



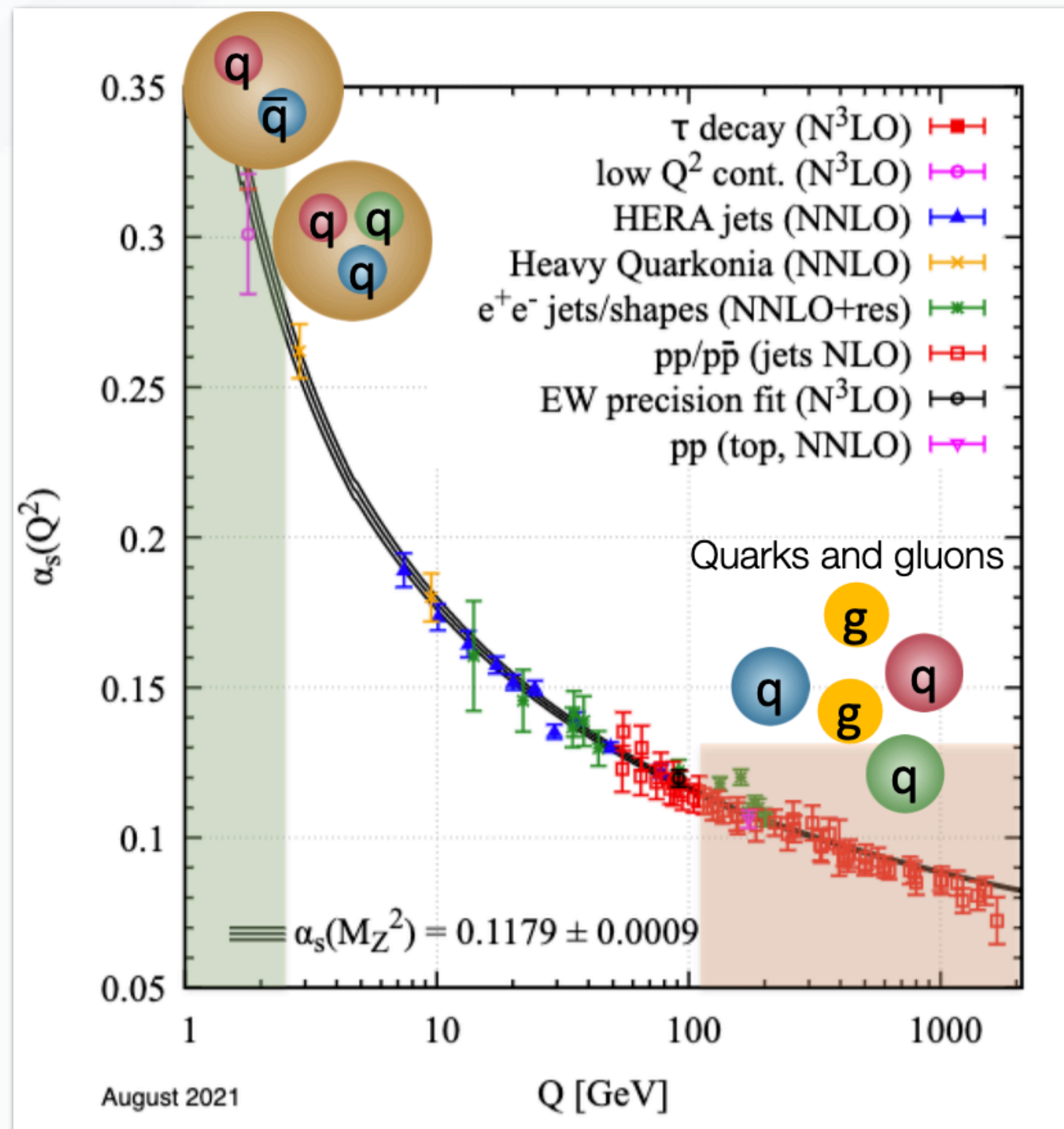
Femtoscopy Measurements to Understand **Baryon Interactions** in Heavy-ion Collisions

Ke Mi (米柯)

University of Chinese Academy of Sciences (UCAS)

2026-01-07 @ UCAS

Strong interaction between hadrons... from fm to km

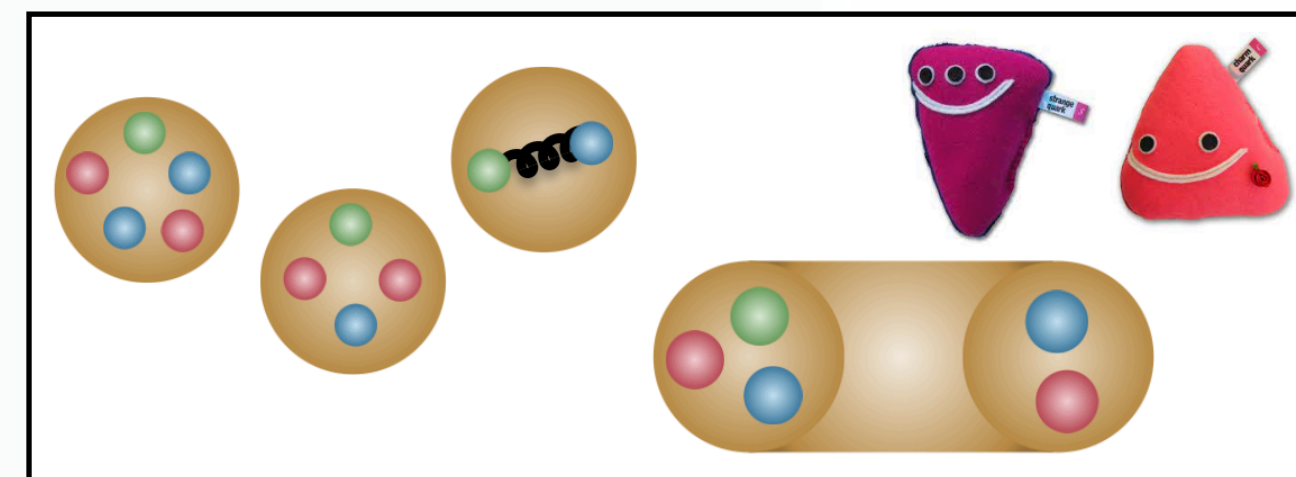


Understanding how QCD evolves from high- to low-energy regime

How do hadrons emerge?

How is the QCD spectrum organized?

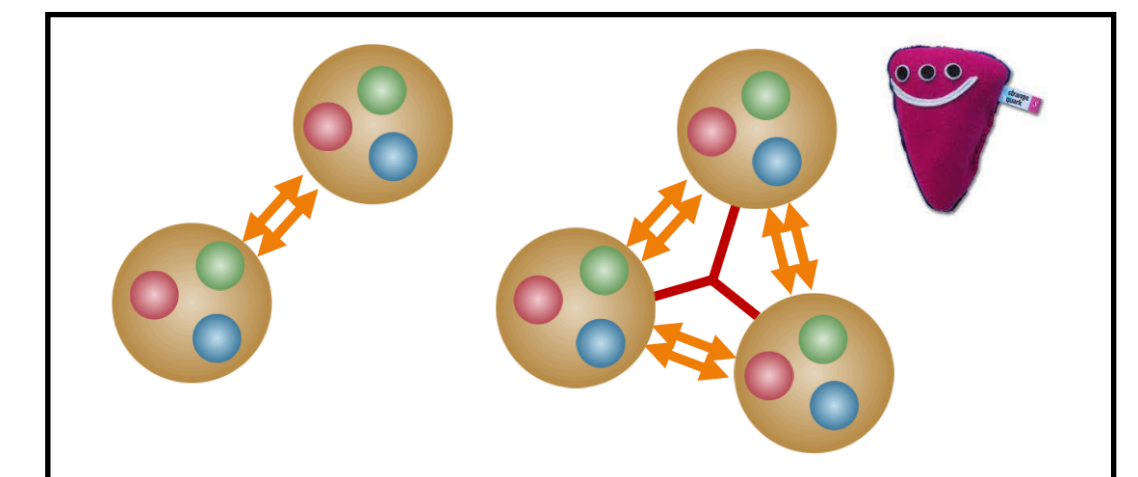
Bound states / resonances



Searches for exotic states

How do hadrons interact?

