International Symposium on Spin Polarization in Relativistic Heavy Ion Collisions 2026

Progress on Spin Polarization of Light (Hyper-)Nuclei

FUDAN UNIVERSITY

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

Outline

I Background: polarizations from hadrons to (hyper)nuclei

II Spin polarization of (anti-)(hyper-)nuclei

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

III Decoding proton spin polarization

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

IV Spin alignment of unstable ^{4}Li

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

V Summary and outlook

Spin polarization of hyperons in heavy-ion collisions (1)

Spin polarization of Lambda hyperon

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

Globally Polarized Quark-Gluon Plasma in Noncentral $A + A$ Collisions

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]

Produced partons have a large local relative orbital angular momentum along the direction opposite to the reaction plane in the early stage of noncentral heavy-ion collisions. Parton scattering is shown to polarize quarks along the same direction due to spin-orbital coupling. Such global quark polarization will lead to many observable consequences, such as left-right asymmetry of hadron spectra and global transverse polarization of thermal photons, dileptons, and hadrons. Hadrons from the decay of polarized resonances will have an azimuthal asymmetry similar to the elliptic flow. Global hyperon polarization is studied within different hadronization scenarios and can be easily tested.

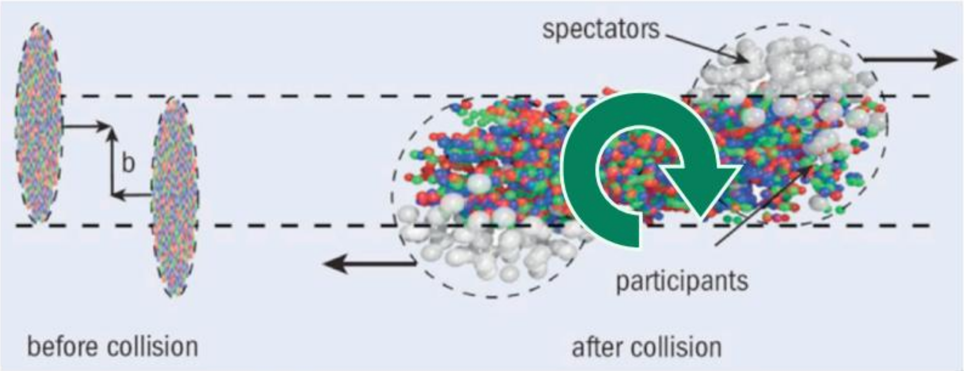
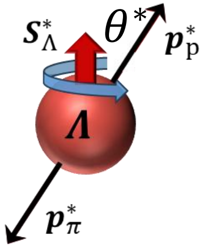


figure: M. Lisa, talk @ "Strangeness in Quark Matter 2016"

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



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

Decay constant (α_Λ) Spin polarization ($\mathcal{P}_\Lambda$)

For overview, see the next talk by X. L. Sheng

F. Becattini, F. Piccinini, Annals of Physics 323, 2452 (2008)

The ideal relativistic spinning gas: Polarization and spectra

F. Becattini [a,*], F. Piccinini [b]

$$\widehat{\rho}_\omega = \frac{1}{Z_\omega} \exp[(-\widehat{h} + \mu\widehat{q} + \boldsymbol{\omega}\cdot\widehat{\mathbf{j}})/T]\mathrm{P}_V$$

$$\boldsymbol{\Pi} = \mathrm{tr}[\widehat{\mathbf{S}}\widehat{\rho}_\omega(p)] = \frac{\sum_{n=-S}^{S} n e^{n\omega/T}}{\sum_{n=-S}^{S} e^{n\omega/T}}\hat{\boldsymbol{\omega}}$$

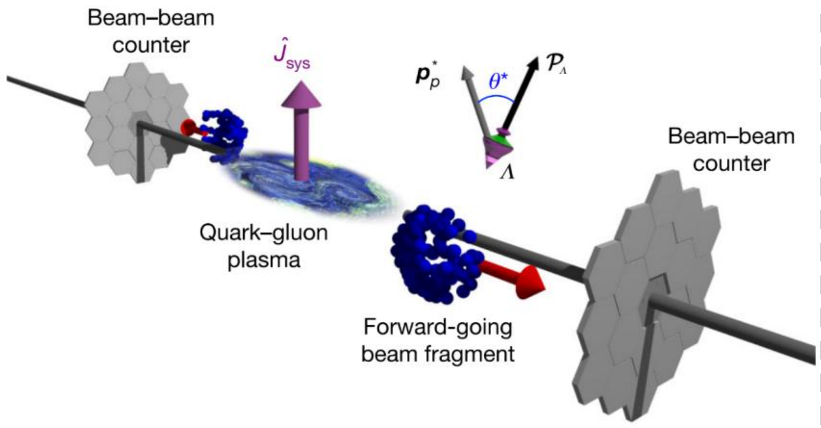
Vorticity ← **Spin polarization**

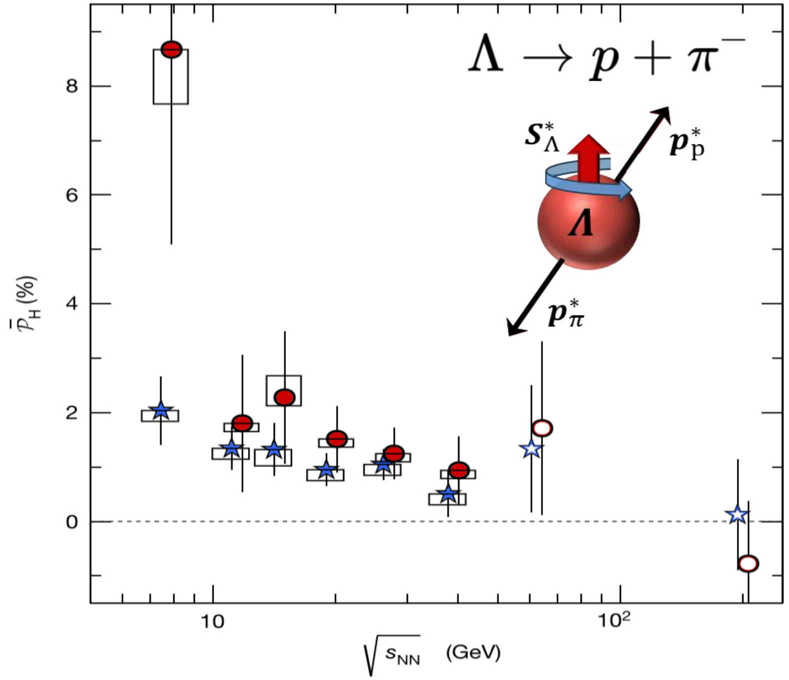
$$\omega \approx k_B T(\mathcal{P}_\Lambda + \mathcal{P}_{\bar{\Lambda}})/\hbar$$

Experimental progress

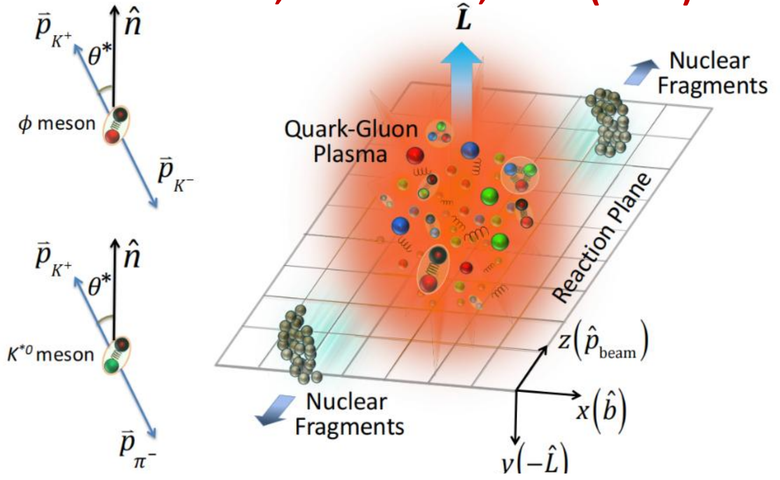
For overview, see talks by D. Y. Shen and X. M. Zhang

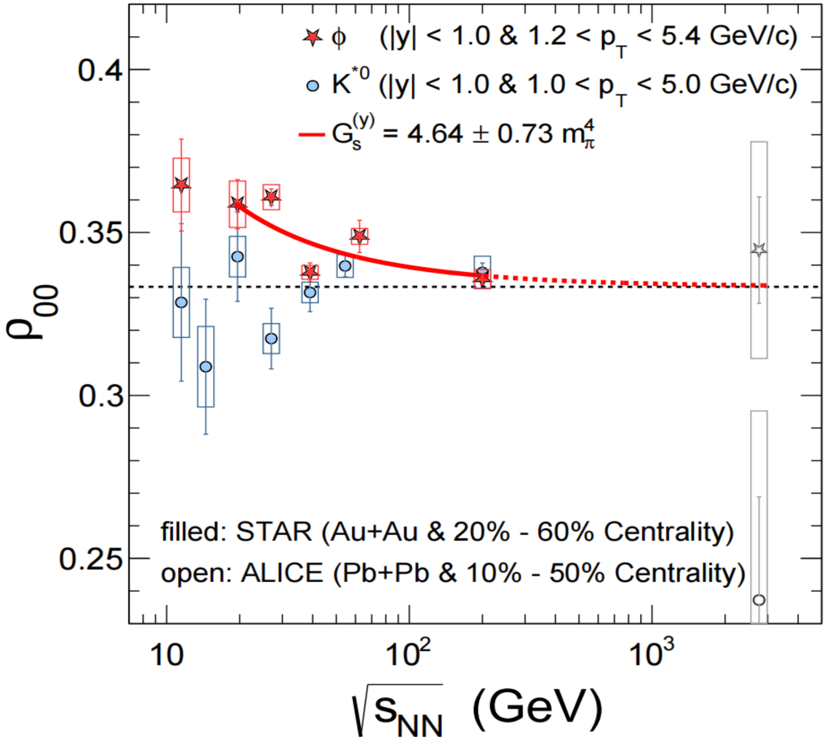
STAR, Nature 548, 62 (2017)



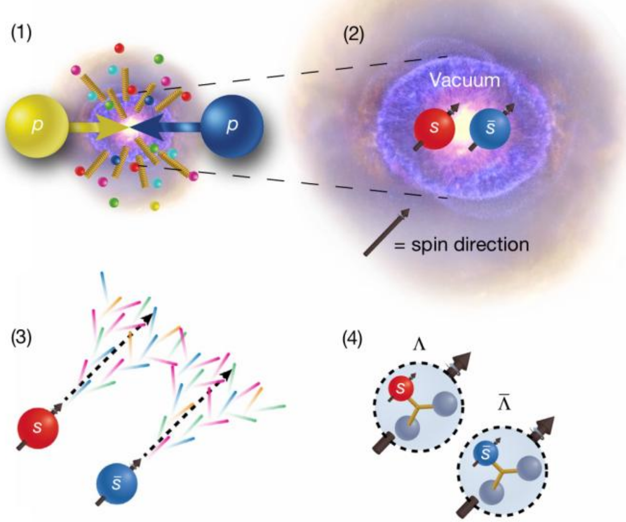


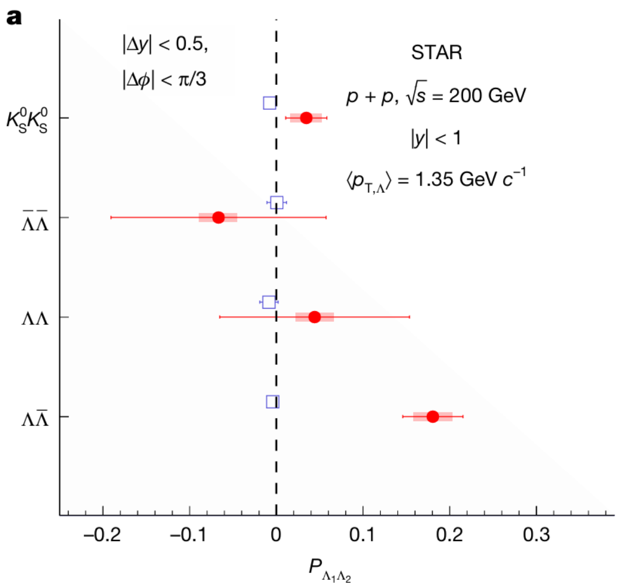
STAR, Nature 614, 7947 (2023)





STAR, Nature 650, 5 (2026)





From polarization of hadrons to light (hyper-)nuclei (3)

K. J. Sun et al., Phys. Rev. Lett. 134, 022301 (2025)
K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024)
R.-J. Liu and J. Xu, Phys. Rev. C 109, 014615 (2024).

