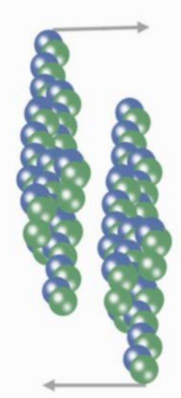
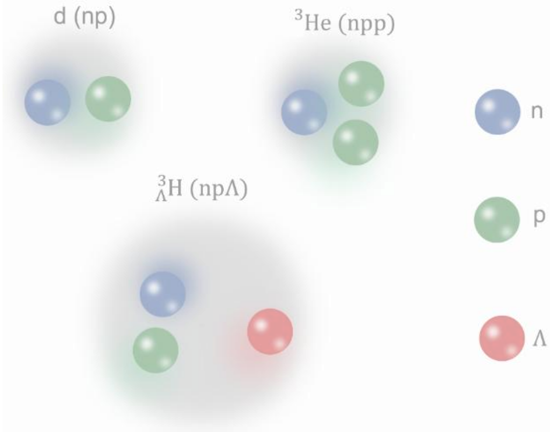
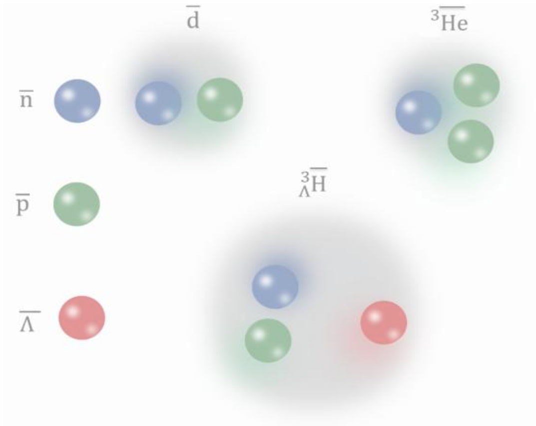
中国科学院大学高能核物理课题组前沿讲座

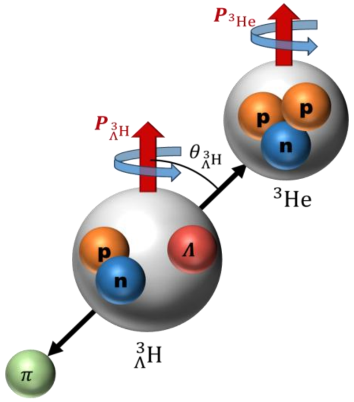
Production and Polarization of Hypernuclei in Heavy-Ion Collisions

KJ Sun, Dai-Neng Liu, Yun-Peng Zhen, Jin-Hui Chen, Che Ming Ko, Yu-Gang Ma **arXiv:2405.12015**









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Oct. 24, 2024

复旦大學
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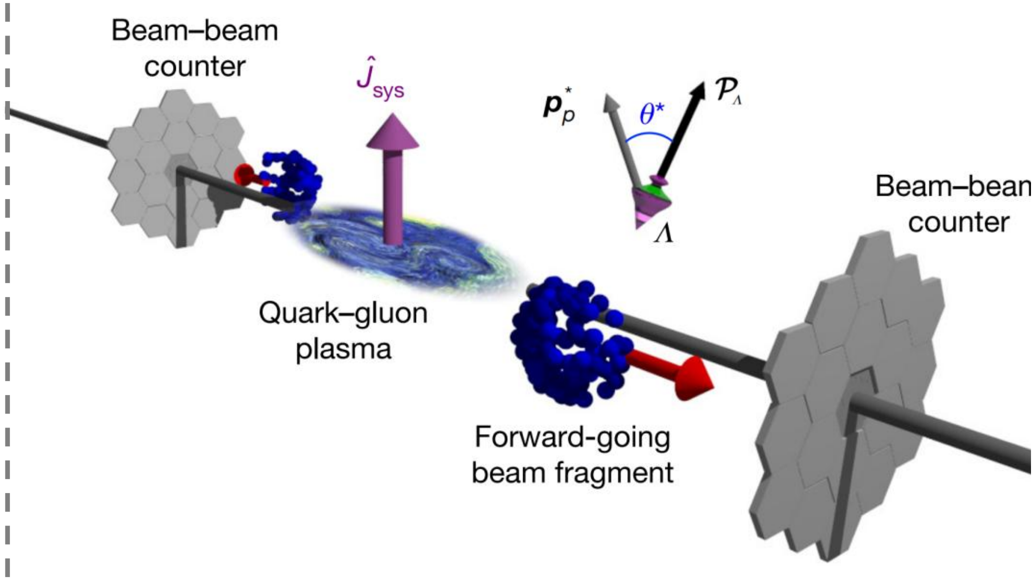
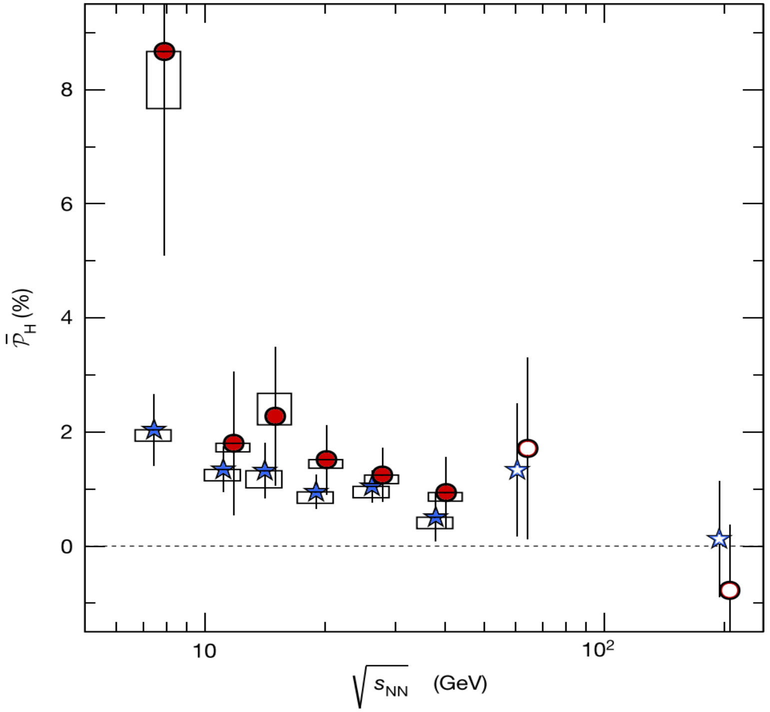
Outline

1. Polarization in heavy-ion collisions
2. The property and production of (anti-)hypertriton
3. Results: (Anti-)Hypertriton polarization and its spin structure
4. Discussions: Effects of baryon spin correlations
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)





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

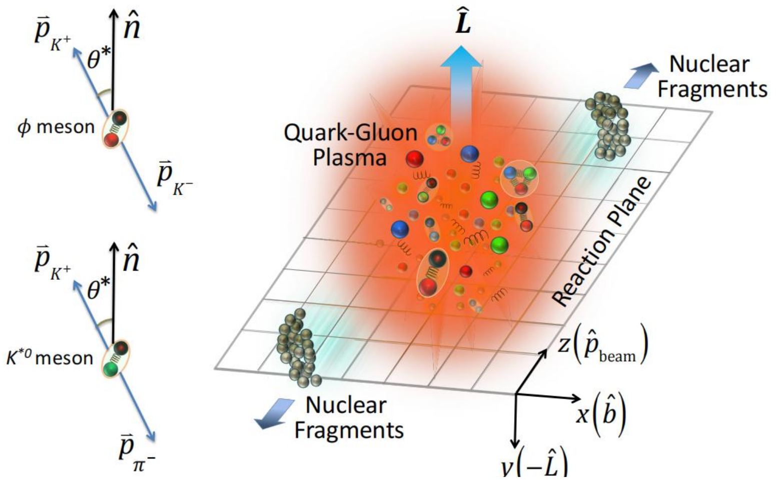
$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle\sin(\Psi_1^{\mathrm{obs}}-\phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}$$

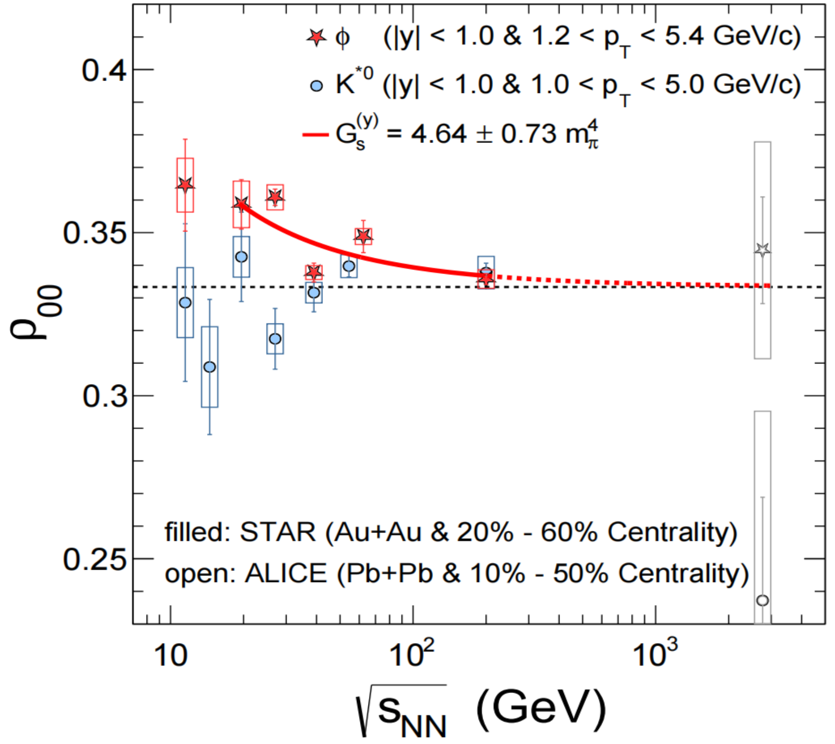
$$\omega \approx k_{\mathrm{B}}T(\overline{\mathcal{P}}_{\Lambda'}+\overline{\mathcal{P}}_{\overline{\Lambda}'})/\hbar$$

