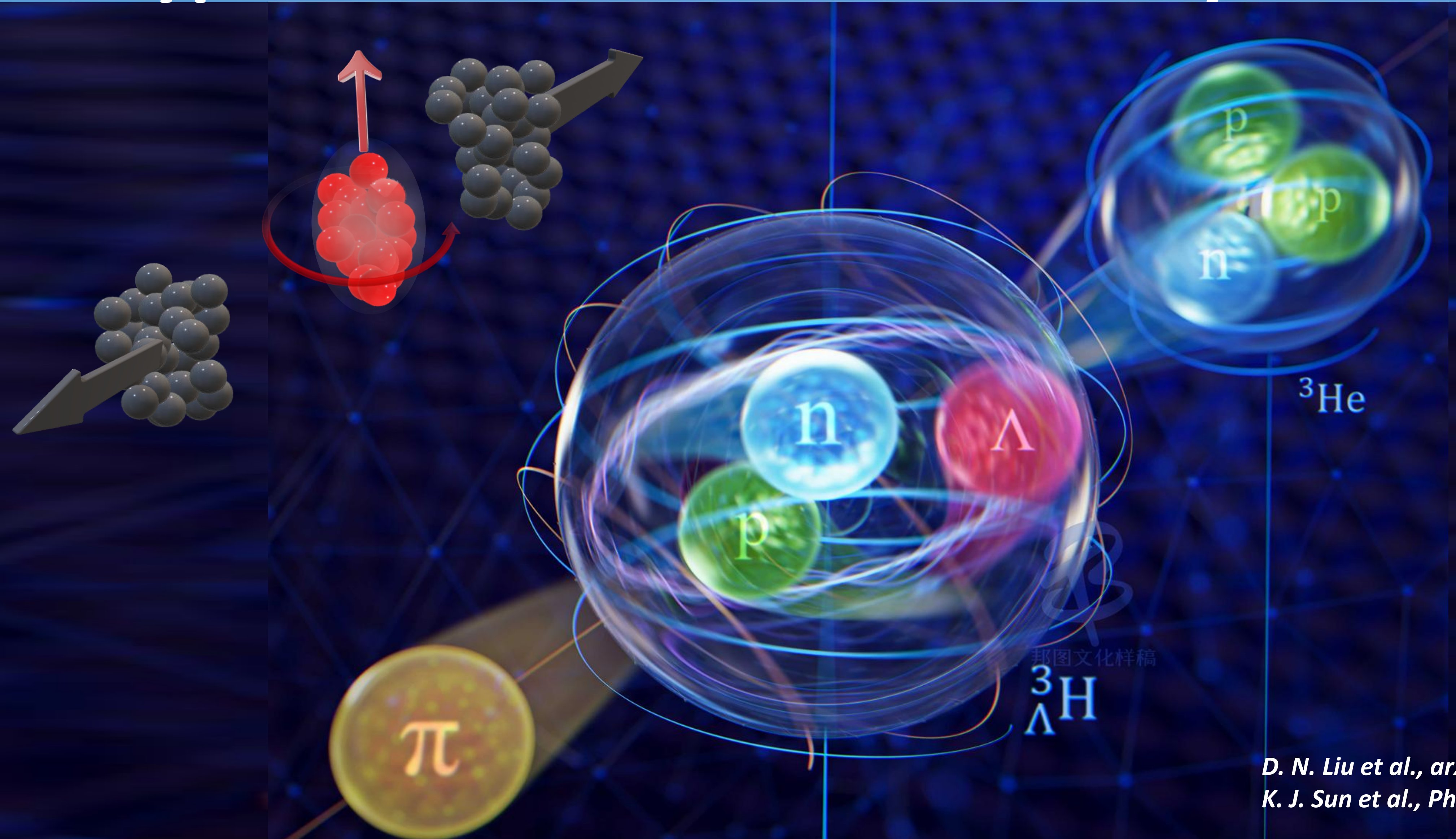
Revealing Proton Spin Polarization via Hypertriton Production in Heavy-Ion Collisions



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2025-08-27
北京

D. N. Liu et al., arXiv:2508. 12193 (2025)
K. J. Sun et al., Phys. Rev. Lett. 134, 022301 (2025)

缘起

The 7th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

Jul 15 – 19, 2023

I. Background

重离子碰撞中超子的自旋极化效应 (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.

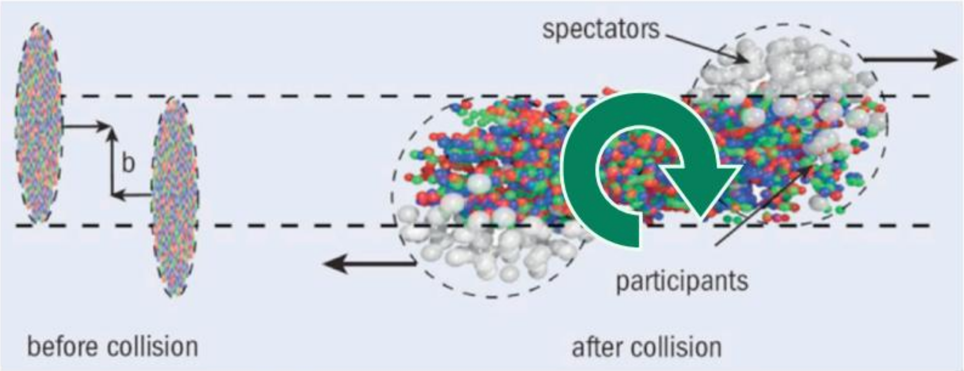
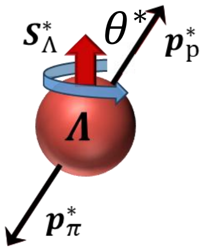


figure: M. Lisa, talk @ “Strangeness in Quark Matter 2016”

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



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

Decay constant

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

The ideal relativistic spinning gas: Polarization and spectra

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

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

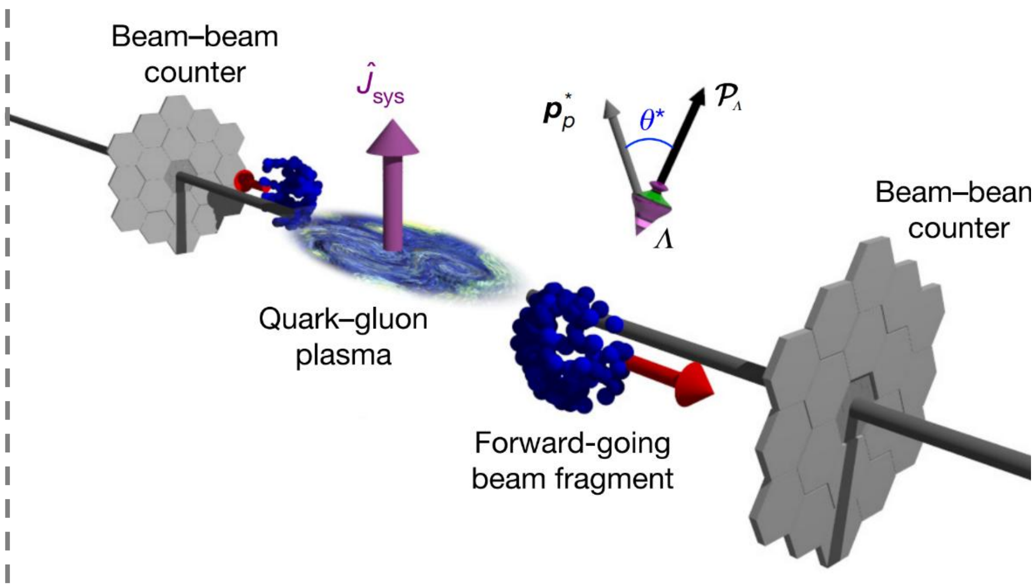
$$\mathbf{\Pi} = \mathrm{tr}[\widehat{\mathbf{S}}\widehat{\rho}_\omega(p)] = \frac{\sum_{n=-S}^{S} n e^{n\omega/T}}{\sum_{n=-S}^{S} e^{n\omega/T}}\hat{\boldsymbol{\omega}}$$

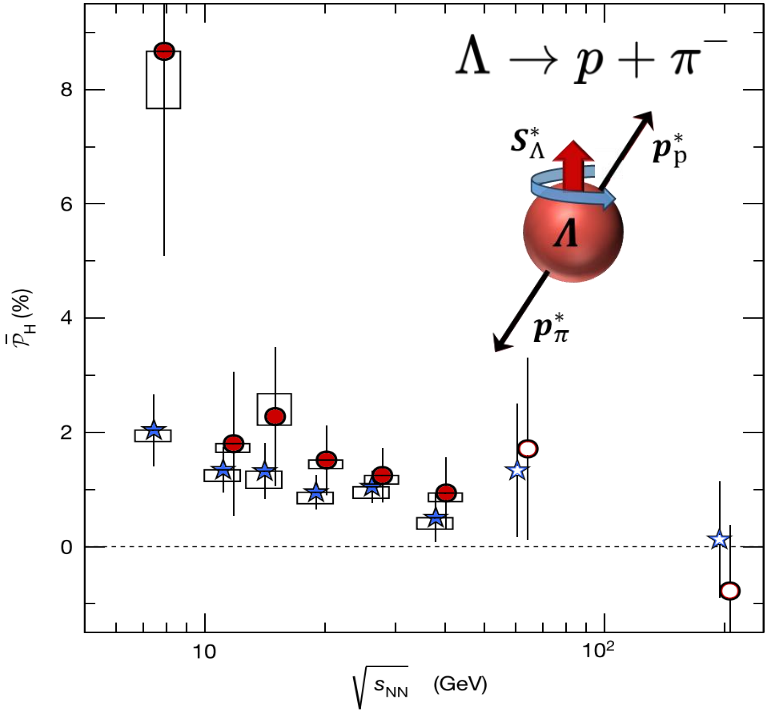
Vorticity ⟵ **Spin polarization**

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

重离子碰撞中超子的自旋极化效应 (2)

STAR, Nature 548, 62 (2017)





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

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

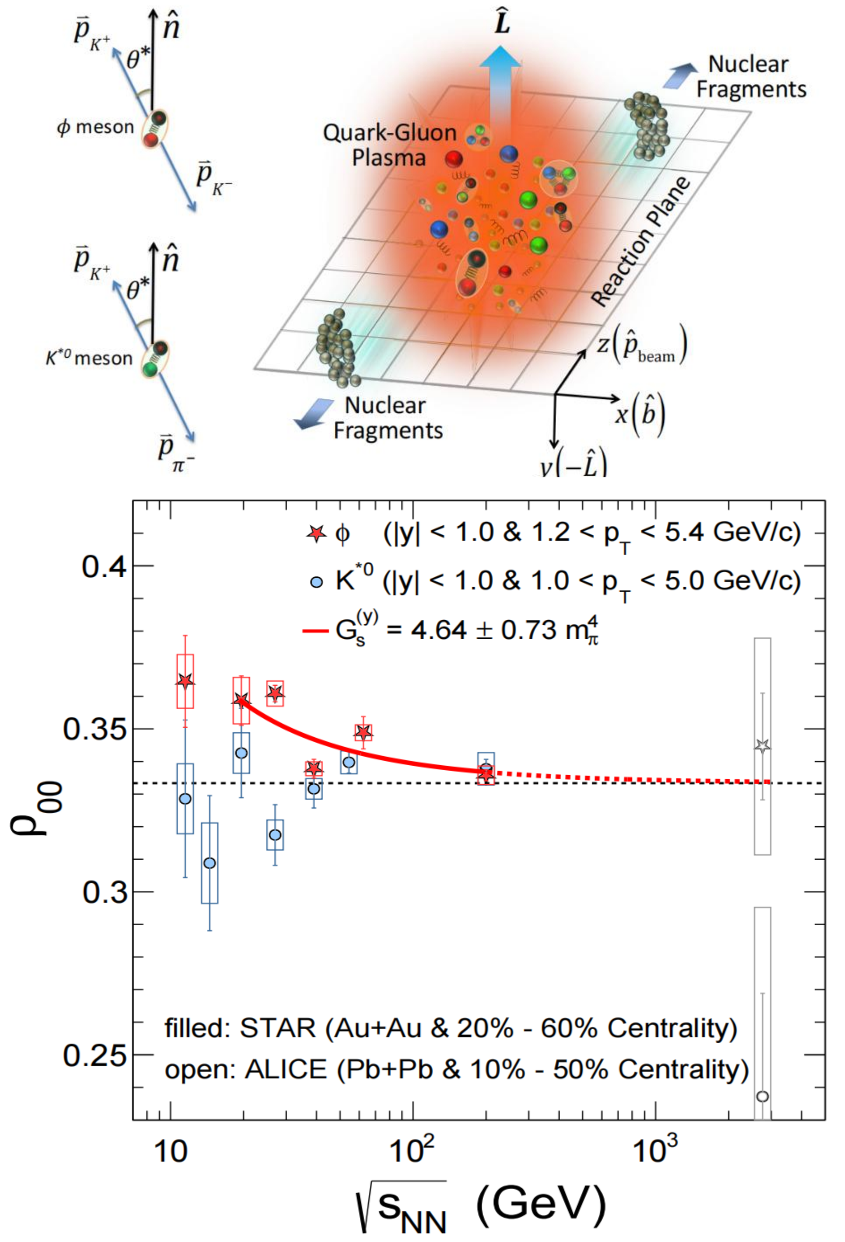
$$\omega \approx k_B T(\overline{\mathcal{P}}_\Lambda + \overline{\mathcal{P}}_{\bar{\Lambda}})/\hbar \approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$$

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

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

重离子碰撞中矢量介子的自旋排列效应 (3)

STAR, Nature 614, 7947 (2023)



Spin alignment of vector 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

In-medium meson spectral property

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

F. Li and S. Liu, arXiv:2206.11890

Local spin density fluctuation

Kun Xu and M. Huang, Phys. Rev. D 110, 094034 (2024)

Gluon polarization

H. A. Ahmed, Y. Chen, and M. Huang, Phys. Rev. D 111, 086006 (2025)

质子自旋极化 (4)

SU(6) quark coalescence model

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

$$P_\Lambda = P_s$$

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

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

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

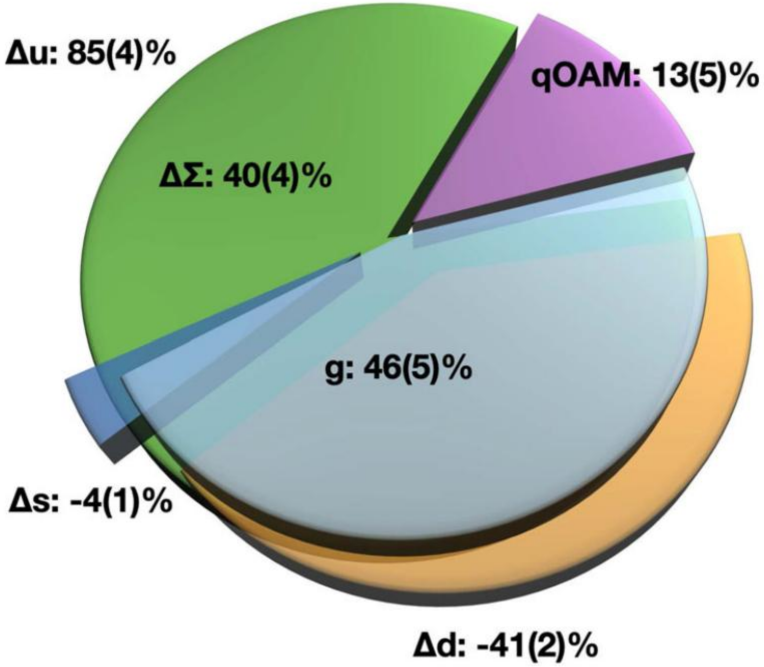
Hyperon polarization is dominated by the spin polarization of the strange quark

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

Proton spin polarization is a good probe to the spin dynamics of light quarks

质子自旋困惑(proton spin puzzle)

LQCD tells us that only about 40% of proton spin comes from quarks



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)

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

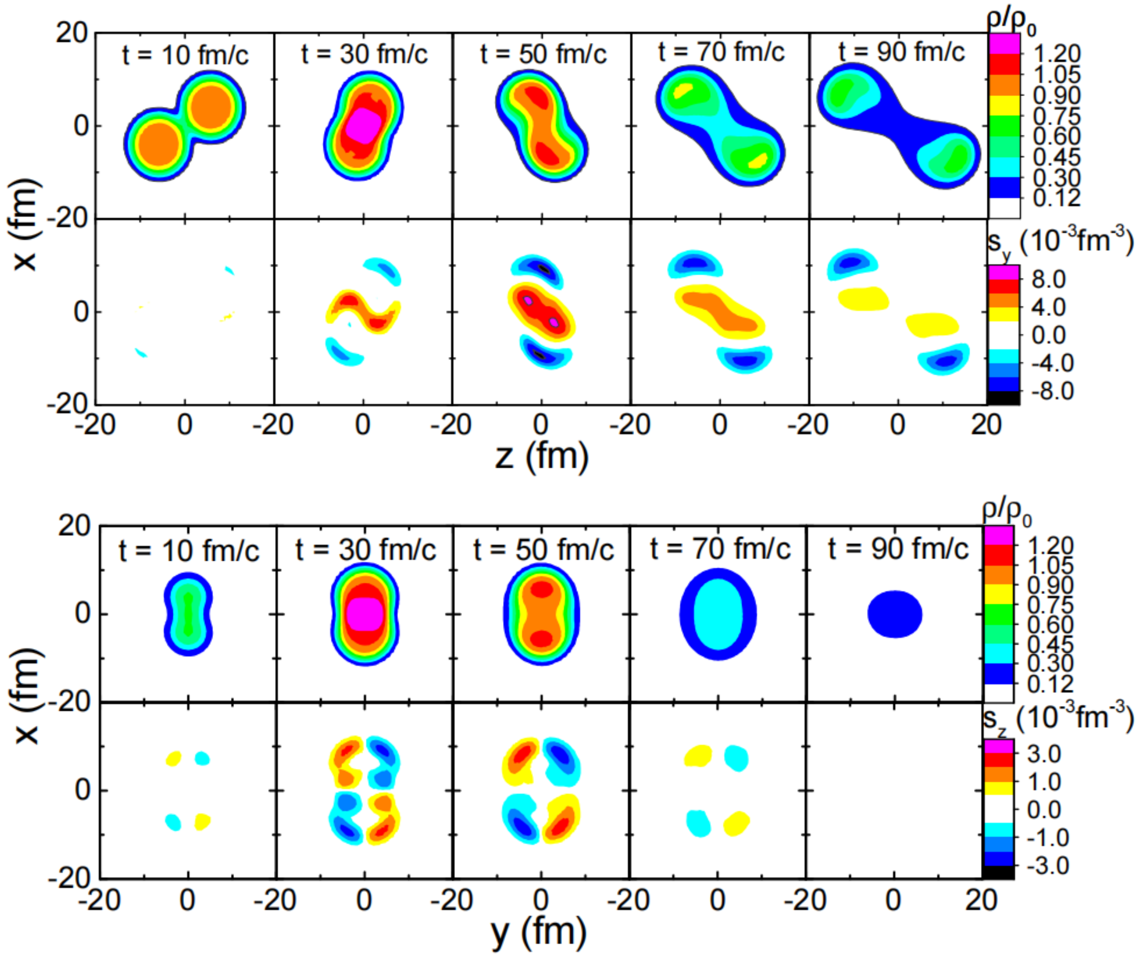
- ΔG is the gluon helicity, ℓ_q and ℓ_g are canonical OAM;
- All terms have partonic interpretations, ℓ_q and ℓ_g are twist-three quantities;
- ΔG is measurable from e.g. RHIC-spin and EIC; ℓ_q and ℓ_g can be extracted from GPDs.

