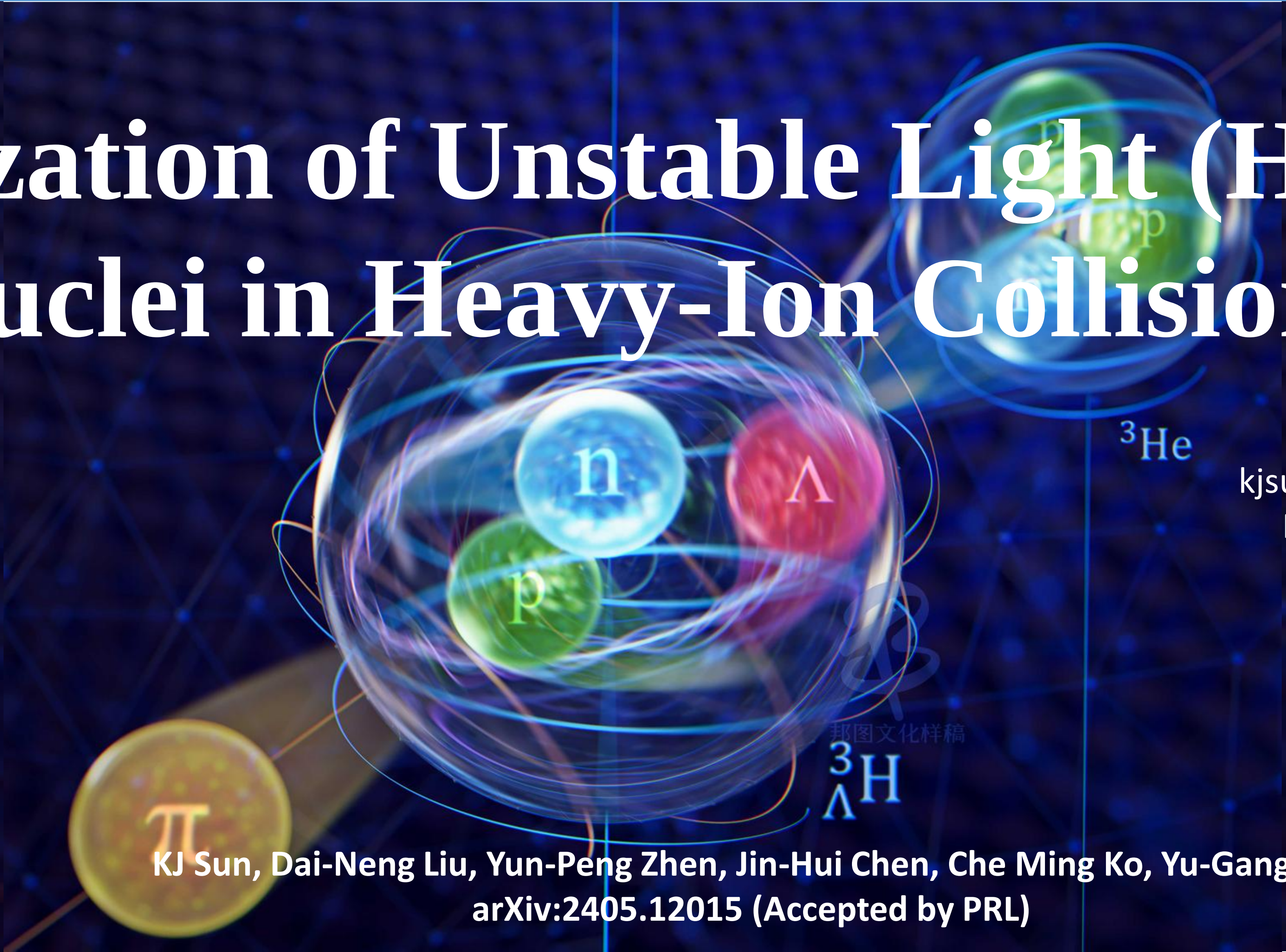
USTC-PNP-Nuclear Physics Mini Workshop Series

Polarization of Unstable Light (Hyper-) Nuclei in Heavy-Ion Collisions



孙开佳
kjsun@fudan.edu.cn;
Fudan University

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KJ Sun, Dai-Neng Liu, Yun-Peng Zhen, Jin-Hui Chen, Che Ming Ko, Yu-Gang Ma

arXiv:2405.12015 (Accepted by PRL)

Outline

1. From polarization of hadrons to polarization of loosely-bound nuclei

2. Production of light (hyper-)nuclei in heavy-ion collisions

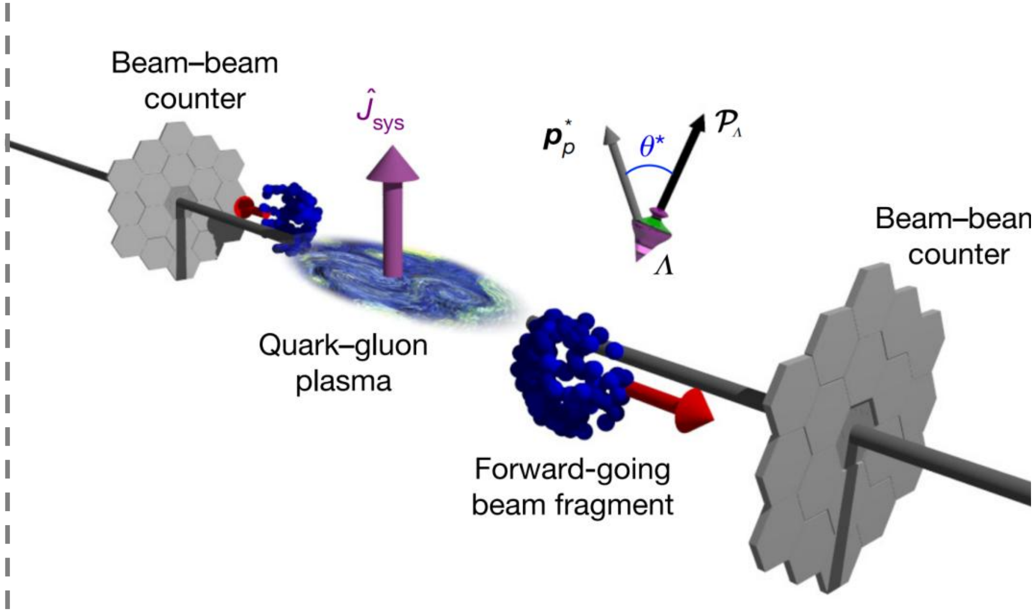
3. (Anti-)Hypertriton polarization and its spin structure

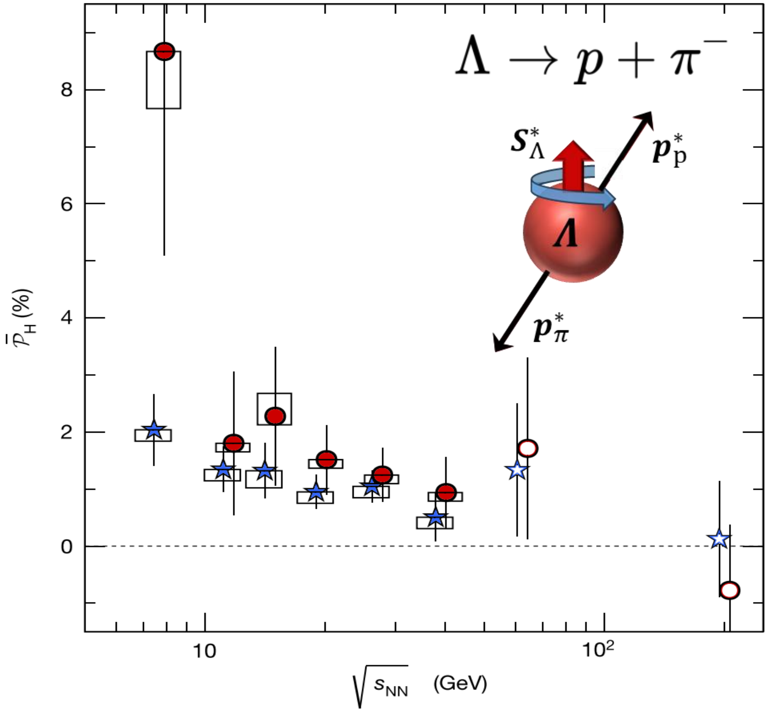
4. Discussions: Effects of baryon spin correlations & Polarization of nucleons

5. Summary and outlook

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

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





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

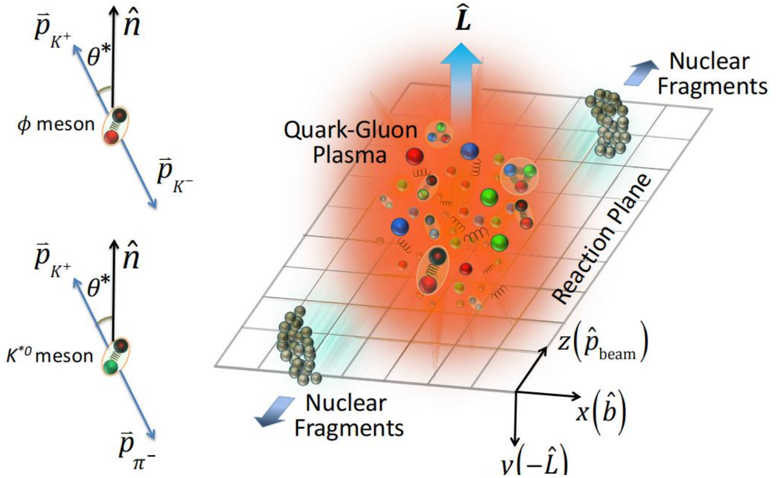
$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle \sin(\Psi_1^{obs} - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}$$

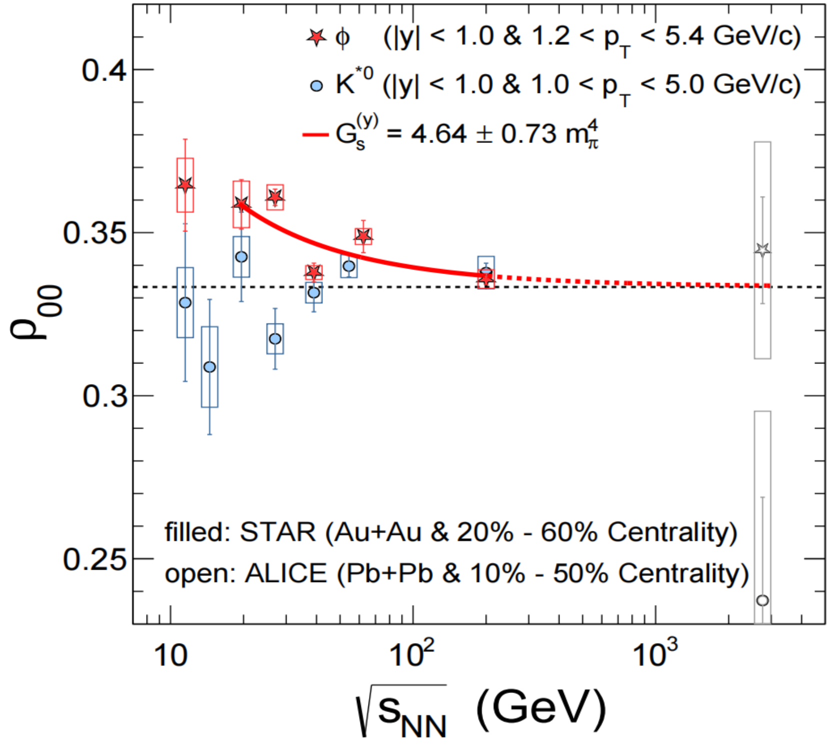
$$\omega \approx k_B T(\overline{\mathcal{P}}_\Lambda + \overline{\mathcal{P}}_{\bar{\Lambda}})/\hbar$$
$$\approx (9 \pm 1) \times 10^{21}\ s^{-1}$$

