Spin polarization from hadrons to (anti-)(hyper-) nuclei in high-energy nuclear collisions

The 26th international symposium on spin physics (SPIN2025)

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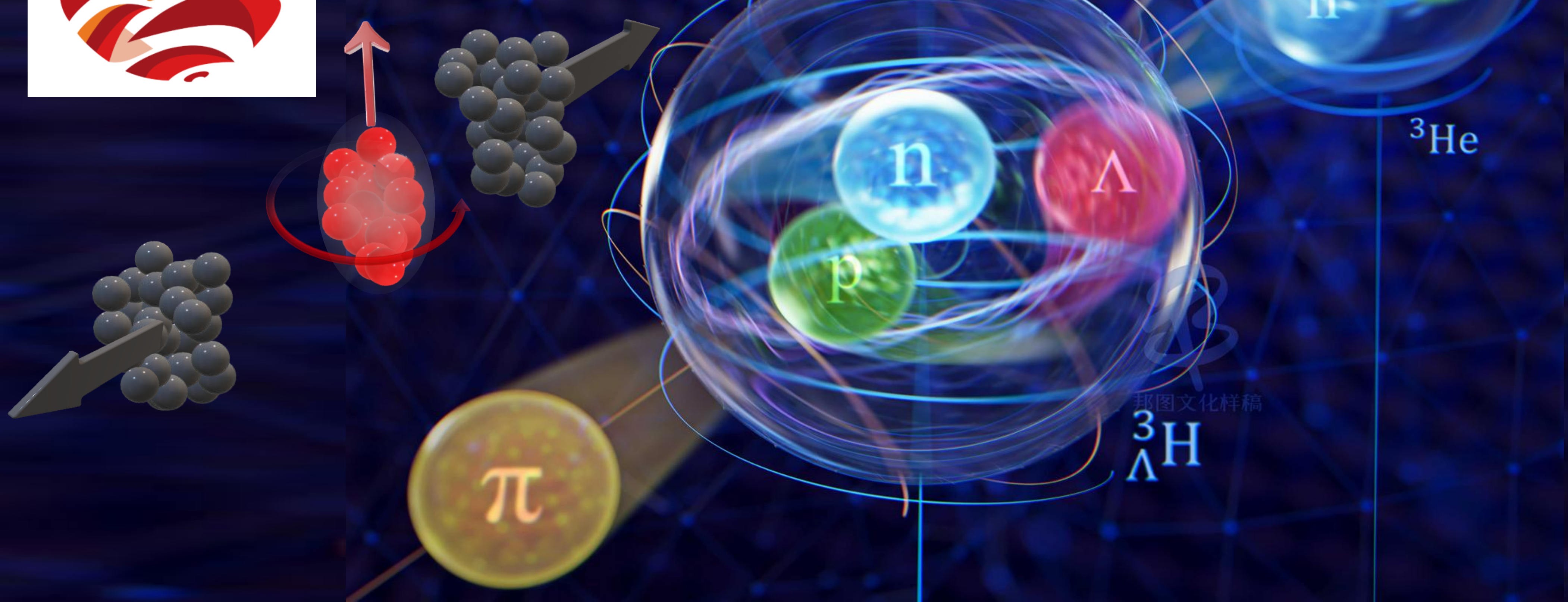
Sep. 23, 2025



Outline

1. **Spin polarization of hadrons in heavy-ion collisions**

2. **Spin polarization of (anti-)hypertriton**

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

3. **Spin polarization of proton**

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

4. **Spin alignment of $^4\mathrm{Li}$**

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

5. **Summary and outlook**

1 Polarization of hadrons in relativistic 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.

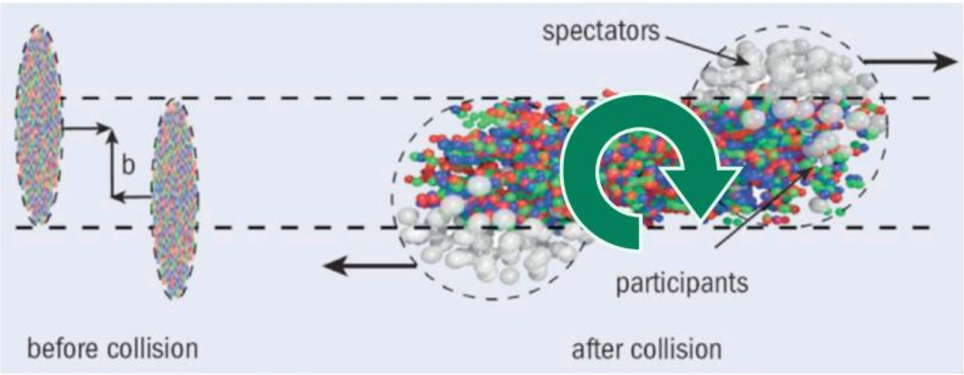
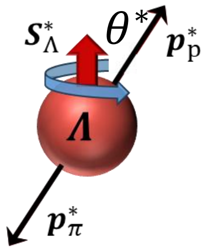


figure: M. Lisa, talk @ "Strangeness in Quark Matter 2016"

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



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

α_Λ → **Decay constant**

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

The ideal relativistic spinning gas: Polarization and spectra

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

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

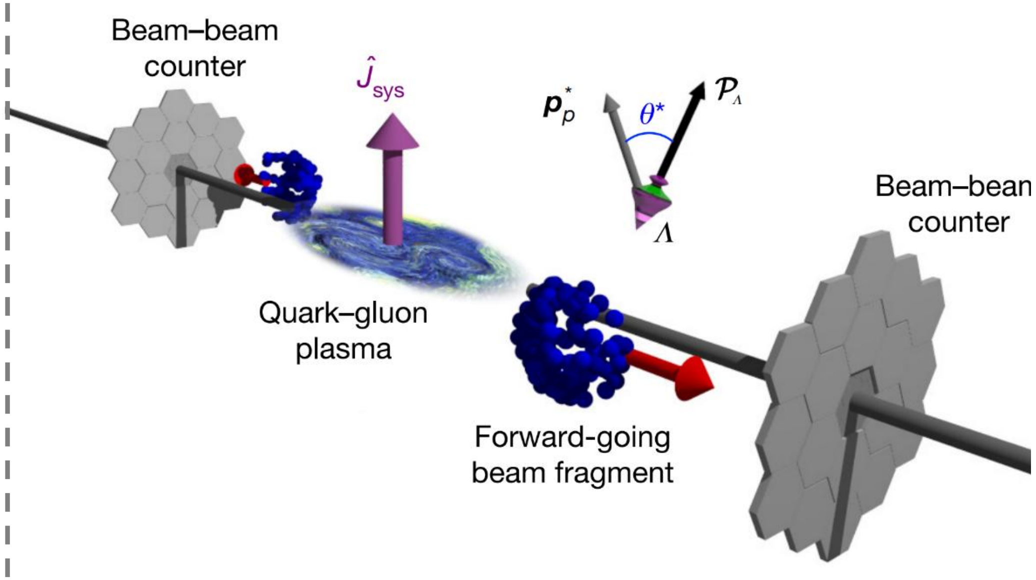
$$\mathbf{\Pi} = \mathrm{tr}[\widehat{\mathbf{S}}\widehat{\rho}_\omega(p)] = \frac{\sum_{n=-S}^{S} n e^{n\omega/T}}{\sum_{n=-S}^{S} e^{n\omega/T}}\hat{\boldsymbol{\omega}}$$

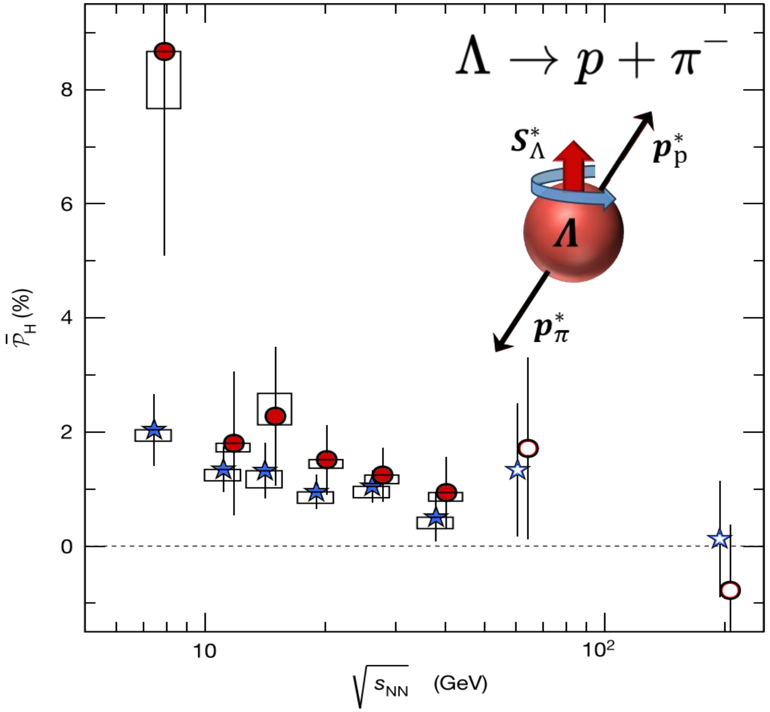
Vorticity ⟵ **Spin polarization**

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

1 Polarization of hadrons in relativistic heavy-ion collisions (2)

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





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

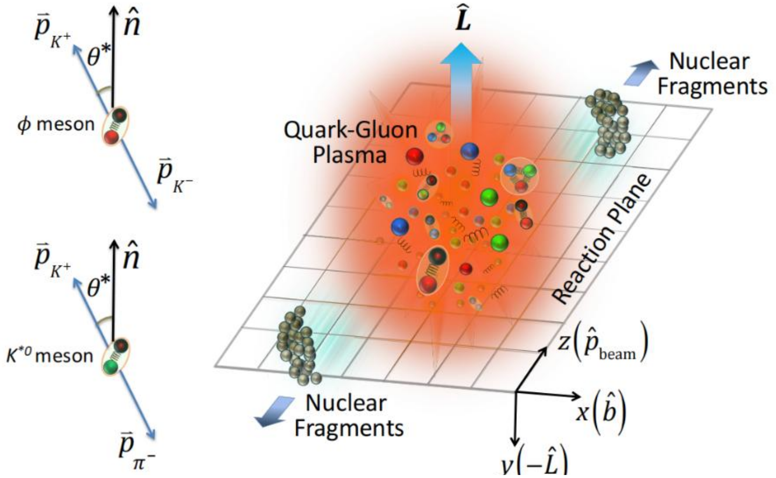
$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1^{obs} - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

