Search for the Strange Dibaryons with Baryon Correlations in Isobar Collisions at STAR

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STAR Collaboration

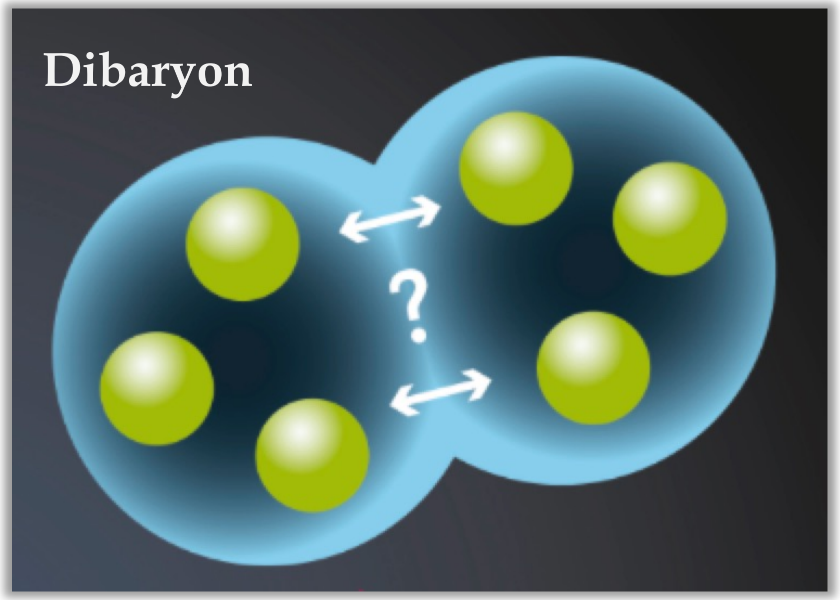
Outline

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

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

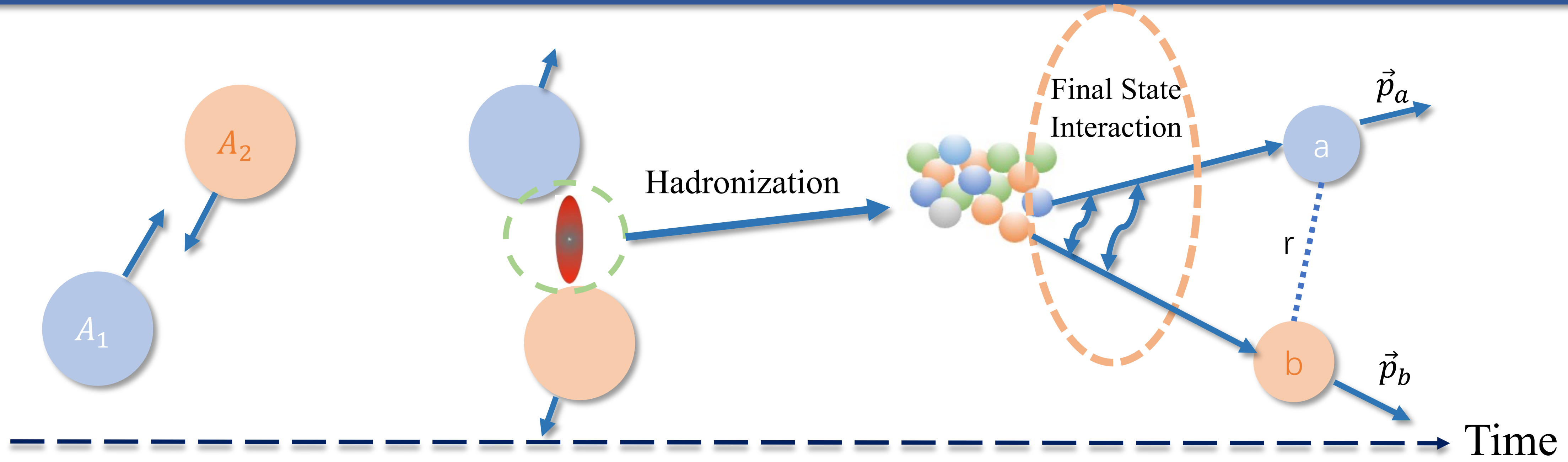
  (|S|=2)Dibaryon $\Leftrightarrow \Lambda + \Lambda$

  - *(See ID 669 poster by Ke Mi)*

- 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***

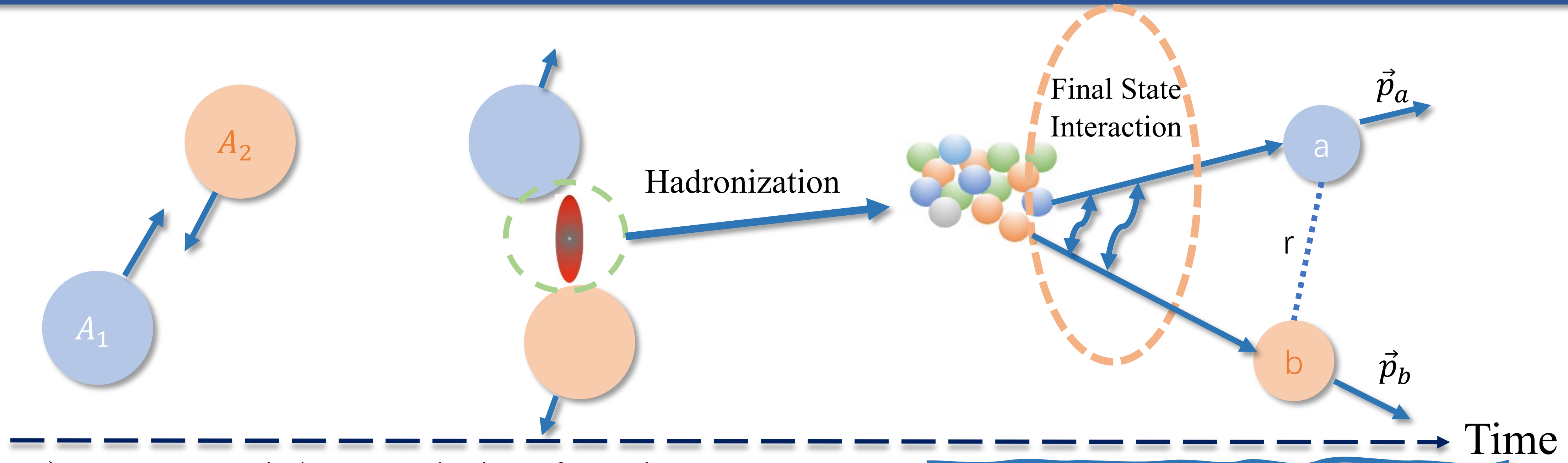
$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