Elementary hadrons

$\Lambda(uds)$ $\Xi(uss)$ $\Omega(sss)$

$\phi(s\bar{s})$ $K^{*0}(d\bar{s})$ $\rho^+(u\bar{d})$

$J/\psi(c\bar{c})$ …

Stable (anti-)nuclei

Spin $\frac{1}{2}$ 1 $\frac{1}{2}$

$p(uud)$ $d(np)$ $^3\mathrm{He}(npp)$

$\bar{p}(\bar{u}\bar{u}\bar{d})$ $\bar{d}(\bar{n}\bar{p})$ $^3\overline{\mathrm{He}}(\bar{n}\bar{p}\bar{p})$

…

Unstable (anti-)(hyper-)nuclei

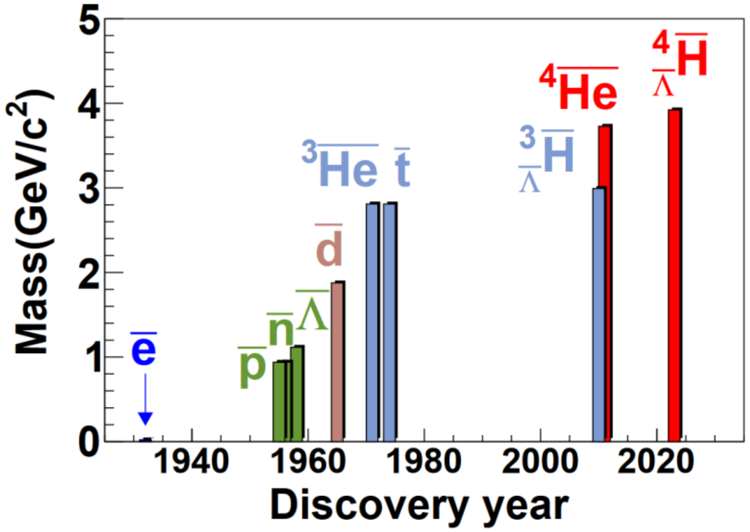
Spin $\frac{1}{2}, \frac{3}{2}$? $2\ (g.s.)$

$^3_\Lambda\mathrm{H}(np\Lambda)$ $^4\mathrm{Li}(\mathrm{nppp})$

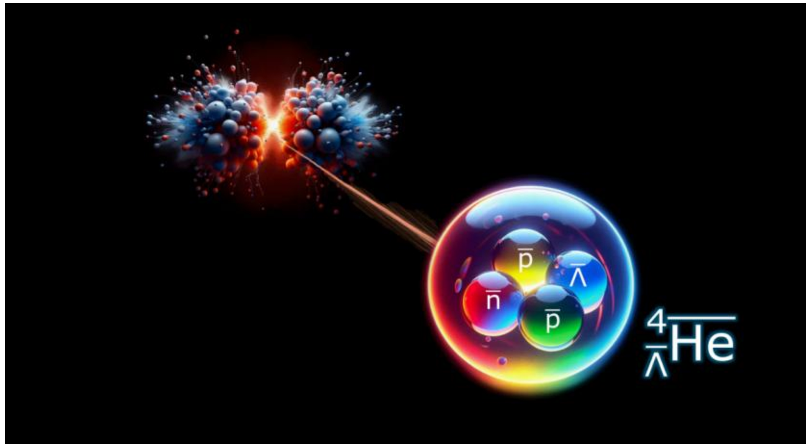
$^3_{\bar{\Lambda}}\overline{\mathrm{H}}(\bar{n}\bar{p}\bar{\Lambda})$ $^4\overline{\mathrm{Li}}(\bar{n}\bar{p}\bar{p}\bar{p})$

…

STAR, *Nature* 632, 8027 (2024)



ALICE, Phys. Rev. Lett. 134 (2025) 16, 162301



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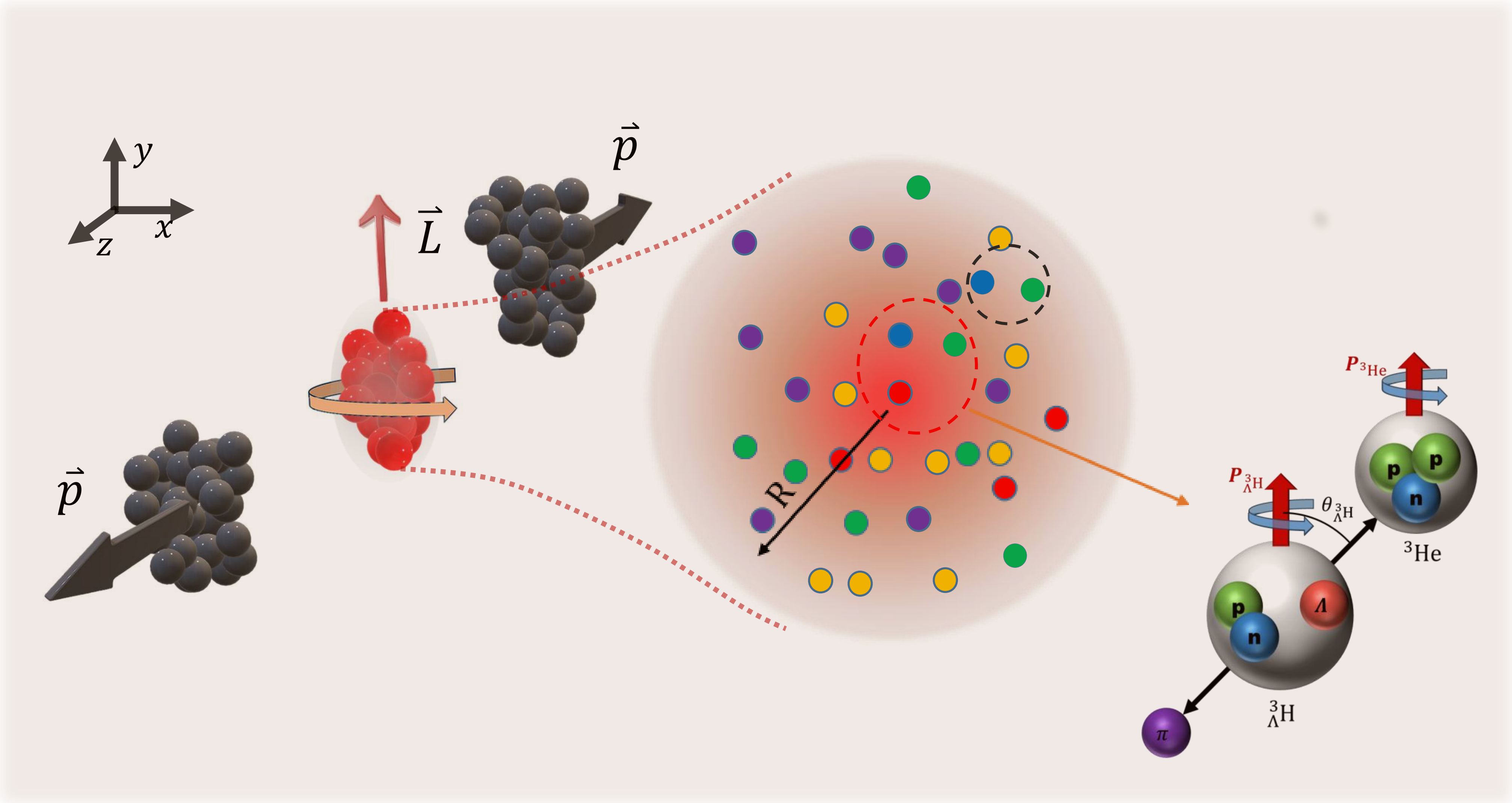
Yun-Peng Zheng *et al.*, arXiv:2509.15286 (2025)

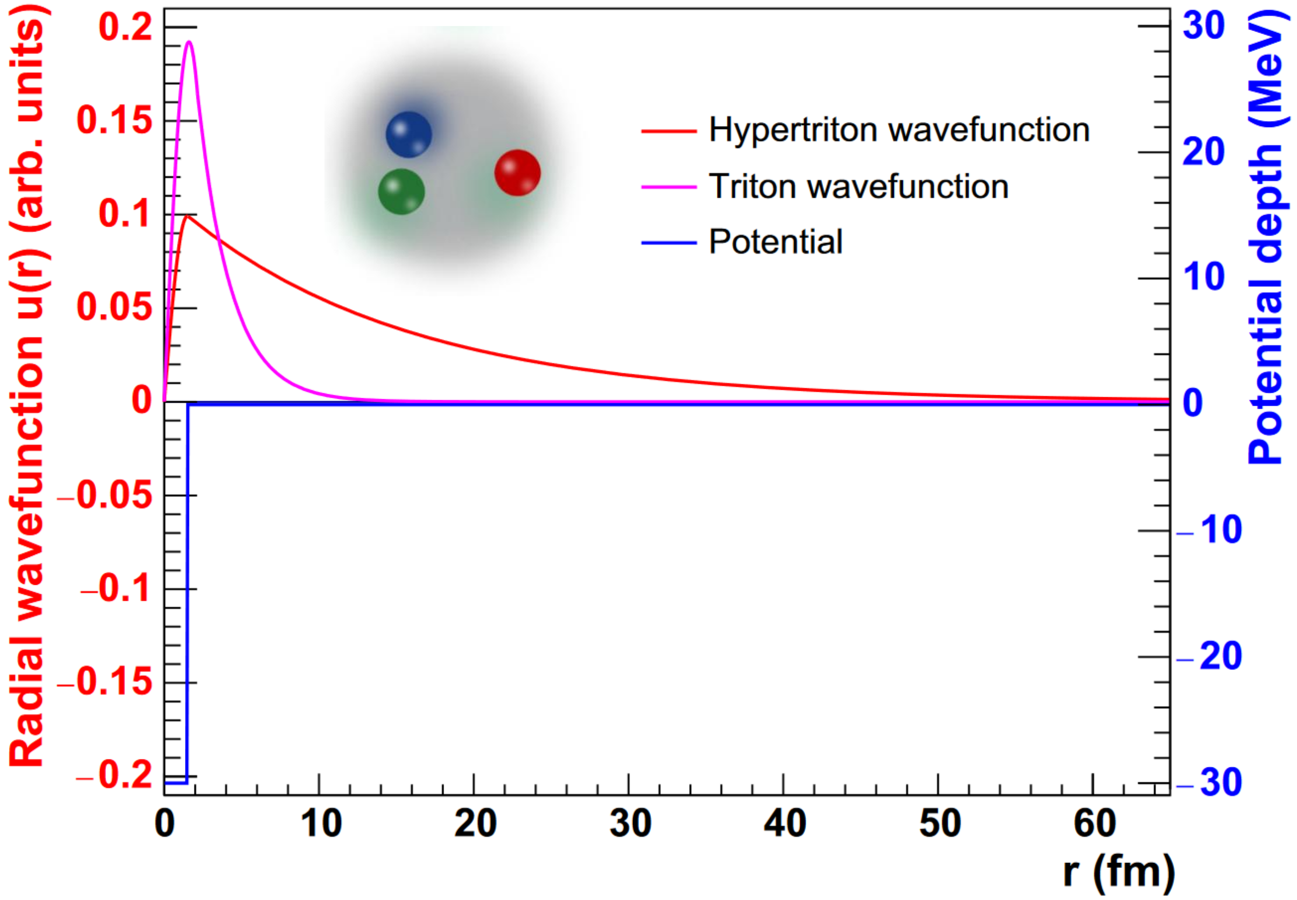
V Summary and outlook

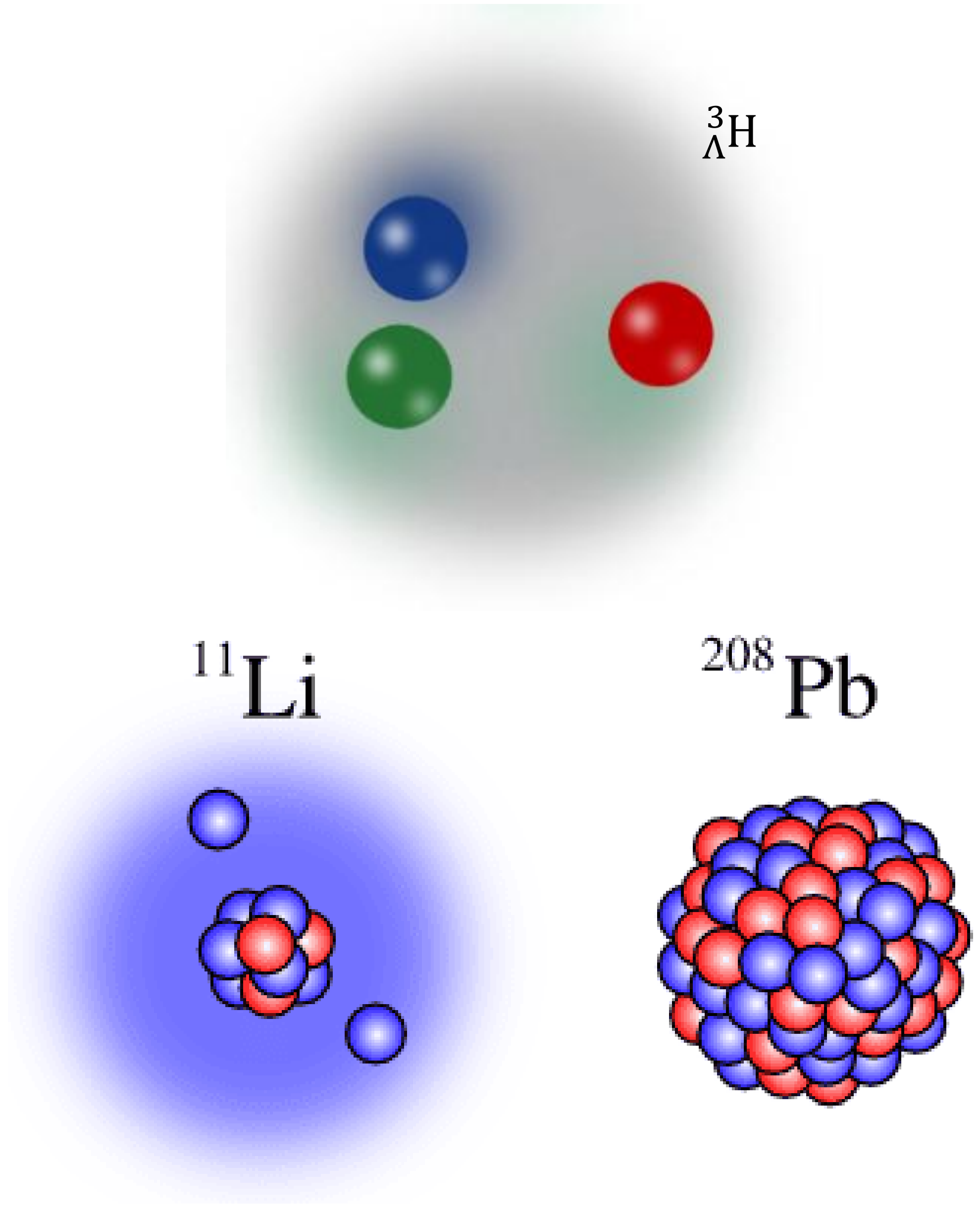
Global spin polarization of (anti-)hypertriton

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



Strange halo nucleus: (anti-)hypertriton (5)





