Measurements of Light Nuclei Femtoscopy at High Baryon Density

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Central China Normal University

STAR区域研讨会

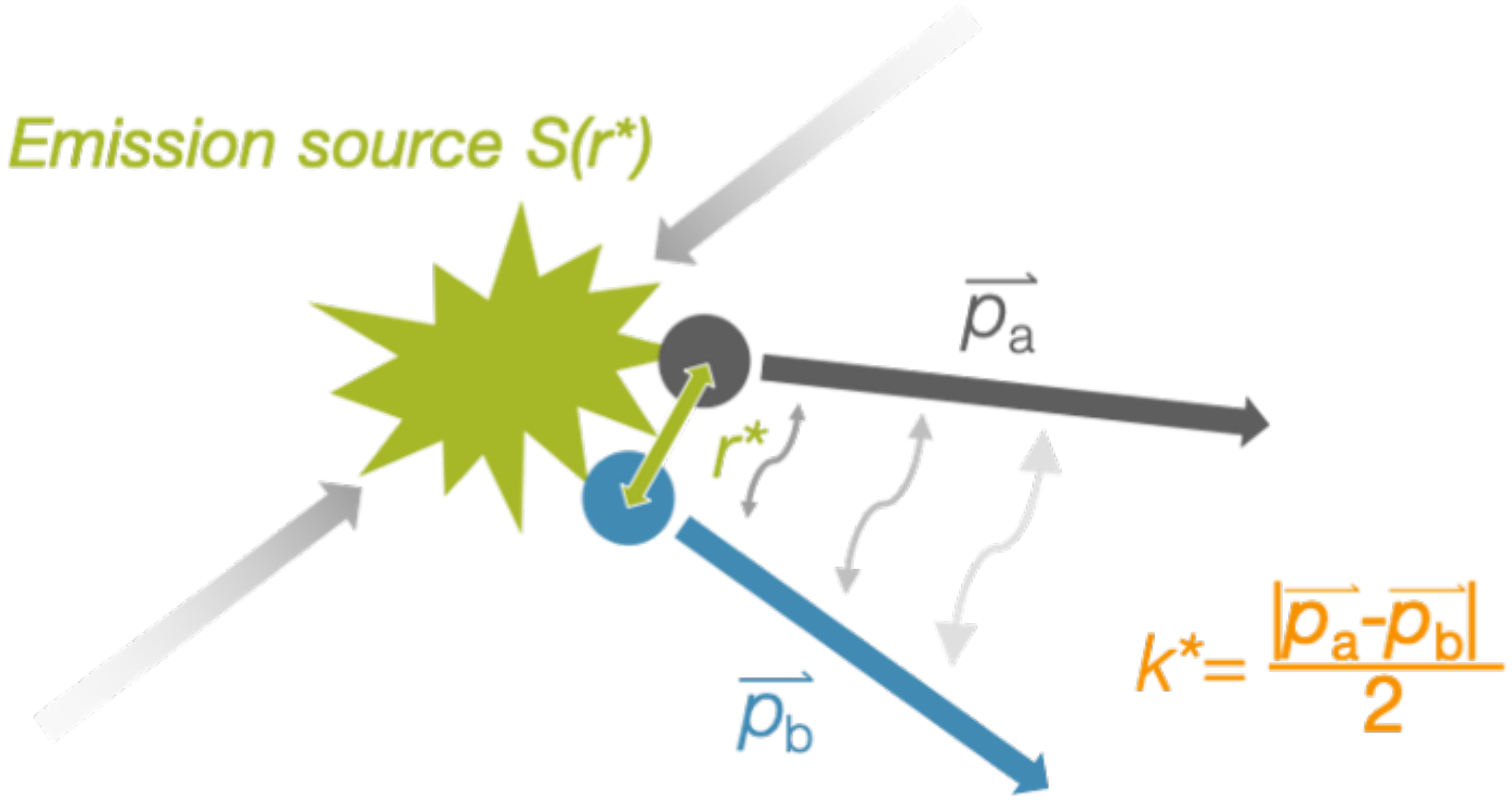
2024年10月10-15日，重庆，中国

14th Oct, 2024

Outline

1. Femtoscopy and Two-particle Correlation Function
2. Lednicky-Lyuboshitz (L-L) Model
3. Motivation
4. STAR Experiment
5. Results
   - p-d, d-d correlation at 3 GeV
   - d-Λ correlation at 3 GeV
6. Summary & Outlook

Femtoscopy



⇒ **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

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

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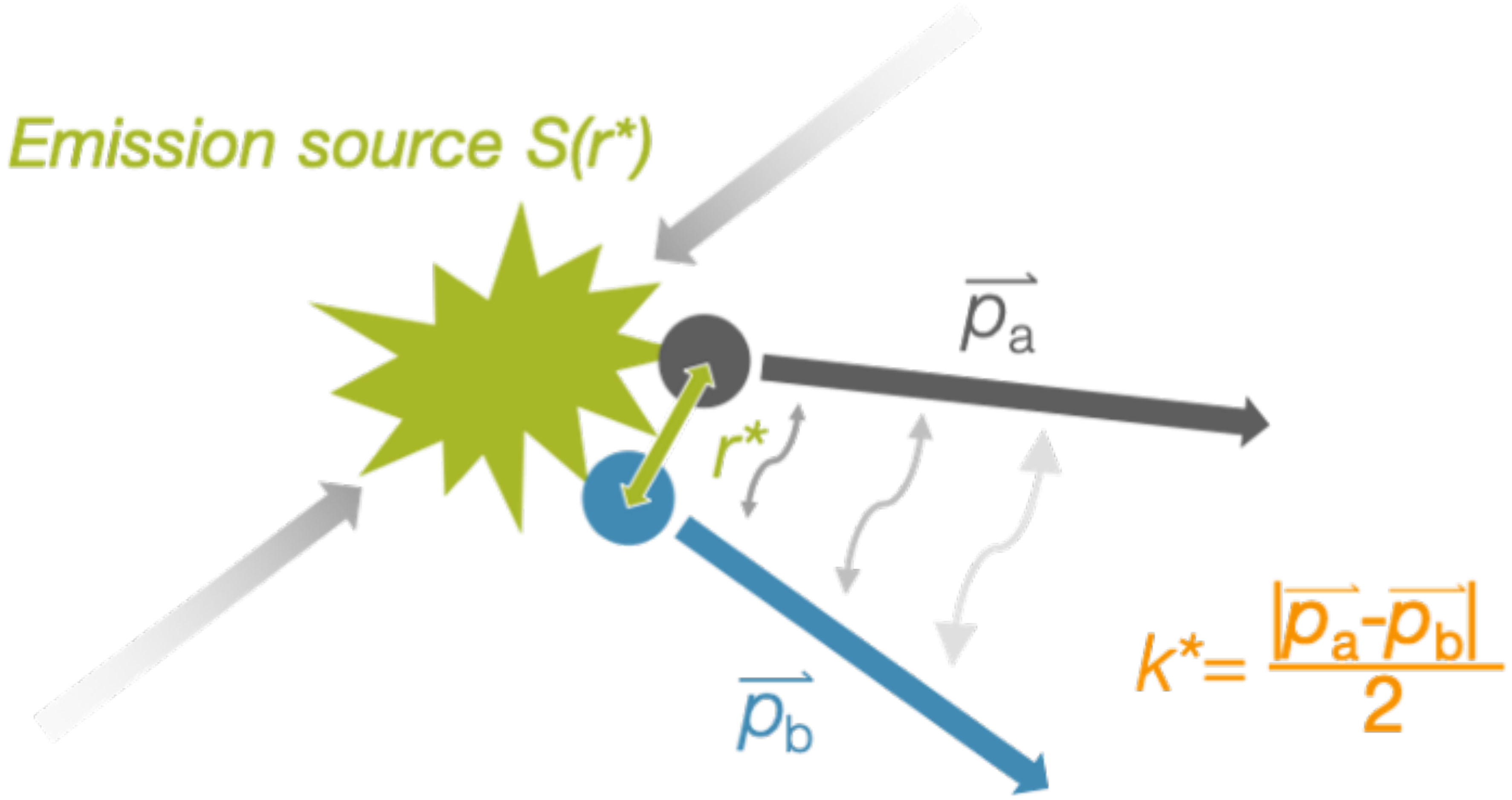

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✓Two-particle correlation function:

<u>*Model*</u> <u>*Experimental*</u>

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

$S(\vec{r})$: *Source function*
$\Psi(\vec{k}^*,\vec{r})$: *Pair wave function*
$k^* = \frac{1}{2}|\vec{p}_a - \vec{p}_b|$, *relative momentum*
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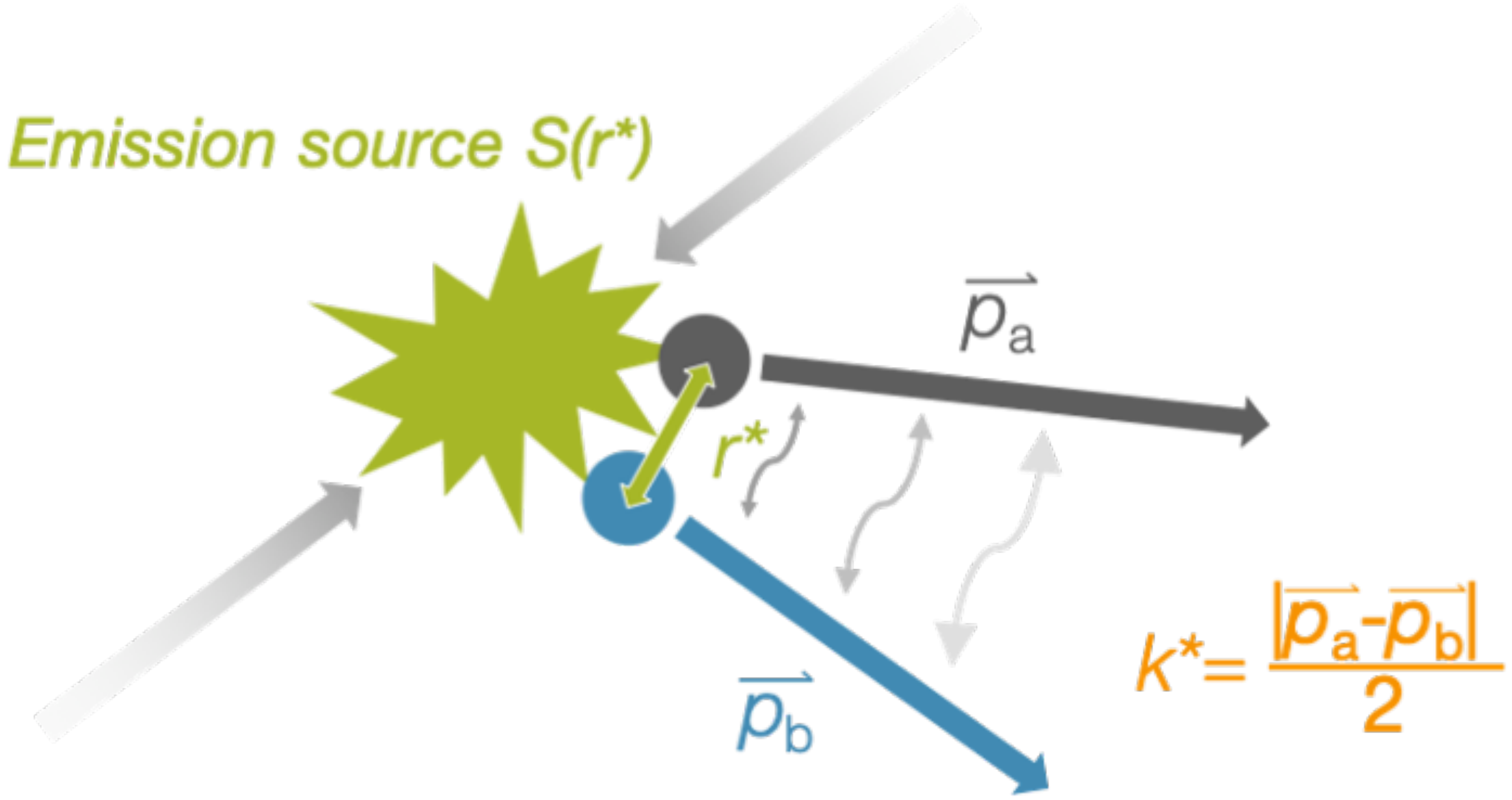

