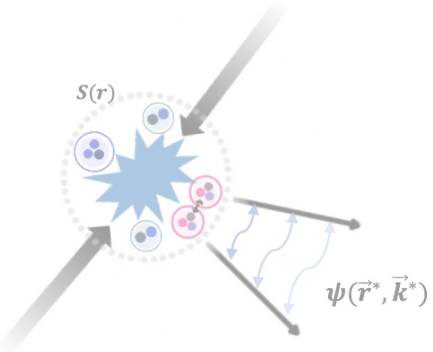


Femtoscopy of Strange Baryons in Heavy-ion Collisions at RHIC-STAR

Kehao Zhang (for the STAR Collaboration)

Central China Normal University

PHD 2026

10-13 November, 2026, Dalian, China

Outline

I. Femtoscopy

II. Motivation

III. RHIC-STAR Experiment

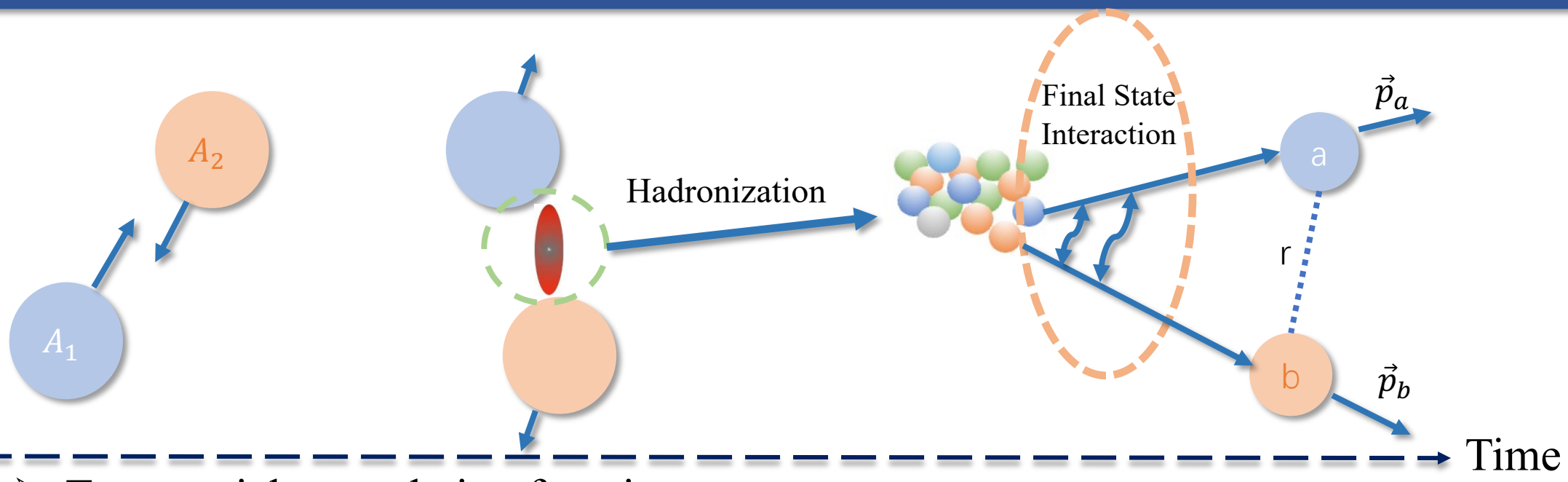
IV. Results

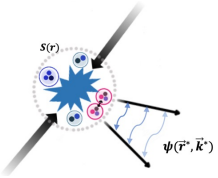
- d−Λ, t-Λ, ^{3}He-Λ Correlation
- p-Λ, p-Ξ^-, p-Ω^- Correlation

V. Spin-Femtoscopy Method

VI. Summary

Femtoscopy





➢ Two-particle correlation function:

Model ***Experimental***

$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$S(\vec{r})$: *Source function*

$\Psi(\vec{k}^*,\vec{r})$: *Pair wave function*

$k^* = \frac{1}{2}|\vec{p}_a - \vec{p}_b|$, *relative momentum*

$\vec{r}$: *relative distance*

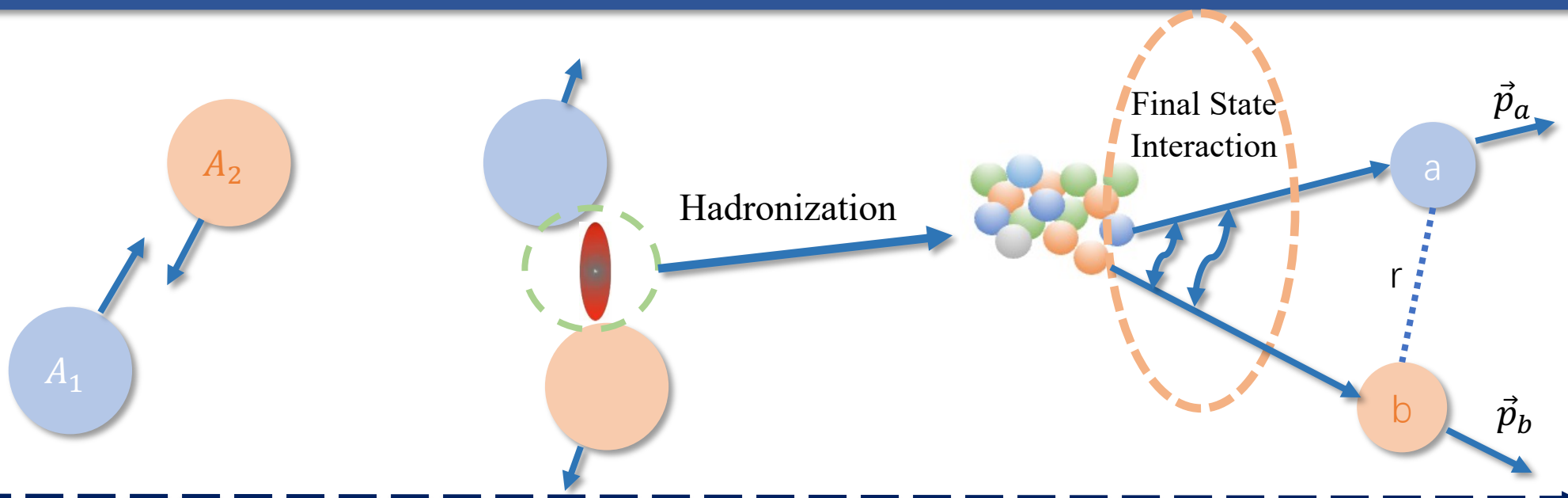
Depends on ...

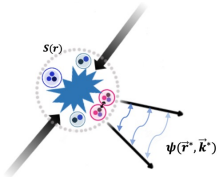
- ➢ Emission source
- ➢ Strong interaction
- ➢ Coulomb interaction

R. Lednicky, et al. Sov.J.Nucl.Phys.35(1982)770

L. Michael, et al. Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

Femtoscopy





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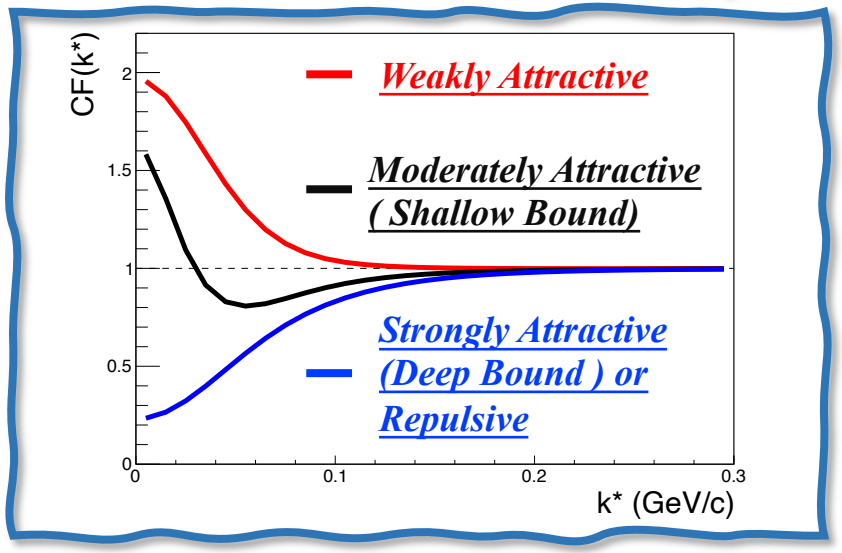


R. Lednicky, et al. Sov.J.Nucl.Phys.35(1982)770
L. Michael, et al. Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

Zhi-Wei Liu, et al., Phys. Rev. D 107, 074019 (2023)

Lednicky-Lyuboshitz Model

$$CF(k^*) = \int d^3r^* S(r^*)|\psi(r^*, k^*)|^2 = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

➢ **Formalism with Lednicky-Lyuboshitz (L-L) model:**

- Only consider s-wave
- Effective range expansion for $\psi(r^*, k^*)$
- Static and spherical Gaussian source assumed

R. Lednicky and V. L. Lyuboshitz, Sov. J. Nucl. Phys. 35, 770 (1982)

➢ **Wave function:**

- $\psi(r^*, k^*) = e^{-ik^*r^*} + f(k^*)\frac{e^{ik^*r^*}}{r^*}$

➢ **Scattering amplitude:**

- $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - ik^*]^{-1}$ (No Coulomb)
- $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - \frac{2}{a_c}h(\eta) - ik^*A_c(\eta)]^{-1}$ (Include Coulomb)

a_c: Bohr radius $\quad \eta = (k^*a_c)^{-1}$

A_c, h: Coulomb interaction factor

L-L Fitting by **Bayesian method**

➢ **Physics quantity:**

- f_0: Scattering Length
- d_0: Effective Range
- R_G: Spherical Gaussian Source Size

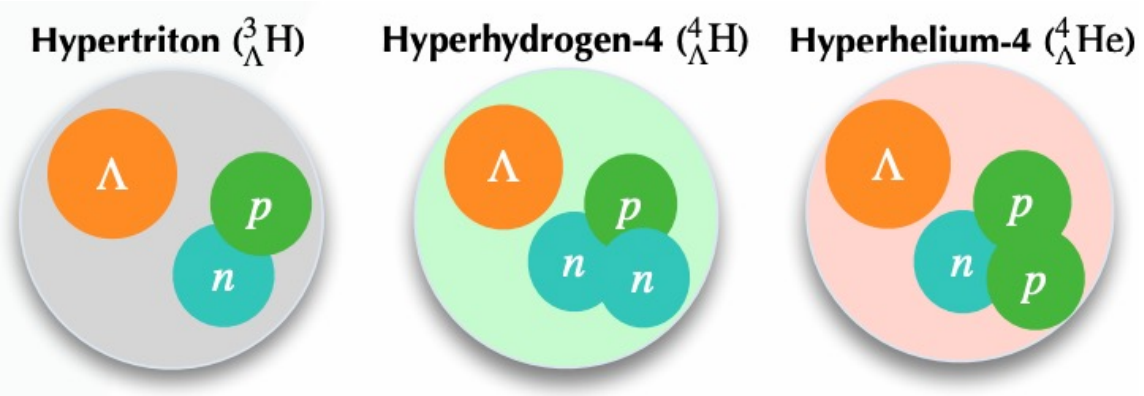
$f_0 > 0$: Attractive Interaction
$f_0 < 0$: Repulsive Interaction or Bound State

Bayesian method: *https://github.com/chunshen1987/bayesian_analysis*
Mäntysaari, H., et al., Phys. Lett. B 833 (2022) 137348

Motivation

- Light nuclei - Λ correlation : insights to hyper-nuclei structure and properties

  d-Λ, t-Λ, ^{3}He-Λ pair



J.Cleymans et al, Phys.Rev.C 74, 034903 (2006)
K. Blum et al, Phys.Rev.C 99, 04491 (2019)
St. Mrówczyński and P. Słoń, Acta Physica Polonica B 51, 1739 (2020)
St. Mrówczyński and P. Słoń, Physical Review C 104, 024909 (2021)

Motivation

- Light nuclei - Λ correlation : insights to hyper-nuclei structure and properties

