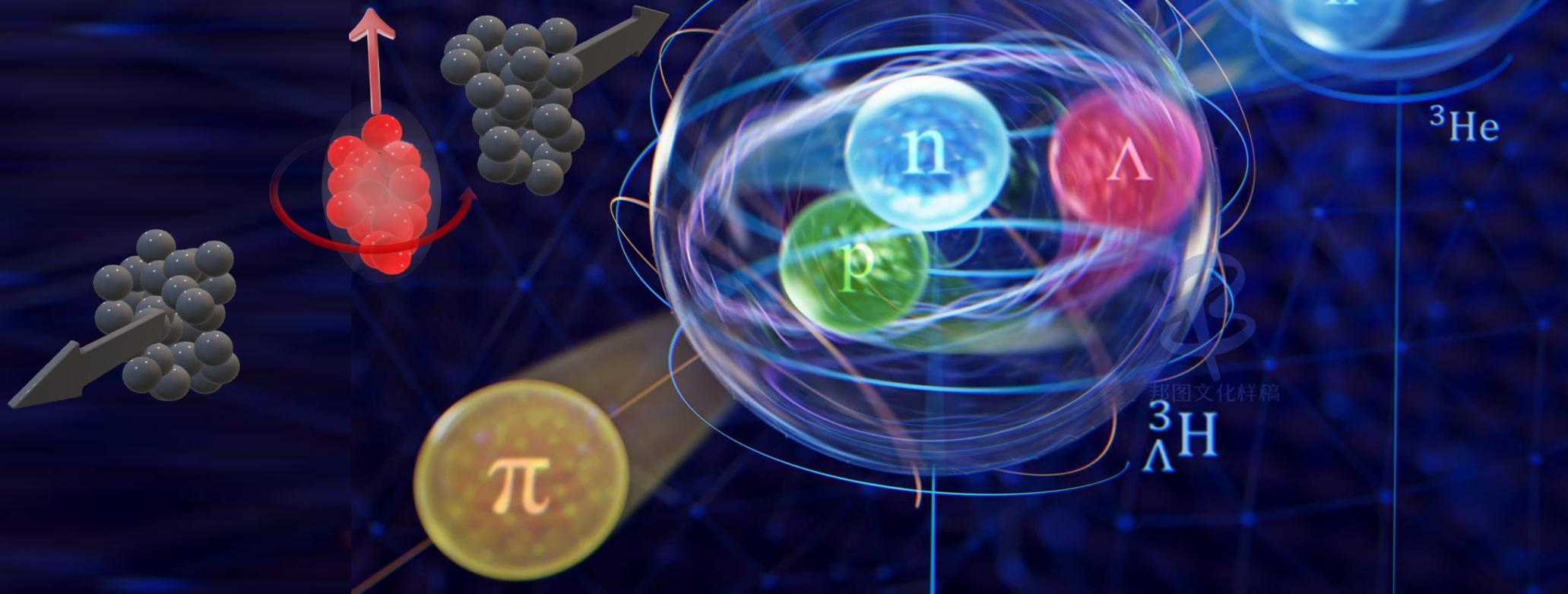# Spin polarization from hadrons to (anti-)(hyper-)nuclei in heavy-ion collisions

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Jeju
Nov. 13, 2025

Outline

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)

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.
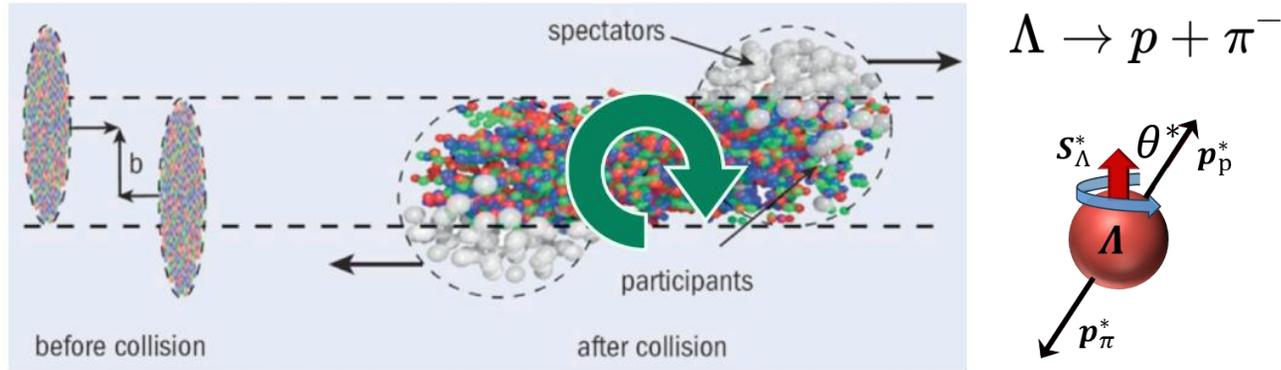