2-body and many-body interactions

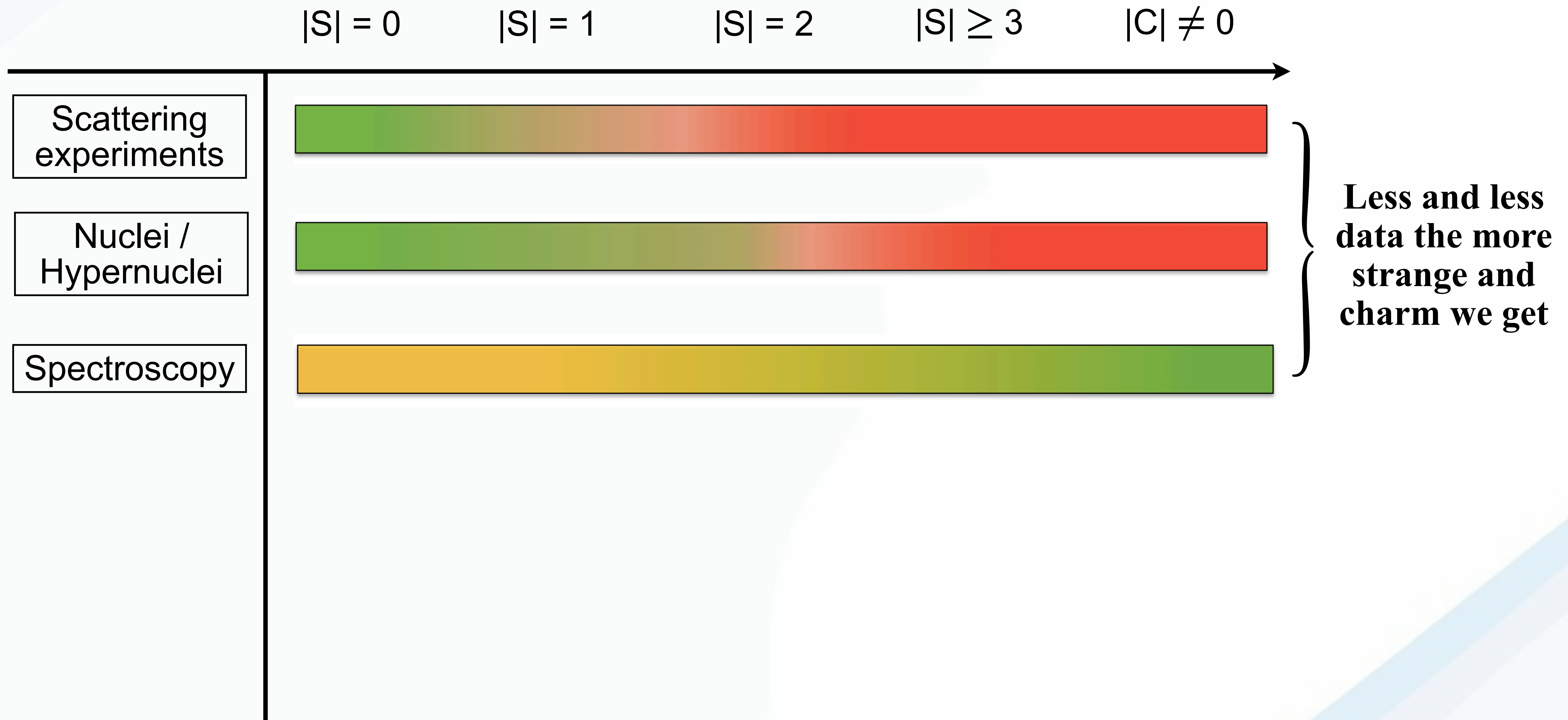


Physics of neutron stars

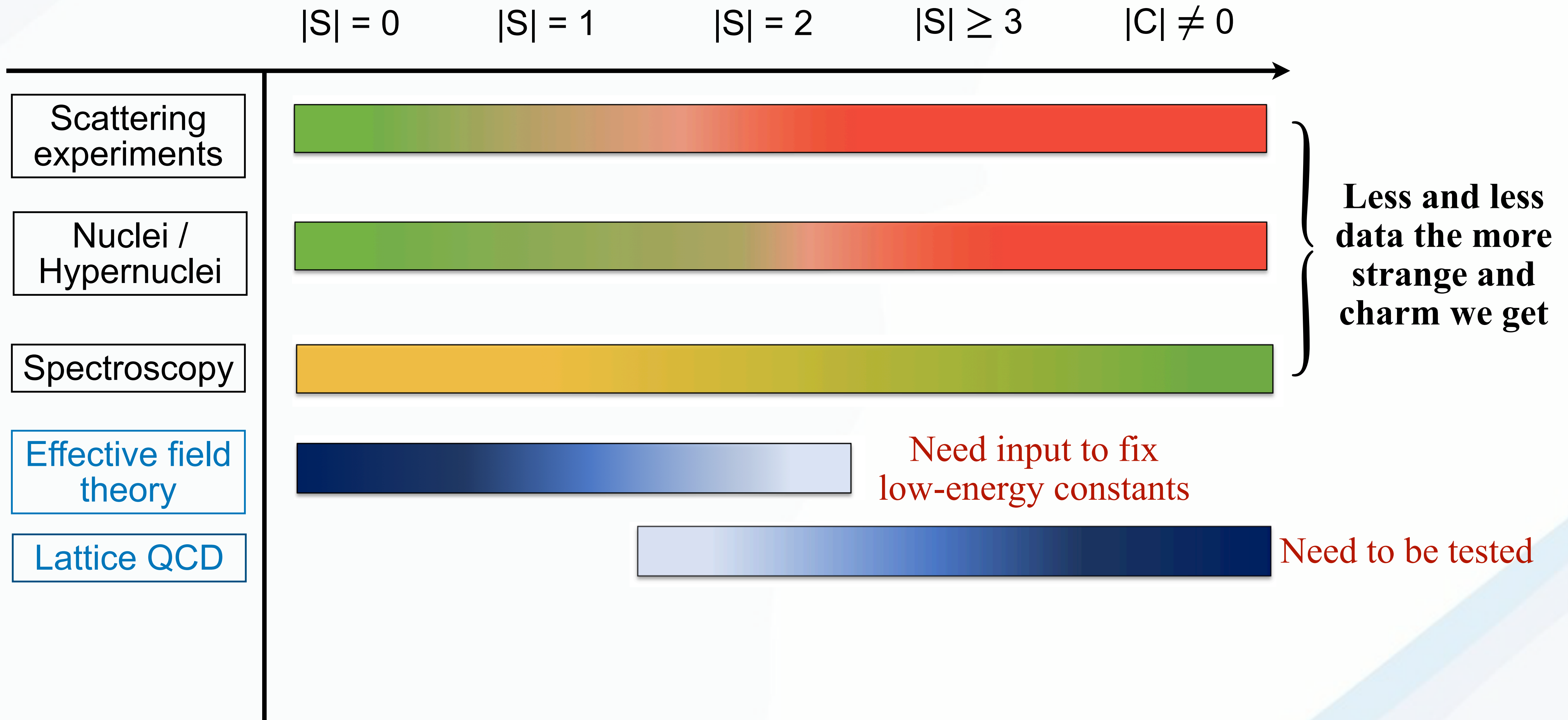
Experimental data are needed.

PDG, Prog.Theor.Exp.Phys 2022, 083C01(2022)

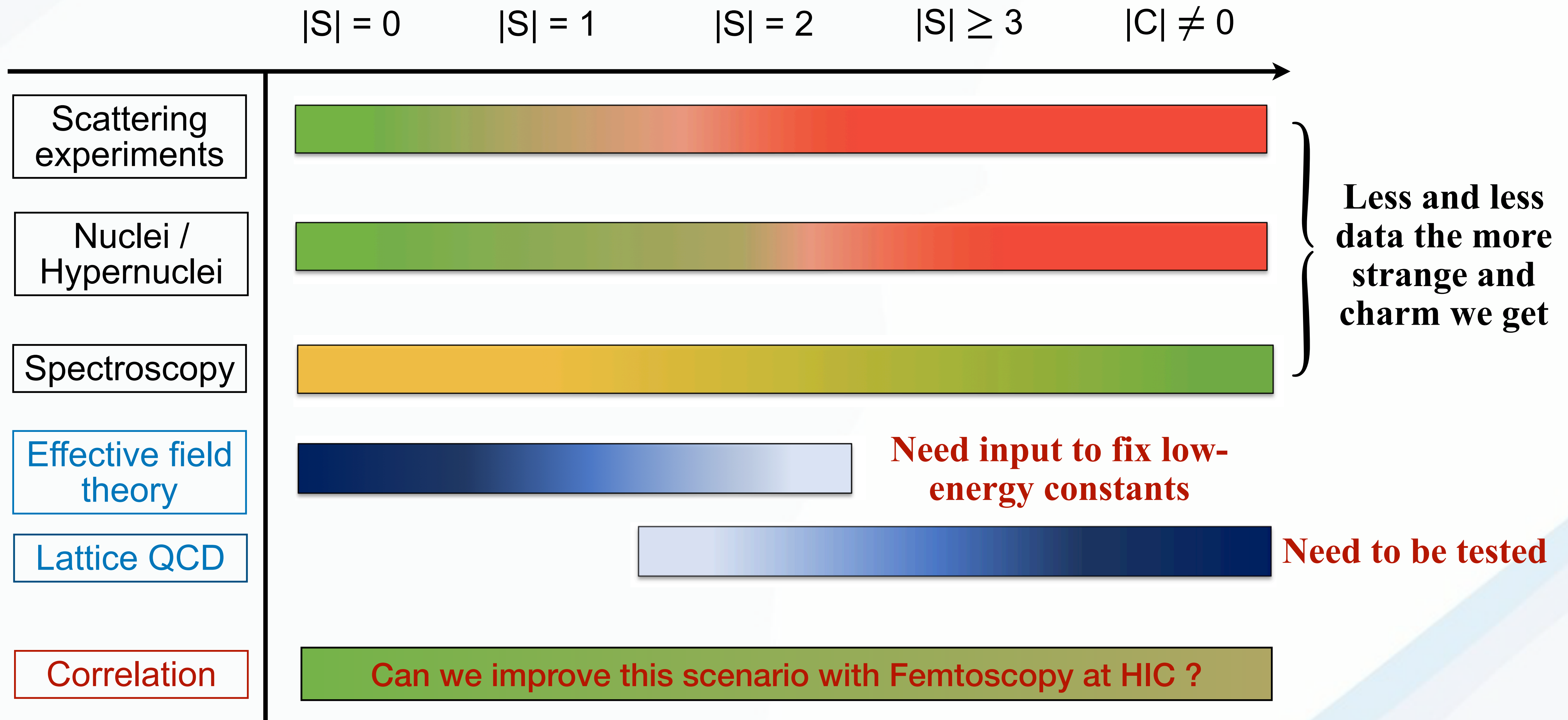
Understanding and measuring the hadronic interactions



Understanding and measuring the hadronic interactions

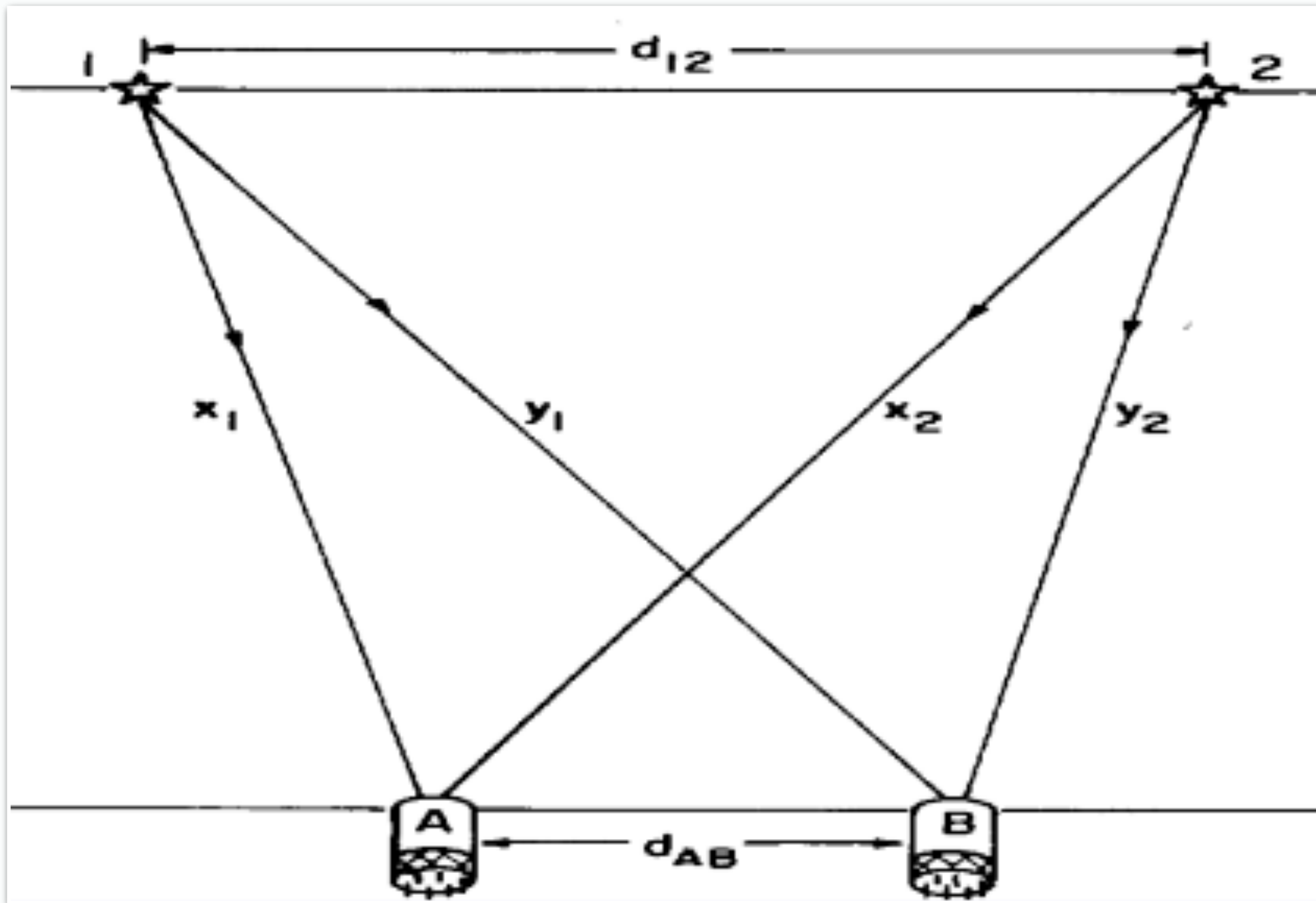


Understanding and measuring the hadronic interactions



From HBT to Femtoscopy

HBT: Robert Hanbury Brown - Richard Quentin Twiss



- HBT in astronomy measures the spatial extent of stars using intensity correlations of **photons**, rather than phase interference
- The loss of correlation with increasing telescope separation is used to determine the stellar size

