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

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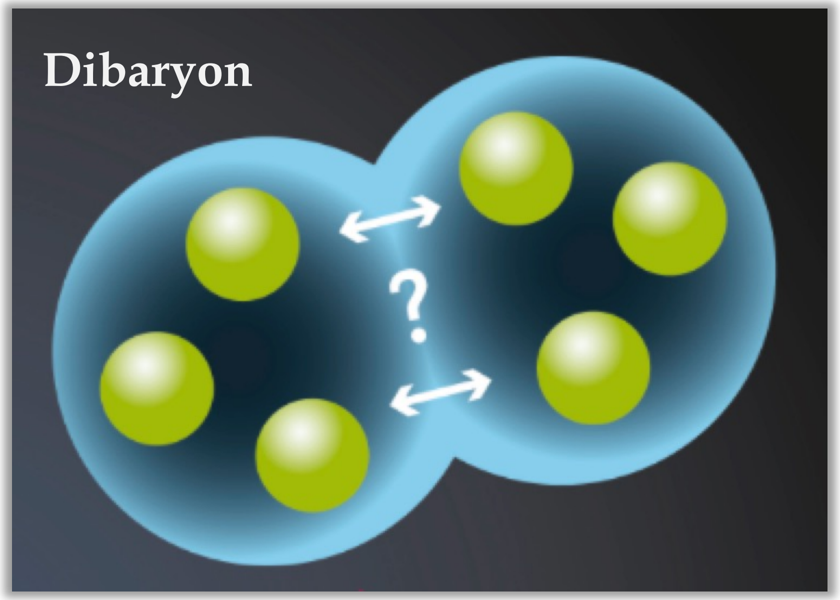
Outline

I. **Motivation**
II. **Femtoscopy**
III. **Analysis Details**
IV. **Lednicky-Lyuboshitz Model**
V. **Results**
   - $|S| = 2$: p-Ξ^- Correlation
   - $|S| = 2$: Λ-Λ Correlation
   - $|S| = 3$: p-Ω^- Correlation

VI. **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	$q\bar{q}q\bar{s}$	$K\pi\pi$
$\Lambda(1405)$	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 $\Leftrightarrow p + \Xi^-$

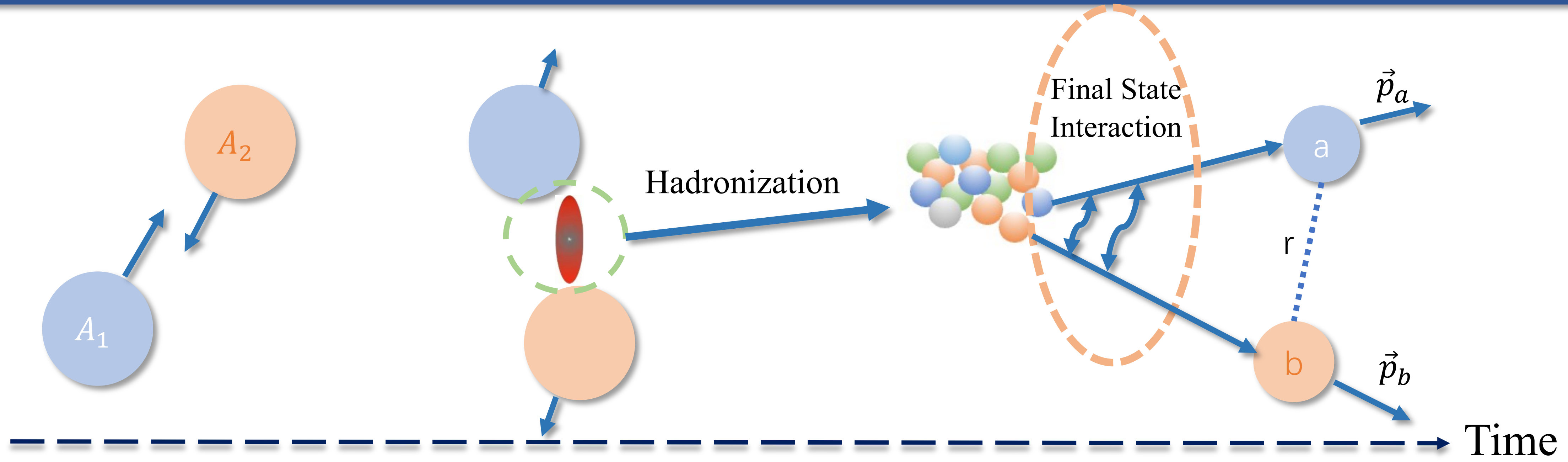
(|S|=2)Dibaryon $\Leftrightarrow \Lambda + \Lambda$

(|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:

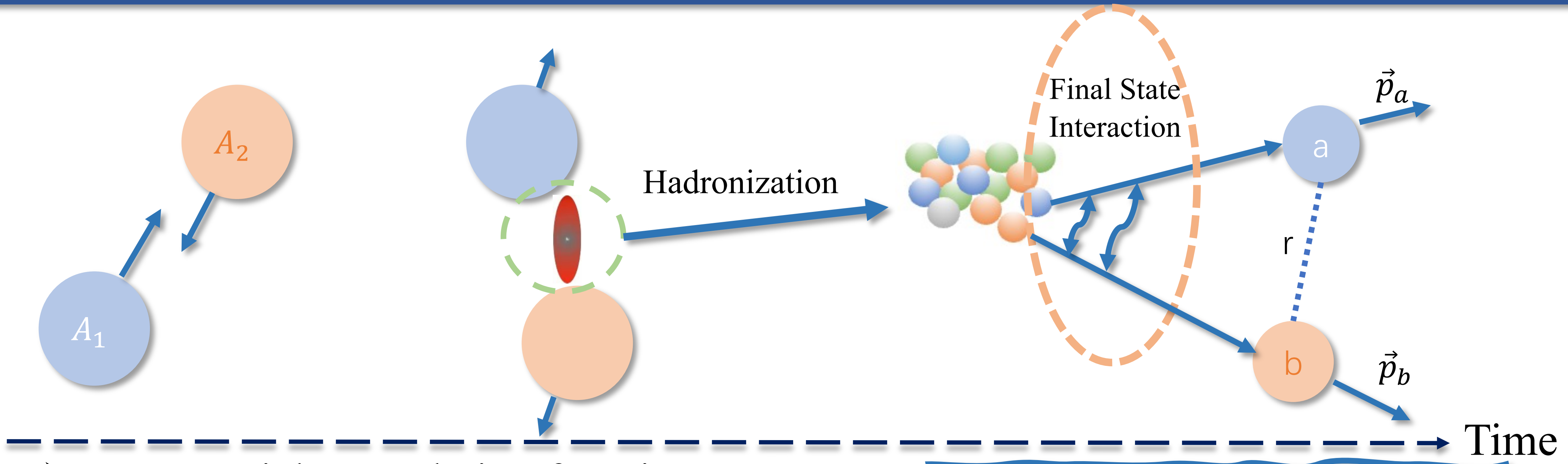
$$C(k^*) = \underbrace{\int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r}}_{\text{Model}} = \underbrace{\frac{N_{same}(k^*)}{N_{mixed}(k^*)}}_{\text{Experimental}}$$