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., arXiv:2402.13721

Meson spectral property

F. Li and S. Liu, arXiv:2206.11890

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

Unstable 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

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

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

…

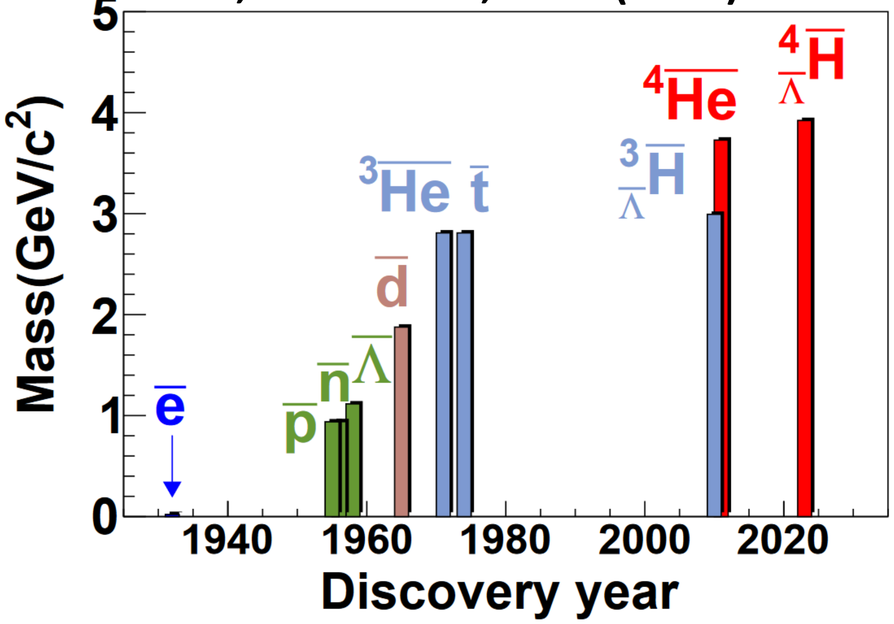
Stable (anti-)nuclei

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

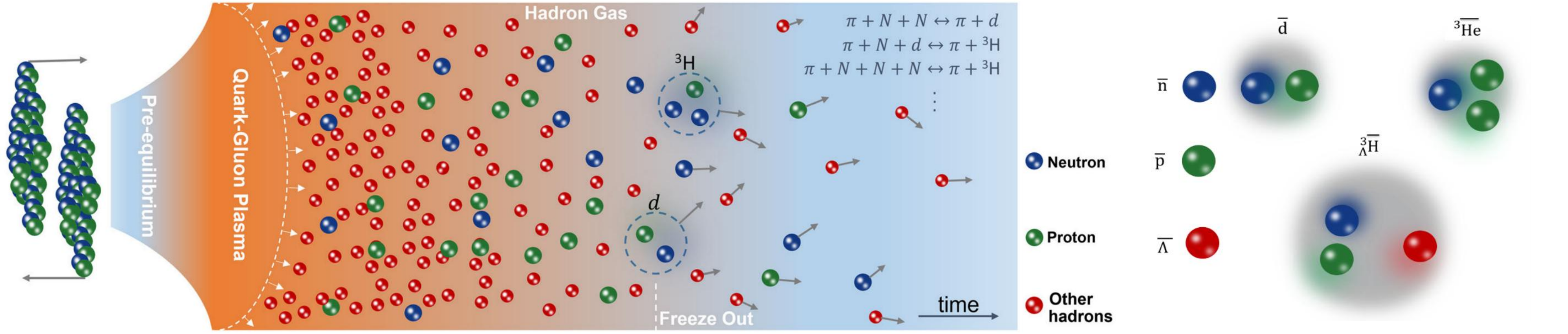
$\bar{d}(\bar{n}\bar{p})$ ${}^{3}\overline{\mathrm{He}}(\bar{n}\bar{p}\bar{p})$

…

STAR, Nature 632, 1026 (2024)

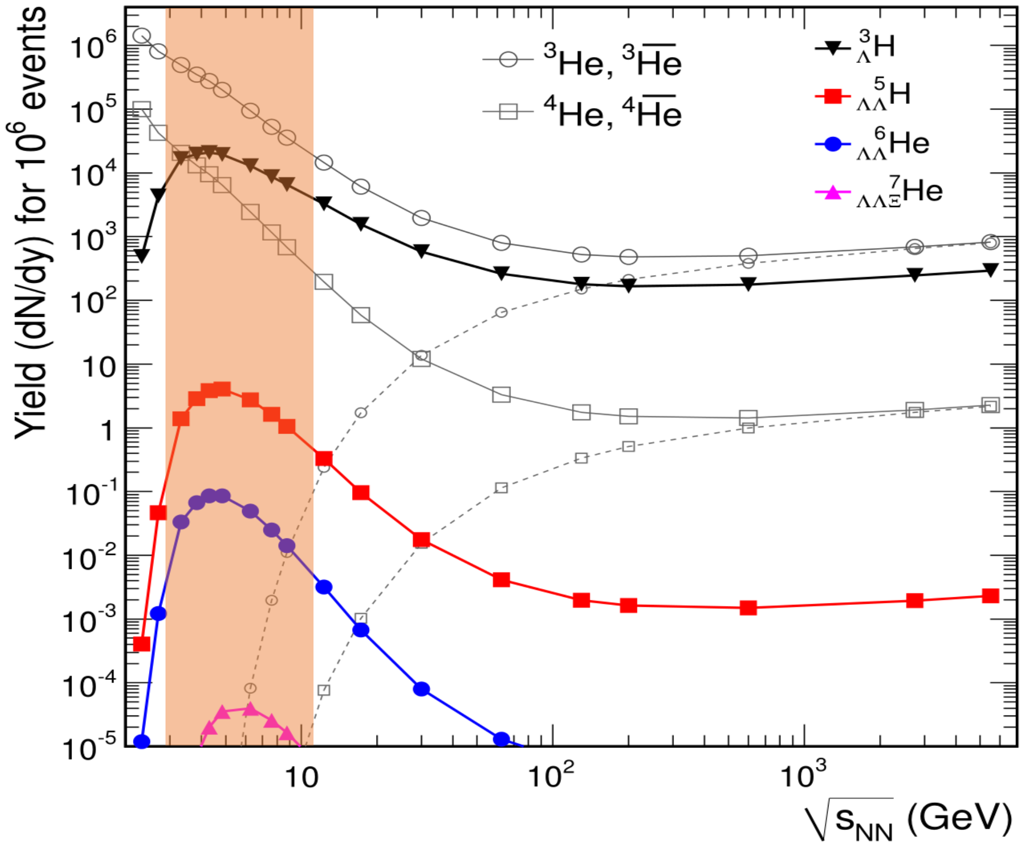


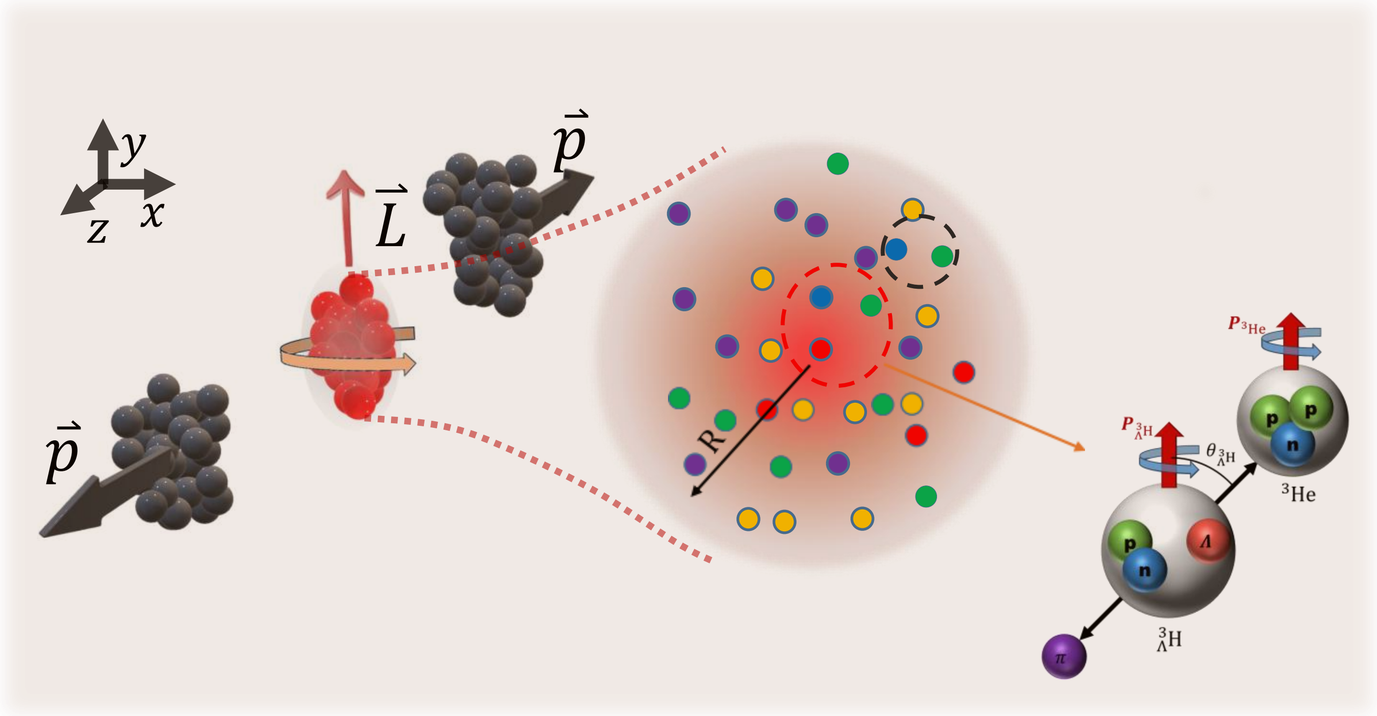
K. J. Sun, R. Wang, C. M. Ko, Y. G. Ma, C. Shen, Nature Commun. 15, 1074 (2024)



