Search for Strange Dibaryons with Baryon Correlations at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV in Nuclear Collisions

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STAR区域研讨会, 中国重庆, Oct.10th – 15th, 2024

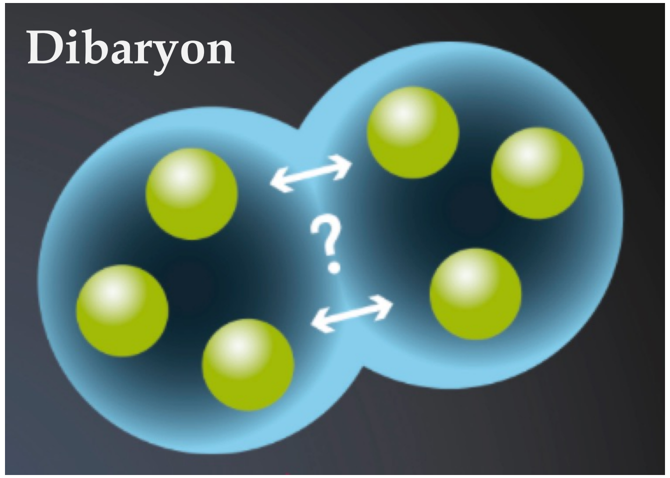
Outline

- **Motivation**
- **Femtoscopy & Correlation Function**
- **RHIC-STAR Experiment & Analysis Details**
- **Lednicky-Lyuboshitz model**
- **Results**
  - $|S| = 2$: $p - \Xi$ & $\Lambda - \Lambda$ correlation
  - $|S| = 3$: $p - \Omega$ correlation
- **Summary & outlook**

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	$\Lambda K^- + \Lambda K^-$



- The possible channel:
  - H-Dibaryon ⇔ $p + \Xi$
  - H-Dibaryon ⇔ $\Lambda + \Lambda$
  - $N\Omega$ Dibaryon ⇔ $N + \Omega$

- 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

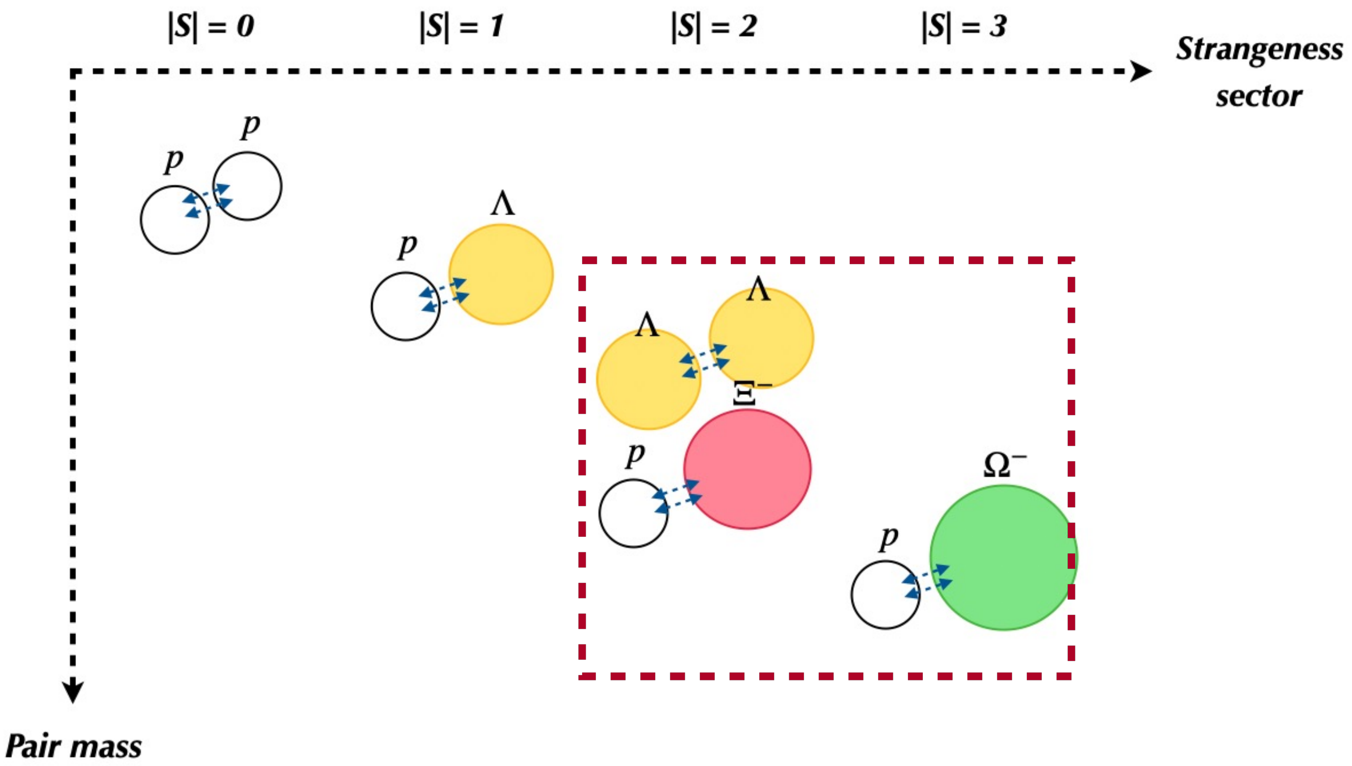
Phys. Rev. C 84, 064910 (2011)

Experiment measurements are needed !

Motivation

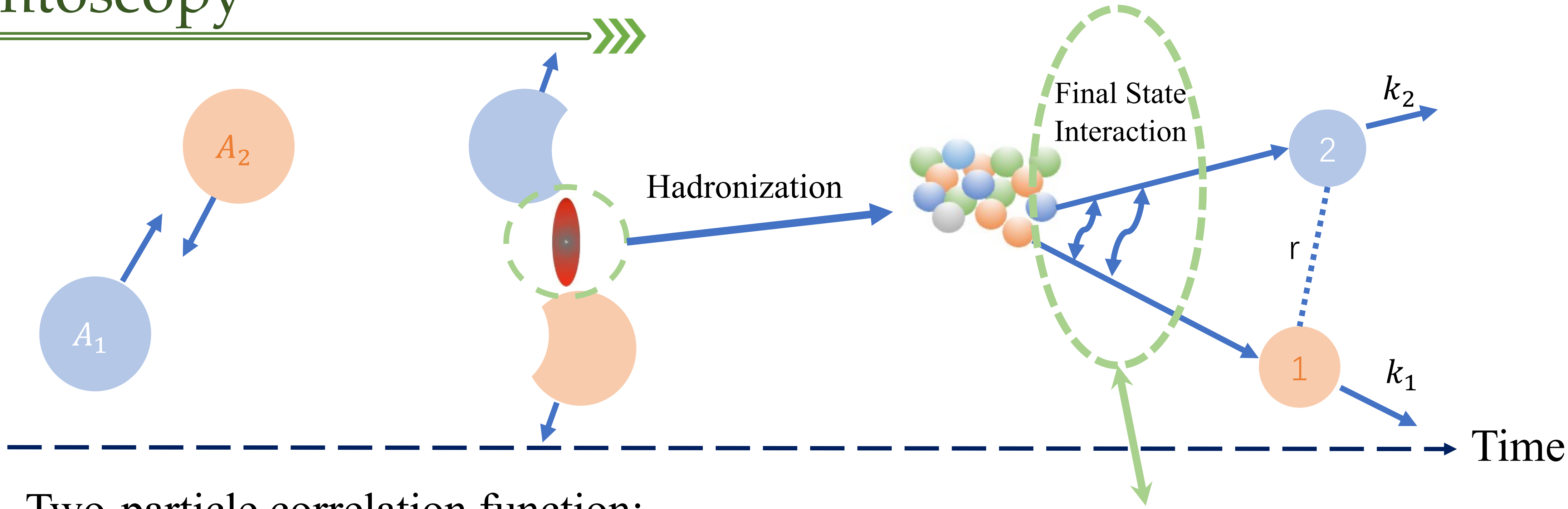
- *<u>Momentum correlation (Femtoscopy)</u>*, a powerful tool to study strong interaction and to search possible bound state

- At top RHIC energy, large amount of hyperons are produced, provide opportunity to study various Y-N/Y-Y correlations



Phys. Rev. C 84, 064910 (2011)

Femtoscopy



- Two-particle correlation function:

Model **Experimental**

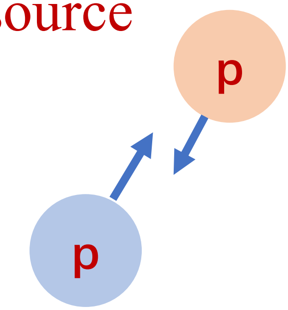
$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$S(\vec{r})$: 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

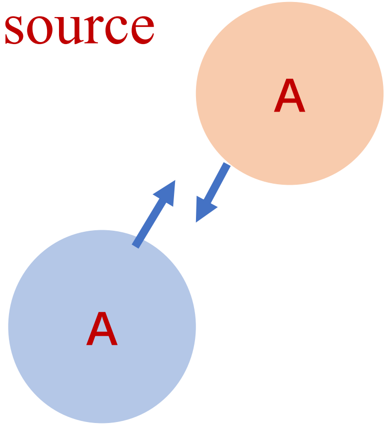
Depends on ...
- Emission source
- Strong interaction
- Coulomb interaction
- Quantum statistics (Fermion, boson)

