Physics of High net-baryon Densities - PHD 2025

Recent Femtoscopy Correlation Measurement in Heavy-ion Collisions at RHIC-STAR

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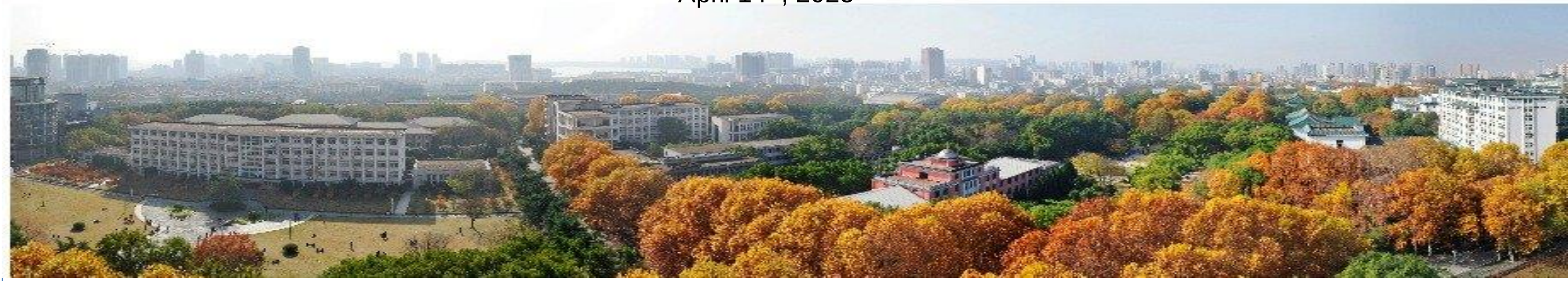
April 14th, 2025



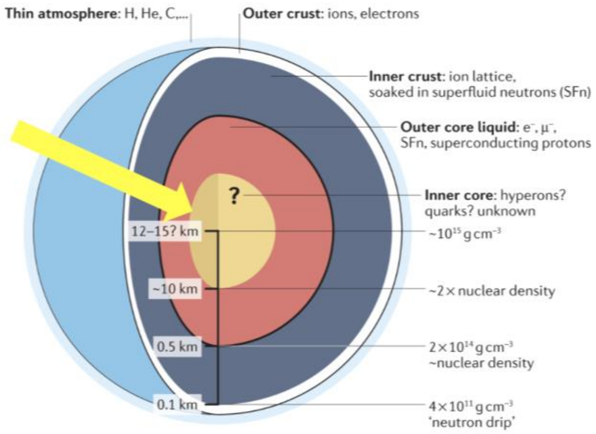
Outline

- Introduction
- Results: Baryon-Baryon and Two-Pion Femtoscopy
  1) Au+Au 3 GeV : p-p,p-d,d-d, d-Λ, t-Λ, ^{3}He-Λ, Λ-Λ
  2) Isobar 200 GeV : p-Ξ^{-}, p-Ω^{-}
  3) FXT energies : Two-pion femtoscopy and Third-body Coulomb Effect
- Summary and Outlook

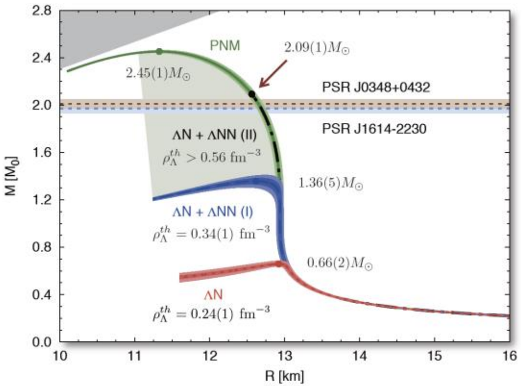
Nucleon (N) - Hyperon (Y) Interactions

Understand the hadron interactions and search for exotic hadrons:

1) Role of N-N, Y-N, Y-Y interactions in Equation-of-State at high baryon density

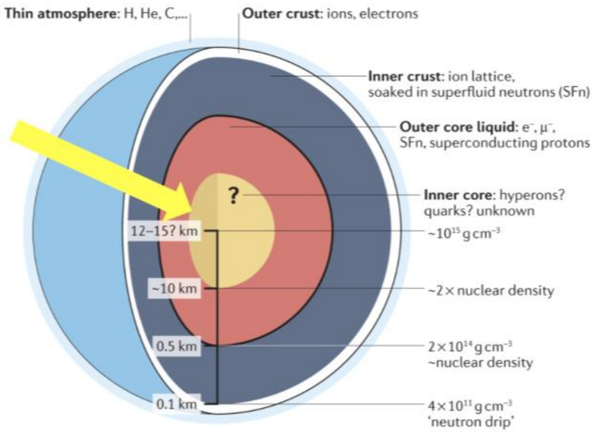


PRL**114**, 092301(2015), HYP2018, 1512.06832



Phys.Rev.C 99, 064905 (2019)
Phys.Rev.C 84, 064910 (2011)
Phys.Rev.C 83 (2011) 015202

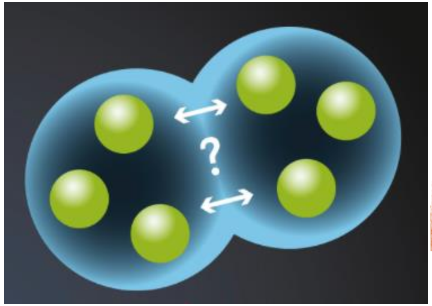
Nucleon (N) - Hyperon (Y) Interactions



Understand the hadron interactions and search for exotic hadrons:

1) Role of N-N, Y-N, Y-Y interactions in Equation-of-State at high baryon density

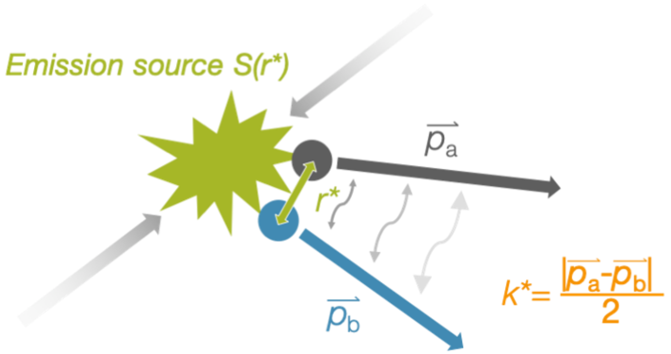
2) Strange Dibaryons : not found experimentally before
Possible bound state:
H-dibaryon ⇒ Λ+Λ / p + Ξ^-
(Strange)Dibaryon ⇒ p + Ω



Particle	Mass (MeV)
f_0	980
a_0	980
K(1460)	1460
Λ(1405)	1405
Θ^+(1530)	1530
H	2245
NΩ	2573

Phys.Rev.C 99, 064905 (2019)
Phys.Rev.C 84, 064910 (2011)
Phys.Rev.C 83 (2011) 015202

Observable : Femtoscopy



⇒ **Femtoscopy is inspired by Hanbury Brown and Twiss (HBT) interferometry.**

→ **Spatial and temporal extent of emission source**

→ Final-state Interactions (Coulomb, Strong interaction)

→ Bound state

Two-particle correlation function:

Model / *Experimental*

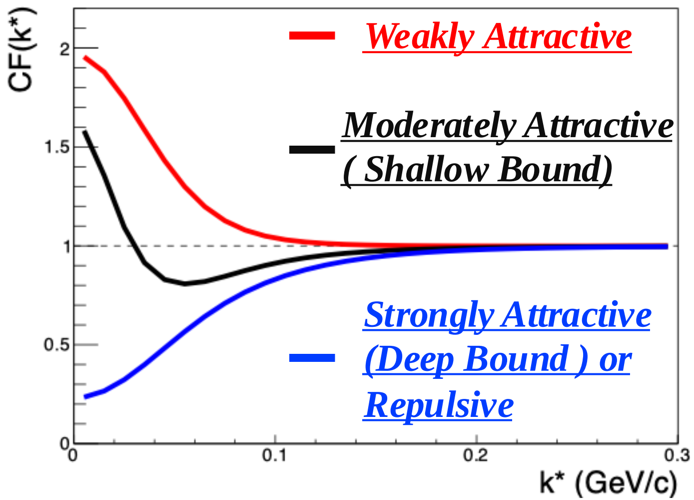
$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

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



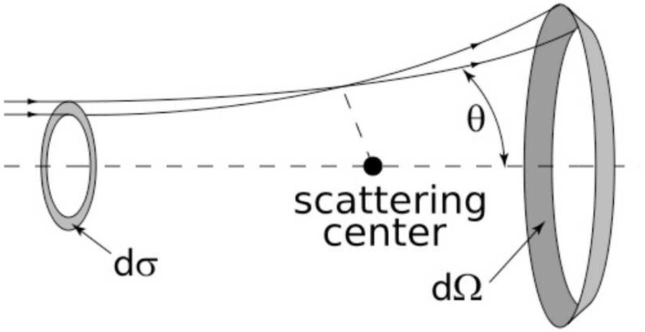
R. Lednicky, et al. Sov.J.Nucl.Phys.35(1982)770

