Baryon Correlations and Strange Di-baryon Search at RHIC-STAR

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The 2nd International Workshop on Physics at High Baryon Density

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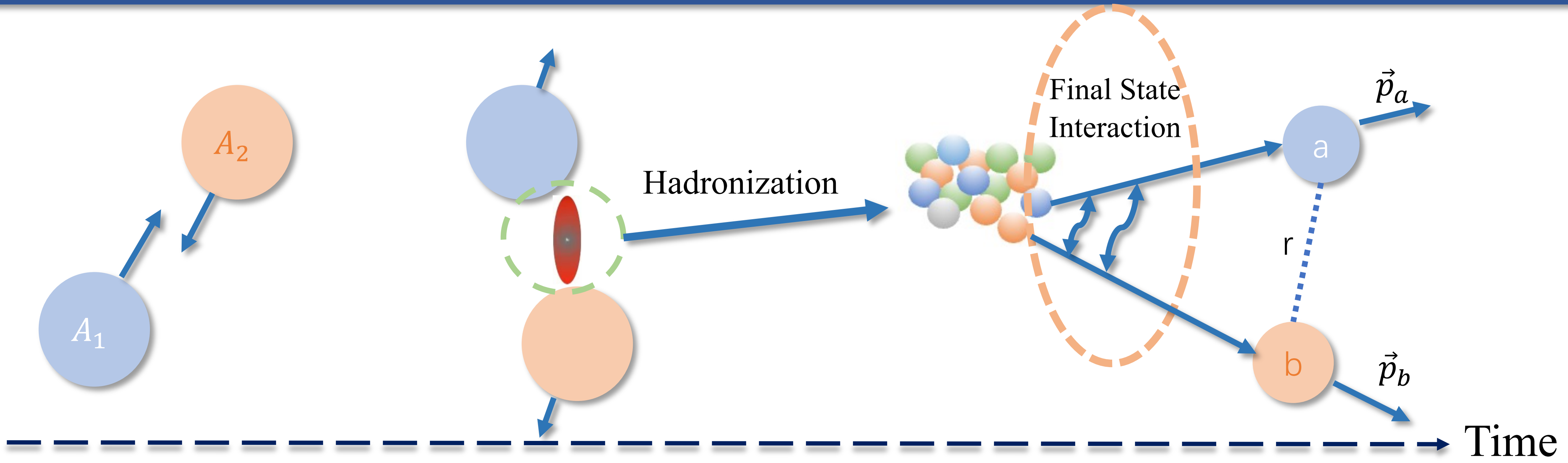
Outline

I. **Femtoscopy**
II. **Motivation**
III. **RHIC-STAR Experiment**
IV. **Results**
- p-d, d-d Correlation
- d–Λ, t-Λ, ^{3}He-Λ Correlation
- p-Λ, Λ-Λ, p-Ξ^-, p-Ω^- Correlation

V. **Summary**

Femtoscopy



- Two-particle correlation function:

Model | **Experimental**

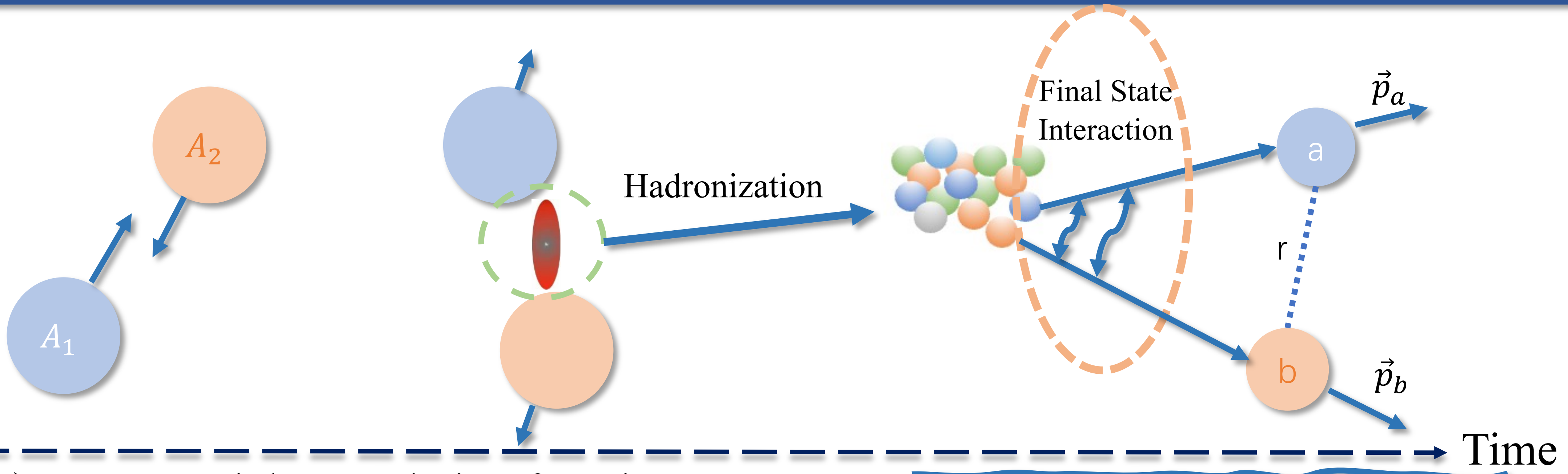
$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$S(\vec{r})$: 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



➢ Two-particle correlation function:

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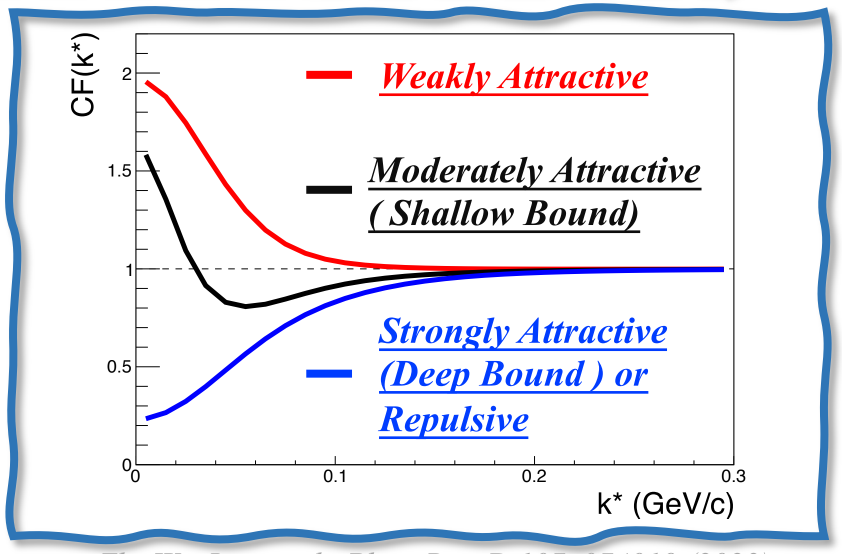


Zhi-Wei Liu, et al., Phys. Rev. D 107, 074019 (2023)

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:**
  - $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - ik^*]^{-1}$ (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

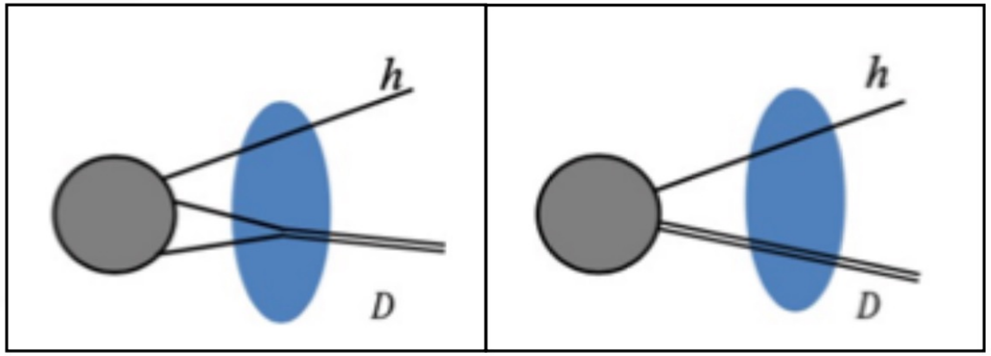
Bayesian method: *https://github.com/chunshen1987/bayesian_analysis*

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

Motivation

- Formation mechanism of light nuclei are under debate
  - ➢ Coalescence : final-state interaction
  - ➢ Thermal : produced directly from fireball

p-d, d-d pair



Coalescence   Direct production

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)

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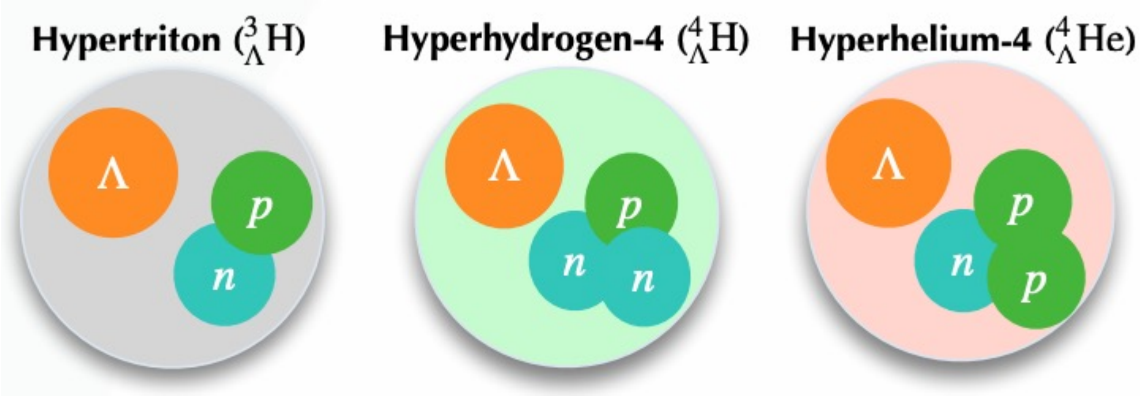
- Light nuclei - Λ correlation : insights to hyper-nuclei structure and properties

d-Λ, t-Λ, ^{3}He-Λ pair



J.Cleymans et al, Phys.Rev.C 74, 034903 (2006)
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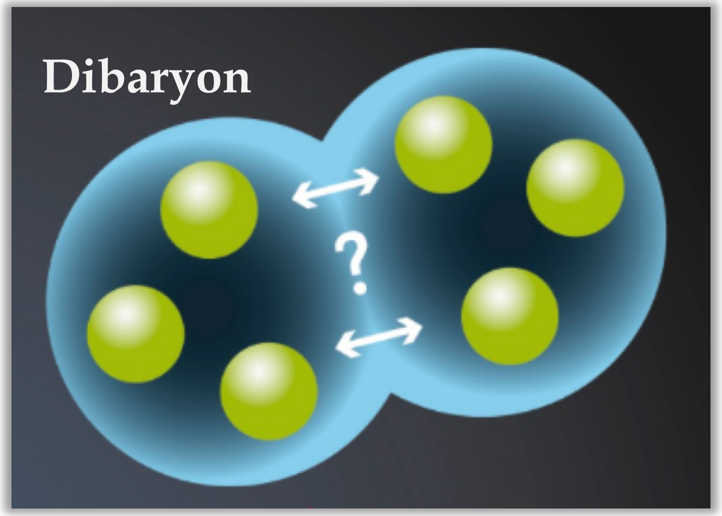
d-Λ, t-Λ, ^{3}He-Λ pair