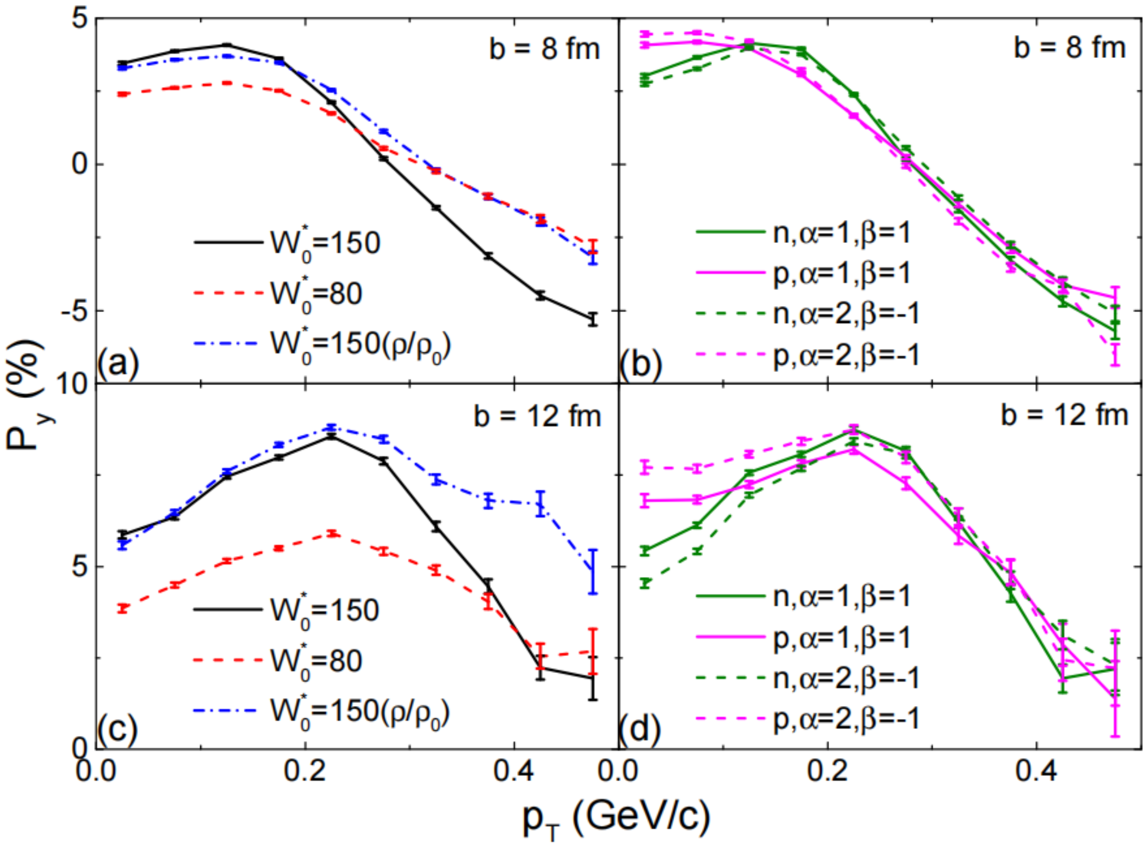
X. D. Ji, F. Yuan, and Y. Zhao, Nature Rev. Phys. 3 (2021) 1, 27-38

Probing properties of nuclear spin-orbit interaction with nucleon spin polarization in intermediate-energy heavy-ion collisions

Jun Xu[1,*]

[1]School of Physics Science and Engineering, Tongji University, Shanghai 200092, China





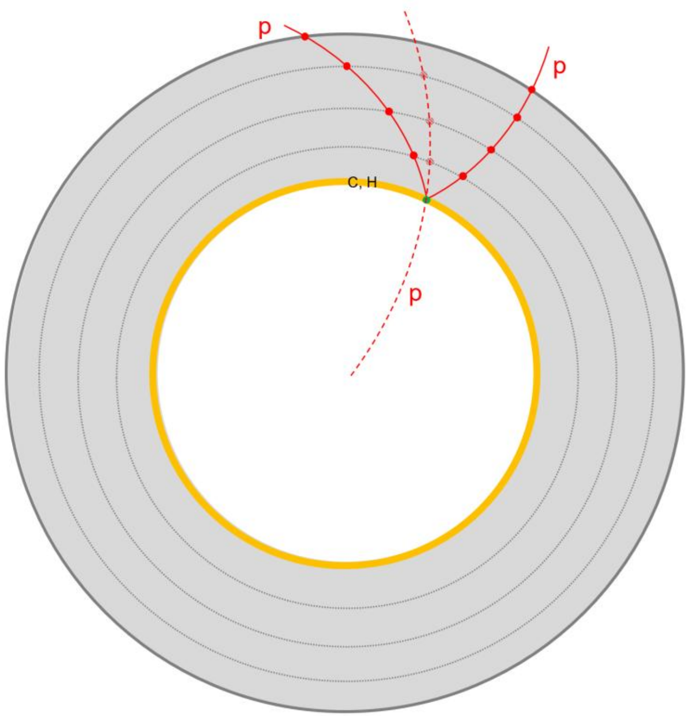
质子自旋极化测量难点

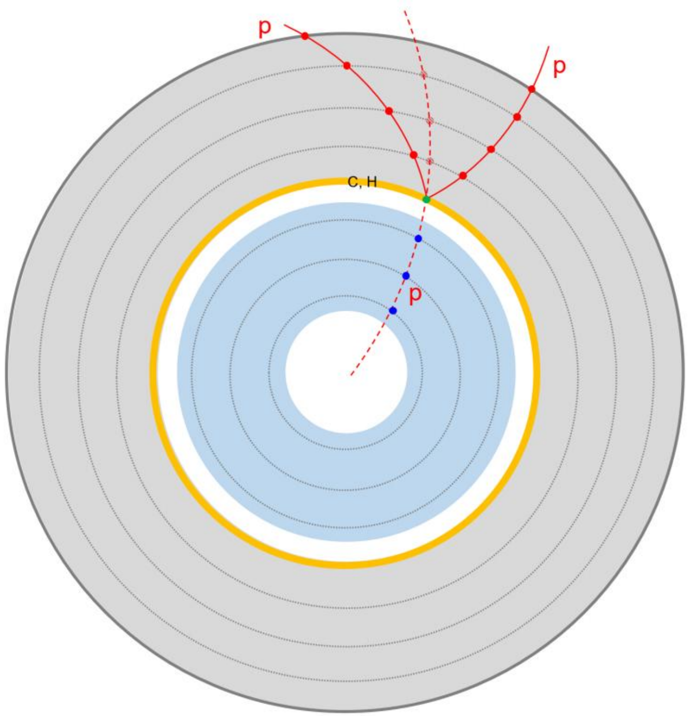
Proton is a stable particle, making conventional polarization measurement based on particle decay infeasible!

How to determine nucleon polarization at existing collider experiments?

Yu-Tie Liang,[1, 2, *] Xiao-Rong Lv,[1] Andrzej Kupsc,[3, 4, †] Boxing Gou,[1, 2] and Hai-Bo Li[5, 2, ‡]

arXiv:2501.02439





II. A New Idea

从强子极化到（反物质）超核的自旋极化 (8)

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

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

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

…

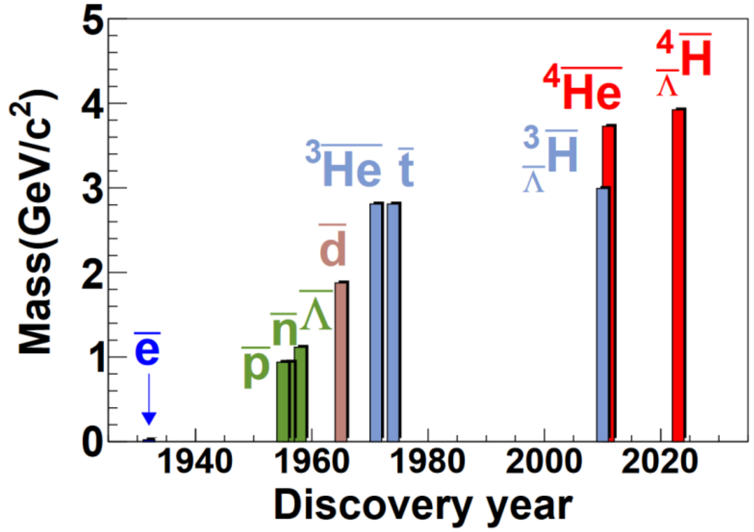
Unstable (anti-)(hyper-)nuclei

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

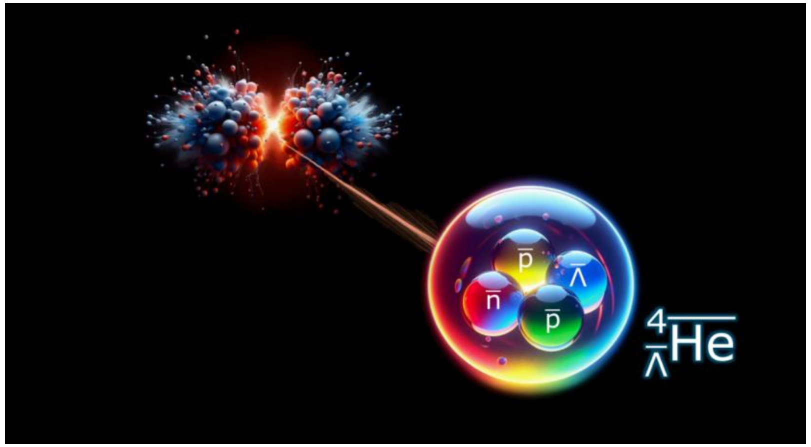
$^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}(\bar{n}\bar{p}\bar{\Lambda})$ $^{4}\overline{\mathrm{Li}}(\bar{n}\bar{p}\bar{p}\bar{p})$

…

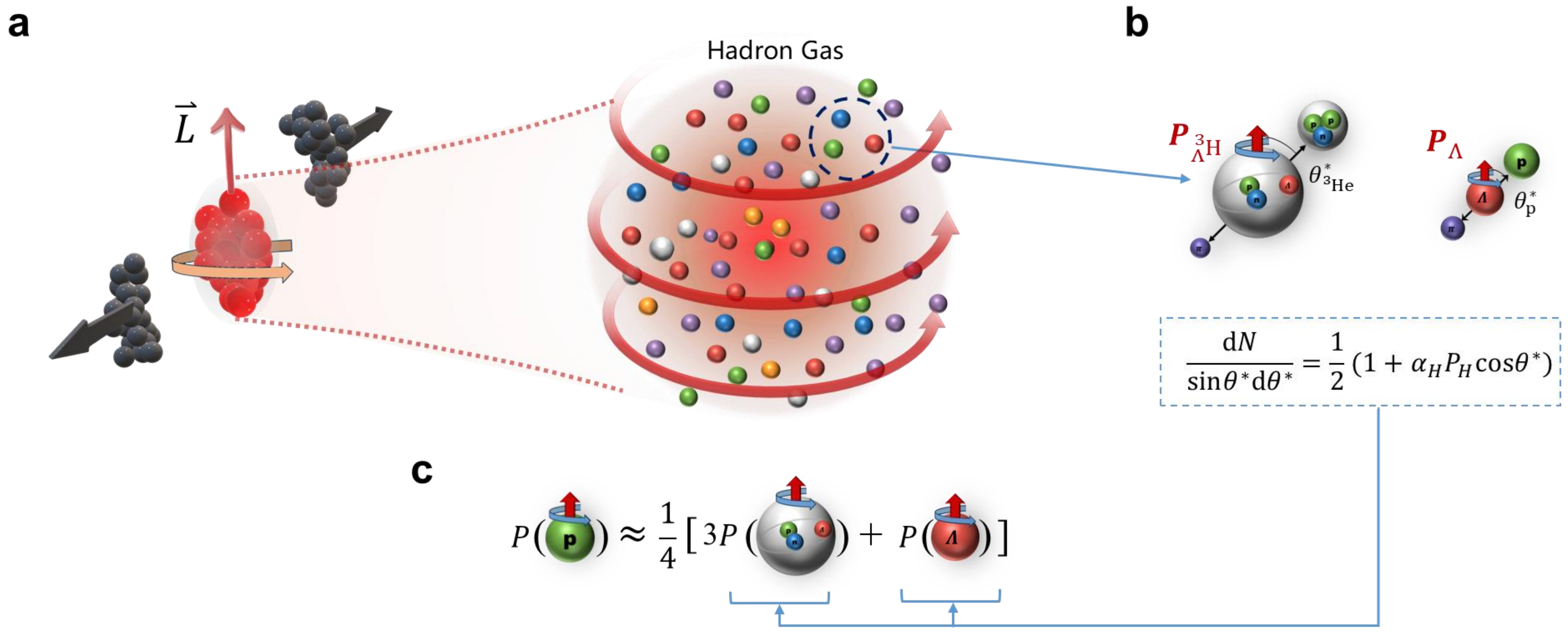
STAR, *Nature* 632, 8027 (2024)



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

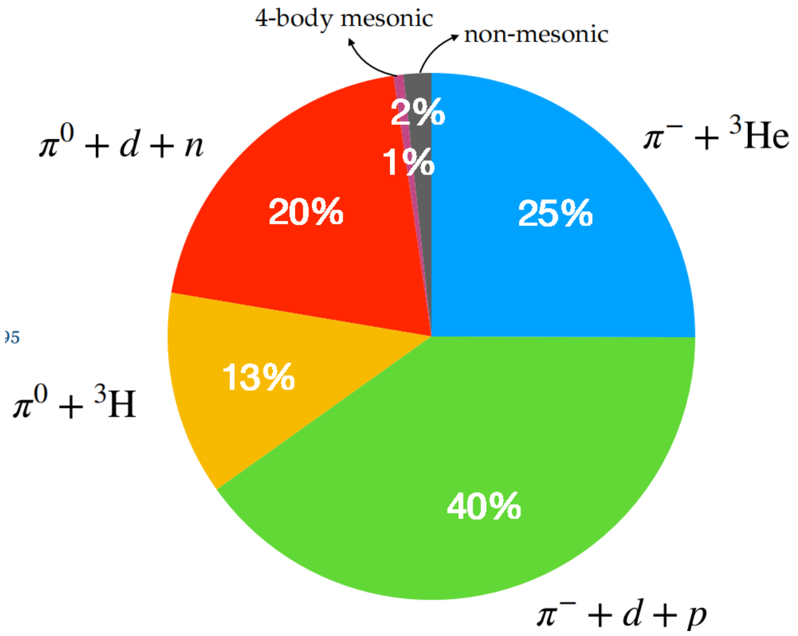


利用超核测量质子自旋极化



利用超核测量质子自旋极化

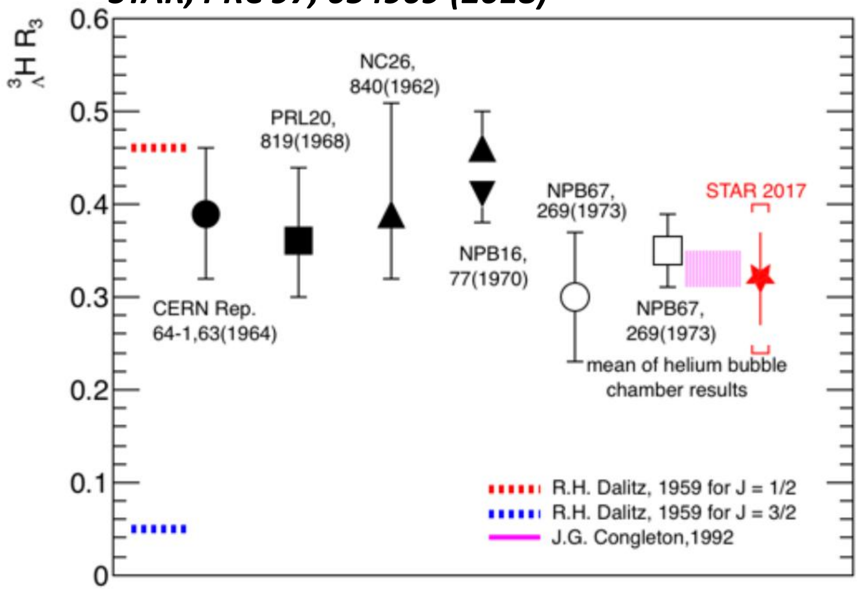
$$
\begin{aligned}
&{}^3_\Lambda\mathrm{H} \mapsto \pi^- + {}^3\mathrm{He}, && {}^3_\Lambda\mathrm{H} \mapsto \pi^0 + {}^3\mathrm{H},\\
&{}^3_\Lambda\mathrm{H} \mapsto \pi^- + d + p, && {}^3_\Lambda\mathrm{H} \mapsto \pi^0 + d + n,\\
&{}^3_\Lambda\mathrm{H} \mapsto \pi^- + p + n + p, && {}^3_\Lambda\mathrm{H}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



Relative branching ratio:

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

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	$1/2^+$	$\overline{\mathbf{35}}$	-
${}^3_\Lambda$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

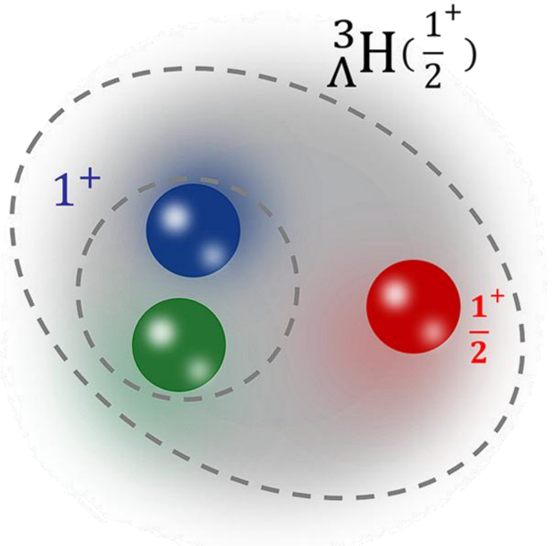
利用超核测量质子自旋极化

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

➢ Spin wavefunction

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

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



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

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

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

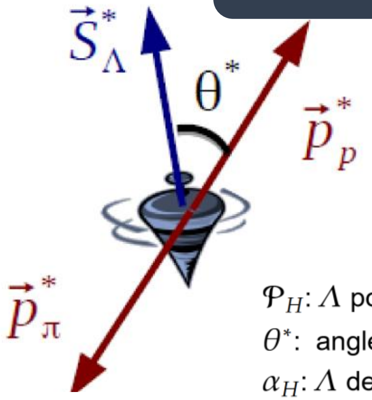
$$
\begin{aligned}
\mathcal{P}_{{}^3_\Lambda\mathrm{H}} &\approx \frac{\frac{2}{3}\mathcal{P}_n + \frac{2}{3}\mathcal{P}_p - \frac{1}{3}\mathcal{P}_\Lambda - \mathcal{P}_n\mathcal{P}_p\mathcal{P}_\Lambda}{1 - \frac{2}{3}(\mathcal{P}_n + \mathcal{P}_p)\mathcal{P}_\Lambda + \frac{1}{3}\mathcal{P}_n\mathcal{P}_p} \\
&\approx \frac{2}{3}\mathcal{P}_n + \frac{2}{3}\mathcal{P}_p - \frac{1}{3}\mathcal{P}_\Lambda \\
&\approx \frac{4}{3}\mathcal{P}_N - \frac{1}{3}\mathcal{P}_\Lambda
\end{aligned}
$$

