WPCF 2024

Recent Results of Baryon Correlations at RHIC-STAR

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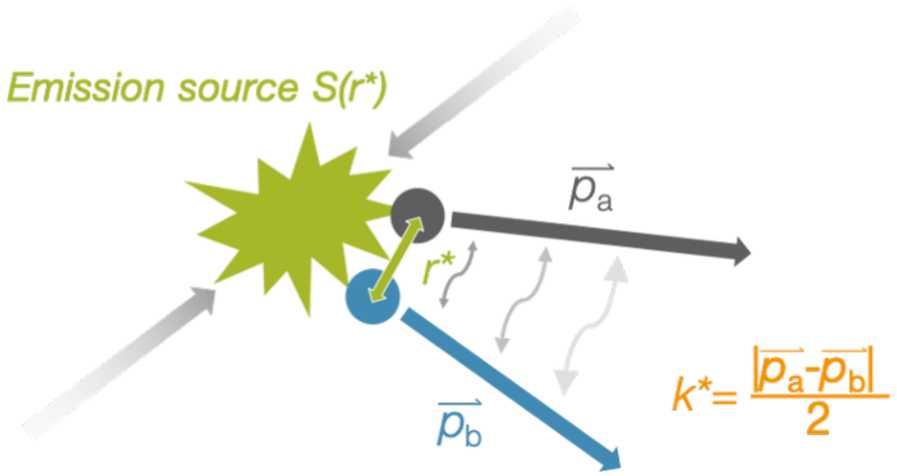
5th Nov, 2024

Outline

1. Femtoscopy and Two-particle Correlation Function
2. Motivation
3. RHIC-STAR Experiment
4. Results
   - p-d, d-d, d-Λ correlation at $\sqrt{s_{NN}}$ = 3 GeV
   - p-Ξ, Λ-Λ, p-Ω correlation at $\sqrt{s_{NN}}$ = 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*

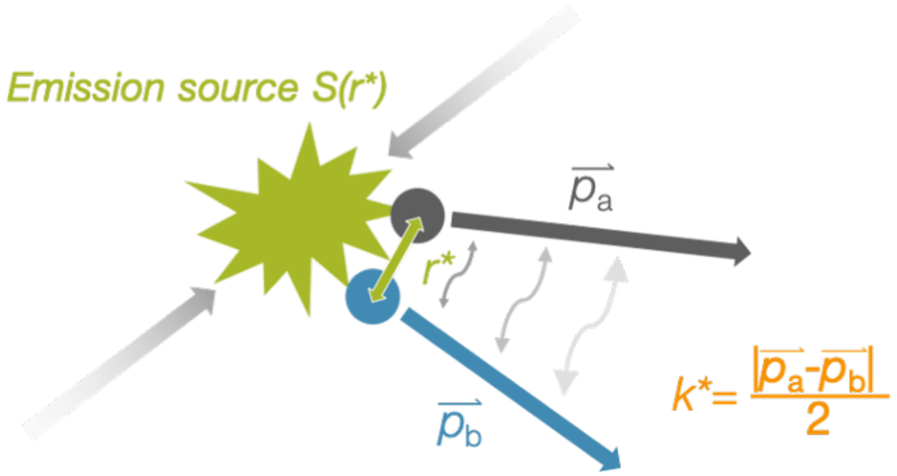
$\Psi(\vec{k}^*,\vec{r})$: *Pair wave function*

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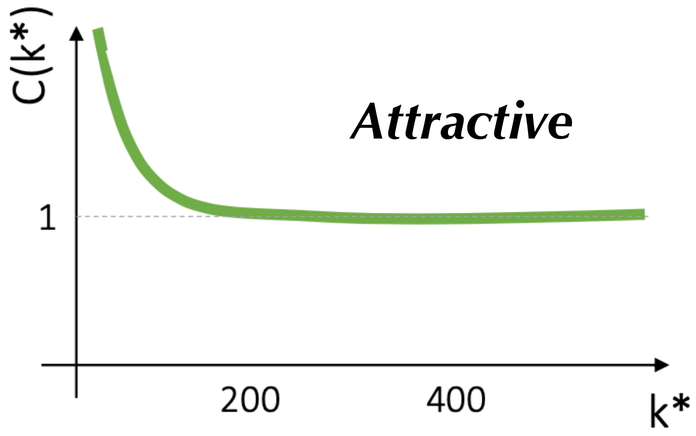

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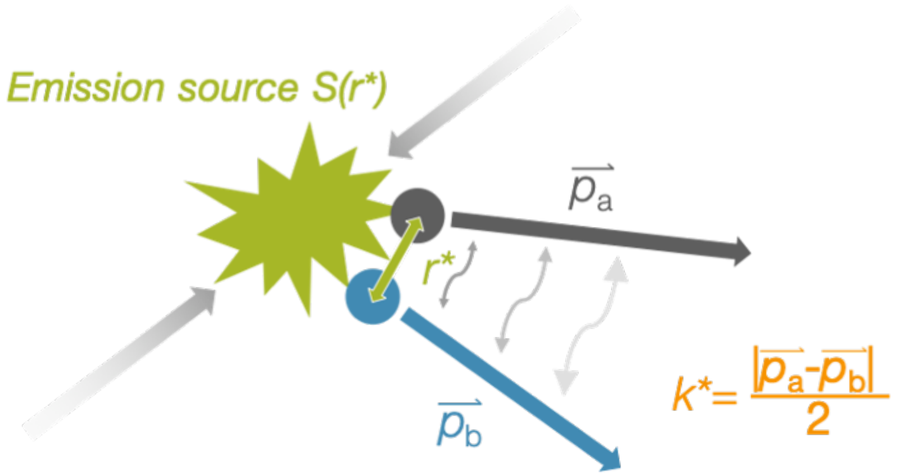

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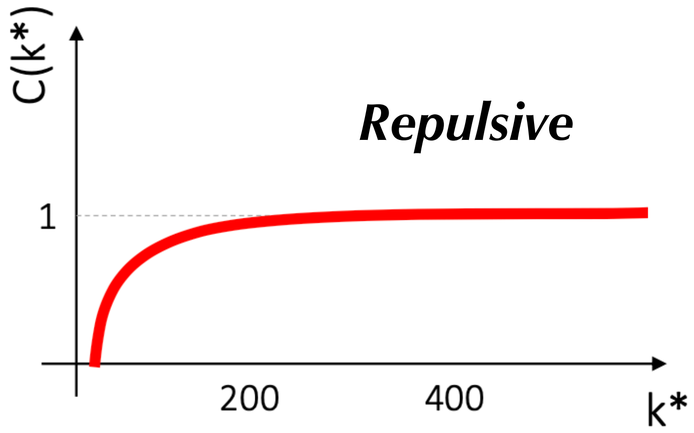

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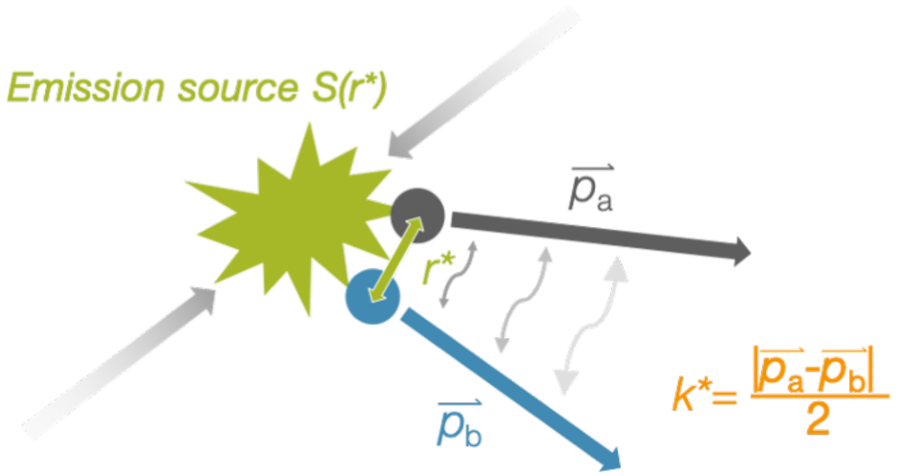

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⇒ Formalism with Lednicky-Lyuboshitz (LL) model

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

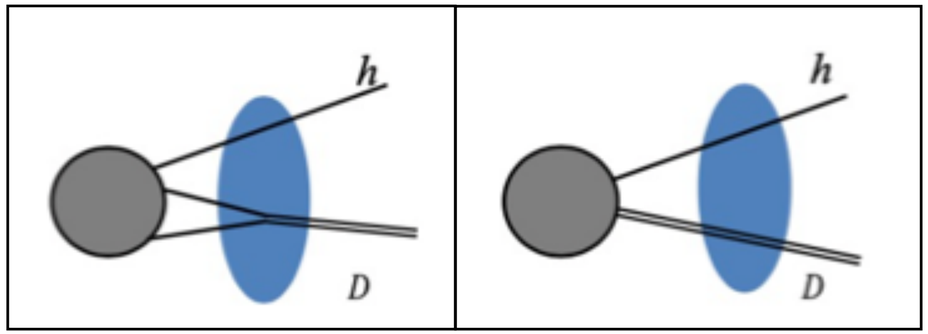
Motivation

- **Formation mechanism of light nuclei are under debate**

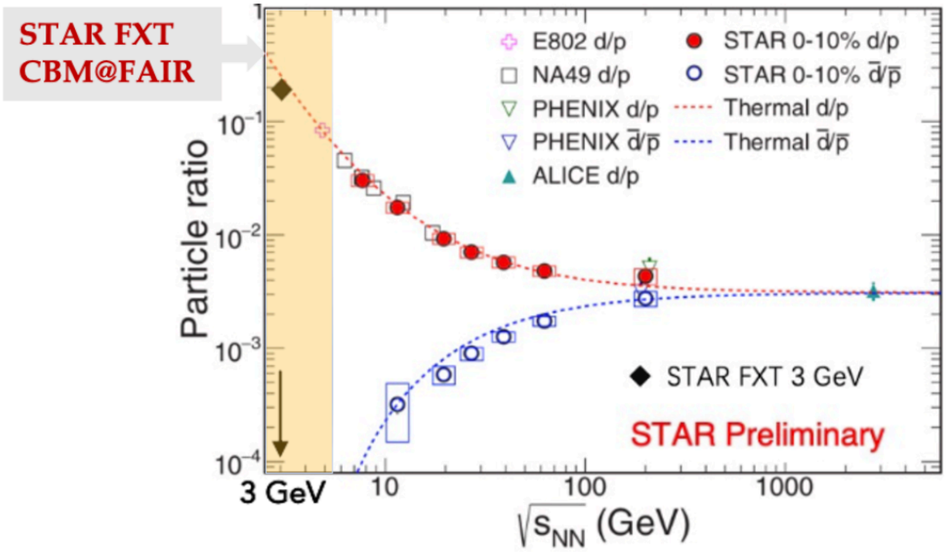
  ⇒ Coalescence : final-state interaction

  ⇒ Thermal : produced directly from fireball

- **Indirect approach of many body interactions**



Coalescence Direct production



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)

