Femtoscopy of Strange Baryons in Heavy-ion Collisions at RHIC-STAR

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Outline

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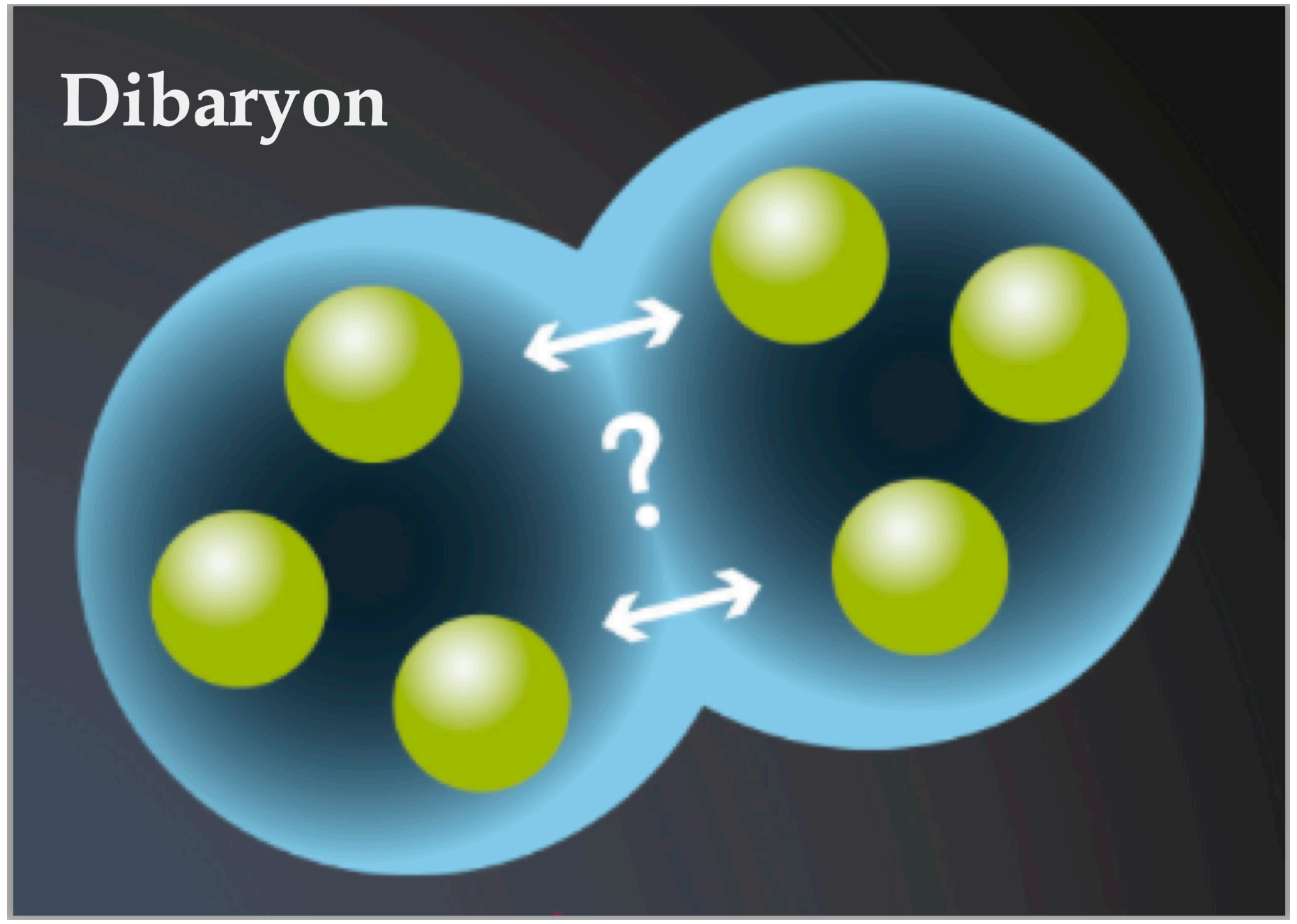
Motivation

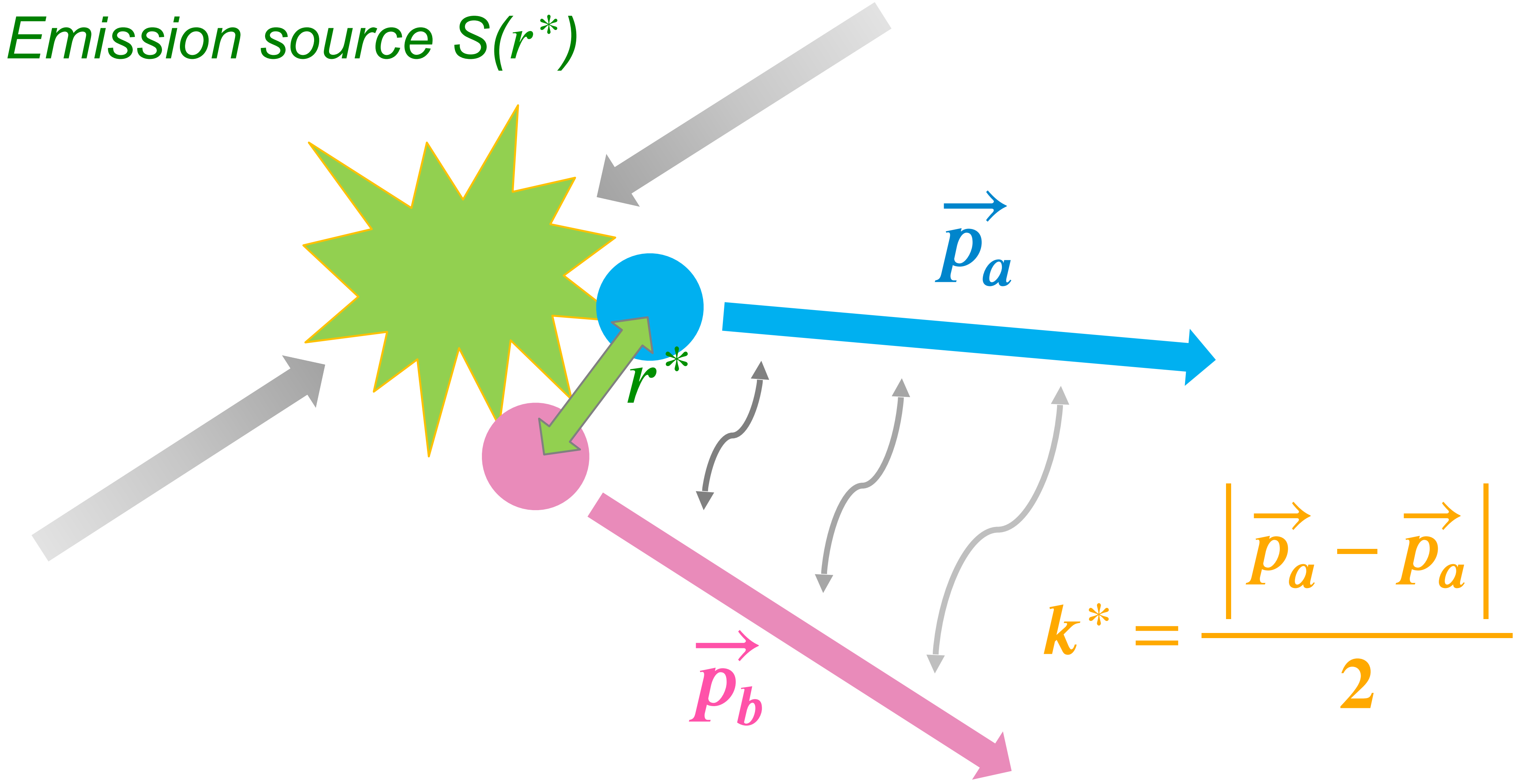
- Strange Dibaryons have never been found experimentally
  - Possible bound state: **H-dibaryon** $\rightarrow \Lambda + \Lambda$ / $p + \Xi^-$, **(Strange)Dibaryon** $\rightarrow p + \Omega^-$
- Hyperon-Nucleon (Y-N) and Hyperon-Hyperon (Y-Y) interactions provide important information to constrain the Equation-of-State and help to understand the inner structure of compact stars