1. Polarization of light (anti-)(hyper-)nuclei (4)

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

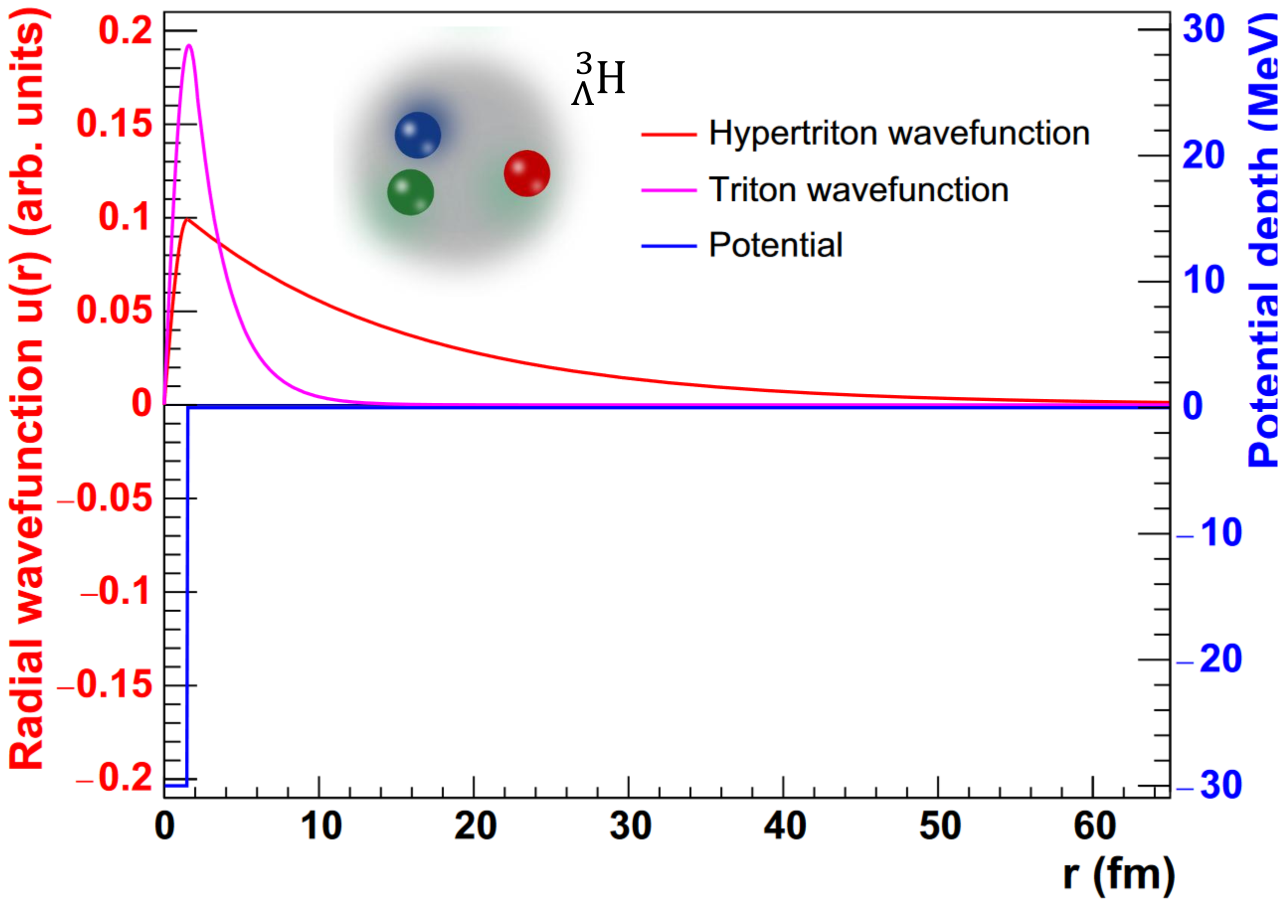




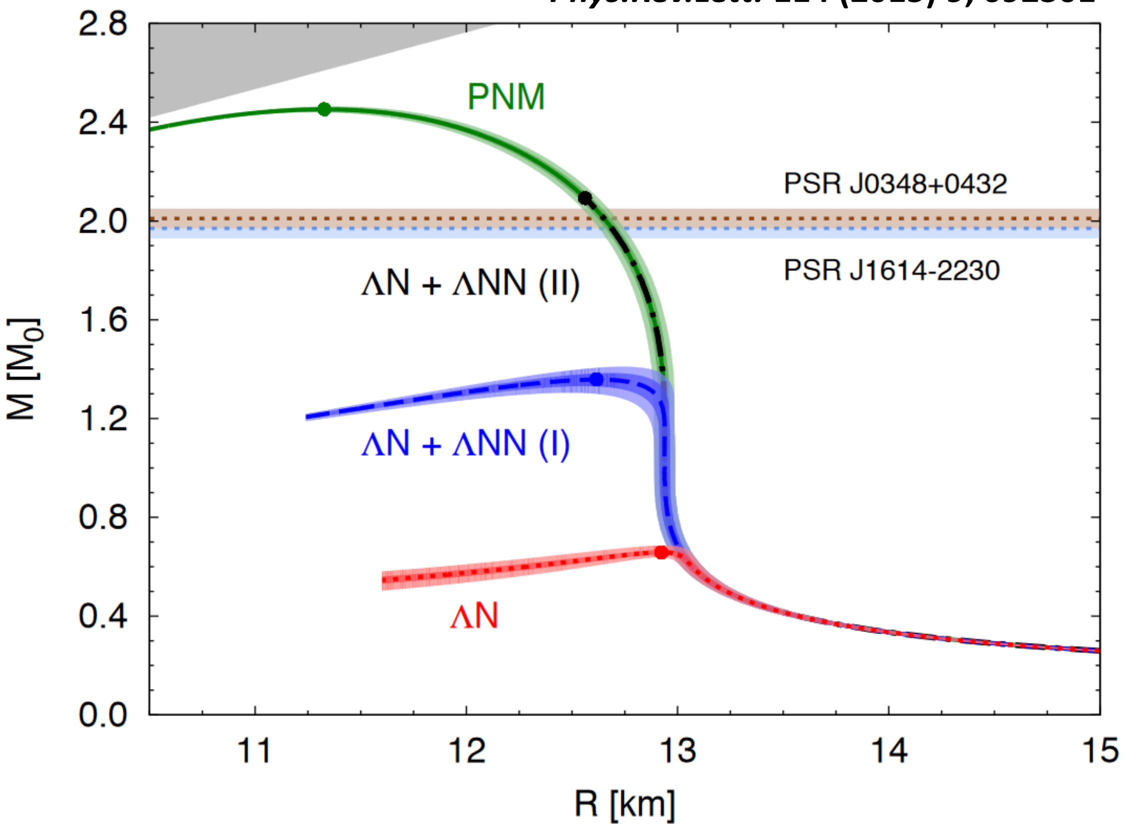
- **FAIR/CBM (2.4-4.9 GeV)**
- **HIAF/CEE (2.1-4.5 GeV)**
- **NICA/MPD (4-11 GeV)**

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

2. The halo-like nucleus: (anti-)hypertriton (5)



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

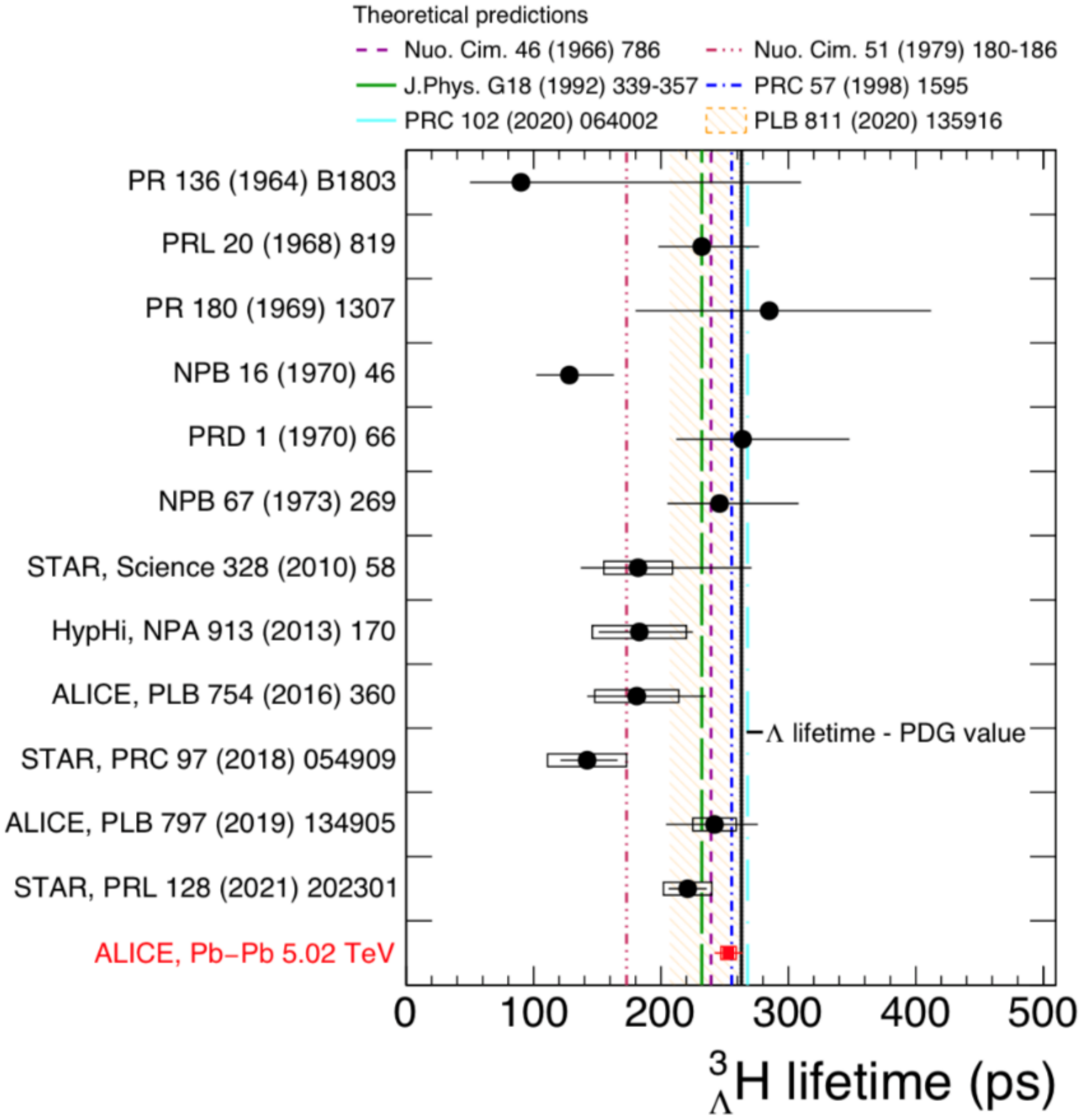


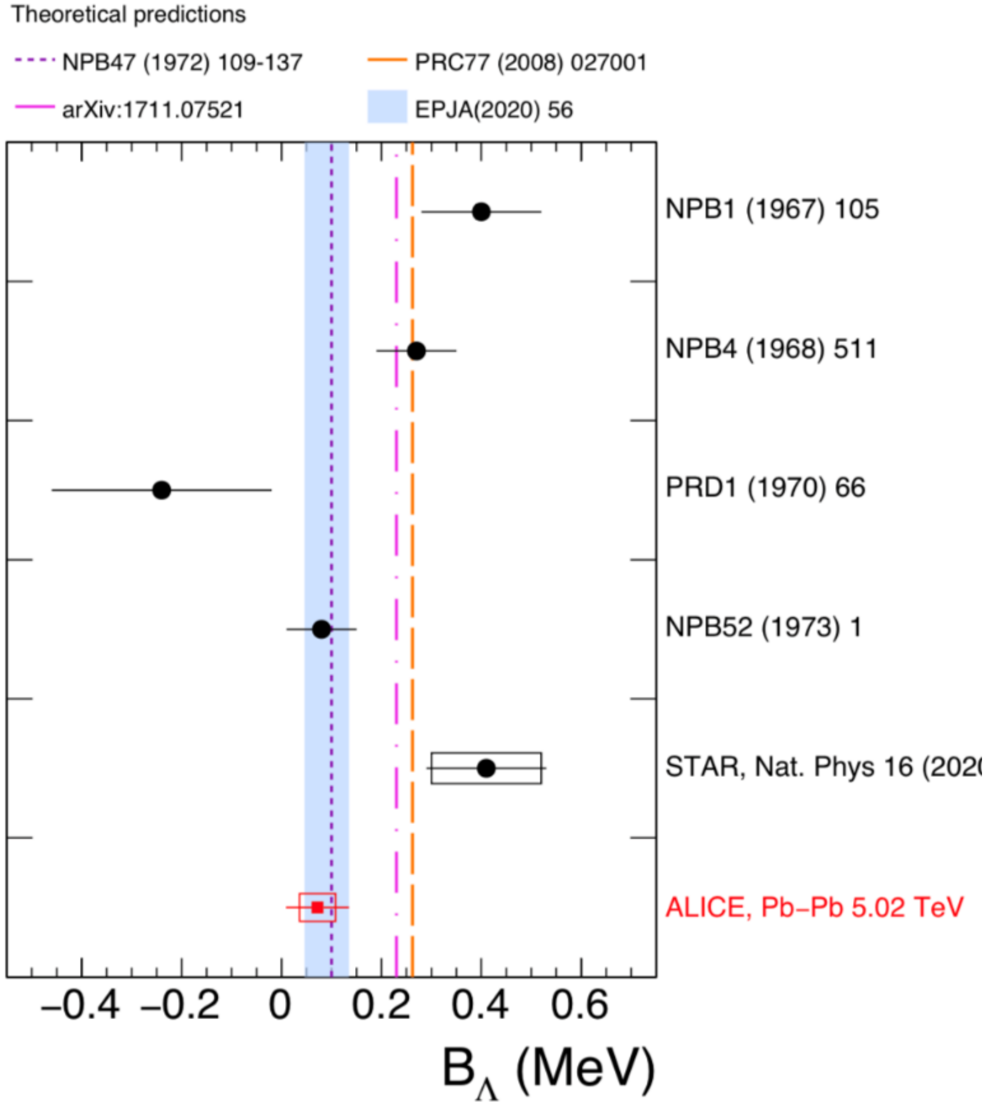
J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)
D. N. Liu et al. Phys. Lett. B 855, 138855 (2024)