Motivation

- Formation mechanism of light nuclei are under debate
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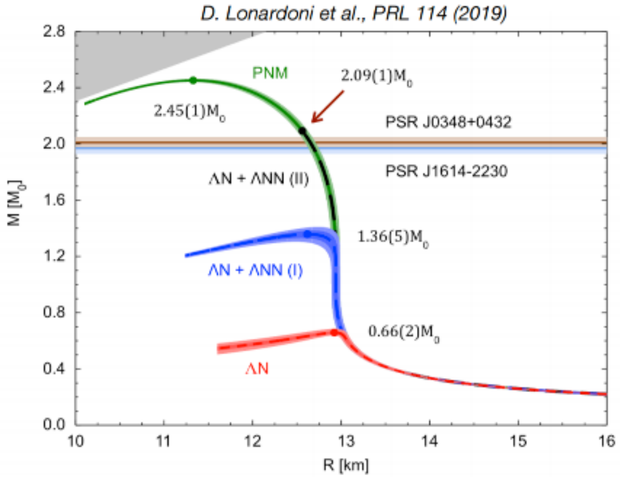
- Indirect approach of many body interactions

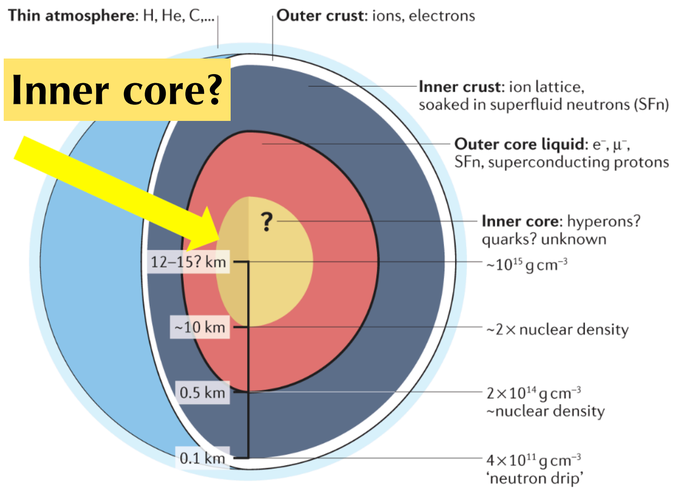
- **Nucleon-nucleon (N-N), hyperon-nucleon (Y-N) and hyperon-hyperon (Y-Y) interactions**
  - ⇒ **Equation of state of matter inside neutron stars**
  - ⇒ **(Strange) Dibaryons, have never been found experimentally**

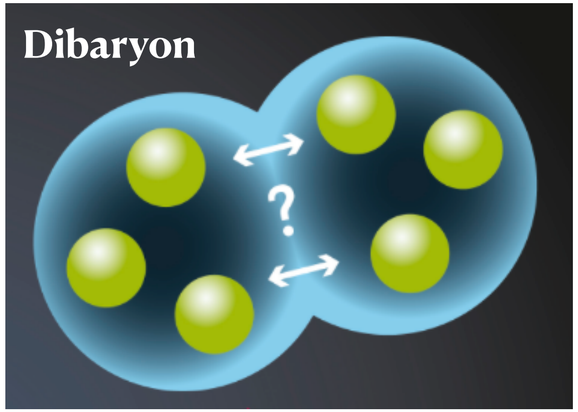
Possible bound state:

H-dibaryon ⇒ $\Lambda + \Lambda$ / p + Ξ^-

(Strange)Dibaryon ⇒ p + Ω







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

Experimental measurements are needed!

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

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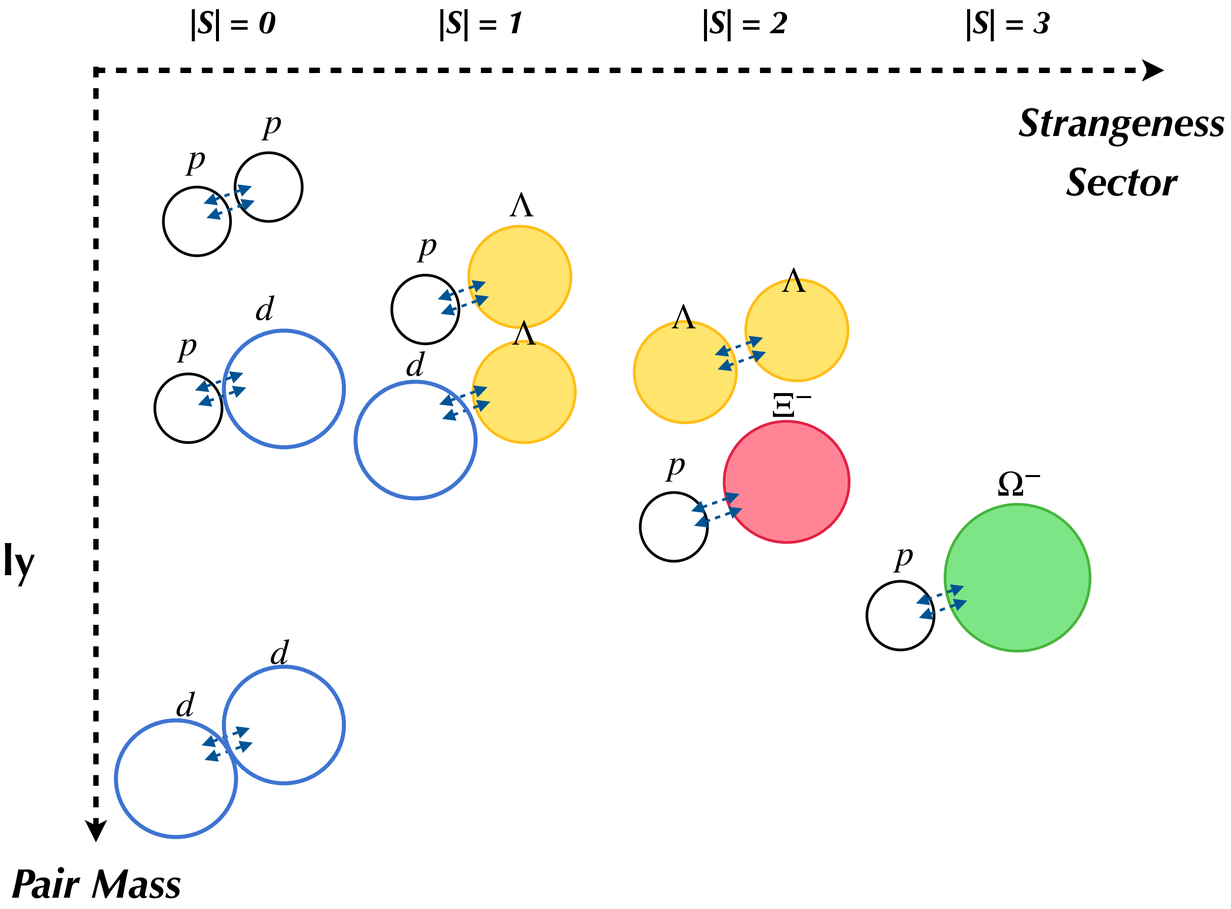

Experimental measurements are needed!

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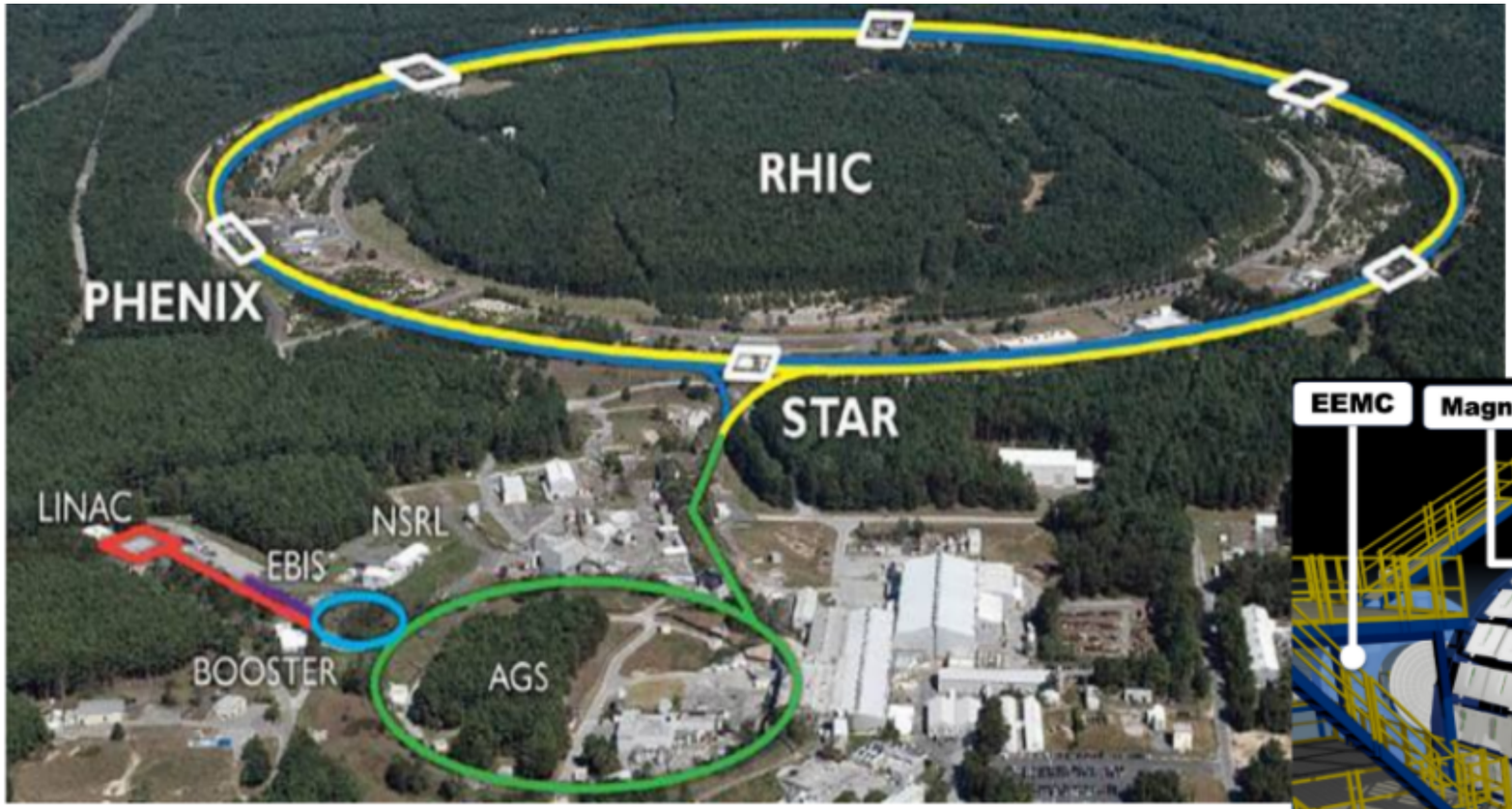
RHIC-STAR Experiment