$S(\vec{r})$: 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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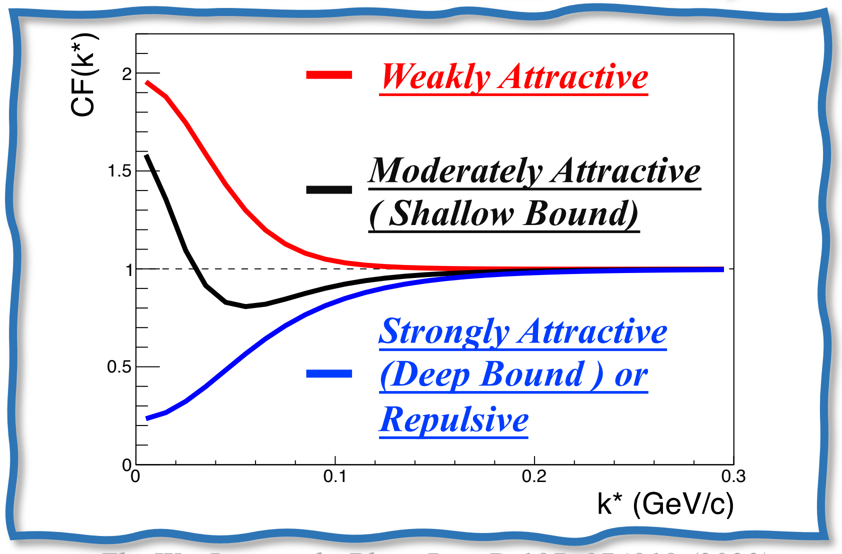
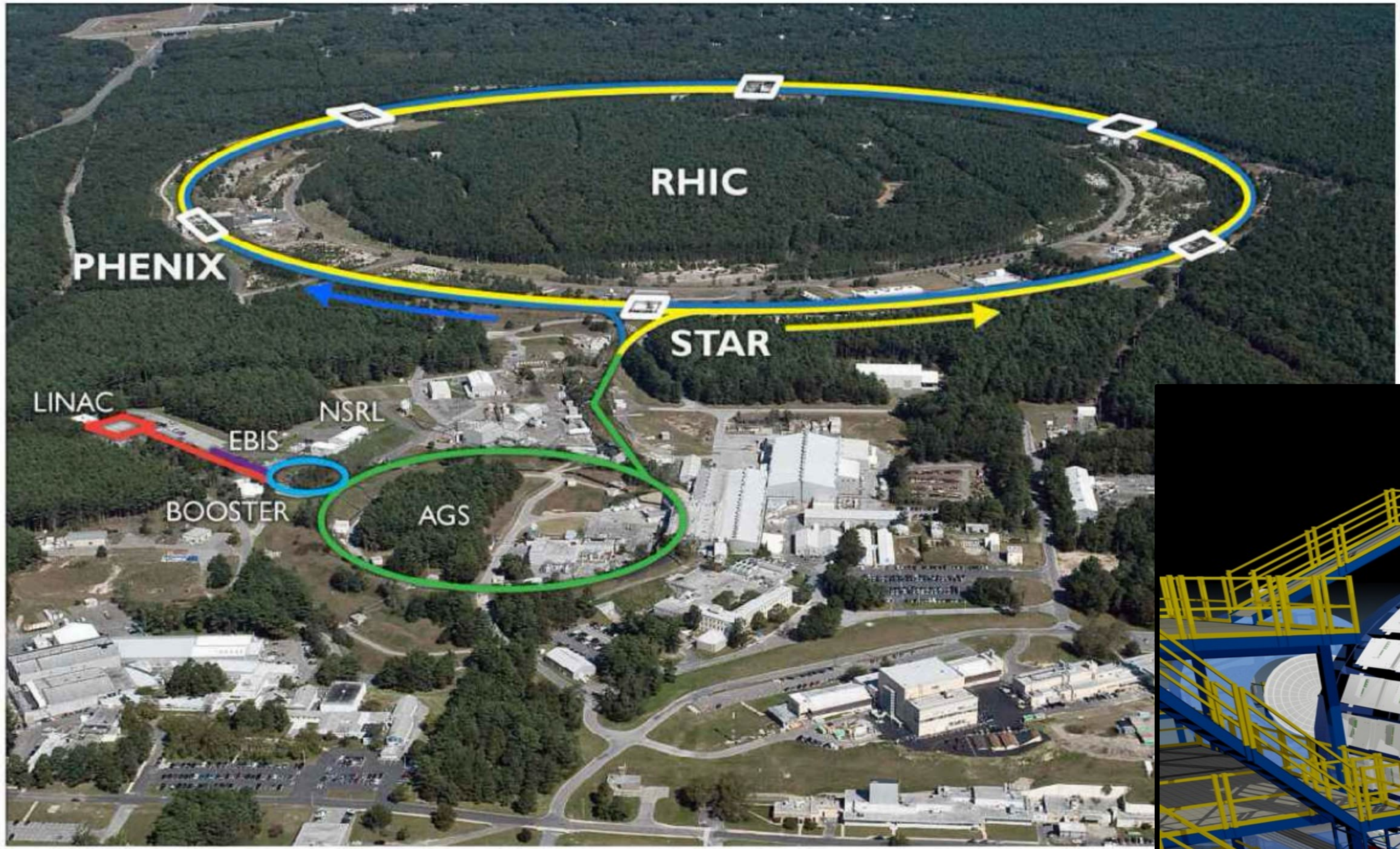


R. Lednicky, et al. Sov.J.Nucl.Phys.35(1982)770
L. Michael, et al. Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

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

RHIC-STAR Experiment



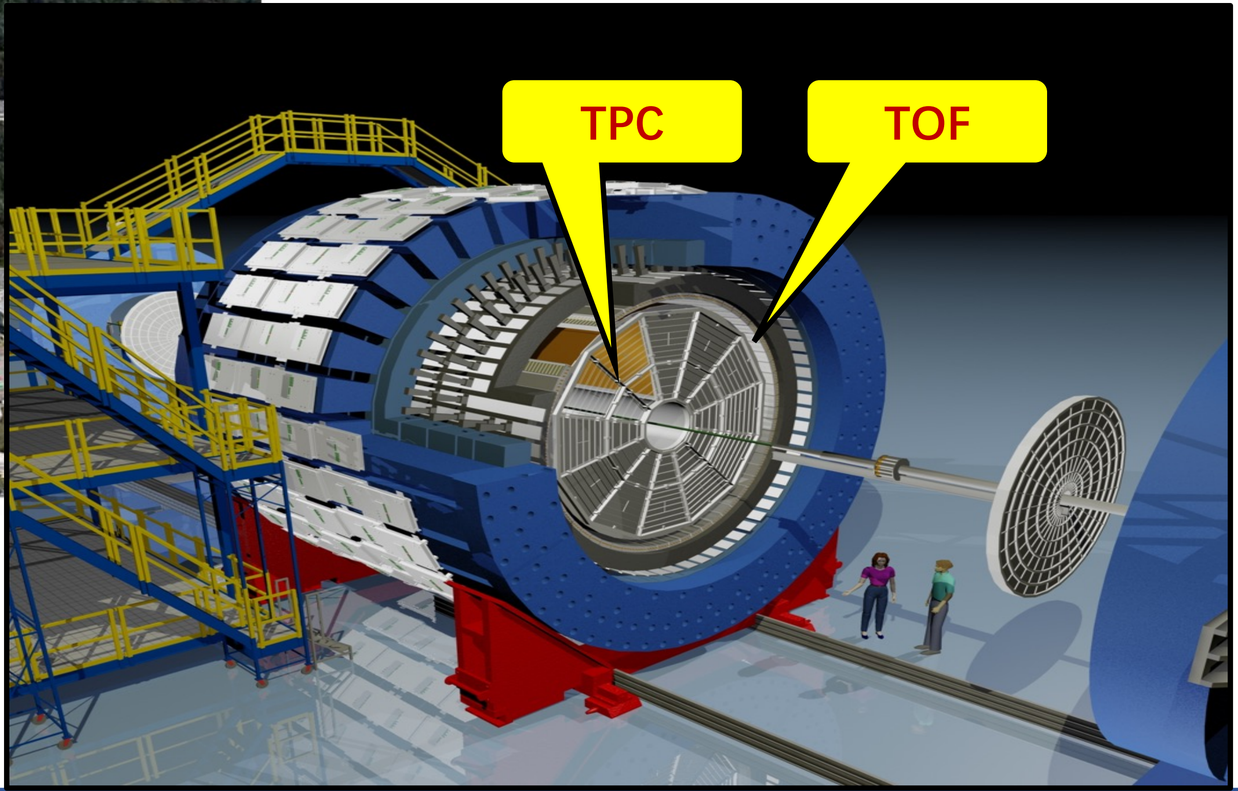
Relativistic Heavy Ion Collider (RHIC)

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)