L. Michael, et al. Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

Effective Range Expansion in Low Energy Scatterings

1) Schrodinger equation :

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r)\right]\psi(\mathbf{r}) = E\psi(\mathbf{r}),$$



2) Two particle scattering wave function ($r\to\infty$) :

$$\psi_{\rm rel}(\mathbf{r}) \approx e^{i\mathbf{k}\cdot\mathbf{r}} + f(\theta,\phi)\frac{e^{ikr}}{r},$$

H. A. Bethe, Phy. Rev. 76 (1949) 38

3) scattering amplitude:

$$k\cot\delta_0 = -\frac{1}{a} + \frac{1}{2}r_0k^2 + \mathcal{O}(k^4),$$

$$f(\theta) = \sum_{l=0}^{\infty}\frac{(2l+1)}{k}e^{i\delta_l}\sin\delta_l P_l(\cos\theta).$$

s wave (L=0)

$$f^S(k^*) = \left(\frac{1}{f_0^S} + \frac{1}{2}d_0^S k^{*2} - ik^*\right)^{-1}$$

δ(k): phase shift
a: Fermi scattering length at zero energy
r_0: effective range

$$\lim_{k\to 0}\sigma_e = 4\pi a^2$$

notation change:
$-a \to f_0 \quad r_0 \to d_0$

Lednicky-Lyuboshitz Approach for Particle Correlations

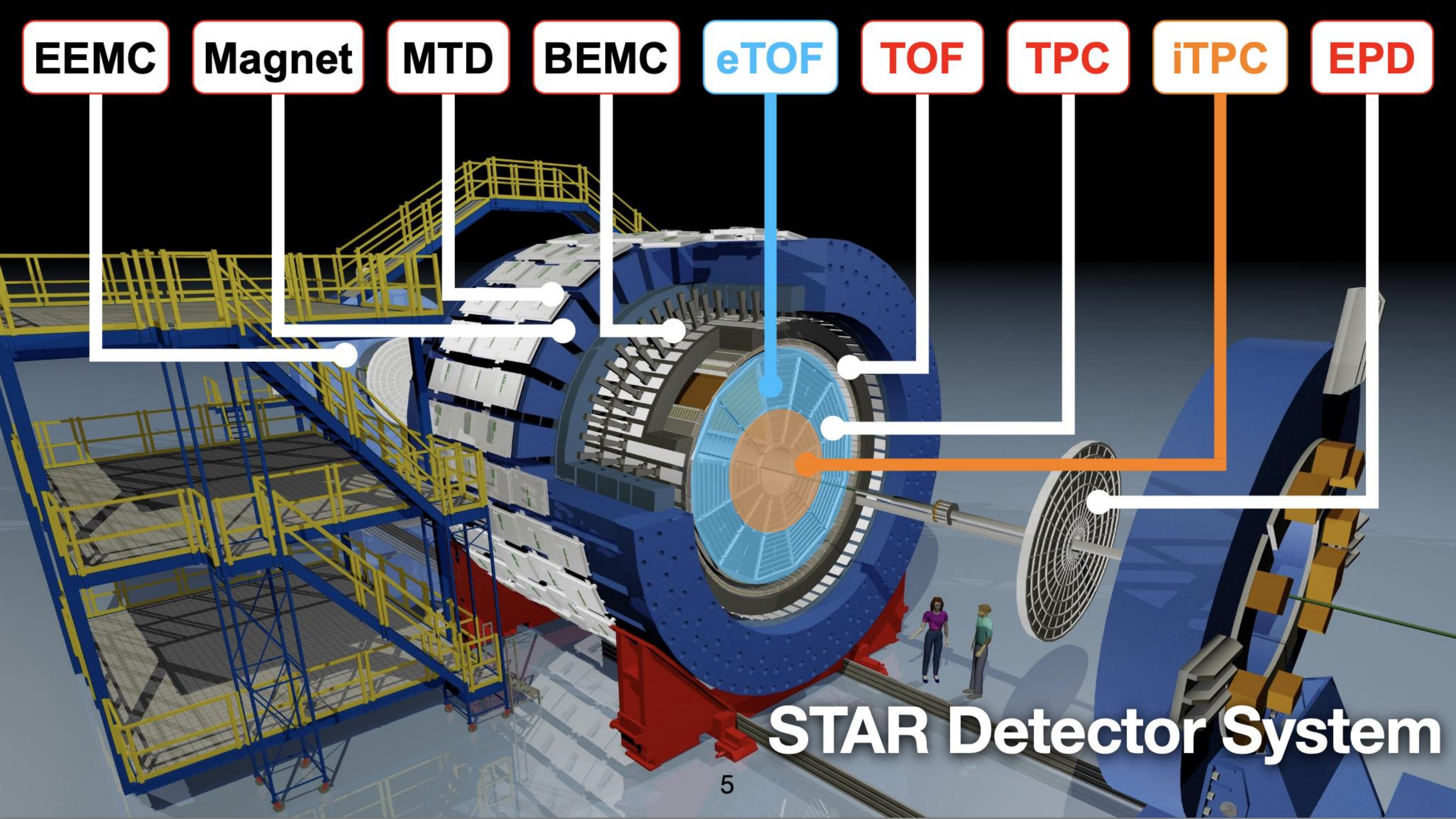
Gaussian source approximation: $S(\mathbf{r}^*) = (2\sqrt{\pi}R_G)^{-3} e^{-\mathbf{r}^{*2}/4R_G^2}$

$$C(\mathbf{k}^*) = \int d\mathbf{r}^* \; S(\mathbf{r}^*) \; |\Psi(\mathbf{r}^*, \mathbf{k}^*)|^2$$
$$= 1 + \frac{|f(k^*)|^2}{2R_G^2} F(d_0) + \frac{2\mathbf{Re}f(k^*)}{\sqrt{\pi}R_G} F_1(2k^* R_G) - \frac{\mathbf{Im}f(k^*)}{R_G} F_2(2k^* R_G)$$

Assumptions:
- factorization between source and strong interaction
- effective range expansion for wave function
  scattering length f_0, effective range d_0

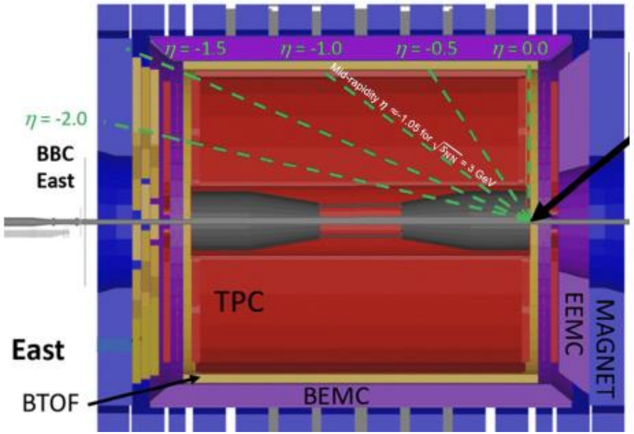
$$F_1(z) = \frac{e^{-z^2}}{z}\int_0^z e^{x^2} dx$$
$$F_2(z) = \frac{1}{z}(1 - e^{-z^2})$$

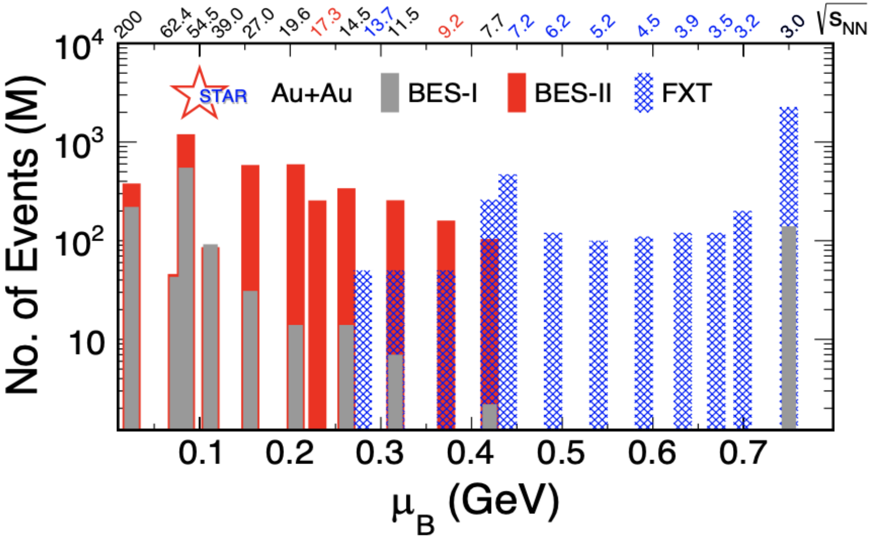
R.Lednicky, V.L.Lyuboshitz, 1981


EEMC
Magnet
MTD
BEMC
eTOF
TOF
TPC
iTPC
EPD
STAR Detector System

RHIC Beam Energy Scan (BES) Program (2010-2021)