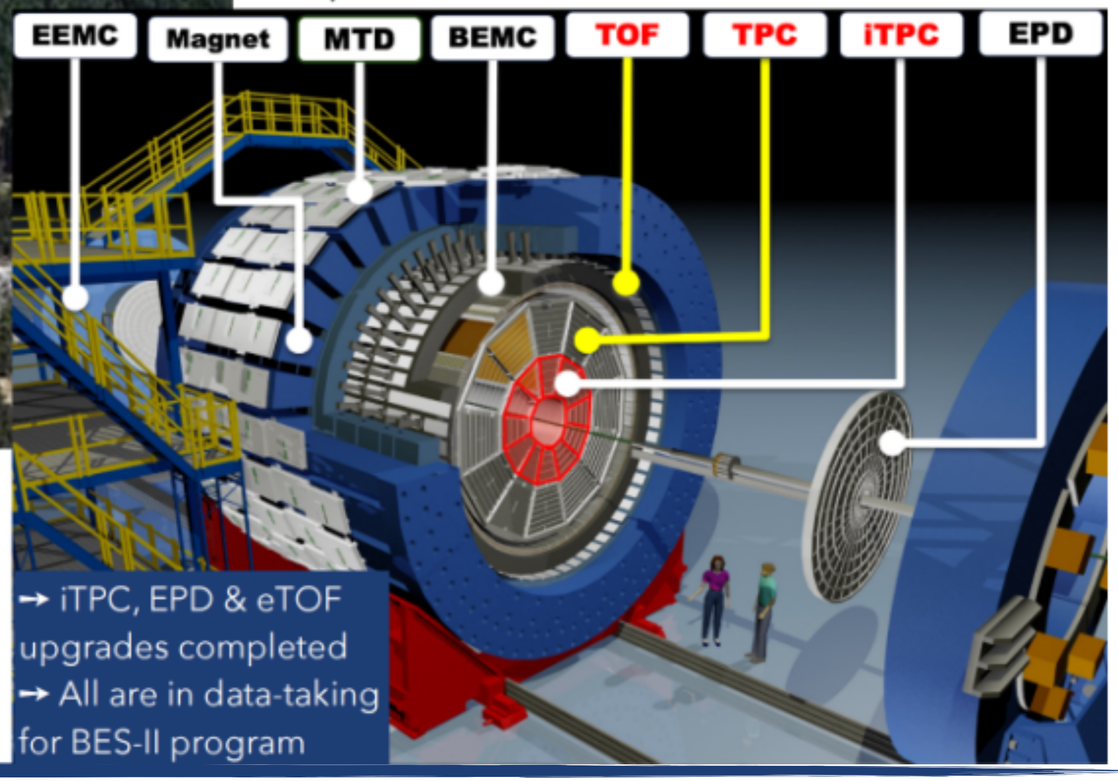
Relativistic Heavy Ion Collider (RHIC)

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



→ iTPC, EPD & eTOF upgrades completed

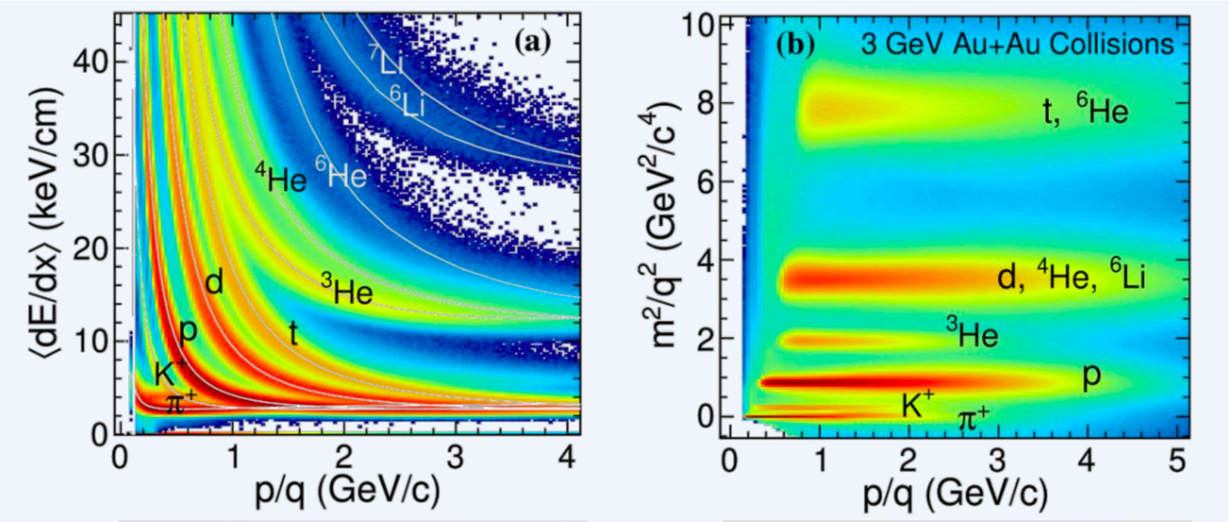
→ All are in data-taking for BES-II program

The Solenoid Tracker At RHIC (STAR)

→ Excellent Particle Identification

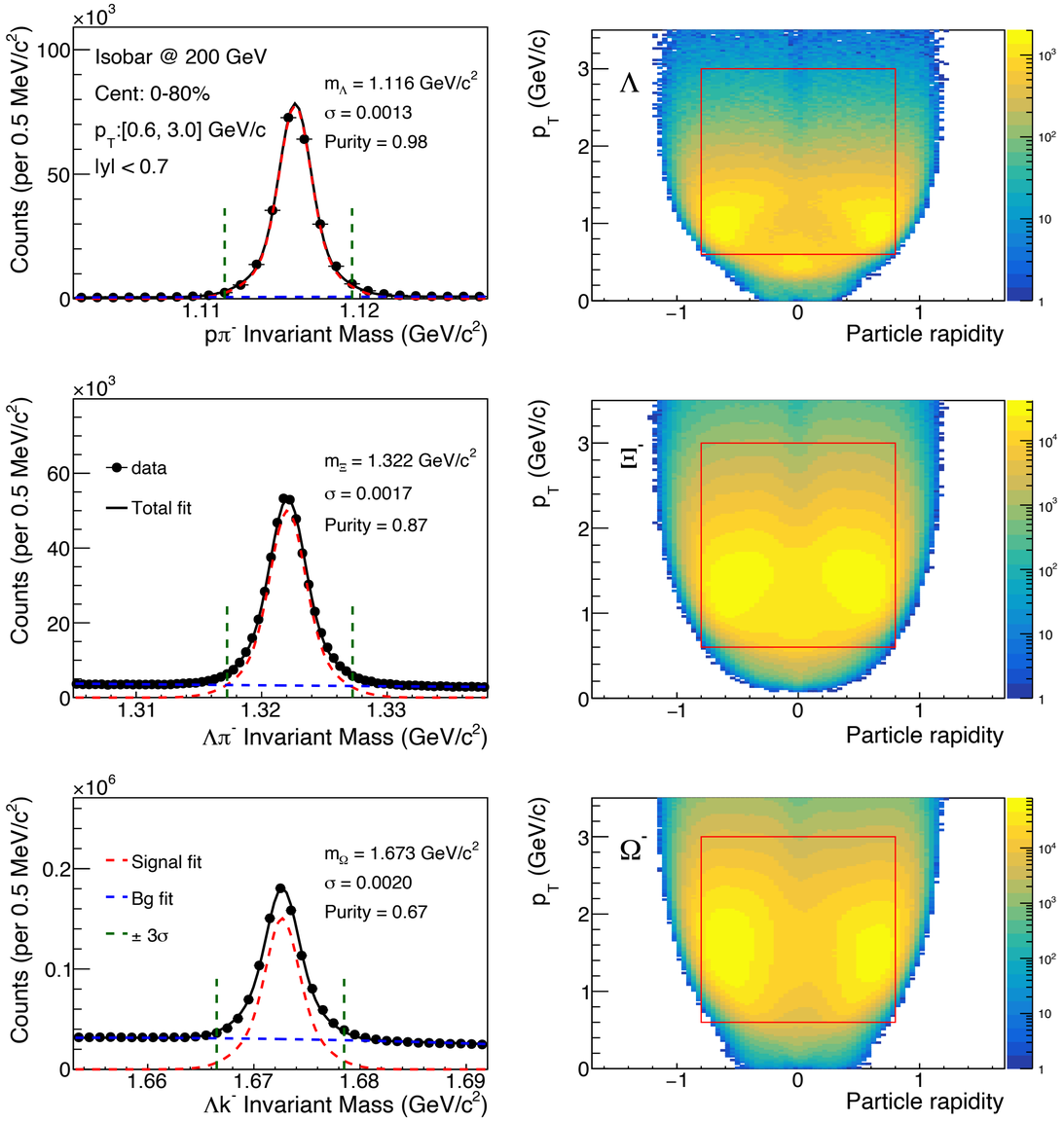
→ Large, Uniform Acceptance at Mid-rapidity