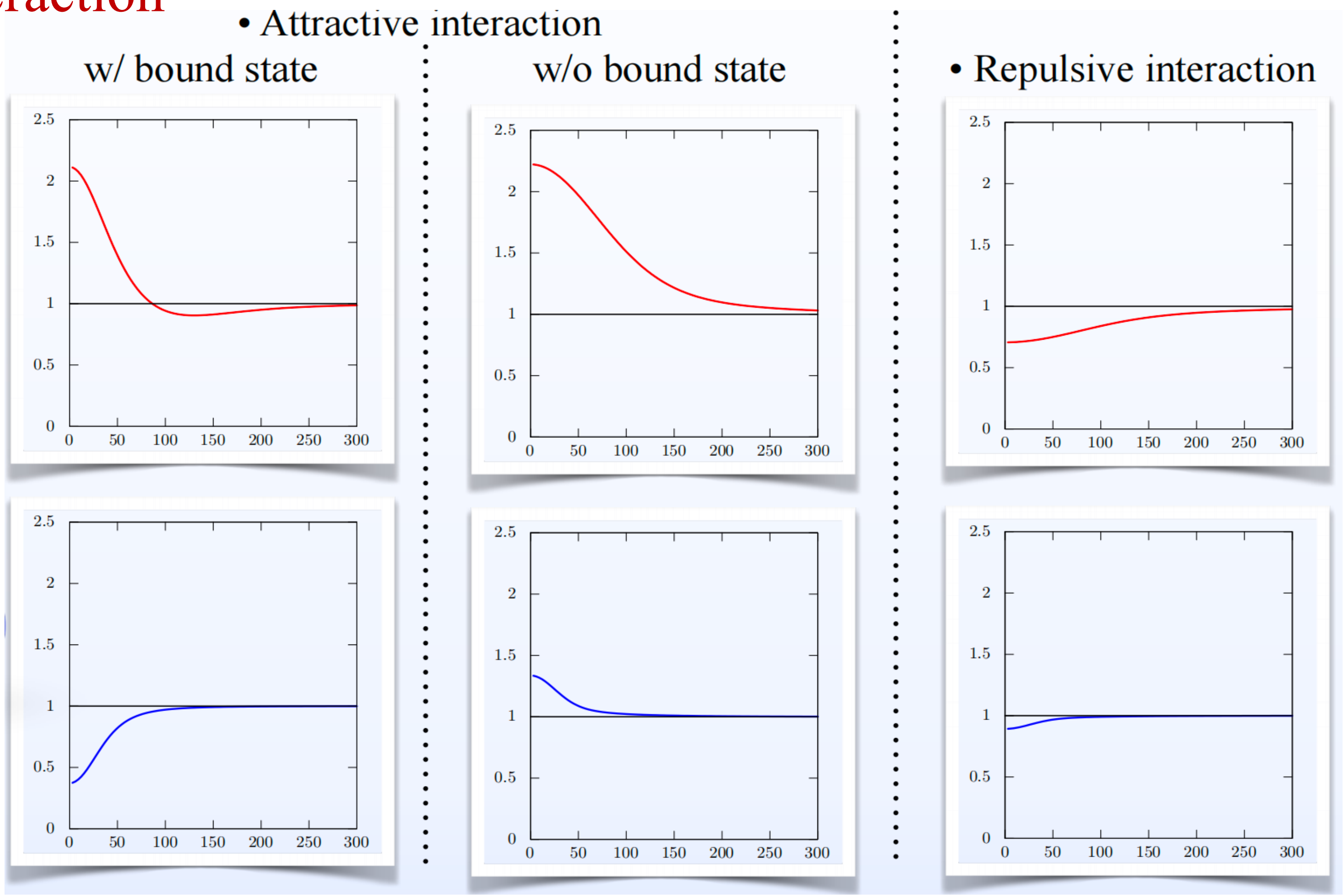
Femtoscopy

- Just consider strong interaction
- $C(k^*)$ shape: related to interaction
  - Small source

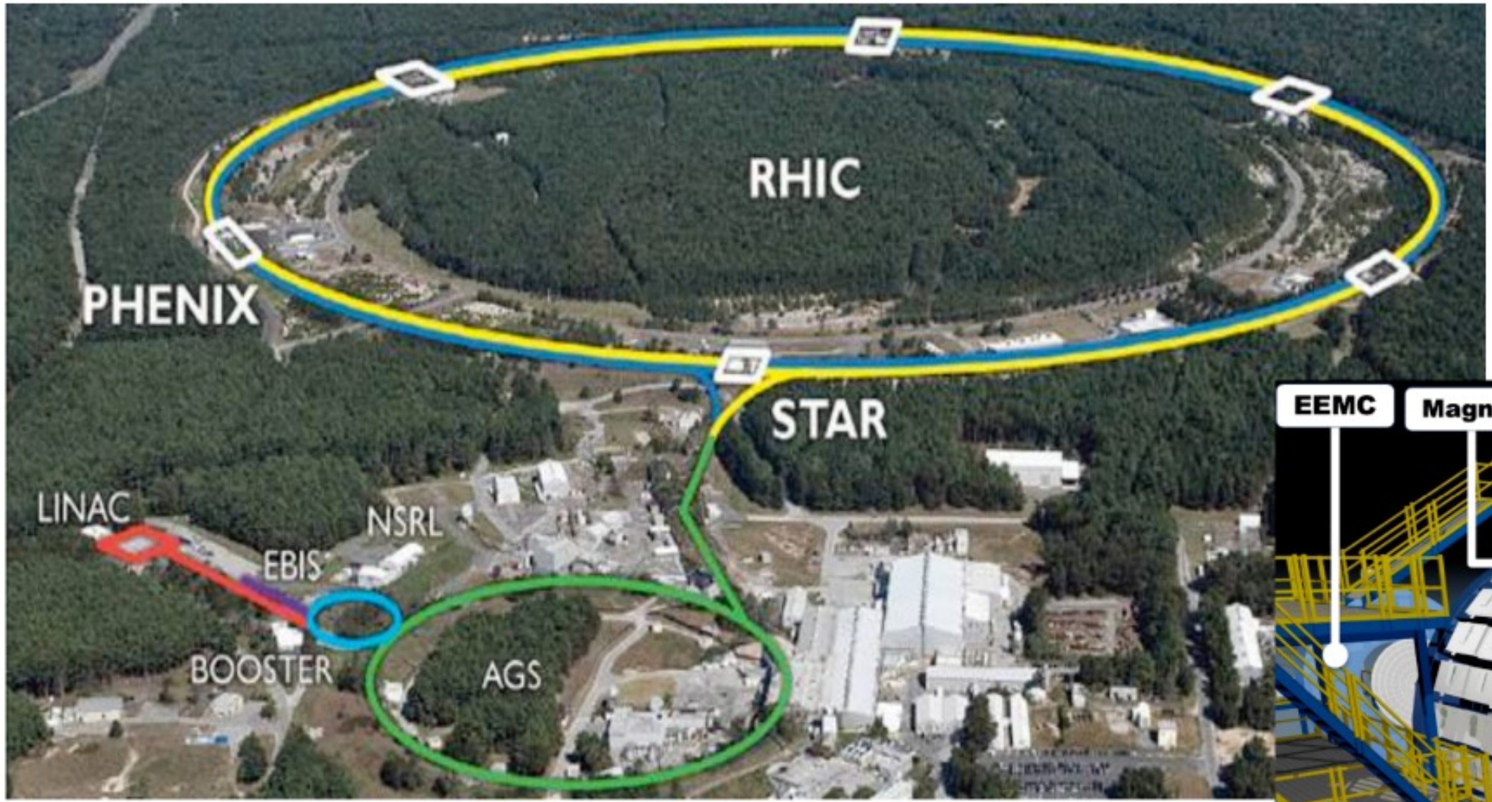


  - Large source



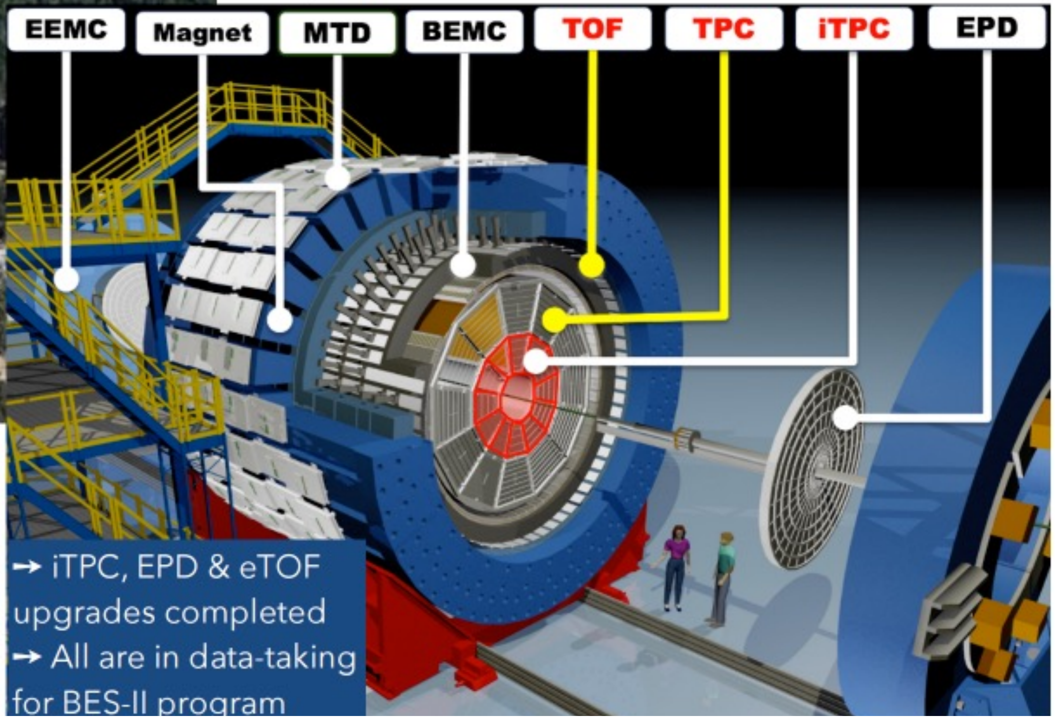


RHIC-STAR Experiment



Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Laboratory, Upton
→ Au+Au, p+p, d+Au, Zr+Zr, Ru+Ru ..
→ Beam Energy Scan Program I, II

$\sqrt{s_{NN}}$ = 3.0 - 200 GeV



The Solenoid Tracker At RHIC (STAR)
→ Excellent Particle Identification
→ Large, Uniform Acceptance at Mid-rapidity