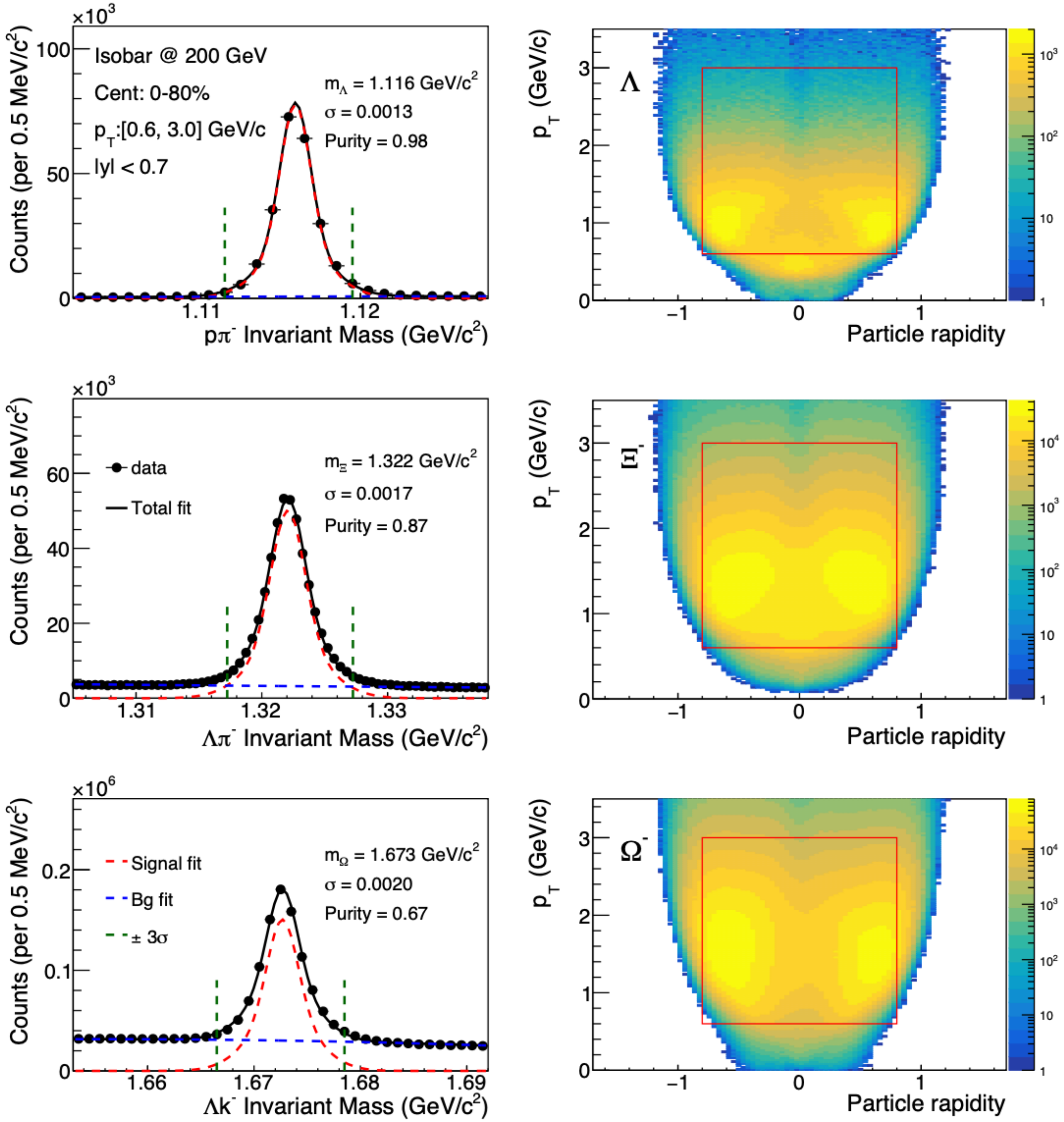
~ 2 billion minimum-bias events

- Hyperon reconstruction via Helix-swimming method

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

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

$\Omega^- \rightarrow \Lambda + K^-$, 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:

- $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - ik^*]^{-1}$ (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

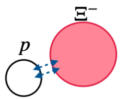
$f_0 < 0$: Repulsive Interaction or Bound State

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

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

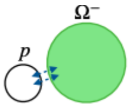
Lednicky-Lyuboshitz Model

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



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

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

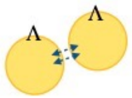


In p-Ω^- pair, there are two spin states:

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

Predicted bound state （HAL QCD）

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



In ΛΛ pair , there only one spin state:

$$C_{\Lambda-\Lambda} = C_{J=0,singlet}$$

<u>Spin-averaged method:</u>

Two spin states consider same Coulomb and strong interaction

<u>Quintet method:</u>

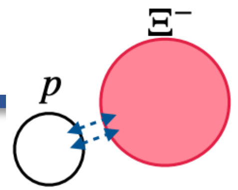
In quintet state, consider Coulomb and strong interaction

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

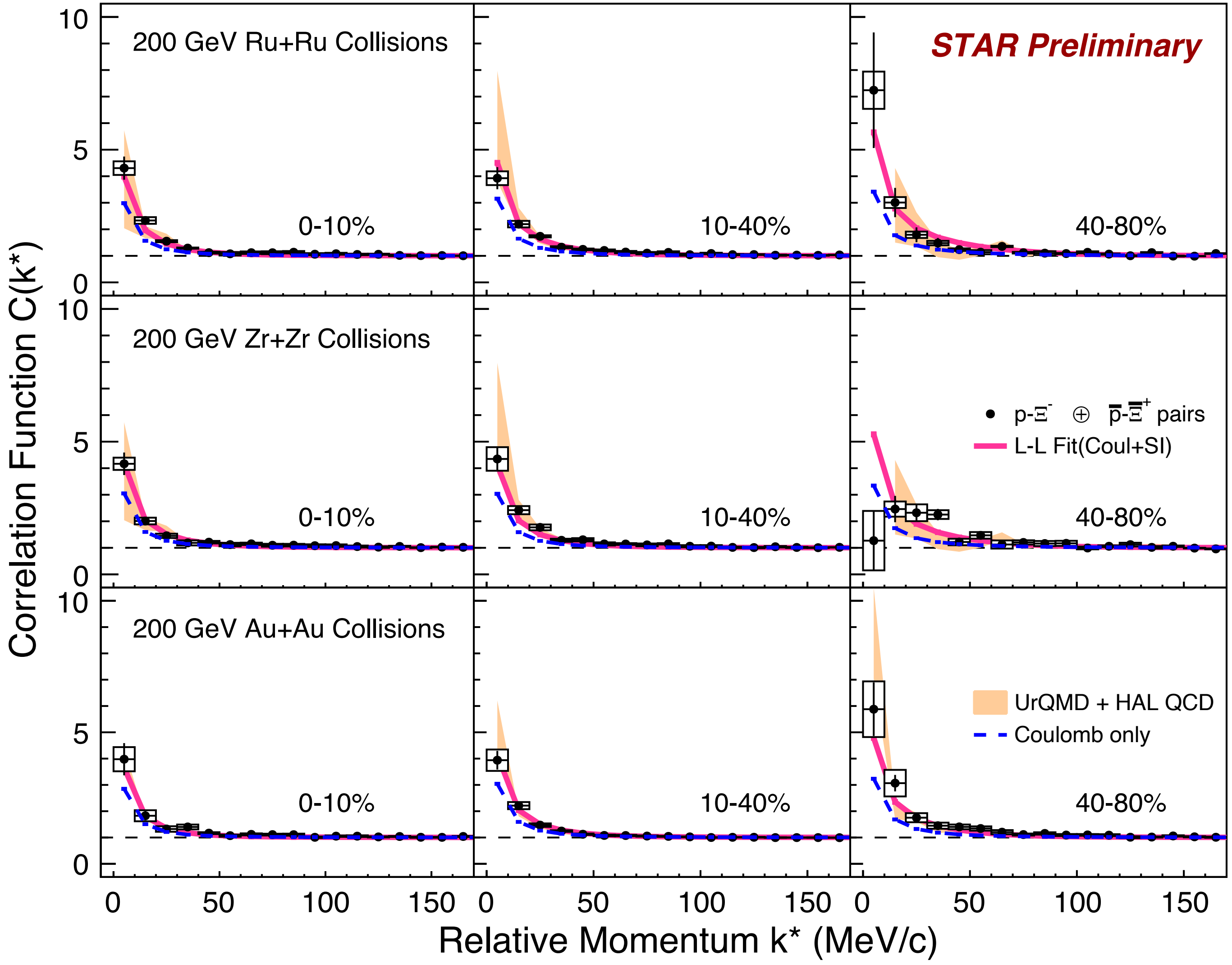
Kenji Morita, et al., Phys. Rev. C 101, 015201 (2020)

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

p-Ξ⁻ Correlation Function (|S| =2)



See poster by Boyang Fu



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

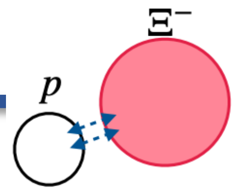
IV. UrQMD + HAL QCD model is consistent with data