2. Binding energy and lifetime (6)

ALICE, PRL 131, 102302 (2023)

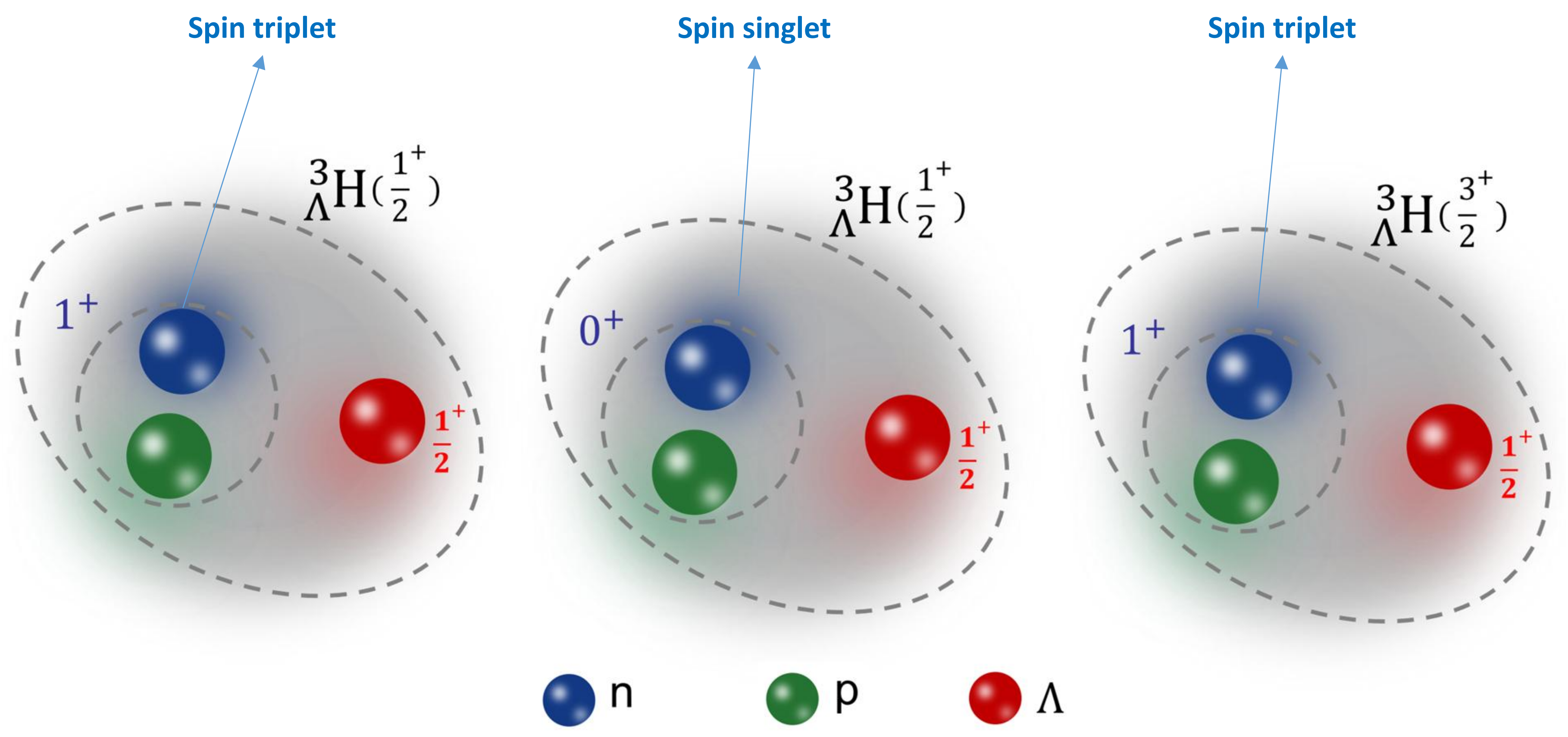
Y. G. Ma, Nucl. Sci. Tech. 3497 (2023)





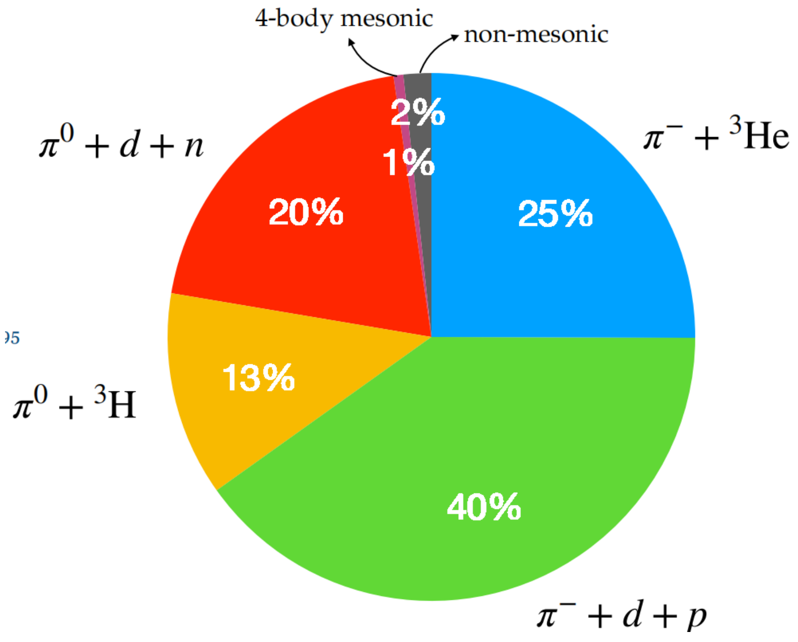
J. Chen et al., Phys. Rep. 760, 1 (2018);P. Braun-Munzinger and B. Donigus NPA987, 144 (2019)

2. Spin of (anti-)hypertriton ?



2. Spin of (anti-)hypertriton ?

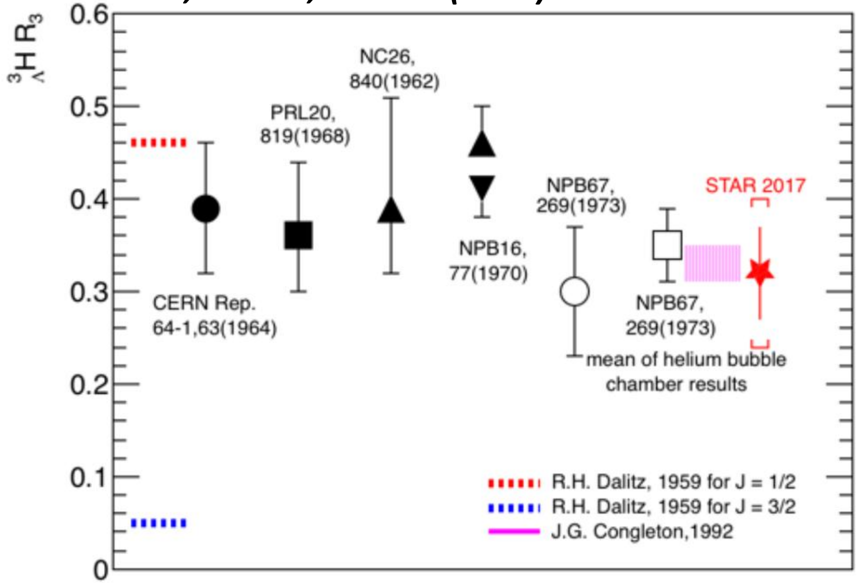
$${}^3_\Lambda\mathrm{H} \mapsto \pi^- + {}^3\mathrm{He}, \qquad {}^3_\Lambda\mathrm{H} \mapsto \pi^0 + {}^3\mathrm{H},$$
$${}^3_\Lambda\mathrm{H} \mapsto \pi^- + d + p, \qquad {}^3_\Lambda\mathrm{H} \mapsto \pi^0 + d + n,$$
$${}^3_\Lambda\mathrm{H} \mapsto \pi^- + p + n + p, \quad {}^3_\Lambda\mathrm{H}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



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)

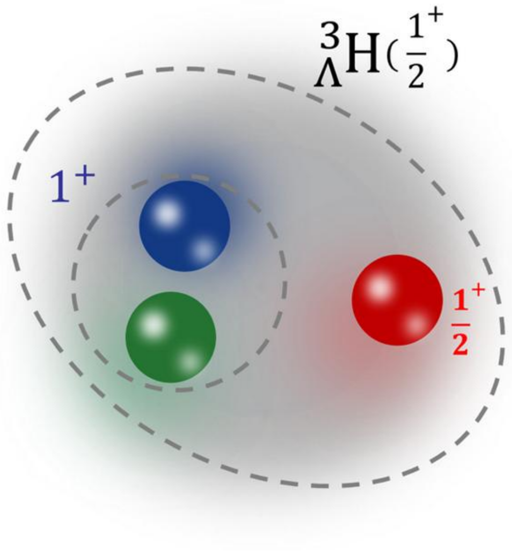
Light nuclei and hypernuclei from quantum chromodynamics in the limit of SU(3) flavor symmetry

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

3. (Anti-)hypertriton polarization and its spin structure (9)



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

Coalescence model for hypertriton production (without baryon spin correlation)

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

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

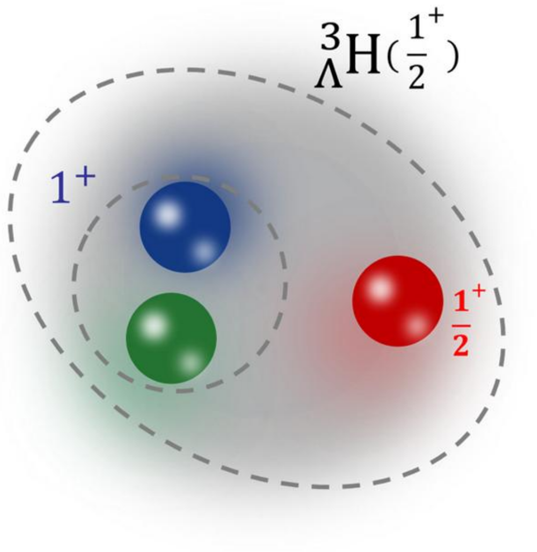
$$\hat{\rho}_i = \mathrm{diag}\left(\tfrac{1+\mathcal{P}_i}{2}, \tfrac{1-\mathcal{P}_i}{2}\right)$$

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

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

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

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



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

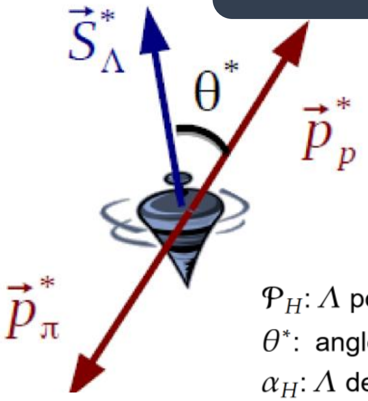
$$\approx \frac{2}{3}\mathcal{P}_n + \frac{2}{3}\mathcal{P}_p - \frac{1}{3}\mathcal{P}_\Lambda$$

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

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 a

α_H: Λ decay parameter

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

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

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

The transition matrix

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

The angular distribution

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

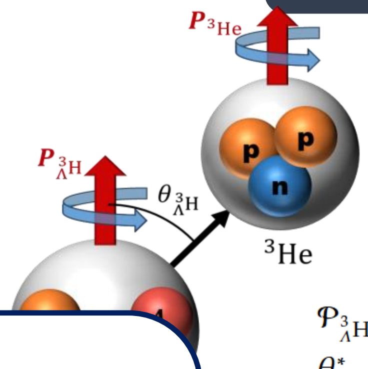
H denotes Λ and $\bar{\Lambda}$

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

$$\approx -\frac{1}{2.58}\alpha_\Lambda$$

Sign flip !