Analysis details

- Dataset:

Isobar collisions (Ru+Ru, Zr+Zr) @ 200 GeV

~ 4 billion minimum-bias events

Au+Au collisions @ 200 GeV (run11, run14, run16)

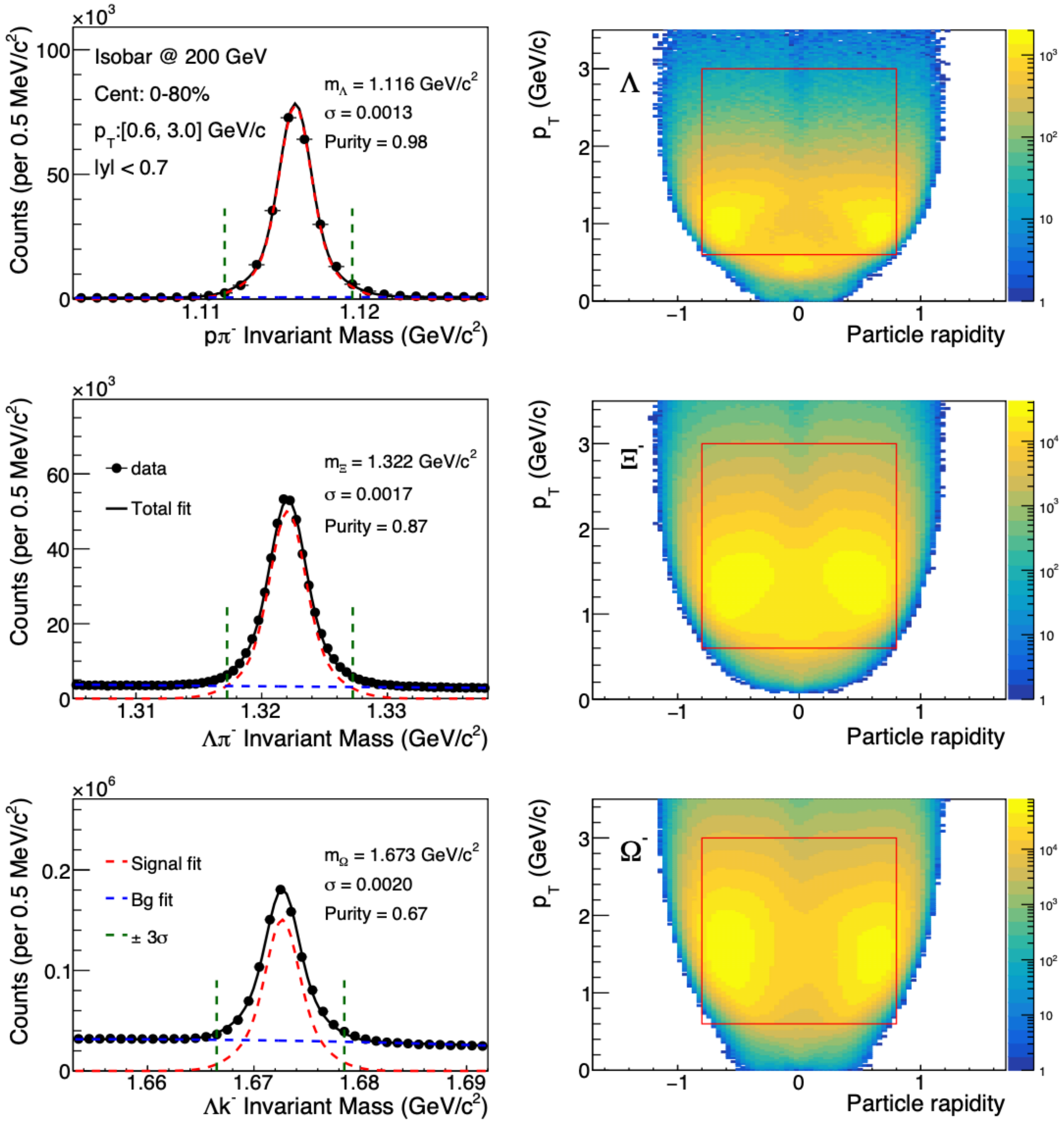
~ 2 billion minimum-bias events

- Hyperon reconstruction via Helix-swimming method

Λ-> p + π^- , BR = 63.9%
Ξ^--> Λ + π^- -> p + π^- + π^- , BR = 99.9%
Ω^--> Λ + k^- -> p + π^- + k^- , BR = 67.8%

- High purity achieved in selected kinetic region

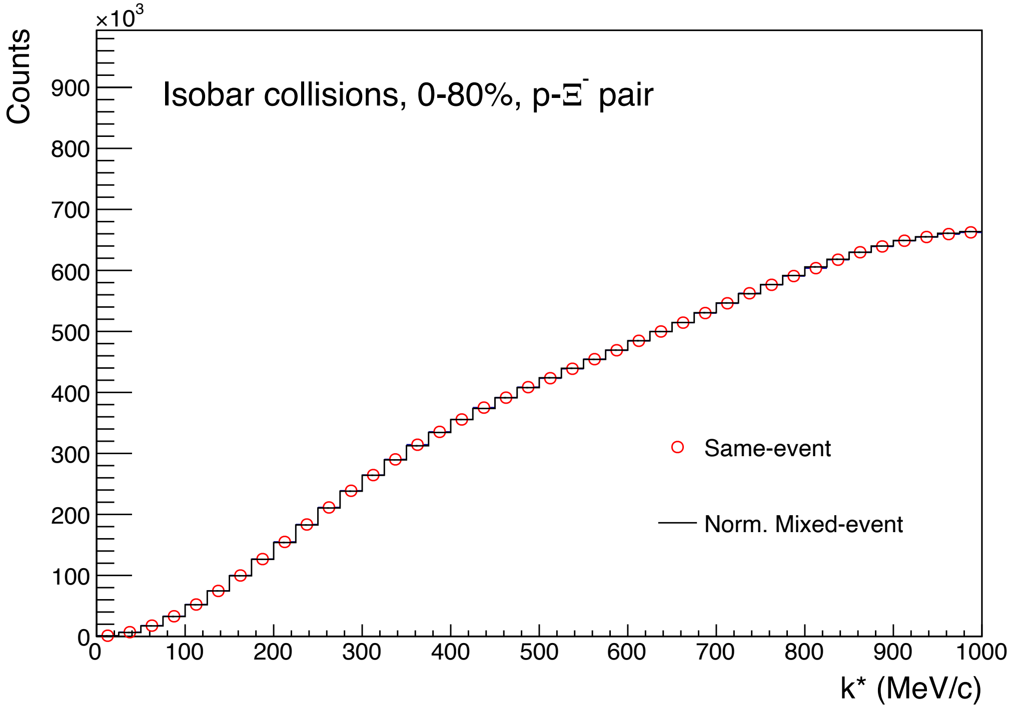
(p_T: [0.6, 3.0] GeV/c, |y| < 0.7)

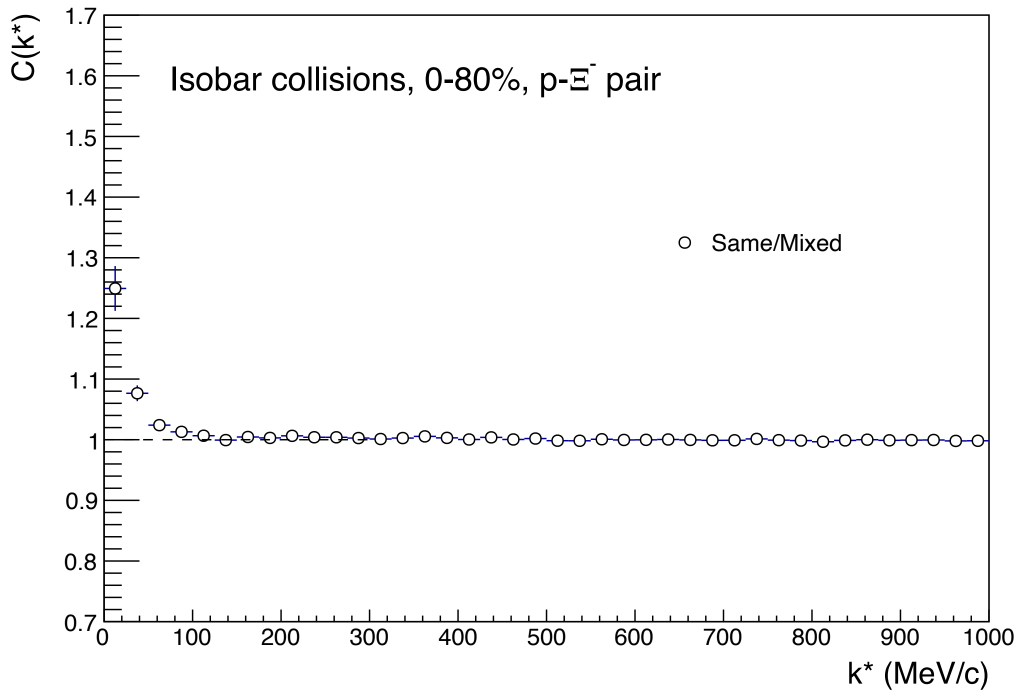


Correlation function

Model **Experimental**

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





- Count the correlated pairs in same-event and un-correlated pairs in mixed-event
- Normalize range: typically far away from signal region, k* > 200 MeV/c
- Need to be corrected by: detector effect, feed-down effect .... (backup)

Lednicky-Lyuboshitz (L-L) Model

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*

⇒ Formalism with Lednicky-Lyuboshitz (L-L) approach

- Only consider s-wave
- Smoothness approximation for source function
- Effective range expansion for $\Psi(r^*, k^*)$
- Static and spherical Gaussian source assumed
- Coulomb effect included

Physics quantity:

1. R_G: Spherical Gaussian source size
2. f_0: Scattering length
3. d_0: Effective range

$f_0 > 0$:attractive interaction

$f_0 < 0$:repulsive interaction
or
bound state ($|f_0| > 2d_0$)