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

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

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

1. Polarization of light (anti-)(hyper-)nuclei (3)

Elementary hadrons

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

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

$J/\psi(c\bar{c})$ …

→

Unstable (anti-)(hyper-)nuclei

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

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

…

Stable (anti-)nuclei

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

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

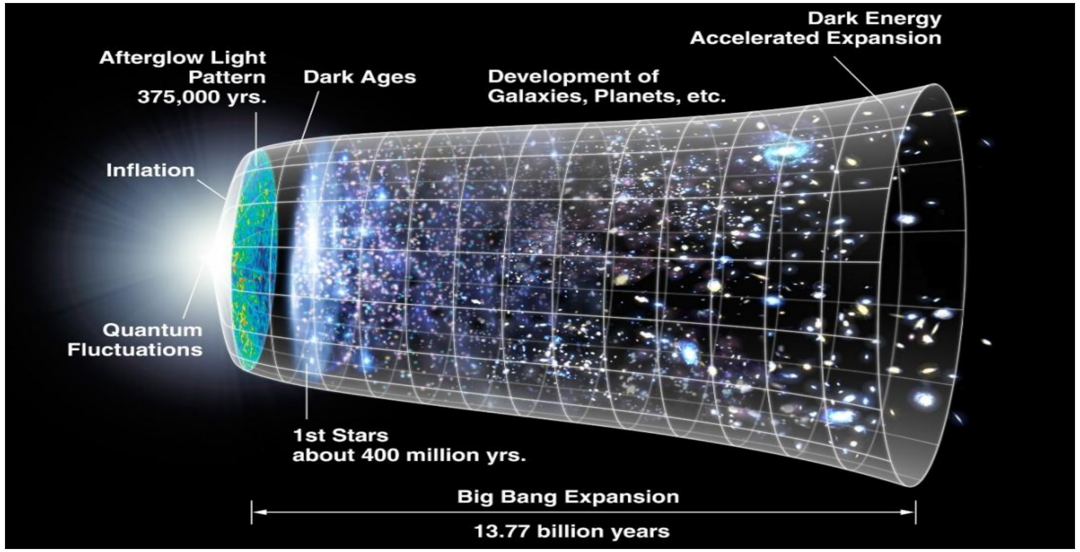
…

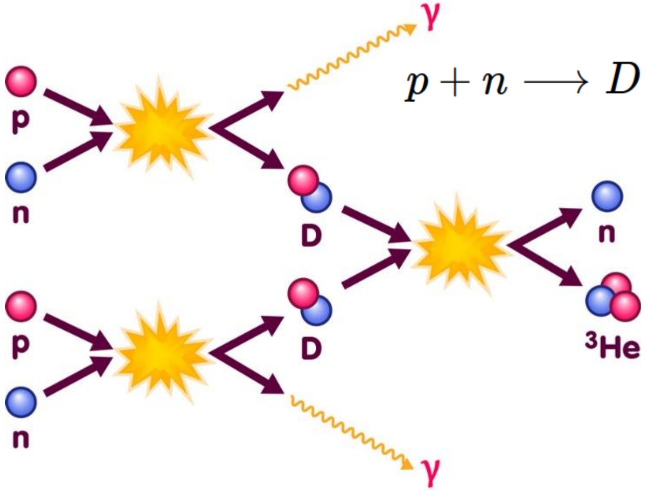
2. Little-Bang Nucleosynthesis

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

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

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





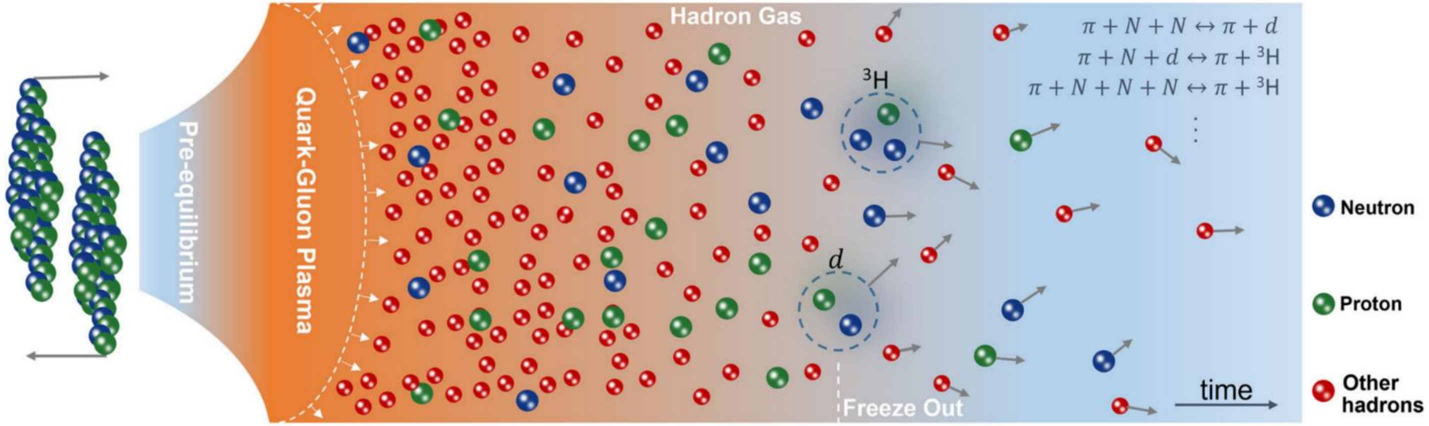
$$p + n \longrightarrow D + \gamma$$

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

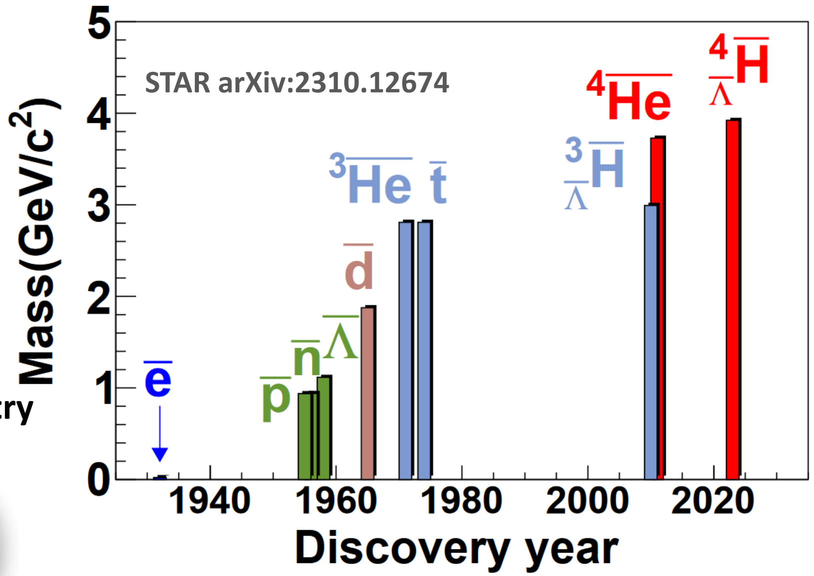
Synthesis of antimatter nuclei in little bangs of relativistic heavy-ion collisions

$t \sim 10^{-22}\ s, kT \sim 100\ \mathrm{MeV}$

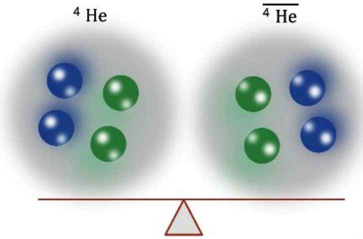
K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024)



Antimatter factory



Matter-antimatter asymmetry



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

2. Production Mechanisms : When? Where? How?

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, PLB 697, 203 (2011)
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561, 321 (2018)
V. Vovchenko et al., PLB785, 171 (2018);PLB800, 135131 (2020) (Saha Eq.);
T. Neidig et al., PLB827,136891(2022)(Rate Eq.);...

Thermal Production from QGP (**canonical effect**)

$$N_A \approx g_A V (2\pi m_A T)^{3/2} e^{(A\mu_B - m_A)/T}$$

Little Bang Nucleosynthesis

Final-sate Coalescence (**quantum correction**)

J. I. Kapusta, Phys. Rev. C 21, 1301 (1980)
H. Sato and K. Yazaki, PLB98, 153 (1981);
E. Remler, Ann. Phys. 136, 293 (1981);
M. Gyulassy, K. Frankel, and E. Remler, NPA402,596 (1983);
S. Mrowczynski, J. Phys. G 13, 1089 (1987);
S. Leupold and U. Heinz, PRC50, 1110 (1994);
R. Scheibl and U. W. Heinz, PRC59. 1585(1999);
K. J. Sun, C. M. Ko and B. Donigus, PLB 792, 132 (2019);
S. Sombun et al., PRC99, 014901 (2019)
F. Bellini et al., PRC99,054905(2019);
PRC 103, 014907(2021);
W. Zhao et al., PLB 820, 136571(2021);
S. Wu et al., arXiv:2205.14302(2022);...

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

Regeneration & Dissociation (**re-scattering effect**)

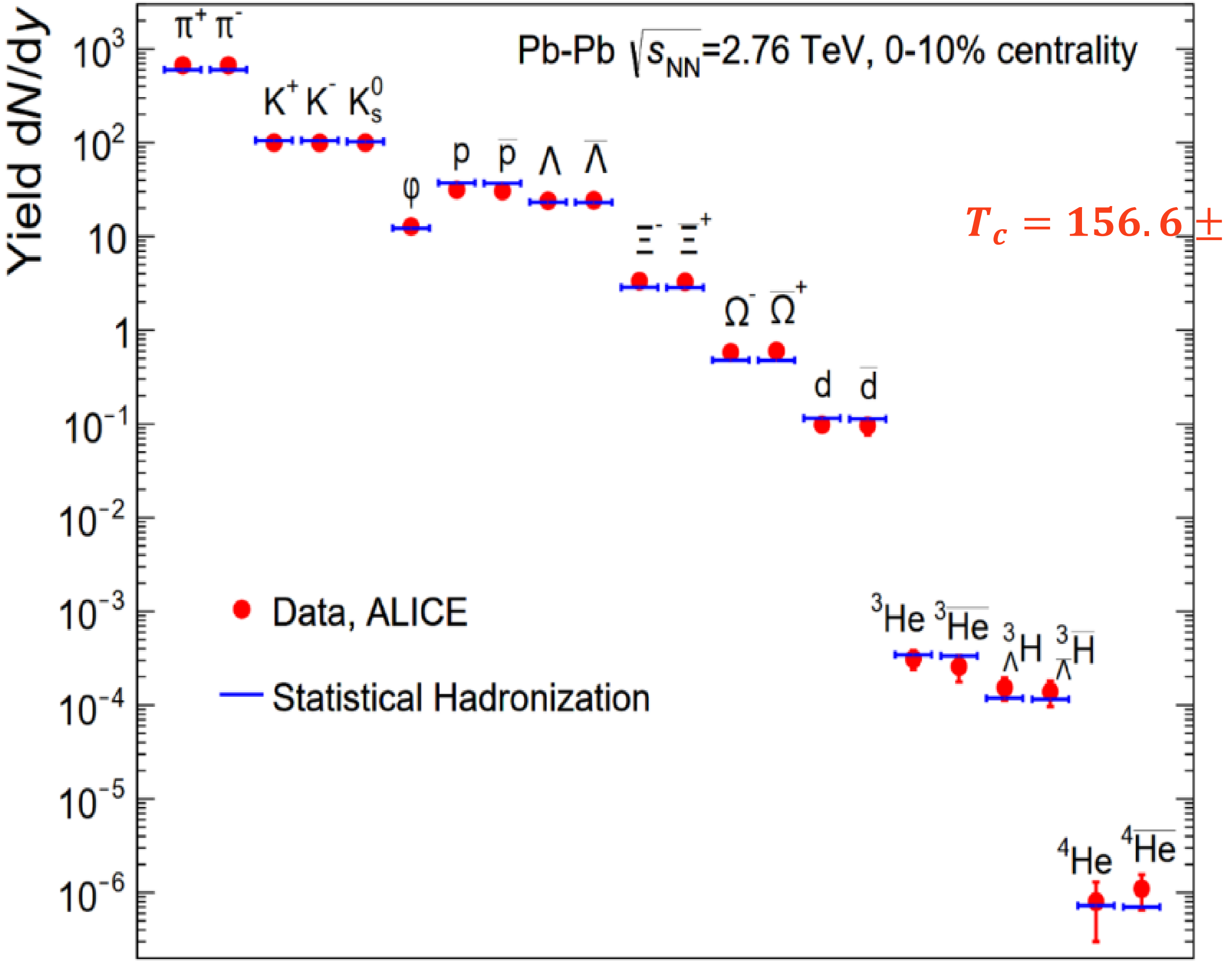
A.Z. Mekjian, PRC17,1051 (1978); P. Danielewicz, G.F. Bertsch, NPA533, 712 (1991); P. Danielewicz and P. Schuck, PLB274, 268 (1992);Y. Oh and C. M. Ko PRC76, 054910(2007);PRC80, 064902(2009);D. Oliinychenko, L. G. Pang, H. Elfner, and V. Koch, PRC99, 044907 (2019); K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, and C. Shen, 2207.12532(2022)

$$\pi NN \leftrightarrow \pi d$$
$$\pi NNN \leftrightarrow \pi t(h), \pi Nd \leftrightarrow \pi t(h)$$

1. Statistical hadronization or final-state coalescence?
2. Does finite nuclear size play any role?
3. Does post-hadronization dynamics have visible effects?
4. Any medium effect?