Particle Identification & Reconstruction

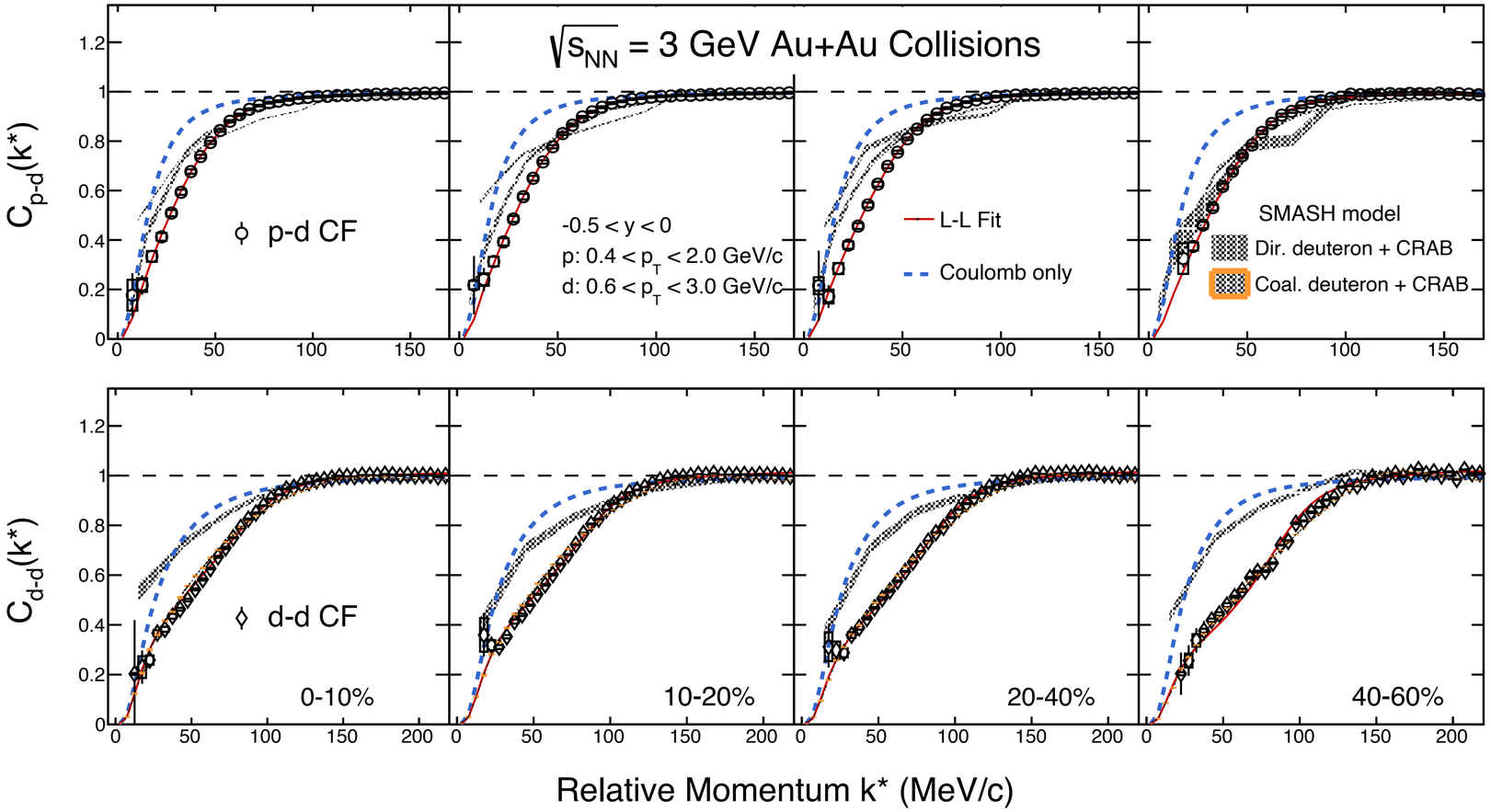


- Use Time Projection Chamber (TPC) and Time-Of-Flight (TOF) to identify π^-, p, K and d

- Excellent coverage at mid-rapidity



Results — p-d, d-d Correlation



- First measurements of p-d/d-d correlation functions at STAR
- Clear depletion in low k*
  - Coulomb repulsive & strong interaction
- Fitted with L-L model simultaneously, in different centrality:
  - Different R_G
  - Common spin-averaged 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
R. Lednicky, et al, Sov.J.Nucl.Phys. 35 (1982) 770

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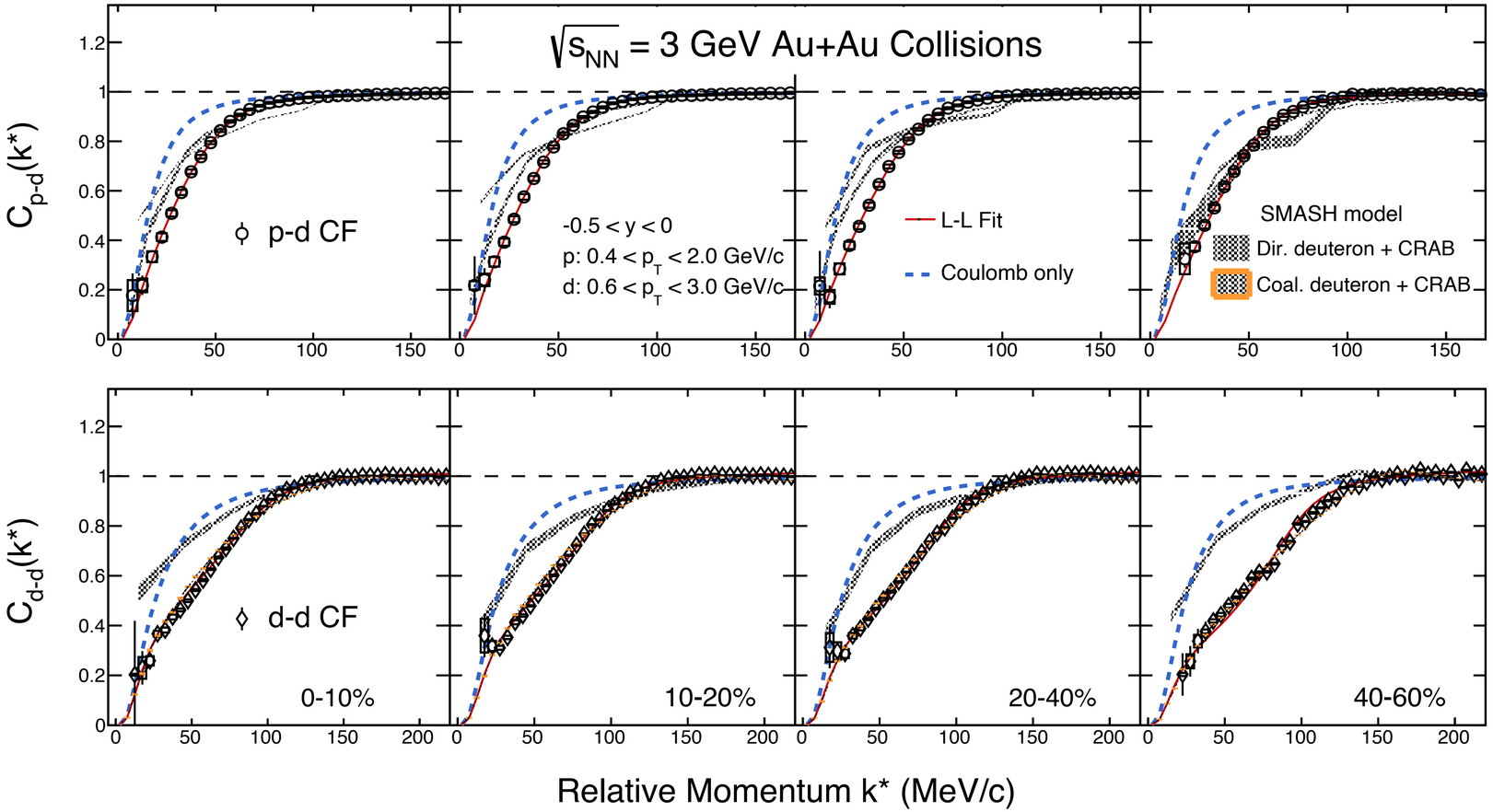

- **Simulated with SMASH model, consider two deuteron formation mechanism:**
  - **Direct production (grey band)**
    - **Hadronic scattering**
    - **Fail to describe data at certain k***
  - **Coalescence production (orange band)**
    - **Wigner function**
    - **Well description to data**
    - ***Coalescence* is the dominant process for deuteron formation in the high-energy nuclear collisions**

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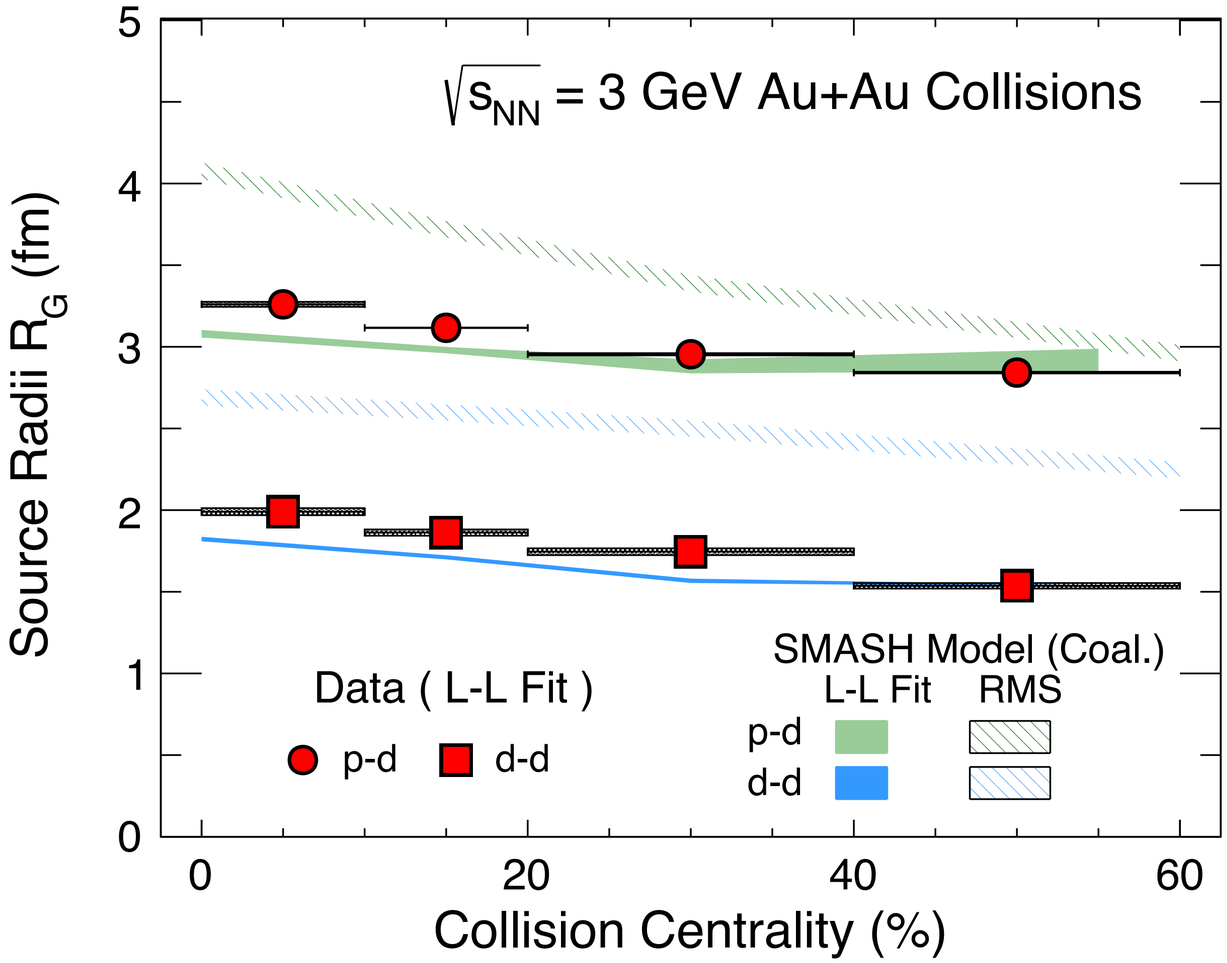
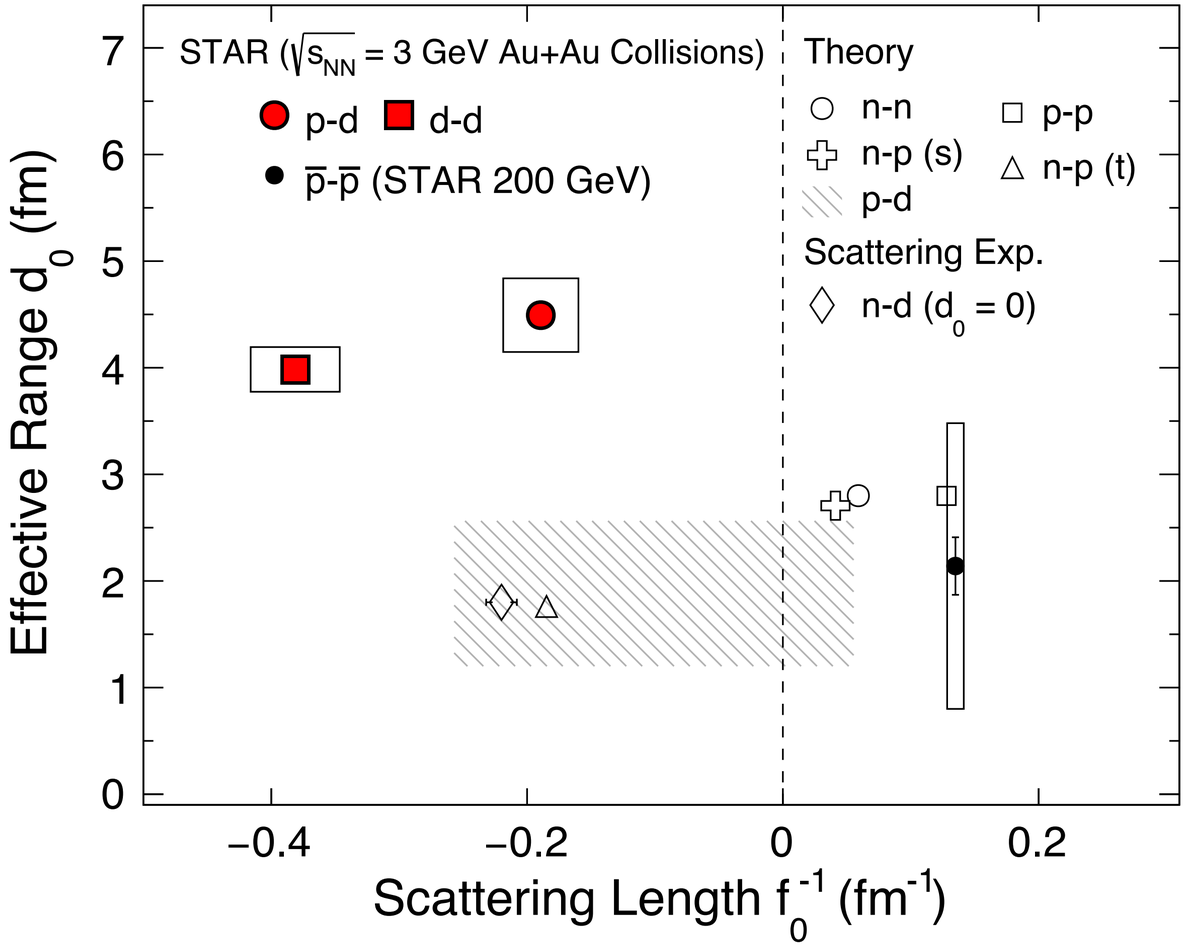


