

# Baryon Correlations at STAR

Pre-SQM Workshop 2026 held at LBNL

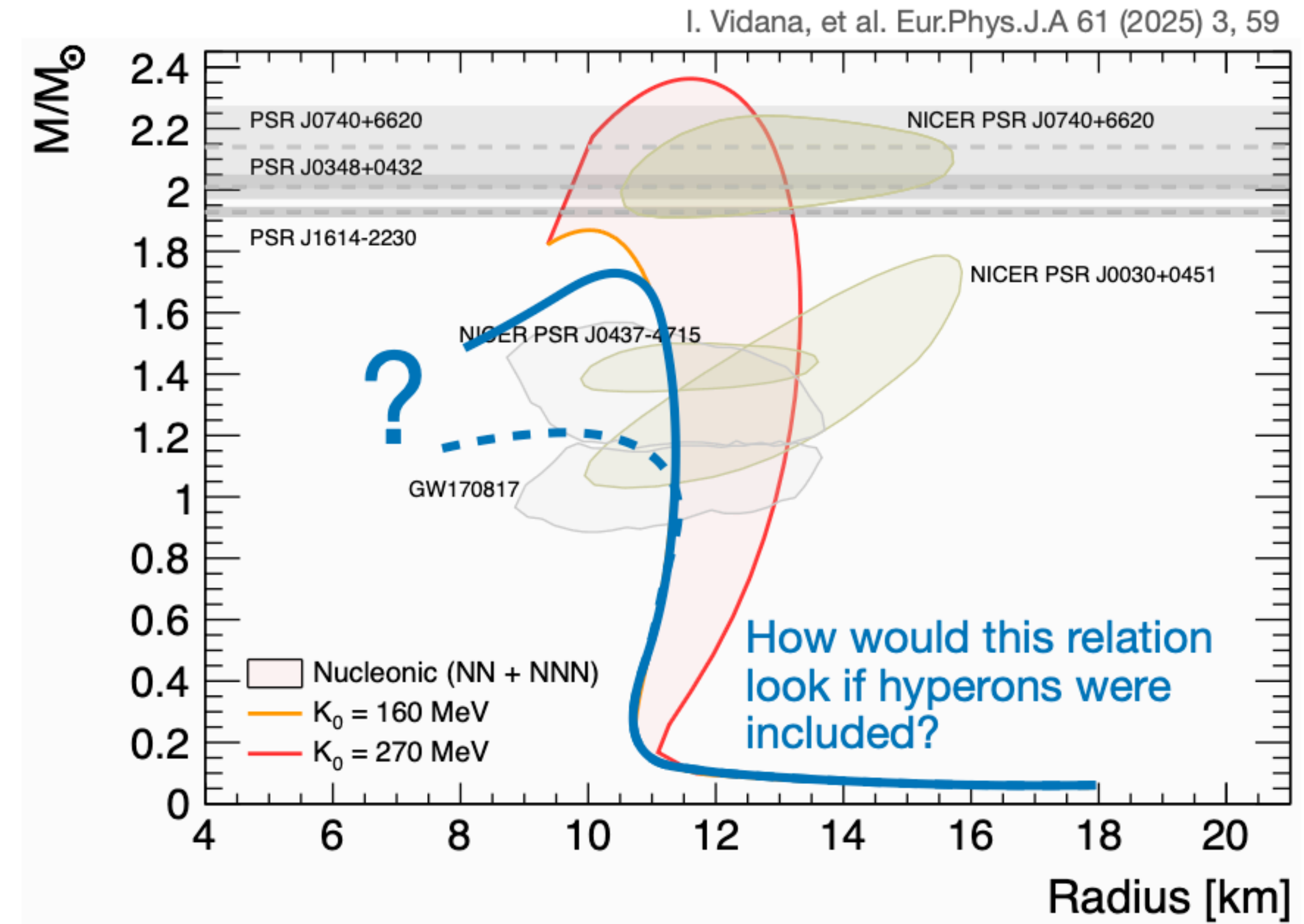
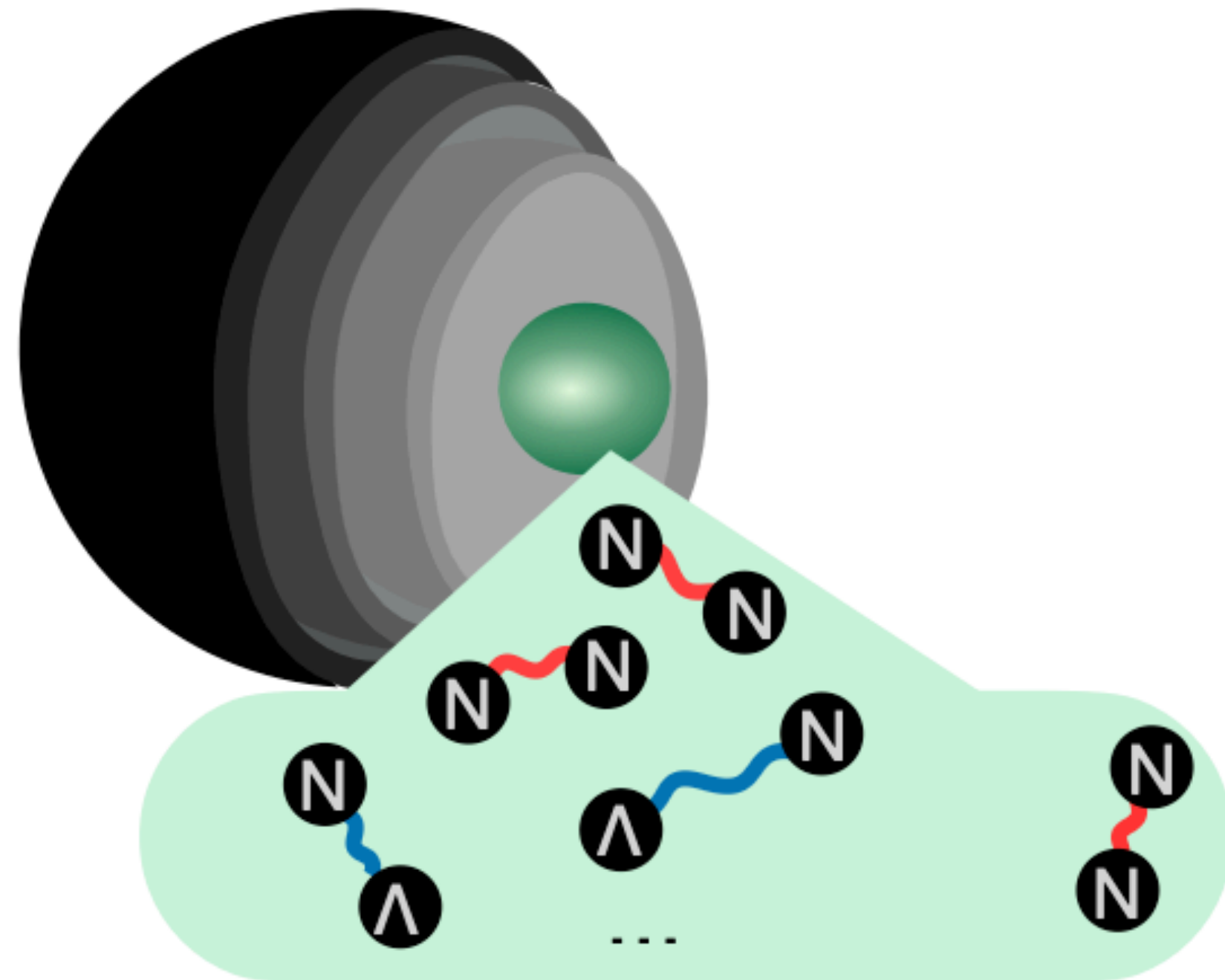
Yingjie Zhou



Mar. 20, 2026

# Motivation

- Density at inner core of neutron star can reach  $> 2\rho_0$
- Hyperons might appear in the system



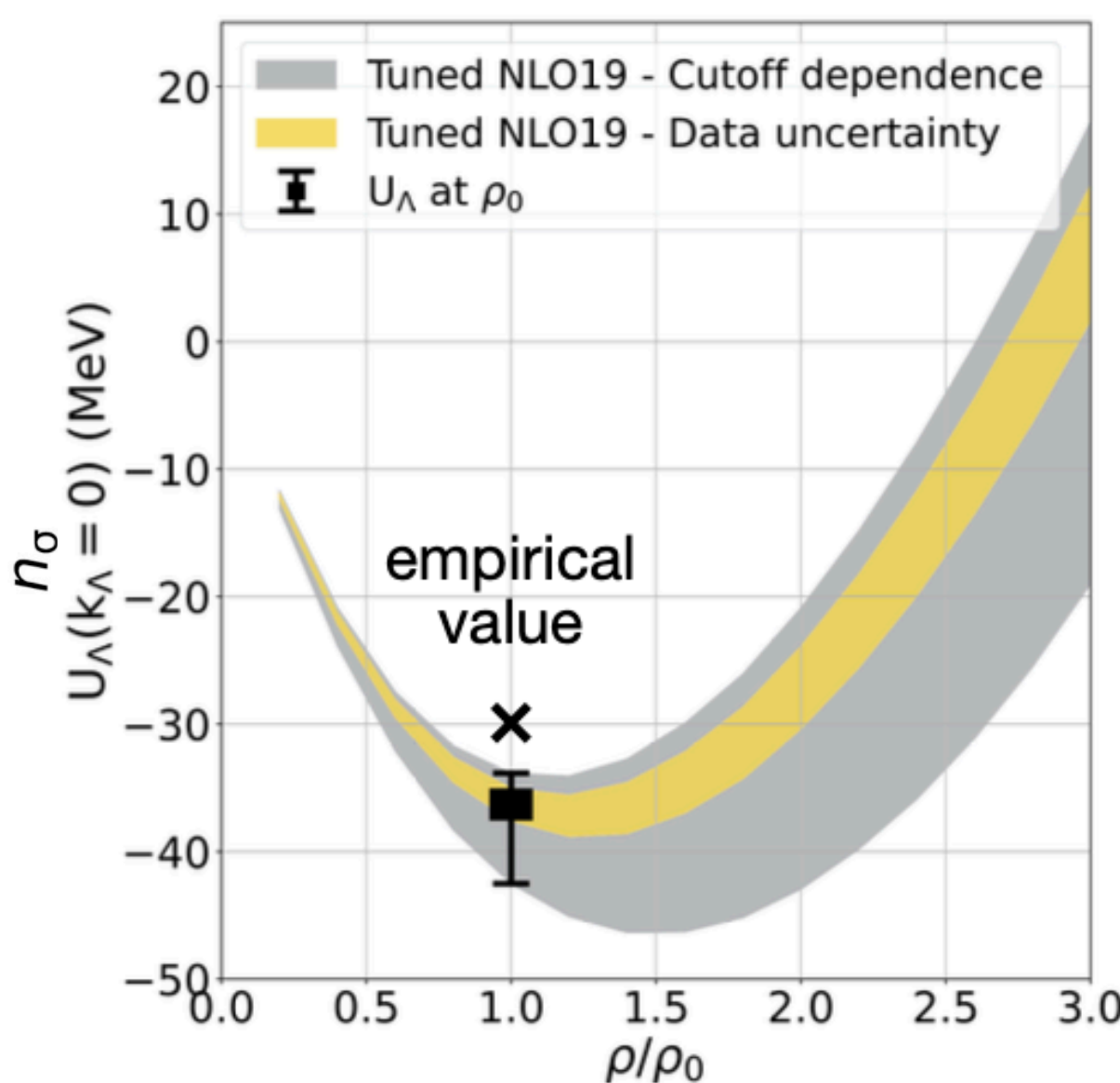
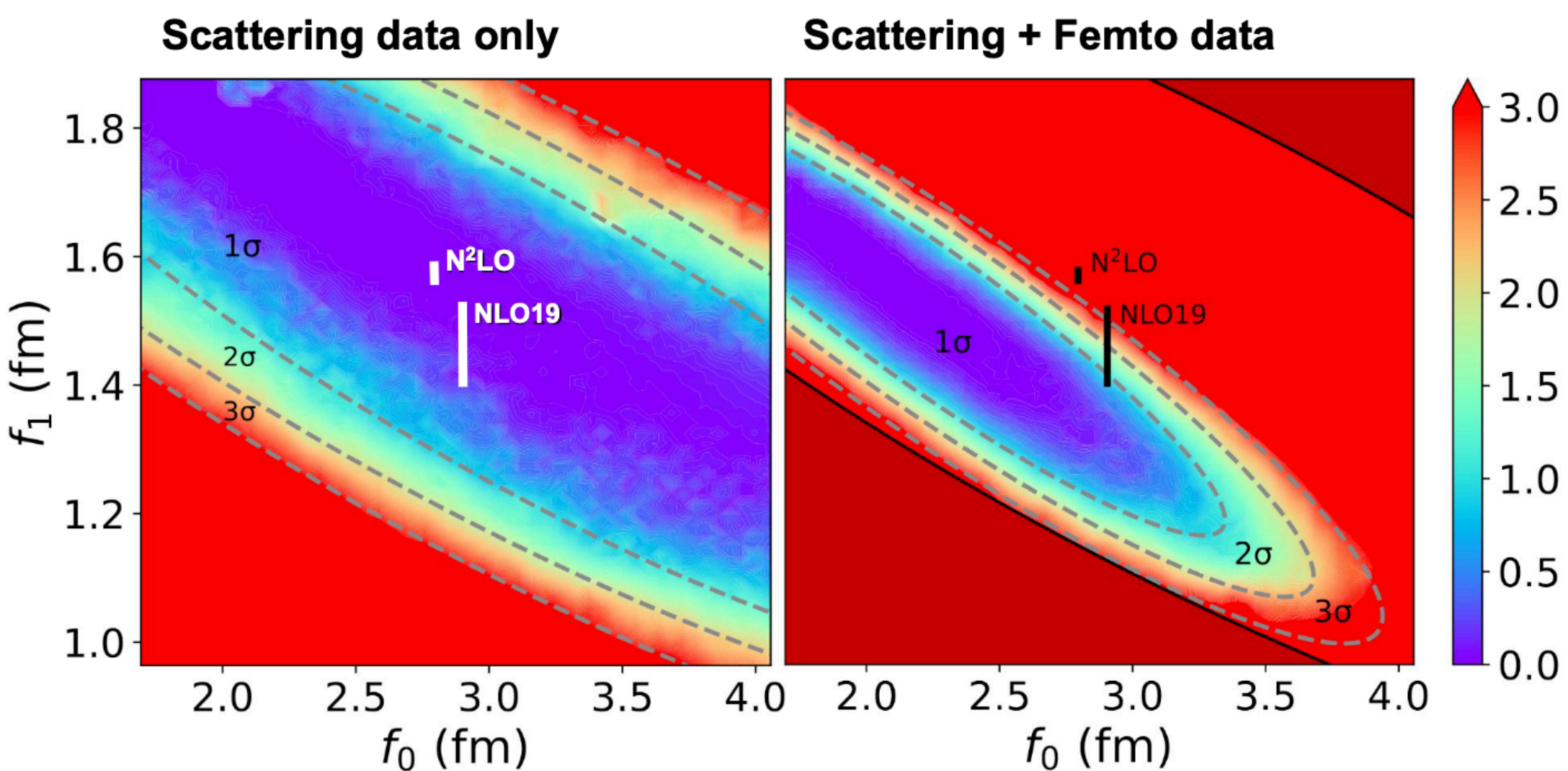
*Use femtoscopy to constrain hyperon–nucleon (YN) interactions with high precision!*