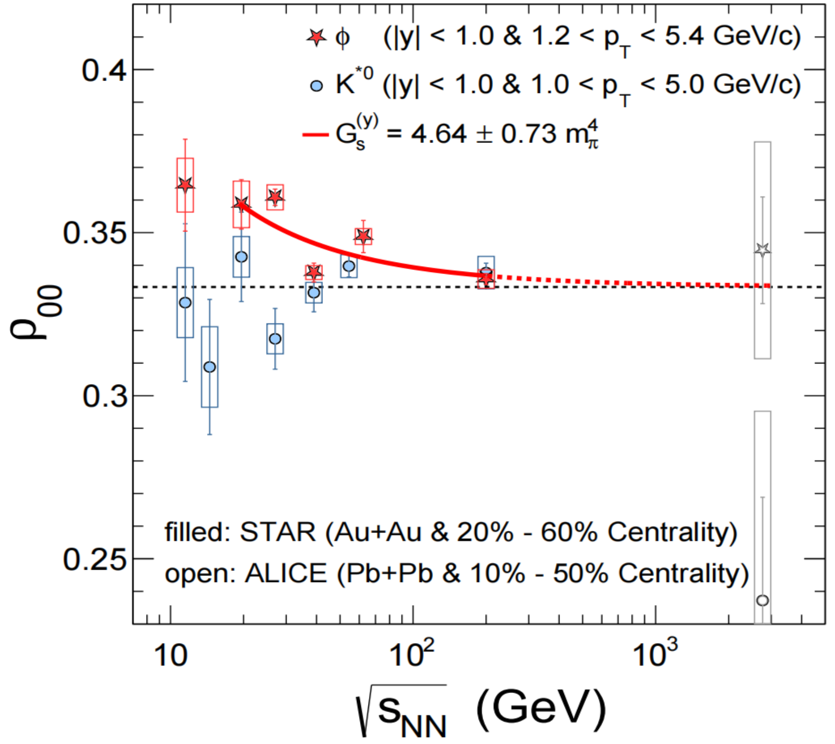
$$\omega \approx k_B T(\overline{\mathcal{P}}_\Lambda + \overline{\mathcal{P}}_{\bar{\Lambda}})/\hbar \approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$$

Spin polarization of Lambda hyperon → Vorticity of QGP

1 Polarization of hadrons in relativistic heavy-ion collisions (3)

STAR, Nature 614, 7947 (2023)





Spin alignment of mesons

$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

Fluctuation/correlation of strong force field

X. L. Sheng et al., PRL 131, 042304 (2023)

$$G_s^{(y)} \equiv g_\phi^2\left[3\langle B_{\phi,y}^2\rangle + \frac{\langle \mathbf{p}^2\rangle_\phi}{m_s^2}\langle E_{\phi,y}^2\rangle - \frac{3}{2}\langle B_{\phi,x}^2 + B_{\phi,z}^2\rangle - \frac{\langle \mathbf{p}^2\rangle_\phi}{2m_s^2}\langle E_{\phi,x}^2 + E_{\phi,z}^2\rangle\right]$$

Quark-antiquark spin correlation

J. P. Lv et al., Phys.Rev.D 109 (2024) 11, 114003

Meson spectral property

F. Li and S. Liu, arXiv:2206.11890

Y. L. Yin, W. B. Dong, J. Y. Pang, S. Pu, and Q. Wang, Phys. Rev. C 110 (2024) 2, 024905

2 Polarization of light (anti-)(hyper-)nuclei (4)

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)
E. Jobst, M. Puccio, and S. Kundu https://repository.cern/records/w44qe-33g73
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

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

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

…

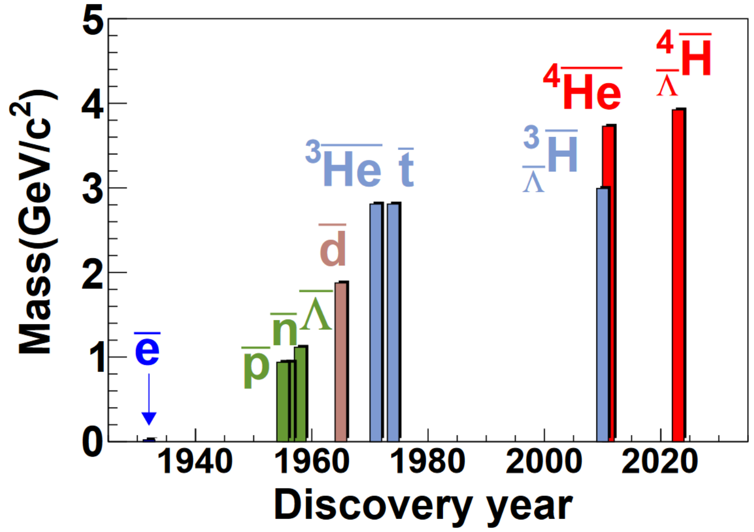
Unstable (anti-)(hyper-)nuclei

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

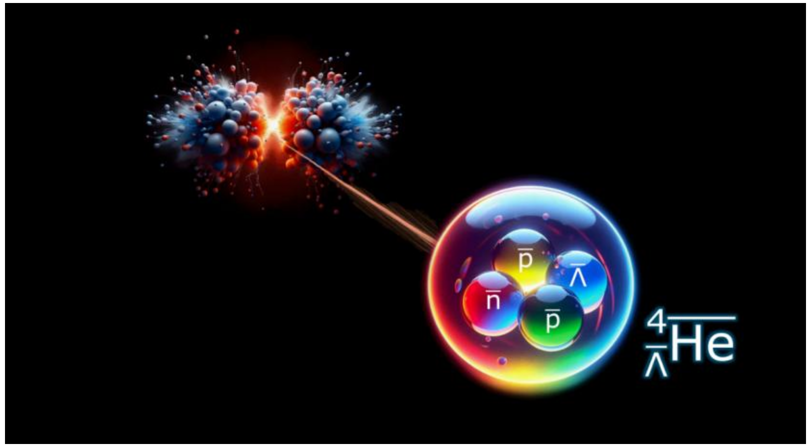
$^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}(\bar{n}\bar{p}\bar{\Lambda})$ $^{4}\overline{\mathrm{Li}}(\bar{n}\bar{p}\bar{p}\bar{p})$

…

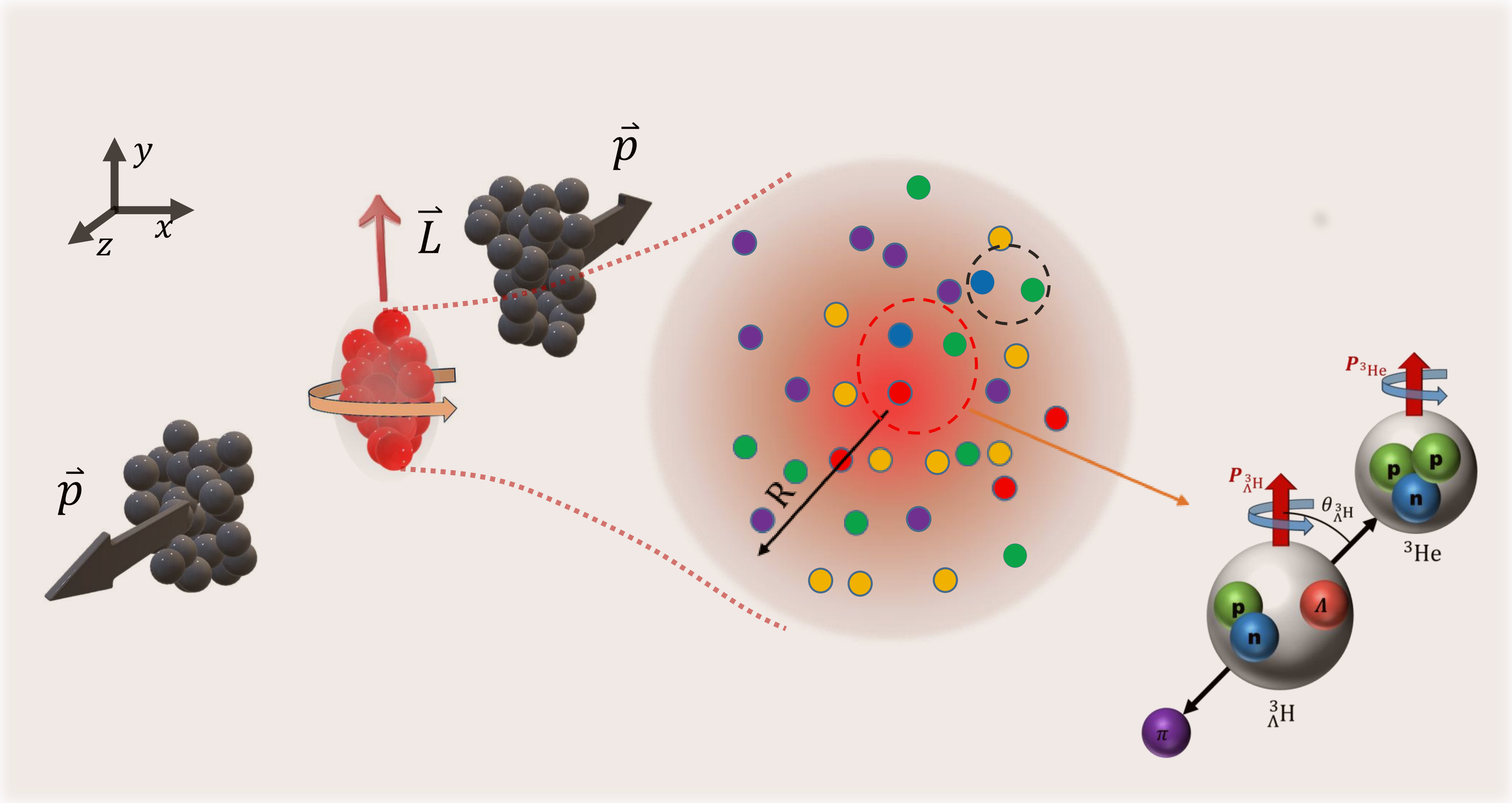
STAR, *Nature* 632, 8027 (2024)