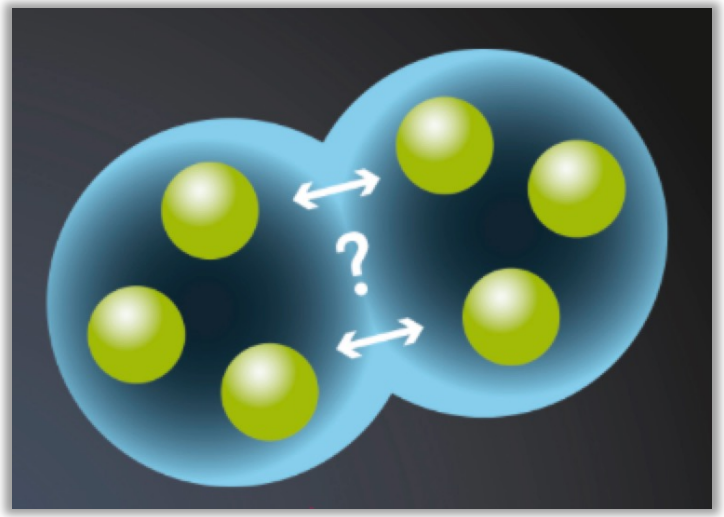
  d-Λ, t-Λ, ^{3}He-Λ pair

- (Strange) Dibaryons have never been found experimentally
  - ➢ The possible formation channels:

H-dibaryon **(|S|=2)Dibaryon ⇔ p-Ξ$^-$**

(|S|=2)Dibaryon ⇔ Λ-Λ

NΩ-dibaryon **(|S|=3)Dibaryon ⇔ p-Ω$^-$**



Particle	Mass (MeV)	Quark com-position	Decay mode
f_0	980	$q\bar{q}s\bar{s}$	$\pi\pi$
a_0	980	$q\bar{q}s\bar{s}$	$\pi\eta$
K(1460)	1460	$q\bar{q}q\bar{s}$	K$\pi\pi$
Λ(1405)	1405	qqqs$\bar{q}$	$\pi\Sigma$
Θ^+(1530)	1530	qqqq$\bar{s}$	KN
H	2245	uuddss	ΛΛ
NΩ	2573	qqqsss	ΛΞ
ΞΞ	2627	qqssss	ΛΞ
ΩΩ	3228	ssssss	$\Lambda K^- + \Lambda K^-$

Sungtae Cho, et al. (ExHIC), Phys. Rev. C 84, 064910 (2011)

Motivation

- Light nuclei - Λ correlation : insights to hyper-nuclei structure and properties

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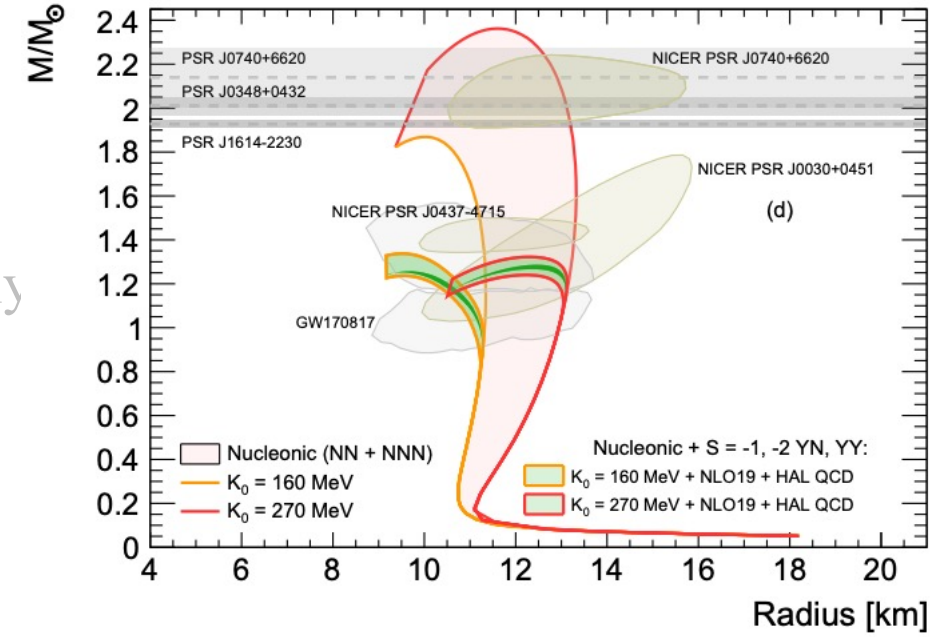
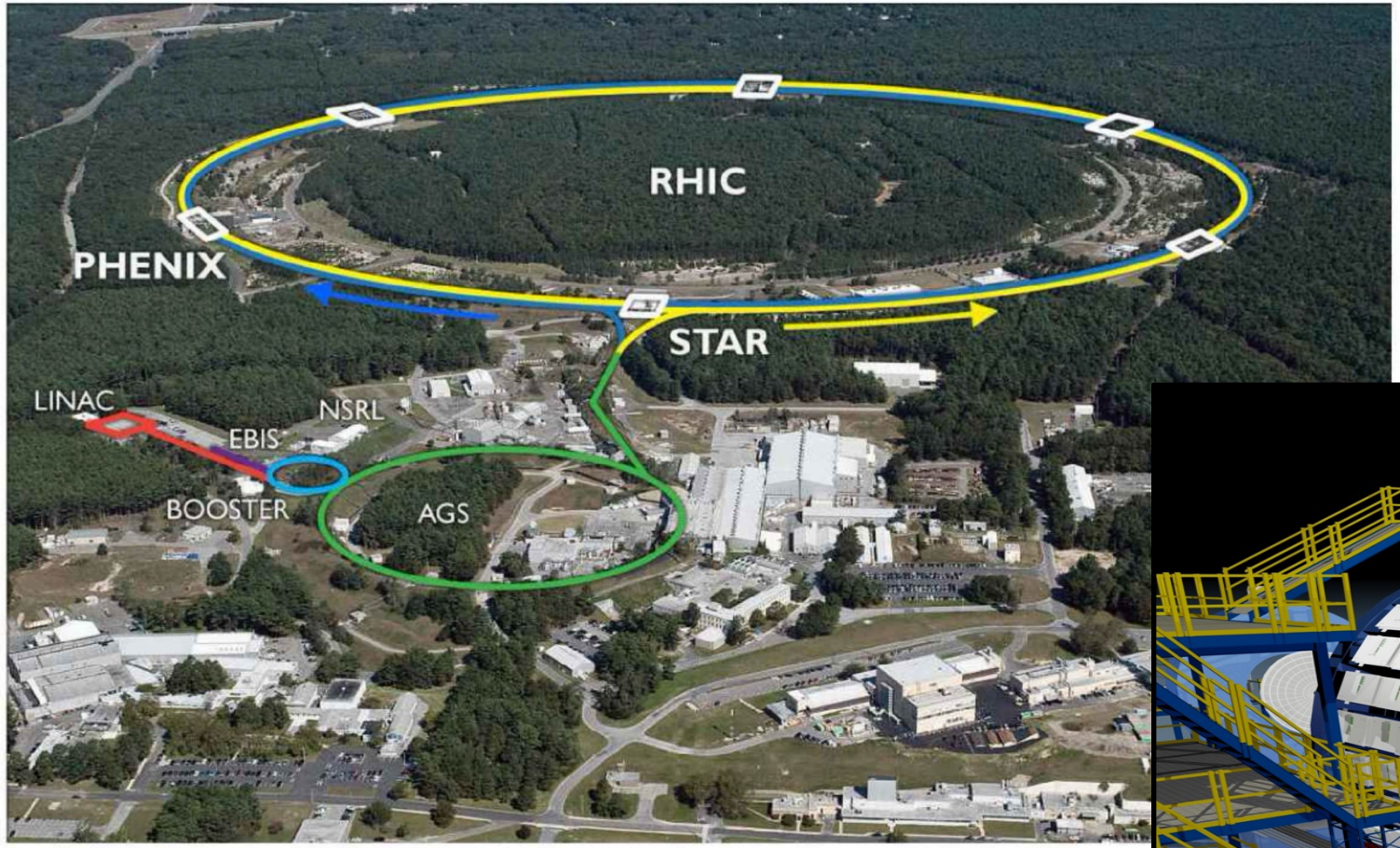


EPJ.A 61 (2025) 3, 59

- Hyperon-Nucleon (Y-N) and Hyperon-Hyperon (Y-Y) interactions provide important information to constrain the Equation-of-State and help to understand the inner structure of compact stars

More experimental measurements are needed !

RHIC-STAR Experiment



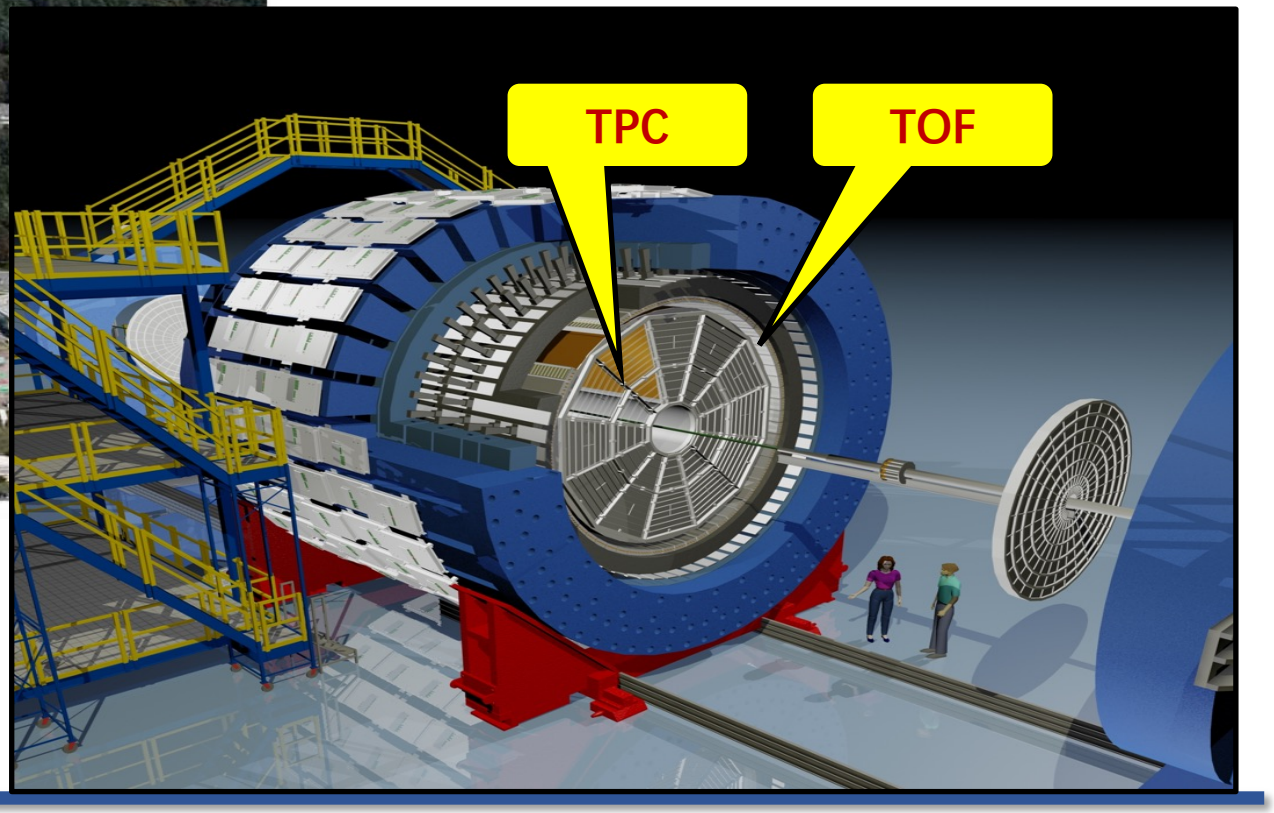
Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory, Upton

➔ p+p, Au+Au, Zr+Zr, Ru+Ru, d+Au…

➔ Beam Energy Scan Program I, II （Au+Au）

$\sqrt{s_{NN}}$ = 3.0 – 200 GeV



The Solenoidal Tracker At RHIC (STAR)

➔Excellent particle identification

➔Large, uniform acceptance at Mid-rapidity

Analysis Details

- Dataset:

Isobar collisions (Ru+Ru, Zr+Zr) @ 200 GeV

~ 3.9 billion minimum-bias events

Au+Au collisions @ 200 GeV (run11, run14, run16)