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

(|S|=2)Dibaryon ⇔ p-Ξ^-

(|S|=2)Dibaryon ⇔ Λ-Λ

(|S|=3)Dibaryon ⇔ p-Ω^-

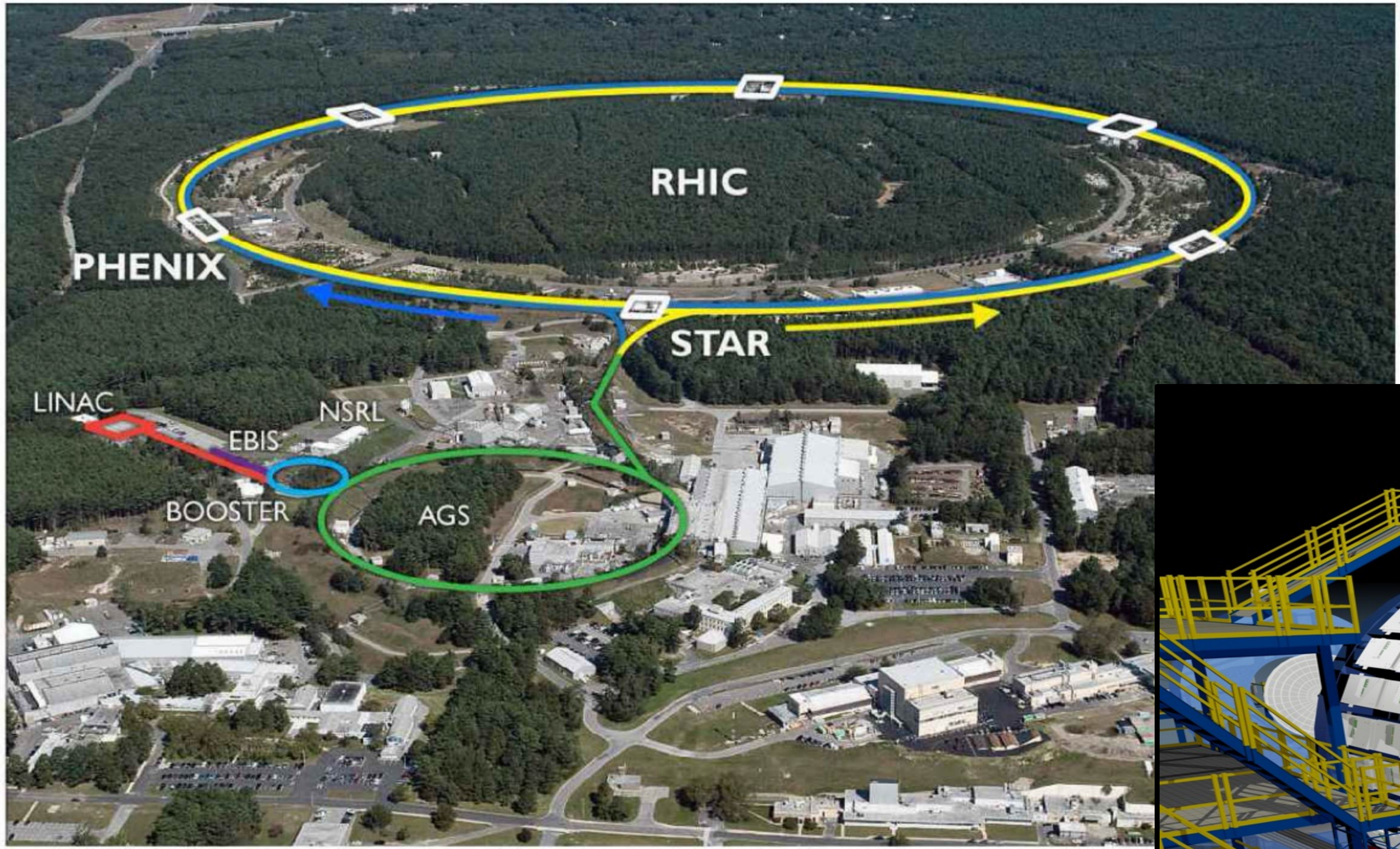


Particle	Mass (MeV)	Quark com-position	Decay mode
f_0	980	$q\bar{q}s\bar{s}$	$\pi\pi$
a_0	980	$q\bar{q}s\bar{s}$	$\pi\eta$
K(1460)	1460	$q\bar{q}q\bar{s}$	K$\pi\pi$
Λ(1405)	1405	qqqs$\bar{q}$	$\pi\Sigma$
Θ^+(1530)	1530	qqqq$\bar{s}$	KN
H	2245	uuddss	ΛΛ
NΩ	2573	qqqsss	ΛΞ
ΞΞ	2627	qqssss	ΛΞ
ΩΩ	3228	ssssss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

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

More experimental measurements are needed !

RHIC-STAR Experiment



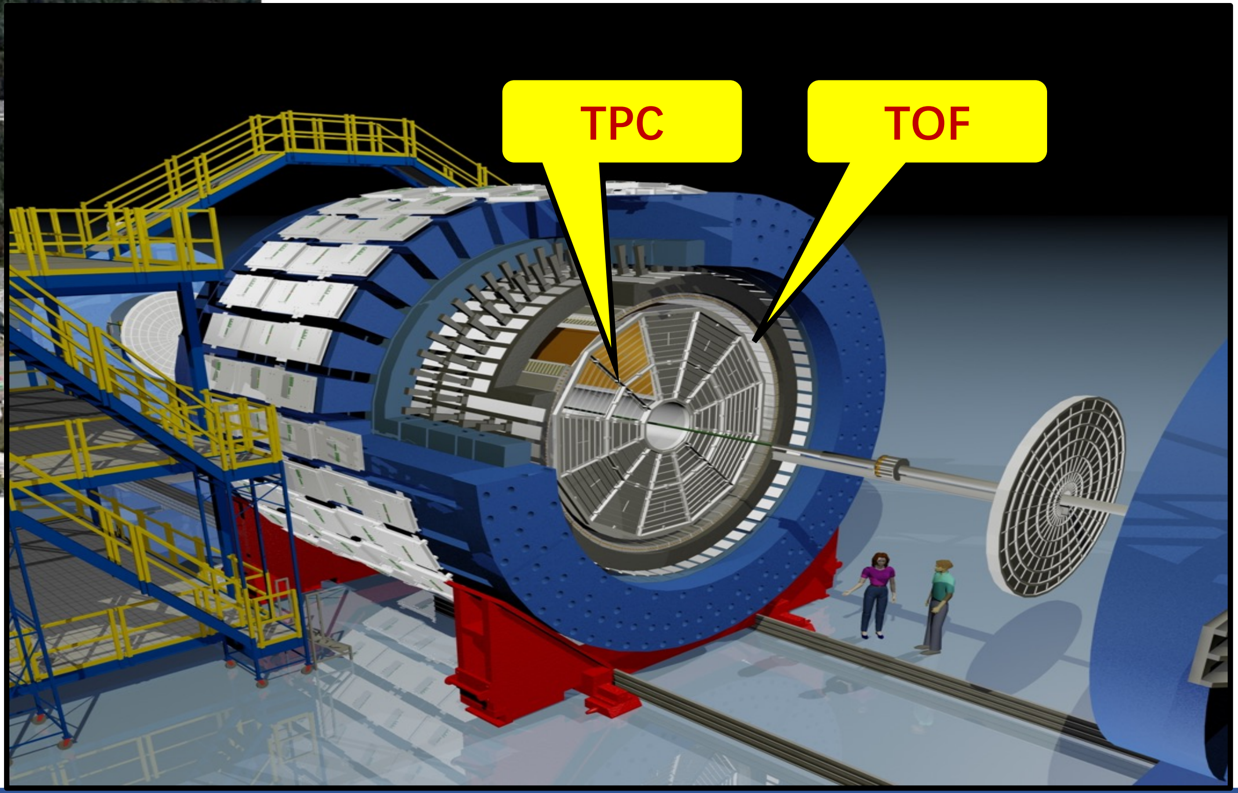
Relativistic Heavy Ion Collider (RHIC)

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)