2. Statistical hadronization

Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561, 321 (2018)



$\boldsymbol{T_c = 156.6 \pm 1.7}$ **MeV**

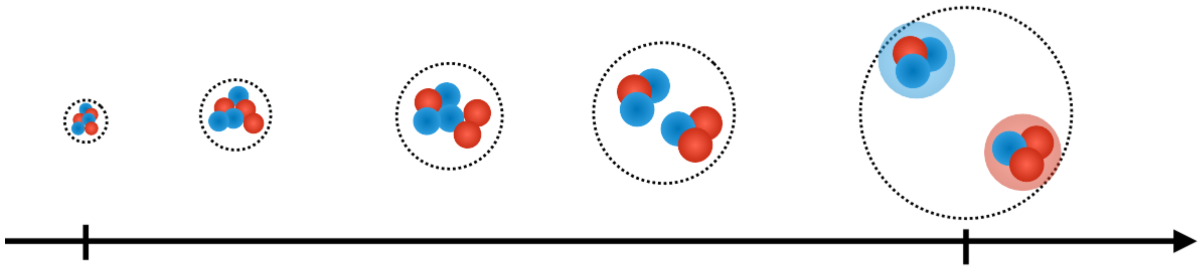
$$N_h \approx \frac{g_h V_C}{2\pi^2} m_h^2 T_C K_2\left(\frac{m_h}{T_C}\right)$$

$$\approx g_h V_C \left(\frac{m_h T_C}{2\pi}\right)^{3/2} e^{-m_h/T_C}$$

T_C: Chemical freeze-out temperature, which is close to the chiral transition temperature (LQCD)

All (stable) particles including light (hyper)nuclei are produced at the QCD phase boundary and share a common chemical freeze-out

Compact multi-quark states loosely bound states

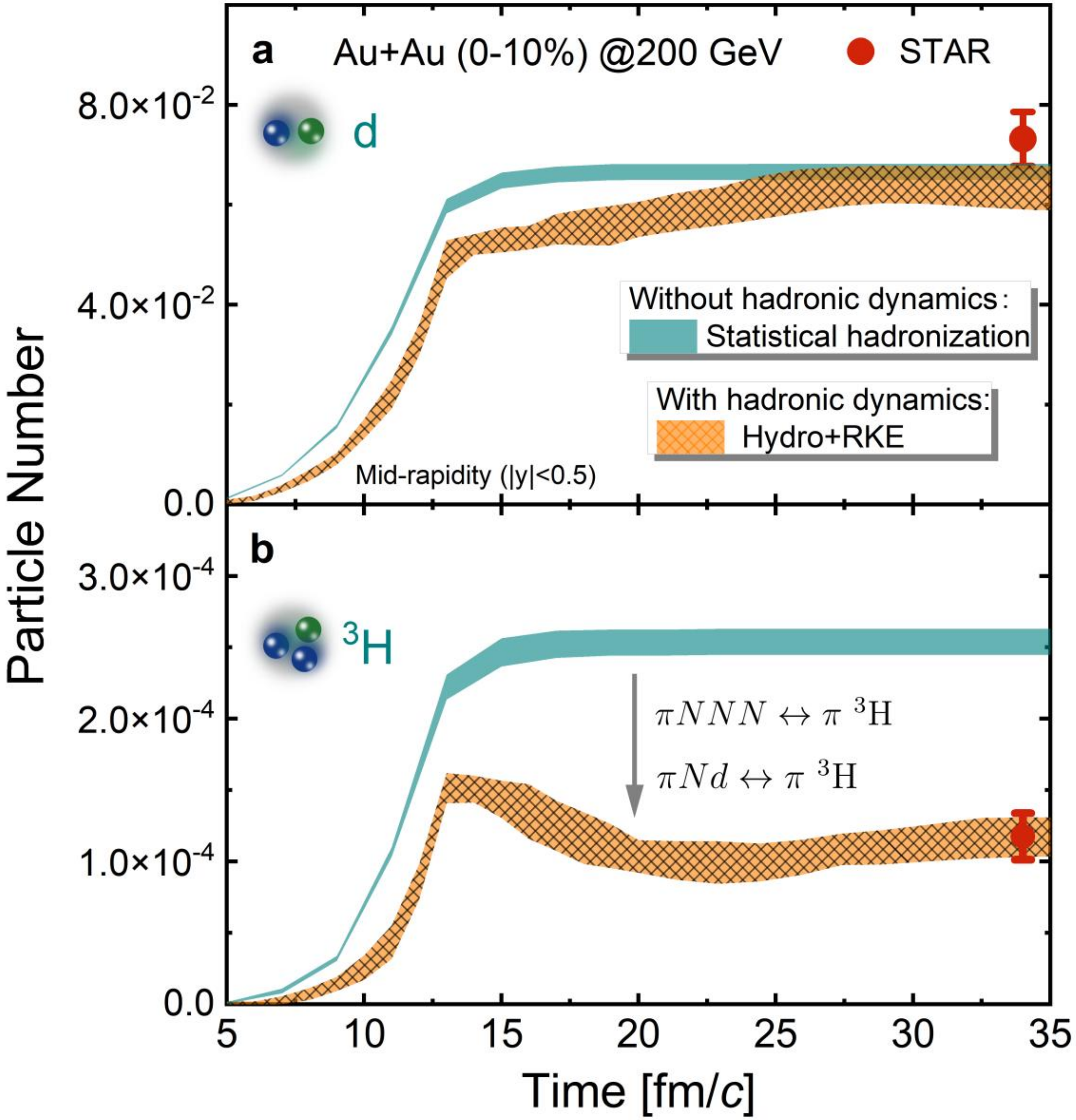


$\tau = 0$ fm/c
Hadronization

$\tau > 10 - 20$ fm/c
Wave function fully developed

2. Hadronic Re-Scattering Effects at RHIC

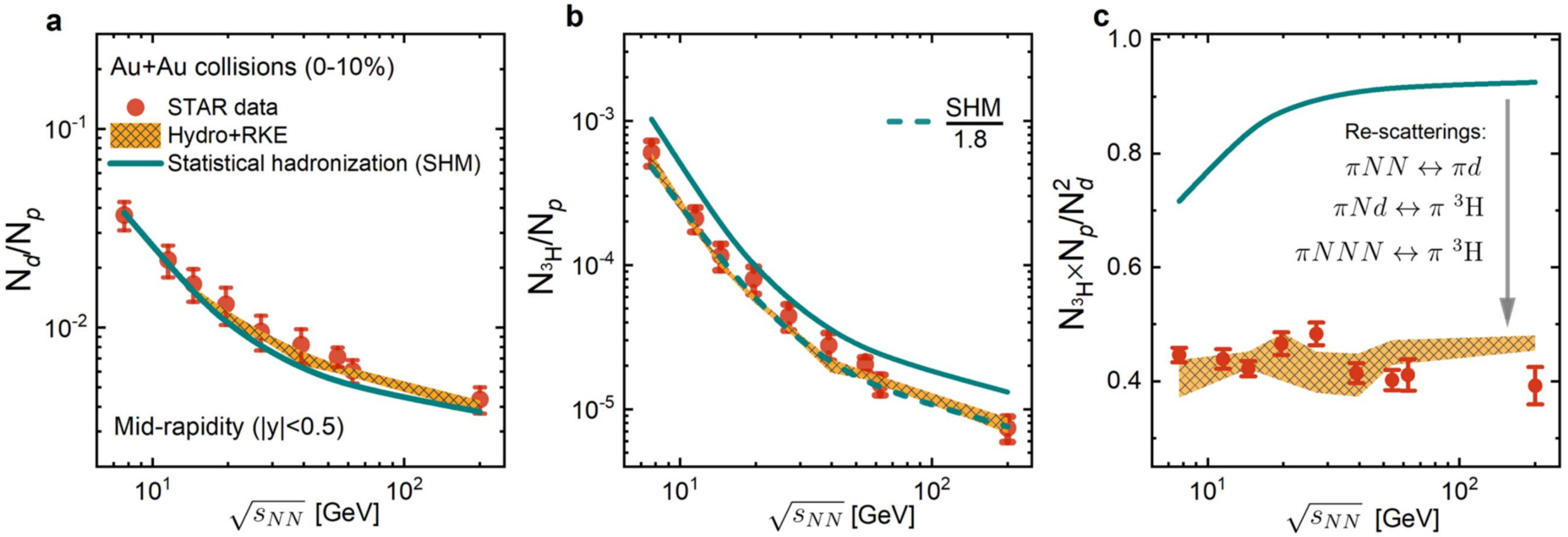
K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)
Data from STAR, PRL 130, 202301 (2023)



- A = 2 $\pi NN \leftrightarrow \pi d$, $NNN \leftrightarrow Nd$
- A = 3 $\pi NNN \leftrightarrow \pi t(h)$, $\pi Nd \leftrightarrow \pi t(h)$, $NNNN \leftrightarrow Nt(h)$, $NNd \leftrightarrow Nt(h)$, and etc.

2. Hadronic Re-Scattering Effects at RHIC

K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nat. Commun. 15, 1074 (2024)
Data from STAR, PRL 130, 202301 (2023)



Hadronic re-scatterings have small effects on the final deuteron yields (see also D. Oliinychenko et al. PRC 99, 044907 (2019)), but they reduce the triton yields by about a factor of 1.8.

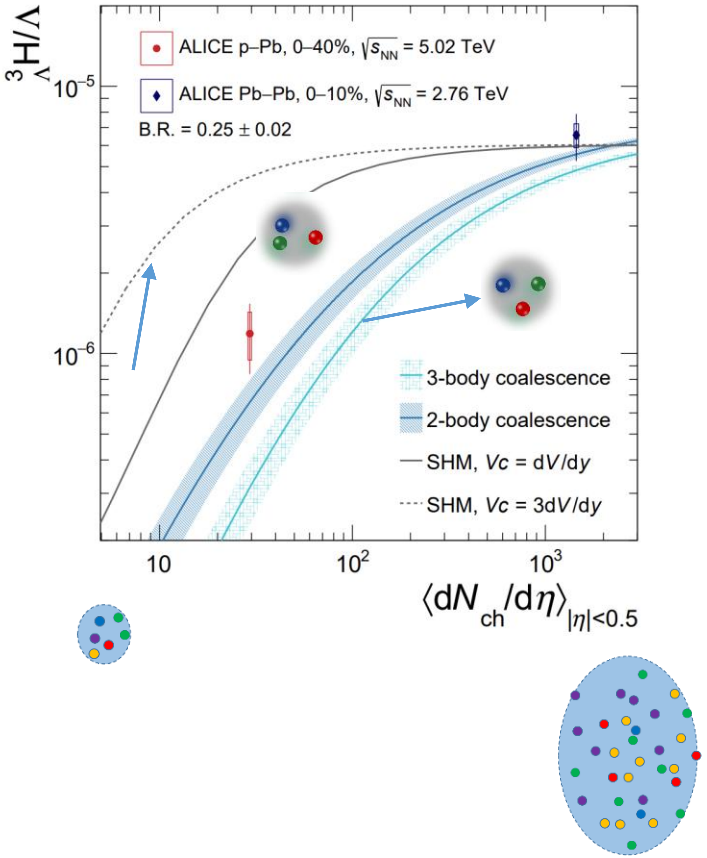
2. Final-state coalescence

Density Matrix Formulation (sudden approximation)

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

ALICE Results（ ${}^3_\Lambda\mathrm{H}$ ）

Phys. Rev. Lett. 128, 055203(2022)



"Quantum mechanical correction"

Two-body coalescence $a + b \to c$:

$$N_c = \frac{2J_c+1}{(2J_a+1)(2J_b+1)} \int \frac{dx_a dk_a}{(2\pi)^3} \frac{dx_b dk_b}{(2\pi)^3} f_a(x_a,k_a) f_b(x_b,k_b) W_c(x,k)$$

$$\approx \frac{2J_c+1}{(2J_a+1)(2J_b+1)} \frac{N_a N_b}{\left(\frac{m_a m_b T}{m_a+m_b}(R_a^2+R_b^2)\right)^{3/2}} \times \frac{1}{\left(1+\frac{\sigma^2}{R_a^2+R_b^2}\right)^{3/2}}$$

$$f_a = \frac{N_a}{(m_a T R_a^2)^{3/2}} e^{-\frac{k_a^2}{2m_a T} - \frac{x_a^2}{2R_a^2}} \qquad W_c = 8e^{-x^2/\sigma^2 - \sigma^2 k^2}$$

$$N_a = \int \frac{dx_a dk_a}{(2\pi)^3} f_a(x_a,k_a) \qquad 1 = \int \frac{dx dk}{(2\pi)^3} W_c(x,k)$$

$$N_d \propto \frac{1}{\left[1+\left(\frac{2r_d^2}{3R^2}\right)\right]^{\frac{3}{2}}}$$

Production

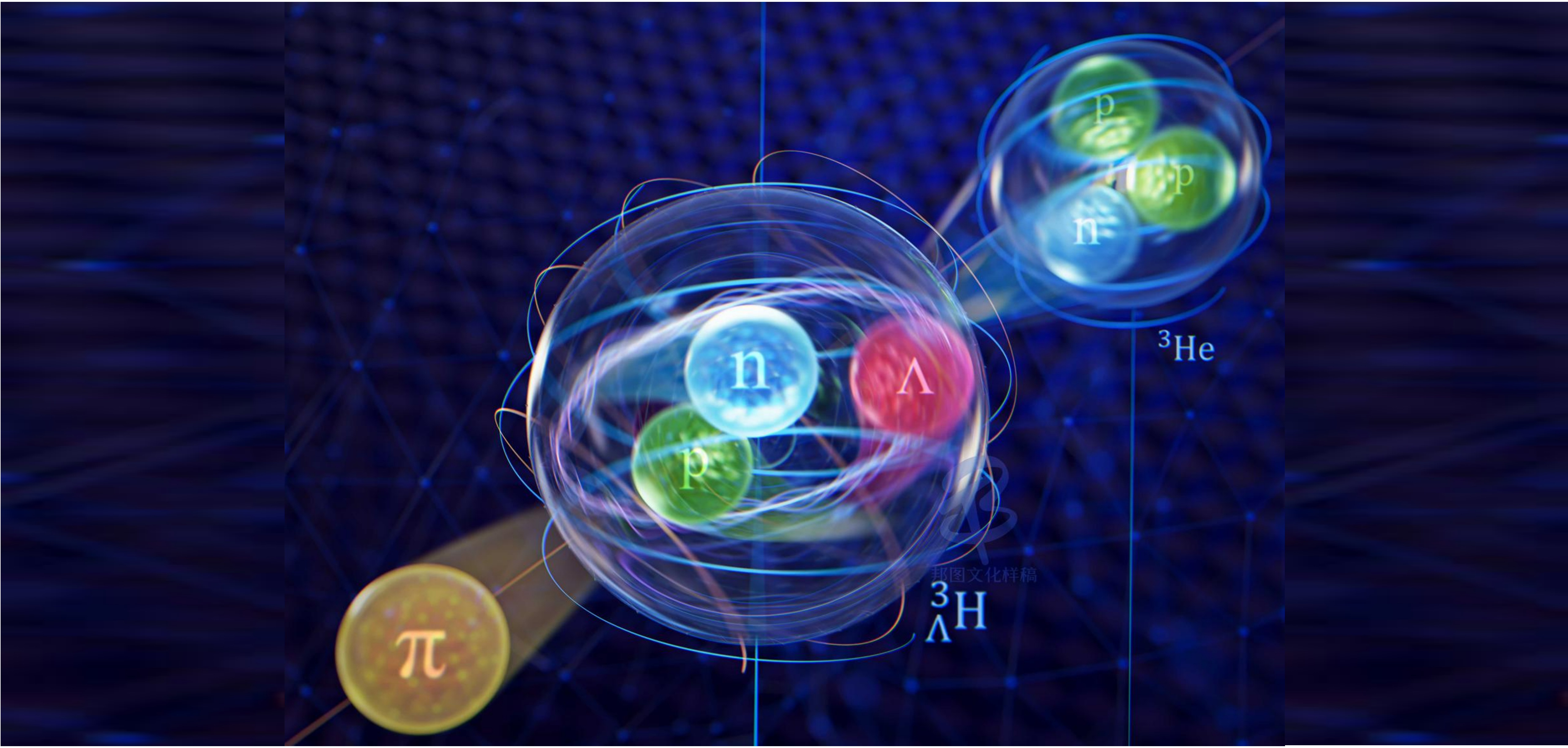
Structure

$$N_{{}^3_\Lambda\mathrm{H}} \propto \frac{1}{\left[1+\left(\frac{r^2_{{}^3_\Lambda\mathrm{H}}}{2R^2}\right)\right]^{3}}$$