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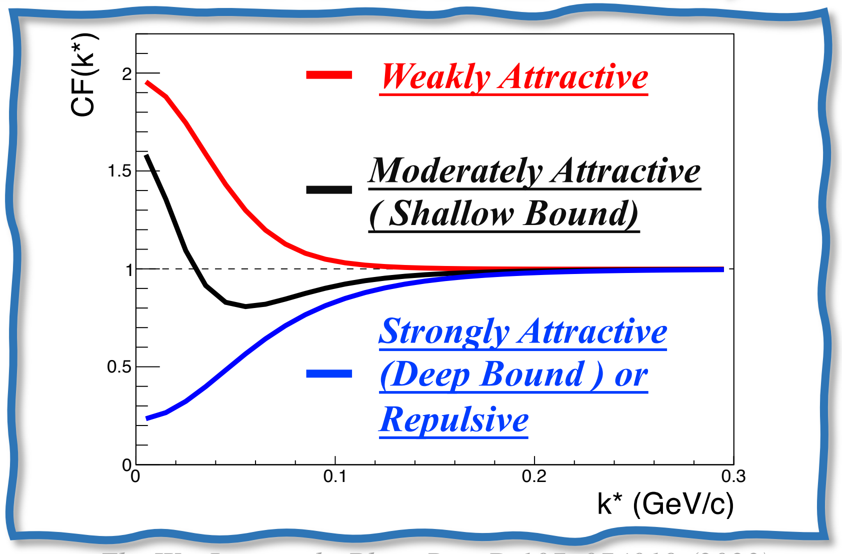
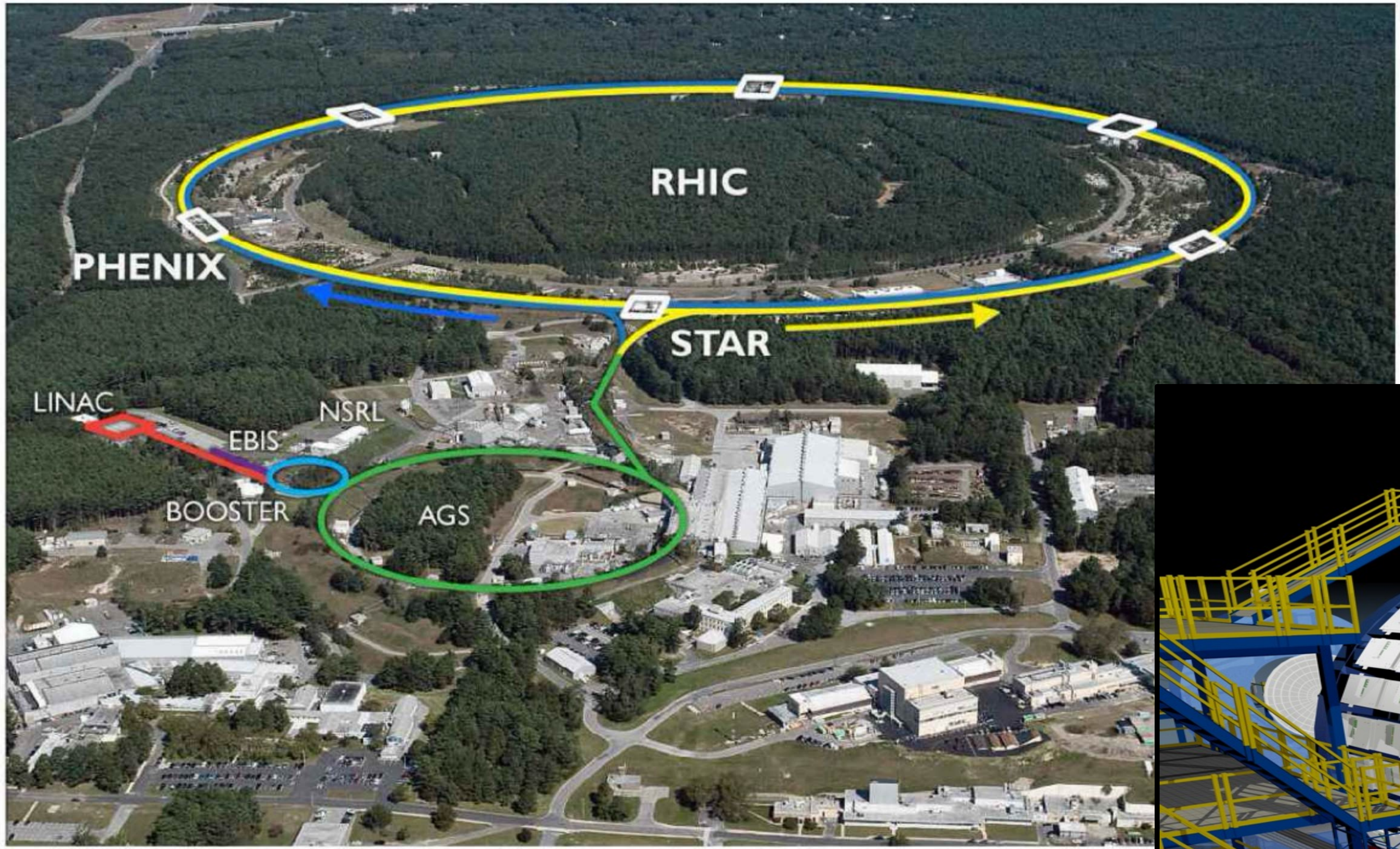


R. Lednicky, et al. Sov.J.Nucl.Phys.35(1982)770
L. Michael, et al. Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402
Zhi-Wei Liu, et al., Phys. Rev. D 107, 074019 (2023)

RHIC-STAR Experiment



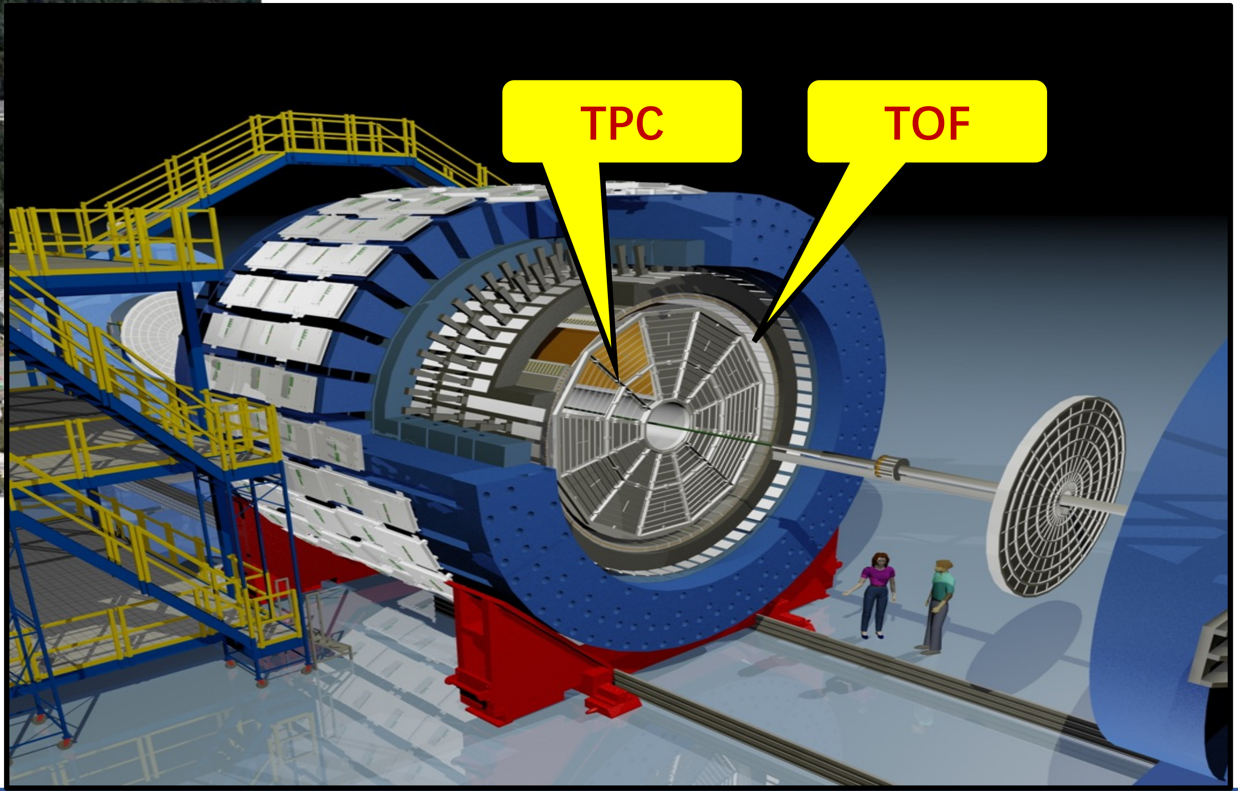
Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory, Upton

➔ Au+Au, p+p, 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)