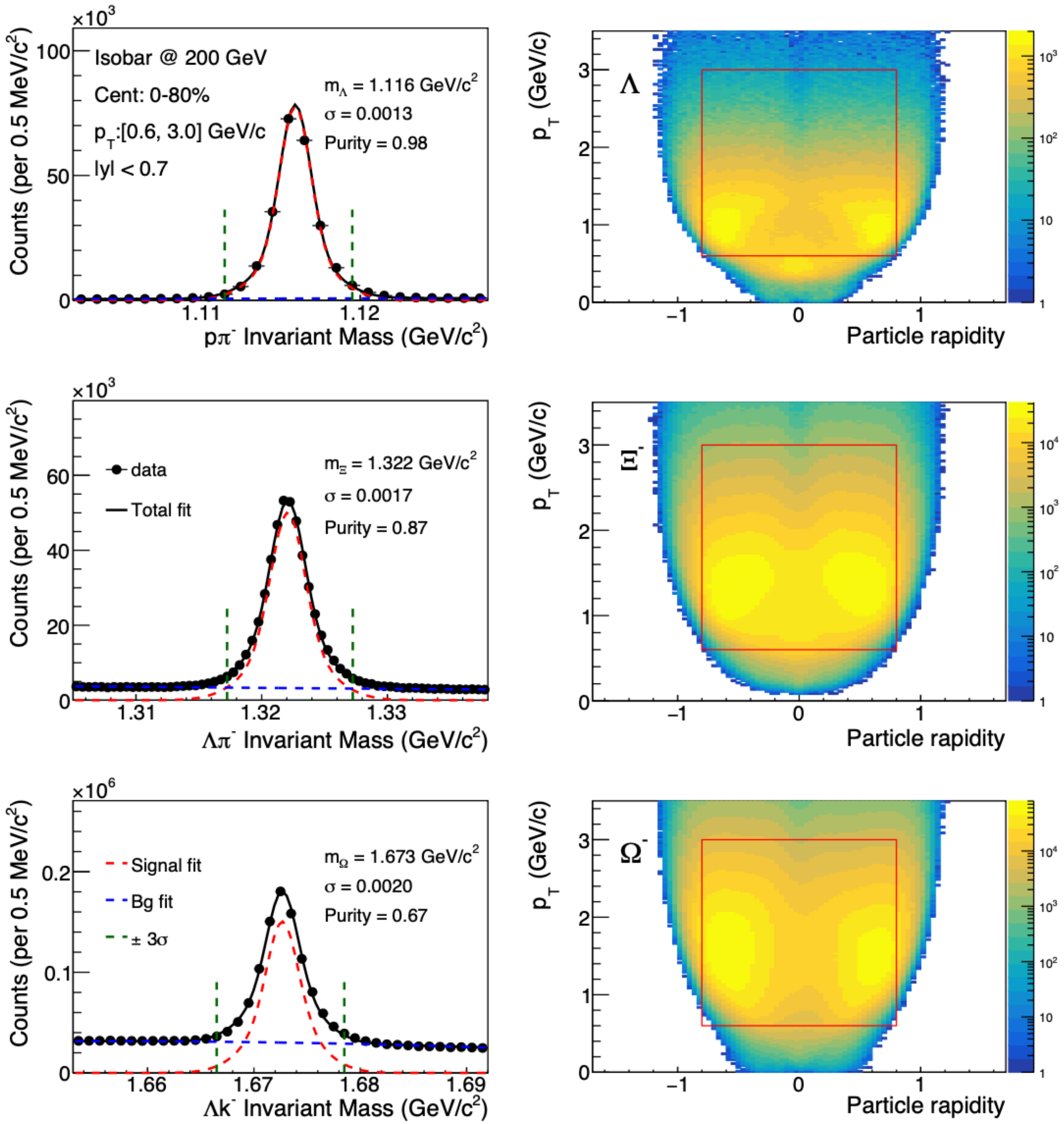
~ 2 billion minimum-bias events

➢ Hyperon reconstruction via Helix-swimming and KFParticle method

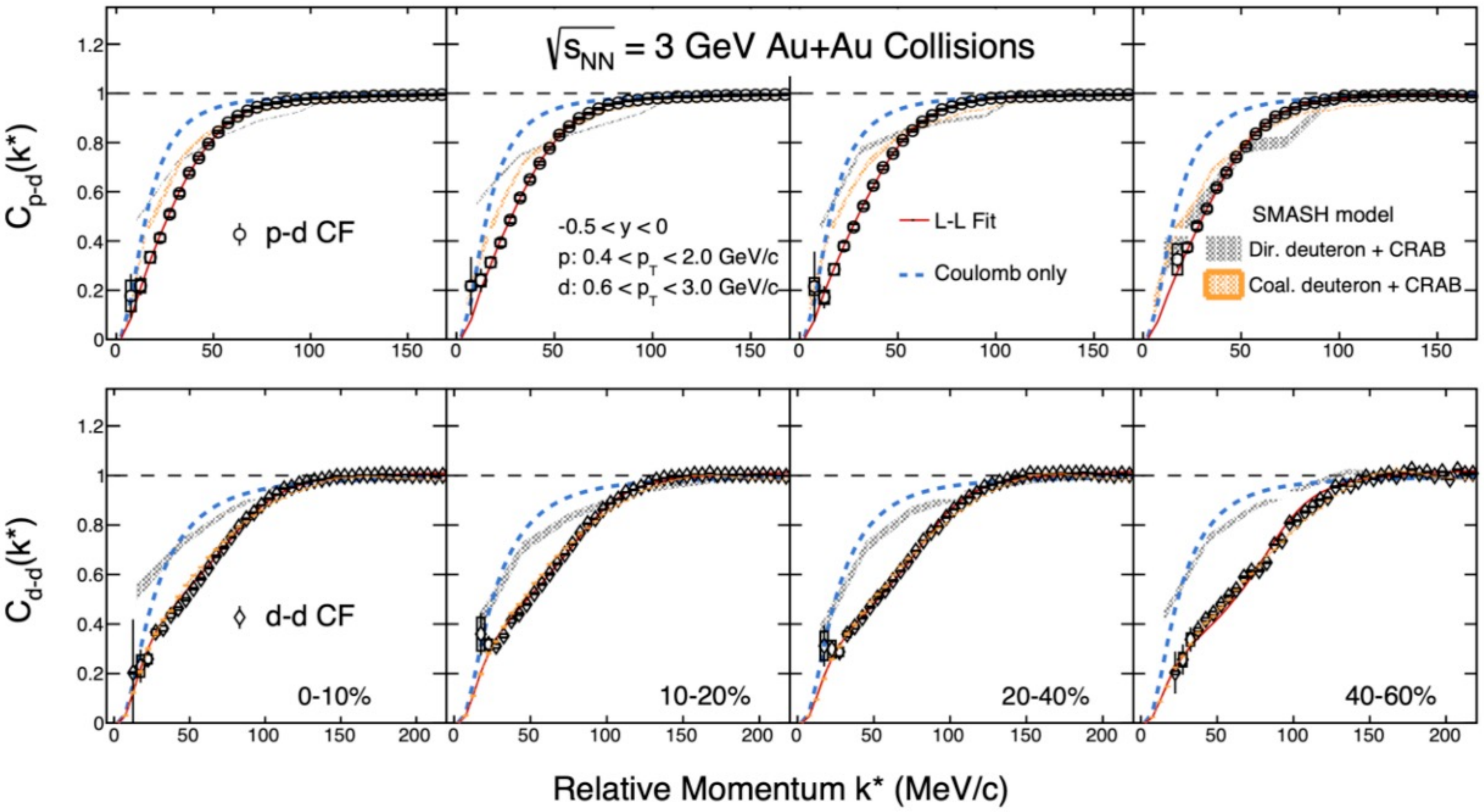
$\Lambda \rightarrow p + \pi^-$, BR = 63.9%

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

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



p-d, d-d Correlation Function



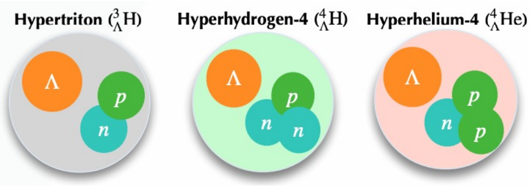
STAR: Phys. Lett. B (2025) 139412
SMASH: J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905
Coalescence: W.Zhao et al. Phys. Rev. C.98 (2018) 5,054905

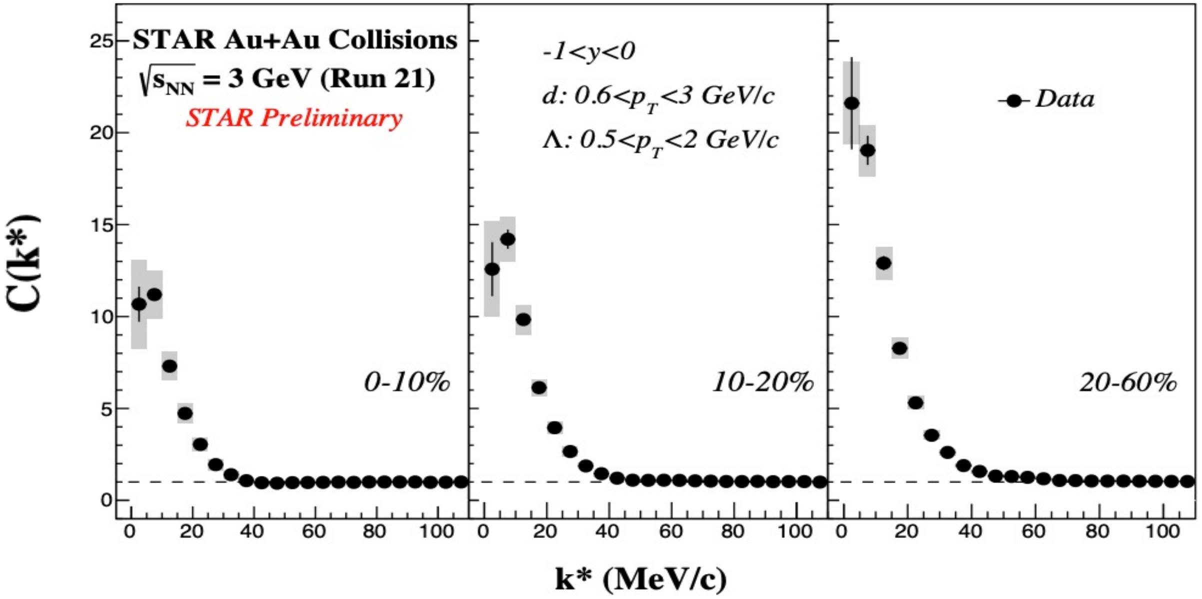
I. First measurements of p-d/d-d correlation functions in HIC
   - CFs show depletion in low k* -> mainly due to the Coulomb repulsive interaction

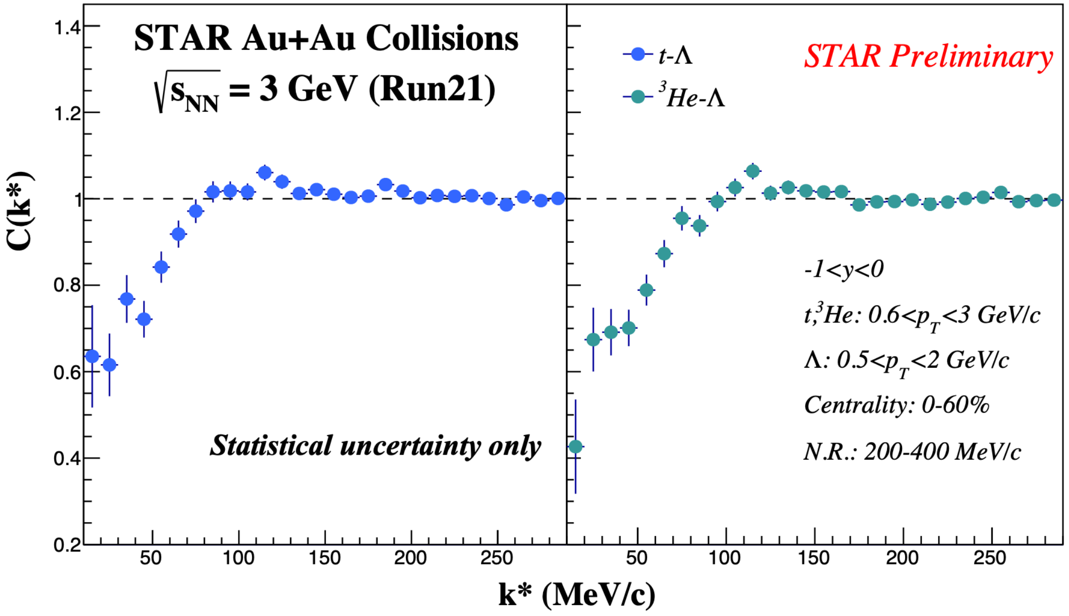
II. Simulated with SMASH model, consider two deuteron formation mechanism:
   - Direct production fail to describe data at certain k*
   - Coalescence production can describe the data well
   - Coalescence is the dominant process for deuteron formation in high-energy nuclear collisions

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

2025 New Result



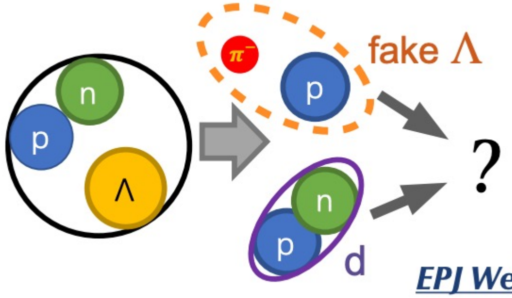




I. Precise measurements of d-Λ correlation functions in Au+Au collisions
   - CFs show enhancement at low k* -> mainly due to the strong interaction

