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

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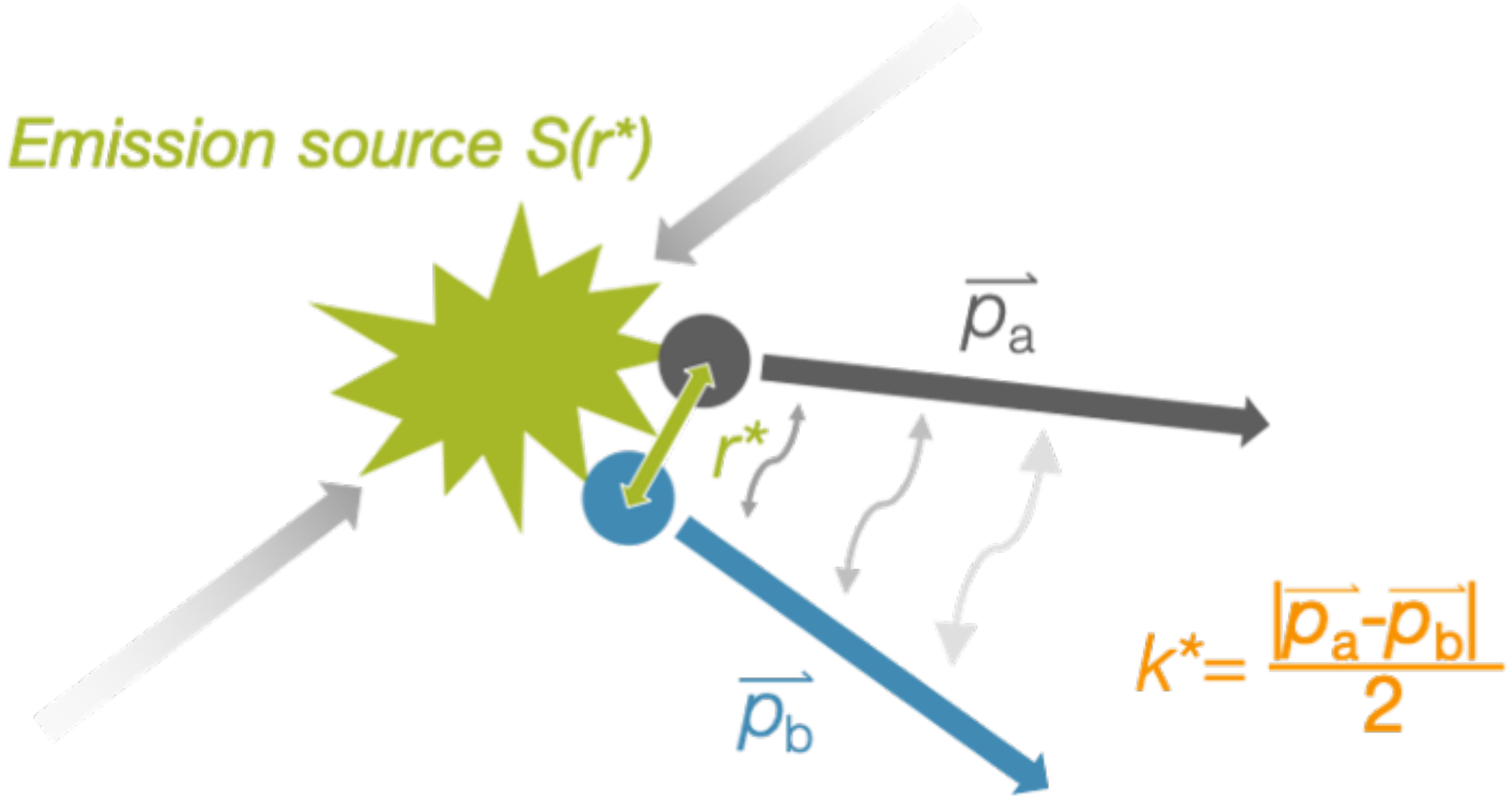
2nd Nov, 2024

Outline

1. Femtoscopy and Two-particle Correlation Function
2. Motivation
3. RHIC-STAR Experiment
4. Results
   - p-d, d-d, d-Λ correlation at 3 GeV
   - p-Ξ, Λ-Λ, p-Ω correlation at 200 GeV
5. Summary & Outlook

Femtoscopy



⇒ **In high energy collisions, Femtoscopy is inspired by Hanbury Brown and Twiss (HBT) interferometry, but different scale (~several fm)**

- → 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

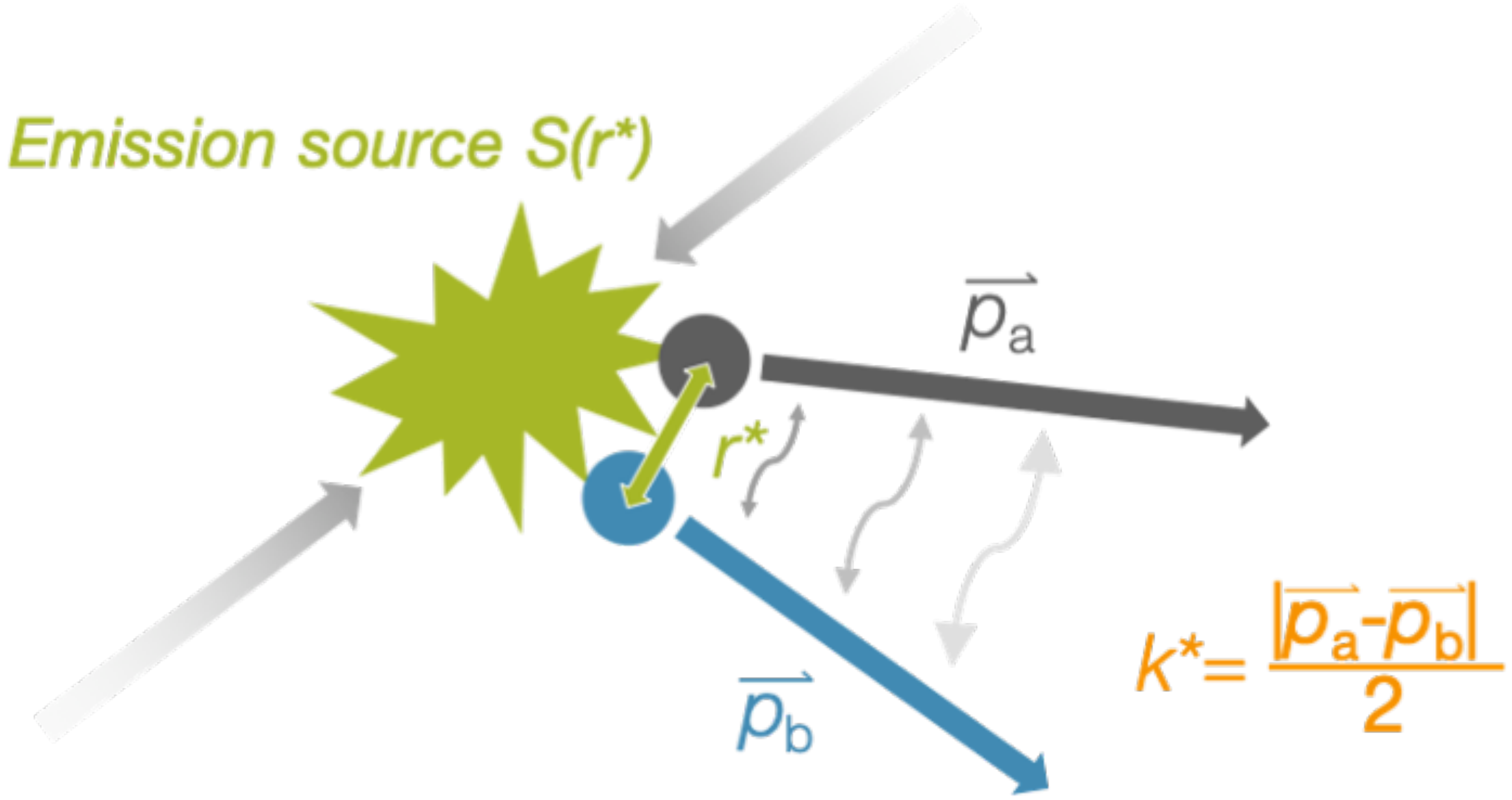
$\Psi(\vec{k}^*,\vec{r})$: Pair wave function

$k^* = \frac{1}{2}|\vec{p}_a - \vec{p}_b|$, relative momentum

$\vec{r}$: relative distance

Nature 178 1046-1048(1956)
ALICE Coll. Nature 588, 232–238 (2020)
R. Lednicky, et al, Sov.J.Nucl.Phys. 35 (1982) 770

Femtoscopy



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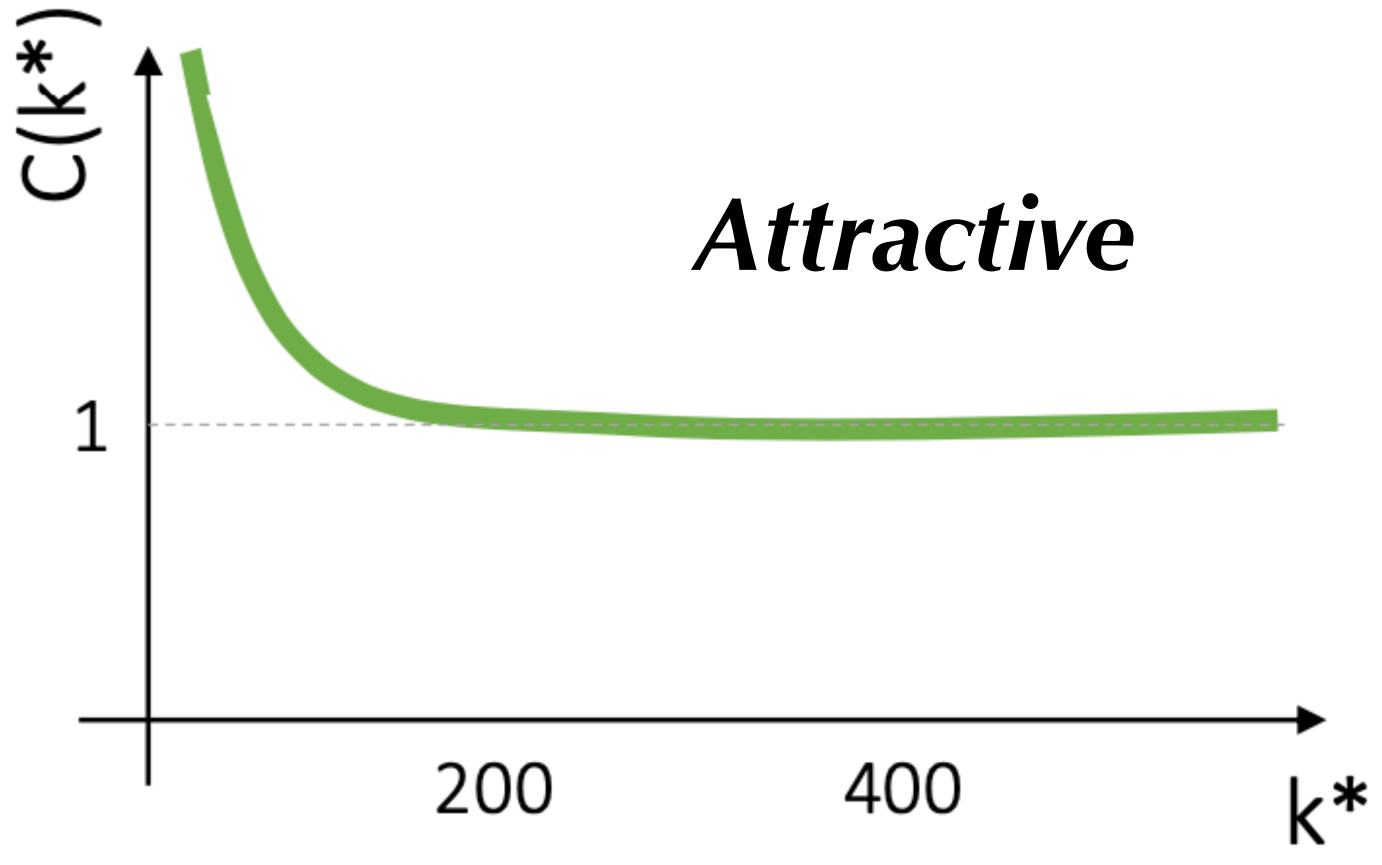

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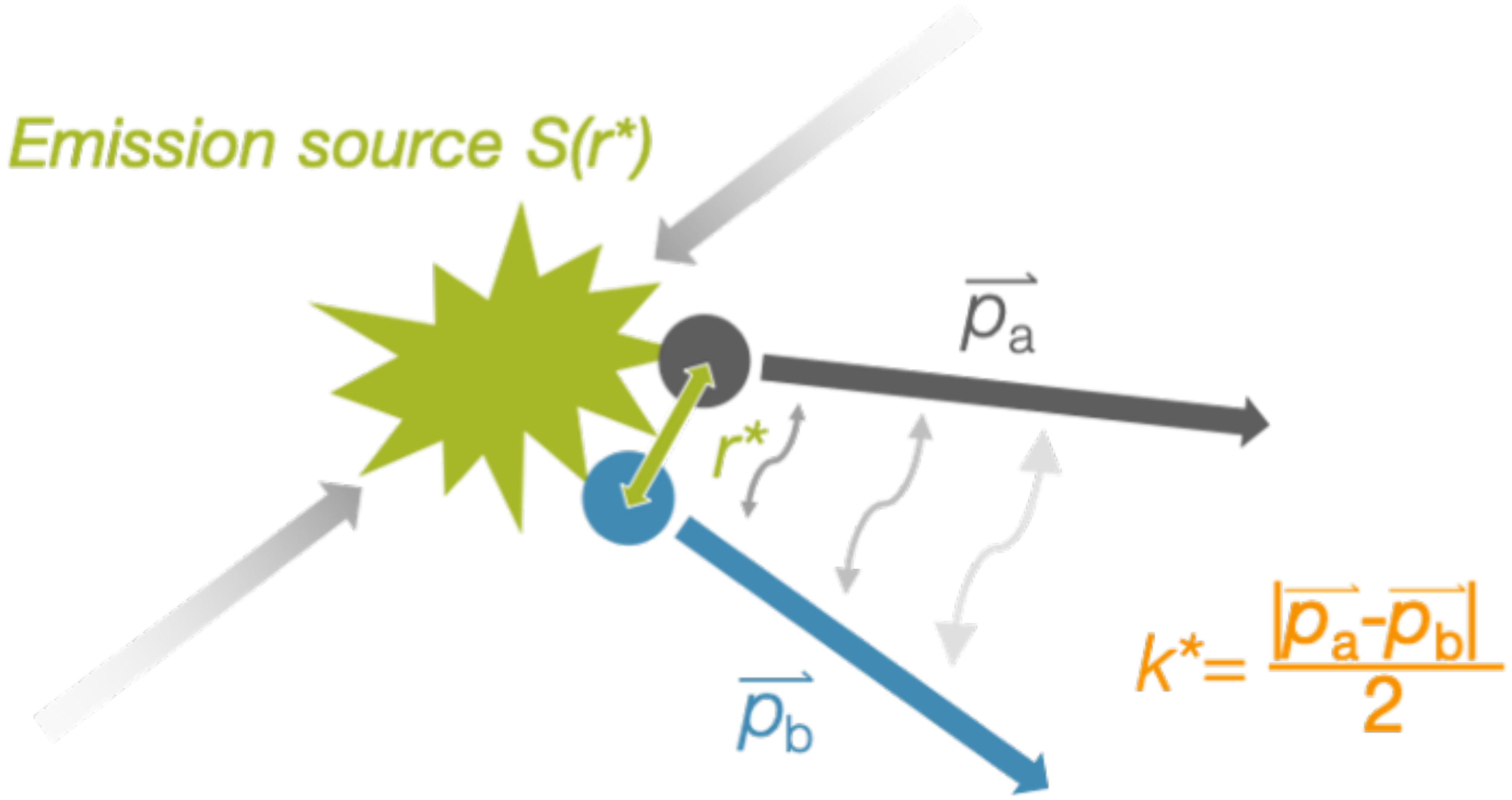