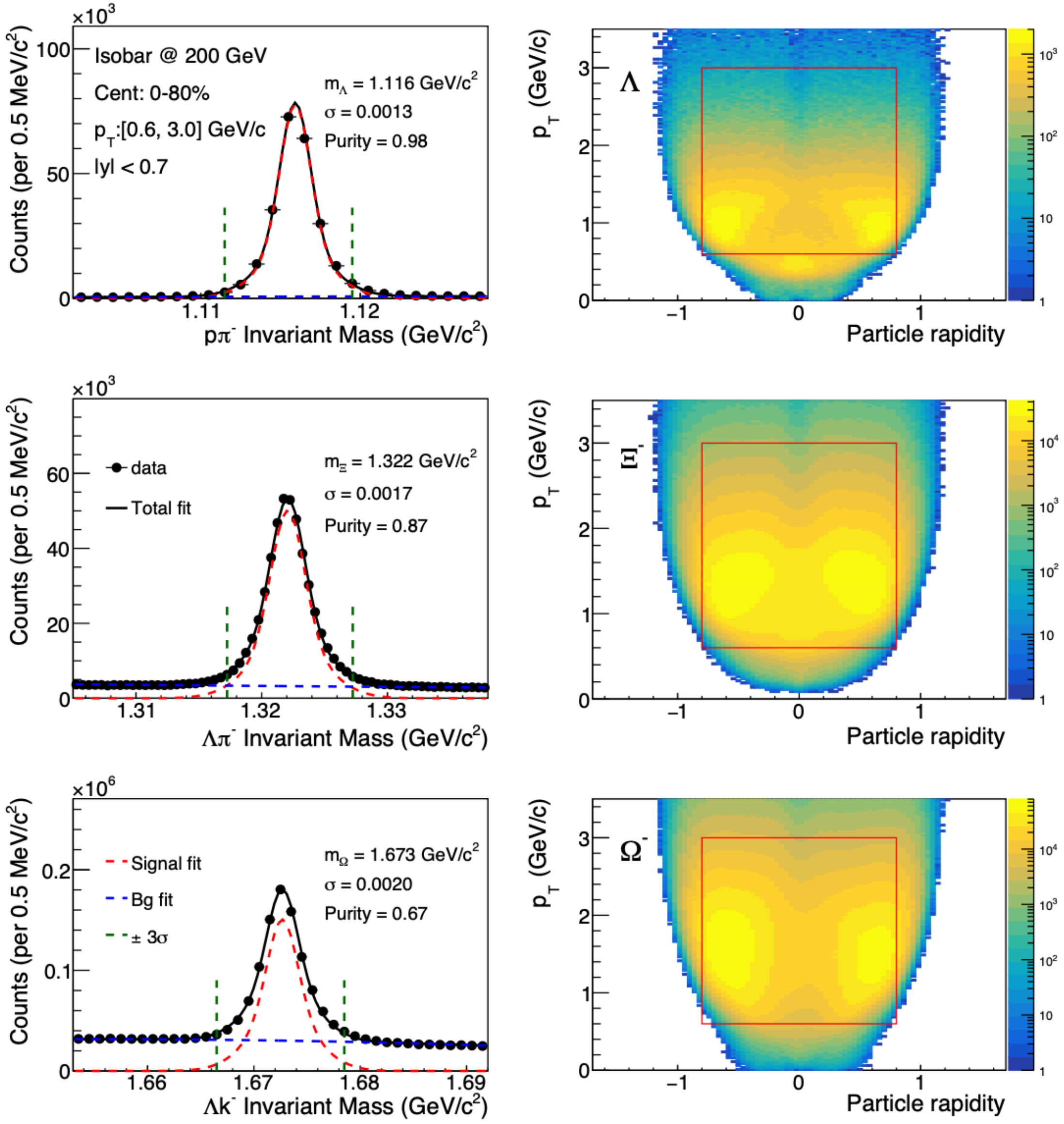
~ 2.5 billion minimum-bias events

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

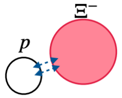
$f_0 < 0$: Repulsive Interaction or Bound State

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

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

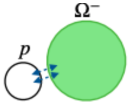
Lednicky-Lyuboshitz Model

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



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:

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

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:

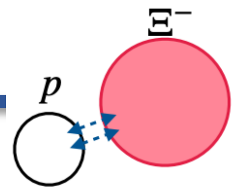
In quintet state, consider Coulomb and strong interaction

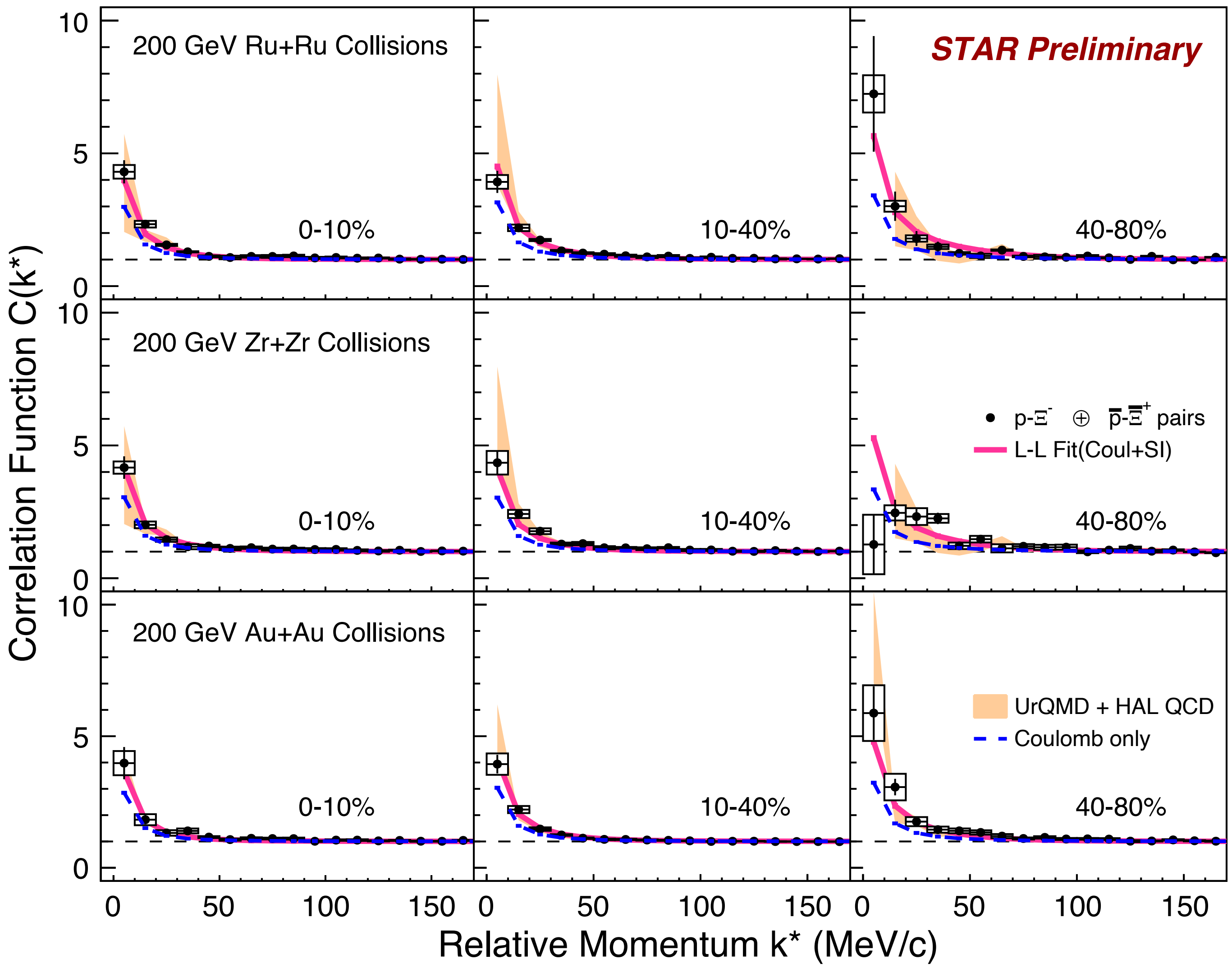
In triplet state, just consider Coulomb since the strong effect of couple channel

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-Ξ^- Correlation Function (|S| =2)