STAR Fixed Target Mode



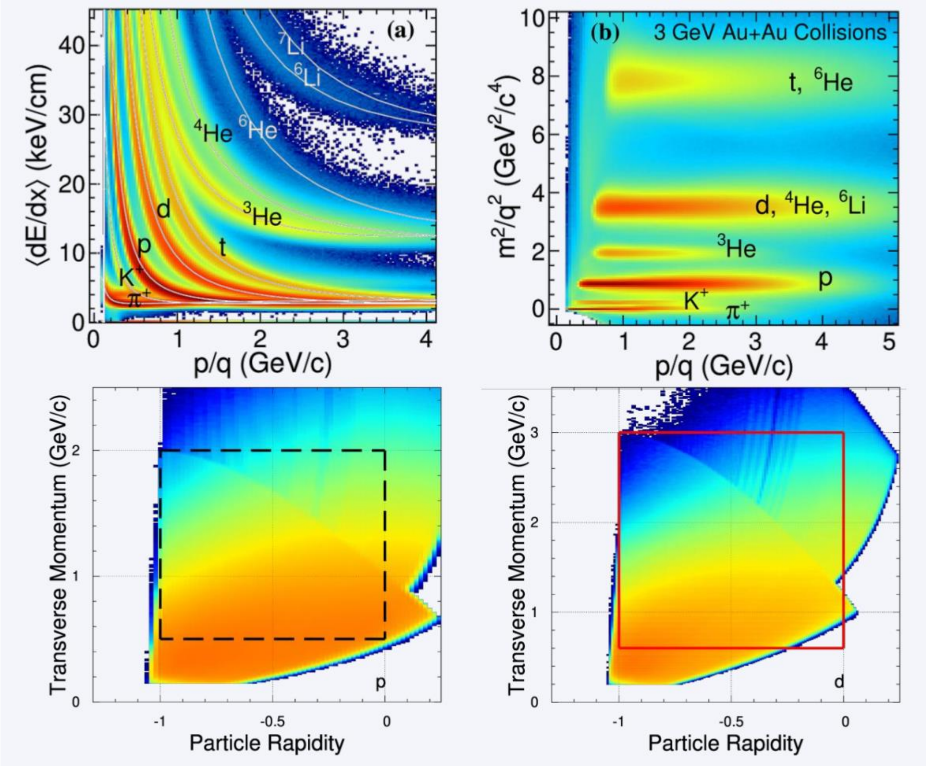


- BES-I (2010 – 2014): 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 GeV.
- BES-II (2018-2021): Collider mode (7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27 GeV), FXT mode: (**3.0, 3.2, 3.5, 3.9, 4.5**, …, 13.7 GeV)
- μ_B coverage : $25 < \mu_B < 750$ MeV

200 GeV Data sets:

Center-of-Mass Energy	Collisions	Year	Mode	#Events
200 GeV	Au+Au	2011/2014/2016	Collider	~ 2 Billion
200 GeV	Isobar (Ru+Ru/ Zr+Zr)	2018	Collider	~4 Billion

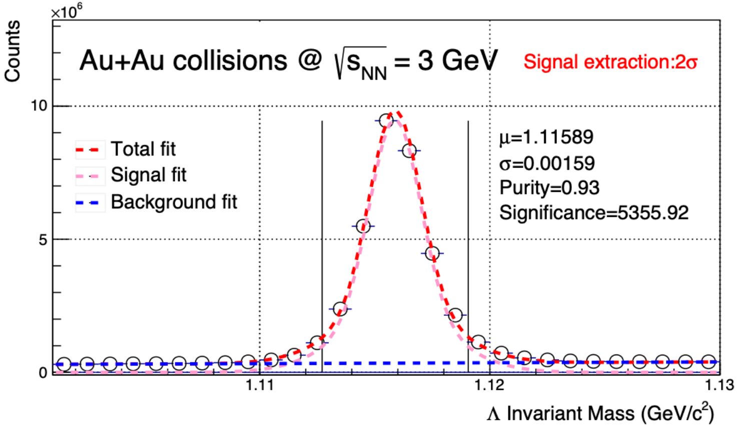
Particle Identification & Reconstruction



