Search for the Strange Dibaryons with Baryon-Baryon Correlations at STAR

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Outline

I. Motivation

II. Femtoscopy

III. Analysis Details

IV. Lednicky-Lyuboshitz Model

V. Results

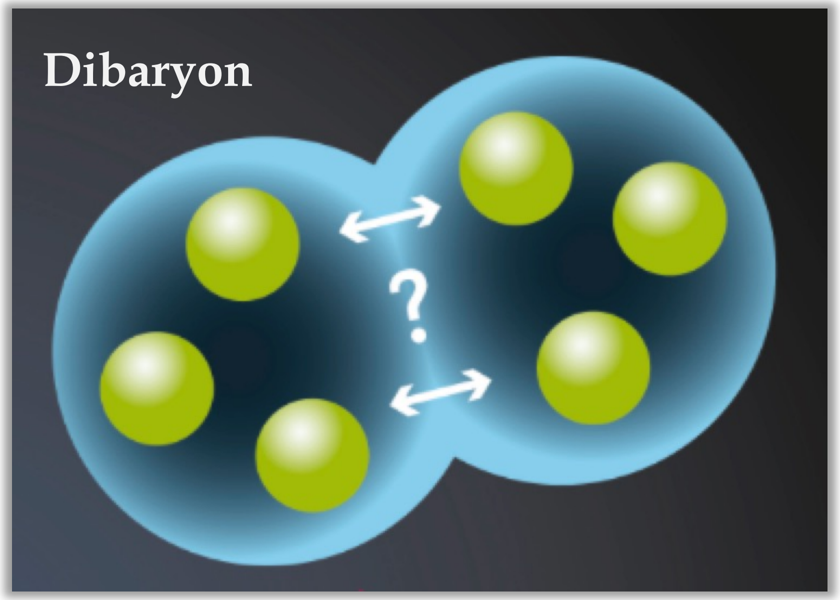
- $|S| = 2$: p-Ξ^- Correlation
- $|S| = 3$: p-Ω^- Correlation

VI. Spin Femtoscopy Method

VII. Summary

Motivation

(Strange) Dibaryons have never been found experimentally



Particle	Mass (MeV)	Quark composition	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	$\Lambda\Lambda$
NΩ	2573	qqqsss	$\Lambda\Xi$
$\Xi\Xi$	2627	qqssss	$\Lambda\Xi$
$\Omega\Omega$	3228	ssssss	ΛK^-+ΛK^-

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

➢ The possible formation channels:

(|S|=2)Dibaryon ⇔ $p + \Xi^-$

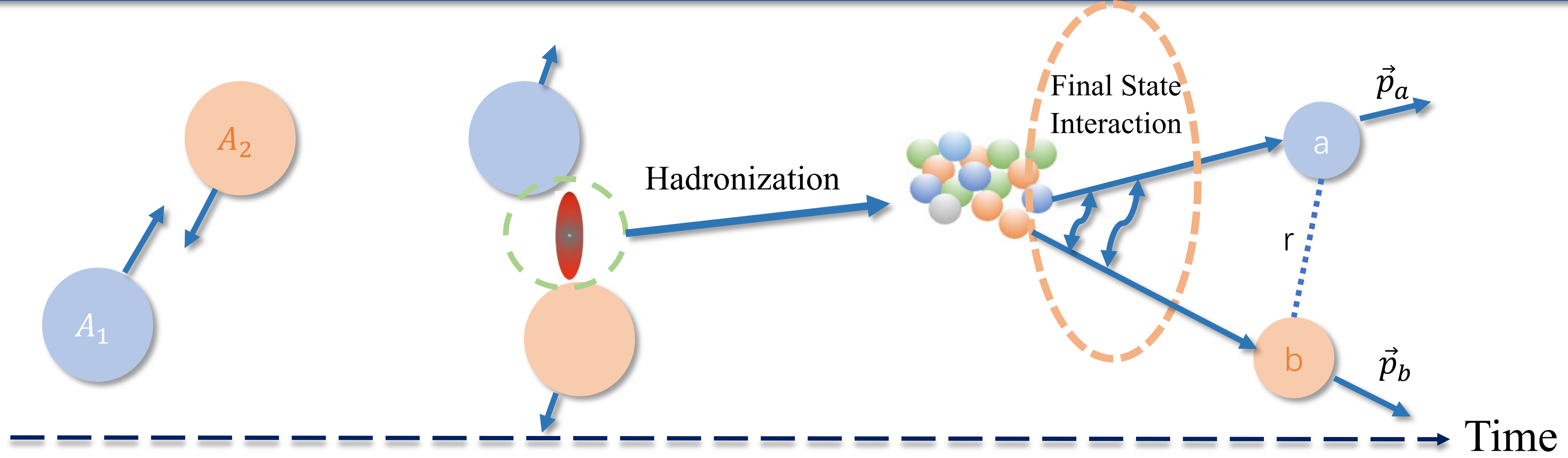
(|S|=2)Dibaryon ⇔ $\Lambda + \Lambda$

(|S|=3)Dibaryon ⇔ $p + \Omega^-$

➢ 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 !