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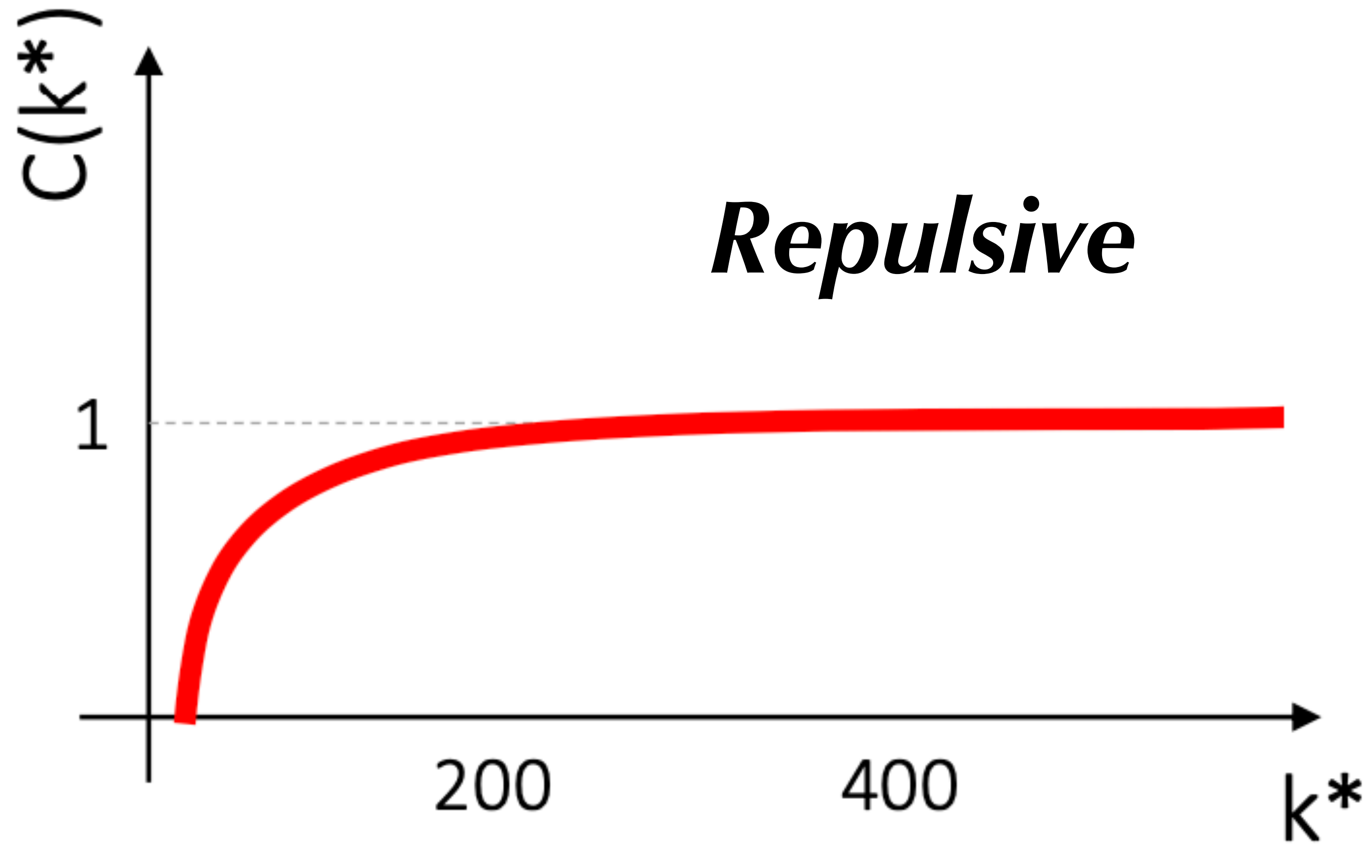

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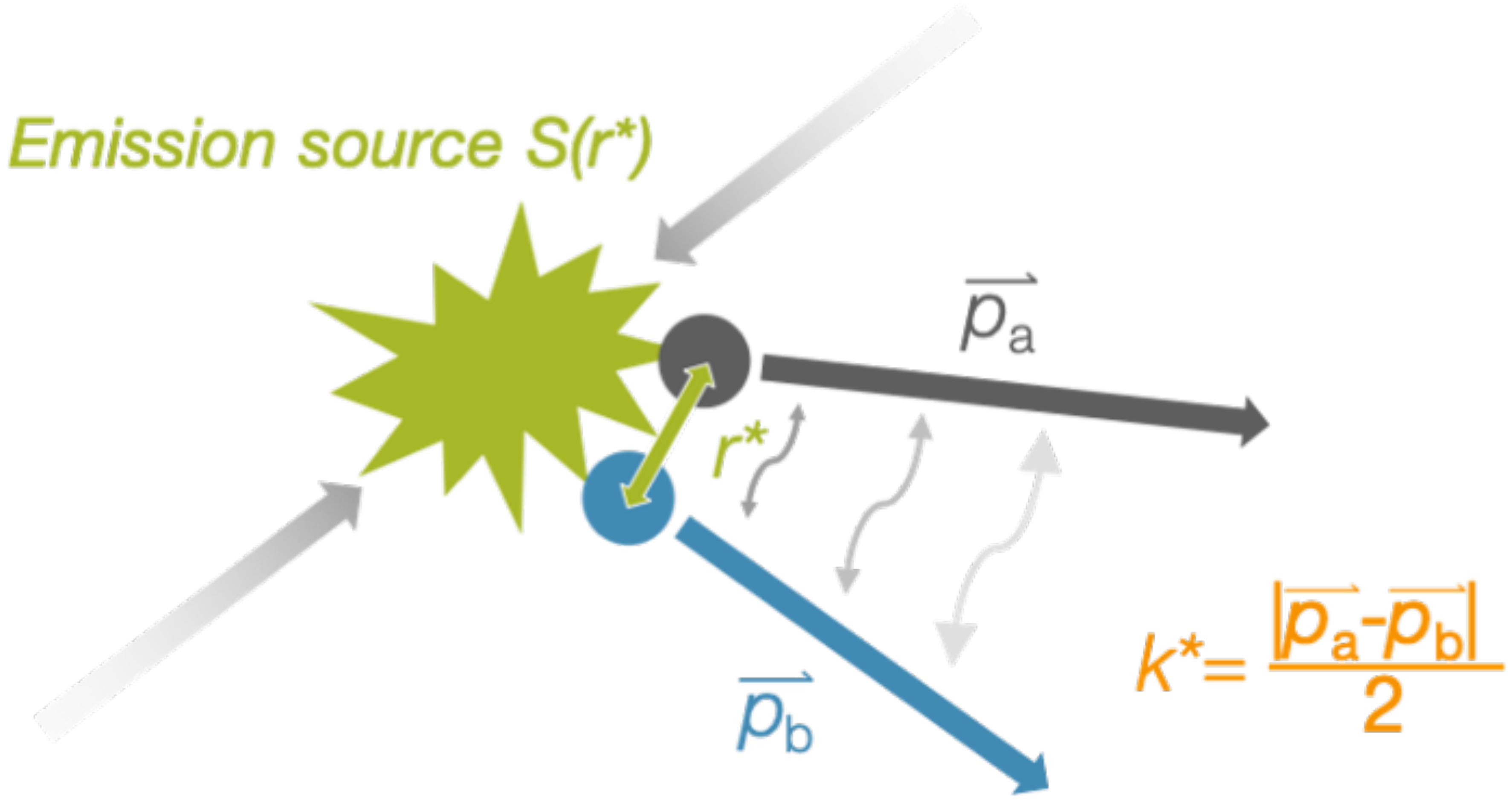

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⇒ **Formalism with Lednicky-Lyuboshitz (LL) model**

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

Physics parameters: R_G: **Spherical Gaussian source size**
f_0: **Scattering length**
d_0: **Effective range**

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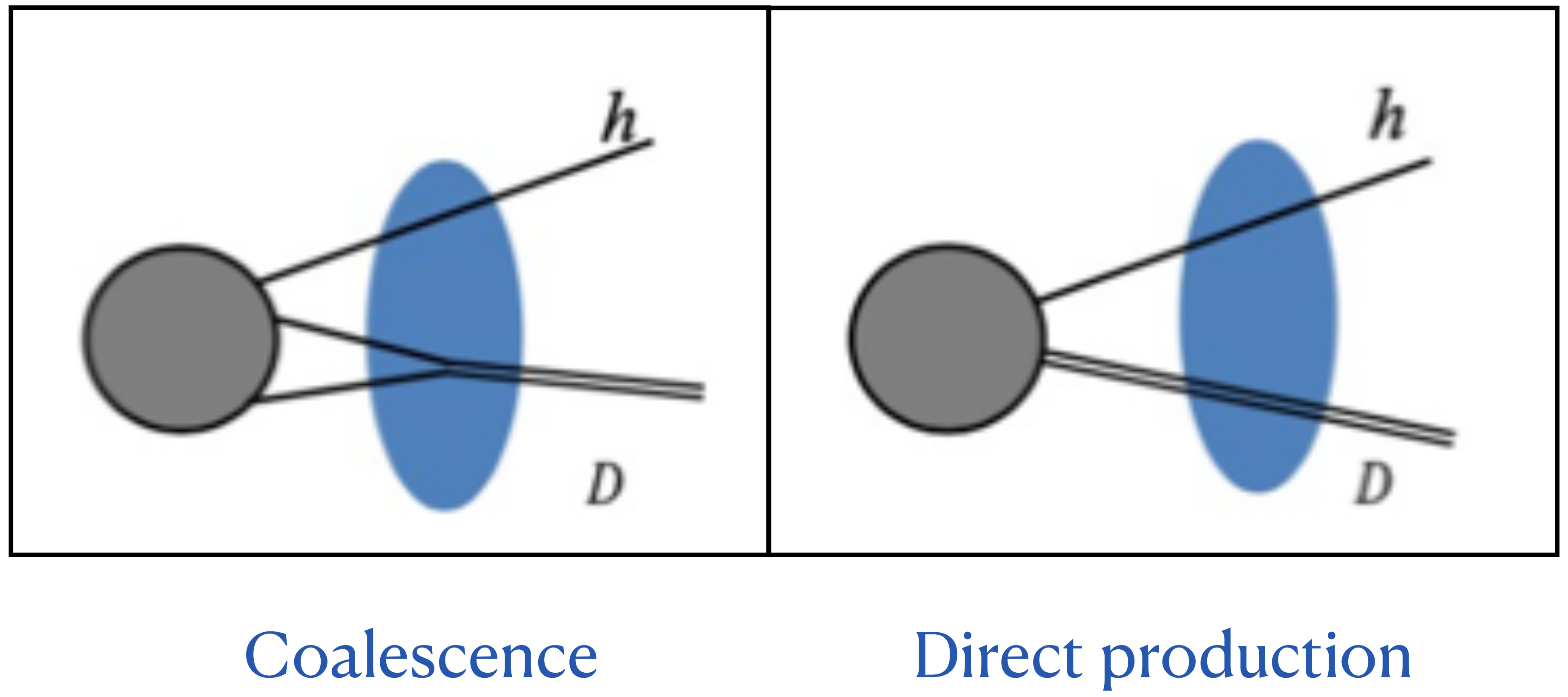
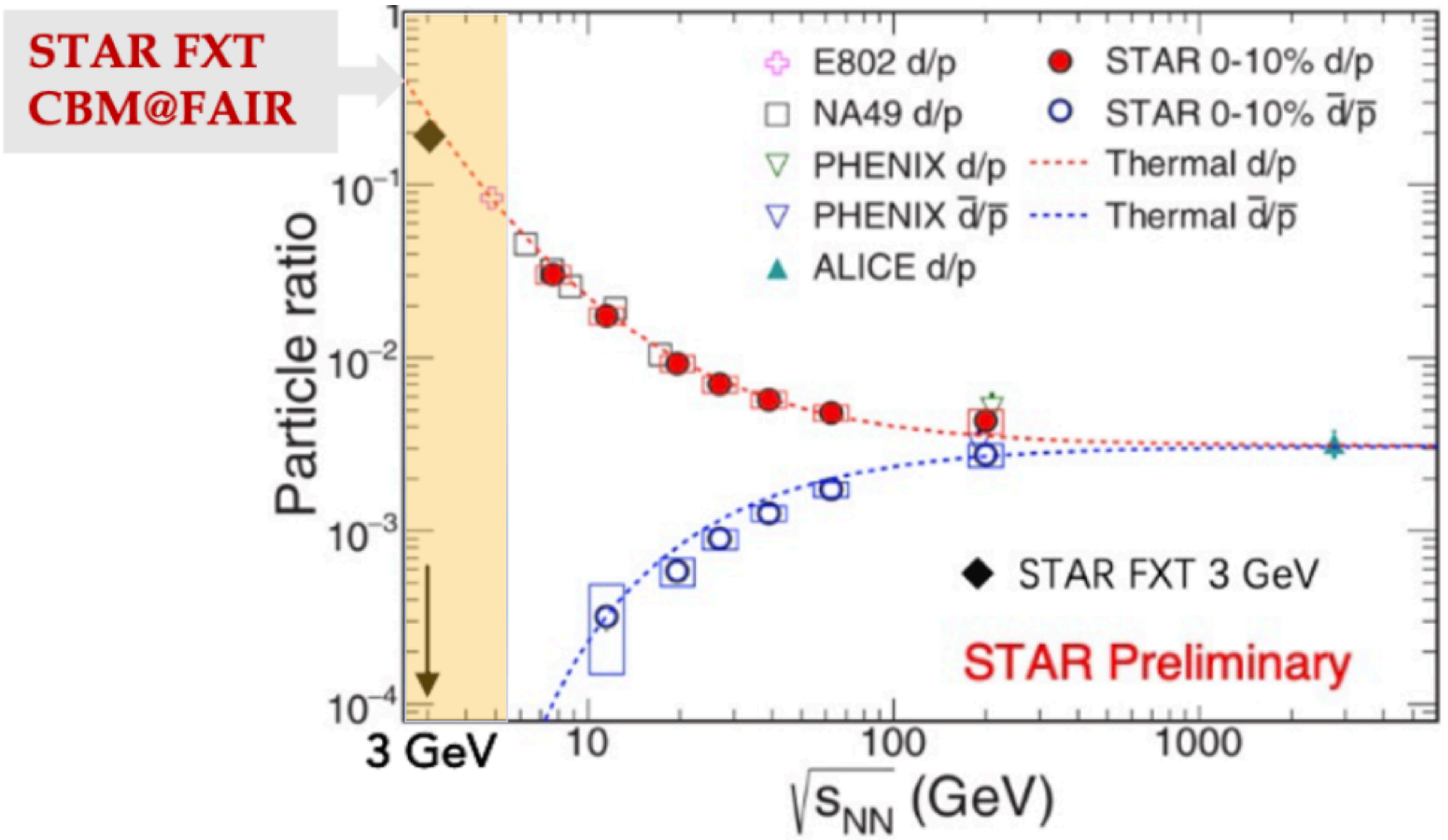
Motivation

- **Formation mechanism of light nuclei are under debate**
  - ⇒ Coalescence : final-state interaction
  - ⇒ Thermal : produced directly from fireball
- **Indirect approach of many body interactions**