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)

Femtoscopy



- In high-energy experiment, Femtoscopy is inspired by **Hanbury Brown and Twiss interferometry (Astronomy)**
- Study the spatial and temporal extent of emission source
  - Quantum Statistics (Fermi-Dirac, Bose-Einstein)
  - Final-state Interactions (Coulomb, Strong interaction)
  - Collision Dynamics

- Two-particle correlation function:

Statistical | *Model* | *Experimental*

$$\boxed{C(k^*) = \frac{P(\vec{p}_a, \vec{p}_b)}{P(\vec{p}_a)\cdot P(\vec{p}_b)} = \int d^3r^* S(r^*)\left|\Psi(r^*, k^*)\right|^2 = \mathcal{N}\frac{N_{same}(k^*)}{N_{mixed}(k^*)}}$$

$\left\{\begin{array}{l} >1\text{: Attraction} \\ =1\text{: No Correlation} \\ <1\text{: Repulsion} \end{array}\right.$

$\vec{p}_a, \vec{p}_b$: Single-particle momentum

$S(r^*)$: Source function
$\Psi(r^*, k^*)$: Pair wave function
PRF: Pair Rest Frame
r^*: relative distance in PRF
$k^* = \frac{1}{2}\left|\vec{p}_a - \vec{p}_a\right|$, relative momentum in PRF

$\mathcal{N}$: Normalization factor
$N_{same}(k^*)$: same event
$N_{mixed}(k^*)$: mixed event

Nature 178 1046-1048(1956)
ALICE Coll. Nature 588, 232–238 (2020)

Lednicky-Lyuboshitz Approach

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$$\boxed{CF(k^*) = \int d^3r^* S(r^*) |\psi(r^*, k^*)|^2}$$

- **Assumptions:**
  - **Smoothness approximation for source function**
  - **Static and spherical Gaussian source**
  - **Only consider s-wave**
  - **Effective range expansion for $\psi(r^*, k^*)$**

- **Physics Parameters:**

  R_G: **Spherical Gaussian source**

  f_0: **Scattering length**

  d_0: **Effective range**

- **Wave function:**

$$\psi(r^*, k^*) = e^{-ik^*r^*} + f(k^*)\frac{e^{-ik^*r^*}}{r^*}$$

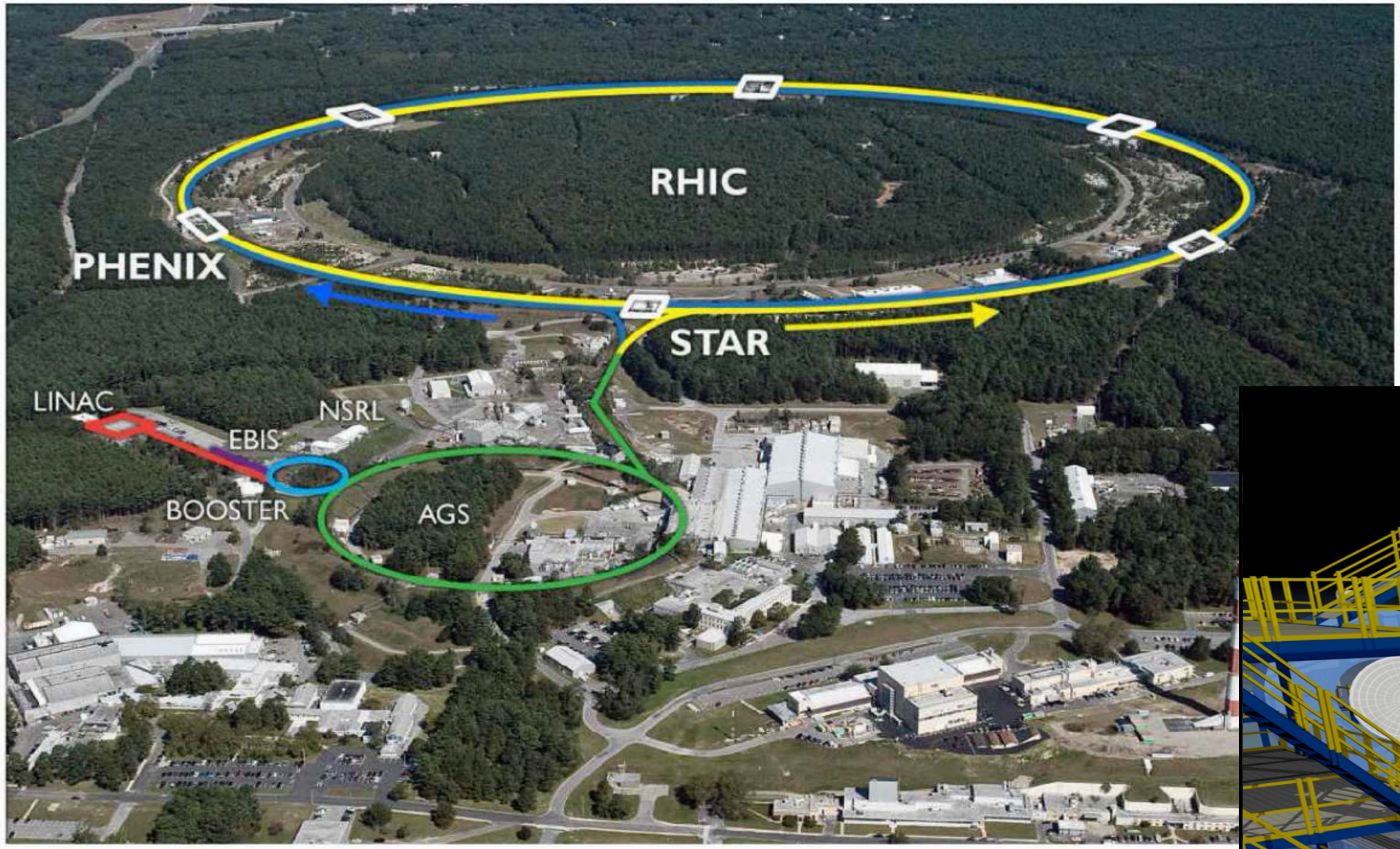
- **Scattering amplitude:**
  - **W/O Coulomb:**

