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Global Spin Polarization of Light (Anti-) (Hyper-)Nuclei at High Baryon Densities

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Outline

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

Spin polarization of Lambda hyperon

For overview, see talks by J. H. Chen, S. Pu *et al.*

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.

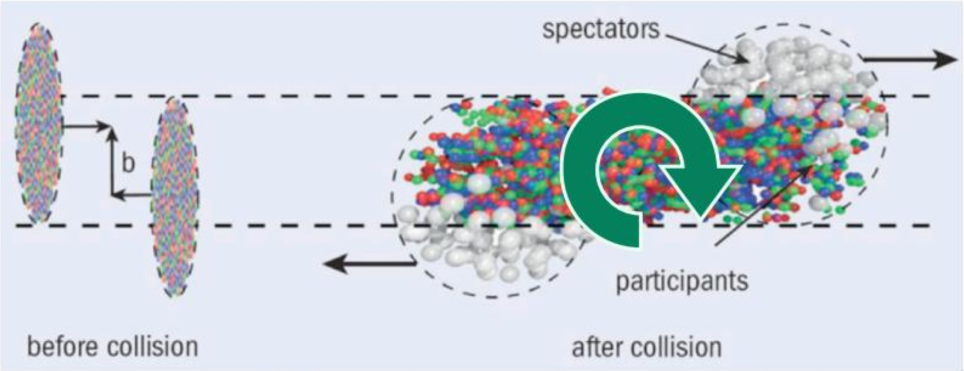
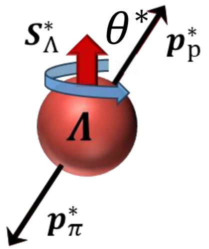


figure: M. Lisa, talk @ “Strangeness in Quark Matter 2016”

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



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

Decay constant Spin polarization

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 $\Leftarrow$ **Spin polarization**

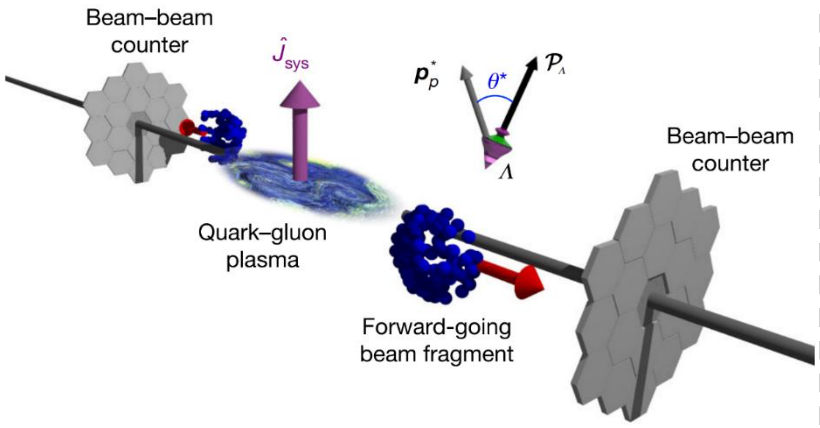
$$\omega \approx k_B T(\mathcal{P}_\Lambda + \mathcal{P}_{\bar\Lambda})/\hbar$$

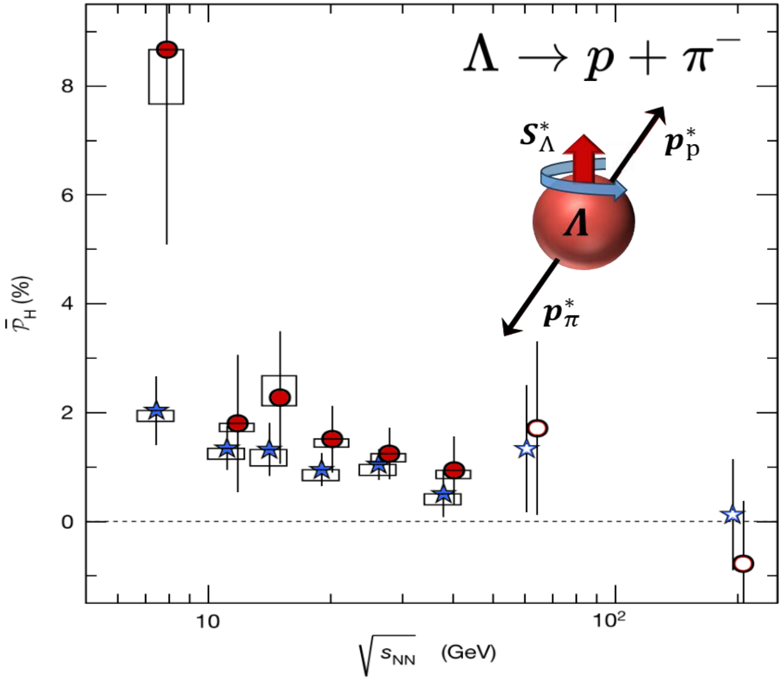
Experimental progress

(2)

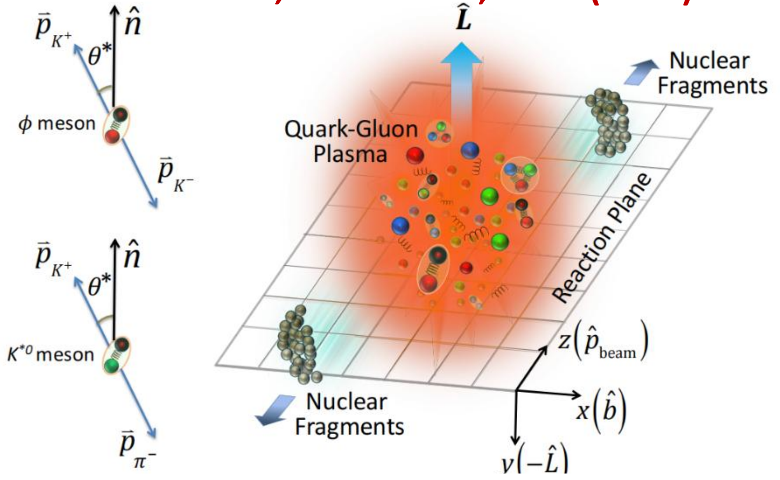
For overview, see talks by J. H. Chen, S. Pu *et al.*

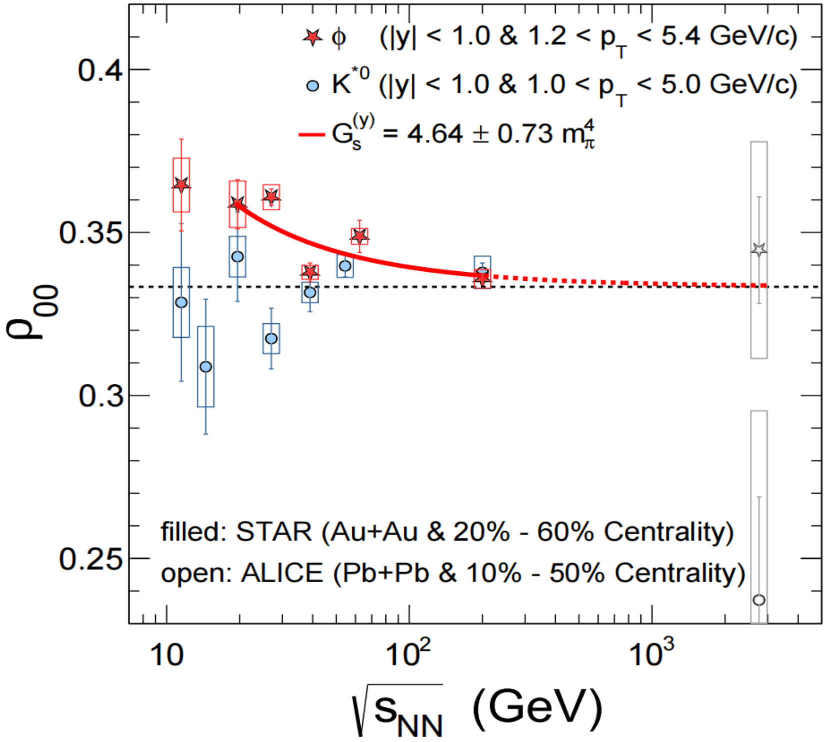
STAR, Nature 548, 62 (2017)



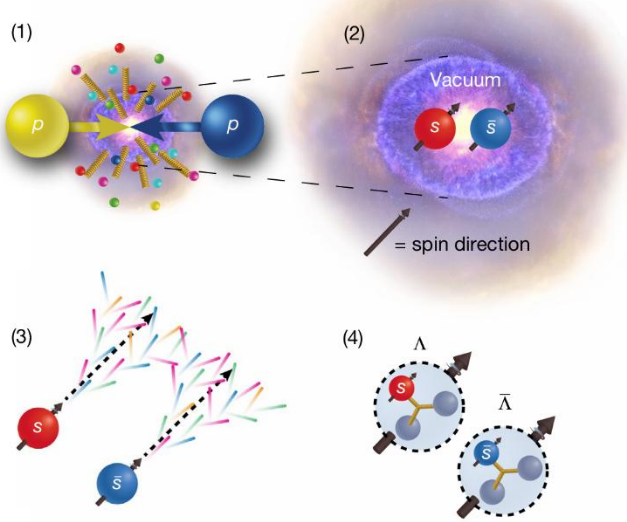


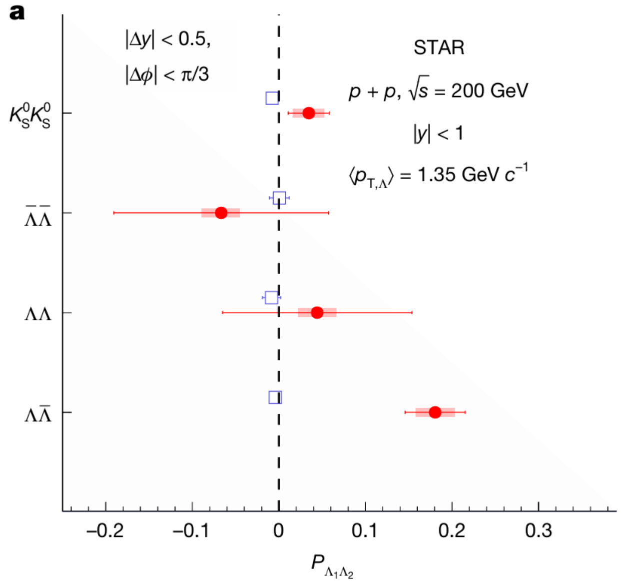
STAR, Nature 614, 7947 (2023)





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

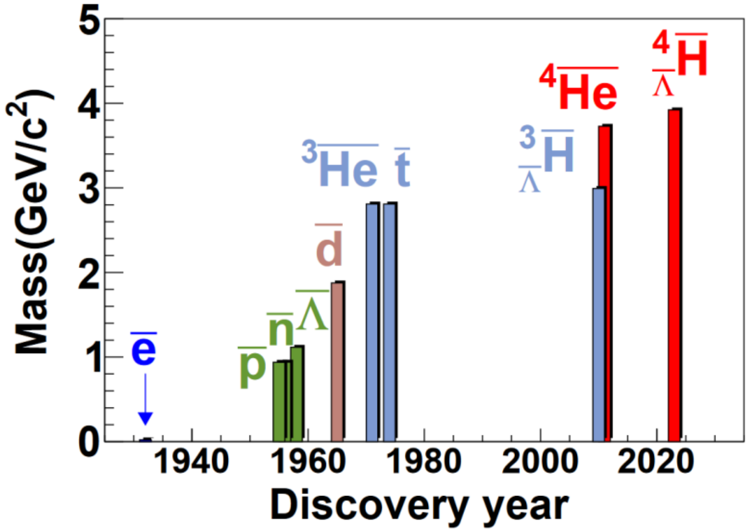
Spin $\frac{1}{2}, \frac{3}{2}?$ $2\ (g.s.)$