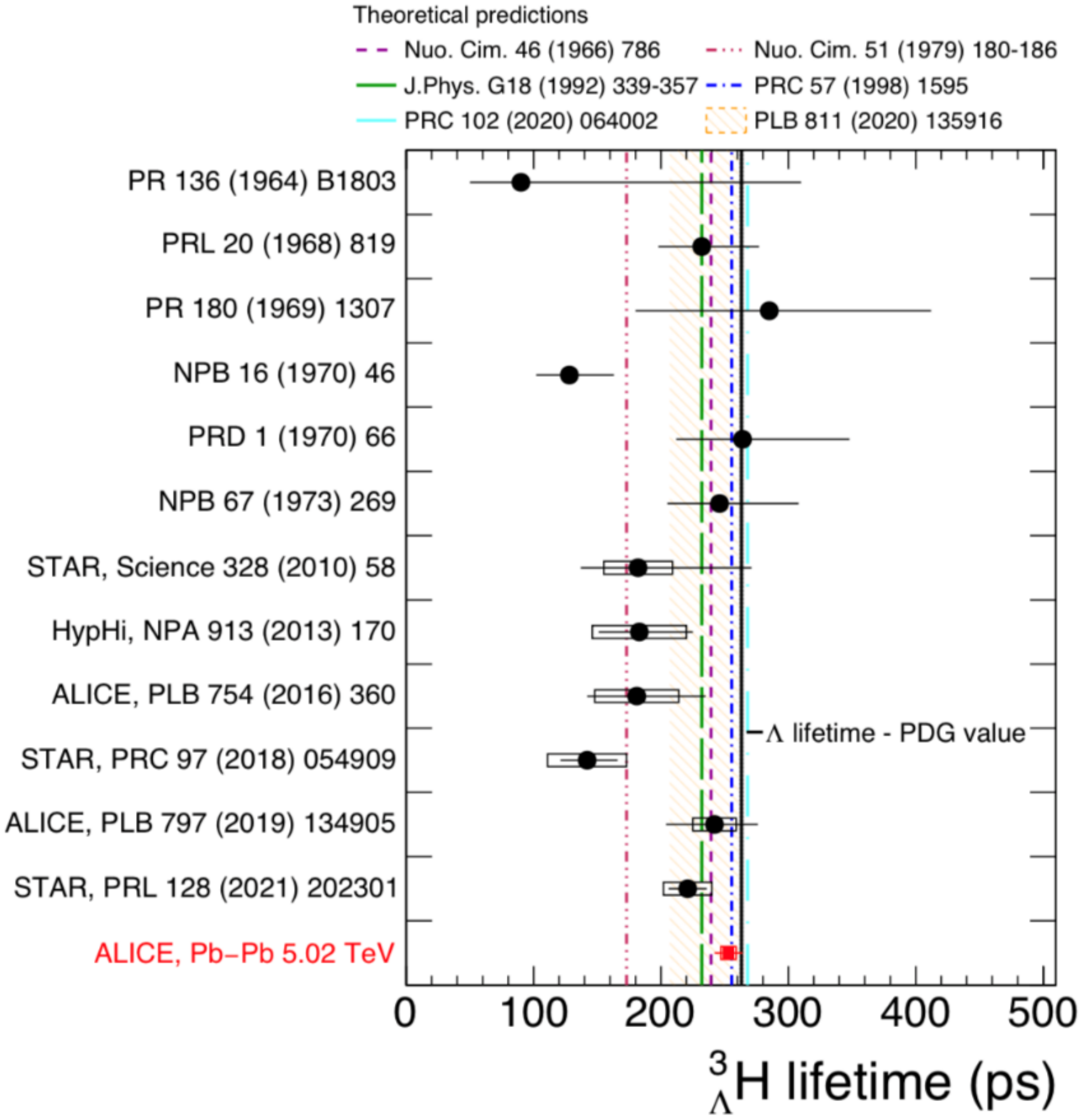
J. Chen et al., Phys. Rep. 760, 1 (2018);
P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)
D. N. Liu et al. Phys. Lett. B 855, 138855 (2024)
X. Zeng, R. Y. Zheng, Z. W. Liu, L. S. Geng, and X. R. Zhou arXiv:2509.16878 (2025)

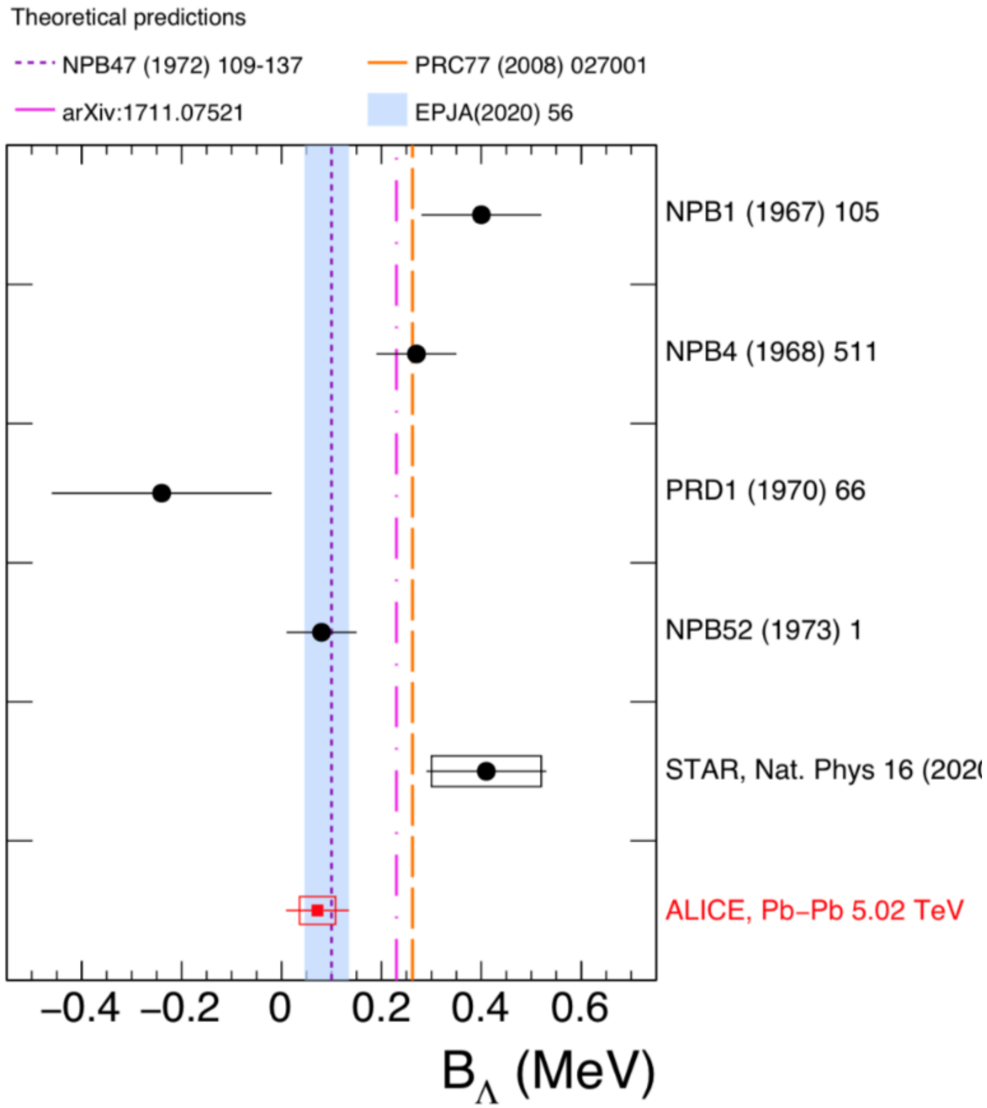
Lifetime and binding energy (anti-hypertriton) (6)

ALICE, PRL 131, 102302 (2023)

Lifetime and binding energy

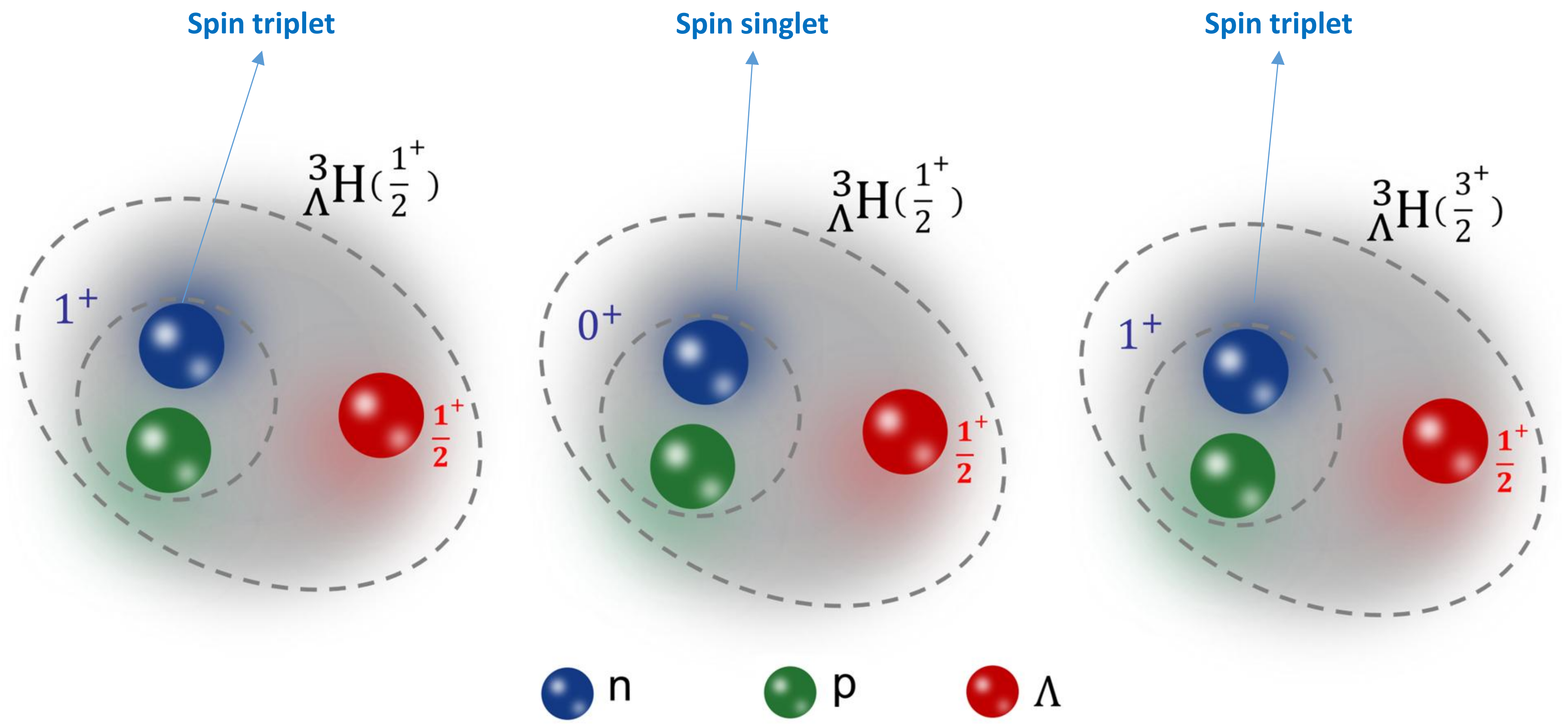
Y. G. Ma, Nucl. Sci. Tech. 3497 (2023)





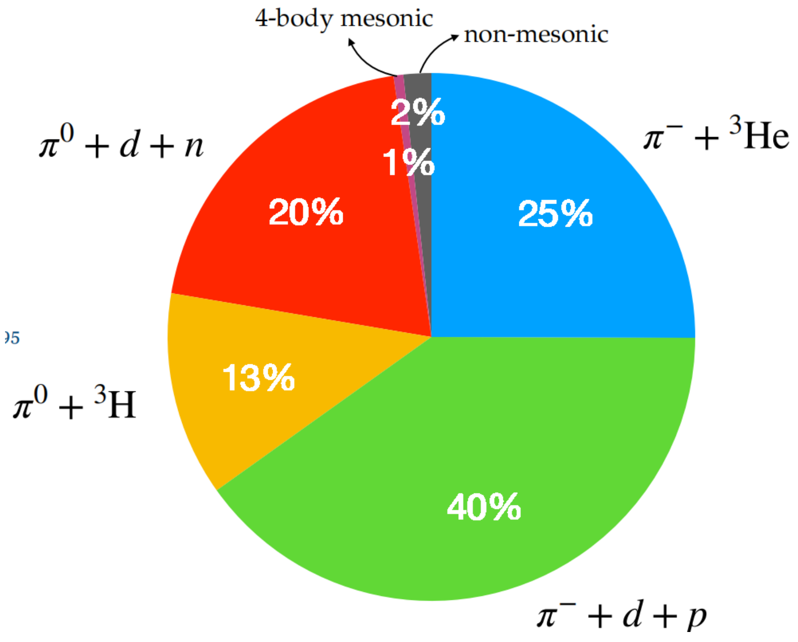
J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)

Spin of (anti-)hypertriton ?



Spin of (anti-)hypertriton ? (8)

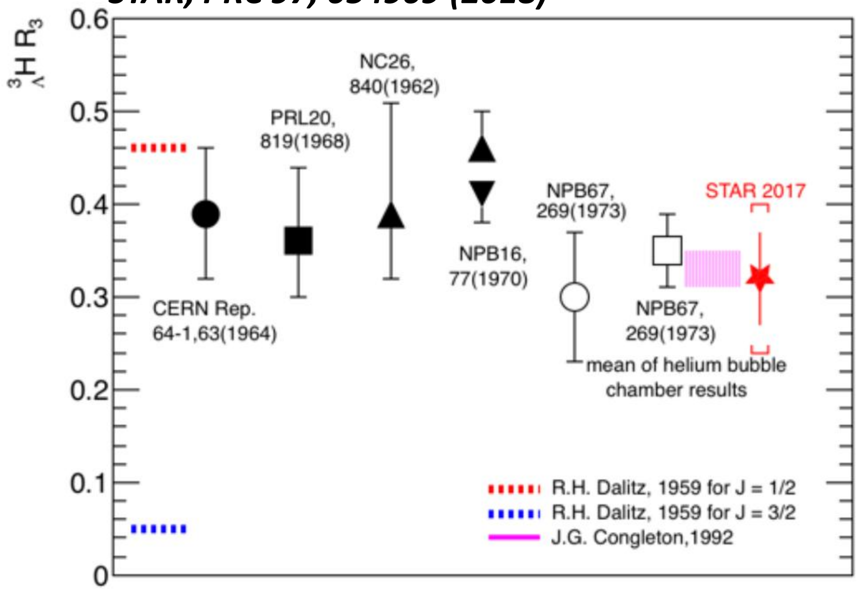
$$^3_\Lambda\mathrm{H} \mapsto \pi^- + {}^3\mathrm{He}, \qquad ^3_\Lambda\mathrm{H} \mapsto \pi^0 + {}^3\mathrm{H},$$
$$^3_\Lambda\mathrm{H} \mapsto \pi^- + d + p, \qquad ^3_\Lambda\mathrm{H} \mapsto \pi^0 + d + n,$$
$$^3_\Lambda\mathrm{H} \mapsto \pi^- + p + n + p, \qquad ^3_\Lambda\mathrm{H} \mapsto \pi^0 + p + n + n.$$



Relative branching ratio:

$$R_3 = \frac{\mathrm{B.R.}(^3_\Lambda\mathrm{H} \to {}^3\mathrm{He}\pi^-)}{\mathrm{B.R.}(^3_\Lambda\mathrm{H} \to {}^3\mathrm{He}\pi^-) + \mathrm{B.R.}(^3_\Lambda\mathrm{H} \to \mathrm{d}p\pi^-)}$$

STAR, PRC 97, 054909 (2018)



Favors spin 1/2

PHYSICAL REVIEW D **87**, 034506 (2013)