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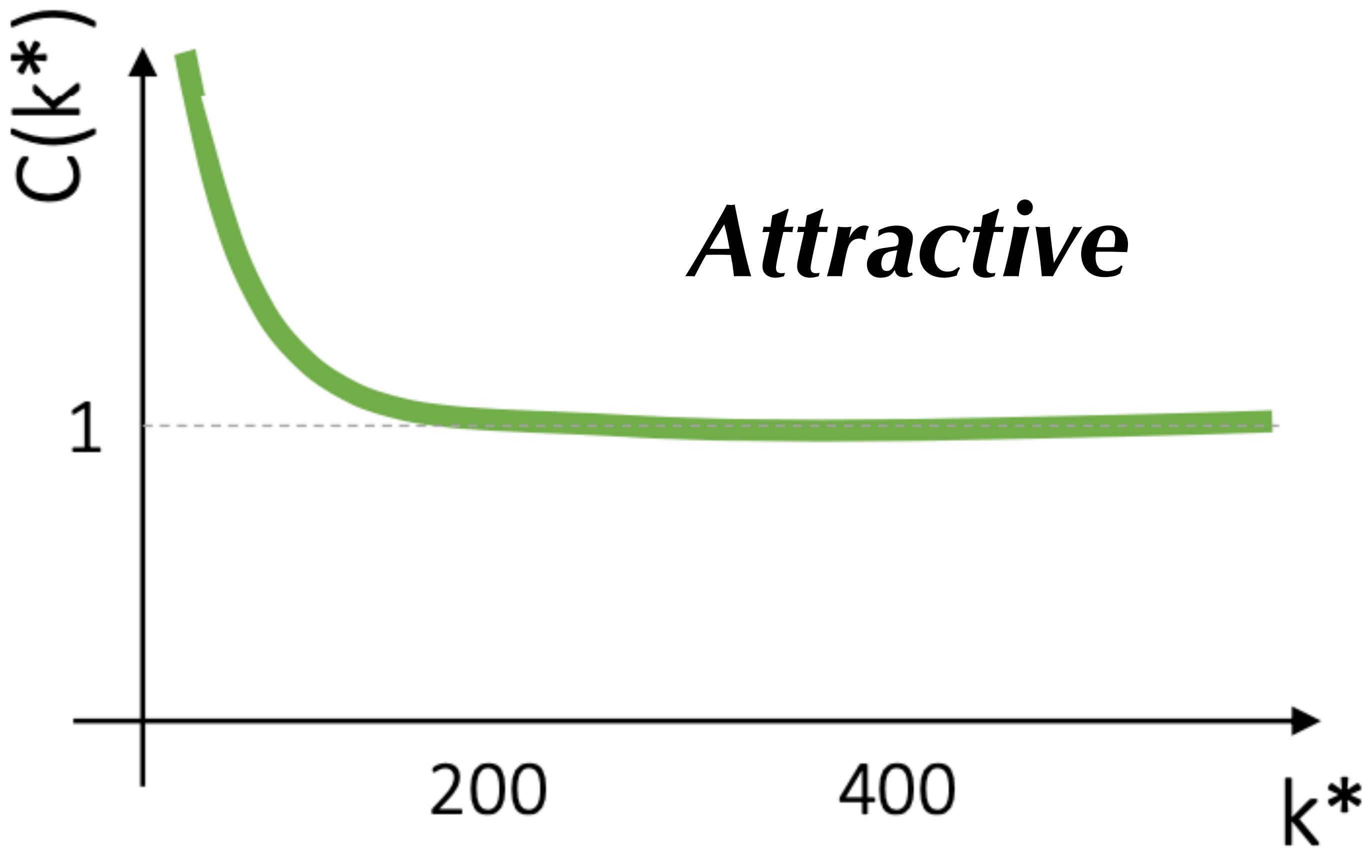

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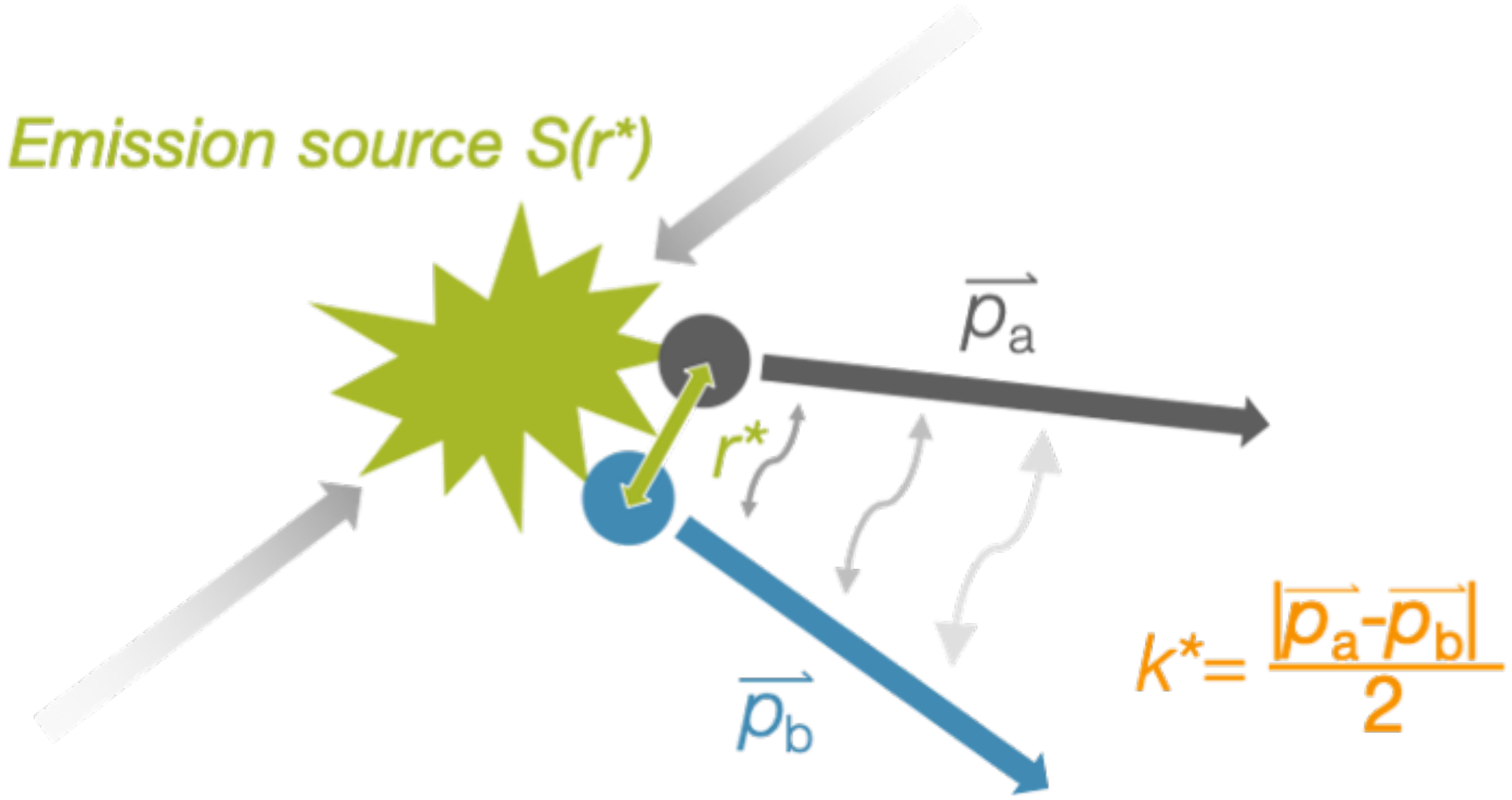

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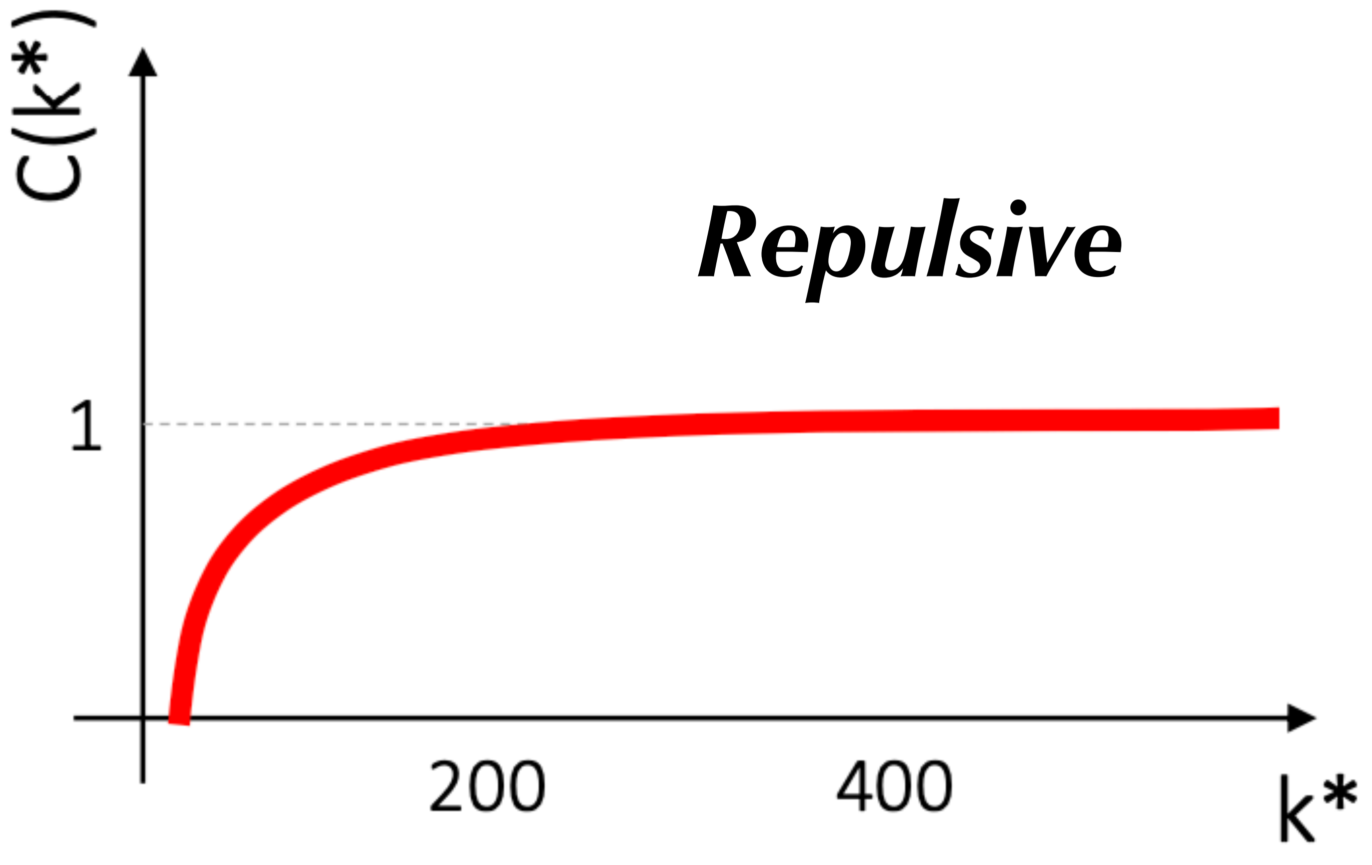

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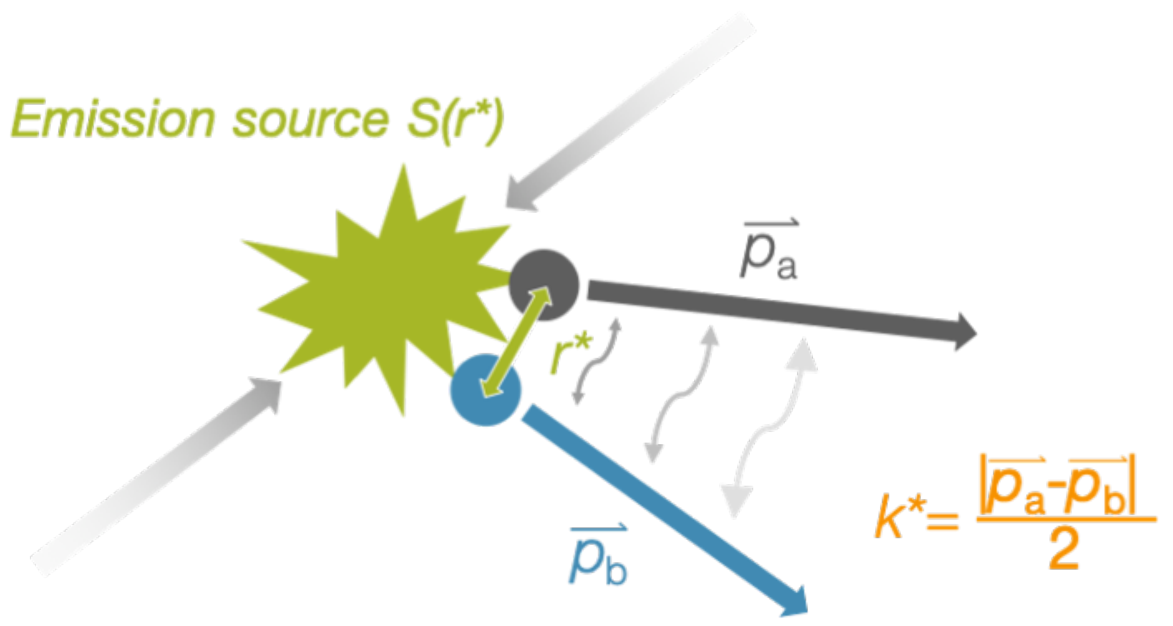
Femtoscopy — Lednicky-Lyuboshitz approach



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

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

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

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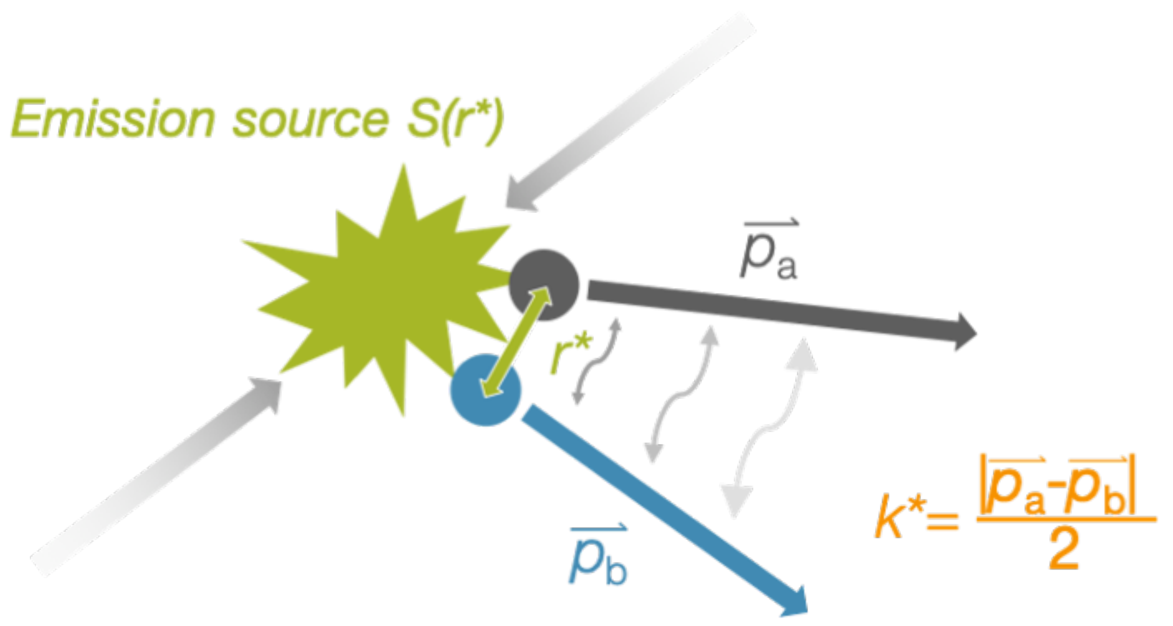