Lednicky-Lyuboshitz (L-L) Model

- Correlation function:

$$C(\boldsymbol{k}^*) = \int d^3r^* S(\boldsymbol{r}^*) |\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$$

- Scattering amplitude (without Coulomb):

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

- Scattering amplitude (with Coulomb):

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

- Different spin states:

$$C = w_i C_i + \mathrm{w_j} \mathrm{C_j}$$

$\boldsymbol{f_0}$: scattering length

$\boldsymbol{d_0}$: effective range

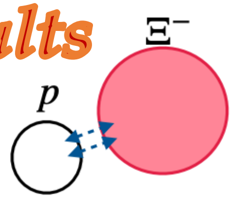
a_c: Bohr radius, $\eta = (k^* a_c)^{-1}$

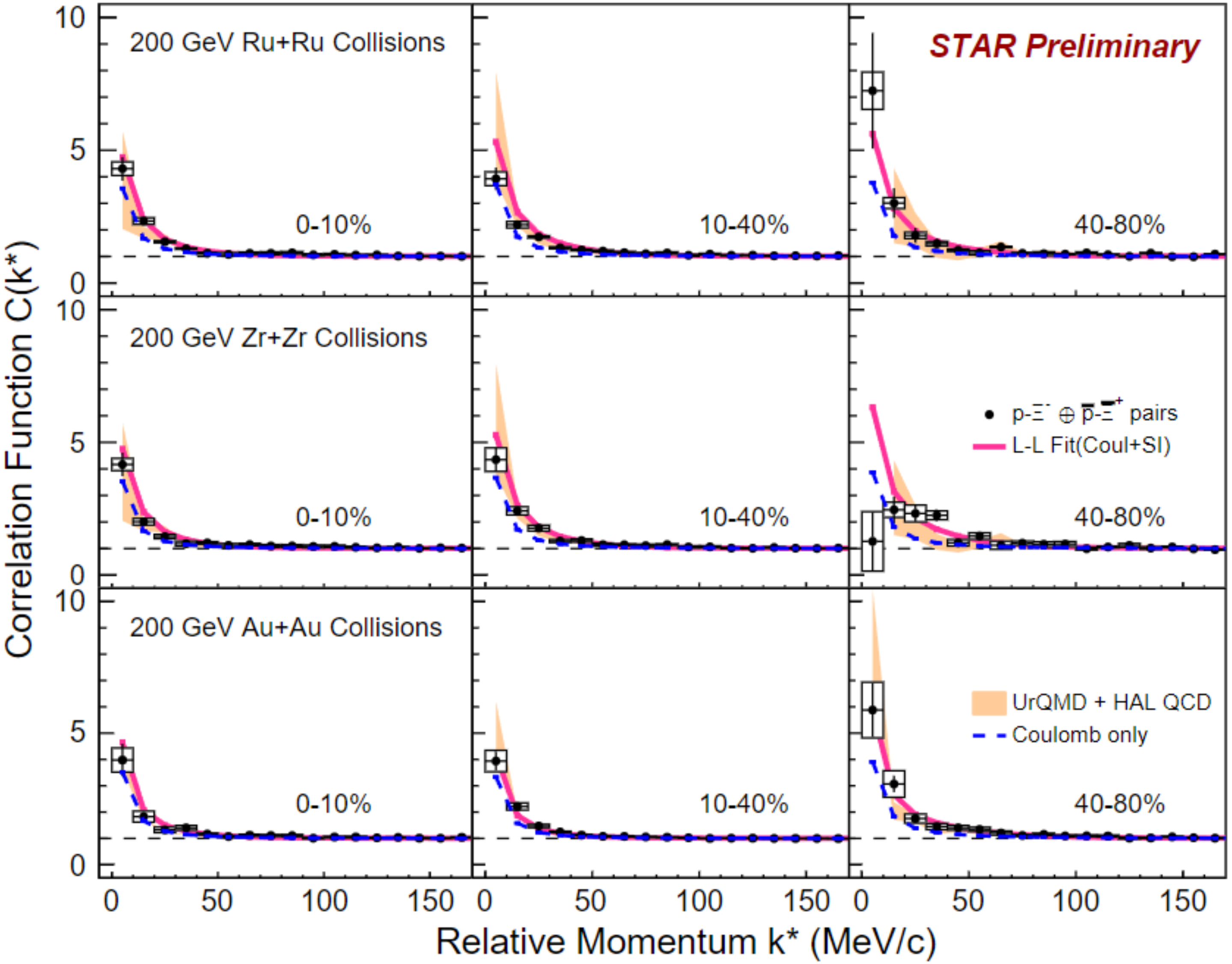
A_c, h: Coulomb interaction

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

$p-\Xi^-$ Correlation ($|S| = 2$)

New results





☆ Measure p-Ξ^- CFs at 200 GeV in Au+Au and Isobar collisions

☆ CFs show enhancement at low k*

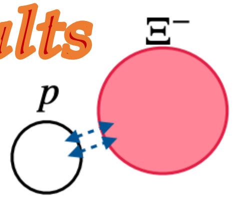
☆ Simultaneously fit with L-L function for different centralities in each collision system to extract R_G, f_0 and d_0 by Bayesian method

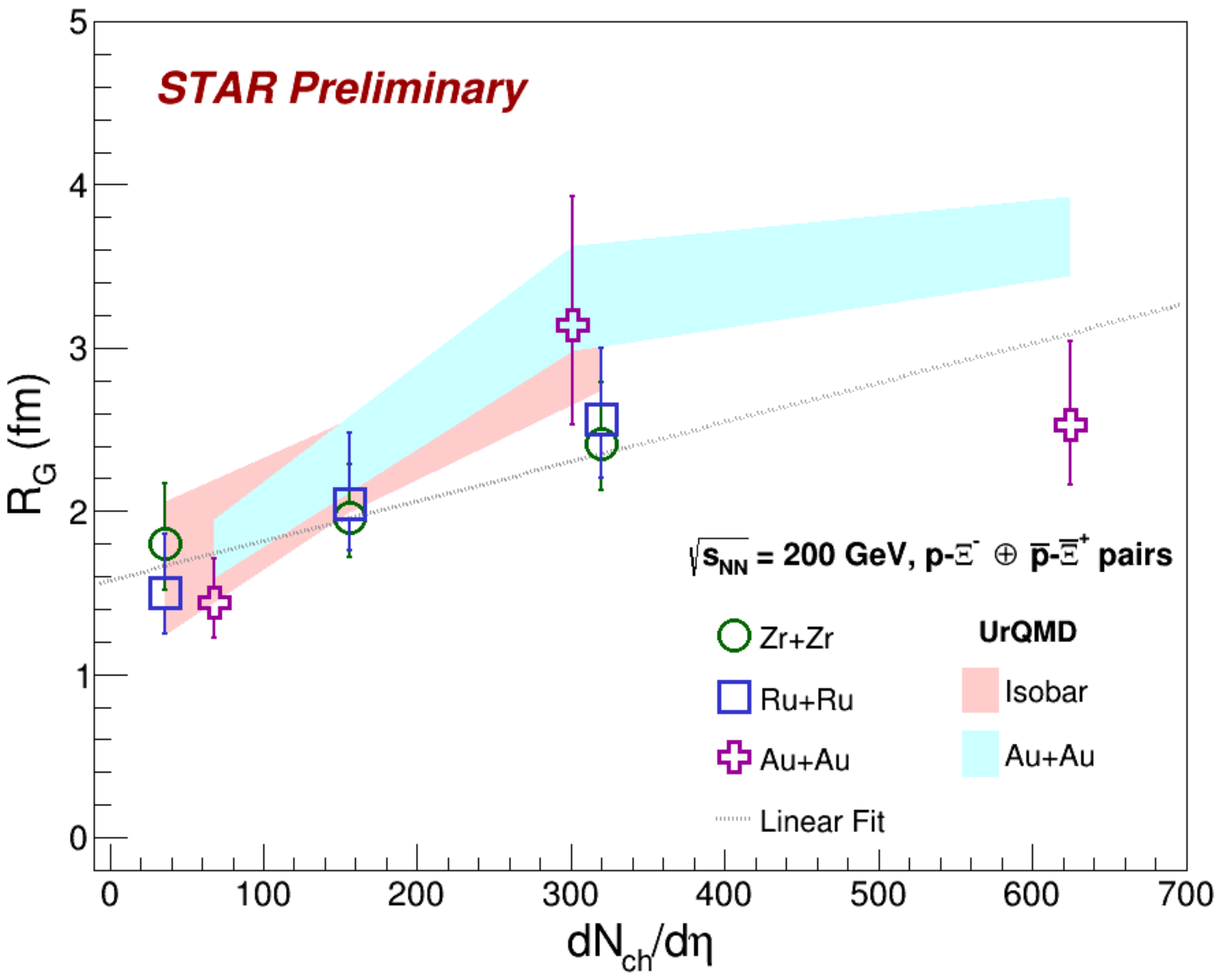
☆ UrQMD + HAL QCD model is consistent with data

◎ Particle phase space provided by UrQMD
◎ Interaction potential provided by HALQCD

$p-\Xi^-$ Correlation (|S| = 2)

New results





☆ Centrality dependence: $R_G^{central} > R_G^{peripheral}$

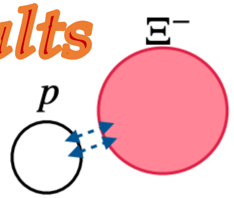
☆ R_G increase as charged multiplicity increase for these collisions