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

  - **W/ Coulomb:**

$$f_c(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta)]^{-1}$$

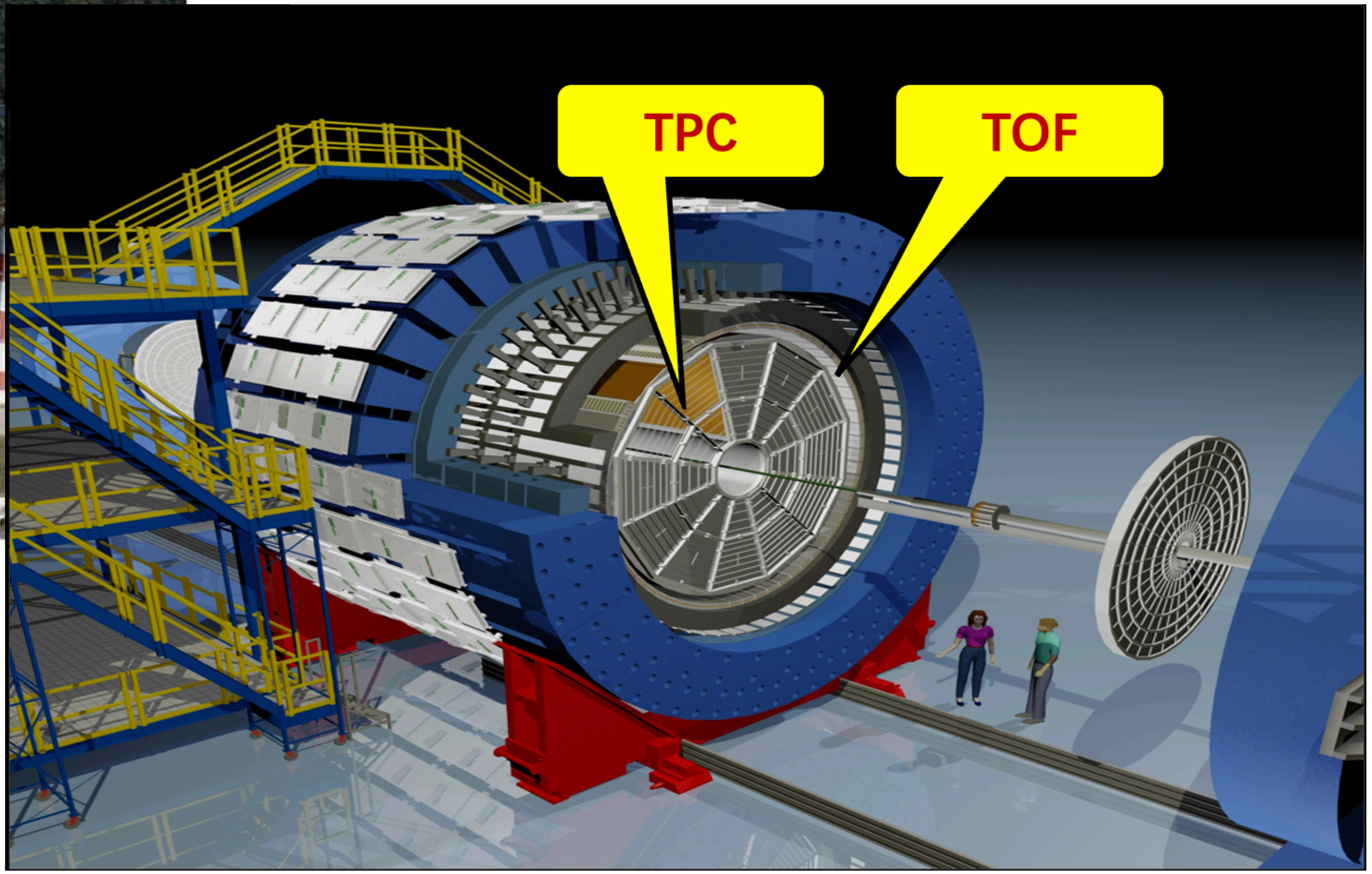
RHIC-STAR Experiment



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)