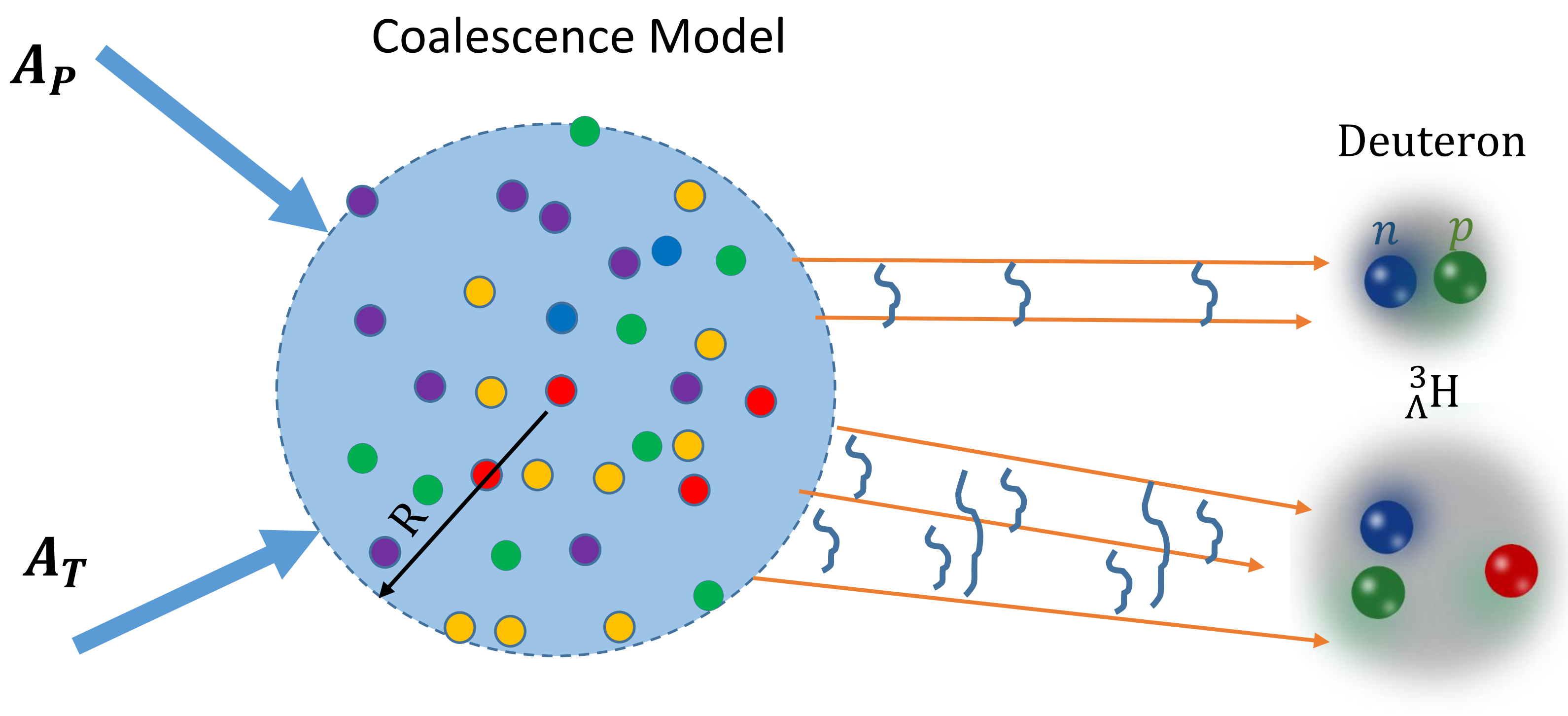
Light nuclei and hypernuclei from quantum chromodynamics in the limit of SU(3) flavor symmetry

S. R. Beane,[1] E. Chang,[2] S. D. Cohen,[3] W. Detmold,[4,5] H. W. Lin,[3] T. C. Luu,[6] K. Orginos,[4,5] A. Parreño,[2] M. J. Savage,[3] and A. Walker-Loud[7,8]

Label	A	s	I	J^π	Local SU(3) irreps	This work
N	1	0	1/2	$1/2^+$	**8**	**8**
Λ	1	−1	0	$1/2^+$	**8**	**8**
Σ	1	−1	1	$1/2^+$	**8**	**8**
Ξ	1	−2	1/2	$1/2^+$	**8**	**8**
d	2	0	0	1^+	$\overline{\mathbf{10}}$	$\overline{\mathbf{10}}$
nn	2	0	1	0^+	**27**	**27**
$n\Lambda$	2	−1	1/2	0^+	**27**	**27**
$n\Lambda$	2	−1	1/2	1^+	$\mathbf{8}_A$, $\overline{\mathbf{10}}$	-
$n\Sigma$	2	−1	3/2	0^+	**27**	**27**
$n\Sigma$	2	−1	3/2	1^+	**10**	**10**
$n\Xi$	2	−2	0	1^+	$\mathbf{8}_A$	$\mathbf{8}_A$
$n\Xi$	2	−2	1	1^+	$\mathbf{8}_A$, **10**, $\overline{\mathbf{10}}$	-
H	2	−2	0	0^+	**1**, **27**	**1**, **27**
^{3}H, ^{3}He	3	0	1/2	$1/2^+$	**35**	**35**
$^3_\Lambda$H$(1/2^+)$	3	−1	0	$1/2^+$	**35**	-
$^3_\Lambda$H$(3/2^+)$	3	−1	0	$3/2^+$	$\overline{\mathbf{10}}$	$\overline{\mathbf{10}}$
$^3_\Lambda$He, $^3_\Lambda$H, $nn\Lambda$	3	−1	1	$1/2^+$	**27**, **35**	**27**, **35**
$^3_\Sigma$He	3	−1	1	$3/2^+$	**27**	**27**
^{4}He	4	0	0	0^+	**28**	**28**
$^4_\Lambda$He, $^4_\Lambda$H	4	−1	1/2	0^+	**28**	-
$^4_{\Lambda\Lambda}$He	4	−2	1	0^+	**27**, **28**	**27**, **28**
$\Lambda\Xi^0 pnn$	5	−3	0	$3/2^+$	$\overline{\mathbf{10}} + \cdots$	$\overline{\mathbf{10}}$

Favors spin 3/2

Final-state coalescence model



Density Matrix Formulation
(sudden approximation)

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

Wigner function of light cluster

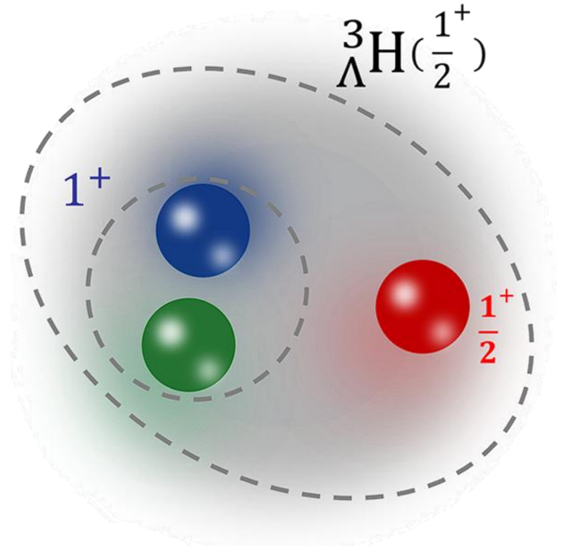
Overlap between source distribution function and Wigner function of light nuclei

R. Scheibl and U. W. Heinz, PRC59. 1585(1999)
F. Bellini et al., PRC99,054905(2019)
K. J. Sun, C. M. Ko and B. Dönigus, PLB 792, 132 (2019)

Zhen Zhang and Che Ming Ko, PLB 780, 191-195 (2018)
K. Blum, M. Takimoto, PRC 99, 044913 (2019)
Hui-Gan Chen and Zhao-Qing Feng, PLB 824, 136849 (2022)

Spin-dependent coalescence model

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



➢ Spin wavefunction

$$|\frac{1}{2},\uparrow\rangle_{{}^3_\Lambda\mathrm{H}} = \frac{\sqrt{6}}{3}|\frac{1}{2},\frac{1}{2}\rangle_n|\frac{1}{2},\frac{1}{2}\rangle_p|\frac{1}{2},-\frac{1}{2}\rangle_\Lambda - \frac{\sqrt{6}}{6}\left(|\frac{1}{2},\frac{1}{2}\rangle_n|\frac{1}{2},-\frac{1}{2}\rangle_p|\frac{1}{2},\frac{1}{2}\rangle_\Lambda + |\frac{1}{2},-\frac{1}{2}\rangle_n|\frac{1}{2},\frac{1}{2}\rangle_p|\frac{1}{2},\frac{1}{2}\rangle_\Lambda\right),$$

$$|\frac{1}{2},\downarrow\rangle_{{}^3_\Lambda\mathrm{H}} = -\frac{\sqrt{6}}{3}|\frac{1}{2},-\frac{1}{2}\rangle_n|\frac{1}{2},-\frac{1}{2}\rangle_p|\frac{1}{2},\frac{1}{2}\rangle_\Lambda + \frac{\sqrt{6}}{6}\left(|\frac{1}{2},\frac{1}{2}\rangle_n|\frac{1}{2},-\frac{1}{2}\rangle_p|\frac{1}{2},-\frac{1}{2}\rangle_\Lambda + |\frac{1}{2},-\frac{1}{2}\rangle_n|\frac{1}{2},\frac{1}{2}\rangle_p|\frac{1}{2},-\frac{1}{2}\rangle_\Lambda\right).$$

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

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

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

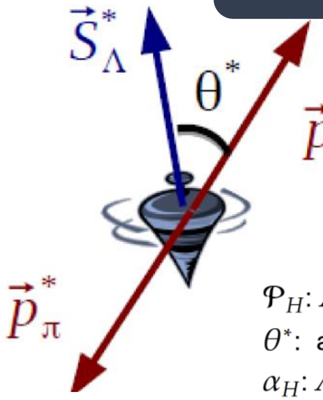
$$\mathcal{P}_{{}^3_\Lambda\mathrm{H}} \approx \frac{\frac{2}{3}\mathcal{P}_n + \frac{2}{3}\mathcal{P}_p - \frac{1}{3}\mathcal{P}_\Lambda - \mathcal{P}_n\mathcal{P}_p\mathcal{P}_\Lambda}{1-\frac{2}{3}(\mathcal{P}_n+\mathcal{P}_p)\mathcal{P}_\Lambda + \frac{1}{3}\mathcal{P}_n\mathcal{P}_p} \approx \frac{2}{3}\mathcal{P}_n + \frac{2}{3}\mathcal{P}_p - \frac{1}{3}\mathcal{P}_\Lambda \approx \mathcal{P}_\Lambda \qquad \mathcal{P}_p \approx \mathcal{P}_n \approx \mathcal{P}_\Lambda$$

Assuming spin polarizations and correlations are small

(Anti-)hypertriton polarization and its spin structure

Parity-violating weak decay

Λ hyperons



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

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

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

$\mathcal{P}_H$: Λ polarization

θ^*: angle between proton momentum in Λ rest frame

α_H: Λ decay parameter

$\alpha_\Lambda = 2\mathrm{Re}(T_s^* T_p) = 0.732 \pm 0.014$

BESIII, Phys. Rev. Lett. 129, 131801 (2022).

The transition matrix

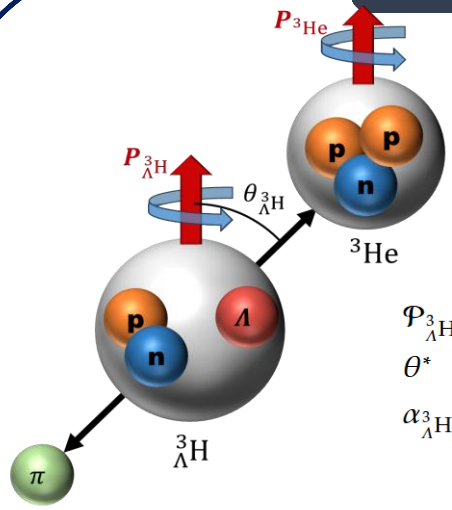
$$T(\Lambda \to \pi^- + p) = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} T_s + T_p\cos\theta_p^* & T_p\sin\theta_p^* e^{i\phi_p^*} \\ T_p\sin\theta_p^* e^{-i\phi_p^*} & T_s - T_p\cos\theta_p^* \end{pmatrix}$$

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



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

$\mathcal{P}_{^3_\Lambda\mathrm{H}}$: $^3_\Lambda\mathrm{H}$ polarization

θ^* : Angle between $^3\mathrm{He}$ momentum in $^3_\Lambda\mathrm{H}$ rest frame

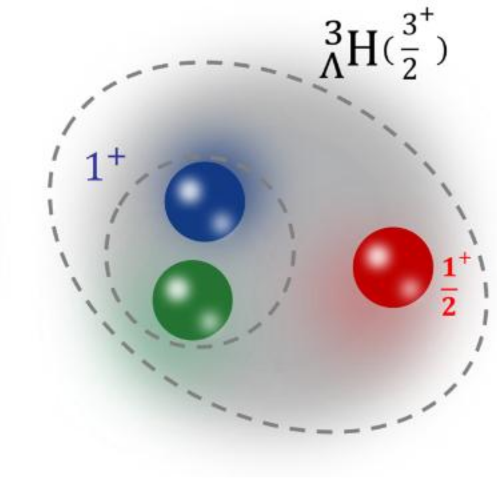
$\alpha_{^3_\Lambda\mathrm{H}}$: $^3_\Lambda\mathrm{H}$ decay parameter

$$T(^3_\Lambda\mathrm{H} \to \pi^- + ^3\mathrm{He}) = \frac{F}{6\sqrt{\pi}} \begin{pmatrix} 3T_s - T_p\cos\theta^* & -T_p\sin\theta^* e^{i\phi^*} \\ -T_p\sin\theta^* e^{-i\phi^*} & 3T_s + T_p\cos\theta^* \end{pmatrix}$$

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

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

Sign flip !