# Strangeness in neutron stars

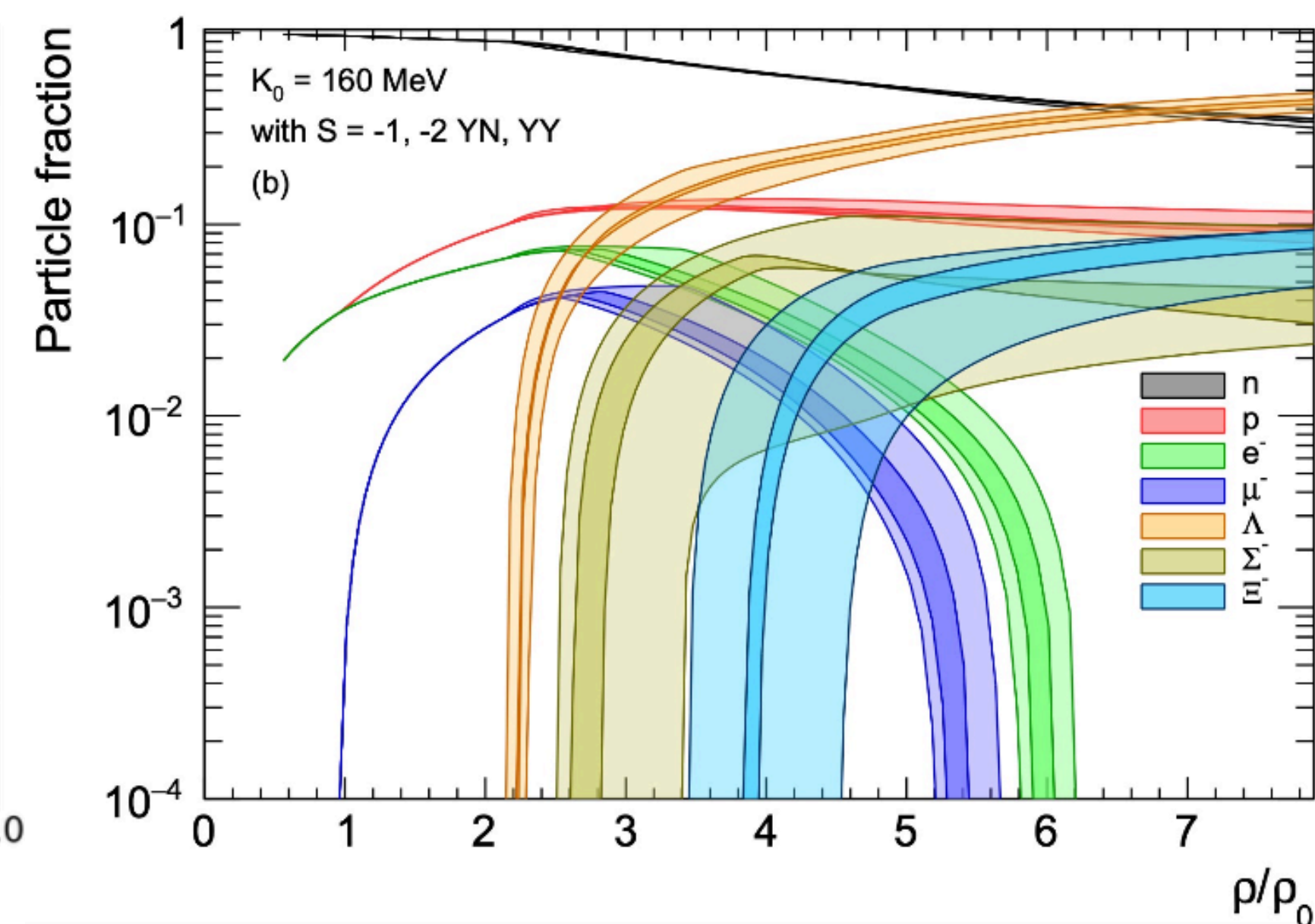
- Constrain low-energy constants of  $\chi$ EFT using new femto data
- Evaluate the in-medium potential  $U_\Lambda$

PLB 850 (2024), 138550

since 2024



I. Vidana, et al. Eur.Phys.J.A 61 (2025) 3, 59



- $N\Lambda$  interactions: relatively well understood  
Attractive, known from scattering + femto
- $N\Sigma$ ,  $N\Lambda$  interactions: scarce knowledge

Constraints on  $f_0$  and  $d_0$  help fix the underlying YN interaction and the in-medium potential  $U_Y$ , which controls when hyperons appear and how strongly they soften the neutron-star EOS

# Effect on neutron stars

- Equation of state with state-of-the-art interactions for NN, NNN, YN ( $S=-1$  and  $S=-2$ ) and YY fail to reproduce observed heavy neutron stars

- Key missing pieces: three body interaction involving hyperons

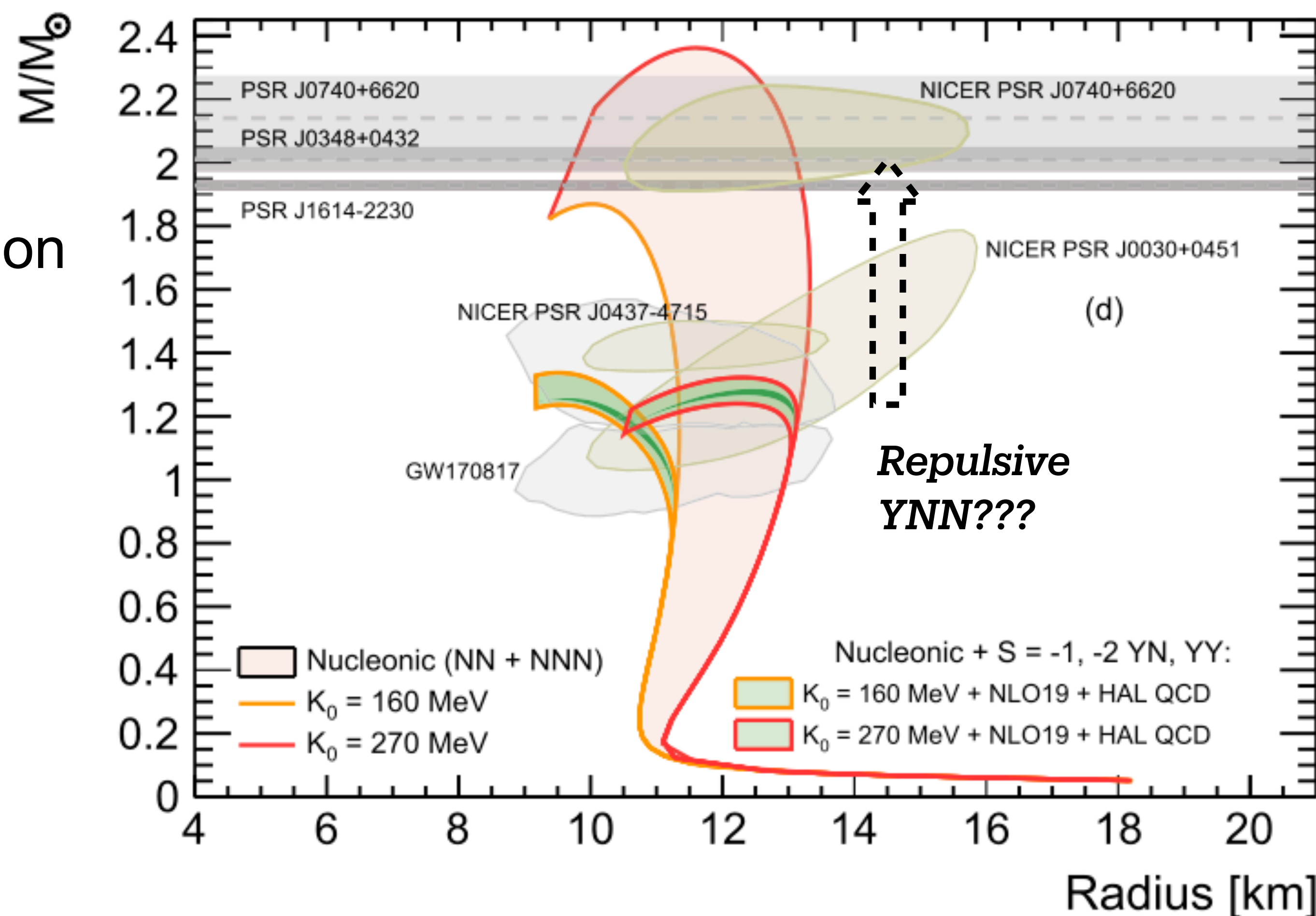
- $\Lambda$ NN: p-p- $\Lambda$ , **d- $\Lambda$**
- $\Xi$ NN: p-p- $\Xi$

Only effective theory from hypernuclei measurements available

Hypernuclear separation energies provide few-body benchmarks for YN interaction models; discrepancies may indicate missing YNN contributions

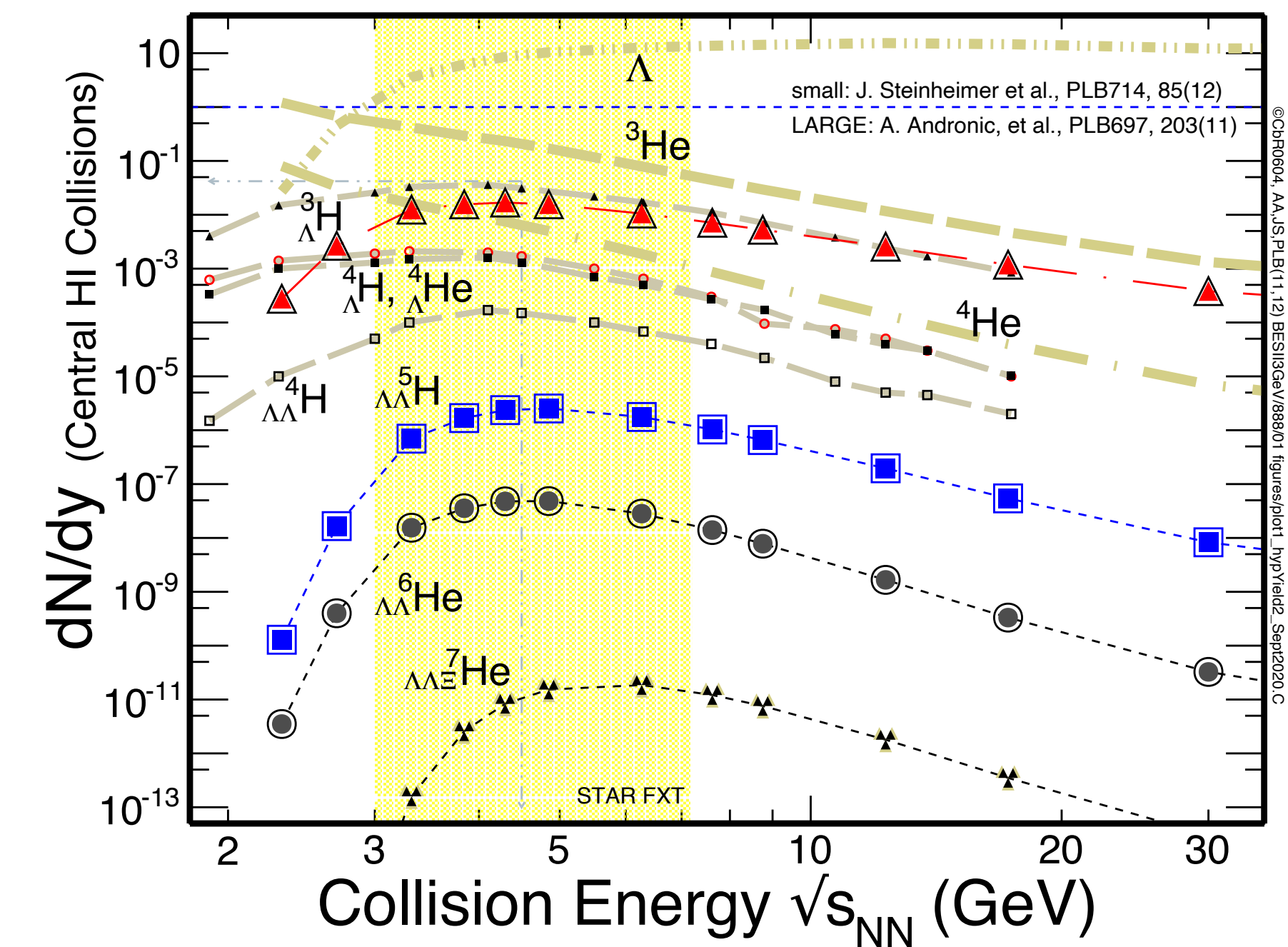
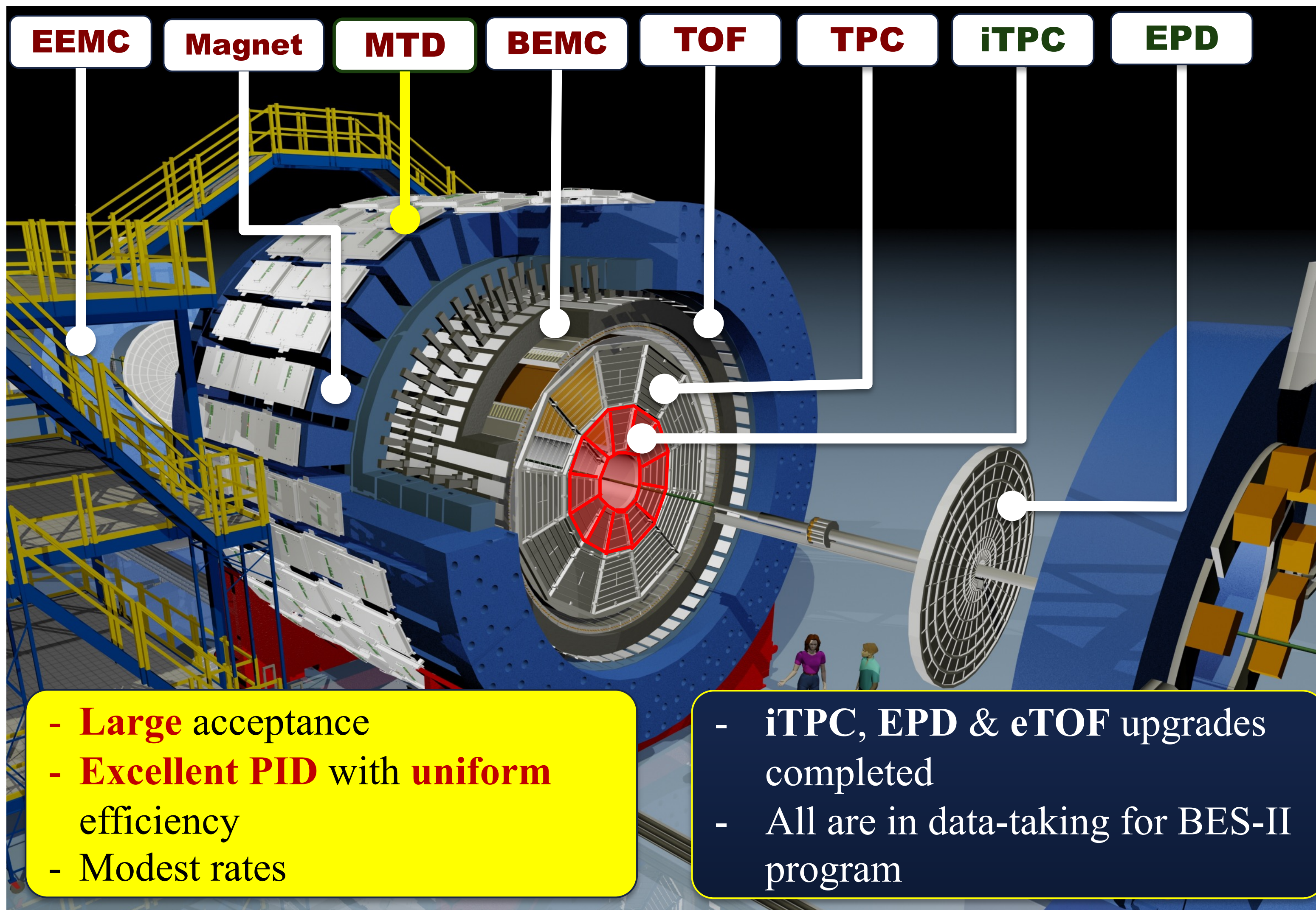
Eur.Phys.J.A 60 (2024) 1, 3