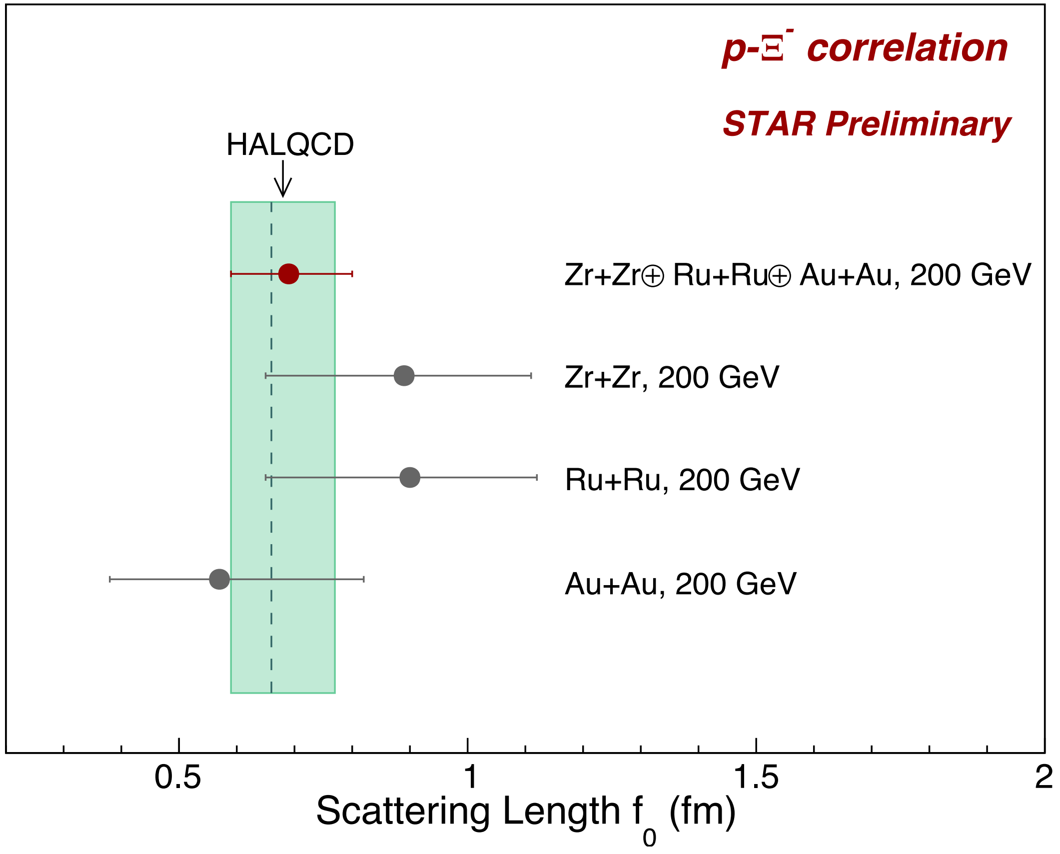
◎ Particle phase space provided by UrQMD

◎ 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

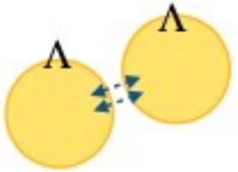
III. Extracted spin averaged scattering length:

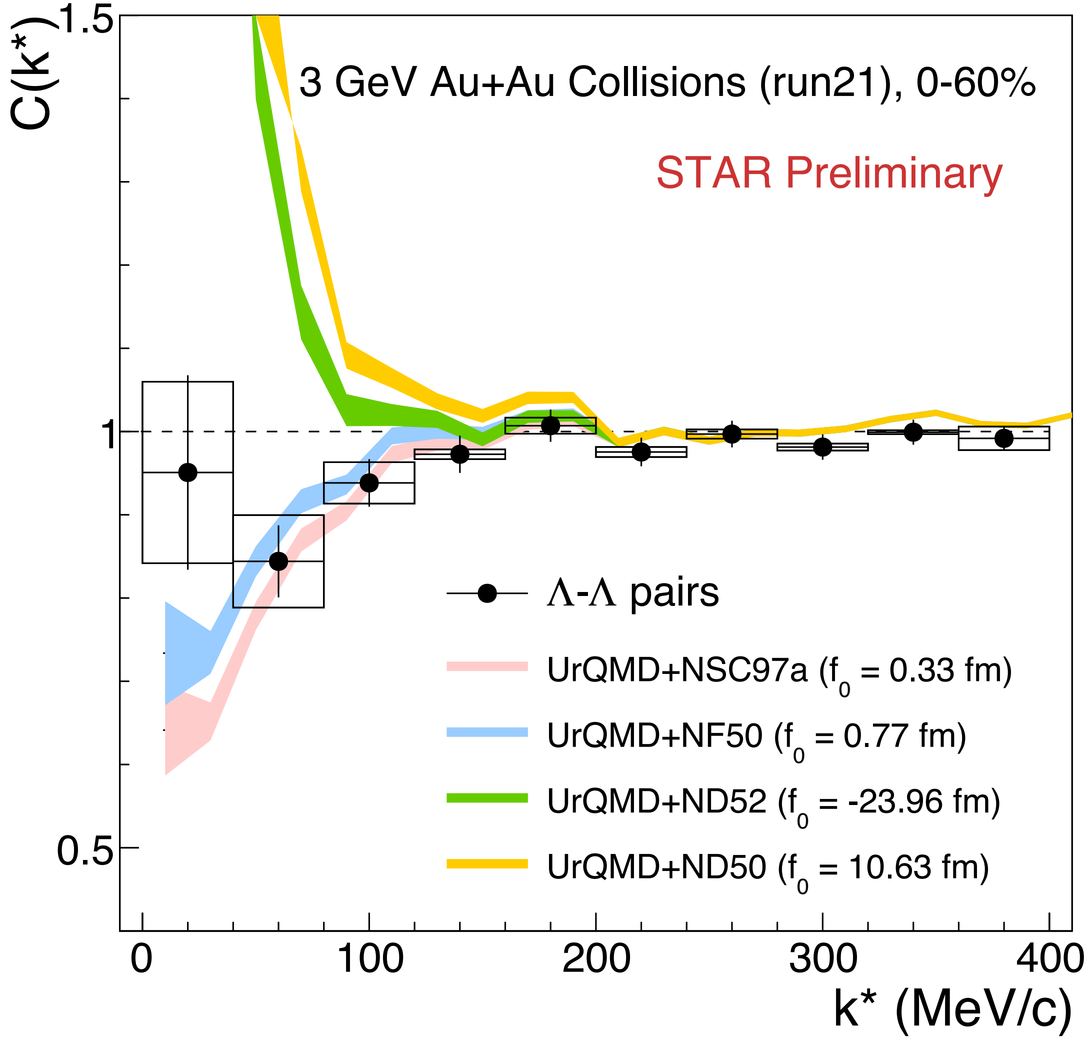
$f_0 = 0.7^{+0.1}_{-0.1}$ fm (stat.+sys.)

- Weakly attractive interaction
- Consistent with HAL QCD prediction

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

Λ-Λ Correlation Function (|S| =2)





I. Λ-Λ correlation function shows suppression at small k*

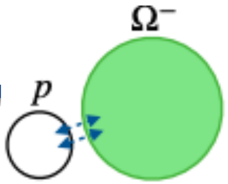
I. Compared with UrQMD + potential, it is found that the simulation with smaller positive f_0 is in better agreement with data
   - Hints an weakly attractive interaction in Λ-Λ pairs

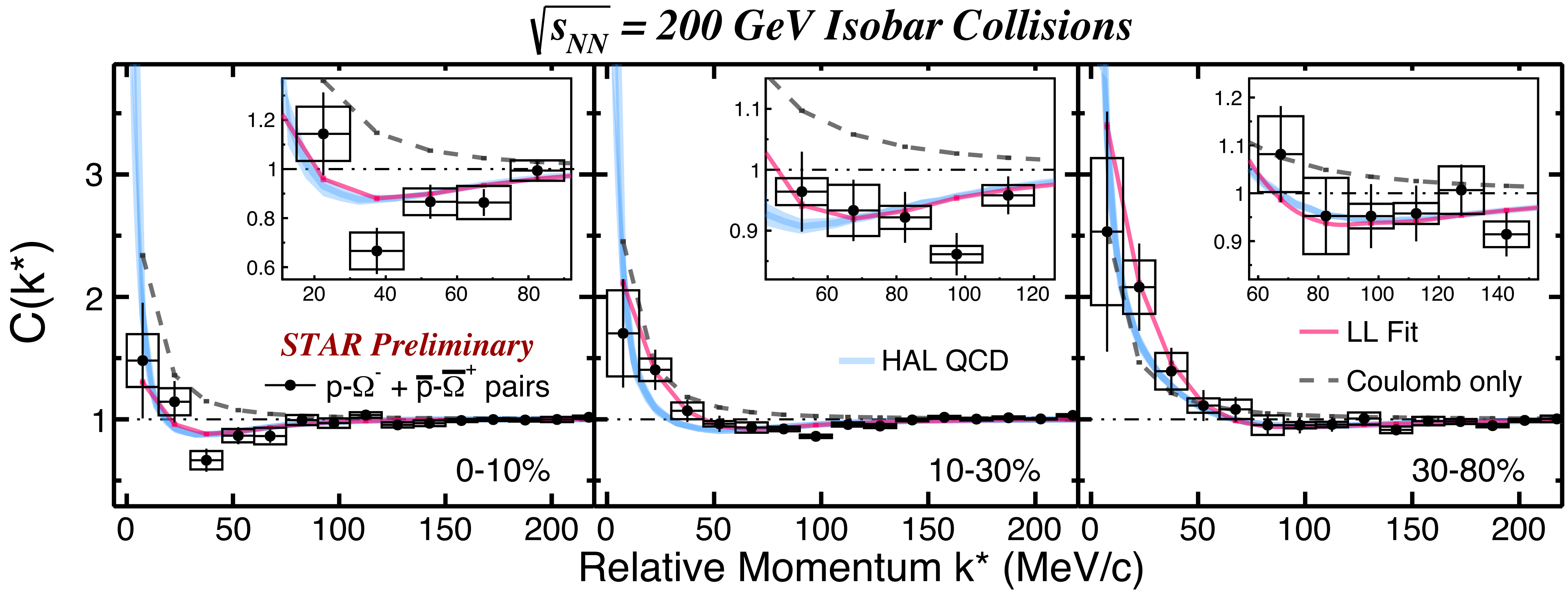
II. Need more precise data to confirm
   - High statistics Isobar and Au+Au collisions