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

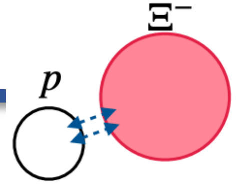
II. CFs show enhancement at low k*

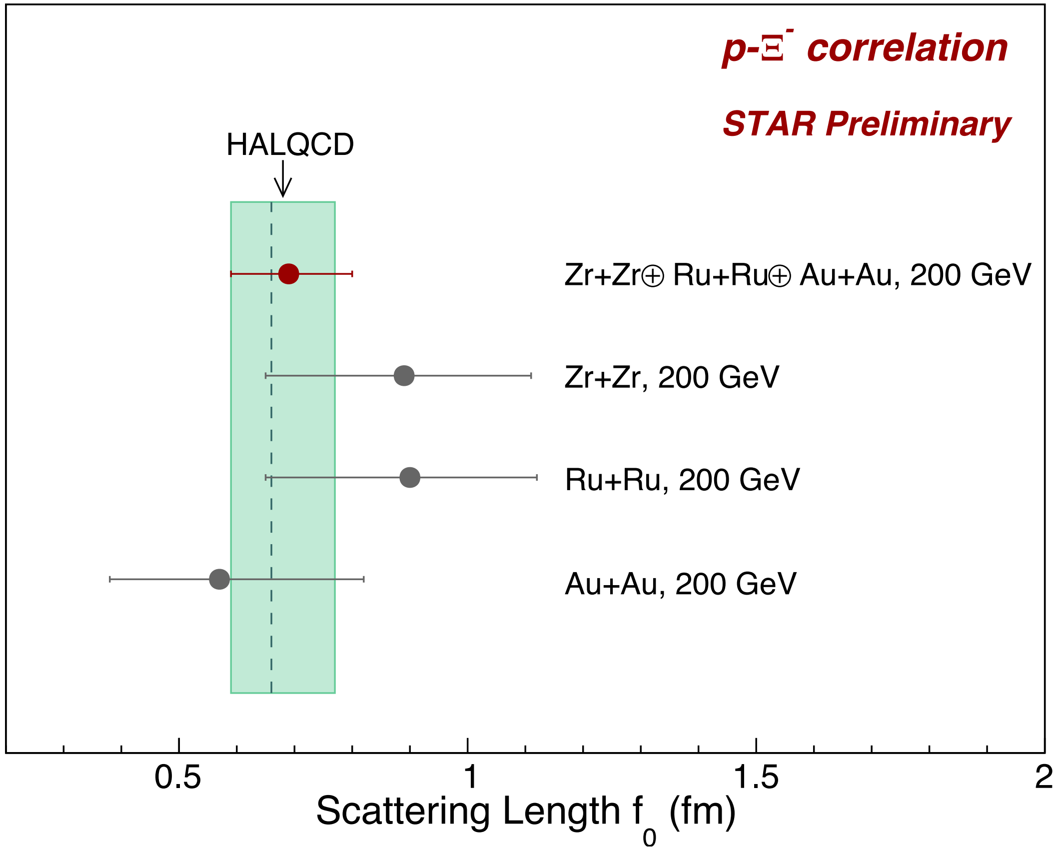
III. Simultaneously fit with L-L function for different centralities in each collision system to extract R_G, f_0 and d_0 by Bayesian method

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

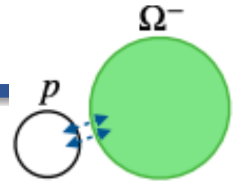
III. Extracted spin averaged scattering length:

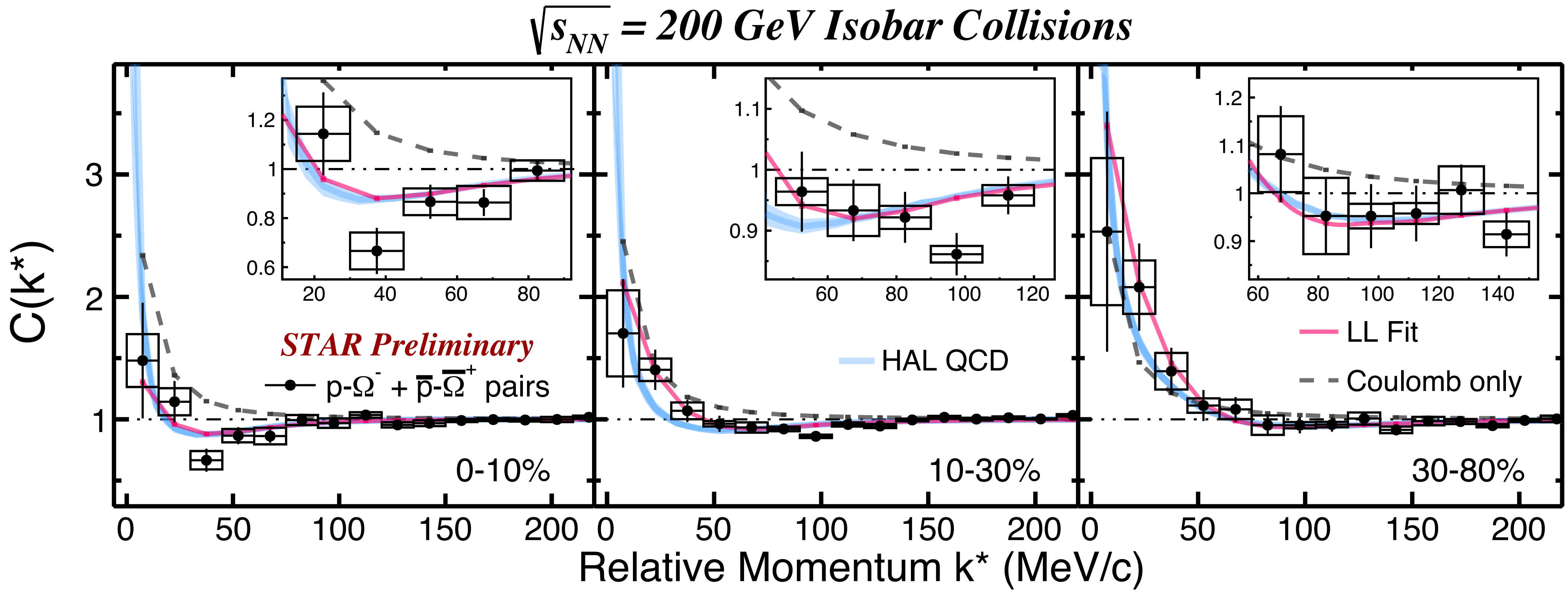
$$f_0 = 0.7^{+0.1}_{-0.1} \text{ fm (stat.+sys.)}$$

- ☐ Weakly attractive interaction
- ☐ Consistent with HAL QCD prediction

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

p-Ω⁻ Correlation Function (|S|=3)





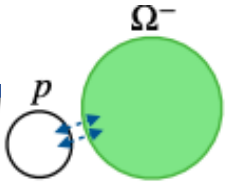
I. Precise measurements of p-Ω⁻ ⊕ p̄-Ω̄⁺ correlation functions in Isobar collisions
   - CFs show enhancement at low k* –> mainly due to Coulomb attraction interaction
   - CFs show depletion at k* ~ 30-100 MeV/c –> mainly due to the strong interaction

