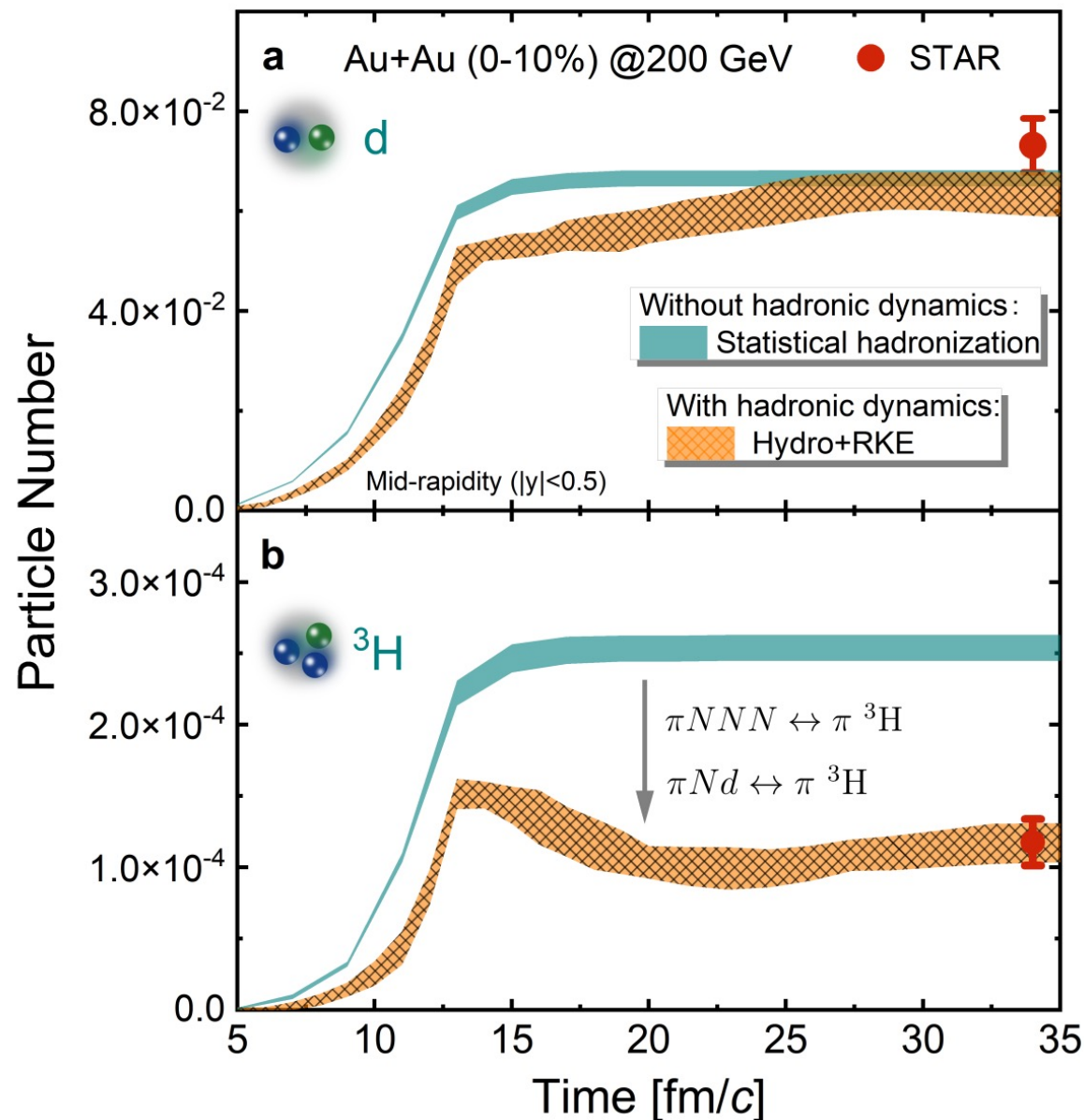


FIG. 1. Diagrams for the reaction $\pi^+ d \leftrightarrow \pi^+ np$ in the impulse approximation. The filled bubble indicates the intermediate states such as a Δ resonance.

