Observation of Strange Dibaryon (|S|=3)

‘ Measurement of p-Ω^- Correlation Function in $\sqrt{s_{NN}} = 200$ GeV Isobar Collisions’

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Outline

I. Motivation

II. Femtoscopy

III. Analysis Details

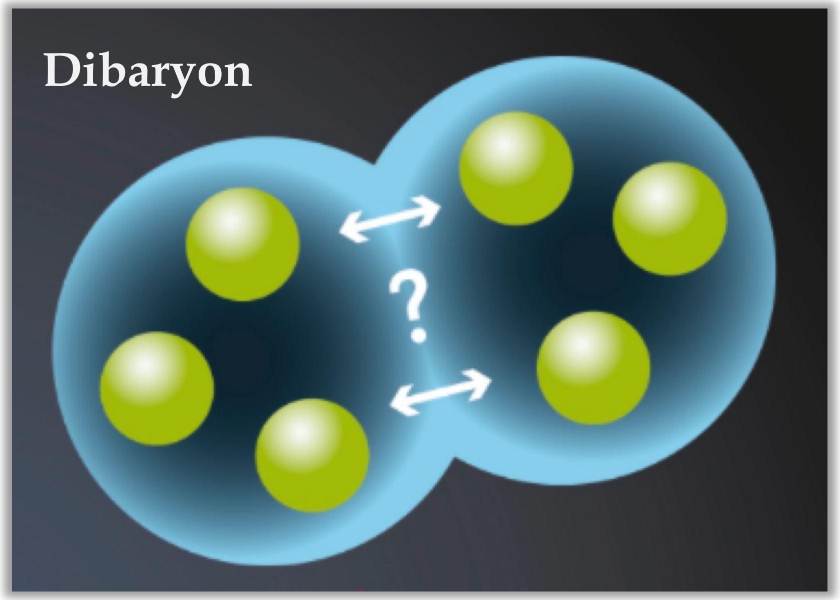
IV. Results

V. Summary

The paper is currently under collaboration review and is being prepared for submission to Nature.

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	$q\bar{q}q\bar{s}$	$K\pi\pi$
$\Lambda(1405)$	1405	$qqqs\bar{q}$	$\pi\Sigma$
$\Theta^+(1530)$	1530	$qqqq\bar{s}$	KN
H	2245	uuddss	$\Lambda\Lambda$
$N\Omega$	2573	qqqsss	$\Lambda\Xi$
$\Xi\Xi$	2627	qqssss	$\Lambda\Xi$
$\Omega\Omega$	3228	ssssss	$\Lambda K^-+\Lambda K^-$

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

- The possible formation channels:

  (|S|=2)Dibaryon $\Leftrightarrow p + \Xi^-$

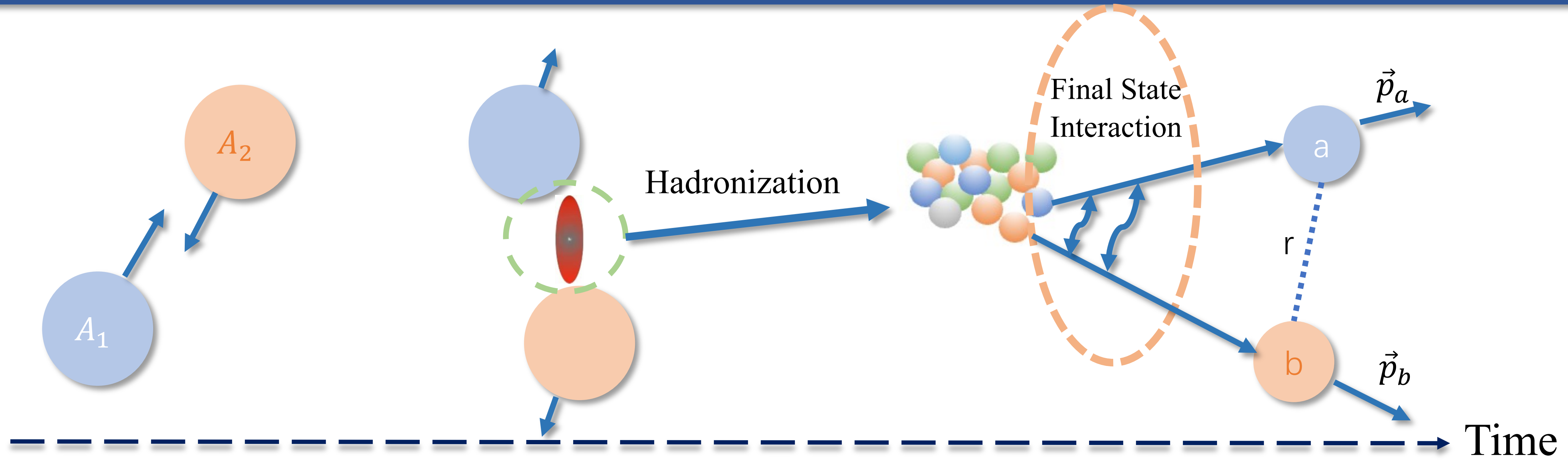
  (|S|=2)Dibaryon $\Leftrightarrow \Lambda + \Lambda$

  This talk (|S|=3)Dibaryon $\Leftrightarrow p + \Omega^-$

- 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:

<u>*Model*</u>   <u>*Experimental*</u>

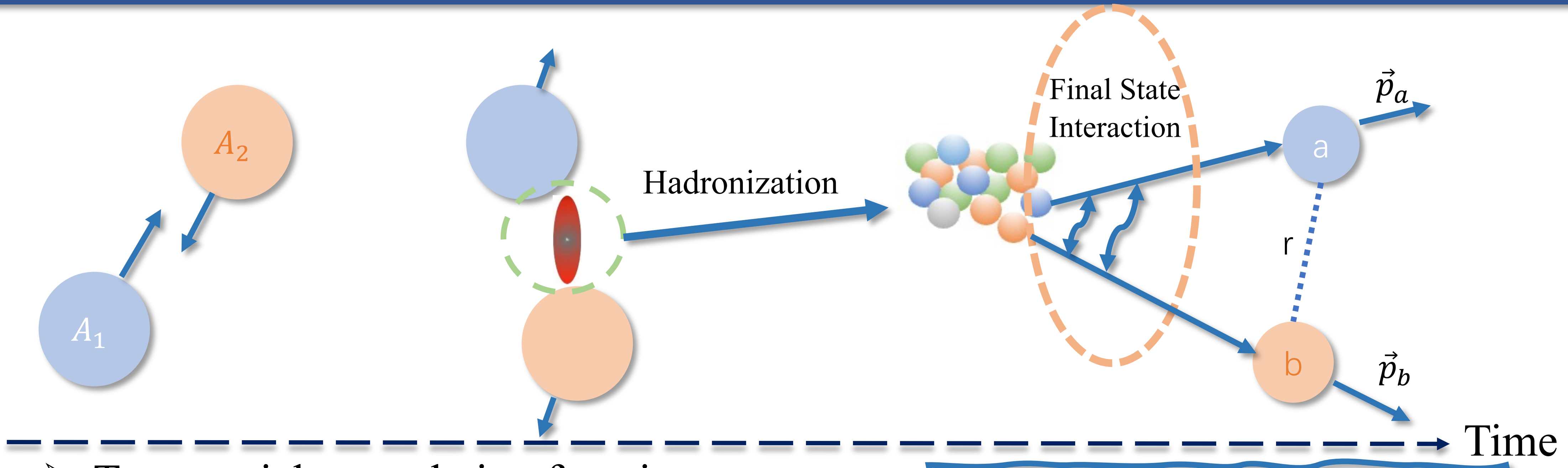
$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$S(\vec{r})$: 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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<u>***Model***</u> <u>***Experimental***</u>

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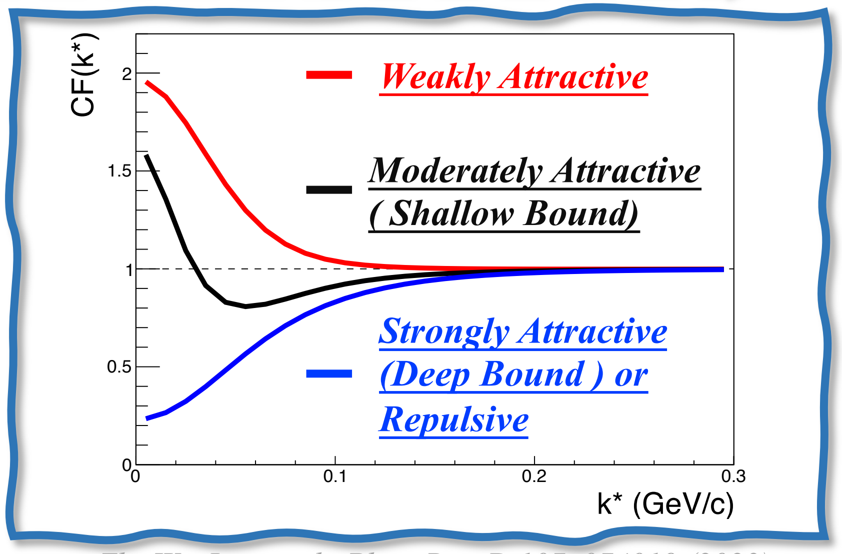
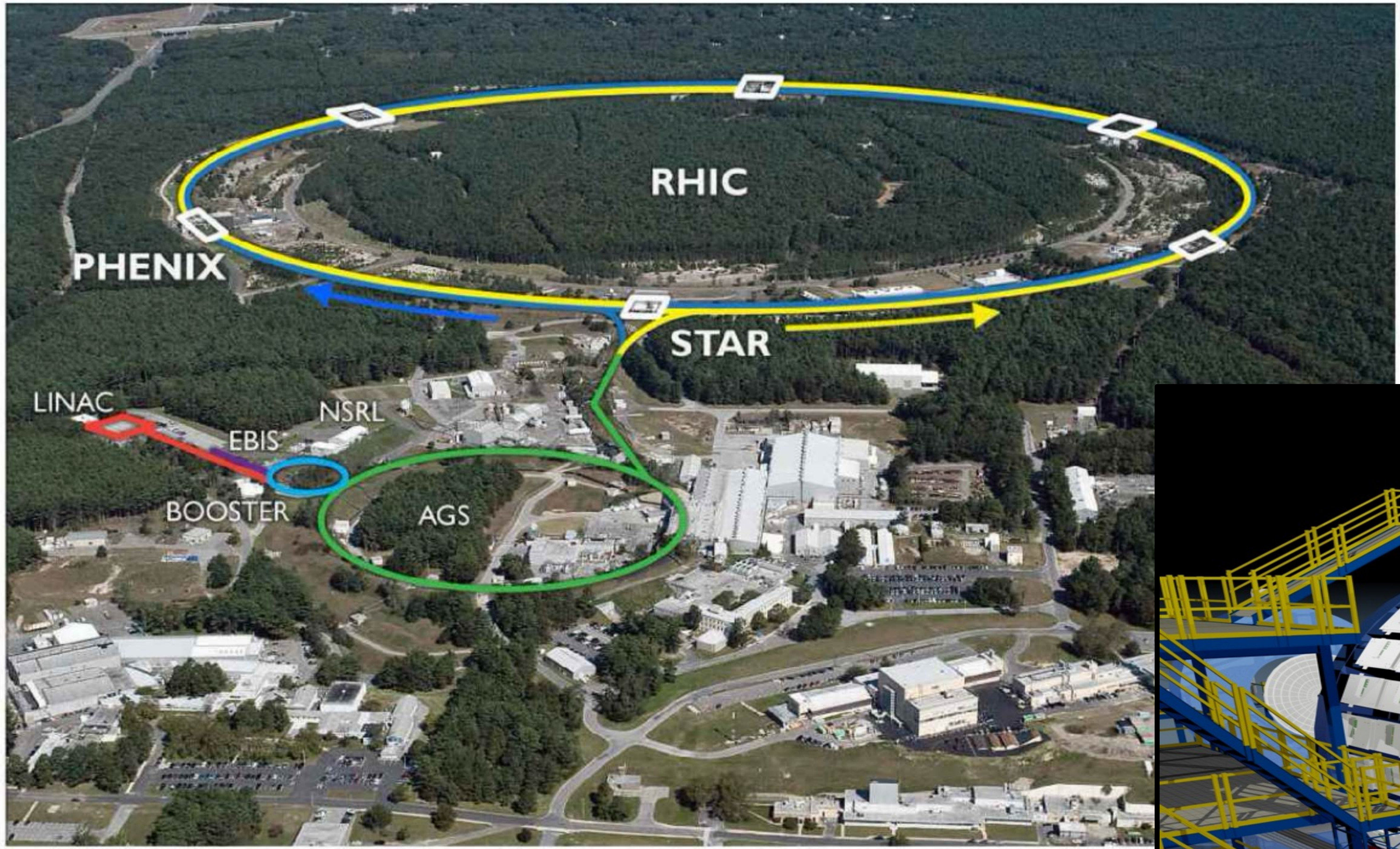