Femtoscopy



- Two-particle correlation function:

Model | **Experimental**

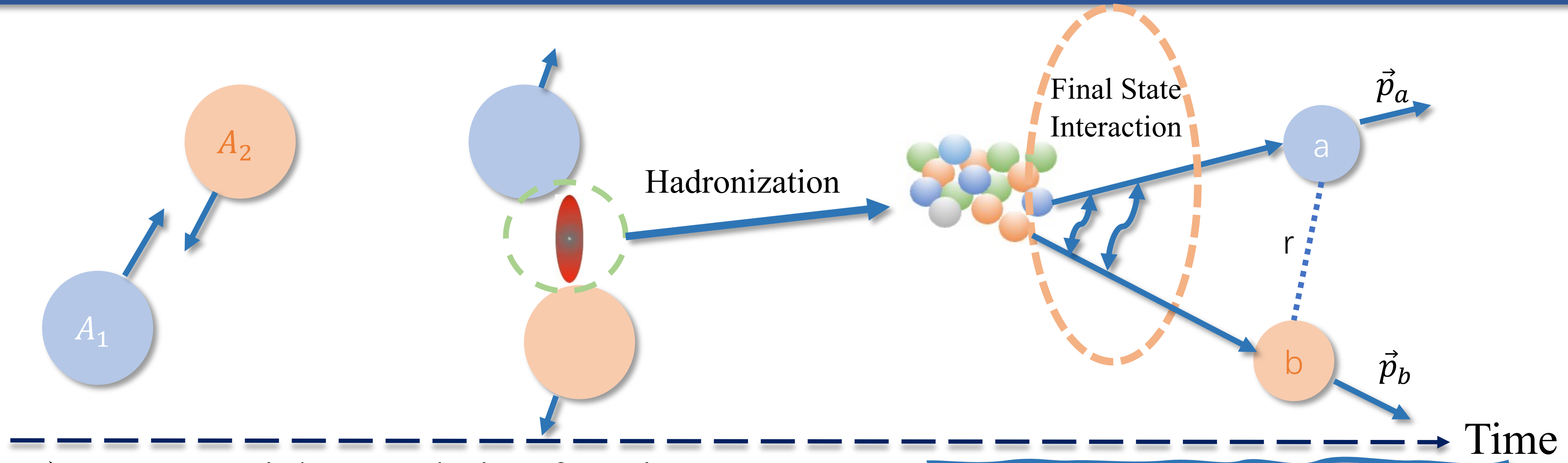
$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$S(\vec{r})$: 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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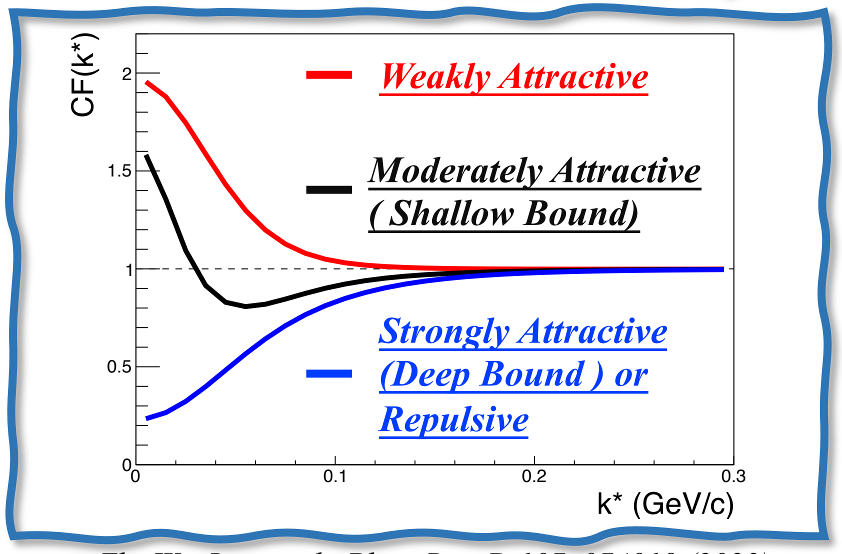
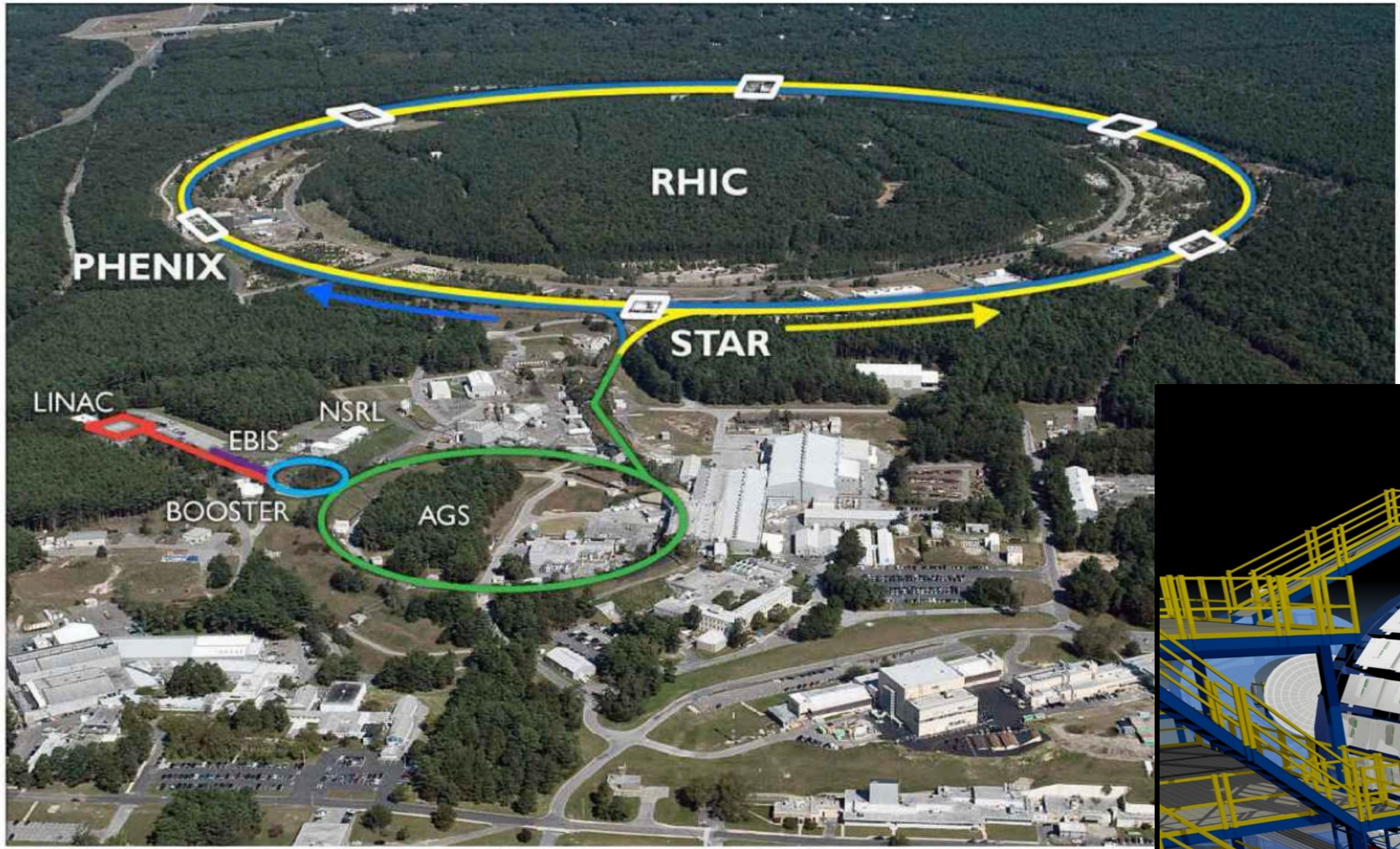