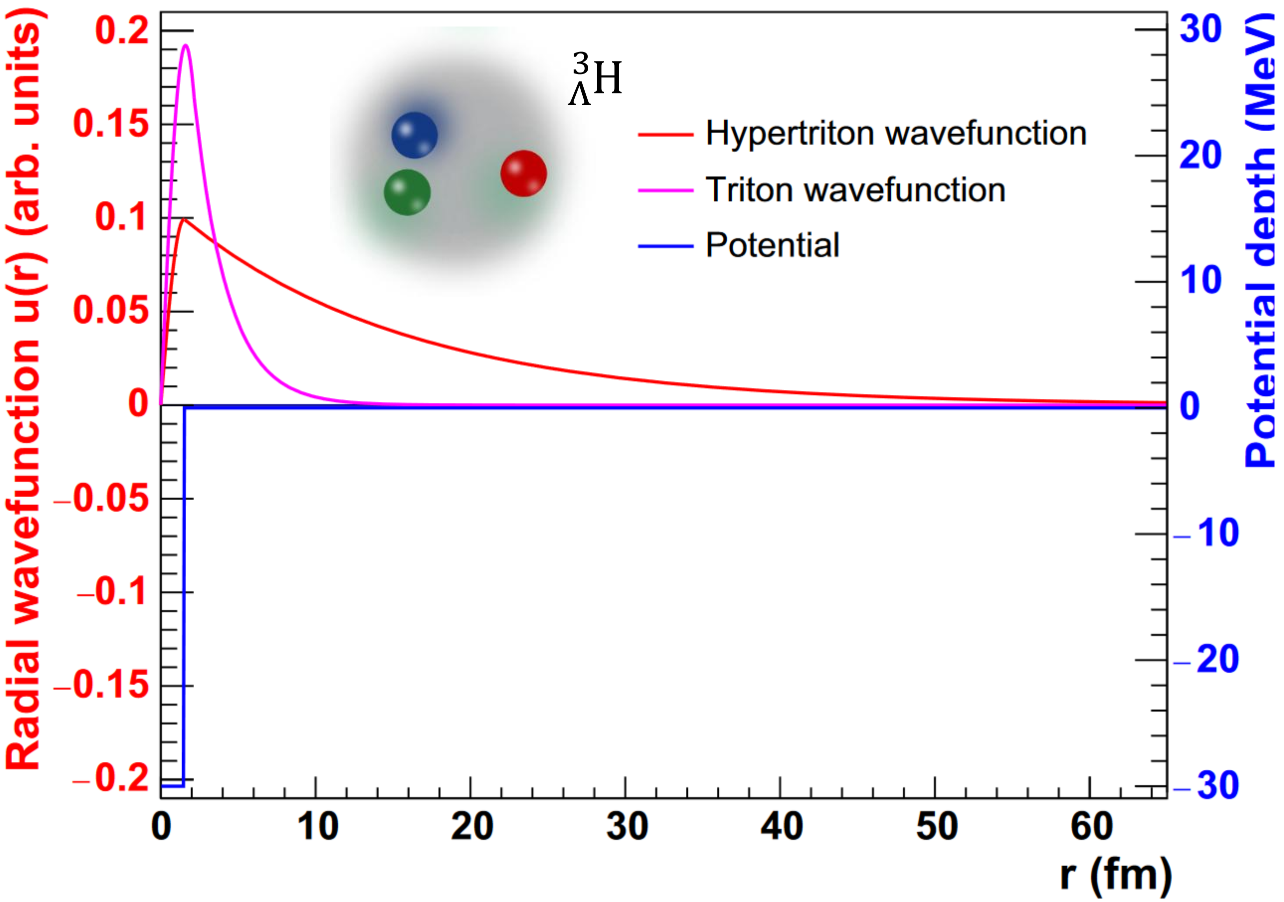
ALICE, Phys. Rev. Lett. 134 (2025) 16, 162301



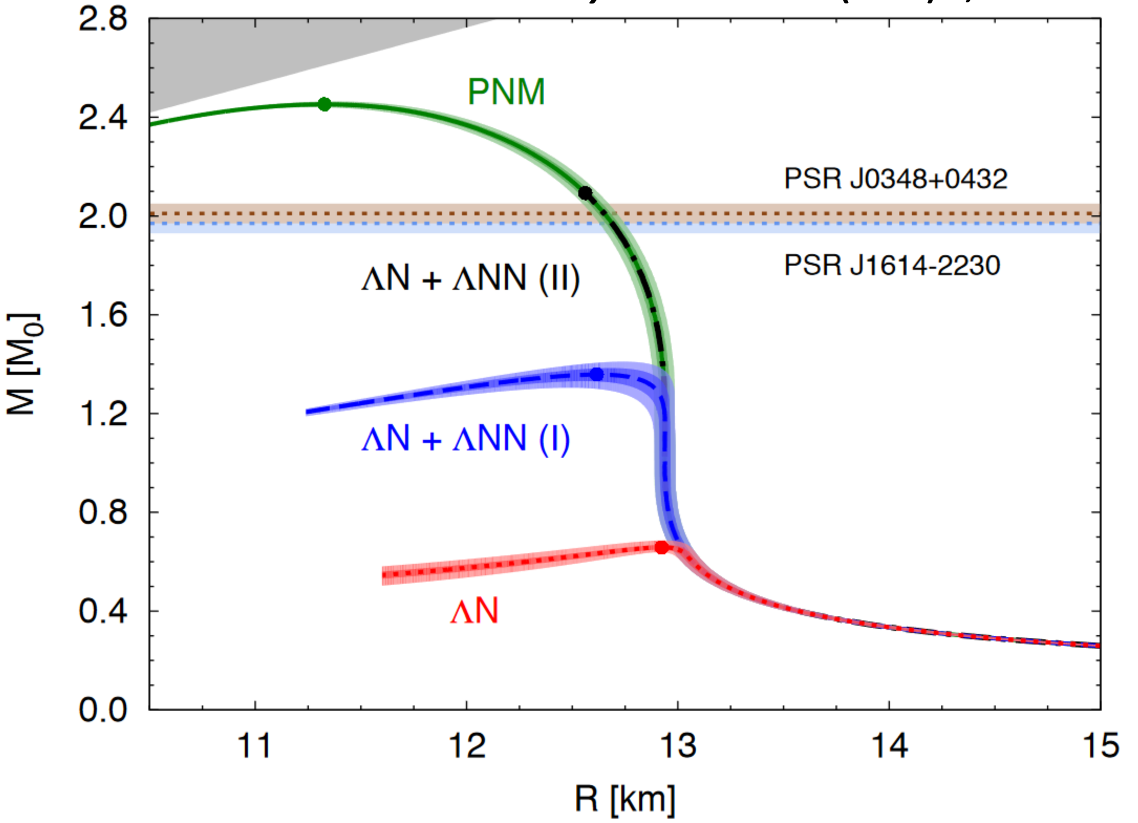
Spin polarization of (anti-)hypertriton



2 The halo-like nucleus: (anti-)hypertriton (6)



Phys.Rev.Lett. 114 (2015) 9, 092301

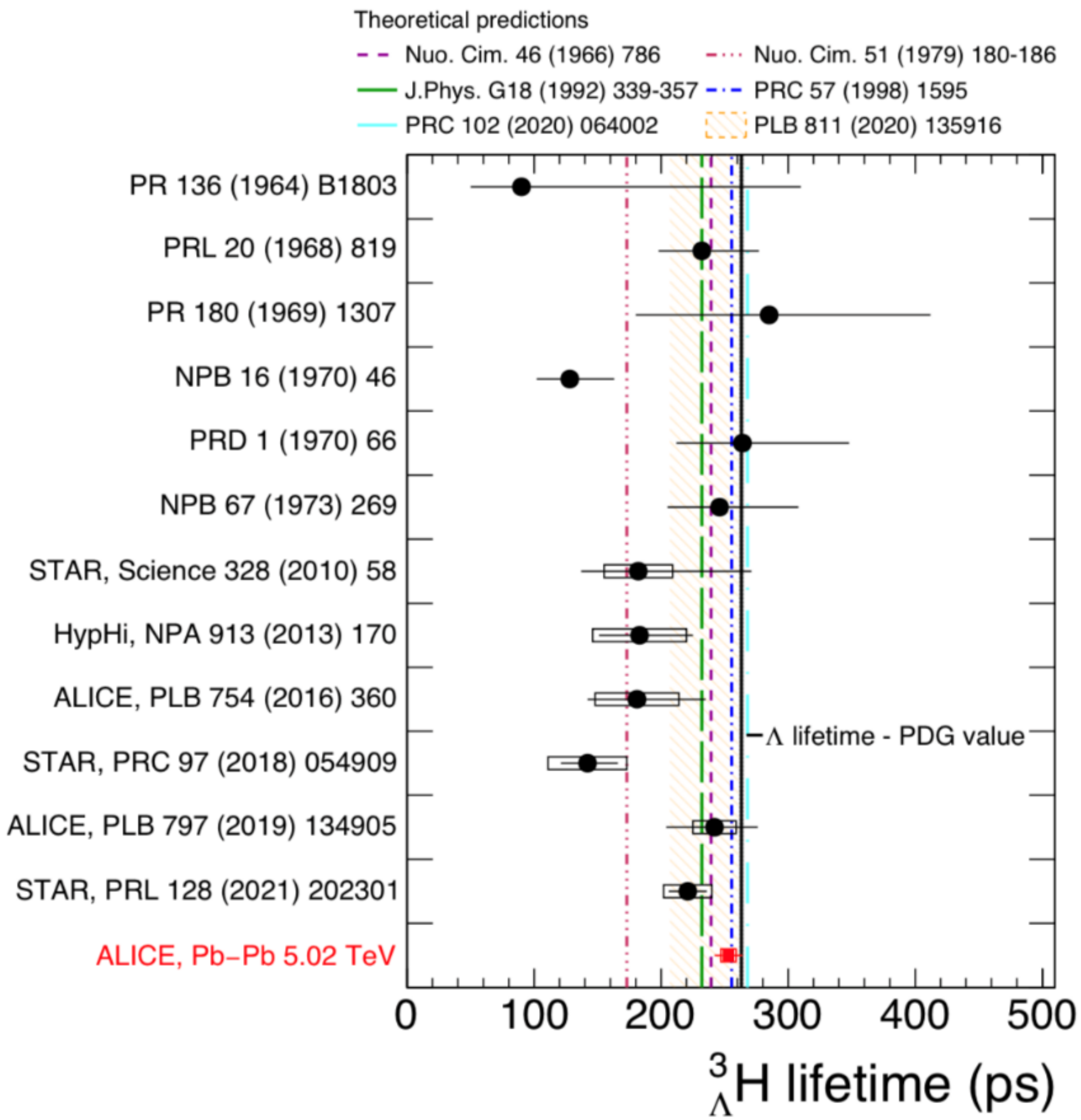


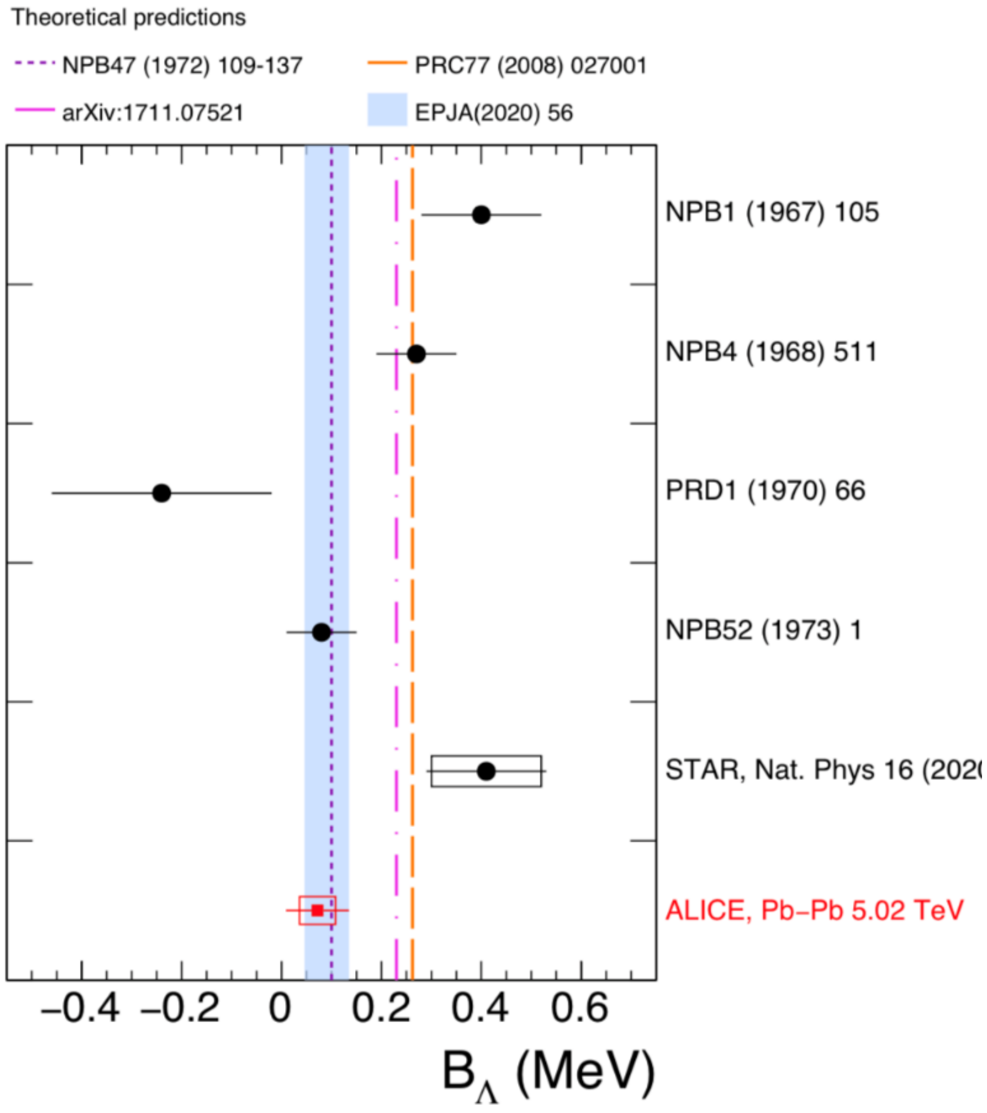
J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)
D. N. Liu et al. Phys. Lett. B 855, 138855 (2024)