Zhi-Wei Liu, et al., Phys. Rev. D 107, 074019 (2023)

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…

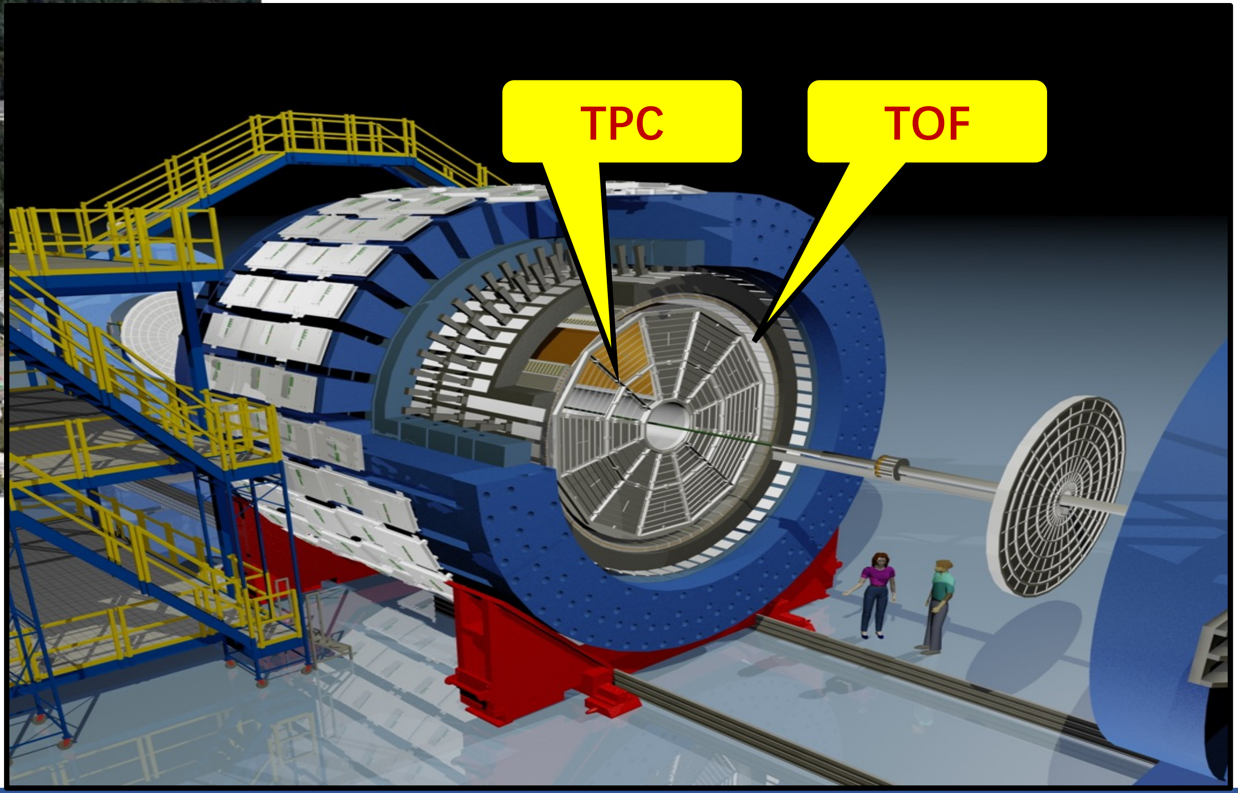
➔ Beam Energy Scan Program I, II（Au+Au）

$\sqrt{s_{NN}}$ = 3.0 – 200 GeV

The Solenoidal Tracker At RHIC (STAR)

➔ Excellent particle identification

➔ Large, uniform acceptance at Mid-rapidity



Analysis Details

- Dataset:

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

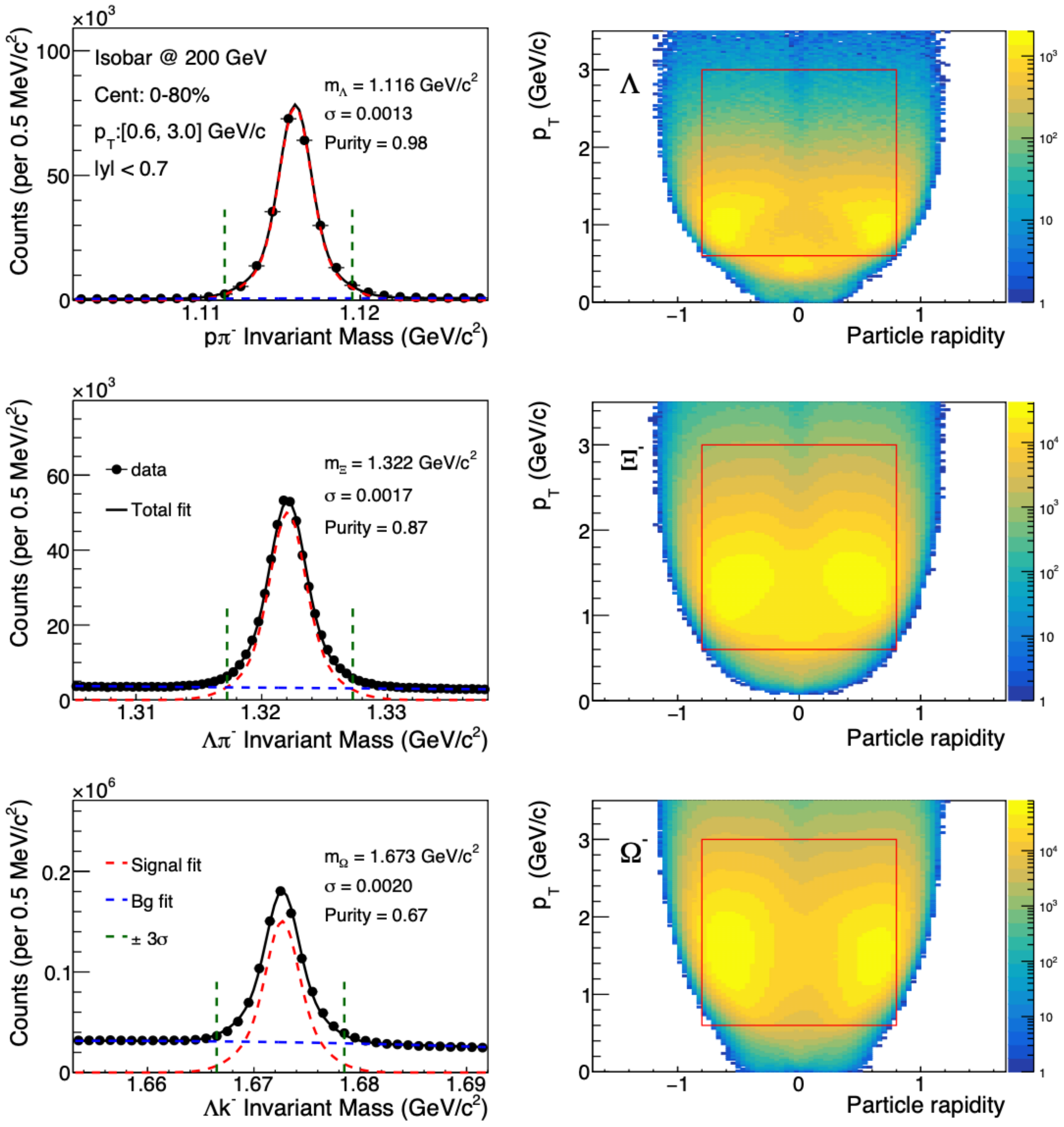
~ 3.9 billion minimum-bias events

- Hyperon reconstruction via Helix-swimming method

Λ -> p + π^-, BR = 63.9%

Ξ^- -> $\Lambda + \pi^-$, BR = 99.9%

Ω^- -> $\Lambda + K^-$, BR = 67.8%



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

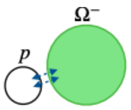
- **Physics quantity:**
  - f_0: Scattering Length
  - d_0: Effective Range
  - R_G: Spherical Gaussian Source Size

$f_0 > 0$: 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

Lednicky-Lyuboshitz Model

In different pairs, there have different spin states: $C = w_i\, C_i + w_j\, C_j$



In p-Ω^- pair, there are two spin states:

$$C_{p-\Omega} = \frac{3}{8} C_{J=1,triplet} + \boxed{\frac{5}{8} C_{J=2,quintet}}$$

Predicted bound state （HAL QCD）

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

Spin-averaged method:

Two spin states consider same Coulomb and strong interaction

Quintet method:

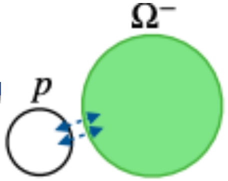
In quintet state, consider Coulomb and strong interaction