Zhi-Wei Liu, et al., Phys. Rev. D 107, 074019 (2023)

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

RHIC-STAR Experiment



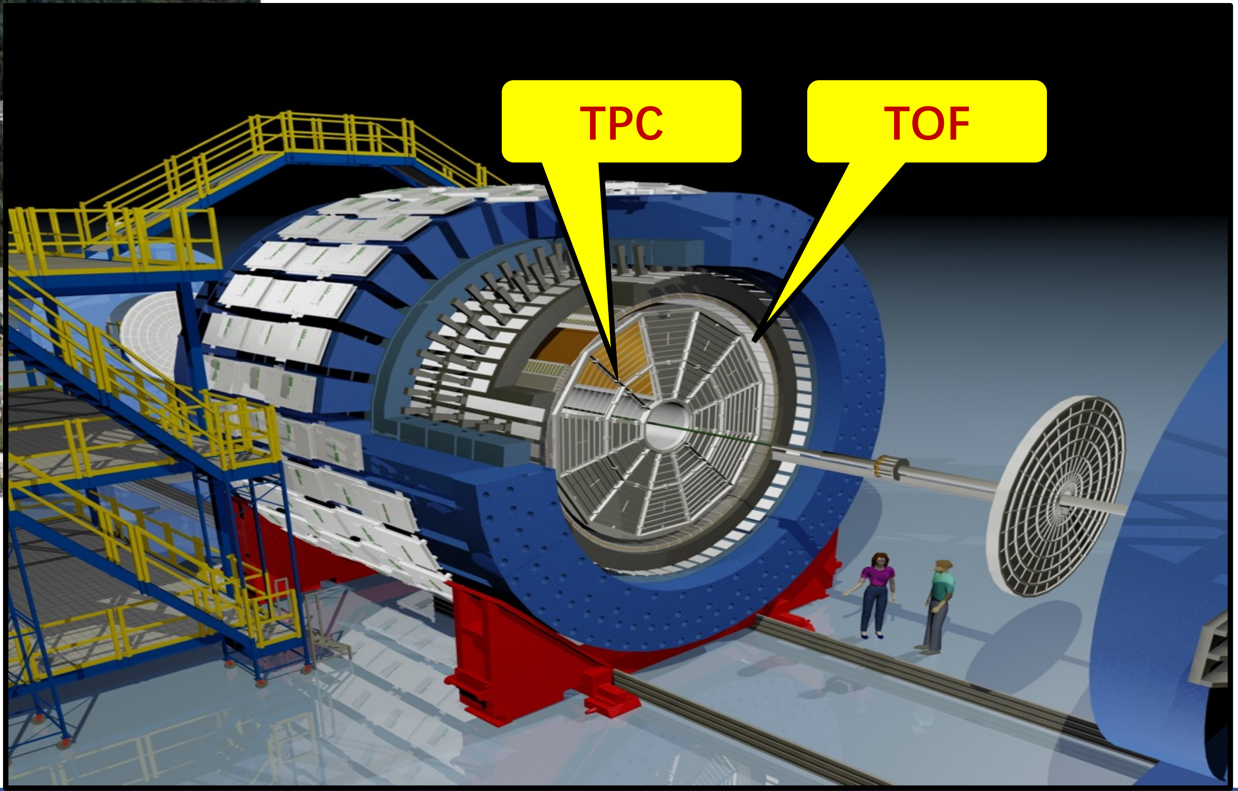
Relativistic Heavy Ion Collider (RHIC)

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

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:**
  - $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - ik^*]^{-1}$ (No Coulomb)
  - $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta)]^{-1}$ (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