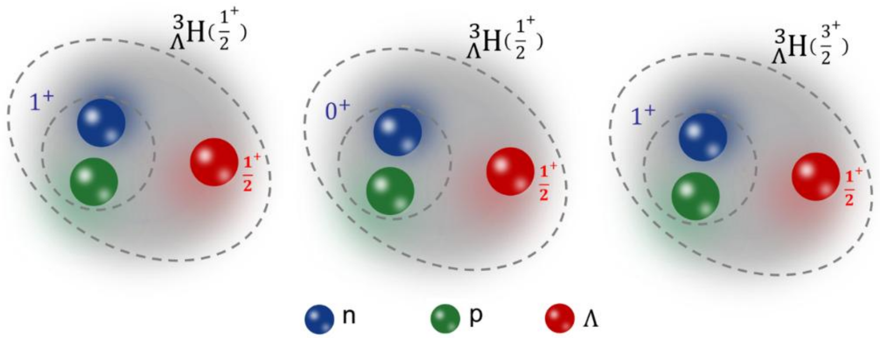


$$\hat{\rho}_{^3_\Lambda\mathrm{H}} \approx \mathrm{diag}\left[\frac{(1+\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)(1+\mathcal{P}_\Lambda)^2}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^2(1+\mathcal{P}_\Lambda)}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}\right]$$

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

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

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



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

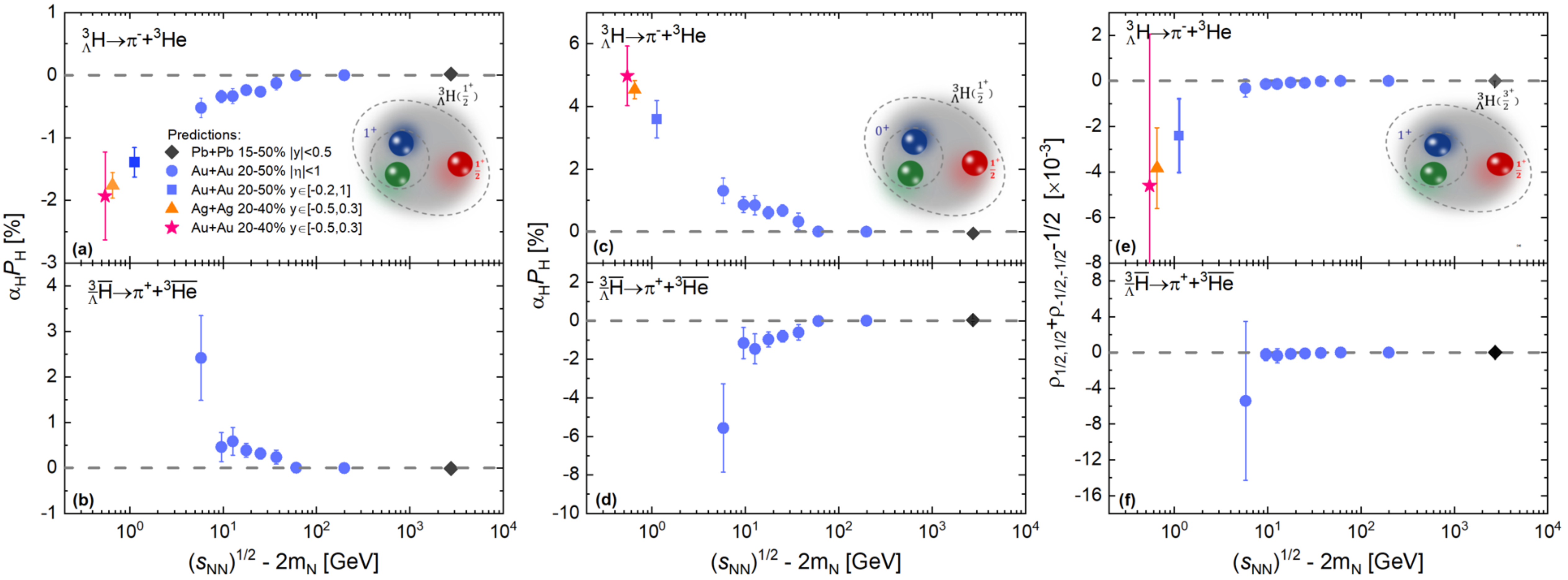
Different polarization and decay patterns!

(Anti-)hypertriton polarization and its spin structure (13)

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

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

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



Outline

I Background: polarizations from hadrons to (hyper)nuclei

II Spin polarization of (anti-)(hyper-)nuclei

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

III Decoding proton spin polarization

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

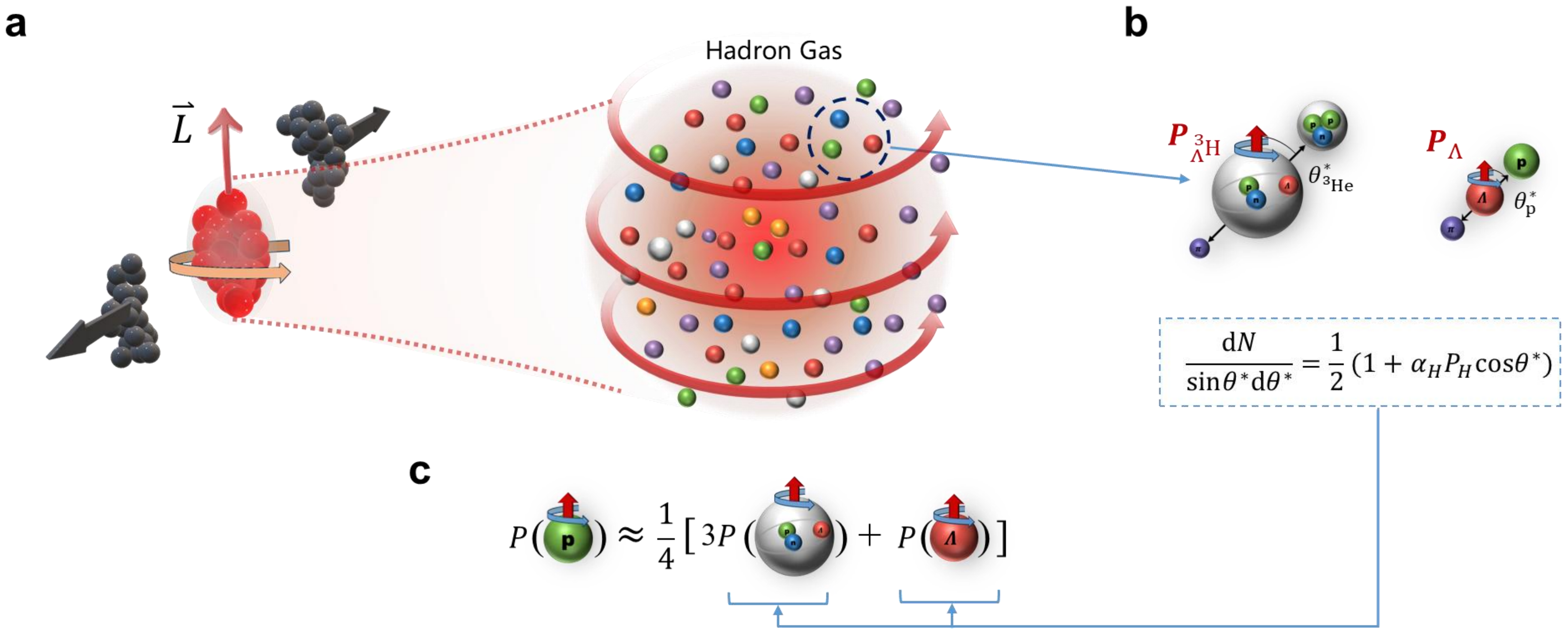
IV Spin alignment of unstable ^{4}Li

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

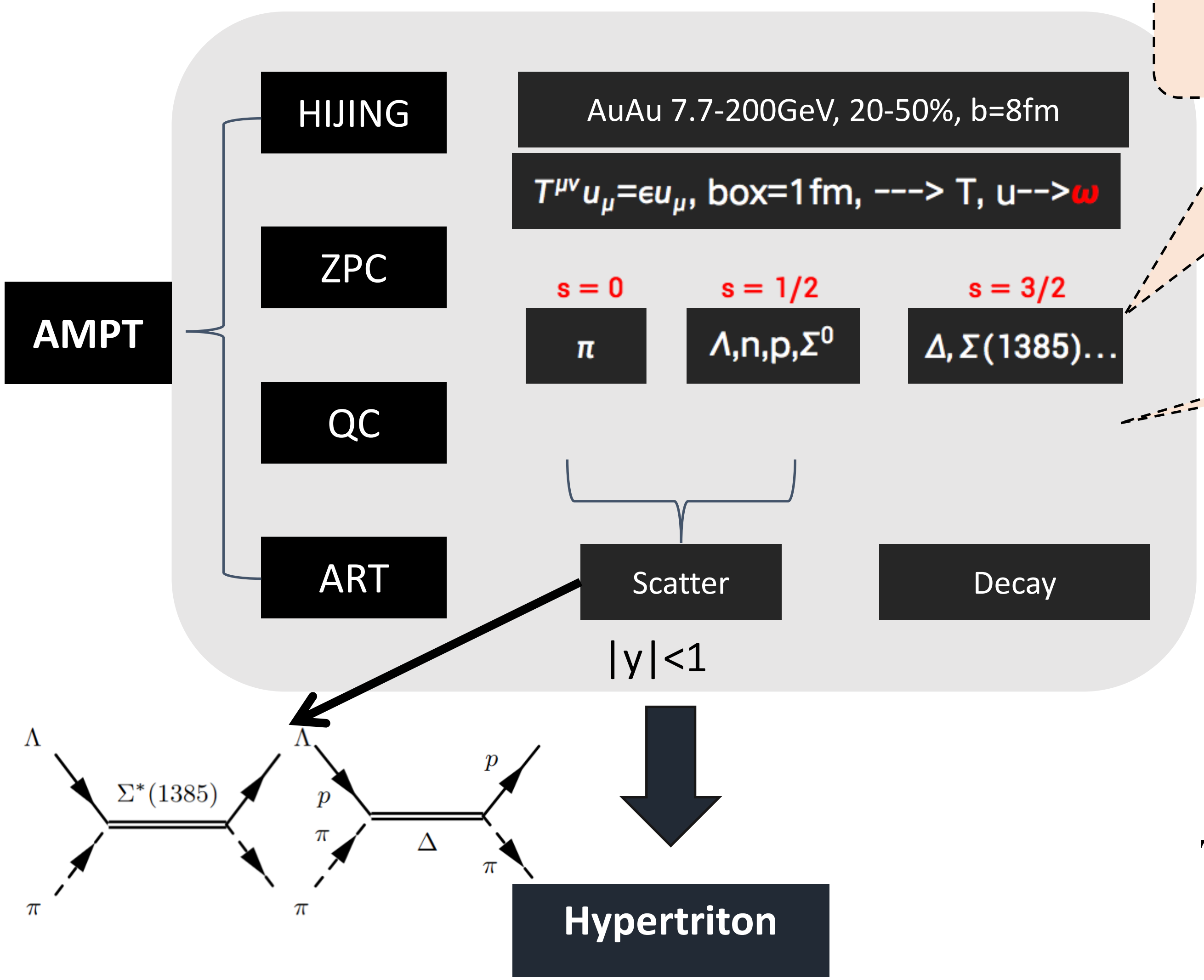
V Summary and outlook

Decoding proton spin polarization from hypertriton production (14)

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



Model setup



Thermal vorticity

$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu). \qquad \beta^\mu = u^\mu / T$$

Spin polarization vector of single pariticle

$$\mathcal{P}^\mu(x,p) = -\frac{s+1}{6m}(1-n_F)\epsilon^{\mu\nu\rho\sigma} p_\nu \varpi_{\rho\sigma}(x),$$

Eigen equation $T^{\mu\nu}u_\mu = \epsilon u^\mu$

Fiuld energy-momentum tensor

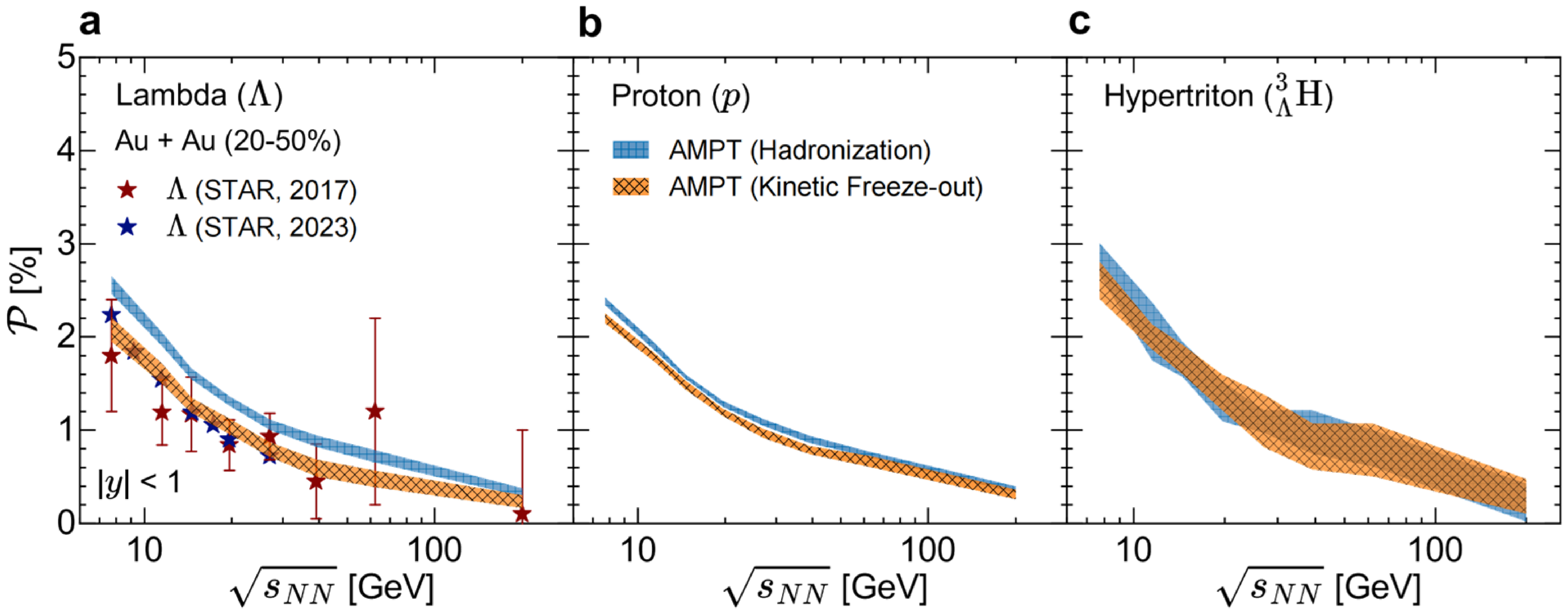
$$T_{\mu\nu} = \frac{1}{N_e \Delta V} \sum_j^{N_e} \sum_i \frac{P_{ij}^\mu P_{ij}^\nu}{E_{ij}}$$

Temperature

$$T = 0.199 \text{ GeV} \left(\frac{\epsilon/\gamma_q}{1+3N_f/4}\right)^{1/4}$$

$$\gamma_q = \frac{1}{2}\left(\left(\frac{N_+}{N_-}\right)^{N_f/2} + \left(\frac{N_-}{N_+}\right)^{N_f/2}\right)$$

Dai-Neng Liu *et al.*, arXiv:2508.12193 (2025)   C. Yi, S. Pu, L. G. Pang, G. Y. Qin, and X. N. Wang, arXiv:2508.12193 (2025)