I. Vidana, et al. Eur.Phys.J.A 61 (2025) 3, 59

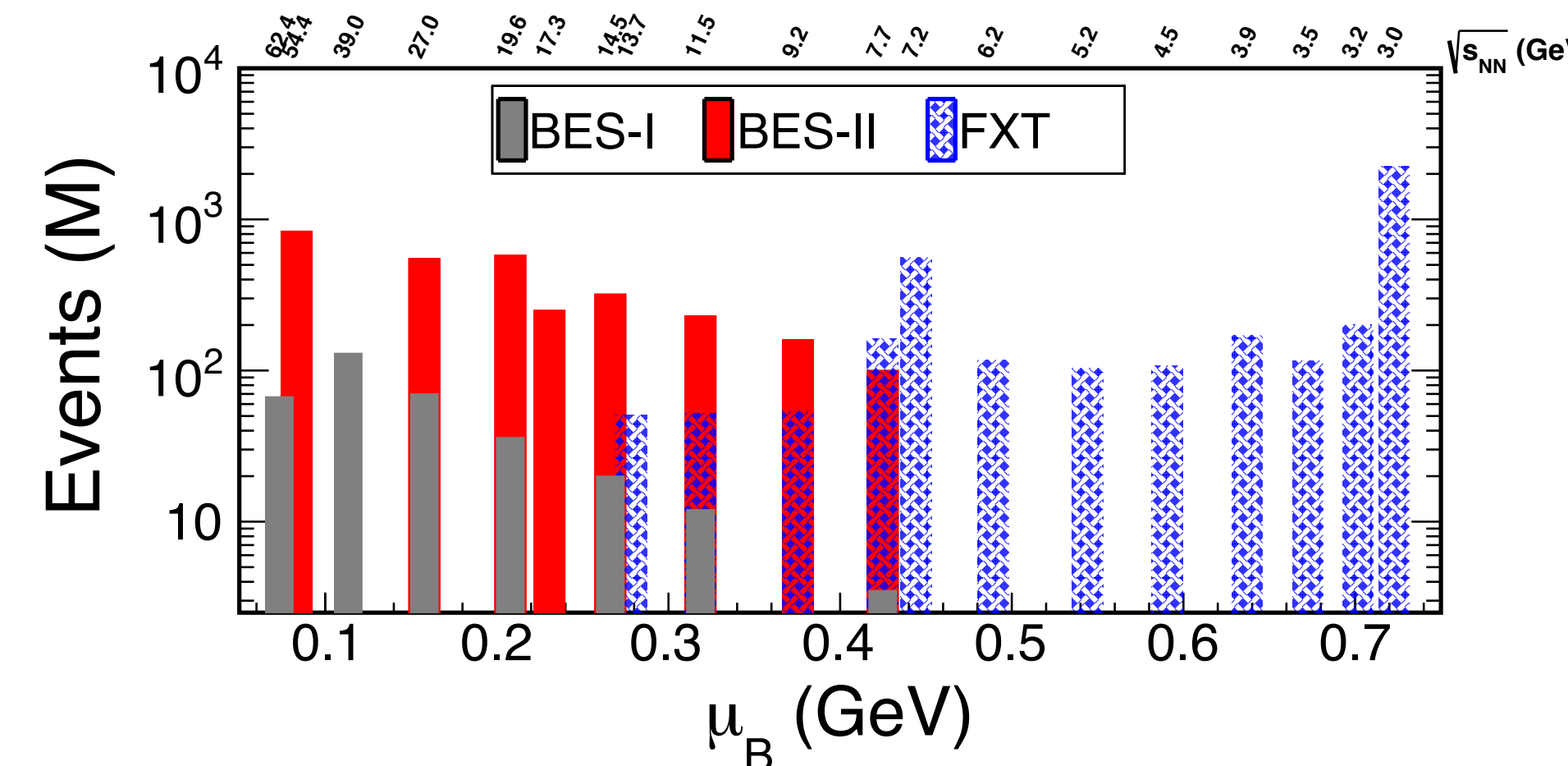


- Goal: more precise information from p- $\Xi$ - and d- $\Lambda$

# Why heavy-ion collisions at STAR?

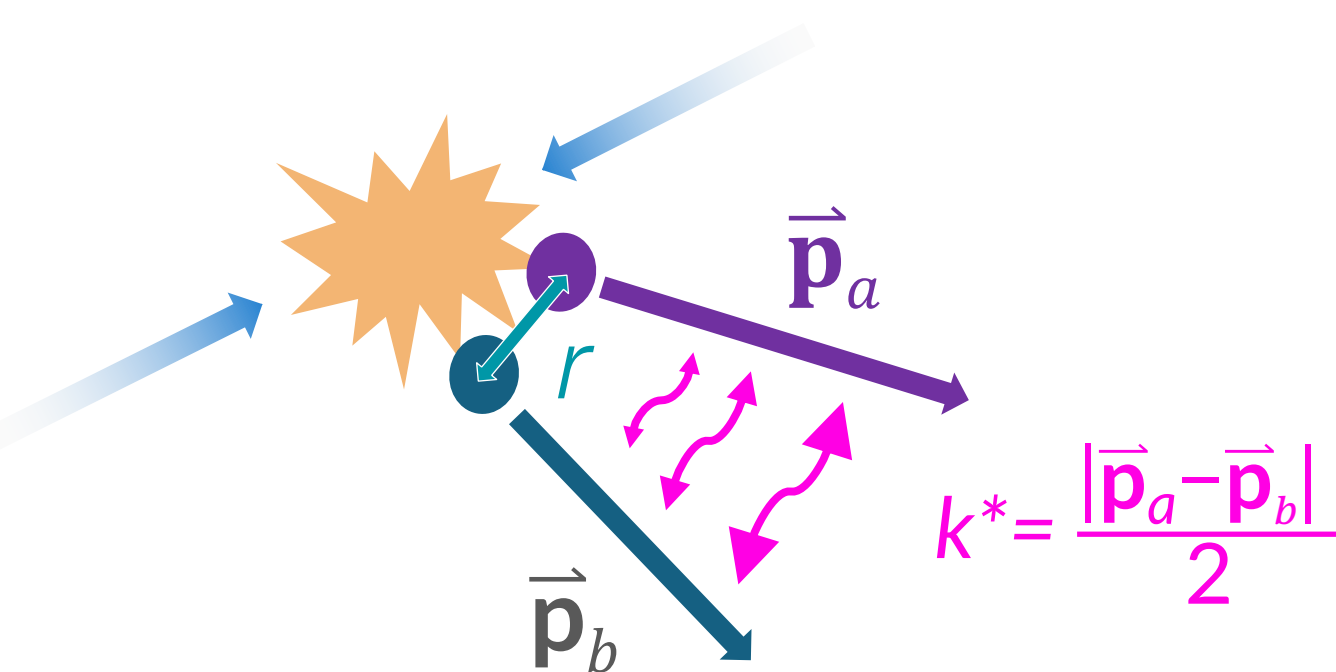


A. Andronic *et al.* Phys.Lett.B 697, 203 (2011)  
J. Steinheimer *et al.* Phys.Lett.B 714, 85 (2012)



- STAR provides a unique laboratory for baryon–hyperon correlations at high baryon density

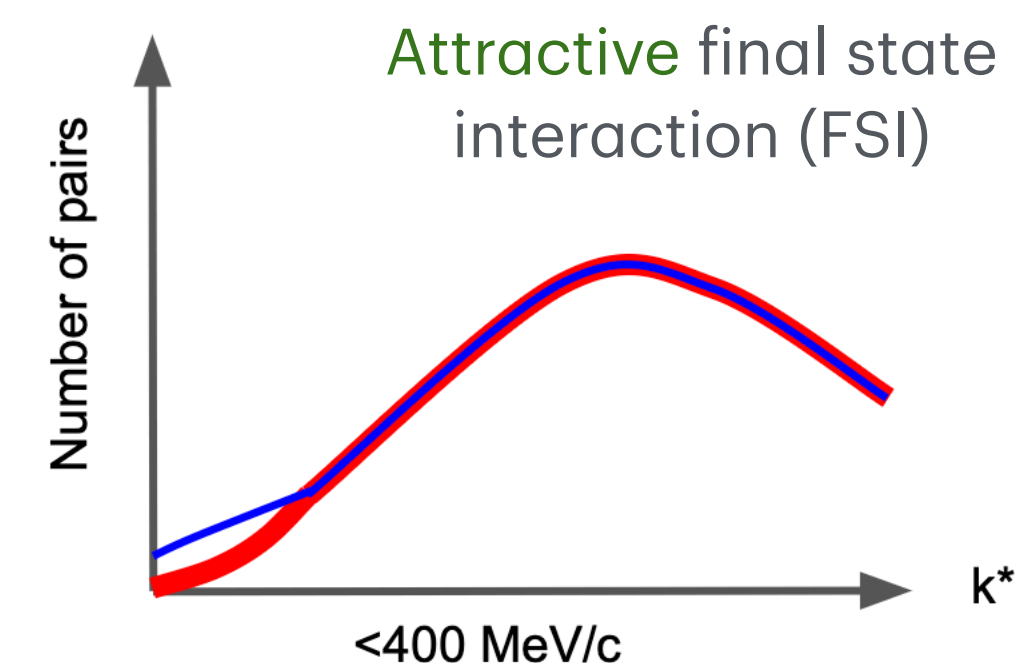
# Femtoscscopy for interactions



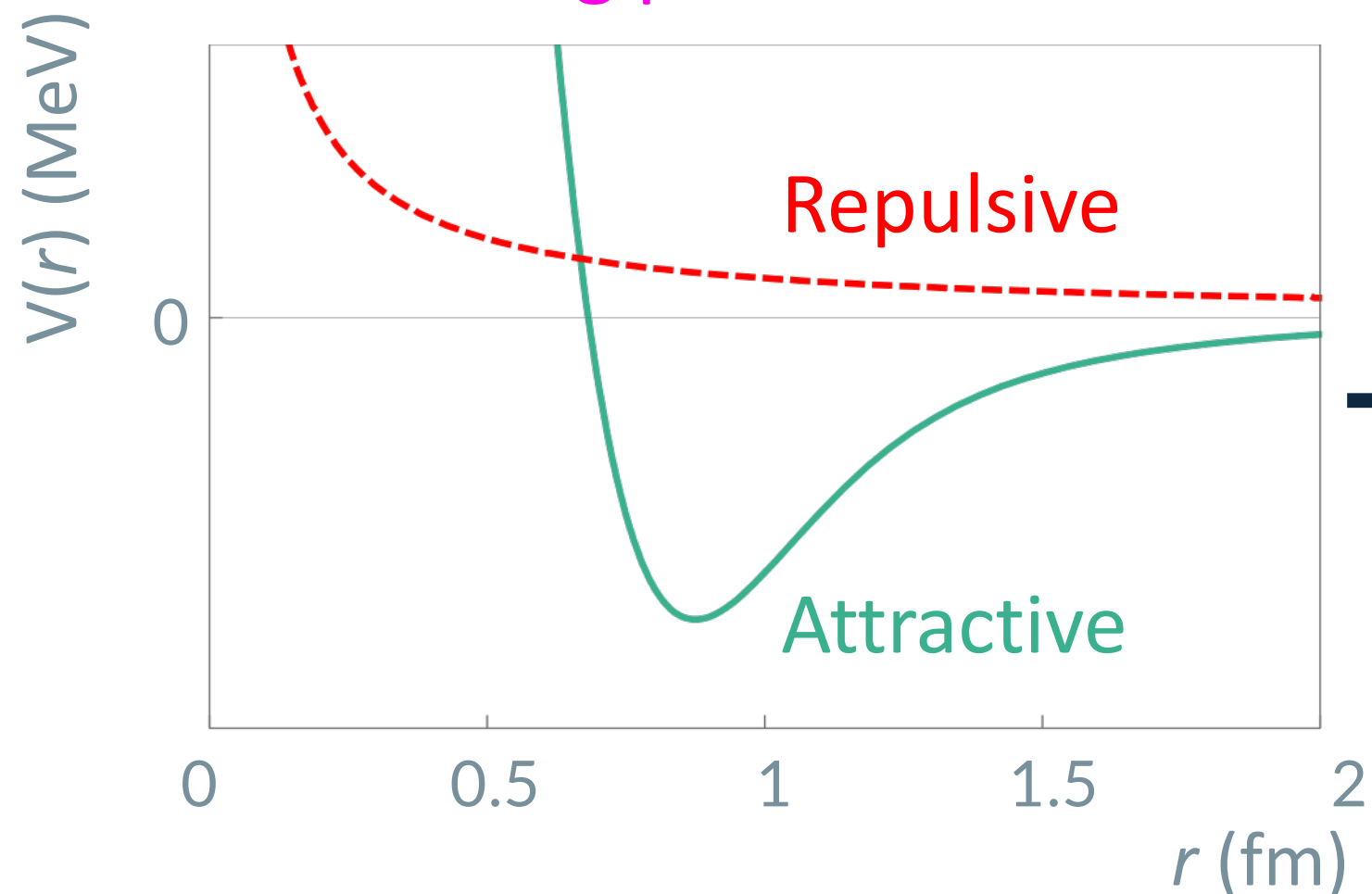
$$C(k^*) = \int S(\vec{r}) |\psi(\vec{k}^*, \vec{r})|^2 d\vec{r} = \mathcal{N}(k^*) \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