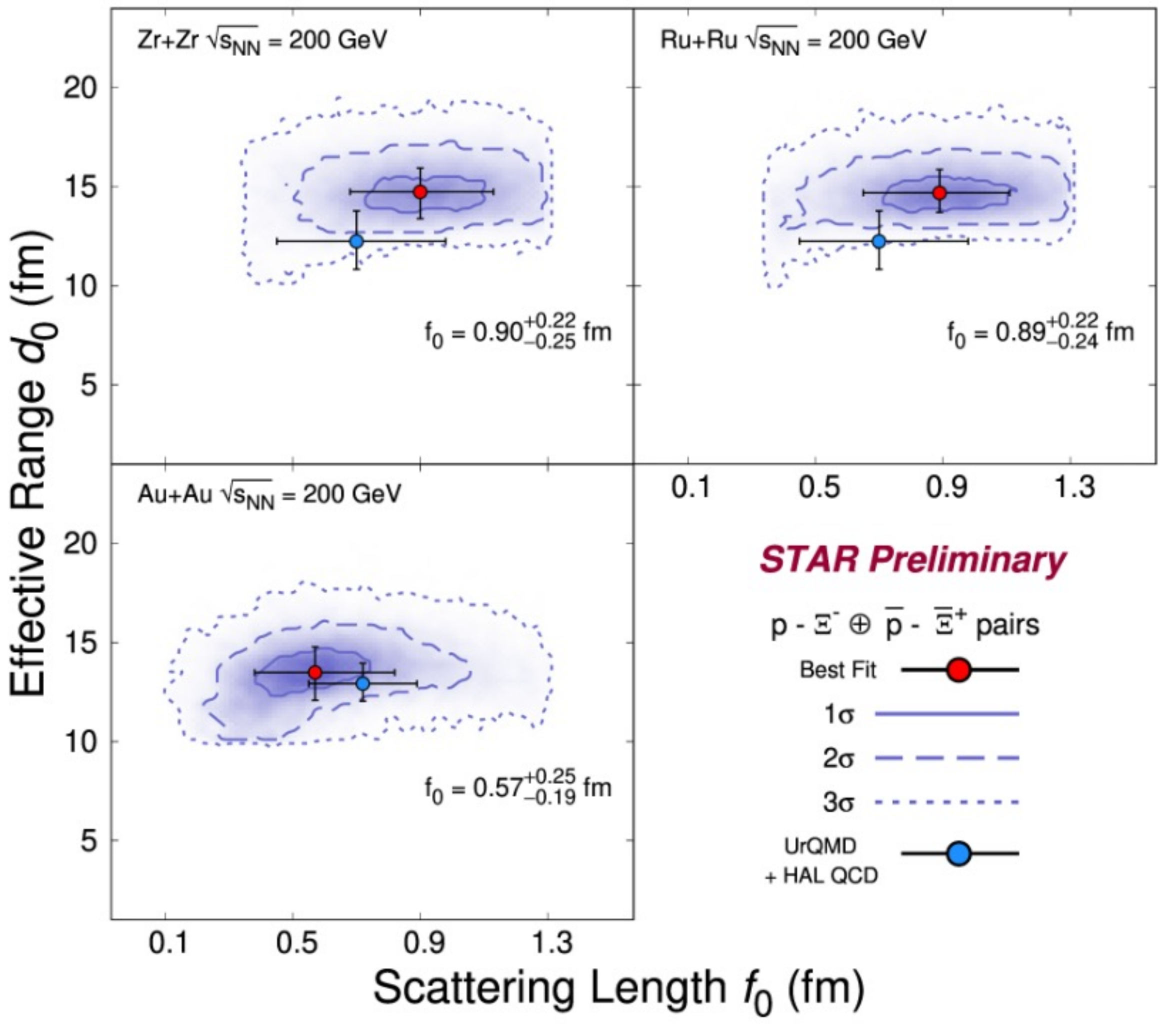
☆ R_G from Au+Au and Isobar collisions follow a linear trend

☆ Consistent results obtained from UrQMD model

$p-\Xi^-$ Correlation (|S| = 2)

New results

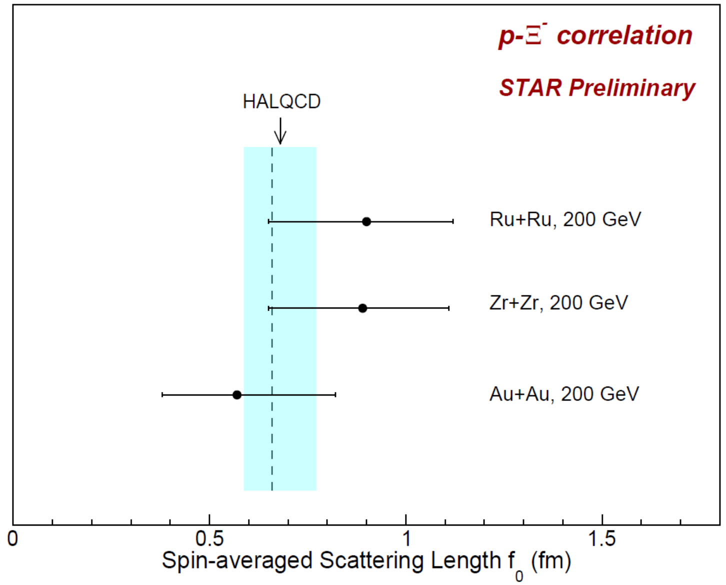




☆ First experimental measurements in heavy-ion collisions of strong interaction parameters in p-Ξ^- pairs

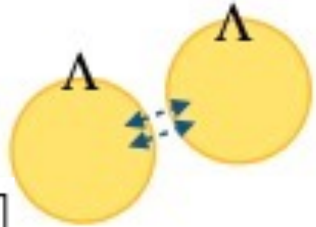
☆ f_0 and d_0 are consistent with those extracted from UrQMD + HAL QCD model within 1sigma

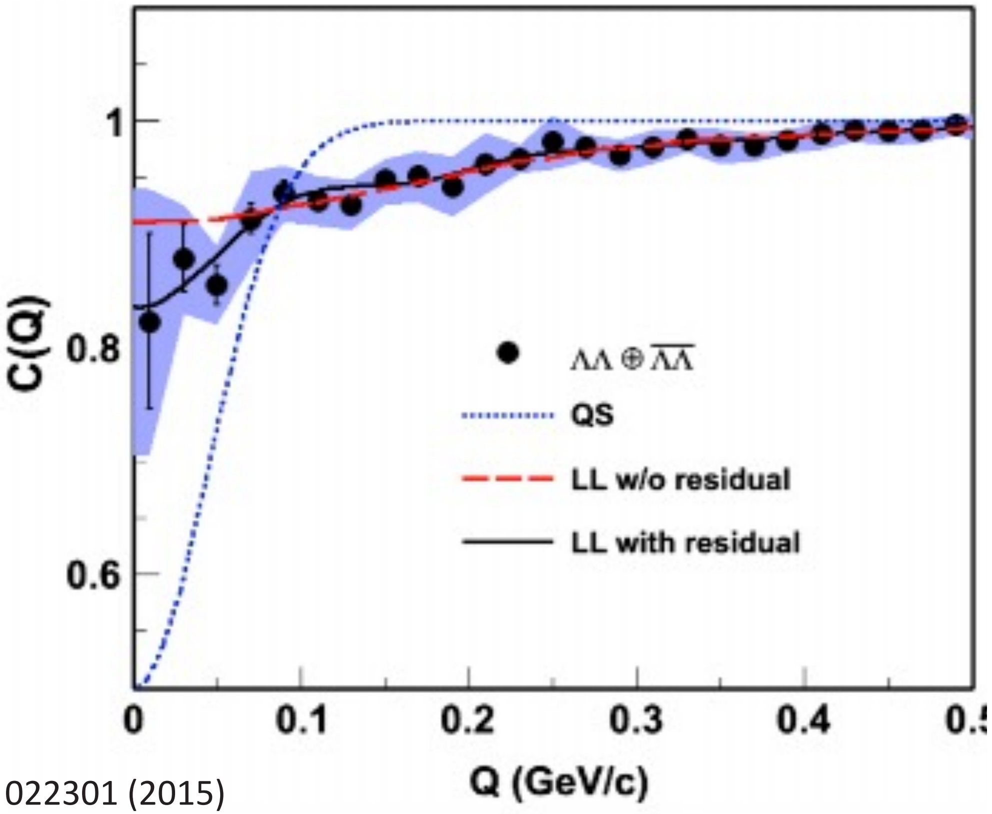
☆ The f_0 measured from Isobar and Au+Au collisions are consistent with the prediction of HAL QCD



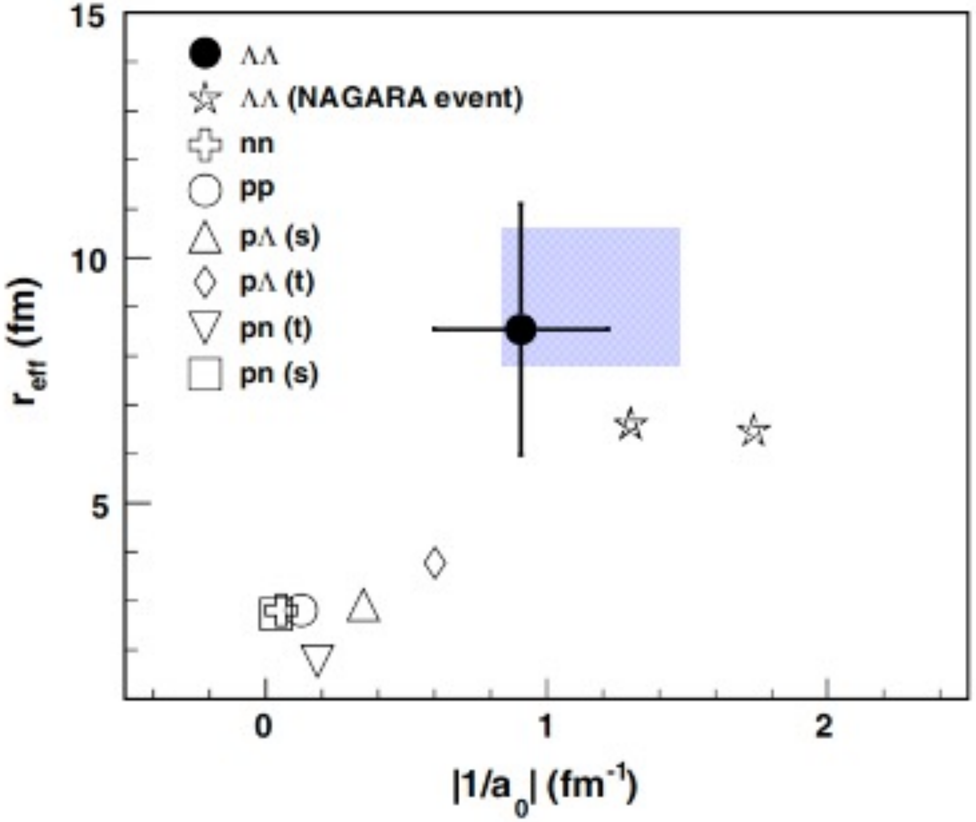
*Edge of f_0 - d_0 contours are shown with Bezier smooth to improve the visibility