~ 2.5 billion minimum-bias events

Au+Au collisions @ 3 GeV (run21)

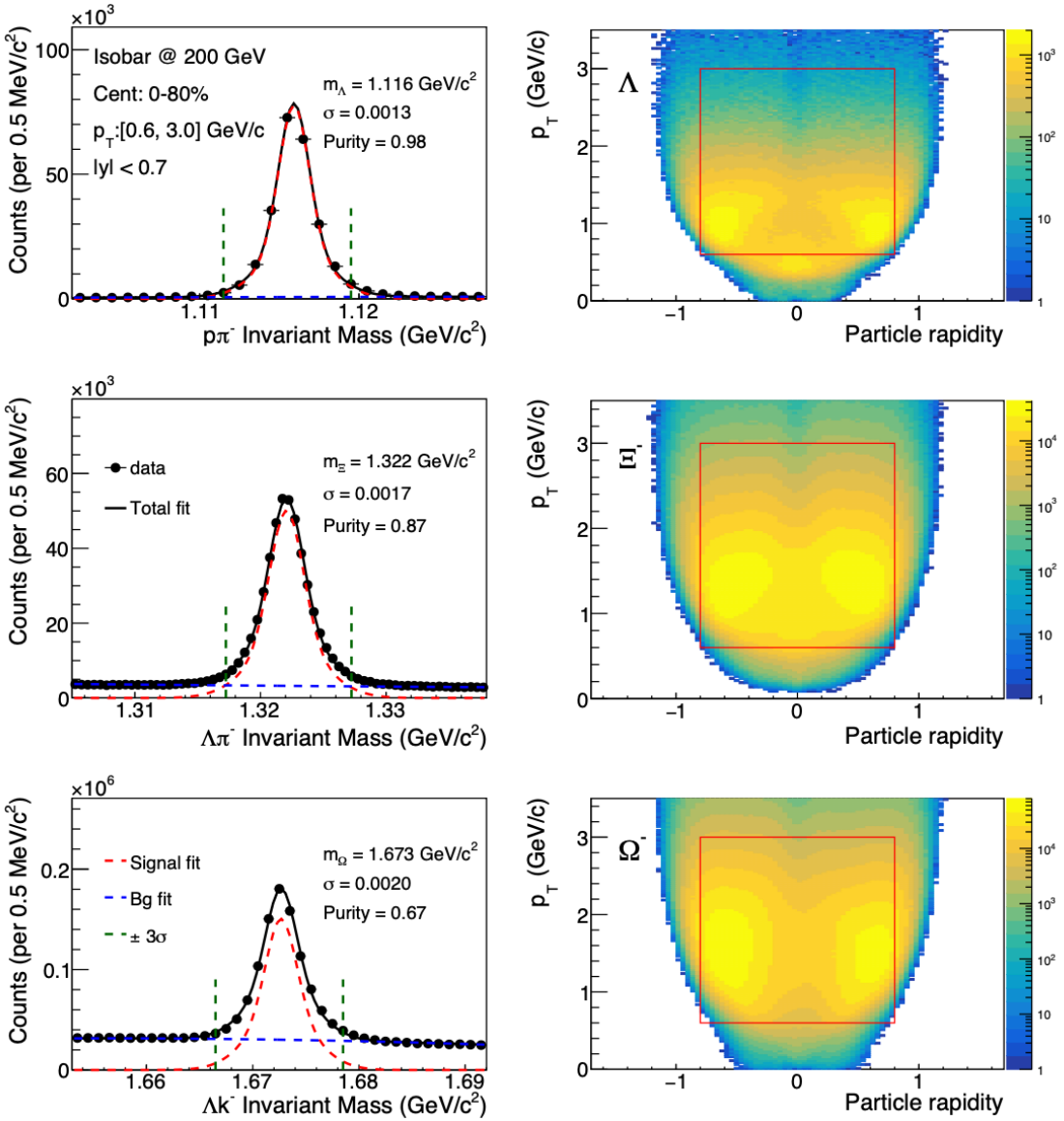
~ 2 billion minimum-bias events

- Hyperon reconstruction via Helix-swimming or KFParticle method

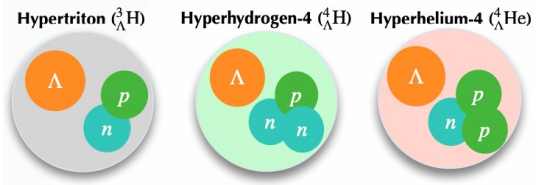
$\Lambda \rightarrow p + \pi^-$, BR = 63.9%

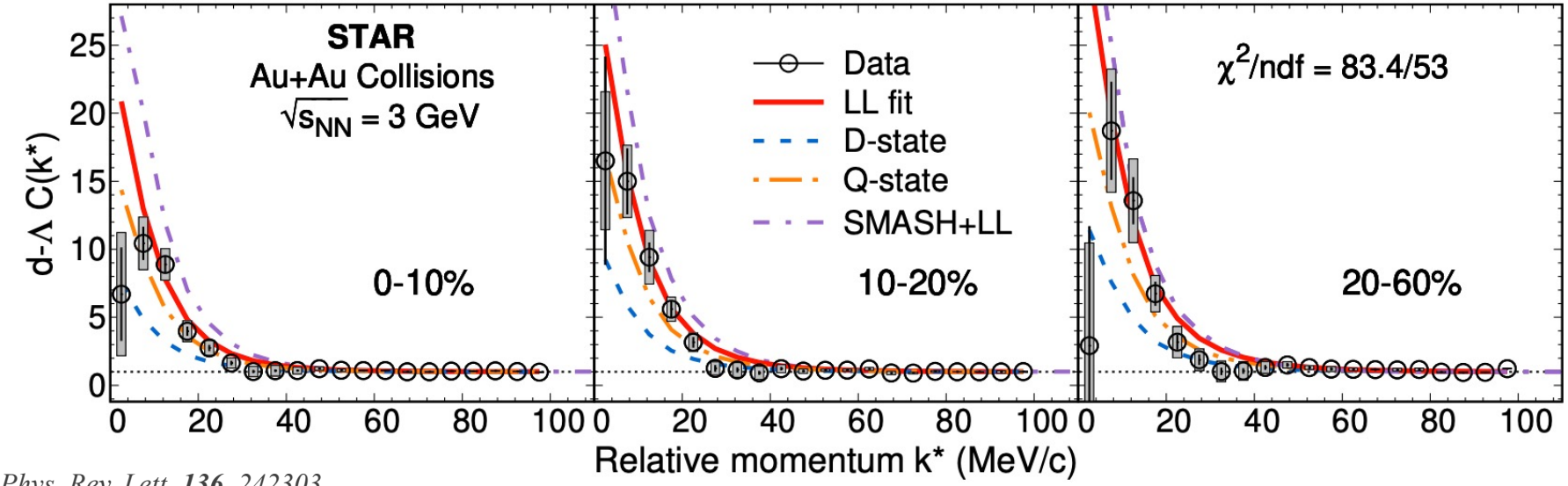
$\Xi^- \rightarrow \Lambda + \pi^-$, BR = 99.9%

$\Omega^- \rightarrow \Lambda + K^-$, BR = 67.8%



d-Λ, t-Λ, ^{3}He-Λ Correlation Function

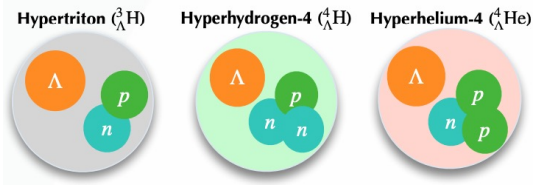


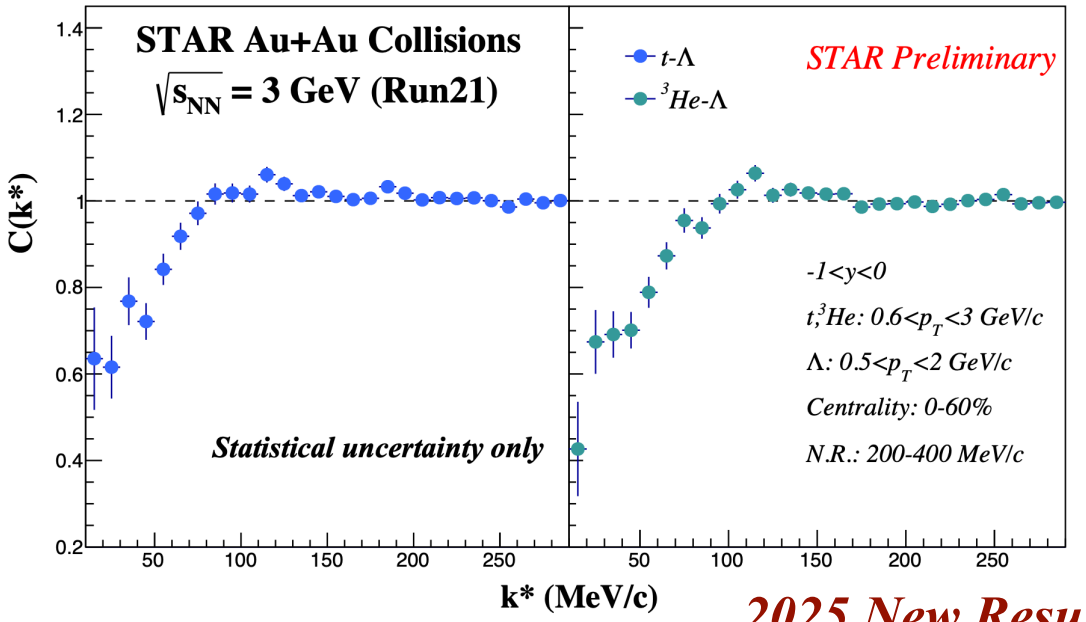


Phys. Rev. Lett. ***136****, 242303*

I. Precise measurements of d-Λ correlation functions in Au+Au collisions
   - CFs show enhancement at low k* -> mainly due to the strong interaction

d-Λ, t-Λ, ^{3}He-Λ Correlation Function





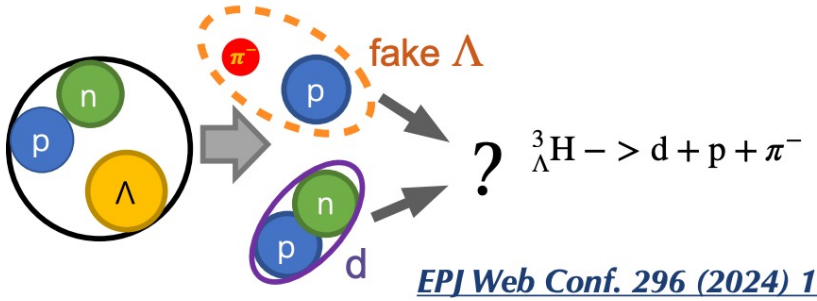
STAR, arXiv: 2511.15493 (PRL in press)

2025 New Result

I. Precise measurements of d-Λ correlation functions in Au+Au collisions
   - CFs show enhancement at low k* -> mainly due to the strong interaction

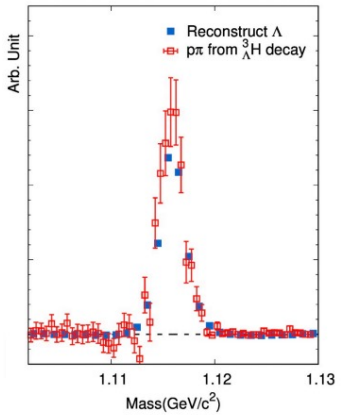
II. First t-Λ and ^{3}He-Λ correlation function measurements in the heavy-ion collisions
   - t-Λ and ^{3}He-Λ exhibit similar correlation structures and show depletion at low k^* -> mainly due to the strong interaction