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Physics quantity:

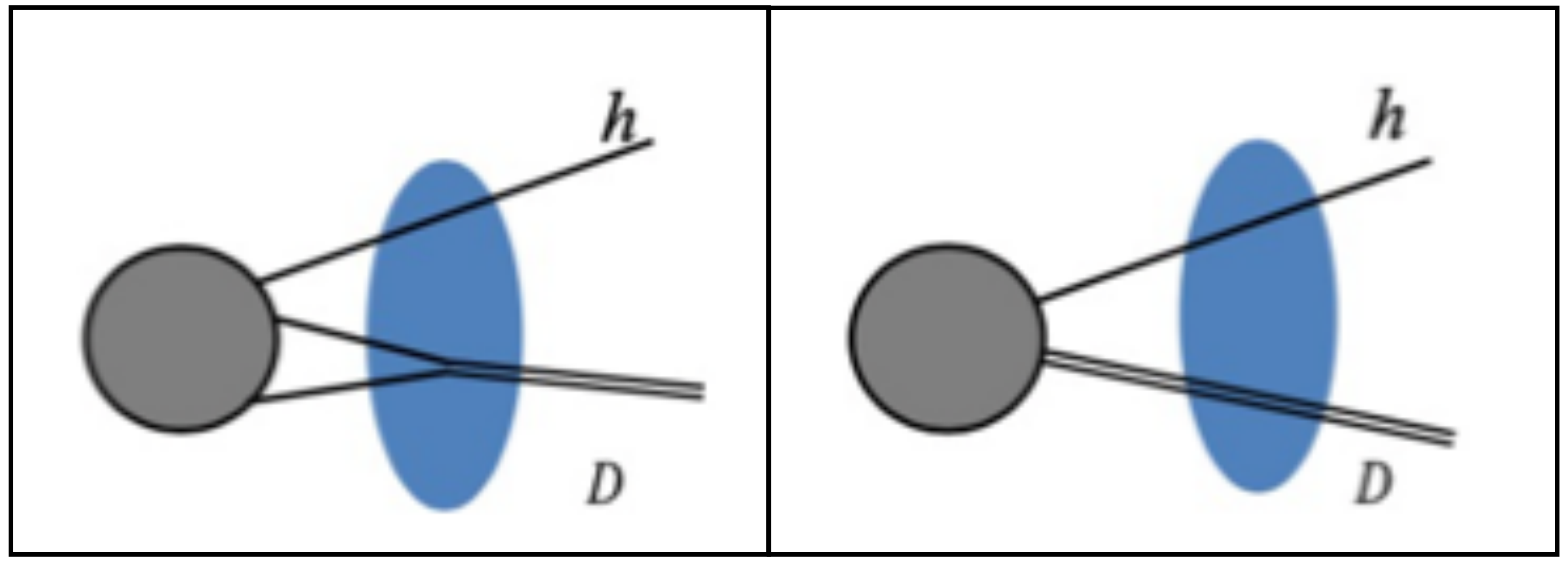
1. R_G: Spherical Gaussian source size
2. f_0: Scattering length
3. d_0: Effective range

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

Motivation

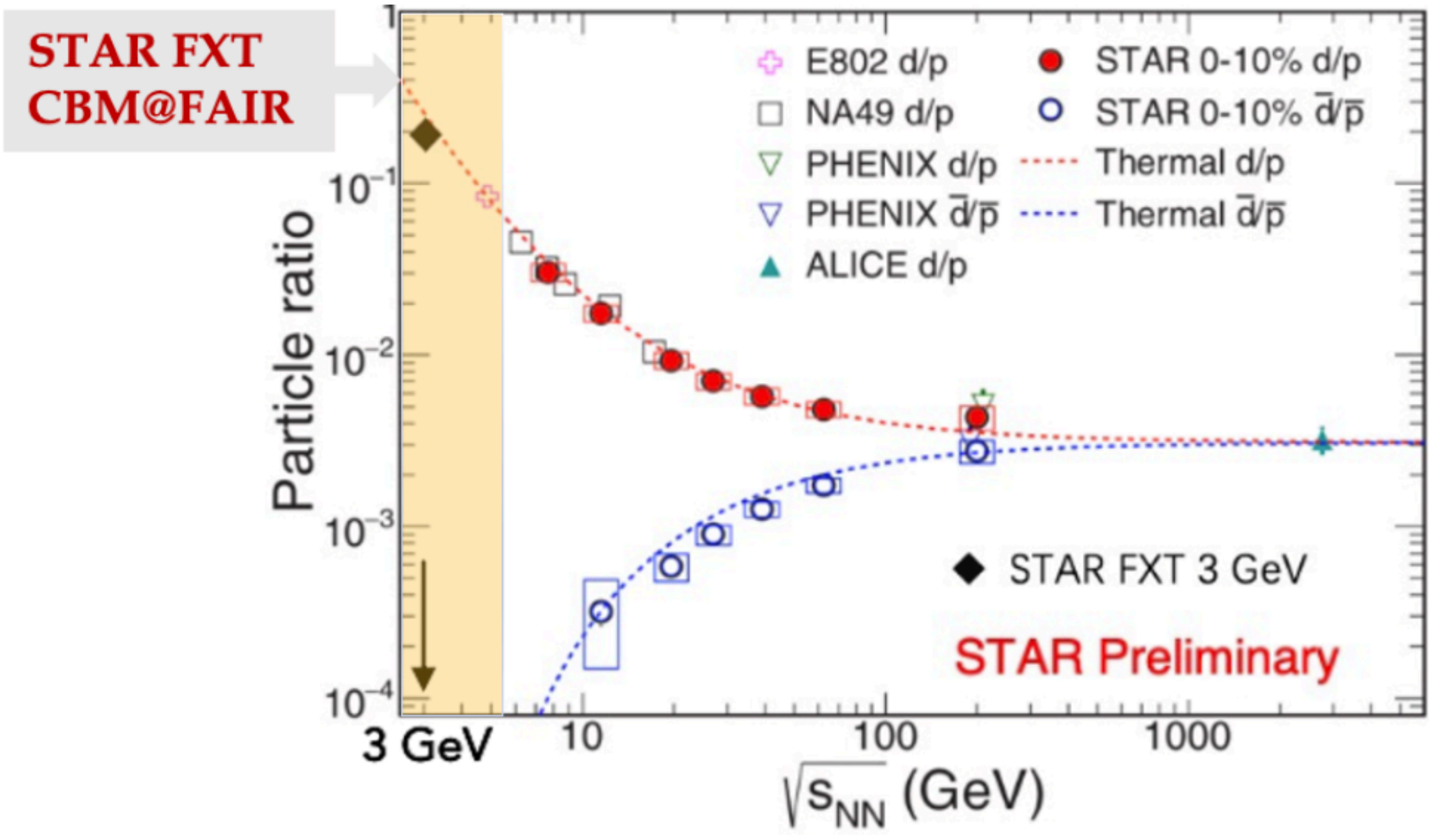
- **Formation mechanism of light nuclei are under debate**
  ⇒ Coalescence : final-state interaction

  ⇒ Thermal : produced directly from fireball



Coalescence Direct production

- **Indirect approach of three-body and four-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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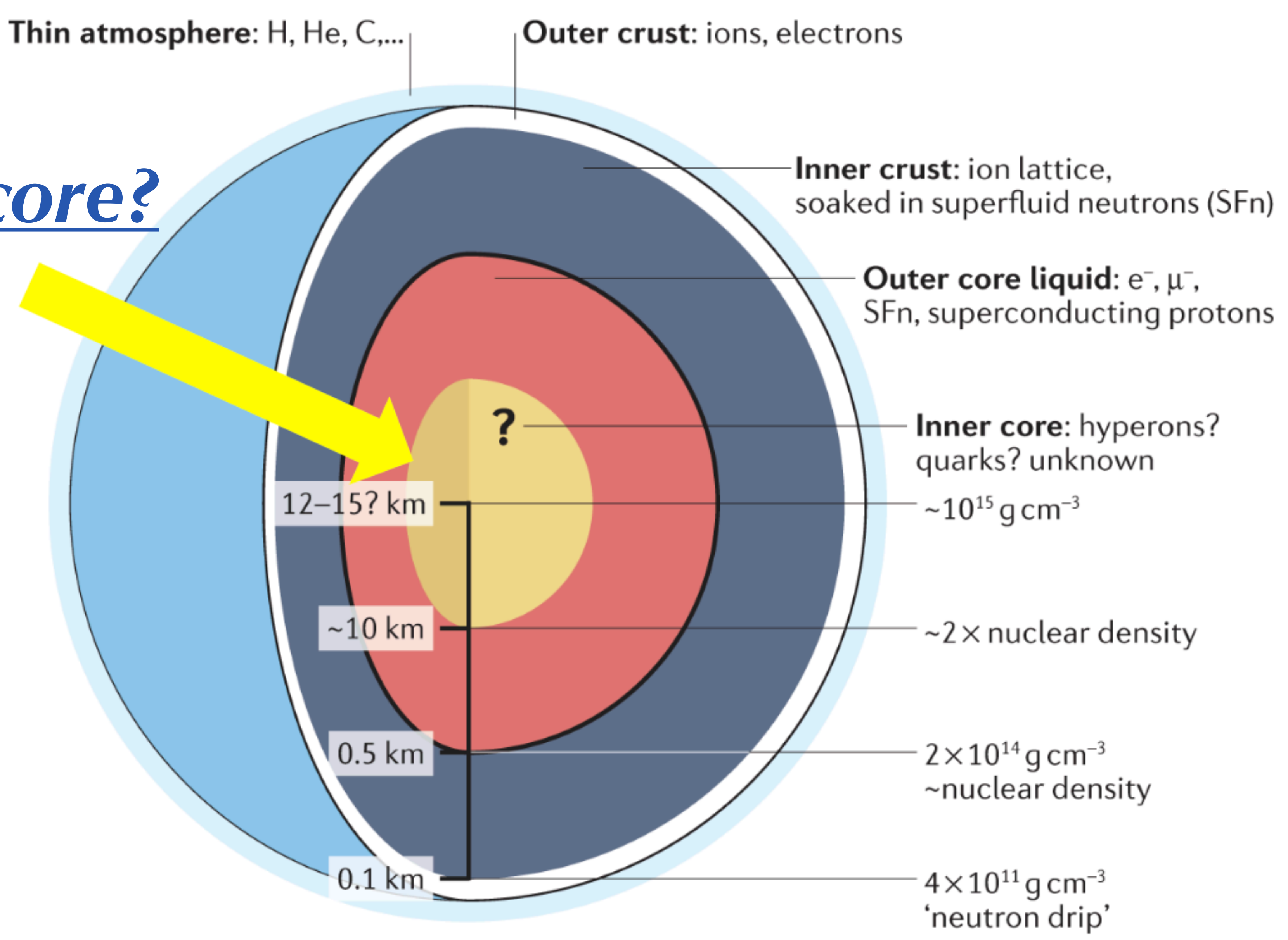
- **Role of Nucleon-Nucleon (N-N) and Hyperon-Nucleon (Y-N) interactions in the Equation-of-State**

  ⇒ Inner structures of neutron star

  ⇒ Light nuclei + hyperon: provide the insights to hypernuclei structure and properties

Inner core?



Phys.Rev.C 99, 064905 (2019)