2 Binding energy and lifetime (7)

ALICE, PRL 131, 102302 (2023)

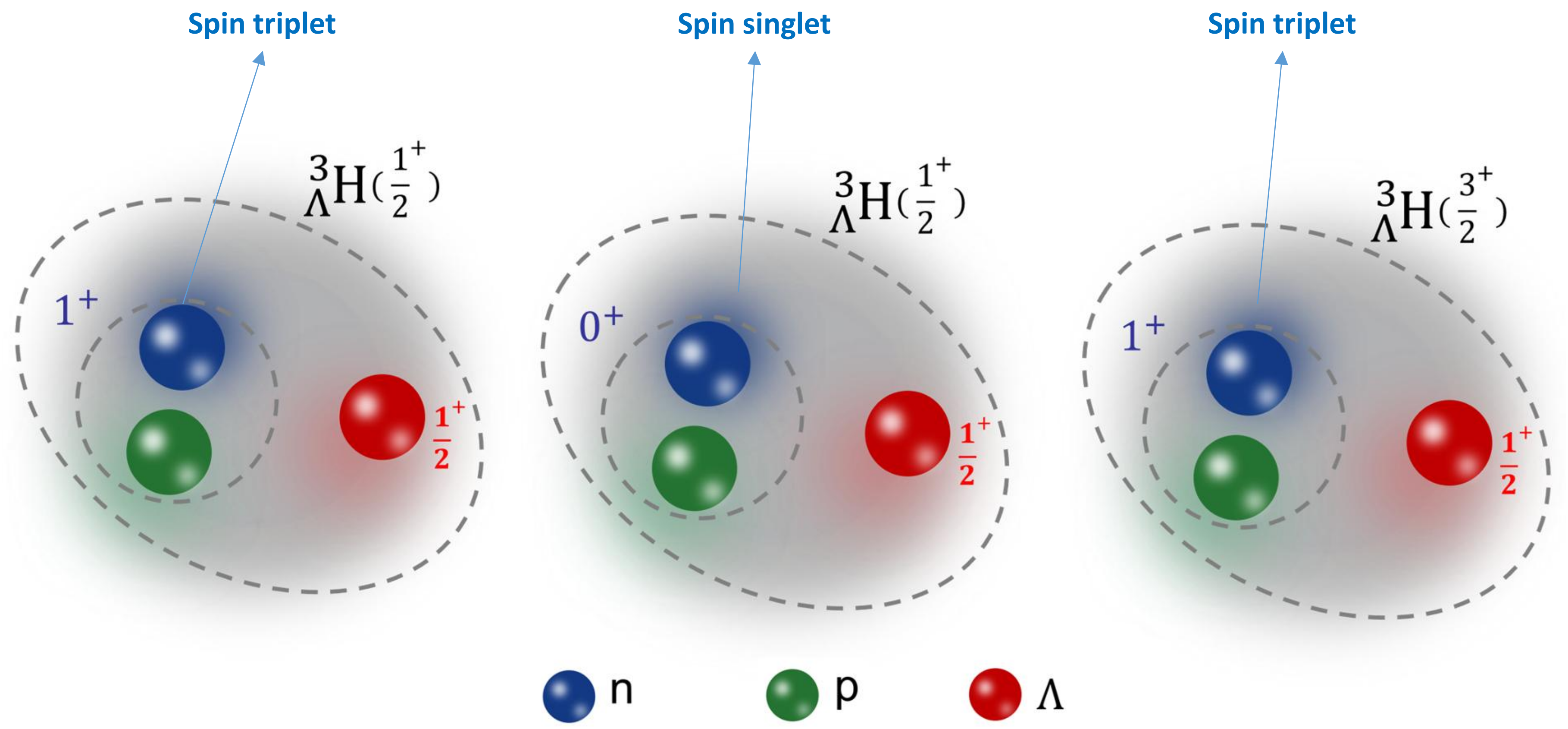
Y. G. Ma, Nucl. Sci. Tech. 3497 (2023)





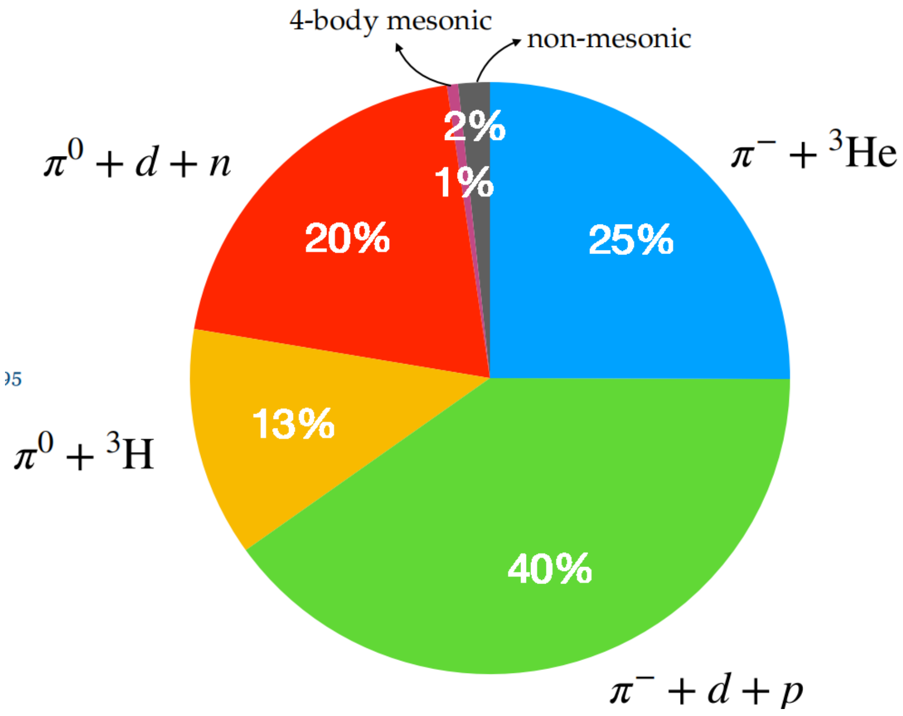
J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)

2 Spin of (anti-)hypertriton ?



2 Spin of (anti-)hypertriton ?

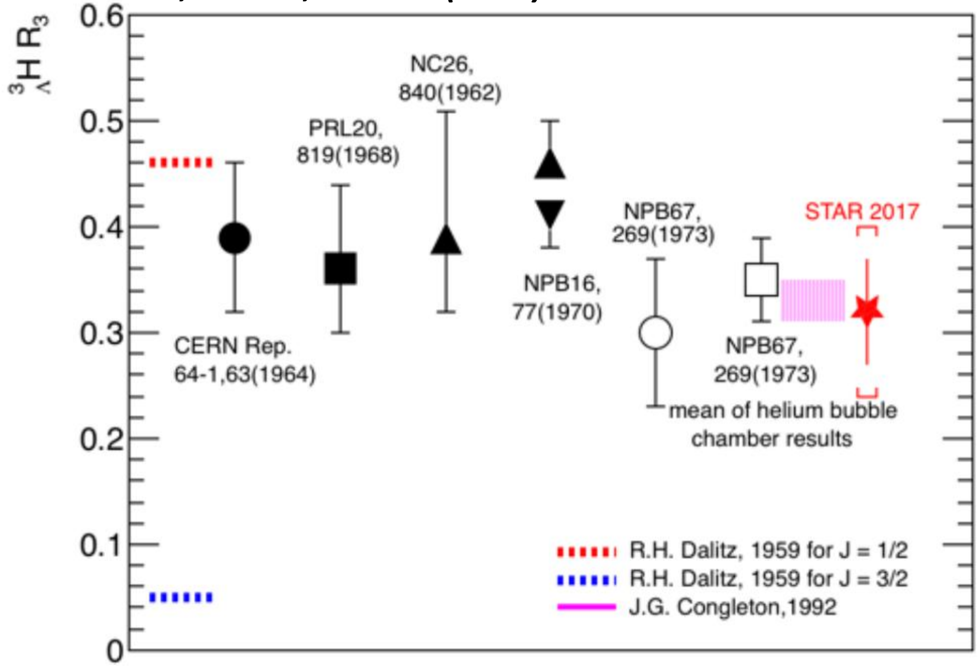
$$
\begin{aligned}
&{}^3_\Lambda\mathrm{H} \mapsto \pi^- + {}^3\mathrm{He}, &&{}^3_\Lambda\mathrm{H} \mapsto \pi^0 + {}^3\mathrm{H},\\
&{}^3_\Lambda\mathrm{H} \mapsto \pi^- + d + p, &&{}^3_\Lambda\mathrm{H} \mapsto \pi^0 + d + n,\\
&{}^3_\Lambda\mathrm{H} \mapsto \pi^- + p + n + p, &&{}^3_\Lambda\mathrm{H}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



Relative branching ratio:

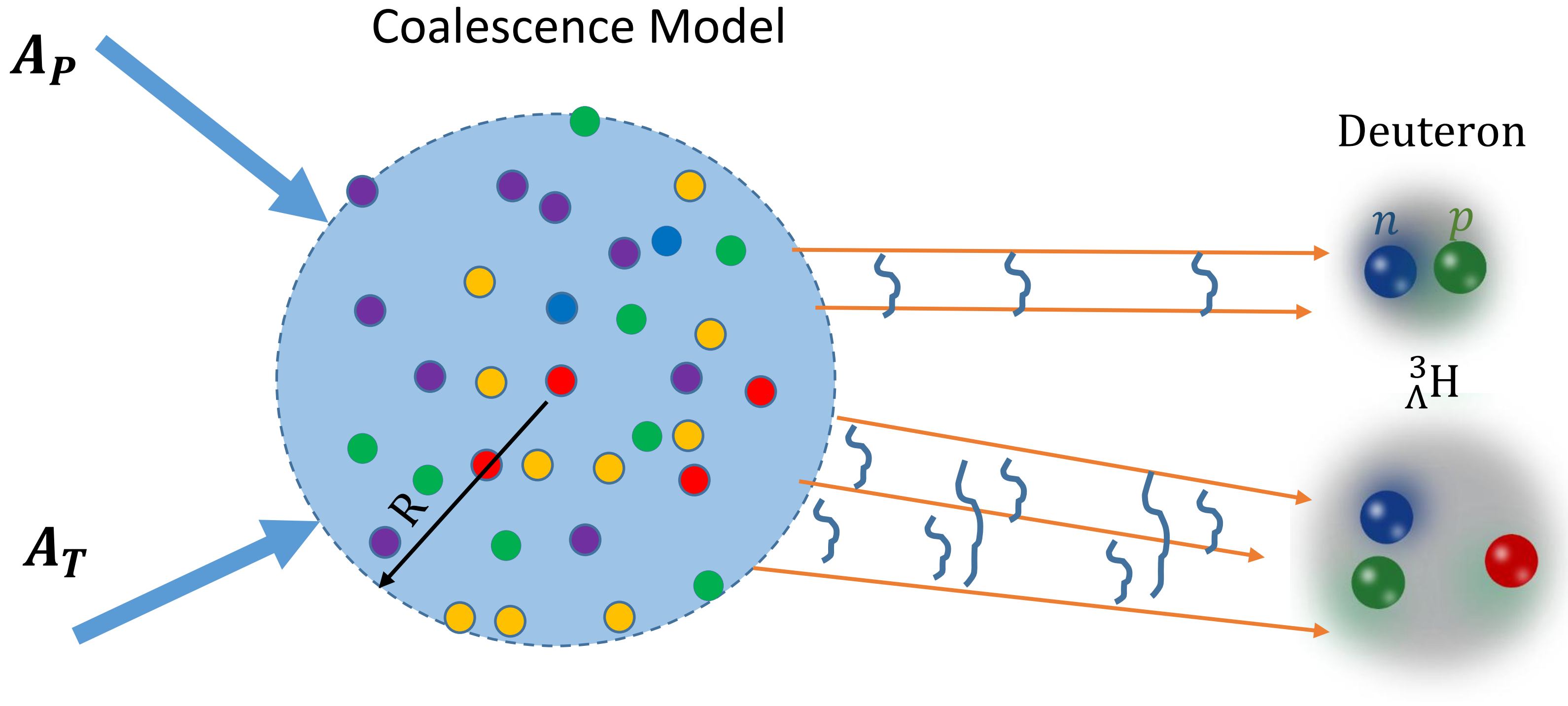
$$
R_3 = \frac{B.R.({}^3_\Lambda H \to {}^3He\pi^-)}{B.R.({}^3_\Lambda H \to {}^3He\pi^-) + B.R.({}^3_\Lambda H \to dp\pi^-)}
$$

STAR, PRC 97, 054909 (2018)



Favors spin 1/2

2. Coalescence model



Density Matrix Formulation (sudden approximation)

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

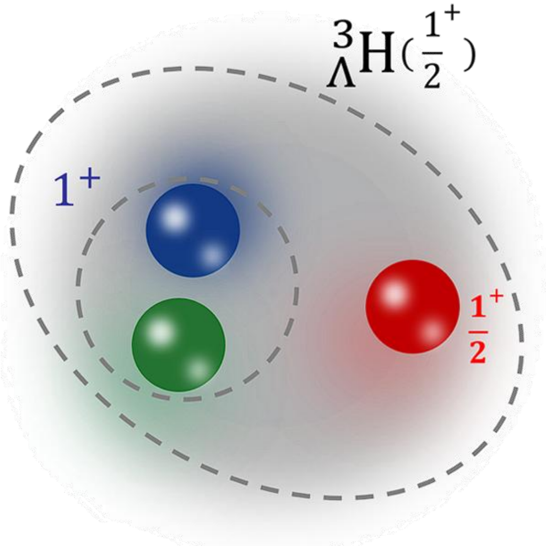
Wigner function of light cluster

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)

2. Spin-dependent coalescence model

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



➢ Spin wavefunction

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

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

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

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

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

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

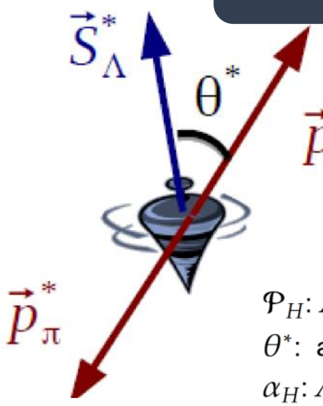
$$\mathcal{P}_p \approx \mathcal{P}_n \approx \mathcal{P}_\Lambda$$

Spin polarizations and correlations are small

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

Parity-violating weak decay

Λ hyperons



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

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

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

$\mathcal{P}_H$: 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

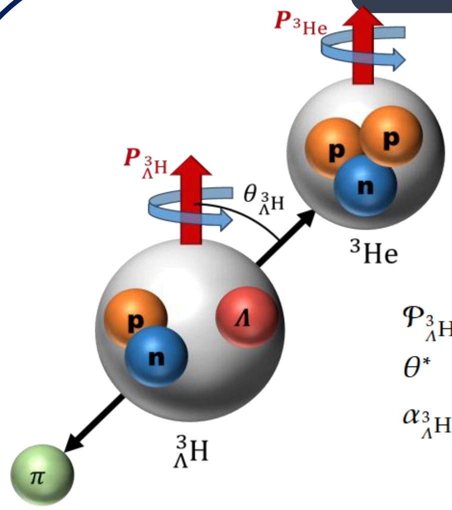
$$T(\Lambda \rightarrow \pi^- + p) = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} T_s + T_p\cos\theta_p^* & T_p \sin\theta_p^* e^{i\phi_p^*} \\ T_p\sin\theta_p^* e^{-i\phi_p^*} & T_s - T_p\cos\theta_p^* \end{pmatrix}$$

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



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

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

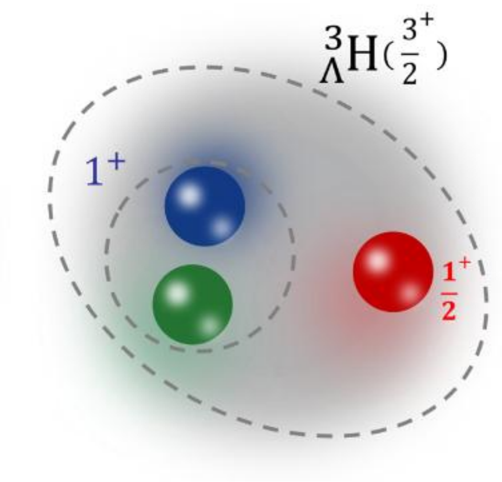
$$T(^3_\Lambda\mathrm{H} \rightarrow \pi^- + {}^3\mathrm{He}) = \frac{F}{6\sqrt{\pi}} \begin{pmatrix} 3T_s - T_p\cos\theta^* & -T_p\sin\theta^* e^{i\phi^*} \\ -T_p\sin\theta^* e^{-i\phi^*} & 3T_s + T_p\cos\theta^* \end{pmatrix}$$

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

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

Sign flip !

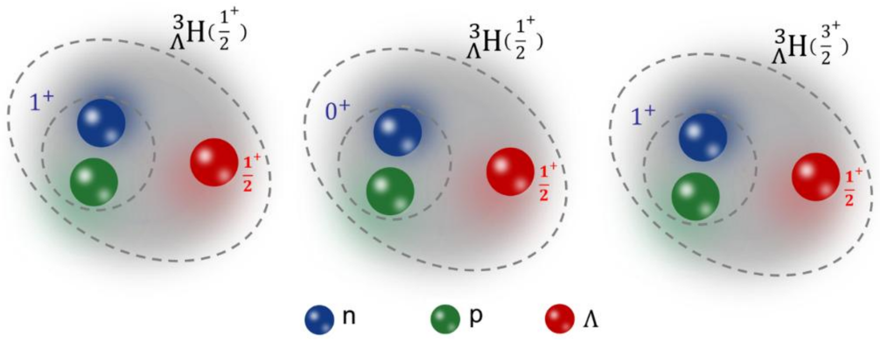
2. (Anti-)hypertriton polarization and its spin structure



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

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

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



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

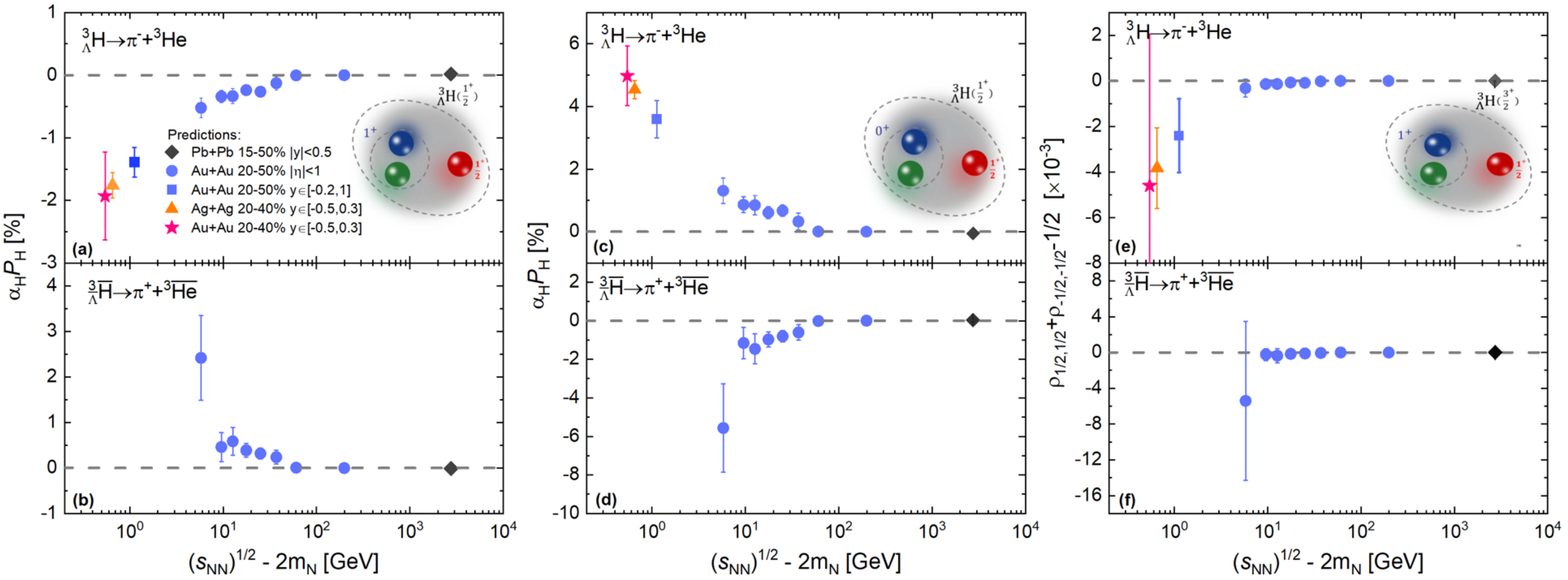
Different polarization and decay patterns!