Hypertriton polarization

Spin-dependent Coalescence model

$$N_{A,\pm\frac{1}{2}} = \int \left(\prod_{i=1}^{A} p_i^{\mu} d\sigma_{i\mu} \frac{d^3 p_i}{E_i} f(x_i, p_i) \right) \times \left(\frac{2}{3} w_{n,\pm\frac{1}{2}} w_{p,\pm\frac{1}{2}} w_{\Lambda\mp\frac{1}{2}} + \frac{1}{6} w_{n,\mp\frac{1}{2}} w_{p,\pm\frac{1}{2}} w_{\Lambda\pm\frac{1}{2}} + \frac{1}{6} w_{n,\pm\frac{1}{2}} w_{p,\mp\frac{1}{2}} w_{\Lambda\pm\frac{1}{2}}\right) p_s(x_i, p_i) \times W_c(x_i, p_i)$$

$$w_{i,\pm\frac{1}{2}} = \frac{1}{2}(1 \pm \mathcal{P}_i)$$

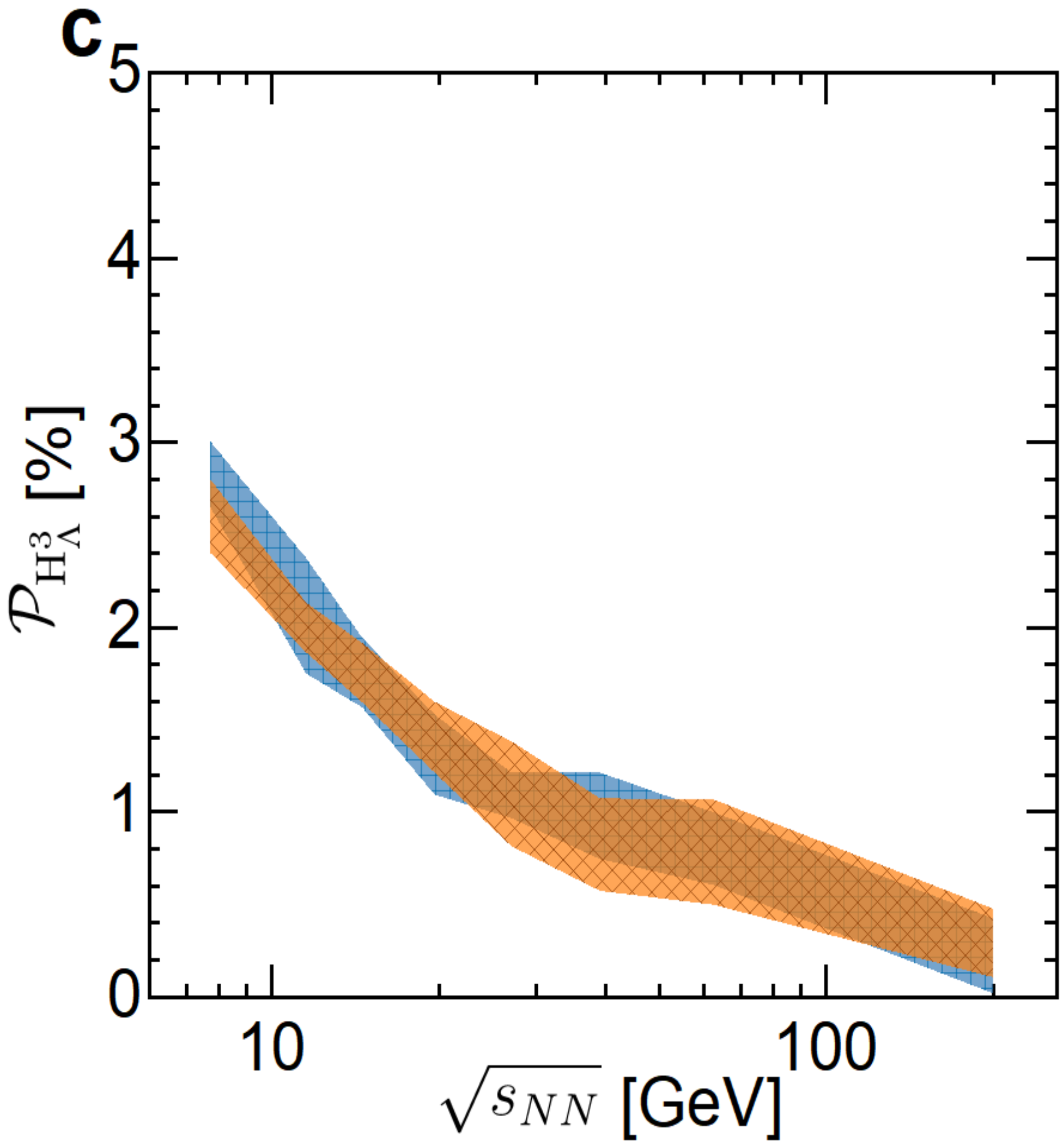
$$W_3(\rho, \lambda, p_\rho, p_\lambda) = 8^2 \exp\left[-\frac{\rho^2}{\sigma_\rho^2} - \frac{\lambda^2}{\sigma_\lambda^2} - p_\rho^2 \sigma_\rho^2 - p_\lambda^2 \sigma_\lambda^2\right]$$

$$\rho = \frac{1}{\sqrt{2}}(x_1' - x_2'), \quad p_\rho = \frac{\sqrt{2}(m_2 p_1' - m_1 p_2')}{m_1 + m_2},$$

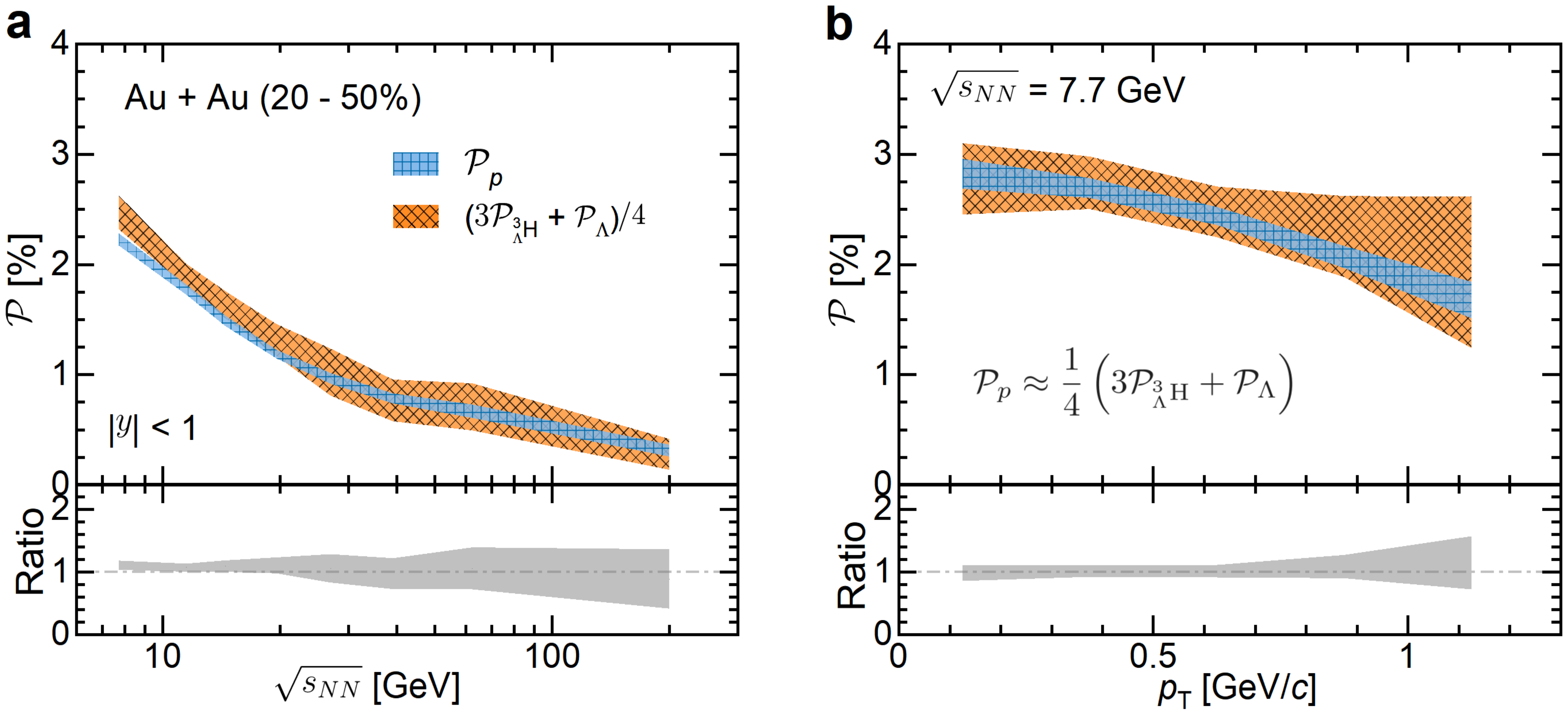
$$\lambda = \sqrt{\frac{2}{3}} \left(\frac{m_1 x_1' + m_2 x_2' - x_3'}{m_1 + m_2} \right),$$

$$p_\lambda = \sqrt{\frac{3}{2}} \frac{m_3(p_1' + p_2') - (m_1 + m_2) p_3'}{m_1 + m_2 + m_3}.$$

$$\mathcal{P}_{^3_\Lambda\mathrm{H}} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



Decoding proton spin polarization



A direct observation of proton spin polarization requires a baryon polarimeter
(see Y. T. Liang et al., Phys. Rev. D 112 (2025) 3, L031502)

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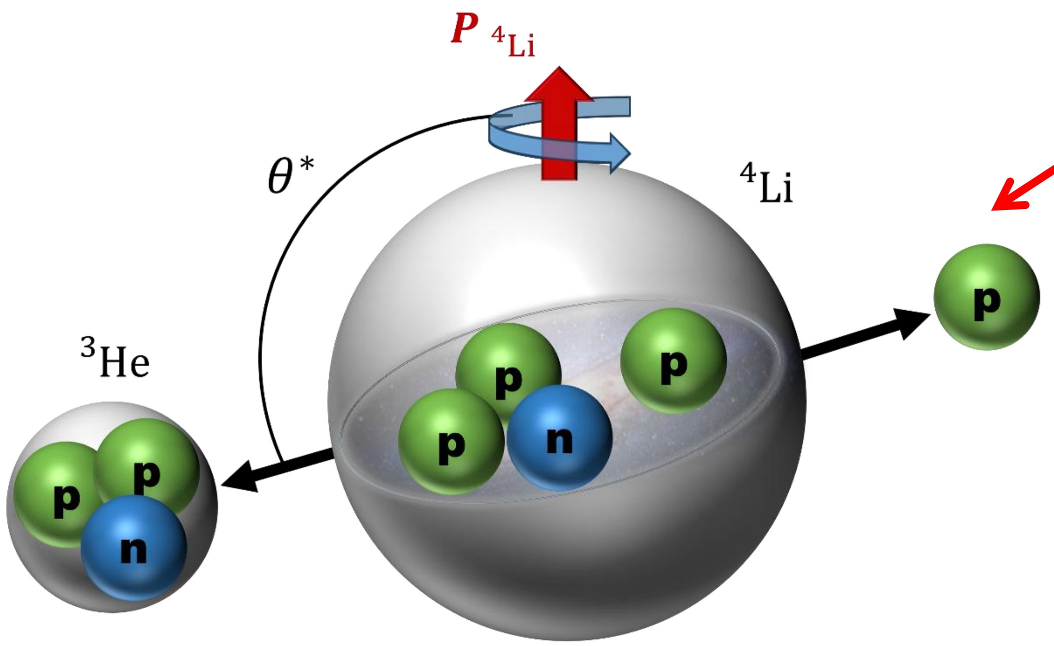
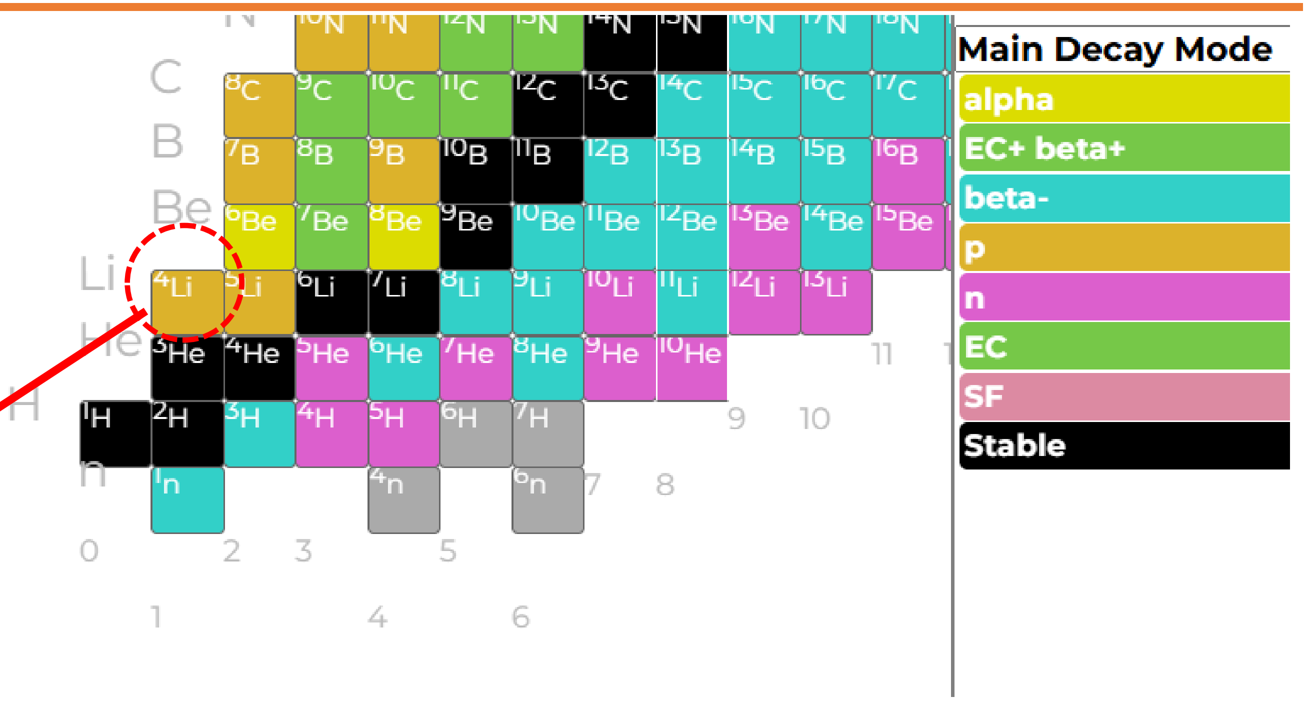
Spin alignment of Li-4

Yun-Peng Zheng *et al.*, arXiv:2509. 15286 (2025)