Potential	f_0 **(fm)**	d_0 **(fm)**	**Chi2/NDF**
NSC97a[1]	0.33	12.37	1.53
NF50[2]	0.77	4.27	1.61
ND52[3]	-23.96	2.59	2.24
ND50[3]	10.63	2.04	4.02

[1] P. M. M. Maessen, et al, Phys. Rev. C 40 (1989) 2226
[2] M. M. Nagels, et al, Phys. Rev. D 20 (1979) 1633
[3] M. M. Nagels, et al, Phys. Rev. D 15 (1997) 2547

p-Ω⁻ Correlation Function (|S|=3)





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

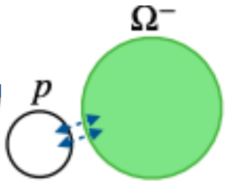
- CFs show enhancement at low k* –> mainly due to Coulomb attraction interaction
- CFs show depletion at k* ~ 30-100 MeV/c –> mainly due to the strong interaction

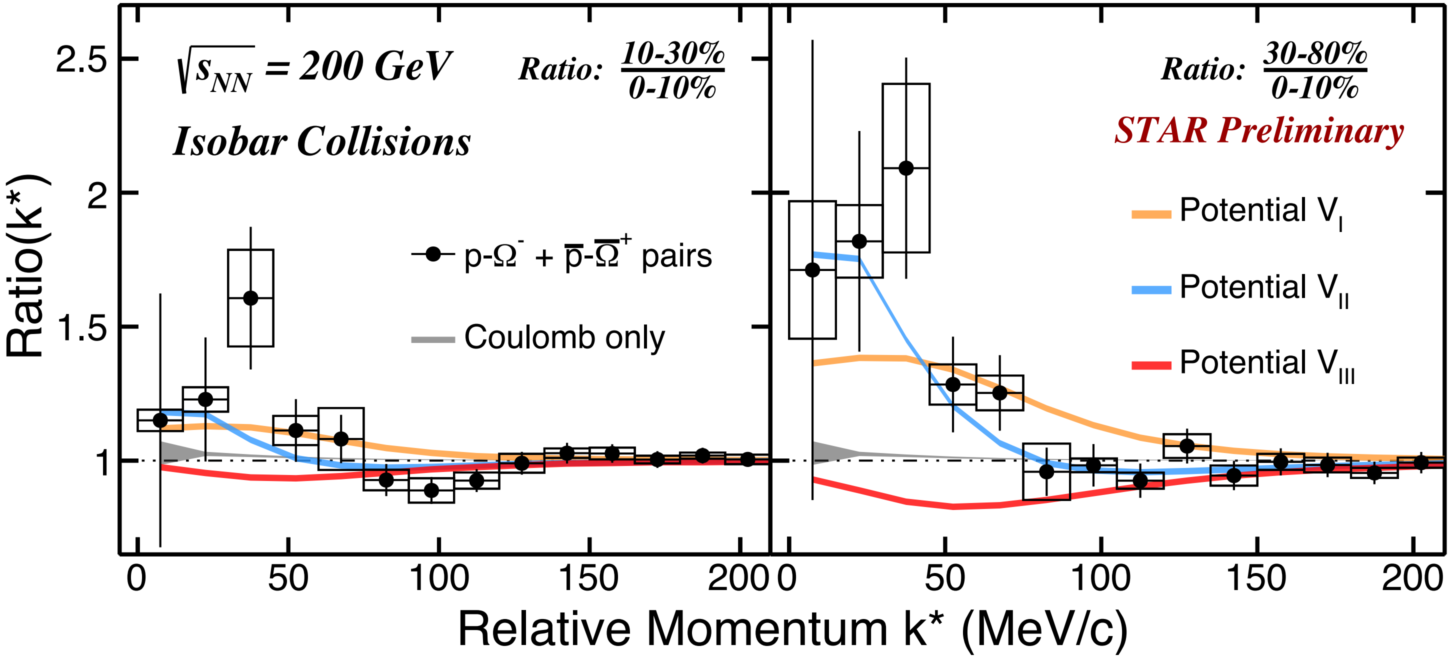
II. Simultaneously fit with L-L function for 3 centralities to extract R_G, f_0 and d_0 by Bayesian method

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

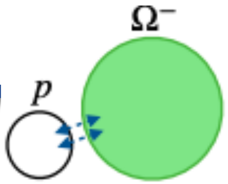
II. CF Ratio shows enhancement at low k* and depletion around k* ~ 100 MeV/c

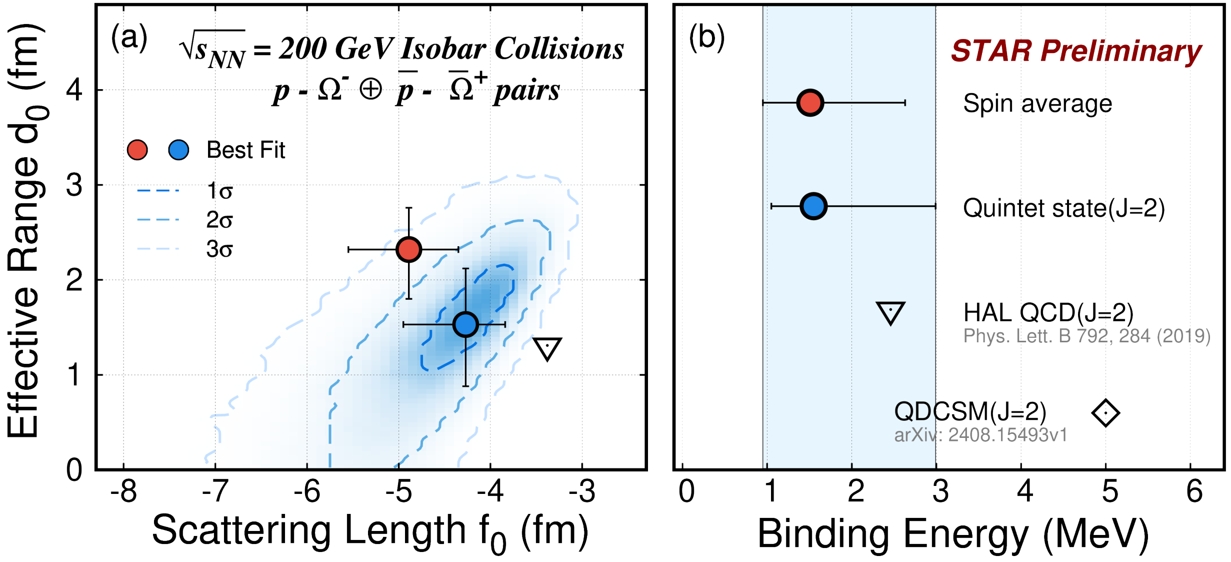
- Due to the presence of shallow bound state