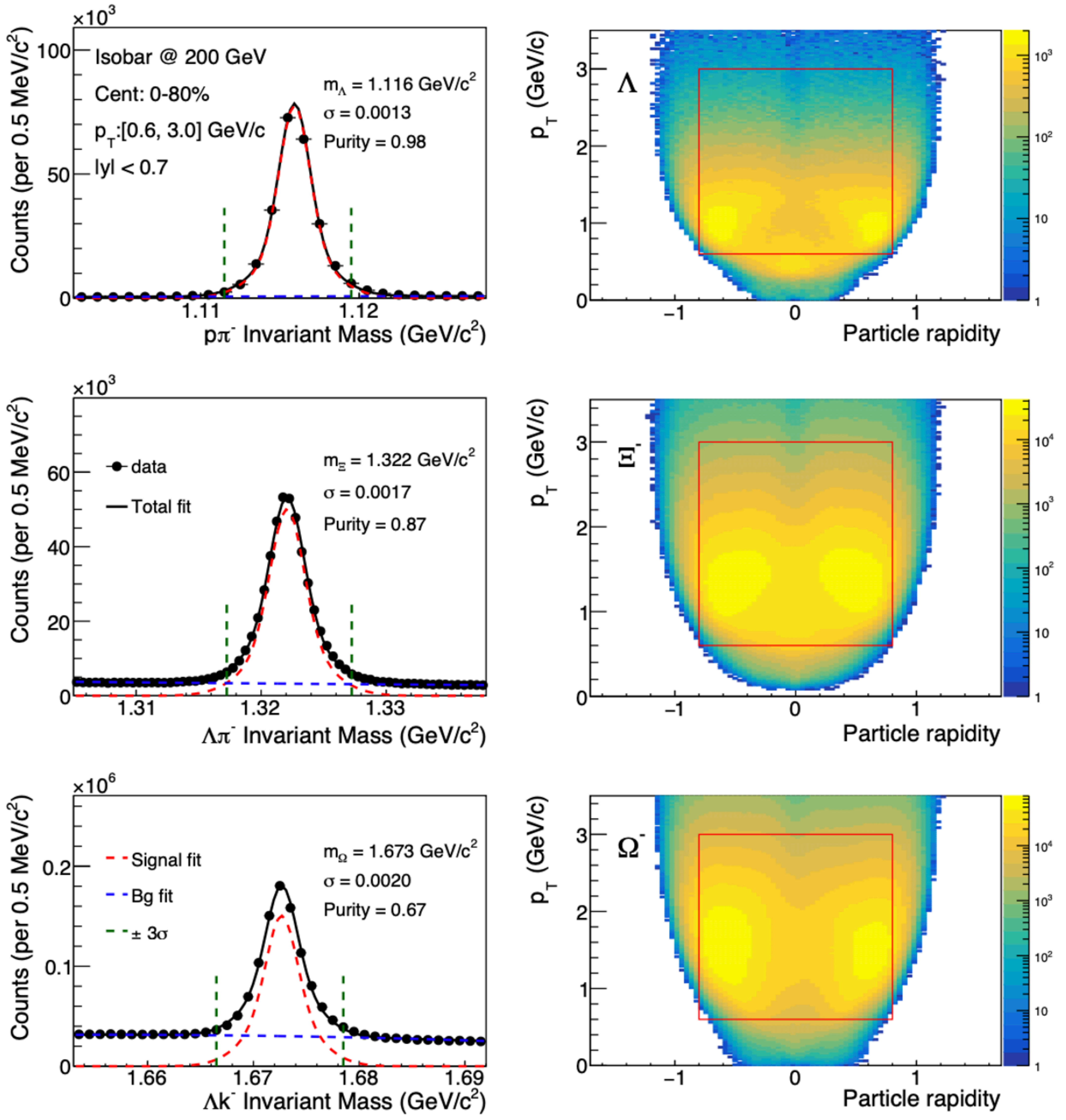
~ 2 billion minimum-bias events

- Hyperon reconstruction via Helix-swimming method

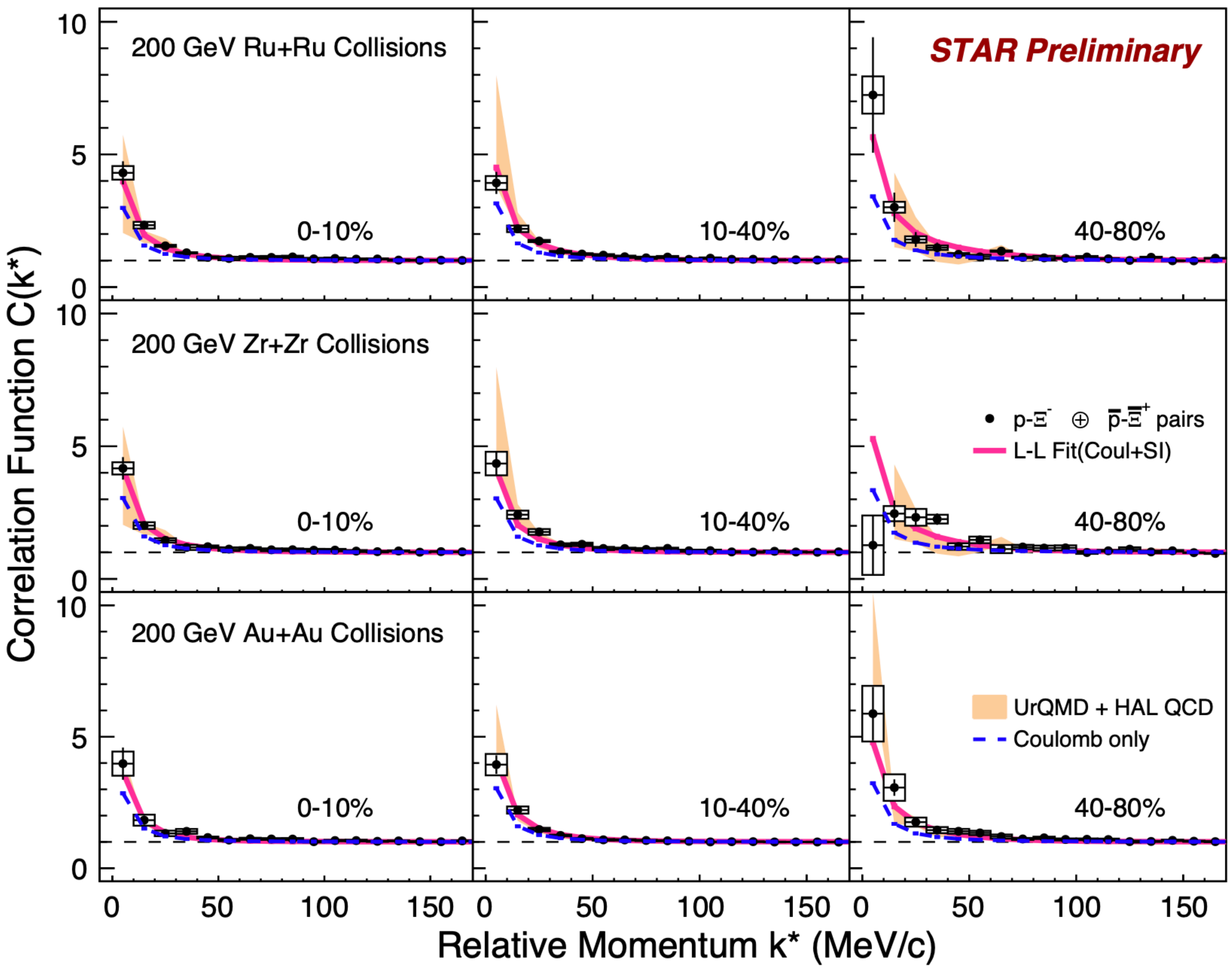
Λ -> p + π^-, BR = 63.9%

Ξ^- -> Λ + π^-, BR = 99.9%

Ω^- -> Λ + K^-, BR = 67.8%



p-Ξ^- Correlation Function @ 200 GeV

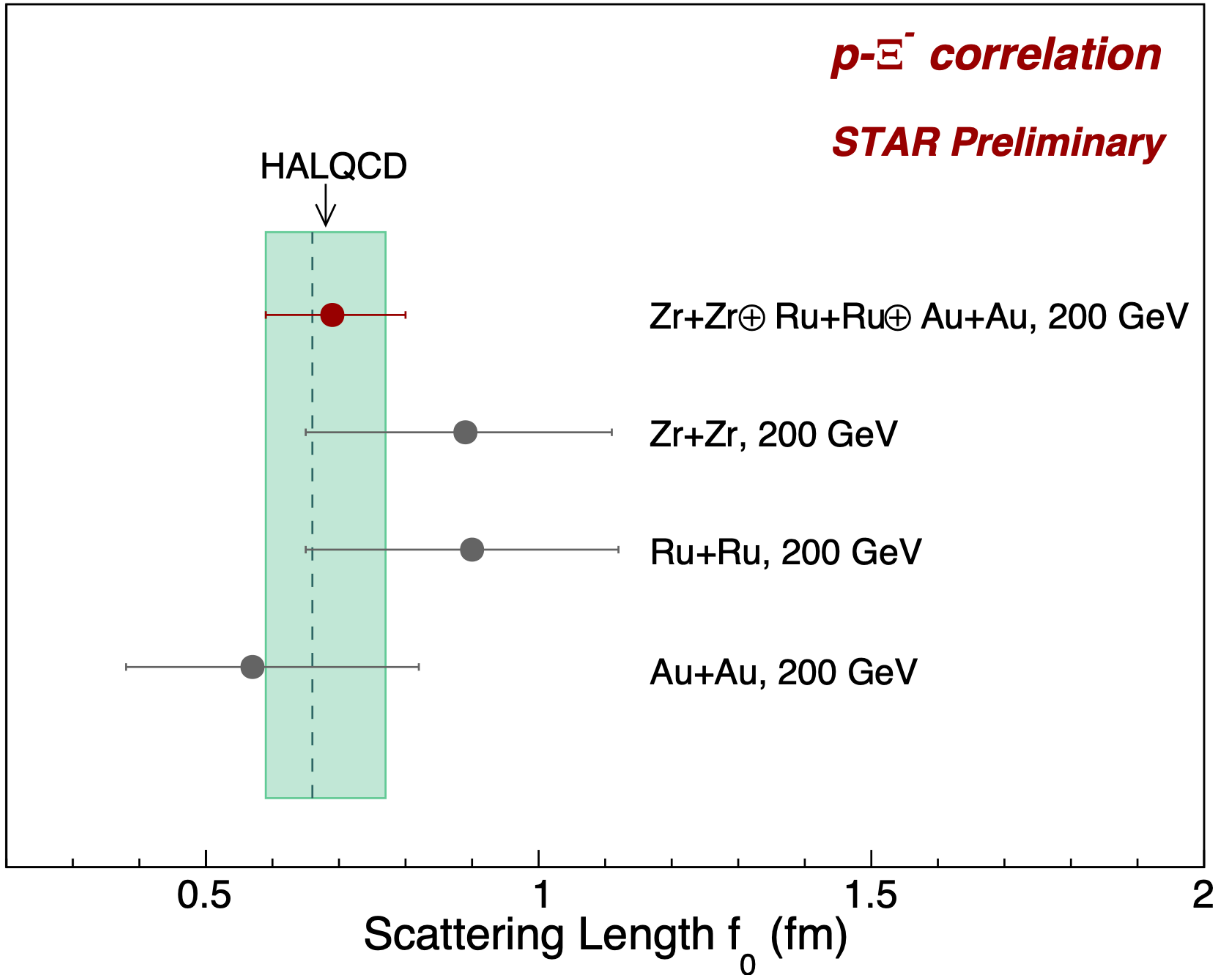


- **CFs show enhancement at low k***
- **Simultaneously fit with L-L function for 9 centralities (Au+Au and Isobar) to extract R_G, f_0 and d_0 by Bayesian method**
- **UrQMD + HAL QCD model is consistent with data**

LL Fit	f_0 (fm)	d_0 (fm)	χ^2/ndf
Ru+Ru			
Zr+Zr	$0.69^{+0.11}_{-0.10}$	$12.60^{+5.12}_{-7.00}$	1.23
Au+Au			