- $\Delta L = (x_1 + y_2) - (x_2 + y_1) \approx \frac{d_{AB} \cdot d_{12}}{R}, \Delta\phi = \frac{2\pi}{\lambda} \Delta L$

- $g(A, B) = \frac{\langle I_1(t) I_2(t) \rangle}{\langle I_1(t) \rangle \langle I_2(t) \rangle}$

- $g(A, B) = 1 + |\gamma(d_{AB})|^2$, γ : fourier transform of the stellar brightness distribution

From HBT to Femtoscopy

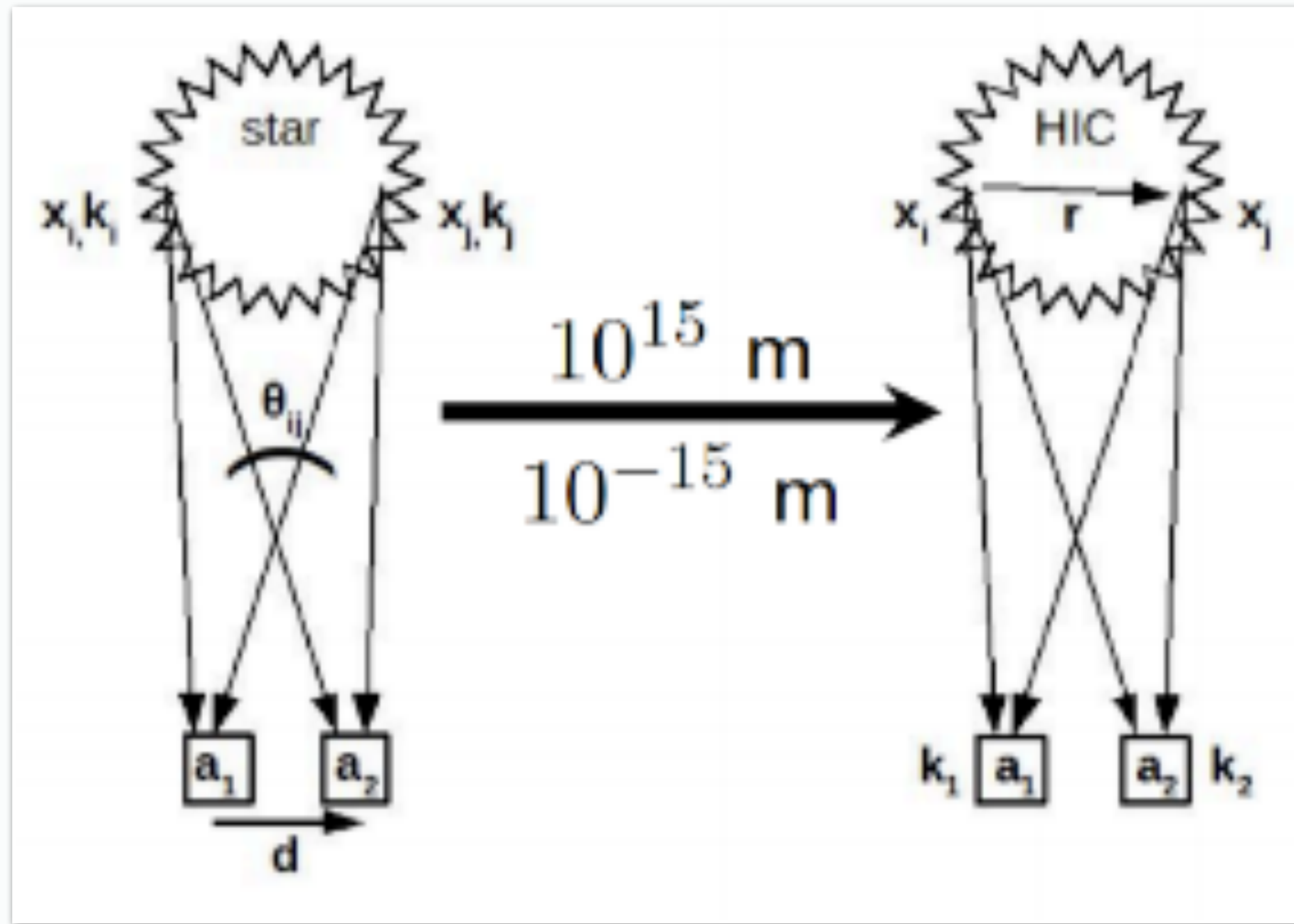
HBT in HIC

- Replace photons with identical mesons (e.g., π , K)
- Replace $d_{AB} \rightarrow r$; $d_{12} \rightarrow k^*$
- Measure two-particle correlation function

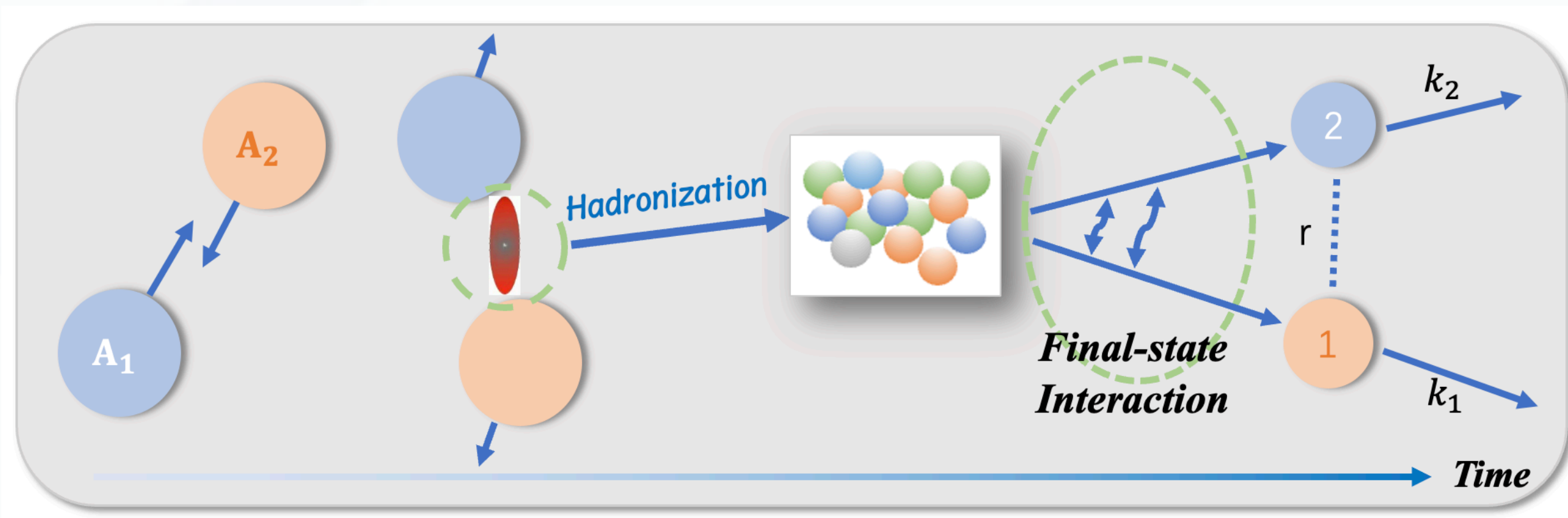
$$C(\mathbf{q}) = 1 + \lambda \left| \int d^3r S(\mathbf{r}) e^{i\mathbf{q} \cdot \mathbf{r}} \right|^2$$

Femtoscopy in HIC

- Not limited to identical mesons $\rightarrow$ use ANY particle pairs
- Include final-state interactions
 - Coulomb
 - Strong interactions

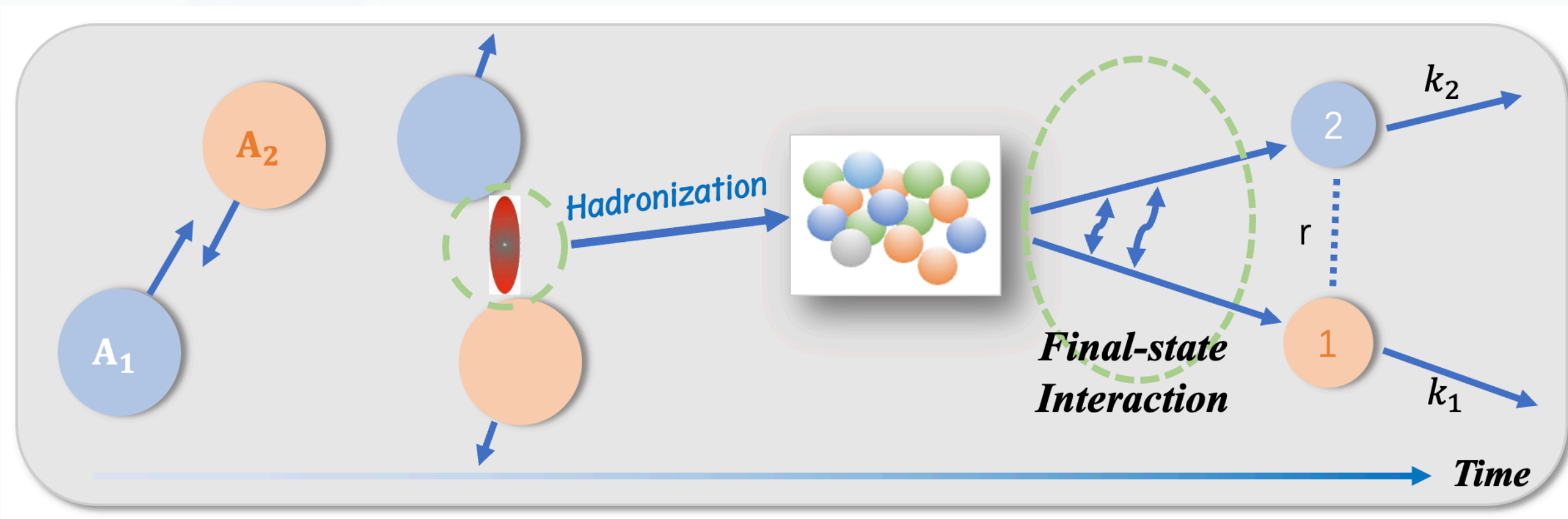


Femtoscscopy & Correlation Function



M.Lisa, S.Pratt et al, ARNPS, 55(2005), 357-402
 L. Fabbietti et al, Ann. Rev. Nucl. Part. Sci. 71 (2021)
 Lednicky Sov. J. Nucl. Phys. 35 (1982) 770
 ALICE Coll. Nature 588 (2020) 232-238
 S.E.Koonin, Phys. Lett. B 70, 43(1977)