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

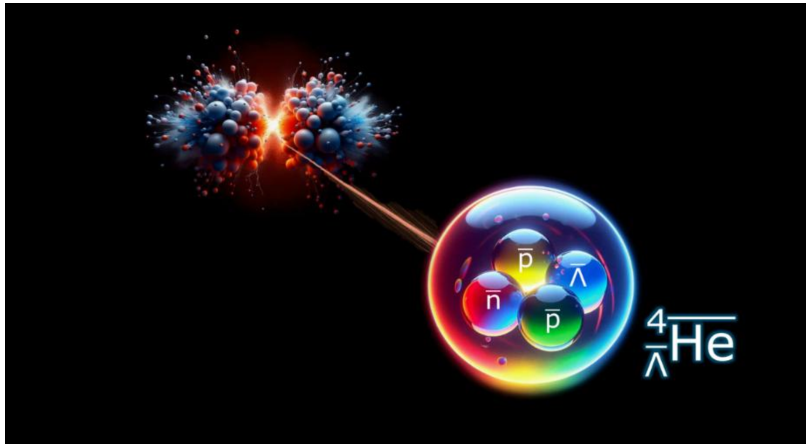
${}^{3}_{\Lambda}\overline{\mathrm{H}}(\bar{n}\bar{p}\bar{\Lambda})$ ${}^{4}\overline{\mathrm{Li}}(\bar{n}\bar{p}\bar{p}\bar{p})$

…

STAR, *Nature* 632, 8027 (2024)



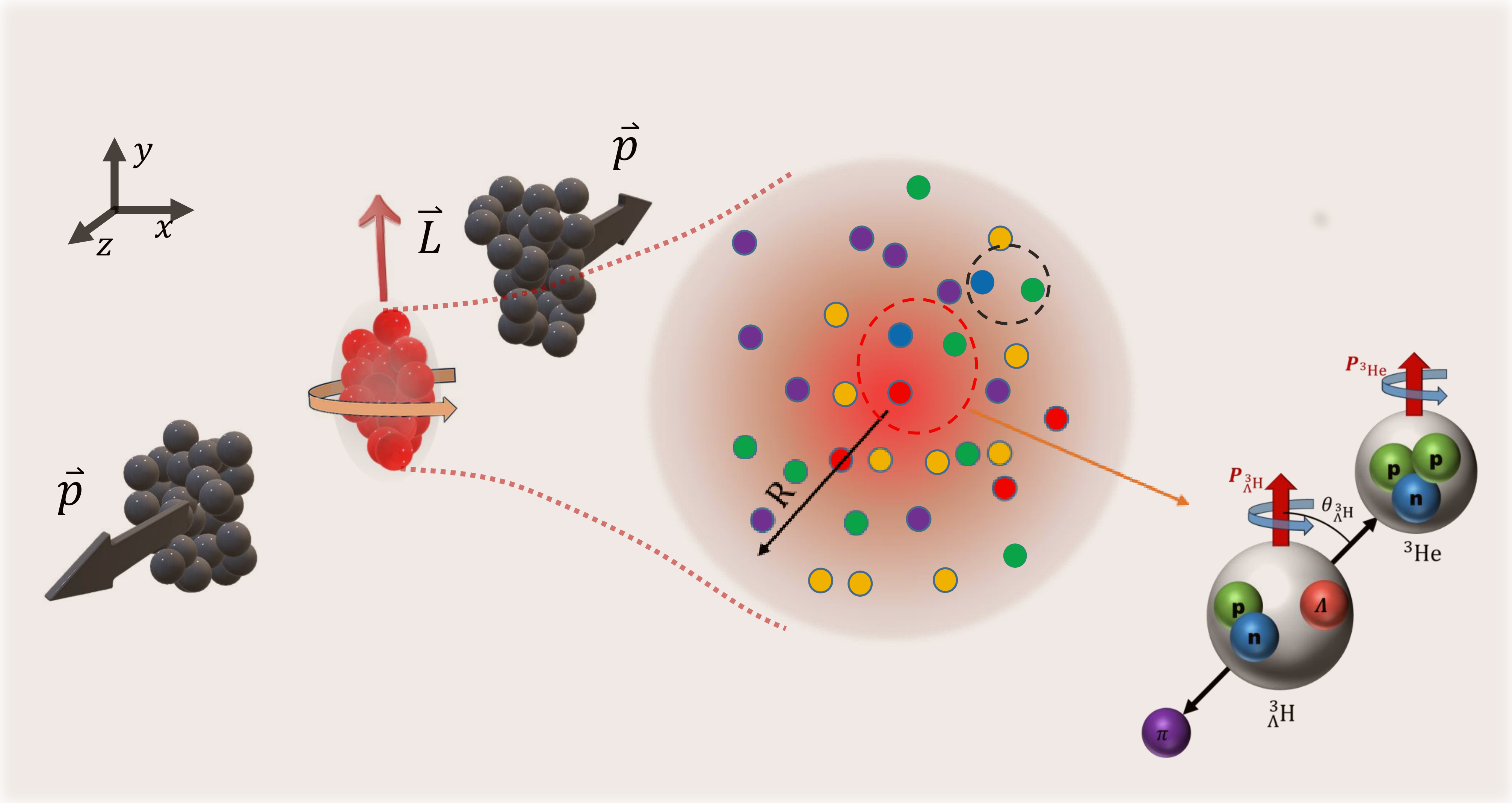
ALICE, Phys. Rev. Lett. 134 (2025) 16, 162301



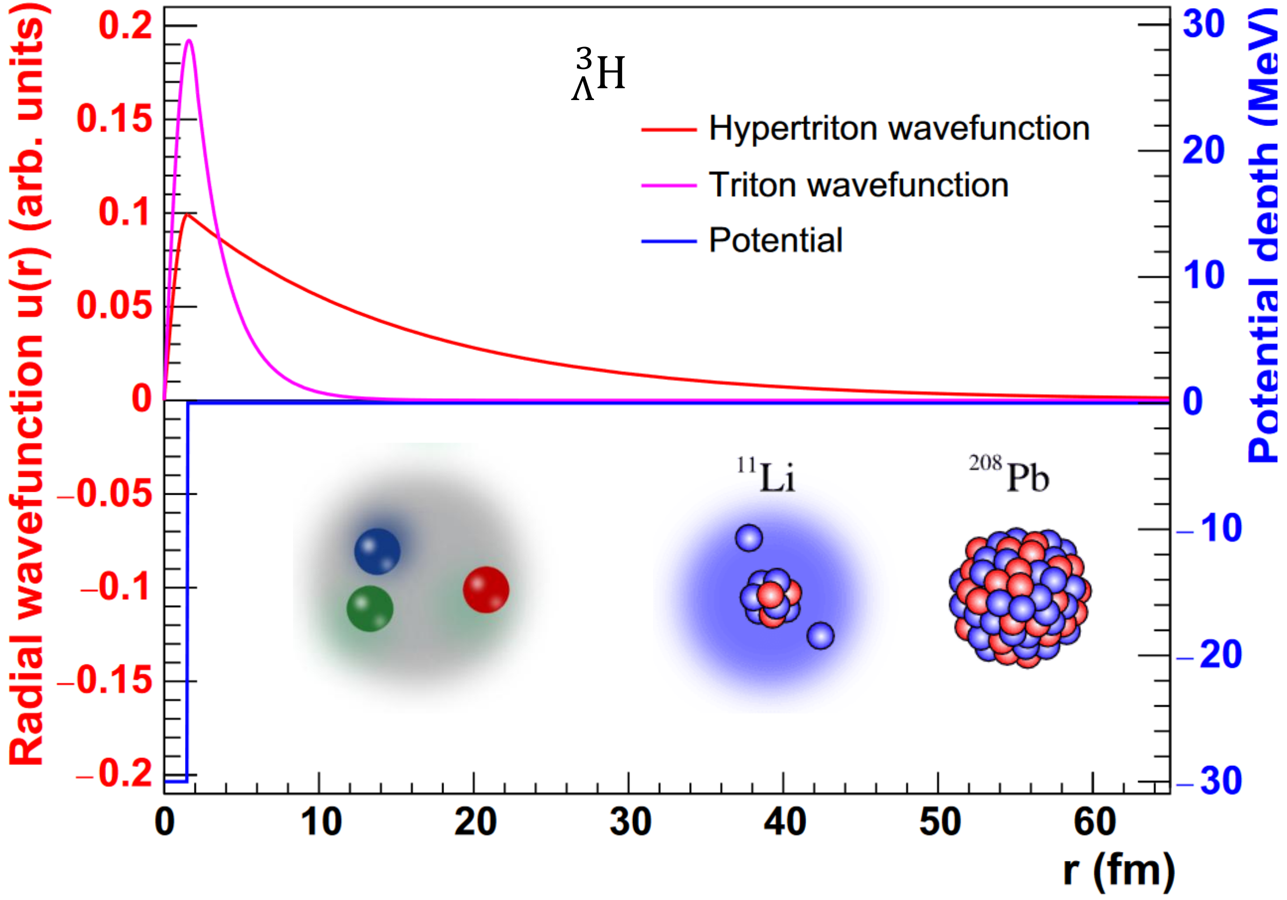
Outline

Global spin polarization of (anti-)hypertriton (4)

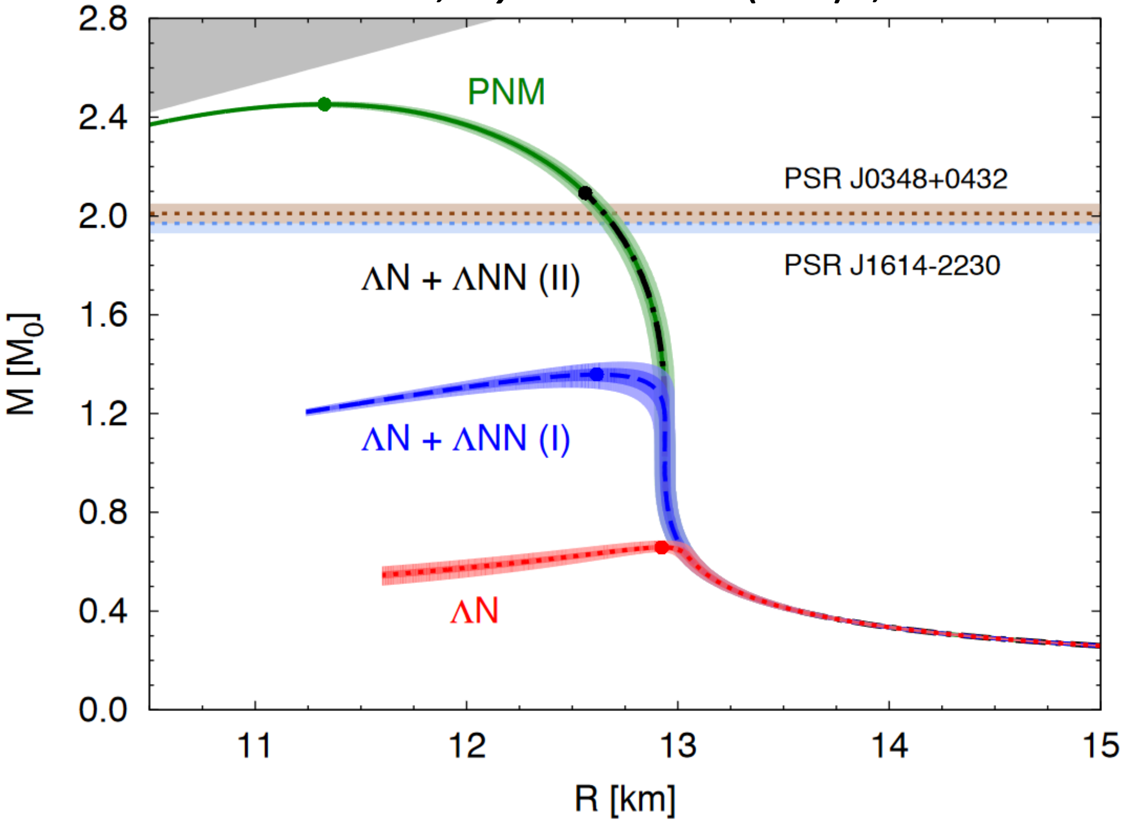
Kai-Jia Sun et al., Phys. Rev. Lett. 134, 022301 (2025)