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

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

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

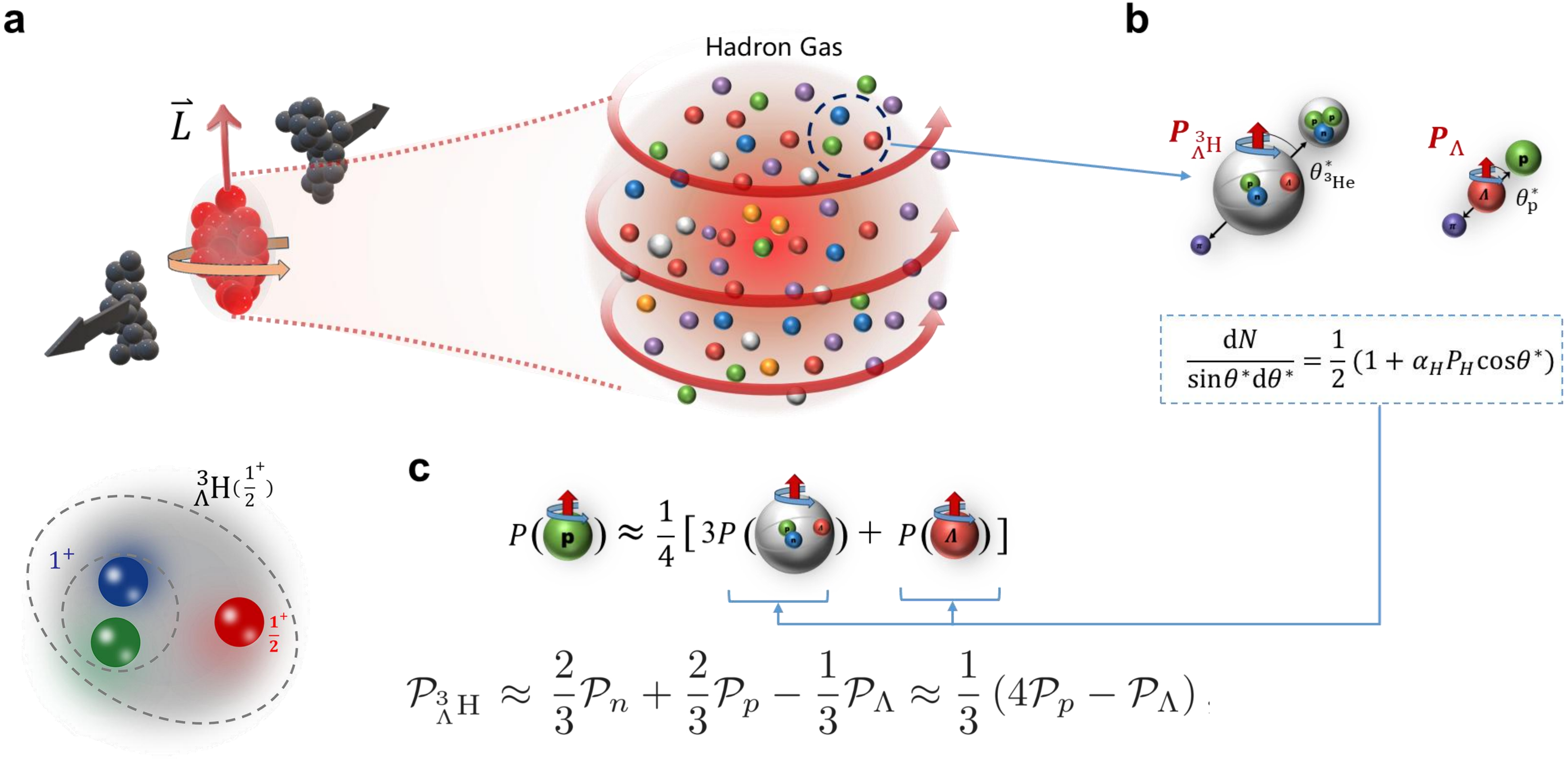
$$\alpha_{^3_\Lambda H} \approx \alpha_\Lambda$$



3. Spin polarization of proton

D. N. Liu, Y. P. Zheng, W. H. Zhou et al. arXiv:2508. 12193 (2025)

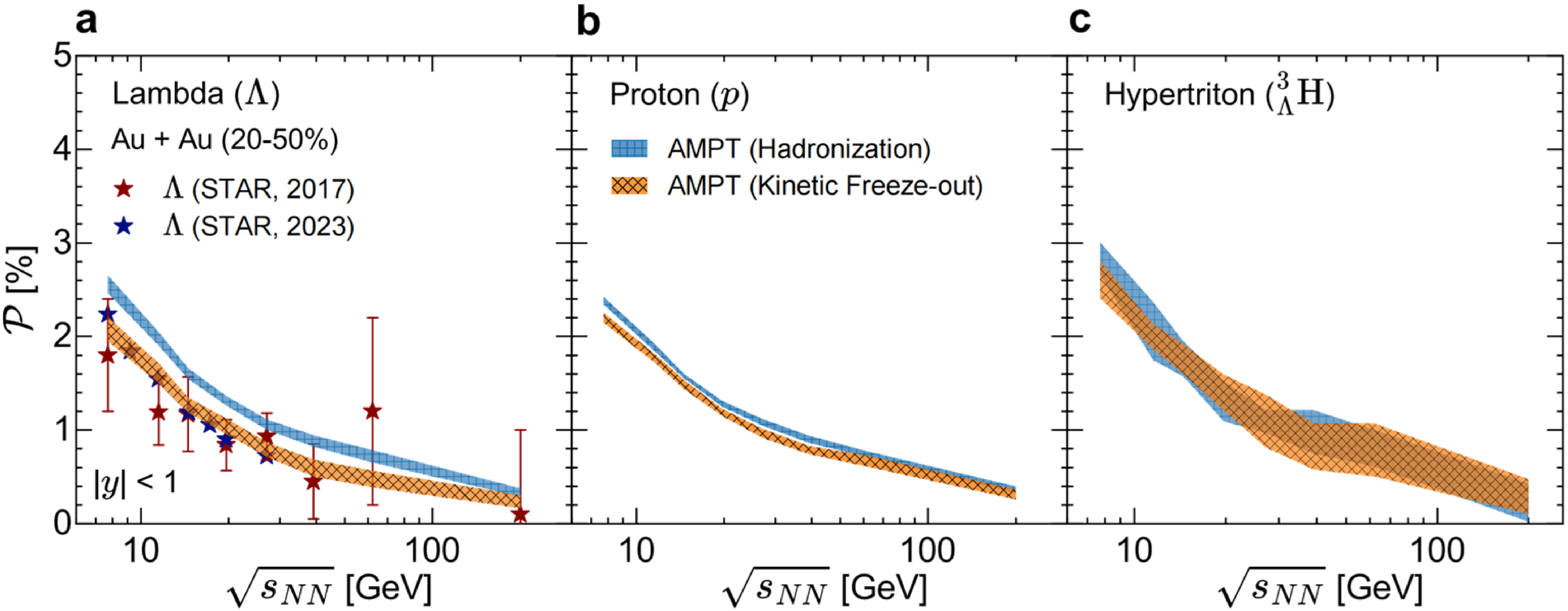
See talks by D. N. Liu at 17:25-17:50 Meeting Room 3, Sep. 23th



3. Spin polarization of proton

D. N. Liu, Y. P. Zheng, W. H. Zhou et al. arXiv:2508. 12193 (2025)

New



3. Spin polarization of proton

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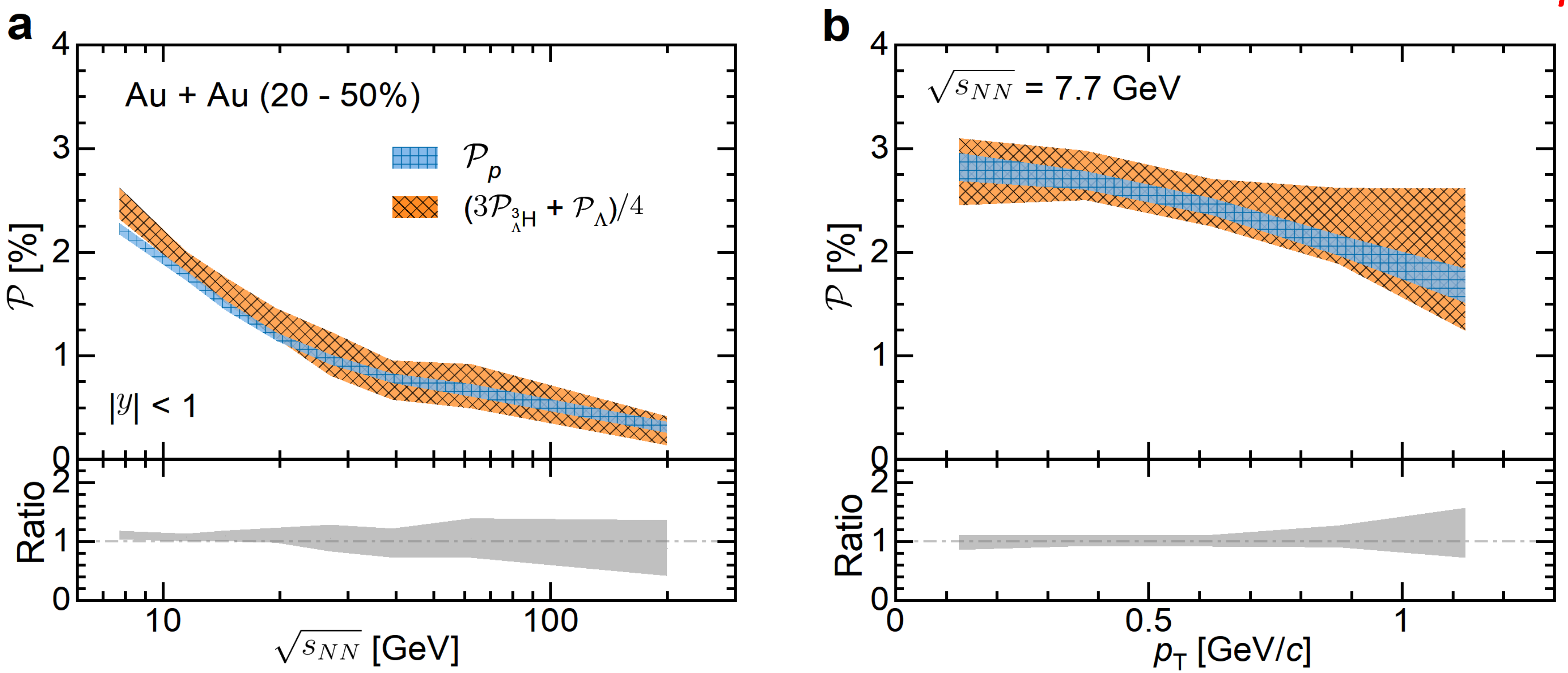
New