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

p-Ξ⁻ Interaction



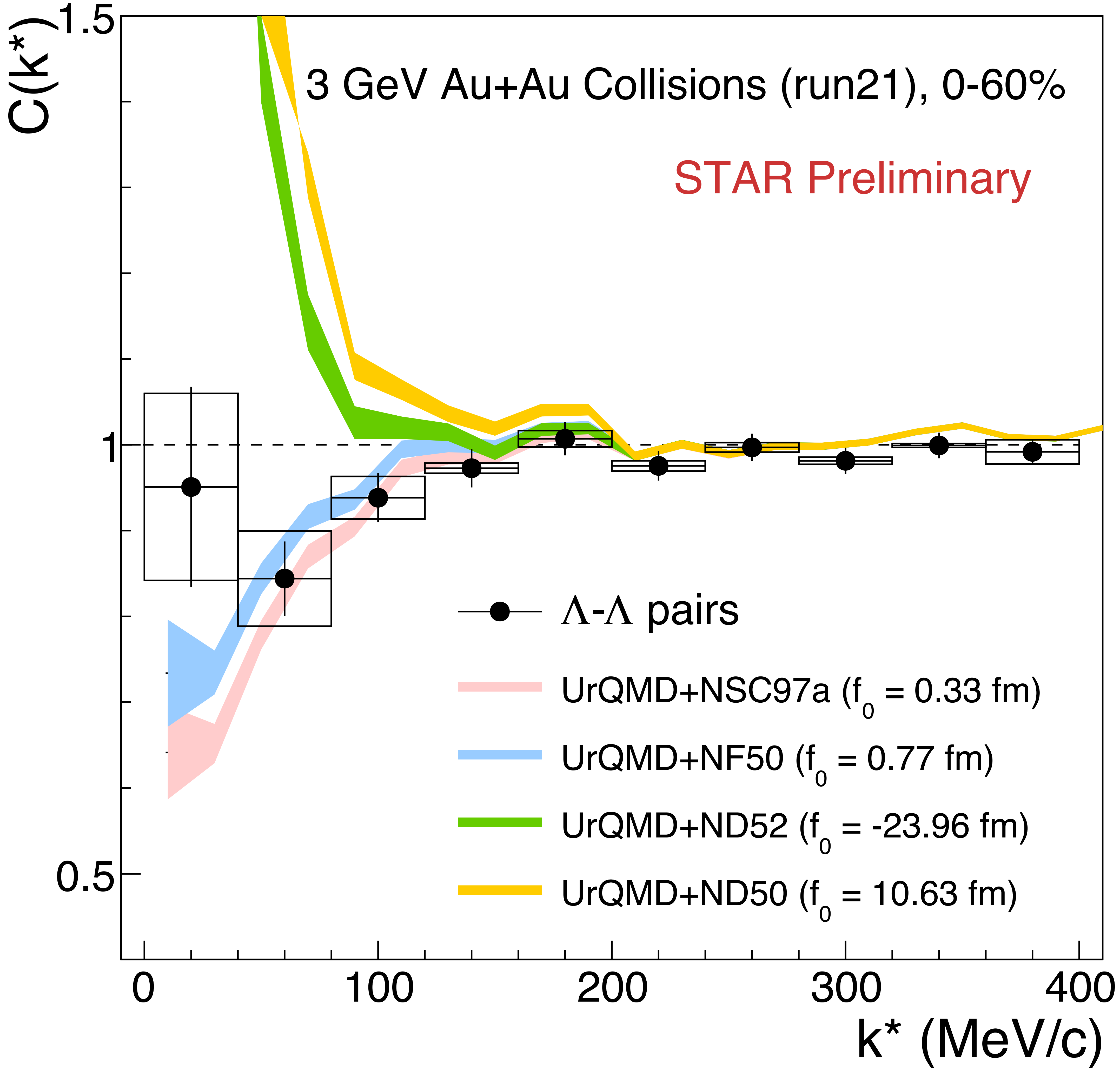
- **First experimental constraints of strong interaction parameters in p-Ξ⁻ Paris in heavy-ion collisions**
- **Extracted spin averaged scattering length:**

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

  - ***Attractive*** **strong interaction**
  - **Shallow interaction compared to p-p interaction**
  - **Consistent with HAL QCD prediction**

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

Λ-Λ Correlation Function @ 3 GeV

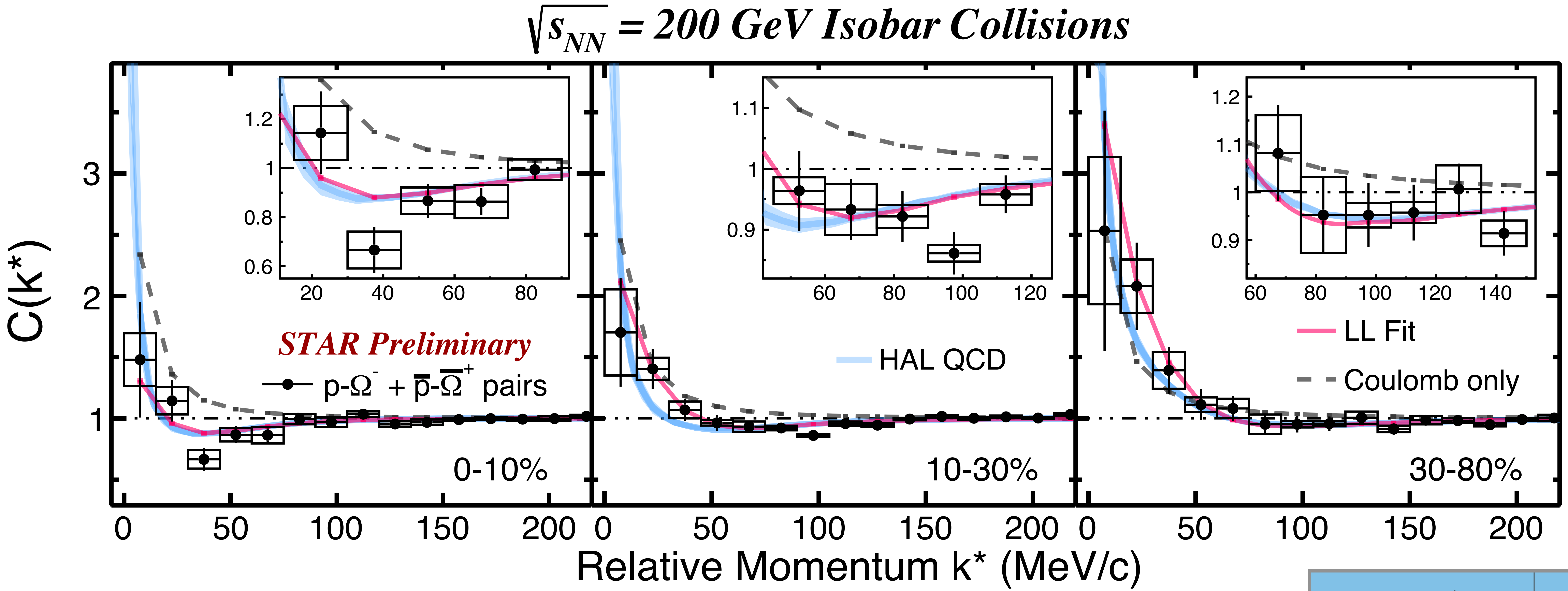


- **Λ-Λ correlation function shows suppression at small k***
- **Compared with UrQMD + potential, it is found that the simulation with positive f_0 is in better agreement with data**
  => Hints at an attractive interaction in Λ-Λ pairs
- **Need more precise data to confirm**
  => High statistics Isobar and Au+Au collisions

Potential	f_0 (fm)	d_0 (fm)	χ^2/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 @ 200 GeV