Λ-Λ Correlation (|S| = 2)





PRL 114, 022301 (2015)

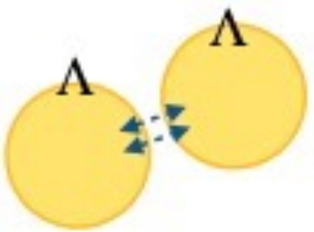


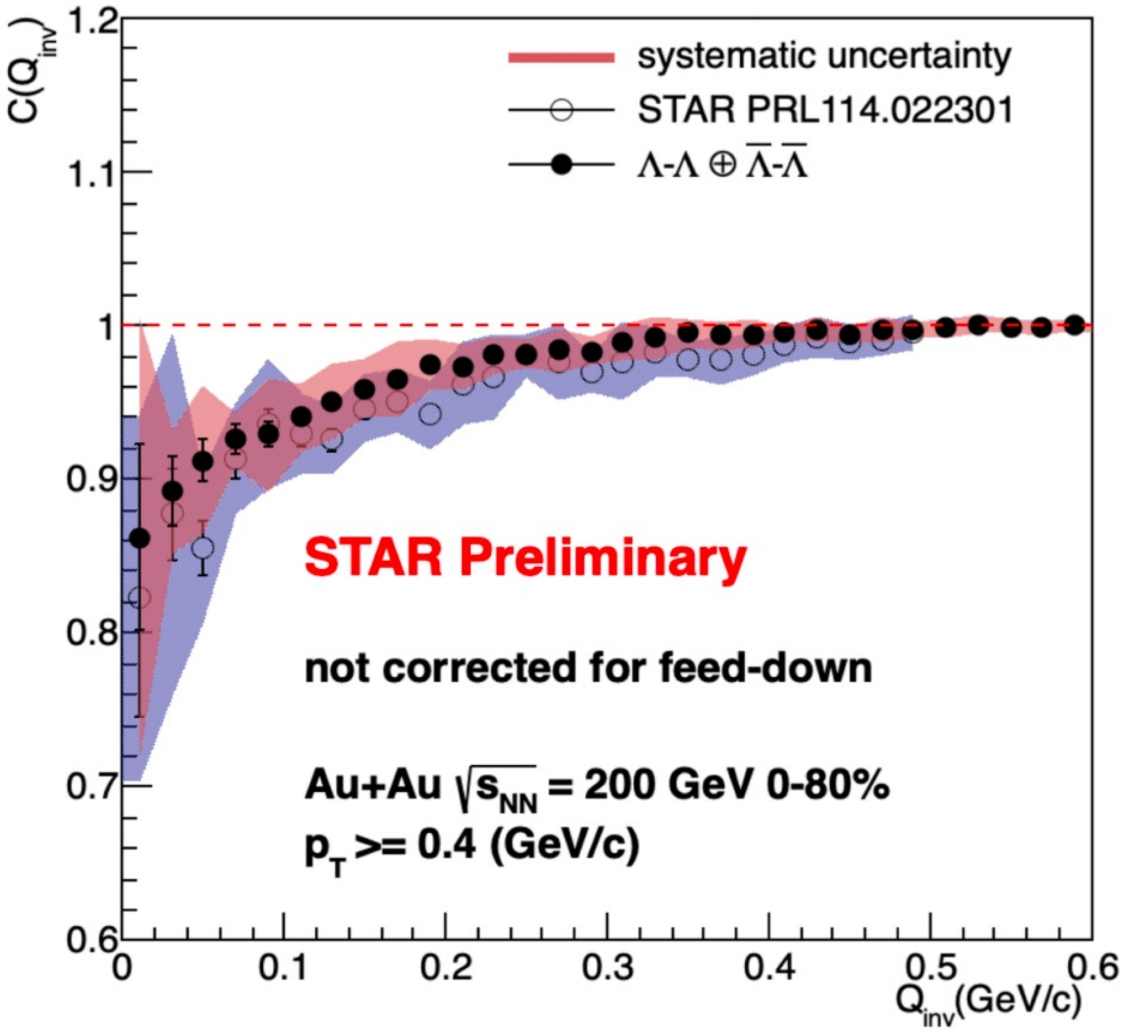
⇒ STAR published Λ-Λ correlation functions at 200 GeV in Au+Au collisions with run10 + run11 data

⇒ With L-L fit, a negative f_0 was found which indicated a repulsive interaction

⇒ However, the published data was NOT corrected for feed-down which will strongly affect the sign of f_0

Λ-Λ Correlation (|S| = 2)





⇒ Re-do Λ-Λ correlation functions with high statistics data (2 billion)

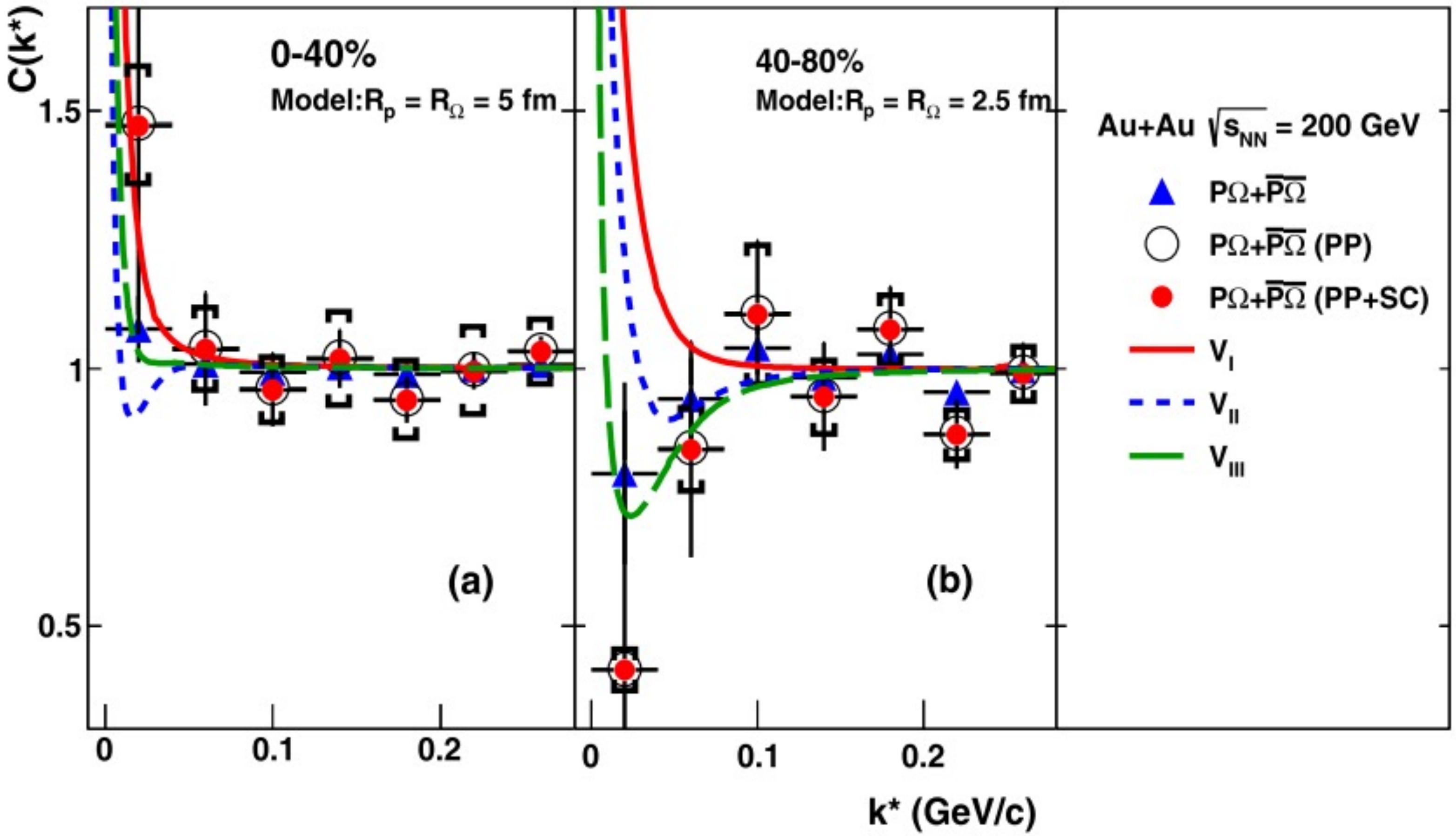
- ⇒ Consistent between two results
- ⇒ Still suffer from large uncertainties

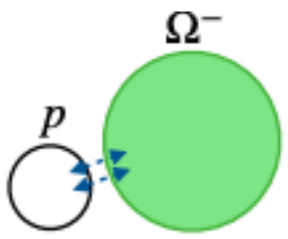
⇒ Isobar collisions have ~ 4 billion statistics

- ⇒ Able to measure different centralities
- ⇒ Able to extract the strong interaction parameter more precisely
- ⇒ Will release new results on QM2025

STAR Coll, Phys.Rev.Lett, 114(2015) 022301
EPJ Web of Conferences 259, 11015 (2022)

$p - \Omega^-$ Correlation (|S| = 3)