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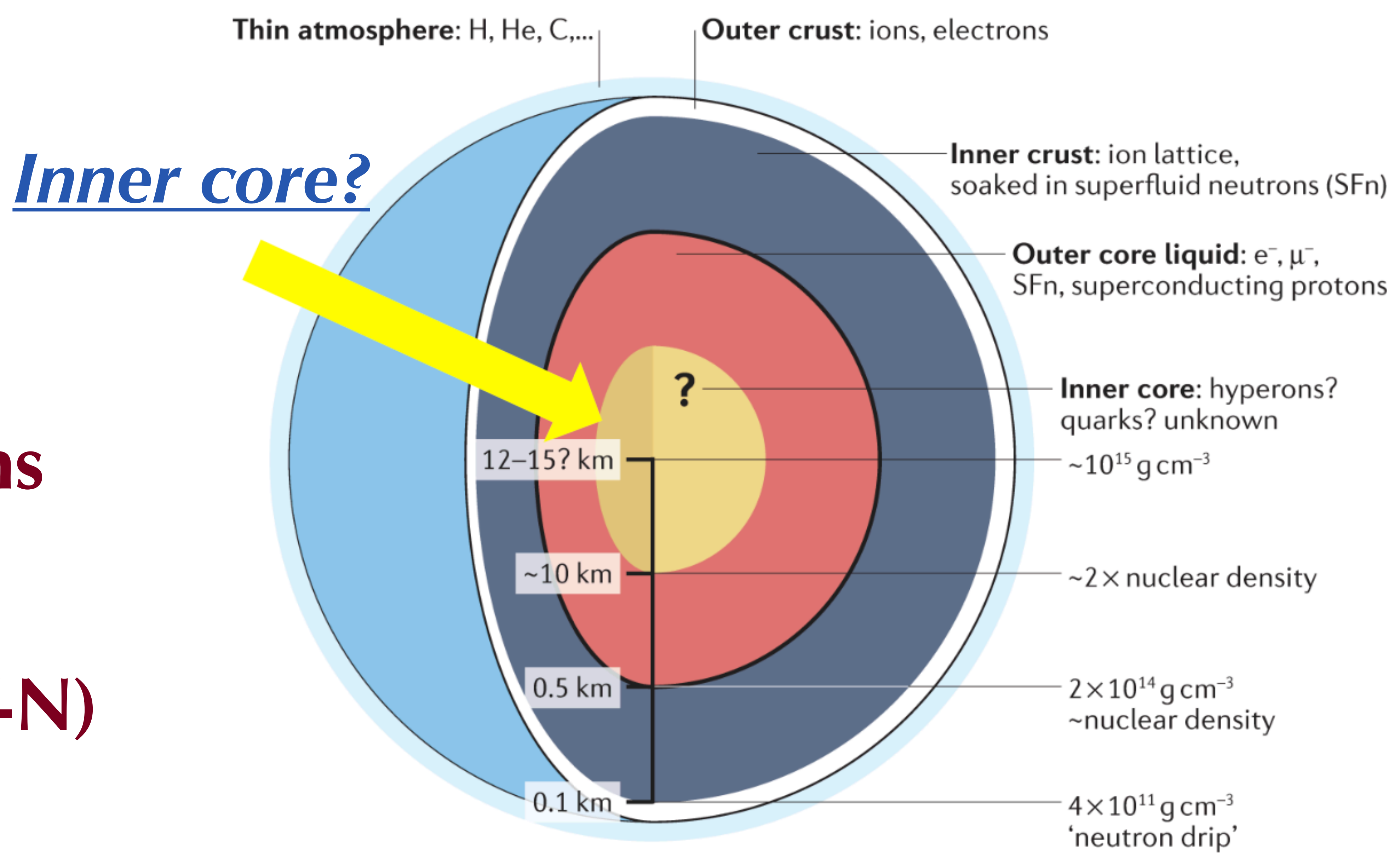
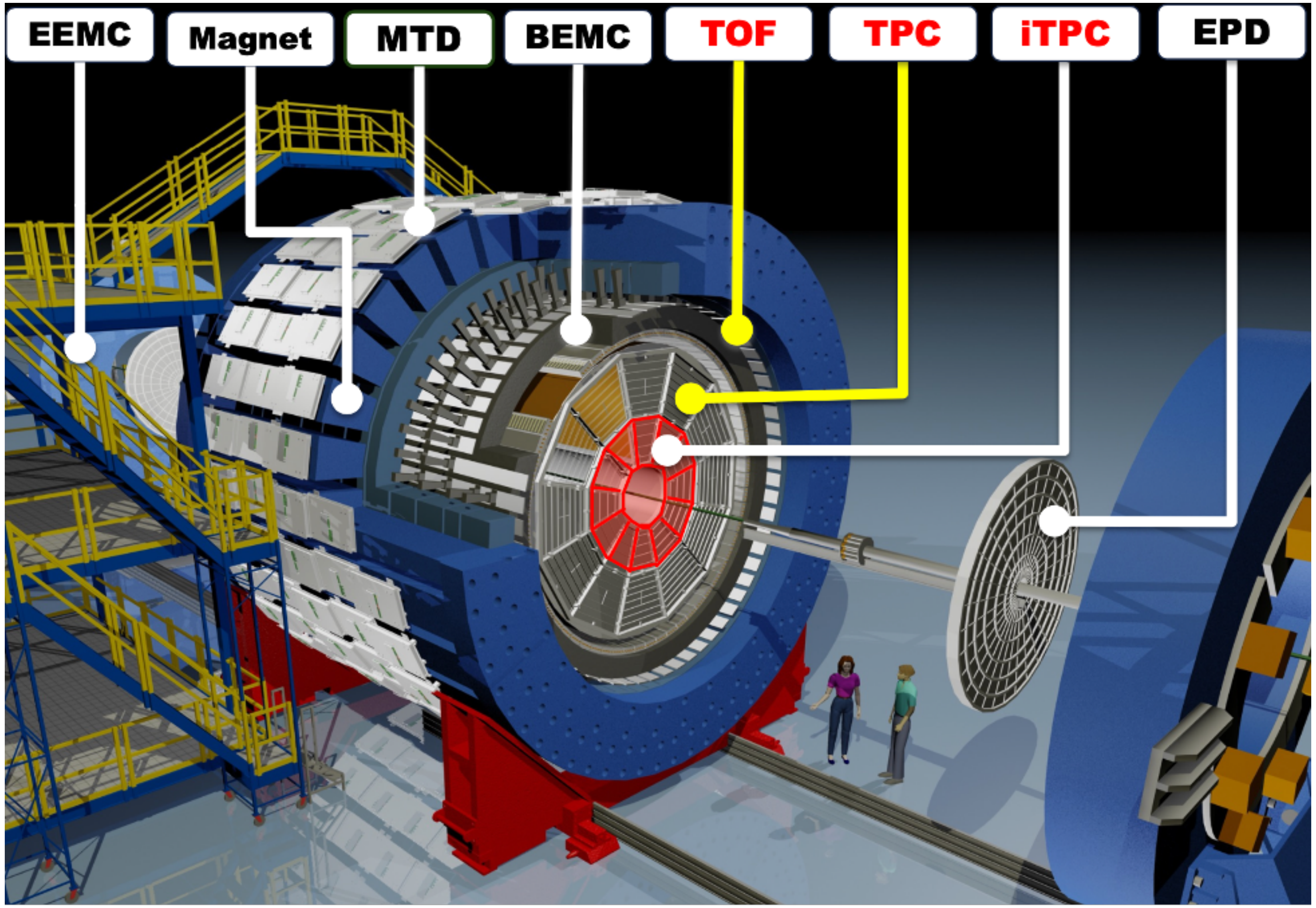


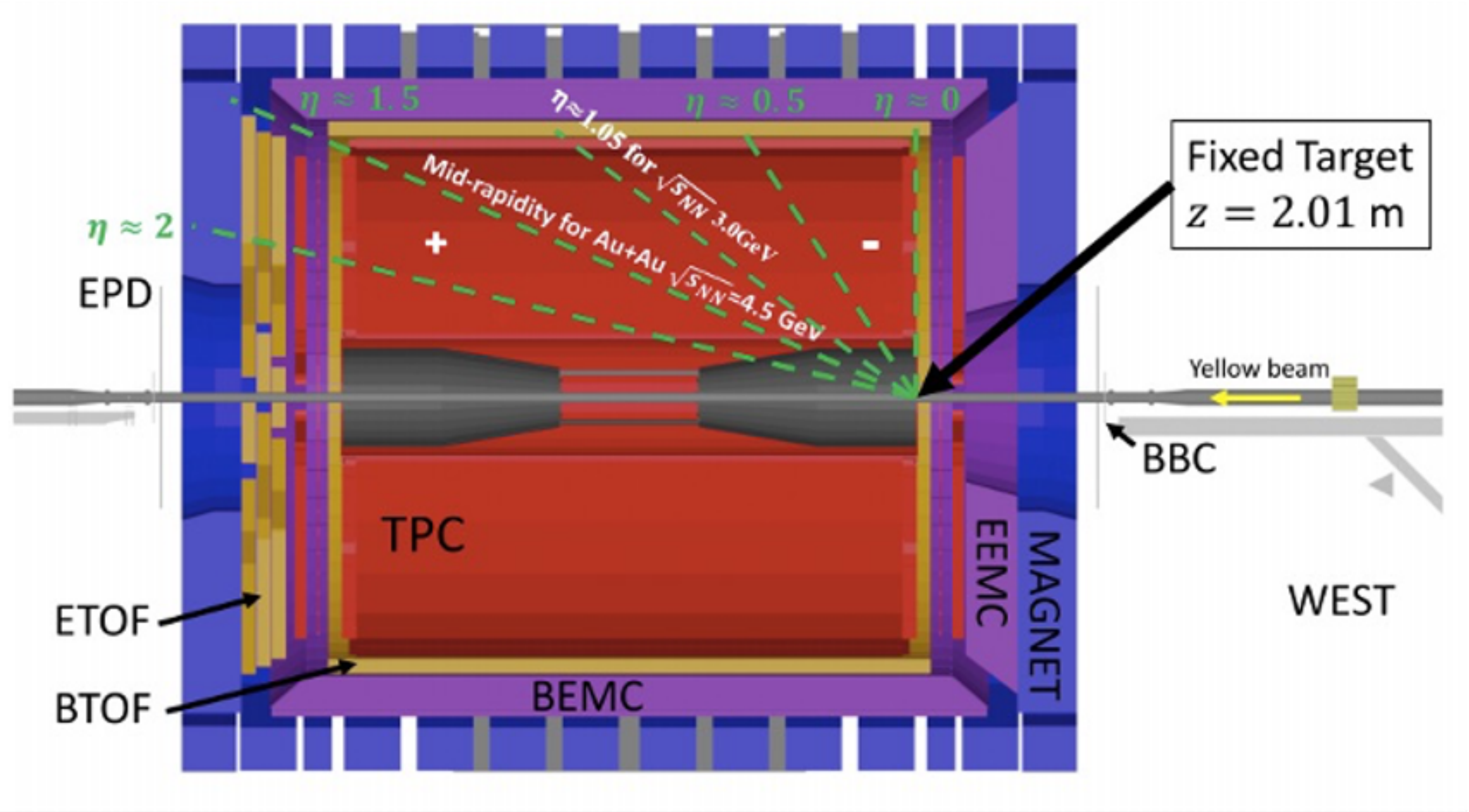
In this talk:

p-d, d-d, d-Λ correlation @ 3 GeV

Phys.Rev.C 99, 064905 (2019)