Two-particle wave function

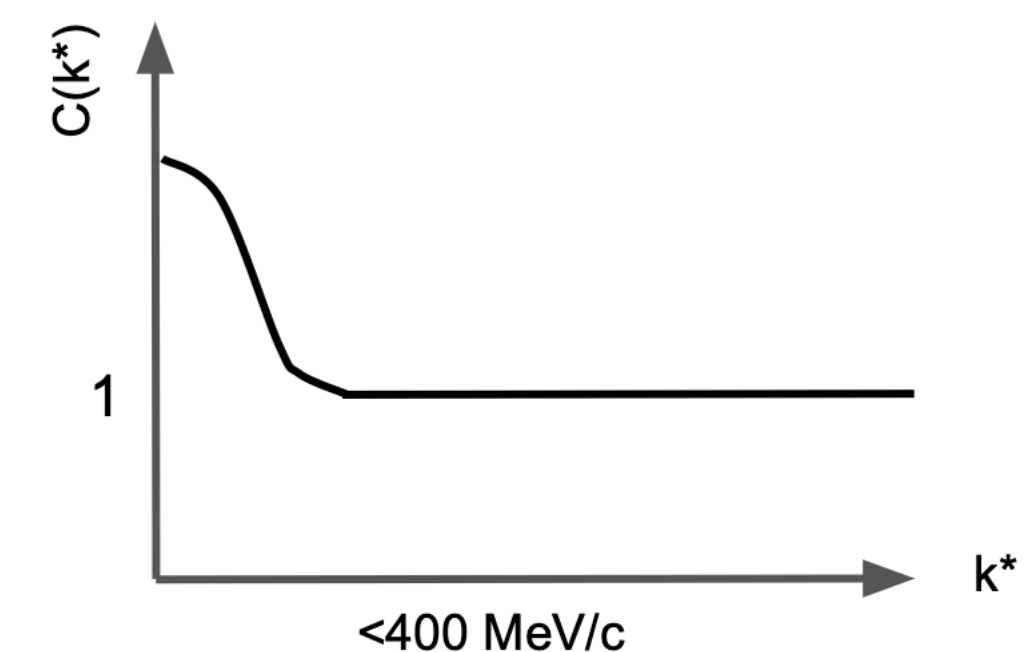
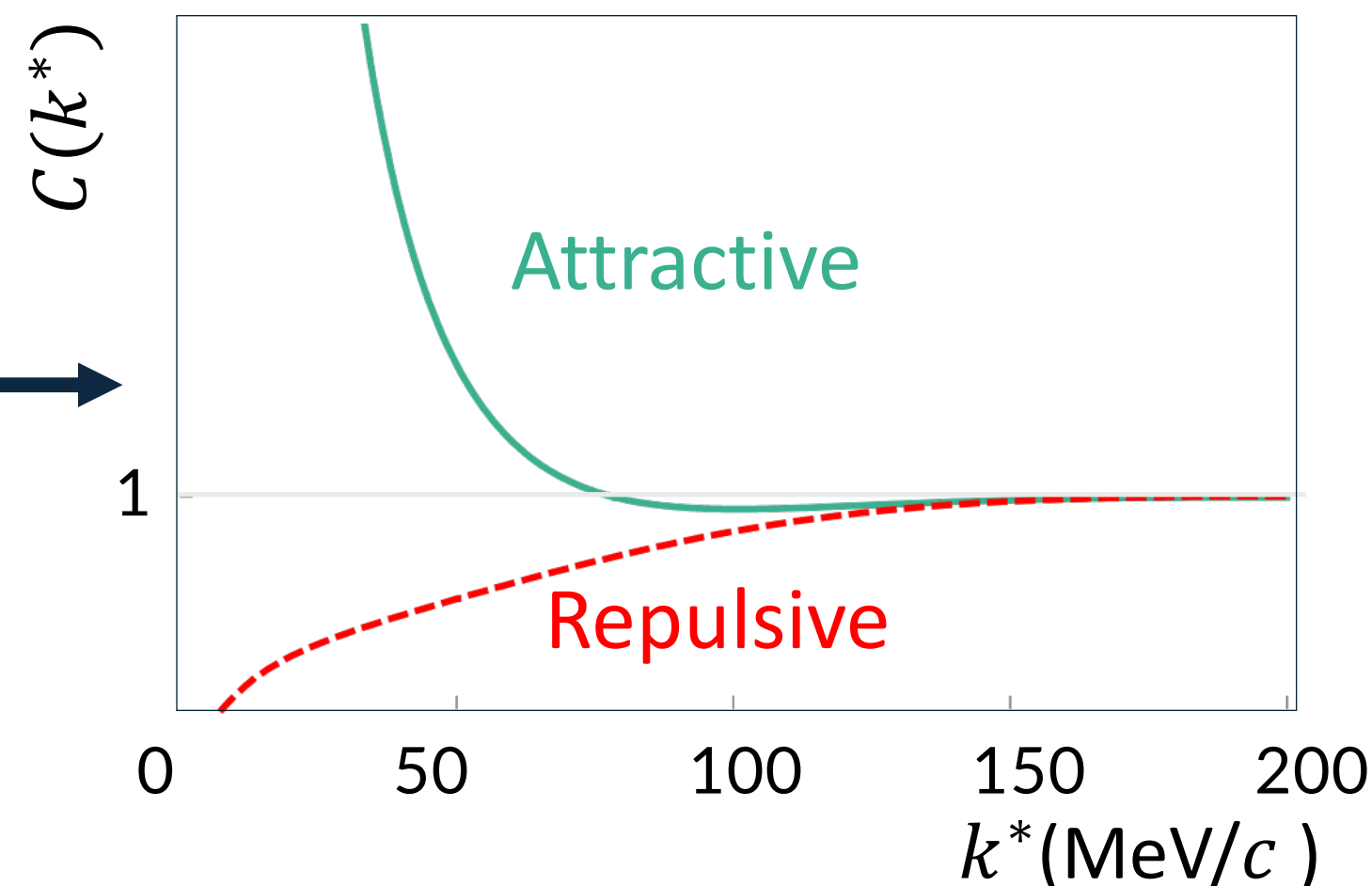
*M. Lisa, S. Pratt et al., ARNPS 55 (2005), 357-402*  
*L. Fabbietti et al., ARNPS 71 (2021), 377-402*  
*D. Mihaylov et al., EPJC 78 (2018), 5, 394*



Interacting potential



Correlation function



- The measured  $C(k^*)$  encodes both the emission source  $S(r^*)$  and the final-state interaction. To infer the interaction, one needs a controlled description of the source

# Lednický-Lyuboshitz (L-L) Approach

## Strategy 1:

- Use the L-L model to fit correlation functions to extract source size and effective range

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

### ➤ Formalism with Lednický-Lyuboshitz (L-L) model:

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

*R. Lednický and V. L. Lyuboshitz, Sov. J. Nucl. Phys. 35, 770 (1982)*

### ➤ Wave function:

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

### ➤ Scattering amplitude:

- ❑  $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - ik^*]^{-1}$  (No Coulomb)

- ❑  $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - \frac{2}{a_c}h(\eta) - ik^*A_c(\eta)]^{-1}$  (Include Coulomb)

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

$A_c, h$ : Coulomb interaction factor

L-L Fitting by  
Bayesian method

### ➤ Physics quantity:

- ❑  $f_0$ : Scattering Length
- ❑  $d_0$ : Effective Range
- ❑  $R_G$ : Spherical Gaussian Source Size

$f_0 > 0$ : Attractive Interaction

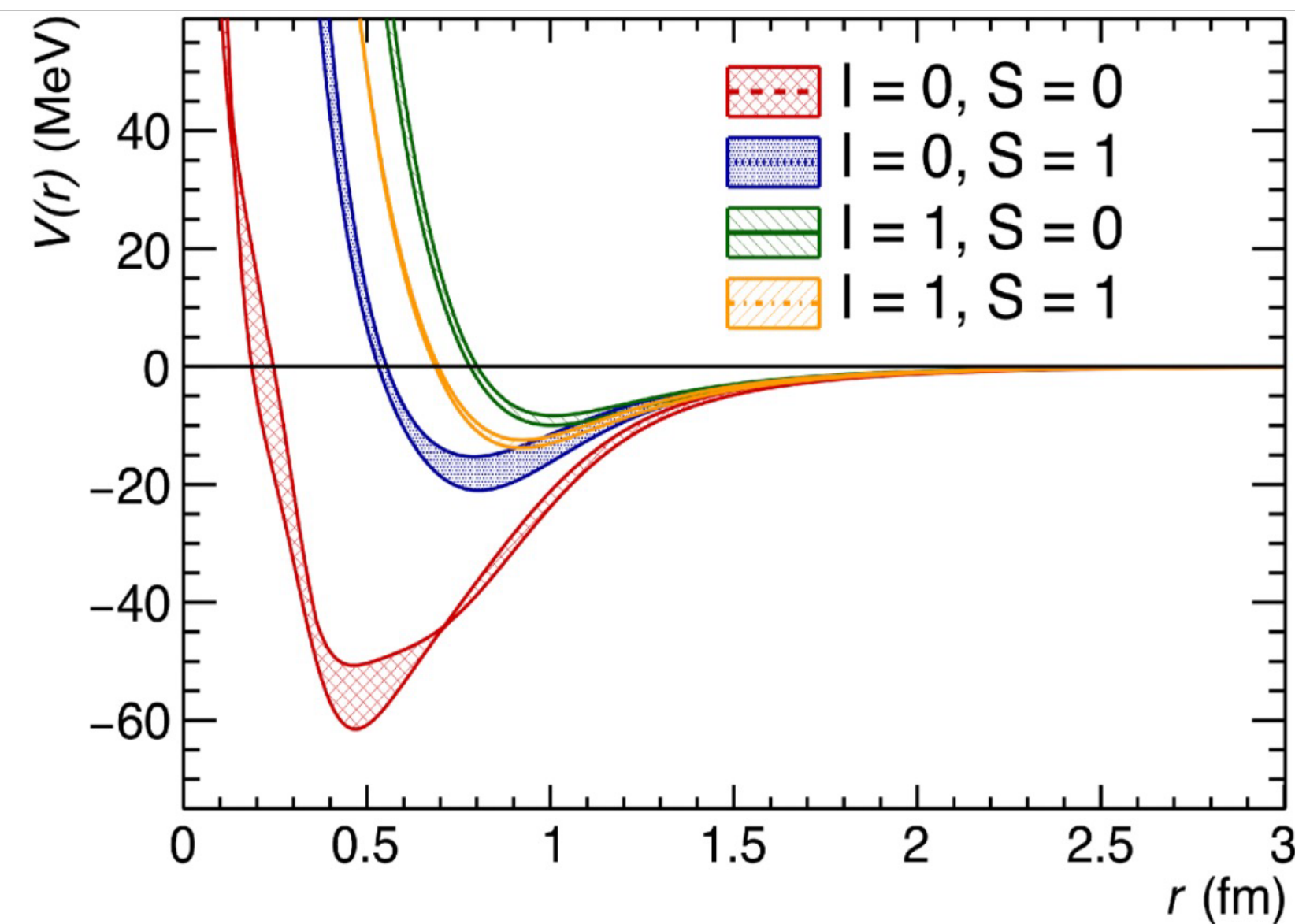
$f_0 < 0$ : Repulsive Interaction or Bound State

# Modelling of the correlation function

## Strategy 2:

- Construct a correlation function from a potential and compare with data directly

Local potentials for the  $N\Xi$  interactions



HAL QCD Coll. NPA 998 (2020)

Correlation function

$$C(k^*) = \frac{1}{8} C_{I=0,S=0}(k^*) + \frac{3}{8} C_{I=0,S=1}(k^*) + \frac{1}{8} C_{I=1,S=0}(k^*) + \frac{3}{8} C_{I=1,S=1}(k^*)$$