Hypertriton



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

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

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

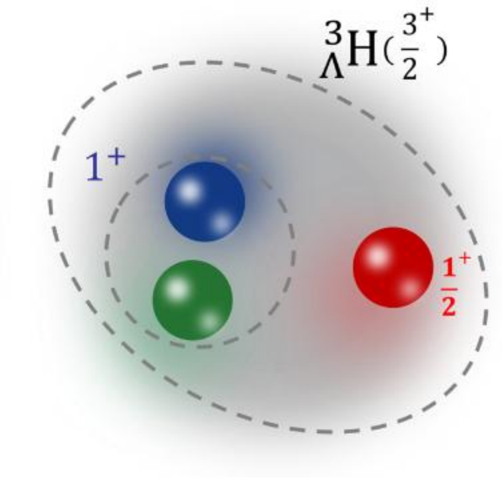
$\alpha_{^3_\Lambda H}$: $^3_\Lambda$H decay parameter

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

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

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

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

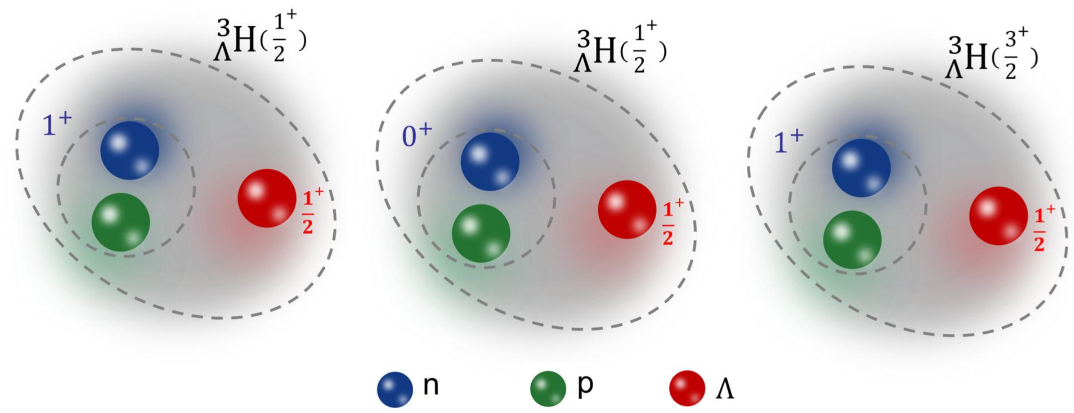


$$\hat{\rho}_{^3_\Lambda H} \approx \mathrm{diag}\left[\frac{(1+\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)(1+\mathcal{P}_\Lambda)^2}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^2(1+\mathcal{P}_\Lambda)}{4(1+\mathcal{P}_\Lambda^2)}, \frac{(1-\mathcal{P}_\Lambda)^3}{4(1+\mathcal{P}_\Lambda^2)}\right]$$

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

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

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



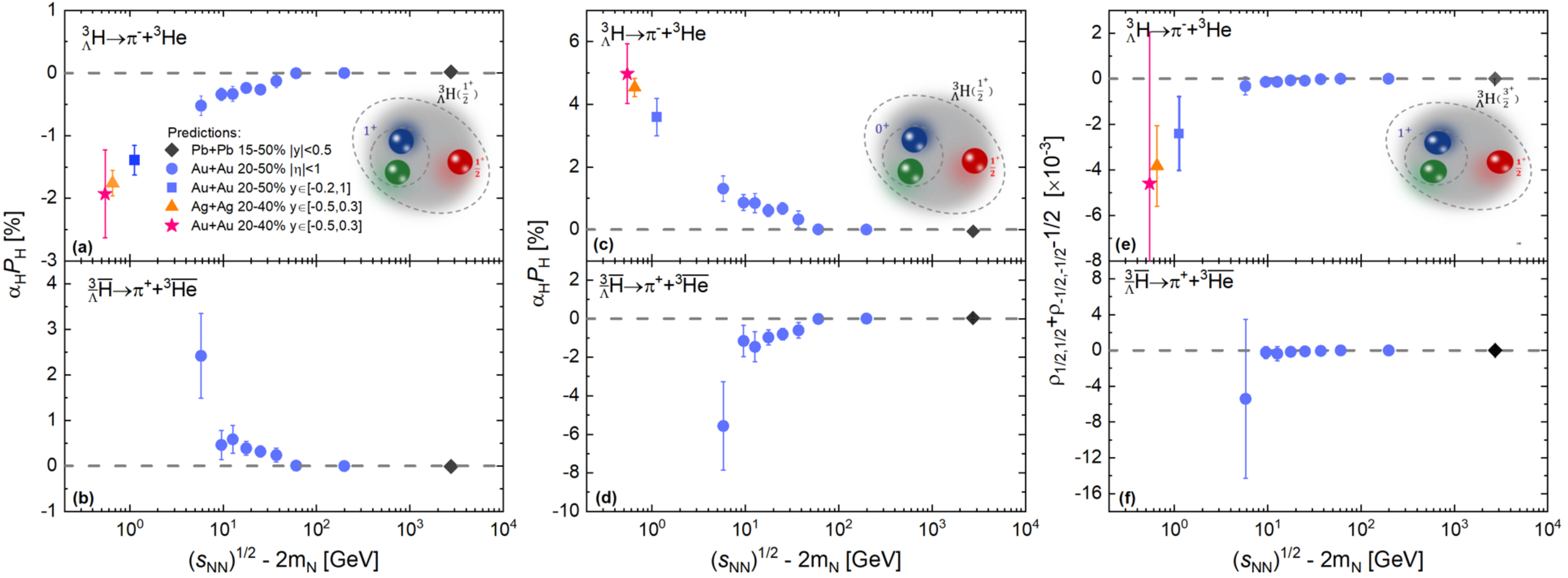
J^P	structure	decay mode	$\frac{dN}{d\cos\theta^*}$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(1^+)$	$^3_\Lambda H \to \pi^- + ^3He$	$\frac{1}{2}(1-\frac{1}{2.58}\alpha_\Lambda \mathcal{P}_\Lambda\cos\theta^*)$
$\frac{1}{2}^+$	$\Lambda(\frac{1}{2}^+) - np(0^+)$	$^3_\Lambda H \to \pi^- + ^3He$	$\frac{1}{2}(1+\alpha_\Lambda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

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

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

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

sensitive to the long range correlation

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

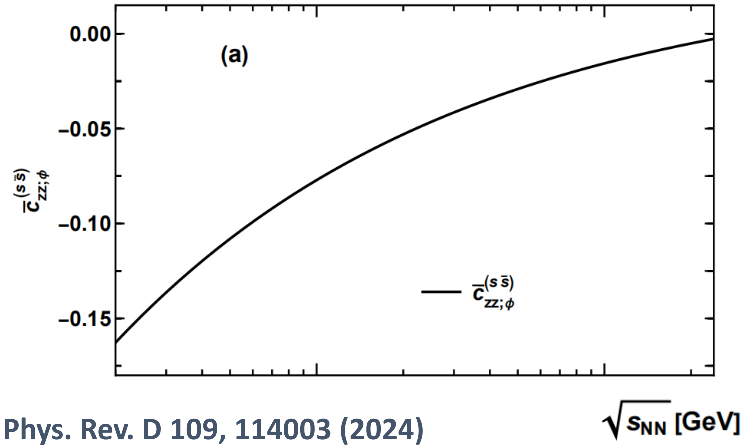
$$\rho_{0-1}^{V}=\frac{P_{qz}(1-P_{\bar q y})+(1-P_{qy})P_{\bar q z}-iP_{qx}(1-P_{\bar q y})-i(1-P_{qy})P_{\bar q x}}{\sqrt{2}(3+\vec P_q\cdot\vec P_{\bar q})}$$

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

They should be sensitive to the local correlations.

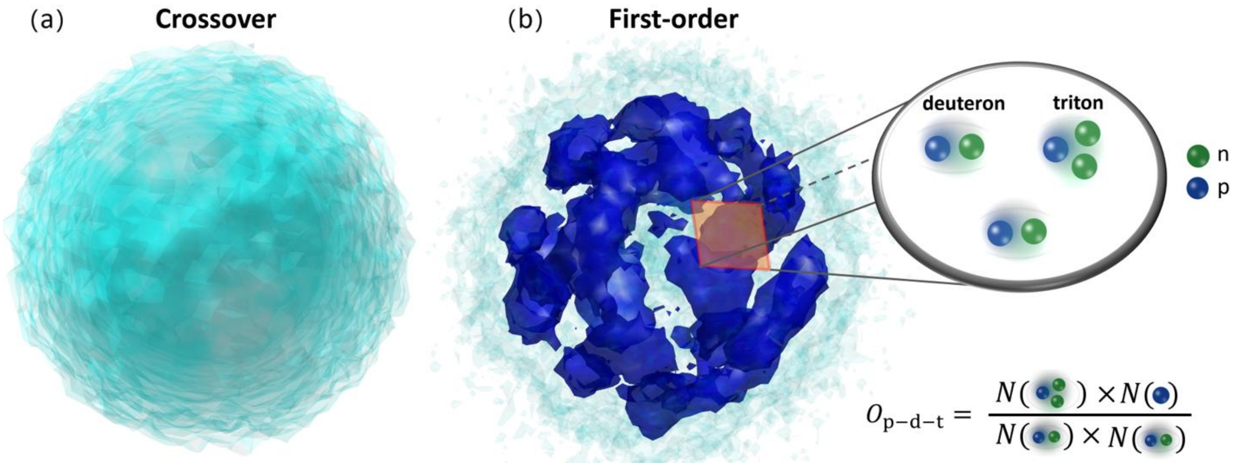
Global quark spin correlations in relativistic heavy ion collisions

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).