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

超子和超核极化测量 (12)

Parity-violating weak decay

Λ hyperons



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

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

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

$\mathcal{P}_H$: Λ polarization

θ^*: angle between proton momentum and 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

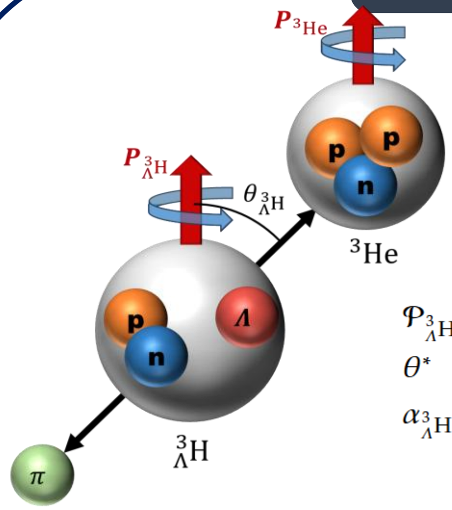
$$T(\Lambda \rightarrow \pi^- + p) = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} T_s + T_p\cos\theta^*_p & T_p\sin\theta^*_p e^{i\phi^*_p} \\ T_p\sin\theta^*_p e^{-i\phi^*_p} & T_s - T_p\cos\theta^*_p \end{pmatrix}$$

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 and $^3_\Lambda\mathrm{H}$ rest frame

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

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

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

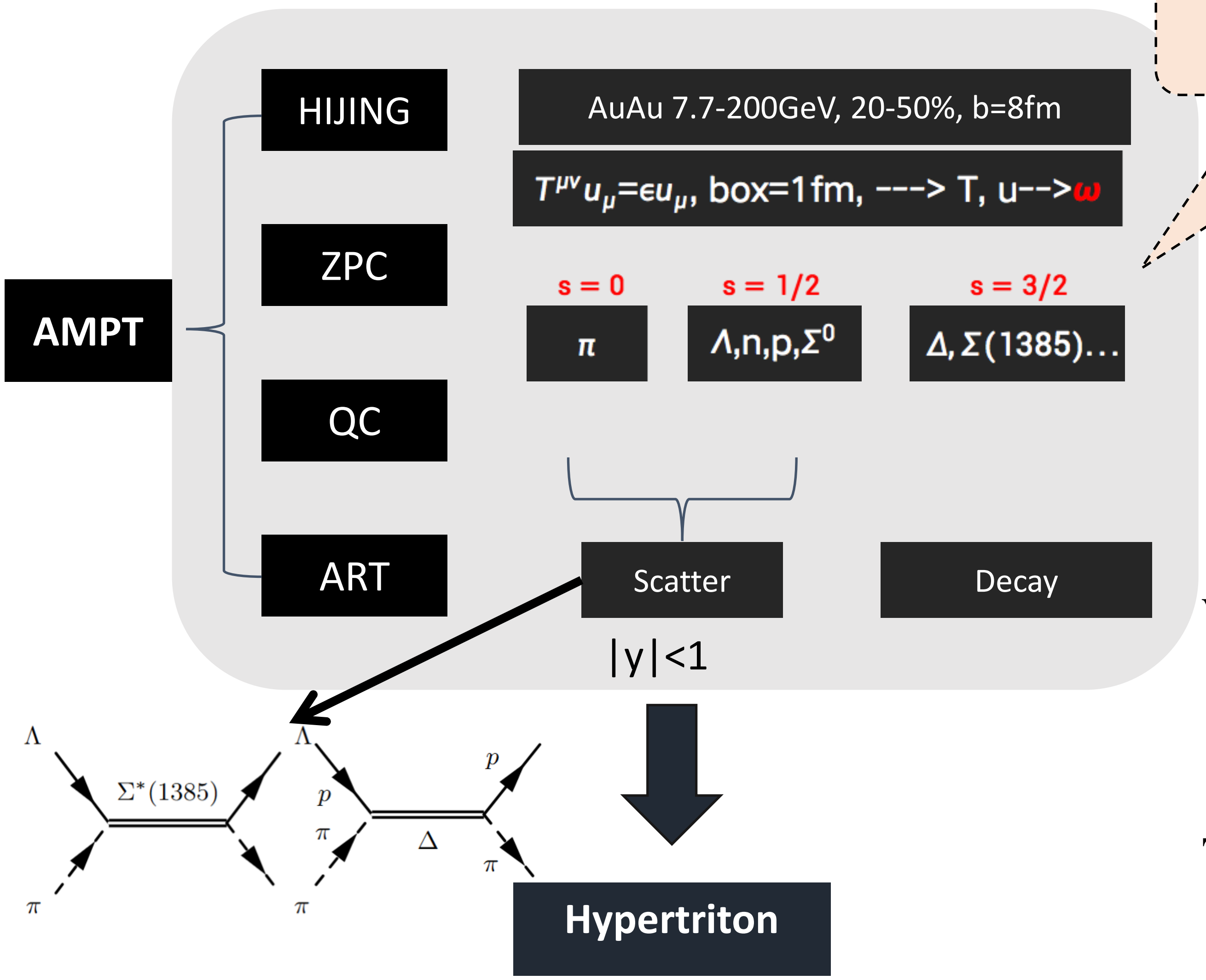
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_{^3_\Lambda\mathrm{H}}\mathcal{P}_{^3_\Lambda\mathrm{H}}\cos\theta^*\right)$$

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

Sign flip !

III. Model Validation

模型设置-强子化阶段



Thermal vorticity

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

Eigen equation

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

Fiuld energy-momentum tensor

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

Velocity field

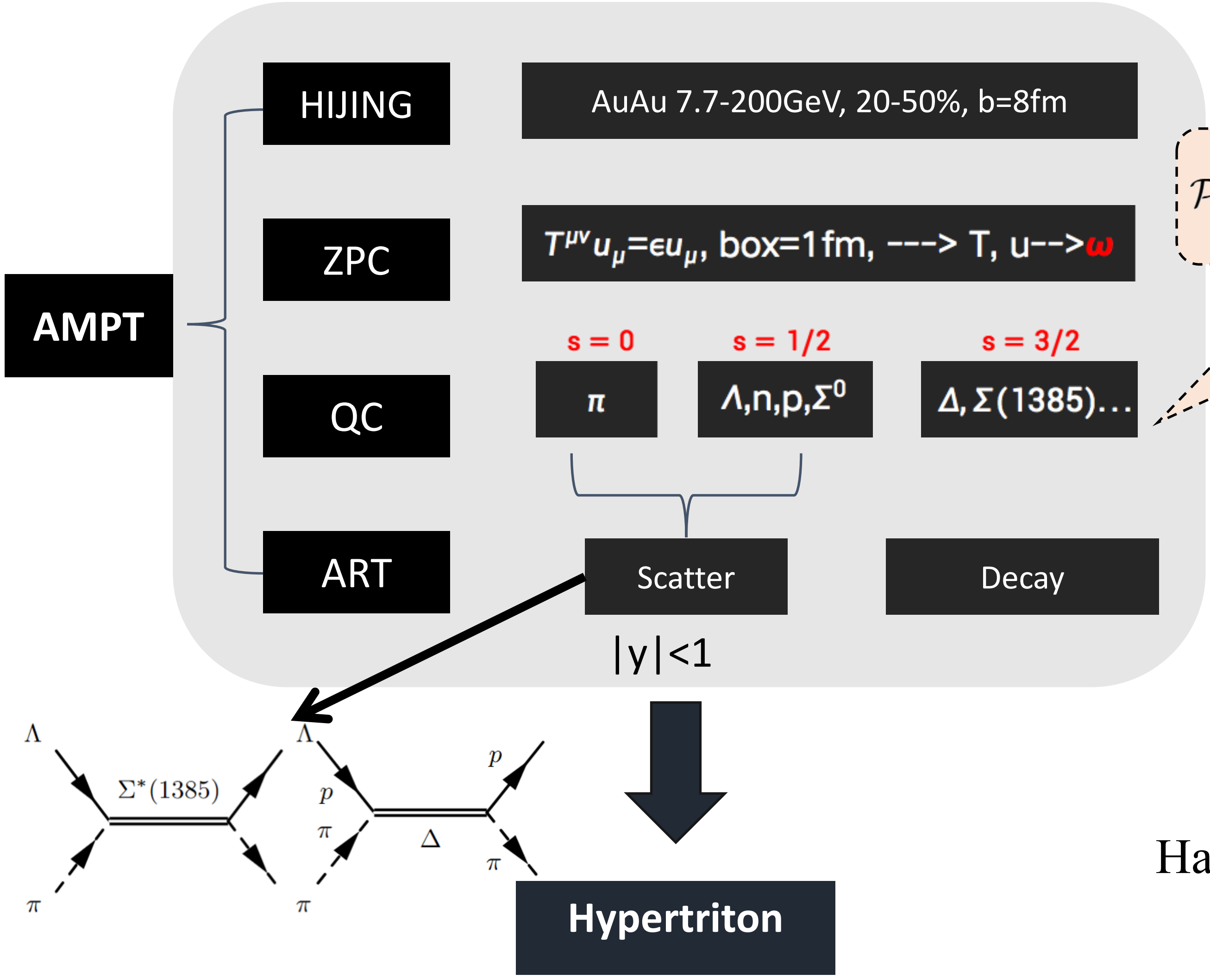
$$u^\mu u_\mu = 1$$

$$g_{\mu\nu} = \mathrm{diag}(1,-1,-1,-1)$$

Temperature

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

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



Spin polarization vector of single pariticle

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

in the c.m. frame by a Lorentz boost

$$\boldsymbol{\mathcal{P}}^{*} = \boldsymbol{\mathcal{P}} - \frac{\boldsymbol{p}\cdot\boldsymbol{\mathcal{P}}}{E(m+E)}\boldsymbol{p},$$

$$\mathcal{P} = \frac{S^{\mu}}{s} \propto (s+1)$$

Hadronization

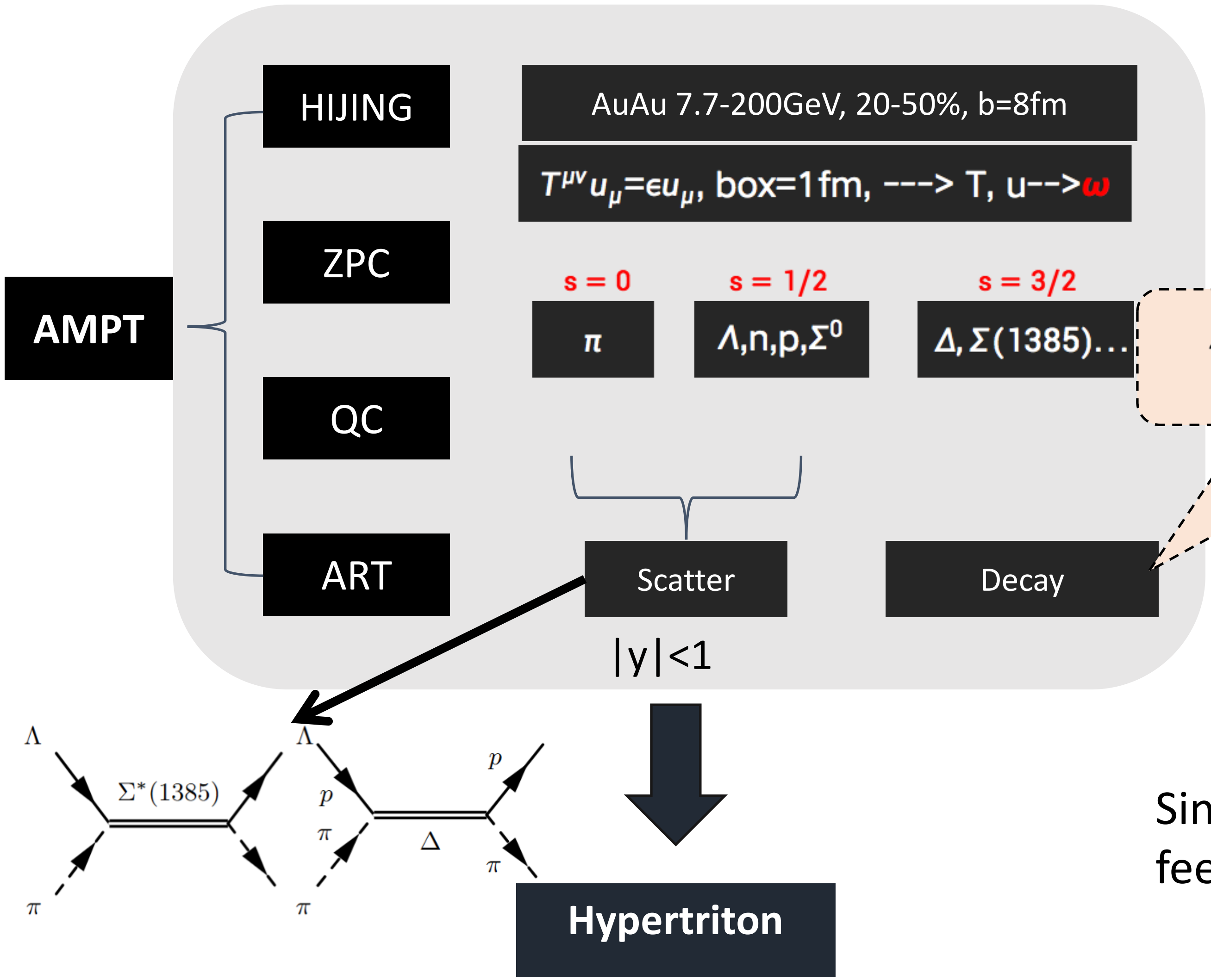
$$\mathcal{P}_{\Sigma^*} = \frac{5}{3}\mathcal{P}_{\Lambda}$$

$$\mathcal{P}_{\Delta} = \frac{5}{3}\mathcal{P}_{N}$$

模型设置-强子散射和衰变

Xia, Li, Huang, Huang, Phys.Rev.C **100**, 014913 (2019)

	Spin and parity	$\mathcal{C}$
Strong decay	$1/2^+ \to 1/2^+ 0^-$	-1/3
	$1/2^- \to 1/2^+ 0^-$	1
	$3/2^+ \to 1/2^+ 0^-$	1
	$3/2^- \to 1/2^+ 0^-$	-3/5
Weak decay	$1/2 \quad \to 1/2 \;\; 0$	$(2\gamma + 1)/3$
	$3/2 \quad \to 1/2 \;\; 0$	$(4\gamma + 1)/5$
EM decay	$1/2^+ \to 1/2^+ 1^-$	-1/3



$$\mathcal{P}_D = \mathcal{C}_{M\to D}\mathcal{P}_M$$

Decay from mother particles

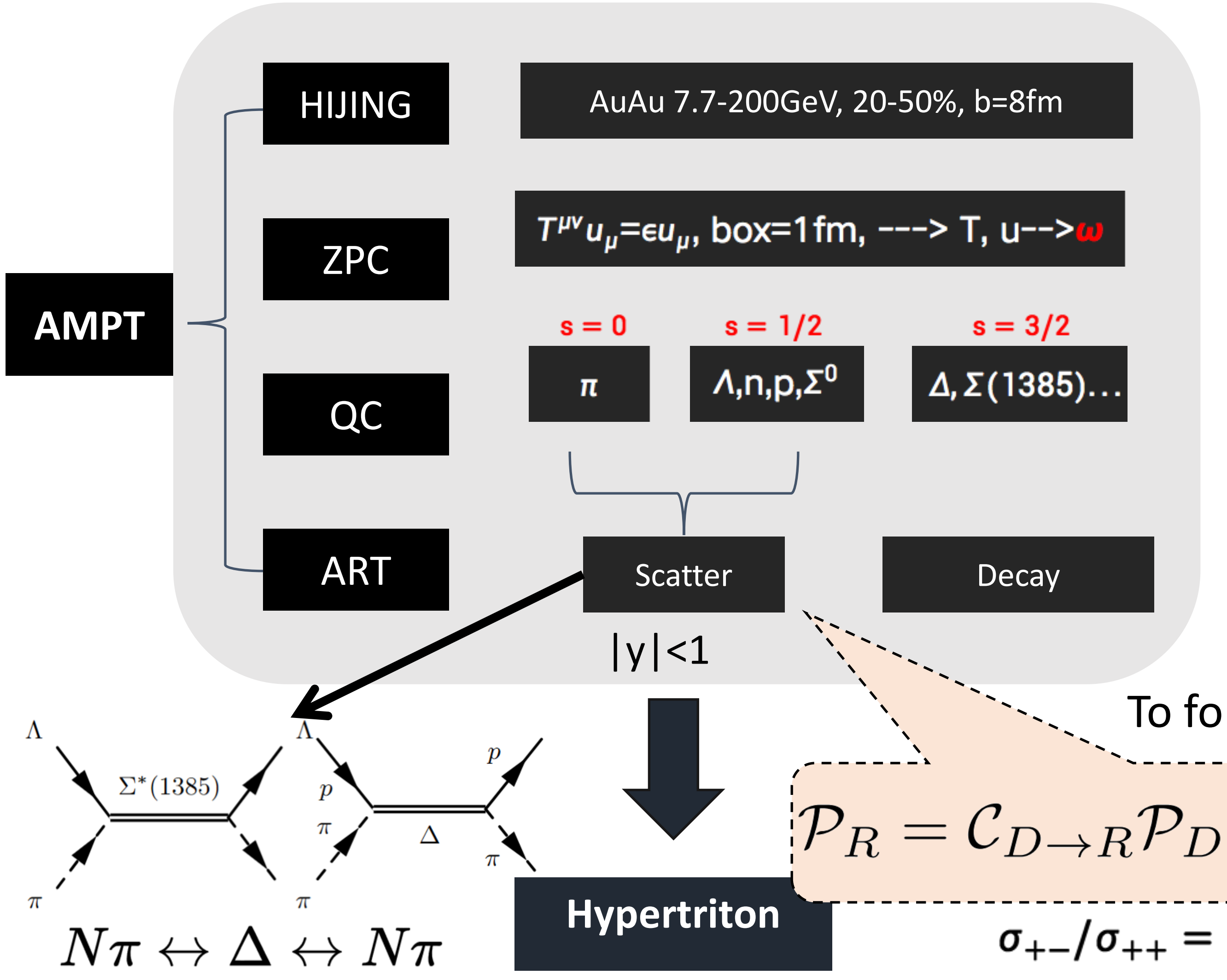
Single particle feed-down

$$\mathcal{P}_N = \mathcal{P}_\Delta$$

$$\mathcal{P}_\Lambda = \mathcal{P}_{\Sigma^*(1385)}$$

$$\mathcal{P}_\Lambda = -\frac{1}{3}\mathcal{P}_{\Sigma^0}$$

模型设置-强子散射和衰变



$$N\pi \leftrightarrow \Delta \leftrightarrow N\pi$$

$$\Lambda(\Sigma^0)\pi \leftrightarrow \Sigma^*(1385) \leftrightarrow \Lambda(\Sigma^0)\pi$$