$R_G = 3.0 \text{ fm}$

↓

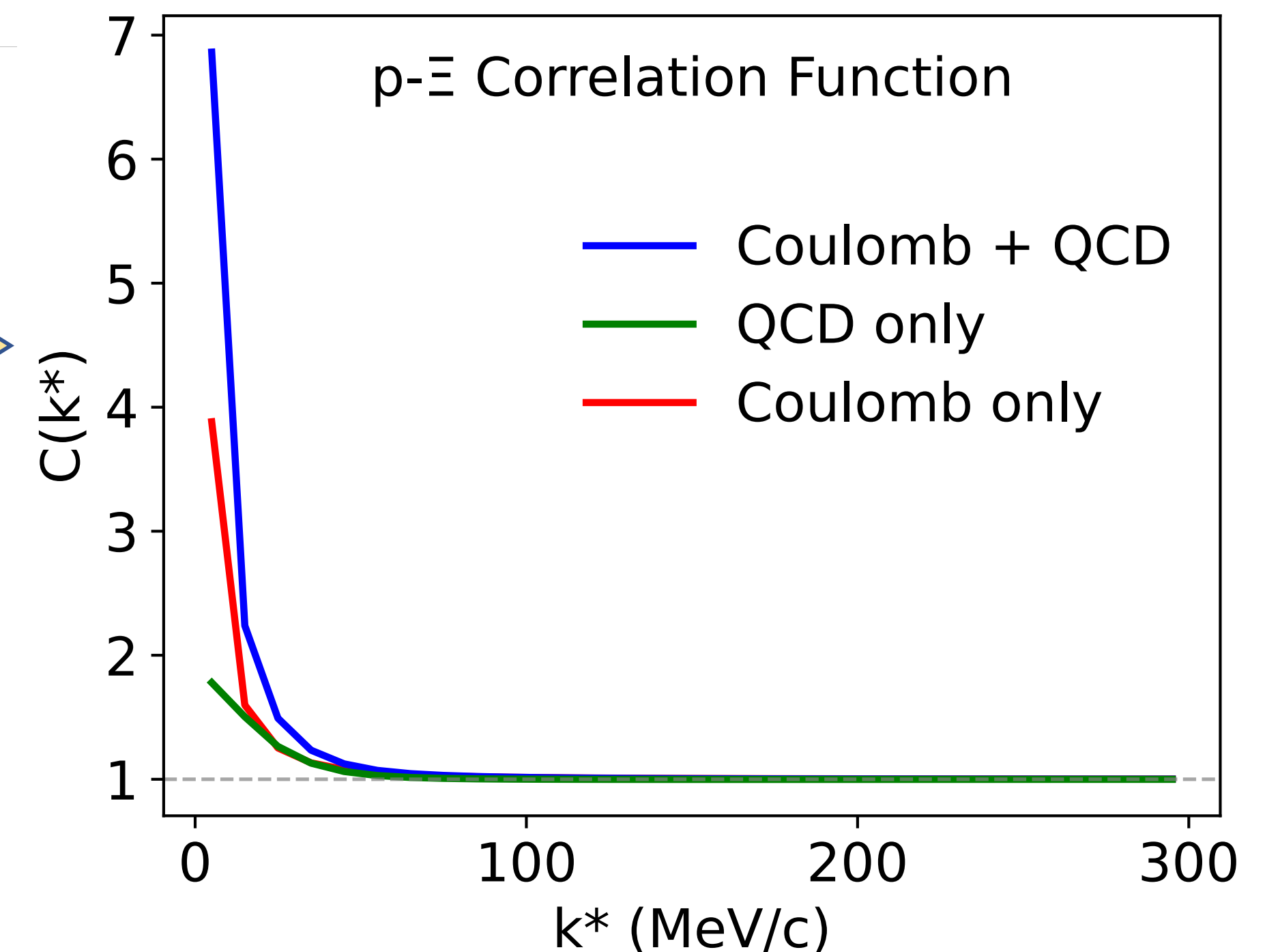
$$C(k^*) = \int s(\vec{r}) |\psi(\vec{k}^*, \vec{r})|^2 d\vec{r}$$

↑

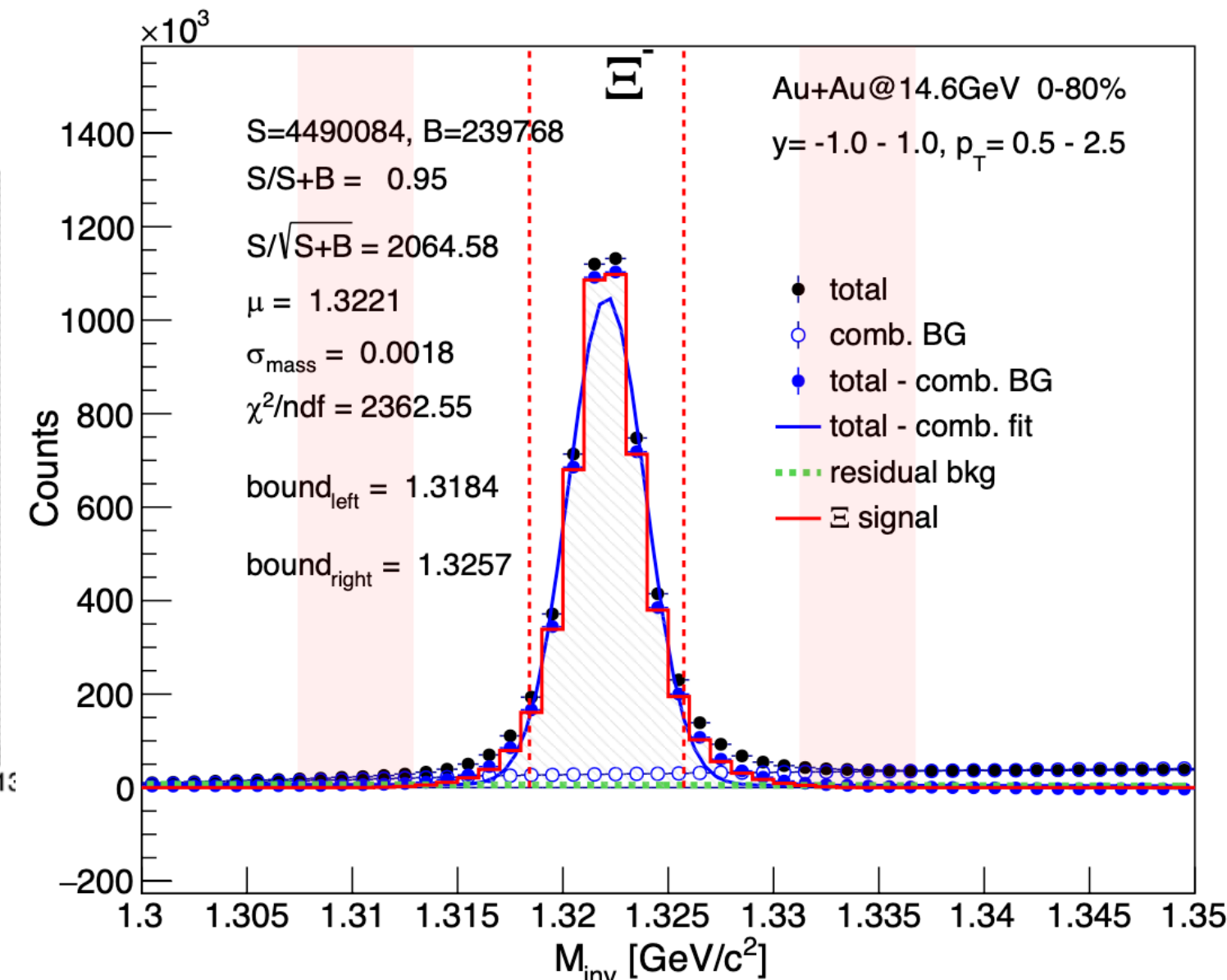
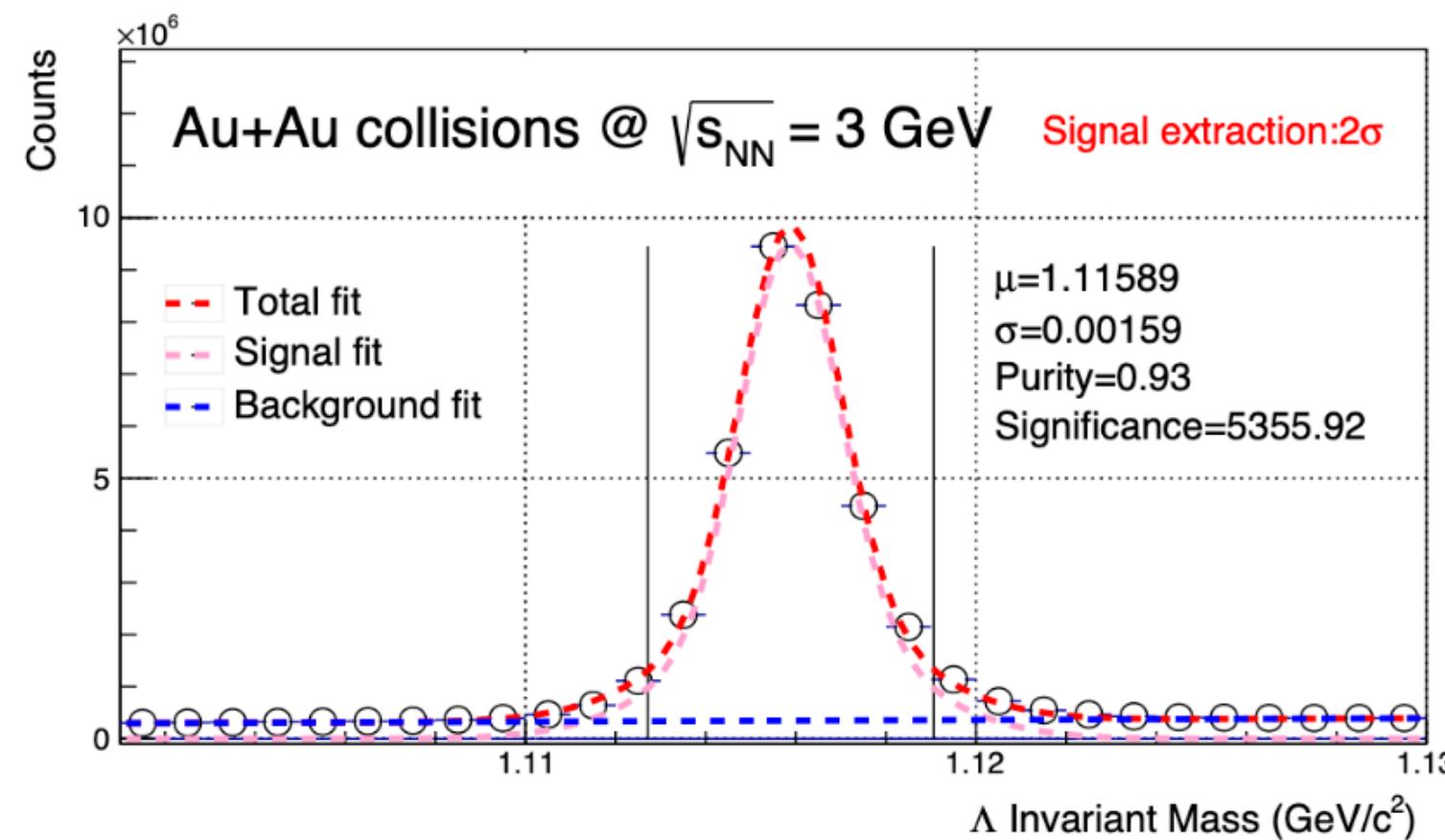
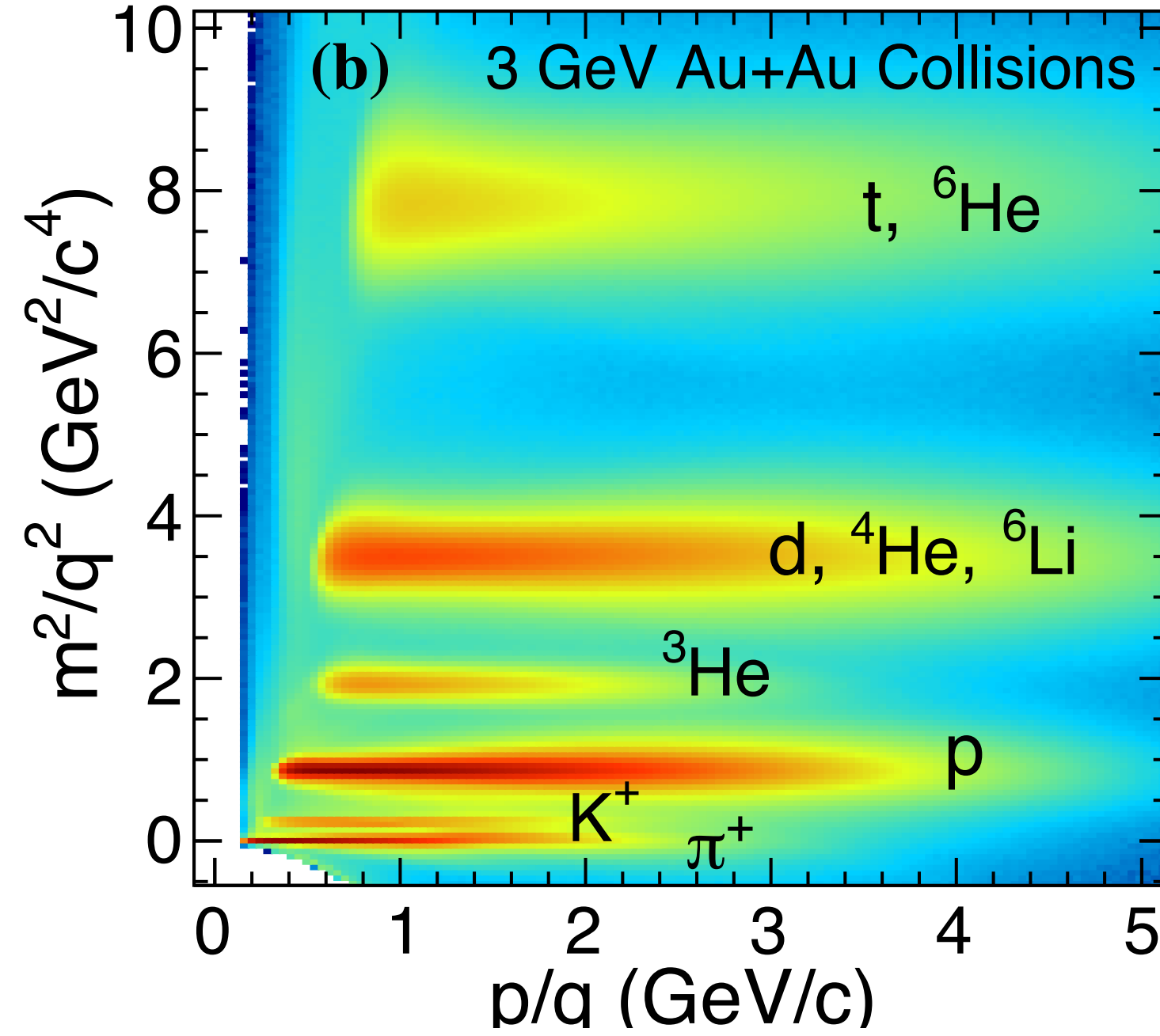
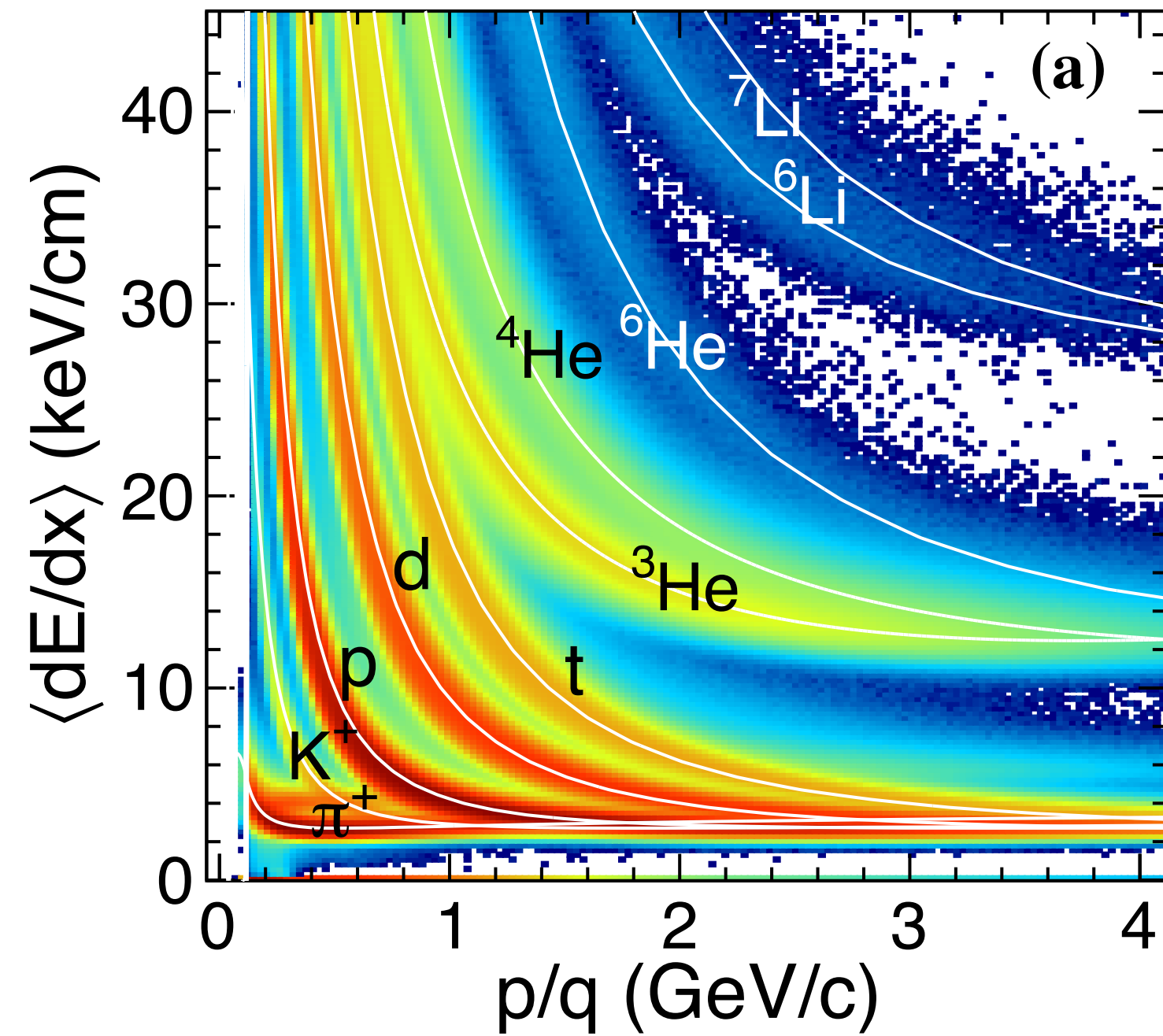
Schrödinger equation