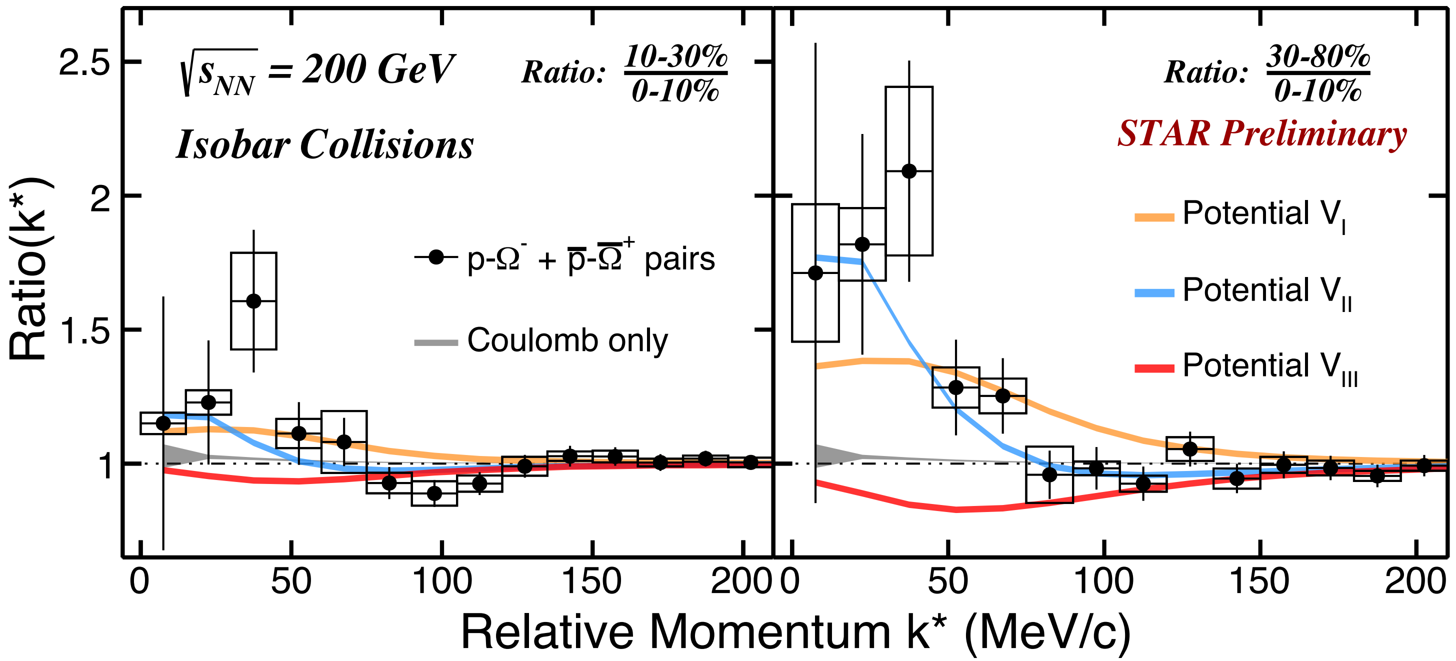
II. Simultaneously fit with L-L function for 3 centralities to extract R_G, f_0 and d_0 by Bayesian method

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)





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

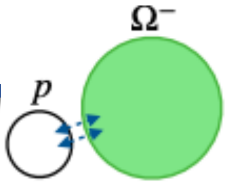
- Due to the presence of shallow bound state

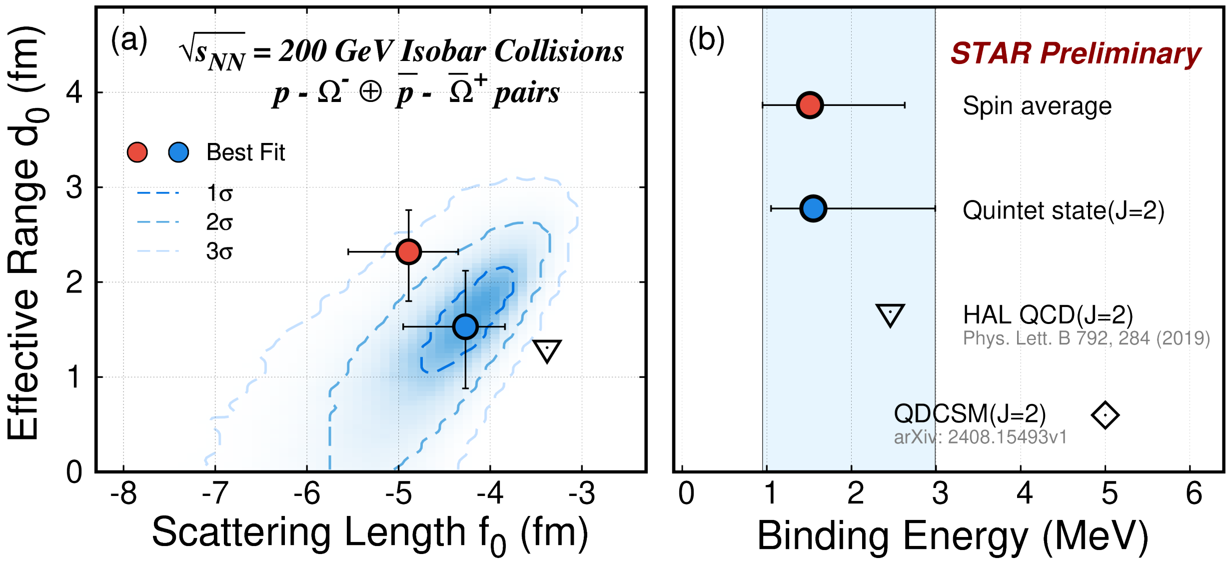
Type	f_0 (fm)	d_0 (fm)	BE (MeV)	χ^2/ndf	p-value	
V_I [1]	1.12	1.16	--	48.2/29	0.014	No Bound
V_{II} [2]	-3.38	1.31	2.15	22.2/29	0.812	Shallow Bound
V_{III} [1]	-1.29	0.65	26.9	58.7/29	0.001	Deeply Bound

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)





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

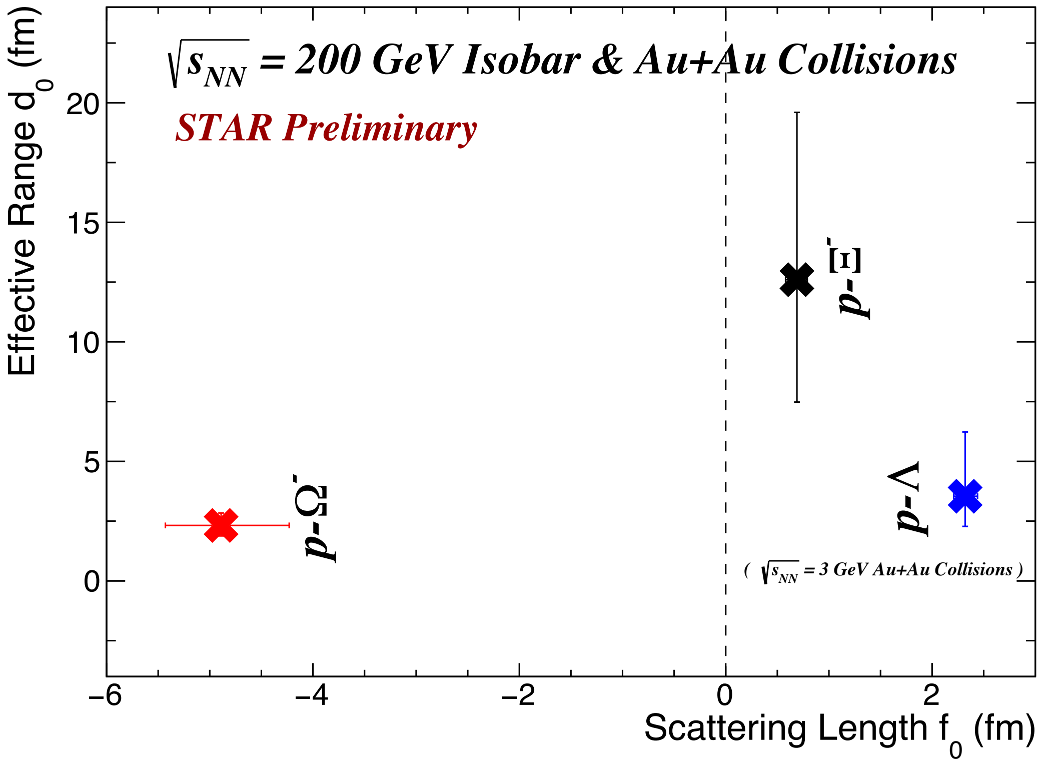
$$BE_{p\Omega} = \frac{1}{2m_{p\Omega}d_0^2}\left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\right)^2$$