$$\Lambda \to p + \pi^-$$

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

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

→ **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]

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

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

Vorticity ⟵ **Spin polarization**

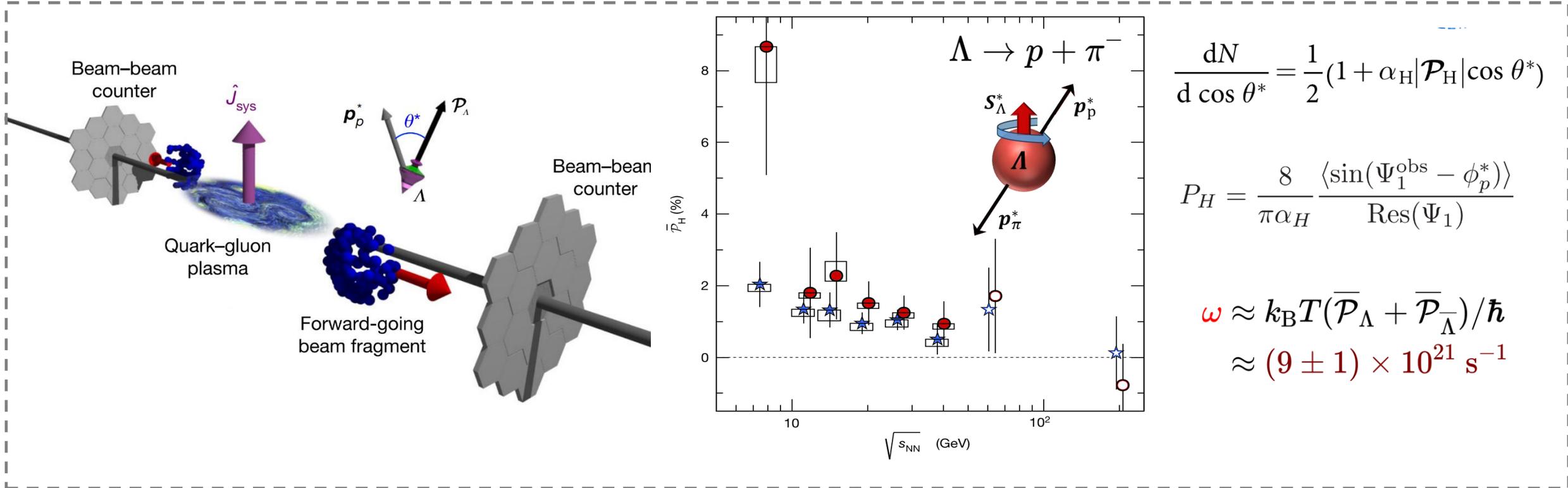$$\omega \approx k_{\mathrm{B}}T(\mathcal{P}_\Lambda + \mathcal{P}_{\overline{\Lambda}})/\hbar$$

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
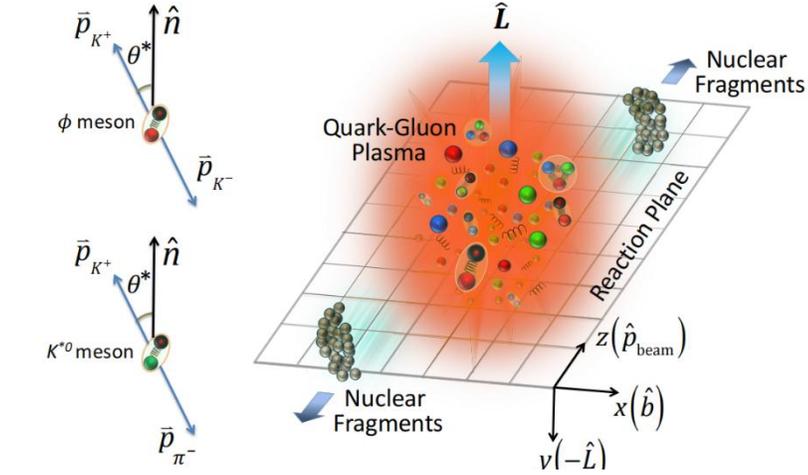