*D. Mihaylov et al., EPJC 78 (2018), 5, 394*

Correlation Afterburner (CRAB): <https://web.pa.msu.edu/people/pratts/freecodes/crab/home.html>



# Particle identification and reconstruction



High purity particle selection:

- TPC and TOF/eTOF used for particle identification
- Strange hadron reconstructed via hadronic decay channels
- KFParticle package utilising information from error matrices applied to maximise significance

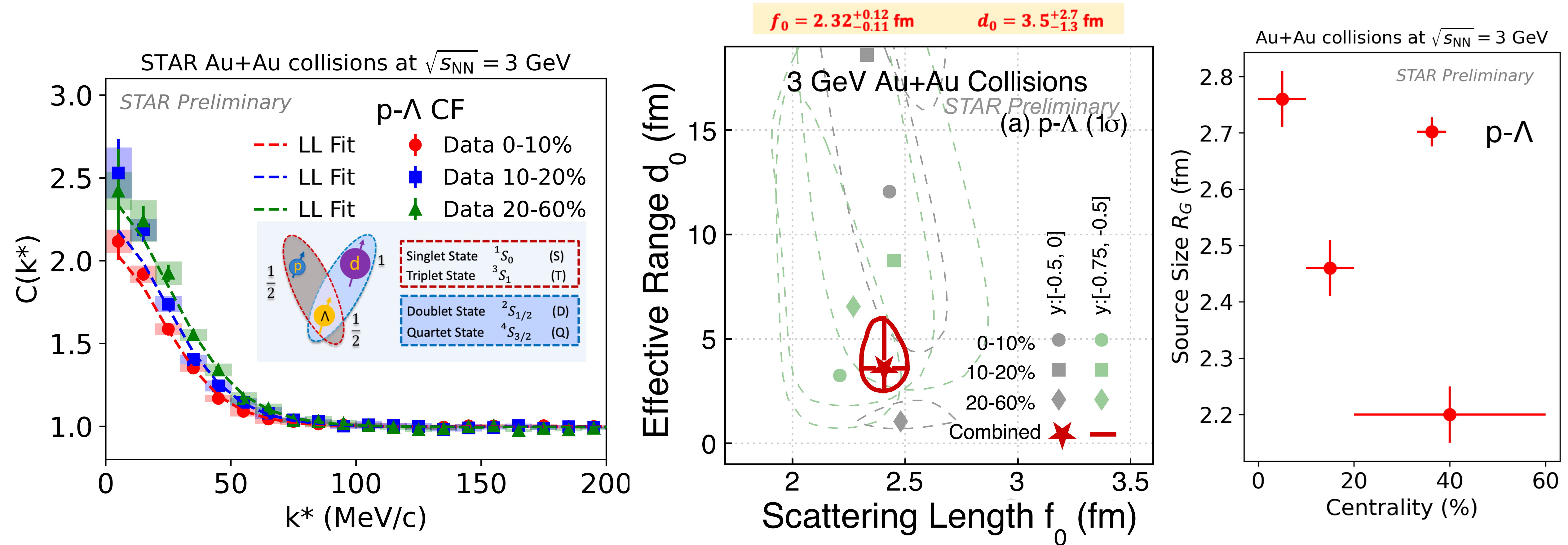
Proton purity: > 95 % for  $k^* < 200$  MeV/c

$\Lambda$  purity: ~ 93 % for  $k^* < 200$  MeV/c

$\Xi$  purity: ~ 95 % for  $k^* < 200$  MeV/c

# p- $\Lambda$ correlation function

Benchmark channel: validates source extraction and femtoscopy-to-potential comparison



- Simultaneously fit with L-L function for different centralities/rapidities
- $R_G$ , spin averaged scattering length( $f_0$ ), and effective range ( $d_0$ ) is extracted
- Centrality dependence of source size

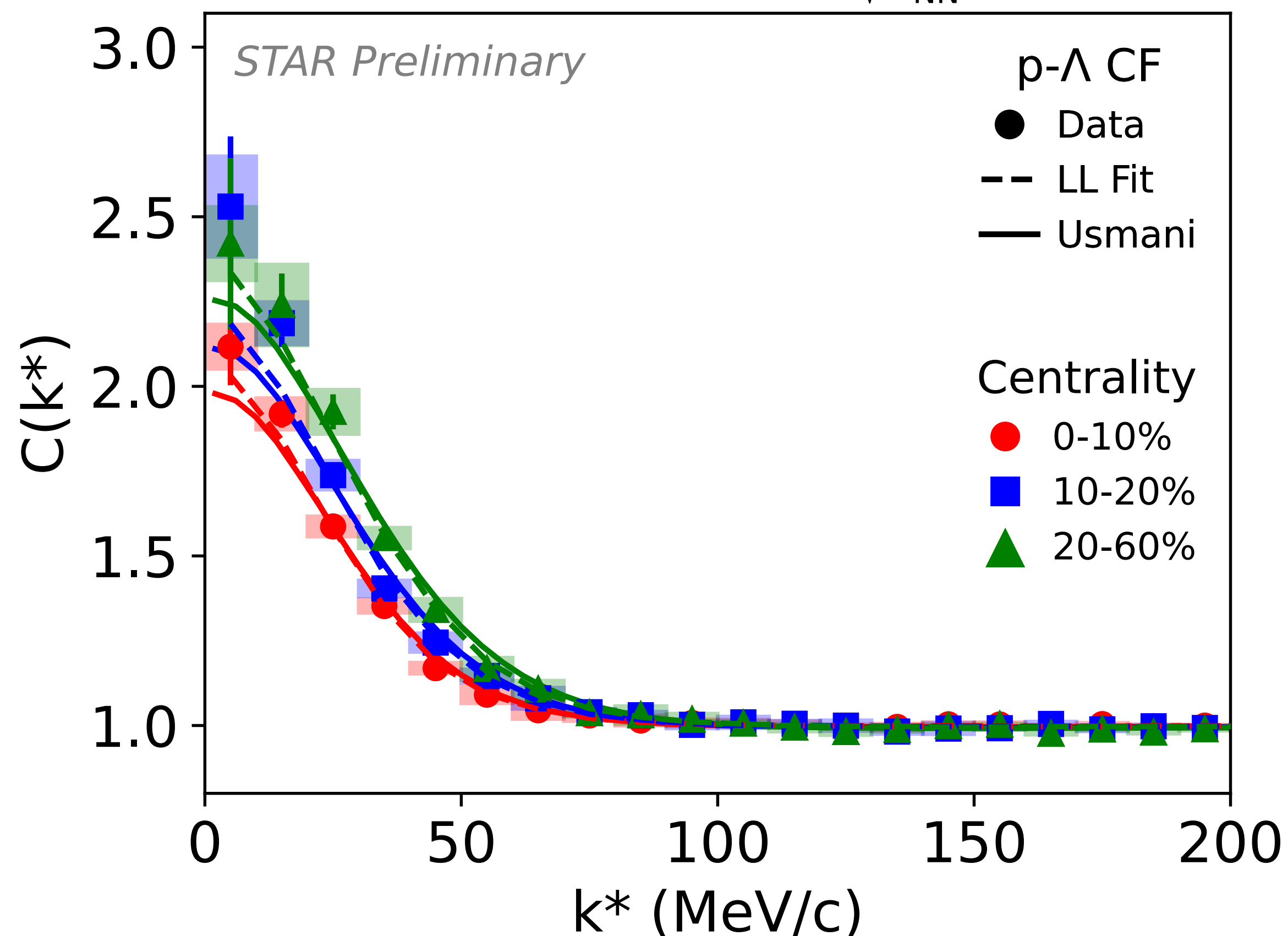
Limited sensitivity to spin channels  $\rightarrow$  spin-averaged fit

# p- $\Lambda$ correlation function

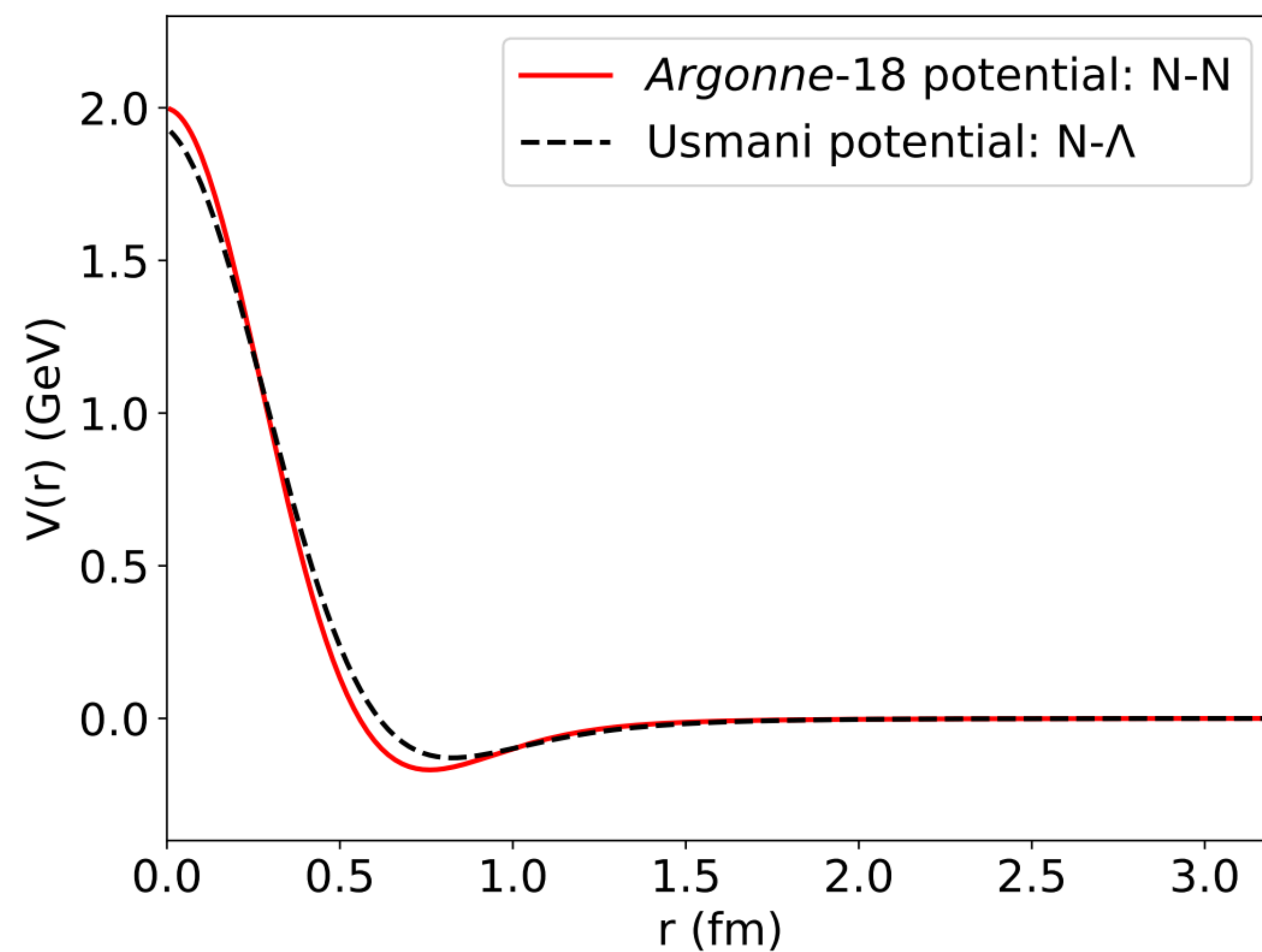
Benchmark channel: validates source extraction and femtoscopy-to-potential comparison