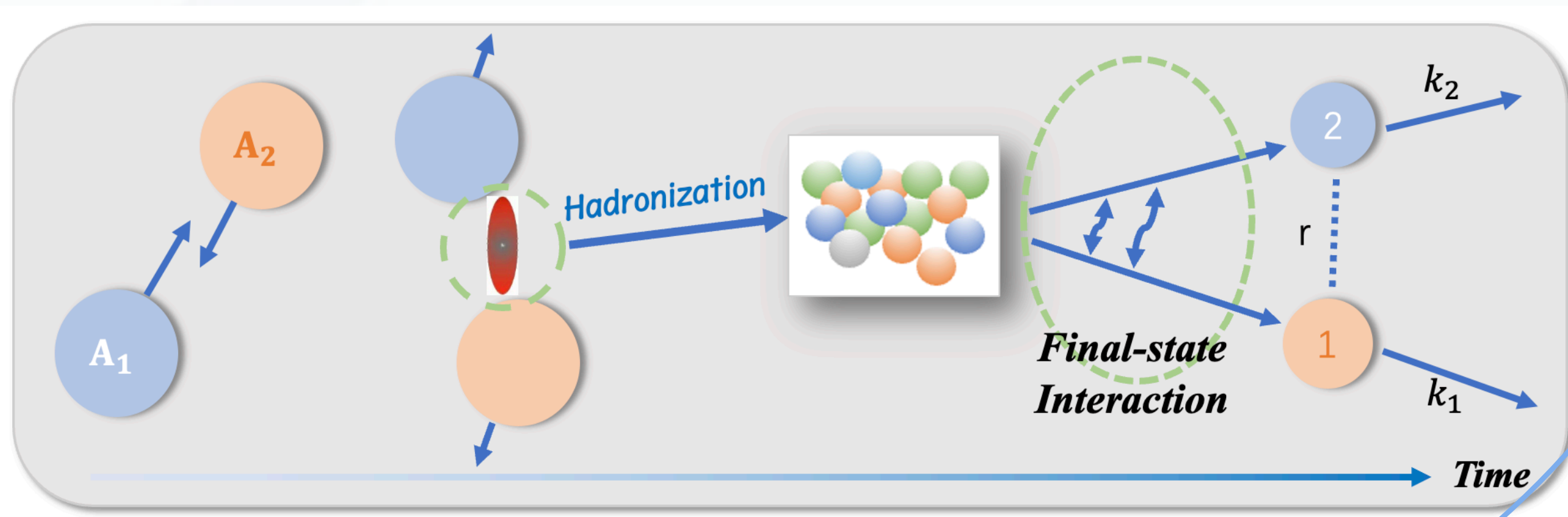
Femtoscscopy & Correlation Function



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

M.Lisa, S.Pratt et al, ARNPS, 55(2005), 357-402
 L. Fabbietti et al, Ann. Rev. Nucl. Part. Sci. 71 (2021)
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Femtoscscopy & Correlation Function



Koonin-Pratt Equation

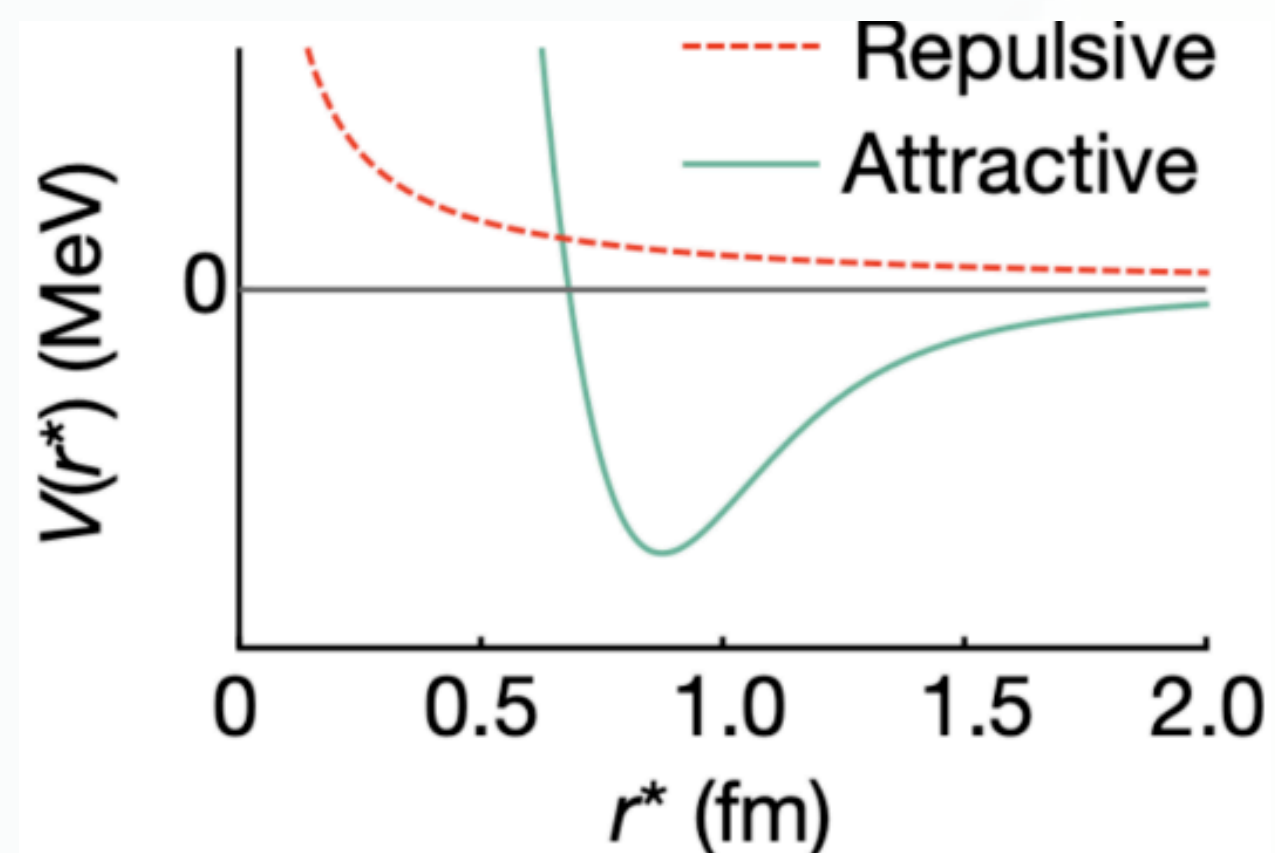
$$C(k^*) = \int S(\vec{r}^*) |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3\vec{r}^*$$

k^* : relative momentum in PRF
 r^* : relative distance in PRF

Emitting Source

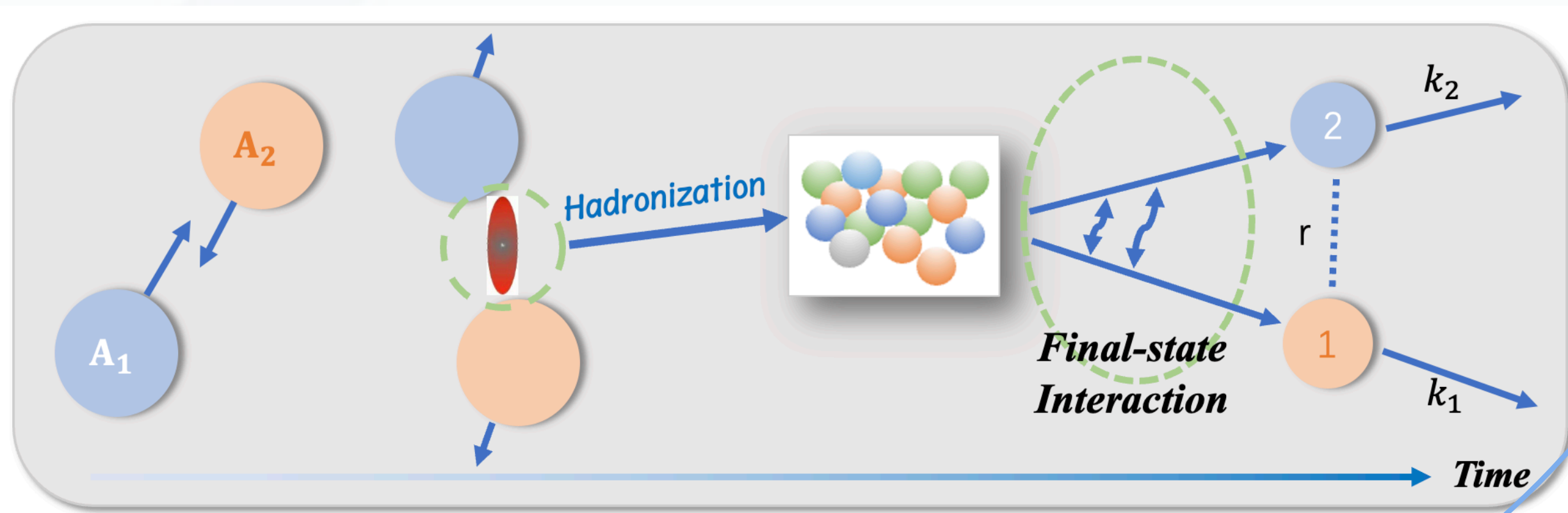
- Average relative r_{AB}^* distances at which particles are produced
- Depends on the collision dynamics

Interaction



M.Lisa, S.Pratt et al, ARNPS, 55(2005), 357-402
 L. Fabbietti et al, Ann. Rev. Nucl. Part. Sci. 71 (2021)
 Lednicky Sov. J. Nucl. Phys. 35 (1982) 770
 ALICE Coll. Nature 588 (2020) 232-238
 S.E.Koonin, Phys. Lett. B 70, 43(1977)