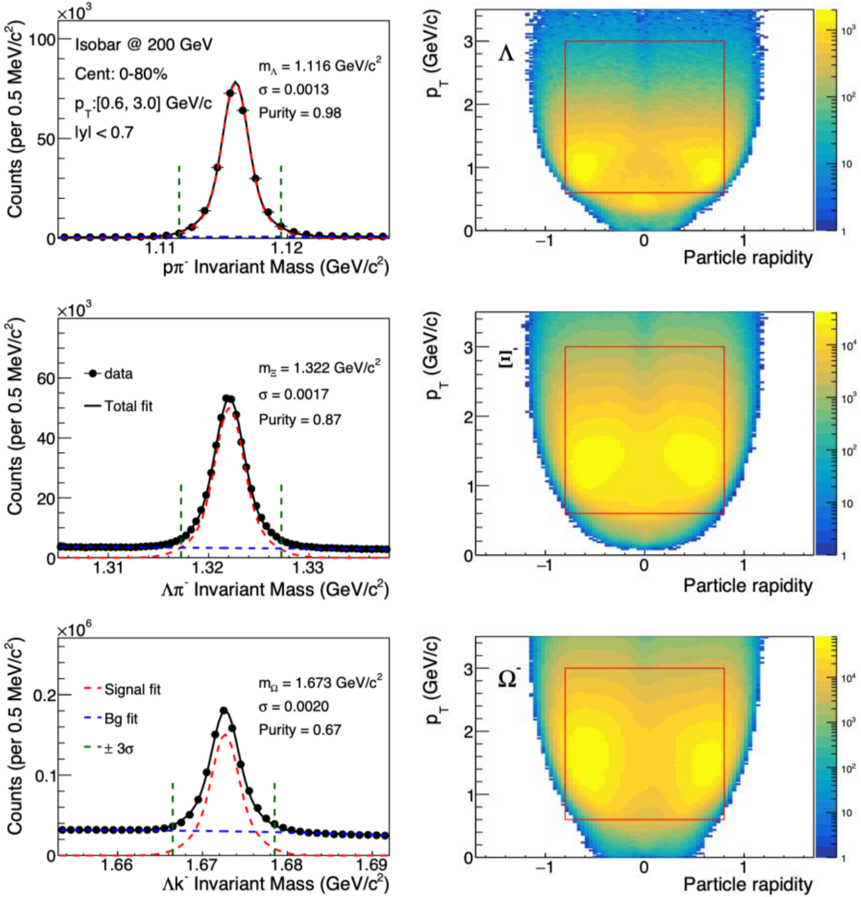
STAR, Phys. Lett. B 827 (2022) 136941

⇒ **protons and deuterons are identified by TPC, TOF**

- **Low p_T : TPC**
- **High p_T : TPC + TOF**
- **Purity > 95%**



Particle Identification & Reconstruction



⇒ **protons and deuterons are identified by TPC, TOF**

- **Low p_T : TPC**
- **High p_T : TPC + TOF**
- **Purity > 95%**

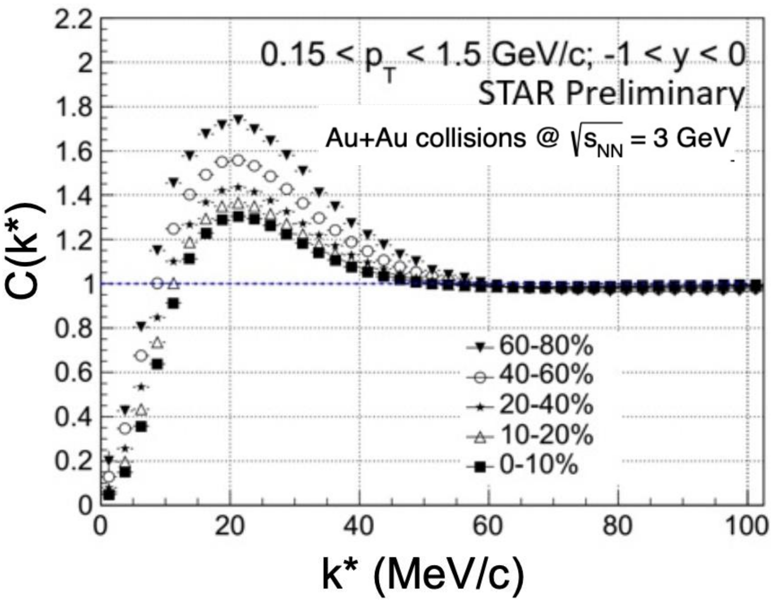
⇒ **Reconstruct hyperons (Λ, Ξ, Ω)**

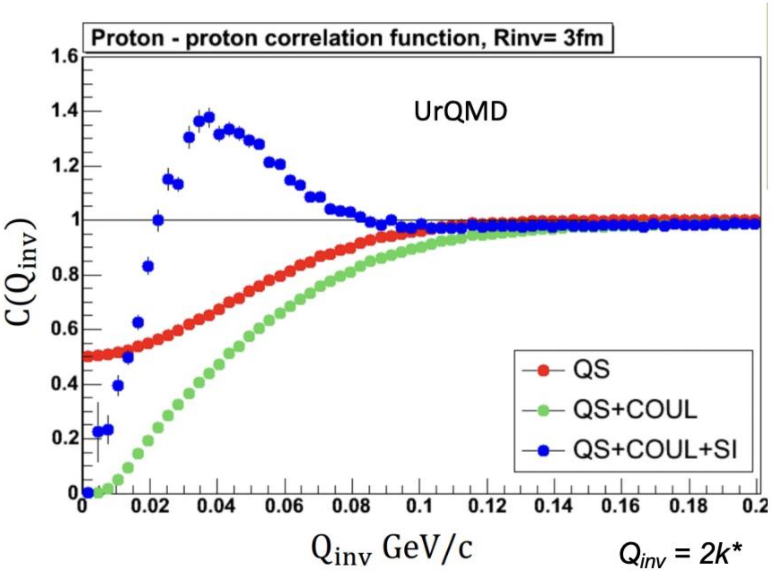
Λ -> p + π^- ,BR = 63.9%

Ξ^- <- Λ + π^- ,BR = 99.9%

Ω^- <-Λ + K^- ,BR = 67.8%

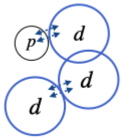
Proton - Proton Interactions at 3 GeV

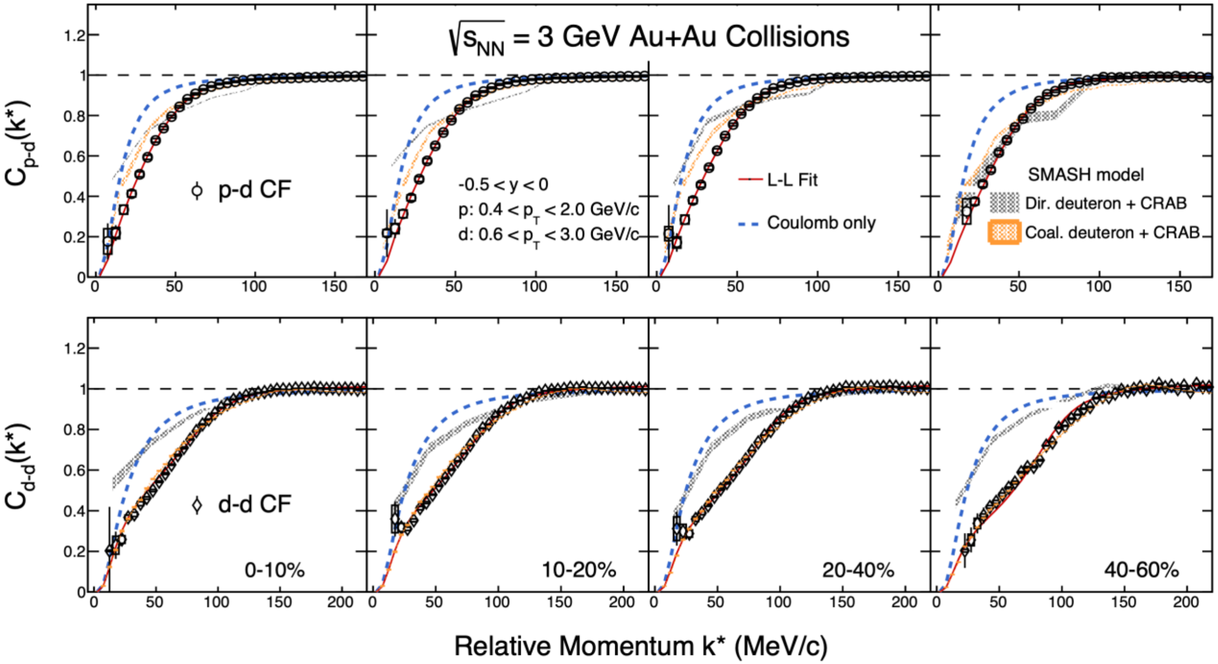




1) Repulsion at small k* due to Coulomb and quantum statistics
2) Attractive strong interaction with ***f_0 ~ 7 fm*** (low-E scattering) consistent with data
3) Bayesian fit to extract source size and scattering parameters simultaneously

p-d / d-d Correlation @ 3 GeV

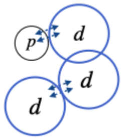


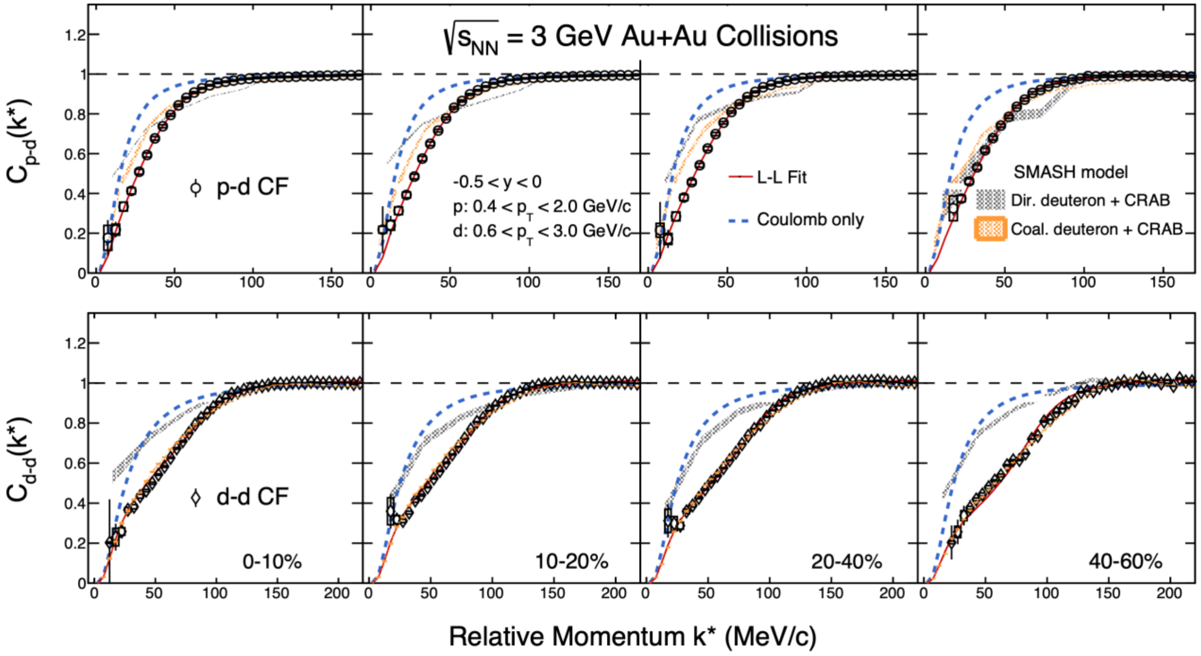


- **First measurements of p-d/d-d correlation functions in HIC**
- **Clear depletion in low k***
  - **Coulomb repulsive & strong interaction**
- **Fitted with L-L model simultaneously, assuming in different centrality:**
  - **Different R_G**
  - **Common f_0 and d_0**

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

p-d / d-d Correlation @ 3 GeV



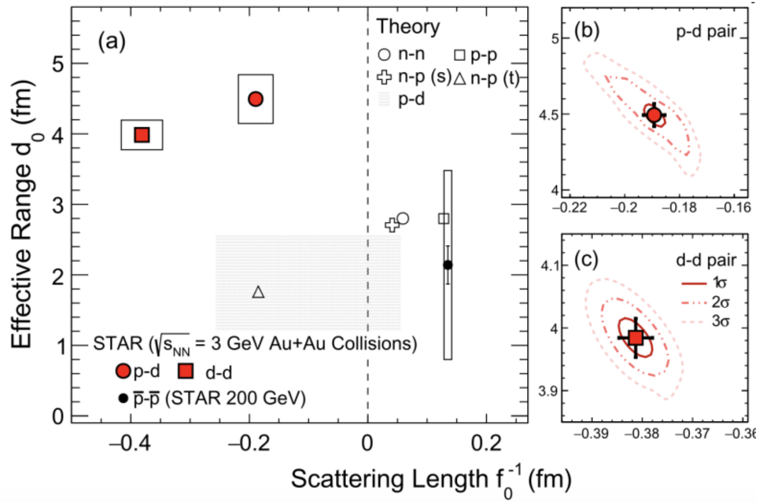


Simulated with SMASH model, consider two deuteron formation mechanism:

- **Direct production**
  - **Hadronic scattering**
  - **Fail to describe data at certain k***
- **Coalescence production**
  - **Wigner function**
  - **Well description to data**
  - **Coalescence is the dominant process for deuteron formation in the high-energy nuclear collisions**

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

p-d / d-d Correlation @ 3 GeV



1) For both p-d and d-d interaction, the spin-averaged f0 is negative

2) No collision centrality dependence is observed in f0 and d0.