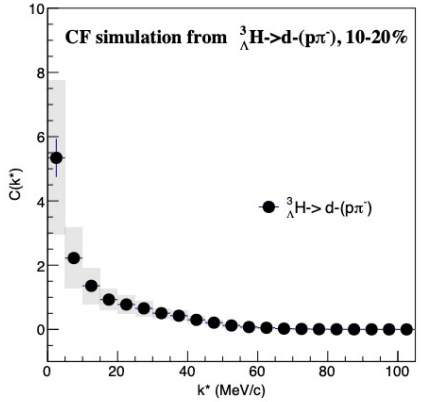
Contamination from Hyper-nuclei Decay

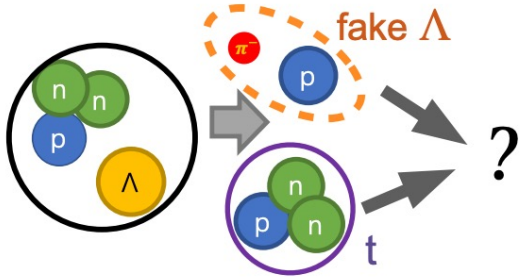


$^{3}_{\Lambda}\mathrm{H} -> \mathrm{d} + \mathrm{p} + \pi^{-}$

EPJ Web Conf. 296 (2024) 14010





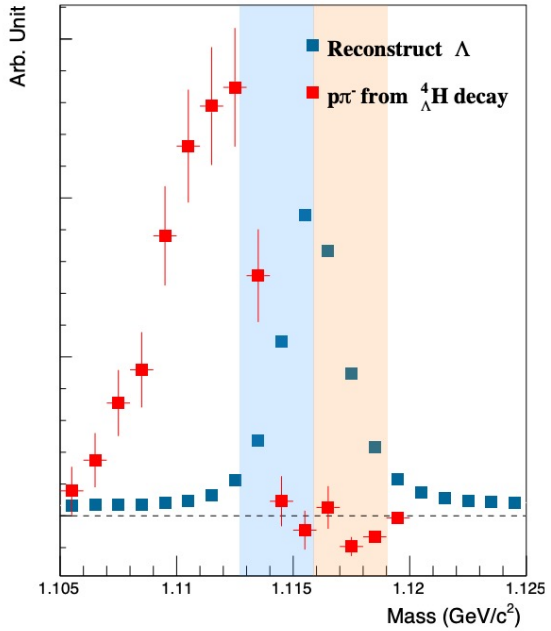


$^{4}_{\Lambda}\mathrm{H} -> \mathrm{t} + \mathrm{p} + \pi^{-}$

$^{4}_{\Lambda}\mathrm{He} -> {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$

Left signal: 1.11271~1.11589 GeV/c^2

Right signal: 1.11589~1.11906 GeV/c^2

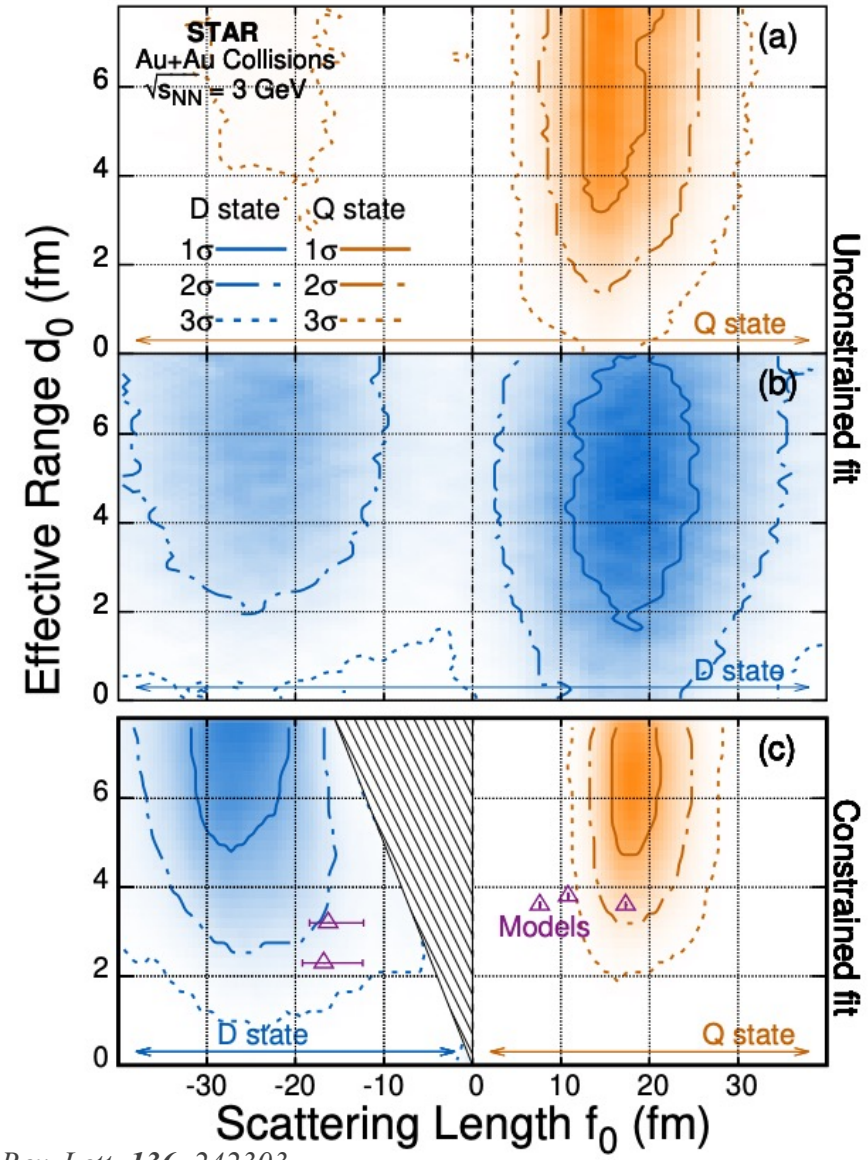


I. The $^{3}_{\Lambda}\mathrm{H}$, $^{4}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{He}$ decayed $\mathrm{p} + \pi^{-}$ are not experimentally distinguishable with the reconstructed Λ

II. For d-Λ, since we cannot separate them experimentally, we need to estimate their contribution and remove it from the CF

III. For t-Λ and 3He-Λ, we can experimentally remove the contribution by selecting the right side of the Λ invariant mass peak

d-Λ Interaction Parameters



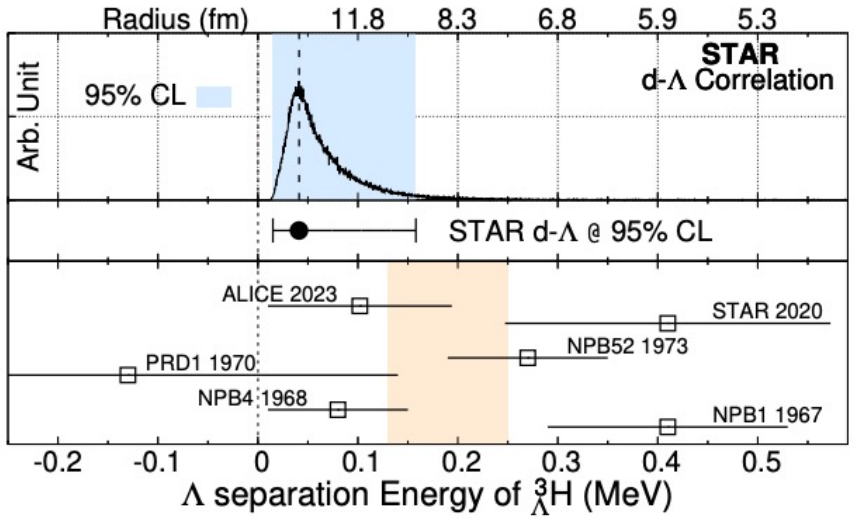
Phys. Rev. Lett. ***136***, *242303*

- Successfully separate two spin components in **d-Λ pair**

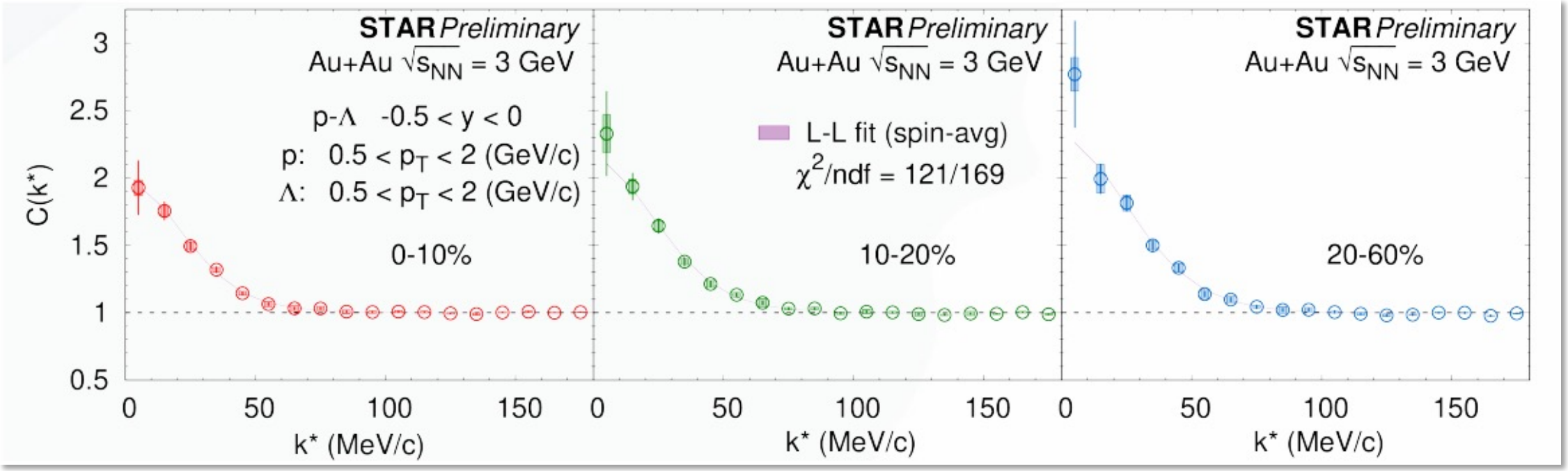
$$f_0(D) = -26.1^{+5.6}_{-5.6}\ \text{fm} \rightarrow \text{Related to } {}^{3}_{\Lambda}\text{H}$$
$$f_0(Q) = 18.7^{+2.8}_{-2.8}\ \text{fm} \rightarrow \text{Attractive interaction}$$

- Extracted binding energy via Bethe formula consistent with world average

$$BE_{{}^{3}_{\Lambda}\text{H}} = \frac{1}{2m_{d-\Lambda}d_0^2}\left(1-\sqrt{1+\frac{2d_0}{f_0}}\right)^2 \qquad BE = 0.04^{+0.12}_{-0.03}\ (\text{MeV})$$



p-Λ Correlation Function (|S| =1)



I. Measure p-Λ CFs at $\sqrt{s_{NN}} = 3$ GeV in Au+Au collisions

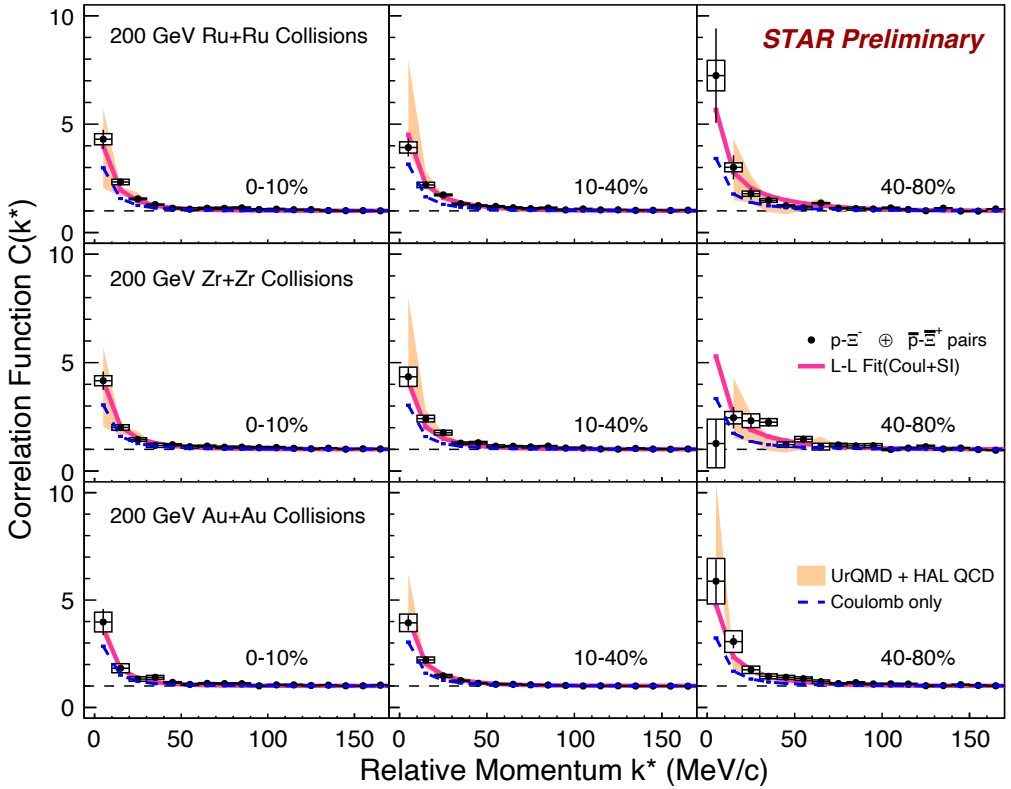
- CFs show enhancement at low k* -> mainly due to the attractive strong interaction