Strange halo nucleus: (anti-)hypertriton



D. Lonardoni et al., Phys.Rev.Lett. 114 (2015) 9, 092301

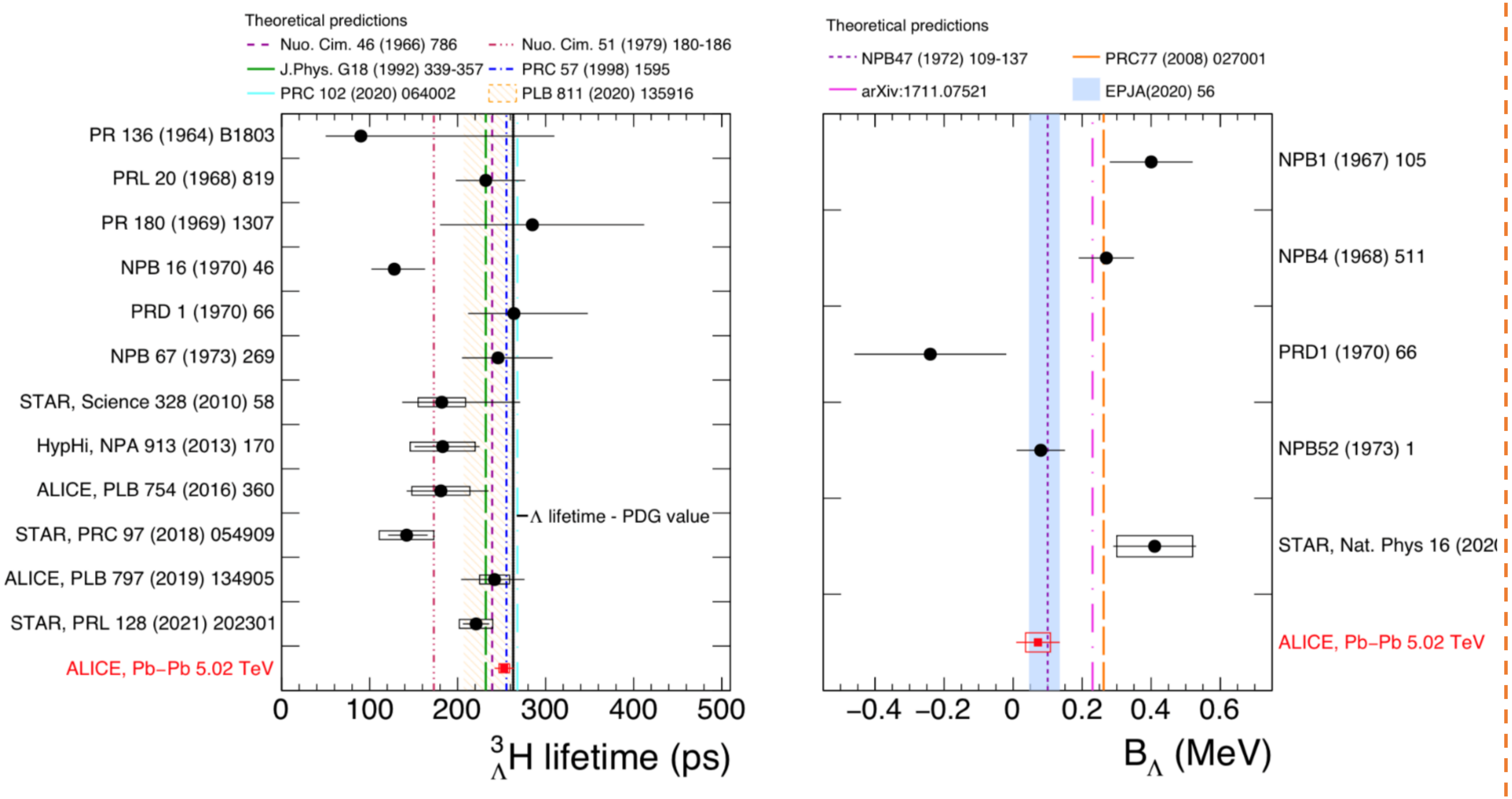


J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)
D. N. Liu et al. Phys. Lett. B 855, 138855 (2024)

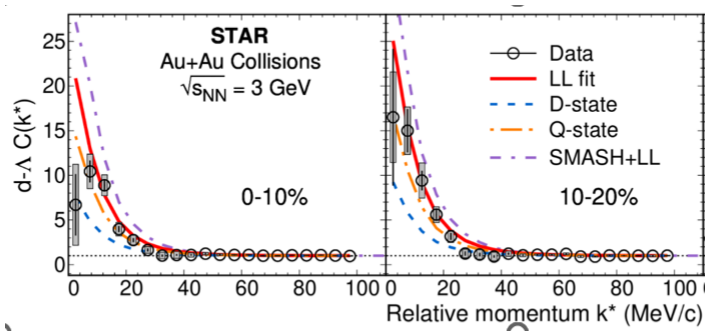
Lifetime, binding energy, and femtoscopy (6)

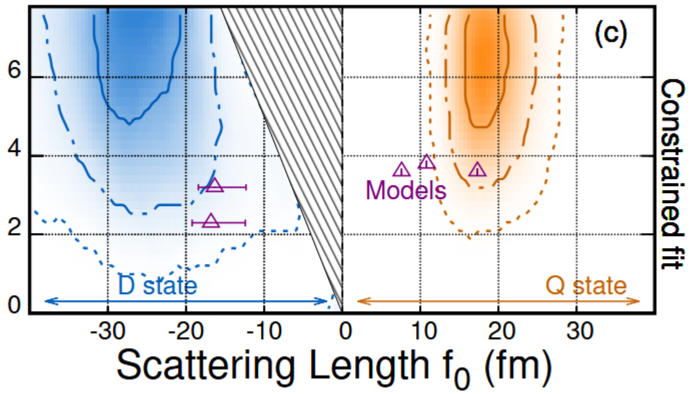
ALICE, PRL 131, 102302 (2023)

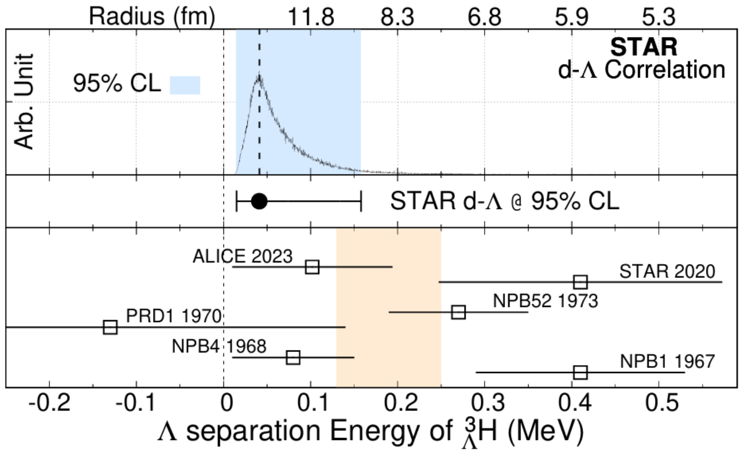
Y. G. Ma, Nucl. Sci. Tech. 3497 (2023)



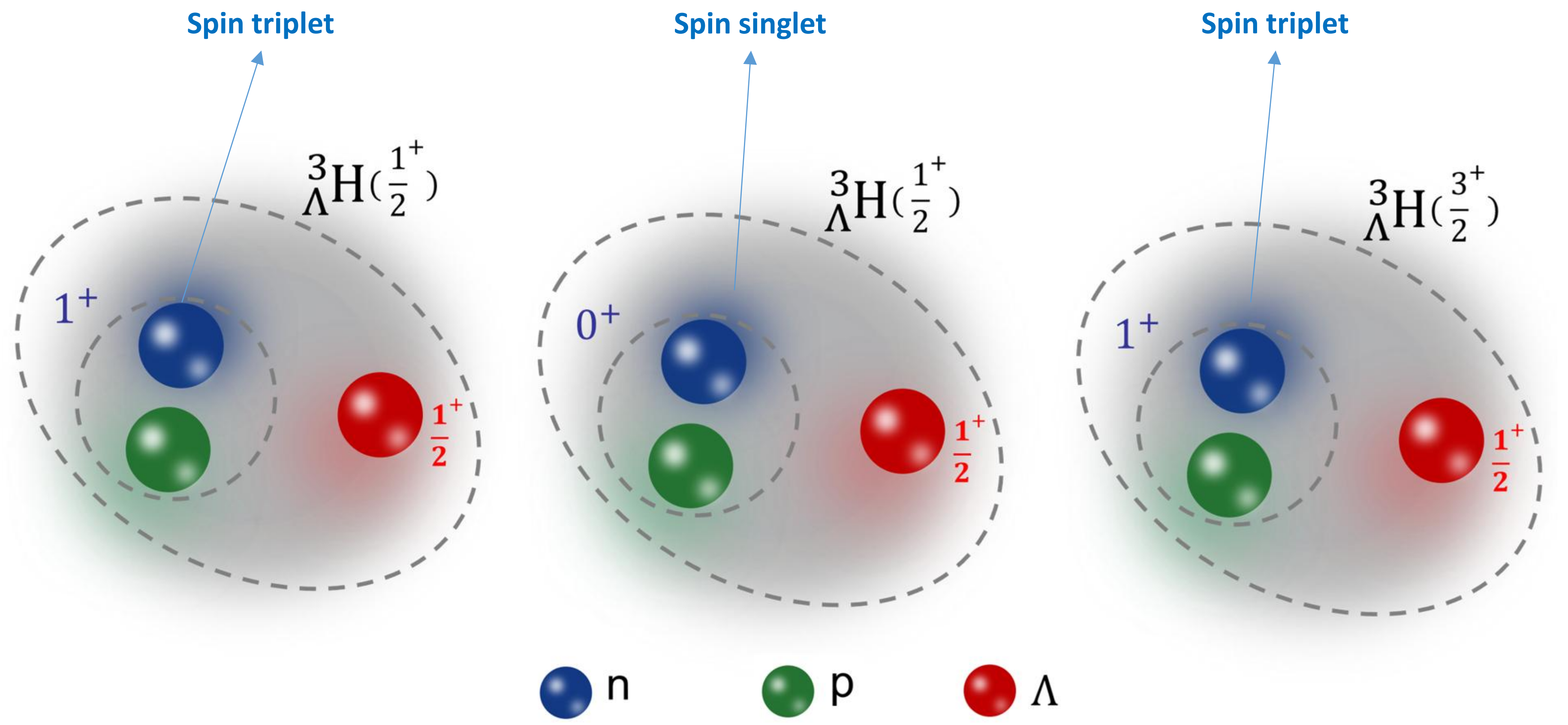
STAR, Phys. Rev. Lett. 136, 242303 (2026)







Spin of (anti-)hypertriton ? (7)

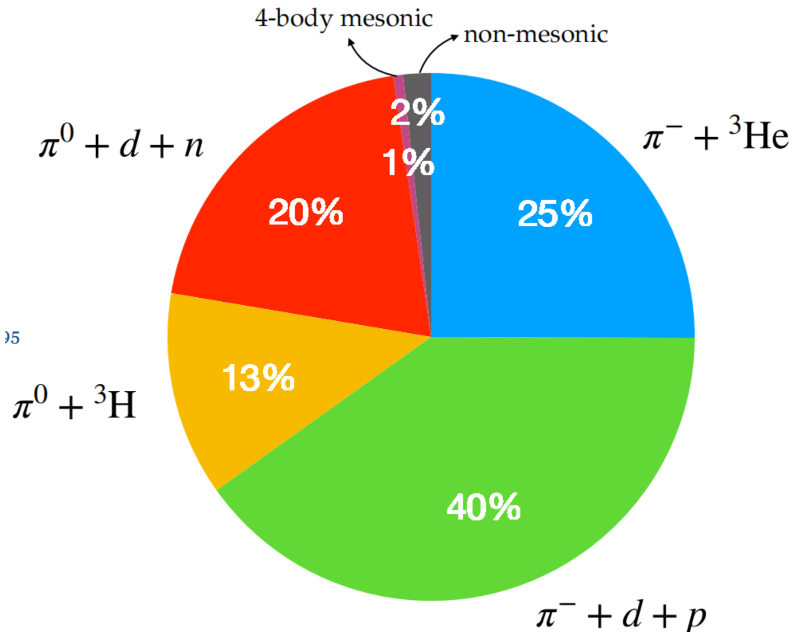


Spin of (anti-)hypertriton ? (8)