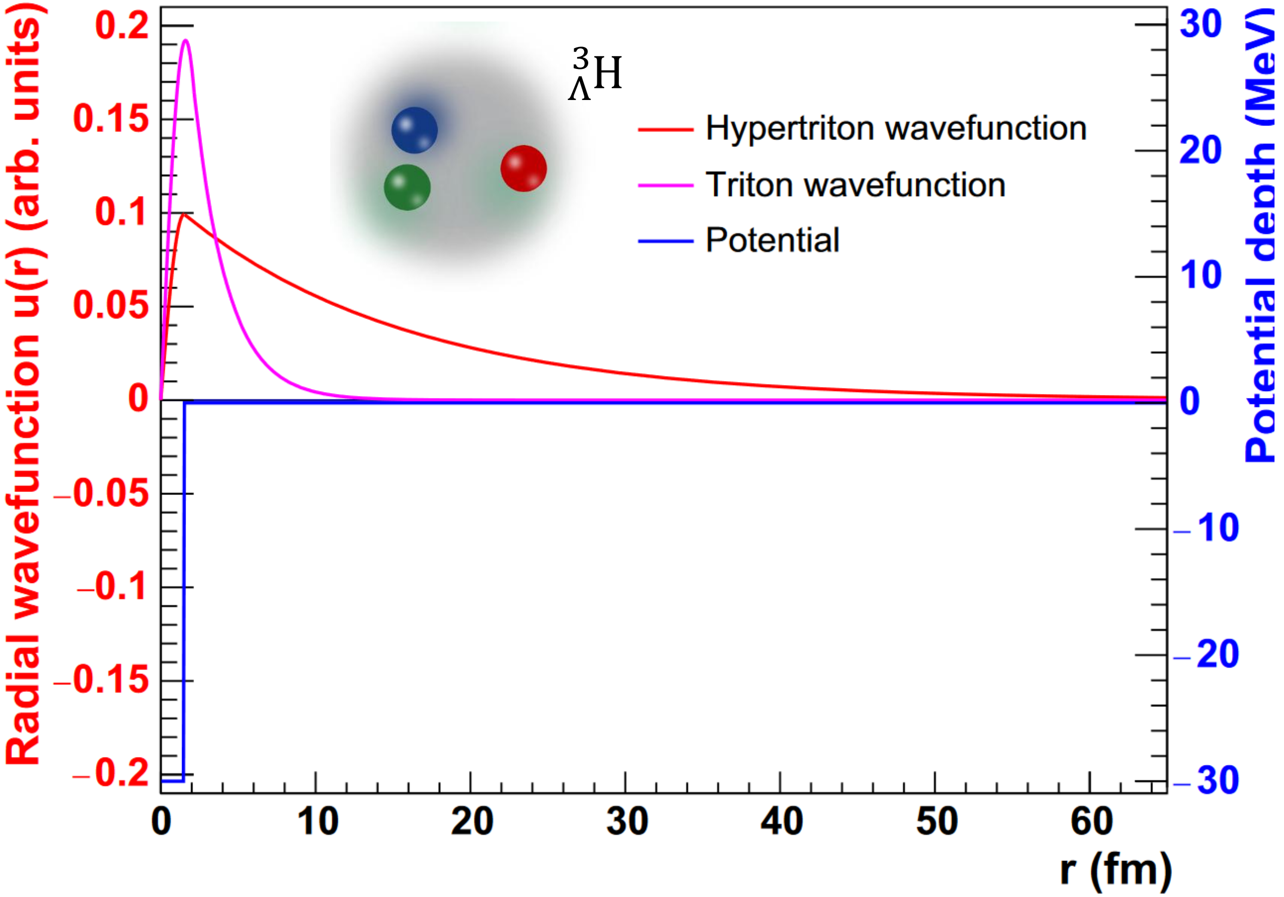
can be inferred from Femtoscopy

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);

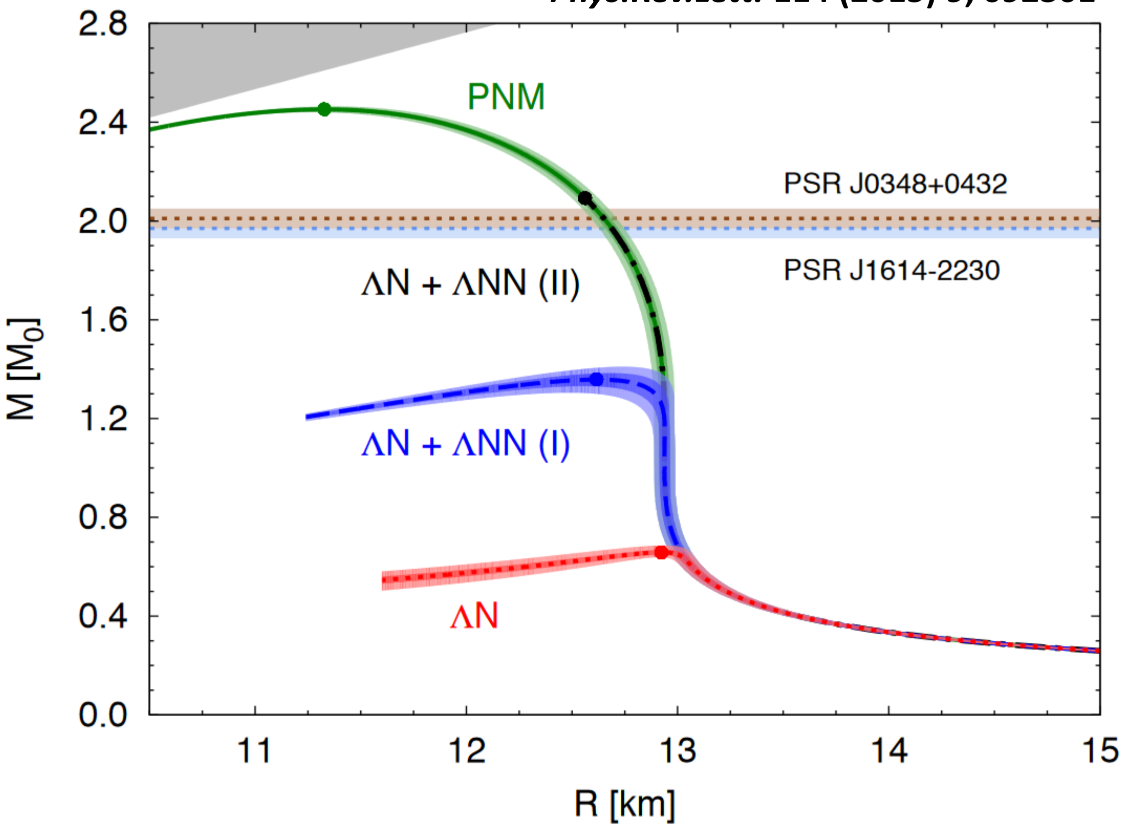
(Anti-)Hypertriton Polarization



3. The halo-like nucleus: (anti-)hypertriton



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

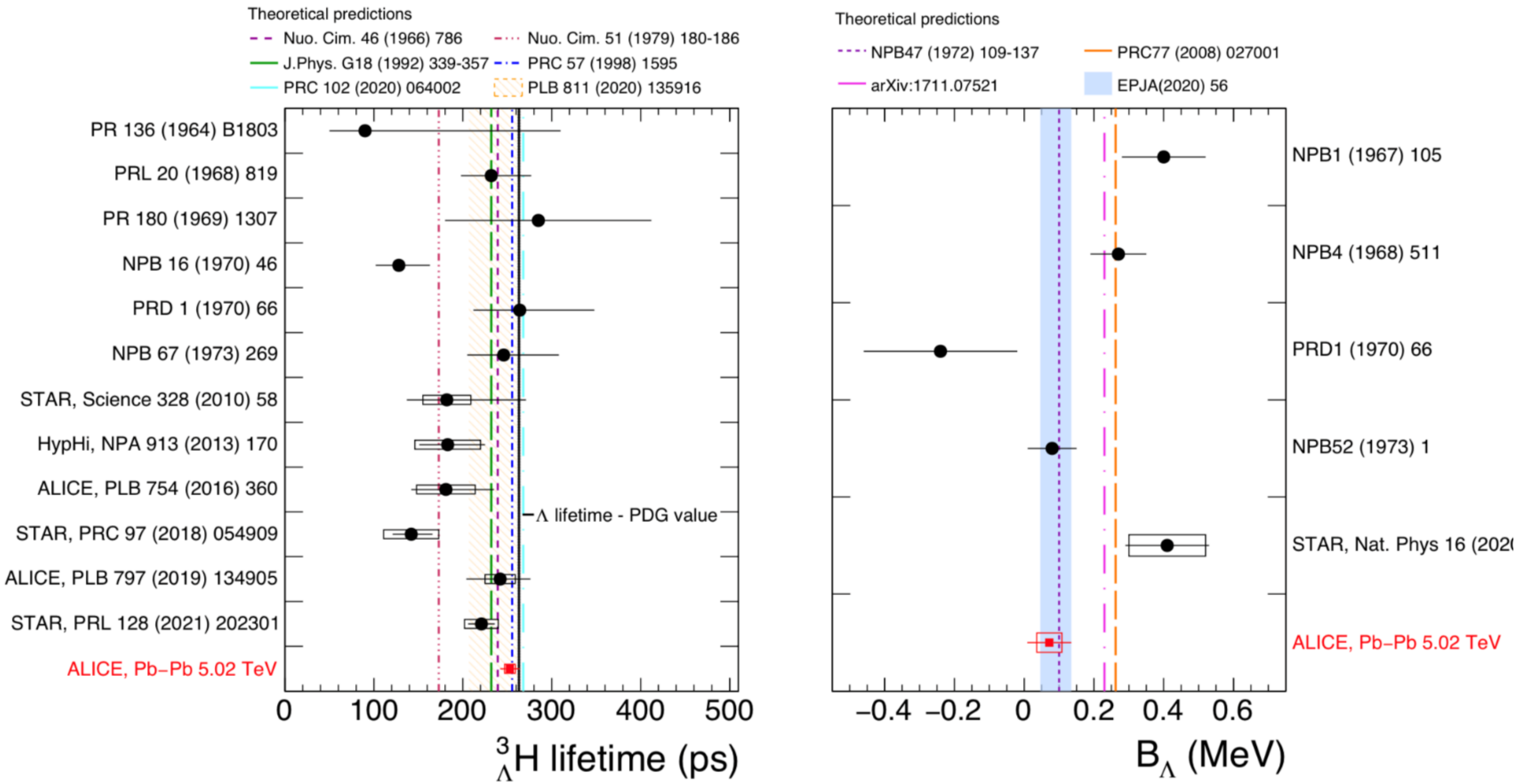


J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)
D. N. Liu et al. Phys. Lett. B 855, 138855 (2024)