STAR Detector & Datasets





⇒ 3 GeV Au+Au collisions @ 2018

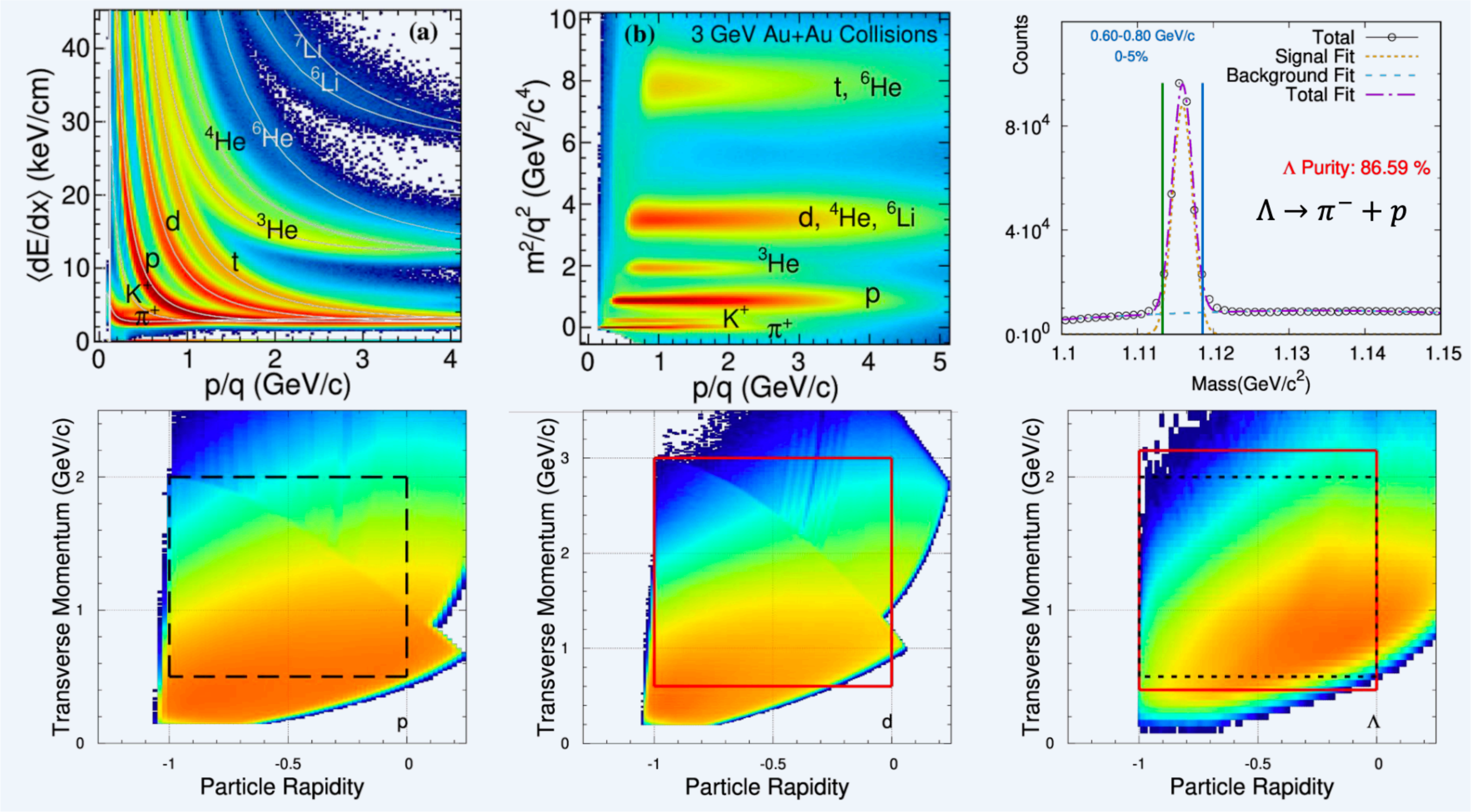
-> μ_B ~ 720 MeV

⇒ 0-60% centrality

⇒ Excellent particle identification

⇒ Large, uniform acceptance at mid-rapidity

Particle Identification & Reconstruction

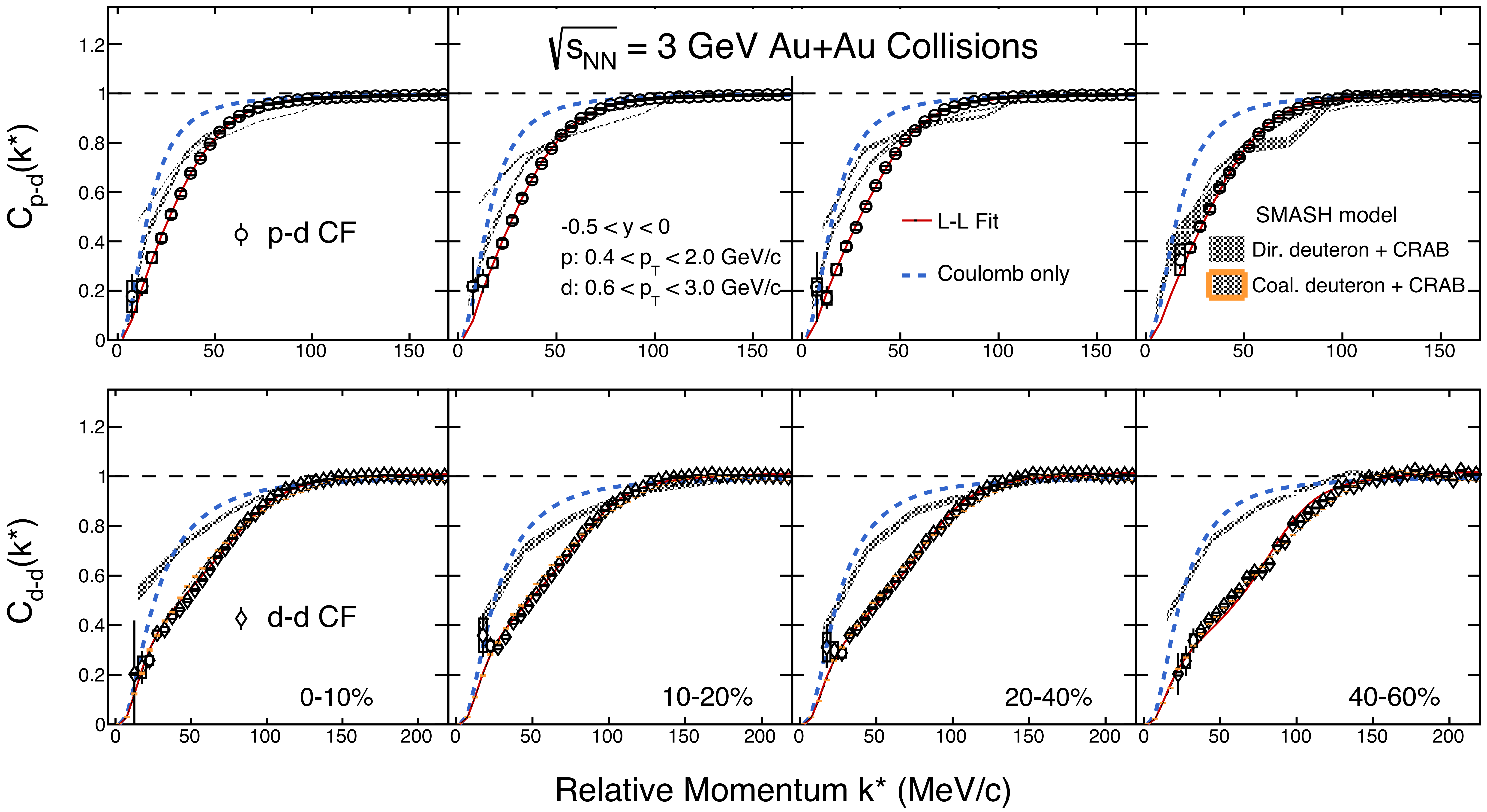


⇒ π^-, p and d are identified by Time Projection Chamber (TPC) and Time-Of-Flight (TOF)

⇒ Reconstruct Λ candidates with KFParticle package -> Improve significance

Phys. Lett. B 827 (2022) 136941

Results — p-d, d-d Correlation



⇒ First measurements of p-d/d-d correlation functions in HIC

⇒ Clear depletion in low k*

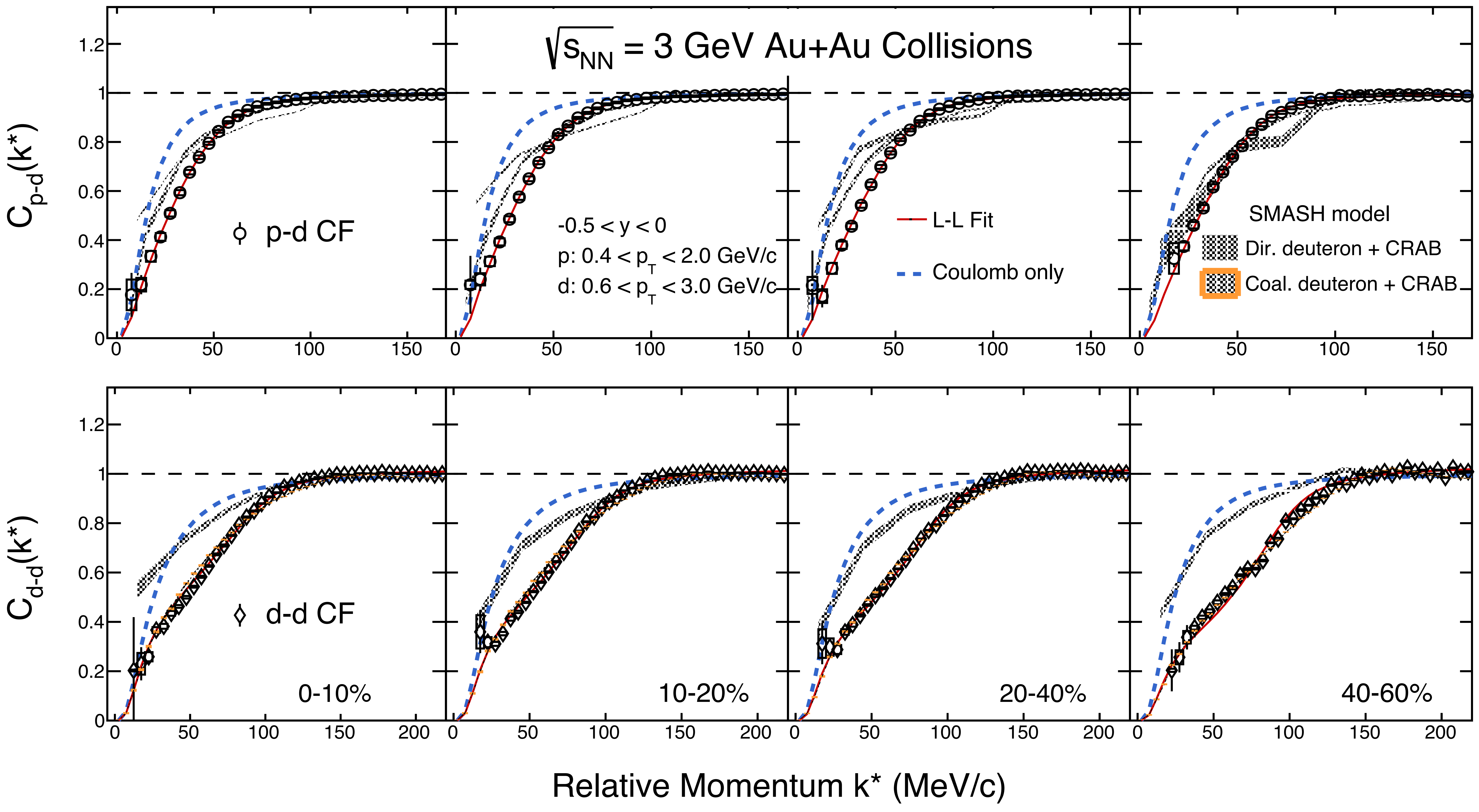
- **Coulomb repulsive & strong interaction**

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

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

STAR: 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

Results — p-d, d-d Correlation



⇒ 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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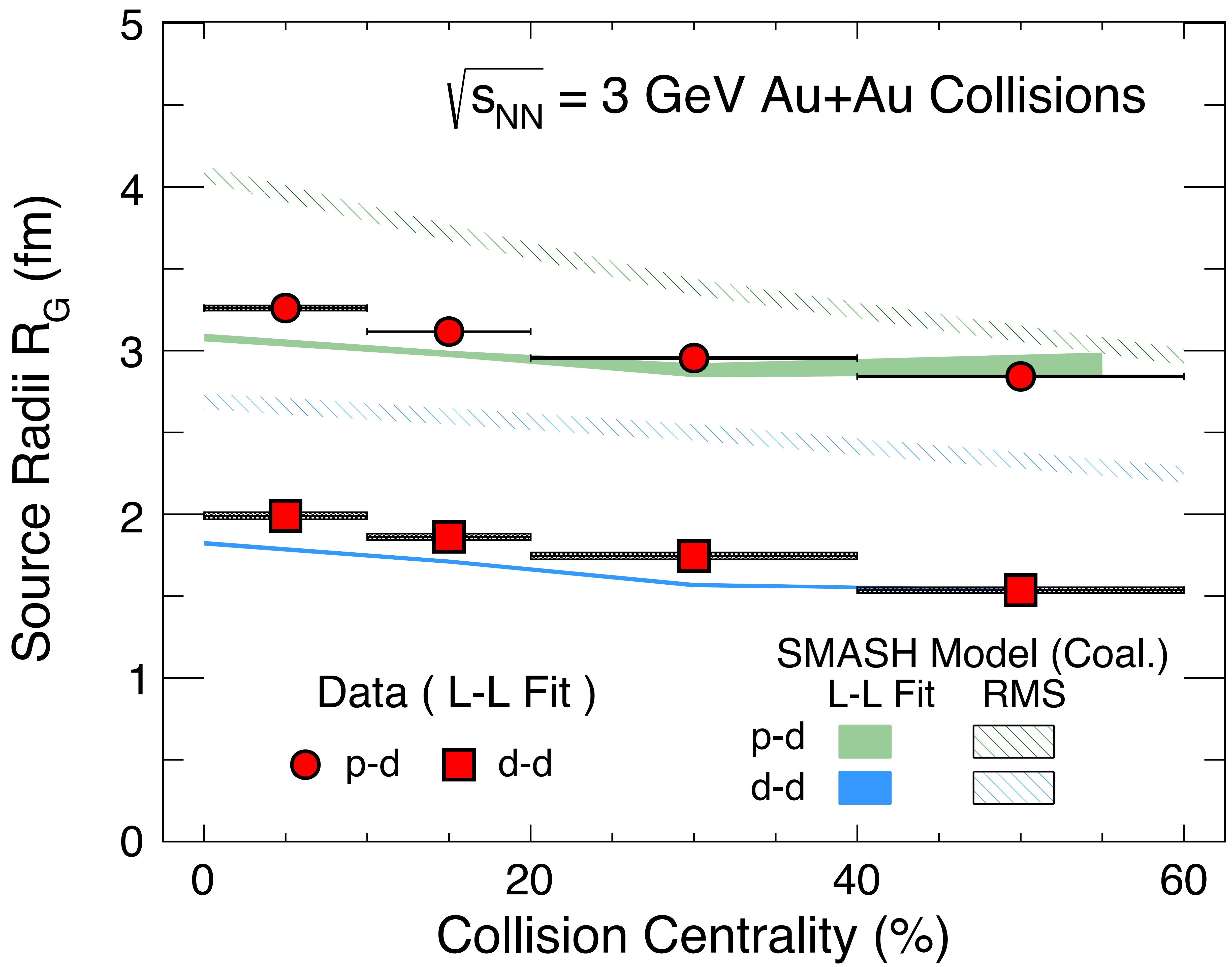


⇒ **Extracted source size (R_G) with LL model**

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

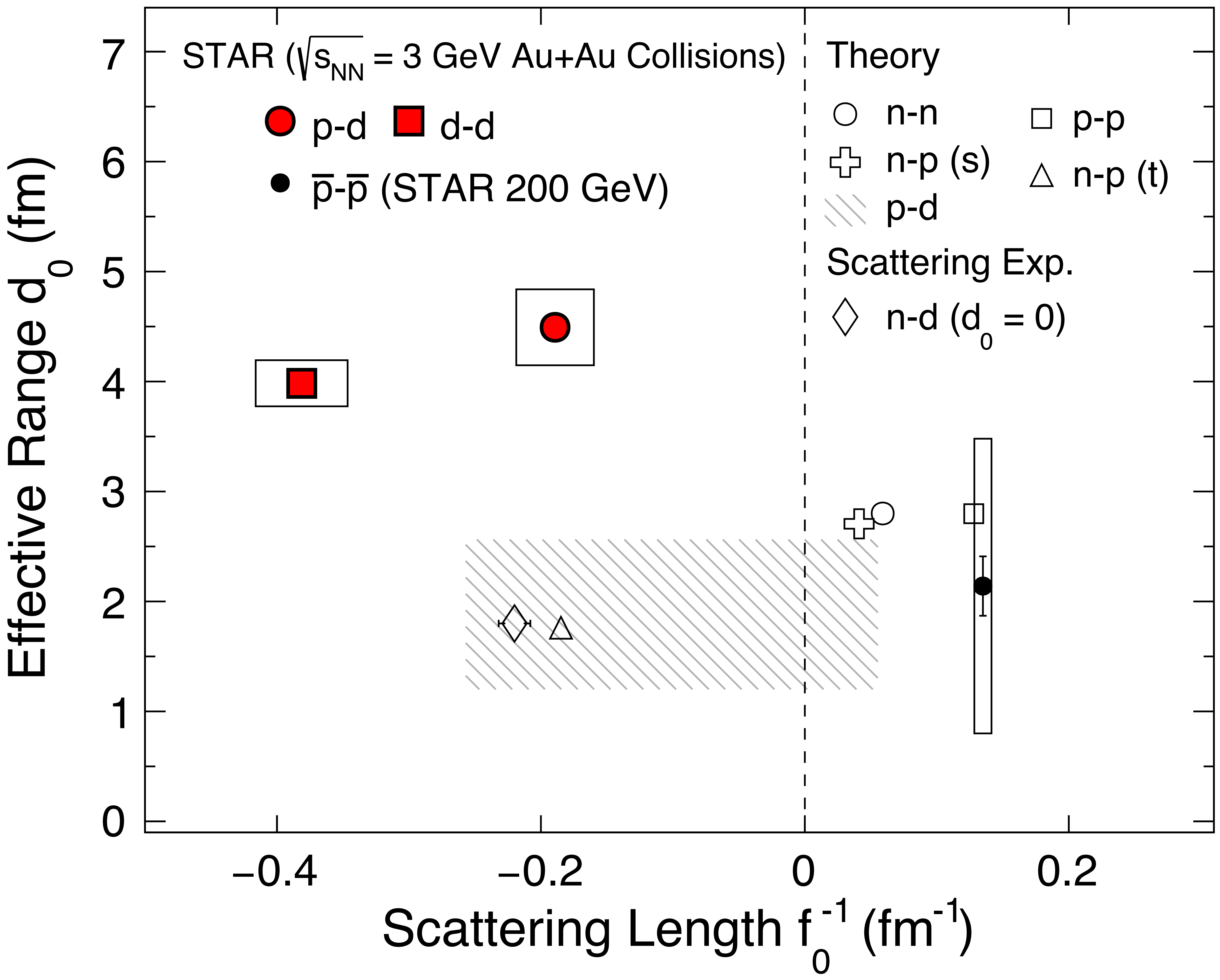
⇒ **Using same fit, source size from SMASH (R_G^{SMASH}) is closely match the data**