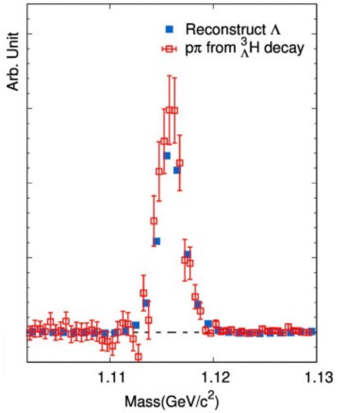
II. First t-Λ and ^{3}He-Λ correlation function measurements in the heavy-ion collisions
   - t-Λ and ^{3}He-Λ exhibit similar correlation structures and show depletion at low k^* -> mainly due to the strong interaction

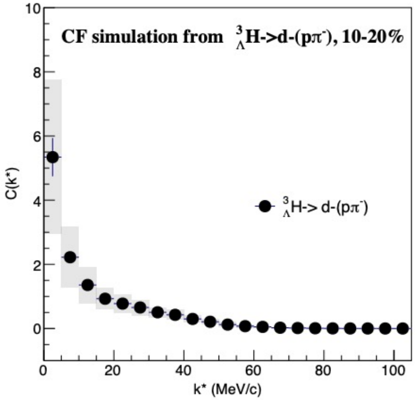
Contamination from Hyper-nuclei Decay

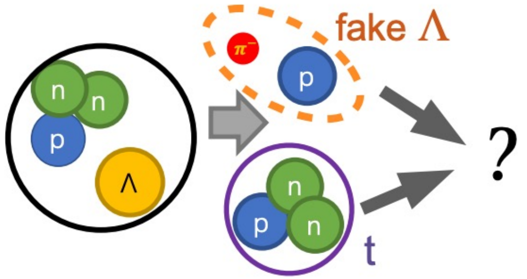


$^{3}_{\Lambda}\mathrm{H} -> \mathrm{d} + \mathrm{p} + \pi^{-}$

EPJ Web Conf. 296 (2024) 14010





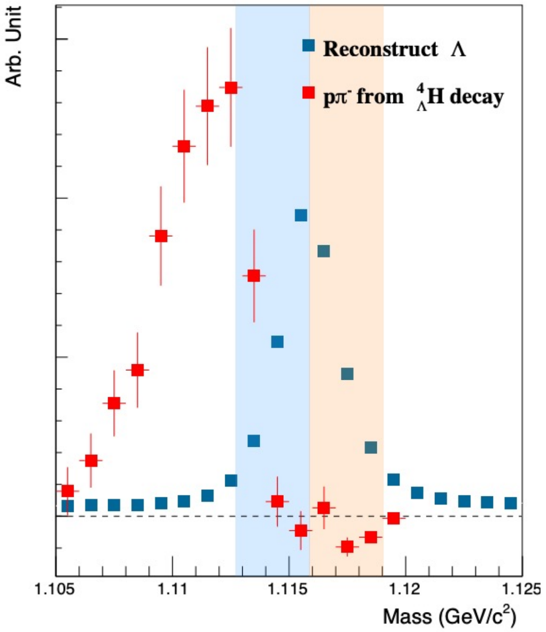


$^{4}_{\Lambda}\mathrm{H} -> \mathrm{t} + \mathrm{p} + \pi^{-}$

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

Left signal: 1.11271~1.11589 GeV/c^2

Right signal: 1.11589~1.11906 GeV/c^2



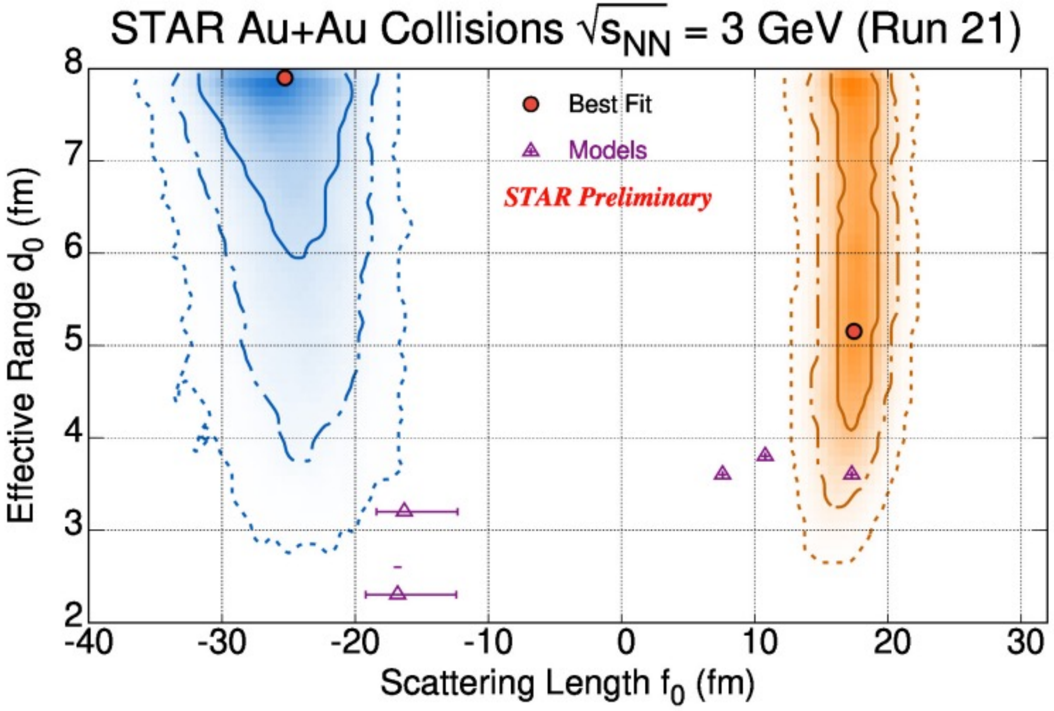
I. The $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He decayed p + π⁻ are not experimentally distinguishable with the reconstructed Λ

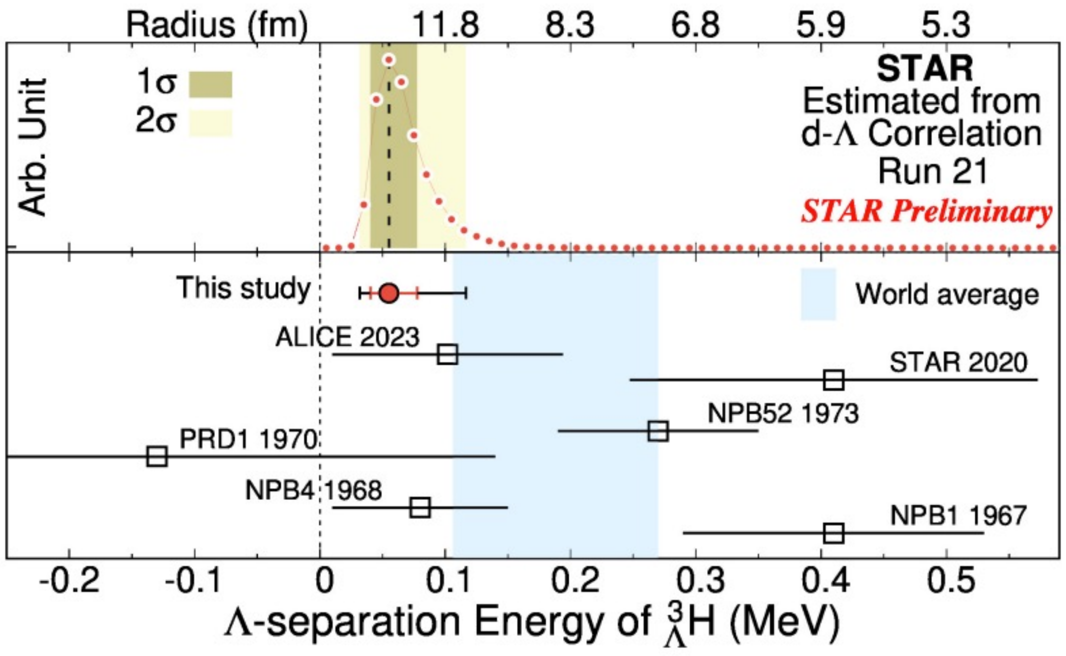
II. For d-Λ, since we cannot separate them experimentally, we need to estimate their contribution and remove it from the CF

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

d-Λ Interaction Parameters

2025 New Result





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

$f_0(D) = -25.3^{+3.3}_{-3.3}$ fm -> Related to ${}^3_\Lambda$H

$f_0(Q) = 17.5^{+1.6}_{-1.6}$ fm -> Attractive interaction

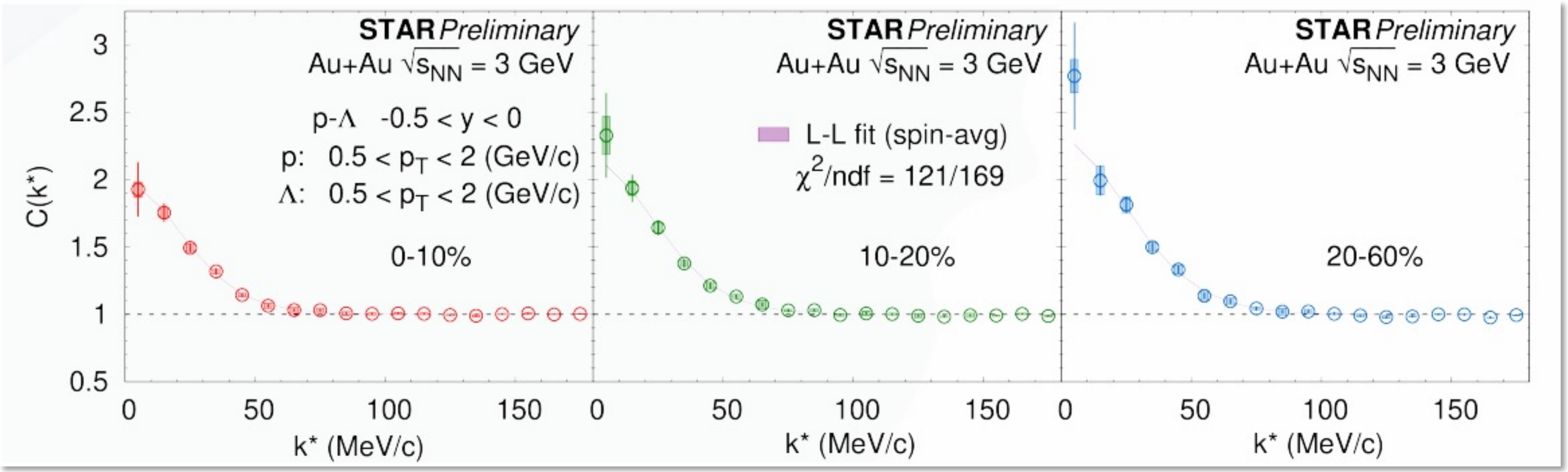
- Extract the most accurate results of binding energy and radius of ${}^3_\Lambda$H

$$BE_{{}^3_\Lambda\mathrm{H}} = \frac{1}{2\mathrm{m}_{\text{d-}\Lambda} d_0^2}\left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\right)^2$$