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

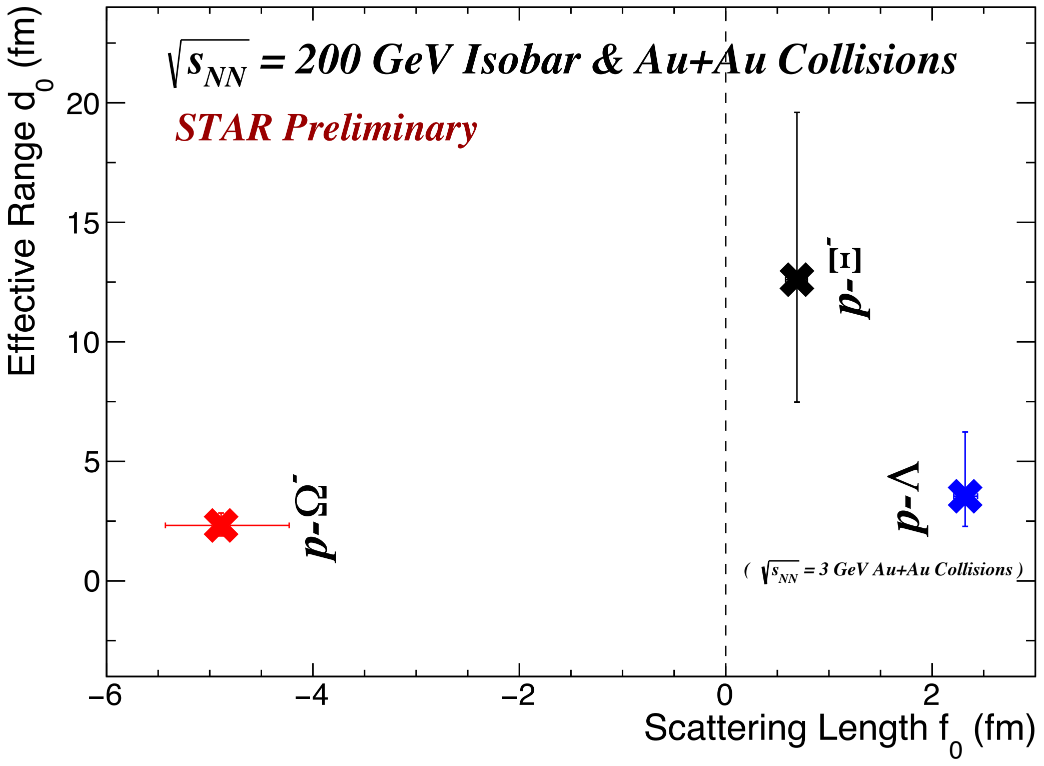
III. Calculate Binding Energy (BE) via Betha formula:

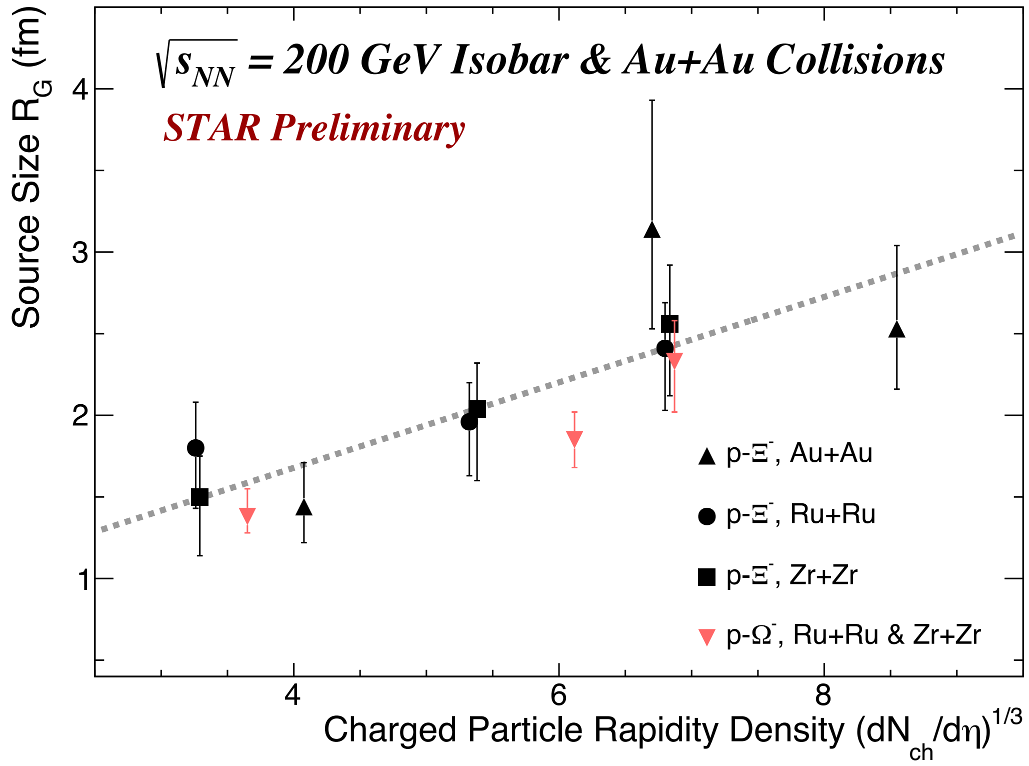
Reduced mass: $m_{p\Omega} = \frac{m_p m_\Omega}{m_p + m_\Omega}$

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

- ☐ Calculated BE are consistent with HAL QCD prediction

Strong Interaction Parameters





- ☐ Extracted positive f_0 in 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 distribution (Centrality denpendence $R_G^{central}$ > $R_G^{peripheral}$)

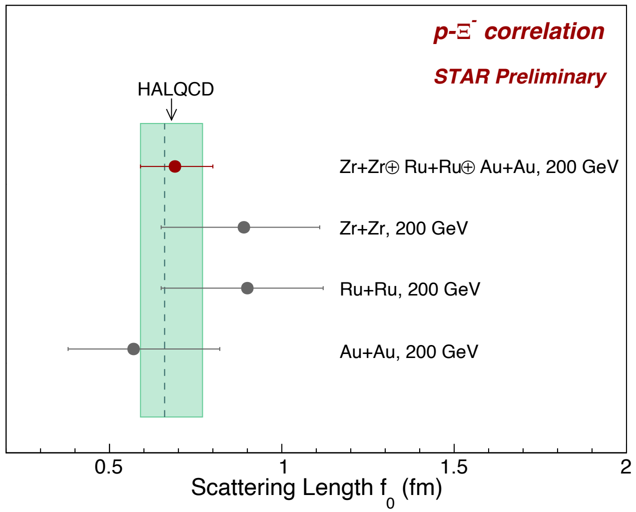
Summary

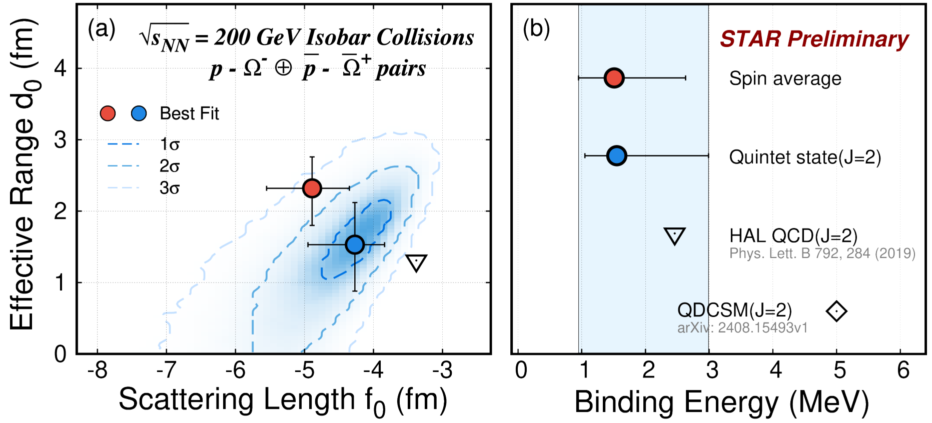
I. Precision measurements of **p-Ξ^- $\oplus$ $\bar{p}$-$\bar{\Xi}^+$**, **Λ-Λ** and **p-Ω^- $\oplus$ $\bar{p}$-$\bar{\Omega}^+$** correlation function at STAR

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

- **p-Ξ^- $\oplus$ $\bar{p}$-$\bar{\Xi}^+$** pairs: $f_0 > 0$ **->** Weakly attractive interaction
- **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