$$\Lambda \to p + \pi^-$$

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

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

$$\omega \approx k_{\mathrm{B}}T(\overline{\mathcal{P}}_\Lambda + \overline{\mathcal{P}}_{\overline{\Lambda}})/\hbar$$

$$\approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$$

Spin polarization of Lambda hyperon ⟹ **Vorticity of QGP**

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)

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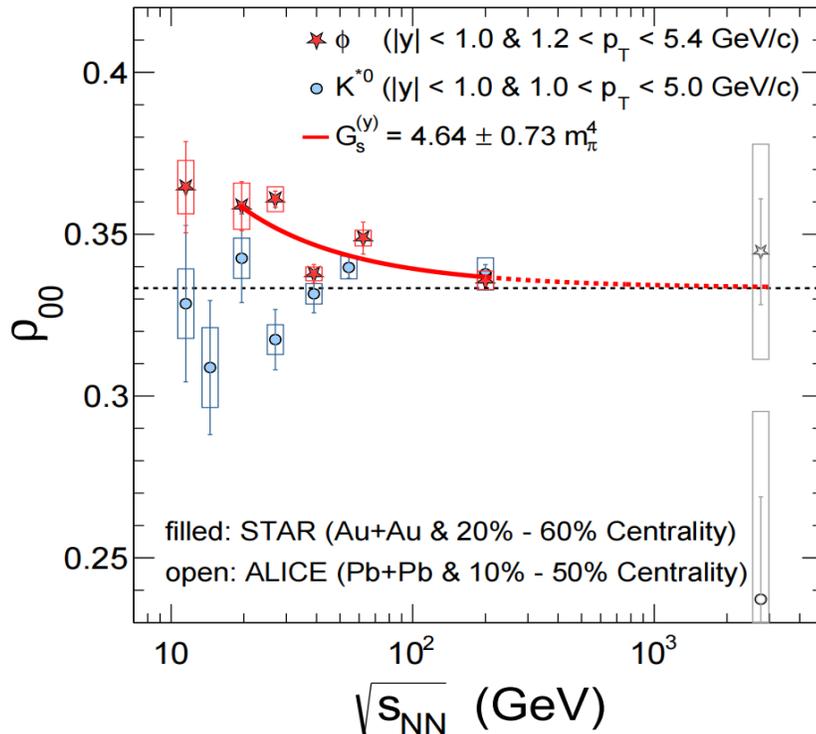
Quark-antiquark spin correlation

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

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).

STAR, *Nature* 632, 8027 (2024)

Elementary hadrons

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

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

$$J/\psi(c\bar{c}) \quad \ldots$$

Stable (anti-)nuclei

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

$$\bar{p}(\bar{u}\bar{u}\bar{d}) \quad \bar{d}(\bar{n}\bar{p}) \quad {}^3\overline{\text{He}}(\bar{n}\bar{p}\bar{p})$$
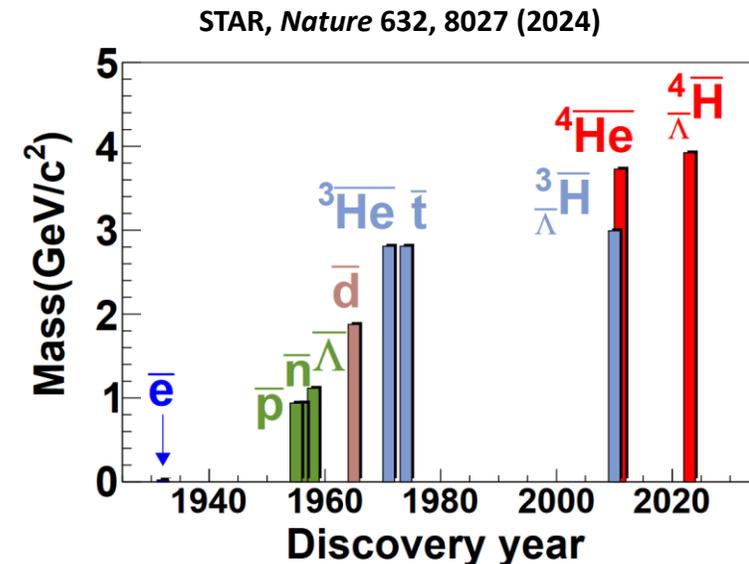
$$\ldots$$