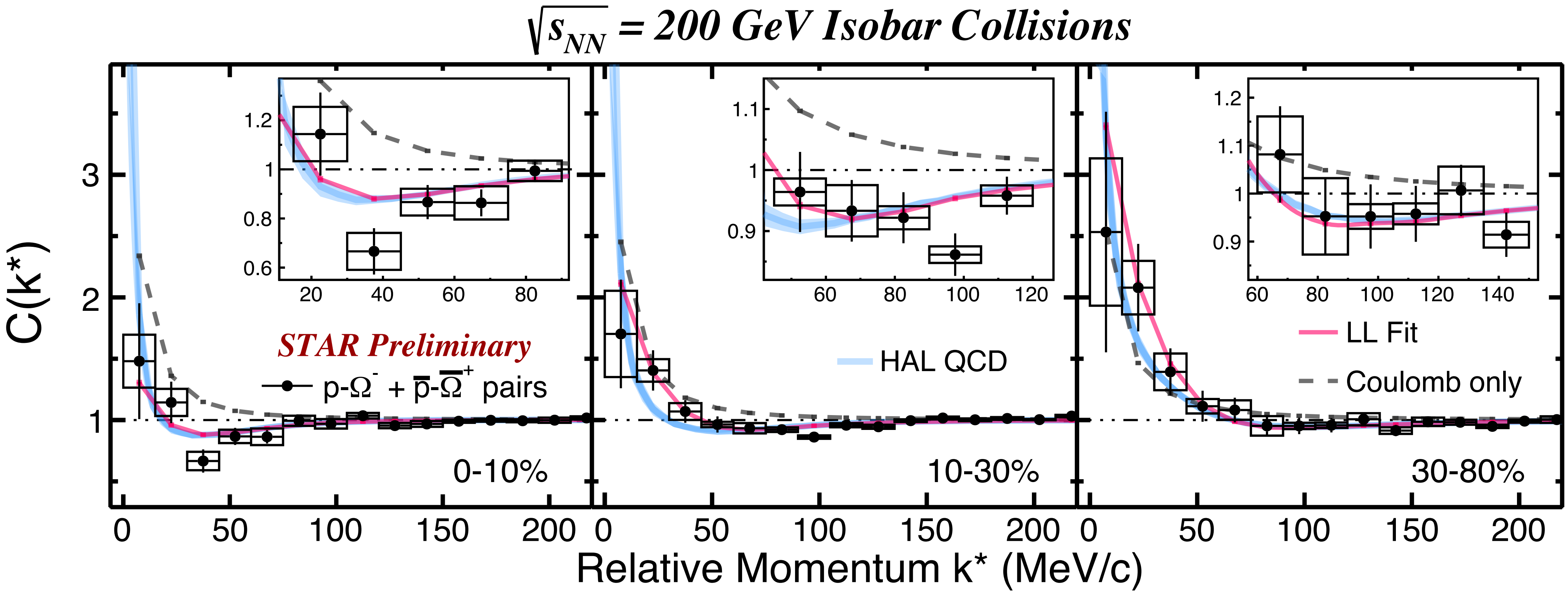
In triplet state, just consider Coulomb since the strong effect of couple channel

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

Spin	Weight	Spin-ave.	Quintet
Triplet (J=1)	3/8	Coul. + SI	Coul.
Quintet (J=2)	5/8	Coul. + SI	Coul. + SI

p-Ω^- Correlation Function (|S|=3)





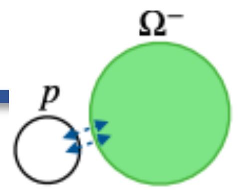
I. Precise measurements of p-Ω^- $\oplus$ $\bar{p}$-$\bar{\Omega}^+$ correlation functions in Isobar collisions

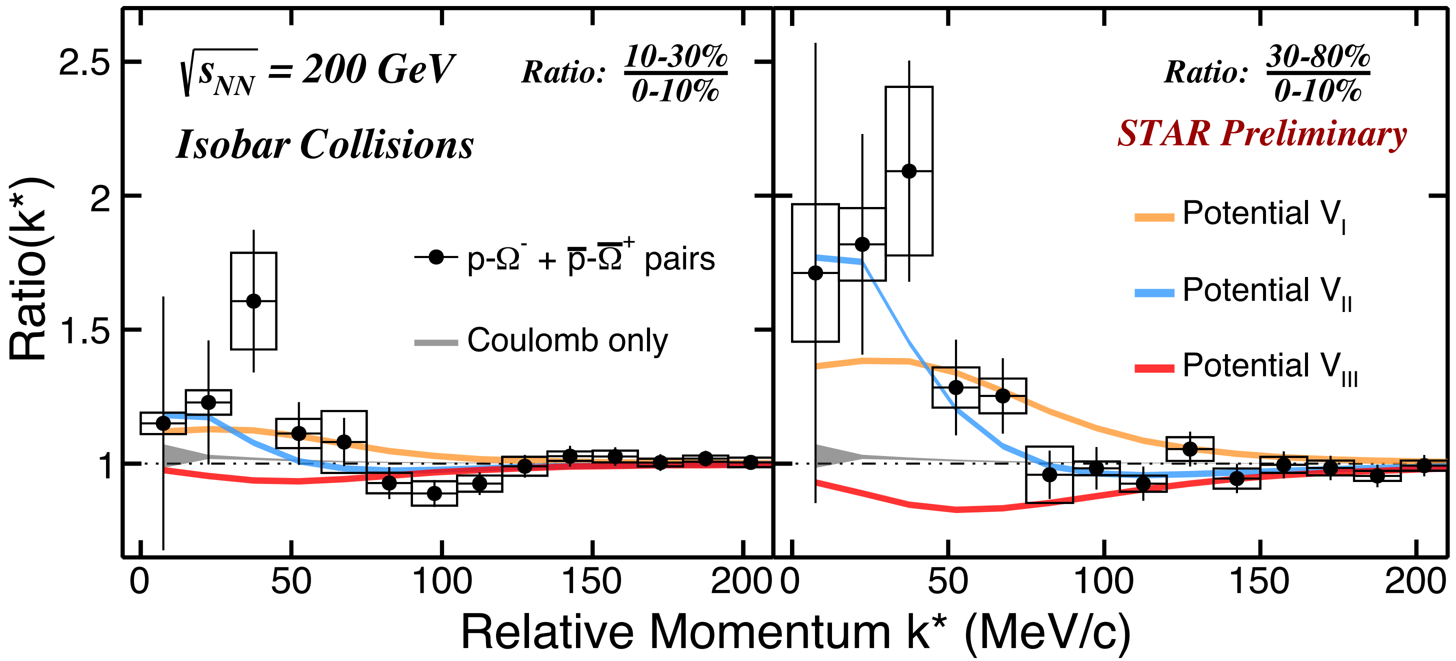
- CFs show enhancement at low k* –> mainly due to Coulomb attraction interaction
- CFs show depletion at k* ~ 30-100 MeV/c –> mainly due to the formation of Strange Dibaryon

II. CFs obtained by HAL QCD theory 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

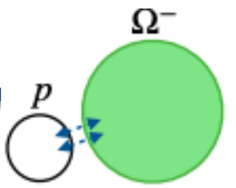
II. CF Ratio shows enhancement at low k* and depletion around k* ~ 100 MeV/c