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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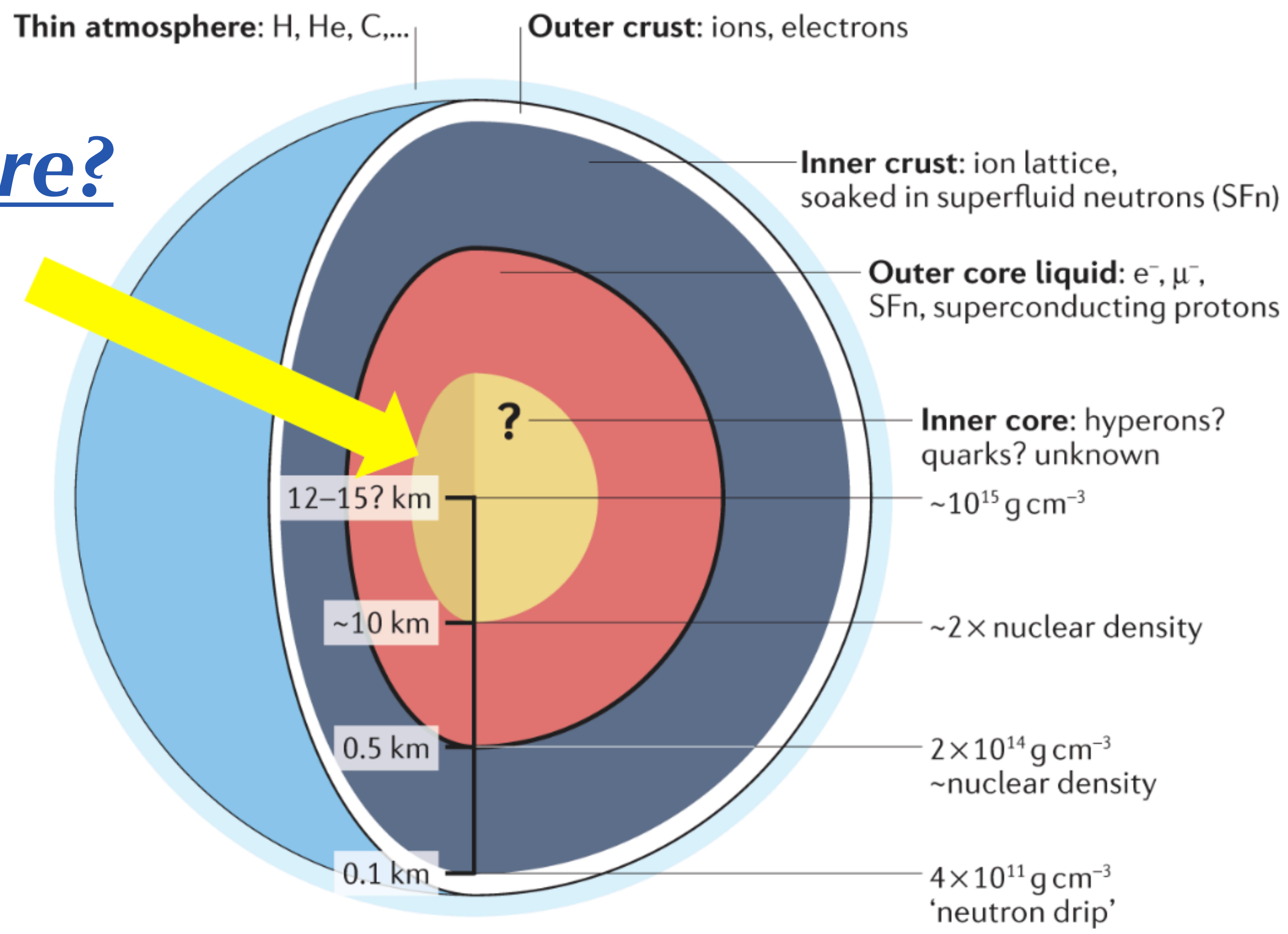
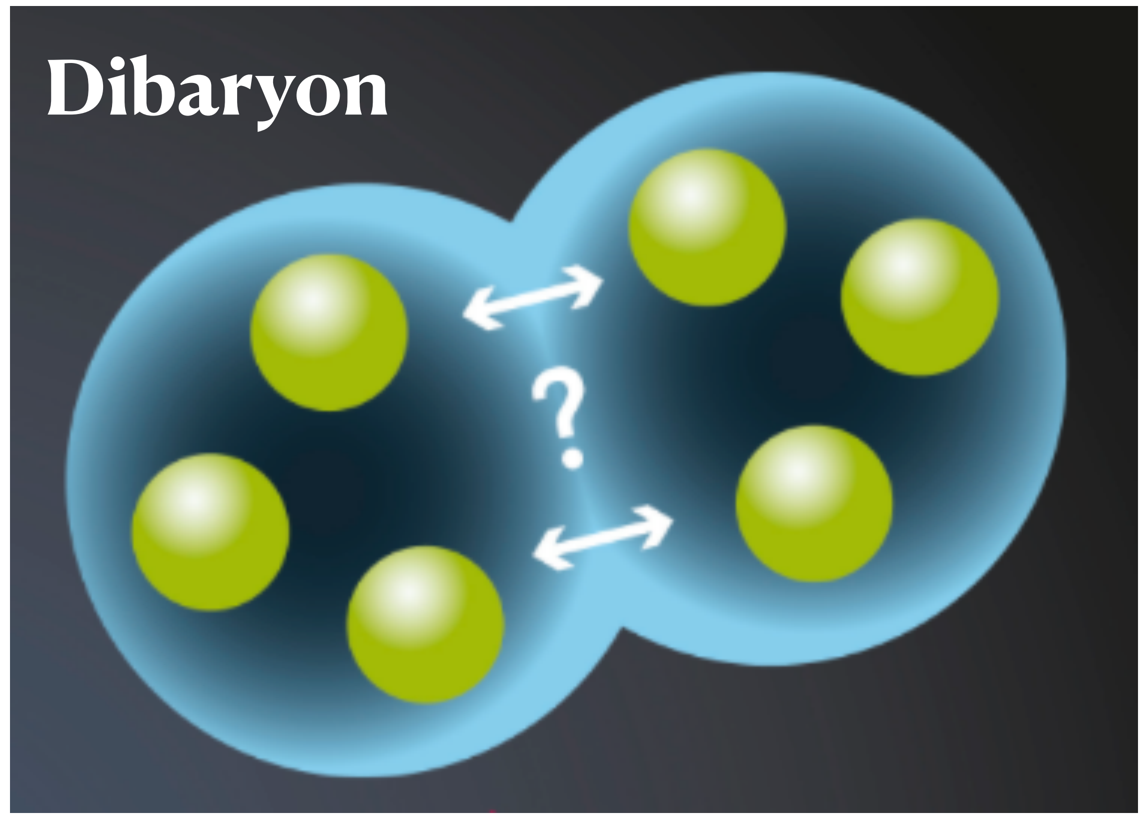
- **Strange Dibaryons, have never been found experimentally**
  - Possible bound state:
    - H-dibaryon ⇒ $\Lambda + \Lambda$ / p + Ξ^-
    - (Strange)Dibaryon ⇒ p + Ω
  - *Momentum correlation provides a new way to explore*

Experimental measurements are needed!

Inner core?





Particle	Mass (MeV)	Decay mode
f_0	980	$\pi\pi$
a_0	980	$\pi\eta$
K(1460)	1460	$K\pi\pi$
$\Lambda(1405)$	1405	$\pi\Sigma$
$\Theta^+(1530)$	1530	KN
H	2245	$\Lambda\Lambda$
$N\Omega$	2573	$\Lambda\Xi$

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

Motivation

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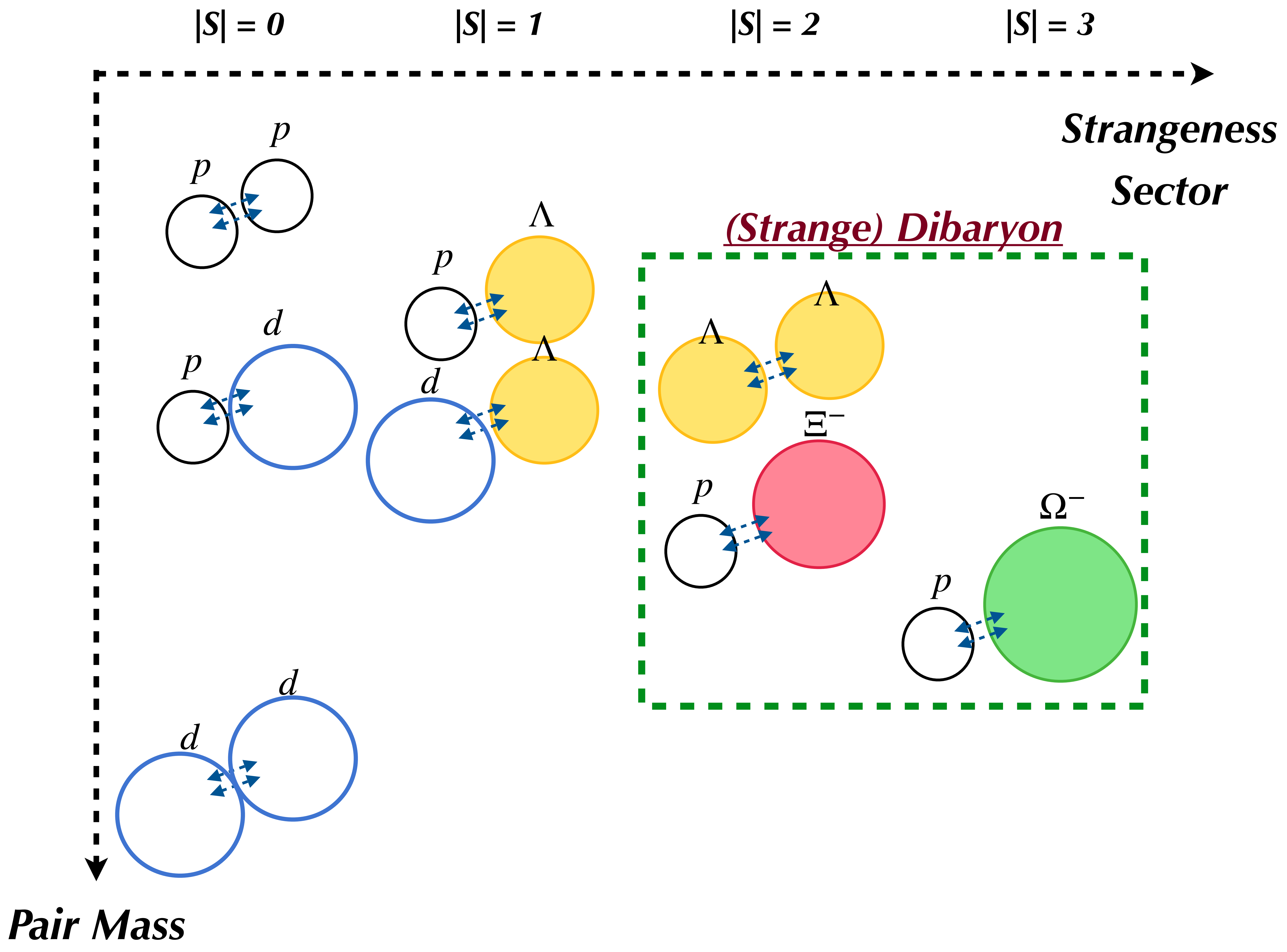

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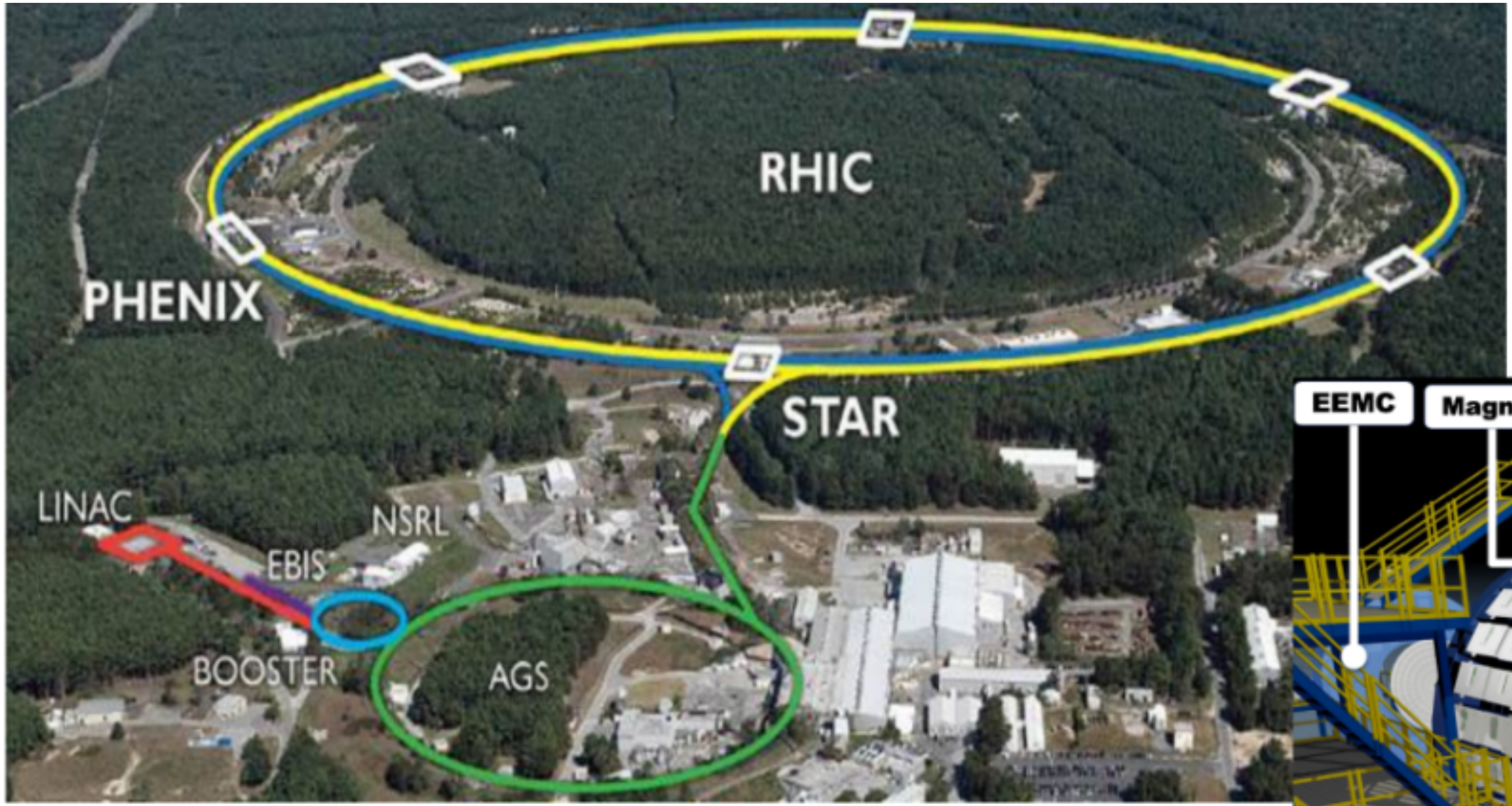
RHIC-STAR Experiment



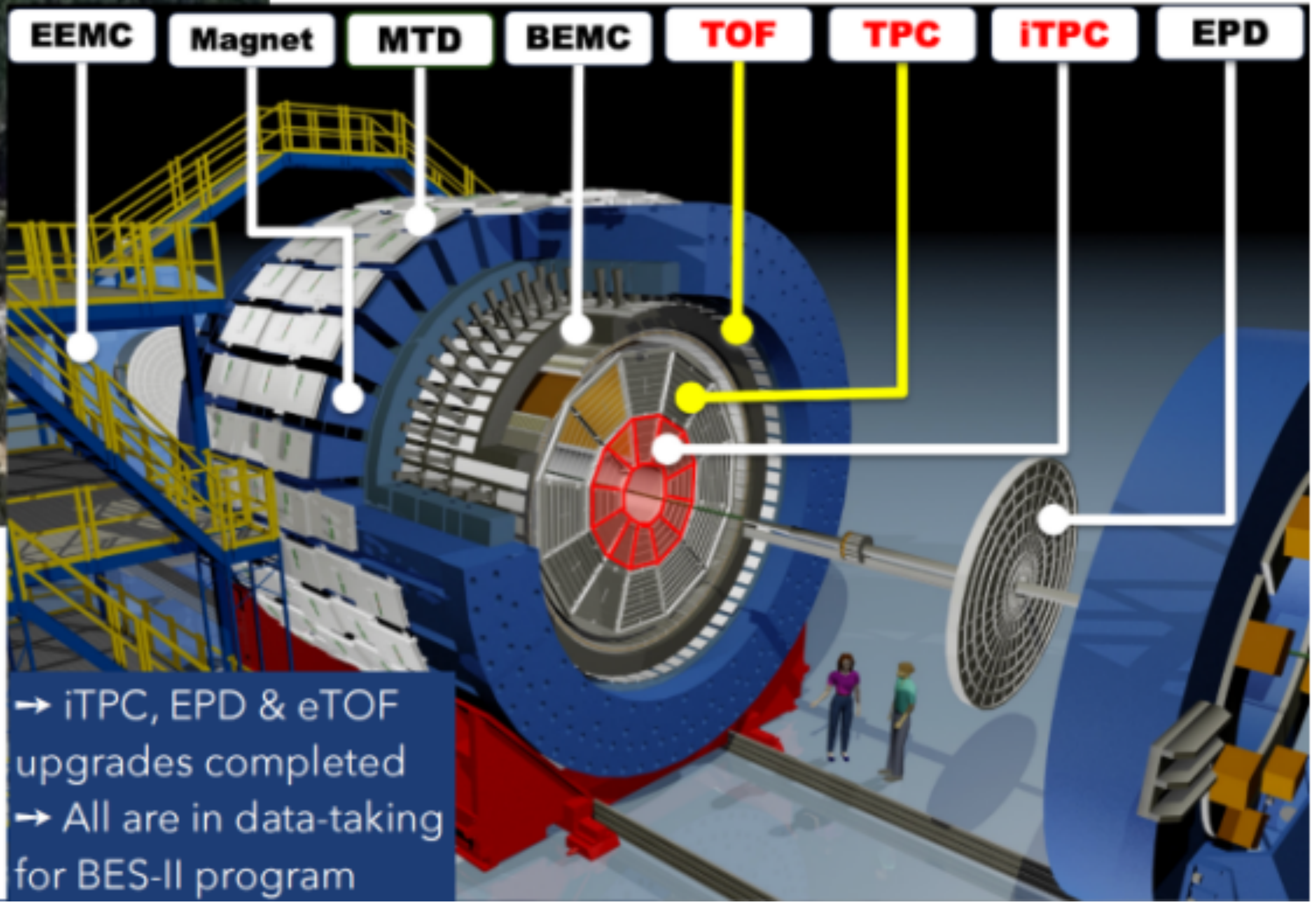
Relativistic Heavy Ion Collider (RHIC)