$A=4$	E_x (MeV)	J^π	Decay channels
^{4}Li	g.s.	2^-	p(100%)
	0.32	1^-	p(100%)
	2.08	0^-	p(100%)
	2.85	1^-	p(100%)

V. Vovchenko, B. Donigus, B. Kardan, M. Lorenz, and H. Stoecker, Phys. Lett. B, 135746 (2020)

Decay angular distribution :

$$\frac{dN}{d\Omega} = \mathrm{Tr}[T^\dagger \rho T]$$

Spin alignment of Li-4

Lithium-4 production within spin-dependent coalescence model (w/o spin correlation) :

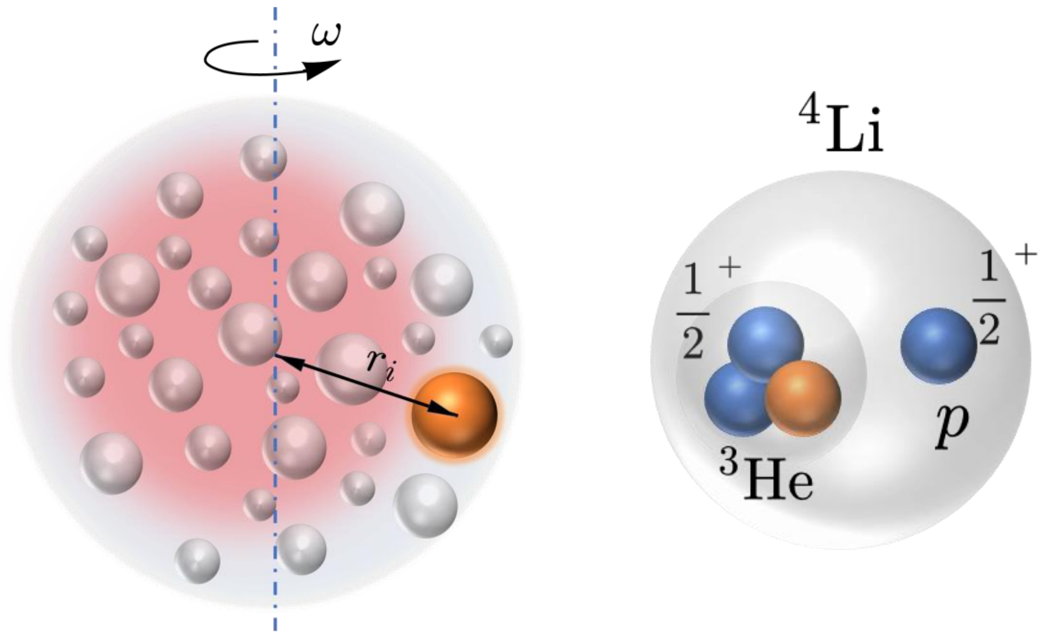
Yun-Peng Zheng *et al.*, arXiv:2509. 15286 (2025)

$$E\frac{d^3N_{^4\mathrm{Li},J_z=m}}{d\mathbf{K}^3} = E\int\left[\prod_{i=1,2,3,4} k_i^{\mu} d^3\sigma_{\mu}\frac{d^3k_i}{E_i}\bar{f}_i(\mathbf{x}_i,\mathbf{k}_i)\right]$$
$$\times\ \mathrm{Tr}_s[\hat{W}(\mathbf{r}'_1,\mathbf{k}'_1,\mathbf{r}'_2,\mathbf{k}'_2,\mathbf{r}'_3,\mathbf{k}'_3;J_z=m)$$
$$\times\ \hat{\sigma}_{p_1p_2p_3n}]\times\delta(\mathbf{K}-\sum_i\mathbf{k}_i).$$

$$W^{m_1m_2m_3m_4}_{\tilde{m}_1\tilde{m}_2\tilde{m}_3\tilde{m}_4} = \int d\eta'_1 d\eta'_2 d\eta'_3 e^{-i(\eta'_1\mathbf{k}'_1+\eta'_2\mathbf{k}'_2+\eta'_3\mathbf{k}'_3)}$$
$$\times\left\langle\mathbf{r}'_1+\frac{\eta'_1}{2},\mathbf{r}'_2+\frac{\eta'_2}{2},\mathbf{r}'_3+\frac{\eta'_3}{2};\tilde{m}_1\ldots\tilde{m}_4\middle|2,m\right\rangle_{\mathrm{rel}}$$
$$\times\left\langle 2,m\middle|\ \mathbf{r}'_1-\frac{\eta'_1}{2},\mathbf{r}'_2-\frac{\eta'_2}{2},\mathbf{r}'_3-\frac{\eta'_3}{2};m_1\ldots m_4\right\rangle_{\mathrm{rel}}.$$

$$\hat{\sigma}_{p_1p_2p_3n} = \hat{\sigma}_{p_1}\otimes\hat{\sigma}_{p_2}\otimes\hat{\sigma}_{p_3}\otimes\hat{\sigma}_{n}$$

$$\hat{\sigma}_j = \mathrm{diag}[\frac{1+\mathcal{P}_j}{2},\frac{1-\mathcal{P}_j}{2}]$$



Single particle distribution in a vortical fluid:

$$f(\mathbf{r}_i,\mathbf{k}_i) = \frac{2\xi_i}{(2\pi)^3}e^{-\frac{(\mathbf{k}_i-m\omega\times\mathbf{r}_i)^2}{2mT}}$$

Spin alignment of Li-4

Decay angular distribution for Li-4 ground state : $^4\mathrm{Li}(^3P_2)$

$$\hat{\rho}\left(^4\mathrm{Li}(2^-)\right) = \mathrm{diag}\left[\frac{3(\mathcal{P}_N+1)^2(2\mathcal{P}_L(\mathcal{P}_L+1)+1)}{4\left(2\mathcal{P}_N^2+5\right)\mathcal{P}_L^2+20\mathcal{P}_N\mathcal{P}_L+5\left(\mathcal{P}_N^2+3\right)}, \frac{3\left(-\mathcal{P}_L(\mathcal{P}_L+1)\mathcal{P}_N^2+\mathcal{P}_N+\mathcal{P}_L^2+\mathcal{P}_L+1\right)}{4\left(2\mathcal{P}_N^2+5\right)\mathcal{P}_L^2+20\mathcal{P}_N\mathcal{P}_L+5\left(\mathcal{P}_N^2+3\right)}, \frac{-\mathcal{P}_N^2-4\mathcal{P}_L\mathcal{P}_N+2\left(\mathcal{P}_N^2+1\right)\mathcal{P}_L^2+3}{4\left(2\mathcal{P}_N^2+5\right)\mathcal{P}_L^2+20\mathcal{P}_N\mathcal{P}_L+5\left(\mathcal{P}_N^2+3\right)}, -\frac{3(\mathcal{P}_N-1)((\mathcal{P}_N+1)(\mathcal{P}_L-1)\mathcal{P}_L+1)}{4\left(2\mathcal{P}_N^2+5\right)\mathcal{P}_L^2+20\mathcal{P}_N\mathcal{P}_L+5\left(\mathcal{P}_N^2+3\right)}, \frac{3(\mathcal{P}_N-1)^2(2(\mathcal{P}_L-1)\mathcal{P}_L+1)}{4\left(2\mathcal{P}_N^2+5\right)\mathcal{P}_L^2+20\mathcal{P}_N\mathcal{P}_L+5\left(\mathcal{P}_N^2+3\right)}\right],$$

$$T = \sqrt{\frac{3}{8\pi}}\begin{bmatrix} -\sin\theta^* e^{i\phi^*} & 0 & 0 & 0 \\ \cos\theta^* & -\frac{1}{2}\sin\theta^* e^{i\phi^*} & -\frac{1}{2}\sin\theta^* e^{i\phi^*} & 0 \\ \sqrt{\frac{1}{6}}\sin\theta^* e^{-i\phi^*} & \sqrt{\frac{2}{3}}\cos\theta^* & \sqrt{\frac{2}{3}}\cos\theta^* & -\sqrt{\frac{1}{6}}\sin\theta^* e^{i\phi^*} \\ 0 & \frac{1}{2}\sin\theta^* e^{-i\phi^*} & \frac{1}{2}\sin\theta^* e^{-i\phi^*} & \cos\theta^* \\ 0 & 0 & 0 & \sin\theta^* e^{-i\phi^*} \end{bmatrix},$$

$$\frac{dN}{\sin\theta^* d\theta^*} = \frac{1}{2} + \left(\frac{3}{8}\hat{\rho}_{1,1} + \frac{3}{8}\hat{\rho}_{-1,-1} + \frac{1}{2}\hat{\rho}_{0,0} - \frac{1}{4}\right)\left(3\cos^2\theta^* - 1\right)$$
$$\approx \frac{1}{2}\left[1 - \frac{7}{30}\left(\mathcal{P}_N^2 + 4\mathcal{P}_N\mathcal{P}_L + \mathcal{P}_L^2\right)\left(3\cos^2\theta^* - 1\right)\right].$$

Nucleon polarization

$$\mathcal{P}_N = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Polarization due to orbital motion

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

Spin alignment of Li-4

Yun-Peng Zheng *et al.*, arXiv:2509. 15286 (2025)

Decay angular distribution for $^4\mathrm{Li}(^3P_1)$ state

$$\hat{\rho}(^4\mathrm{Li}(^3P_1)) = [\frac{-\mathcal{P}_L(\mathcal{P}_L+1)\mathcal{P}_N^2+\mathcal{P}_N+\mathcal{P}_L^2+\mathcal{P}_L+1}{(\mathcal{P}_N-2\mathcal{P}_L)^2+3}, \frac{\mathcal{P}_N^2-4\mathcal{P}_L\mathcal{P}_N+2\left(\mathcal{P}_N^2+1\right)\mathcal{P}_L^2+1}{(\mathcal{P}_N-2\mathcal{P}_L)^2+3}, -\frac{(\mathcal{P}_N-1)((\mathcal{P}_N+1)(\mathcal{P}_L-1)\mathcal{P}_L+1)}{(\mathcal{P}_N-2\mathcal{P}_L)^2+3}].$$

$$\hat{T}(^4\mathrm{Li}(^3P_1)\to{}^3\mathrm{He}+p) = \sqrt{\frac{3}{8\pi}}\begin{bmatrix} -\cos\theta^* & -\frac{1}{2}\sin\theta^* e^{i\phi^*} & -\frac{1}{2}\sin\theta^* e^{i\phi^*} & 0 \\ -\sqrt{\frac{1}{2}}\sin\theta^* e^{-i\phi^*} & 0 & 0 & -\sqrt{\frac{1}{2}}\sin\theta^* e^{i\phi^*} \\ 0 & -\frac{1}{2}\sin\theta^* e^{-i\phi^*} & -\frac{1}{2}\sin\theta^* e^{-i\phi^*} & \cos\theta^* \end{bmatrix}$$

$$\frac{dN}{\sin\theta^* d\theta^*} = \frac{1}{2} - \frac{3}{8}(\hat{\rho}_{0,0}-\frac{1}{3})(3\cos^2\theta^*-1) \approx \frac{1}{2}\left(1-\frac{1}{6}(\mathcal{P}_N^2-4\mathcal{P}_N\mathcal{P}_L+\mathcal{P}_L^2)(3\cos^2\theta^*-1)\right),$$

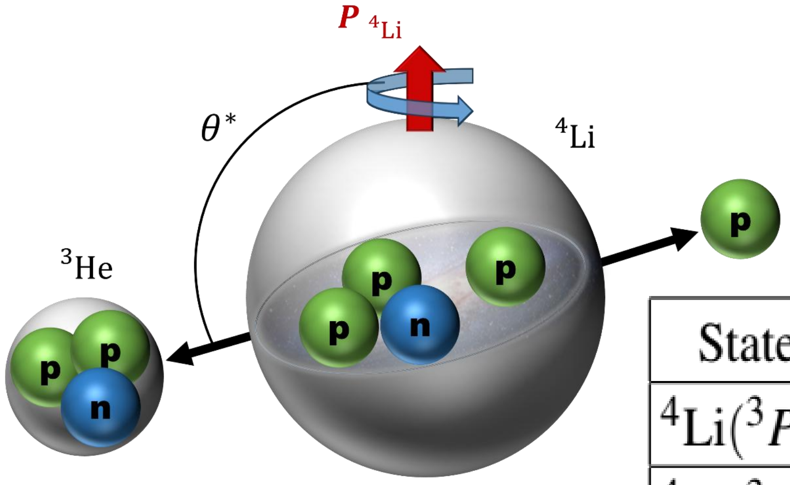
Decay angular distribution for $^4\mathrm{Li}(^1P_1)$ state

$$\hat{\rho}(^4\mathrm{Li}(^1P_1)) = \begin{bmatrix} \frac{2\mathcal{P}_L(\mathcal{P}_L+1)+1}{4\mathcal{P}_L^2+3} & 0 & 0 \\ 0 & \frac{1}{4\mathcal{P}_L^2+3} & 0 \\ 0 & 0 & \frac{2(\mathcal{P}_L-1)\mathcal{P}_L+1}{4\mathcal{P}_L^2+3} \end{bmatrix}$$

$$\hat{T}(^4\mathrm{Li}(^1P_1)\to{}^3\mathrm{He}+p) = \sqrt{\frac{3}{8\pi}}\begin{bmatrix} 0 & -\sqrt{\frac{1}{2}}\sin\theta^* e^{i\phi^*} & \sqrt{\frac{1}{2}}\sin\theta^* e^{i\phi^*} & 0 \\ 0 & \cos\theta^* & -\cos\theta^* & 0 \\ 0 & \sqrt{\frac{1}{2}}\sin\theta^* e^{-i\phi^*} & -\sqrt{\frac{1}{2}}\sin\theta^* e^{-i\phi^*} & 0 \end{bmatrix}$$

$$\frac{dN}{\sin\theta^* d\theta^*} = \frac{1}{2} + \frac{3}{4}(\hat{\rho}_{0,0}-\frac{1}{3})(3\cos^2\theta^*-1) \approx \frac{1}{2}\left(1-\frac{2}{3}\mathcal{P}_L^2(3\cos^2\theta^*-1)\right)$$

Spin alignment of Li-4



Yun-Peng Zheng *et al.*, arXiv:2509. 15286 (2025)

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

Averaged decay angular distribution :

$$\frac{dN}{\sin\theta^* d\theta^*} = \frac{1}{2}\left[1 - \frac{1}{36}\left(5\mathcal{P}_N^2 + 8\mathcal{P}_N\mathcal{P}_L + 11\mathcal{P}_L^2\right)(3\cos^2\theta^* - 1)\right]$$

Spin alignment of Li-4

Yun-Peng Zheng *et al.*, arXiv:2509. 15286 (2025)