Cross section

$$\sigma_{ab\to R}(s) = \frac{8\pi}{k^2}\frac{s\Gamma_{ab\to R}(s)\Gamma_{tot}(s)}{(s-s_0)^2+s\Gamma_{tot}^2(s)}$$

$$\Gamma_{ab\to R} = \Gamma_{R\to ab} \qquad \Gamma = 36\ \text{MeV}$$

$$\Gamma_{\Sigma^*(1385)\to\Lambda\pi} : \Gamma\sigma_{\Sigma^*(1385)\to\Sigma\pi} = 87\% : 11.7\%$$

$$k = \sqrt{\frac{[s-(m_H+m_\pi)^2][s-(m_H-m_\pi)^2]}{4s}}$$

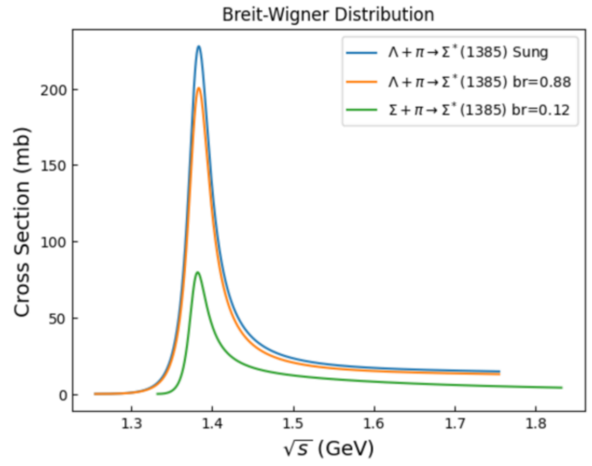
$$m_{\Sigma^0} = 1192\ MeV$$

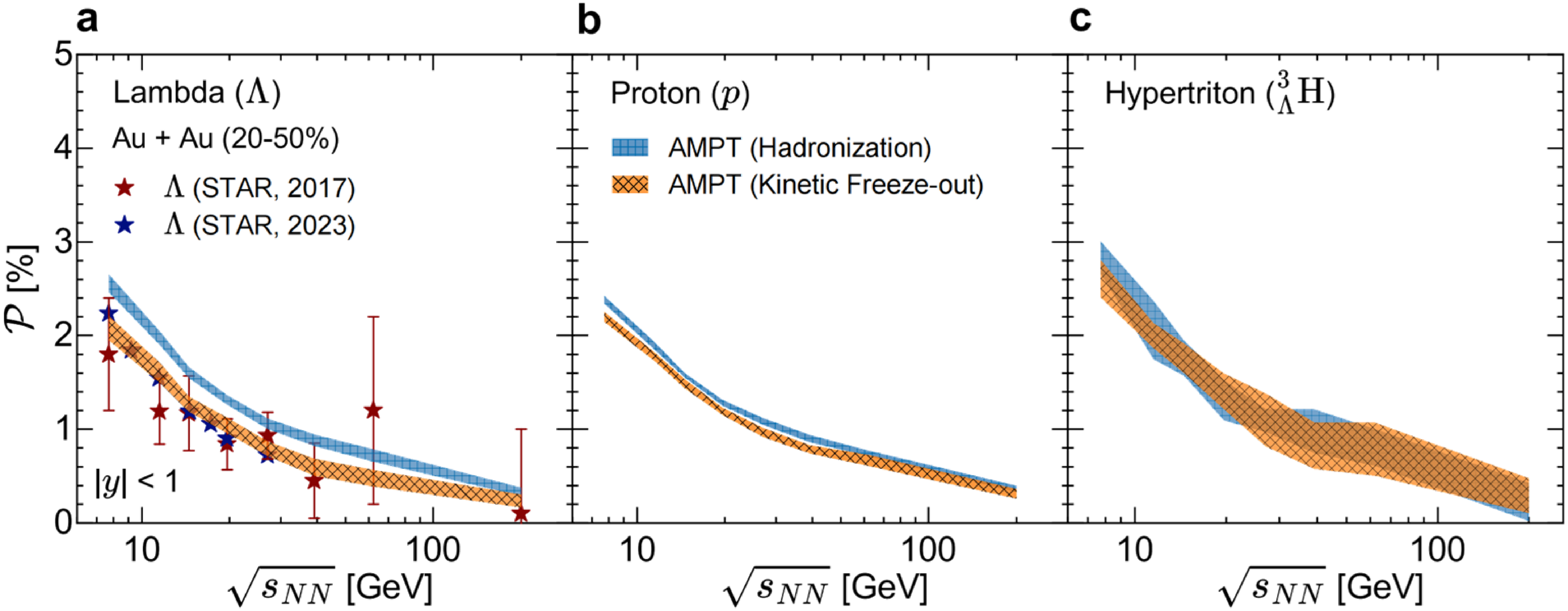
$$m_\Lambda = 1116\ MeV$$

To form a resonance

$$\mathcal{P}_R = \mathcal{C}_{D\to R}\mathcal{P}_D, \mathcal{C}_{D\to R} = 5/9$$

$$\sigma_{+-}/\sigma_{++} = 2/7$$




a
b
c
Lambda (Λ)
Au + Au (20-50%)
Λ (STAR, 2017)
Λ (STAR, 2023)
|y| < 1
Proton (p)
AMPT (Hadronization)
AMPT (Kinetic Freeze-out)
Hypertriton ($^3_\Lambda$H)
$\mathcal{P}$ [%]
$\sqrt{s_{NN}}$ [GeV]
0
1
2
3
4
5
10
100

Spin-dependent Coalescence model

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

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

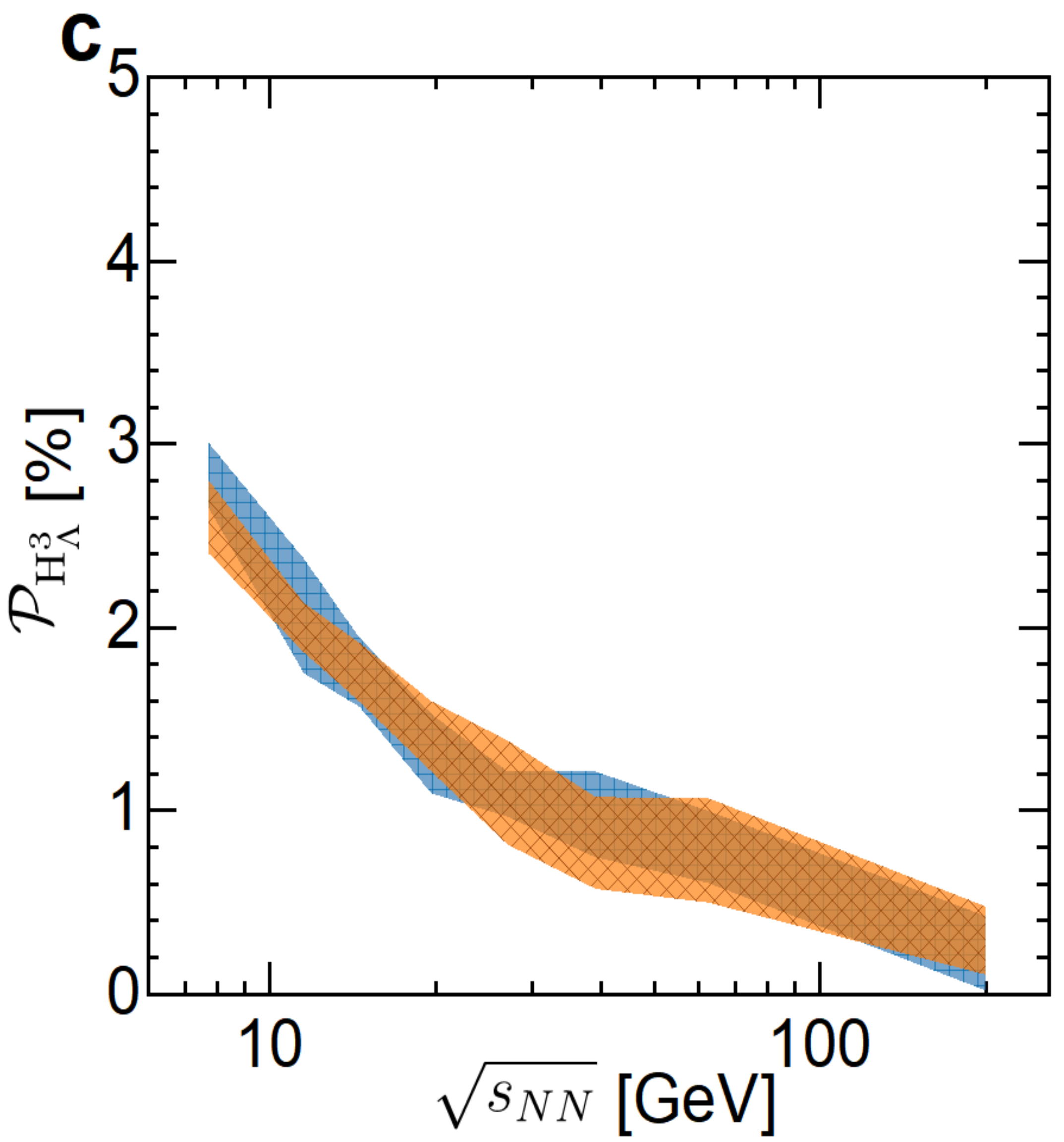
$$W_3(\rho,\lambda,p_\rho,p_\lambda) = 8^2 \exp\left[-\frac{\rho^2}{\sigma_\rho^2} - \frac{\lambda^2}{\sigma_\lambda^2} - p_\rho^2\sigma_\rho^2 - p_\lambda^2\sigma_\lambda^2\right]$$

$$\rho = \frac{1}{\sqrt{2}}(x_1' - x_2'), \quad p_\rho = \frac{\sqrt{2}(m_2p_1' - m_1p_2')}{m_1+m_2},$$

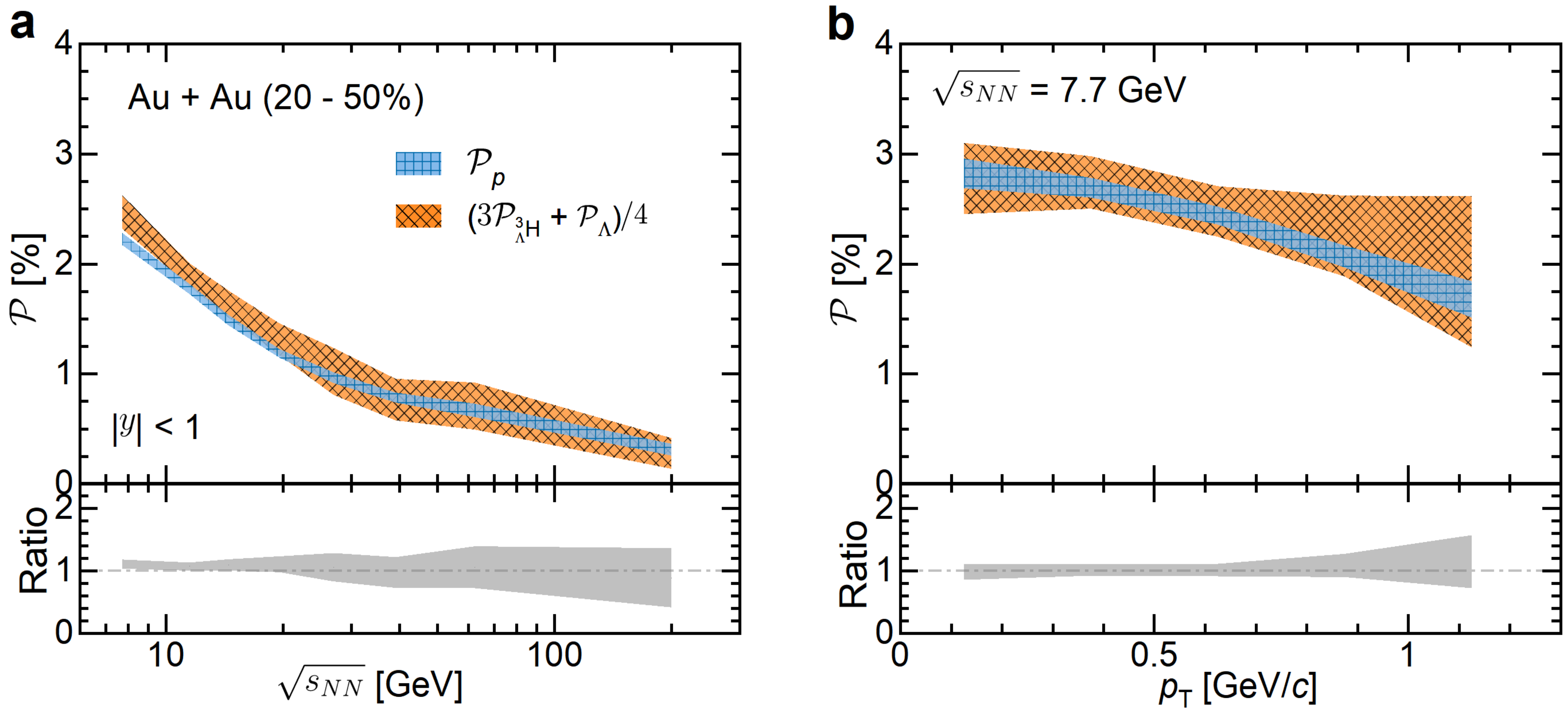
$$\lambda = \sqrt{\frac{2}{3}}\left(\frac{m_1x_1' + m_2x_2' - x_3'}{m_1+m_2}\right),$$

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

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



讨论:测量质子极化

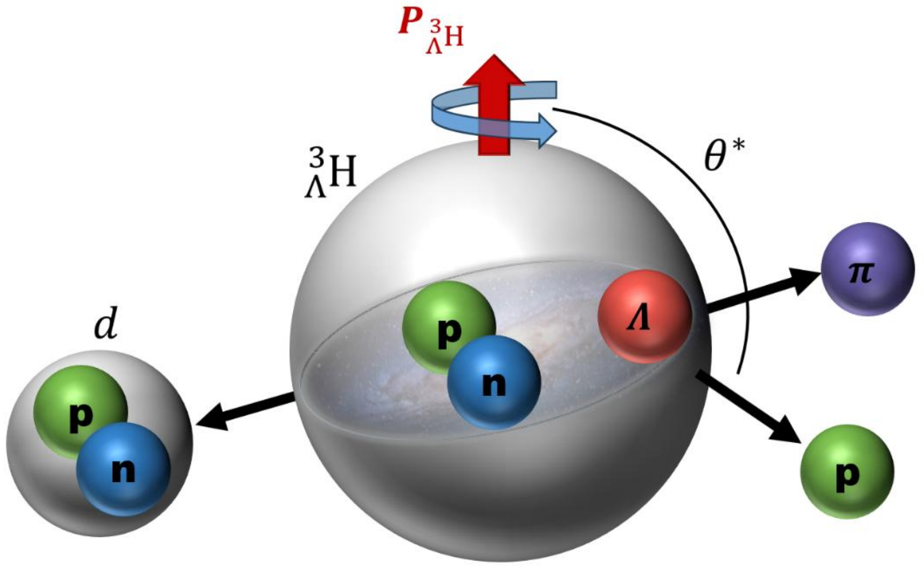


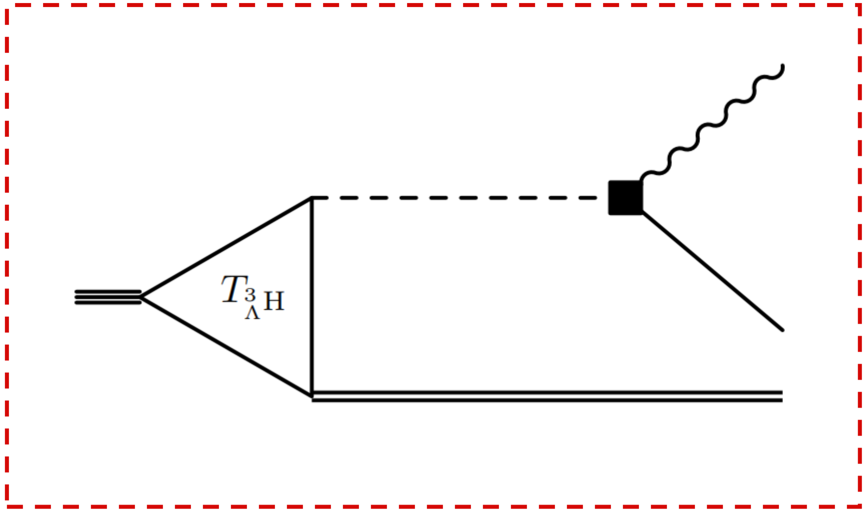
$$\mathcal{P}_p \approx \frac{1}{4}\left(3\mathcal{P}_{^3_\Lambda H} + \mathcal{P}_\Lambda\right)$$

IV. Discussion

三体衰变（初步）

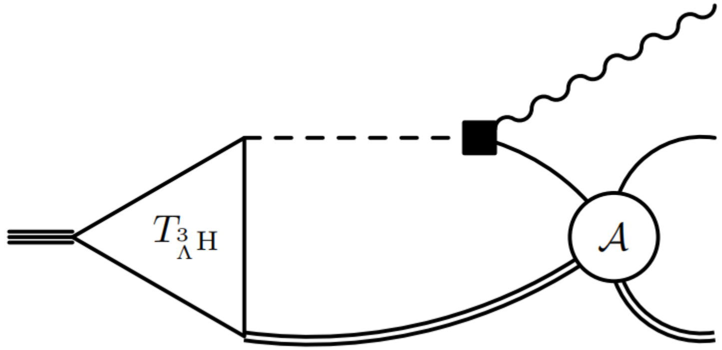
F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 102, 064002 (2020)