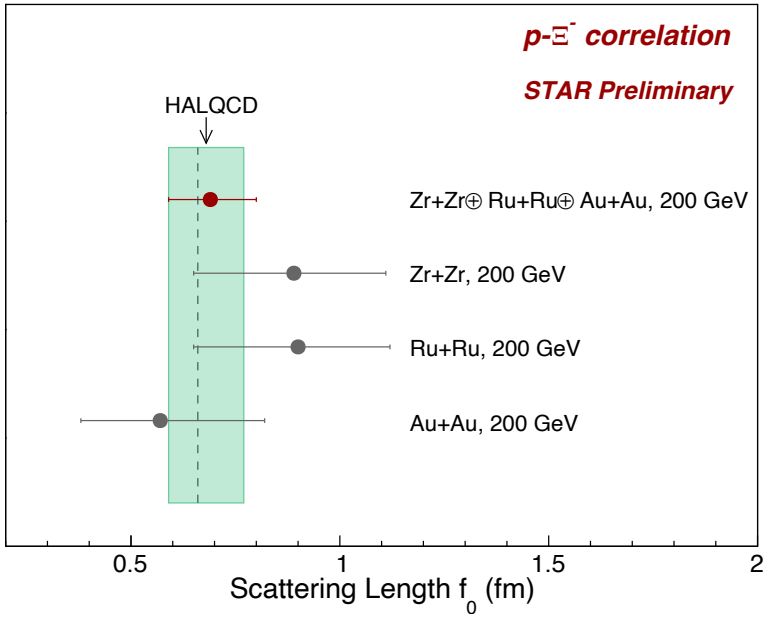
II. Simultaneously fit with L-L function for different centralities to extract R_G, f_0 and d_0

III. Extracted spin averaged scattering length f_0 and effective range d_0 :

$f_0 = 2.32^{+0.12}_{-0.11}$ fm (stat.+sys.) $d_0 = 3.5^{+2.7}_{-1.3}$ fm (stat.+sys.)

p-Ξ⁻ Correlation Function (|S| =2)





I. Measure p-Ξ⁻ ⊕ p̄-Ξ̄⁺ CFs at $\sqrt{s_{NN}} = 200$ GeV in Au+Au and Isobar collisions

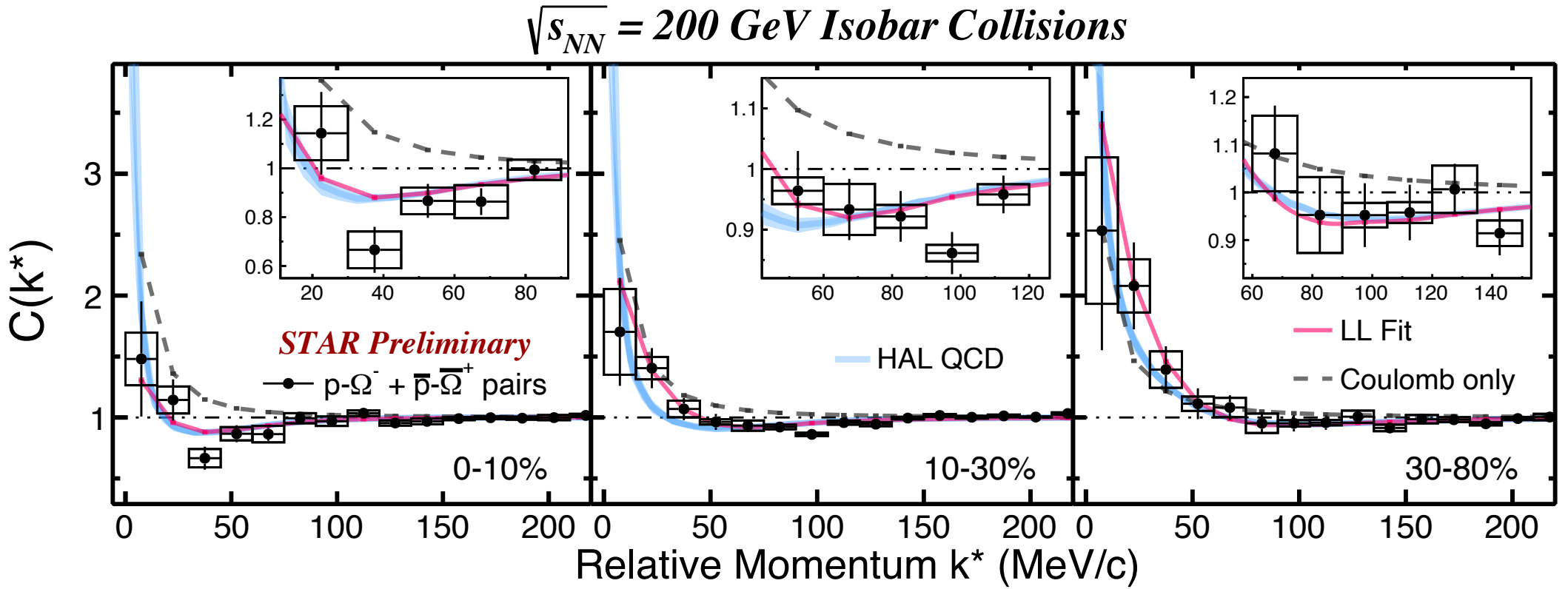
- CFs show enhancement at low k* -> mainly due to the attractive Coulomb interaction

II. Simultaneously fit with L-L function for different centralities in each collision system to extract R_G, f_0 and d_0 by Bayesian method

III. Extracted spin averaged scattering length: $f_0 = 0.7^{+0.1}_{-0.1}$ fm (stat.+sys.)

Y. Kamiya, et al., Phys. Rev. C 105, 014915 (2022)

p-Ω^- Correlation Function (|S|=3)



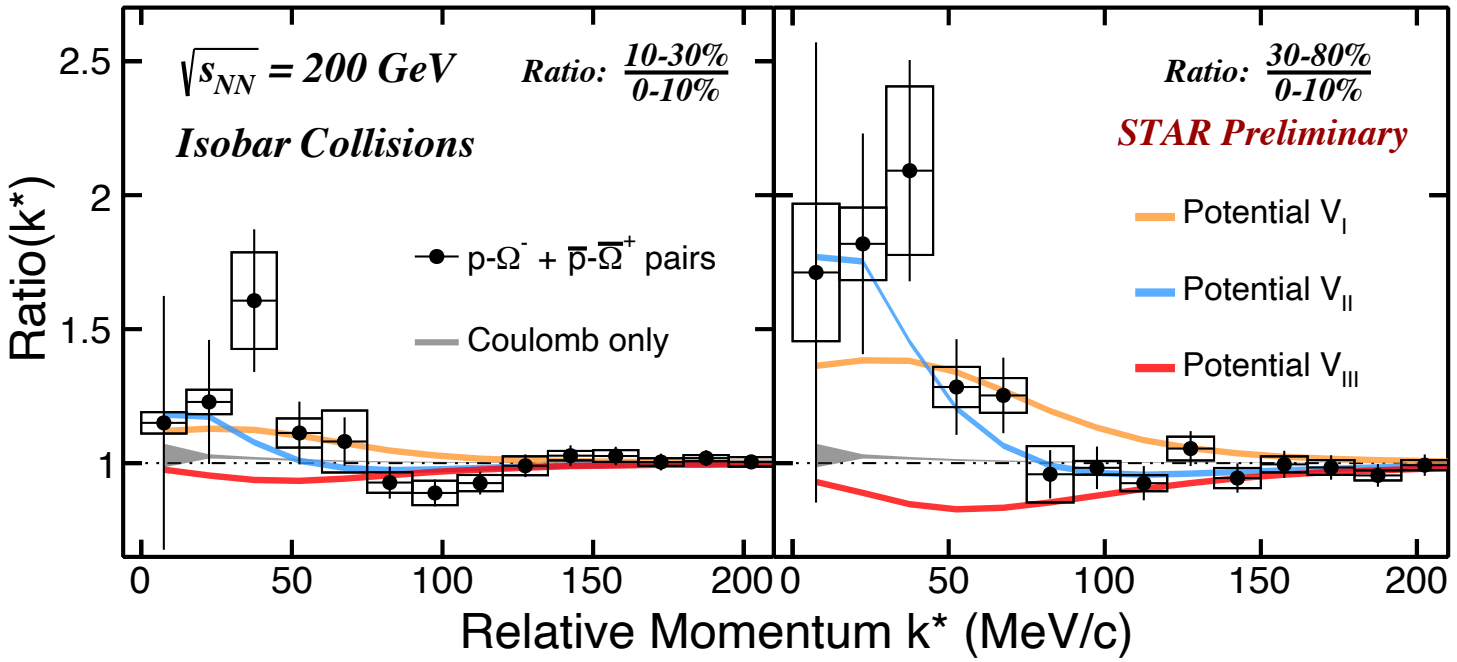
I. Precise measurements of p-Ω^- $\oplus$ $\bar{p}$-$\bar{\Omega}^+$ correlation functions in Isobar collisions
   - CFs show enhancement at low k* –> mainly due to Coulomb attraction interaction
   - CFs show depletion at k* ~ 30-100 MeV/c –> mainly due to the strong interaction

II. Simultaneously fit with L-L function for 3 centralities to extract R_G, f_0 and d_0 by Bayesian method

III. CFs obtained by HAL QCD theory with extracted R_G by L-L model is consistent with the data

Takumi Iritani, et al. (HAL QCD), Phys. Lett. B792 (2019)

p-Ω⁻ CF Ratio (|S|=3)



Type	f_0 (fm)	d_0 (fm)	BE (MeV)	χ^2/ndf	p-value	
V_I [1]	1.12	1.16	--	48.2/29	0.014	No Bound
V_{II} [2]	-3.38	1.31	2.15	22.2/29	0.812	Shallow Bound
V_{III} [1]	-1.29	0.65	26.9	58.7/29	0.001	Deeply Bound

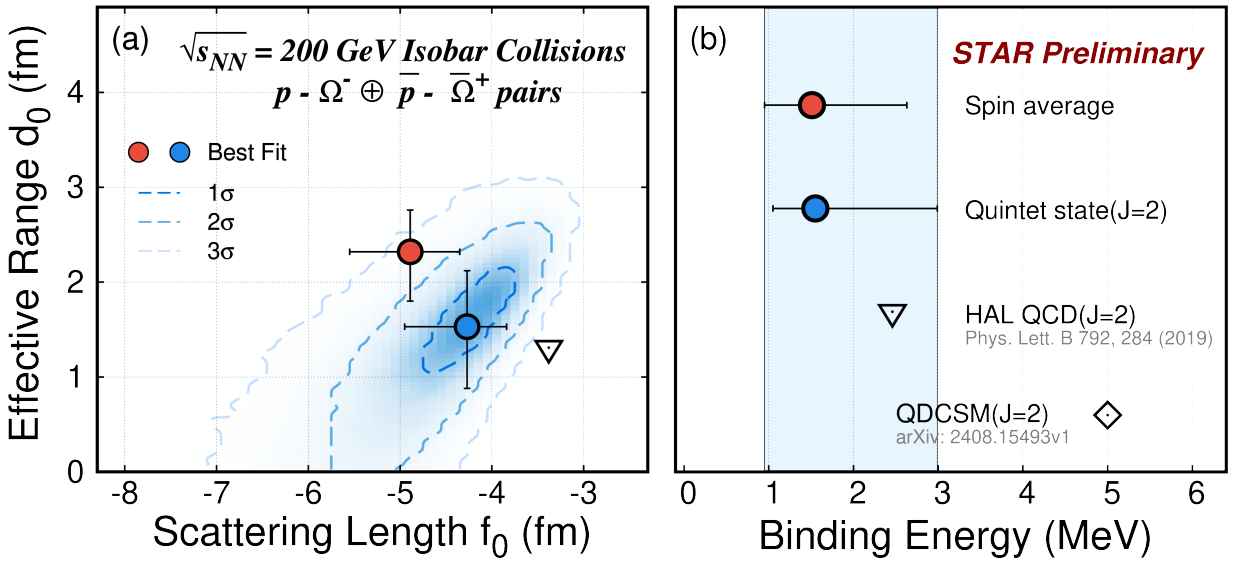
I. By taking CF ratio, Coulomb effect can be largely canceled