3. Binding energy and lifetime

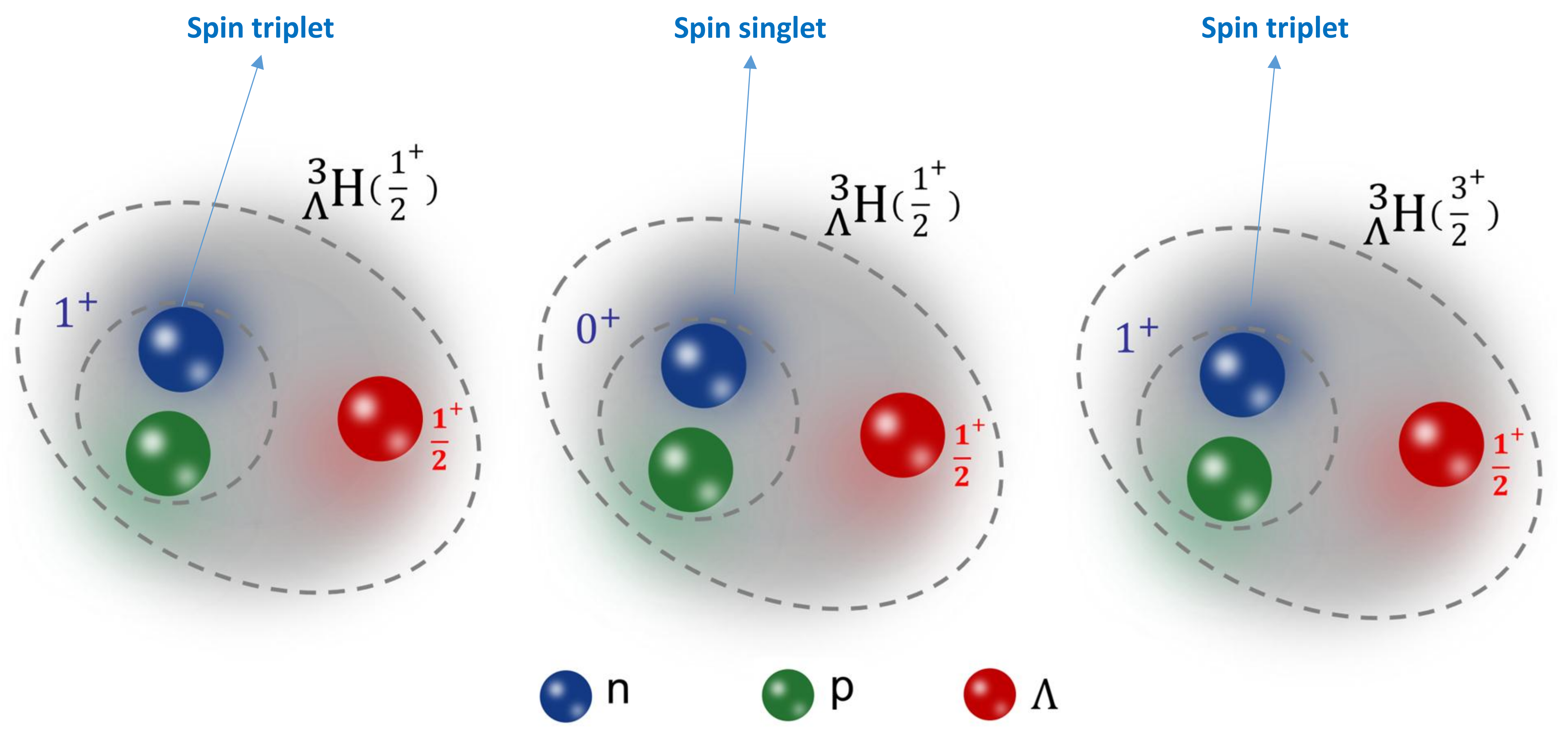
ALICE, PRL 131, 102302 (2023)

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



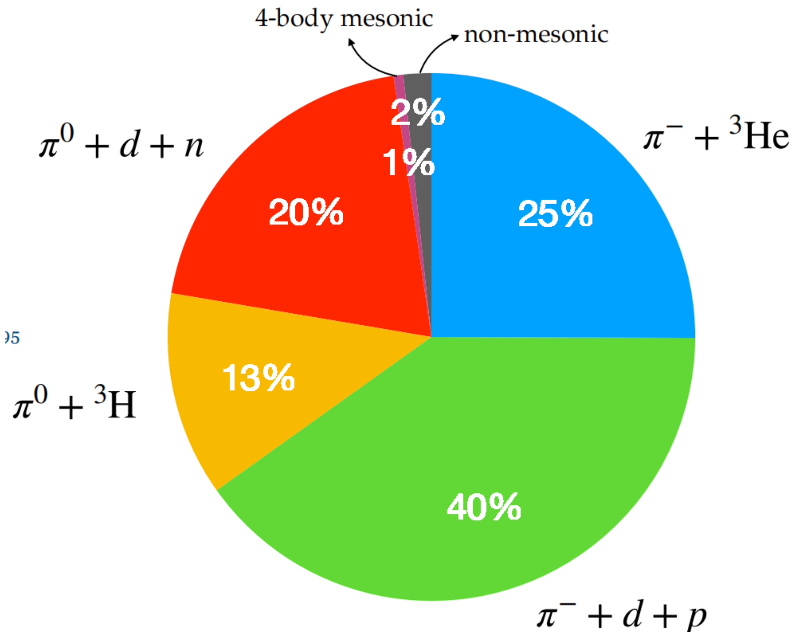
J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)

3. Spin of (anti-)hypertriton ?



3. Spin of (anti-)hypertriton ?

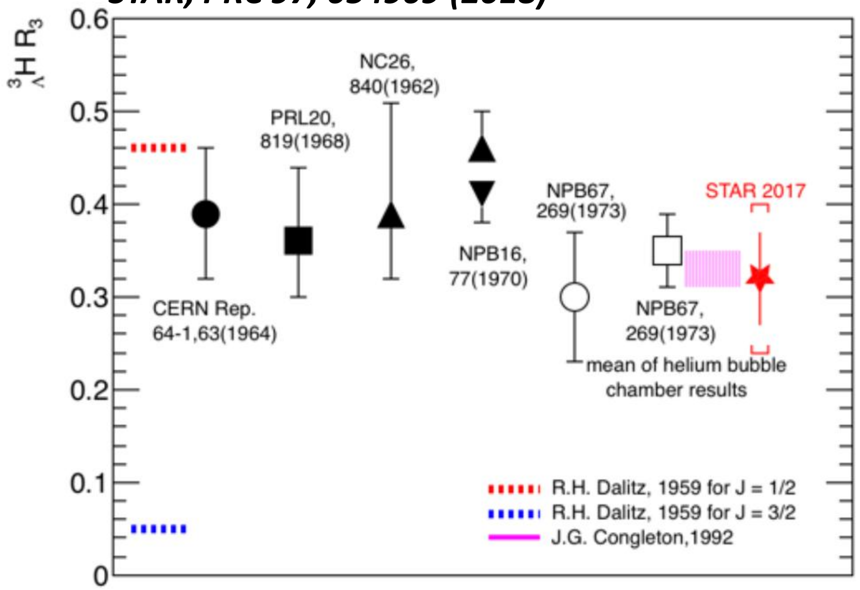
$^3_\Lambda H \mapsto \pi^- + ^3He$, $^3_\Lambda H \mapsto \pi^0 + ^3H$,
$^3_\Lambda H \mapsto \pi^- + d + p$, $^3_\Lambda H \mapsto \pi^0 + d + n$,
$^3_\Lambda H \mapsto \pi^- + p + n + p$, $^3_\Lambda H \mapsto \pi^0 + p + n + n$.



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

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

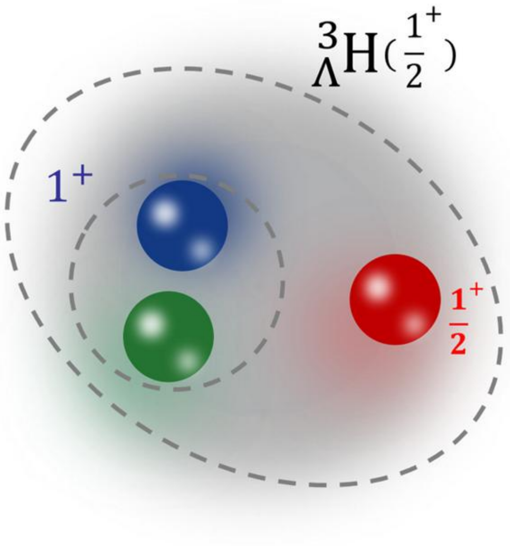
Light nuclei and hypernuclei from quantum chromodynamics in the limit of SU(3) flavor symmetry

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**
^3H, ^3H	3	0	1/2	$1/2^+$	**35**	**35**
$^3_\Lambda H(1/2^+)$	3	−1	0	$1/2^+$	**35**	-
$^3_\Lambda H(3/2^+)$	3	−1	0	$3/2^+$	$\overline{\mathbf{10}}$	$\overline{\mathbf{10}}$
$^3_\Lambda He$, $^3_\Lambda H$, $nn\Lambda$	3	−1	1	$1/2^+$	**27**, **35**	**27**, **35**
$^3_\Sigma He$	3	−1	1	$3/2^+$	**27**	**27**
^4He	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

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



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

Coalescence model for hypertriton production (without baryon spin correlation)

$$E_i\frac{d^3N_{i,\pm\frac{1}{2}}}{d\mathbf{p}_i^3} = \int_{\Sigma^\mu} d^3\sigma_\mu p_i^\mu w_{i,\pm\frac{1}{2}}(\mathbf{x}_i,\mathbf{p}_i)\bar{f}_i(\mathbf{x}_i,\mathbf{p}_i)$$

$$w_{i,\pm\frac{1}{2}} = \tfrac{1}{2}[1\pm\mathcal{P}_i(\mathbf{x}_i,\mathbf{p}_i)]$$

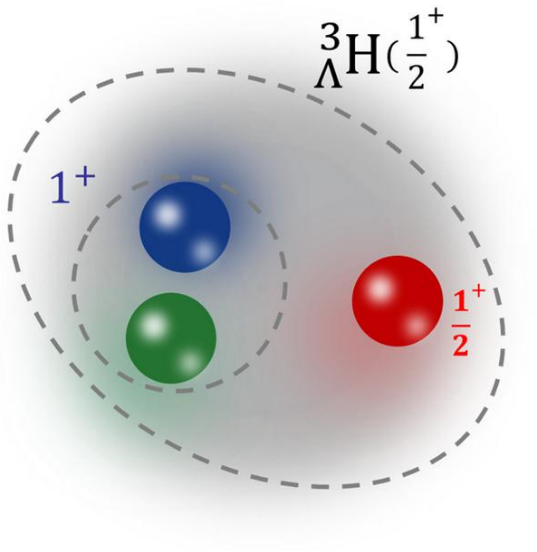
$$\hat{\rho}_i = \mathrm{diag}\left(\tfrac{1+\mathcal{P}_i}{2},\tfrac{1-\mathcal{P}_i}{2}\right)$$

$$\bar{f}_i = \tfrac{g_i}{(2\pi)^3}\left[\exp(p_i^\mu u_\mu/T)/\xi_i+1\right]^{-1}$$

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

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

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



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

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

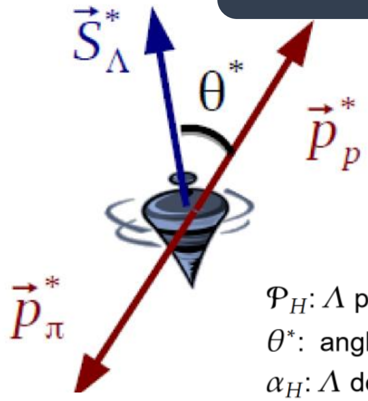
$$\approx \mathcal{P}_\Lambda$$

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

K. J. Sun *et al.*, arXiv:2405. 12015(2024)

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 and 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

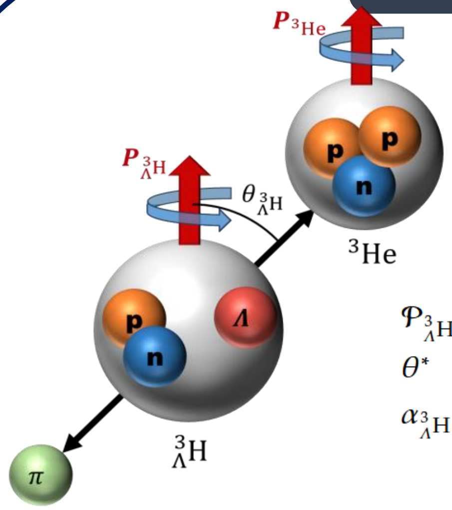
$$T(\Lambda \to \pi^- + p) = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} T_s + T_p\cos\theta_p^* & T_p\sin\theta_p^* e^{i\phi_p^*} \\ T_p\sin\theta_p^* e^{-i\phi_p^*} & T_s - T_p\cos\theta_p^* \end{pmatrix}$$

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



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

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

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

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

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

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

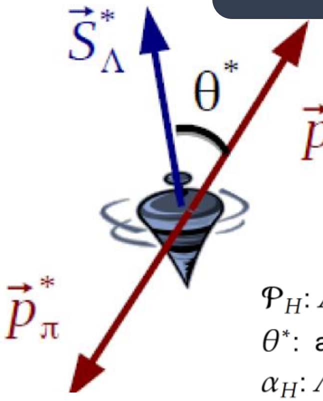
$$\frac{dN}{\mathrm{d}\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_{^3_\Lambda\mathrm{H}}\mathcal{P}_{^3_\Lambda\mathrm{H}}\cos\theta^*\right)$$

3. (Anti-)hypertriton polarization and its spin structure (16)

K. J. Sun *et al.*, arXiv:2405. 12015(2024)

Parity-violating weak decay

Λ hyperons



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

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

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

$\mathcal{P}_H$: Λ polarization

θ^*: angle between proton momentum a…

α_H: Λ decay parameter

$\alpha_\Lambda = 2\mathrm{Re}(T_s^* T_p) = 0.732 \pm 0.01$…

BESIII, Phys. Rev. Lett. 129, 131801 (2…

The transition matrix

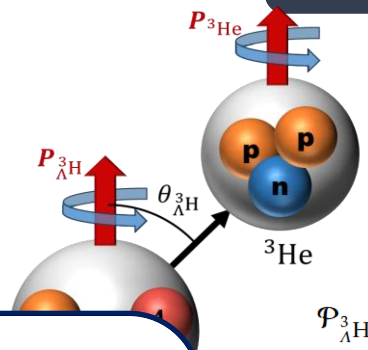
$$T(\Lambda \to \pi^- + p) = \frac{1}{\sqrt{4\pi}} \begin{pmatrix} T_s + T_p\cos\theta_p^* & \ldots \\ T_p \sin\theta_p^* e^{-i\phi_p^*} & \ldots \end{pmatrix}$$

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



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

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

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

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

$$\ldots \pi^- + ^3\mathrm{He})$$

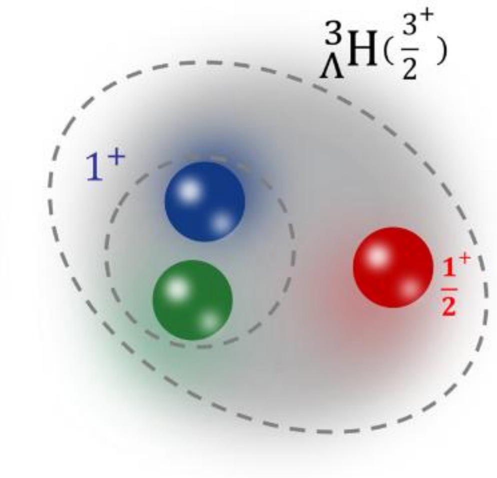
$$\ldots \begin{pmatrix} 3T_s - T_p\cos\theta^* & -T_p\sin\theta^* e^{i\phi^*} \\ -T_p\sin\theta^* e^{-i\phi^*} & 3T_s + T_p\cos\theta^* \end{pmatrix}$$

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

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

Sign flip !