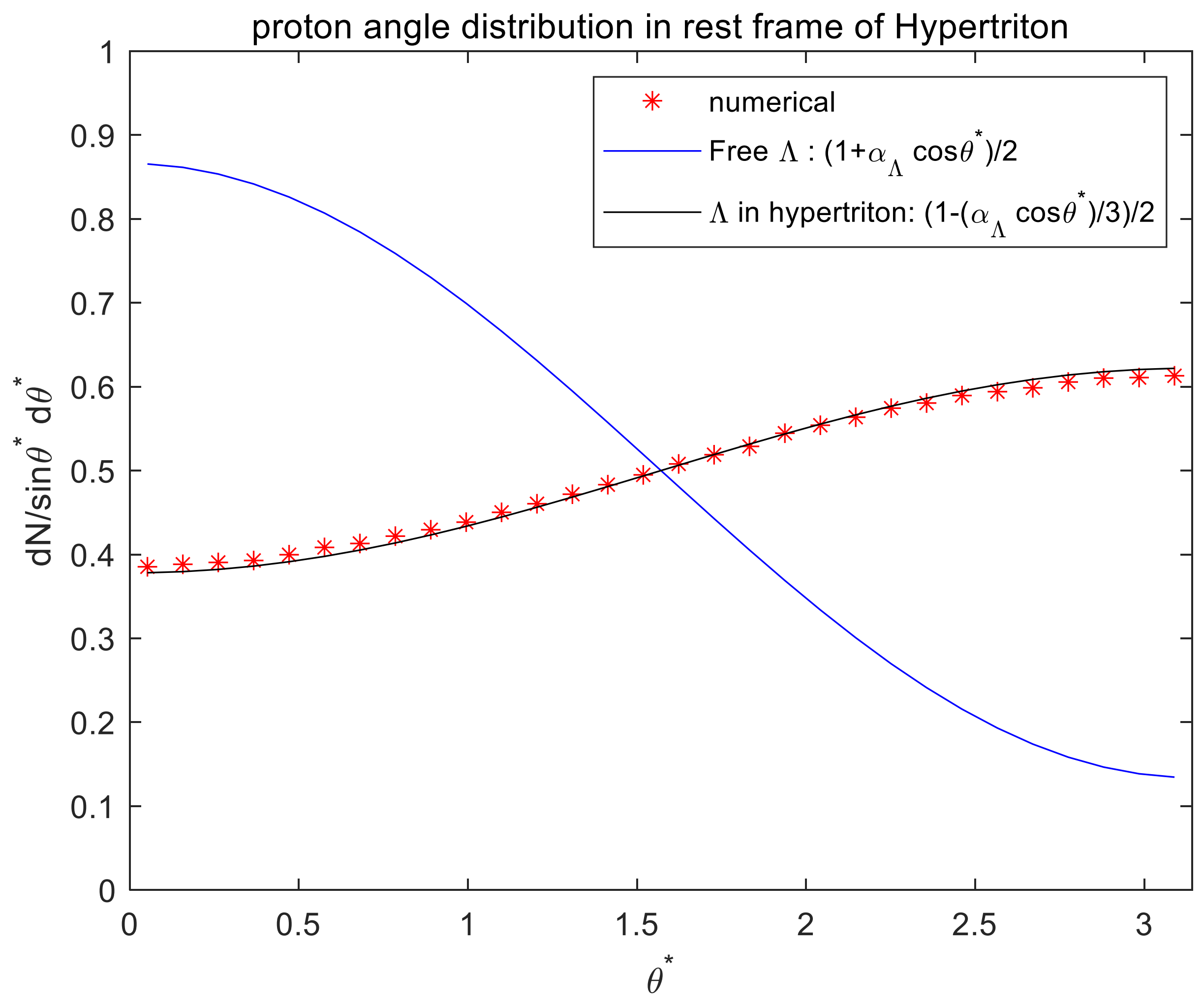
+

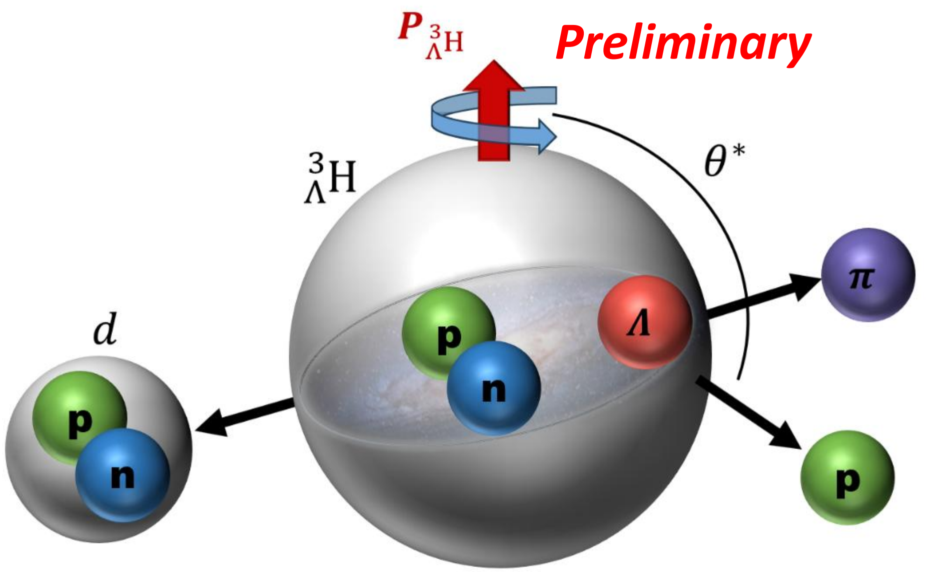
Final-state interaction (FSI)

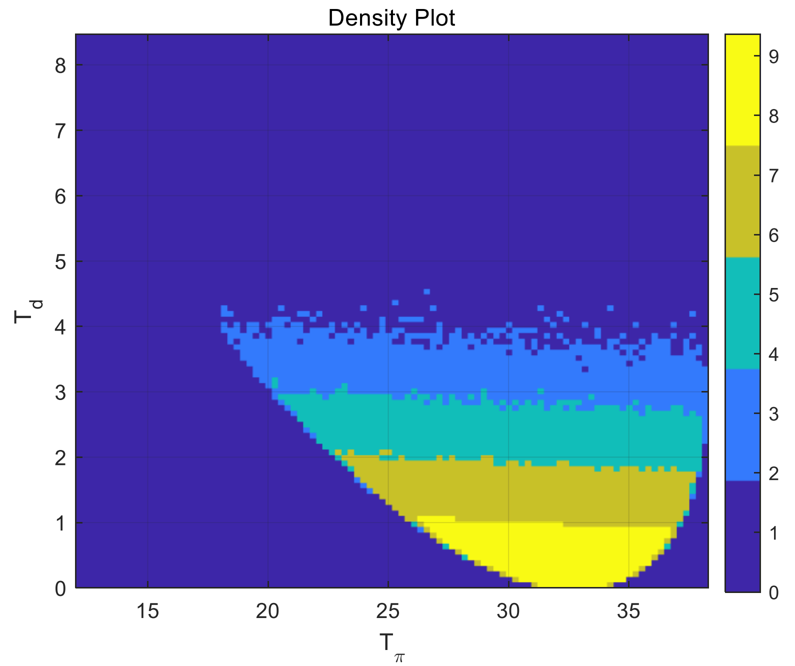


三体衰变（初步）

No final-state interaction



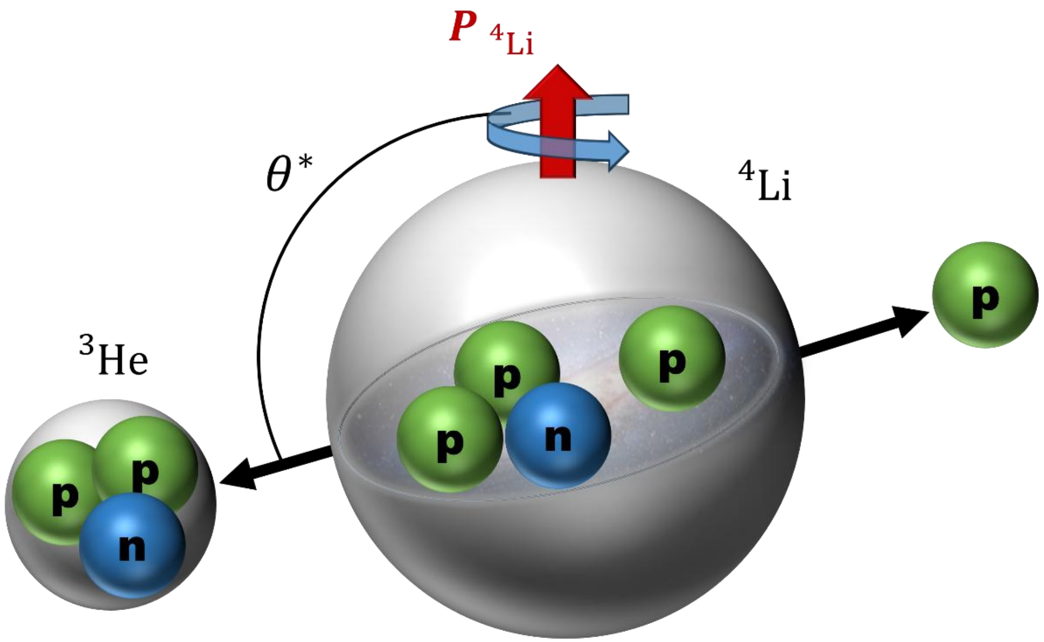




C:\Users\Administrator\OneDrive\Research\37LightNucleiSpinThreebody\code\Decay

Li4自旋排列

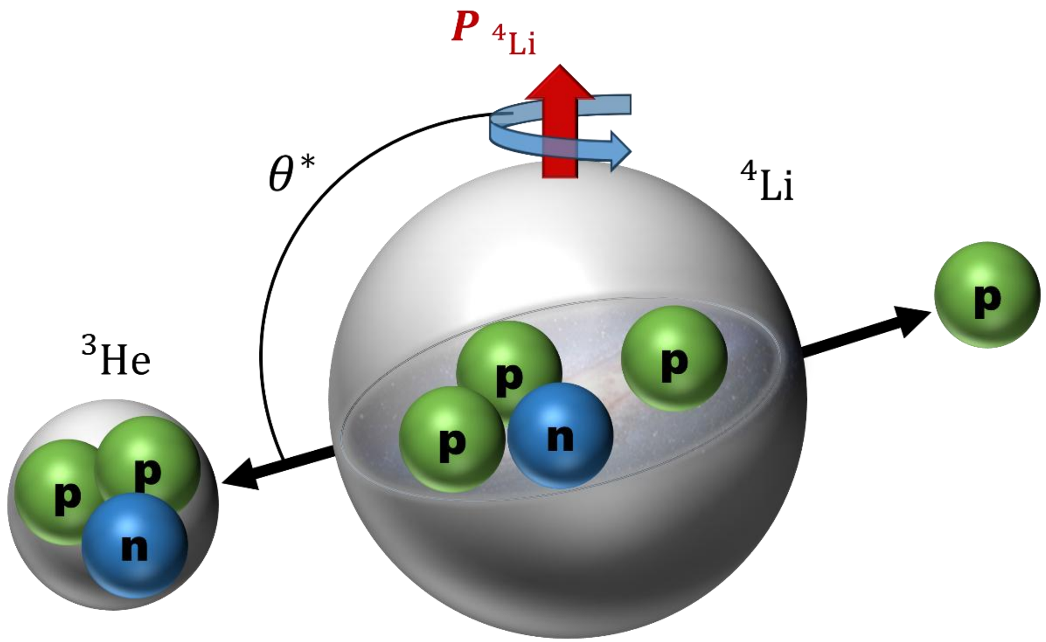
Preliminary



state	E(MeV)	structure	L	decay mode	Γ(MeV)
$^4\mathrm{Li}(^3P_2)$	g.s.	$^3\mathrm{He}(\frac{1}{2}^+) - p(\frac{1}{2}^+)$	1	$^4\mathrm{Li} \to ^3\mathrm{He} + p$	6.03
$^4\mathrm{Li}(^3P_1)$	0.32	$^3\mathrm{He}(\frac{1}{2}^+) - p(\frac{1}{2}^+)$	1	$^4\mathrm{Li} \to ^3\mathrm{He} + p$	7.35
$^4\mathrm{Li}(^1P_0)$	2.08	$^3\mathrm{He}(\frac{1}{2}^+) - p(\frac{1}{2}^+)$	1	$^4\mathrm{Li} \to ^3\mathrm{He} + p$	9.35
$^4\mathrm{Li}(^1P_1)$	2.85	$^3\mathrm{He}(\frac{1}{2}^+) - p(\frac{1}{2}^+)$	1	$^4\mathrm{Li} \to ^3\mathrm{He} + p$	13.51

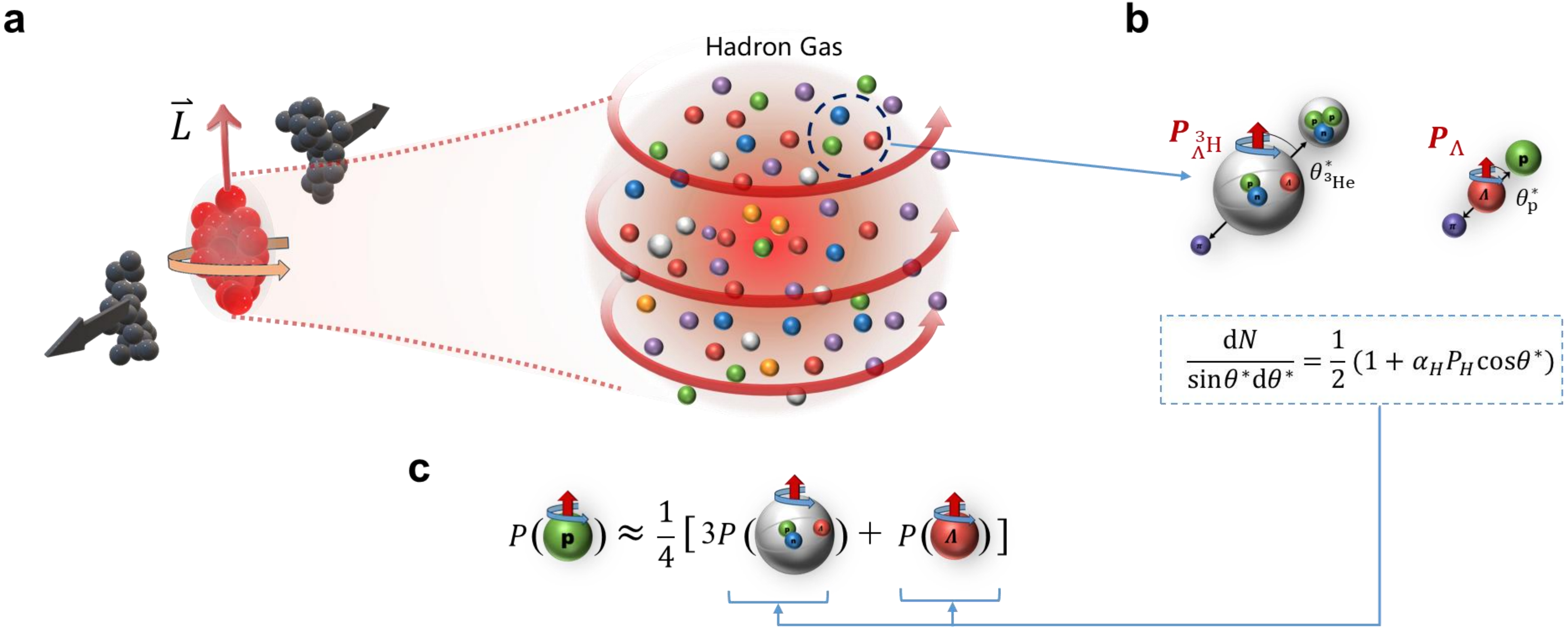
Li4自旋排列

Preliminary



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

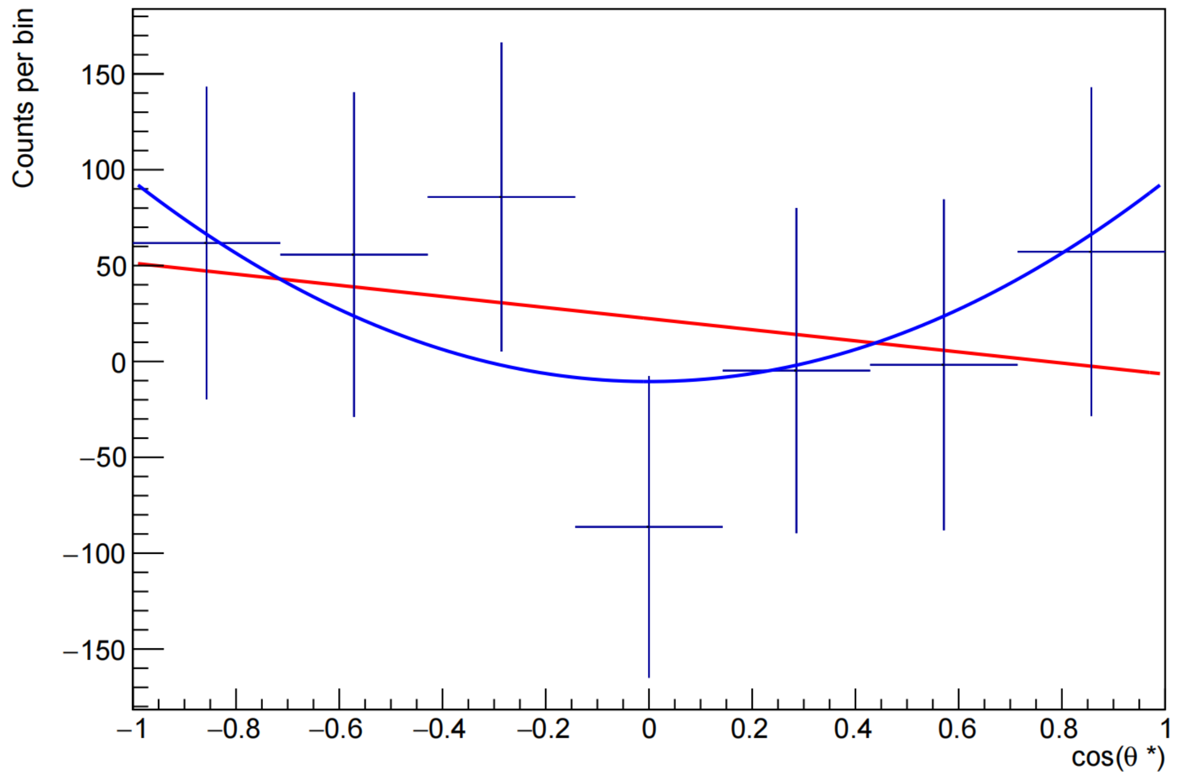
1. **(Anti-)hypertriton is globally polarized in non-central heavy-ion collisions.**
2. **Combining the measurements of Lambda and hypertriton polarizations, one can reveal the proton spin polarization.**