II. CF Ratio shows enhancement at low k* and depletion around k* ~ 100 MeV/c
   - Due to the presence of shallow bound state

III. The potential V_{II}, with a p-value of 0.812, provides the best description of the data

[1] *Kenji Morita, et al., Phys. Rev. C 94, 031901 (2016)*
[2] *Kenji Morita, et al., Phys. Rev. C 101, 015201 (2020)*

p-Ω⁻ Interaction Parameters (|S|=3)



	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.9^{+0.5}_{-0.7}$	$-4.3^{+0.4}_{-0.7}$	-3.4
d_0 (fm)	$2.3^{+0.4}_{-0.5}$	$1.5^{+0.5}_{-0.7}$	1.3
BE (MeV)	$1.5^{+1.1}_{-0.6}$	$1.6^{+1.4}_{-0.5}$	2.3

Kenji Morita, et al., Phys. Rev. C 101, 015201 (2020)

I. First experimental constraints in heavy-ion collisions of strong interaction parameters in p-Ω⁻ pair

II. Extracted negative f_0 ($|f_0| > 2d_0$) by Spin average method and Quintet method

- First experimental evidence of strange dibaryon

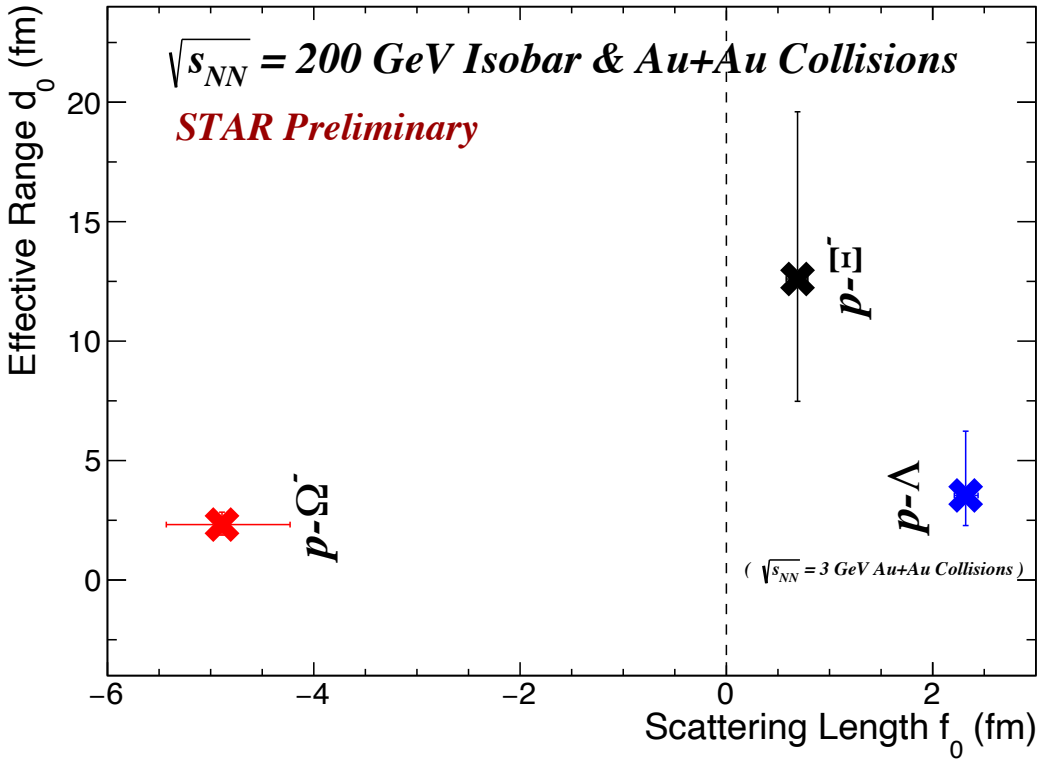
III. Calculate Binding Energy (BE) via Bethe formula:

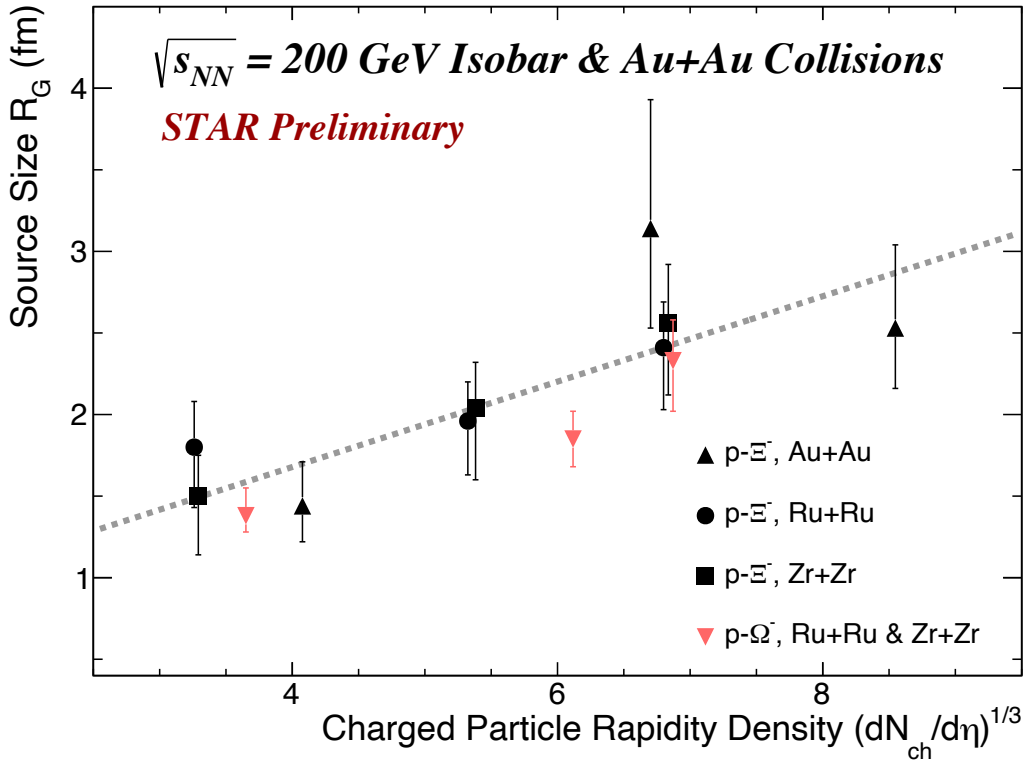
Reduced mass: $m_{p\Omega} = \frac{m_p m_\Omega}{m_p + m_\Omega}$

$$BE_{p\Omega} = \frac{1}{2m_{p\Omega}d_0^2}\left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\right)^2$$

- Calculated BE are consistent with HAL QCD prediction

Strong Interaction Parameters





- Extracted positive f_0 in p-Λ and p-Ξ^- pair –> Weakly attractive interaction
- Extracted negative f_0 in p-Ω^- pair –> Support the formation of bound state

- Extracted source size in p-Ξ^-, p-Ω^-pairs show a linear trend (Centrality dependence $R_G^{central} > R_G^{peripheral}$)

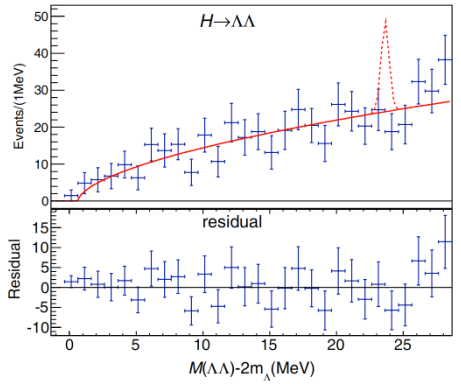
H-dibaryon Search

- **Search for the H-dibaryon**

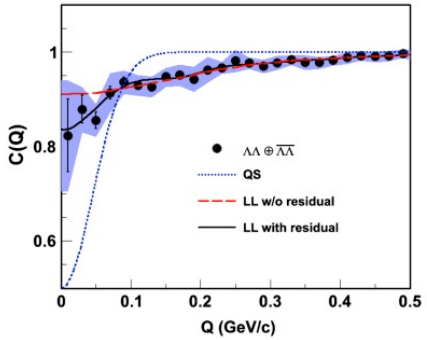
The H-dibaryon is a hypothesized six-quark ($uuddss$) state with strangeness $S = -2$ and spin J = 0, first predicted by Robert L. Jaffe in 1977.

Jaffe, Phys. Rev. Lett. 38, 195

Invariant Mass Method



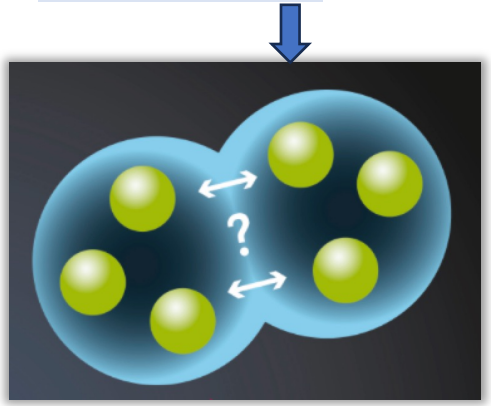
Femtoscopy Method



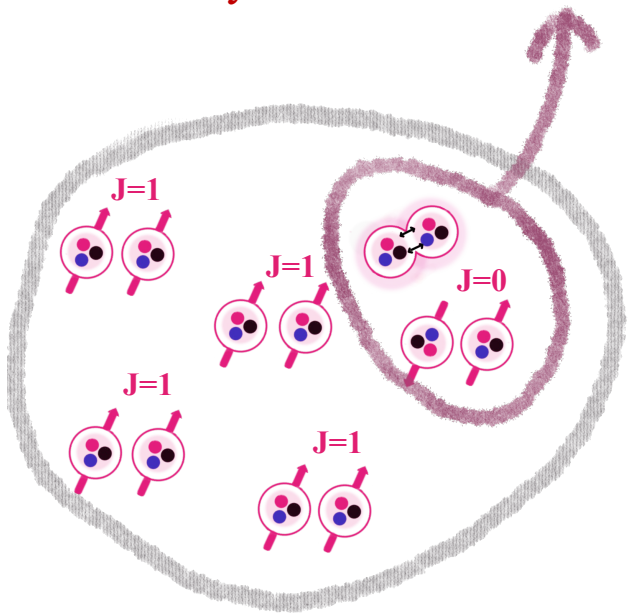
In ΛΛ and p-Ξ^- pairs, there are two spin states:

$$C_{p-\Xi} = \frac{1}{4}C_{J=0,singlet} + \frac{3}{4}C_{J=1,triplet}$$

$$C_{\Lambda-\Lambda} = \frac{1}{4}C_{J=0,singlet} + \frac{3}{4}C_{J=1,triplet}$$

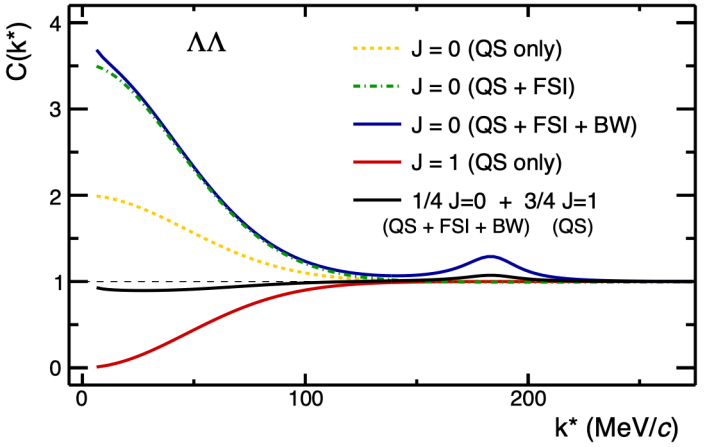


If the spin state (J=0) can be selected, a signal of the H-dibaryon may become observable.