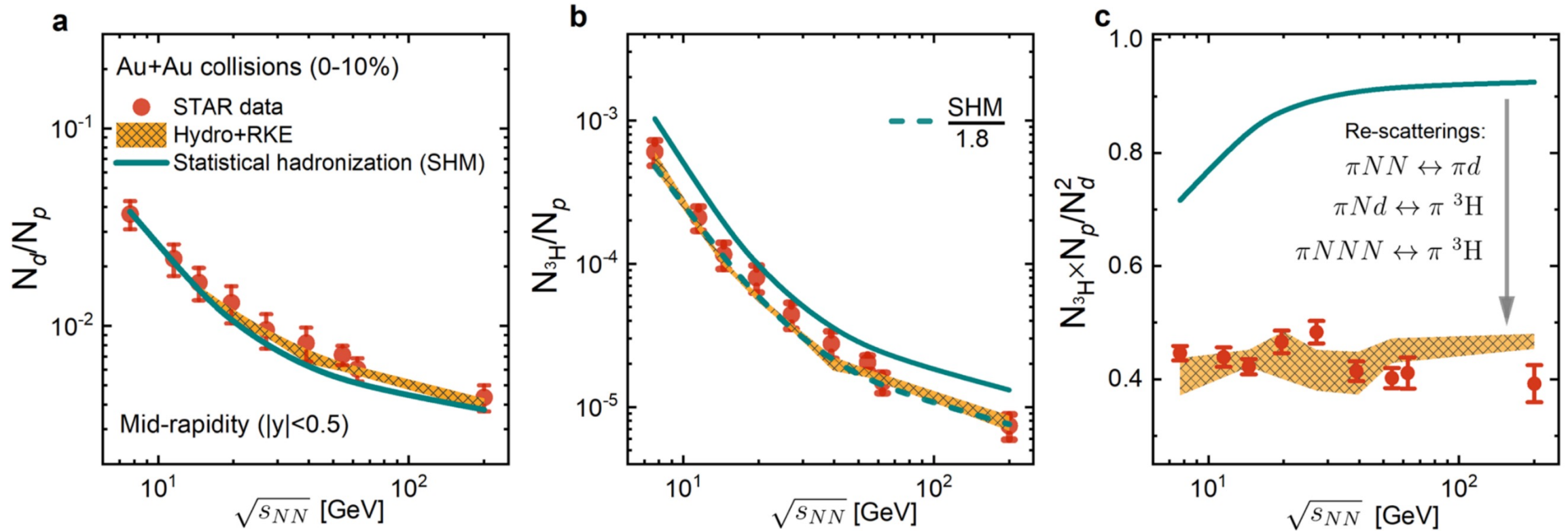
- $A = 2$ $\pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd$
- $A = 3$ $\pi NNN \leftrightarrow \pi t(h), \pi Nd \leftrightarrow \pi t(h), NNN \leftrightarrow Nt(h), NNd \leftrightarrow Nt(h)$, and etc.

Hadronic re-scattering effects at RHIC

(26)