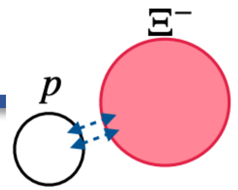
$f_0 > 0$: Attractive Interaction

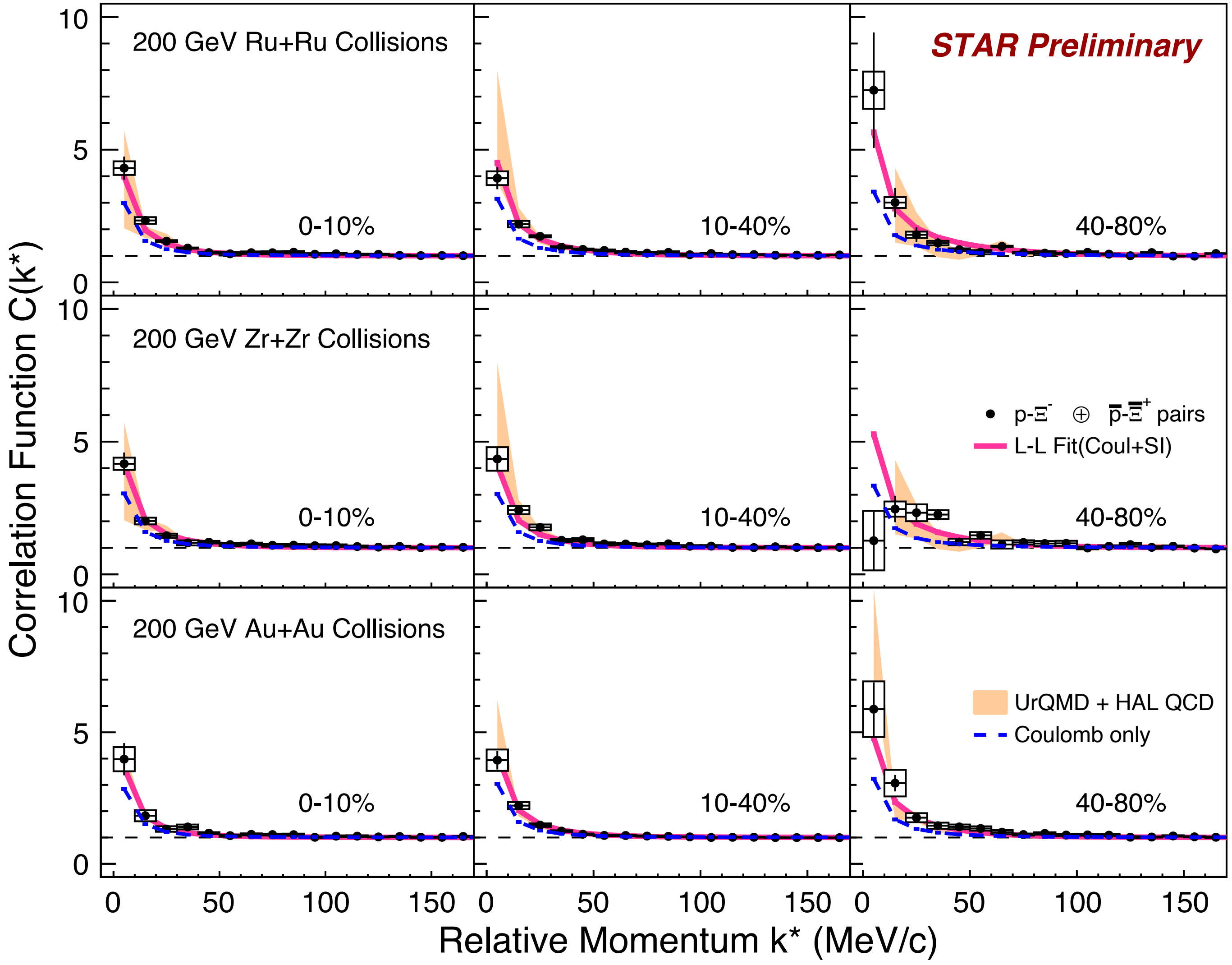
$f_0 < 0$: Repulsive Interaction or Bound State

Bayesian method: *https://github.com/chunshen1987/bayesian_analysis*

Mäntysaari, H., et al., Phys. Lett. B 833 (2022) 137348

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

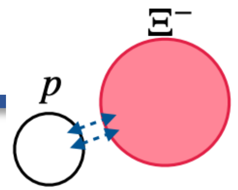
II. CFs show enhancement at low k*

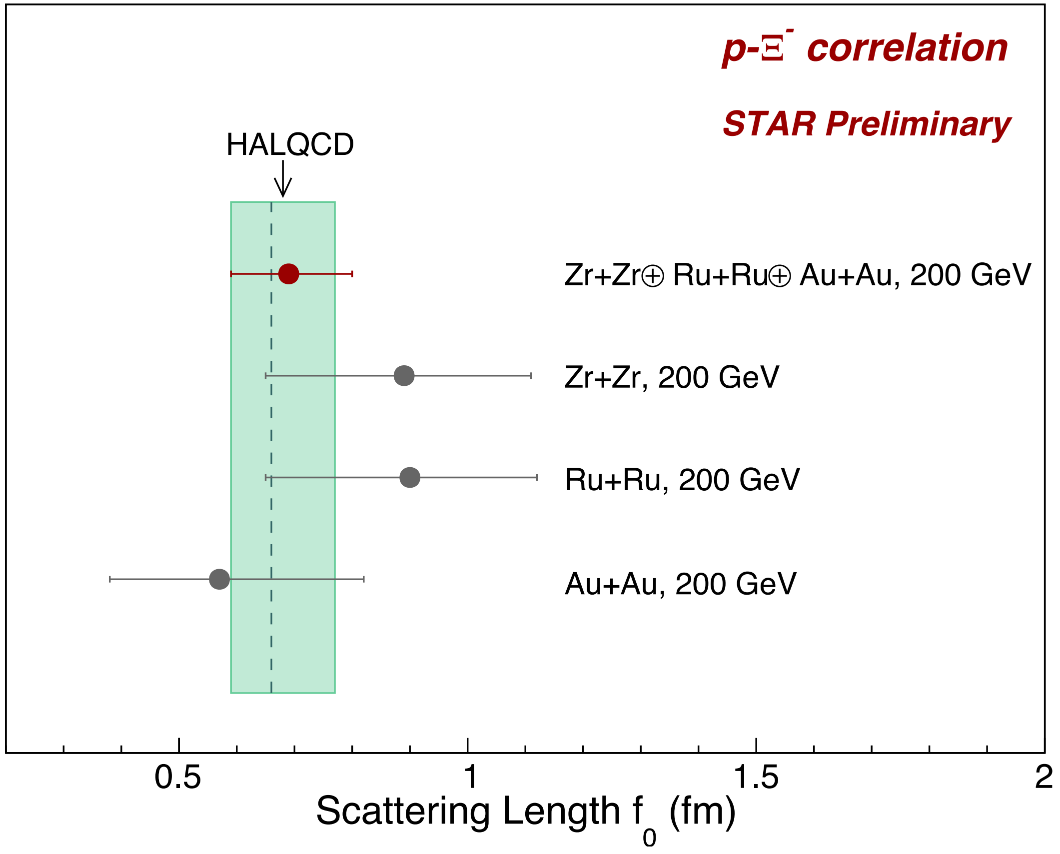
III. Simultaneously fit with L-L function for different centralities in each collision system to extract R_G, f_0 and d_0 by Bayesian method