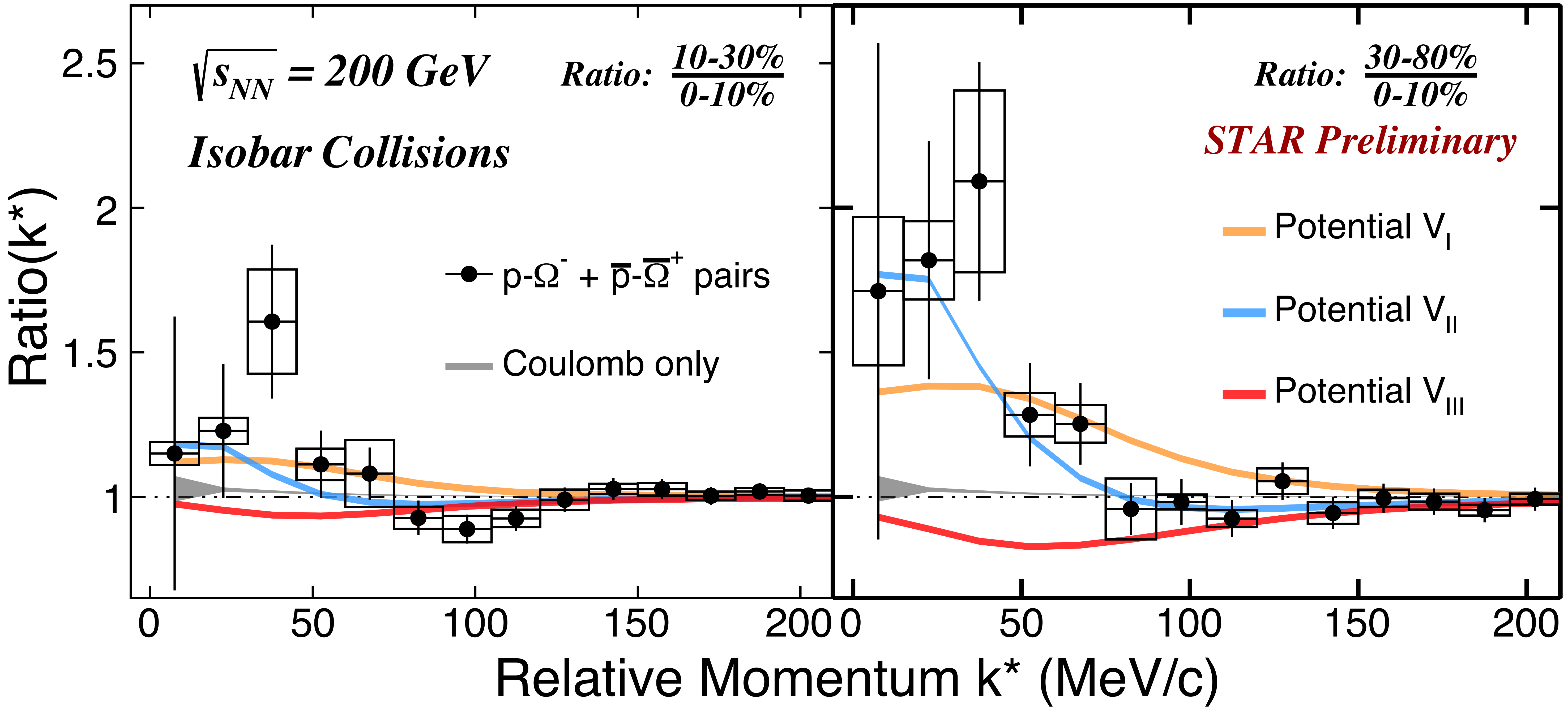


LL Fit	χ^2/ndf
Spin ave.	0.65
Quintet	0.67

- **Precise measurements of p-$\Omega^-\oplus\bar{p}$-$\bar{\Omega}^+$ correlation functions in Isobar collisions**
  - **CFs show enhancement at low k* -> mainly due to Coulomb attractive interaction**
  - **CFs show depletion at k* ~ 30-100 MeV/c -> mainly due to the strong interaction**
- **Simultaneously fit with L-L function for 3 centralities to extract R_G, f_0 and d_0 by Bayesian method**
- **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^- Correlation Function Ratio

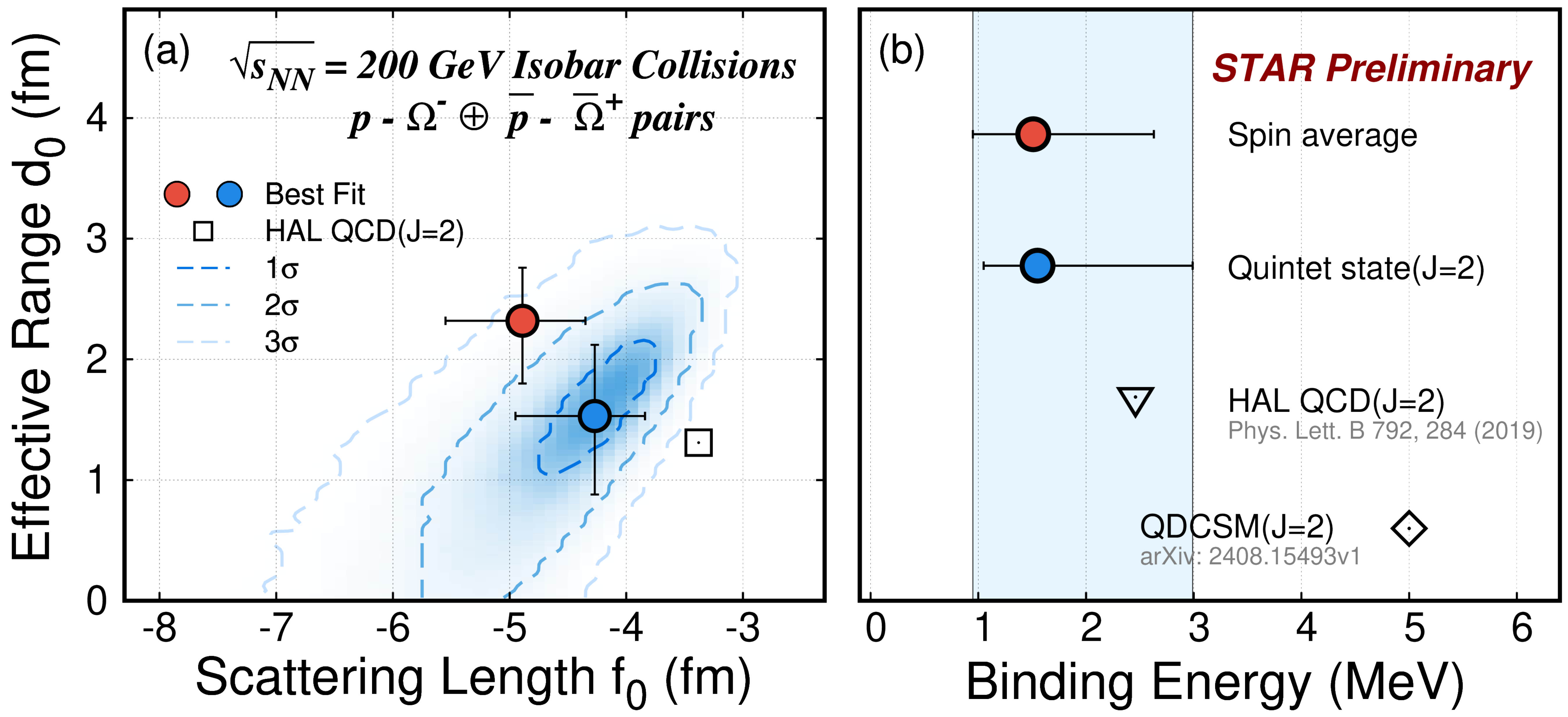


Type	f_0 (fm)	d_0 (fm)	BE (MeV)	χ^2/ndf	p-value	
V_I [1]	1.12	1.16	--	1.66	0.014	No Bound
V_{II} [2]	-3.38	1.31	2.15	0.76	0.812	Shallow Bound
V_{III} [1]	-1.29	0.65	26.9	2.02	0.001	Deeply Bound

- **By taking CF ratio, Colomb effect can be largely canceled**
- **CF ratio shows enhancement at low k* and depletion around k* ~ 100 MeV/c**
  - **Due to the presence of shallow bound state**
- **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