Li-4 decay angular distribution within thermal model:

$$\hat{\rho}(^4\mathrm{Li}(2^-)) = \frac{1}{1+2\cosh(\frac{\omega}{T})+2\cosh(\frac{2\omega}{T})}\begin{bmatrix} e^{\frac{2\omega}{T}} & 0 & 0 & 0 & 0 \\ 0 & e^{\frac{\omega}{T}} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & e^{-\frac{\omega}{T}} & 0 \\ 0 & 0 & 0 & 0 & e^{-\frac{2\omega}{T}} \end{bmatrix}$$

$$\hat{\rho}(^4\mathrm{Li}(0^-)) = 1$$

$$\hat{\rho}(^4\mathrm{Li}(1^-)) = \frac{1}{1+2\cosh(\frac{\omega}{T})}\begin{bmatrix} e^{\frac{\omega}{T}} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-\frac{\omega}{T}} \end{bmatrix}$$

Let $\mathcal{P} = \frac{\omega}{2T}$, **average angular distribution:**

$$\frac{dN}{\sin\theta^* d\theta^*} = \frac{1}{2}\left[1 - \frac{2}{3}\mathcal{P}^2(3\cos^2\theta^* - 1)\right]$$

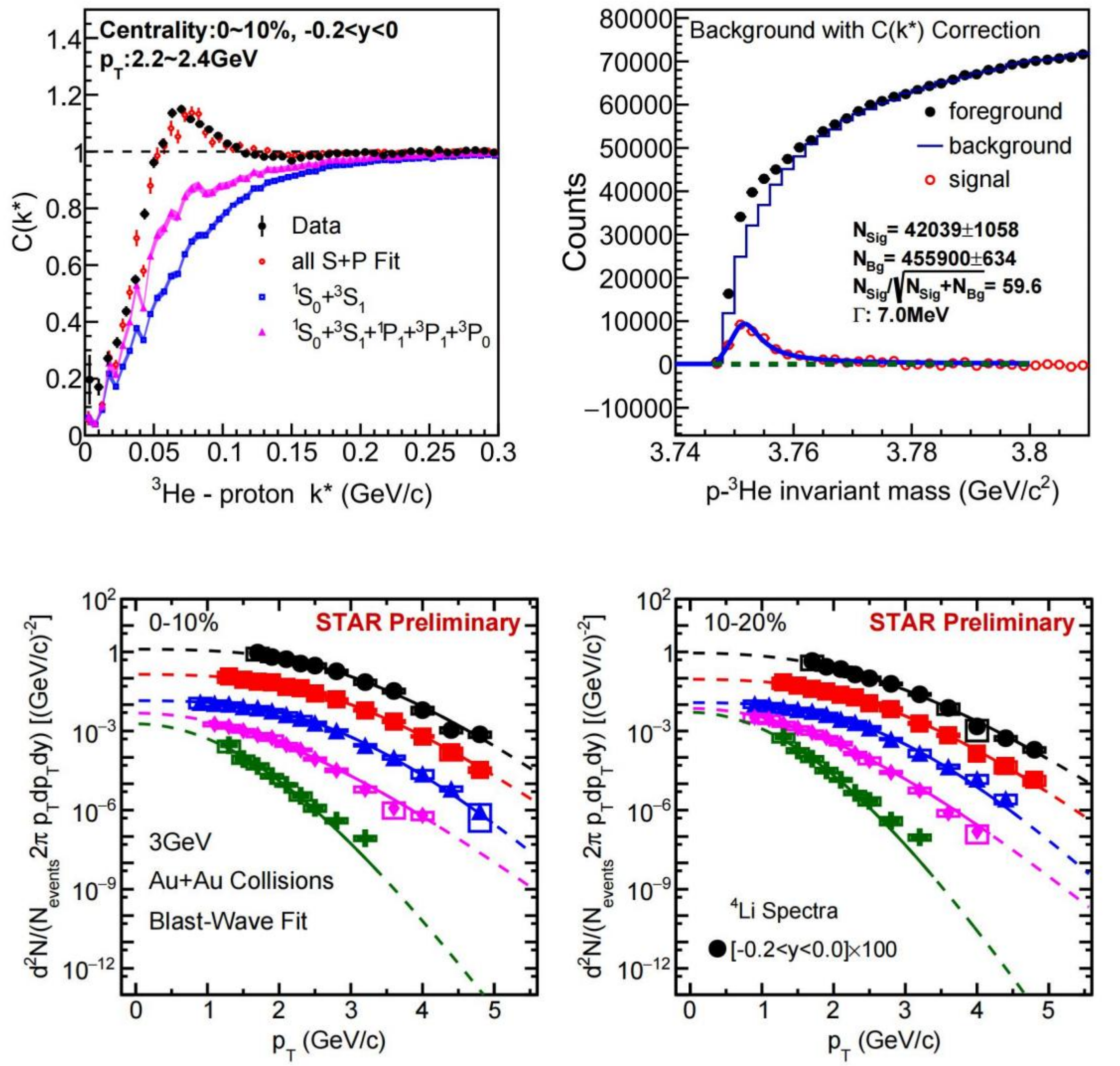
$\mathcal{P}_L = \mathcal{P}_N = \mathcal{P}$ ⟷

Coalescence model:

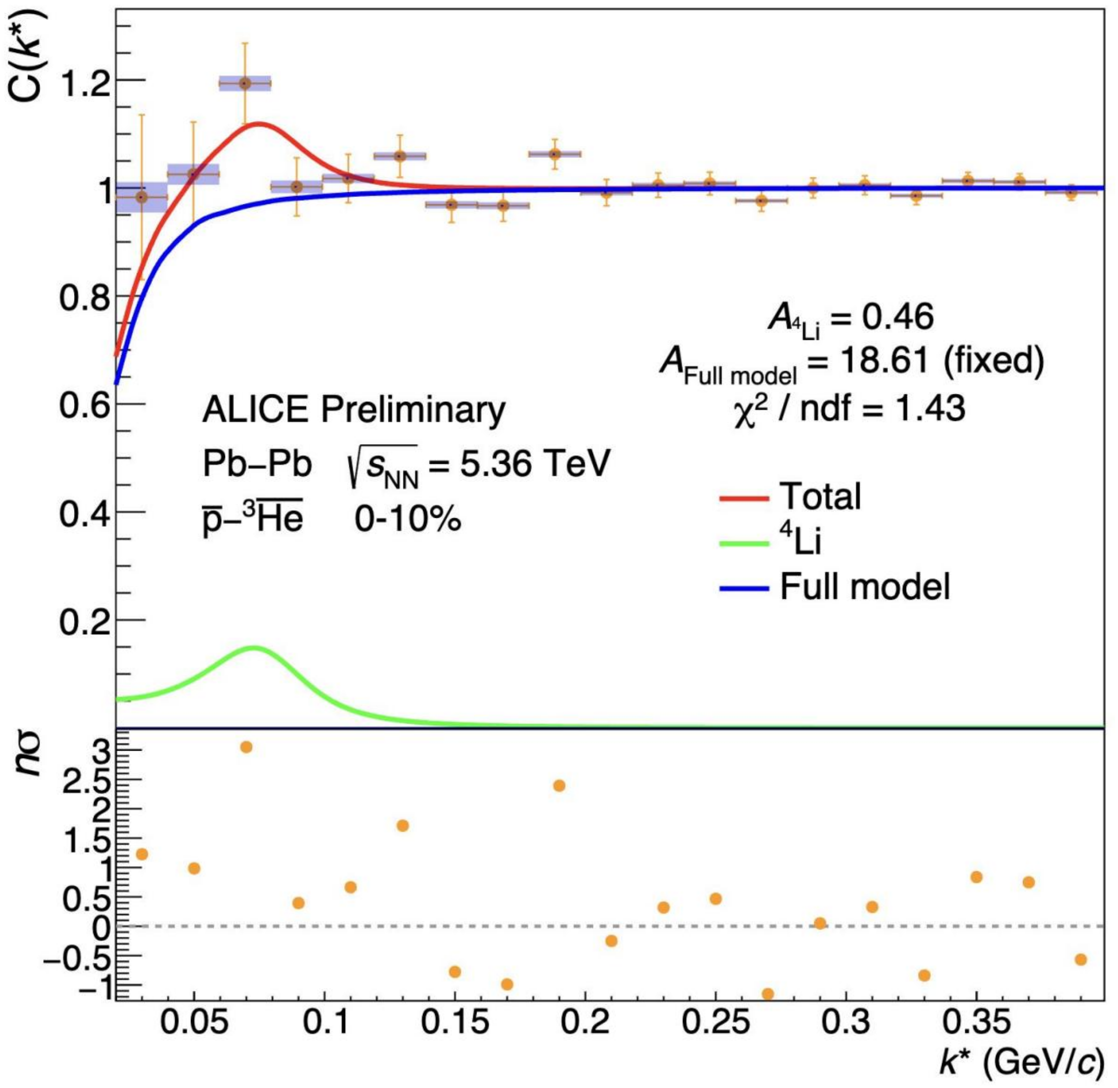
$$\frac{dN}{\sin\theta^* d\theta^*} = \frac{1}{2}\left[1 - \frac{1}{36}\left(5\mathcal{P}_N^2 + 8\mathcal{P}_N\mathcal{P}_L + 11\mathcal{P}_L^2\right)(3\cos^2\theta^* - 1)\right]$$

Recent experimental progress

STAR Preliminary (J. L. Wu, C. L. Hu, G. N. Xie et al.)
SQM2026



ALICE Preliminary **SQM2026**



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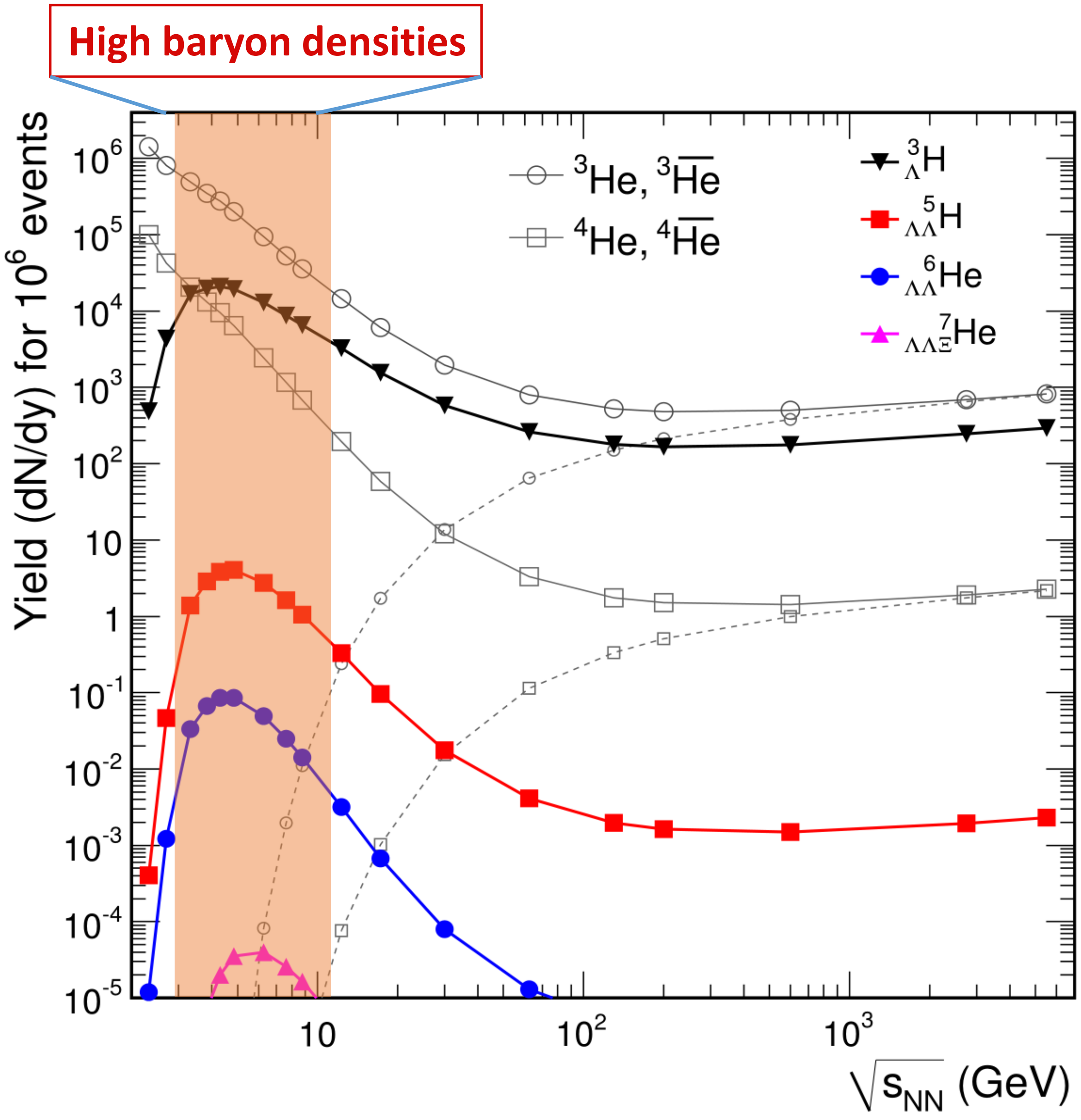
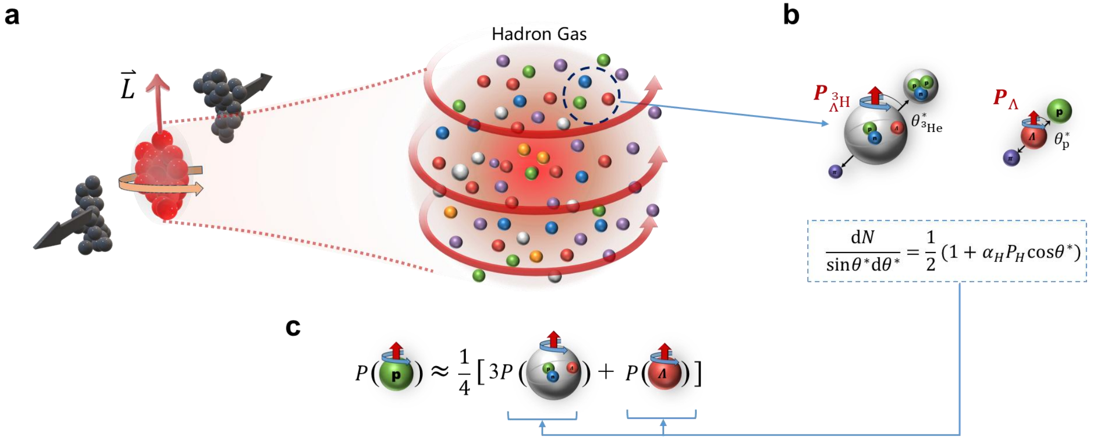
5、Summary and outlook

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



Experimental observation soon?

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



- ➢ **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)**