- **Extracted source size (R_G) with LL model**
  - **Centrality dependence:** $R_G^{central} > R_G^{peripheral}$
  - **$\langle m_T \rangle$ dependence:** $R_G^{p-d} > R_G^{d-d}$
- **Using same fit, source size from SMASH (R_G^{SMASH}) closely matches the data**
- ***The root mean square (RMS) values 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**

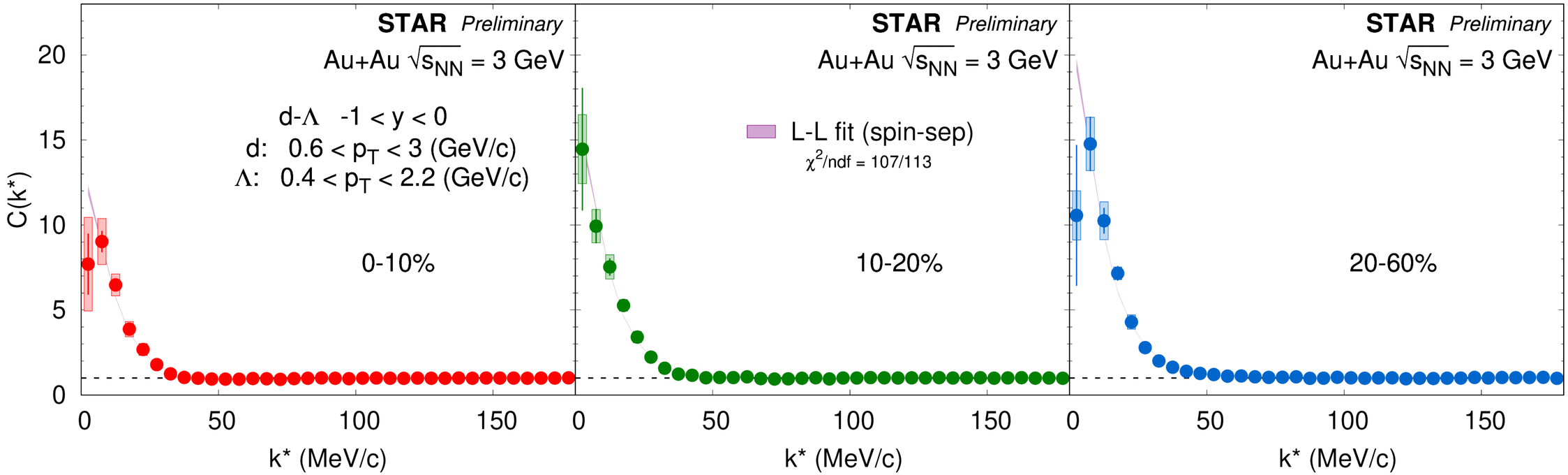
- **For both p-d and d-d interaction, the spin-averaged f_0 is negative**
  - **Combination of repulsive interactions in quartet (quintet) spin state for p-d (d-d) along with the presence of bound states (^{3}He for p-d and ^{4}He for d-d)**

- **For p-d interaction, the is f_0 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

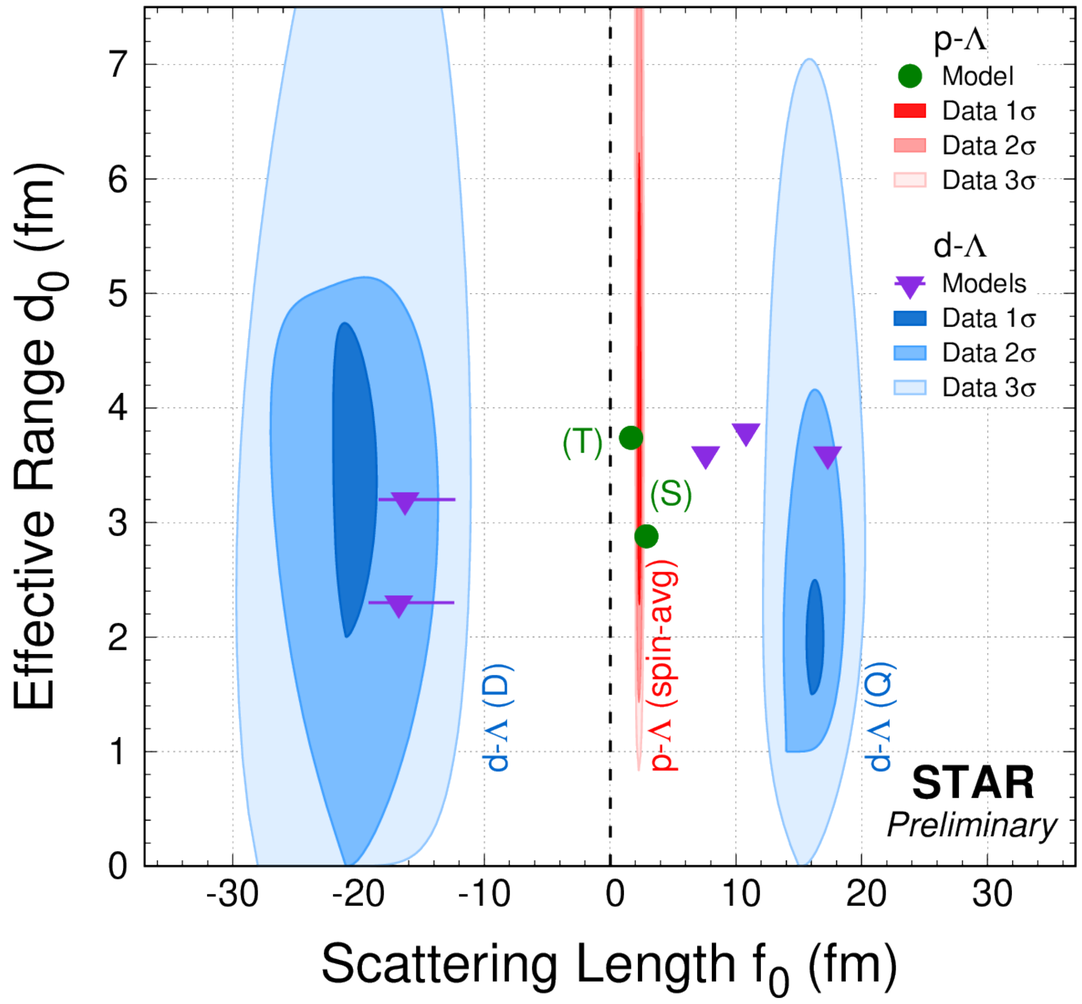
⇒ Simultaneously fit to data in different centralities with L-L approach