STAR, Phys.Rev.Lett. 114 (2015) 2, 022301

Belle, Phys. Rev. Lett. 110, 222002 (2013)



K. Zhang, X. Wang, X. Luo, arXiv:2607.00413

Spin-Femtoscopy Method

- **ΛΛ spin correlation:**

$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda^2 P_{\Lambda\Lambda}\cos\theta^* \qquad P_{\Lambda\Lambda} = \frac{1}{3} < \sigma_1 \cdot \sigma_2 >$$

$$\alpha_\Lambda = 0.746$$

- **Different spin states:**

J=0, $P_{\Lambda\Lambda}$= -1 $\quad \frac{dN}{d\cos\theta^*} \propto 1 - \alpha_\Lambda^2\cos\theta^*$

J=1, $P_{\Lambda\Lambda}$= 1/3 $\quad \frac{dN}{d\cos\theta^*} \propto 1 + \frac{1}{3}\alpha_\Lambda^2\cos\theta^*$

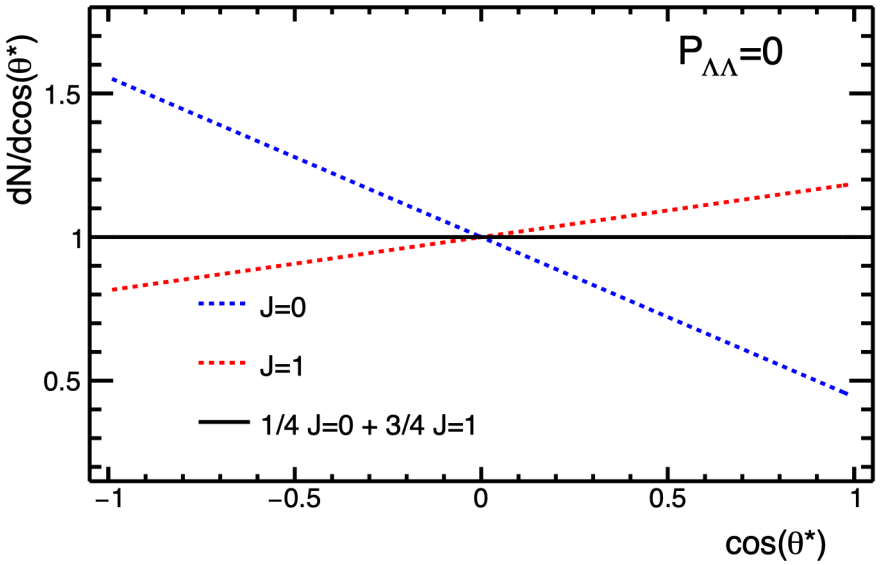
$$\frac{dN}{d\cos\theta^*} \propto w_0(1 - \alpha_\Lambda^2\cos\theta^*) + (1 - w_0)(1 + \frac{1}{3}\alpha_\Lambda^2\cos\theta^*)$$

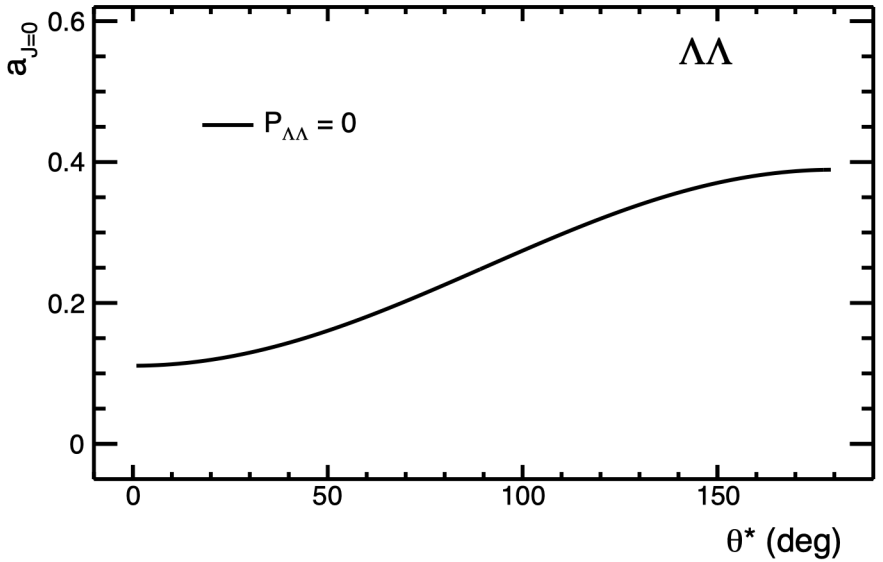
$$= 1 + \alpha_\Lambda^2(\frac{1 - 4w_0}{3})\cos\theta^* \qquad P_{\Lambda\Lambda} = \frac{1-4w_0}{3}$$

w_0 is the total J=0 state weight

- **spin weight dependence on θ^*:**

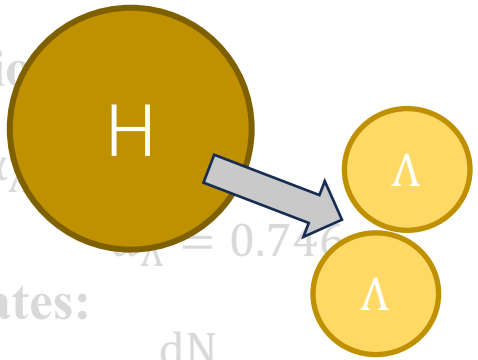
$$a_{J=0}(\theta^*) = \frac{w_0(1 - \alpha_\Lambda^2\cos\theta^*)}{w_0(1 - \alpha_\Lambda^2\cos\theta^*) + (1 - w_0)(1 + \frac{1}{3}\alpha_\Lambda^2\cos\theta^*)}$$

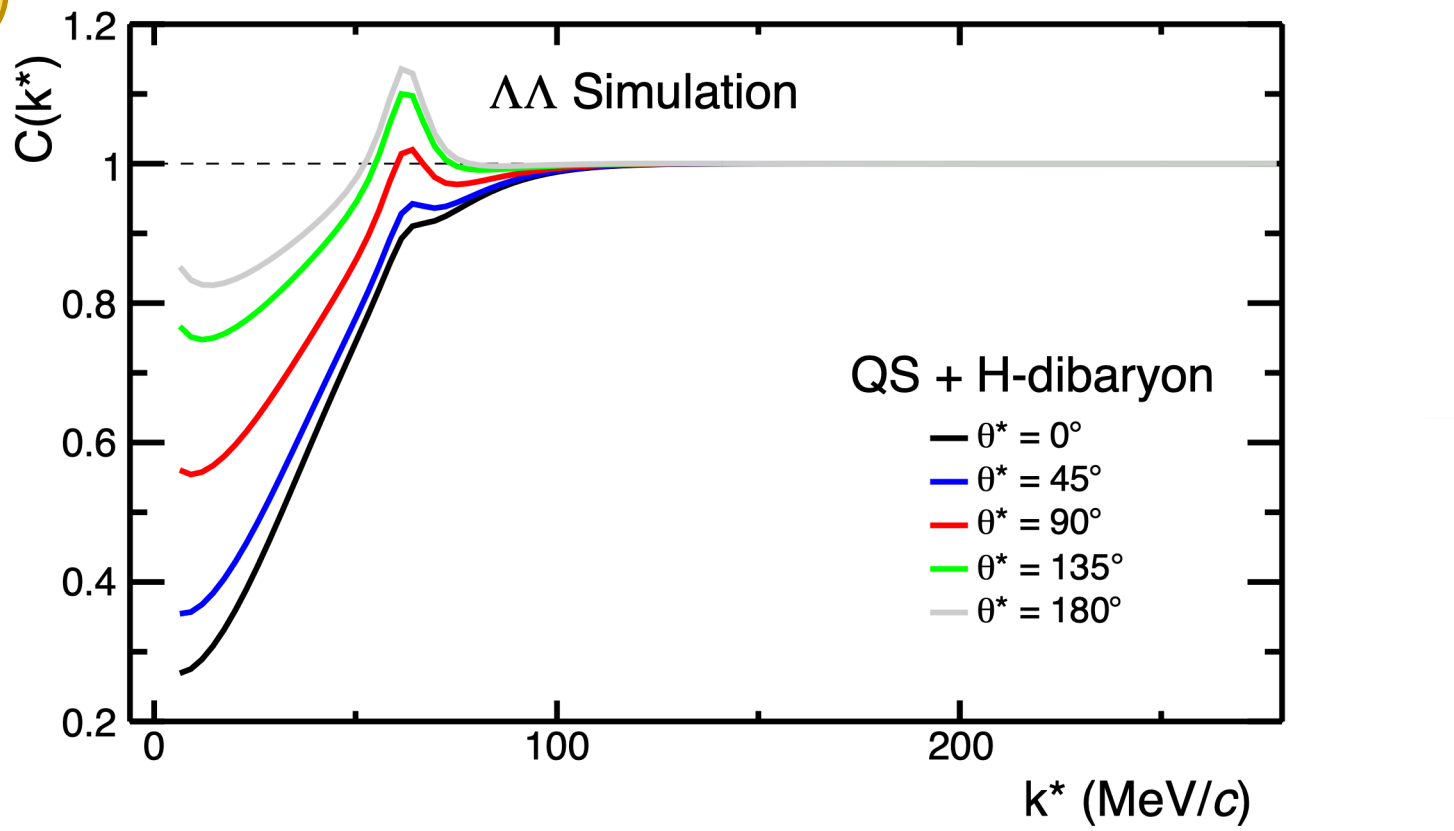




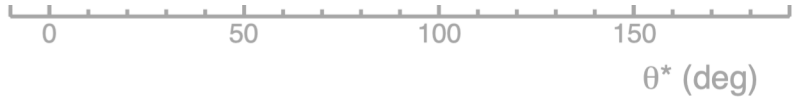
K. Zhang, X. Wang, X. Luo, arXiv:2607.00413

Spin-Femtoscopy Method









K. Zhang, X. Wang, X. Luo, arXiv:2607.00413

Spin-Femtoscopy Method

$C_{\Lambda\Omega} = 1 \quad C_{\Lambda\Xi} = 0.94 \quad \alpha_\Omega = 0.0157 \quad \alpha_\Xi = -0.29$

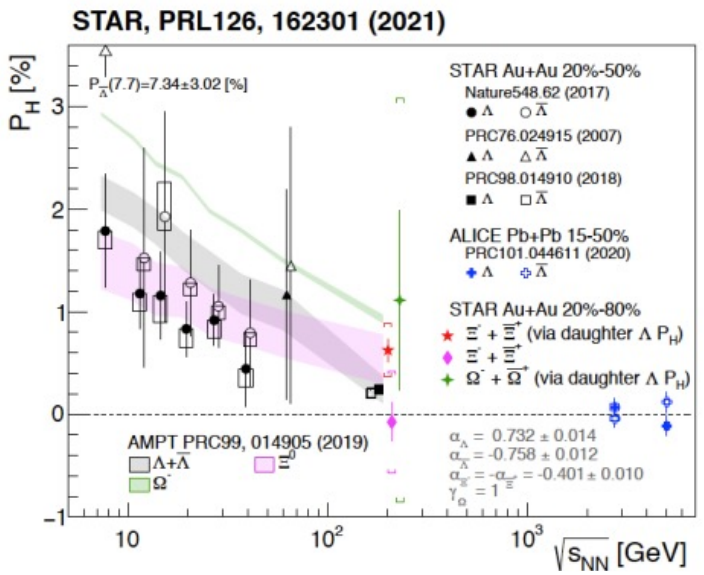
- **ΛΞ spin correlation:**

$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda \alpha_\Xi P_{\Lambda\Xi} \cos\theta^*_{p\Lambda} \qquad P_{\Lambda\Xi} = \frac{1}{3} < \sigma_\Lambda \cdot \sigma_\Xi >$$

$$P_\Lambda = C_{\Lambda\Xi} P_\Xi \qquad P_{\Lambda\Lambda} = C_{\Lambda\Xi} P_{\Lambda\Xi}$$