IV. UrQMD + HAL QCD model is consistent with data
- ◎ Particle phase space provided by UrQMD
- ◎ Interaction potential provided by HAL QCD

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

p-Ξ^- Interaction Parameters (|S| =2)





I. 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

II. First experimental constraints of strong interaction parameters in p-Ξ^- pairs in heavy-ion collisions

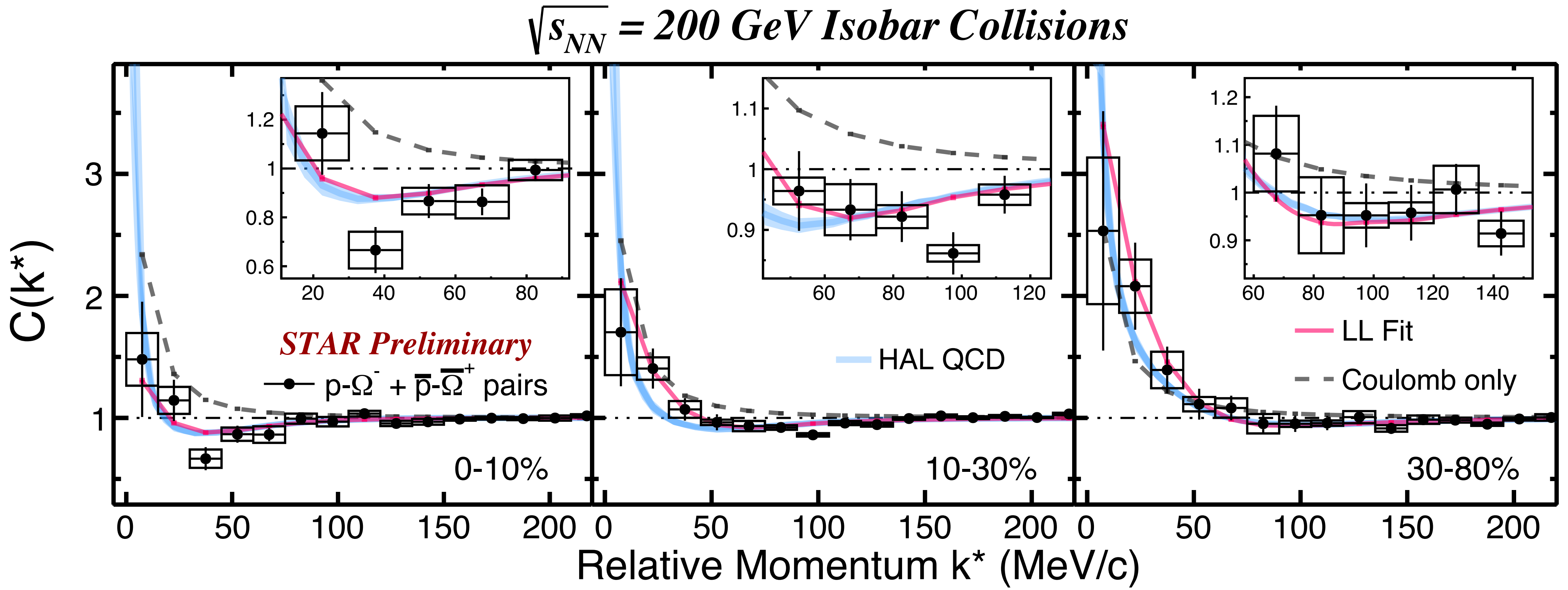
III. Extracted spin averaged scattering length:

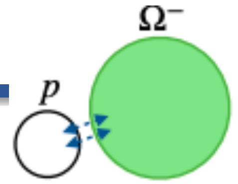
$f_0 = 0.7^{+0.1}_{-0.1}$ fm (stat.+sys.)

- Weakly attractive interaction
- Consistent with HAL QCD prediction

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

p-Ω⁻ Correlation Function (|S|=3)





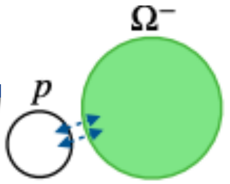
I. Precise measurements of p-Ω^- ⊕ $\bar{p}$-$\bar{\Omega}^+$ correlation functions in Isobar collisions
   - CFs show enhancement at low k* –> mainly due to Coulomb attraction interaction
   - CFs show depletion at k* ~ 30-100 MeV/c –> mainly due to the strong interaction