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

Results — d-Λ Interaction



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

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

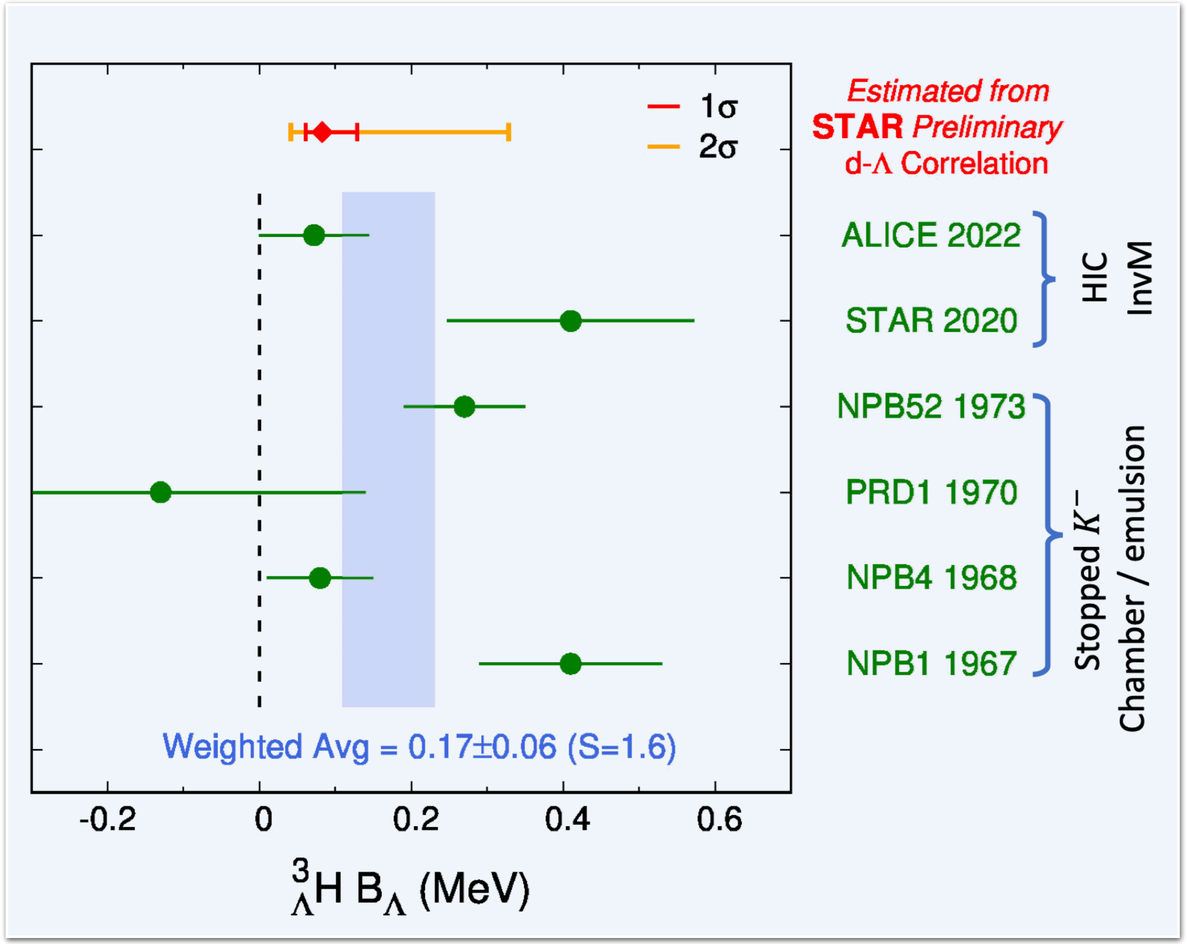
  f_0 (D) = -20 $^{+3}_{-3}$ fm, d_0 (D) = 3 $^{+2}_{-1}$ fm

  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**

EPJ Web Conf. 296 (2024) 14010

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

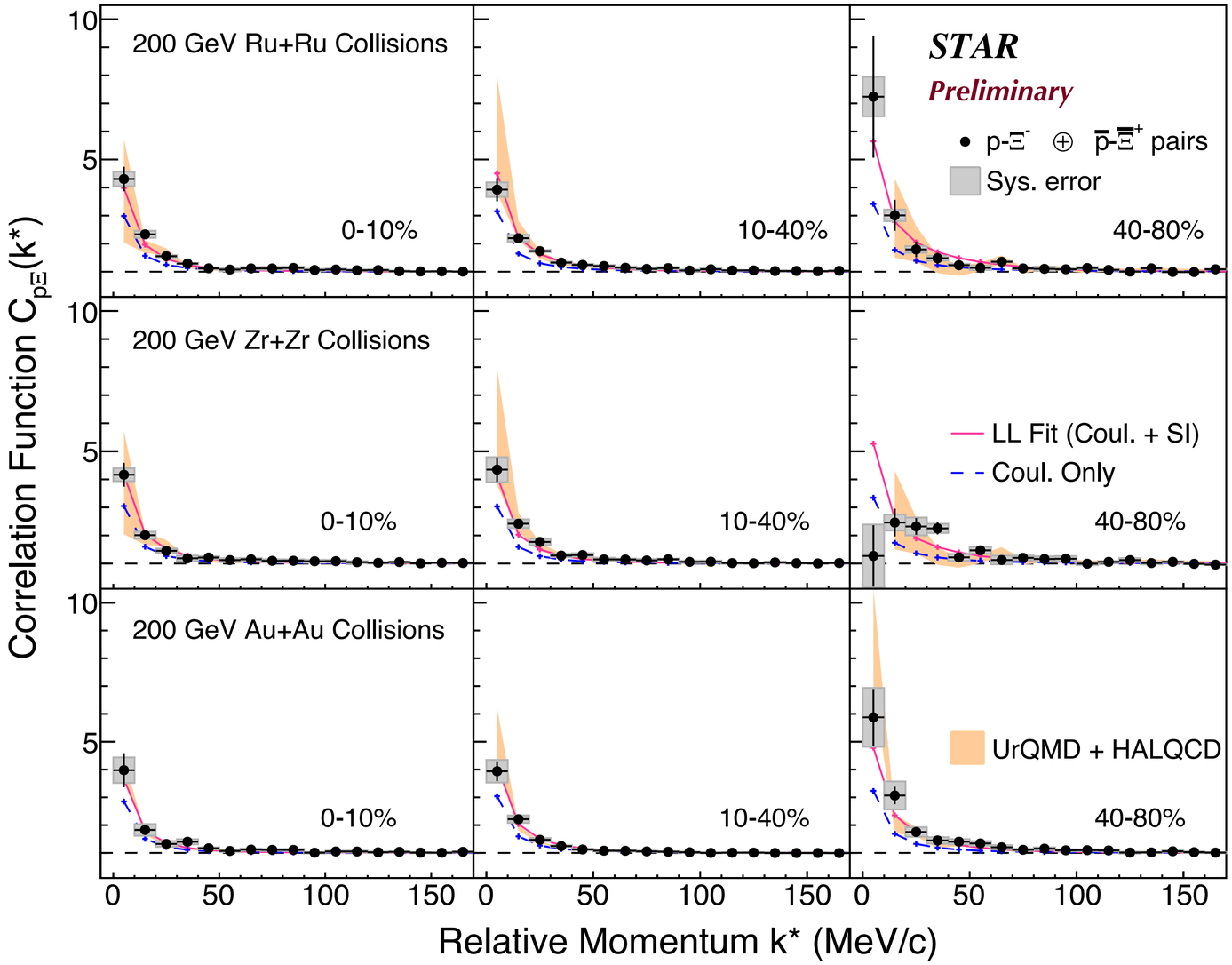
⇒ $^3_\Lambda$H B_Λ = [0.04, 0.33] (MeV) @ 95% CL

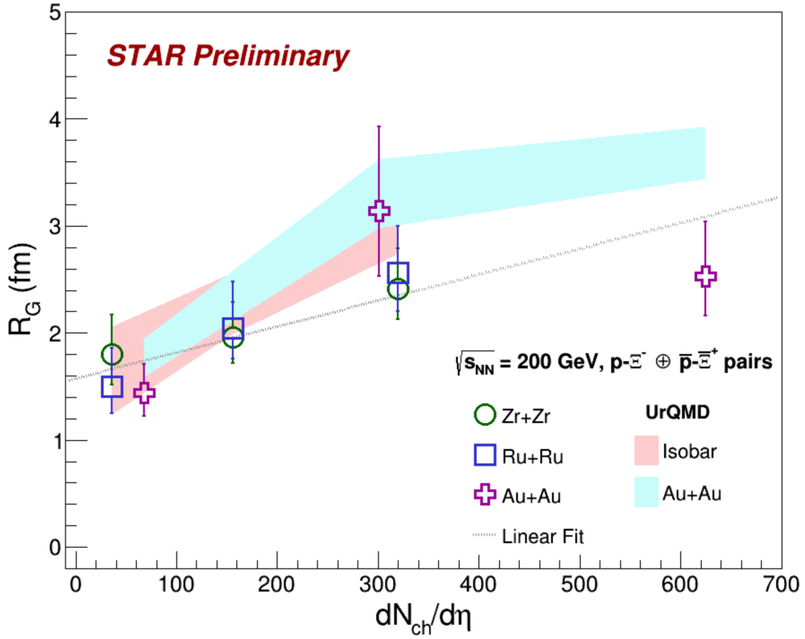
-> Consistent with the world average

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

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

Results — p-Ξ Correlation

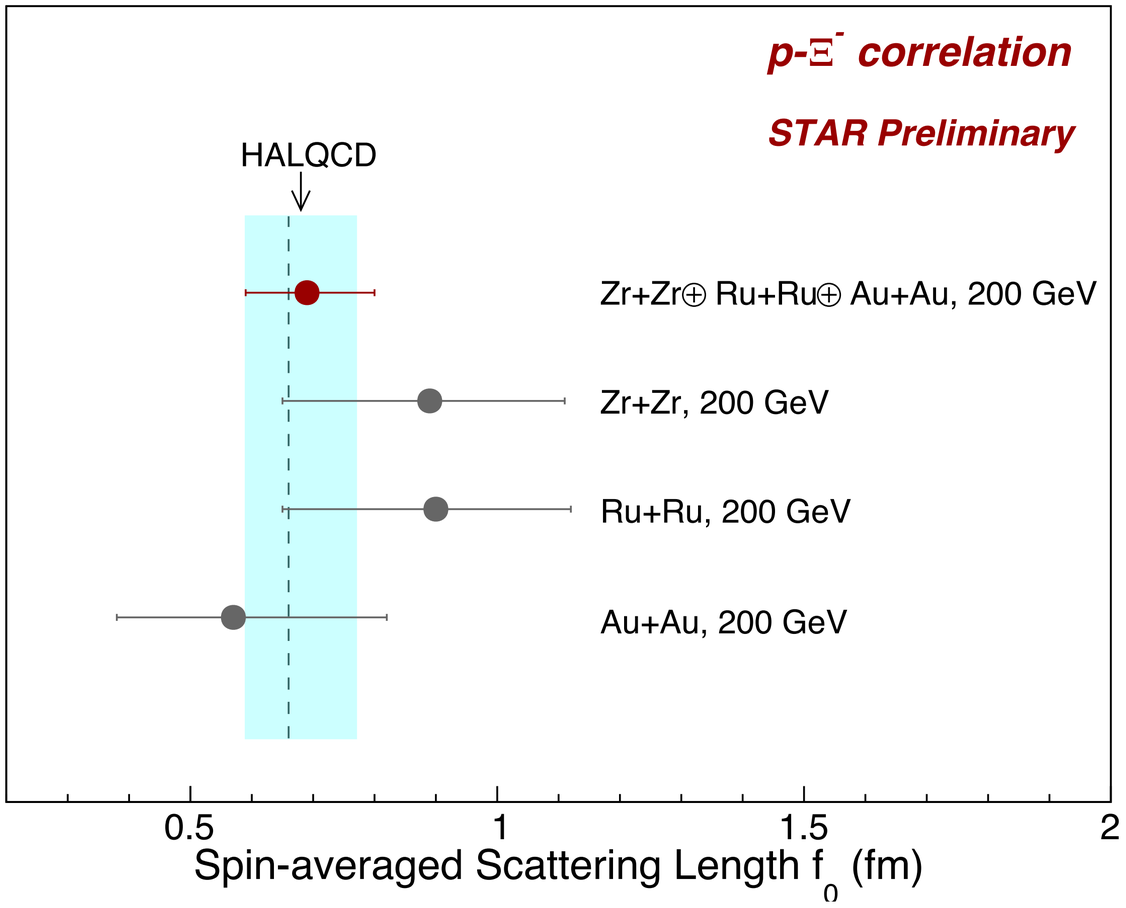




- $p-\Xi^-$ CFs show enhancement at low k*, due to Coulomb attraction and strong interaction
- Simultaneously fit to Isobar and AuAu data
  - 9 centralities +(f_0, d_0)
- UrQMD + HALQCD results are consistent with data