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

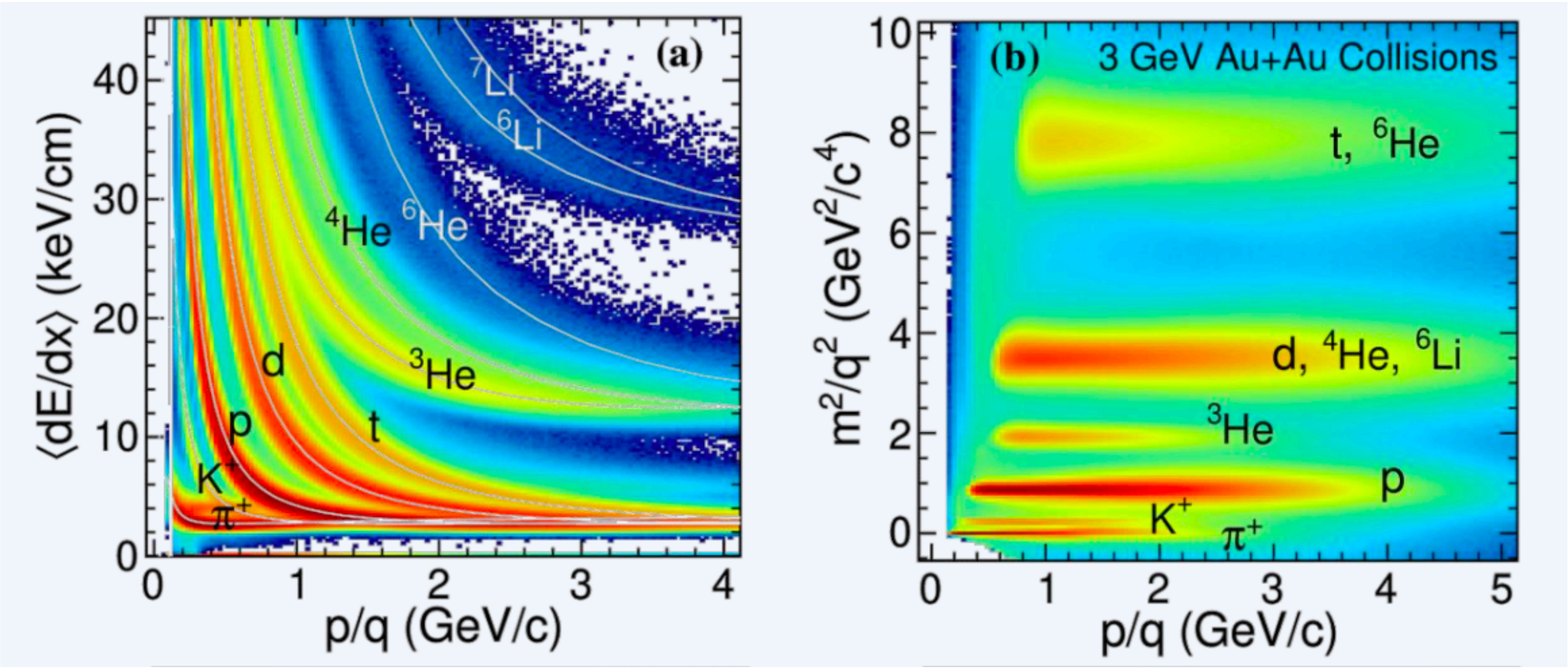


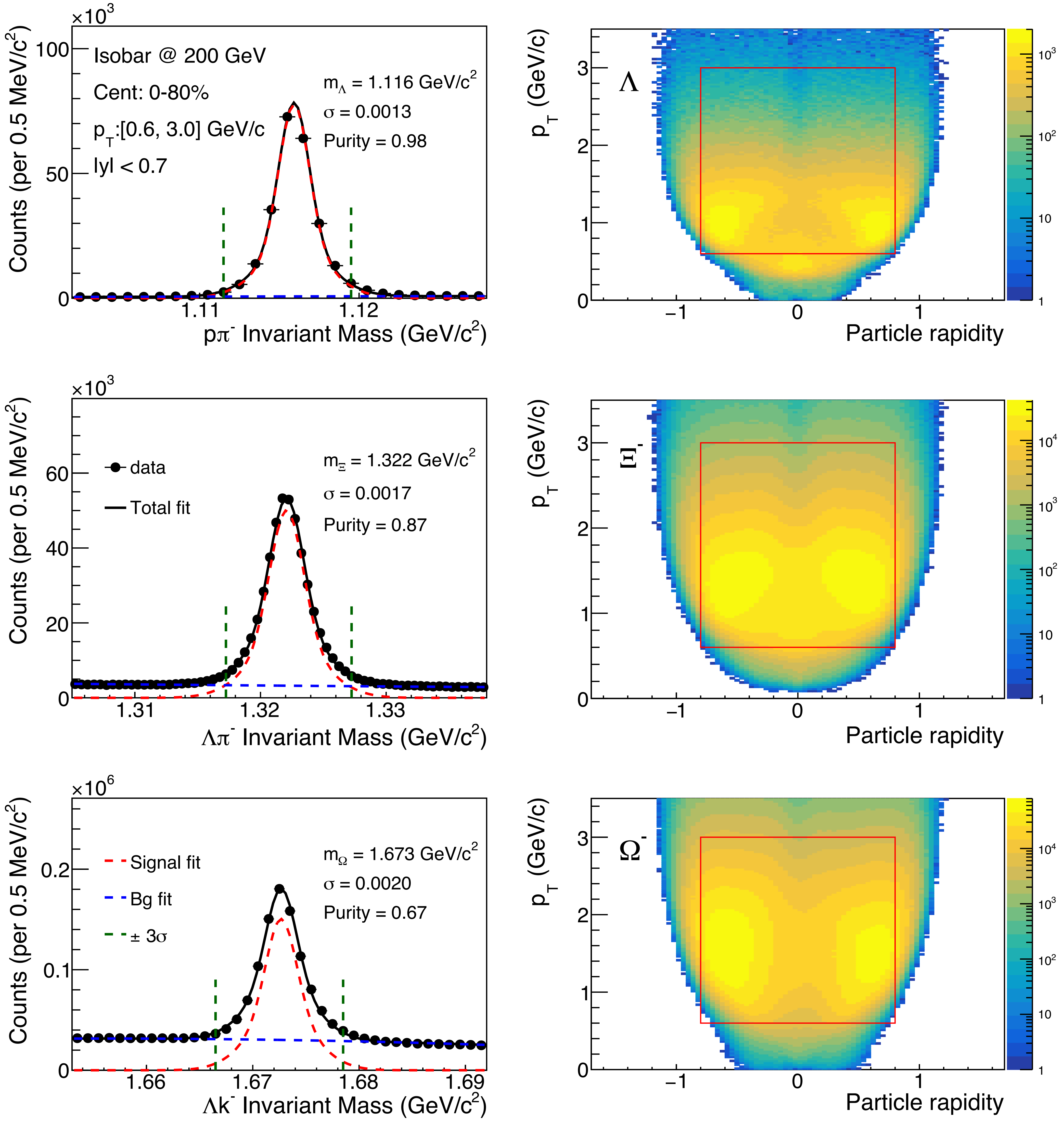
The Solenoid Tracker At RHIC (STAR)

→ Excellent Particle Identification

→ Large, Uniform Acceptance at Mid-rapidity

Particle Identification & Reconstruction

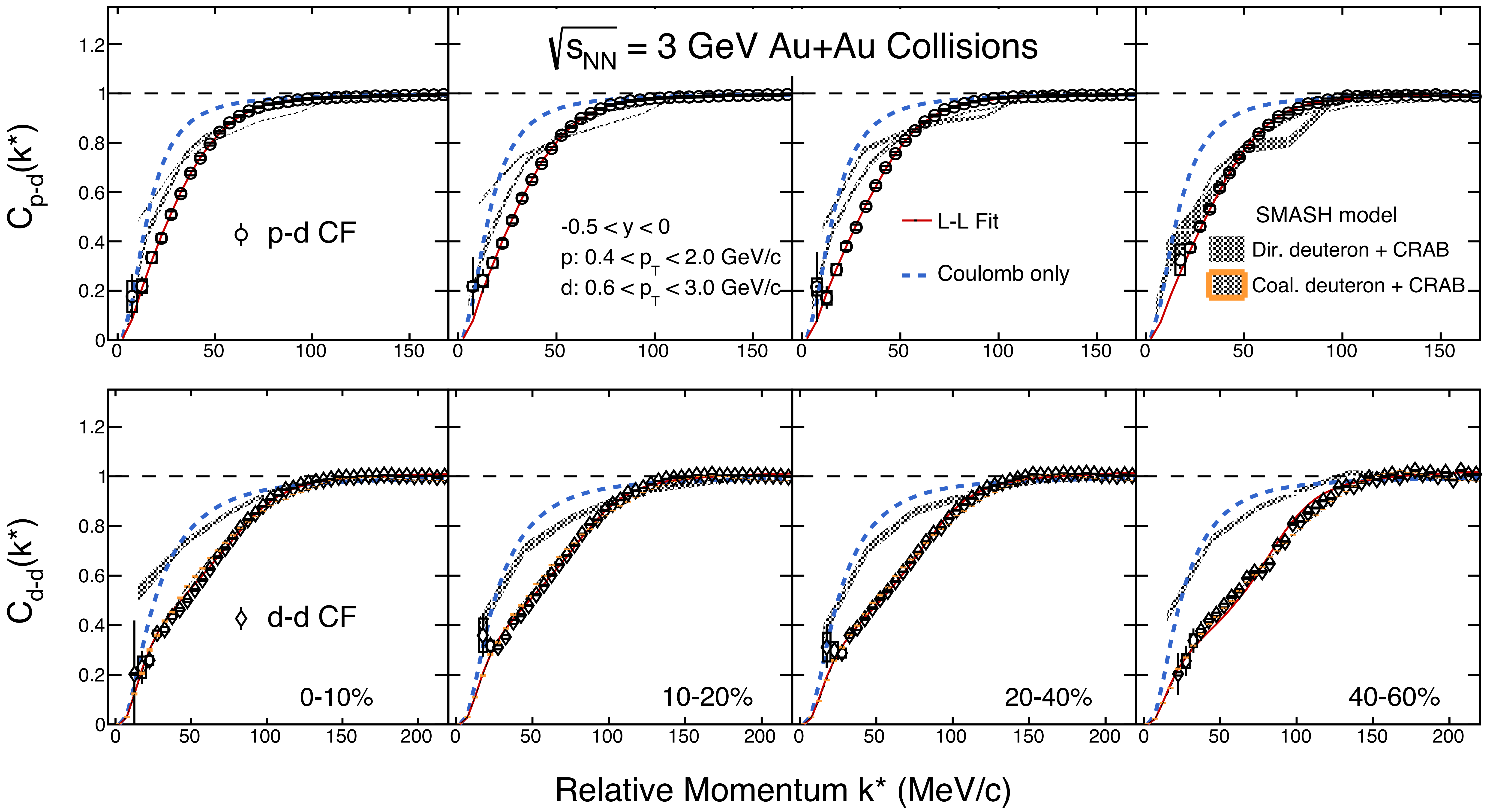




⇒ **Use Time Projection Chamber (TPC) and Time-Of-Flight (TOF) to identify π^-, p, k and d**

⇒ **Excellent coverage at mid-rapidity**

Results — p-d, d-d Correlation



⇒ **First measurements of p-d/d-d correlation functions in STAR**

⇒ **Clear depletion in low k***

- **Coulomb repulsive & strong interaction**

⇒ **Fitted with L-L model simultaneously, in different centrality:**

- **Different R_G**
- **Common f_0 and d_0**

STAR: arXiv:2410.03436v1
SMASH: J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905
Coalescence: W.Zhao et al. Phys. Rev. C.98 (2018) 5,054905

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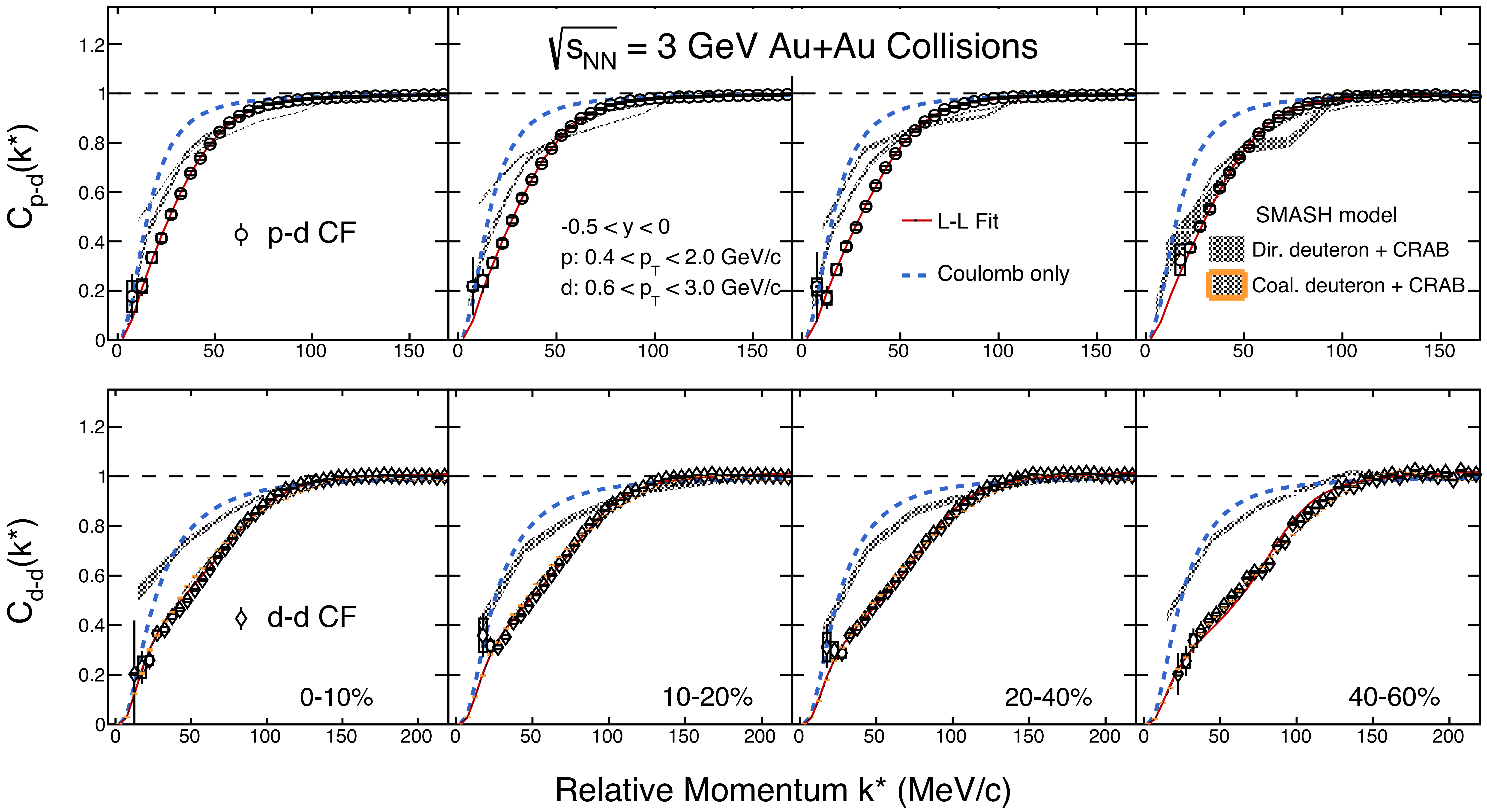

⇒ Simulated with SMASH model, consider two deuteron formation mechanism:

- 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

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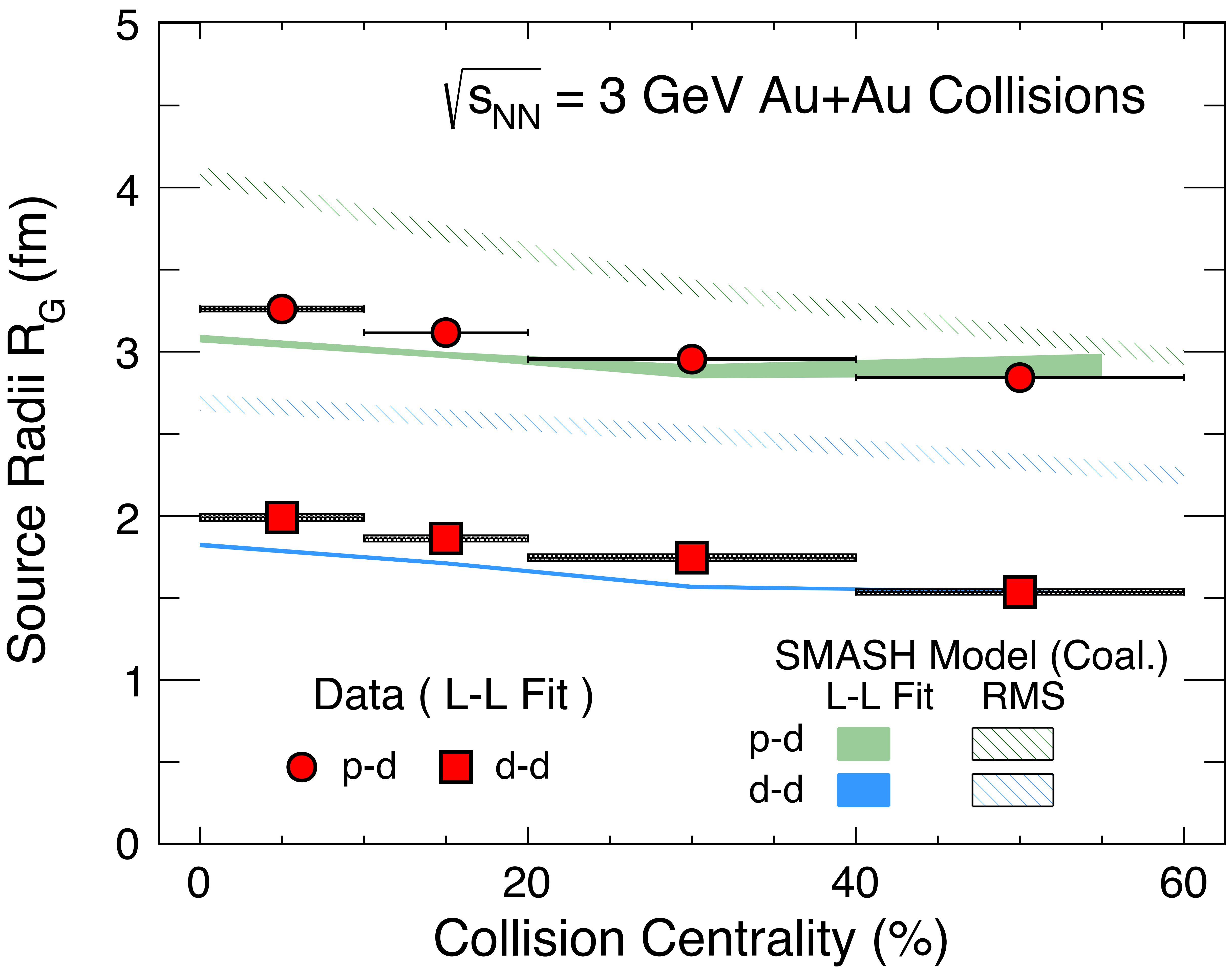