⇒ **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)**

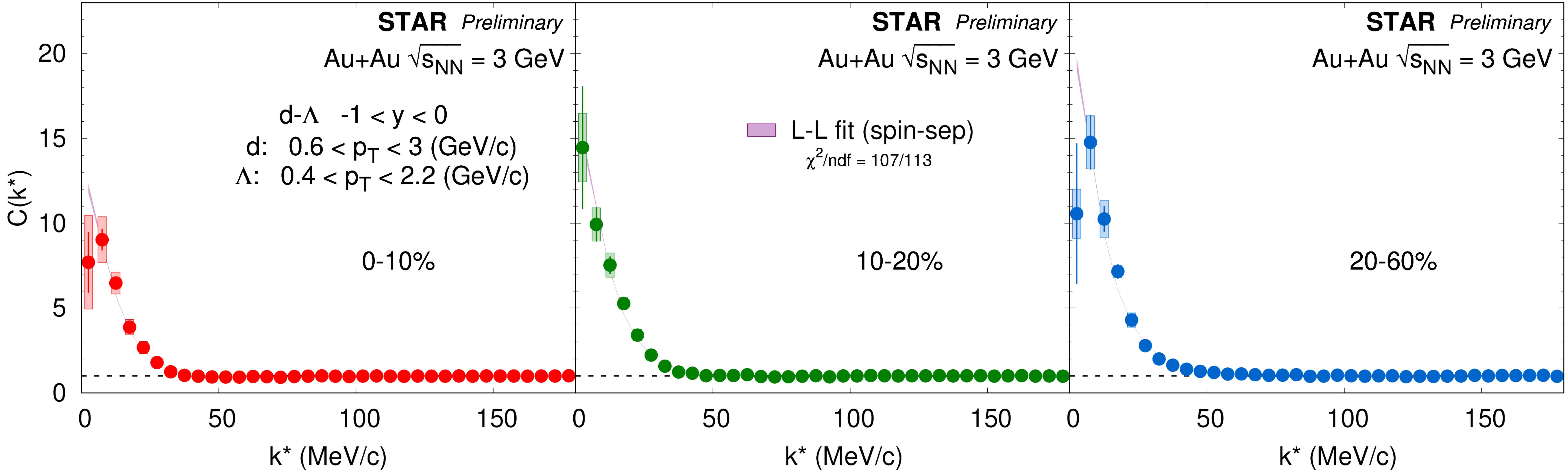
⇒ **For p-d interaction, the result is consistent with theory calculation and low-energy scattering experiment measurement**

- **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**

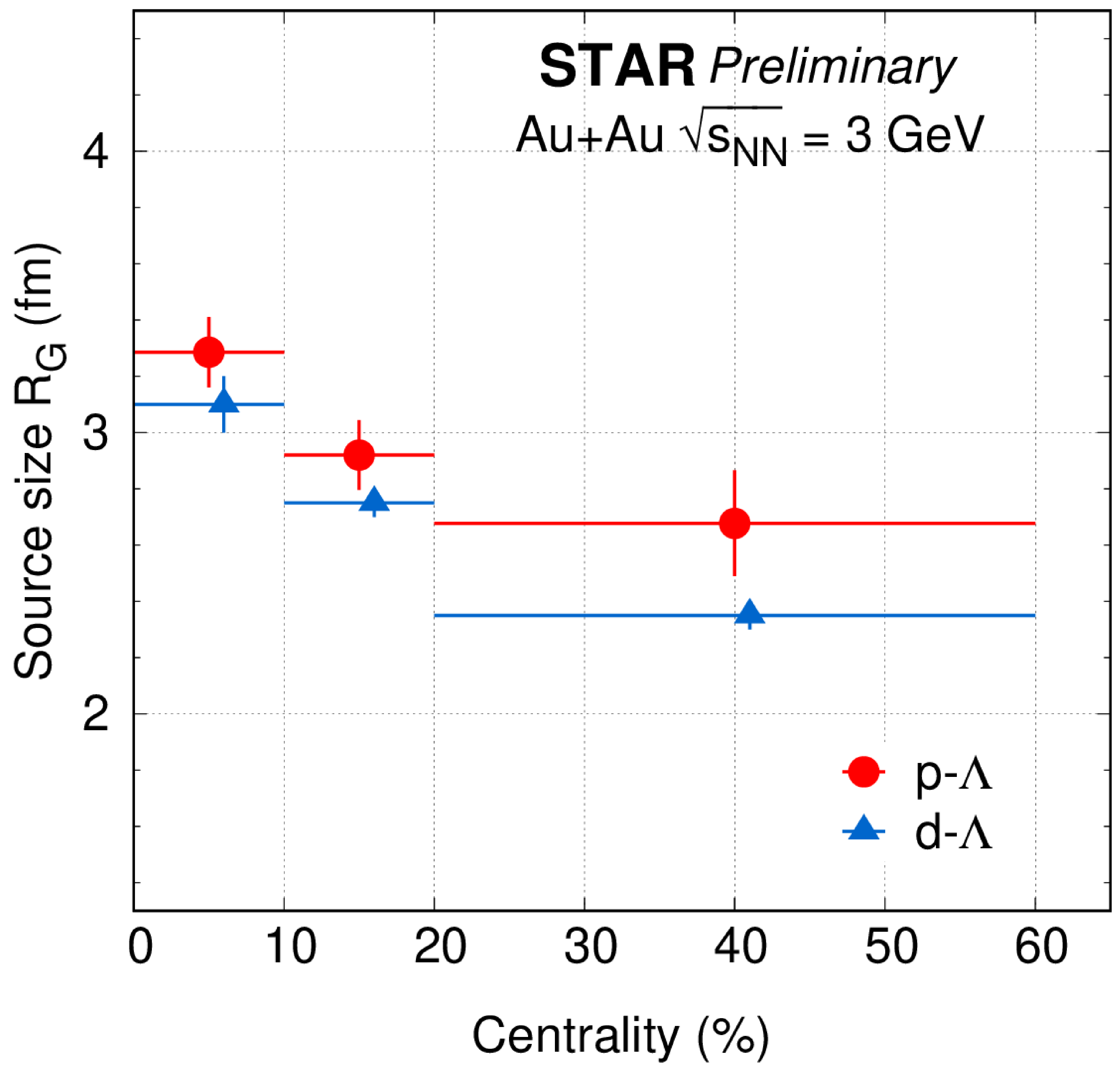
⇒ **Simultaneously fit to data in different centralities with L-L approach**

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

* Λ feed-down correction not applied

EPJ Web Conf. 296 (2024) 14010

Results — d-Λ Correlation



⇒ **Collision dynamics as expected**

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

$p-\Lambda$ correlation at 3 GeV: backup

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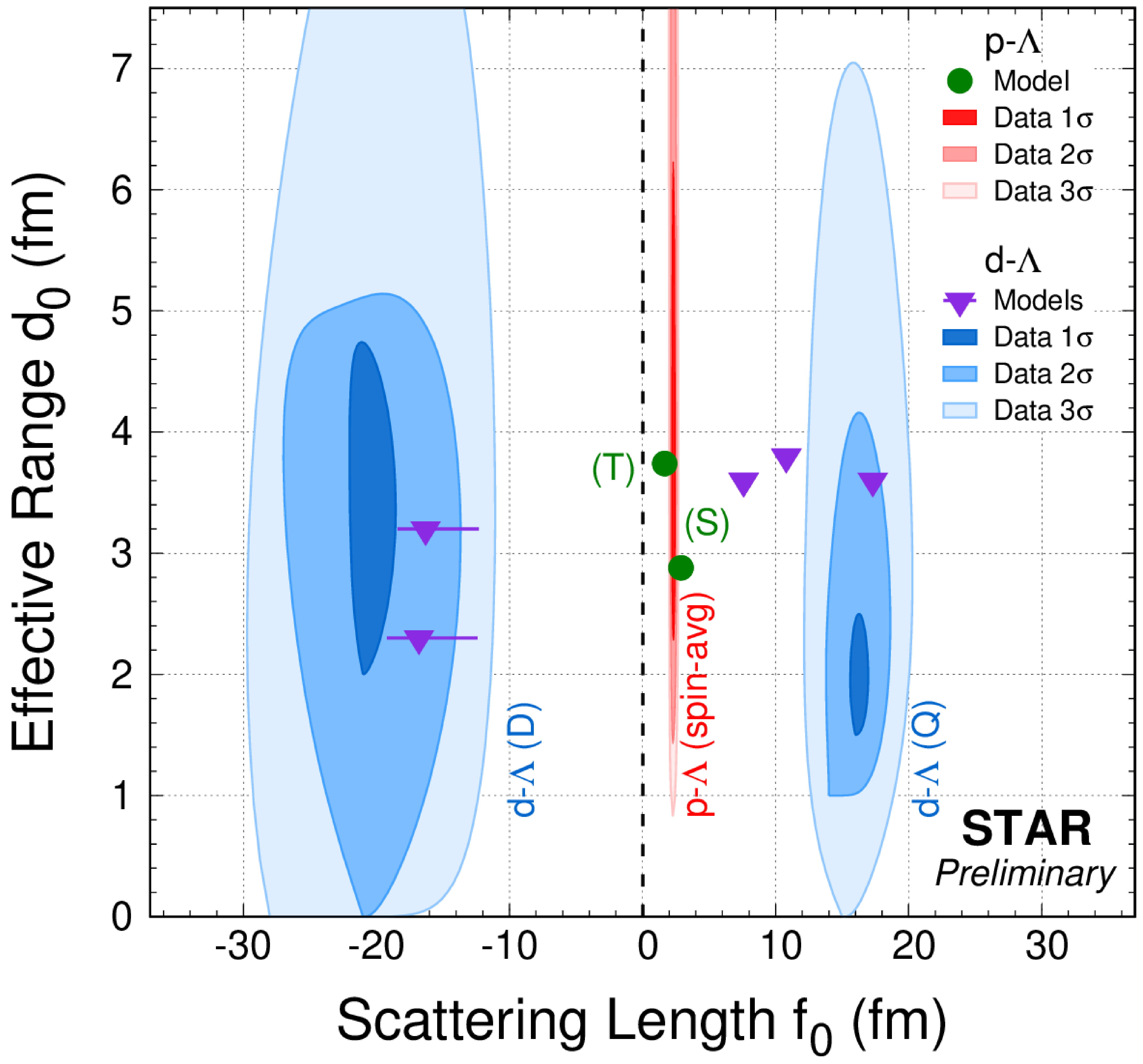
Results — d-Λ Interaction



$p-\Lambda$ correlation at 3 GeV: backup

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

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

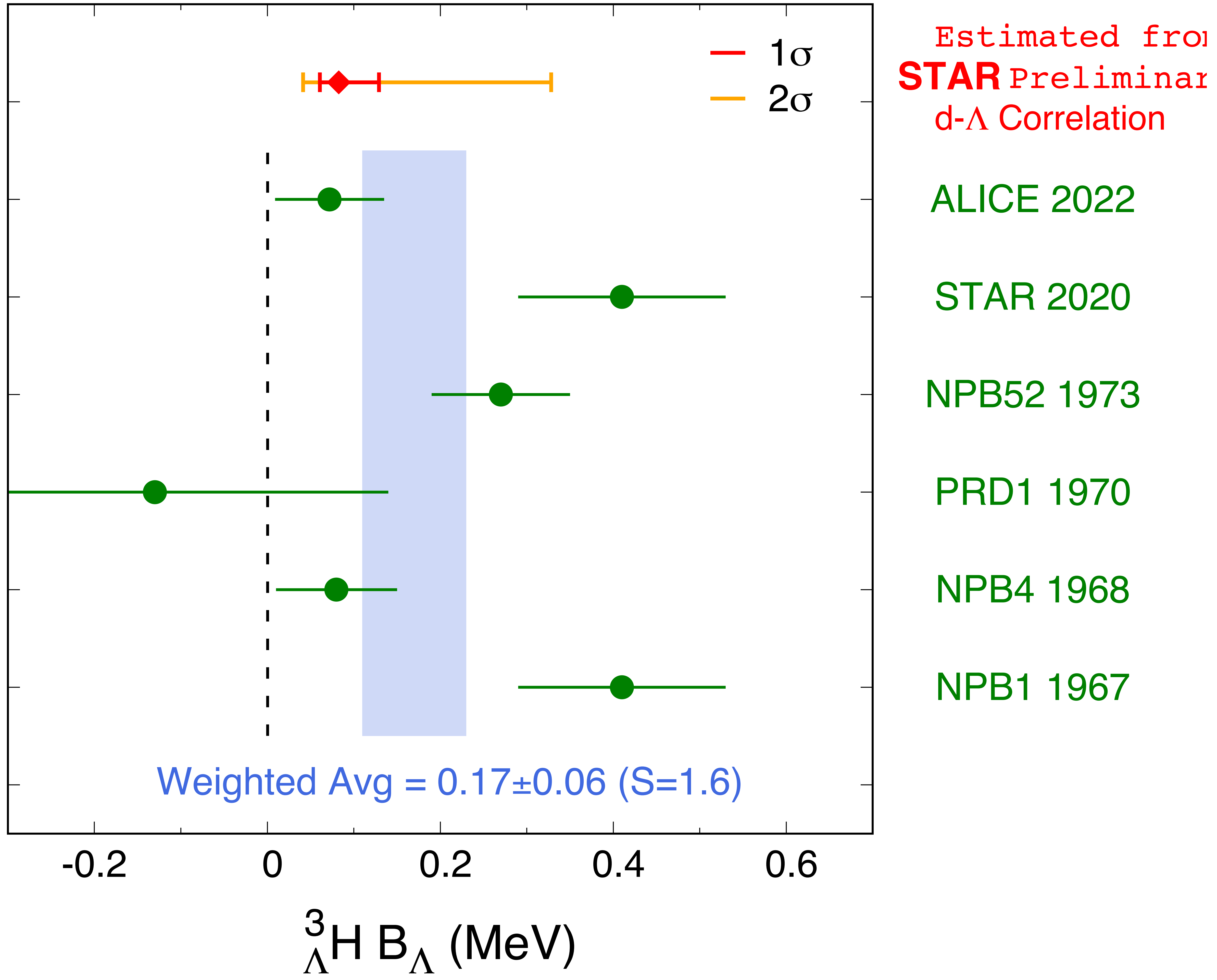
$$f_0\ (D) = -20\ ^{+3}_{-3}\ \text{fm},\ \ d_0\ (D) = 3\ ^{+2}_{-1}\ \text{fm}$$