## Gaussian source + CRAB

STAR Au+Au collisions at  $\sqrt{s_{NN}} = 3$  GeV



An afterburner code, CRAB (v3.0b), is used to include femtoscopy effects

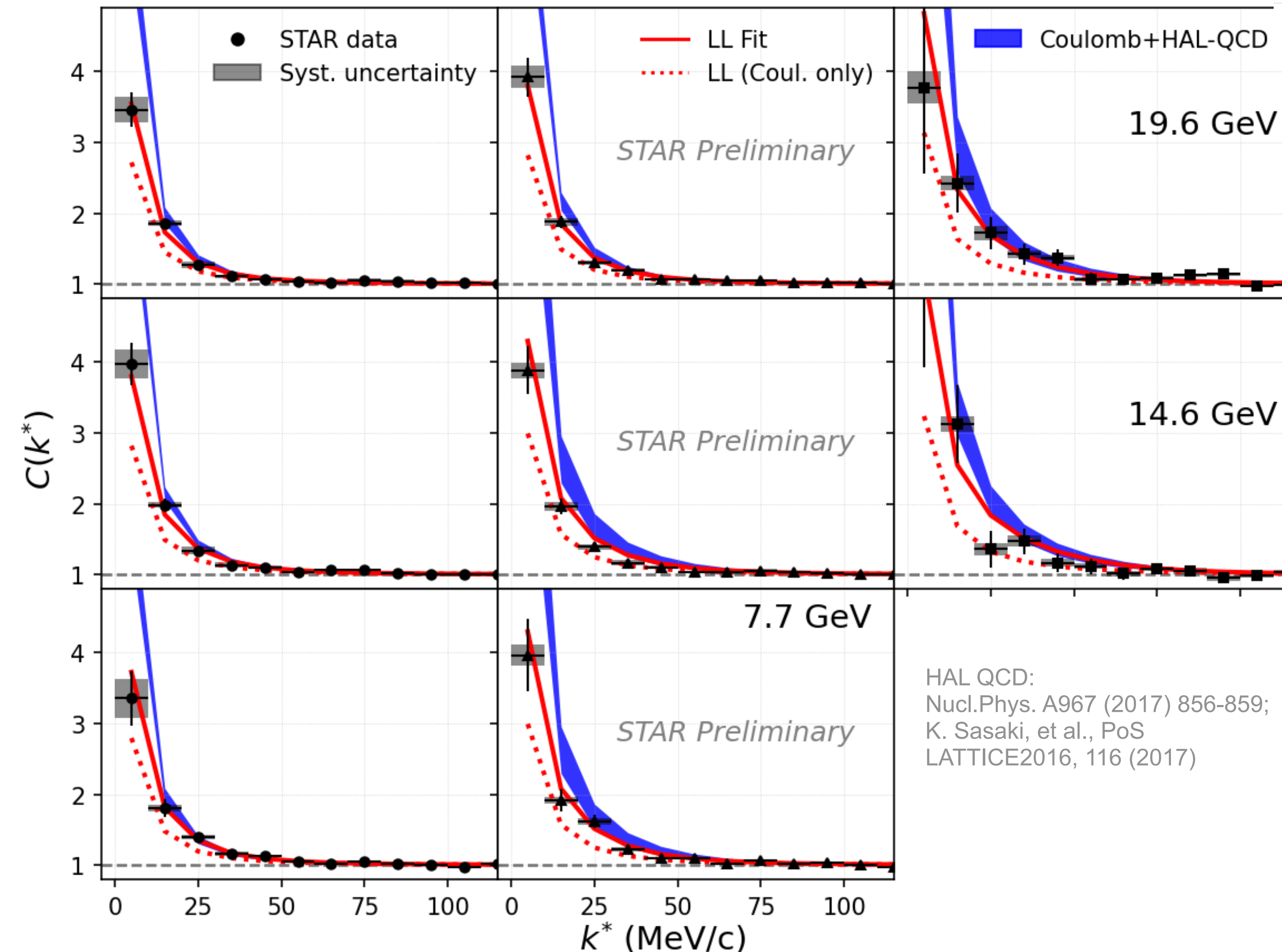


- Consistent with potential with attractive interactions

# $p$ - $\Xi^-$ correlation function

STAR Au+Au collisions 7.7, 14.6, 19.6 GeV  
0-10% 10-40% 40-80%

$$C(k^*) = \frac{1}{8}C_{I=0,S=0}(k^*) + \frac{3}{8}C_{I=0,S=1}(k^*) + \frac{1}{8}C_{I=1,S=0}(k^*) + \frac{3}{8}C_{I=1,S=1}(k^*)$$



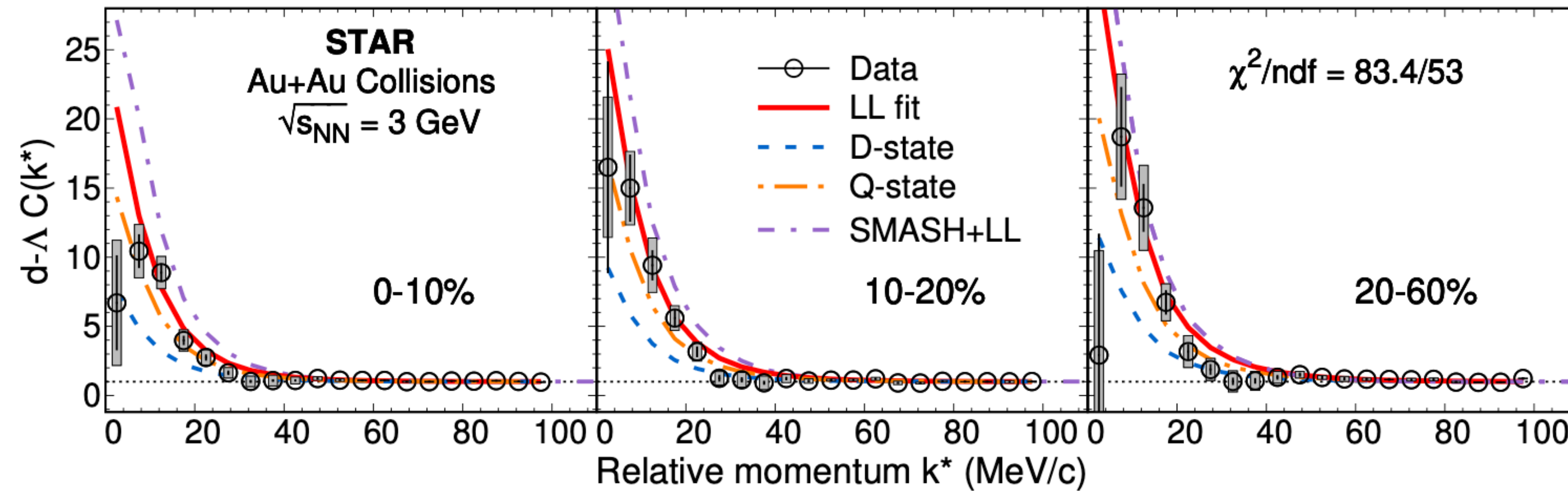
HAL QCD:  
Nucl.Phys. A967 (2017) 856-859;  
K. Sasaki, et al., PoS  
LATTICE2016, 116 (2017)

- Coupled-channel structure and limited sensitivity  $\rightarrow$  no spin-resolved extraction
- Evidence of an attractive strong interaction  
Coulomb-only calculation underestimates data
- Lattice calculations is slightly higher than data at low  $k^*$  ( $\sim 15\text{MeV}/c$ )

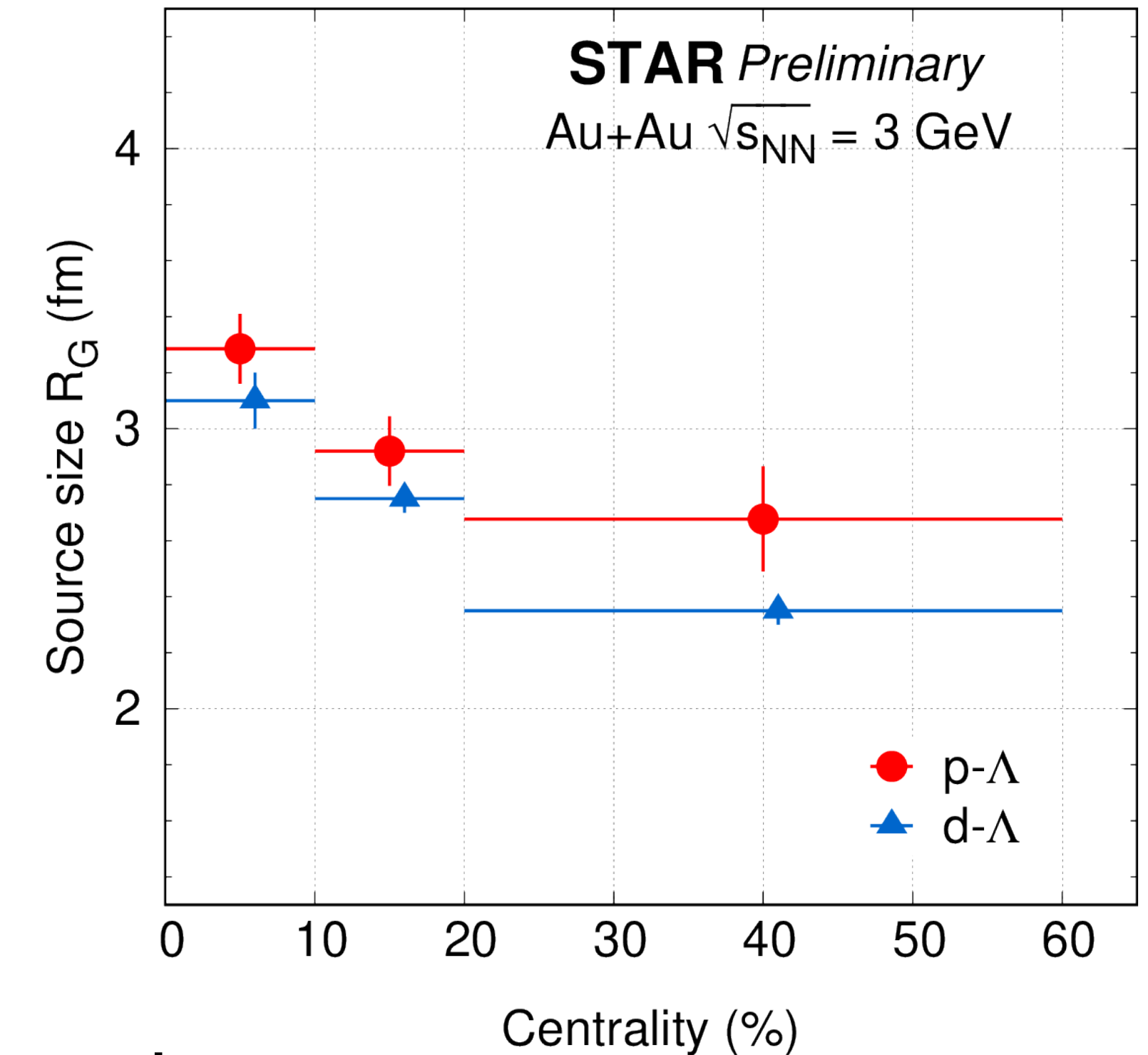
$\Xi N$  attraction providing input on possible  $\Xi$  onset in neutron stars

# d- $\Lambda$ correlation function

arXiv:2511.15493v1



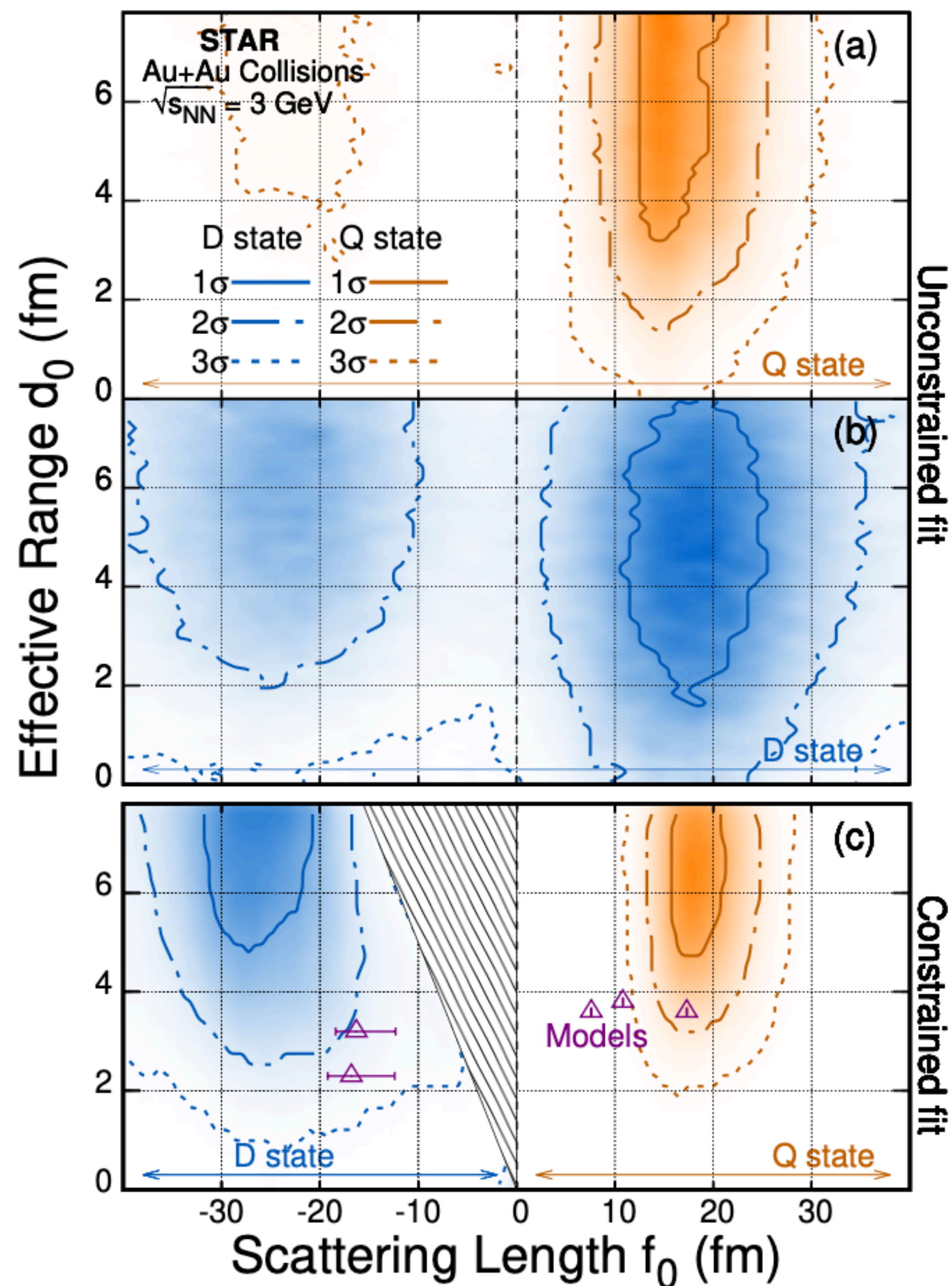
$$R_G(p-\Lambda) > R_G(d-\Lambda)$$



- Modelled as an effective two-body system using the LL approach
- Simultaneously fit across different centralities, separation of emission source from final state interaction
- $R_G(d-\Lambda)$  follow the expected centrality dependence and remain systematically smaller than those of  $R_G(p-\Lambda)$ , consistent with the expected source ordering for heavier pairs