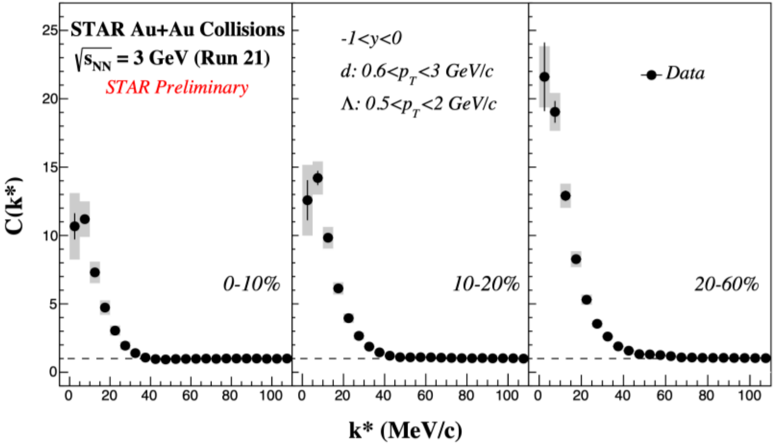
p-d pair

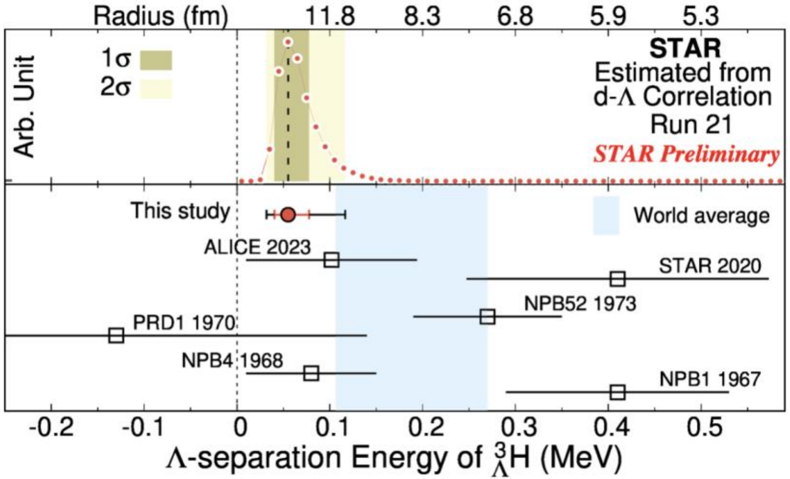
Parameters (fm)	Fit C_{pd}(0-10%)	Fit C_{pd}(10-20%)	Fit C_{pd}(20-40%)	Fit C_{pd}(40-60%)	Simu. Fit
f_0	-5.45 ± 0.31	-5.04 ± 0.25	-5.53 ± 0.25	-5.14 ± 0.24	-5.28 ± 0.11
d_0	4.30 ± 0.15	4.51 ± 0.15	4.46 ± 0.16	4.48 ± 0.21	-4.49 ± 0.08

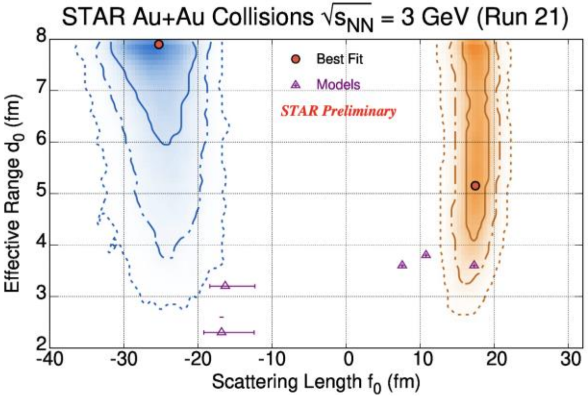
d-d pair

Parameters (fm)	Fit C_{dd}(0-10%)	Fit C_{dd}(10-20%)	Fit C_{dd}(20-40%)	Fit C_{dd}(40-60%)	Simu. Fit
f_0	-2.74 ± 0.04	-2.58 ± 0.04	-2.57 ± 0.03	-2.63 ± 0.05	-2.62 ± 0.02
d_0	3.88 ± 0.08	3.67 ± 0.06	3.98 ± 0.04	3.90 ± 0.08	-3.99 ± 0.03

$d - \Lambda$ Correlation functions at 3.0 GeV (Run21)

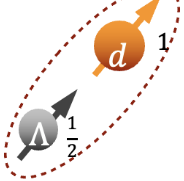






1) The most accurate results of binding energy and radius of $^3_\Lambda$H.
Open a new way to constrain $^3_\Lambda$H properties.

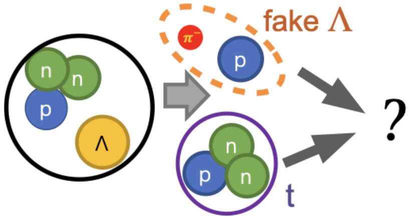
$$^3_\Lambda\text{H}\ B_\Lambda = 0.06^{+0.06}_{-0.03}$$ (MeV) @ 95% CL



Extracted physical parameters:
f_0 (D) = −25.3±3.3 fm
f_0 (Q) = 17.5±1.6 fm

Xialei Jiang's talk@QM2025

$t-\Lambda$ and $^3He-\Lambda$ Correlation Functions at 3.0 GeV (Run21)

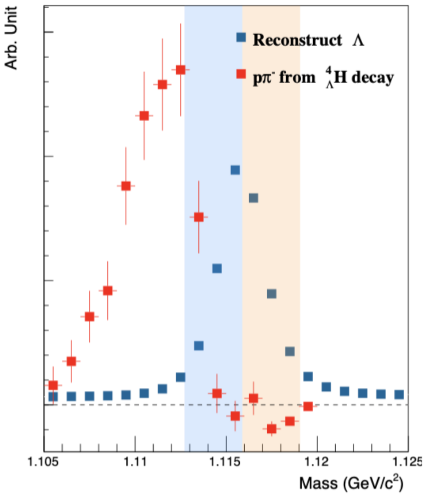


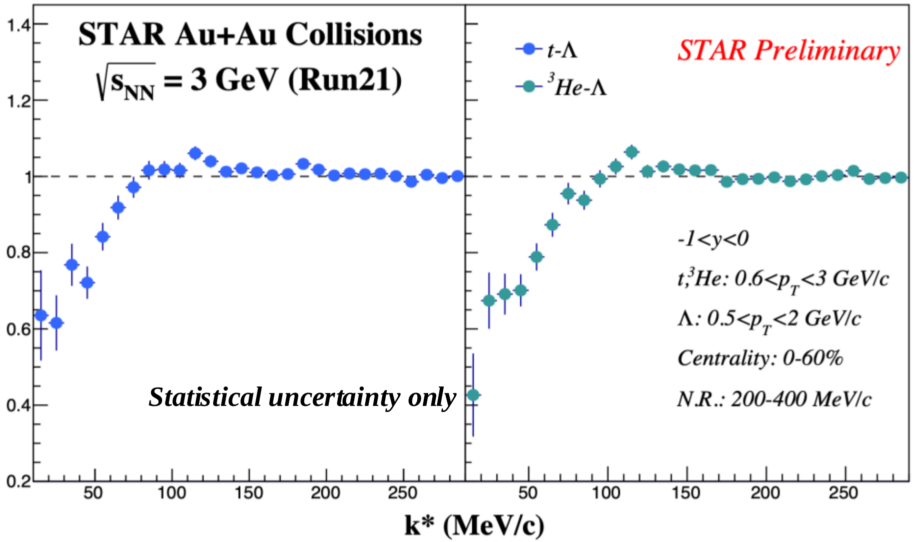
$^4_\Lambda\mathrm{H} -> \mathrm{t} + \mathrm{p} + \pi^-$

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

Left signal: 1.11271~1.11589 GeV/c^2

Right signal: 1.11589~1.11906 GeV/c^2





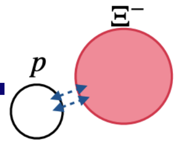
The correlation functions of right side Λ invariant mass region are displayed.

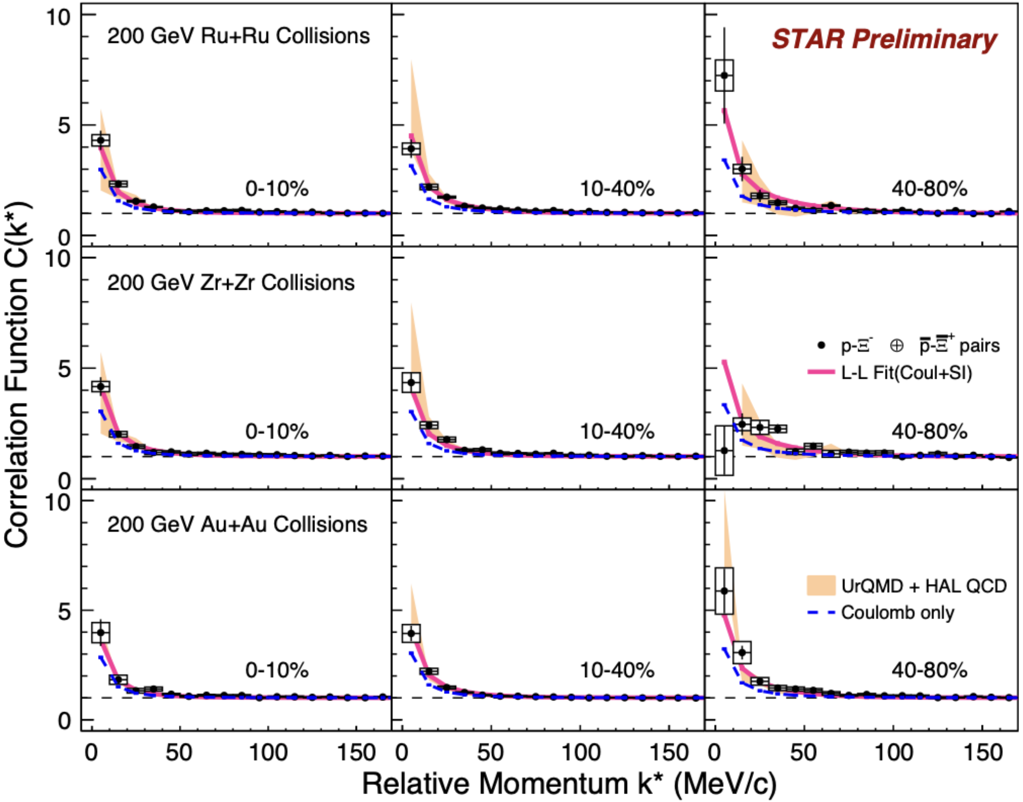
1) First $\mathrm{t}-\Lambda$ and $^3\mathrm{He}-\Lambda$ correlation measurements in the heavy-ion collisions.
   $\mathrm{t}-\Lambda$ and $^3\mathrm{He}-\Lambda$ exhibit similar correlation structures.