总结&展望

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

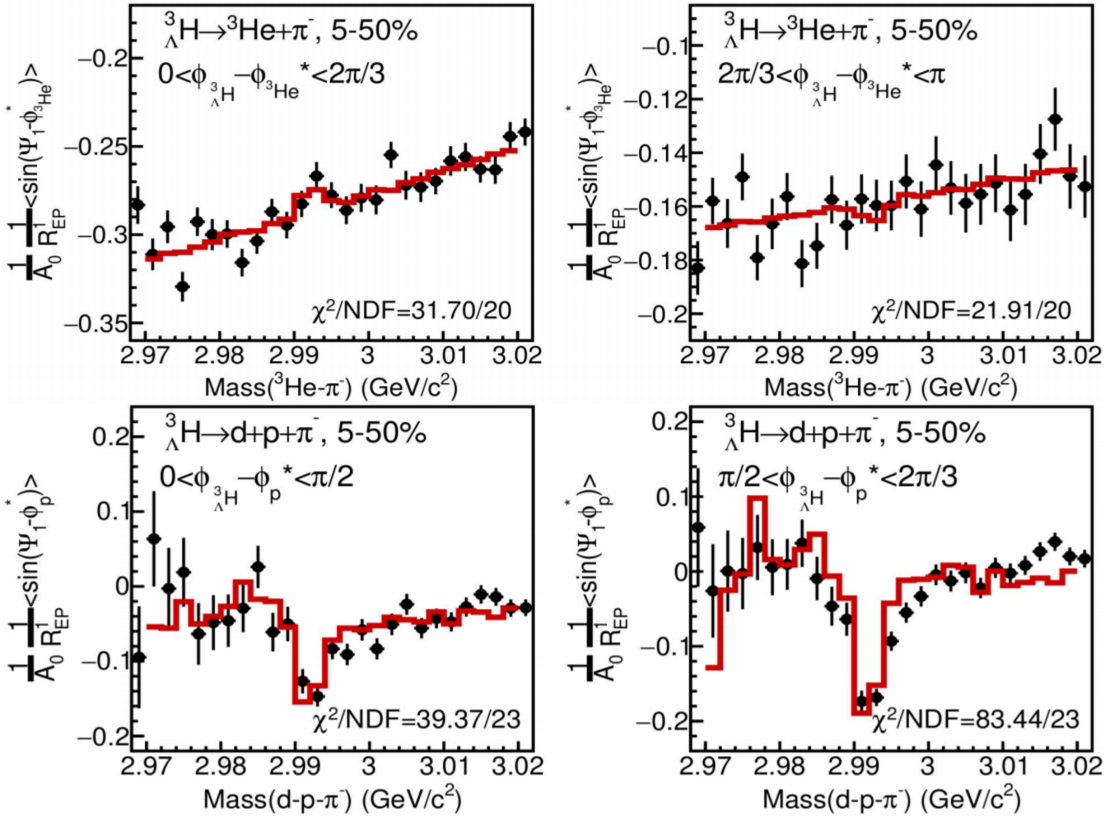
ALICE Run2 Pb-Pb @ 5.02TeV



First Measurements of Hyper-Nucleus $^{3}_{\Lambda}$H Global Polarization in Au+Au Collisions at STAR

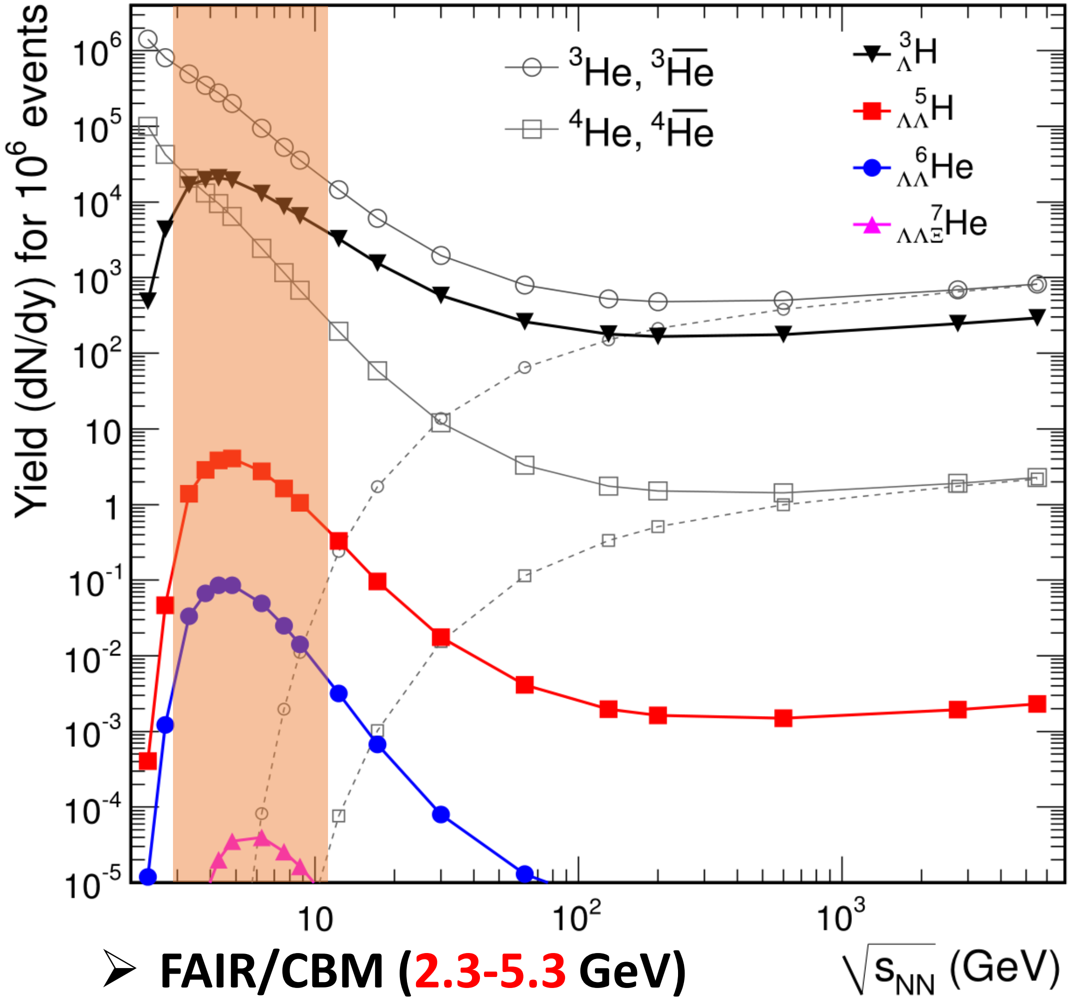
Chenlu Hu (huchenlu@ucas.ac.cn), *for the STAR Collaboration*

$$\frac{8}{\pi\alpha_H R_{EP}} < \sin(\Psi_1 - \phi^*_{\mathrm{decay}}) >_{\mathrm{observe}} = \mathrm{P}^{\mathrm{real}}_{\mathrm{H}} + \mathrm{c}\cdot\sin(\phi_{^3_\Lambda\mathrm{H}} - \phi^*_{\mathrm{decay}})$$

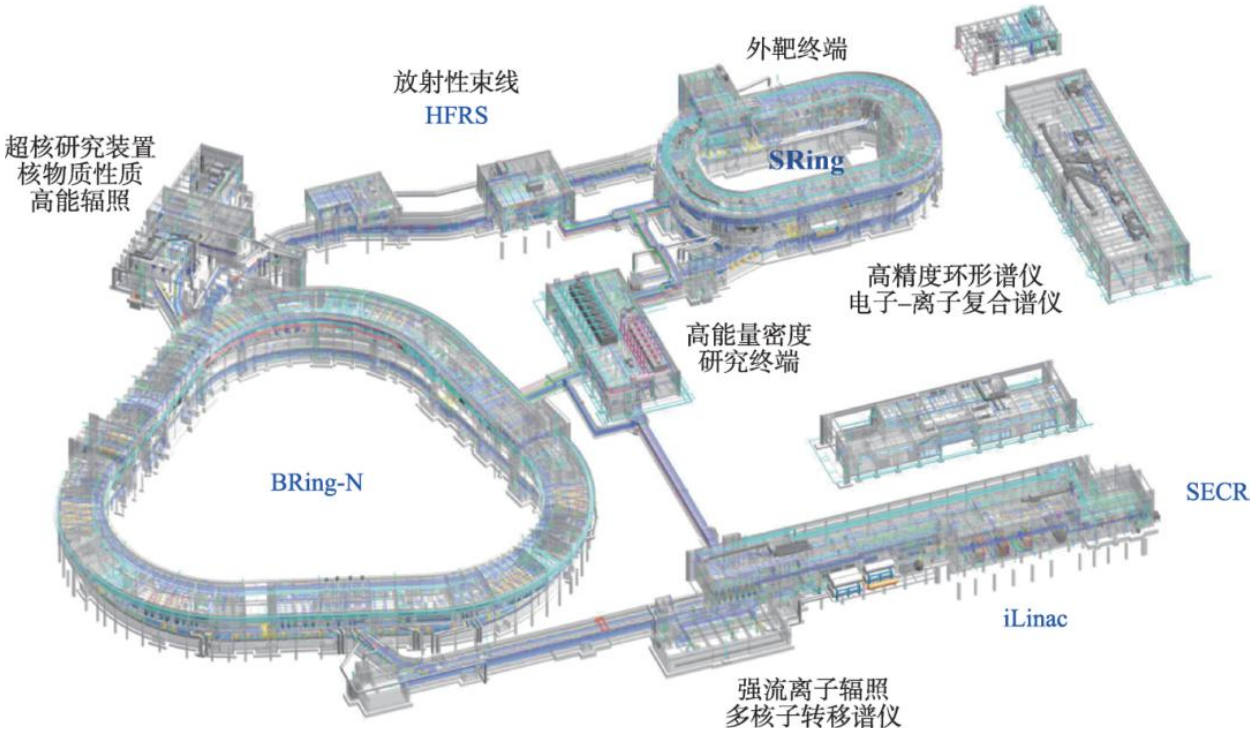


总结&展望

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

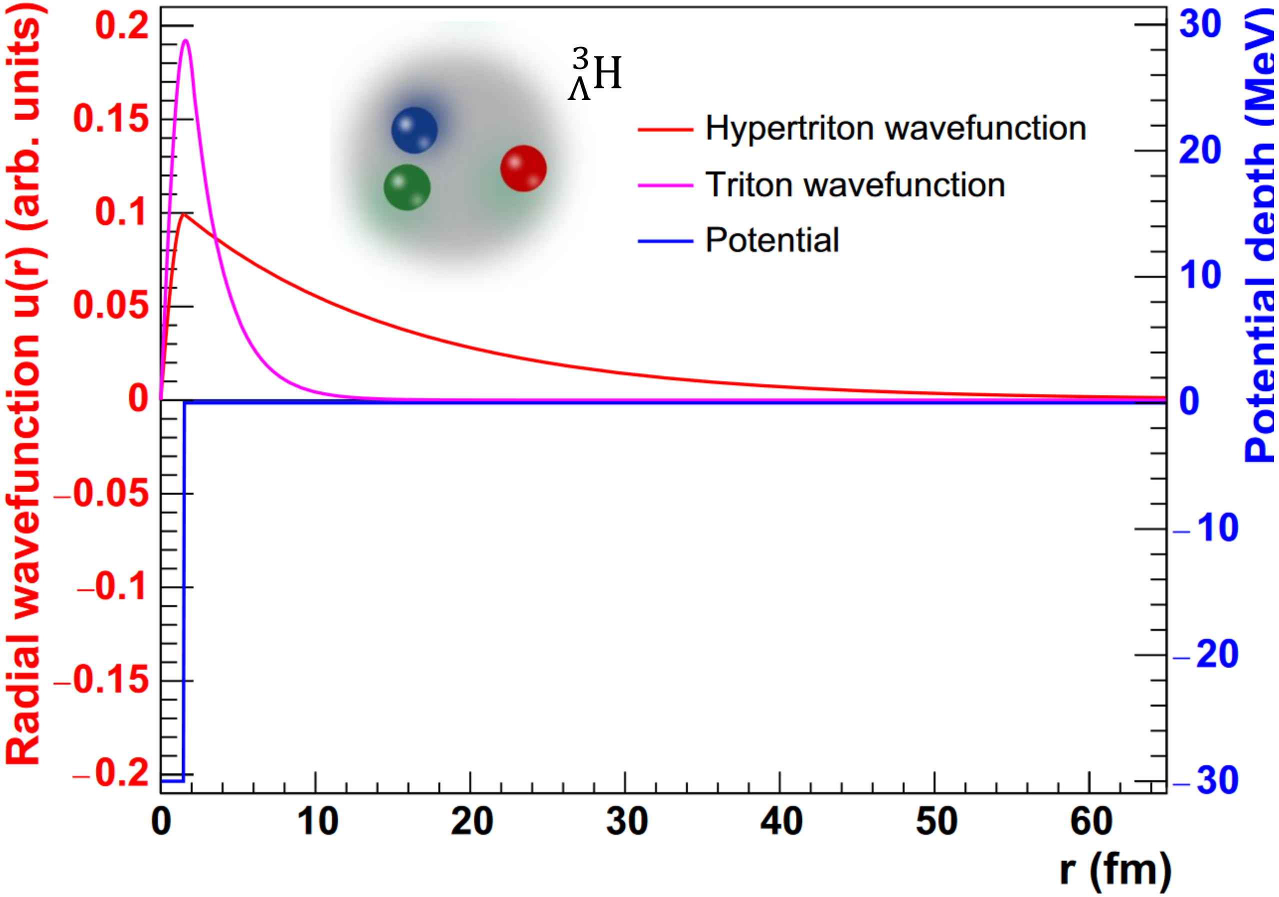


- FAIR/CBM (2.3-5.3 GeV)
- HIAF/CEE (2.1-4.5 GeV)
- NICA/MPD (4-11 GeV)
- J-PARC-HI (2-6.2 GeV)