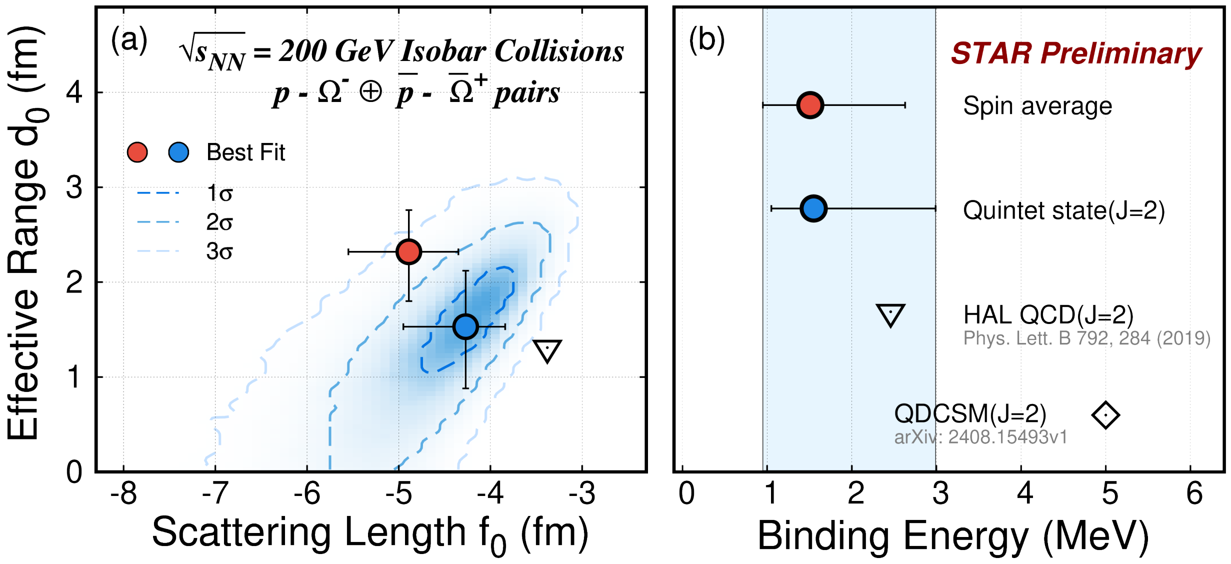
- Due to the presence of shallow bound state

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

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

- ☐ Calculated BE are consistent with HAL QCD prediction

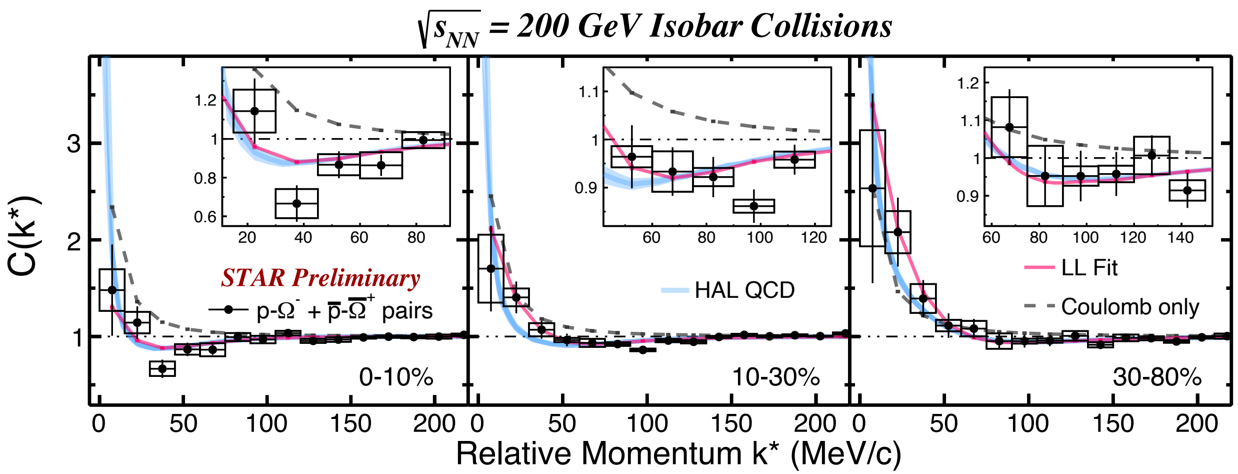
Summary

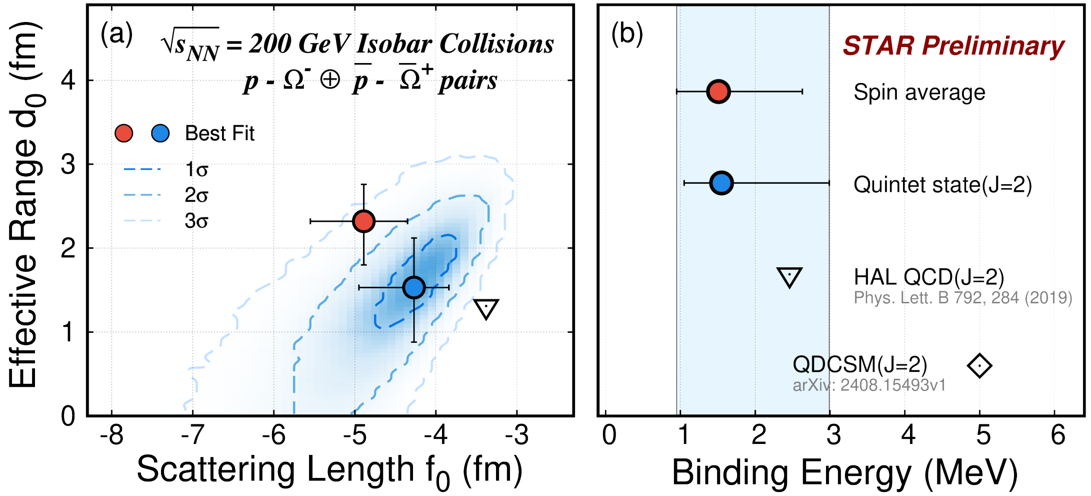
I. Precision measurements of **p-Ω^- $\oplus$ $\bar{p}$-$\bar{\Omega}^+$** correlation function at STAR