2) Structure seen in k* ~120 MeV for both $\mathrm{t}-\Lambda$ and $^3\mathrm{He}-\Lambda$ correlation.
   - Particle decay?
   - Final-state interaction?

Xialei Jiang's talk@QM2025

p-Ξ⁻ Correlation Function (|S| =2)





I. Measure p-Ξ⁻ ⊕ p̄−Ξ̄⁺ CFs at 200 GeV in Au+Au and Isobar collisions

II. CFs show enhancement at low k*

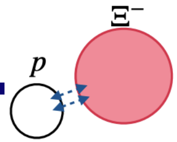
III. Simultaneously fit with L-L function for different centralities in each collision system to extract R_G, f_0 and d_0 by Bayesian method

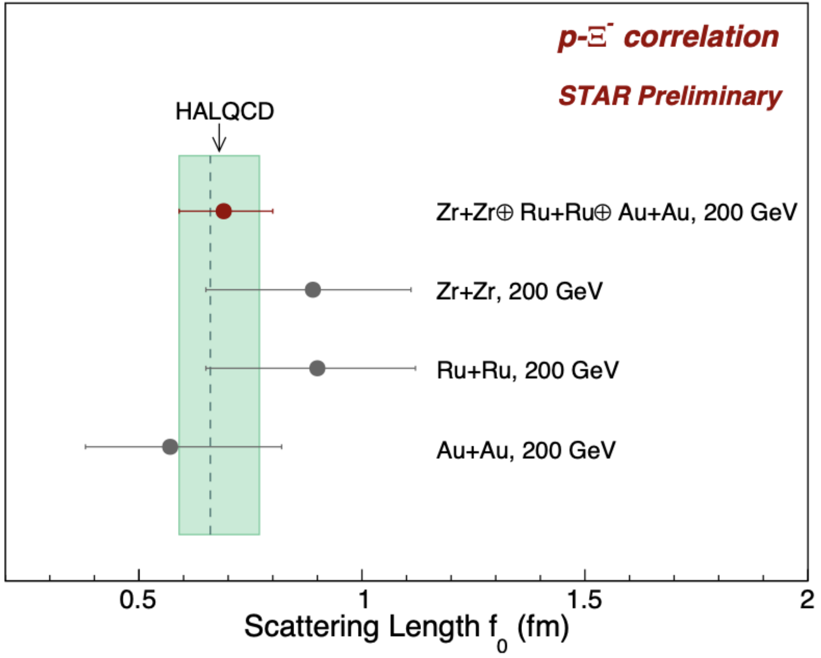
IV. UrQMD + HAL QCD model is consistent with data

◎ 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

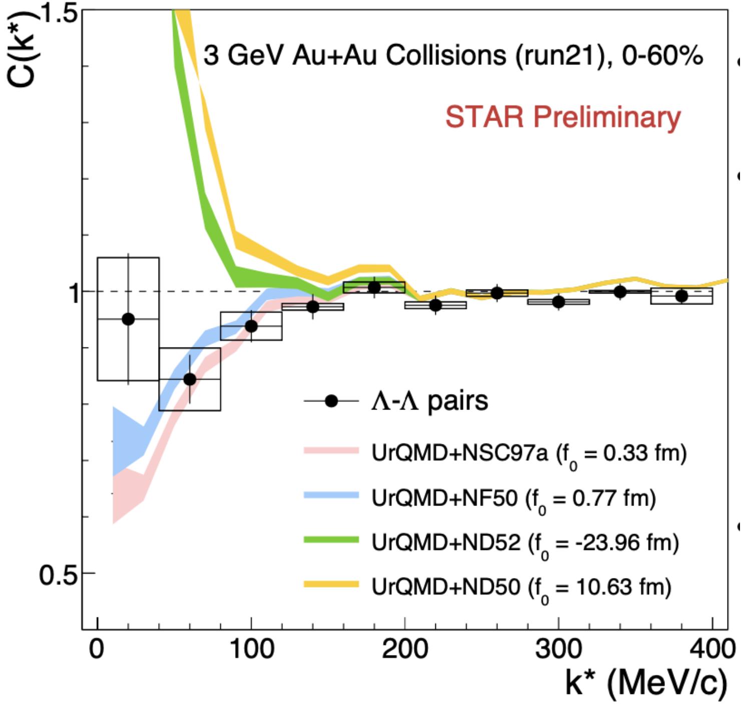
III. Extracted spin averaged scattering length:

$f_0 = 0.69^{+0.11}_{-0.10}$ fm (stat.+sys.)

- Weakly attractive interaction
- Consistent with HAL QCD prediction

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

Λ – Λ (|S|=2) Correlation Functions at 3 GeV (Run 21)



1) Λ-Λ correlation function shows suppression at small k*. Compared with UrQMD+potential, it is found that the simulation with positive *f*0 is in better agreement with data -> Hints at an attractive interaction in Λ-Λ pairs.

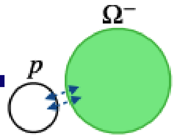
2) Need more precise data to confirm.
-> High statistics Isobar and Au+Au collisions

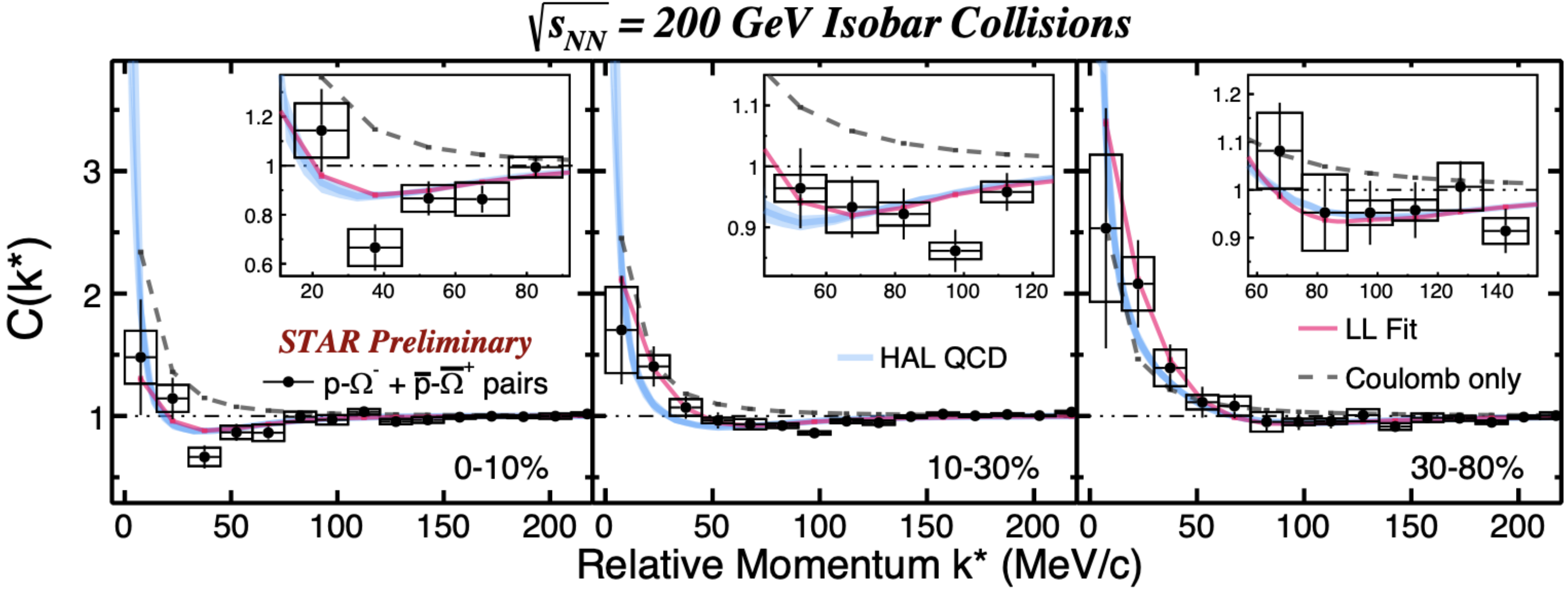
Potential	f0 (fm)	d0 (fm)	Chi2/NDF
NSC97a [5]	0.33	12.37	1.53
NF50 [6]	0.77	4.27	1.61
ND52 [7]	-23.96	2.59	2.24
ND50 [7]	10.63	2.04	4.02