	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

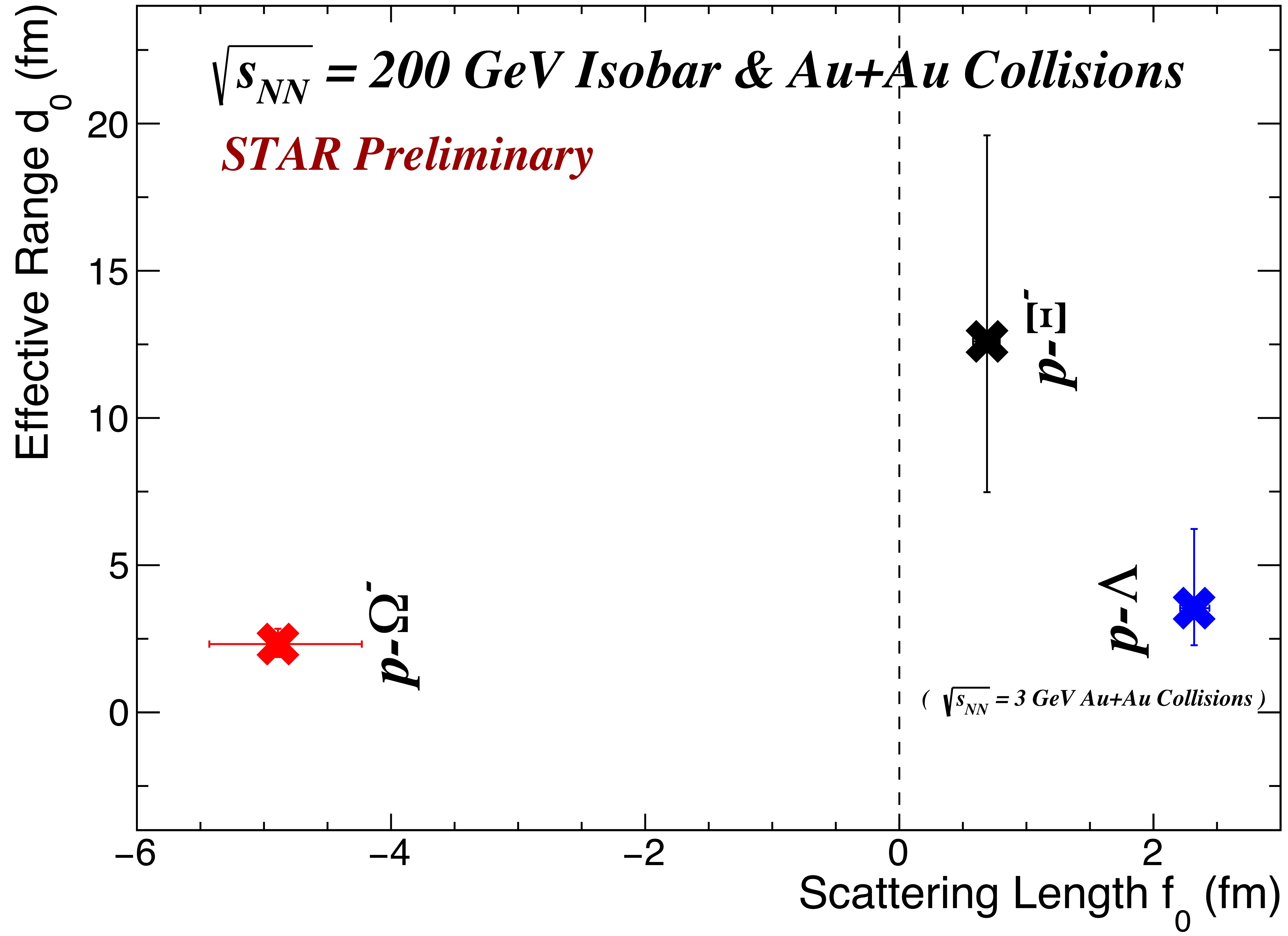
- **First experimental constraints in heavy-ion collisions of strong interaction parameters in p-Ω⁻ pair**
- **Extracted negative f_0 ($|f_0| > 2d_0$) by Spin average method and Quintet method**
  - **First experimental evidence of Strange Dibaryon**
- **Calculate Binding Energy (BE) via Betha formula:**

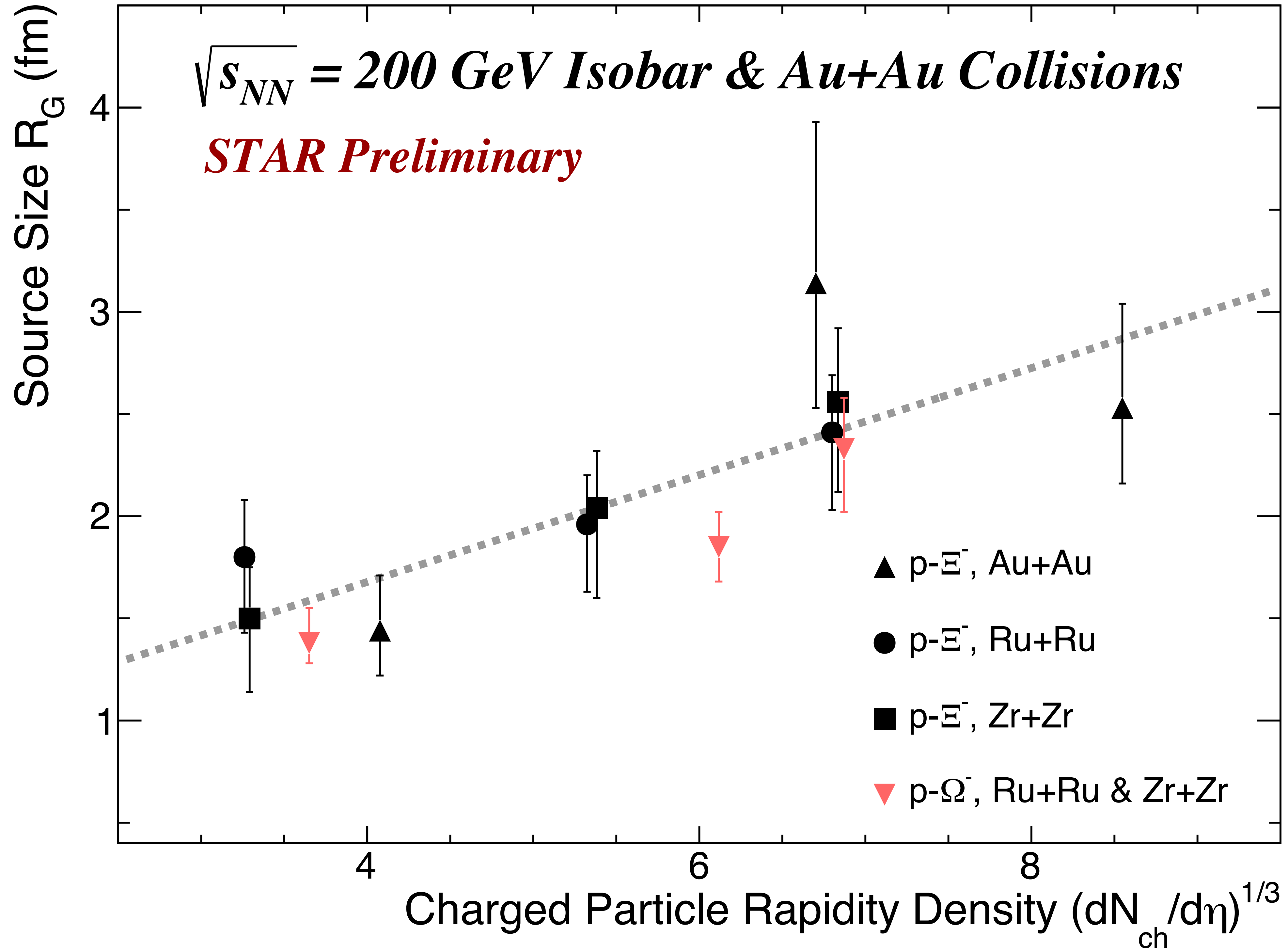
Reduced mass: $m_{p\Omega} = \dfrac{m_p m_\Omega}{m_p + m_\Omega}$

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

  - **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 dependence $R_G^{central} > R_G^{peripheral}$)