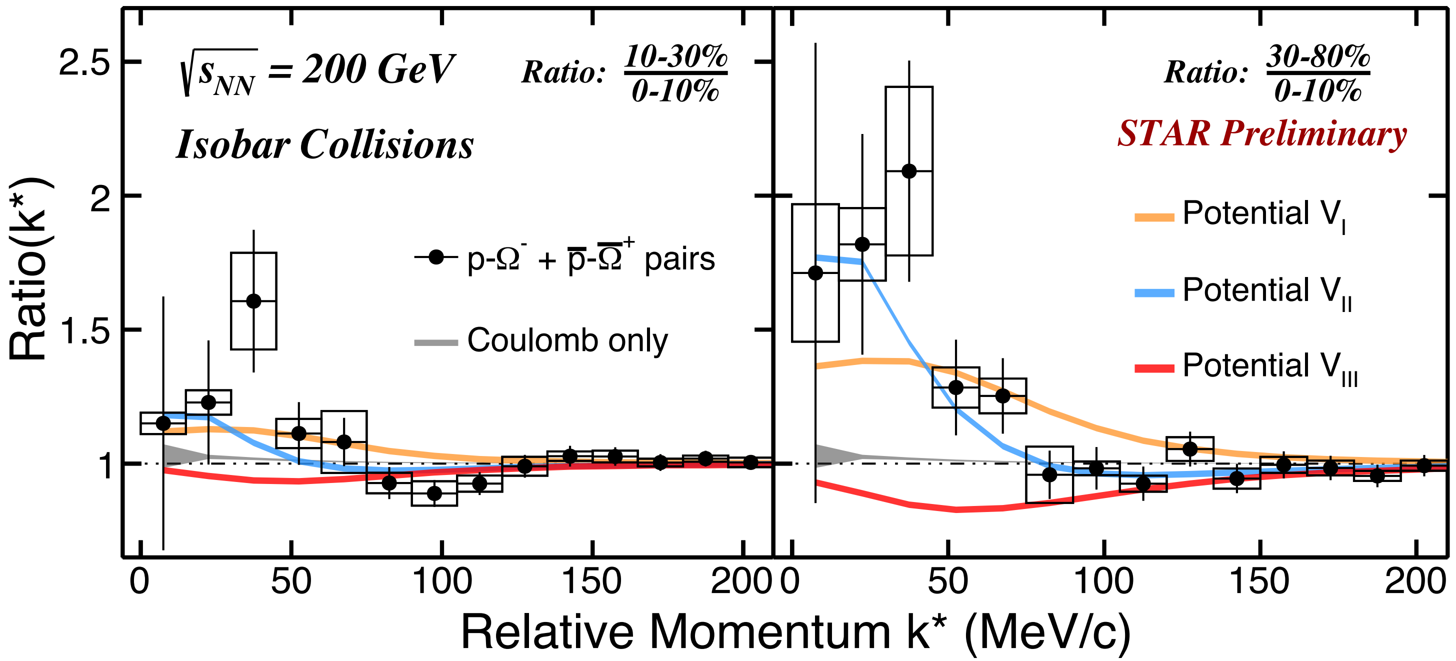
II. Simultaneously fit with L-L function for 3 centralities to extract R_G, f_0 and d_0 by Bayesian method

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

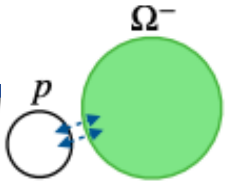
I. By taking CF ratio, Coulomb effect can be largely canceled

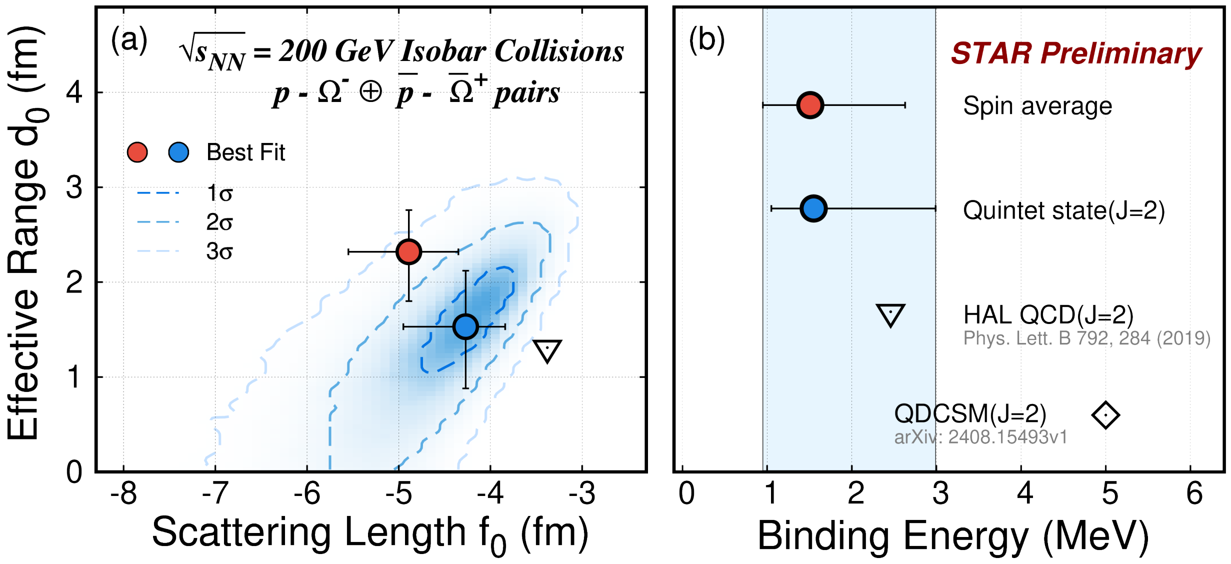
II. CF Ratio shows enhancement at low k* and depletion around k* ~ 100 MeV/c
   - Due to the presence of shallow bound state

III. The potential V_{II}, with a p-value of 0.812, provides a better 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 Betha formula:

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

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

- Calculated BE are consistent with HAL QCD prediction

H-dibaryon Search(S = -2, J = 0)