Femtoscopy & Correlation Function



Koonin-Pratt Equation

$$C(k^*) = \int S(\vec{r}^*) |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3\vec{r}^* = \mathcal{N} \frac{A_{\text{same}}(k^*)}{B_{\text{mixed}}(k^*)}$$

k^* : relative momentum in PRF
 r^* : relative distance in PRF

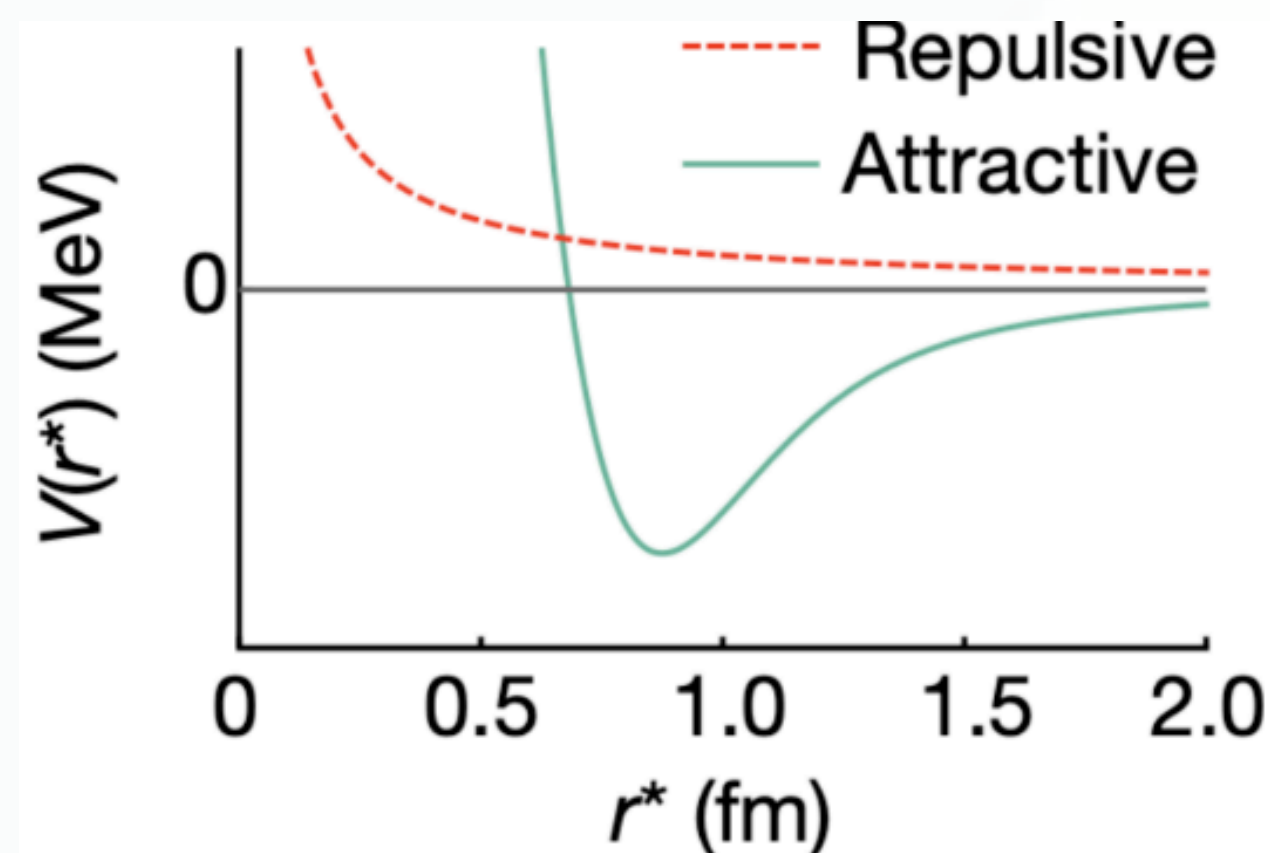
$\mathcal{N}$: normalization factor

Emitting Source

- Average relative r_{AB}^* distances at which particles are produced
- Depends on the collision dynamics

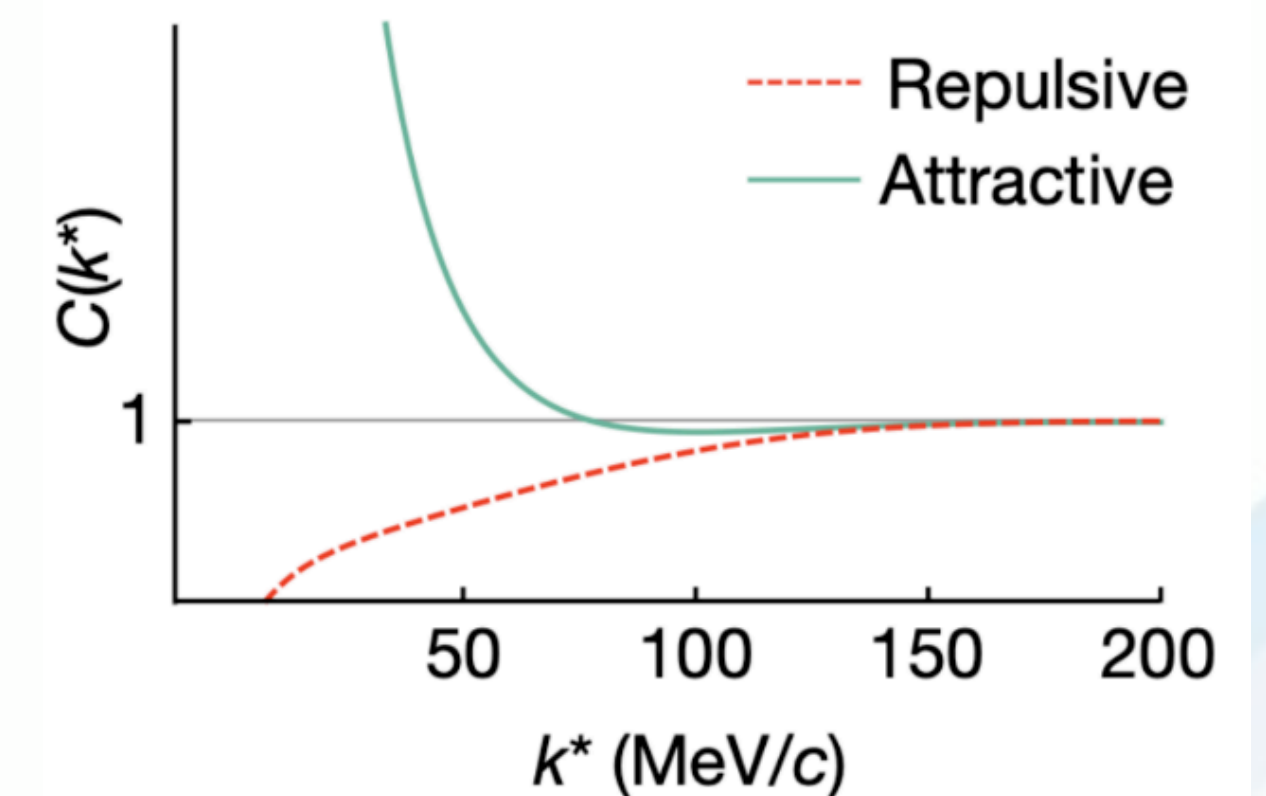


Interaction



=

Correlation Function



M.Lisa, S.Pratt et al, ARNPS, 55(2005), 357-402
 L. Fabbietti et al, Ann. Rev. Nucl. Part. Sci. 71 (2021)
 Lednicky Sov. J. Nucl. Phys. 35 (1982) 770
 ALICE Coll. Nature 588 (2020) 232-238
 S.E.Koonin, Phys. Lett. B 70, 43(1977)

Lednický-Lyuboshitz Approach

$$C_{theory}(k^*) = \int S(\vec{r}^*) |\Psi(\vec{k}^*, \vec{r}^*)|^2 d^3\vec{r}^*$$

○ Assumptions:

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

○ Scattering amplitude:

Notation change:
 $-a \rightarrow f_0; r_0 \rightarrow d_0$

W/O Coulomb:

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - ik^* \right]^{-1}$$

W/ Coulomb:

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta) \right]^{-1}$$

Physics Parameters:

R_G : Spherical Gaussian source

f_0 : Scattering length

d_0 : Effective range

Lednický-Lyuboshitz Approach

$$C_{theory}(k^*) = \int S(\vec{r}^*) |\Psi(\vec{k}^*, \vec{r}^*)|^2 d^3\vec{r}^*$$

Assumptions:

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Physics Parameters:

R_G : Spherical Gaussian source

f_0 : Scattering length

d_0 : Effective range

Sign

$f_0 > 0$: Attractive interaction

$f_0 < 0$: Repulsive interaction/ Bound state

(distinguished by the relation between f_0 and d_0)

In the past



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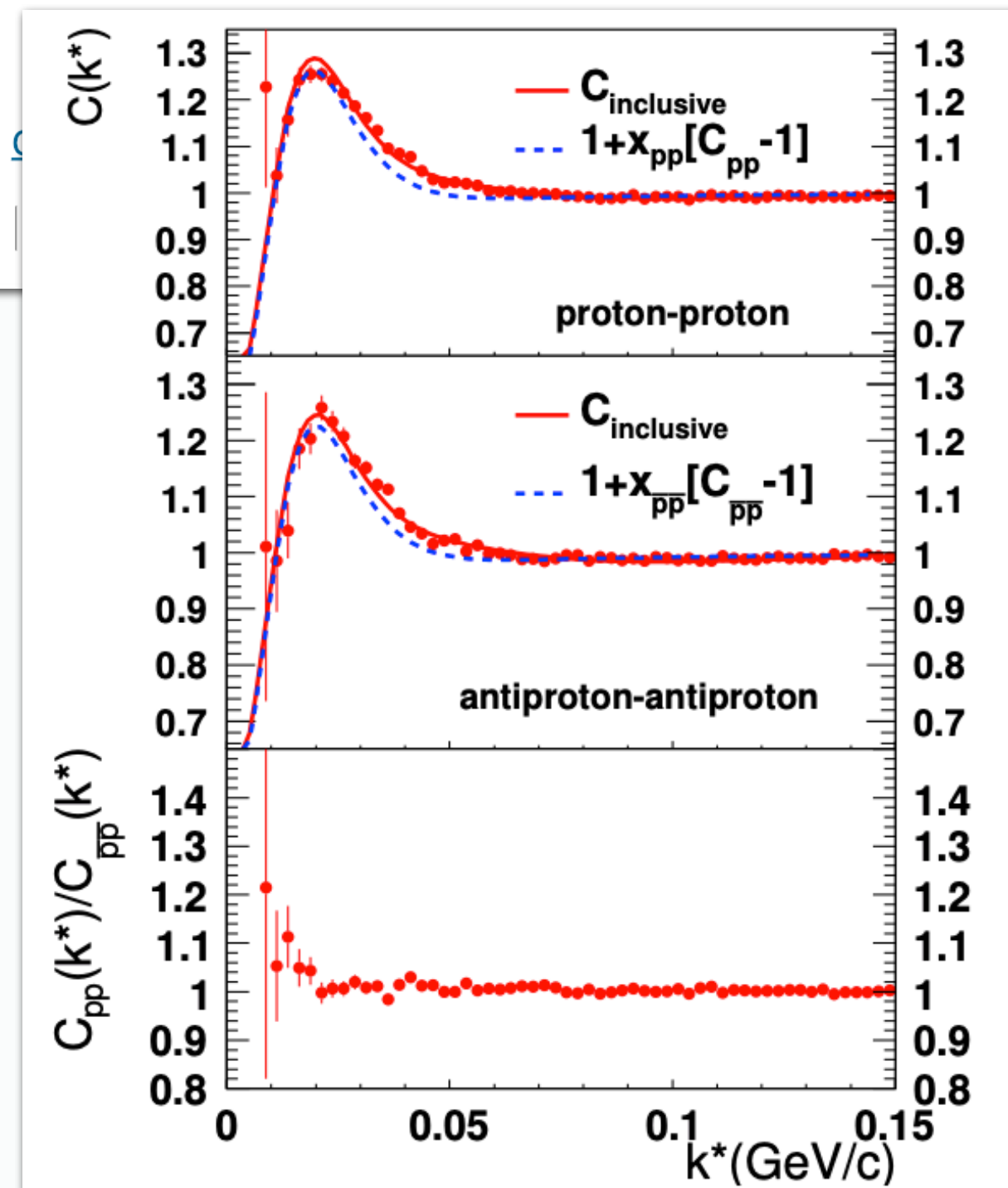
Letter | Published: 04 November 2015