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

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

EPJ Web Conf. 296 (2024) 14010
H. W. Hammer, Nucl. Phys. A 805 (2002) 173
Cobis, et al. J. Phys. G 23 (1997) 401
J. Haidenbauer, Phys. Rev. C 102 (2020) 3, 034001
F. Wang, et al, Phys. Rev. Lett. 83 (1999) 3138
M. Schafer, et al, Phys. Lett. B 808 (2020) 135614
G. Alexander, et al. Phys. Rev. 173 (1968) 1452
J. Haidenbauer, et al. Nucl. Phys. A 915 (2013) 24

Results — $^{3}_{\Lambda}$H Binding Energy



$p-\Lambda$ correlation at 3 GeV: backup

⇒ $^{3}_{\Lambda}$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

EPJ Web Conf. 296 (2024) 14010
H.Bethe, Phys.Rev 76, 38 (1949)

Summary & Outlook

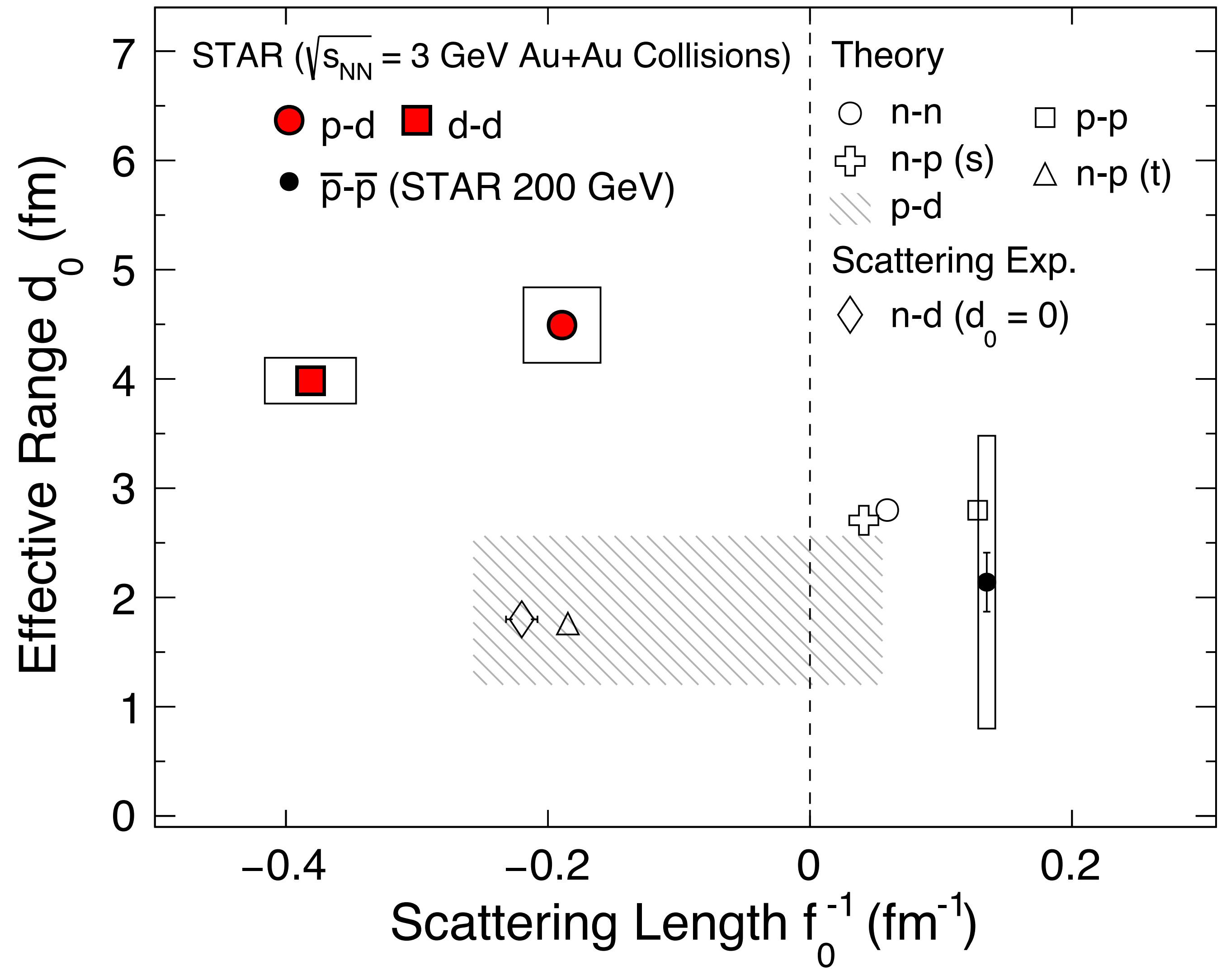
⇒ **Femtoscopy measurements from heavy-ion collisions provides a unique tool to explore strong interactions and evolution dynamics**

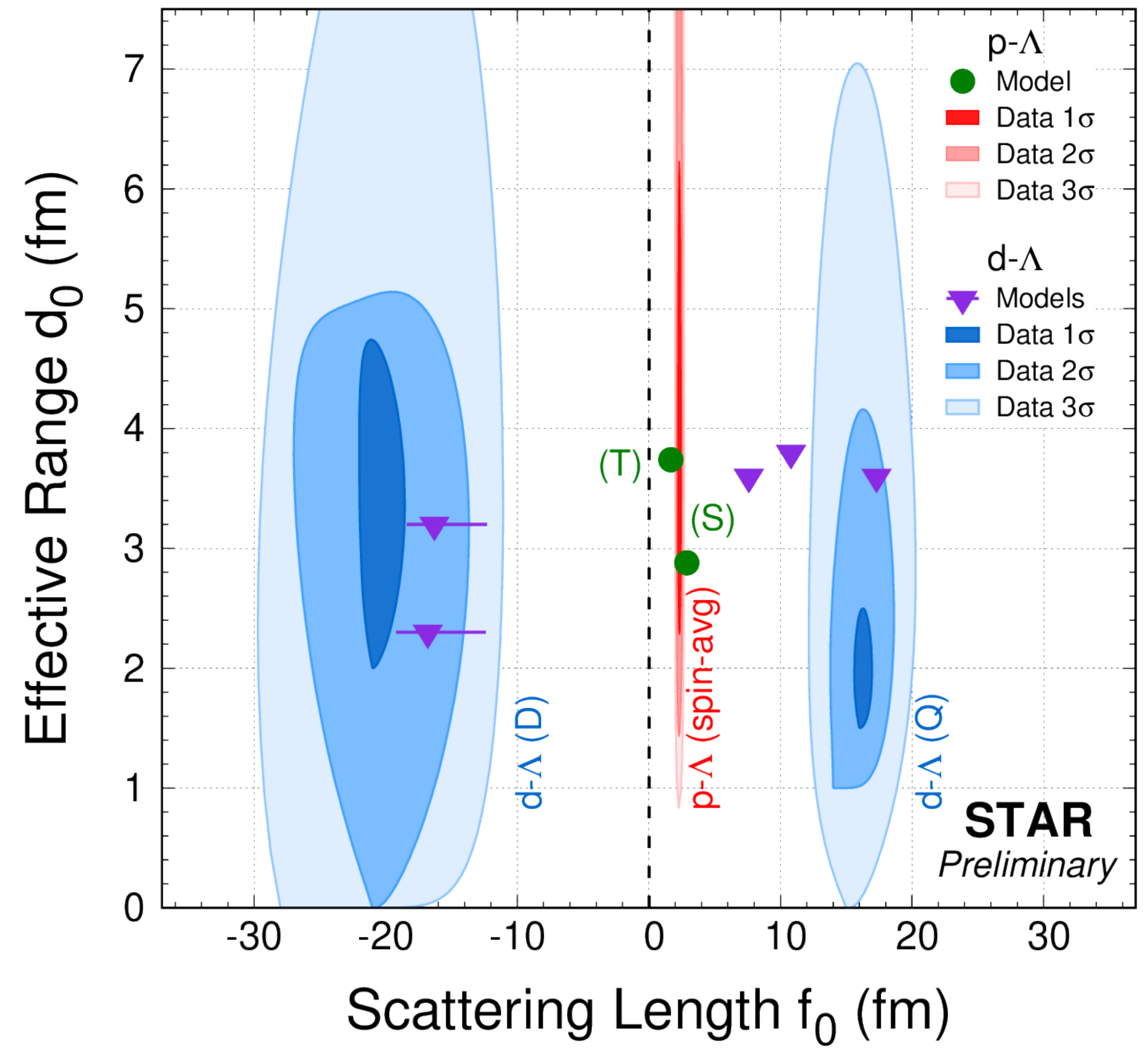
⇒ **N-N interaction (p-d & d-d)**

- **First measurements of p-d / d-d correlation functions in STAR**
- **Coalescence is the dominant process for deuteron formation in the high-energy nuclear collisions**
- **f_0 is consistent with repulsive interaction and bound state formation in p-d / d-d pair**

⇒ **Y-N interaction (d-Λ)**

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





Summary & Outlook

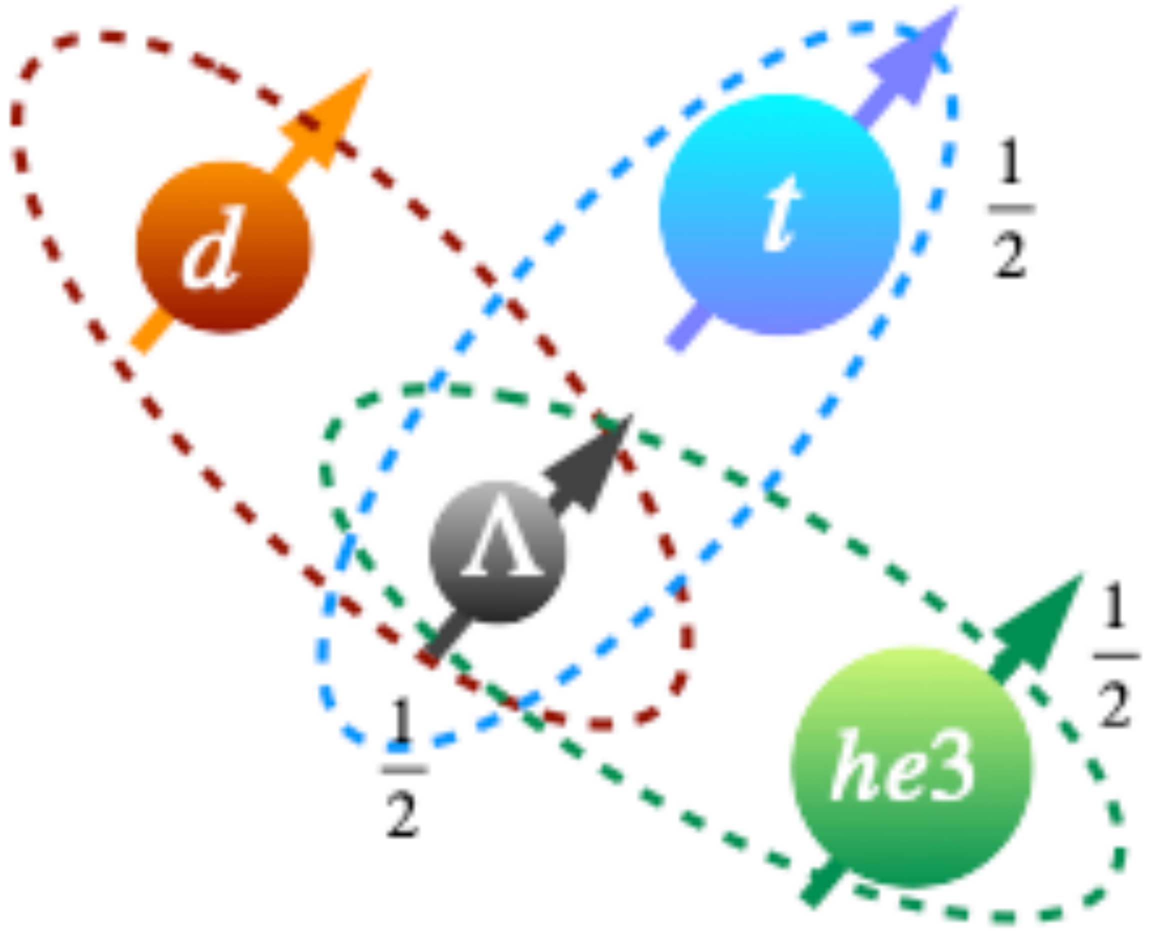
⇒ Femtoscopy measurements from heavy-ion collisions provides a unique tool to explore strong interactions and evolution dynamics