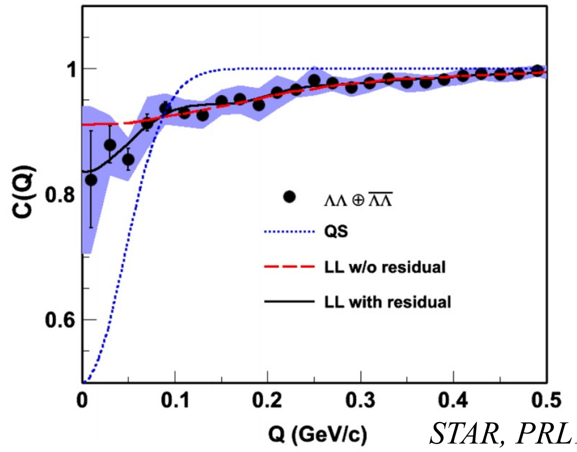
- **Search for the H-dibaryon**

The H-dibaryon is an S=-2, I=0, J=0 state with quark content uuddss, first predicted by Robert L. Jaffe in 1977

R. L. Jaffe, Phys. Rev. Lett. 38, 617 (1977)

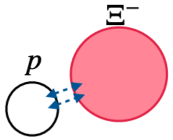
H-dibaryon $\Leftrightarrow p + \Xi^-$

H-dibaryon $\Leftrightarrow \Lambda + \Lambda$

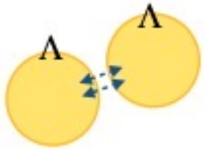


STAR, PRL114('15)022301

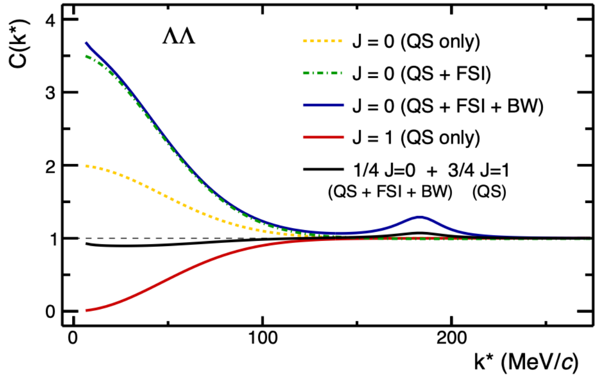
In ΛΛ and p-Ξ^- pairs, there are two spin states:



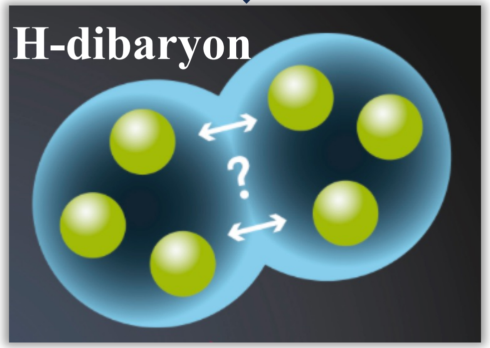
$$C_{p-\Xi} = \frac{1}{4} C_{J=0,singlet} + \frac{3}{4} C_{J=1,triplet}$$

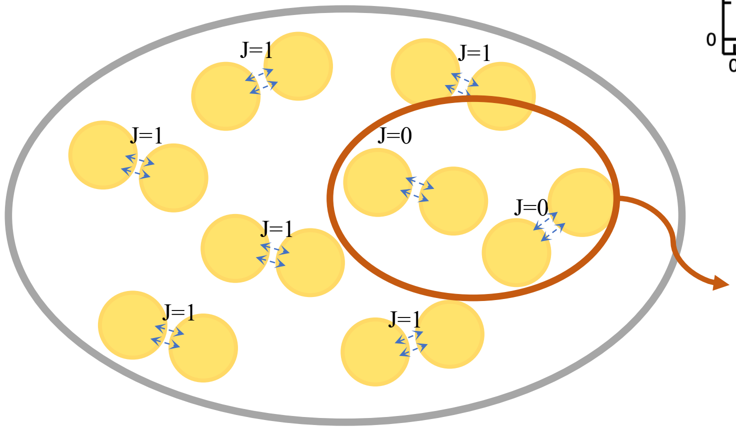


$$C_{\Lambda-\Lambda} = \frac{1}{4} C_{J=0,singlet} + \frac{3}{4} C_{J=1,triplet}$$



K. Zhang, et al., arXiv:2607.00413





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

Spin Femtoscopy Method

- **ΛΛ spin correlation:**

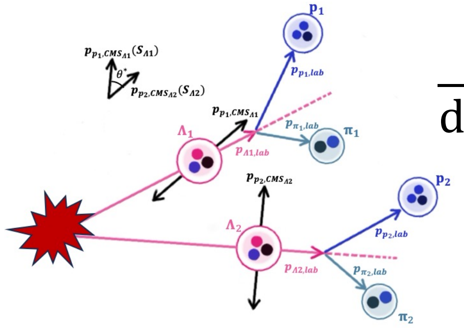
$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_\Lambda^2 P_{\Lambda\Lambda}\cos\theta^* \qquad P_{\Lambda\Lambda} = \frac{1}{3} < \sigma_1 \cdot \sigma_2 >$$

$$\alpha_\Lambda = 0.746$$

- **Different spin states:**

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

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



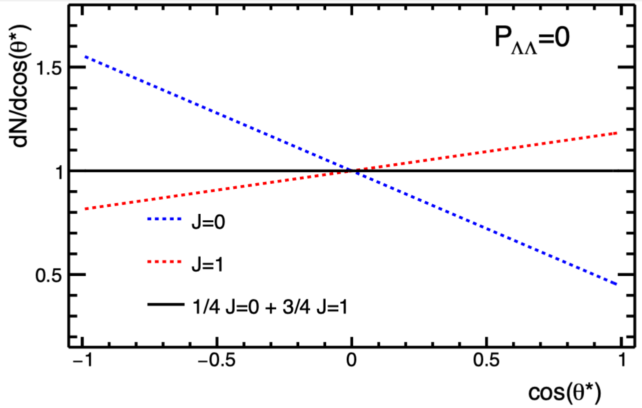
$$\frac{dN}{d\cos\theta^*} \propto w_0(1 - \alpha_\Lambda^2\cos\theta^*) + (1 - w_0)(1 + \frac{1}{3}\alpha_\Lambda^2\cos\theta^*)$$