$$BE = 0.06^{+0.06}_{-0.03}\ (\mathrm{MeV})$$

$$r({}^3_\Lambda\mathrm{H}) = 16^{+5}_{-5}\ (\mathrm{fm})$$

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

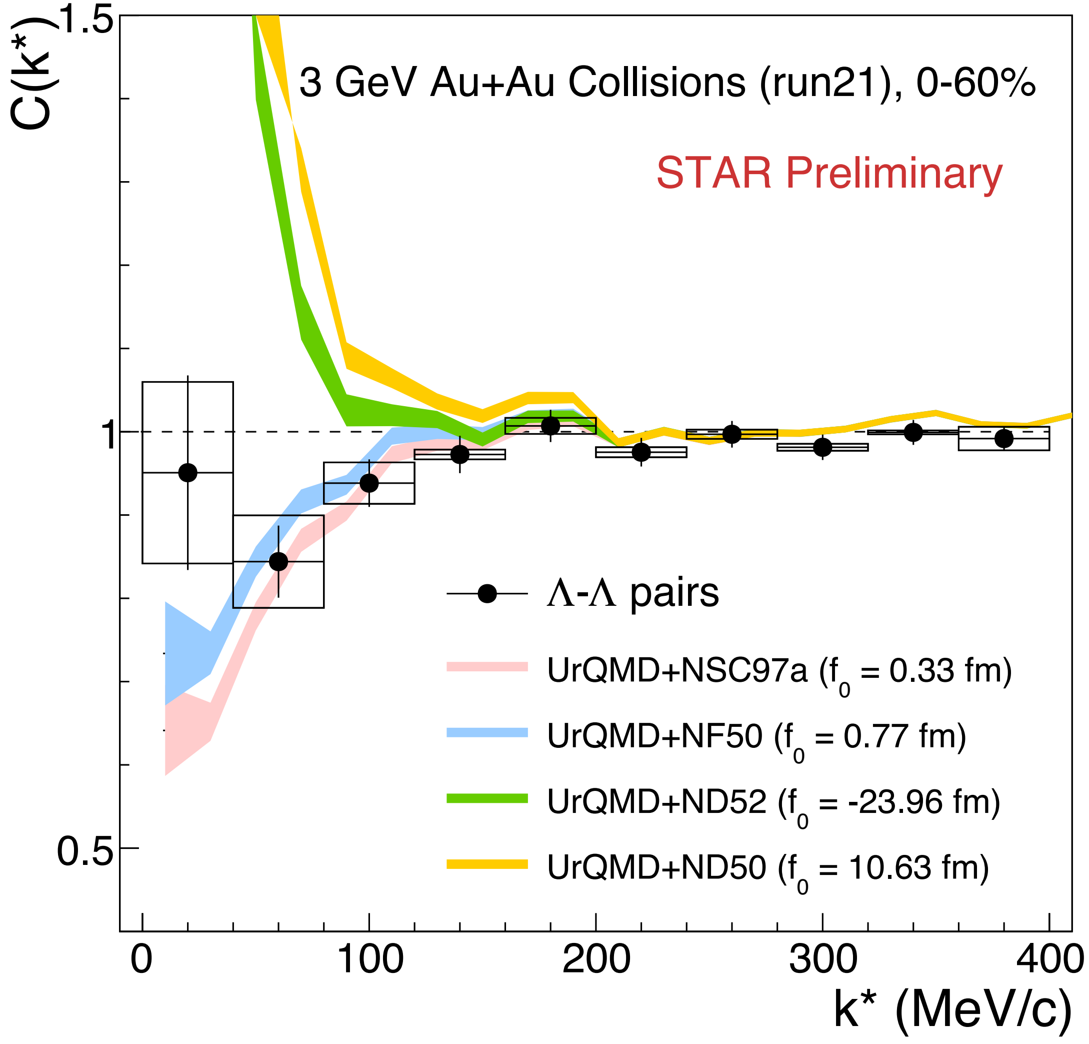
II. Simultaneously fit with L-L function for different centralities to extract R_G, f_0 and d_0

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.)

Λ-Λ Correlation Function (|S| =2)

2025 New Result



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

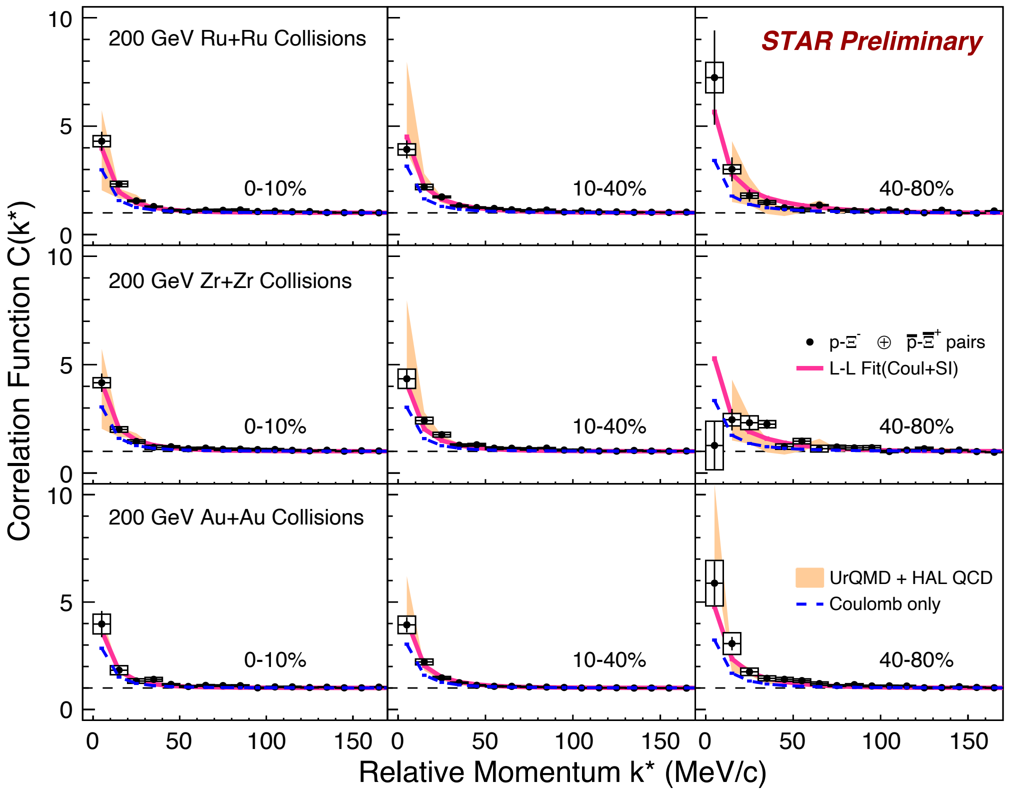
II. Need more precise data to confirm

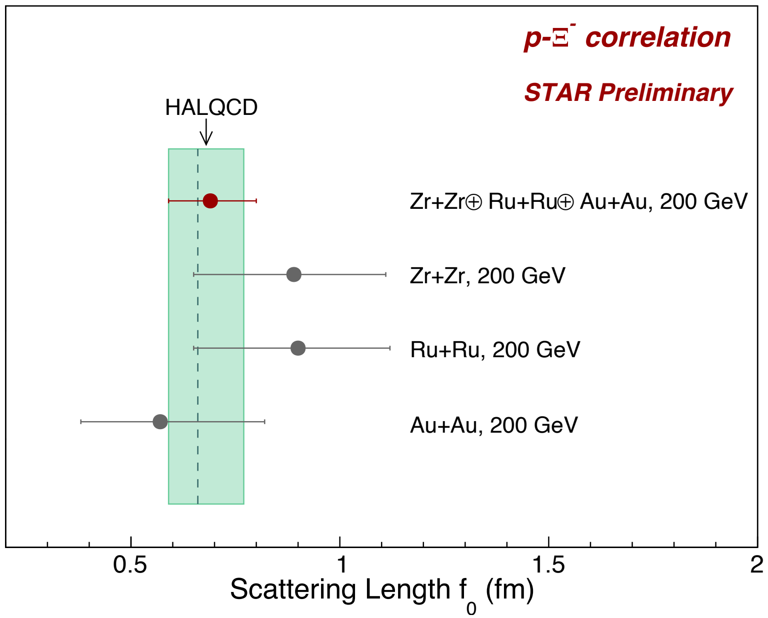
- High statistics Isobar and Au+Au collisions

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-Ξ^- Correlation Function (|S| =2)





I. Measure p-Ξ^- $\oplus$ $\bar{p}$-$\bar{\Xi}^+$ 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

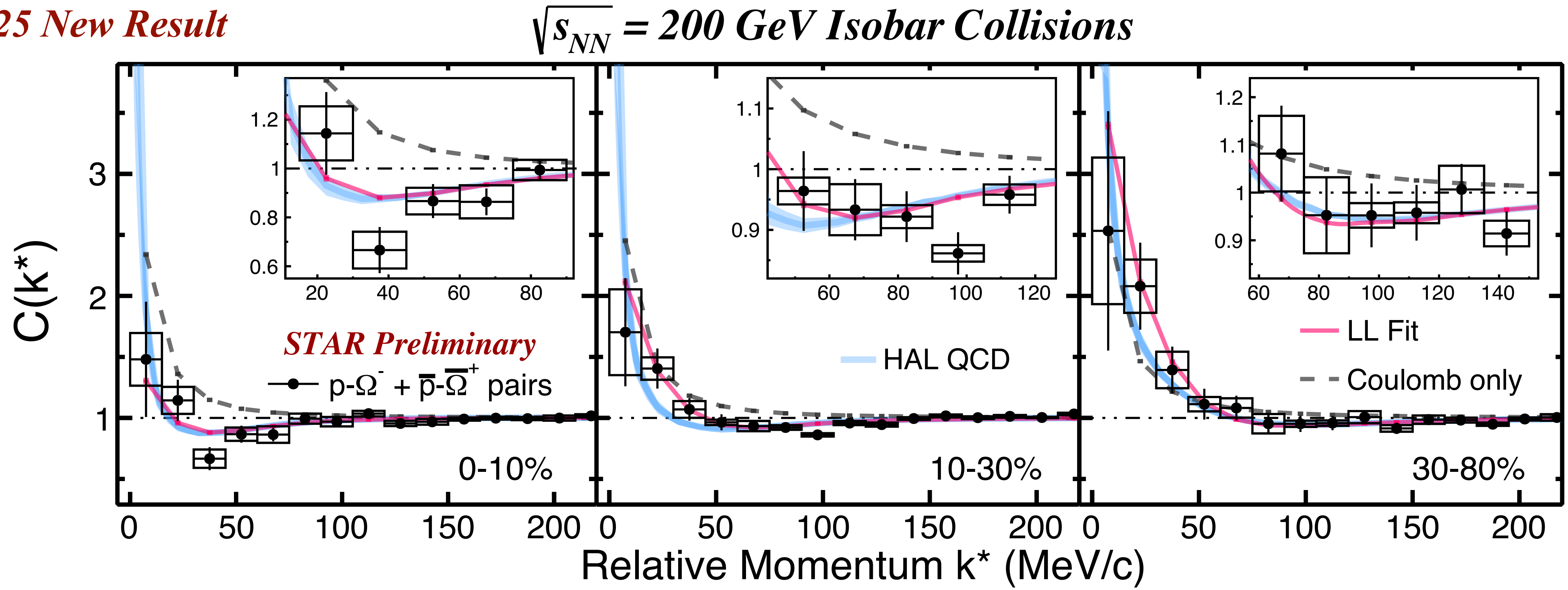
II. Simultaneously fit with L-L function for different centralities in each collision system to extract R_G, f_0 and d_0 by Bayesian method