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

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

$$N_{\rm t}\approx\frac{3^{3/2}}{4}\left(\frac{2\pi}{mT}\right)^3\int d^3\mathbf{x}_1 d^3\mathbf{x}_2 d^3\mathbf{x}_3\rho_{\rm nnp}(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3)\times\frac{1}{3^{3/2}(\pi\sigma_t^2)^3}e^{-\frac{(\mathbf{x}_1-\mathbf{x}_2)^2}{2\sigma_t^2}-\frac{(\mathbf{x}_1+\mathbf{x}_2-2\mathbf{x}_3)^2}{6\sigma_t^2}},$$

$$\rho_{\rm nnp}(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3)\approx\rho_{\rm n}(\mathbf{x}_1)\rho_{\rm n}(\mathbf{x}_2)\rho_{\rm p}(\mathbf{x}_3)+C_2(\mathbf{x}_1,\mathbf{x}_2)\rho_{\rm p}(\mathbf{x}_3)+C_2(\mathbf{x}_2,\mathbf{x}_3)\rho_{\rm n}(\mathbf{x}_1)+C_2(\mathbf{x}_3,\mathbf{x}_1)\rho_{\rm n}(\mathbf{x}_2)+C_3(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3)$$

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

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);

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

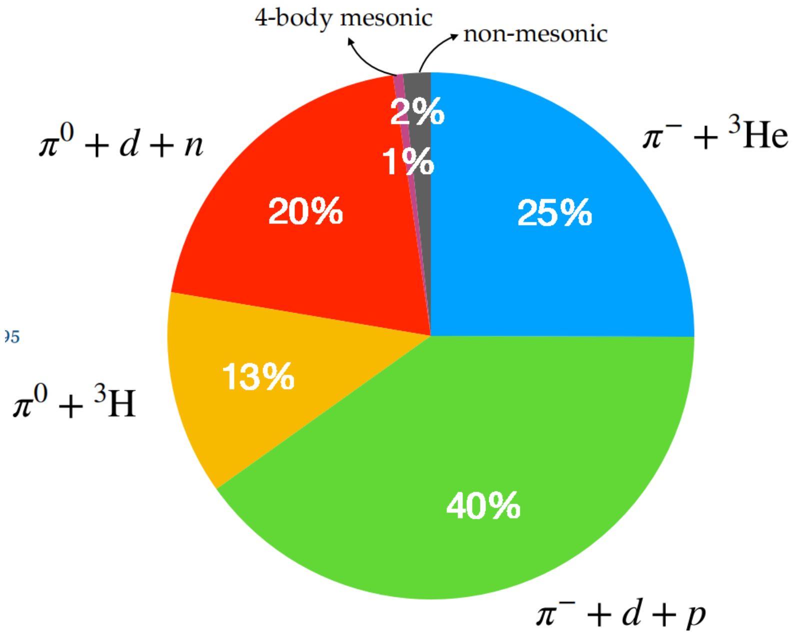
We can express the polarization of a particle as $\mathcal{P} = \langle\mathcal{P}\rangle + \delta\mathcal{P}$ with $\delta\mathcal{P}$ denoting its space and momentum dependent fluctuations, which leads to the relations $\langle\mathcal{P}_n\mathcal{P}_p\rangle = \langle\mathcal{P}_n\rangle\langle\mathcal{P}_p\rangle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

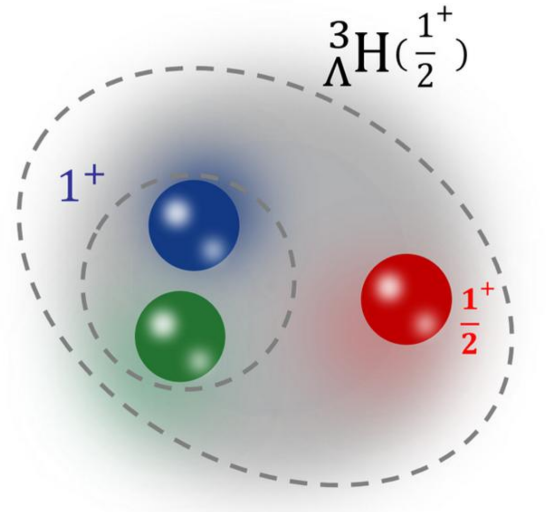
4. Three-body decay

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



Relative branching ratio:

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



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

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

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

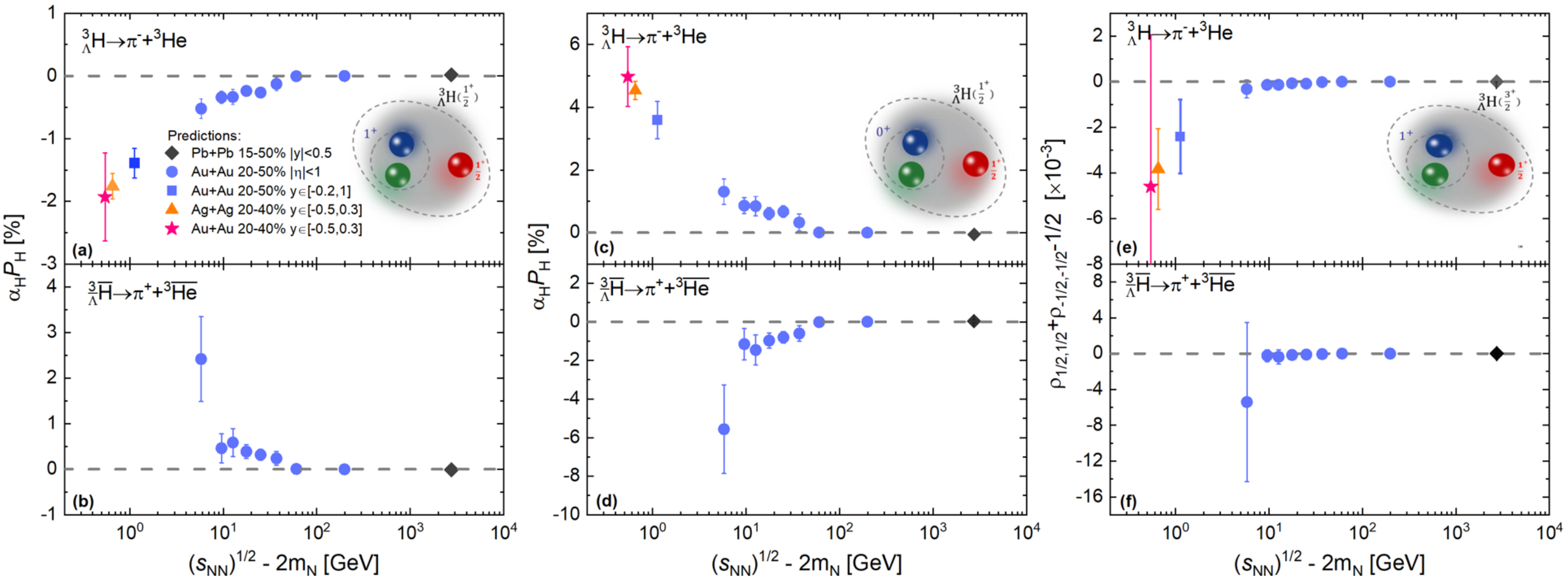
${}^3_\Lambda\mathrm{H} \mapsto \pi^- + d + p,$

$$\alpha_{{}^3_\Lambda\mathrm{H}} \approx -\frac{1}{3.2}\alpha_\Lambda$$

with $R_3 = 0.25$

Summary and outlook

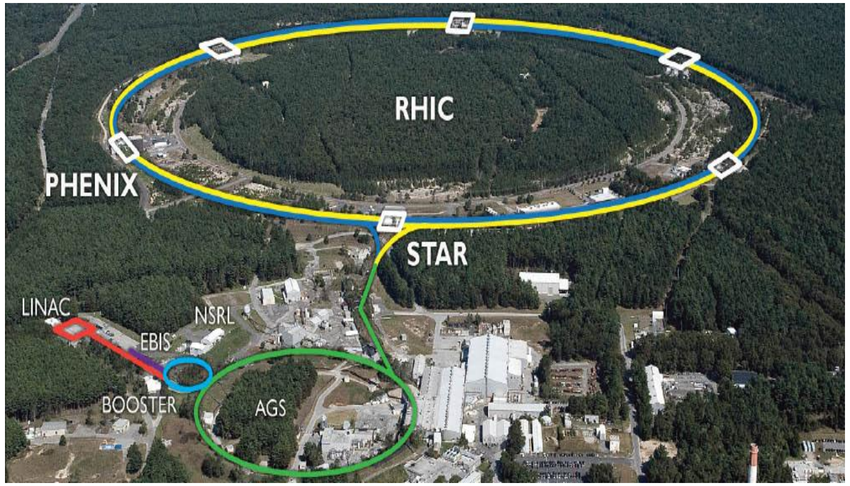
1. (Anti-)hypertriton is globally polarized in non-central heavy-ion collisions.
2. (Anti-)hypertriton polarization and its decay pattern provide a novel method to uniquely determine the spin structure of its wavefunction.

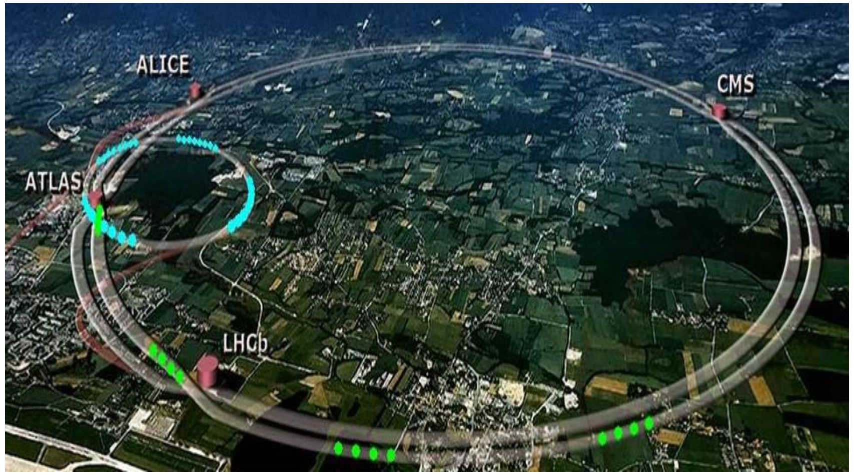


Backup

Little Bang Nucleosynthesis

Antimatter factory

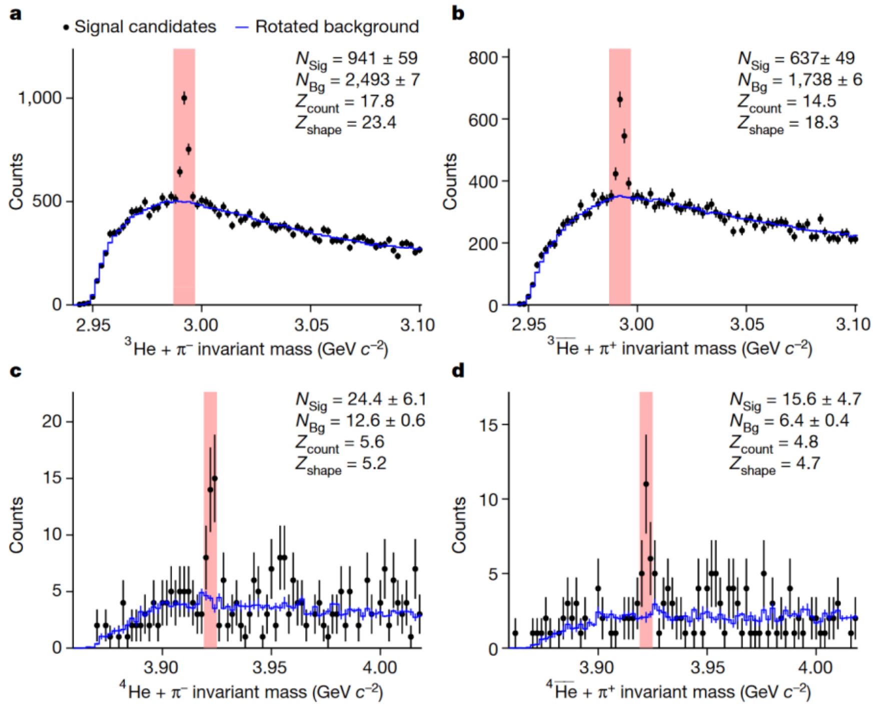




Observation of the antimatter hypernucleus $^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$

STAR Collaboration

Nature (2024) | Cite this ar



PHYSICAL REVIEW C **93**, 064909 (2016)

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*

(Received 26 April 2016; published 29 June 2016)

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.