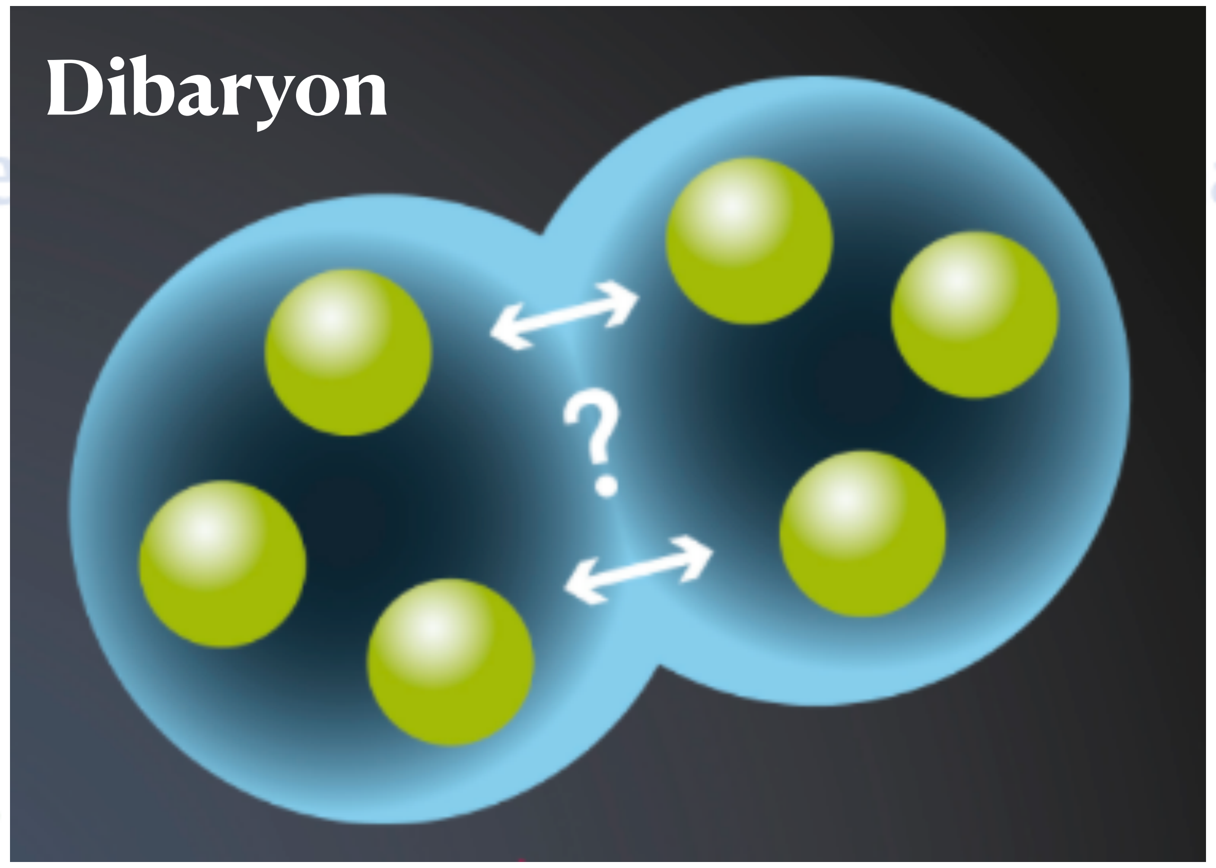
More precise femtoscopy results with large statistics is coming soon!

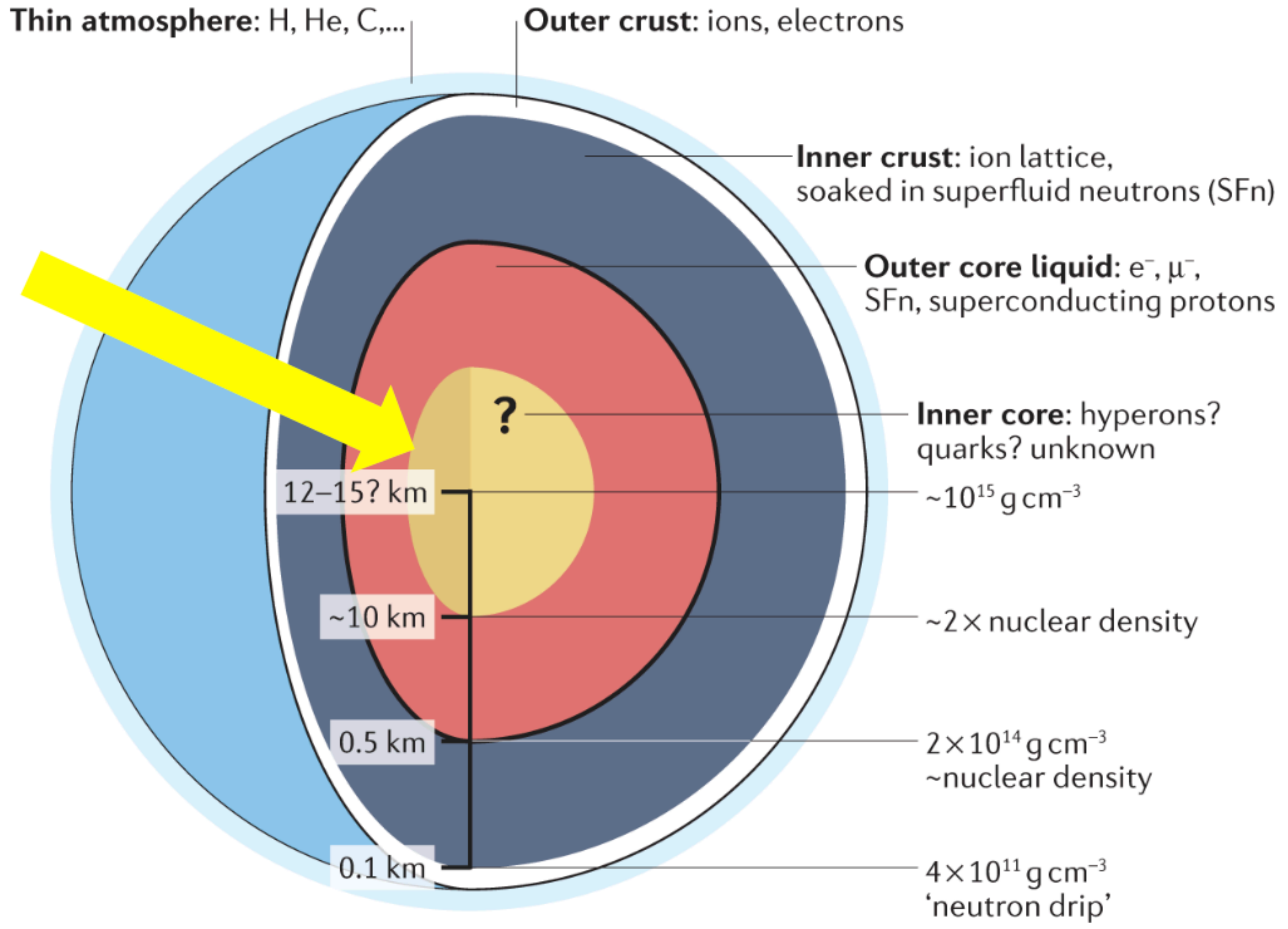
(hypernuclei, many body, exotica …)

cess for deuteron formation in the

per-nuclei properties



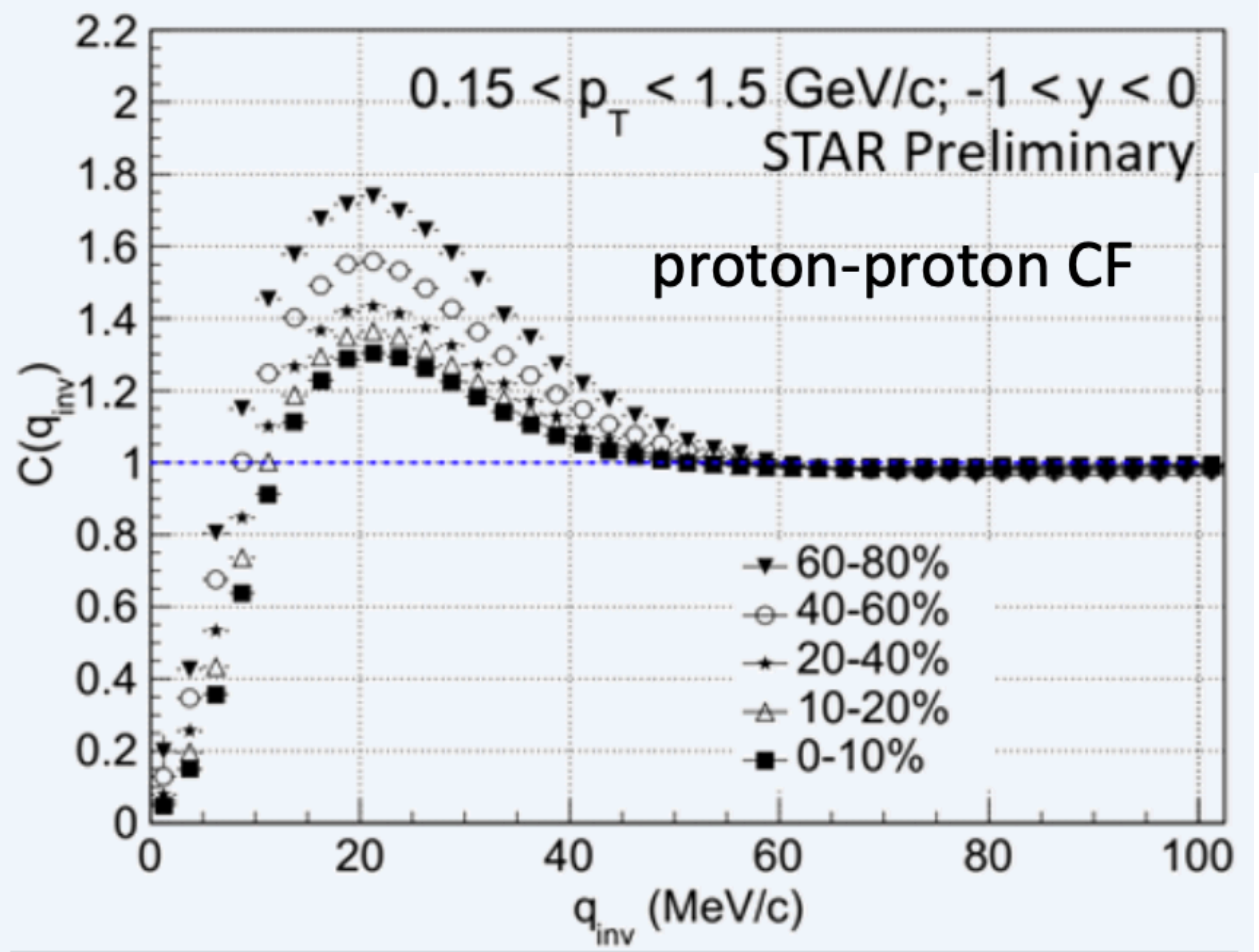




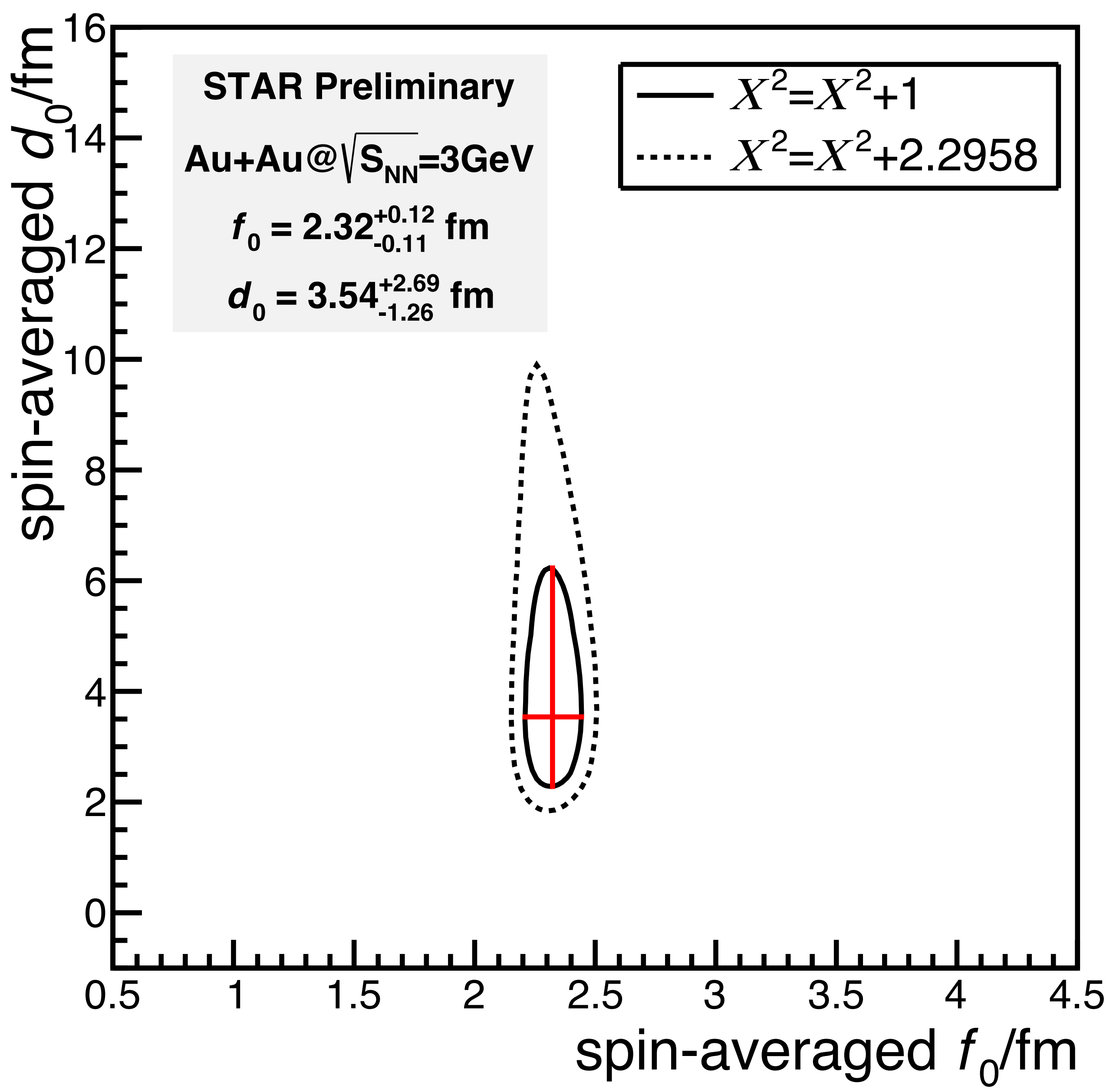
Thank you for your attention!

Backup

p-p, p-Λ correlation functions @ 3 GeV



X^2 contour of spin-averaged d_0 and f_0 for $p\Lambda$ (-1<y<0)



QM2022/ QM2023

STAR Preliminary

Au+Au@$\sqrt{S_{NN}}$=3GeV

$p\Lambda$ Correlation Function with Lednicky-Lyuboshit Fitting