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

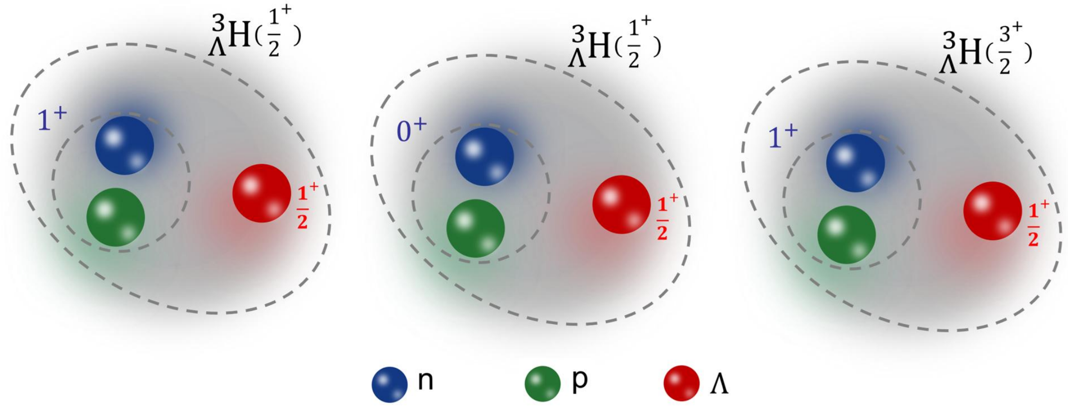


$$\hat{\rho}_{^3_\Lambda H} \approx \mathrm{diag}\left[\frac{(1+\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)(1+\mathcal{P}_\Lambda)^2}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^2(1+\mathcal{P}_\Lambda)}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}\right]$$

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

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

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



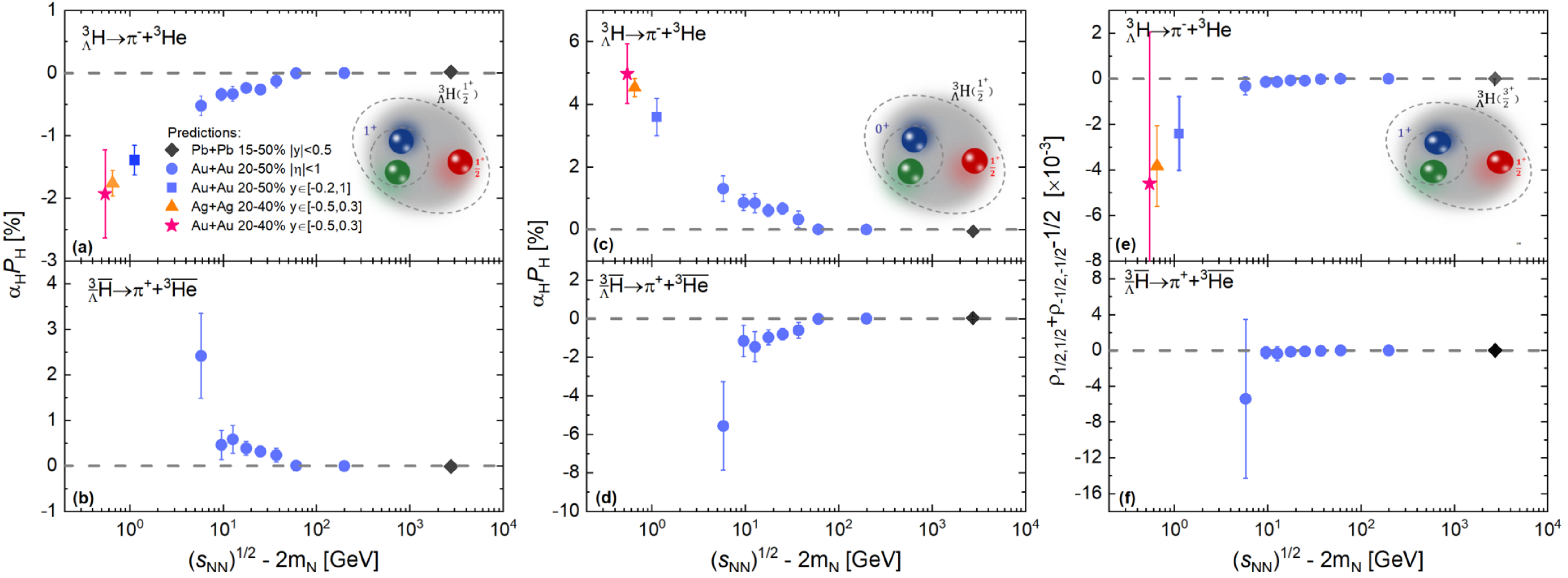
J^P	structure	decay mode	$\frac{dN}{d\cos\theta^*}$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}(1-\frac{1}{2.58}\alpha_\Lambda\mathcal{P}_\Lambda\cos\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(0^+)$	$^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}(1+\alpha_\Lambda\mathcal{P}_\Lambda\cos\theta^*)$
$\frac{3}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda\mathrm{H} \to \pi^- + {}^3\mathrm{He}$	$\frac{1}{2}(1-\mathcal{P}_\Lambda^2(3\cos^2\theta^*-1))$
$\frac{1}{2}^-$	$\bar\Lambda(\frac{1}{2}^-) - \overline{np}(1^-)$	$^3_{\bar\Lambda}\overline{\mathrm{H}} \to \pi^+ + {}^3\overline{\mathrm{He}}$	$\frac{1}{2}(1-\frac{1}{2.58}\alpha_{\bar\Lambda}\mathcal{P}_{\bar\Lambda}\cos\theta^*)$
$\frac{1}{2}^-$	$\bar\Lambda(\frac{1}{2}^-) - \overline{np}(0^-)$	$^3_{\bar\Lambda}\overline{\mathrm{H}} \to \pi^+ + {}^3\overline{\mathrm{He}}$	$\frac{1}{2}(1+\alpha_{\bar\Lambda}\mathcal{P}_{\bar\Lambda}\cos\theta^*)$
$\frac{3}{2}^-$	$\bar\Lambda(\frac{1}{2}^-) - \overline{np}(1^-)$	$^3_{\bar\Lambda}\overline{\mathrm{H}} \to \pi^+ + {}^3\overline{\mathrm{He}}$	$\frac{1}{2}(1-\mathcal{P}_{\bar\Lambda}^2(3\cos^2\theta^*-1))$

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

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

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

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



4. 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

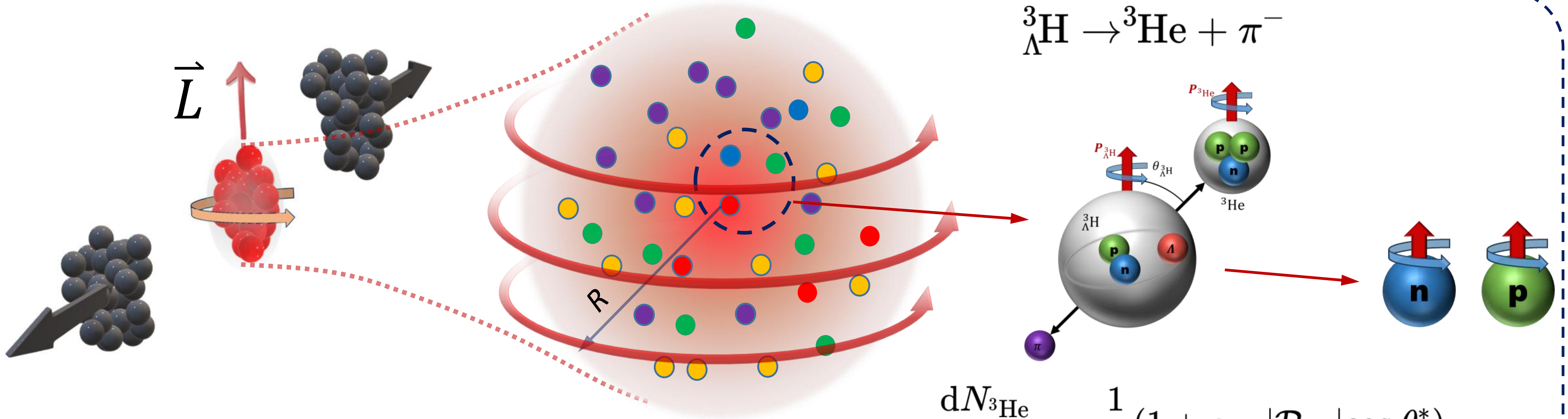
We can express the polarization of a particle as $\mathcal{P} = \langle \mathcal{P} \rangle + \delta\mathcal{P}$ with $\delta\mathcal{P}$ denoting its space and momentum dependent fluctuations, which leads to the relations $\langle \mathcal{P}_n \mathcal{P}_p \rangle = \langle \mathcal{P}_n \rangle \langle \mathcal{P}_p \rangle + \langle \delta\mathcal{P}_n \delta\mathcal{P}_p \rangle$ 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.

4. A possible way to probe polarization of nucleons

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



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

Production of hypertriton

$$ N_A = \int \mathrm{d}\Gamma \, g_c \, p_s(x_i, p_i) \times W_c(x_i, p_i) $$

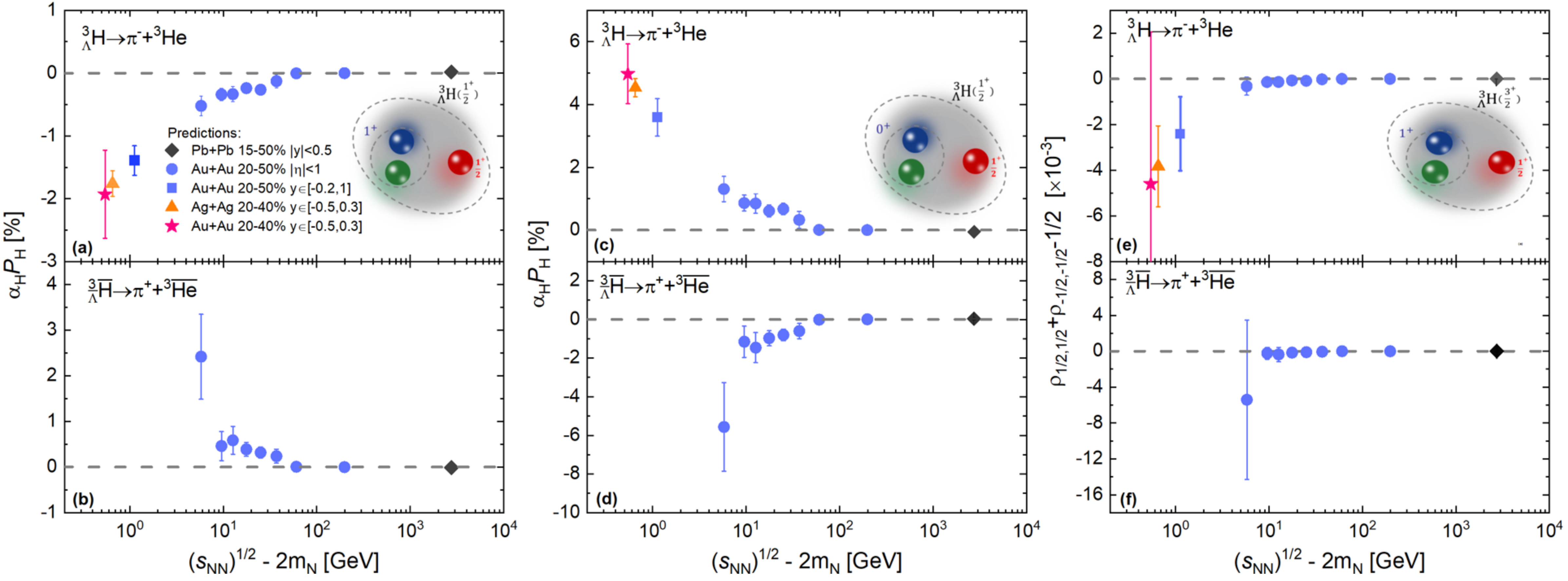
$$ \mathcal{P}_{{}^3_\Lambda\mathrm{H}} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} $$