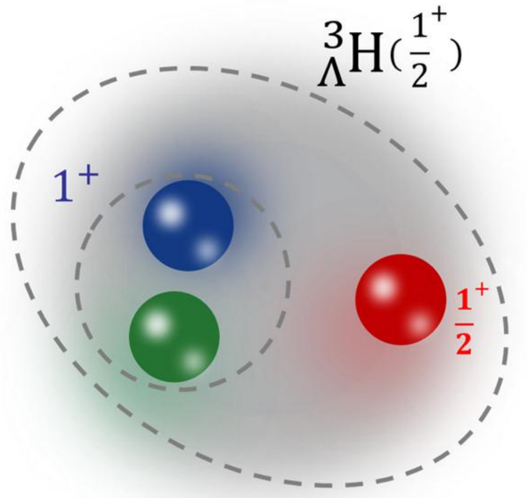
(Anti-)hypertriton polarization and its spin structure

Parity-violating weak decay:

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

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

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



Sign flip !

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

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

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

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

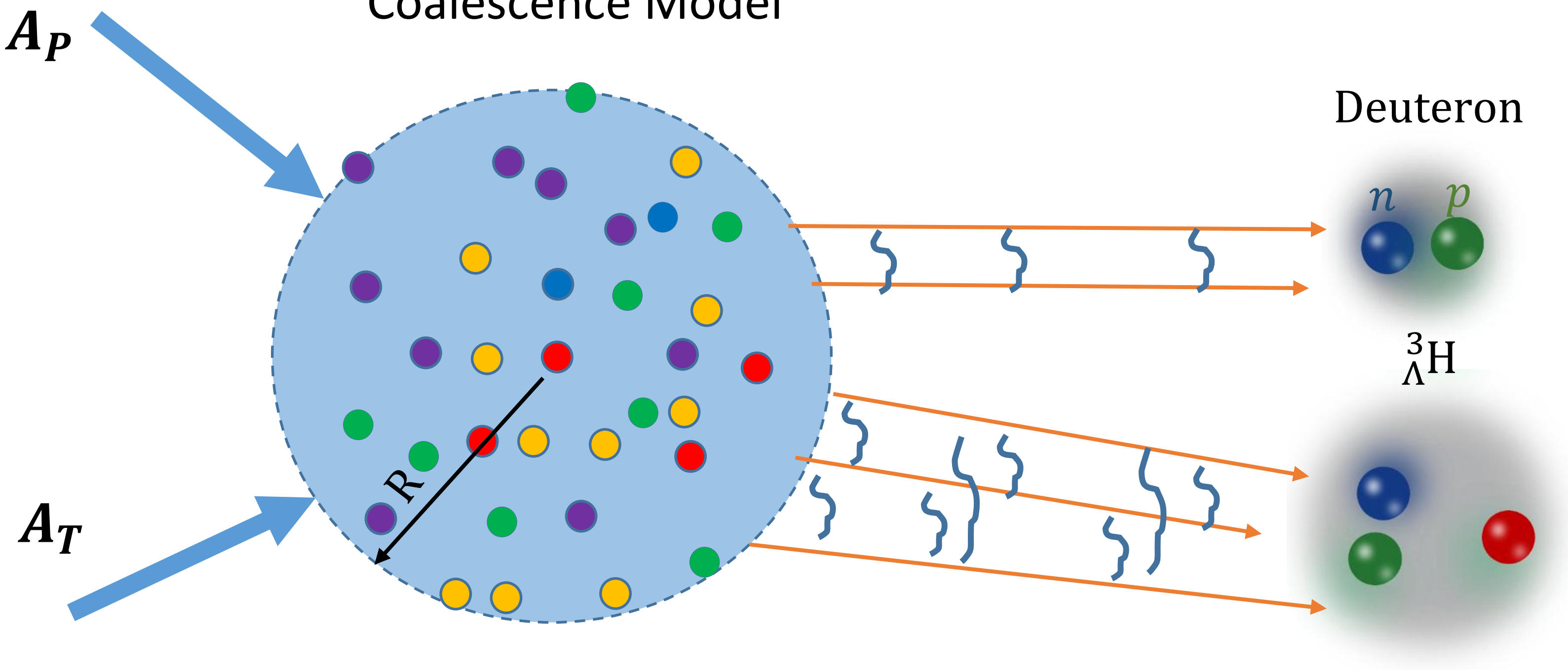
Compared to the angular distribution of the proton in the Λ decay, which has the form

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

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

Final-state coalescence

Coalescence Model

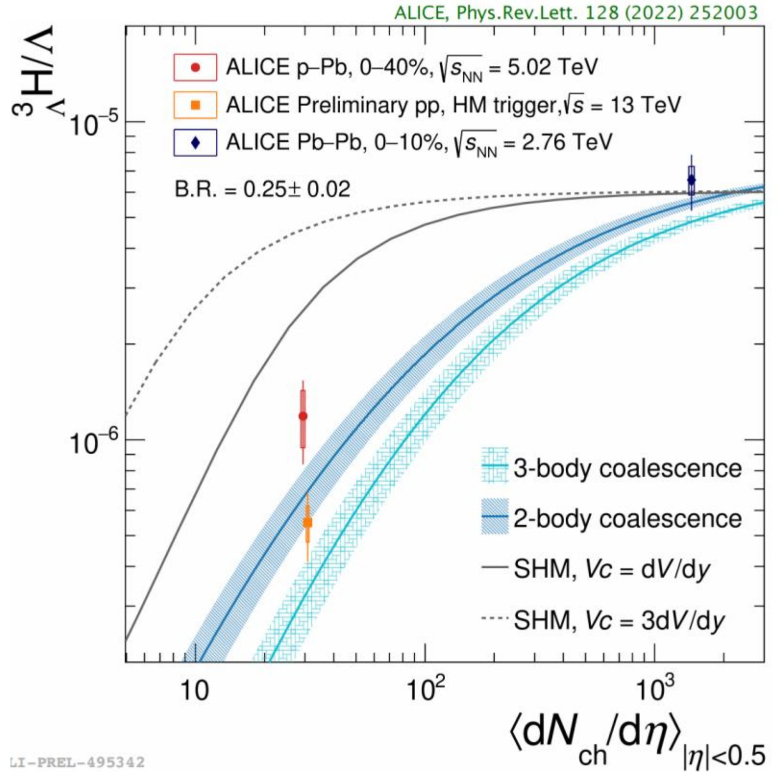


Density Matrix Formulation (sudden approximation)