Unstable (anti-)(hyper-)nuclei

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

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

$$\ldots$$

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

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)

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

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

Relative branching ratio:

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

Pie chart labels: 4-body mesonic, non-mesonic, $\pi^- + {}^3He$ 25%, $\pi^0 + d + n$ 20%, 2%, 1%, $\pi^0 + {}^3H$ 13%, $\pi^- + d + p$ 40%

STAR, PRC 97, 054909 (2018)

$\begin{smallmatrix} {}^3_\Lambda H & R_3 \end{smallmatrix}$ versus experiment plot. Labels: NC26, 840(1962); PRL20, 819(1968); NPB67, 269(1973); STAR 2017; CERN Rep. 64-1,63(1964); NPB16, 77(1970); NPB67, 269(1973); mean of helium bubble chamber results; R.H. Dalitz, 1959 for J = 1/2; R.H. Dalitz, 1959 for J = 3/2; J.G. Congleton,1992

Favors spin 1/2

Coalescence Model

A_P

A_T

R

Deuteron

n p

$^3_\Lambda H$

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)
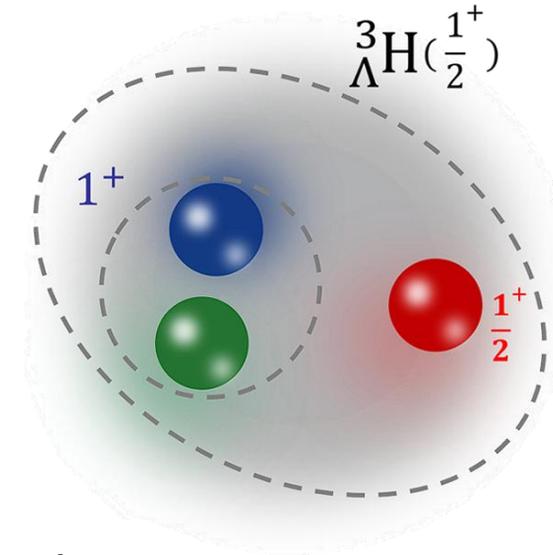Hui-Gan Chen and Zhao-Qing Feng, PLB 824, 136849 (2022)

> ## Spin wavefunction

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

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

$^3_\Lambda H(\tfrac{1^+}{2})$

1^+

$\tfrac{1^+}{2}$

> ## Coalescence model for hypertriton production (without baryon spin correlation)

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

$$E\frac{d^3 N_{^3_\Lambda H, \pm\frac{1}{2}}}{dP^3} = E\int \prod_{i=n,p,\Lambda} p_i^\mu d^3\sigma_\mu \frac{d^3 p_i}{E_i} \bar{f}_i(\mathbf{x}_i, \mathbf{p}_i)$$

$$\times \left(\frac{2}{3} w_{n,\pm\frac{1}{2}} w_{p,\pm\frac{1}{2}} w_{\Lambda,\mp\frac{1}{2}} + \frac{1}{6} w_{n,\pm\frac{1}{2}} w_{p,\mp\frac{1}{2}} w_{\Lambda,\pm\frac{1}{2}}\right.$$
$$\left.+ \frac{1}{6} w_{n,\mp\frac{1}{2}} w_{p,\pm\frac{1}{2}} w_{\Lambda,\pm\frac{1}{2}}\right)$$

$$\times W_{^3_\Lambda H}(\mathbf{x}_n, \mathbf{x}_p, \mathbf{x}_\Lambda; \mathbf{p}_n, \mathbf{p}_p, \mathbf{p}_\Lambda)\delta(\mathbf{P} - \sum_i \mathbf{p}_i)$$

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

$$\approx \frac{2}{3}\mathcal{P}_n + \frac{2}{3}\mathcal{P}_p - \frac{1}{3}\mathcal{P}_\Lambda$$