Polarization of nucleons

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

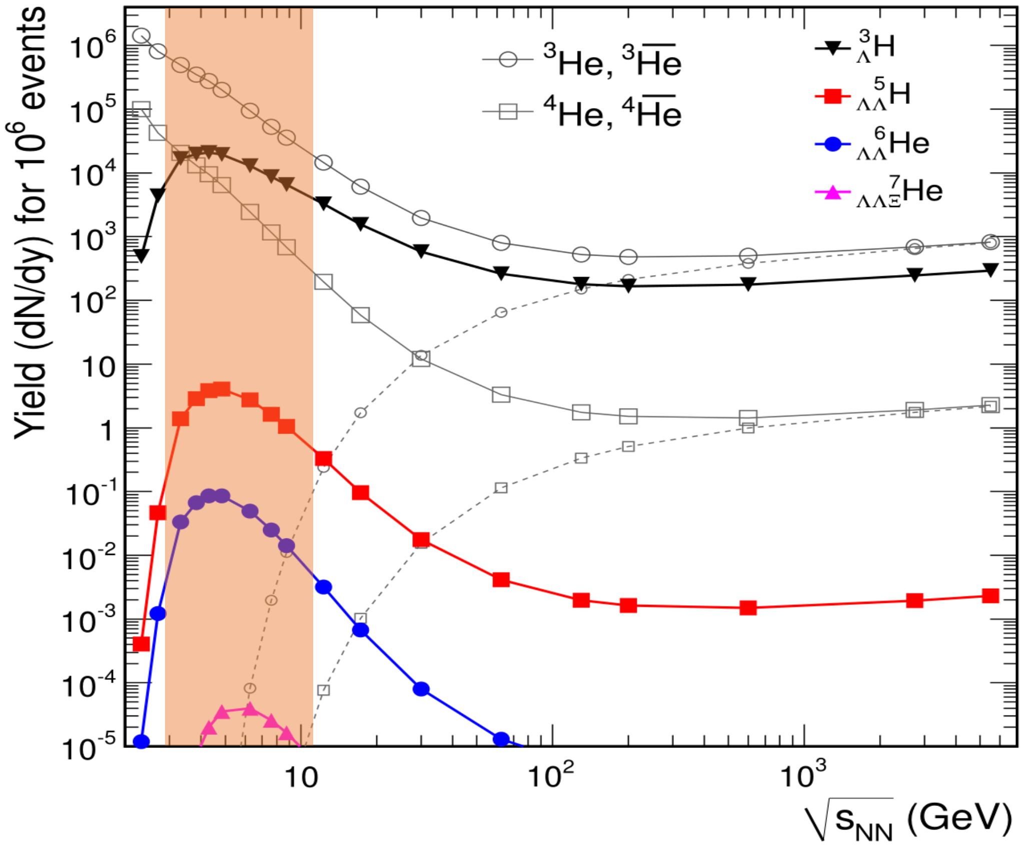
Summary and outlook

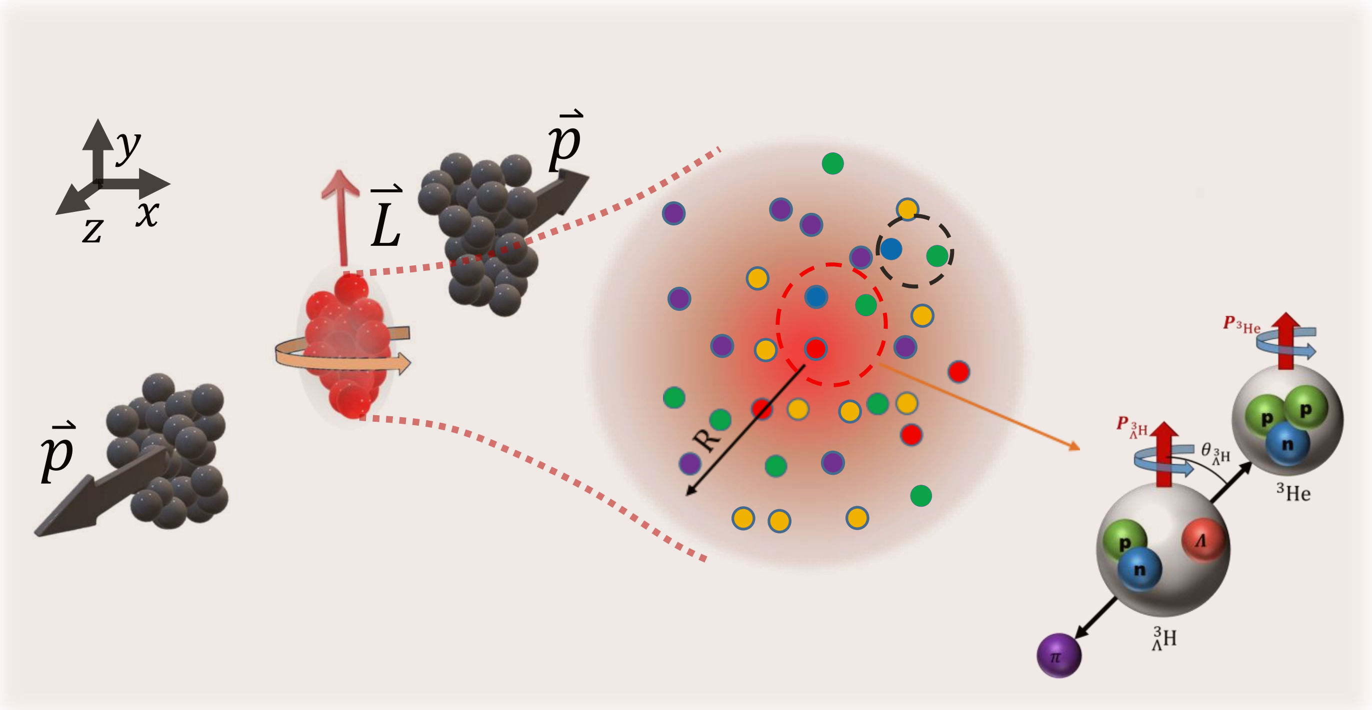
1. **(Anti-)hypertriton is globally polarized in non-central heavy-ion collisions.**
2. **(Anti-)hypertriton polarization and its decay pattern provide a novel method to uniquely determine the spin structure of its wavefunction.**



Summary and outlook

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





- FAIR/CBM (2.4-4.9 GeV)
- HIAF/CEE (2.1-4.5 GeV)
- NICA/MPD (4-11 GeV)

A novel tool to study the evolution of strongly-interacting matter at high-baryon density region

Backup

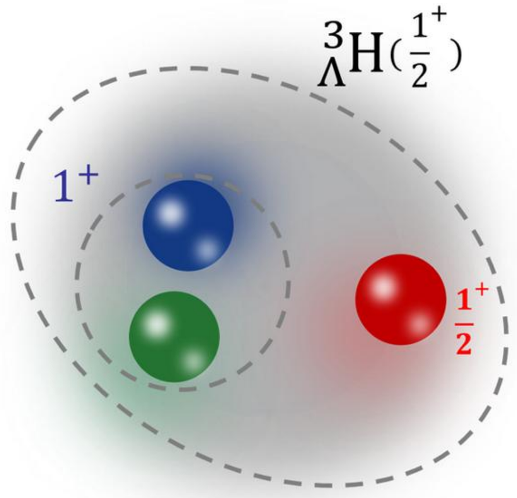
3. (Anti-)hypertriton polarization and its spin structure (8)

Parity-violating weak decay:

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

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

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



The normalized angular distribution of the ^{3}He in the decay ${}^3_\Lambda\text{H} \to \pi^- + {}^3\text{He}$ is given by

$$\frac{dN}{d\cos\theta^*} = \text{Tr}[T^+ \hat{\rho} T] = \frac{1}{2}(1 + \alpha_{{}^3_\Lambda\text{H}} \mathcal{P}_{{}^3_\Lambda\text{H}} \cos\theta^*), \quad (7)$$

in terms of the hypertriton decay parameter $\alpha_{{}^3_\Lambda\text{H}} \approx -\frac{1}{3T_s^2 + \frac{1}{3}T_p^2}\alpha_\Lambda \approx -\frac{1}{2.58}\alpha_\Lambda$. The angular distribution of ^{3}He in the decay ${}^3_\Lambda\text{H} \to \pi^- + {}^3\text{He}$ can thus be further expressed as

$$\frac{dN}{d\cos\theta^*} \approx \frac{1}{2}(1 - \frac{1}{2.58}\alpha_\Lambda \mathcal{P}_\Lambda \cos\theta^*). \quad (8)$$

Sign flip !

Compared to the angular distribution of the proton in the Λ decay, which has the form

$$\frac{dN}{d\cos\theta_p^*} = \frac{1}{2}(1 + \alpha_\Lambda \mathcal{P}_\Lambda \cos\theta_p^*), \quad (9)$$

the ^{3}He in ${}^3_\Lambda$H decay has an opposite sign in its angular dependence.

4. Effects of baryon spin correlation

Z. T. Liang, Chirality 2023

$$\left|\rho_{00}^{V}-\frac{1}{3}\right| \gg P_{\Lambda}^{2} \sim P_{q}^{2}$$

$$\rho_{00}^{V}-\frac{1}{3} \sim \langle P_q P_{\bar q}\rangle$$

The STAR data show that: $\langle P_q P_{\bar q}\rangle \neq \langle P_q\rangle\langle P_{\bar q}\rangle$ $\quad \langle P_q P_{\bar q}\rangle \gg \langle P_q\rangle\langle P_{\bar q}\rangle$

By studying P_H, we study the average of quark polarization P_q;

by studying ρ_{00}^V, we study the correlation between P_q and $P_{\bar q}$.

How to separate long range or local correlations

$$\rho_{10}^{V}=\frac{P_{qz}(1+P_{\bar q y})+(1+P_{qy})P_{\bar q z}-iP_{qx}(1+P_{\bar q y})-i(1+P_{qy})P_{\bar q x}}{\sqrt{2}(3+\vec P_q\cdot\vec P_{\bar q})}$$

$$\rho_{0-1}^{V}=\frac{P_{qz}(1-P_{\bar q y})+(1-P_{qy})P_{\bar q z}-iP_{qx}(1-P_{\bar q y})-i(1-P_{qy})P_{\bar q x}}{\sqrt{2}(3+\vec P_q\cdot\vec P_{\bar q})}$$

$$\rho_{1-1}^{V}=\frac{P_{qz}P_{\bar q z}-P_{qx}P_{\bar q x}+i(P_{qx}P_{\bar q y}+P_{qy}P_{\bar q x})}{3+\vec P_q\cdot\vec P_{\bar q}}$$

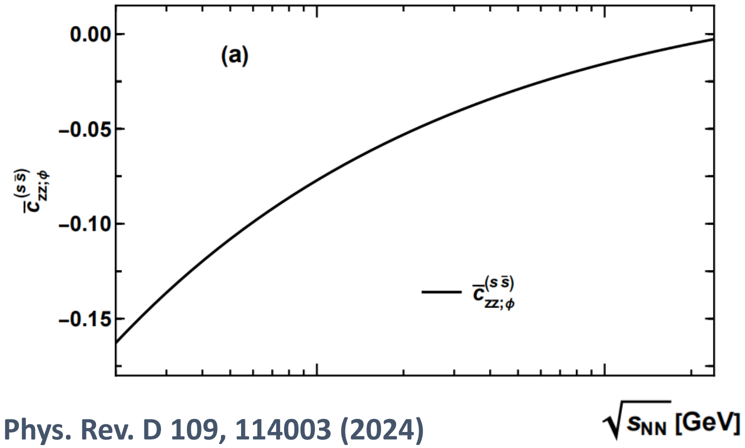
$$C_{NN}^{H_i\bar H_j} \equiv \frac{N_{H_i\bar H_j}^{\uparrow\uparrow}+N_{H_i\bar H_j}^{\downarrow\downarrow}-N_{H_i\bar H_j}^{\uparrow\downarrow}-N_{H_i\bar H_j}^{\downarrow\uparrow}}{N_{H_i\bar H_j}^{\uparrow\uparrow}+N_{H_i\bar H_j}^{\downarrow\downarrow}+N_{H_i\bar H_j}^{\uparrow\downarrow}+N_{H_i\bar H_j}^{\downarrow\uparrow}}$$

sensitive to the long range correlation

They should be sensitive to the local correlations.

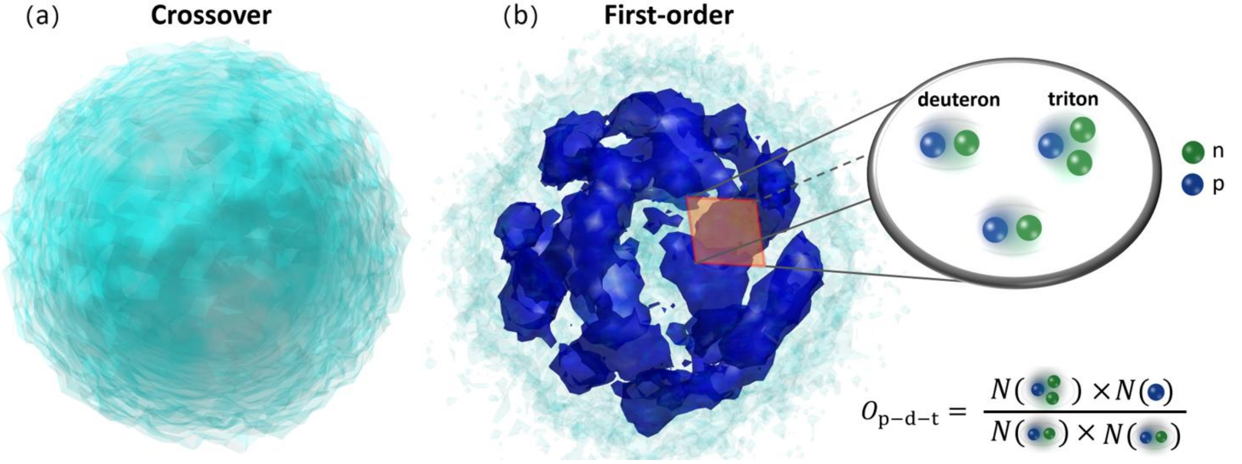
Global quark spin correlations in relativistic heavy ion collisions

Ji-peng Lv,[1,*] Zi-han Yu,[1,†] Zuo-tang Liang,[1,‡] Qun Wang,[2,3,§] and Xin-Nian Wang[4,¶]