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

Ke Mi's poster@QM2025

p-Ω^- Correlation Function (|S|=3)





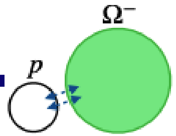
I. Precise measurements of p-Ω^- ⊕ $\bar{p}$-$\bar{\Omega}^+$ correlation functions in Isobar collisions
   - CFs show enhancement at low k* -> mainly due to Coulomb attraction interaction
   - CFs show depletion at k* ~ 30-150 MeV/c -> mainly due to the strong interaction

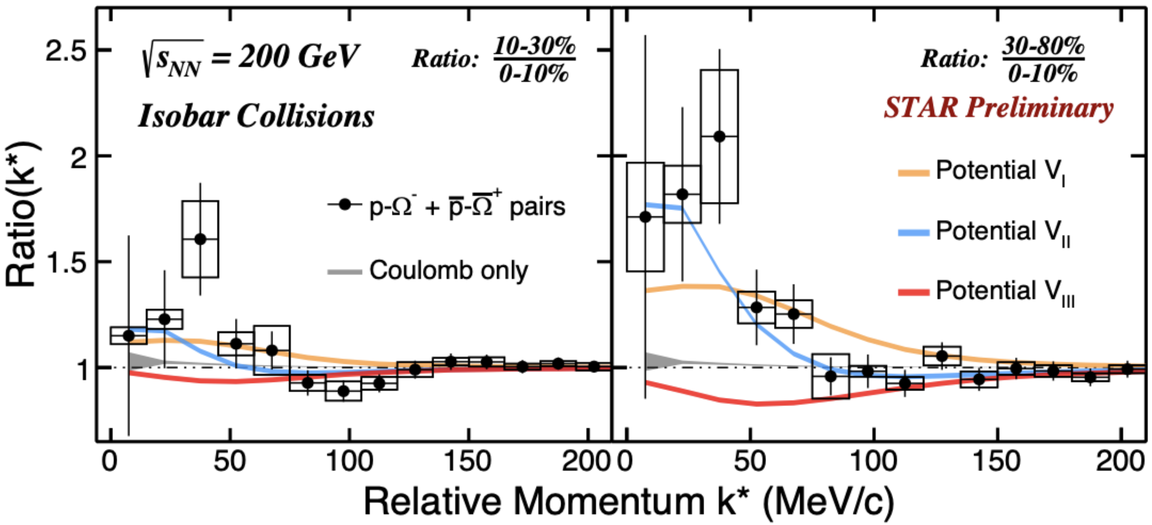
II. Simultaneously fit with L-L function for 3 centralities to extract R_G, f_0 and d_0 by Bayesian method

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

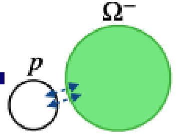
I. By taking CF ratio, Coulomb effect can be largely canceled

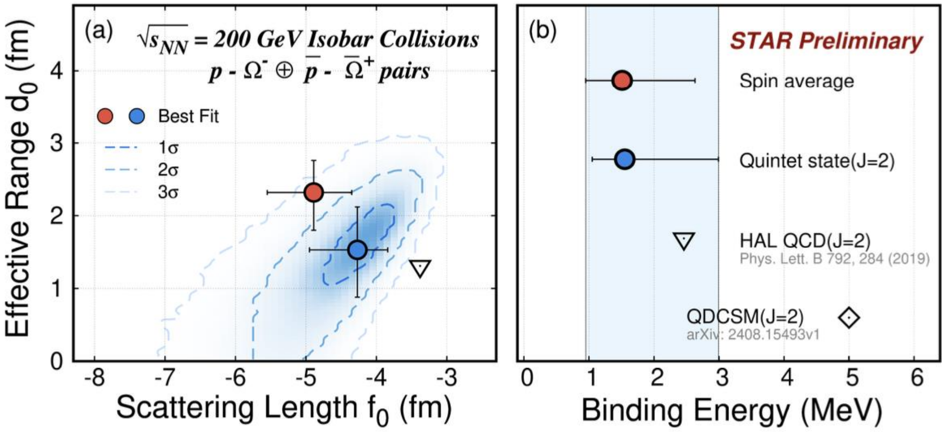
II. CF Ratio shows enhancement at low k* and depletion around k* ~ 100 MeV/c
   - Due to the presence of shallow bound state

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)





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

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

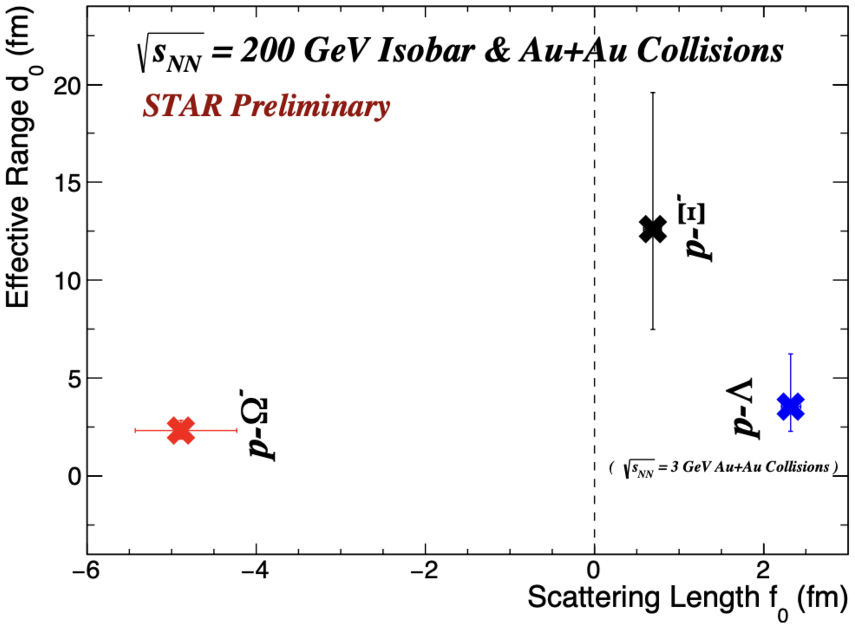
- Calculated BE are consistent with HAL QCD prediction

	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.89^{+0.54}_{-0.66}$	$-4.27^{+0.43}_{-0.68}$	−3.38
d_0 (fm)	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	1.31
BE (MeV)	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	2.27

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

Kehao Zhang's talk@QM2025

Strong Interaction Parameters



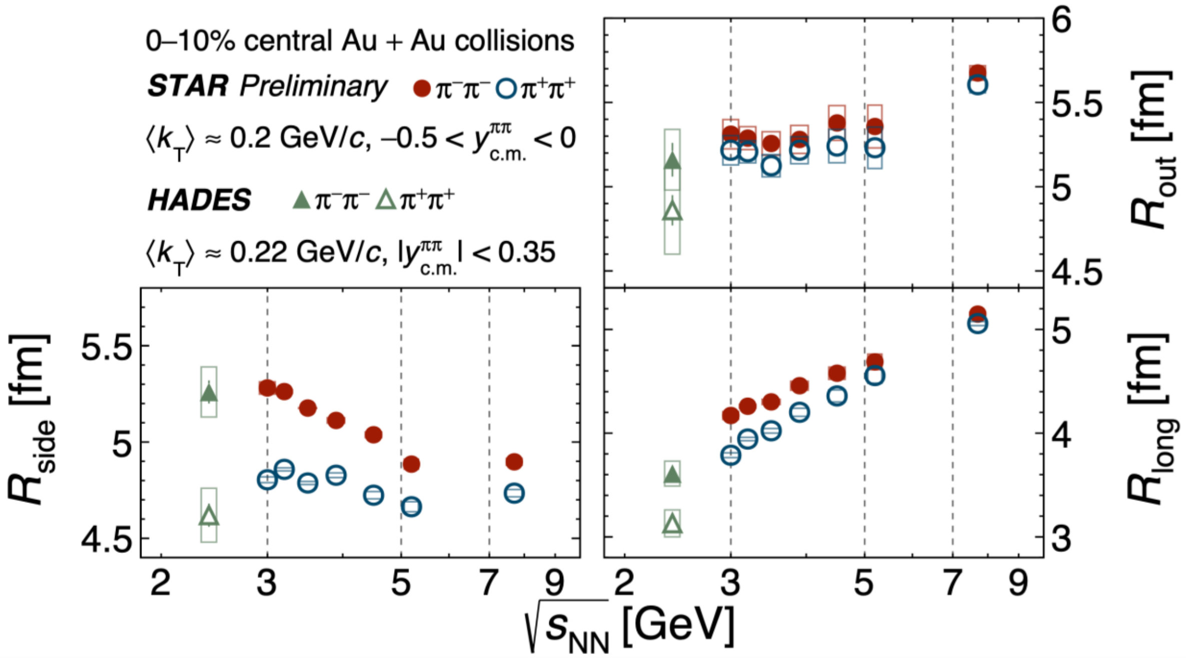
- Extracted negative f_0 in p-Ω^- pair -> Support the formation of bound state
- Interaction section is proportional to f_0^2, the observation implies that the strength of the interaction depends on strangeness;