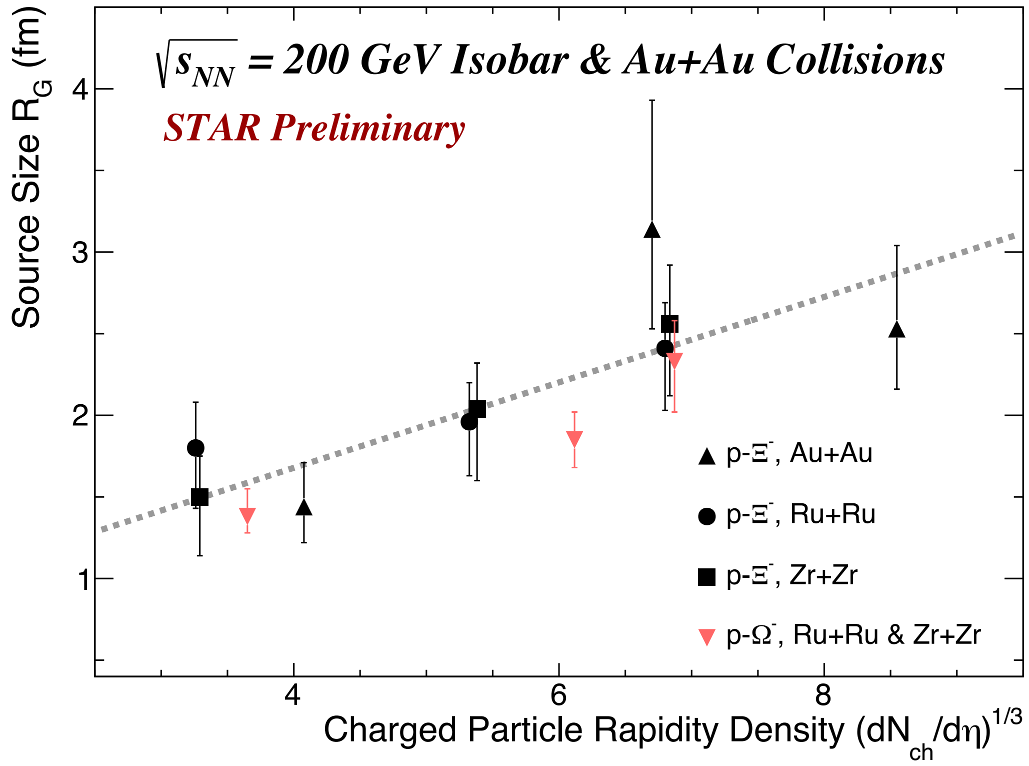
- Calculated BE are consistent with HAL QCD prediction

	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)

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 $R_G^{central} > R_G^{peripheral}$)

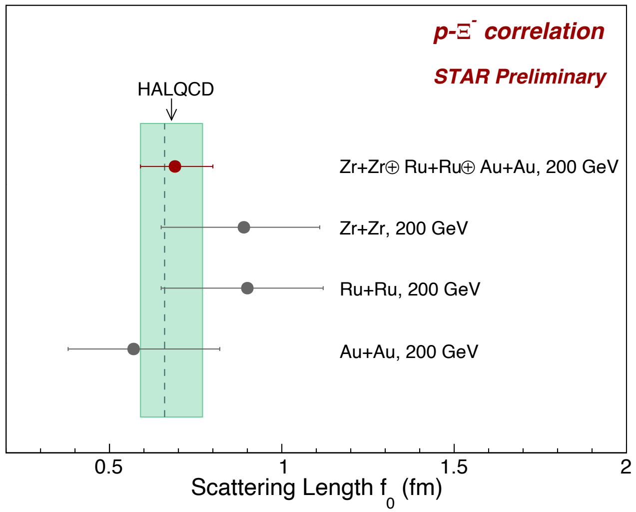
Summary

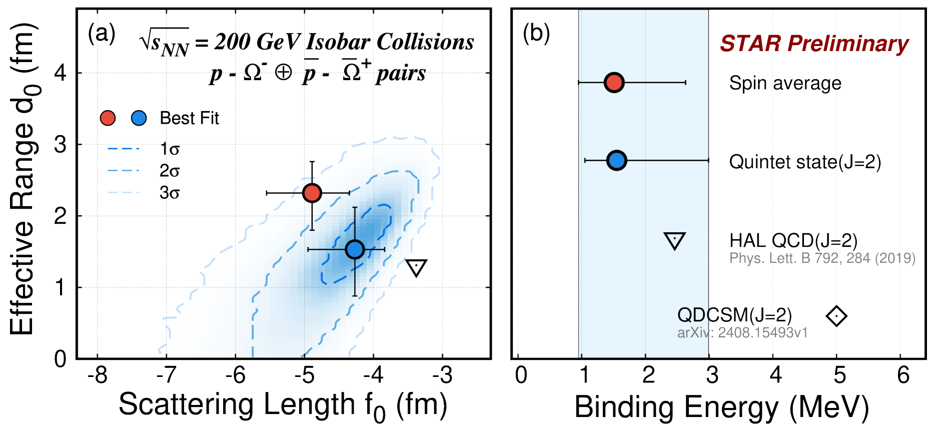
I. Precision measurements of **p-Ξ⁻ ⊕ p̄-Ξ̄⁺** and **p-Ω⁻ ⊕ p̄-Ω̄⁺** correlation function at $\sqrt{s_{NN}} = 200$ GeV in Isobar collisions

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

- **p-Ξ⁻ ⊕ p̄-Ξ̄⁺** pairs: $f_0 > 0$ **->** Weakly attractive interaction
- **p-Ω⁻ ⊕ p̄-Ω̄⁺** pairs: $f_0 < 0$ **->** Bound state

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

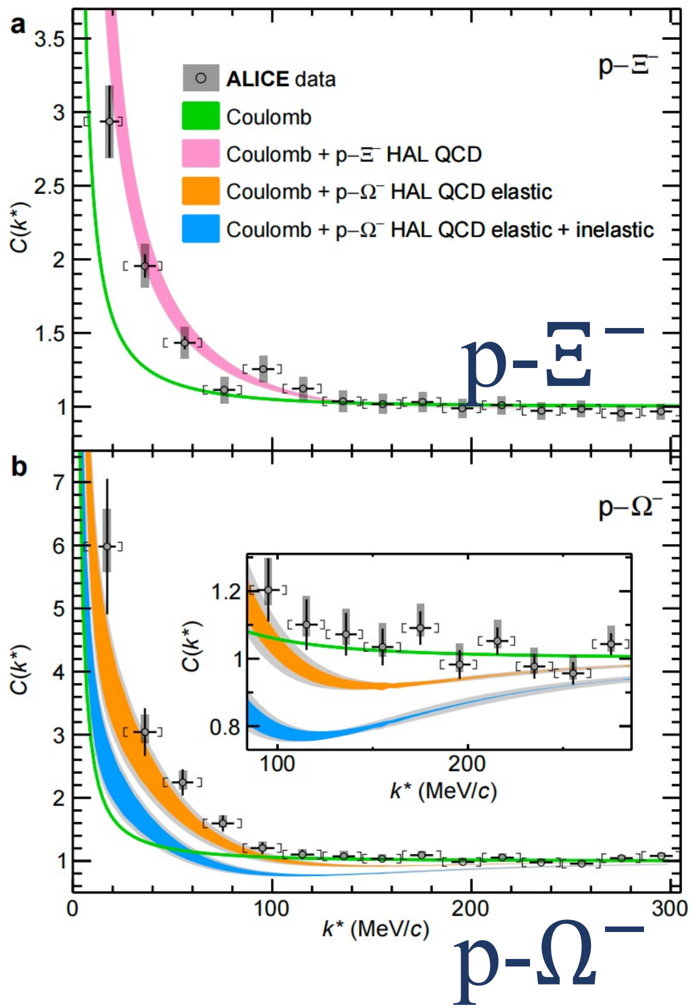




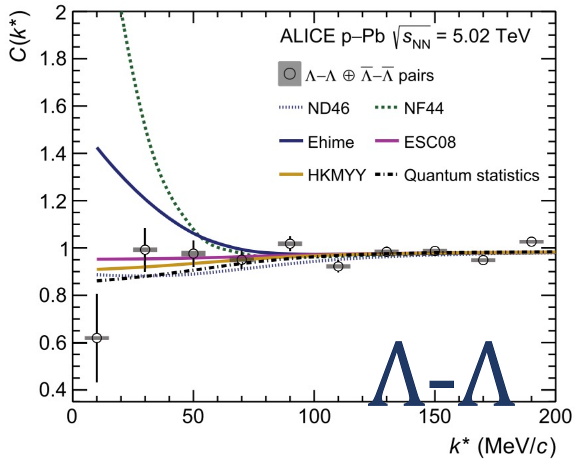
First experimental evidence of Strange Dibaryon