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

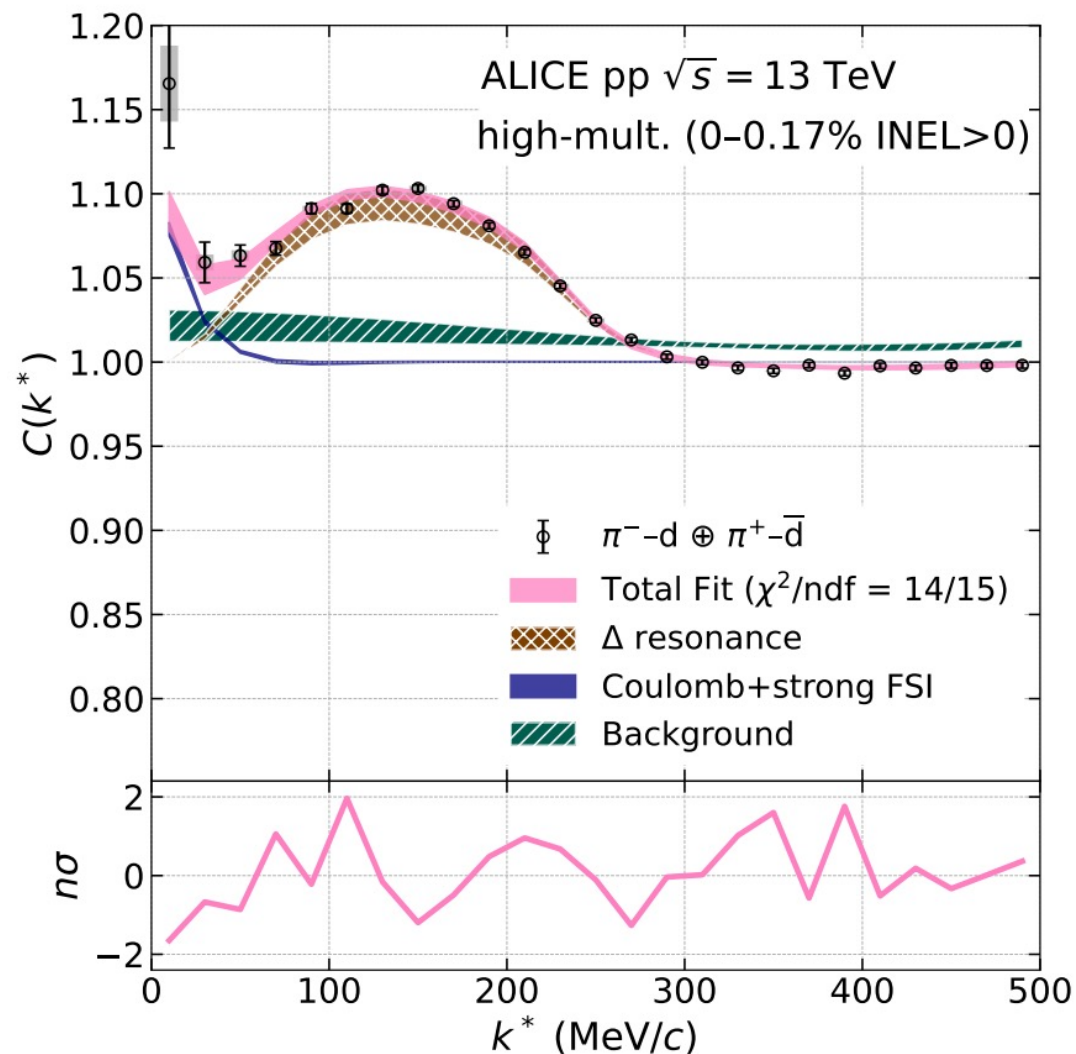
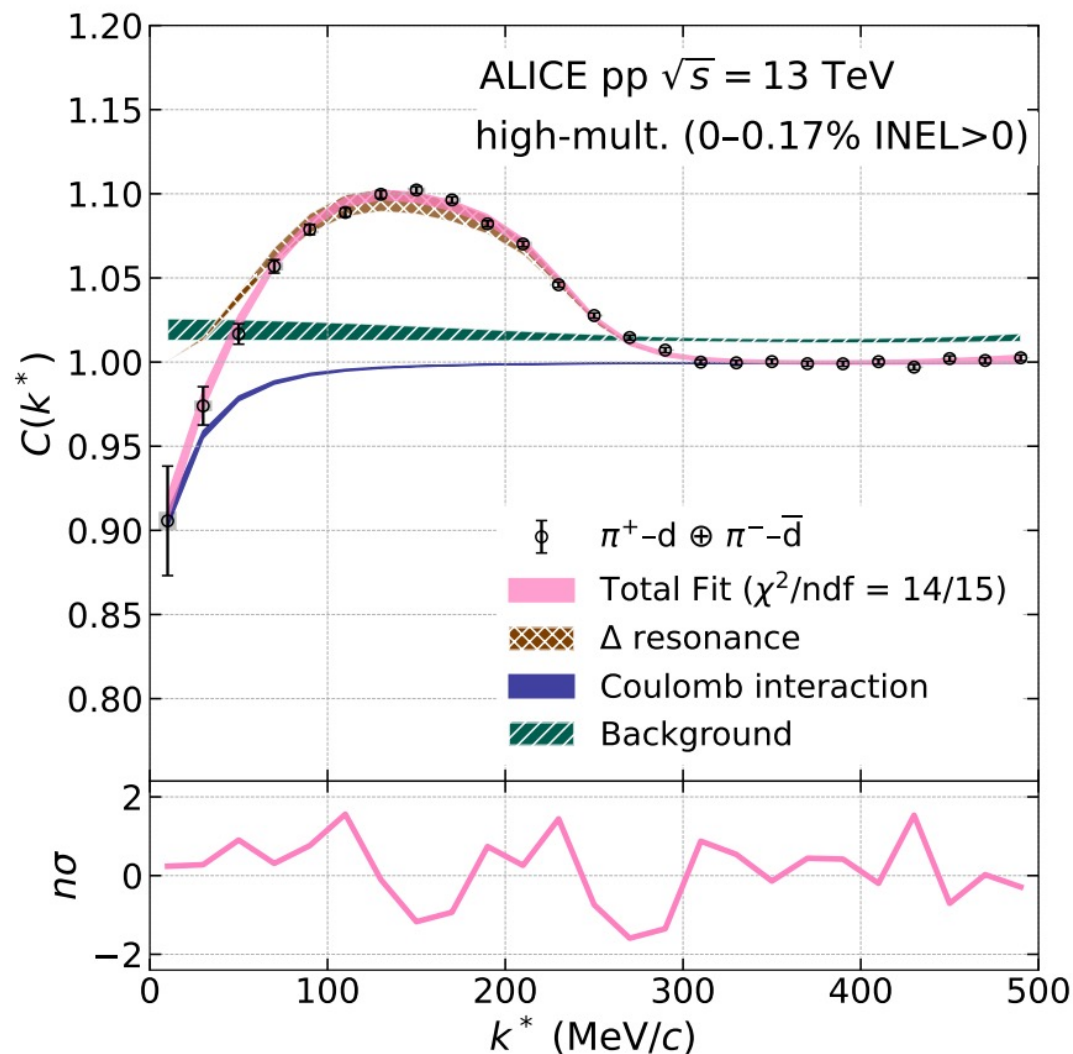
Data from STAR, *PRL* 130, 202301 (2023)