⇒ **Extracted source size (R_G) with LL model**

- **Centrality dependence:** $R_G^{central} > R_G^{peripheral}$
- **$<m_T>$ dependence:** $R_G^{p-d} > R_G^{d-d}$

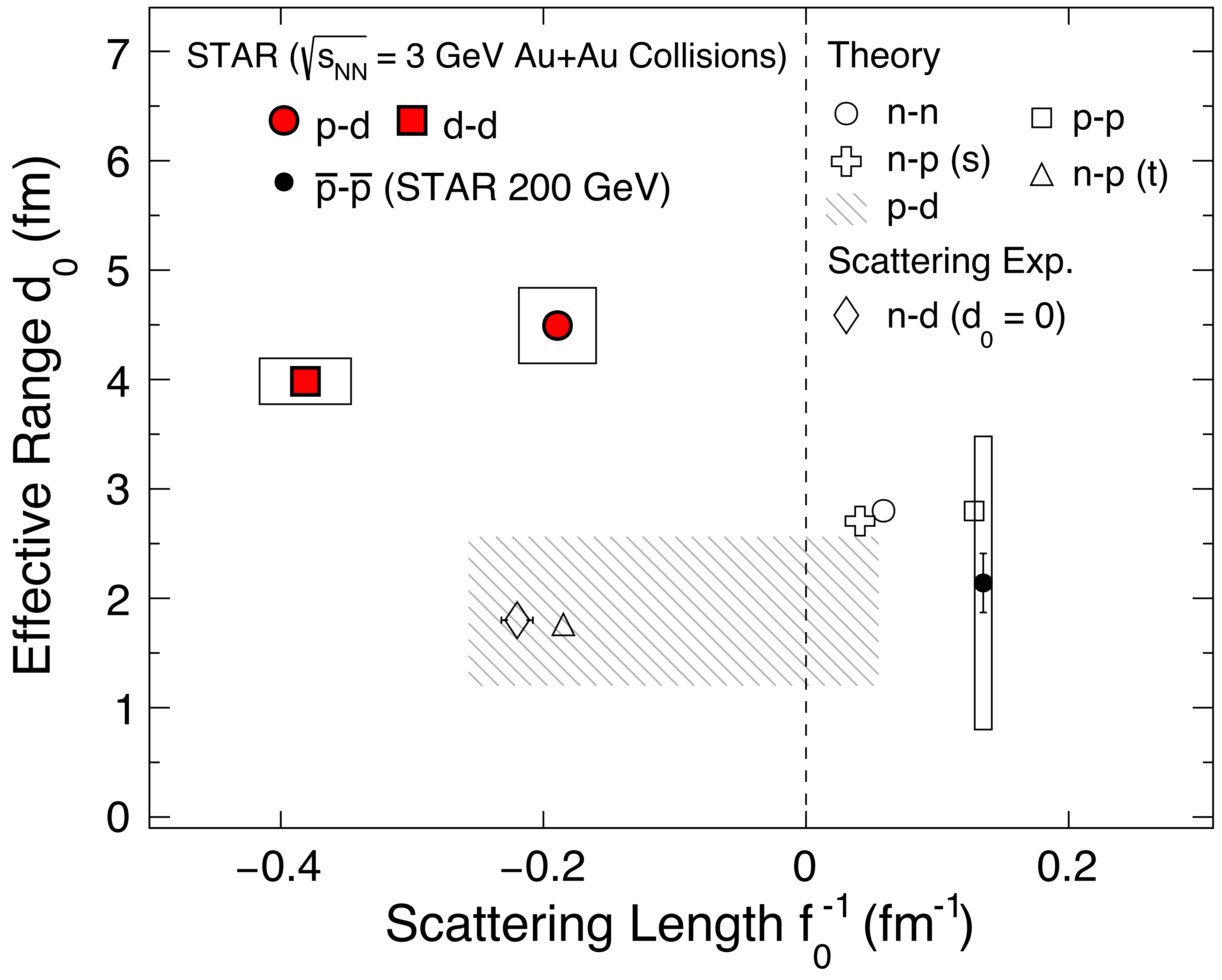
⇒ **Using same fit, source size from SMASH (R_G^{SMASH}) is closely match the data**

⇒ ***The root mean square (RMS) values from SMASH are larger than*** R_G

- **Dynamical expansion of the system**

STAR: arXiv:2410.03436v1

Results — p-d, d-d Interaction



⇒ **Extracted spin-averaged final state interaction parameters (f_0, d_0) with LL model**

⇒ **For both p-d and d-d interaction, the spin-averaged f_0 is negative**

- **Combination of repulsive interactions in quartet (quintet) spin state for p-d (d-d) along with the presence of bound states (^{3}He for p-d and ^{4}He for d-d)**

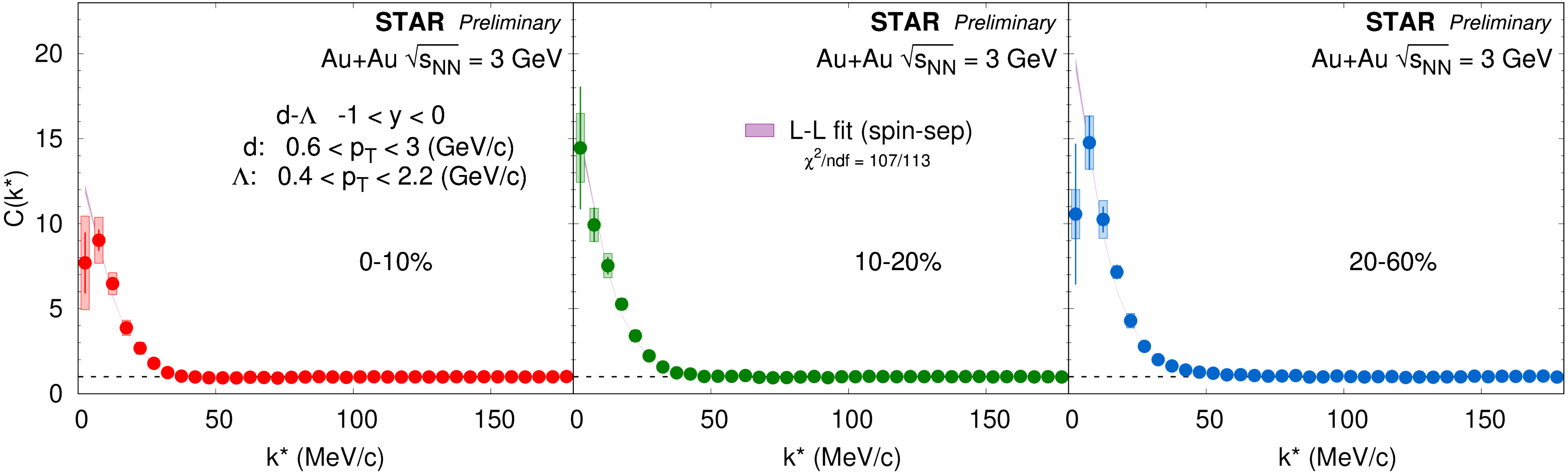
⇒ **For p-d interaction, the result is consistent with theory calculation and low-energy scattering experiment measurement**

- **Support the feasibility of extracting interaction parameters with Femtoscopy technique**

STAR: arXiv:2410.03436v1

Results — d-Λ Correlation

First measurement of d-Λ CF at STAR



⇒ **Strong enhancements at small k^* range -> Attractive interactions**

⇒ **Simultaneously fit to data in different centralities with L-L approach**

- **Consider two-spin components: D (doublet, S = 1/2), Q (quartet, S=3/2)**

* Λ feed-down correction not applied

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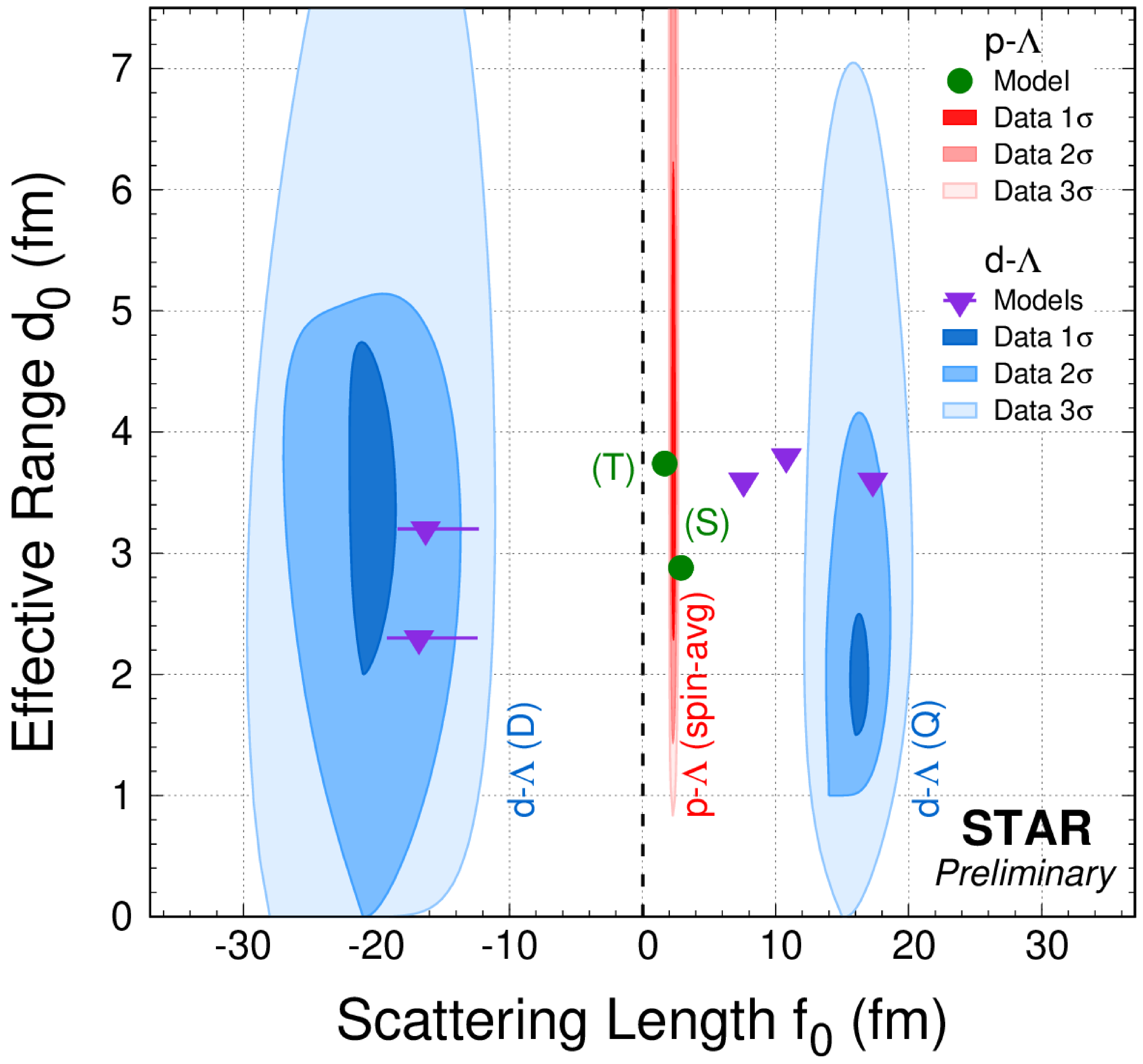
Results — d-Λ Interaction



⇒ First experimental extraction of strong interaction parameters of d-Λ pair

⇒ Successfully separate two spin components in d-Λ

f_0 (D) = -20 $^{+3}_{-3}$ fm, d_0 (D) = 3 $^{+2}_{-1}$ fm

f_0 (Q) = 16 $^{+2}_{-1}$ fm, d_0 (Q) = 2 $^{+1}_{-1}$ fm

- Negative f_0 in doublet state -> ${}^{3}_{\Lambda}$H bound state
- Positive f_0 in quartet state -> Attractive interaction

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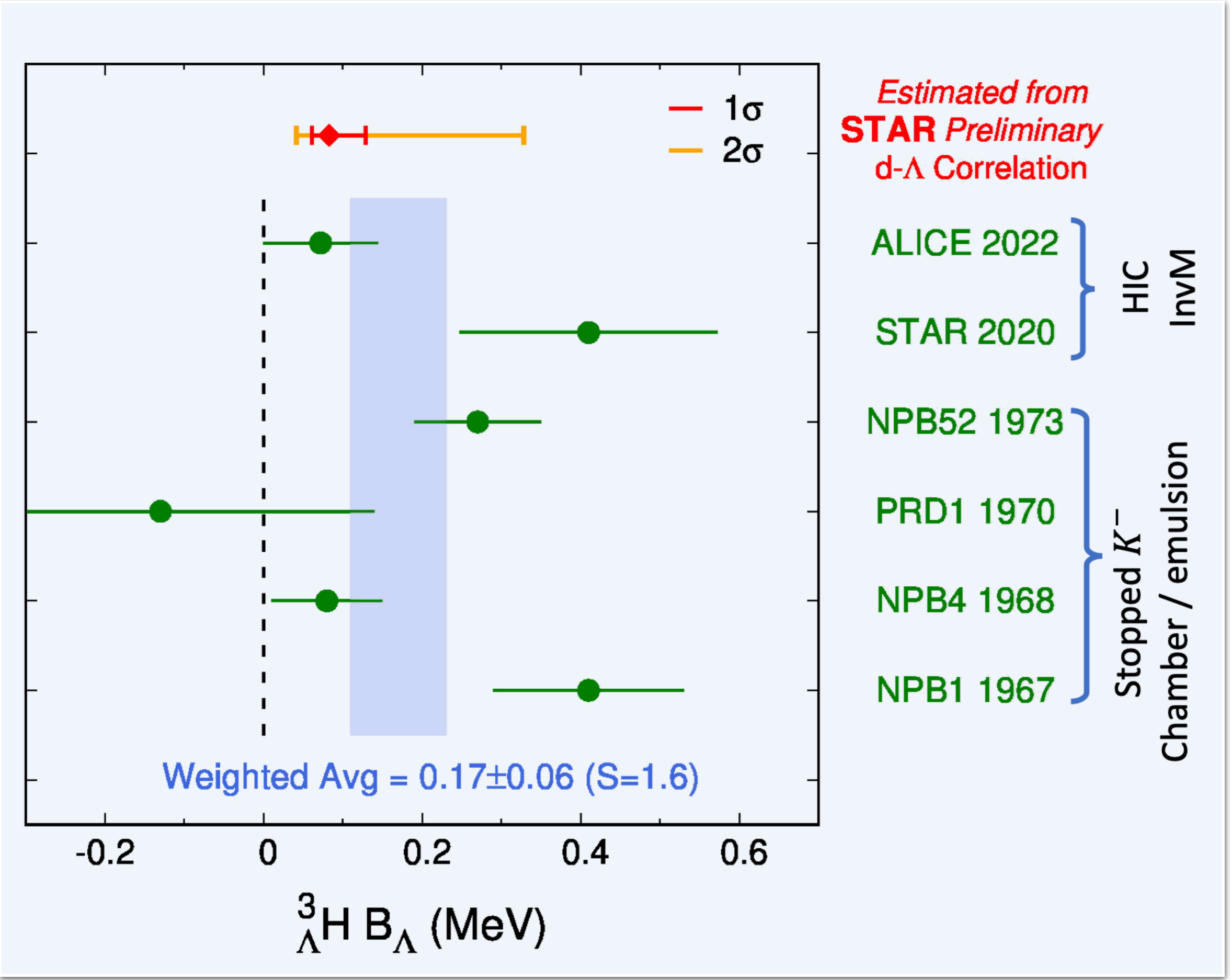
Results — d-Λ Interaction



⇒ $^{3}_{\Lambda}$H binding energy (B_Λ):

Bethe formula from Effective Range Expansion (ERE)

$$B_\Lambda = \frac{\gamma^2}{2\mu_{d\Lambda}} \qquad \frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2$$