$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda^2 P_{\Lambda\Lambda} \cos\theta^*_{pp} \longrightarrow \frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda^2 C_{\Lambda\Xi} P_{\Lambda\Xi} \cos\theta^*_{pp}$$

(Consider one Λ from Ξ decay)

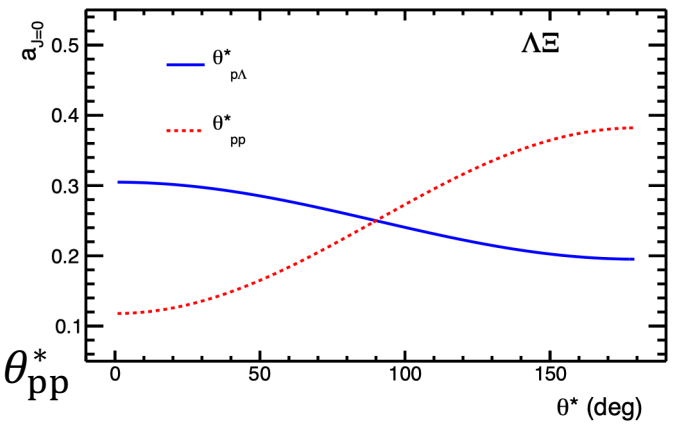


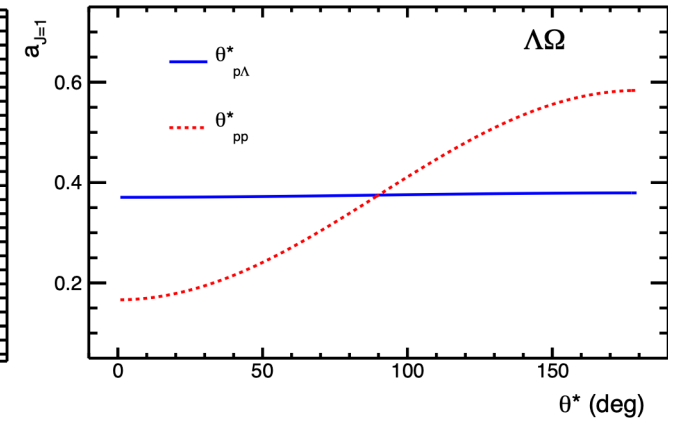
- **ΛΩ spin correlation:**

$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda \alpha_\Omega P_{\Lambda\Omega} \cos\theta^*_{p\Lambda} \quad (1)$$

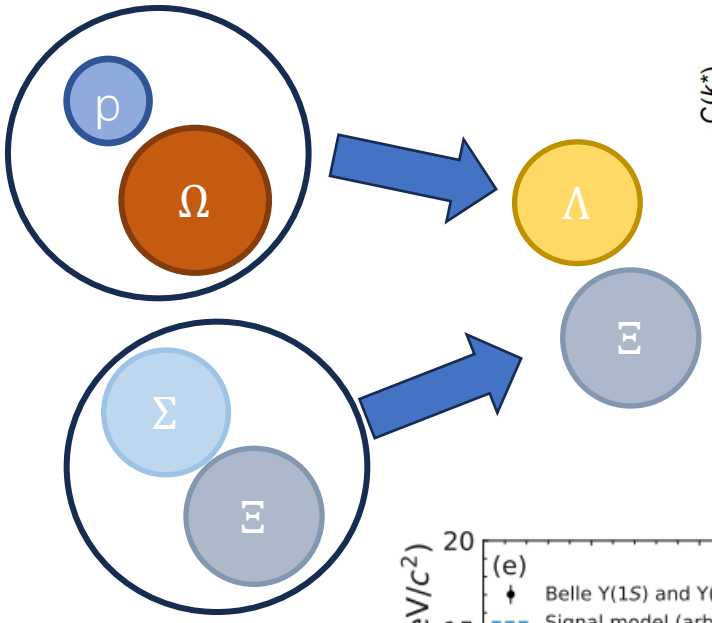
$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda^2 P_{\Lambda\Lambda} \cos\theta^*_{pp}$$ (Consider one Λ from Ω decay)

$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda^2 C_{\Lambda\Omega} P_{\Lambda\Omega} \cos\theta^*_{pp}$$

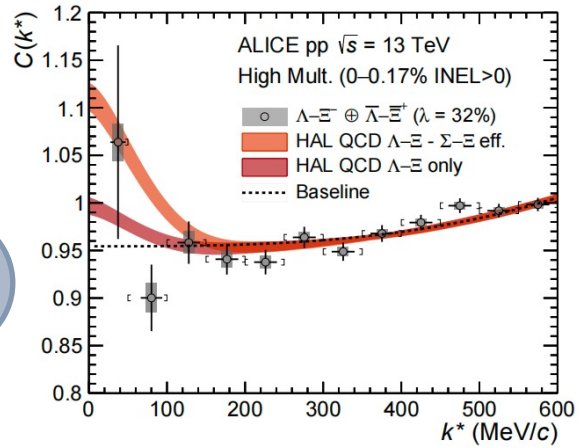




Strange Dibaryons (S=-3, -4) Search



Phys. Lett. B 844 (2023) 137223



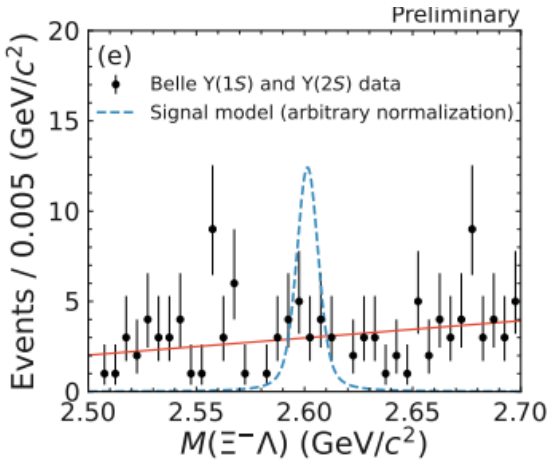
$e_{\Lambda\Xi} = 2437$ MeV $e_{\Xi\Xi^*} = 2854$ MeV

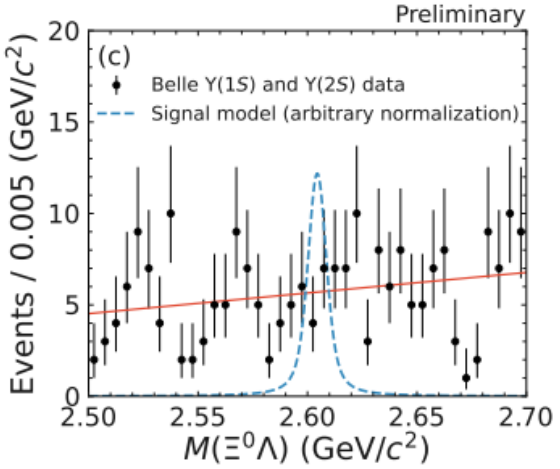
$e_{\Sigma\Xi} = 2513$ MeV $e_{\Xi^*\Xi^*} = 3060$ MeV

$e_{N\Omega} = 2612$ MeV $e_{\Lambda\Omega} = 2788$ MeV

$S = -4, J = 2, I = 0: \Lambda\Omega, \Xi\Xi^*$

$S = -4, J = 1, I = 0: \Lambda\Omega, \Xi\Xi^*, \Xi^*\Xi^*$

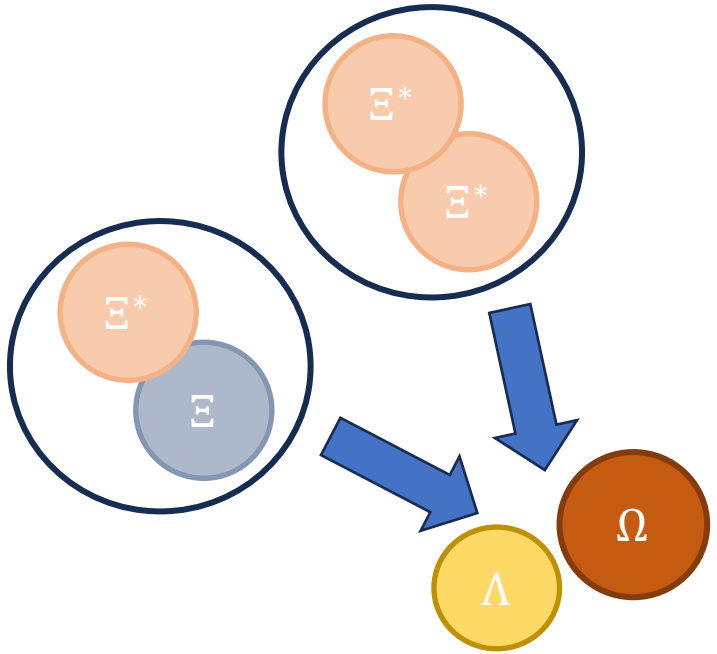




$S = -3, J = 1, I = 1/2: \ \Lambda\Xi, \Sigma\Xi, N\Omega$

$S = -3, J = 0, I = 1/2: \ \Lambda\Xi, \Sigma\Xi$

arXiv:2605.29778



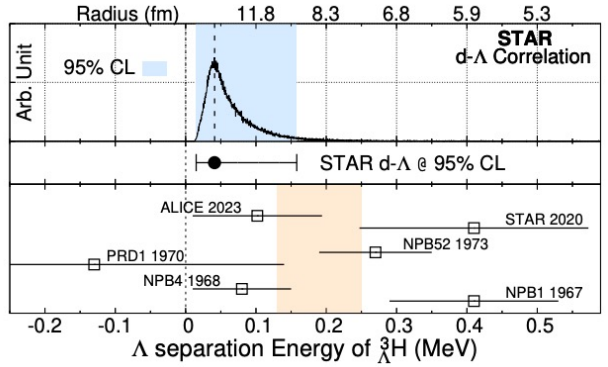
Summary

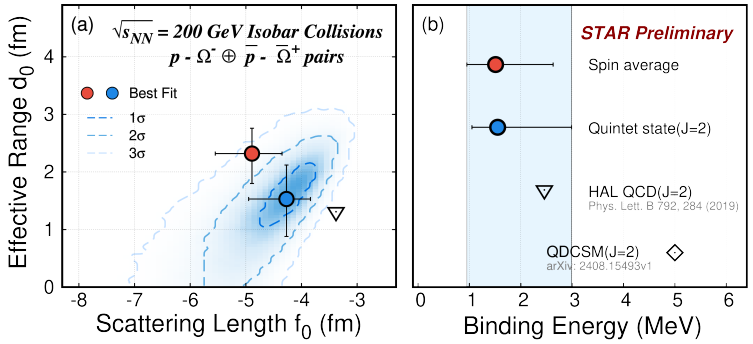
- Femtoscopy measurements from HIC provides a unique tool to explore strong interaction and search for exotic states

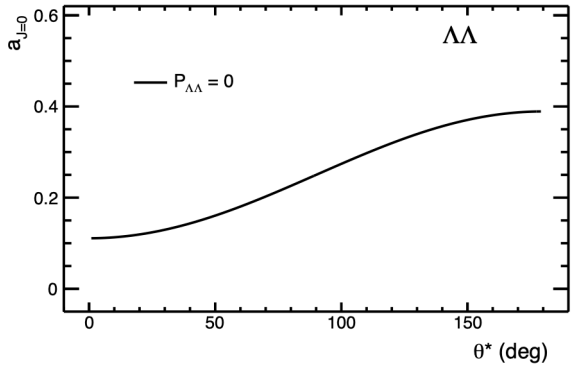
I. d−Λ, t-Λ, ^{3}He-Λ Correlation
  - Extracted $^3_\Lambda$H binding energy consistent with world average
  - Provide a new way to explore hypernuclei properties

II. p-Λ, p-Ξ^-, p-Ω^- Correlation
  - Extracted positive f_0 in p-Λ and p-Ξ^- pair hints weakly attractive strong interaction
  - First experimental evidence of strange dibaryon in **p-Ω^- ⊕ $\bar{\mathbf{p}}$-$\bar{\Omega}^+$** pairs, with Binding Energy BE = $1.6^{+1.4}_{-0.5}$ MeV

III. Spin-Femtoscopy Method
  - Propose spin femtoscopy method as a powerful tool to study spin-dependent hadronic physics and search for exotic bound states.







Thank you for your attention!