Measurement of interaction between antiprotons

[The STAR Collaboration](#)

[Nature](#) 527, 345–348 (2015) | [DOI](#)

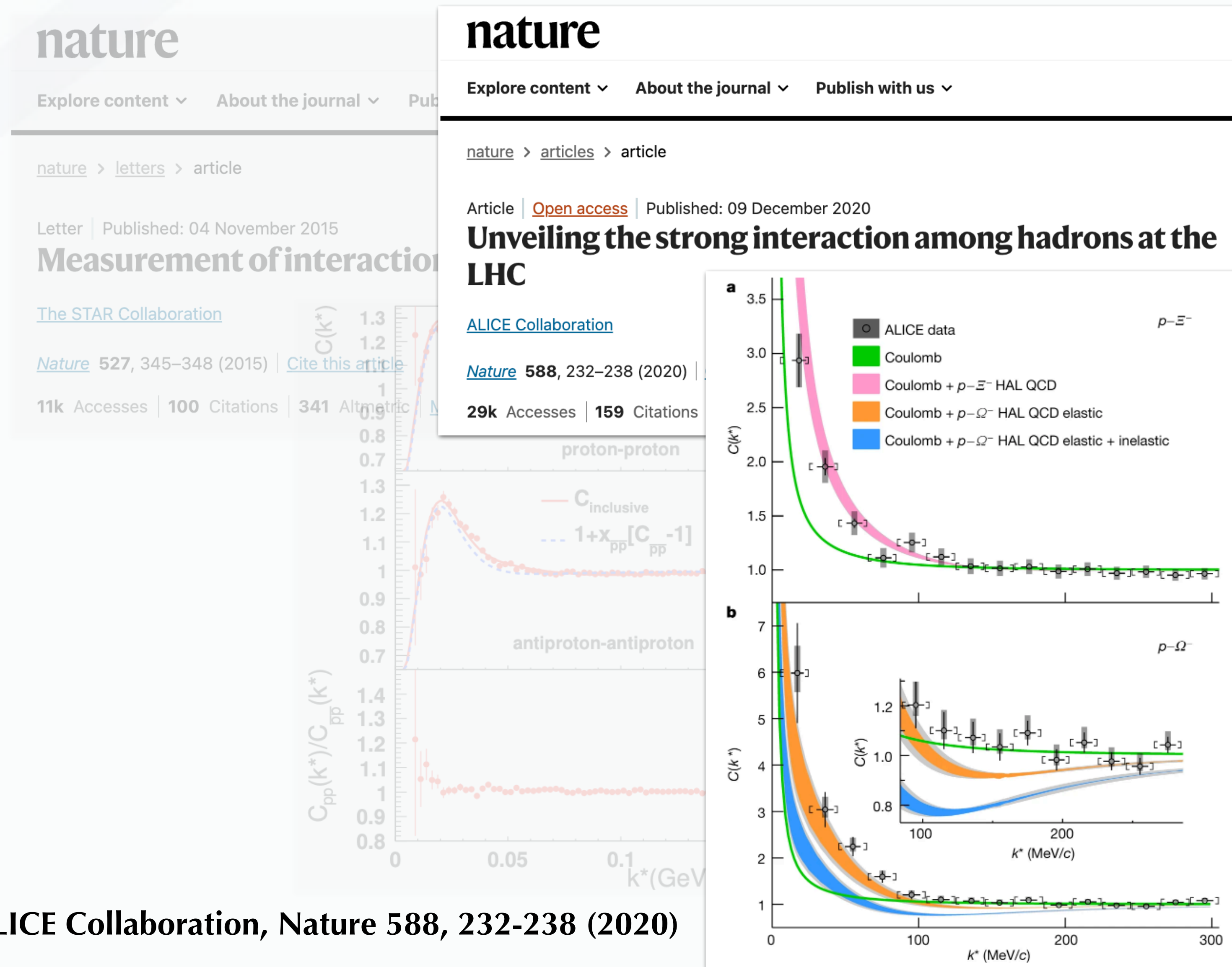
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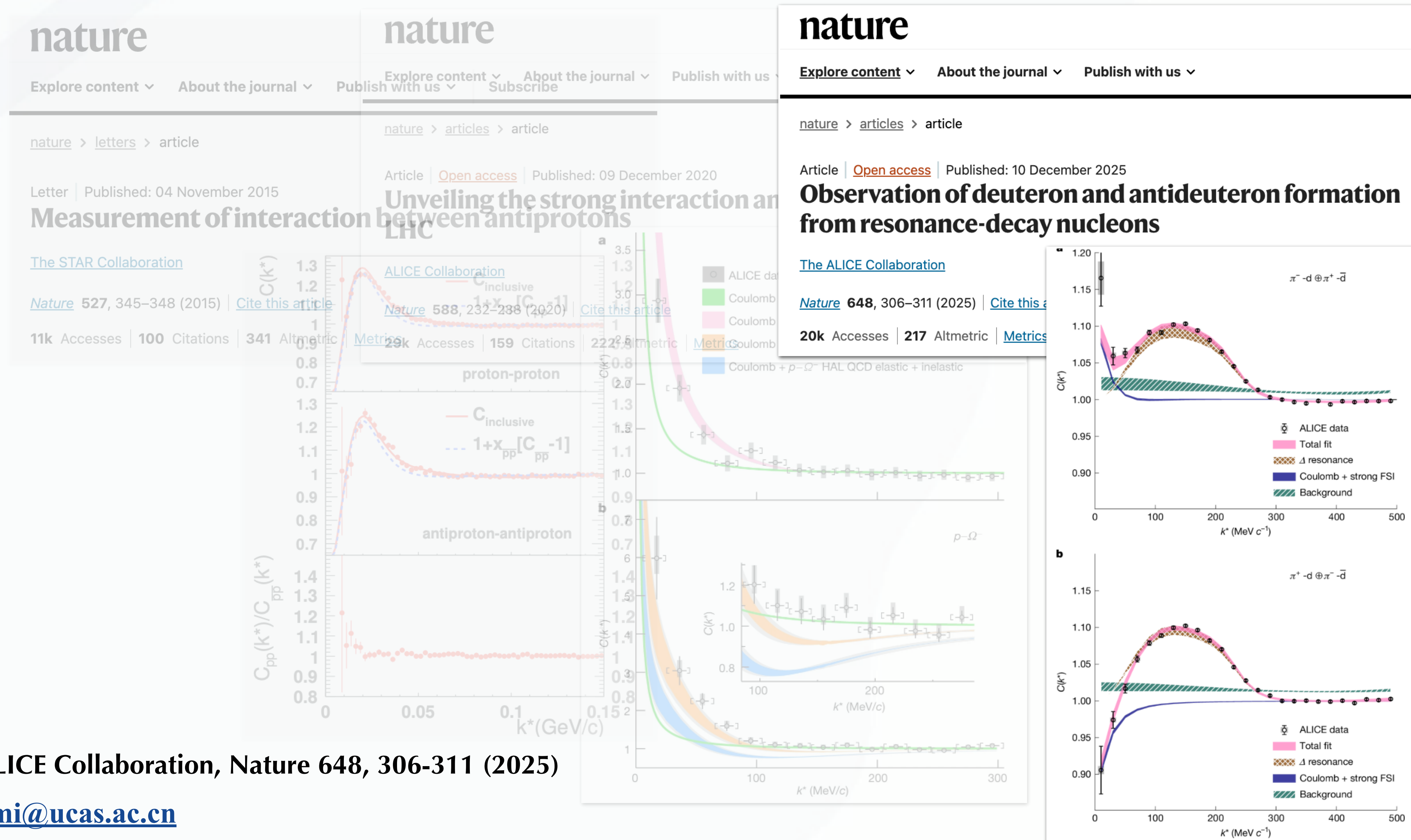
STAR Collaboration, Nature 527, 345-348