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

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

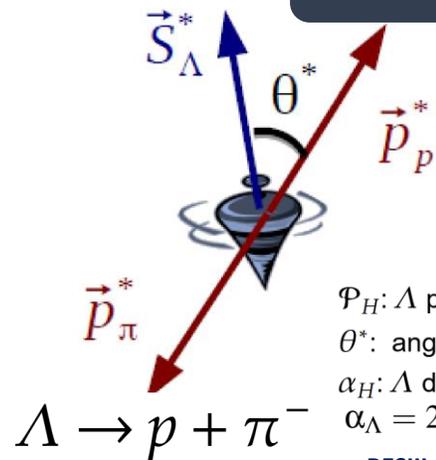**Spin polarizations and correlations are small**

Parity-violating weak decay

Λ hyperons

Hypertriton

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

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

$\mathcal{P}_H$: 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).

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

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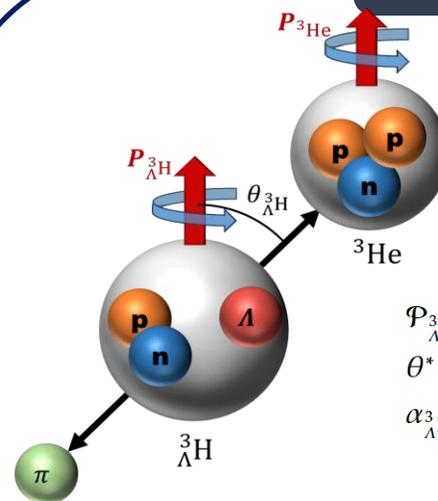
$$T(\Lambda \to \pi^- + p) = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} T_s + T_p\cos\theta_p^* & T_p\sin\theta_p^* e^{i\phi_p^*} \\ T_p\sin\theta_p^* e^{-i\phi_p^*} & T_s - T_p\cos\theta_p^* \end{pmatrix}$$

The angular distribution

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

H denotes Λ and $\bar{\Lambda}$

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

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

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

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

$$T(^3_\Lambda H \to \pi^- + ^3 He)$$

$$= \frac{F}{6\sqrt{\pi}} \begin{pmatrix} 3T_s - T_p\cos\theta^* & -T_p\sin\theta^* e^{i\phi^*} \\ -T_p\sin\theta^* e^{-i\phi^*} & 3T_s + T_p\cos\theta^* \end{pmatrix}$$
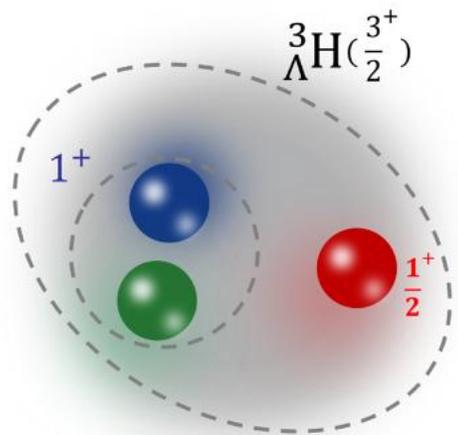
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_{^3_\Lambda H}\mathcal{P}_{^3_\Lambda H}\cos\theta^*\right)$$

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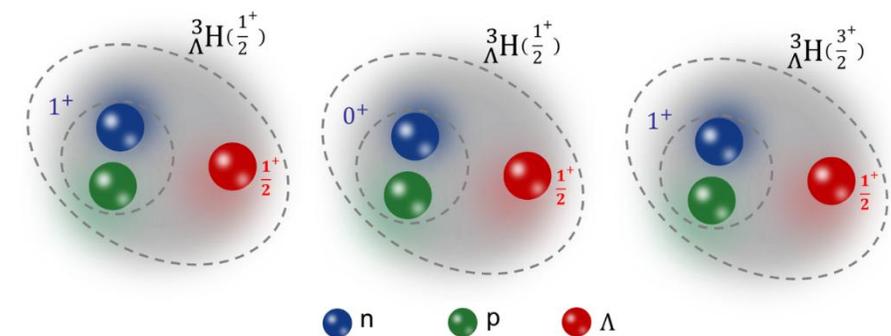
Sign flip !