$^3_\Lambda\mathrm{H} \mapsto \pi^- + {}^3\mathrm{He}$, $\quad$ $^3_\Lambda\mathrm{H} \mapsto \pi^0 + {}^3\mathrm{H}$,

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

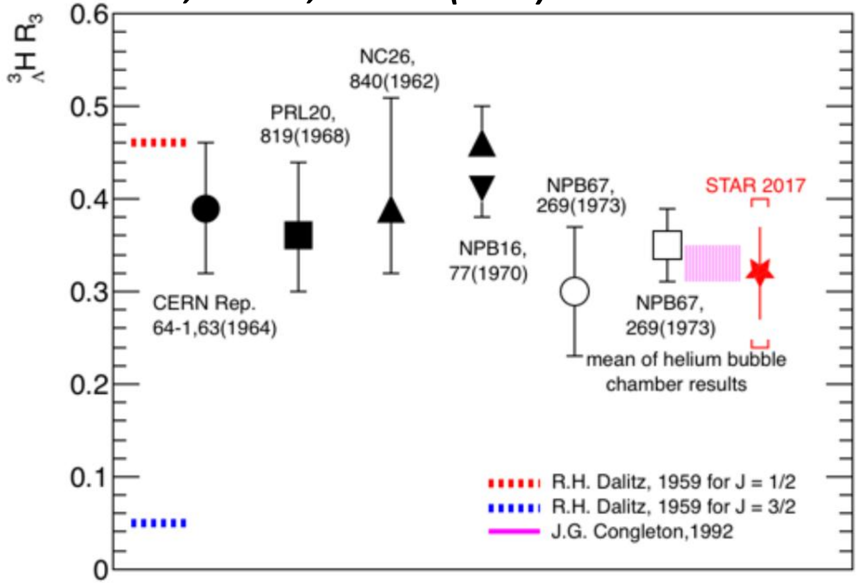
$^3_\Lambda\mathrm{H} \mapsto \pi^- + p + n + p$, $\quad$ $^3_\Lambda\mathrm{H} \mapsto \pi^0 + p + n + n$.



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

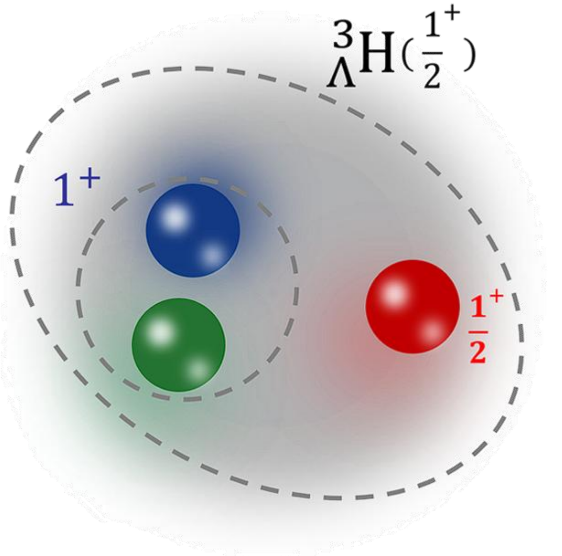
S. R. Beane,[1] E. Chang,[2] S. D. Cohen,[3] W. Detmold,[4,5] H. W. Lin,[3] T. C. Luu,[6] K. Orginos,[4,5] A. Parreño,[2] M. J. Savage,[3] and A. Walker-Loud[7,8]

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}H	3	0	1/2	$1/2^+$	$\overline{\mathbf{35}}$	$\overline{\mathbf{35}}$
$^3_\Lambda$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^+	$\overline{\mathbf{28}}$	$\overline{\mathbf{28}}$
$^4_\Lambda$He, $^4_\Lambda$H	4	−1	1/2	0^+	$\overline{\mathbf{28}}$	-
$^4_{\Lambda\Lambda}$He	4	−2	1	0^+	**27**, $\overline{\mathbf{28}}$	**27**, $\overline{\mathbf{28}}$
$\Lambda\Xi^0 pnn$	5	−3	0	$3/2^+$	$\overline{\mathbf{10}} + \cdots$	$\overline{\mathbf{10}}$

Favors spin 3/2

Spin-dependent coalescence model

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



➢ Spin wavefunction

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

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

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

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

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

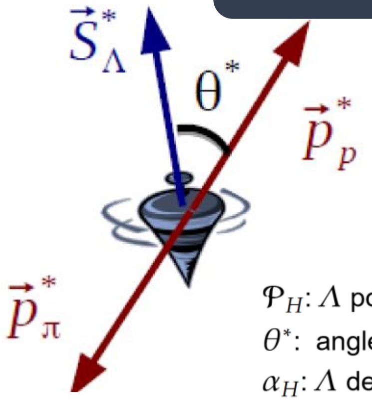
$$
\begin{aligned}
\mathcal{P}_{^3_\Lambda\mathrm{H}} &\approx \frac{\frac{2}{3}\mathcal{P}_n + \frac{2}{3}\mathcal{P}_p - \frac{1}{3}\mathcal{P}_\Lambda - \mathcal{P}_n\mathcal{P}_p\mathcal{P}_\Lambda}{1 - \frac{2}{3}(\mathcal{P}_n+\mathcal{P}_p)\mathcal{P}_\Lambda + \frac{1}{3}\mathcal{P}_n\mathcal{P}_p}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

Assuming spin polarizations and correlations are small

(Anti-)hypertriton polarization and its spin structure (10)

Parity-violating weak decay

Λ hyperons



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

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

$\mathcal{P}_H$: Λ polarization

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

α_H: Λ decay parameter

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

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

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

The transition matrix

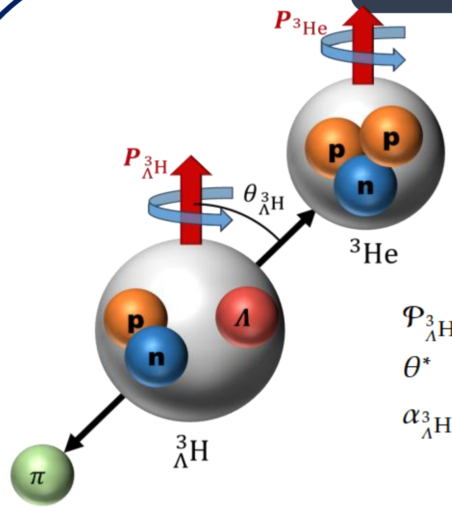
$$T(\Lambda \to \pi^- + p) = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} T_s + T_p\cos\theta_p^* & T_p\sin\theta_p^* e^{i\phi_p^*} \\ T_p\sin\theta_p^* e^{-i\phi_p^*} & T_s - T_p\cos\theta_p^* \end{pmatrix}$$

The angular distribution

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

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

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

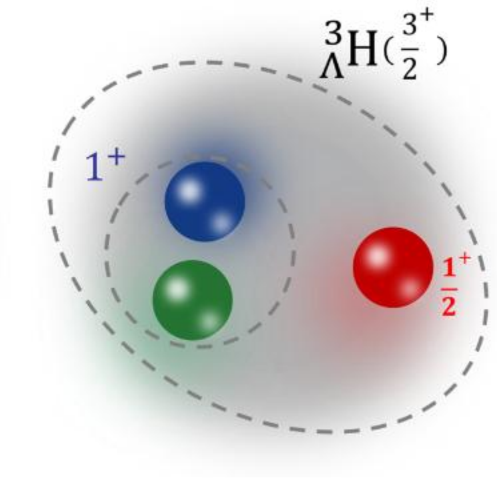
$$= \frac{F}{6\sqrt{\pi}} \begin{pmatrix} 3T_s - T_p\cos\theta^* & -T_p\sin\theta^* e^{i\phi^*} \\ -T_p\sin\theta^* e^{-i\phi^*} & 3T_s + T_p\cos\theta^* \end{pmatrix}$$

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

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

Sign flip !

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

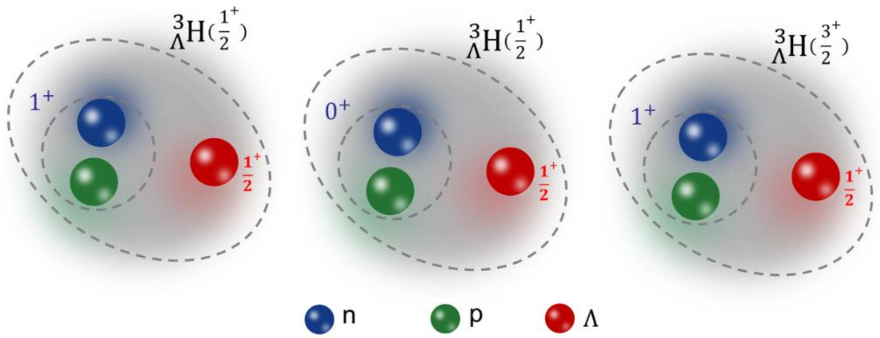


$$\hat{\rho}_{{}^3_\Lambda\mathrm{H}} \approx \mathrm{diag}\left[\frac{(1+\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)(1+\mathcal{P}_\Lambda)^2}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^2(1+\mathcal{P}_\Lambda)}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}\right]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

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

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

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



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!

Outline

I Background: spin polarization

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

III Decoding proton spin polarization

IV Spin alignment of unstable ^{4}Li

V Summary and outlook

Proton spin polarization

SU(6) quark coalescence model

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

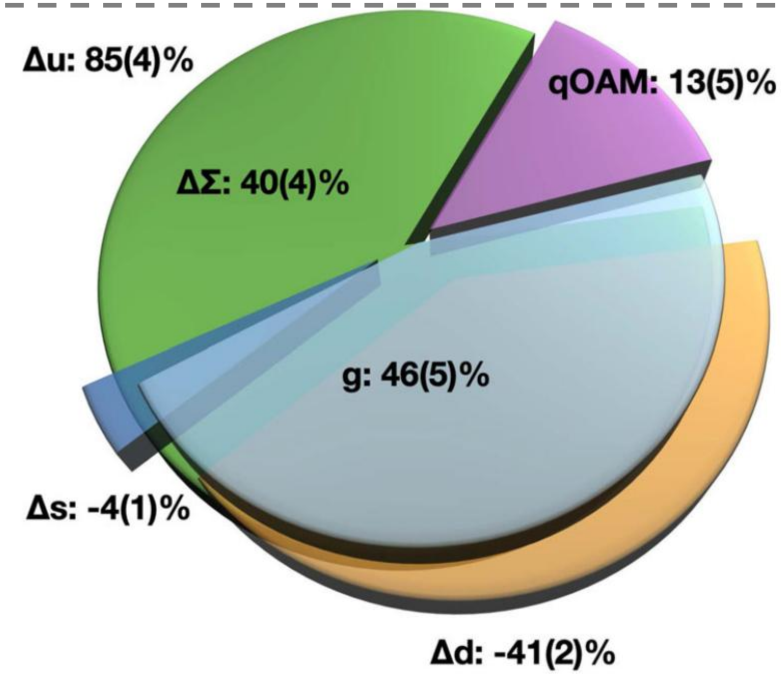
$$P_\Lambda = P_s$$

$$P_\Sigma = (4P_q - P_s - 3P_sP_q^2)/R_\Sigma, \quad R_\Sigma = 3 - 4P_qP_s + P_q^2;$$

$$P_\Xi = (4P_s - P_q - 3P_qP_s^2)/R_\Xi, \quad R_\Xi = 3 - 4P_qP_s + P_s^2;$$

$$P_\Omega = 2P_s(5 + P_s^2)/R_\Omega, \quad R_\Omega = 6(1 + P_s^2).$$

$$\mathcal{P}_p \approx (4\mathcal{P}_u - \mathcal{P}_d)/3$$



Frame-independent spin sum rule (Ji)

$$\frac{1}{2}\Delta\Sigma + L_q^z + J_g = \frac{\hbar}{2}$$

- $\Delta\Sigma/2$ and L_q^z (sum to J_q) are the quark helicity and OAM, respectively;
- Quark and gluon contributions J_q and J_g can be obtained from GPD moments;
- The sum rule also works for the transverse angular momentum in the IMF.