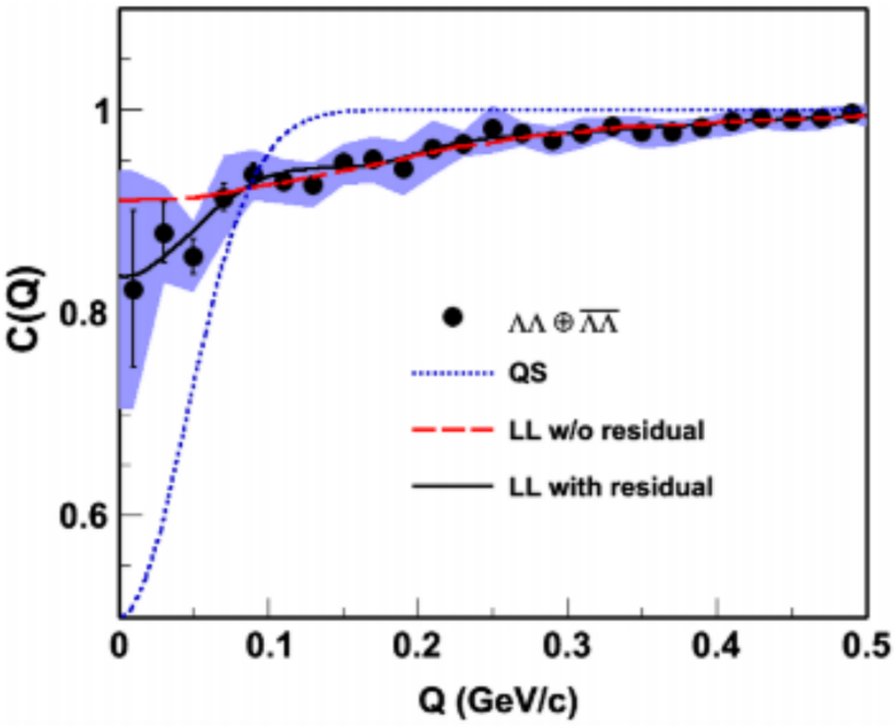
PHYSICAL REVIEW C 105, 014915 (2022)

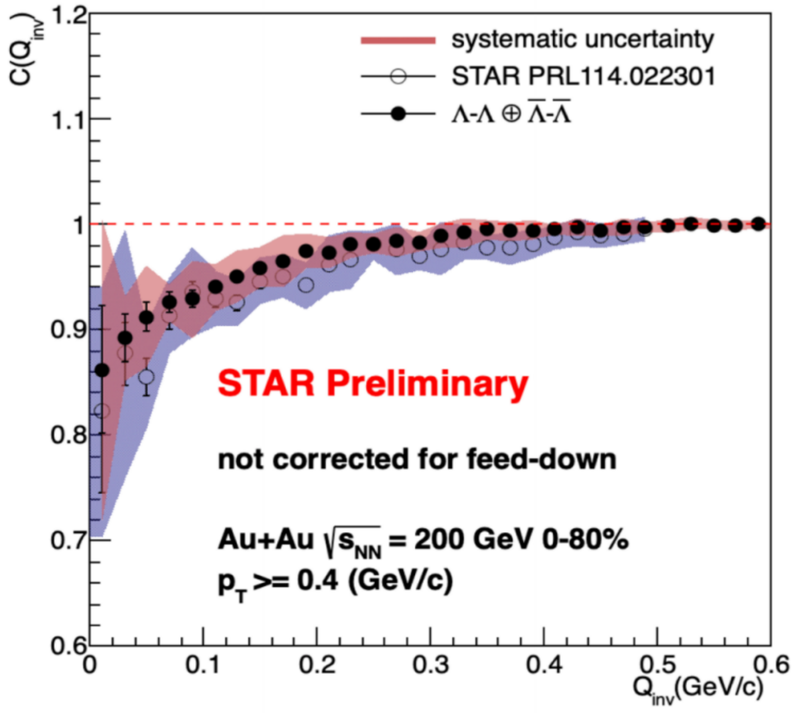
Results — p-Ξ Interaction



- Extracted ***positive*** f_0 ~ 0.69 fm
  - ***Attractive*** strong interaction in $p - \Xi^-$ pair
  - Shallow interaction
  - Consistent with Lattice predictions
-

Results — Λ-Λ Correlation

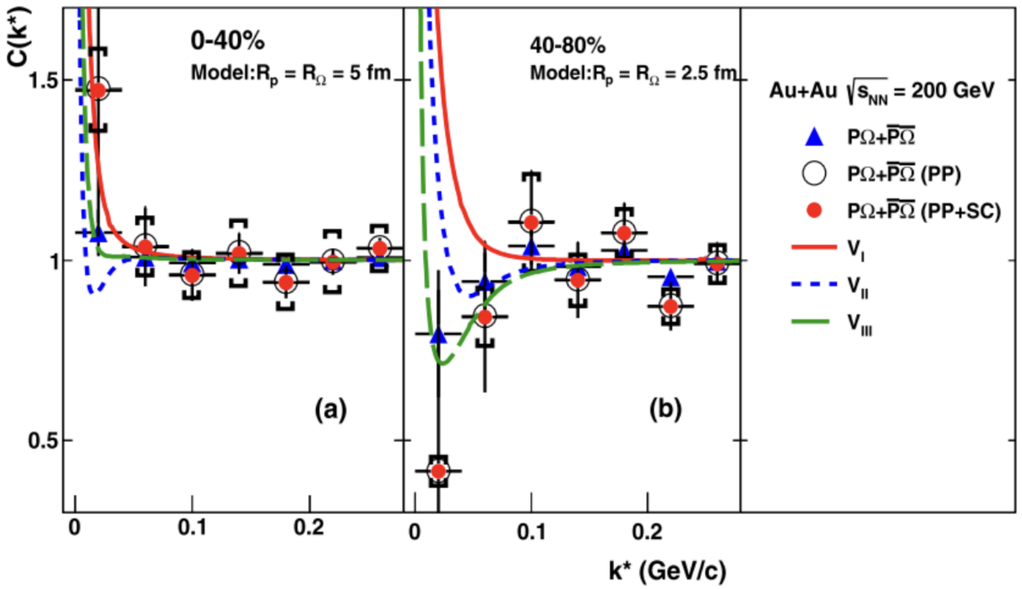




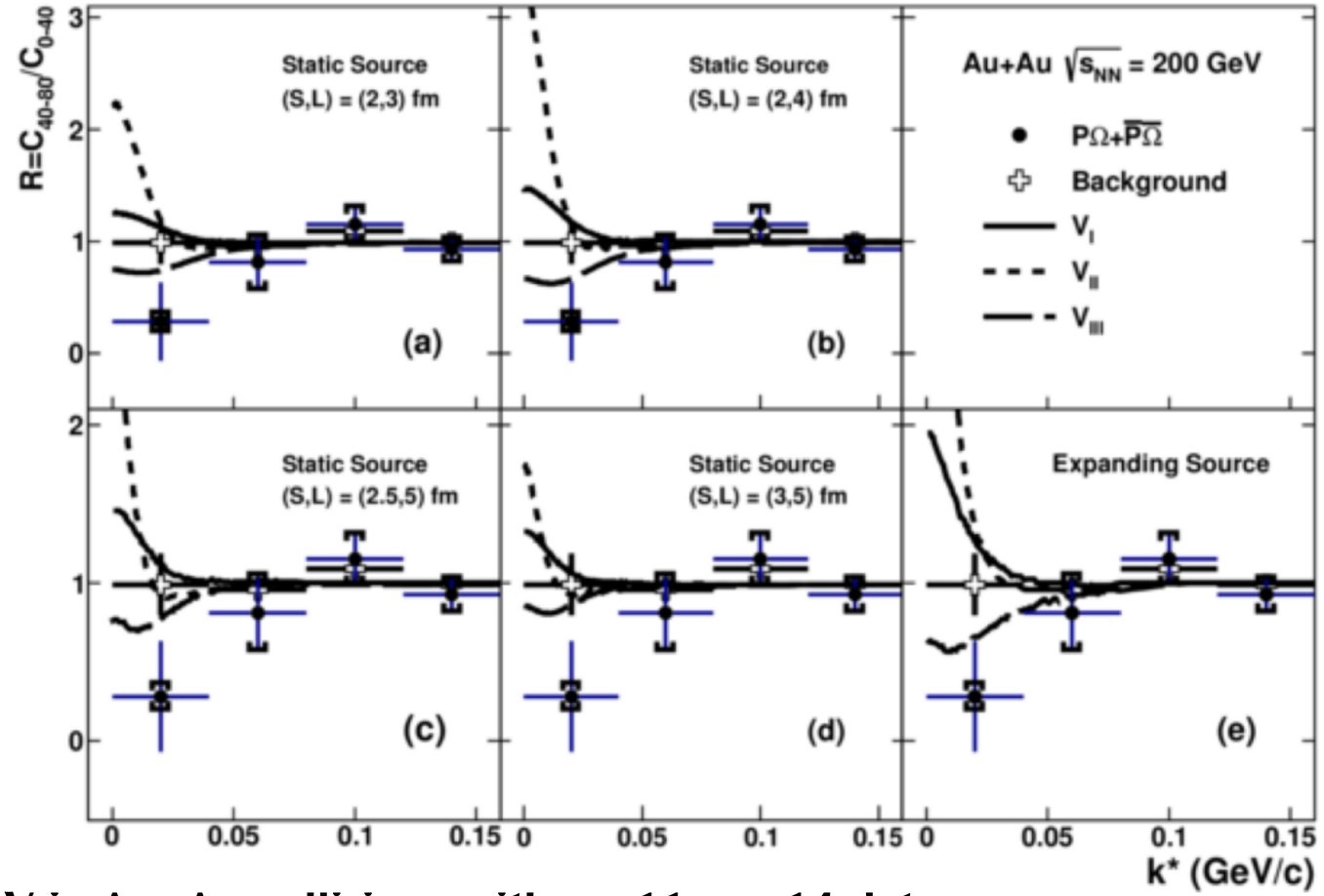
- STAR published Λ-Λ CF at 200 GeV in Au+Au collisions with run10, run11 data
- Re-do Λ-Λ CF in Au+Au collisions at 200 GeV with high-statistics run14, run16 data
- From fitting with analytical LL function, $f_0(\Lambda\Lambda)$ = -1 fm
  - Repulsive interaction concluded from publish paper (without 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