$^3_\Lambda H(\frac{3^+}{2})$

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

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

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

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

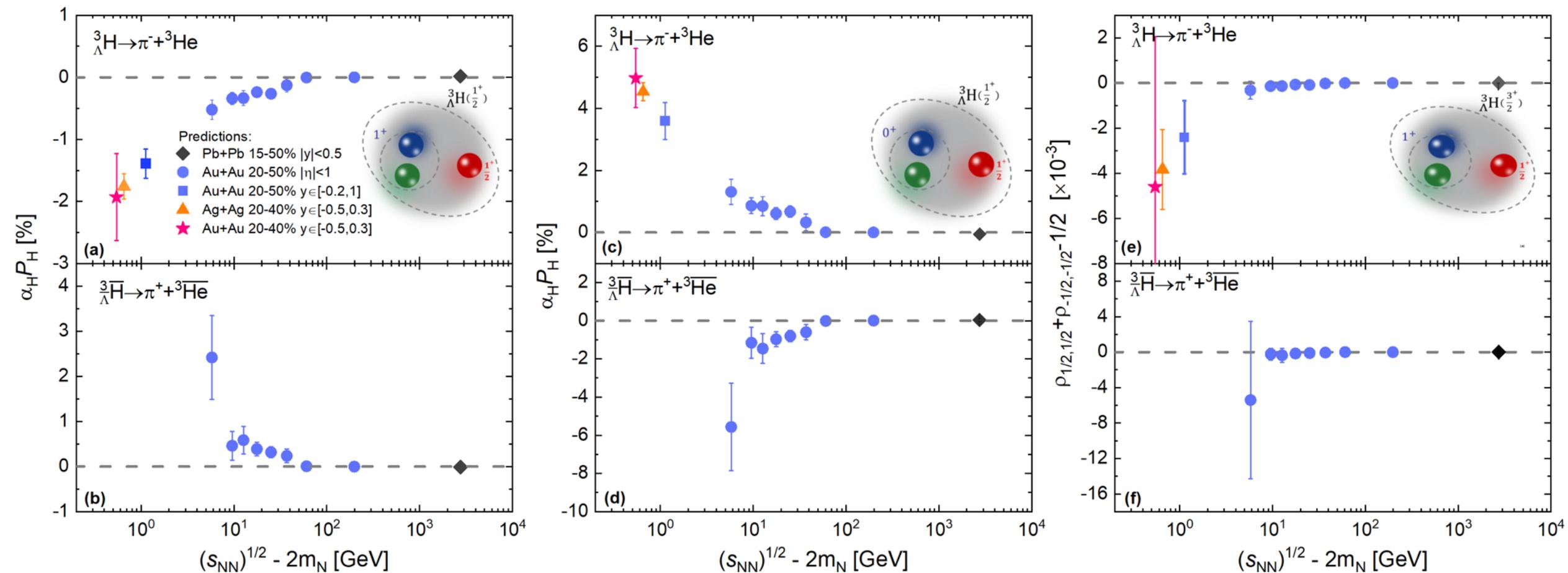| J^π	Structure	Decay mode	$dN/(\sin\theta^* d\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda H \to \pi^- + {}^3He$	$\frac{1}{2}[1-(1/2.58)\alpha_\Lambda\mathcal{P}_\Lambda\cos\theta^*]$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(0^+)$	$^3_\Lambda H \to \pi^- + {}^3He$	$\frac{1}{2}(1+\alpha_\Lambda\mathcal{P}_\Lambda\cos\theta^*)$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

Different polarization and decay patterns!