Summary

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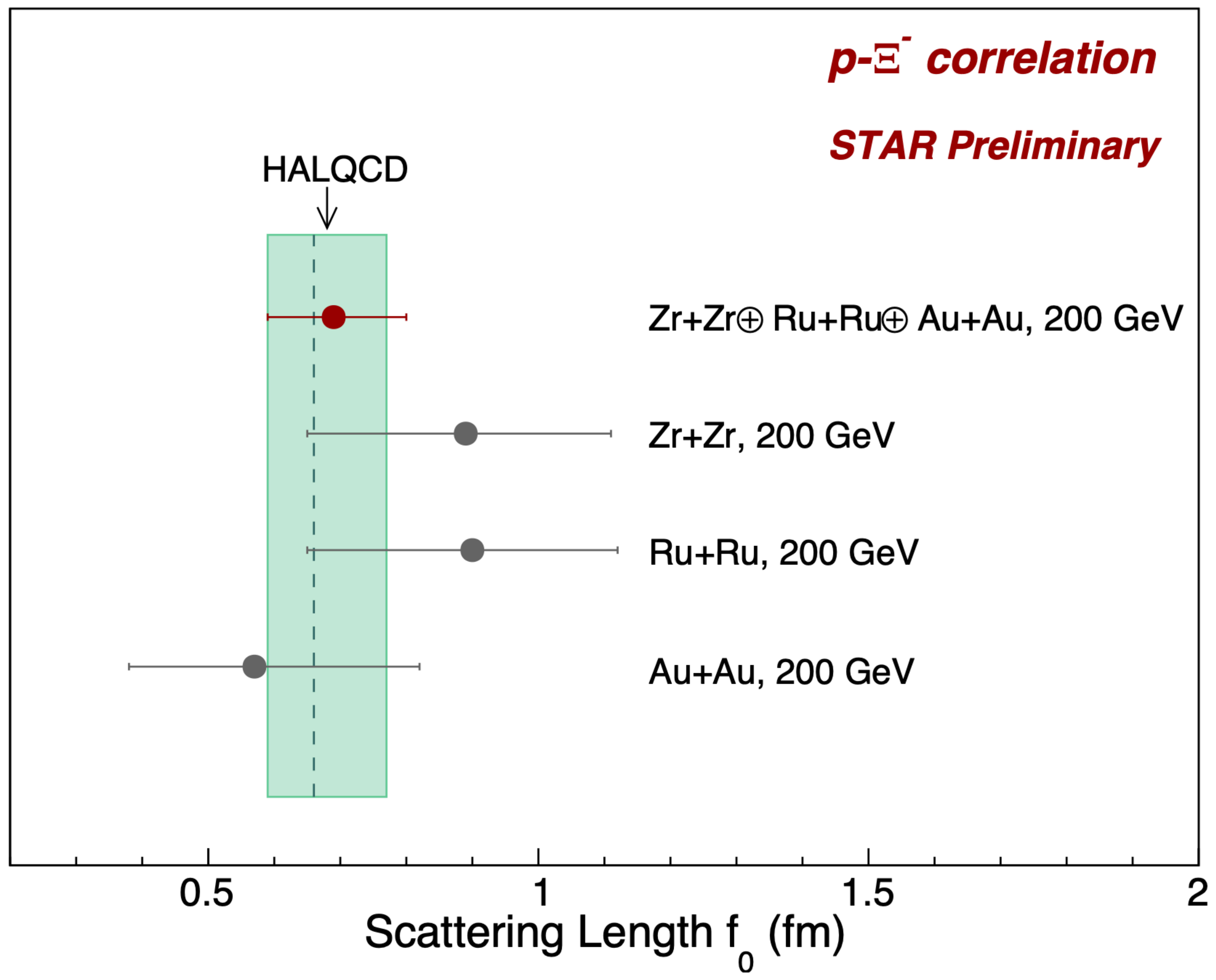
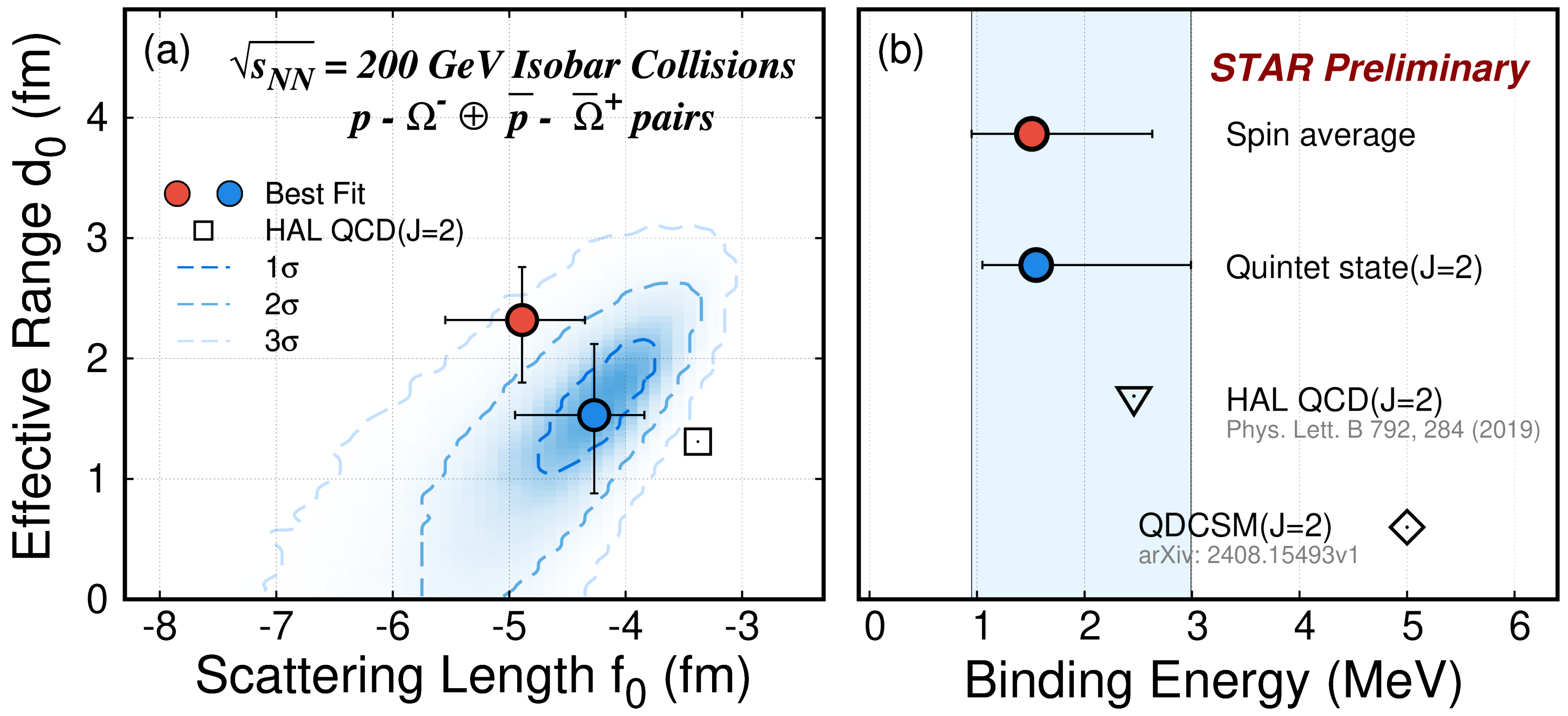
- Measured the correlation function of $p-\Xi^{-} \oplus \bar{p}-\bar{\Xi}^{+}$, $\Lambda-\Lambda$ and $p-\Omega^{-} \oplus \bar{p}-\overline{\Omega}^{+}$ at STAR
- Extracted strong interaction parameters through L-L model
  - First experimental results of $p-\Xi^{-}$ interaction -> Shallow attractive interaction
  - $\Lambda-\Lambda$ hints at weakly attractive interaction
  - First experiment evidence of Strange-Dibaryon in $p-\Omega^{-}$ channel
- Extracted Binding Energy BE = $1.6^{+1.4}_{-0.5}$ MeV in $p-\Omega^{-} \oplus \bar{p}-\overline{\Omega}^{+}$ pair





Thanks for your attention!