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)

2025 New Result



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

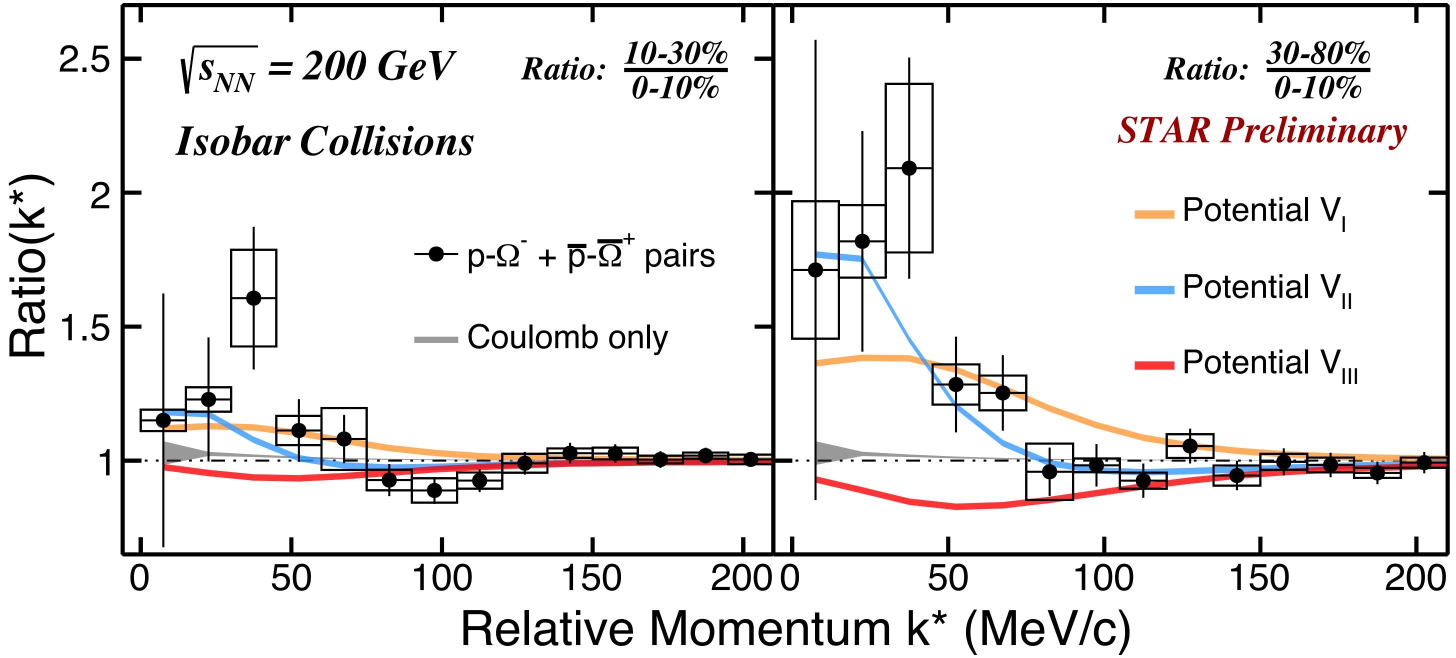
II. Simultaneously fit with L-L function for 3 centralities to extract R_G, f_0 and d_0 by Bayesian method

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)

2025 New Result



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

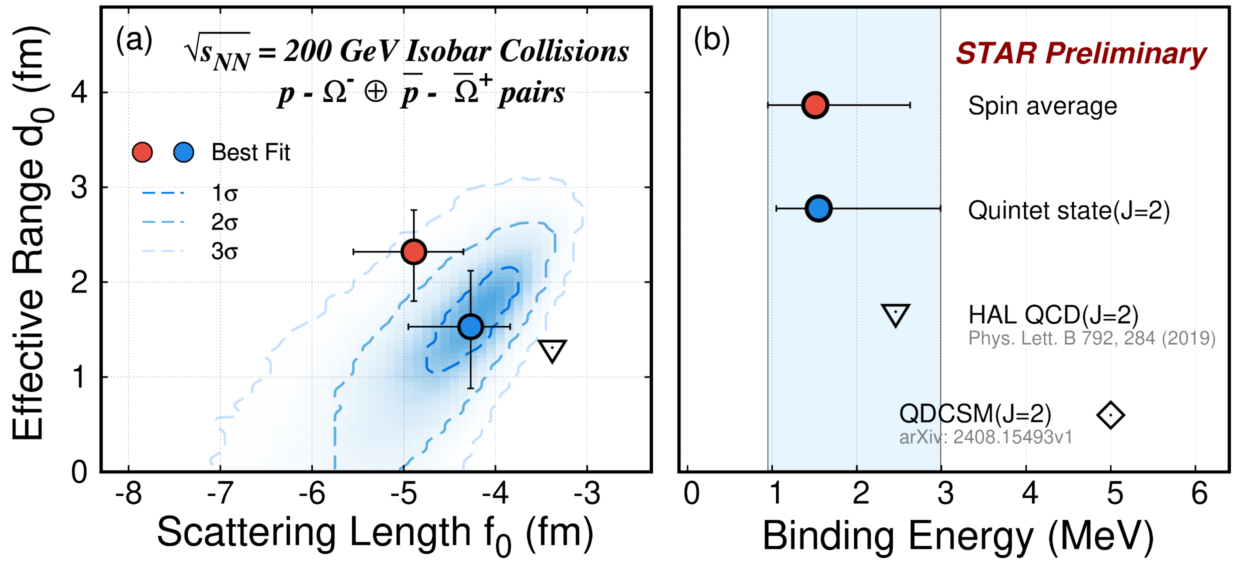
- Due to the presence of shallow bound state

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)

2025 New Result



	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:

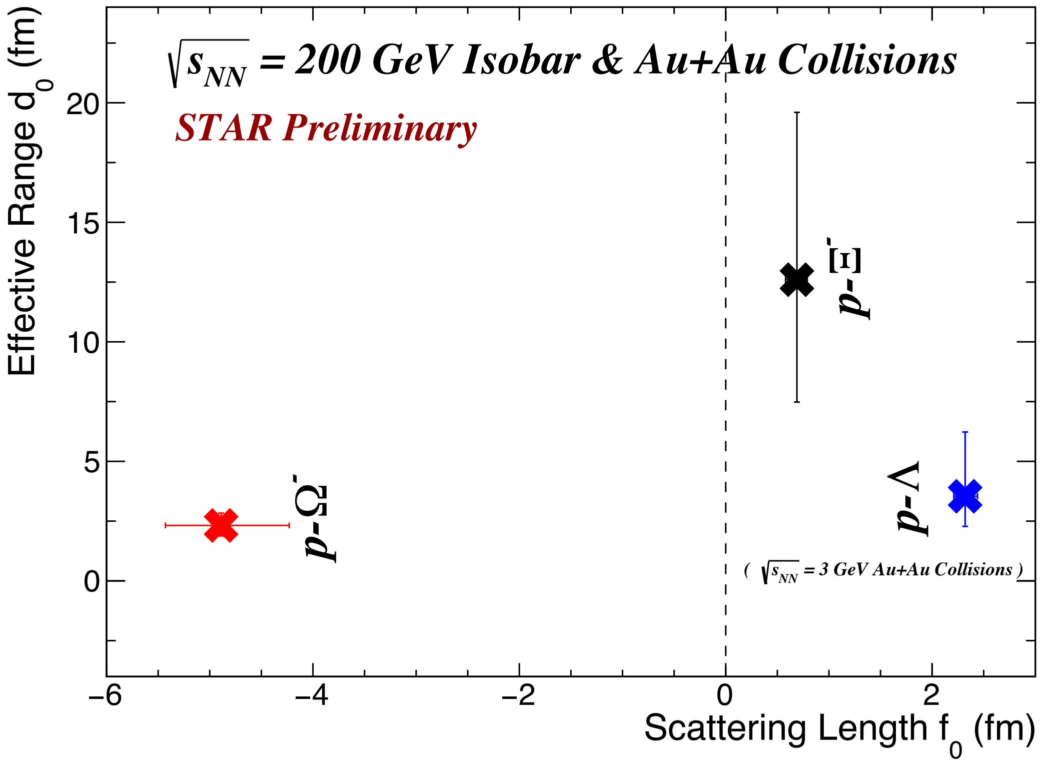
Reduced mass: $m_{p\Omega} = \frac{m_p m_\Omega}{m_p + m_\Omega}$

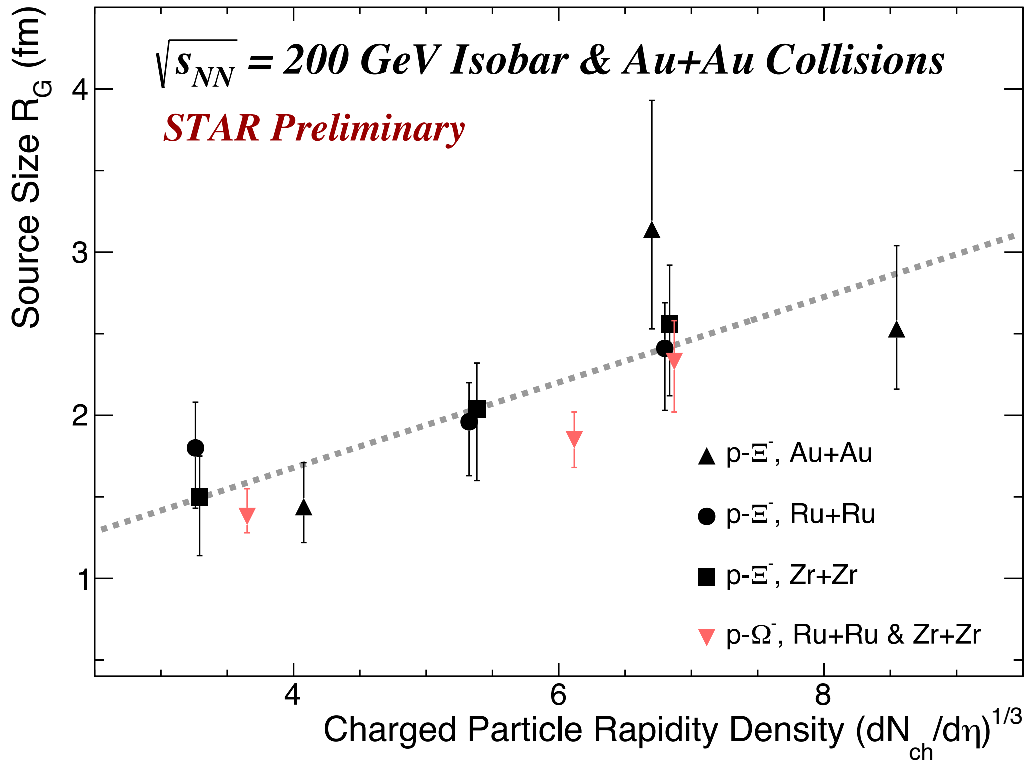
$$BE_{p\Omega} = \frac{1}{2m_{p\Omega}d_0^2}\left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\,\right)^2$$