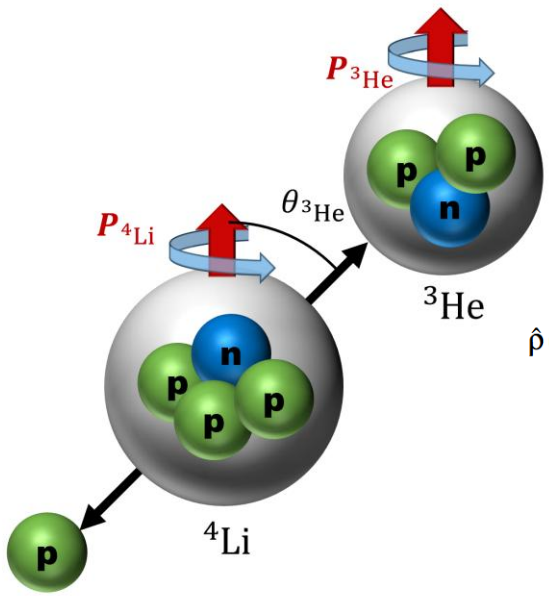


$$\mathcal{P}_{^3_\Lambda \mathrm{H}} \approx \frac{2}{3}\mathcal{P}_n + \frac{2}{3}\mathcal{P}_p - \frac{1}{3}\mathcal{P}_\Lambda \approx \frac{1}{3}\left(4\mathcal{P}_p - \mathcal{P}_\Lambda\right)$$

$$\mathcal{P}_p \approx \frac{1}{4}\left(3\mathcal{P}_{^3_\Lambda \mathrm{H}} + \mathcal{P}_\Lambda\right)$$

4. Spin alignment of ^{4}Li(2^-)

See talks by Y. P. Zheng at 11:20-11:40 Meeting Room 6, Sep. 24th



$$T(^4\mathrm{Li}(2^-)\rightarrow{}^3\mathrm{He}+p)=\sqrt{\frac{3}{8\pi}}\begin{bmatrix} -\sin\theta e^{i\phi} & 0 & 0 & 0\\ \cos\theta & -\frac{1}{2}\sin\theta e^{i\phi} & -\frac{1}{2}\sin\theta e^{i\phi} & 0\\ \sqrt{\frac{1}{6}}\sin\theta e^{-i\phi} & \sqrt{\frac{2}{3}}\cos\theta & \sqrt{\frac{2}{3}}\cos\theta & -\sqrt{\frac{1}{6}}\sin\theta e^{i\phi}\\ 0 & \frac{1}{2}\sin\theta e^{-i\phi} & \frac{1}{2}\sin\theta e^{-i\phi} & \cos\theta\\ 0 & 0 & 0 & \sin\theta e^{-i\phi} \end{bmatrix}$$

$$\hat{\rho}(^4\mathrm{Li}(2^-))=diag[\rho_{2,2},\rho_{1,1},\rho_{0,0},\rho_{-1,-1},\rho_{-2,-2}]$$

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

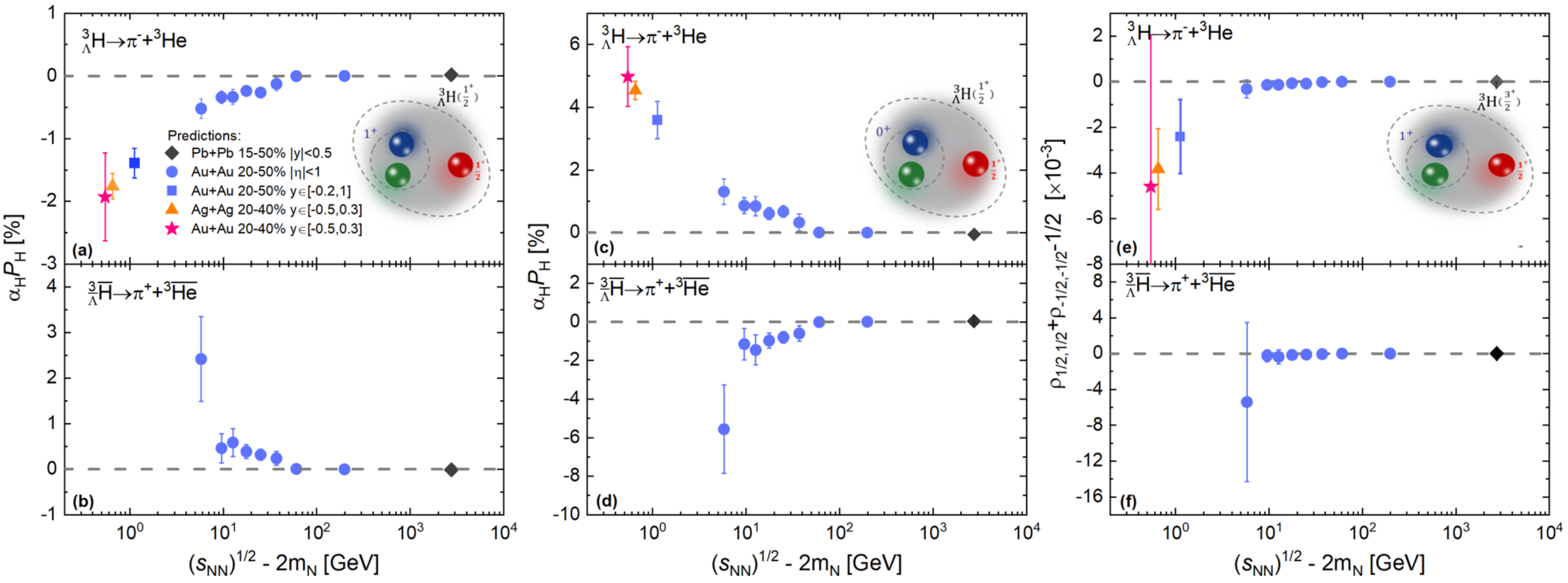
$$P_L=\frac{e^{\frac{\omega}{2T}}-e^{-\frac{\omega}{2T}}}{e^{\frac{\omega}{2T}}+e^{-\frac{\omega}{2T}}}\approx\frac{1}{2}\frac{\omega}{T}$$

New

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

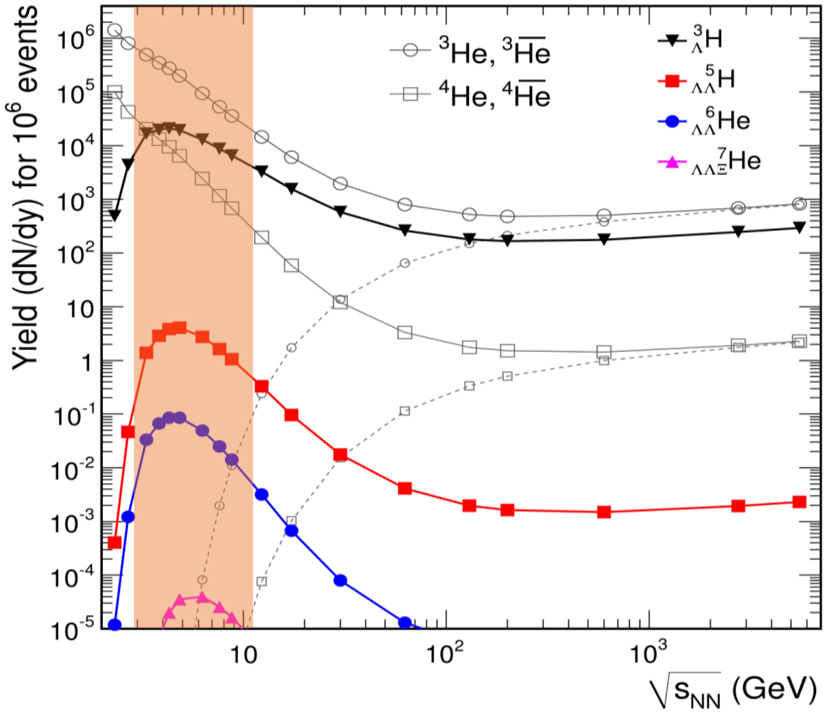
Summary and outlook

1. **(Anti-)hypertriton is globally polarized in non-central heavy-ion collisions.**
2. **(Anti-)hypertriton polarization and its decay pattern provide a novel method to uniquely determine the spin structure of its wavefunction.**



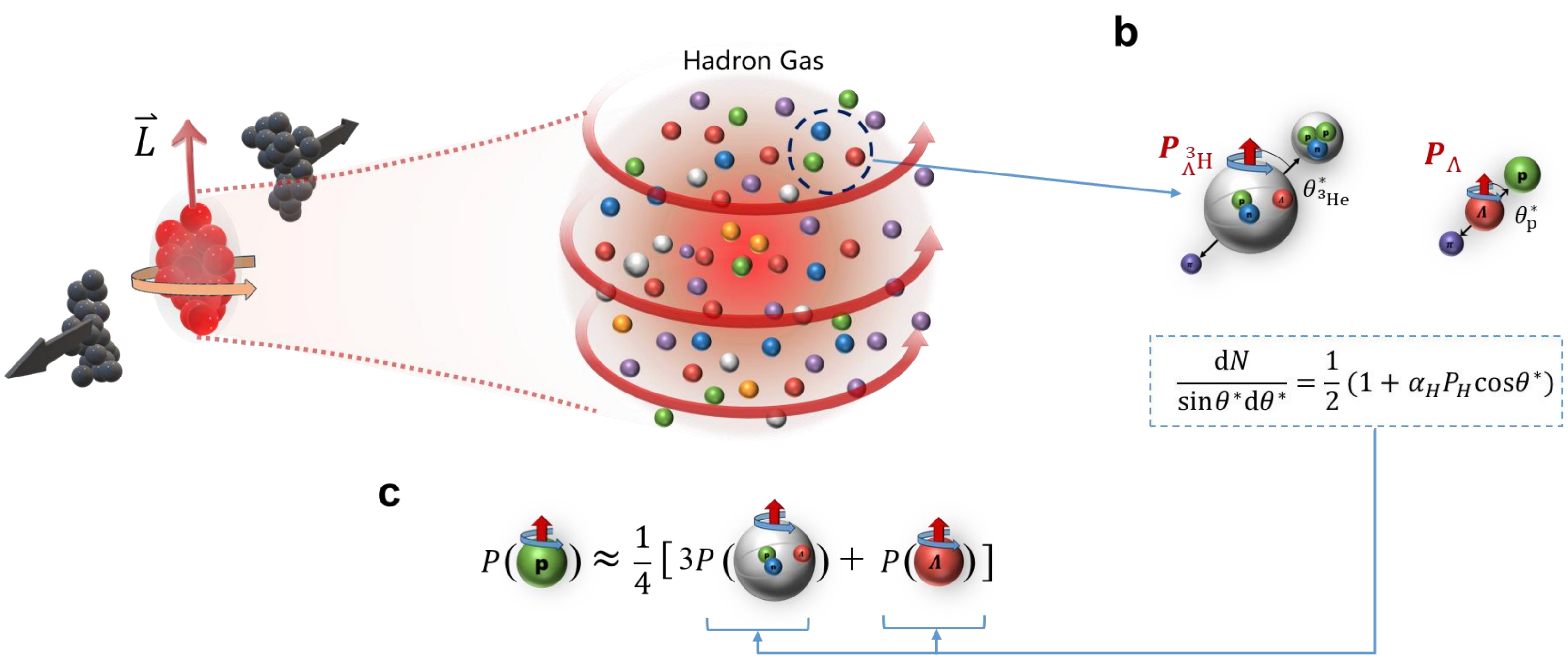
Summary and outlook

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



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

D. N. Liu, Y. P. Zheng, W. H. Zhou et al. arXiv:2508. 12193 (2025)



- ➢ **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)**

Polarization of unstable (hyper-)nuclei provides a novel tool to study the spin evolution of strongly-interacting matter at high-baryon density region

Thanks for your listening!