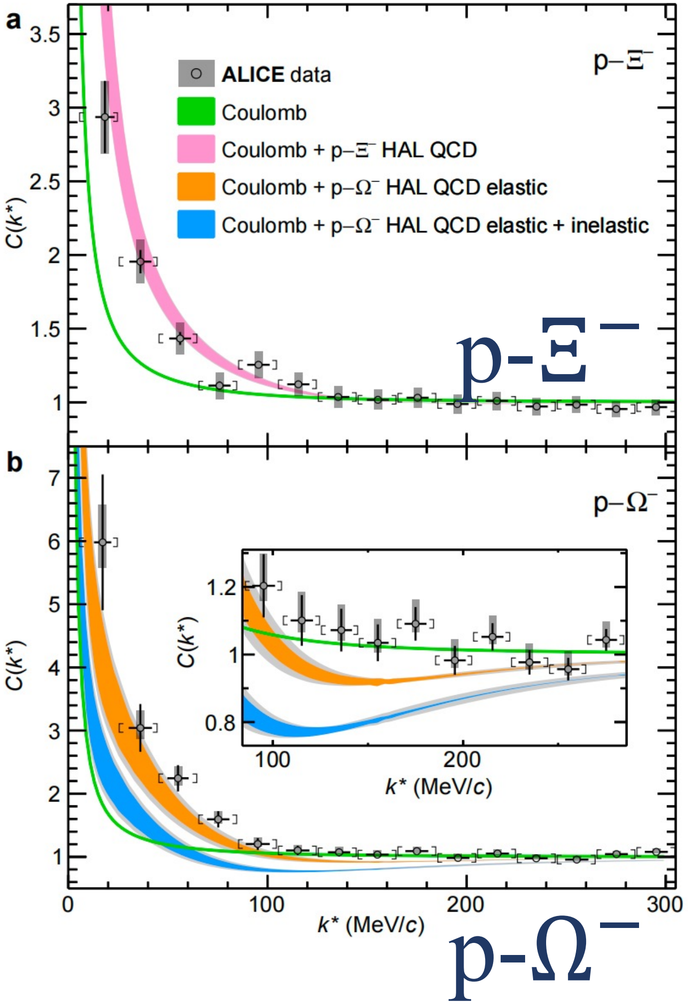


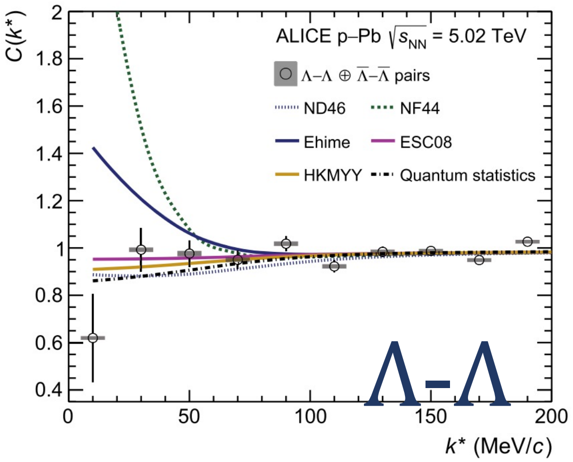


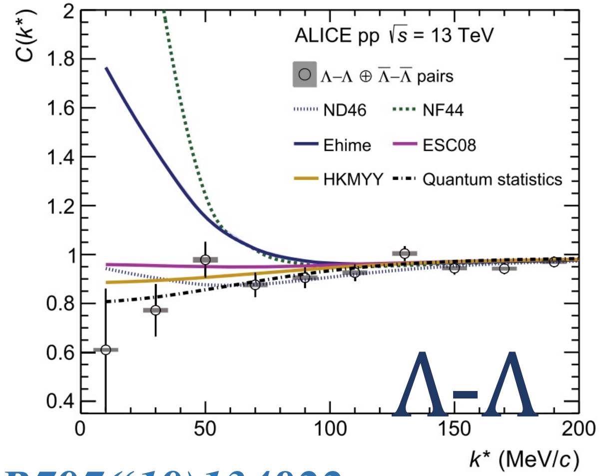
First experimental evidence of Strange Dibaryon

Thank you for your attention!

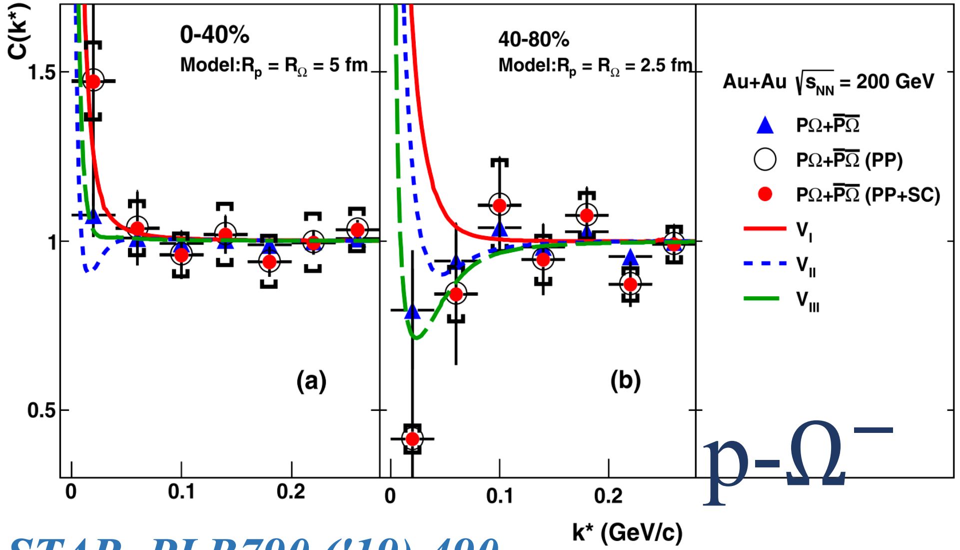
Backup-Motivation

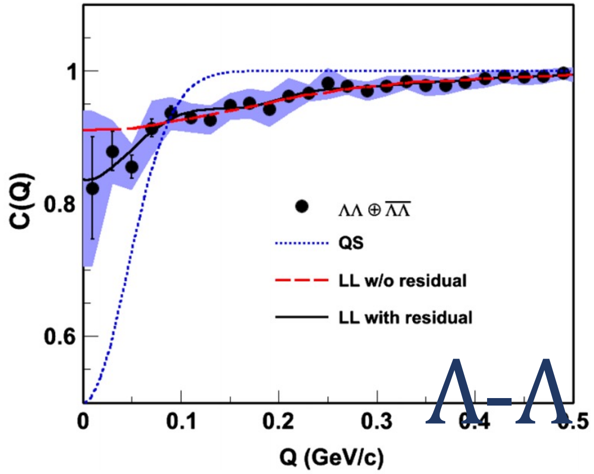






ALICE, PLB797('19)134822





STAR, PRL114('15)022301

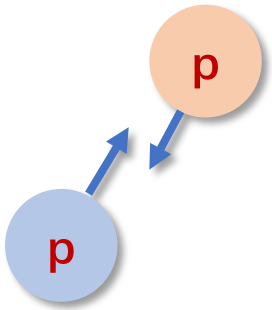
ALICE, Nature588 ('20)232

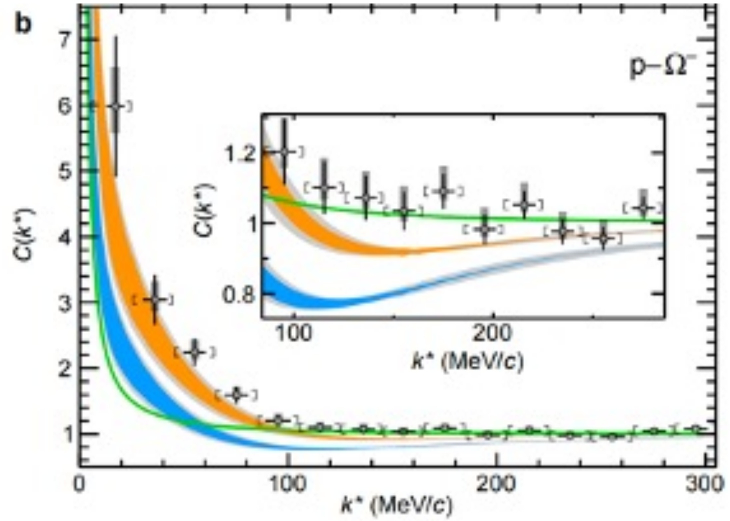
STAR, PLB790 ('19) 490

More Experiment measurements are needed !

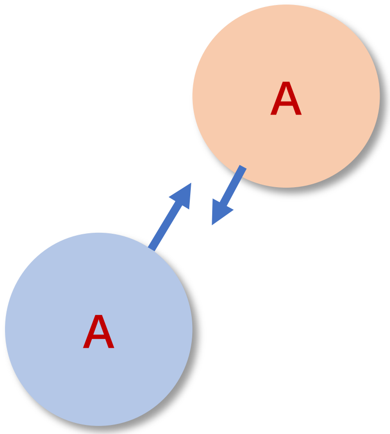
Backup- p-Ω^- Bound?