Infinite-momentum frame spin sum rule (Jaffe-Manohar)

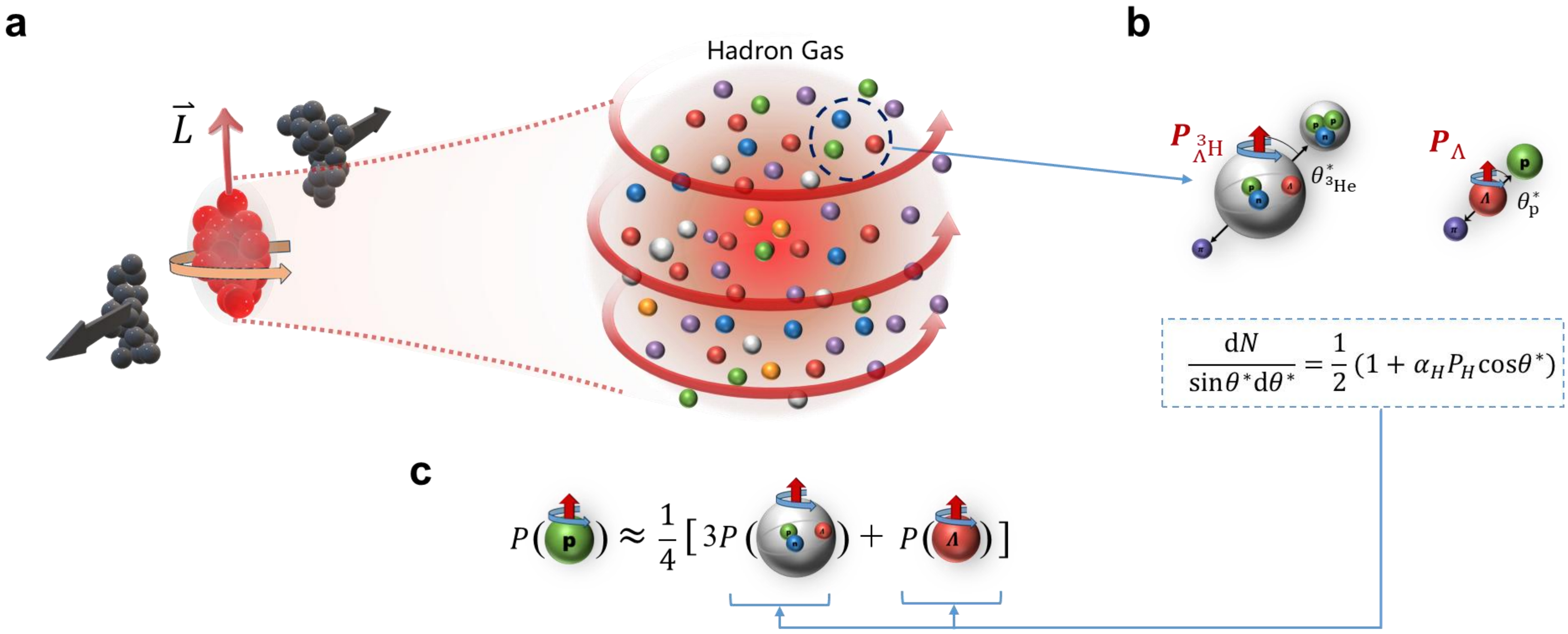
$$\frac{1}{2}\Delta\Sigma + \Delta G + \ell_q + \ell_g = \frac{\hbar}{2}$$

- ΔG is the gluon helicity, ℓ_q and ℓ_g are canonical OAM;
- All terms have partonic interpretations, ℓ_q and ℓ_g are twist-three quantities;
- ΔG is measurable from e.g. RHIC-spin and EIC; ℓ_q and ℓ_g can be extracted from GPDs.

X. D. Ji, F. Yuan, and Y. Zhao, Nature Rev. Phys. 3 (2021) 1, 27-38

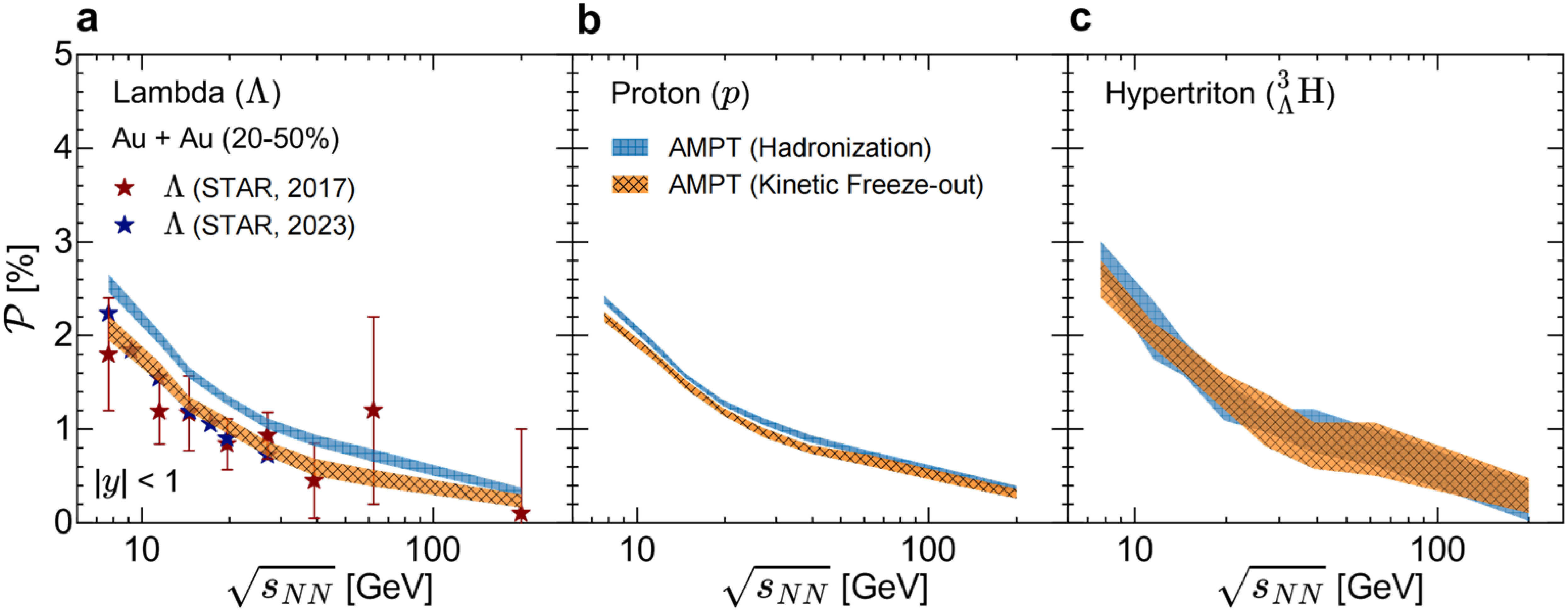
Decoding proton spin polarization from hypertriton production (13)

Dai-Neng Liu *et al.*, Phys. Rev. Res. 8, 033057 (2026)

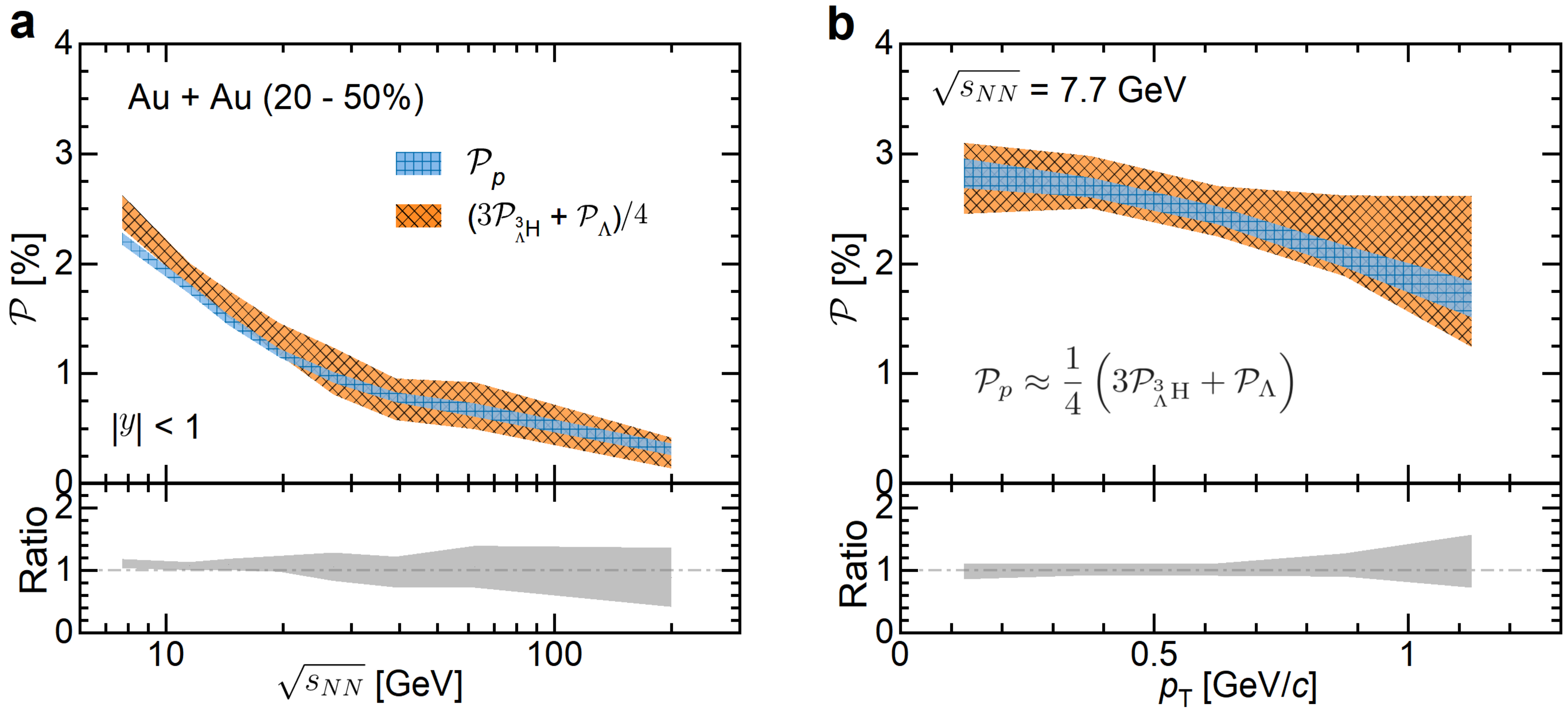


Energy dependence

Dai-Neng Liu *et al.*, Phys. Rev. Res. 8, 033057 (2026)



Decoding proton spin polarization



Proton spin polarization can be decoded from polarizations of hypertriton and Lambda hyperon