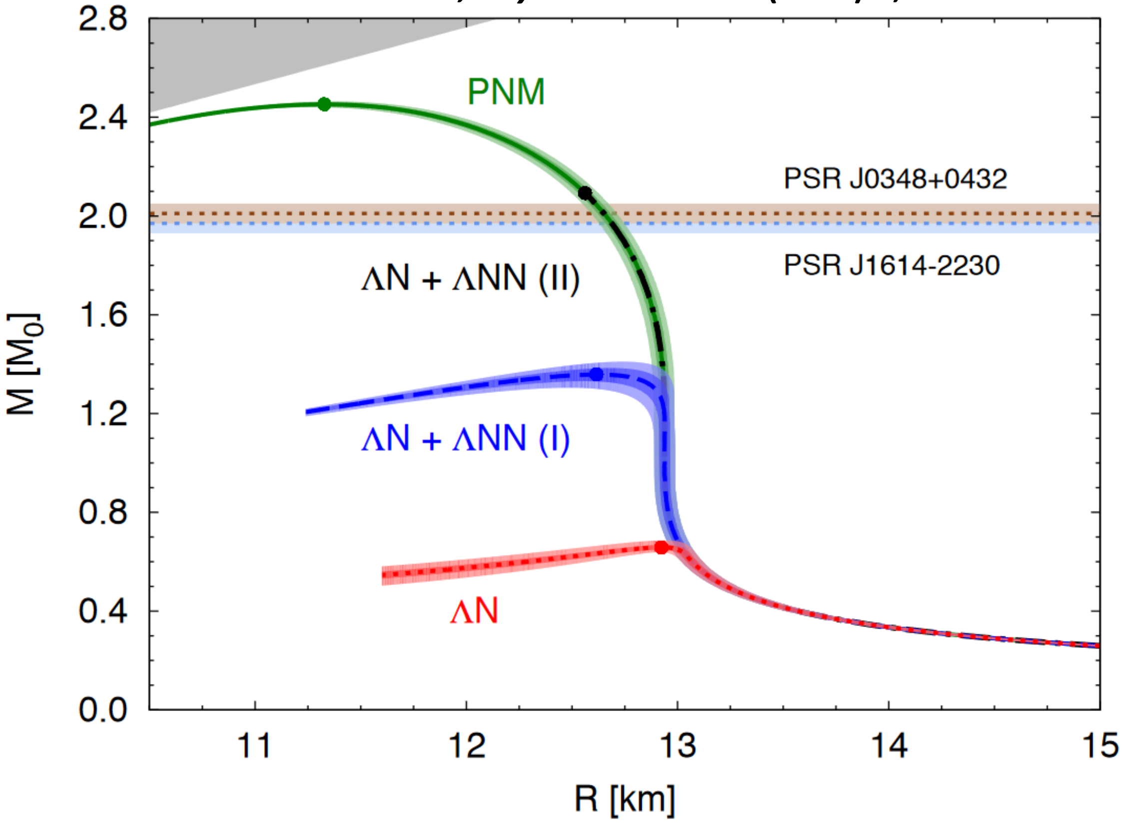


backup

奇异‘晕’核-（反物质）超氚核



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

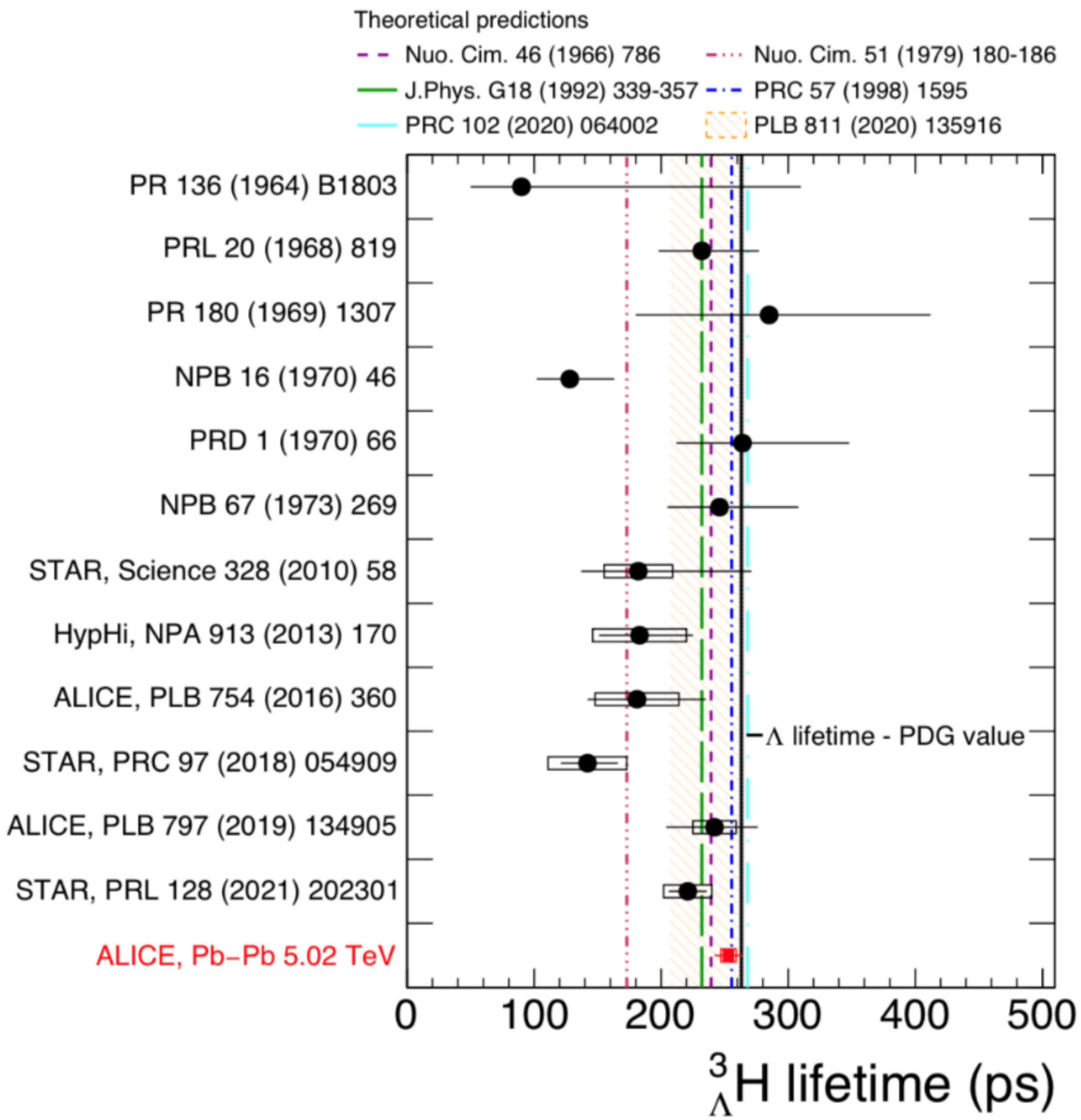


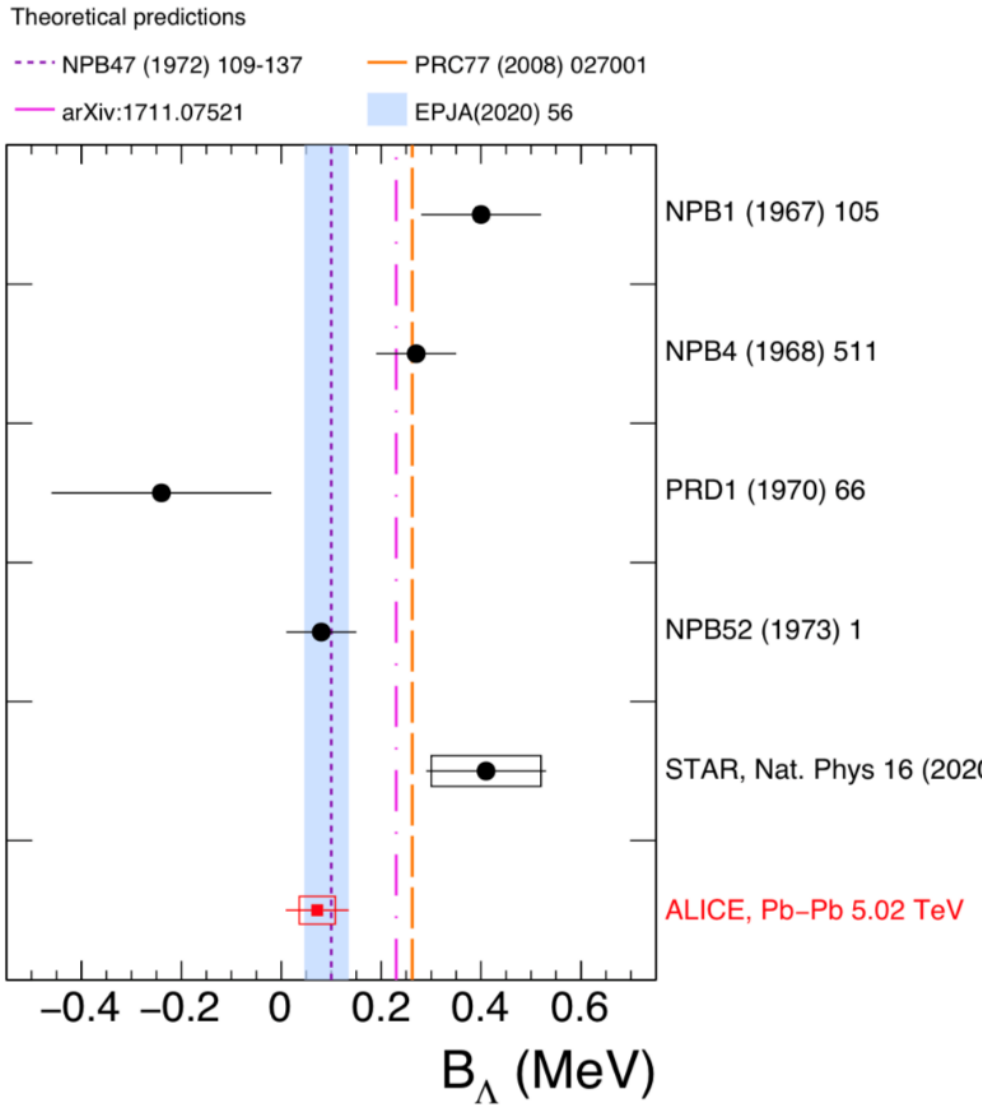
J. Chen et al., Phys. Rep. 760, 1 (2018);
P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)
D. N. Liu et al. Phys. Lett. B 855, 138855 (2024)

结合能和寿命

ALICE, PRL 131, 102302 (2023)

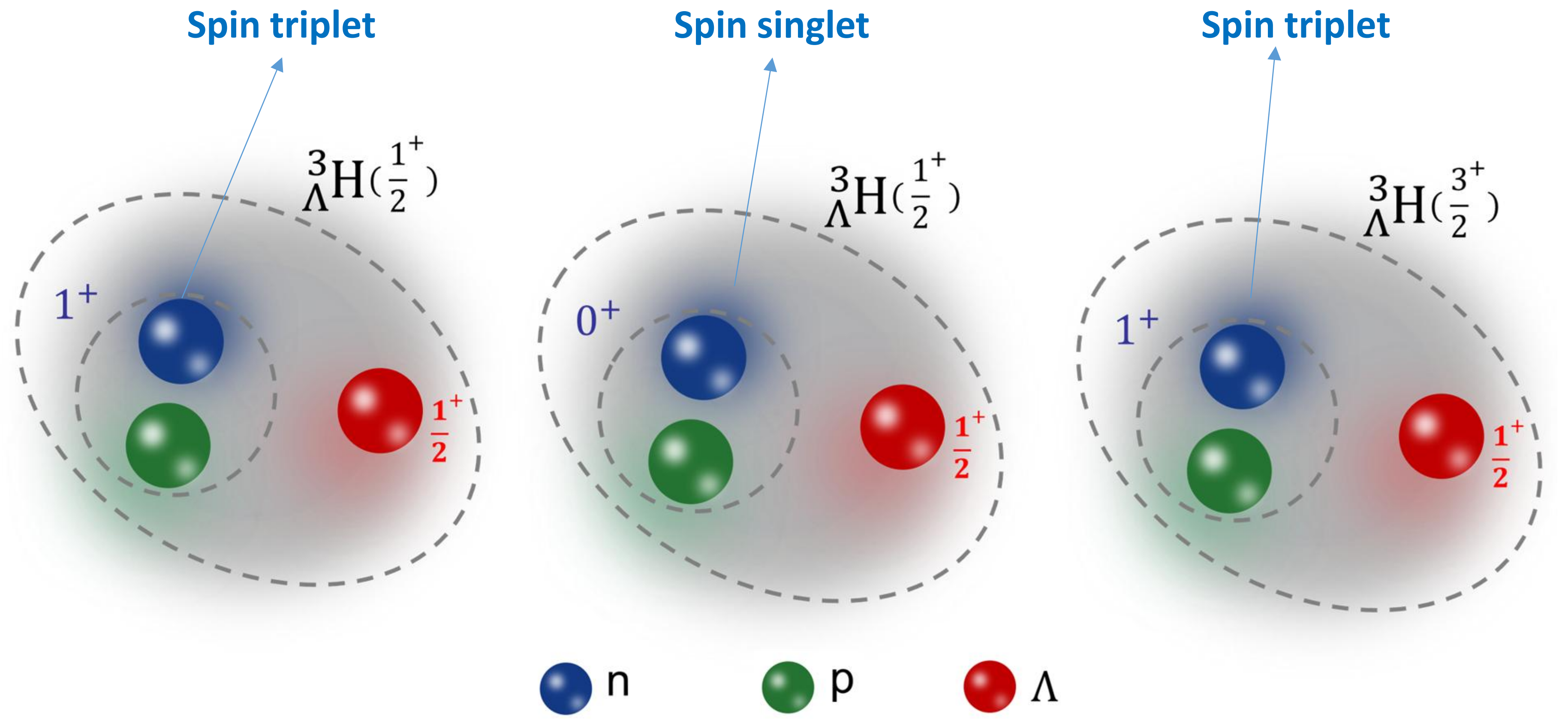
Y. G. Ma, Nucl. Sci. Tech. 3497 (2023)





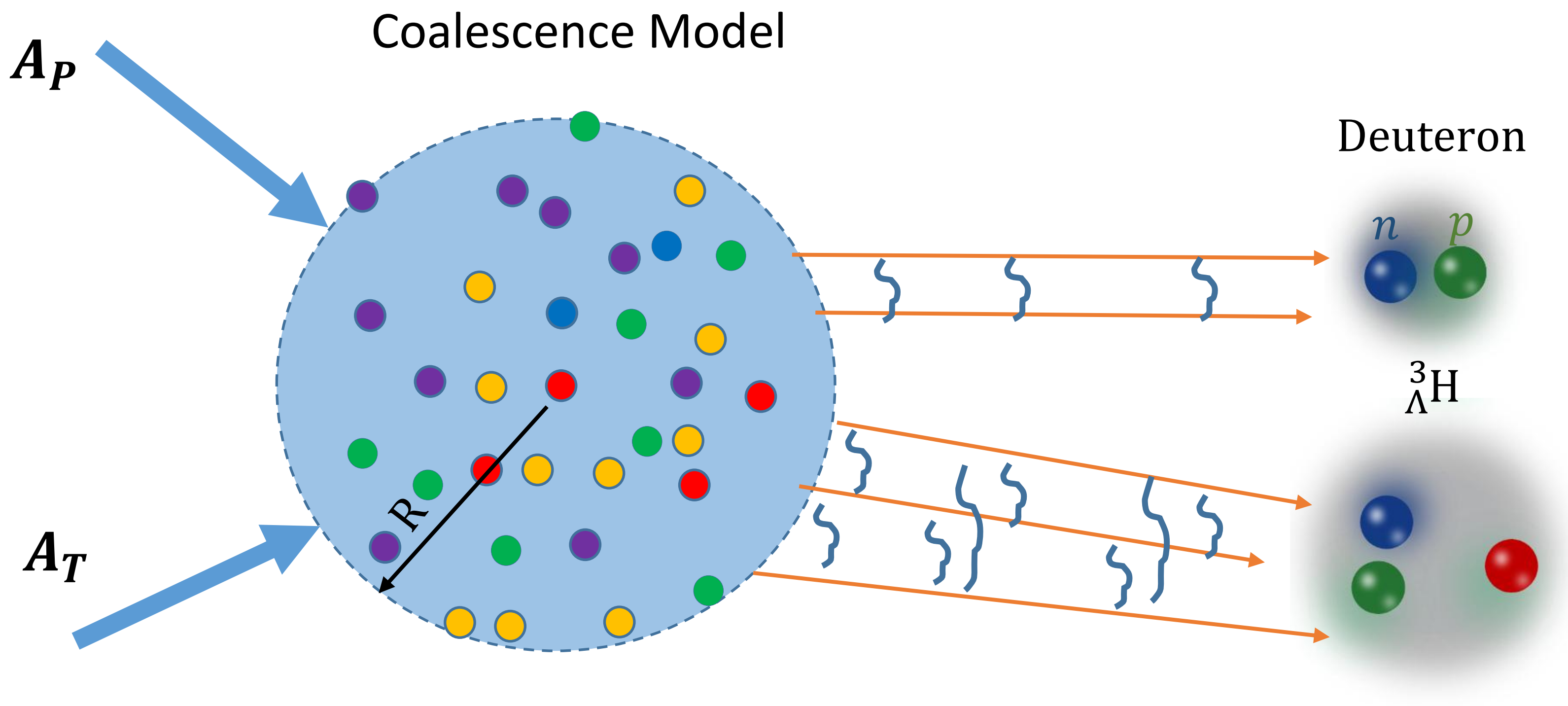
J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)

（反）超氚的自旋？



Spin triplet
Spin singlet
Spin triplet
$^{3}_{\Lambda}H(\frac{1}{2}^{+})$
$^{3}_{\Lambda}H(\frac{1}{2}^{+})$
$^{3}_{\Lambda}H(\frac{3}{2}^{+})$
1^{+}
0^{+}
1^{+}
$\frac{1}{2}^{+}$
$\frac{1}{2}^{+}$
$\frac{1}{2}^{+}$
n
p
Λ

超核产生的并合模型



Density Matrix Formulation
(sudden approximation)

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

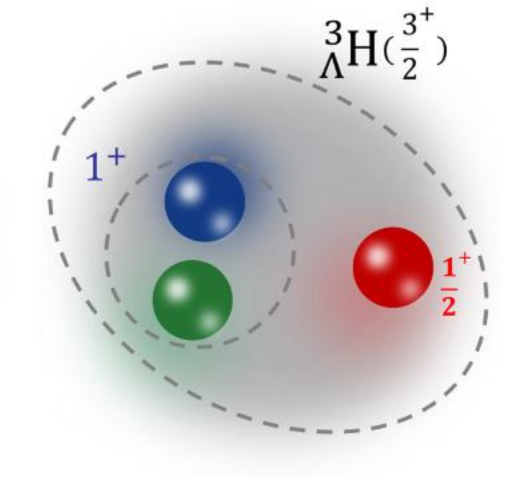
Wigner function of light cluster

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)

（反）超氚的极化和波函数自旋结构

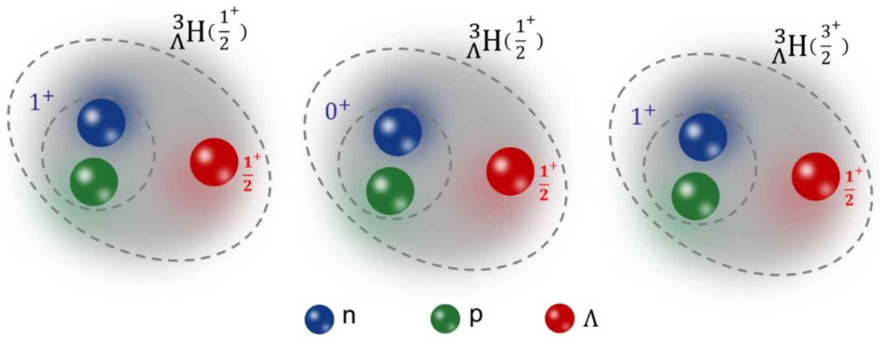


$$\hat{\rho}_{^3_\Lambda H} \approx \mathrm{diag}\left[\frac{(1+\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)(1+\mathcal{P}_\Lambda)^2}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^2(1+\mathcal{P}_\Lambda)}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}\right]$$

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

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

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



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

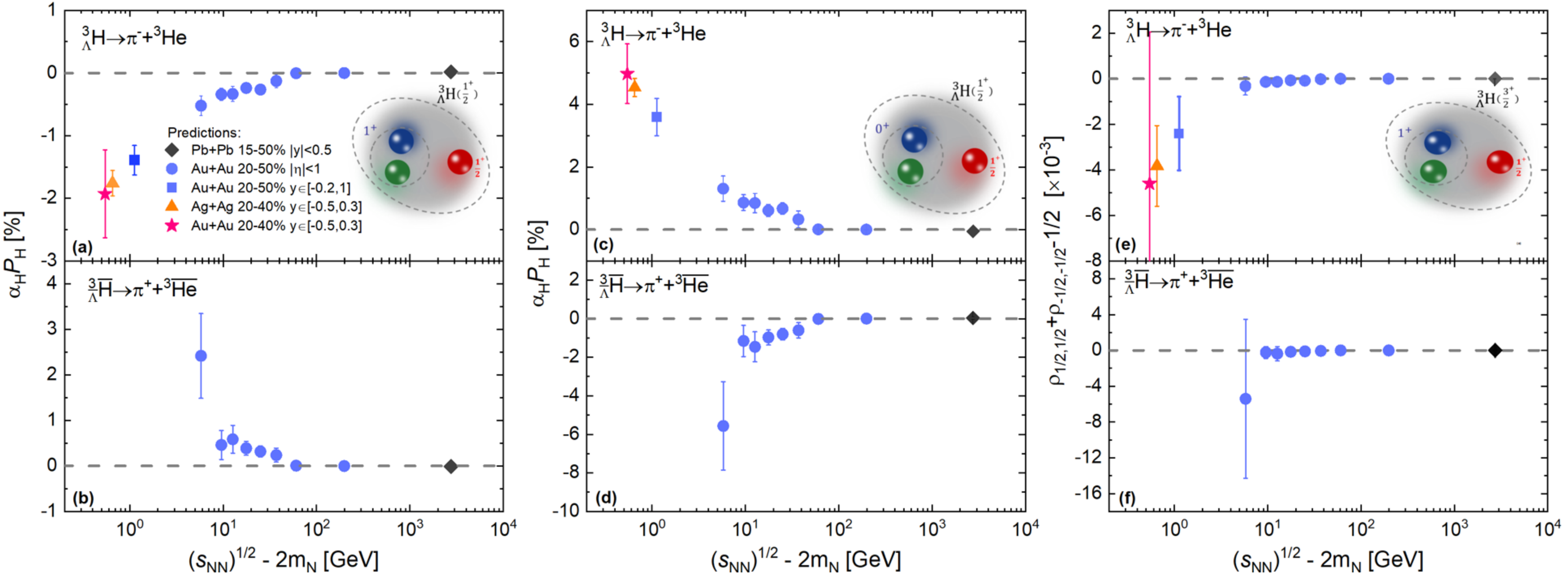
Different polarization and decay patterns!