$\mu_{d\Lambda}$: reduced mass

γ: binding momentum

⇒ $^{3}_{\Lambda}$H B_Λ = [0.04, 0.33] (MeV) @ 95% CL

-> Consistent with the world average

⇒ Open a new way to constrain $^{3}_{\Lambda}$H properties

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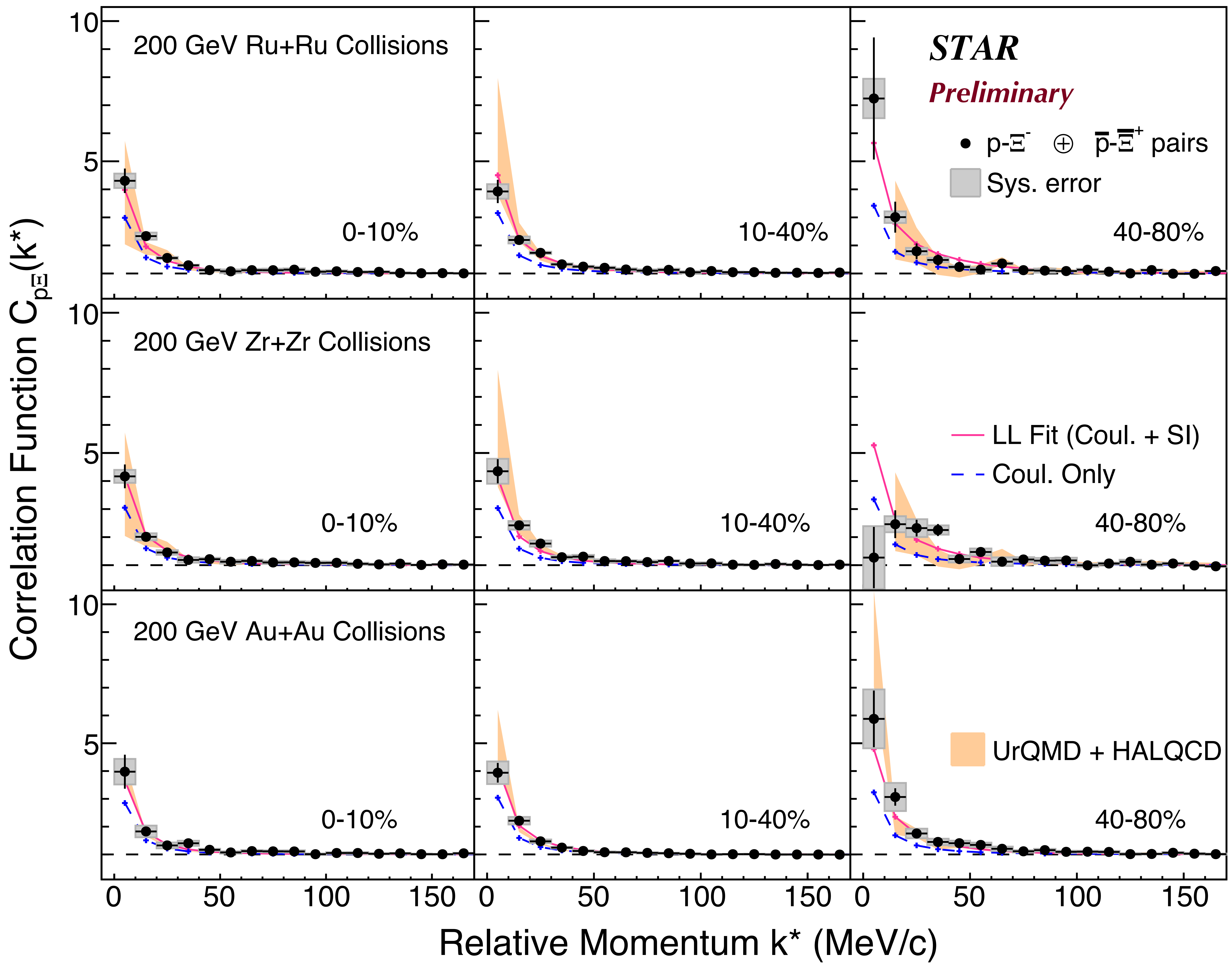
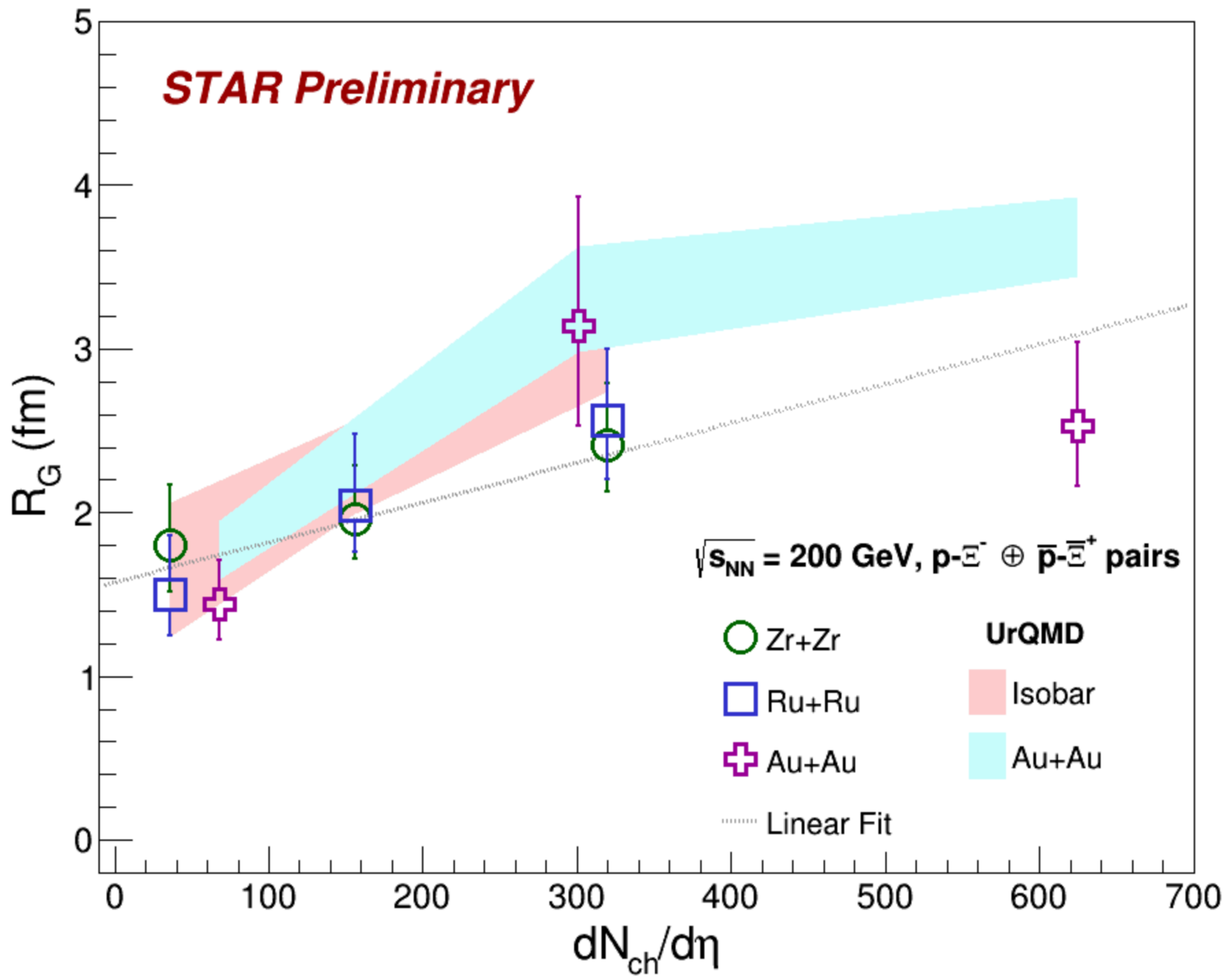
H.Bethe, Phys.Rev 76, 38 (1949)

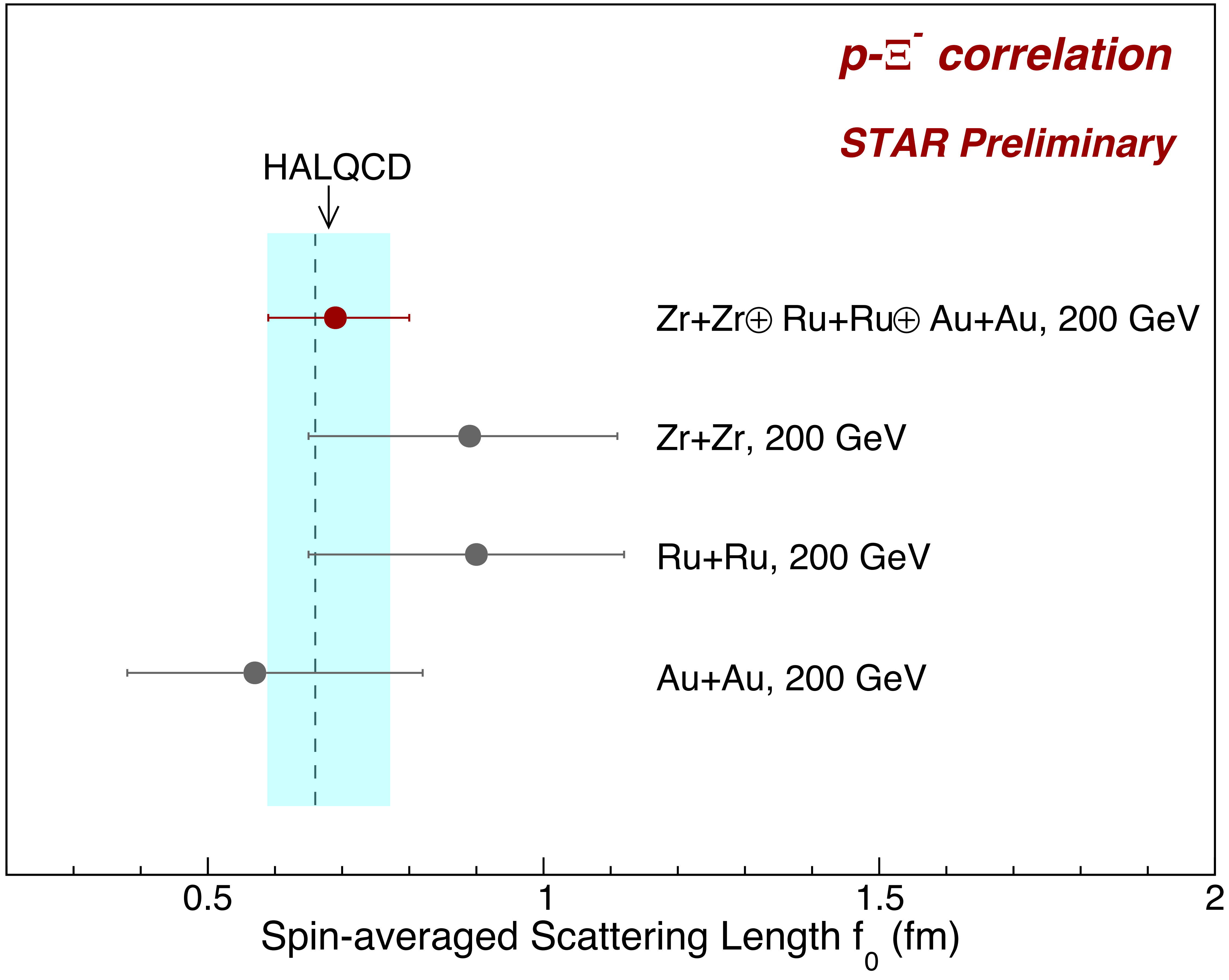
Results — p-Ξ Correlation





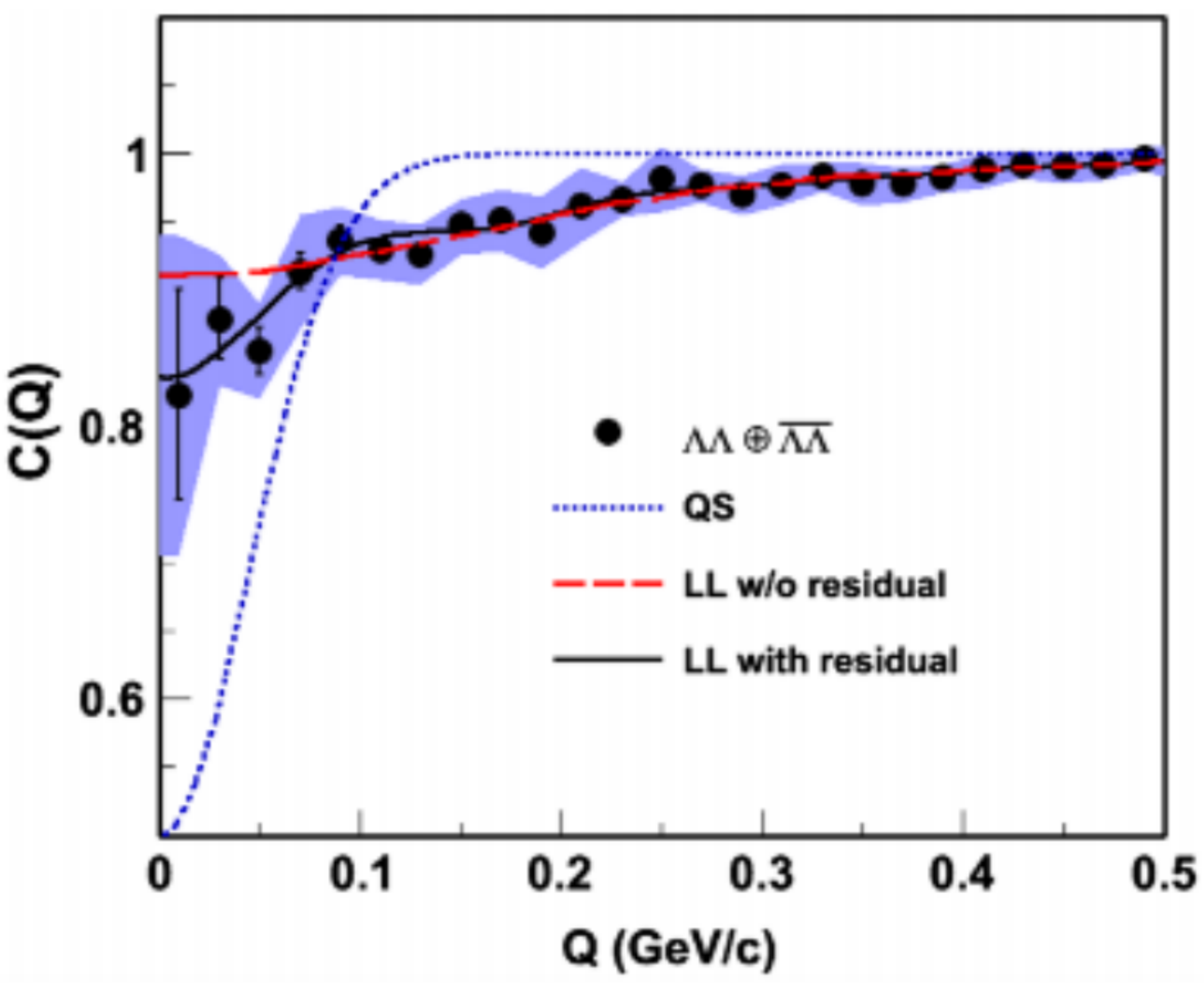
- p-Ξ^- CFs show enhancement at low k*, due to Coulomb attraction and strong interaction
- Simultaneously fit to Isobar and AuAu data
  - 9 cent + f_0 + d_0
- UrQMD + HALQCD results are consistent with data

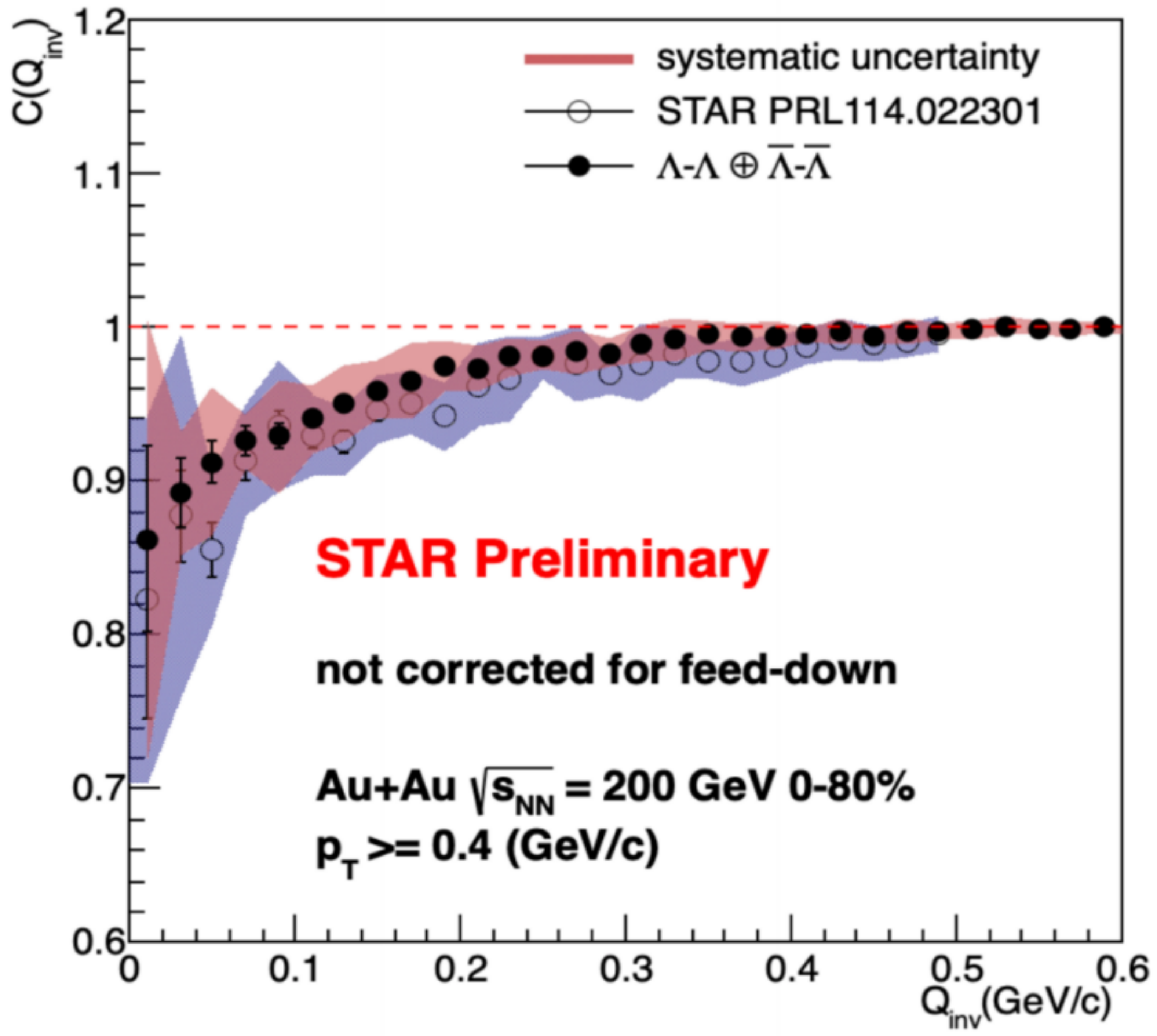
Results — p-Ξ Interaction



- **Extracted *positive* f_0 ~ 0.69 fm**
  - ***Attractive* strong interaction in p-Ξ^- pair**
  - **Shallow interaction compared to p-p interaction**
  - **Consistent with Lattice predictions**