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

- p-Ω^- $\oplus$ $\bar{p}$-$\bar{\Omega}^+$ pairs: $f_0 < 0$ –> Bound state

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

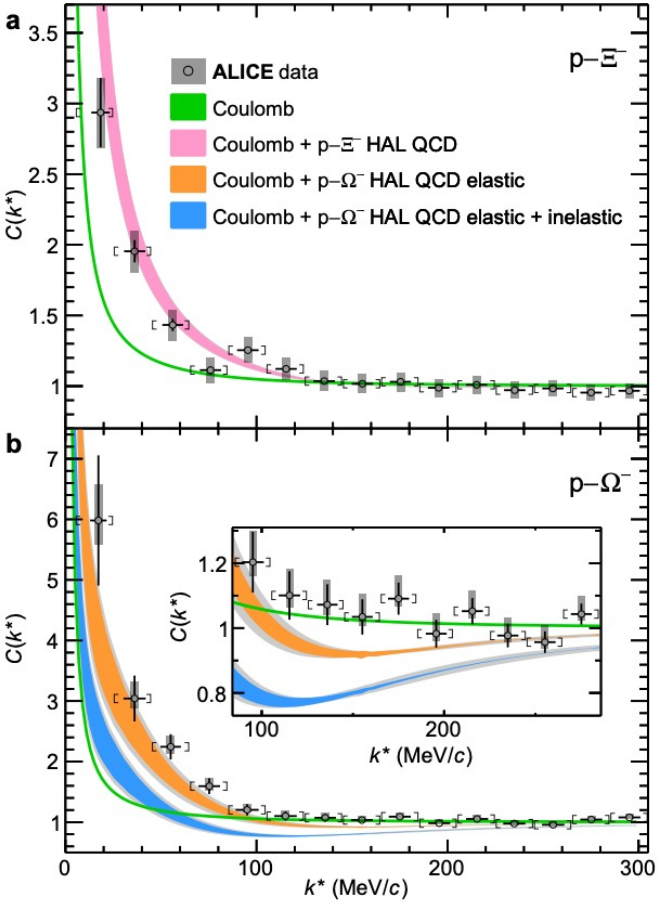




First experimental evidence of Strange Dibaryon

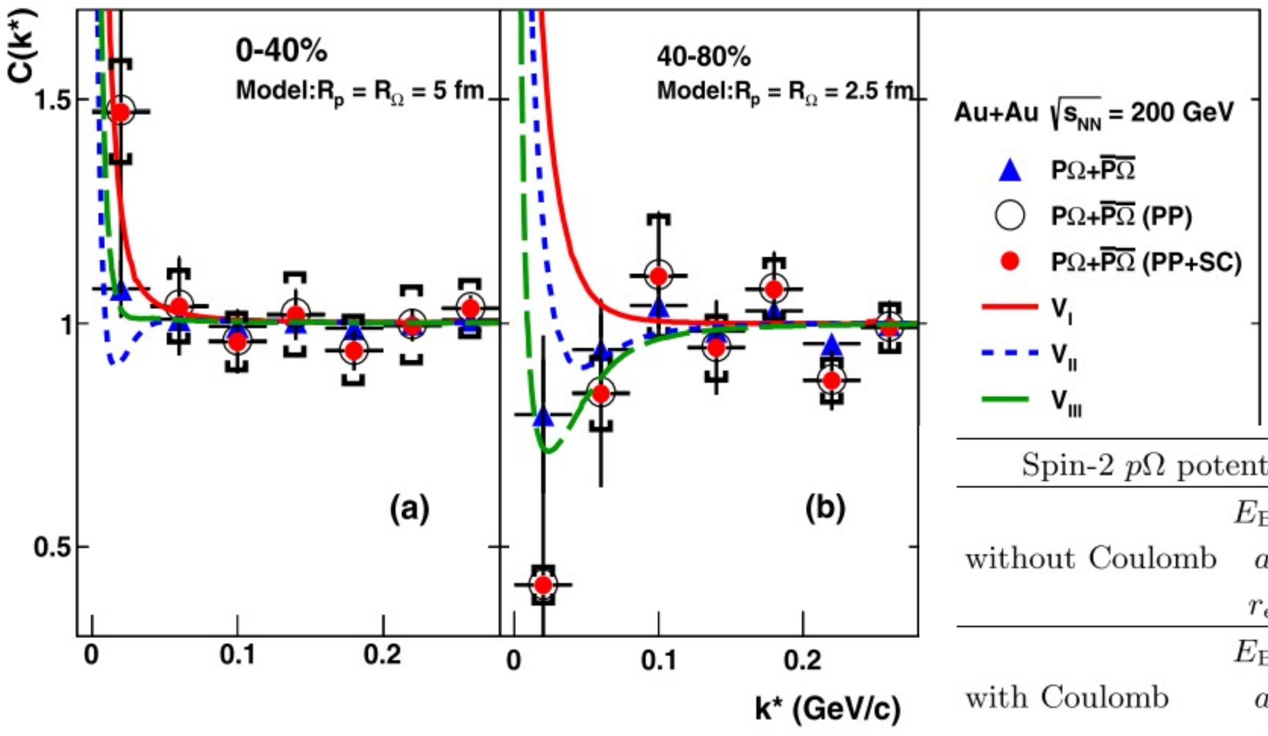
Thank you for your attention!