Discussion: Effects of baryon spin correlation

$$\hat{\rho}_{np\Lambda} = \hat{\rho}_n \otimes \hat{\rho}_p \otimes \hat{\rho}_\Lambda + \frac{1}{2^2}(c_{np}^{\alpha\beta}\hat{\sigma}_{n,\alpha} \otimes \hat{\sigma}_{p,\beta} \otimes \hat{\rho}_\Lambda$$

$$+c_{p\Lambda}^{\alpha\beta}\hat{\sigma}_{p,\alpha} \otimes \hat{\sigma}_{\Lambda,\beta} \otimes \hat{\rho}_n + c_{n\Lambda}^{\alpha\beta}\hat{\sigma}_{n,\alpha} \otimes \hat{\sigma}_{\Lambda,\beta} \otimes \hat{\rho}_p)$$

$$+\frac{1}{2^3}c_{np\Lambda}^{\alpha\beta\gamma}\hat{\sigma}_{n,\alpha} \otimes \hat{\sigma}_{p,\beta} \otimes \hat{\sigma}_{\Lambda,\gamma},$$

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

$$C_- = -\frac{1}{4}(\langle c_{np}^{zz}\mathcal{P}_\Lambda\rangle + \langle c_{p\Lambda}^{zz}\mathcal{P}_n\rangle + \langle c_{n\Lambda}^{zz}\mathcal{P}_p\rangle) - \frac{1}{4}\langle c_{np\Lambda}^{zzz}\rangle,$$

$$C_+ = \frac{1}{12}(\langle c_{np}^{zz}\rangle - 2\langle c_{p\Lambda}^{zz}\rangle - 2\langle c_{n\Lambda}^{zz}\rangle).$$

'genuine' correlation terms

Induced correlations

We can express the polarization of a particle as $\mathcal{P} = \langle\mathcal{P}\rangle + \delta\mathcal{P}$ with $\delta\mathcal{P}$ denoting its space and momentum dependent fluctuations, which leads to the relations $\langle\mathcal{P}_n\mathcal{P}_p\rangle = \langle\mathcal{P}_n\rangle\langle\mathcal{P}_p\rangle + \langle\delta\mathcal{P}_n\delta\mathcal{P}_p\rangle$ and $\langle\mathcal{P}_n\mathcal{P}_p\mathcal{P}_\Lambda\rangle = \langle\mathcal{P}_n\rangle\langle\mathcal{P}_p\rangle\langle\mathcal{P}_\Lambda\rangle + \langle\delta\mathcal{P}_n\delta\mathcal{P}_p\rangle\langle\mathcal{P}_\Lambda\rangle + \langle\delta\mathcal{P}_n\delta\mathcal{P}_\Lambda\rangle\langle\mathcal{P}_p\rangle + \langle\delta\mathcal{P}_p\delta\mathcal{P}_\Lambda\rangle\langle\mathcal{P}_n\rangle + \langle\delta\mathcal{P}_n\delta\mathcal{P}_p\delta\mathcal{P}_\Lambda\rangle$. Assuming again $\langle\mathcal{P}_n\rangle \approx \langle\mathcal{P}_p\rangle \approx \langle\mathcal{P}_\Lambda\rangle$ and neglecting the three-body correlation, we then have

$$\mathcal{P}_{{}^3_\Lambda\mathrm{H}} \approx (1 - \langle\delta\mathcal{P}_n\delta\mathcal{P}_p\rangle - \langle\delta\mathcal{P}_p\delta\mathcal{P}_\Lambda\rangle - \langle\delta\mathcal{P}_n\delta\mathcal{P}_\Lambda\rangle)\langle\mathcal{P}_\Lambda\rangle.$$

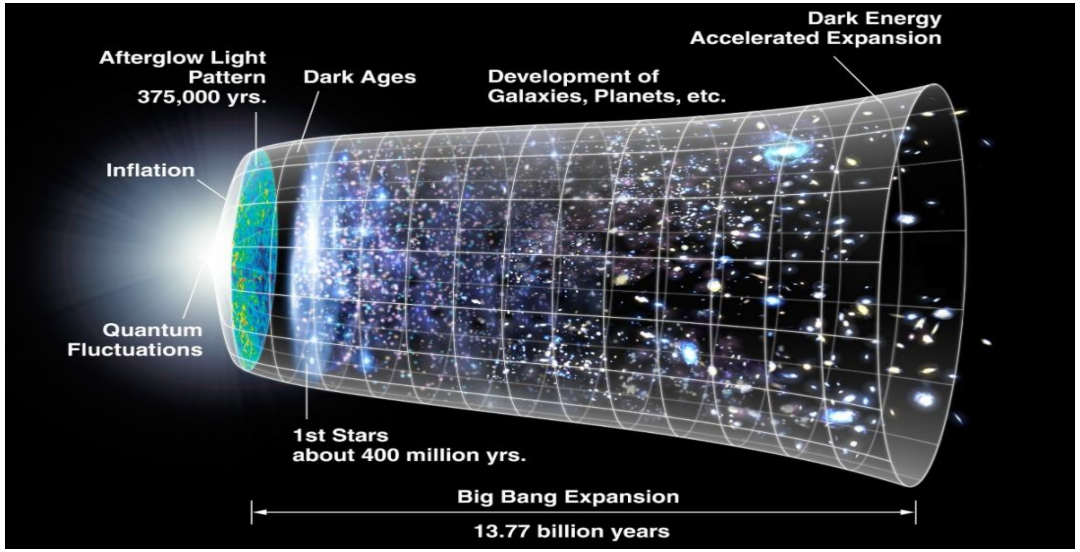
This result suggests that it is possible to extract the information on the spin-spin correlations among nucleons and Λ hyperons from the measurement of hypertriton polarization in heavy-ion collisions, although it is non-trivial in practice.

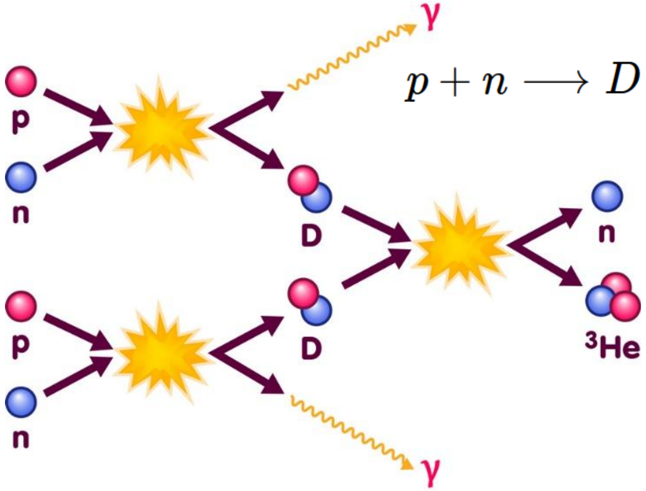
Little-Bang Nucleosynthesis

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

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

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



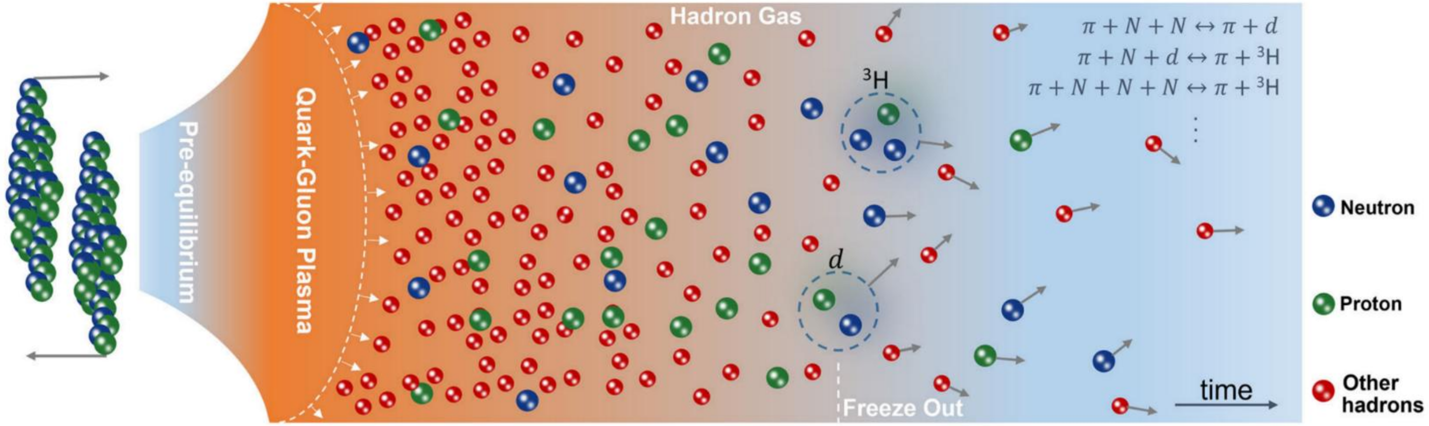


$$p + n \longrightarrow D + \gamma$$

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

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

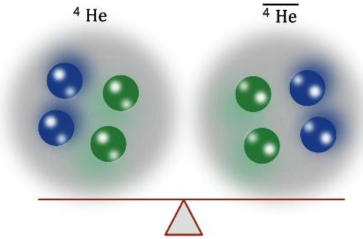
K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024)

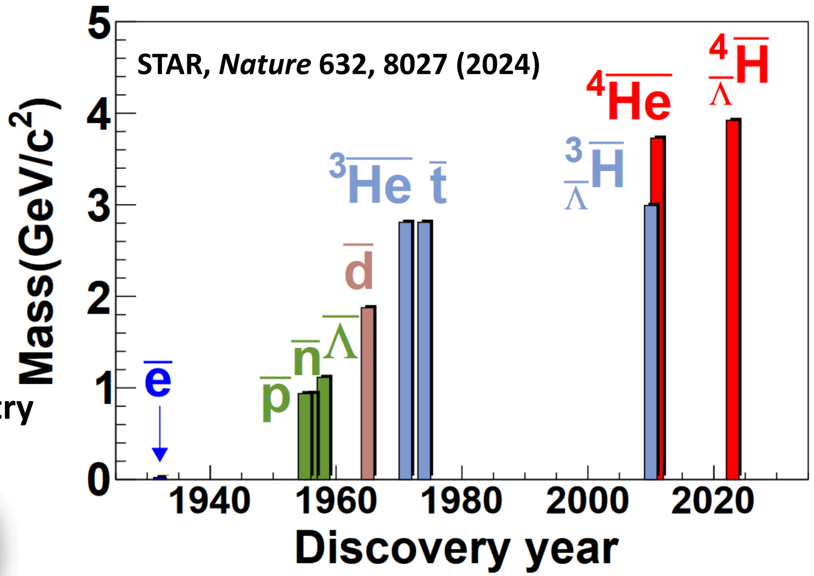


ALICE, arXiv:2410. 17769 (2024)

Antimatter factory

Matter-antimatter asymmetry





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