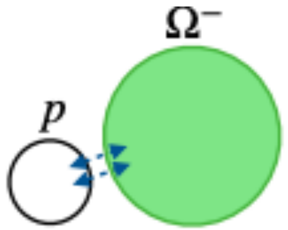


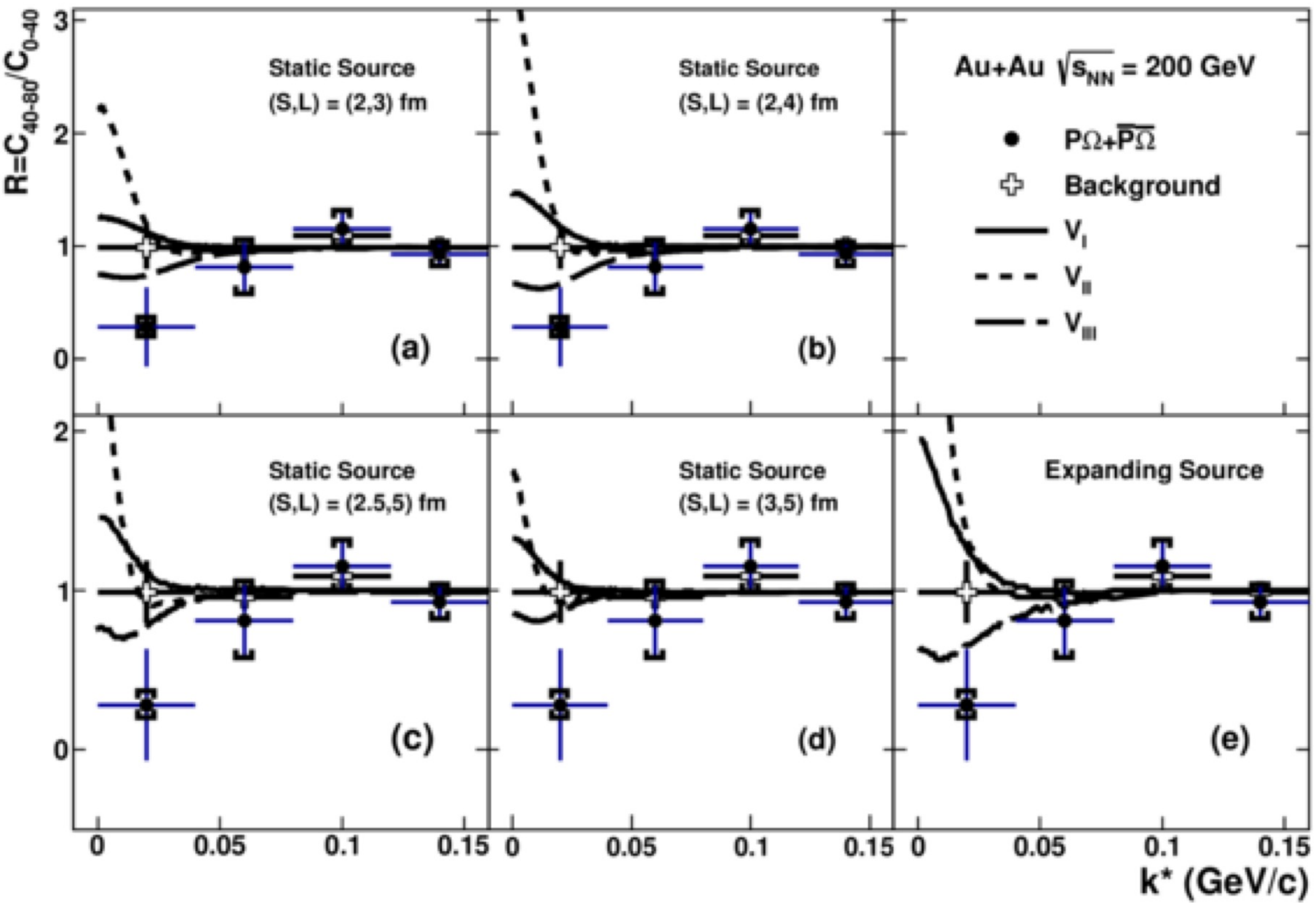
⇒ STAR published p-Ω correlation functions at 200 GeV in Au+Au collisions with run11 + run14 data

⇒ Compared with the model qualitatively

Phys. Lett. B **790** (2019) 490

$p-\Omega^-$ Correlation (|S| = 3)





Spin-2 pOmega potentials	VI	VII	VIII
Binding energy E_B (MeV)	-	6.3	26.9
Scattering length a_0 (fm)	-1.12	5.79	1.29
Effective range r_eff (fm)	1.16	0.96	0.65
	No bound state	Shallow bound	Deep bound

⇒ Small (40-80%) to large (0-40%) system ratio can largely cancel Coulomb effect

⇒ Data supports the existence of a bound state

⇒ New measurements in Isobar collisions will provide more precise results

⇒ Will release new results on QM2025

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Summary

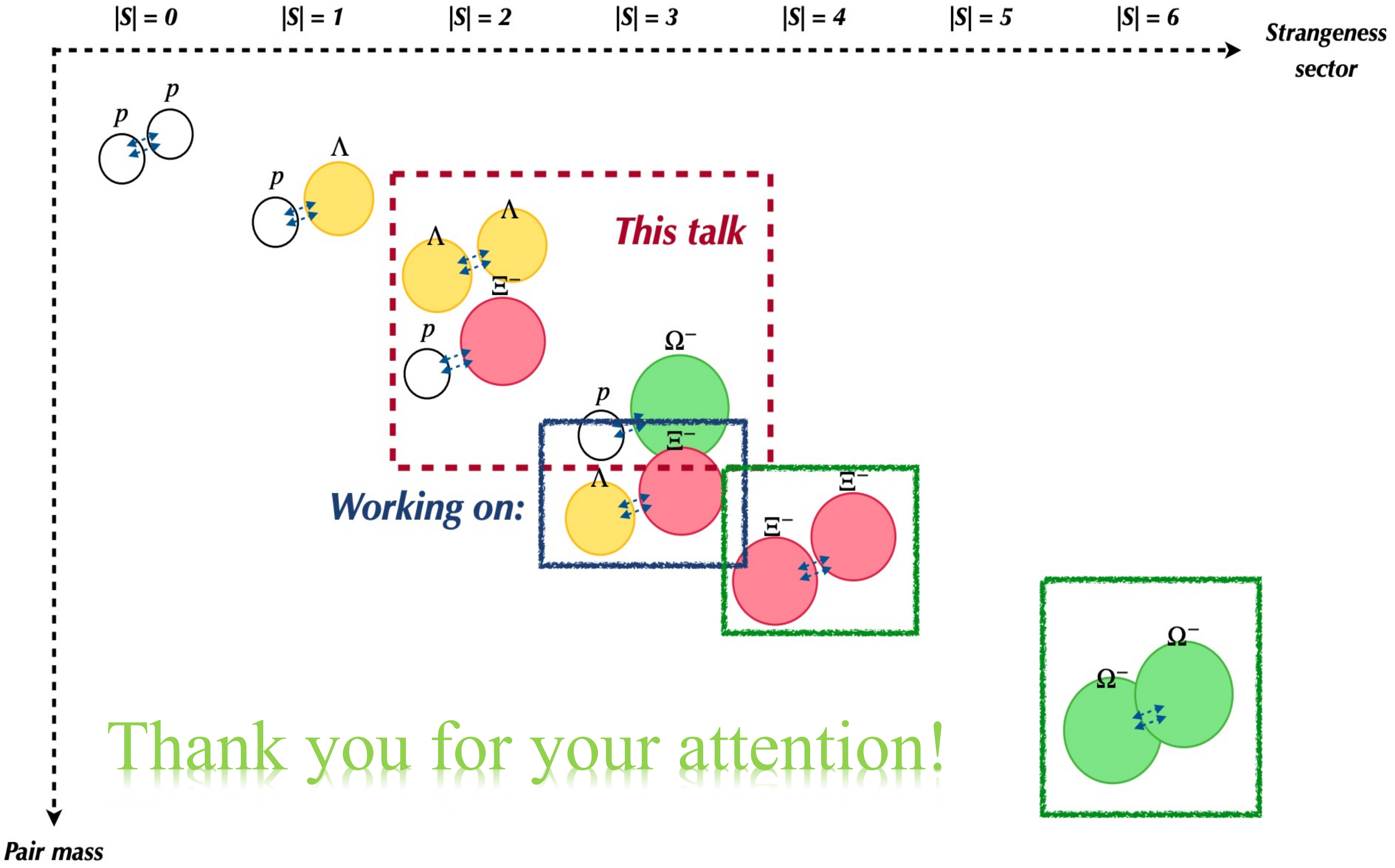
- ✓ Femtoscopy measurements from heavy-ion collisions provides a unique tool to explore Y-N and Y-Y interactions
- ✓ Measure $\mathrm{p} - \Xi$ CF at 200 GeV in Au+Au and Isobar collisions
  - ✓ Extract source size: $R_G^{central} > R_G^{peripheral}$
  - ✓ Extract a positive f_0: Attractive interaction in $\mathrm{p} - \Xi^-$ pairs and no sign of the H-Dibaryon
- ✓ STAR published $\Lambda - \Lambda$ and $\mathrm{p} - \Omega$ CF at 200 GeV in Au+Au collisions
  - ✓ Due to large uncertainties, no definitive conclusions can be drawn regarding on the H-dibaryon or NΩ-Dibaryon search

Outlook

Outlook:

- ☐ Precise measurements of $\Lambda-\Lambda$ and $p-\Omega$ correlation functions in Isobar collisions are ongoing, with the aim of releasing new results at QM2025.

- ☐ Search for $\Xi\Xi$ and $\Omega\Omega$ Dibaryons.



Thank you for your attention!