- Calculated BE are consistent with HAL QCD prediction

Strong Interaction Parameters

2025 New Result





- 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 distribution (Centrality denpendence $R_G^{central}$ > $R_G^{peripheral}$)

Summary

- Femtoscopy measurements from HIC provides a unique tool to explore strong interaction and search the possible Strange Dibaryon

I. p-d, d-d Correlation

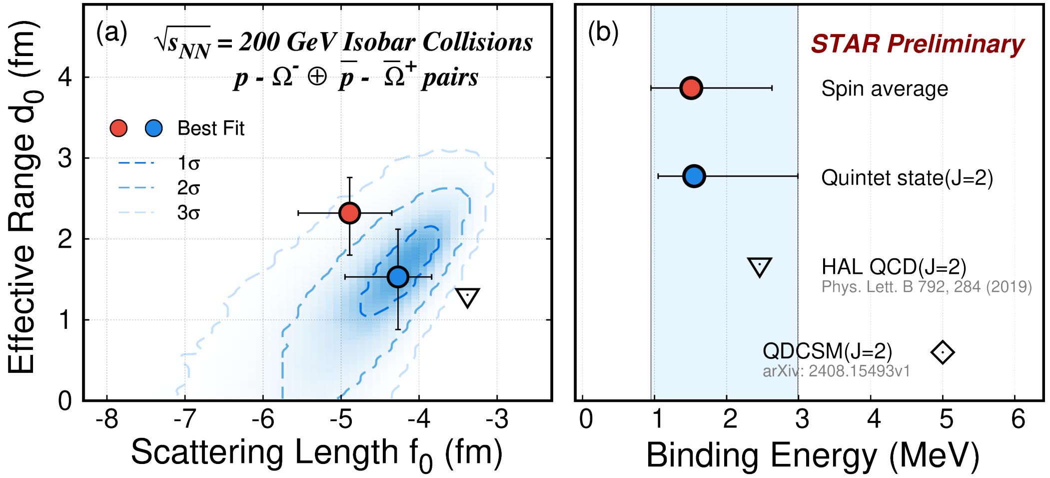
- Coalescence is the dominant process for deuteron formation in the high-energy collisions

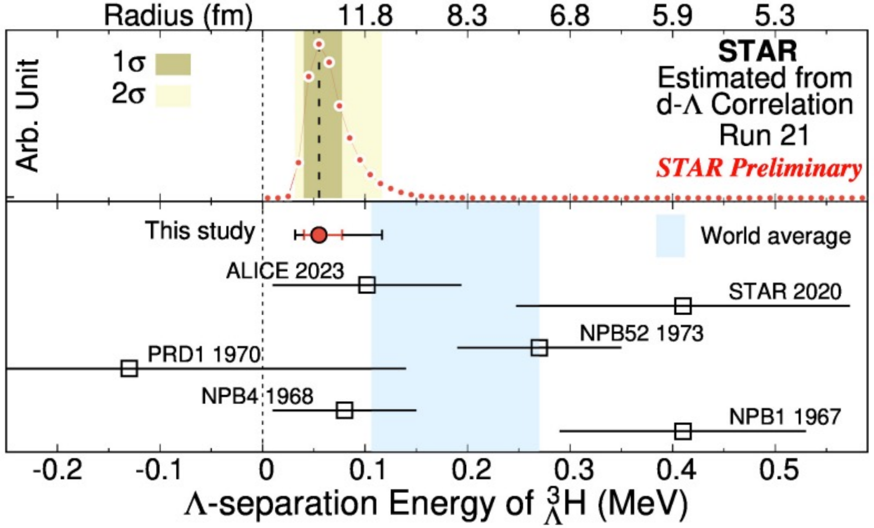
II. d−Λ, t-Λ, ^{3}He-Λ Correlation

- Most accurate results of binding energy and radius of $^{3}_{\Lambda}$H
- Provide a new way to explore hypernuclei properties

III. p-Λ, p-Ξ^{-}, p-Ω^{-} Correlation

- Extracted positive f_0 in p-Λ and p-Ξ^{-} pair hints weakly attractive strong interaction
- 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

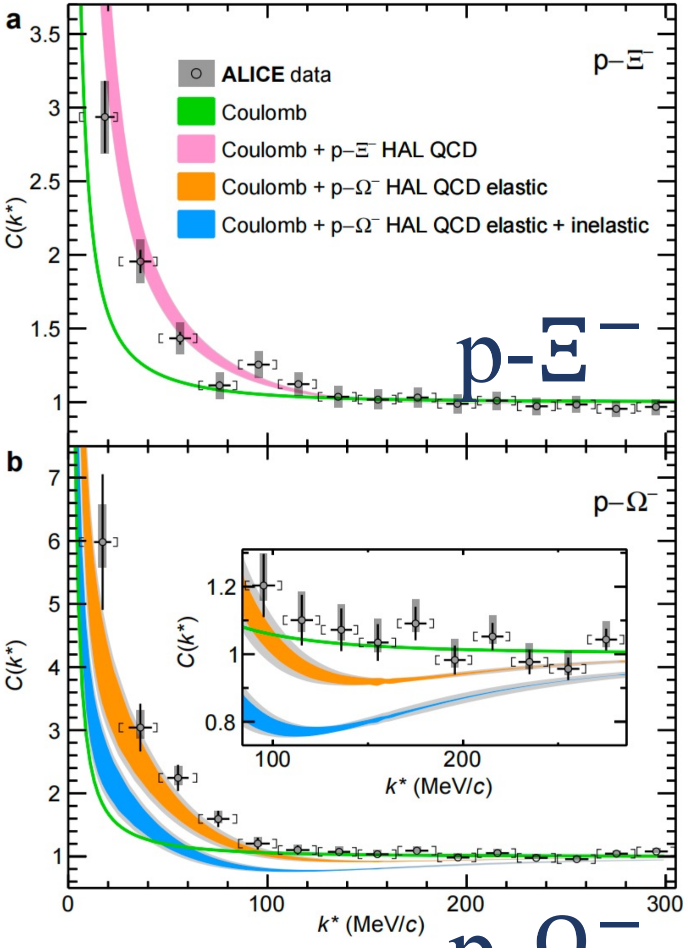




First experiment evidence of Strange-Dibaryon in p-Ω^{-} channel!

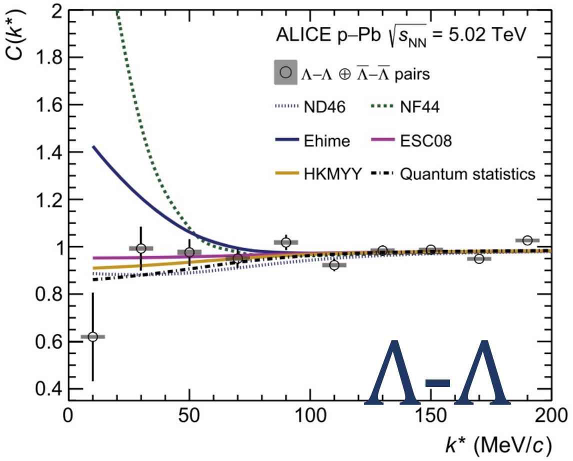
Thank you for your attention!

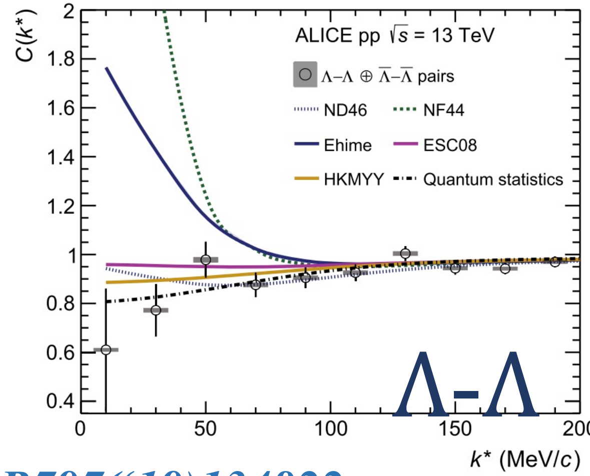
Backup-Motivation



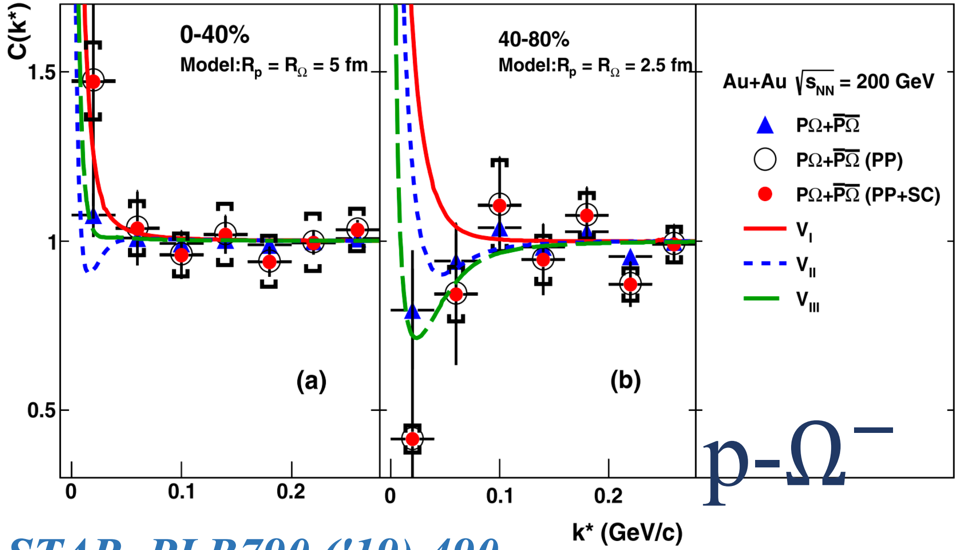
p-Ω⁻

ALICE, Nature588 (‘20)232

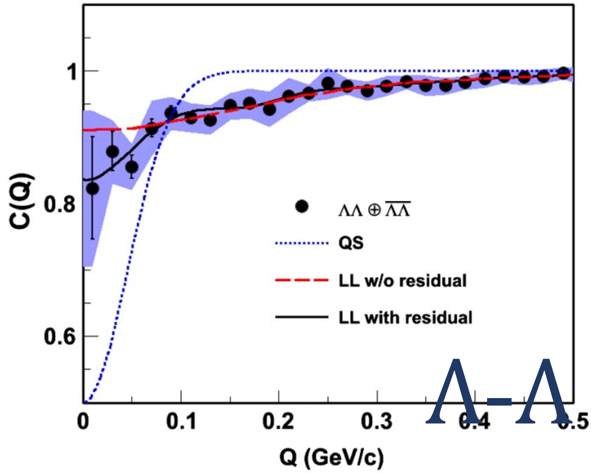




ALICE, PLB797(‘19)134822



STAR, PLB790 ('19) 490

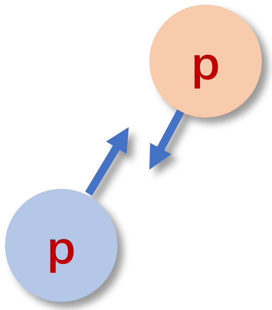


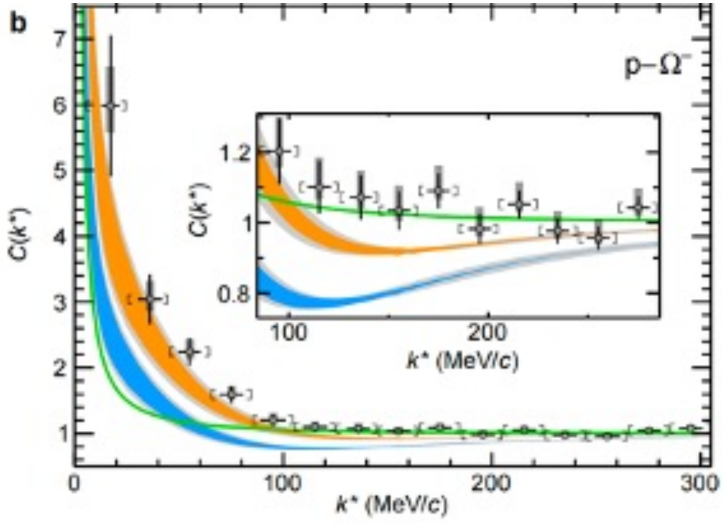
STAR, PRL114(‘15)022301

More Experiment measurements are needed !