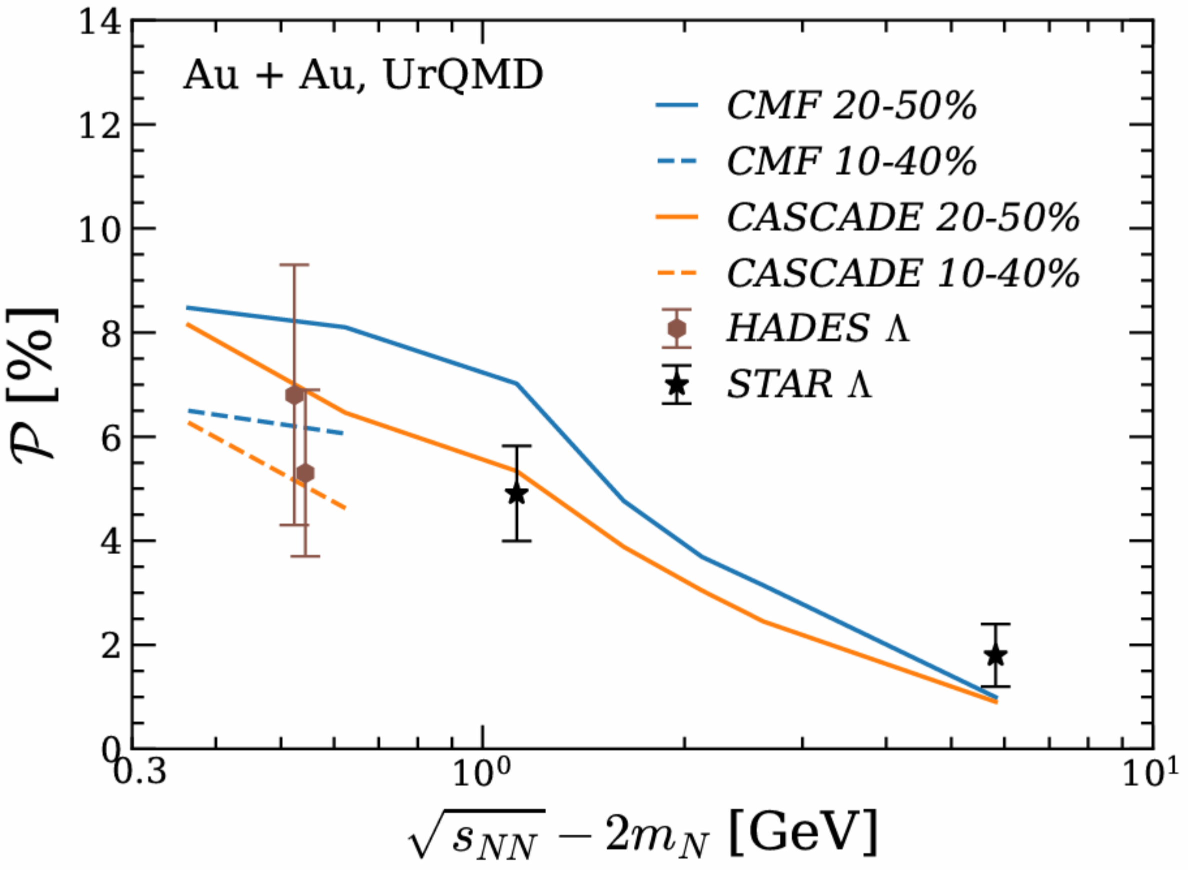
A direct observation of proton spin polarization requires a baryon polarimeter

(see Y. T. Liang et al., Phys. Rev. D 112 (2025) 3, L031502)

Lower collision energies (high baryon densities)

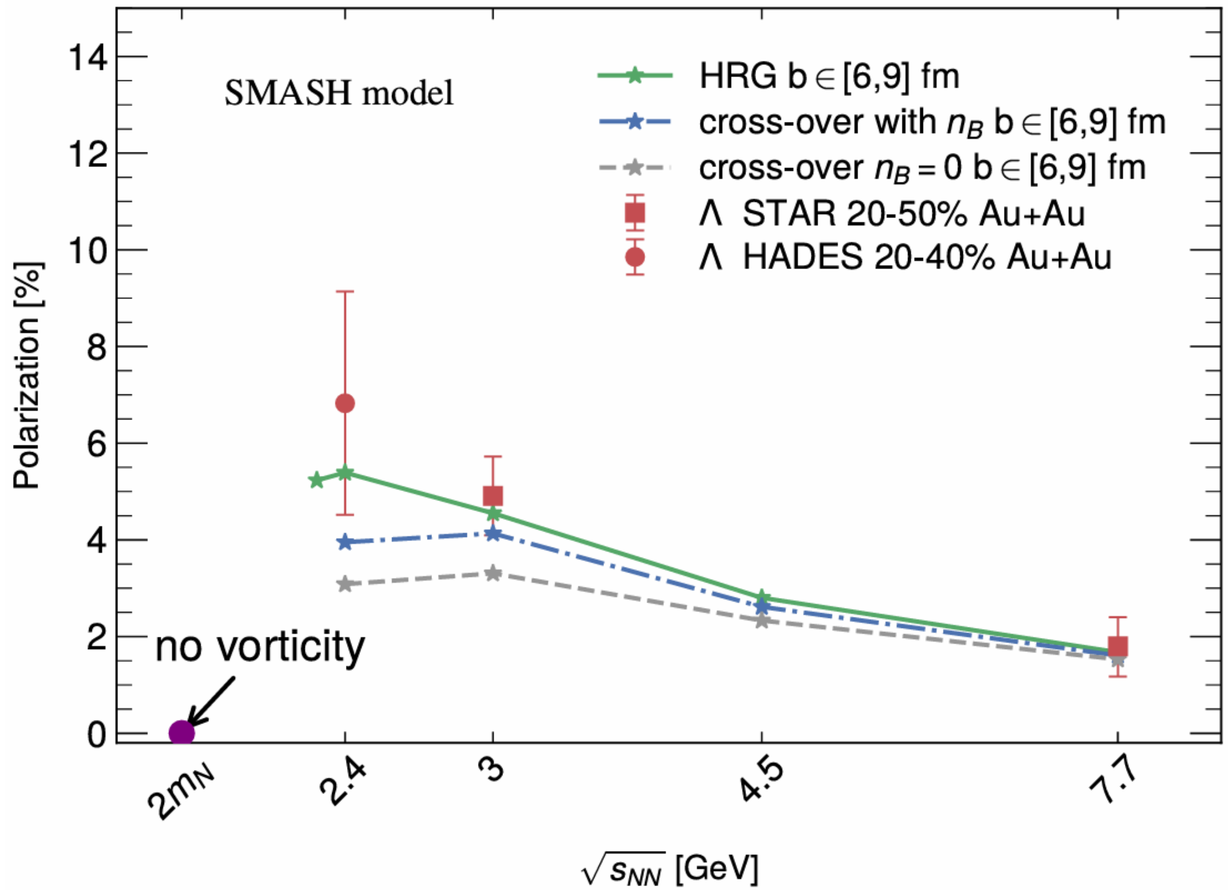
See talk by Dai-Neng Liu (刘代能)（Jul. 29th）

No peak at >2.24 GeV



Dai-Neng Liu *et al.*, arXiv: 2606.13333 (2026)

Small peaks at 2.4-3 GeV



C. Yi *et al.*, arXiv:2603.27521 (2026)

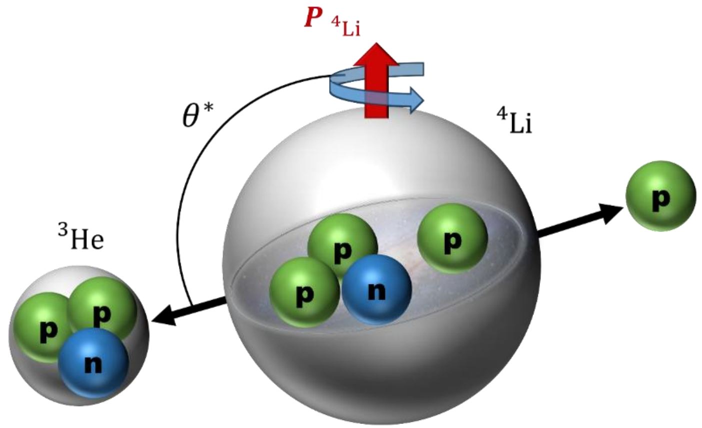
$$\mathcal{P} \approx \frac{w}{2T} \approx \frac{\frac{1}{2}|\nabla \times \mathbf{v}|}{2 \times (\frac{1}{3} m \mathbf{v}^2)} \sim \frac{1}{v}$$

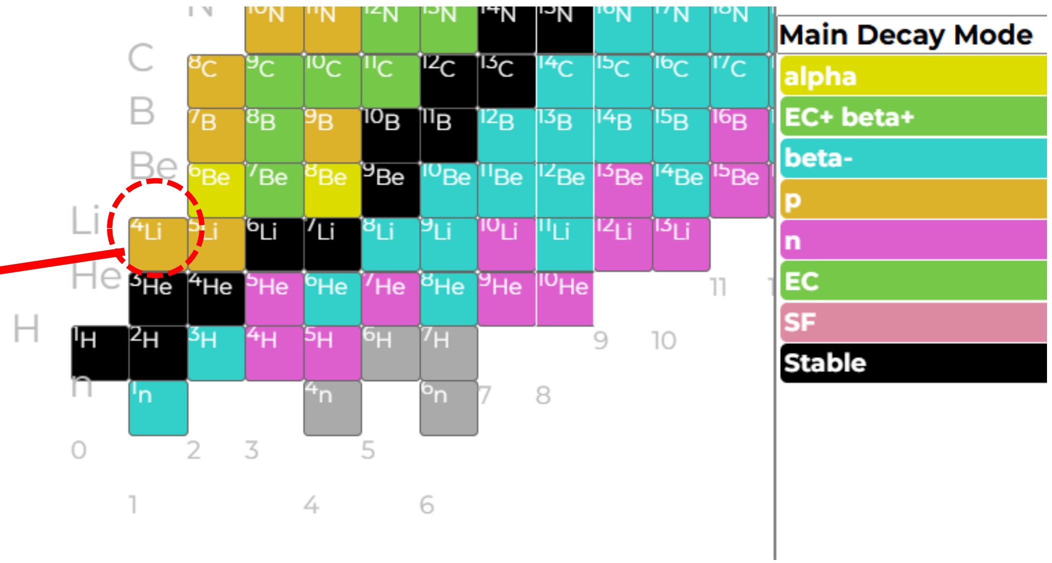
continue to increase as decreasing beam energy

Outline

Spin alignment of Li-4

Yun-Peng Zheng *et al.*, Phys. Rev. C 113, 054906 (2026)





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

Average:

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

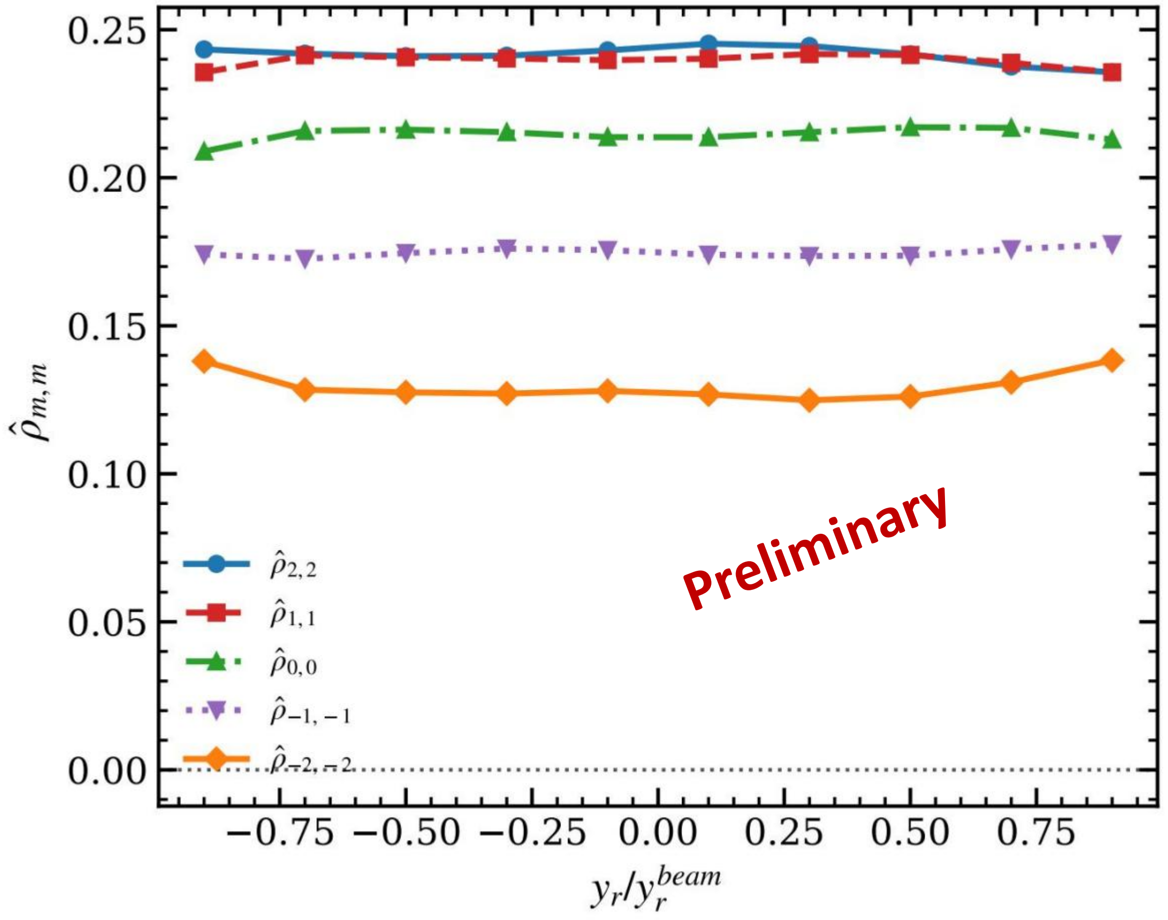
$$\approx \frac{1}{2}\left[1 - \frac{7}{30}\left(\mathcal{P}_N^2 + 4\mathcal{P}_N\mathcal{P}_L + \mathcal{P}_L^2\right)(3\cos^2\theta^* - 1)\right].$$

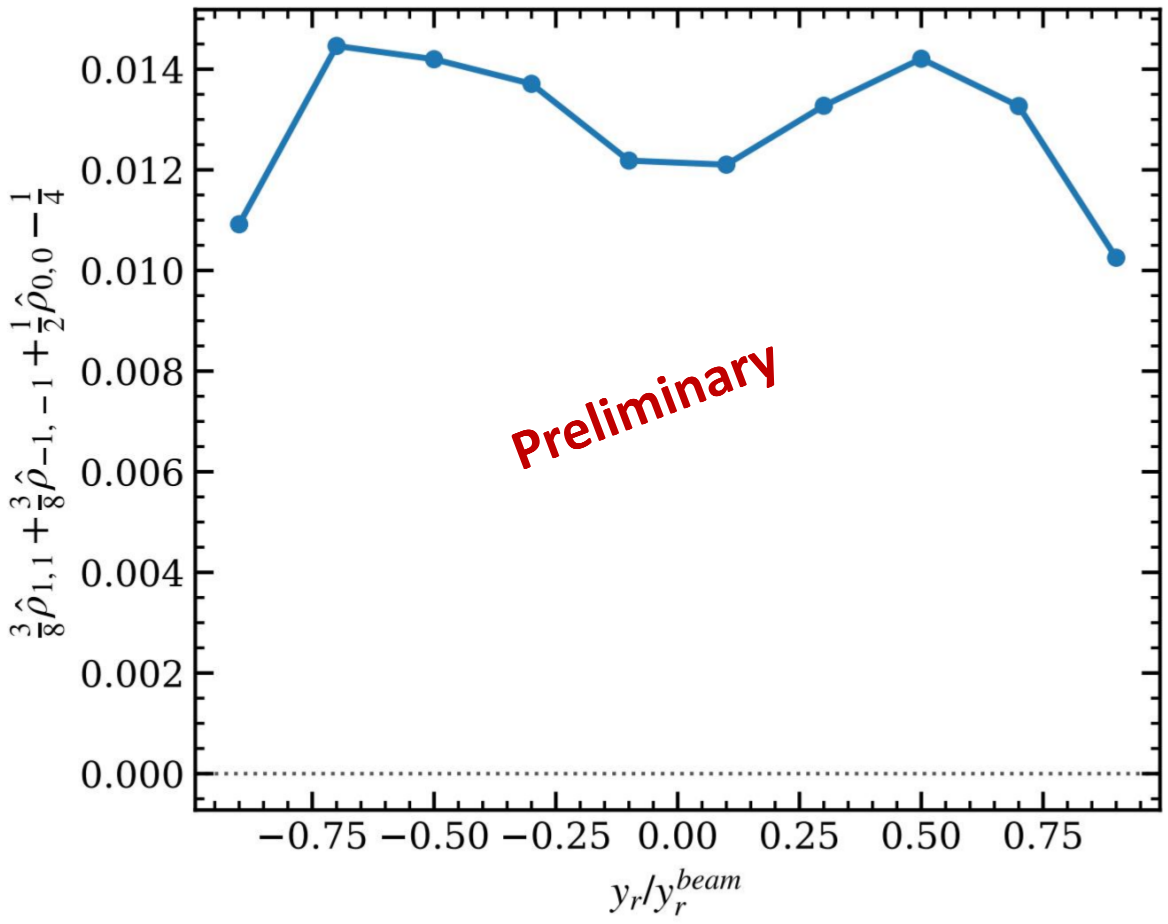
$$\mathcal{P}_N = \frac{w}{2T}$$

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

Spin alignment of Li-4

See talk by Yun-Peng Zheng (郑云鹏)（Jul. 28th）



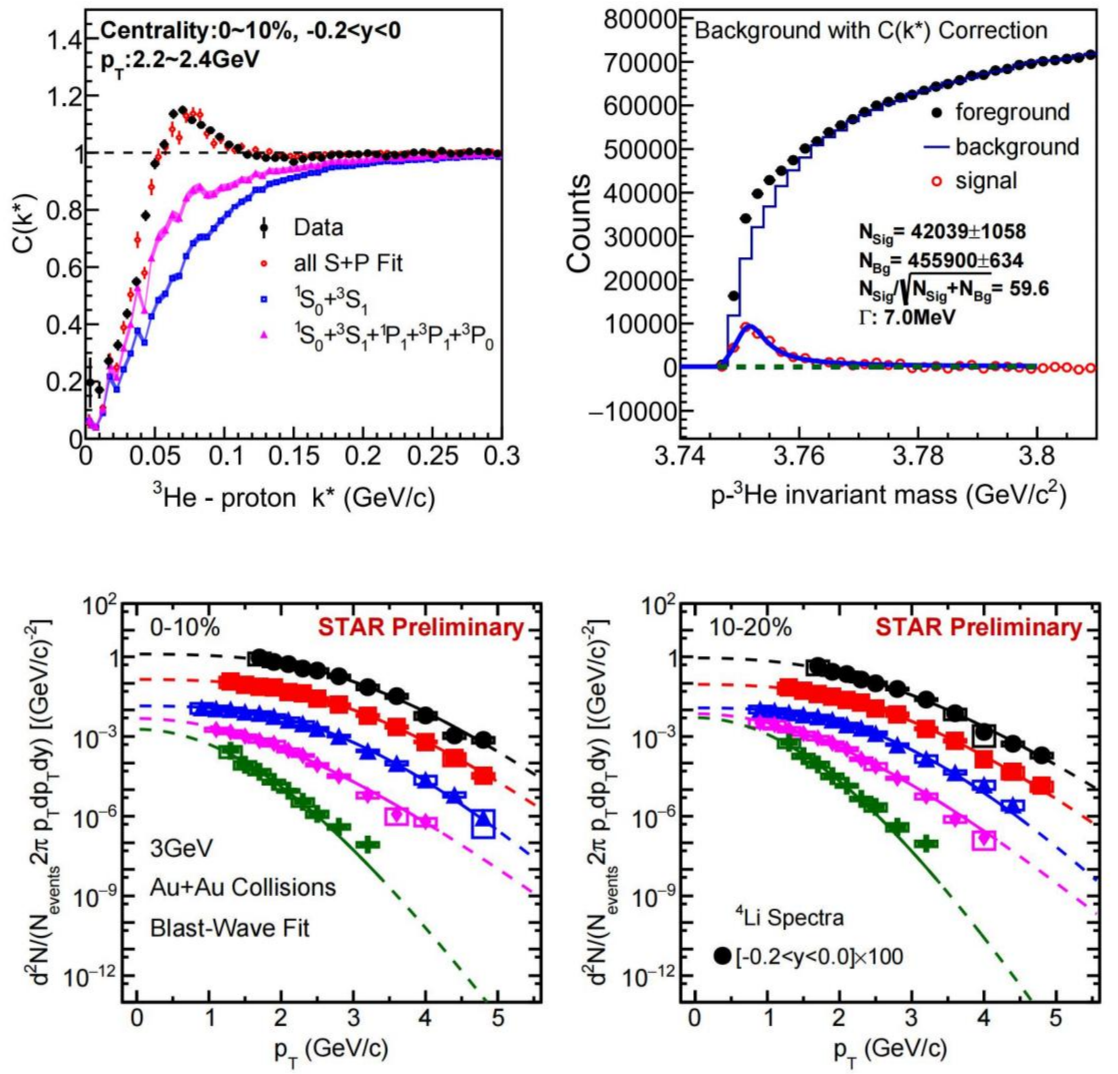


Large spin alignment at the order of 0.01!

Recent experimental progress

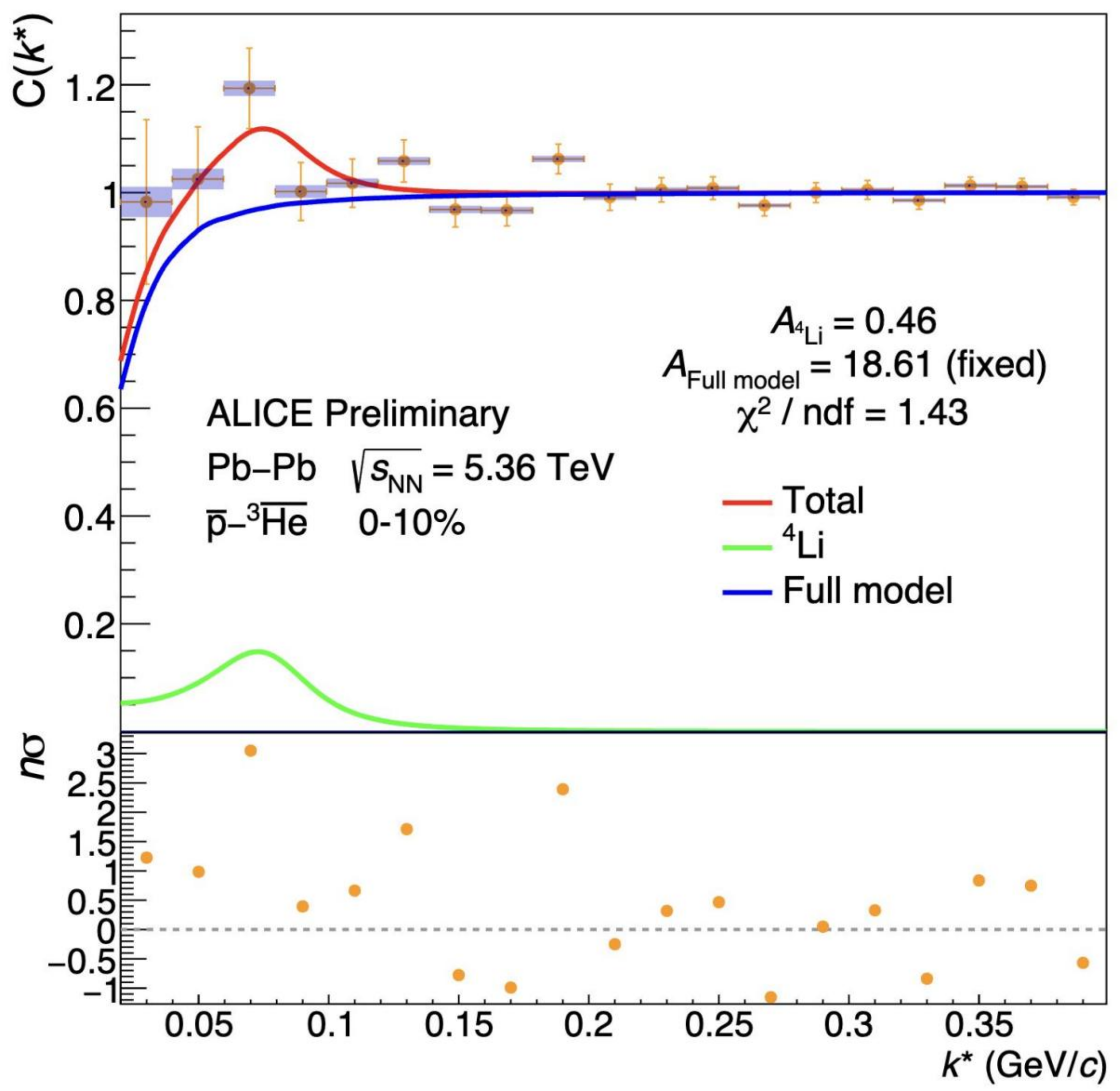
STAR Preliminary (J. L. Wu, C. L. Hu, G. N. Xie et al.)