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

Wigner function of light cluster

Overlap between source distribution function and Wigner function of light nuclei

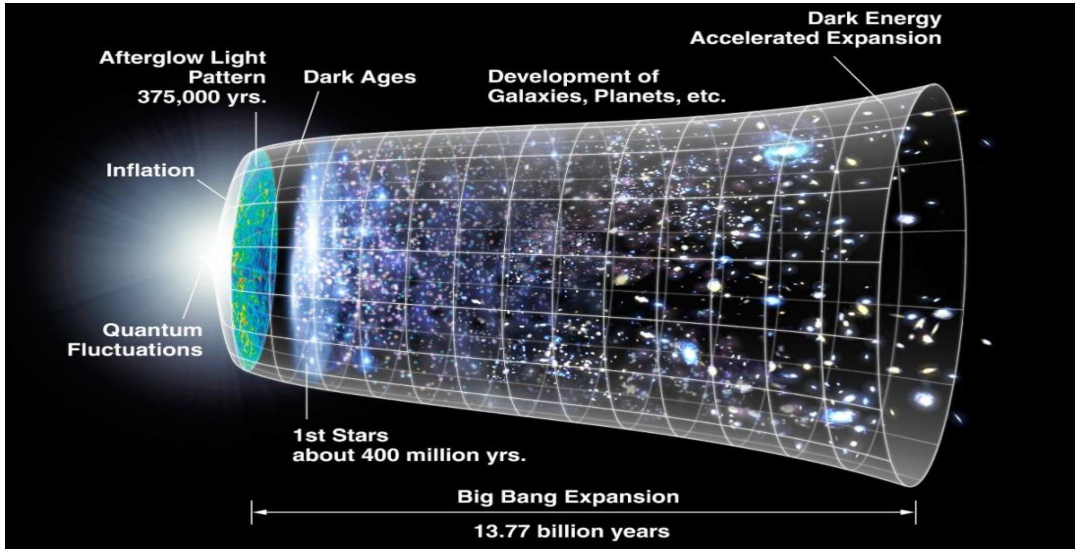


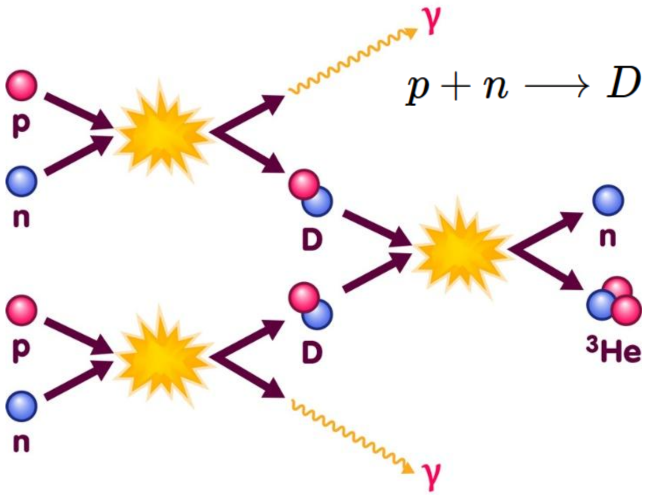
Little Bang Nucleosynthesis

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



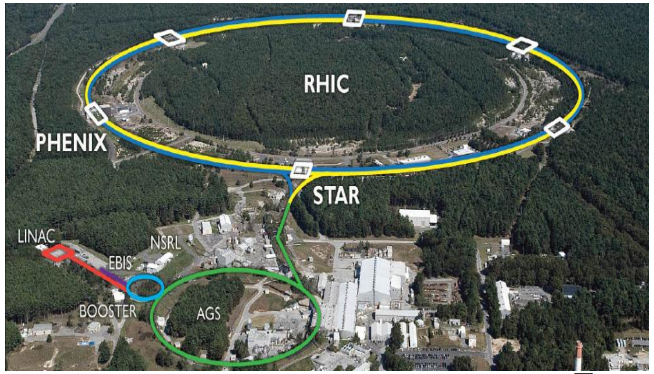


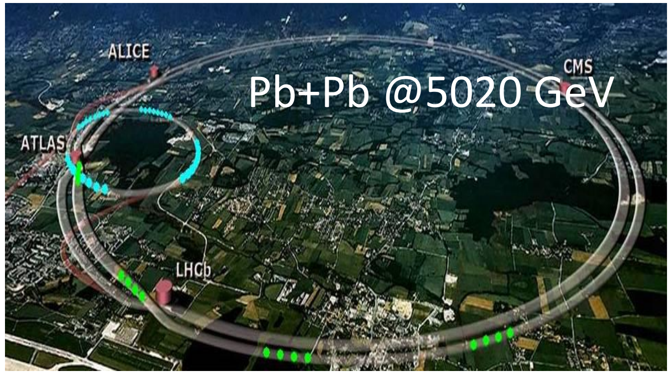
$$p + n \longrightarrow D + \gamma$$

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

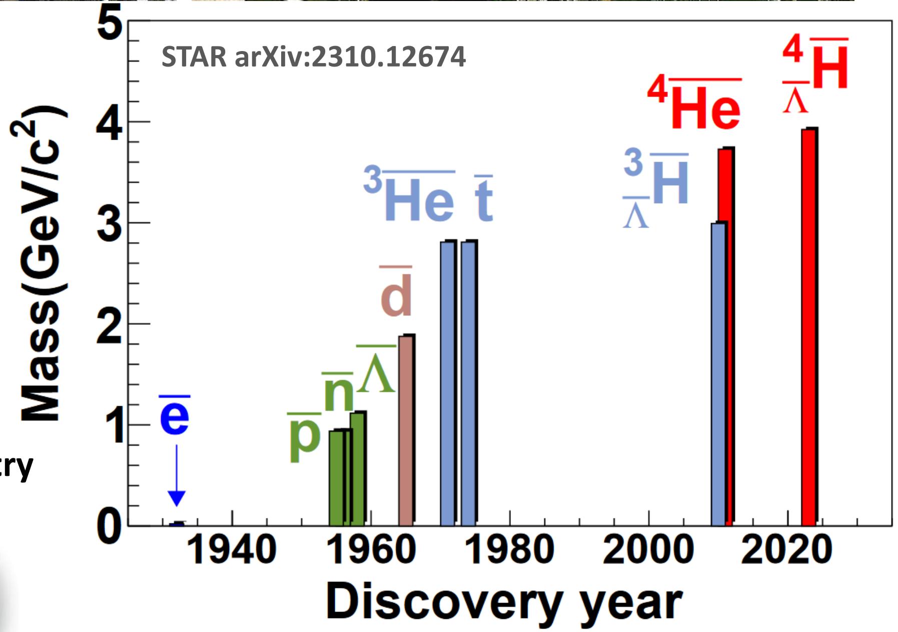
Synthesis of antimatter nuclei in little bangs of relativistic heavy-ion collisions

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

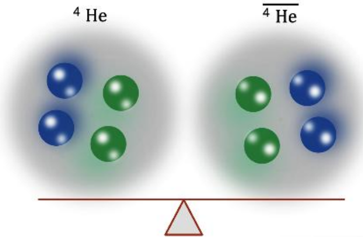




Antimatter factory



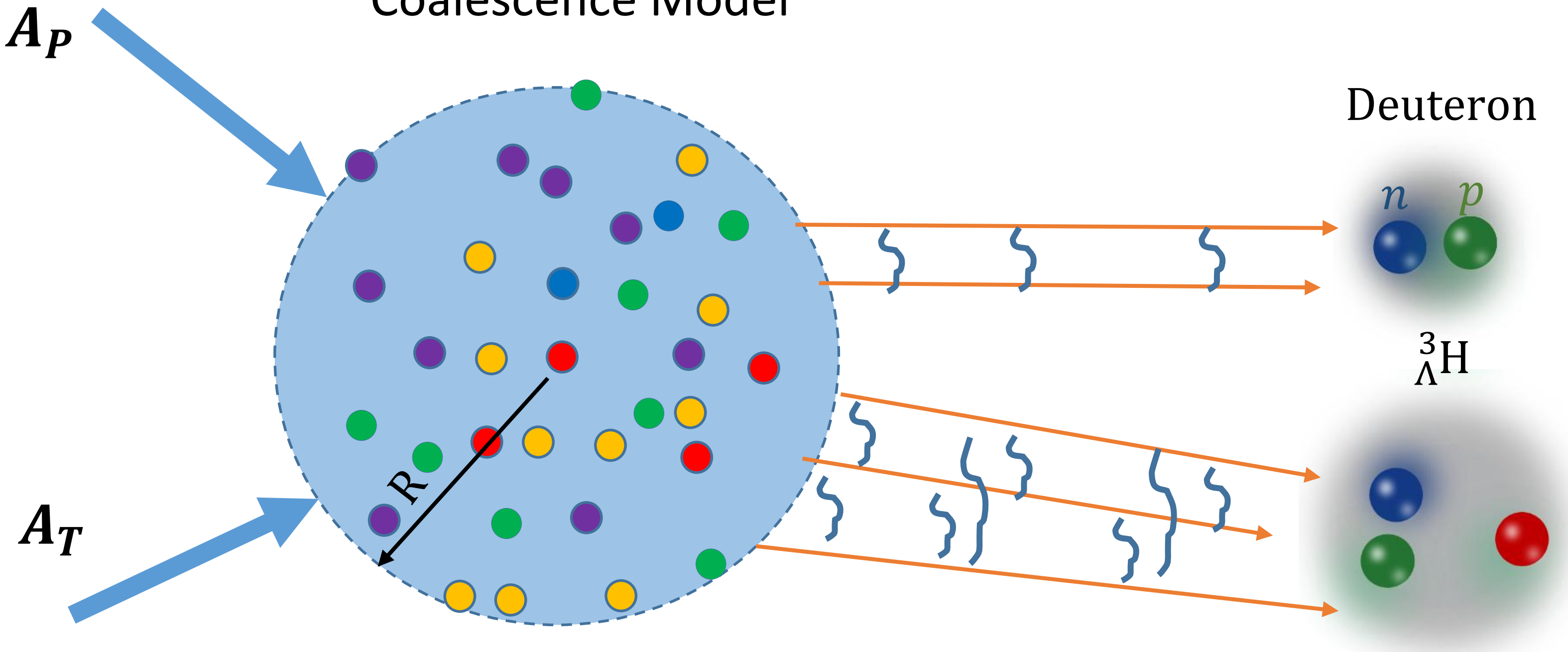
Matter-antimatter asymmetry



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

Final-state coalescence

Coalescence Model



Density Matrix Formulation (sudden approximation)

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Wigner function of light cluster

Overlap between source distribution function and Wigner function of light nuclei

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

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

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

“Quantum mechanical correction”

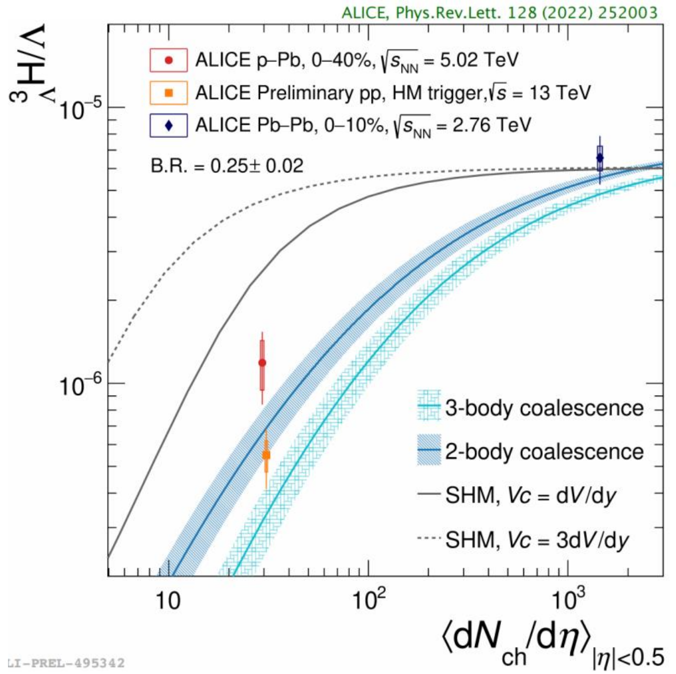
$$N_d \propto \frac{1}{\left[1+\left(\frac{2r_d^2}{3R^2}\right)\right]^{\frac{3}{2}}}$$

Production

Structure

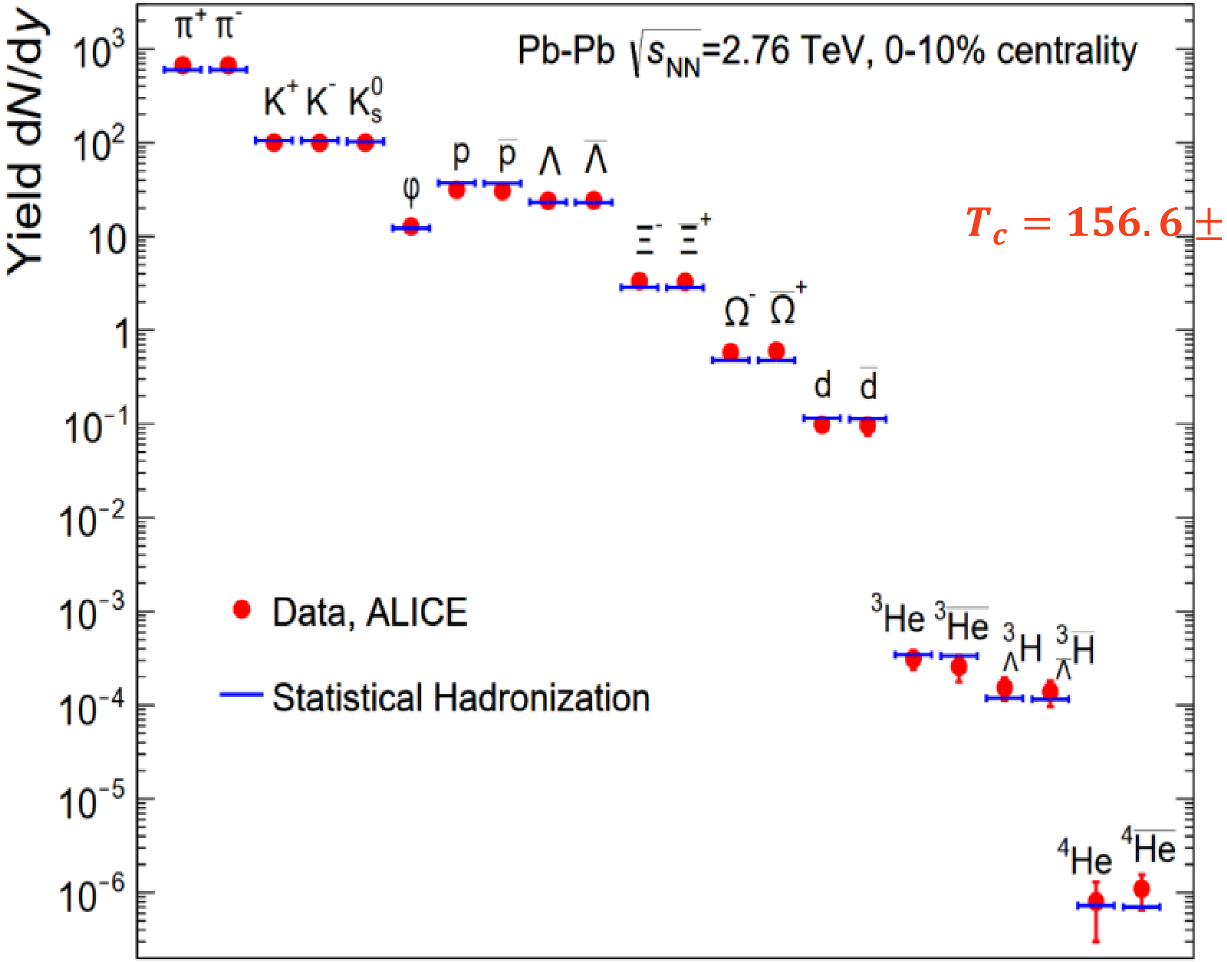
$$N_{^3_\Lambda\mathrm{H}} \propto \frac{1}{\left[1+\left(\frac{r^2_{^3_\Lambda\mathrm{H}}}{2R^2}\right)\right]^3}$$

can be inferred from Femtoscopy



Statistical hadronization

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



$T_c = 156.6 \pm 1.7$ 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