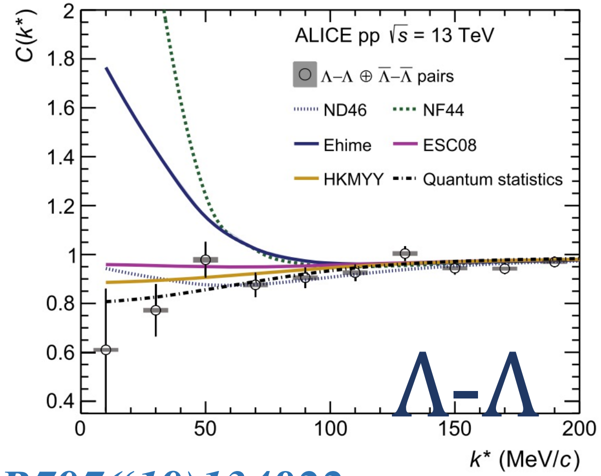
Thank you for your attention!

Backup-Motivation

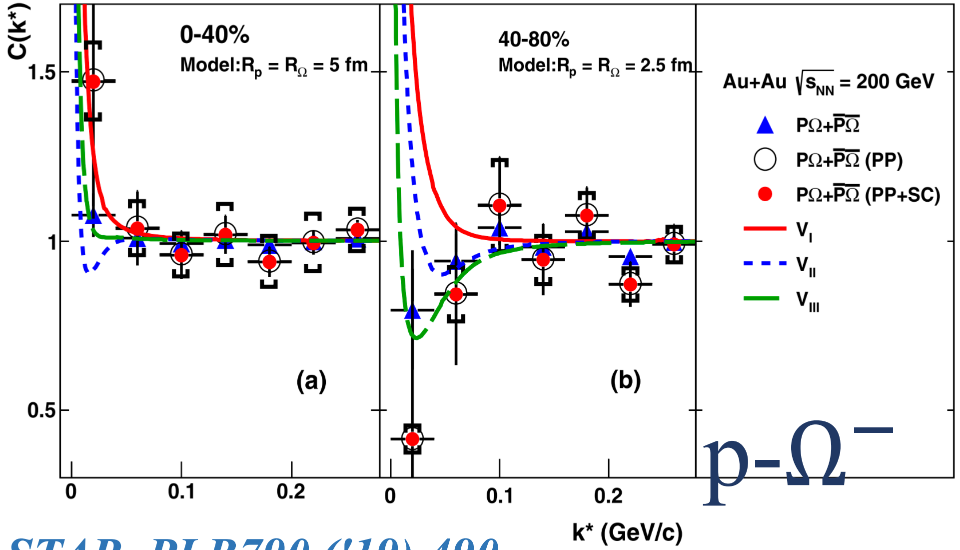


ALICE, Nature588 (‘20)232

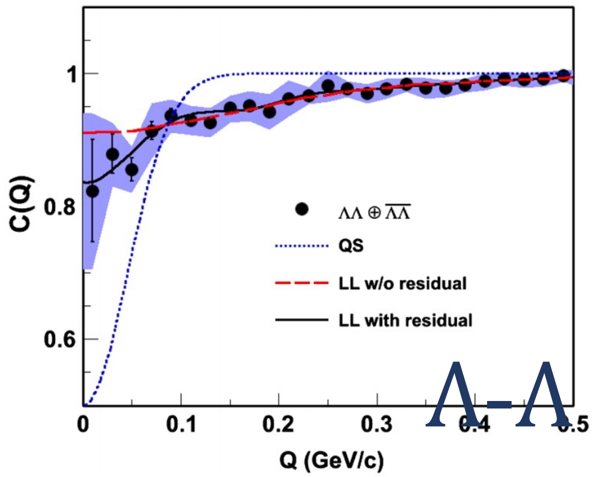




ALICE, PLB797(‘19)134822



STAR, PLB790 ('19) 490

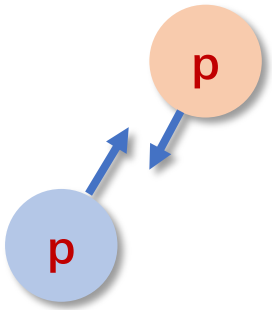


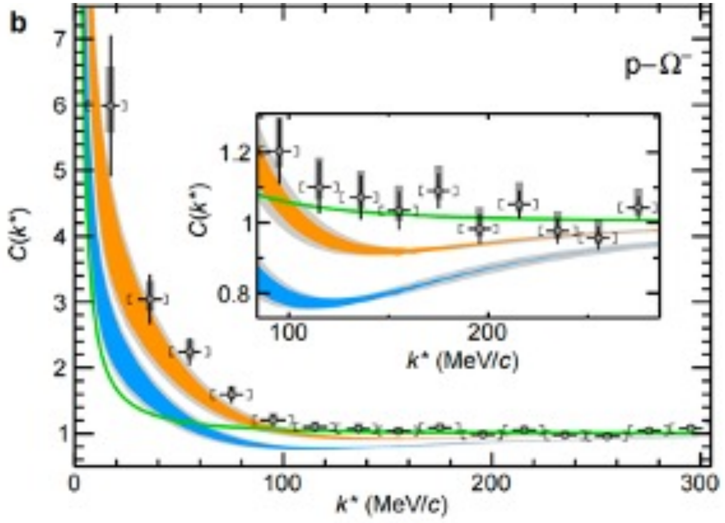
STAR, PRL114(‘15)022301

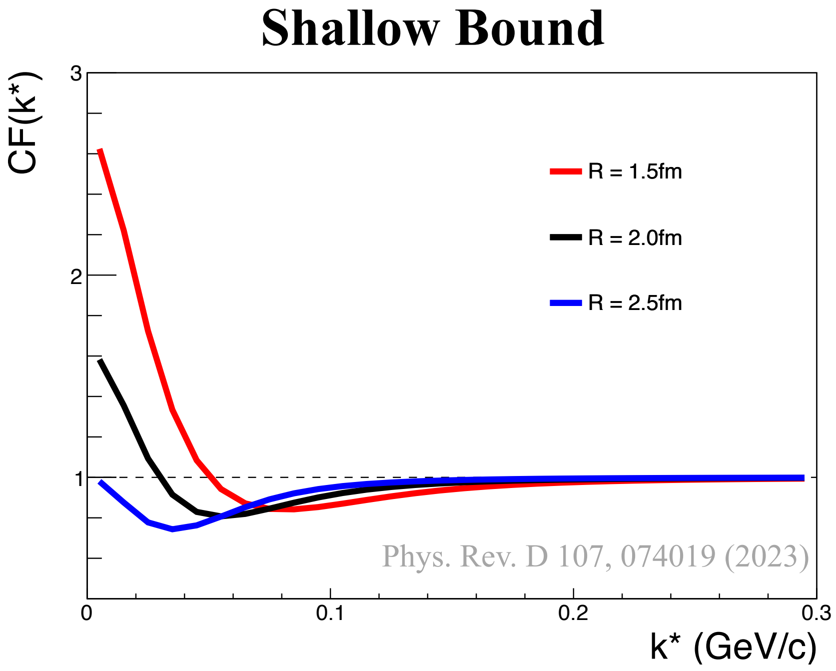
More Experiment measurements are needed !

Backup- p-Ω^- Bound?