Motivation



Nature 588 (2020) 232-238

Physics Letters B 790 (2019) 490–497

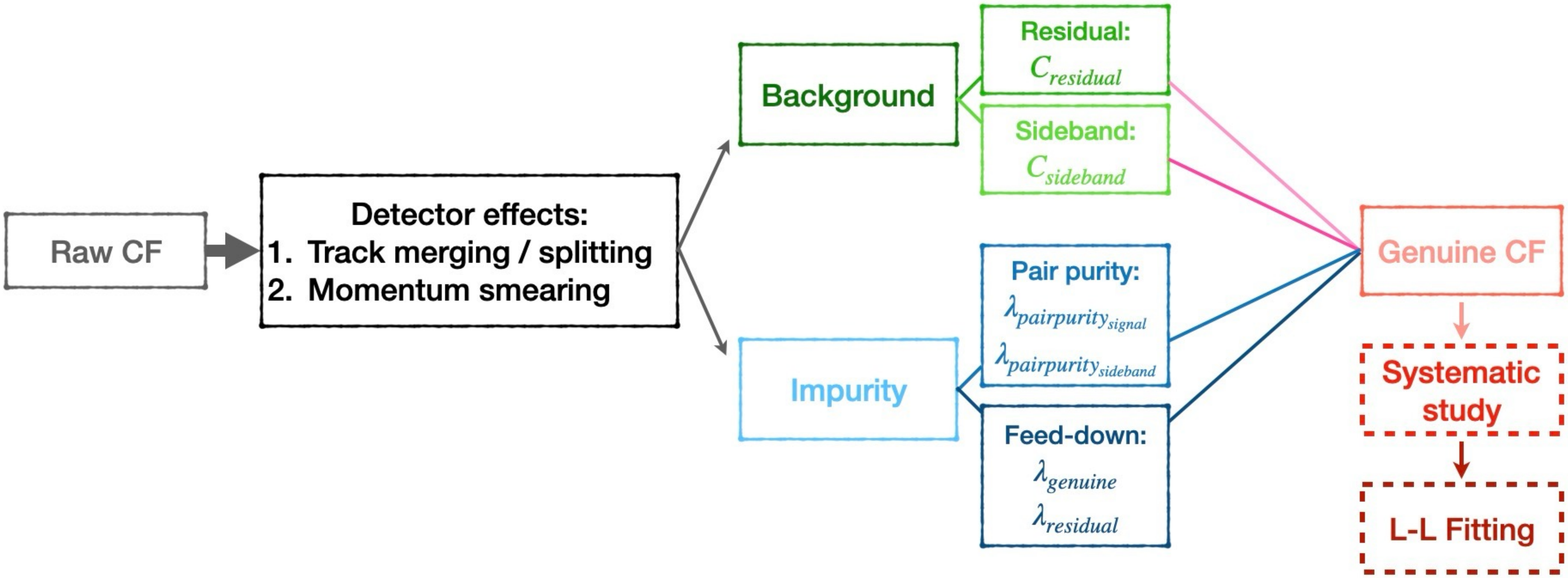


Spin-2 $p\Omega$ potentials		V_{I}	V_{II}	V_{III}
without Coulomb	E_{B} [MeV]	–	0.05	24.8
	a_0 [fm]	−1.0	23.1	1.60
	r_{eff} [fm]	1.15	0.95	0.65
with Coulomb	E_{B} [MeV]	–	6.3	26.9
	a_0 [fm]	−1.12	5.79	1.29
	r_{eff} [fm]	1.16	0.96	0.65

Phys. Rev. C 94, 031901(R)

- STAR and ALICE have measured p-Ω^- correlation functions
- f_0 and d_0 have never been experimentally extracted

Analysis Flow Chat



$$C_{raw} = 1 + \lambda_{pairpurity_{signal}} * [\lambda_{genuine} * (C_{genuine} - 1) + \sum_i \lambda_{residual} * (C_{residual} - 1)] + \lambda_{pairpurity_{sideband}} * (C_{sideband} - 1)$$

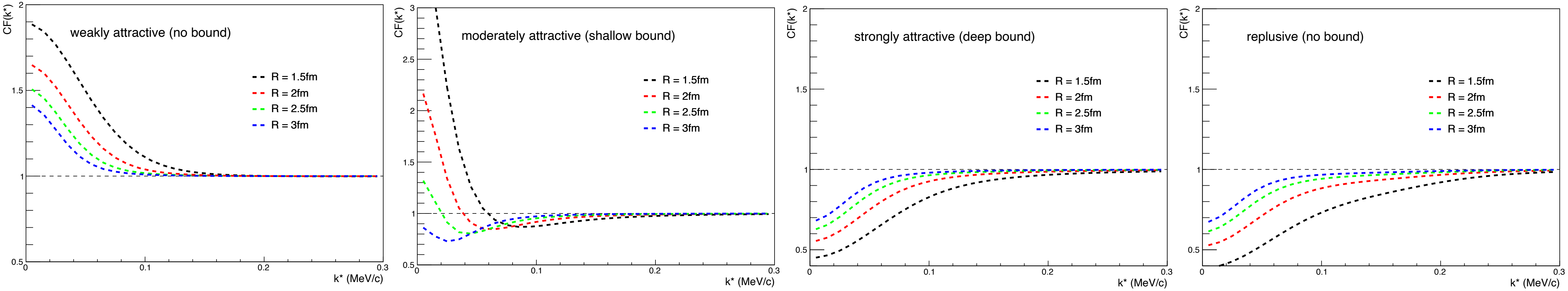
Centrality dependence of CF

- Just consider strong interaction
- $C(k^*)$ shape: related to the type of interaction

Model **Experimental**

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

Attractive interaction **Repulsive interaction**



PRD 107, 074019 (2023)

Source size or centrality dep. of CF
→ To be bound,
or not to be bound