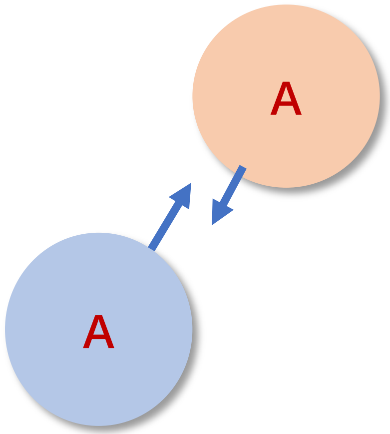
Backup- p-Ω^- Bound?

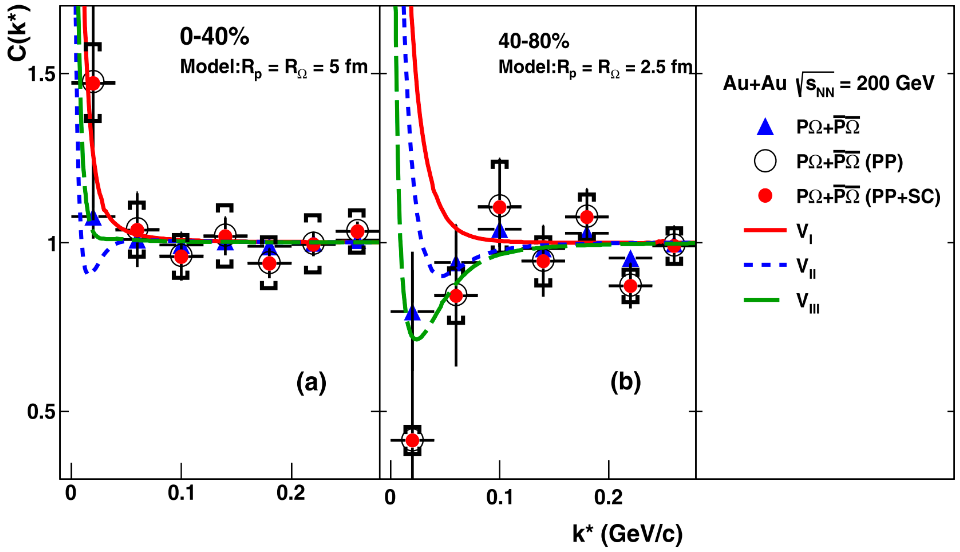
- Small source



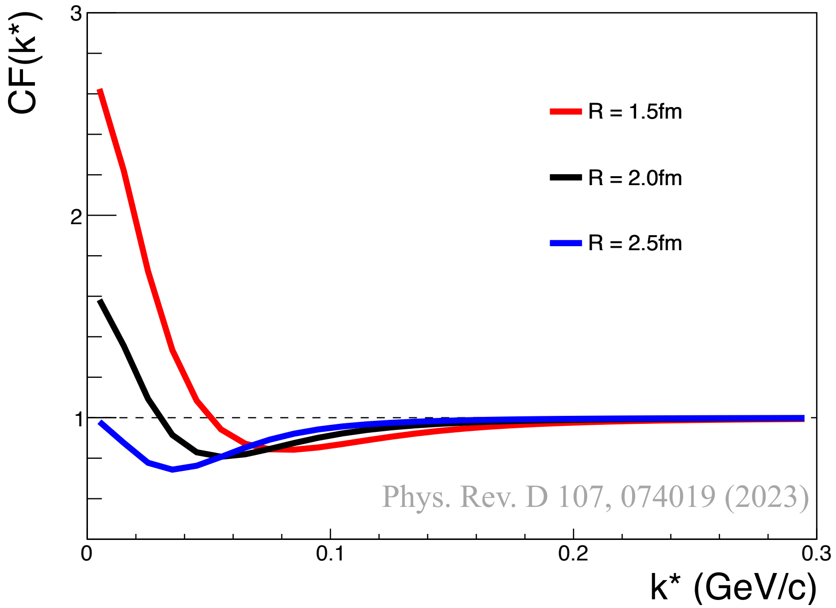


- Large source





Shallow Bound



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

Backup-Bayesian Method

1st Step

Sample Input

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

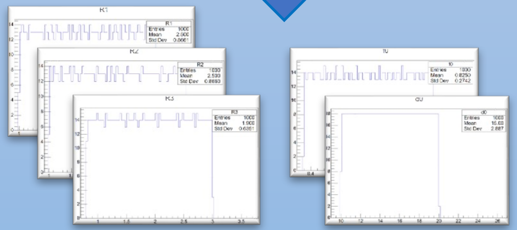
$R_2 = [R_{2min}, R_{2max}]$

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

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

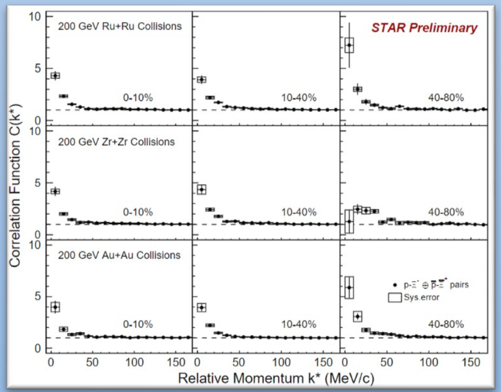
$d_0 = [\, d_{0min}, d_{0max}]$

+ Latin Hypercube Sampling



2nd Step

Data Input



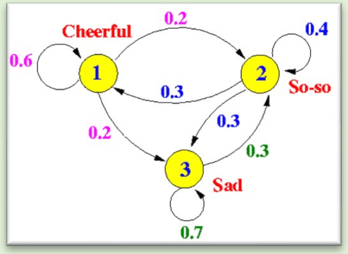
Compare with the samples and predict the parameter's value with error

Study samples

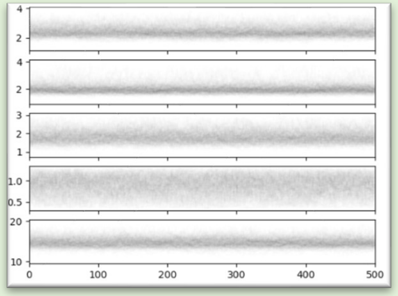
3rd Step

Technique

MC MC Markov Chain Monte Carlo



+ Gaussian Processes Regression



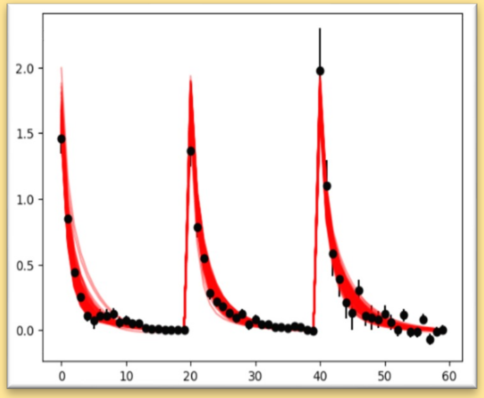
+ Resampling

N_{steps}~500

$N_{walkers}$~400

$N_{burnsteps}$~500

Results

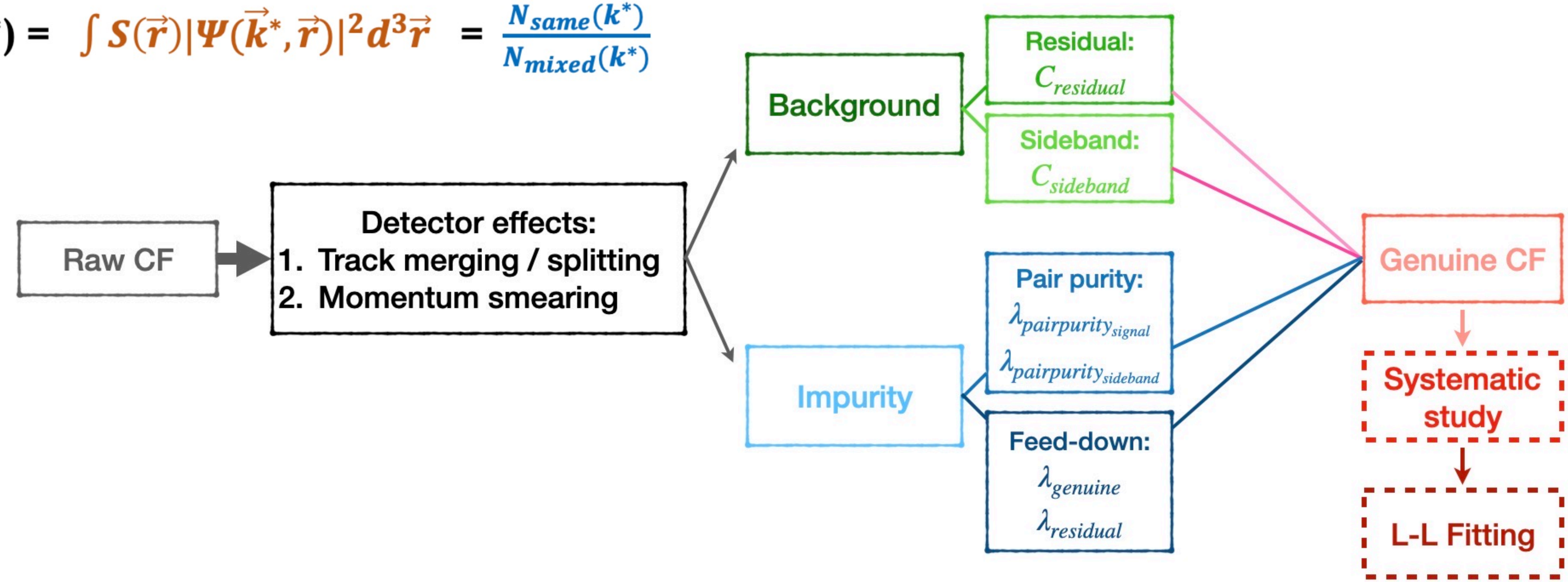


Steps = $N_{walkers} \times N_{steps}$

Analysis Details

Model $\qquad\qquad$ Experimental

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



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