Hierarchy of strangeness content:

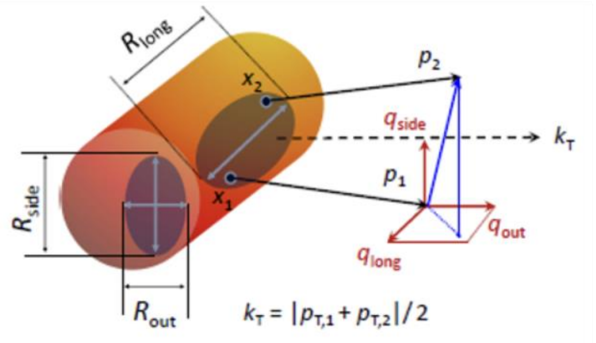
$$\boldsymbol{f_0(|s|=0) > f_0(|s|=1) > f_0(|s|=2) > 0}$$

How to understand this Hierarchy **?**

Two-Pion 3D Femtoscopy： Energy dependence of Radii



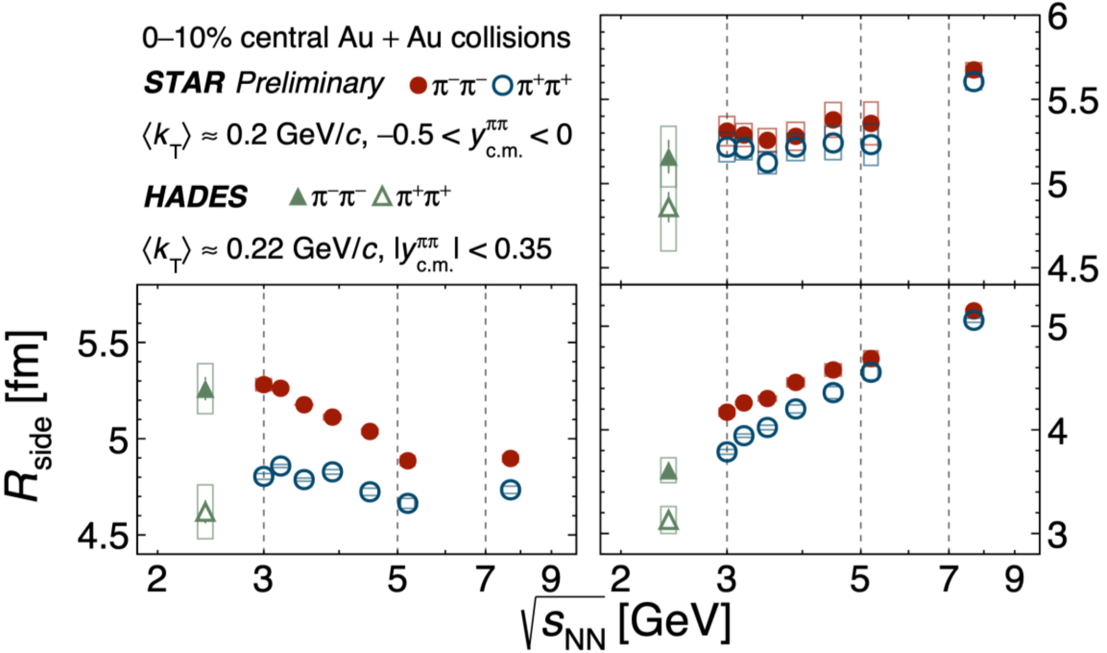
- $R_{\rm out}^{\pi^+\pi^+}$ and $R_{\rm out}^{\pi^-\pi^-}$ agree within uncertainties
- Difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ decreases with increasing $\sqrt{s_{\rm NN}}$ for $R_{\rm side}$ and $R_{\rm long}$



HADES, EPJA 56, 140 (2020)

Vinh’s talk, Youquan Qi’s poster@QM2025

Two-Pion 3D Femtoscopy： Energy dependence of Radii

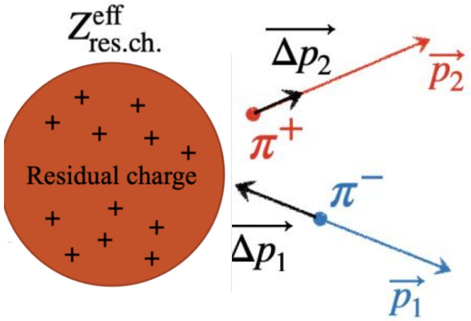


HADES, EPJA 56, 140 (2020)

Vinh's talk, Youquan Qi's poster@QM2025

Two possible reasons :

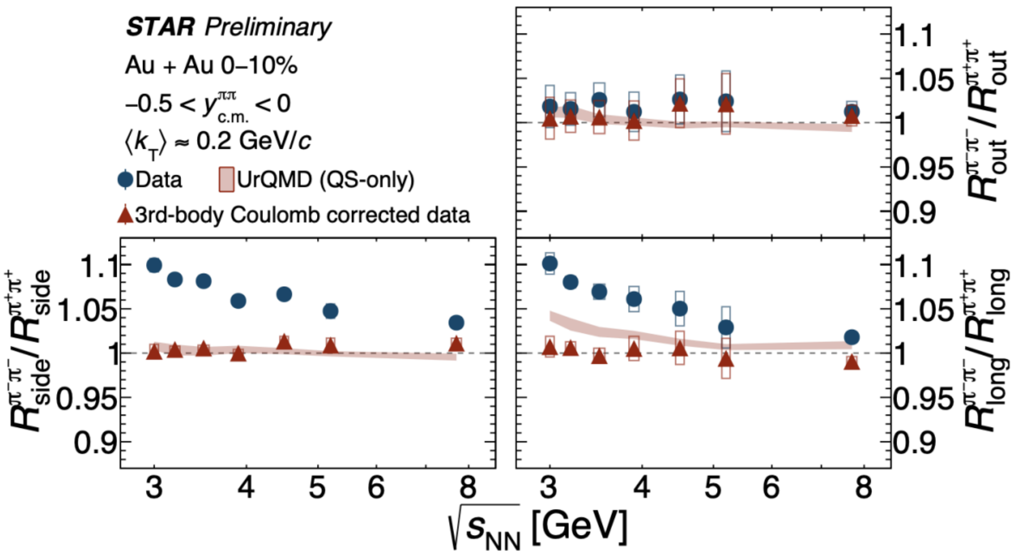
1) Third Body Coulomb



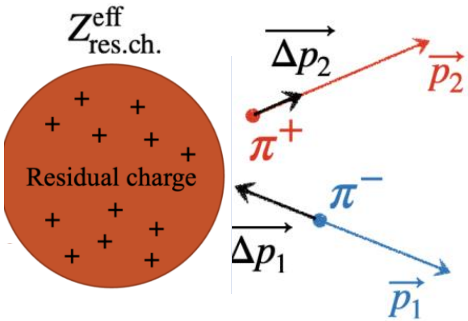
2) Isospin effect

$$p + p \leftrightarrow n + \Delta^{++}, \quad \Delta^{++} \leftrightarrow p + \pi^{+}$$
$$n + n \leftrightarrow p + \Delta^{-}, \quad \Delta^{-} \leftrightarrow n + \pi^{-}$$
$$n + p \leftrightarrow n + \Delta^{+}, \quad \Delta^{+} \leftrightarrow n + \pi^{+}$$
$$n + p \leftrightarrow p + \Delta^{0}, \quad \Delta^{0} \leftrightarrow p + \pi^{-}$$

Remove Third body Coulomb interactions



- Isolate 3rd body Coulomb effect:
  - Extract Z_{res}^{eff} from π^+/π^- yield ratio,
  - Calculate Δp needed to produce the 3rd body Coulomb effect in UrQMD
  - Get correlation functions with the momentum shift



Correlation functions consistent after removal of 3rd body Coulomb effect
No significant isospin contribution seen.

Summary and Outlook

- **Light Nuclei – Λ Interactions :**

  1) First t − Λ and $^{3}\mathrm{He} - \Lambda$ correlation measurements in the heavy-ion collisions
  2) d − Λ : most accurate results of binding energy and radius of $^{3}_{\Lambda}\mathrm{H}$.

  Open a new way to constrain hypernuclei properties

- **Proton – Hyperon Interactions :**

  1) **p-Ξ^{-} ⊕ $\bar{\mathrm{p}}$–$\bar{\Xi}^{+}$** pairs: $f_0 > 0$ -> Weakly attractive interaction
  2) **p-Ω^{-} ⊕ $\bar{\mathrm{p}}$-$\bar{\Omega}^{+}$** pairs: $f_0 < 0$ -> **First Experiment Evidence of Strange-Dibaryon**

- **Two-pion 3D Femtoscopy :**

  Radii difference between pion+ pairs and pion- pairs can be largely described by the third-body Coulomb effect; isospin effect is small.

Stay tuned for more exciting results from RHIC Beam Energy Scan !!

Acknowledgement :

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Theory Colleagues

Thank you for your attention !