kmi@ucas.ac.cn

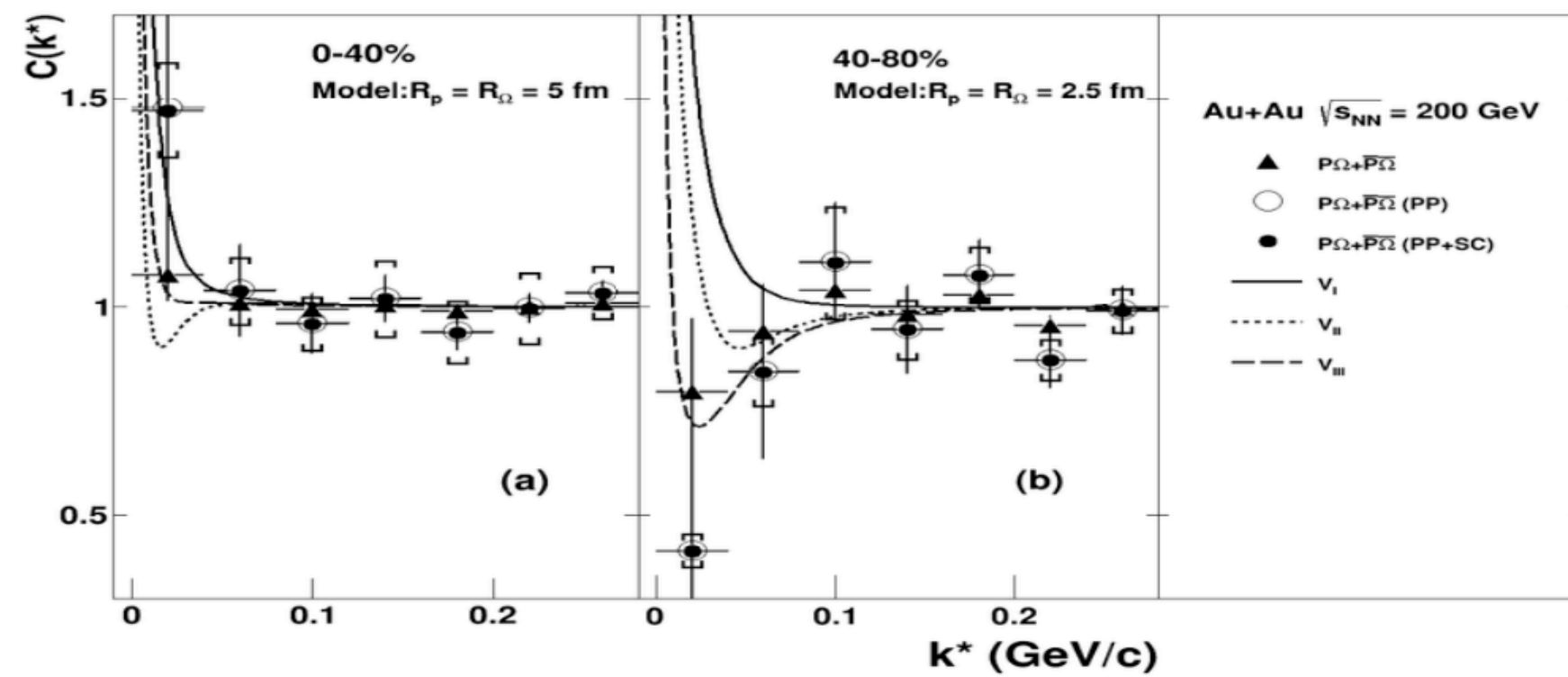
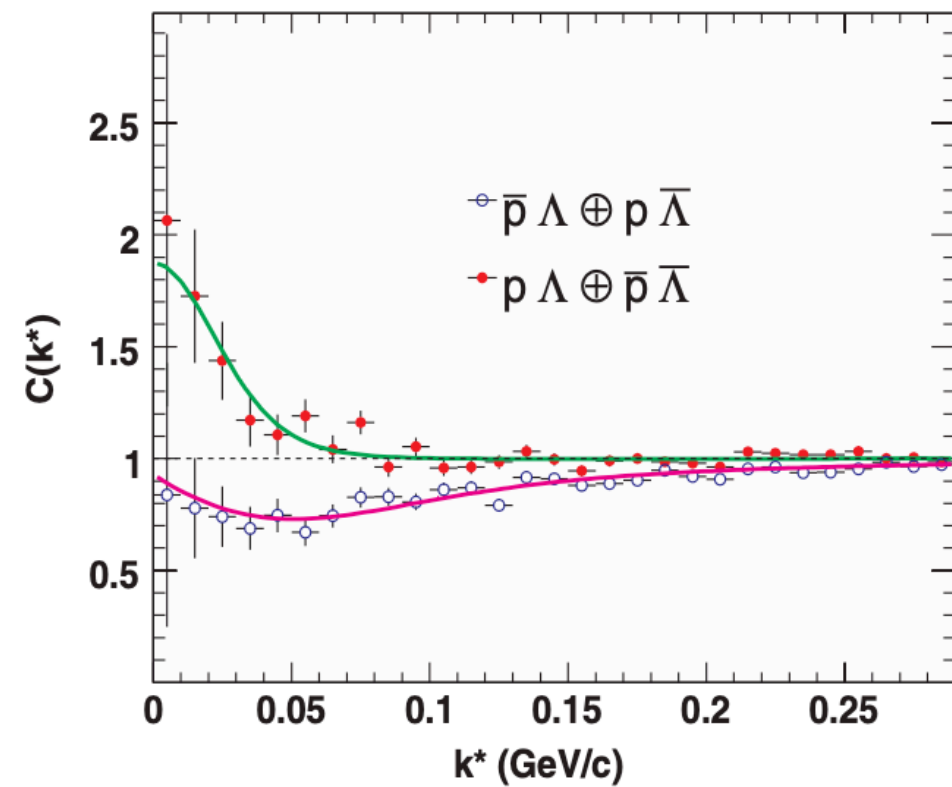
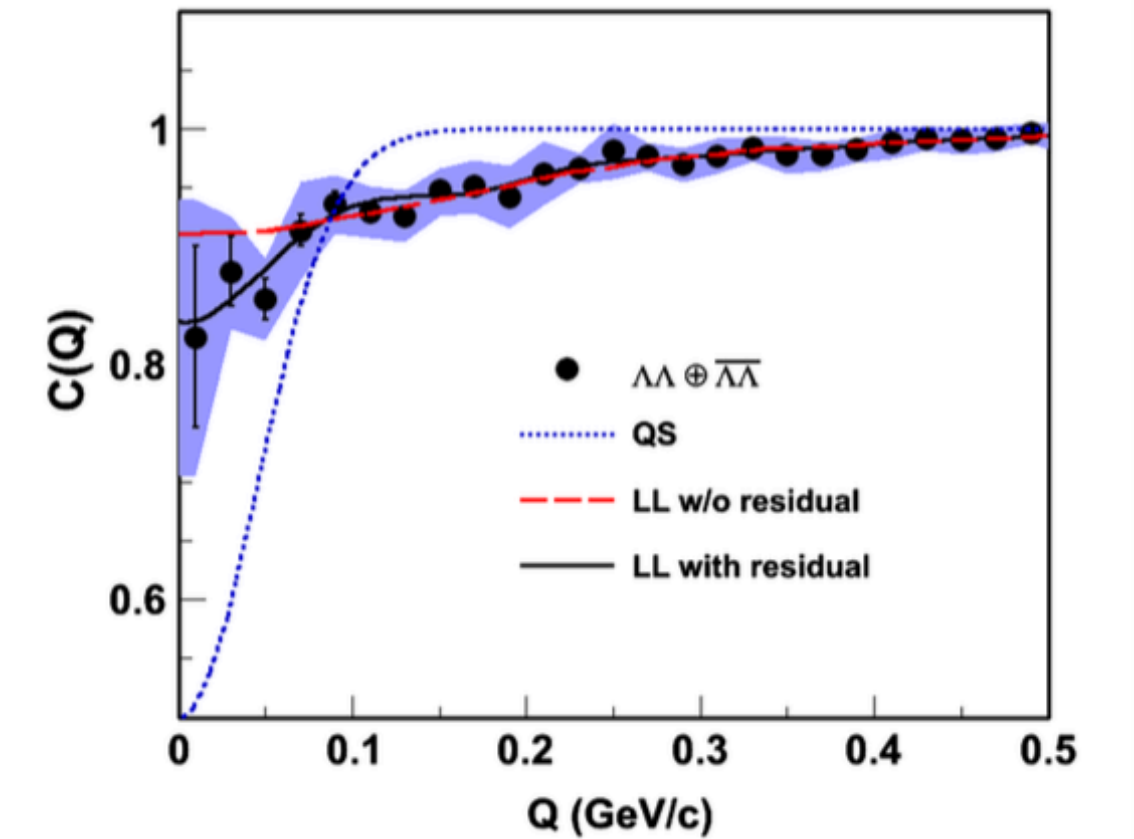
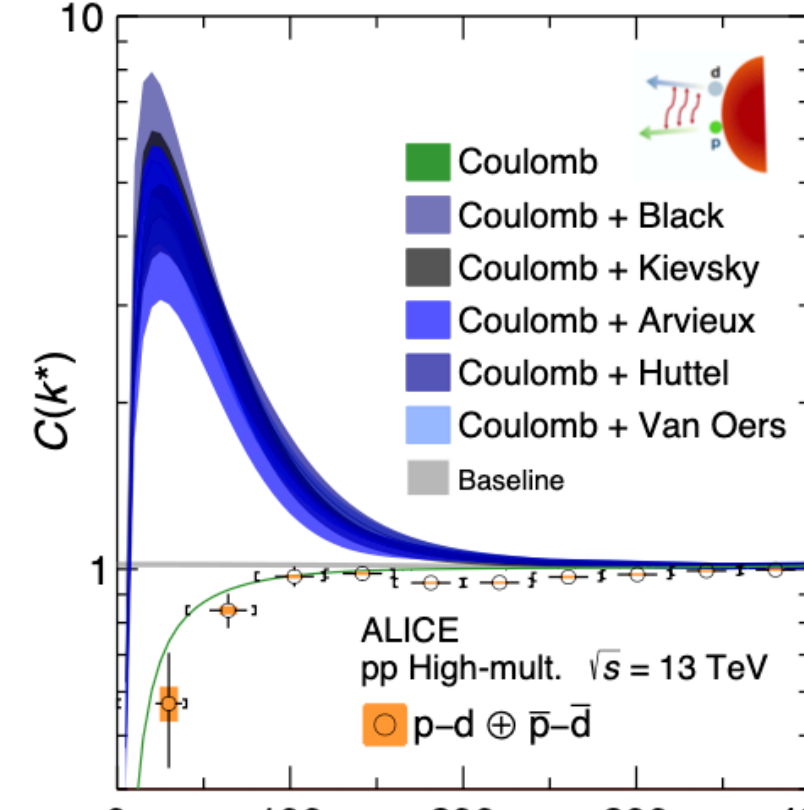