Backup

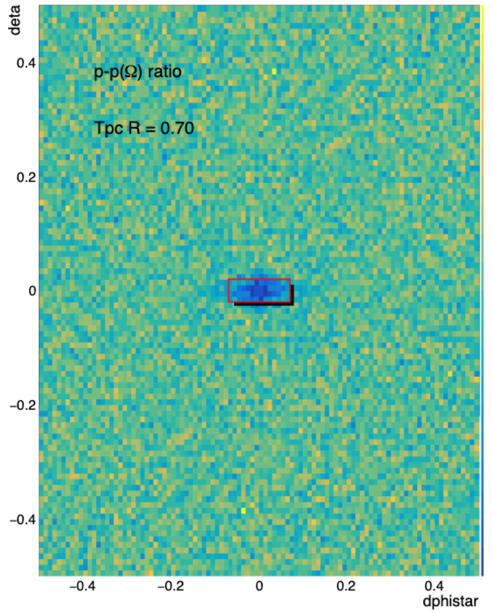
Corrections (I)

1. Track merging / splitting effect:
   Possible merging/splitting track pair:

$$p-\Xi^- \quad : \ p-p(\Xi^-)$$

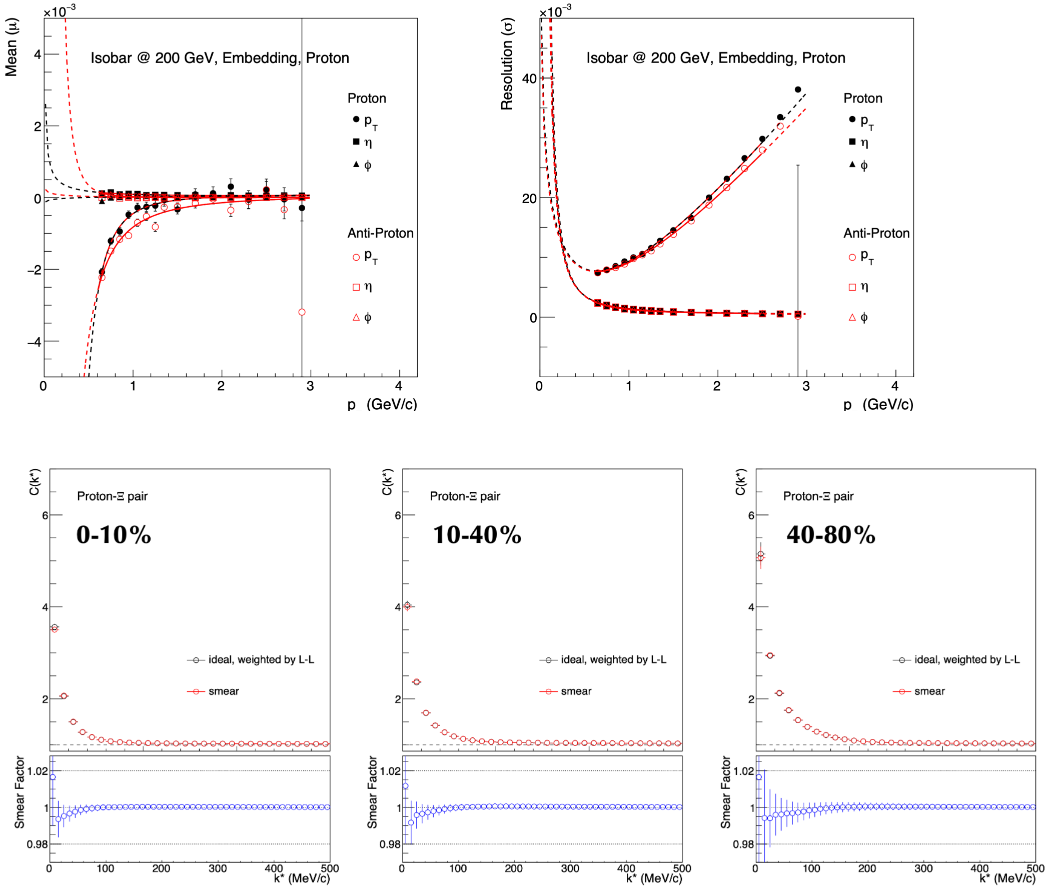
$$\Lambda-\Lambda \quad : \ p(\Lambda_1)-p(\Lambda_2)\ ,\ \pi^-(\Lambda_1)-\pi^-(\Lambda_2)$$

$$p-\Omega^- \quad : \ p-p(\Omega^-)$$



The effect can be removed by ΔΦ* and Δη cut

2. Momentum Smearing correction:



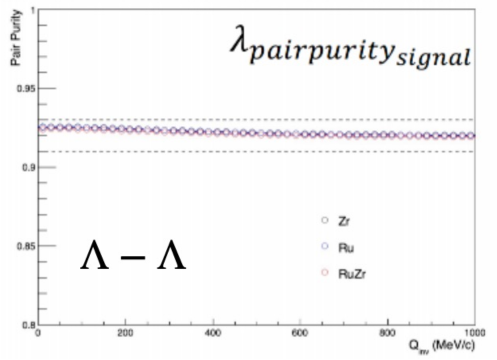
Corrections (II)

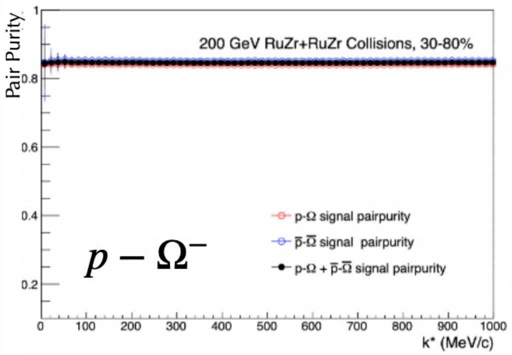
$$CF_{data} = 1 + \lambda_{pairpurity_{signal}} \left(\lambda_{genuine}(CF_{genuine} - 1) + \sum_i \lambda_{i_{residual}}(CF_{residual} - 1) \right) + \lambda_{pairpurity_{sideband}} (CF_{sideband} - 1)$$

1.PairPurity correction

$$\lambda_{pairpurity_{signal}} = \text{purity(1)} * \text{purity (2)}$$

$$\lambda_{pairpurity_{sideband}} = \begin{cases} \text{purity(1)} * \text{(1-purity (2))} \\ \text{(1-purity(1))} * \text{purity (2)} \\ \text{(1-purity(1))} * \text{(1-purity (2))} \end{cases}$$





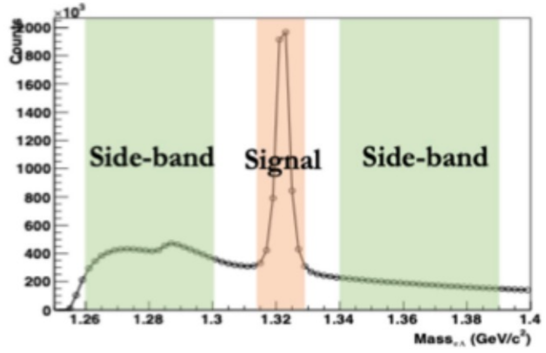
2.Mis-identification correction

Signal:

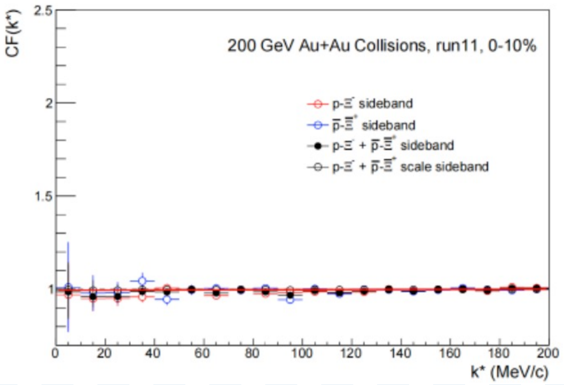
|M - pdgmass| < 7 MeV/c^2

Sideband:

|M - pdgmass| > 5σ



-> **<u>Negligible</u>** effect from the mis-id effect (flat) in interest pairs ($p - \Xi^-$, $\Lambda - \Lambda$, $p - \Omega^-$)



Corrections (II)

$$CF_{data} = 1 + \lambda_{pairpurity_{signal}}\left(\lambda_{genuine}(CF_{genuine} - 1) + \sum_i \lambda_{i_{residual}}(CF_{residual} - 1)\right) + \lambda_{pairpurity_{sideband}}(CF_{sideband} - 1)$$

3.Residual correction

Dominate channels: p - Ξ^- : p - Ξ^{1530} , Λ - Ξ^-

$\Lambda - \Lambda$: Ξ^-- Ξ^-, Ξ^0- Ξ^0, Σ^0- Σ^0 …

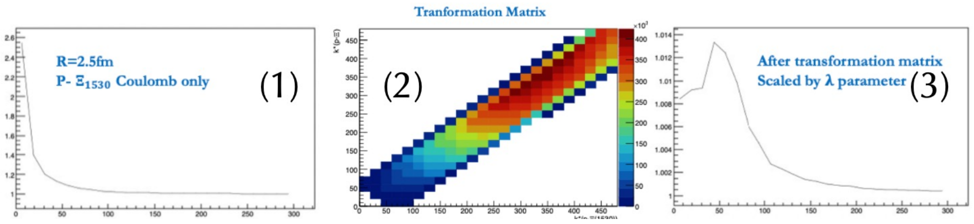
$p - \Omega^-$: N/A

Method: (i.e. $p - \Xi^{1530} -> p - \Xi^-$**)**

① **Generate** $C(p\Xi^{1530})$**, assuming Coulomb only**

② **Transfer** $k^*(p\Xi^{1530})$ **to** $k^*(p\Xi)$

③ **Transfer** $C(p\Xi^{1530}, k^*(p\Xi^{1530}))$ **to** $C(p\Xi^{1530}, k^*(p\Xi))$



4.Feed-down estimation

- Proton: Data-driven method from spectra analysis
- Λ :Data-driven method from BS analysis
- Ξ : Therminator 2 model
- Ω : Negligible feed down

	0-10%	10-40%	40-80%
Proton	0.59	0.61	0.64
Lambda	0.60		
Xi	0.70		
Omega	N/A		