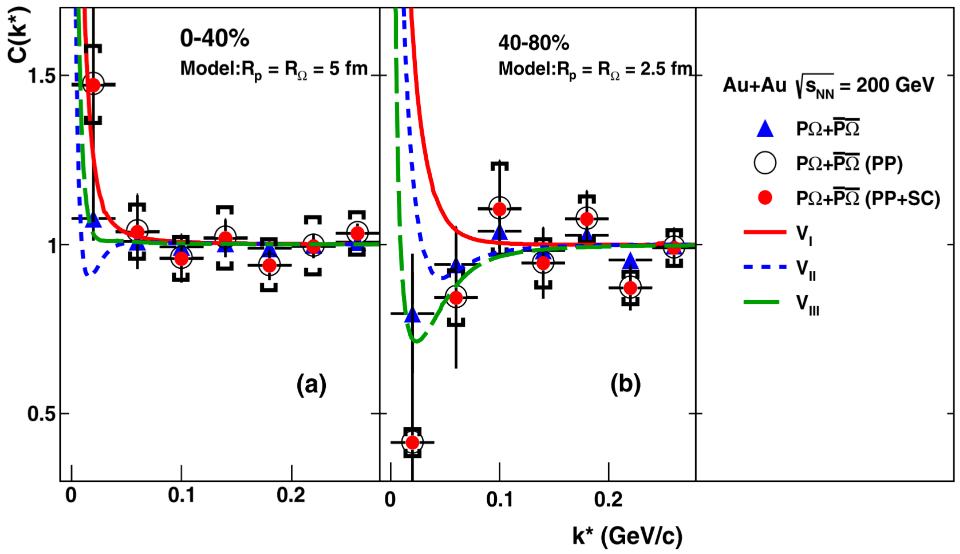
- Small source



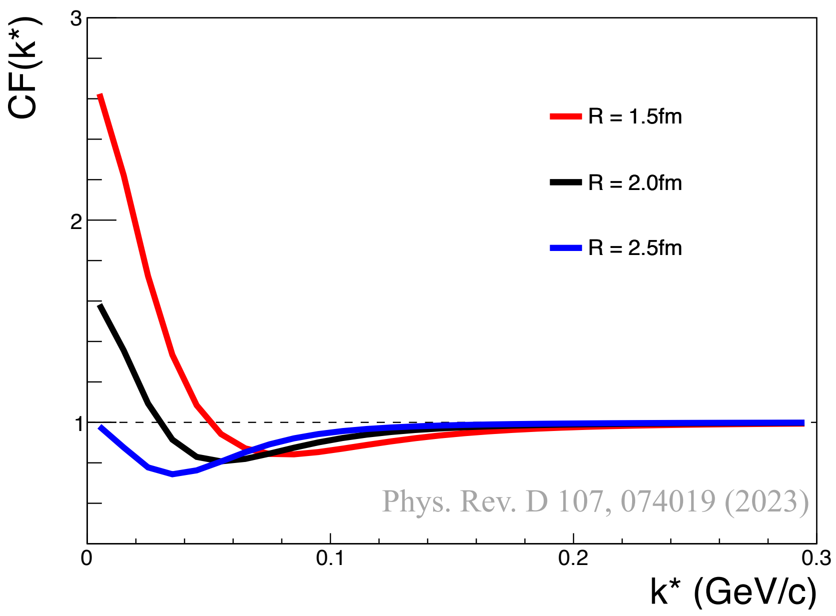


- Large source





Shallow Bound



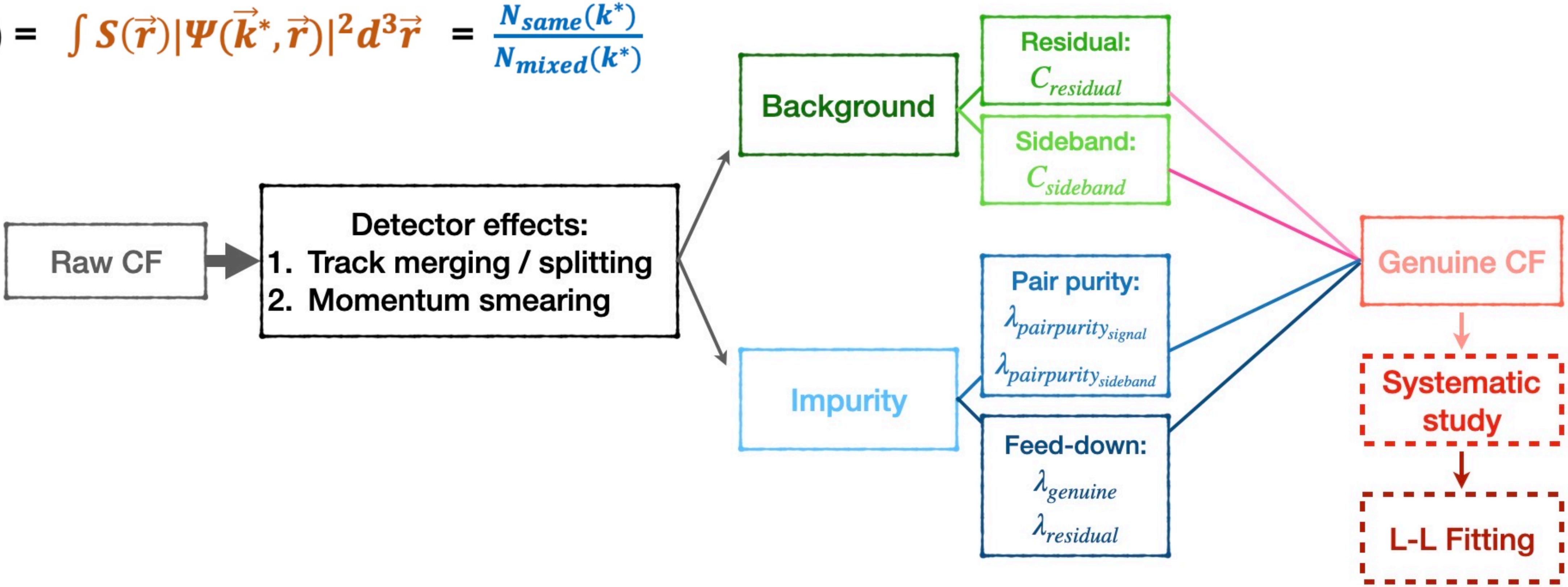
Source size or centrality dep. of CF

→ To be bound,
or not to be bound

Backup-Analysis Details

Model ***Experimental***

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



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

Backup-Bayesian Method

1st Step

Sample Input

$R_1 = [R_{1min}, R_{1max}]$

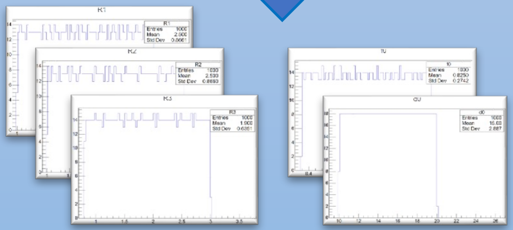
$R_2 = [R_{2min}, R_{2max}]$

$R_3 = [R_{3min}, R_{3max}]$

$f_0 = [f_{0min}, f_{0max}]$

$d_0 = [d_{0min}, d_{0max}]$

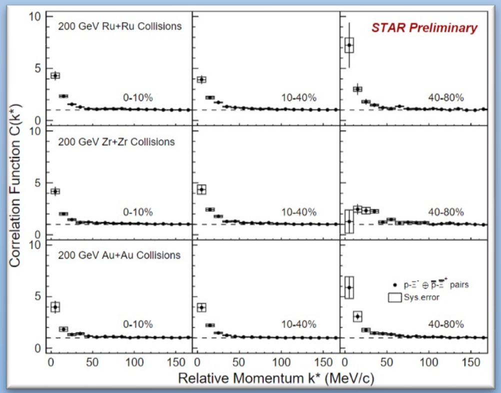
Latin Hypercube Sampling



Study samples

2nd Step

Data Input

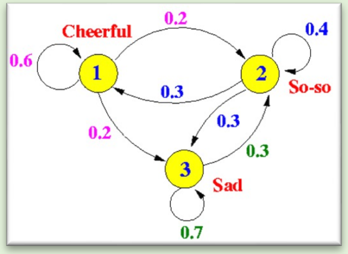


Compare with the samples and predict the parameter's value with error

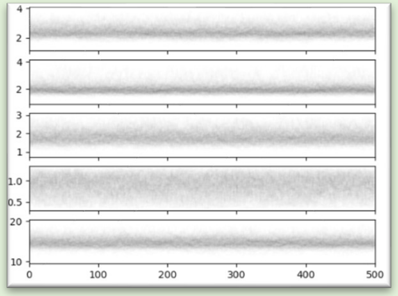
3rd Step

Technique

MC MC
Markov Chain
Monte Carlo



Gaussian Processes Regression



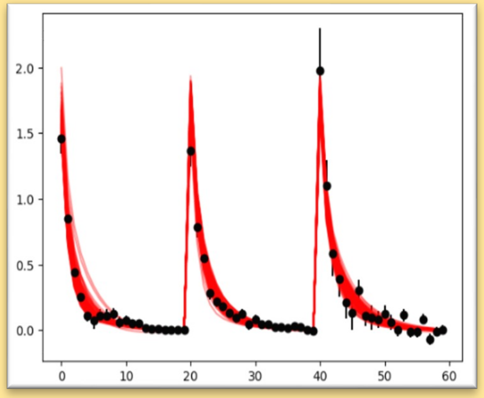
Resampling

N_{steps}~500

$N_{walkers}$~400

$N_{burnsteps}$~500

Results



Steps = $N_{walkers} \times N_{steps}$