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

C. M. Ko, NST 34, 80 (2023).



$$N_{\rm d} \approx N_{\rm d}^{(0)}(1+C_{\rm np}) + \frac{3}{2^{1/2}}\left(\frac{2\pi}{mT}\right)^{3/2} \times \int d^3\mathbf{x}_1 d^3\mathbf{x}_2 C_2(\mathbf{x}_1,\mathbf{x}_2)\frac{e^{-\frac{(\mathbf{x}_1-\mathbf{x}_2)^2}{2\sigma_d^2}}}{(2\pi\sigma_d^2)^{\frac{3}{2}}}$$

$$N_{\rm t} \approx \frac{3^{3/2}}{4}\left(\frac{2\pi}{mT}\right)^3 \int d^3\mathbf{x_1}d^3\mathbf{x_2}d^3\mathbf{x_3}\rho_{\rm nnp}(\mathbf{x_1},\mathbf{x_2},\mathbf{x_3}) \times \frac{1}{3^{3/2}(\pi\sigma_t^2)^3} e^{-\frac{(\mathbf{x_1}-\mathbf{x_2})^2}{2\sigma_t^2}-\frac{(\mathbf{x_1}+\mathbf{x_2}-2\mathbf{x_3})^2}{6\sigma_t^2}},$$

$$\rho_{\rm np}(\mathbf{x}_1,\mathbf{x}_2) = \rho_{\rm n}(\mathbf{x}_1)\rho_{\rm p}(\mathbf{x}_2) + C_2(\mathbf{x}_1,\mathbf{x}_2)$$

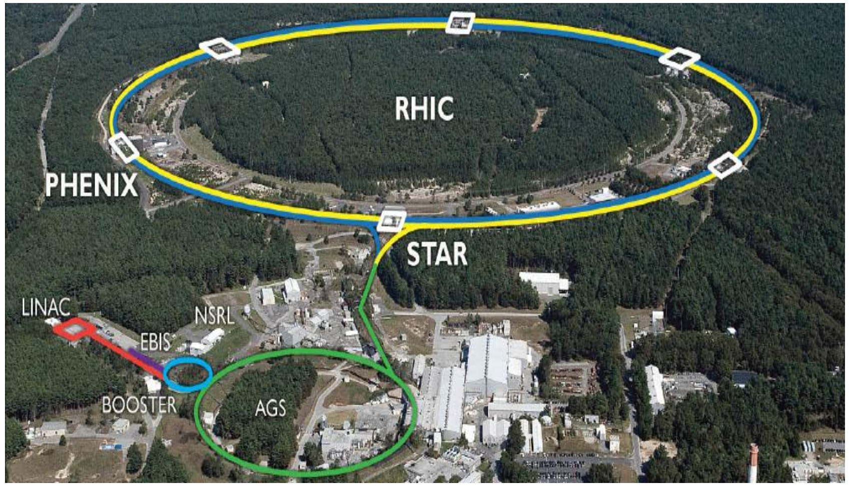
$$\begin{aligned}\rho_{\rm nnp}(\mathbf{x_1},\mathbf{x_2},\mathbf{x_3}) \approx\ & \rho_{\rm n}(\mathbf{x_1})\rho_{\rm n}(\mathbf{x_2})\rho_{\rm p}(\mathbf{x_3})\\ & + C_2(\mathbf{x_1},\mathbf{x_2})\rho_{\rm p}(\mathbf{x_3}) + C_2(\mathbf{x_2},\mathbf{x_3})\rho_{\rm n}(\mathbf{x_1})\\ & + C_2(\mathbf{x_3},\mathbf{x_1})\rho_{\rm n}(\mathbf{x_2}) + C_3(\mathbf{x_1},\mathbf{x_2},\mathbf{x_3})\end{aligned}$$

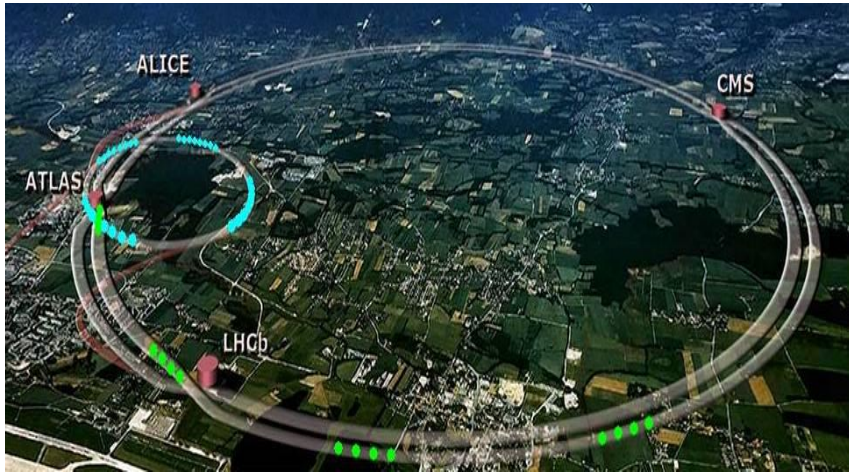
$$\frac{N_{\rm t}N_{\rm p}}{N_{\rm d}^2} \approx \frac{1}{2\sqrt{3}}\left[1+\Delta\rho_n + \frac{\lambda}{\sigma}G\left(\frac{\xi}{\sigma}\right)\right]$$

K. J. Sun, L. W. Chen, C. M. Ko, and Z. Xu, Phys. Lett. B 774, 103 (2017);
K. J. Sun, C. M. Ko, and F. Li, PLB 816, 136258 (2021);

Little Bang Nucleosynthesis

Antimatter factory

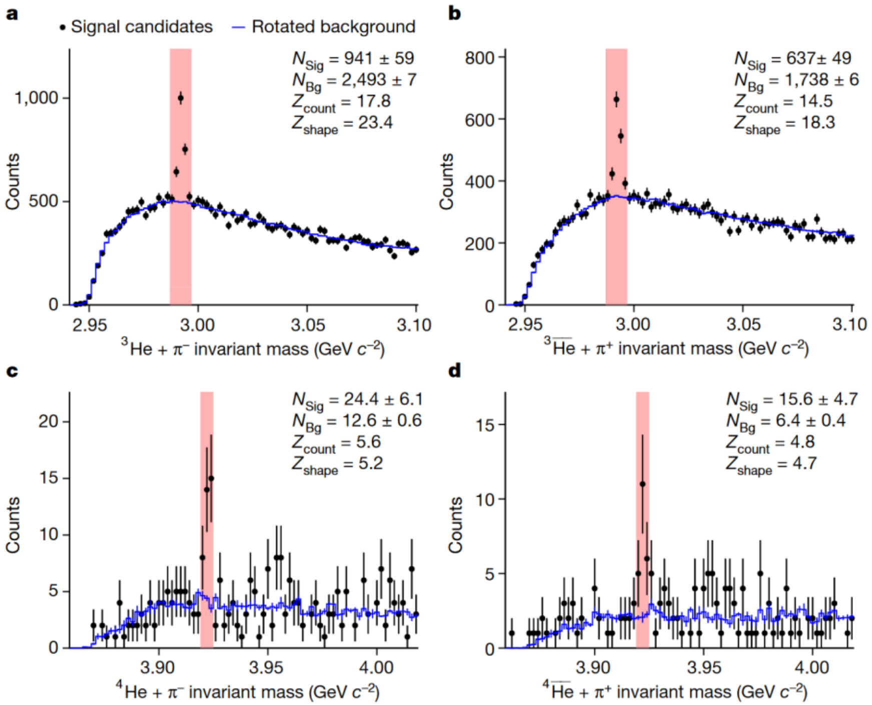




Observation of the antimatter hypernucleus $^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$

STAR Collaboration

Nature (2024) | Cite this ar



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Antimatter $^{4}_{\Lambda}$H hypernucleus production and the $^{3}_{\Lambda}$H/^{3}He puzzle in relativistic heavy-ion collisions

Kai-Jia Sun[1] and Lie-Wen Chen[1,2,*]
[1]*Department of Physics and Astronomy and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

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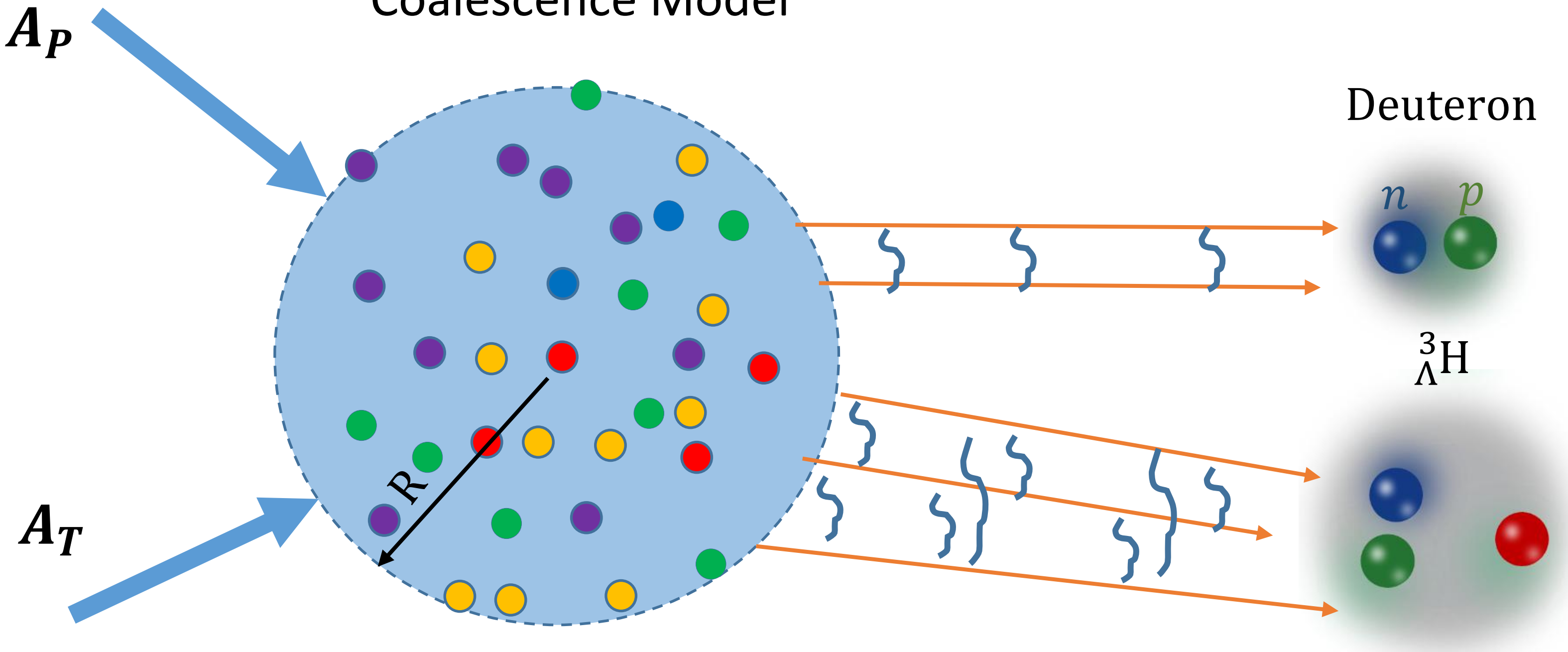
We show that the measured yield ratio $^{3}_{\Lambda}$H/^{3}He ($^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}/^{3}\overline{\mathrm{He}}$) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV can be understood within a covariant coalescence model if (anti-)Λ particles freeze out earlier than (anti-)nucleons but their relative freeze-out time is closer at $\sqrt{s_{NN}} = 2.76$ TeV than at $\sqrt{s_{NN}} = 200$ GeV. The earlier (anti-)Λ freeze-out can significantly enhance the yield of (anti)hypernucleus $^{4}_{\Lambda}$H ($^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$), leading to that $^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$ has a comparable abundance with $^{4}\overline{\mathrm{He}}$ and thus provides an easily measured antimatter candidate heavier than $^{4}\overline{\mathrm{He}}$. The future measurement on $^{4}_{\Lambda}$H ($^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$) would be very useful to understand the (anti-)Λ freeze-out dynamics and the production mechanism of (anti)hypernuclei in relativistic heavy-ion collisions.

Final-state coalescence

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

Two-body coalescence $a + b \to c$:

$$N_c = \frac{2J_c+1}{(2J_a+1)(2J_b+1)} \int \frac{dx_a dk_a}{(2\pi)^3} \frac{dx_b dk_b}{(2\pi)^3} f_a(x_a,k_a) f_b(x_b,k_b) W_c(x,k)$$
$$\approx \frac{2J_c+1}{(2J_a+1)(2J_b+1)} \frac{N_a N_b}{\left(\frac{m_a m_b T}{m_a+m_b}(R_a^2+R_b^2)\right)^{3/2}} \times \frac{1}{\left(1+\frac{\sigma^2}{R_a^2+R_b^2}\right)^{3/2}}$$

$$f_a = \frac{N_a}{(m_a T R_a^2)^{3/2}} e^{-\frac{k_a^2}{2m_a T} - \frac{x_a^2}{2R_a^2}} \qquad W_c = 8e^{-x^2/\sigma^2 - \sigma^2 k^2}$$
$$N_a = \int \frac{dx_a dk_a}{(2\pi)^3} f_a(x_a,k_a) \qquad 1 = \int \frac{dx dk}{(2\pi)^3} W_c(x,k)$$

“Quantum mechanical correction”

$$N_d \propto \frac{1}{\left[1+\left(\frac{2r_d^2}{3R^2}\right)\right]^{\frac{3}{2}}}$$

Production

Structure

$$N_{^3_\Lambda\mathrm{H}} \propto \frac{1}{\left[1+\left(\frac{r_{^3_\Lambda\mathrm{H}}^2}{2R^2}\right)\right]^3}$$

can be inferred from Femtoscopy