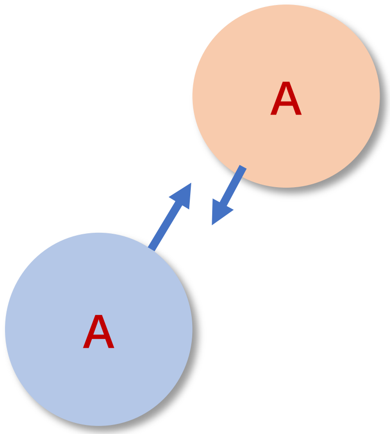
- Small source

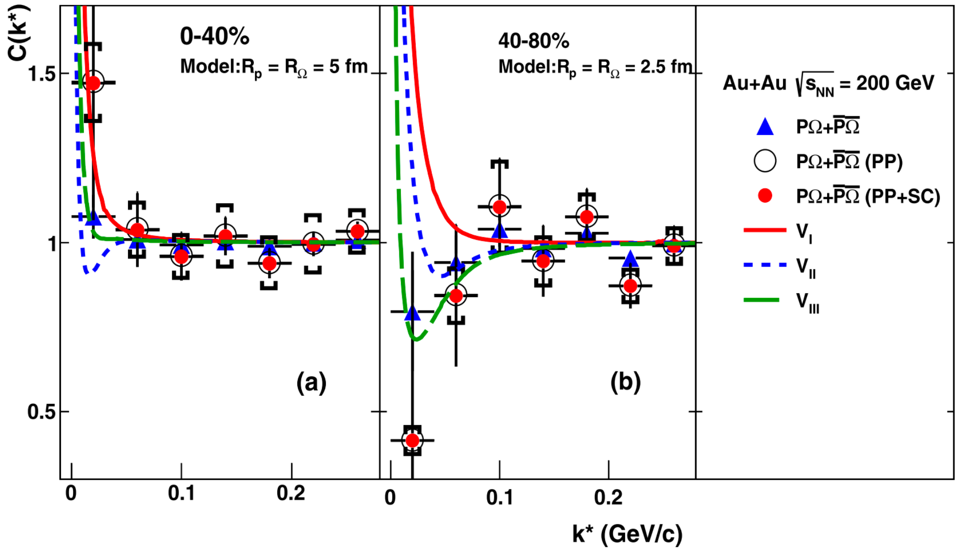






- Large source





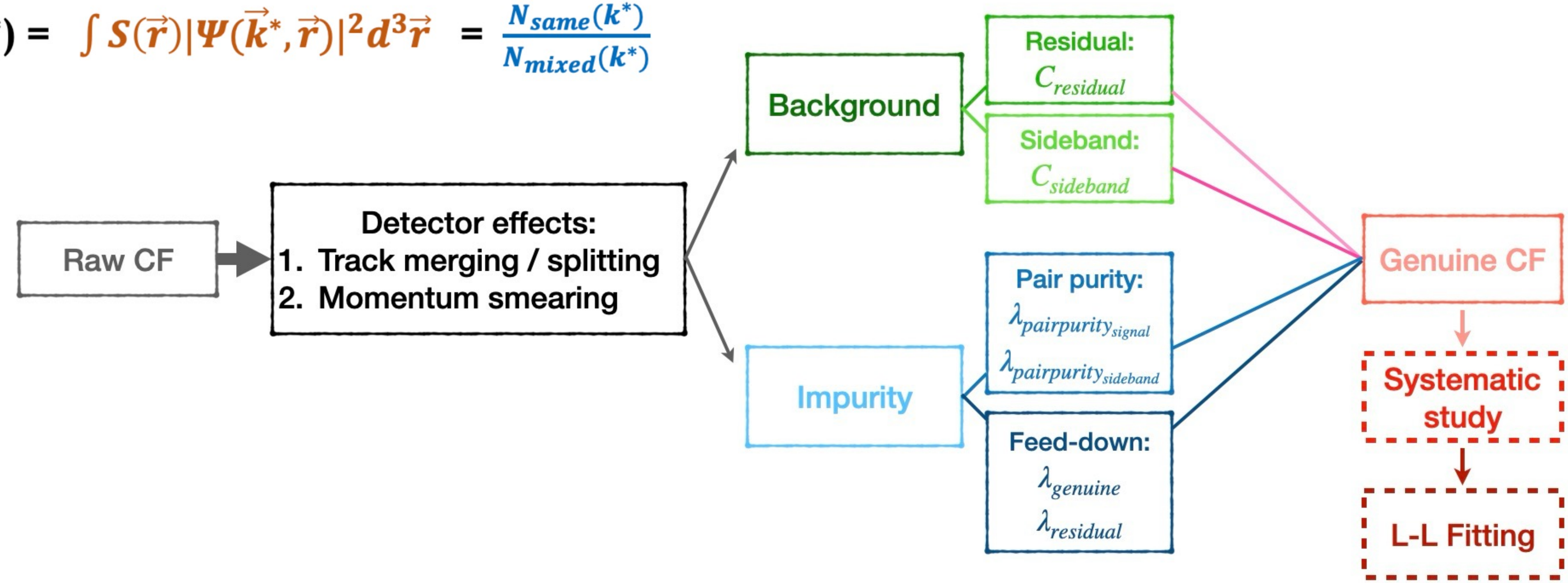
Source size or centrality dep. of CF

→ 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

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

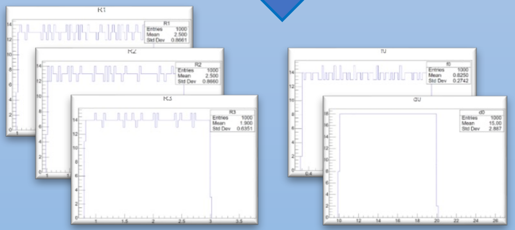
$R_2 = [R_{2min}, R_{2max}]$

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

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

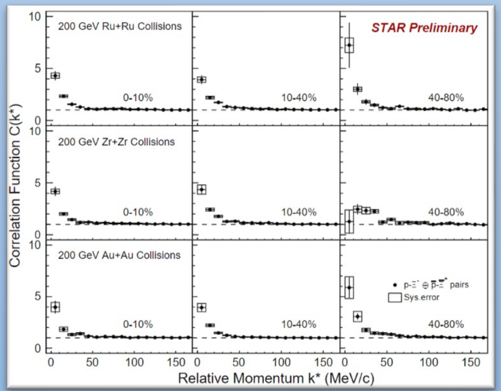
$d_0 = [d_{0min}, d_{0max}]$

\+ **Latin Hypercube Sampling**



2nd Step

Data Input



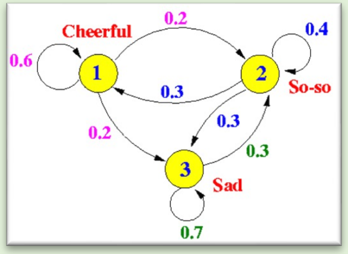
Compare with the samples and predict the parameter's value with error

Study samples

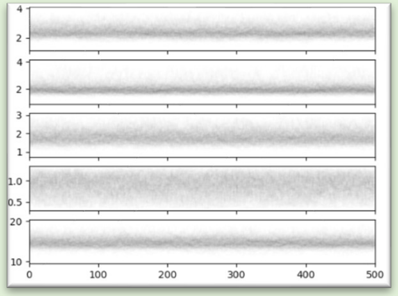
3rd Step

Technique

MC MC Markov Chain Monte Carlo



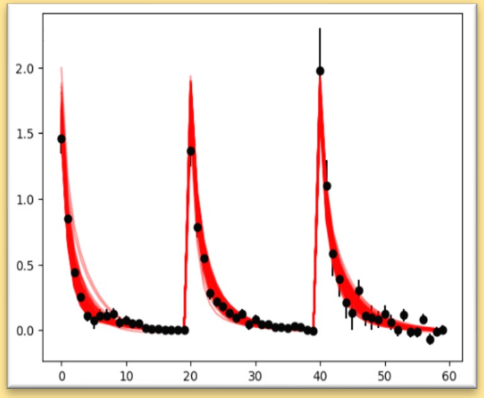
\+ Gaussian Processes Regression



\+ Resampling

N_{steps}~500
$N_{walkers}$~400
$N_{burnsteps}$~500

Results



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