（反）超氚的极化和波函数自旋结构

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

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

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



讨论：自旋关联效应

$$\hat{\rho}_{np\Lambda} = \hat{\rho}_n \otimes \hat{\rho}_p \otimes \hat{\rho}_\Lambda + \frac{1}{2^2}(c_{np}^{\alpha\beta}\hat{\sigma}_{n,\alpha} \otimes \hat{\sigma}_{p,\beta} \otimes \hat{\rho}_\Lambda$$
$$+ c_{p\Lambda}^{\alpha\beta}\hat{\sigma}_{p,\alpha} \otimes \hat{\sigma}_{\Lambda,\beta} \otimes \hat{\rho}_n + c_{n\Lambda}^{\alpha\beta}\hat{\sigma}_{n,\alpha} \otimes \hat{\sigma}_{\Lambda,\beta} \otimes \hat{\rho}_p)$$
$$+ \frac{1}{2^3} c_{np\Lambda}^{\alpha\beta\gamma}\hat{\sigma}_{n,\alpha} \otimes \hat{\sigma}_{p,\beta} \otimes \hat{\sigma}_{\Lambda,\gamma},$$

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

$$C_- = -\frac{1}{4}(\langle c_{np}^{zz}\mathcal{P}_\Lambda\rangle + \langle c_{p\Lambda}^{zz}\mathcal{P}_n\rangle + \langle c_{n\Lambda}^{zz}\mathcal{P}_p\rangle) - \frac{1}{4}\langle c_{np\Lambda}^{zzz}\rangle,$$
$$C_+ = \frac{1}{12}(\langle c_{np}^{zz}\rangle - 2\langle c_{p\Lambda}^{zz}\rangle - 2\langle c_{n\Lambda}^{zz}\rangle).$$

'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

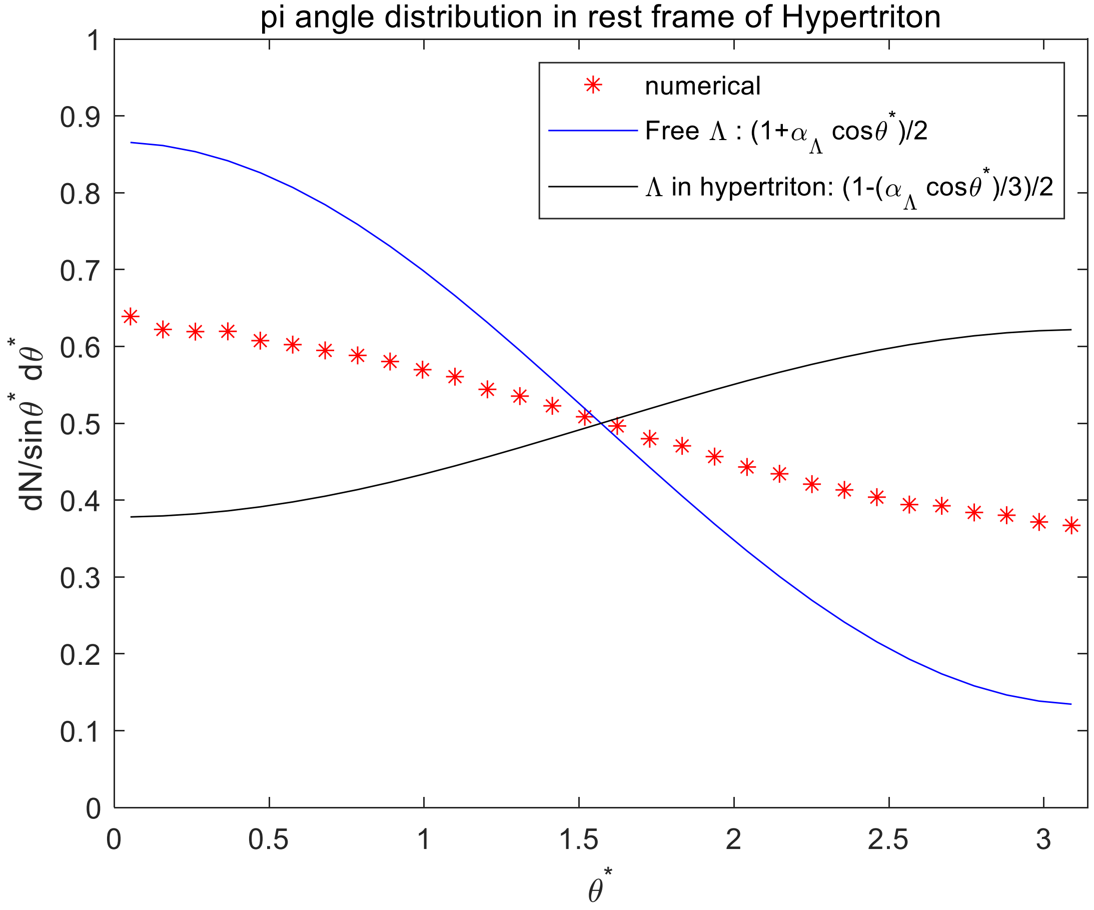
$$\mathcal{P}_{^3_\Lambda\mathrm{H}} \approx (1 - \langle\delta\mathcal{P}_n\delta\mathcal{P}_p\rangle - \langle\delta\mathcal{P}_p\delta\mathcal{P}_\Lambda\rangle - \langle\delta\mathcal{P}_n\delta\mathcal{P}_\Lambda\rangle)\langle\mathcal{P}_\Lambda\rangle.$$

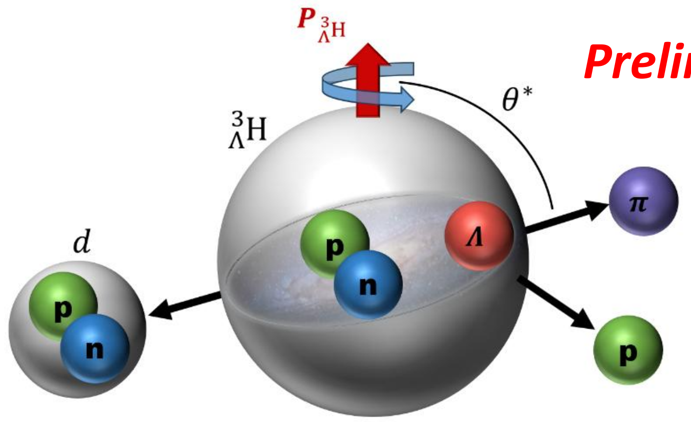
This result suggests that it is possible to extract the information on the spin-spin correlations among nucleons and Λ hyperons from the measurement of hypertriton polarization in heavy-ion collisions, although it is non-trivial in practice.

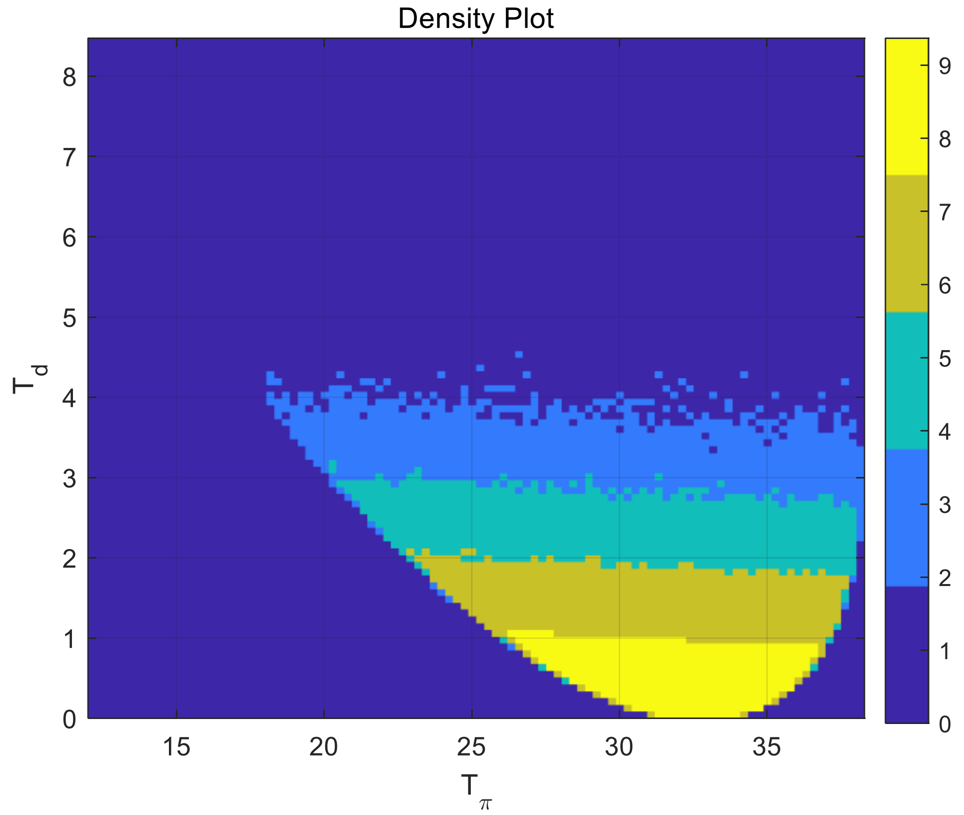
讨论:三体衰变（初步）

No final-state interaction

Preliminary







讨论:三体衰变（初步）

No final-state interaction

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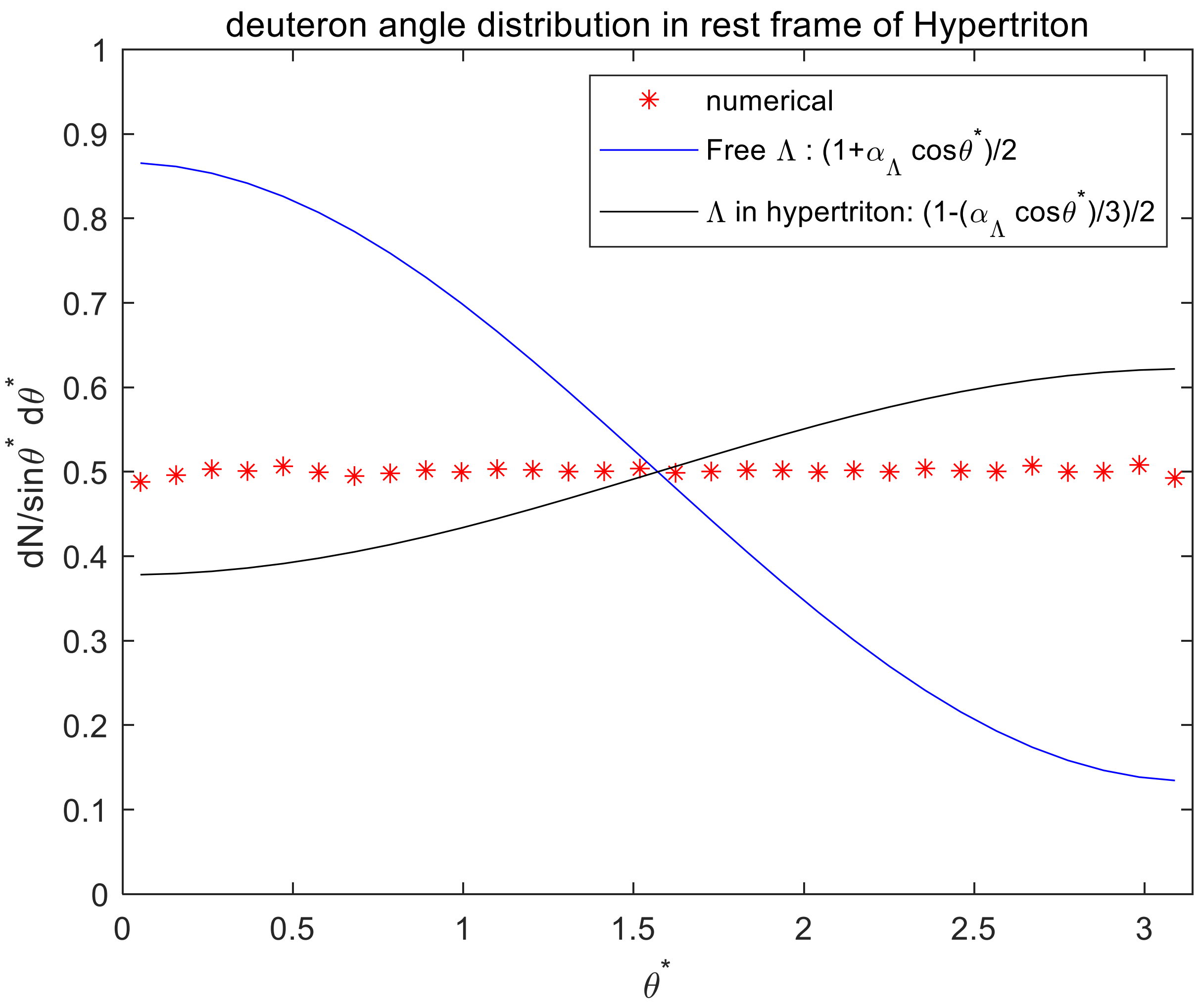
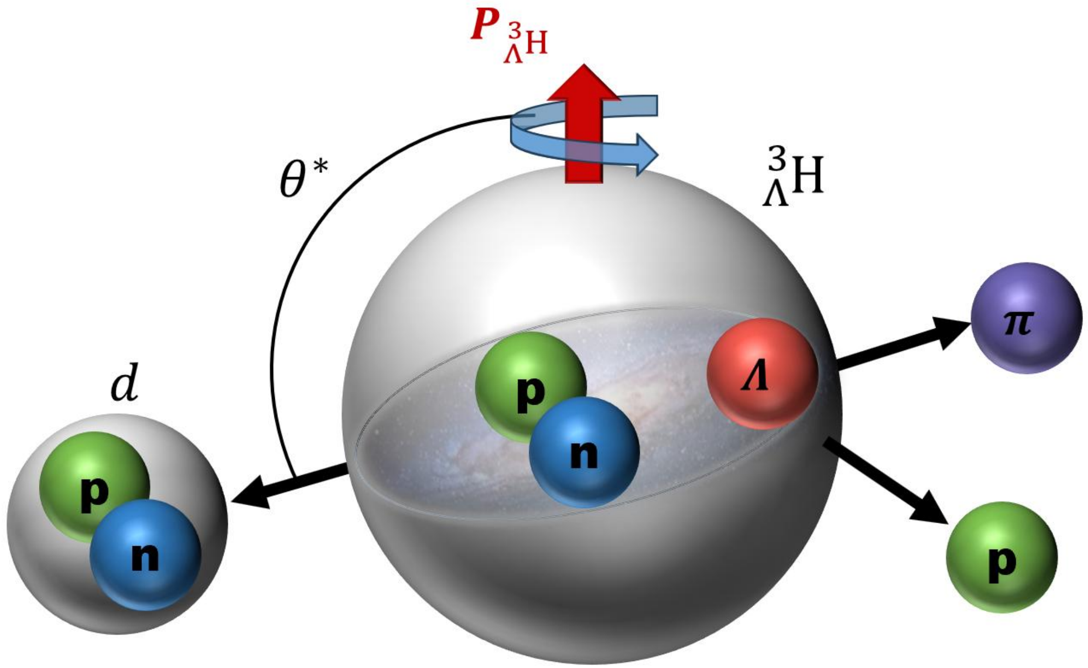
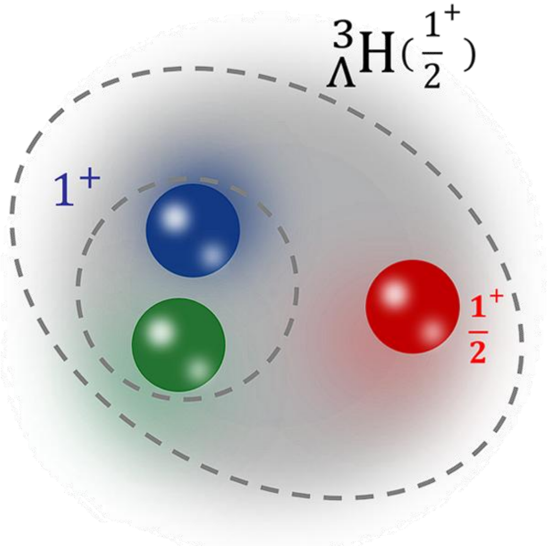




2. (Anti-)Hypertriton Polarization with Spin-1/2 Triglet



➢ Spin wavefunction

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

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

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

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

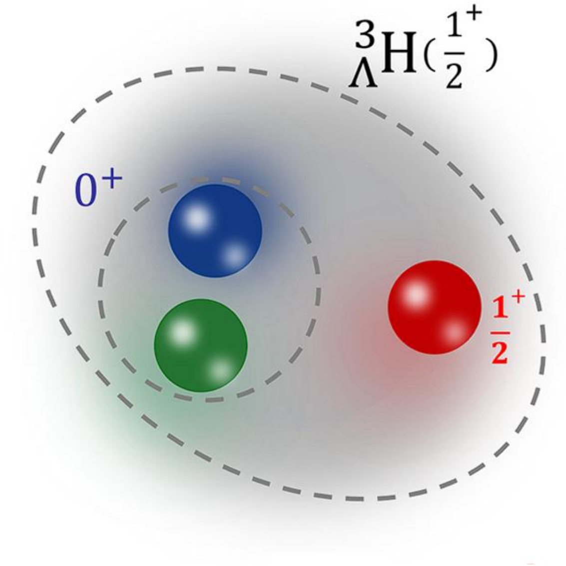
$$E\frac{d^3N_{^3_\Lambda\mathrm{H},\pm\frac{1}{2}}}{d\mathbf{P}^3} = E\int \prod_{i=n,p,\Lambda} p_i^\mu d^3\sigma_\mu \frac{d^3p_i}{E_i}\bar{f}_i(\mathbf{x}_i,\mathbf{p}_i) \times \left(\frac{2}{3}w_{n,\pm\frac{1}{2}}w_{p,\pm\frac{1}{2}}w_{\Lambda,\mp\frac{1}{2}} + \frac{1}{6}w_{n,\pm\frac{1}{2}}w_{p,\mp\frac{1}{2}}w_{\Lambda,\pm\frac{1}{2}}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

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

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

Spin polarizations and correlations are small

2. (Anti-)Hypertriton Polarization with Spin-1/2 Singlet

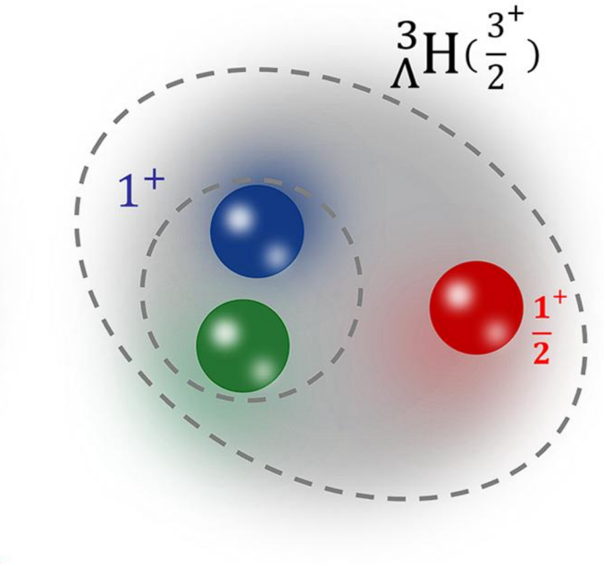


The polarization of hypertriton is solely determined by that of the Λ hyperon

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

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

2. (Anti-)Hypertriton Polarization with Spin-3/2



- **Density matrix**

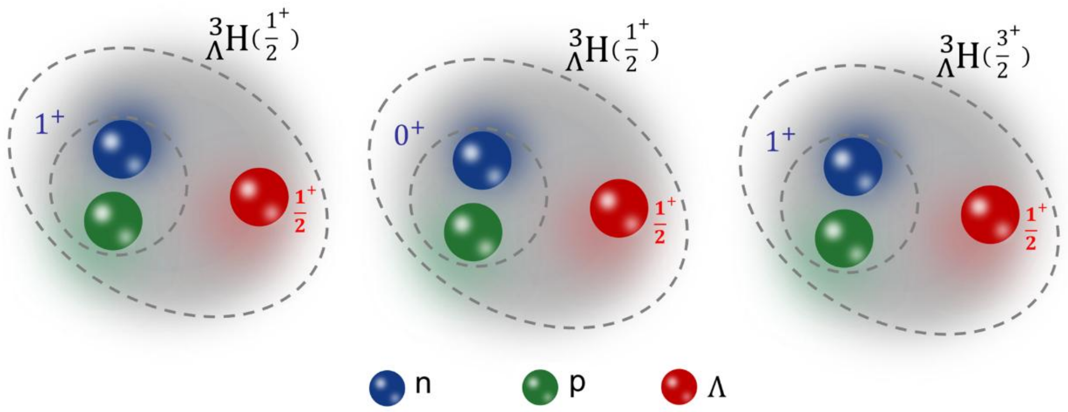
$$\hat{\rho}_{^3_\Lambda\mathrm{H}} \approx \mathrm{diag}\left[\frac{(1+\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)(1+\mathcal{P}_\Lambda)^2}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^2(1+\mathcal{P}_\Lambda)}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}\right]$$

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

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

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

2. (Anti-)Hypertriton Polarization with Spin Structure



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