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.

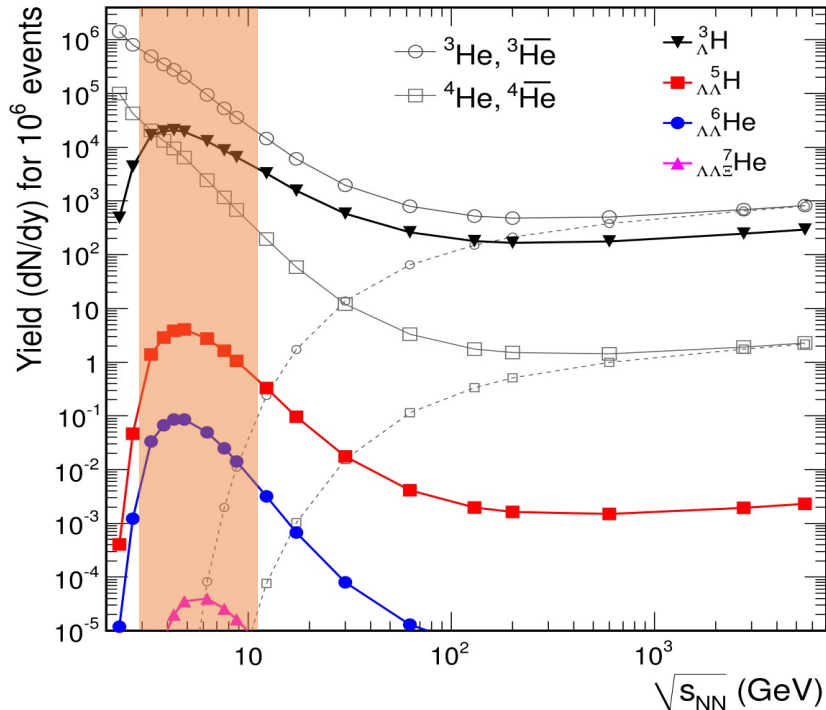
For theoretical explanation: See poster by Li-Yuan Zhang(张立元), Oct. 27

ALICE, arXiv:2504.02393(2025)



Pion-nucleus femtoscopy unveils the dynamics of light (anti-)nuclei production (driven by pion-catalyzed reaction)

A. Andronic et al., Phys. Lett. B 697, 203-207 (2011)



- FAIR/CBM (2.3-5.3 GeV)
- HIAF/CEE (2.1-4.5 GeV)
- NICA/MPD (4-11 GeV)
- J-PARC-HI (2-6.2 GeV)

Formation of loosely-bound (anti-)(hyper-)nuclei in high-energy collisions (**little bang nucleosynthesis**) is of fundamental importance and it is inherently a **non-equilibrium quantum** phenomenon.

Open questions:

- What are their main production mechanisms?
- How they survive?
- What is the role of their wavefunctions
- How their masses and widths are modified in medium?
- Are they polarized in non-central collisions?

Thanks for your listening!