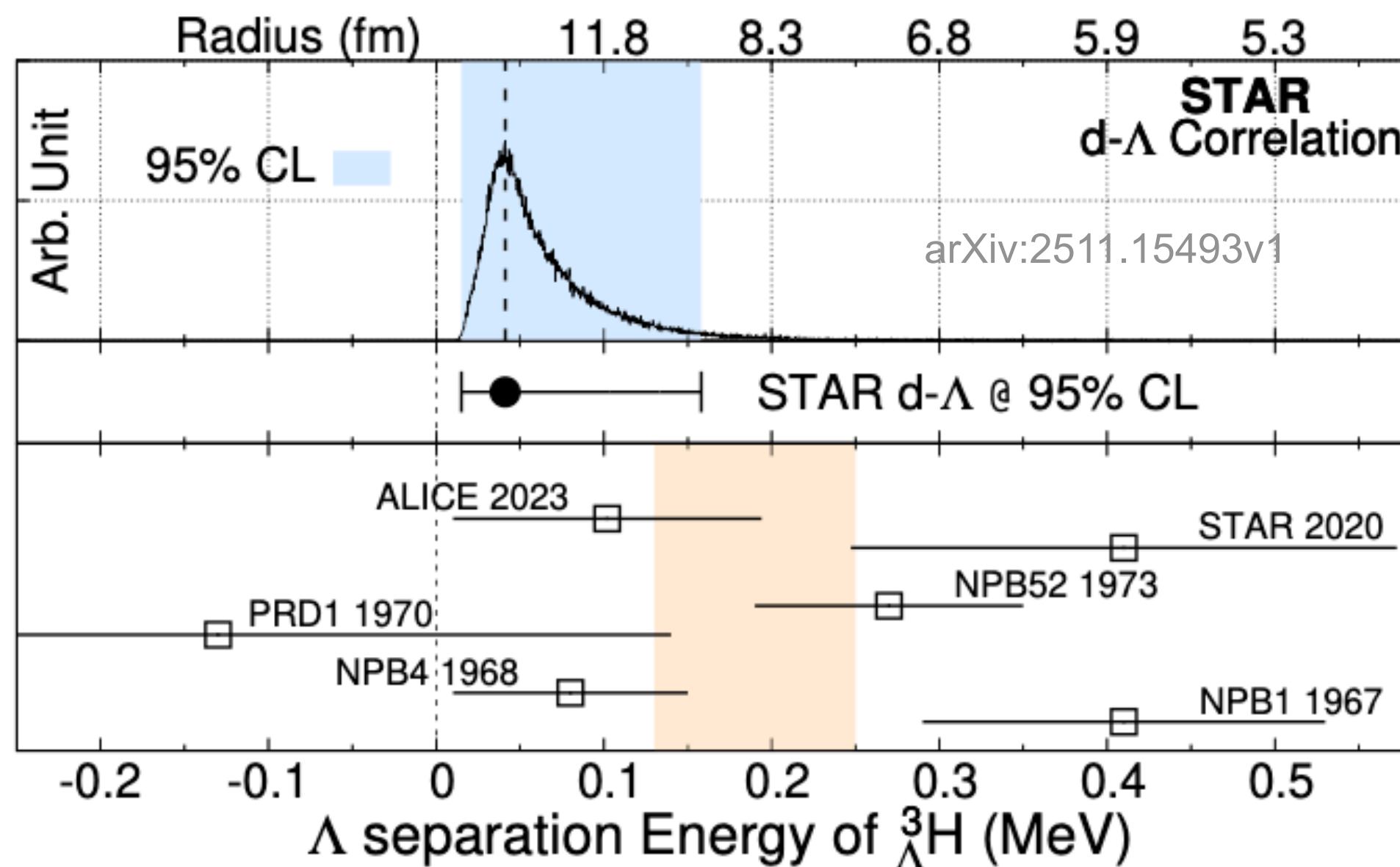
# Hypertriton $\Lambda$ separation energy

arXiv:2511.15493v1



$$|\psi(r, k)|^2 \rightarrow \frac{1}{3} |\psi_{1/2}(r, k)|^2 + \frac{2}{3} |\psi_{3/2}(r, k)|^2$$

$${}^3_{\Lambda}\text{H } B_{\Lambda} = 0.03^{+0.25}_{-0.02} \text{ (MeV) @ 95\% CL}$$



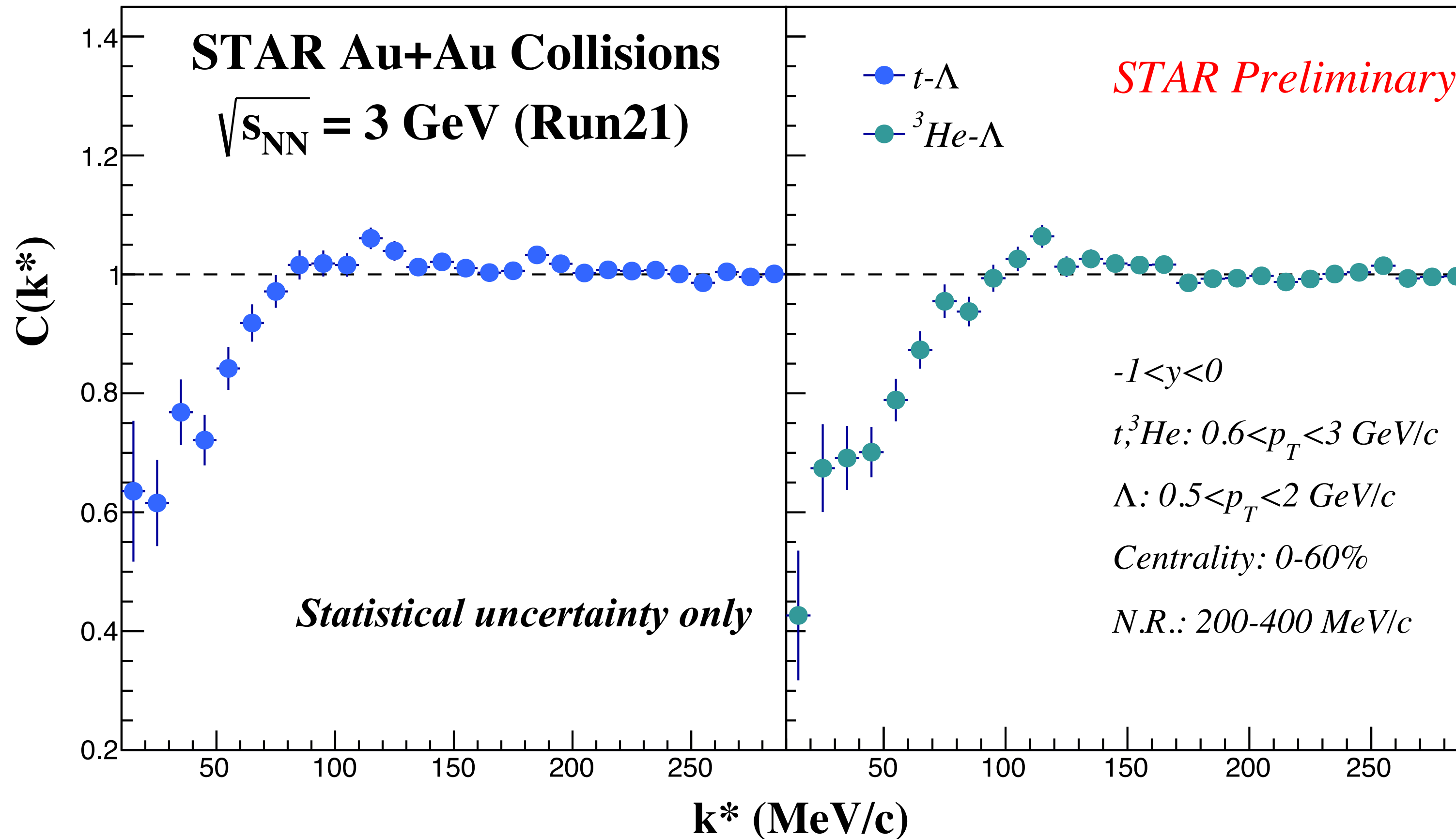
$$B_{\Lambda} = \frac{1}{2 \mu_{\Lambda d} d_0^2} \left( 1 - \sqrt{1 + \frac{2d_0}{f_0}} \right)^2$$

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

	Data
$f_0(\text{D})$ (fm)	$-26.1 \pm 5.6$
$d_0(\text{D})$ (fm)	8 (at fit limit)
$f_0(\text{Q})$ (fm)	$18.7 \pm 2.8$
$d_0(\text{Q})$ (fm)	$6.5 \pm 1.8$

- For the first time, spin dependent states, *D* and *Q*, identified experimentally!
- A new way to constrain the  ${}^3_{\Lambda}\text{H}$  binding energy  
A complementary few-body benchmark to direct hypernuclear measurements
- Future: model with 3-body calculations, study three-body force effects

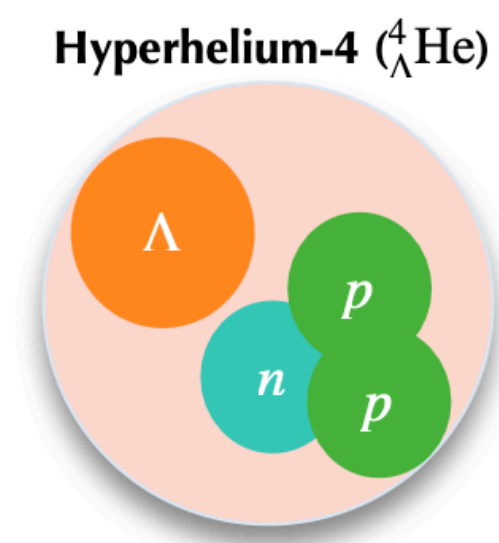
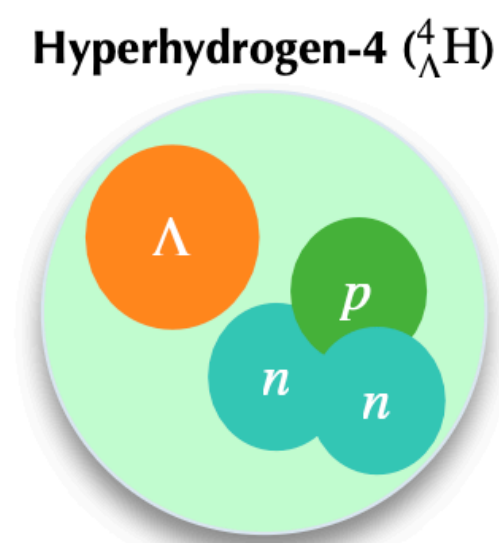
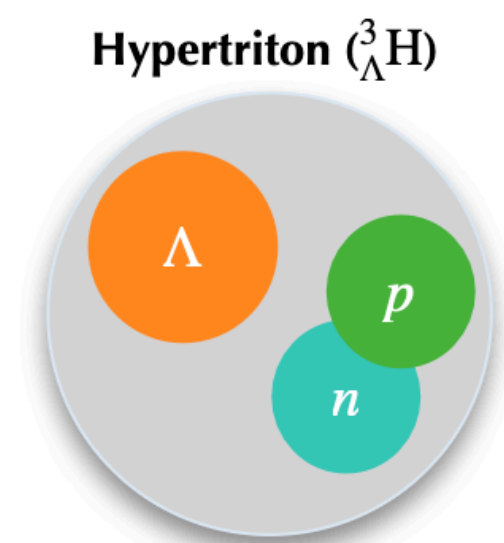
# t- $\Lambda$ and $^3\text{He}$ - $\Lambda$ correlation function



- First  $t/{}^3\text{He}$ - $\Lambda$  correlation function measurements in HIC

$t$ - $\Lambda$  and  ${}^3\text{He}$ - $\Lambda$  exhibit similar correlation structures

- Extend the few-body map beyond the hypertriton and may provide access to denser hypernuclear systems



# Summary and outlook

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STAR measures baryon correlations in the strange sector at high baryon density

1.  $p-\Xi^-$  data support an attractive  $\Xi N$  interaction, but favour a weaker attraction than the HAL-QCD prediction in the low- $k^*$  region
2.  $d-\Lambda$  correlation measurement provides spin-dependent  $d-\Lambda$  scattering constraints and the first femtoscopy-based estimate of the hypertriton separation energy

➡ These results provide experimental input on two-body and few-body hyperon interactions relevant to neutron-star matter

◆ Improved precision and explicit many-body theory are needed to quantify their impact on the hyperon puzzle