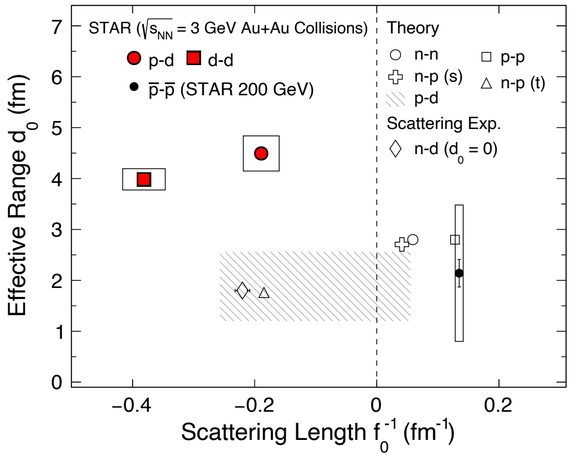
Summary

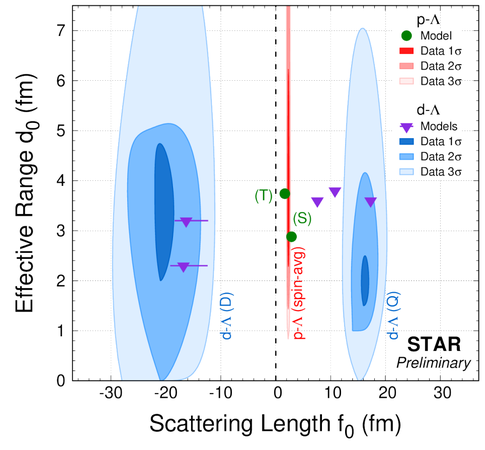
- Femtoscopy measurements from HIC provides a unique tool to explore strong interactions and evolution dynamics

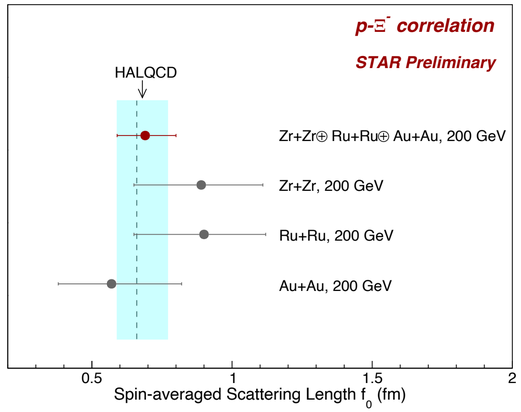
- p-d, d-d interaction
  - First determination of p-d / d-d interaction parameter at STAR
  - *Coalescence* is the dominant process for deuteron formation in the high-energy collisions

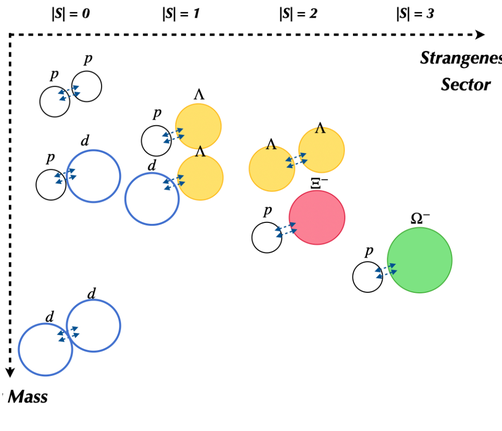
- d-Λ interaction
  - First experimental measurements of f_0 and d_0 in d-Λ pairs
  - Provide a new way to explore hyper-nuclei properties

- 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









Outlook:

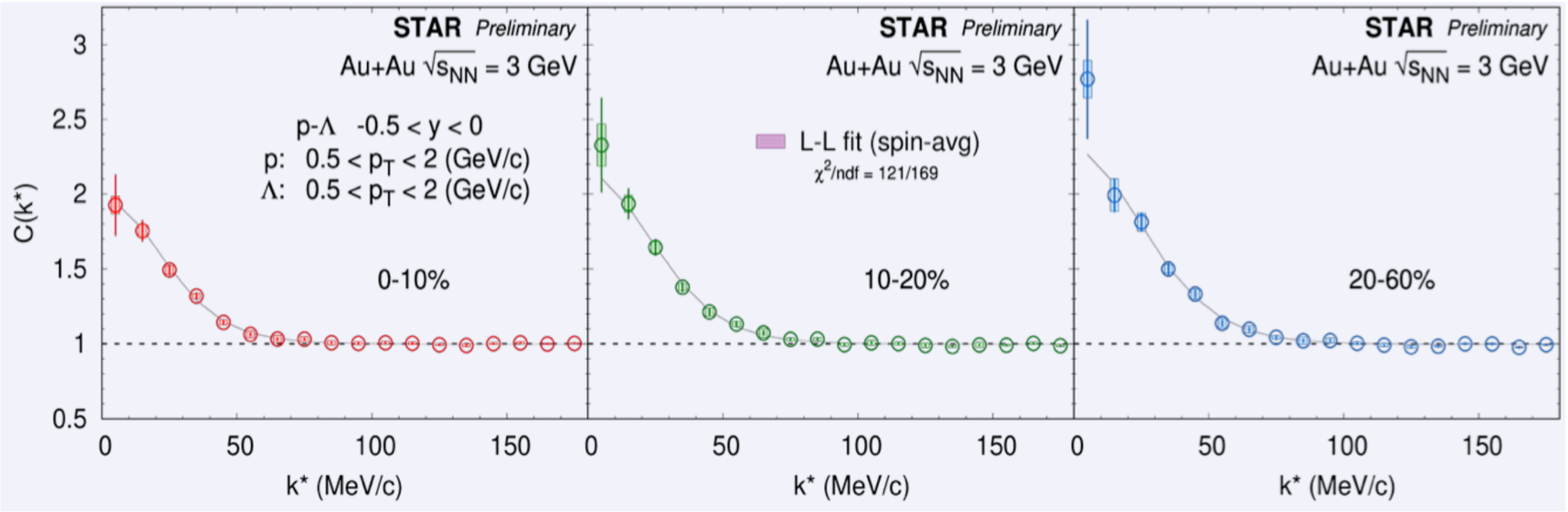
More than 10 times statistics from BES-II

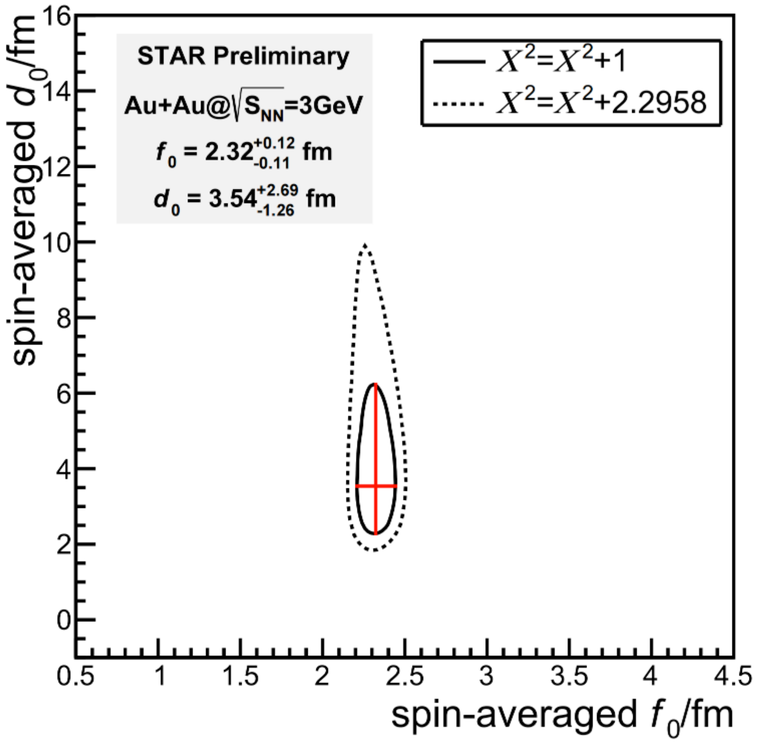
- Emission source size vs. energy, rapidity ….
- Baryon correlations with different species

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**

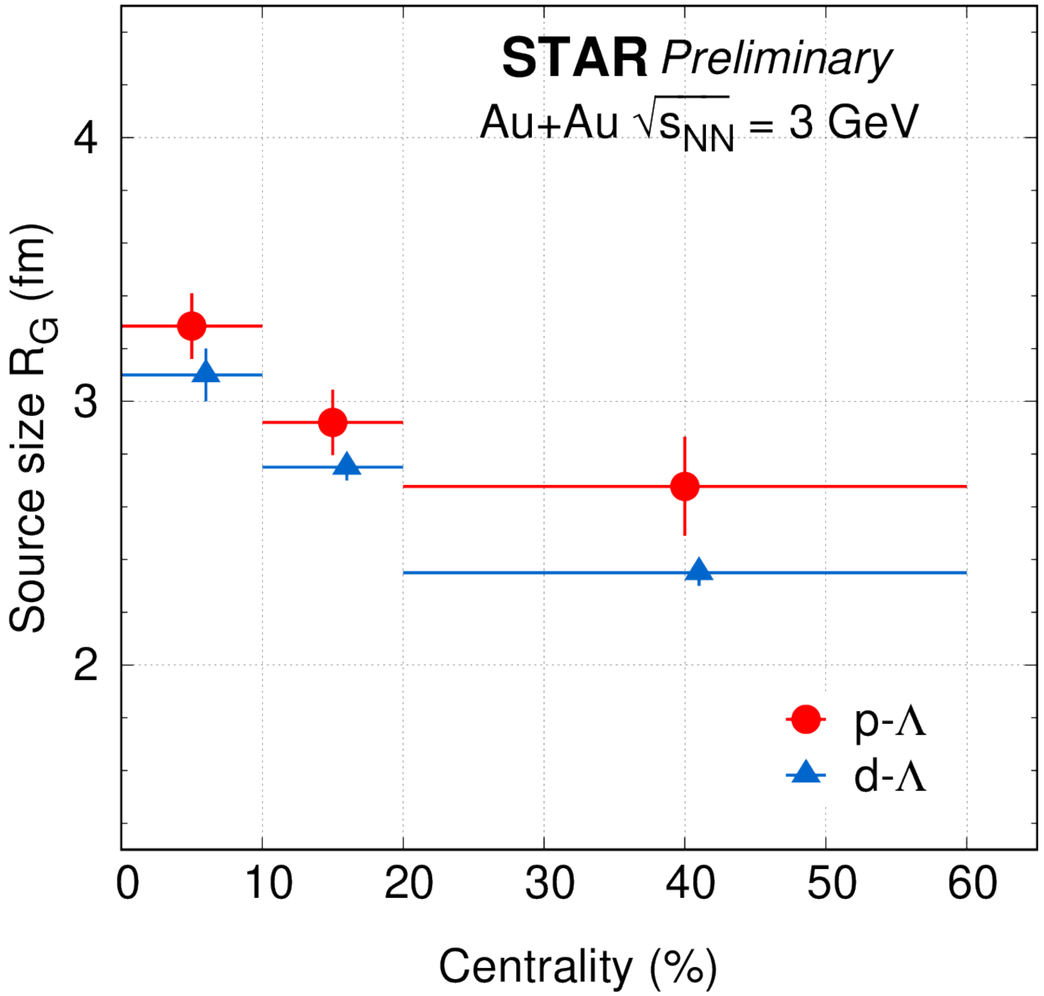
$$f_0 = 2.32^{+0.12}_{-0.11} fm,\ d_0 = 3.54^{+2.69}_{-1.26} fm$$

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

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

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

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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