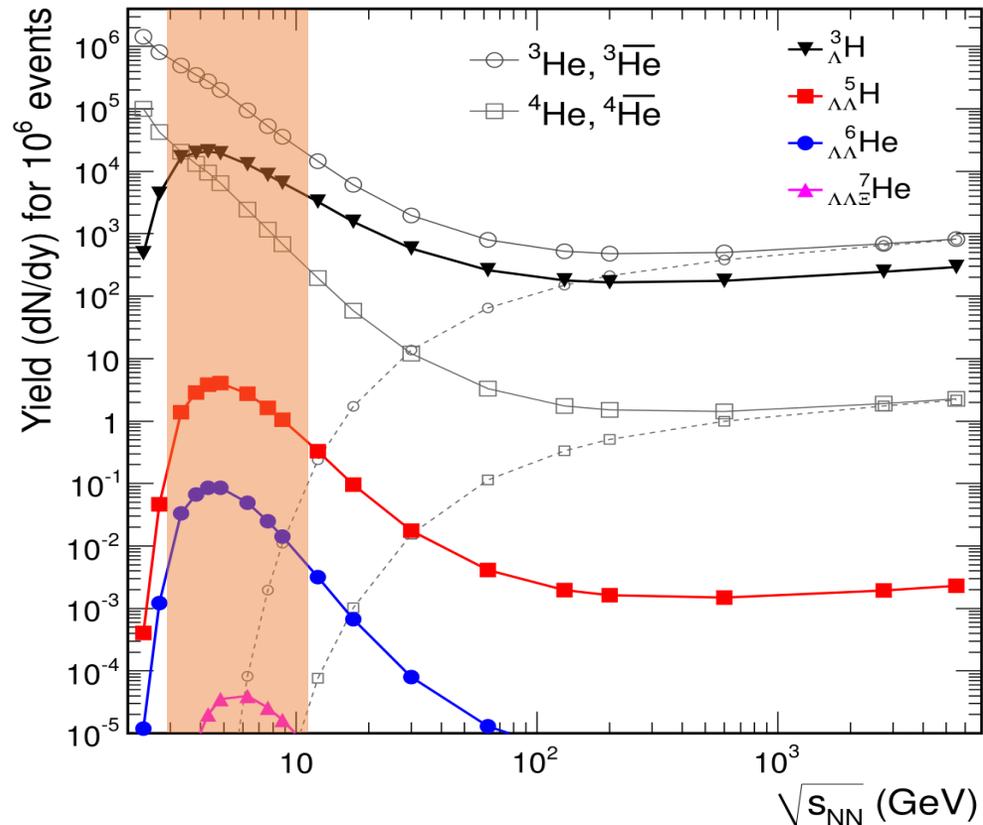**The measurement of hypertriton polarization provides a novel method to uniquely determine its internal spin structure**

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

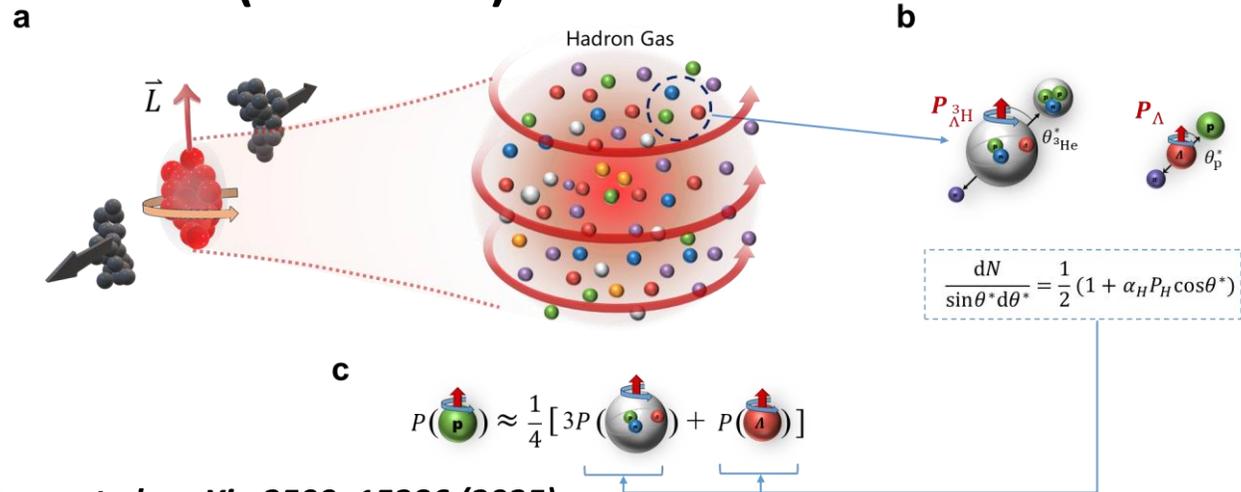$$\alpha_{^3_\Lambda H} \approx \alpha_\Lambda$$

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.

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)**

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

$$P\left(\vec{p}\right) \approx \frac{1}{4}\left[3P\left(\vec{d}\right) + P\left(\vec{\Lambda}\right)\right]$$

Y. P. Zheng et al., arXiv:2509. 15286 (2025)
D. N. Liu, et al. arXiv:2508. 12193 (2025)