SQM2026



ALICE Preliminary

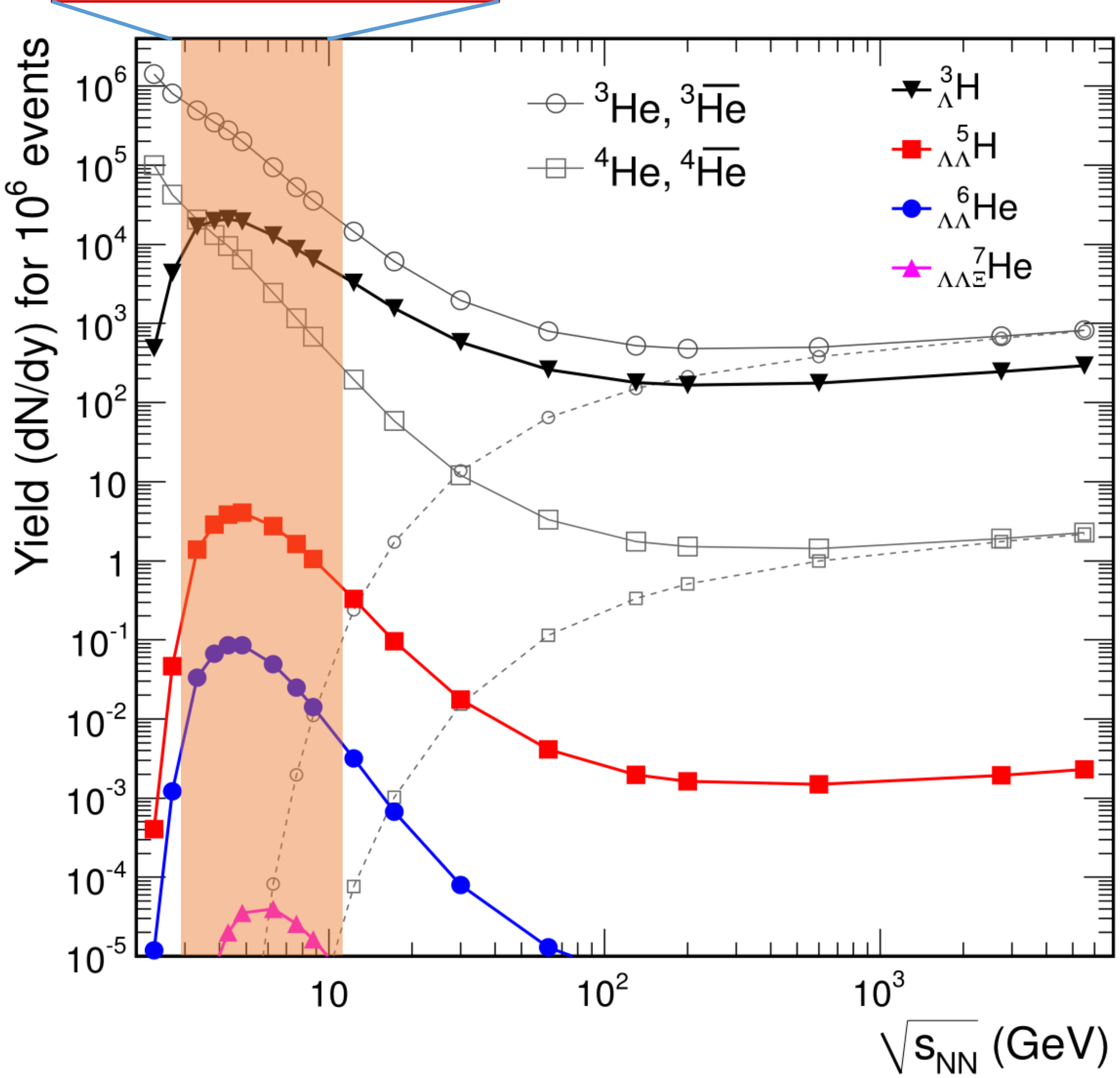
SQM2026



Summary and outlook

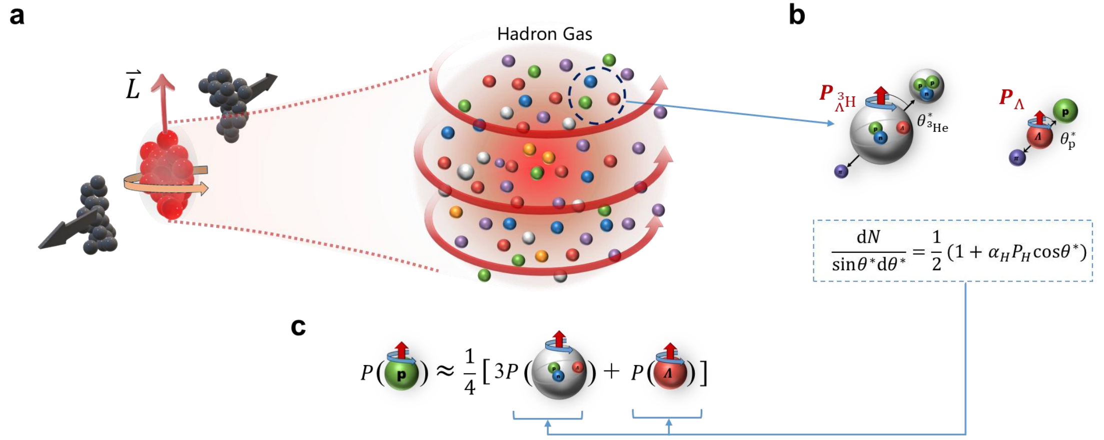
A. Andronic et al., Phys. Lett. B 697, 203-207 (2011)

High baryon densities

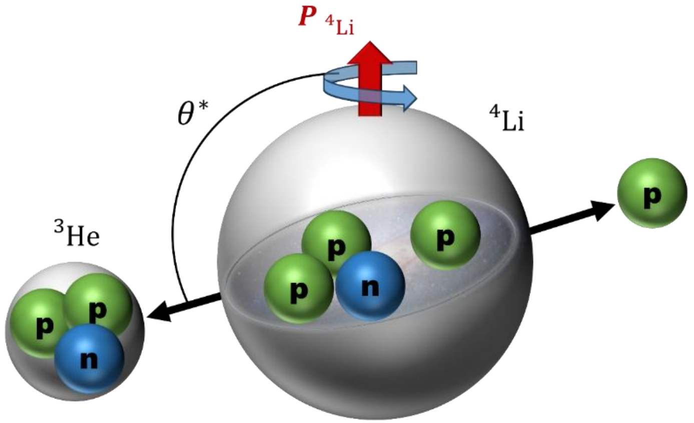


Many interesting physics

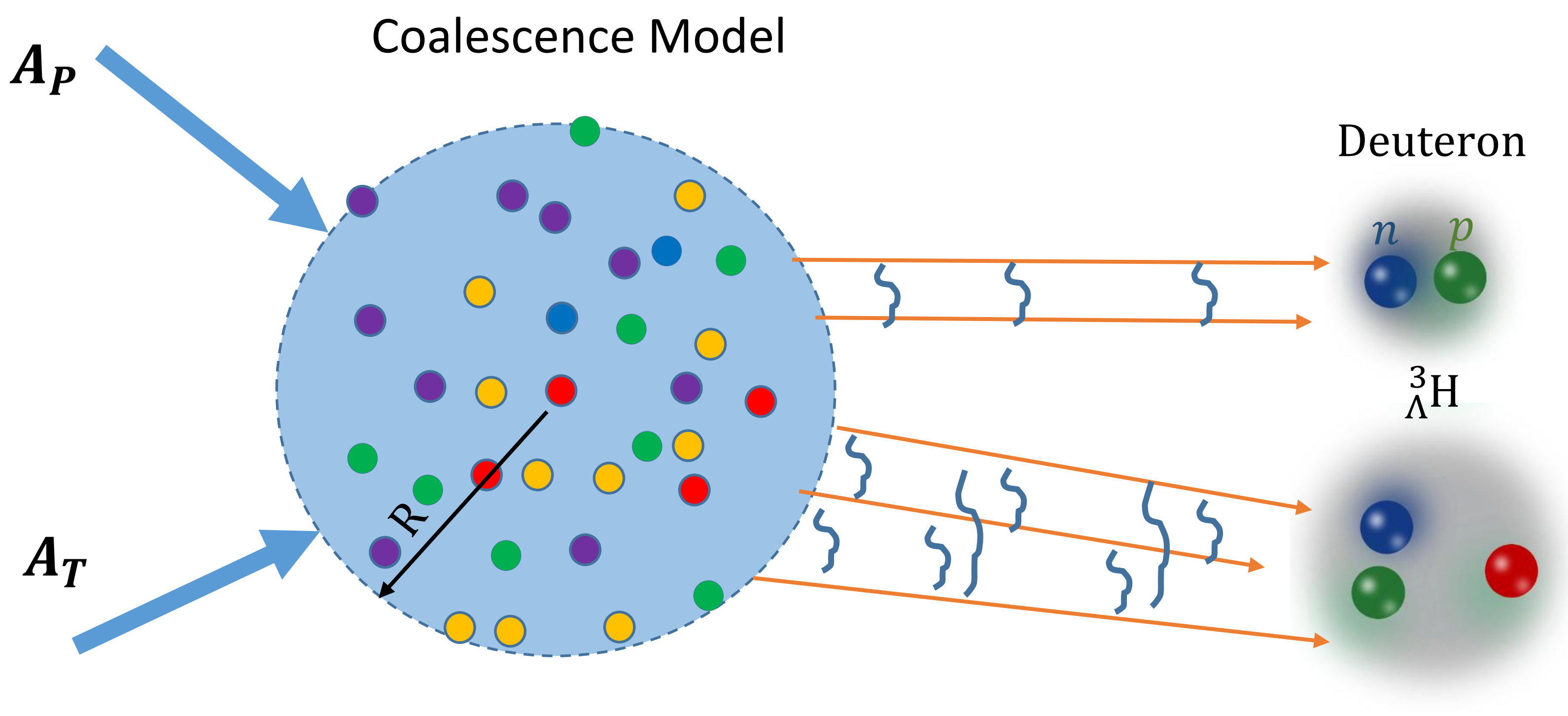
J^π	Structure	Decay mode	$dN/(\sin\theta^* d\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	${}^3_\Lambda\text{H} \to \pi^- + {}^3\text{He}$	$\frac{1}{2}[1 - (1/2.58)\alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*]$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(0^+)$	${}^3_\Lambda\text{H}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



- ➢ **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)**



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)