Results — Λ-Λ Correlation

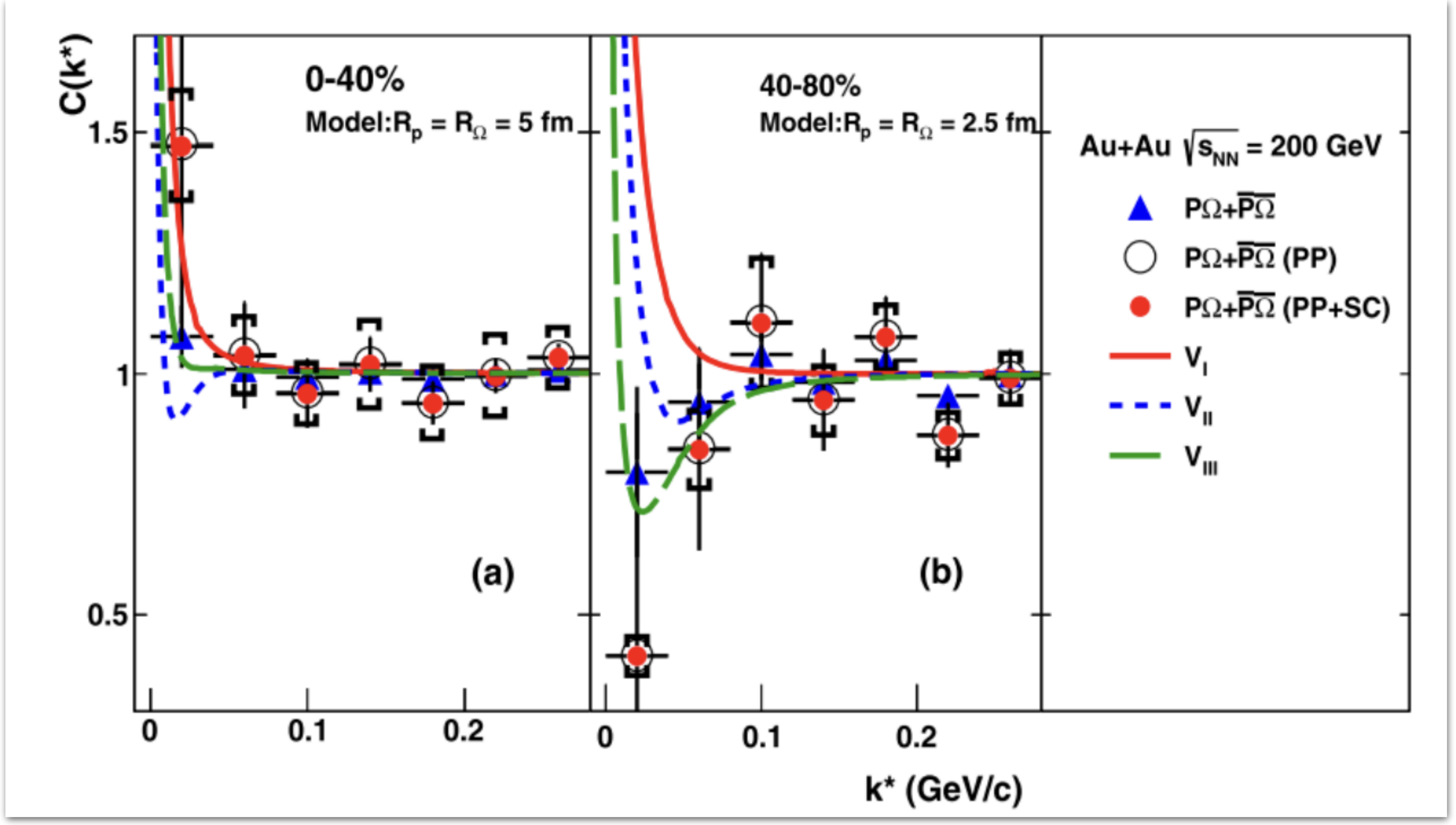




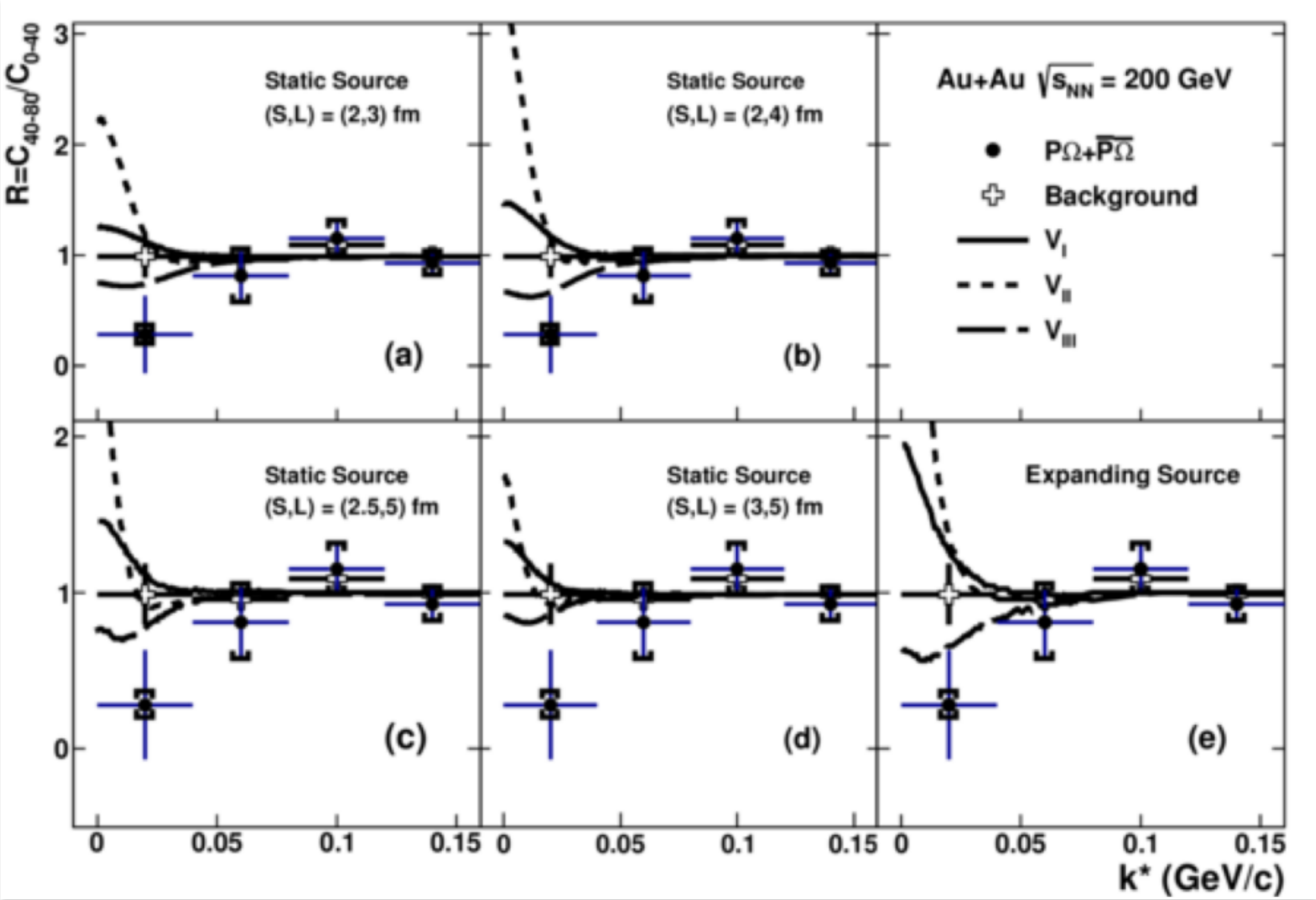
- STAR published Λ-Λ CF at 200 GeV in Au+Au collisions with run10, run11 data
- Re-do Λ-Λ CF in Au+Au collisions at 200 GeV with high-statistics run14, run16 data
- By fitted with analytical LL function, $f_0(\Lambda\Lambda)$ = -1 fm
  - Repulsive interaction conclude from publish paper (without feed-down correction)
  - More detailed study are needed to draw further conclusions

PRL 114, 022301 (2015)
EPJ Web of Conferences 259, 11015 (2022)

Results — p-Ω Correlation



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



- STAR published p-Ω CF at 200 GeV in Au+Au collisions with run11, run14 data
- Compared with theory calculations qualitatively, VIII potential is in better agreement
  - Data supports the existence of bound state

Phys.Lett. B 790 (2019) 490

Summary

⇒ Femtoscopy measurements from HIC provides a unique tool to explore strong interactions and evolution dynamics

⇒ p-d, d-d interaction

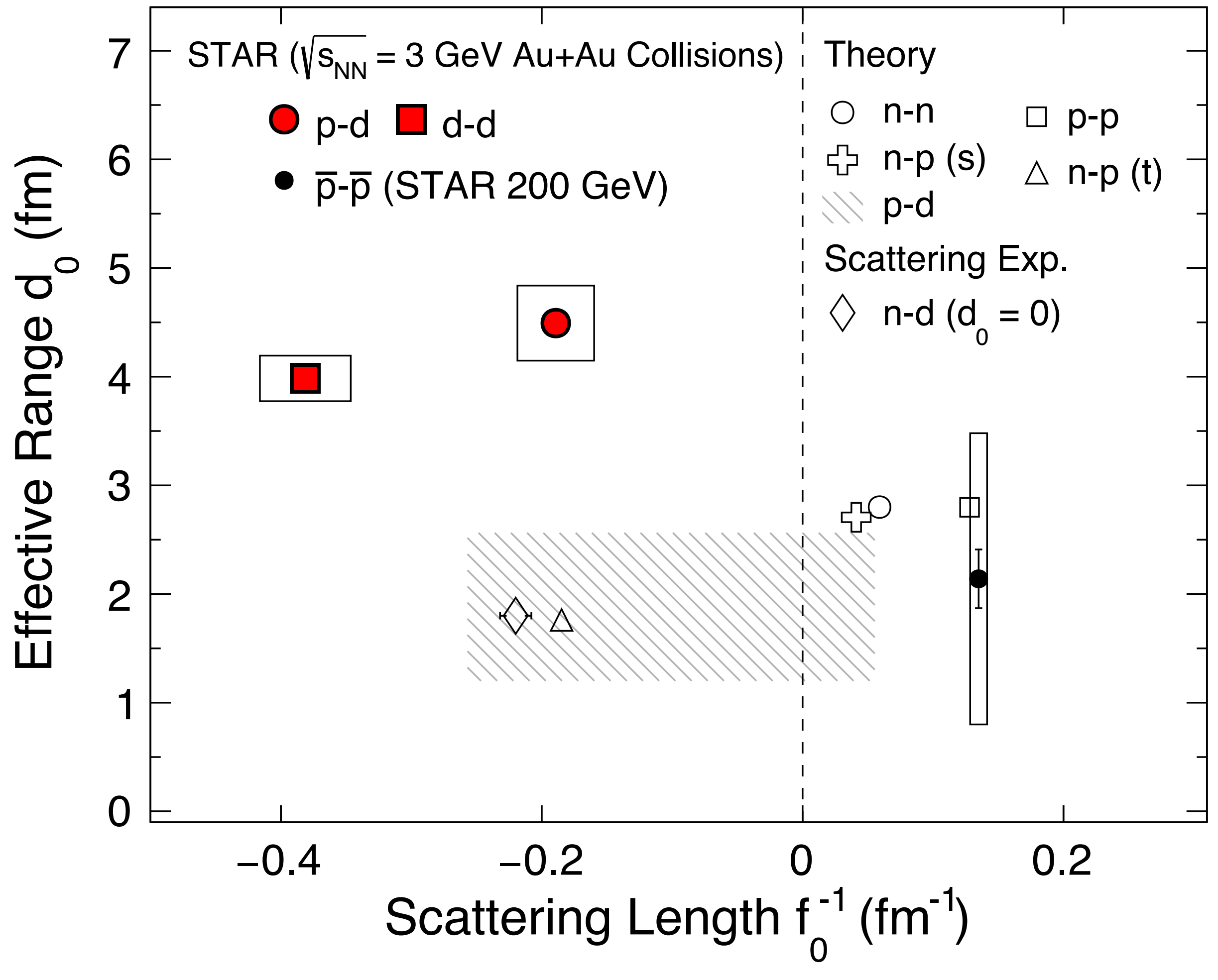
- First determination of p-d / d-d interaction parameters in HIC
- *Coalescence* is the dominant process for deuteron formation in the high-energy collisions