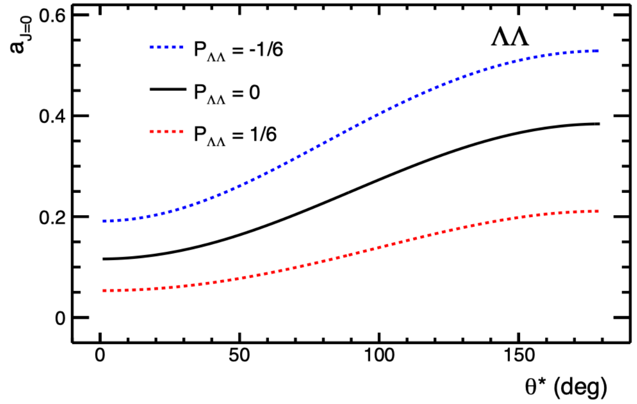
$$= 1 + \alpha_\Lambda^2(\frac{1 - 4w_0}{3})\cos\theta^*$$

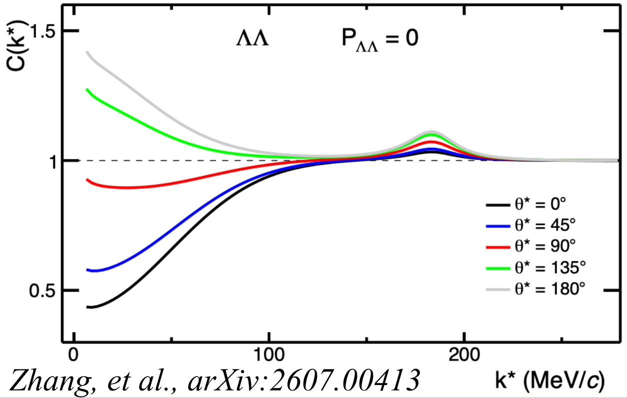
w_0 is the total spin J=0 state weight

- **spin weight dependence on $\boldsymbol{\theta^*}$:**

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







K. Zhang, et al., arXiv:2607.00413

Summary

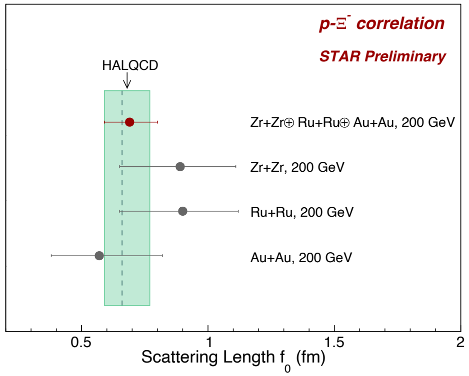
I. Precision measurements of **p-Ξ^- ⊕ $\bar{\text{p}}$-$\bar{\Xi}^+$** and **p-Ω^- ⊕ $\bar{\text{p}}$-$\bar{\Omega}^+$** correlation function at STAR

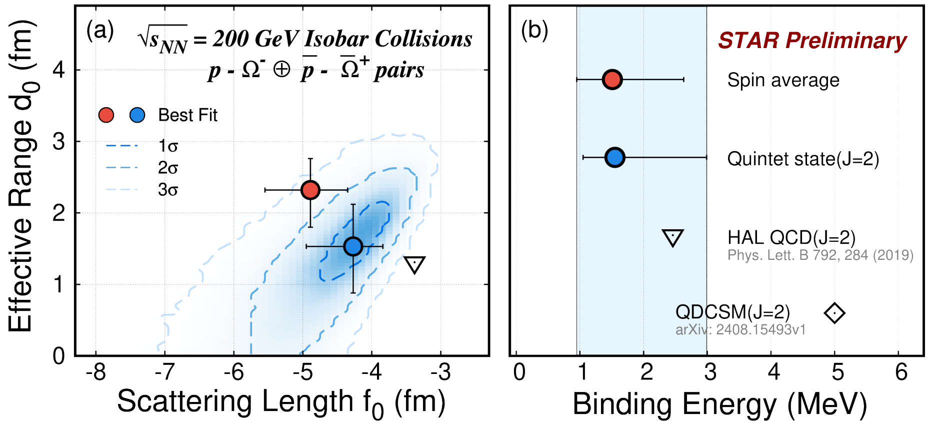
II. Extracted strong interaction parameters using L-L model by Bayesian method

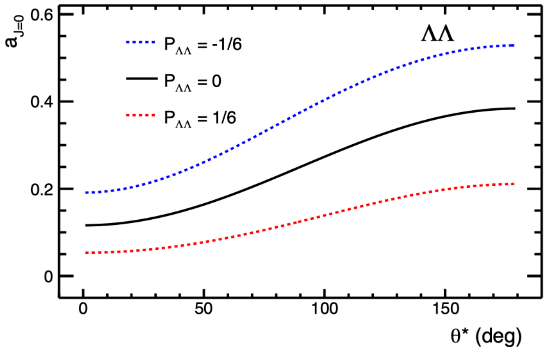
- **p-Ξ^- ⊕ $\bar{\text{p}}$-$\bar{\Xi}^+$** pairs: $f_0 > 0$
- **p-Ω^- ⊕ $\bar{\text{p}}$-$\bar{\Omega}^+$** pairs: $f_0 < 0$ **->** Bound state

III. Extracted Binding Energy BE = $1.6^{+1.4}_{-0.5}$ MeV in **p-Ω^- ⊕ $\bar{\text{p}}$-$\bar{\Omega}^+$** pair consistent with HAL QCD prediction

IV. Spin femtoscopy provides a novel approach to select spin states and enhance the sensitivity to H-dibaryon searches.







Thank you for your attention!