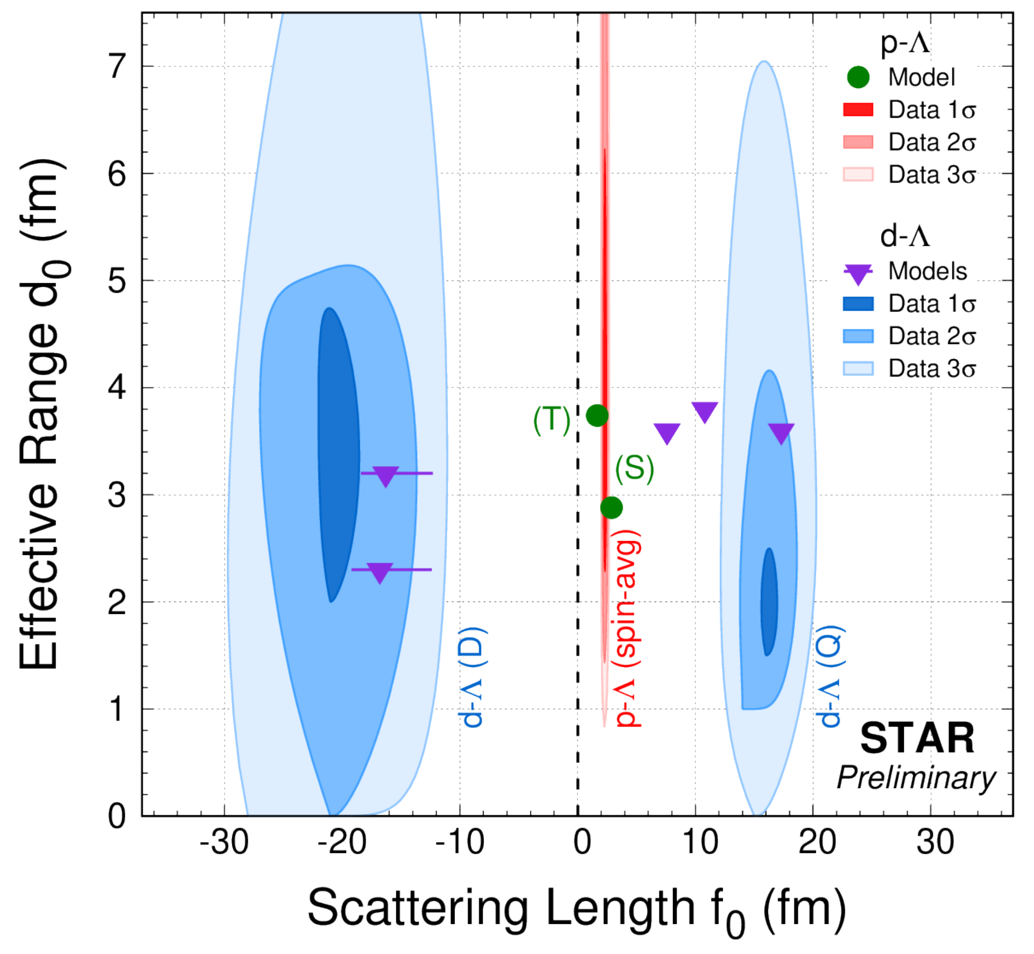
⇒ d-Λ interaction

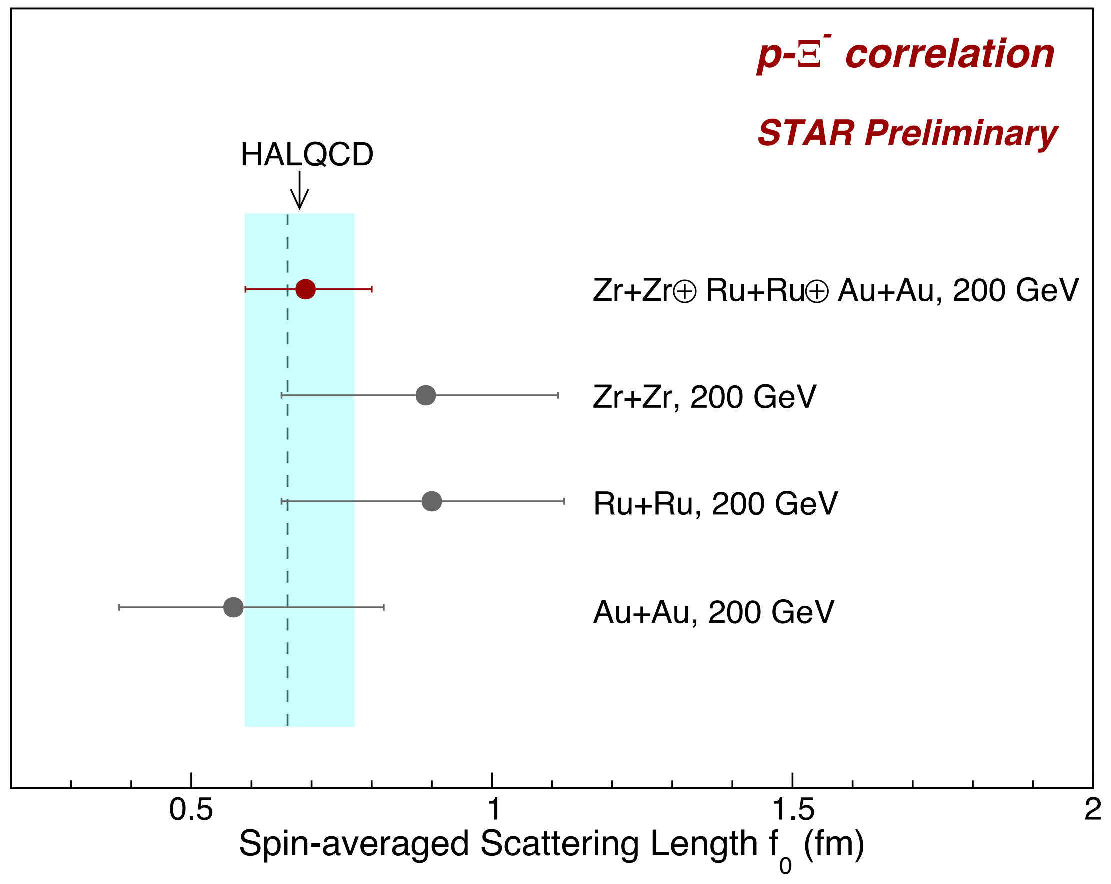
- First experimental measurements of f_0 and d_0 in d-Λ pairs
- Provide a new way to explore hyper-nuclei properties

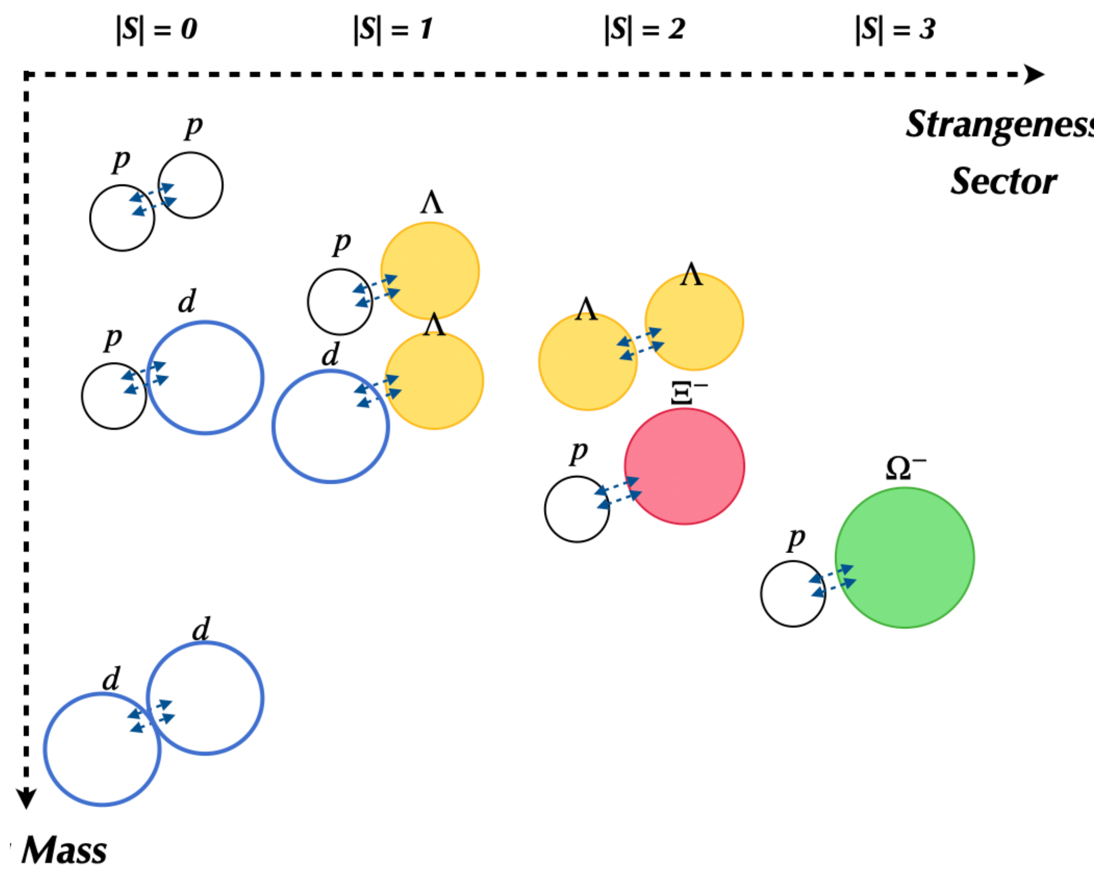
⇒ p-Ξ, Λ-Λ, p-Ω interaction

- Attractive interaction in p-Ξ pair: f_0 ~ 0.69 fm
- High statistics data is needed for studying Y-N / Y-Y interaction





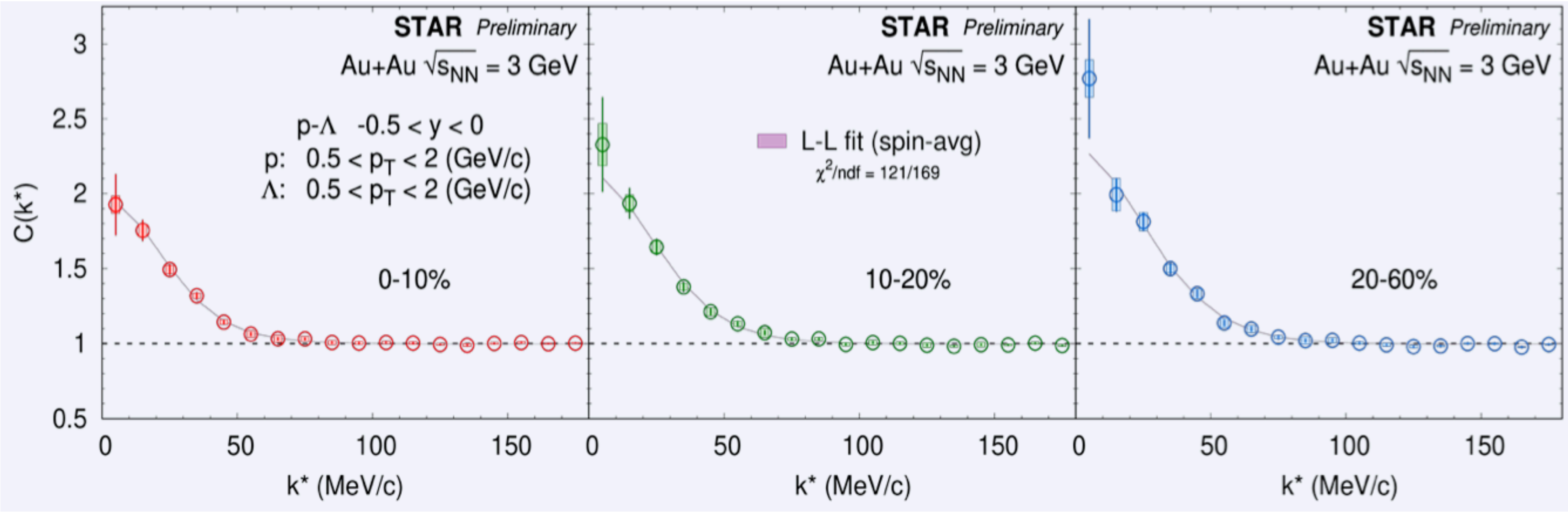


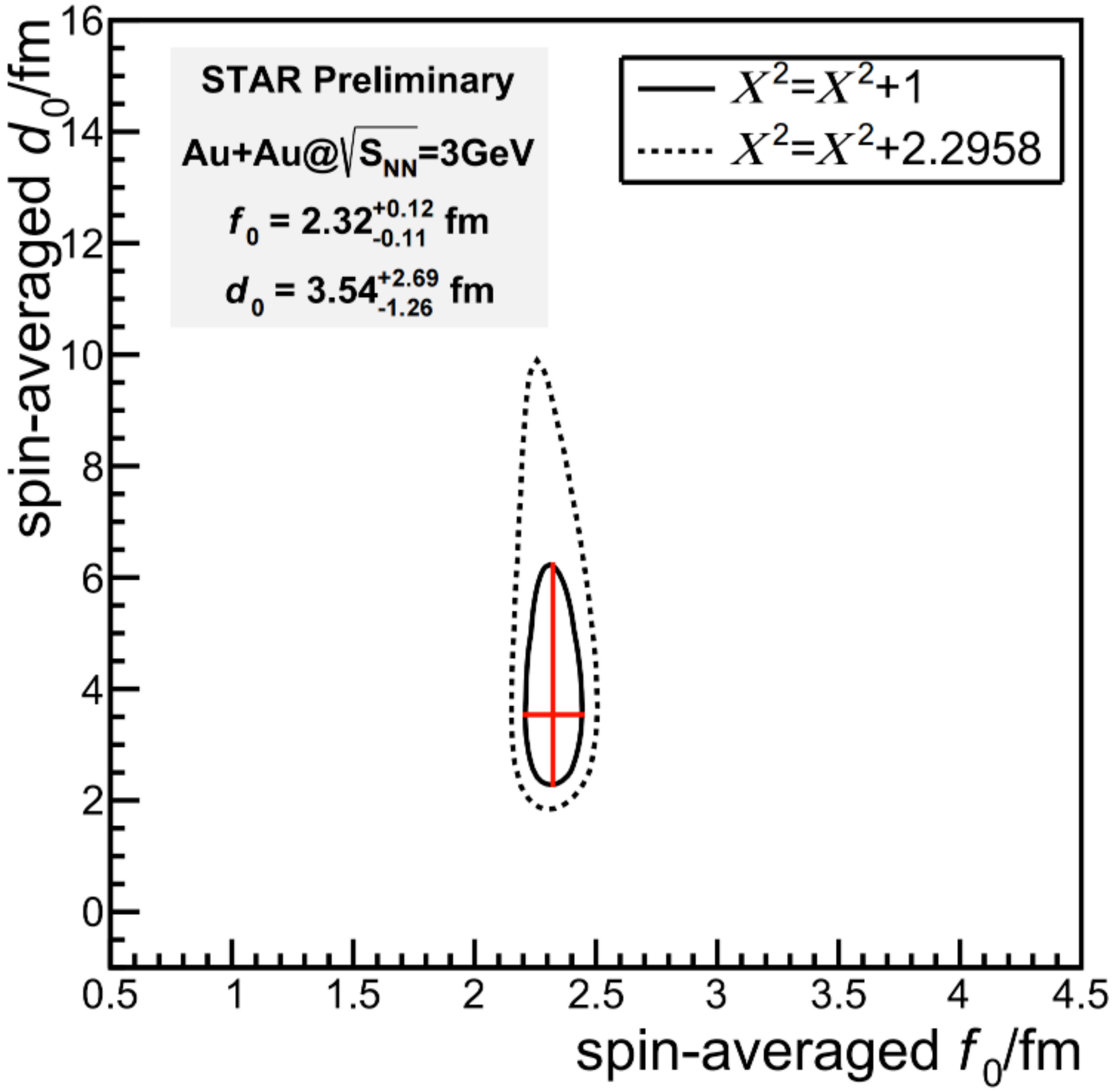


Thank you

Backups

Backup: proton-Λ correlation





- **CF composition ($p-\Lambda$): SI only**
- **$p-\Lambda$ CFs show enhancement at low k*, due to *attractive* strong interaction**
- **Correlation strength (spin-averaged), consistent with theory prediction**

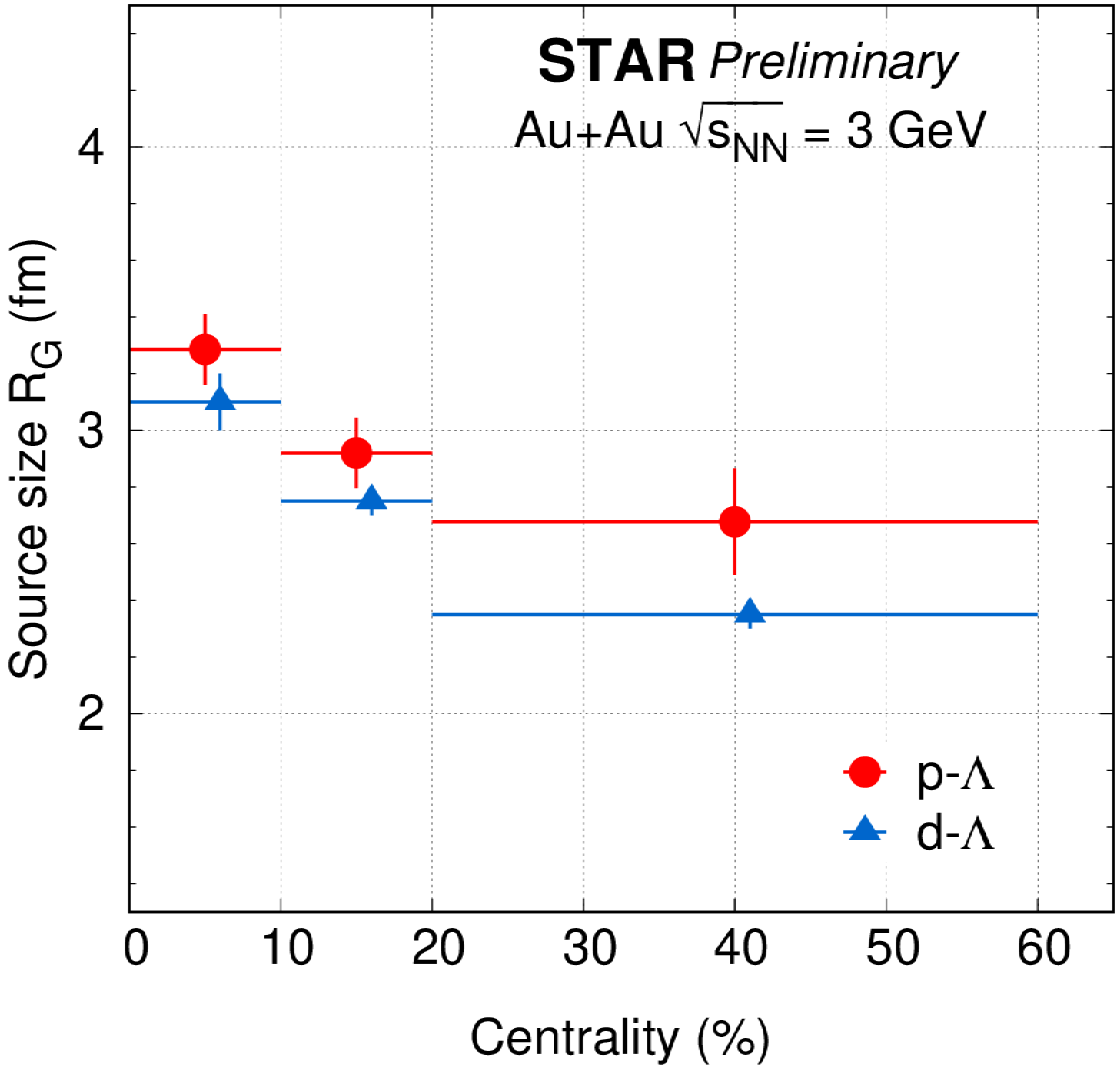
$$f_0 = 2.32^{+0.12}_{-0.11} fm,\ d_0 = 3.54^{+2.69}_{-1.26} fm$$

Theory	f_0 (fm)	d_0 (fm)
Singlet	2.88	2.92
Triplet	1.66	3.78

F.Wang and S.Pratt, PRL 83 (1999) 3138

https://drupal.star.bnl.gov/STAR/system/files/Analysis_Note_pLambda_QinZhi_v0_1.pdf

Results — d-Λ Correlation



⇒ R_G: spherical Gaussian source extracted with L-L approach

⇒ Collision dynamics as expected

- Centrality dependence: $R_G^{central} > R_G^{peripheral}$
- $<m_T>$ dependence: $R_G(p - \Lambda) > R_G(d - \Lambda)$

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