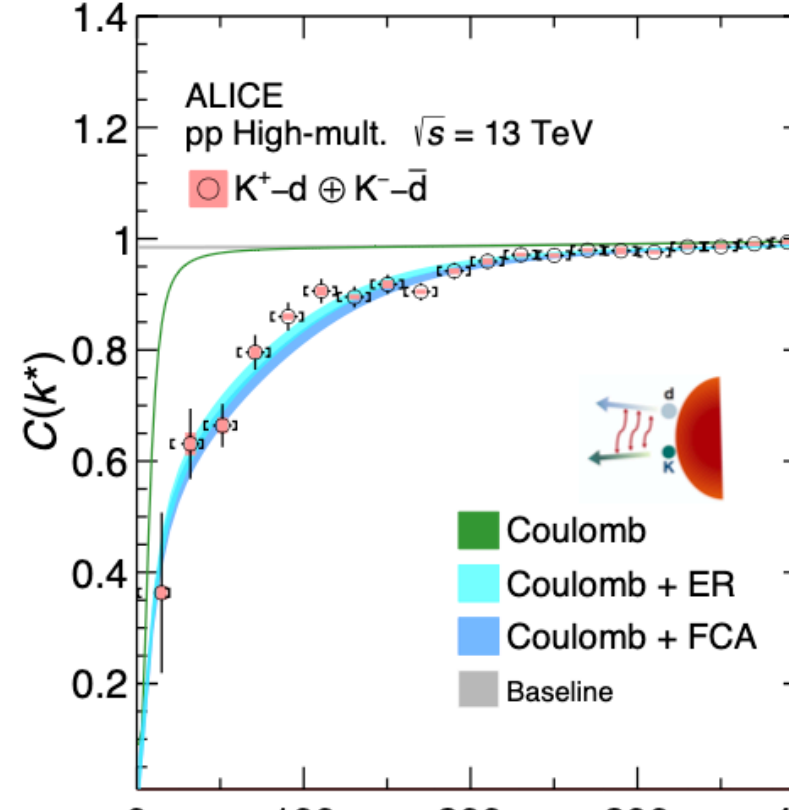
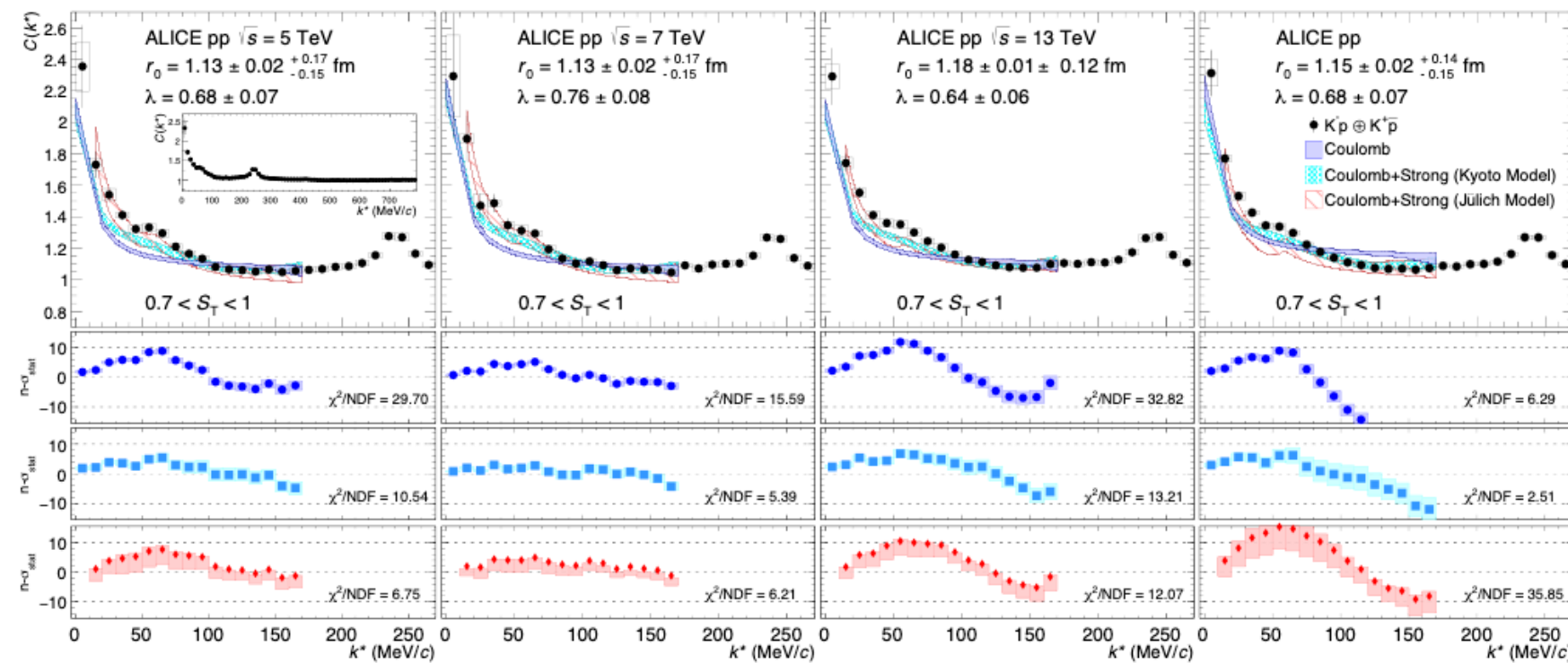
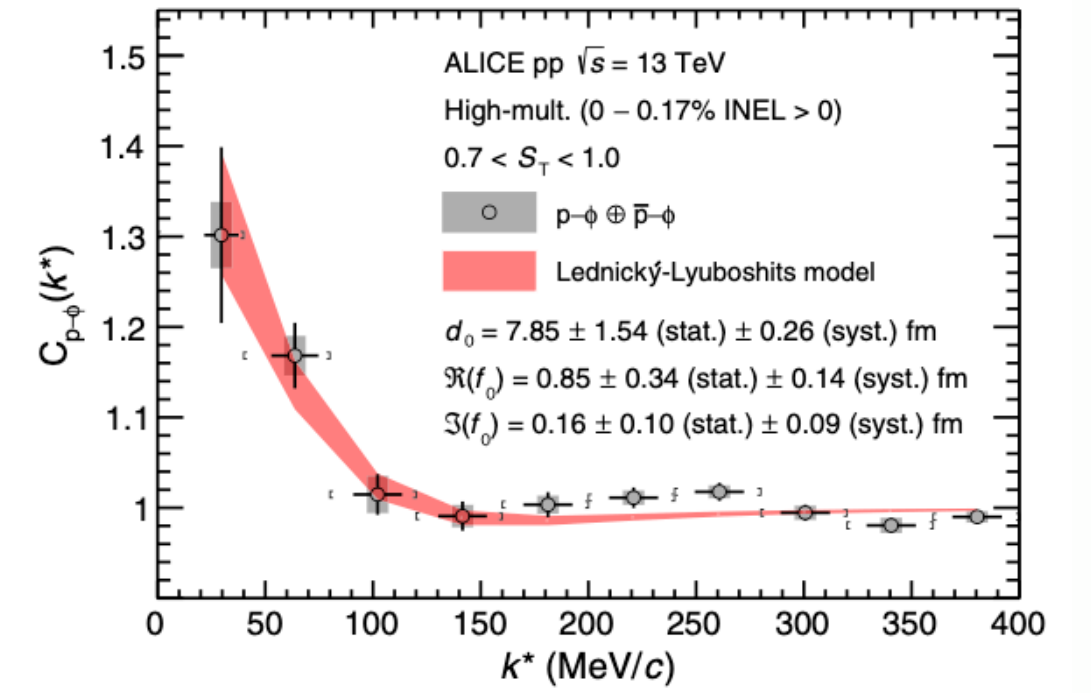
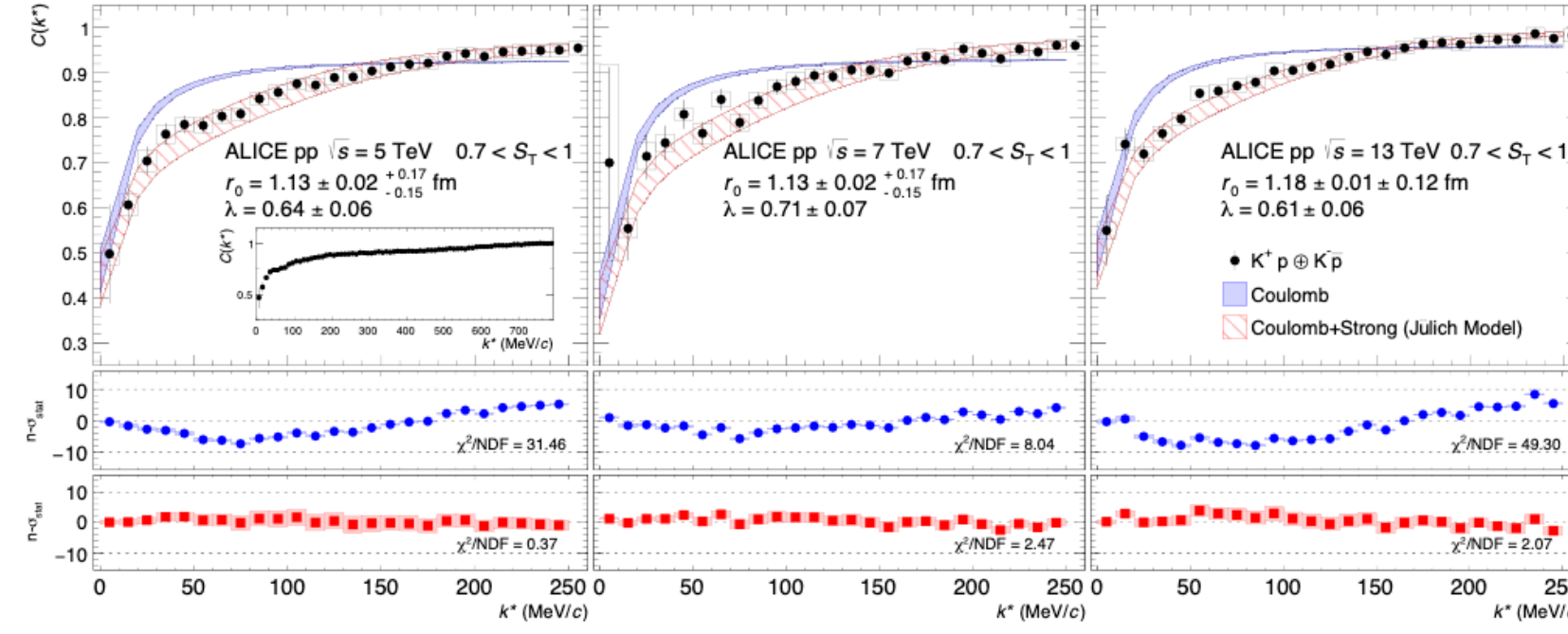
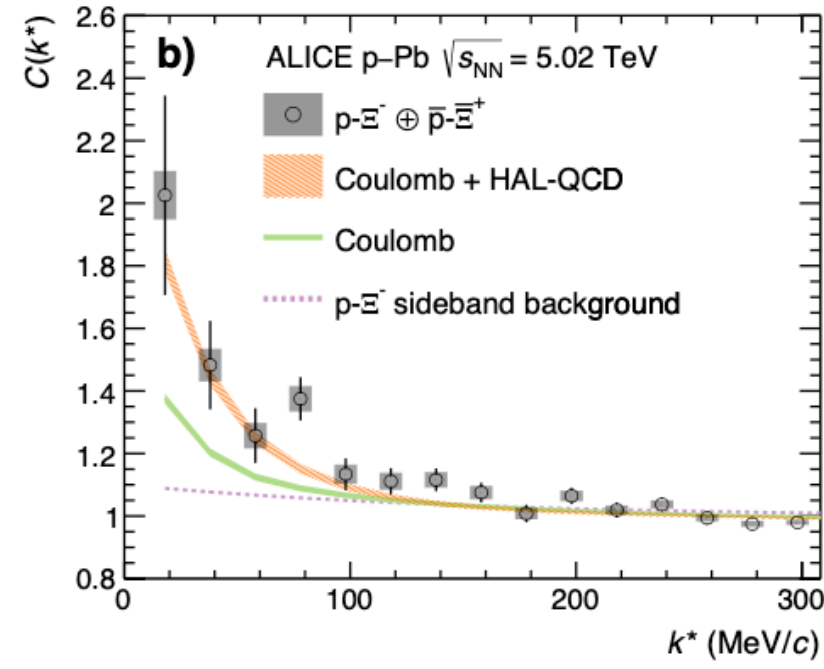
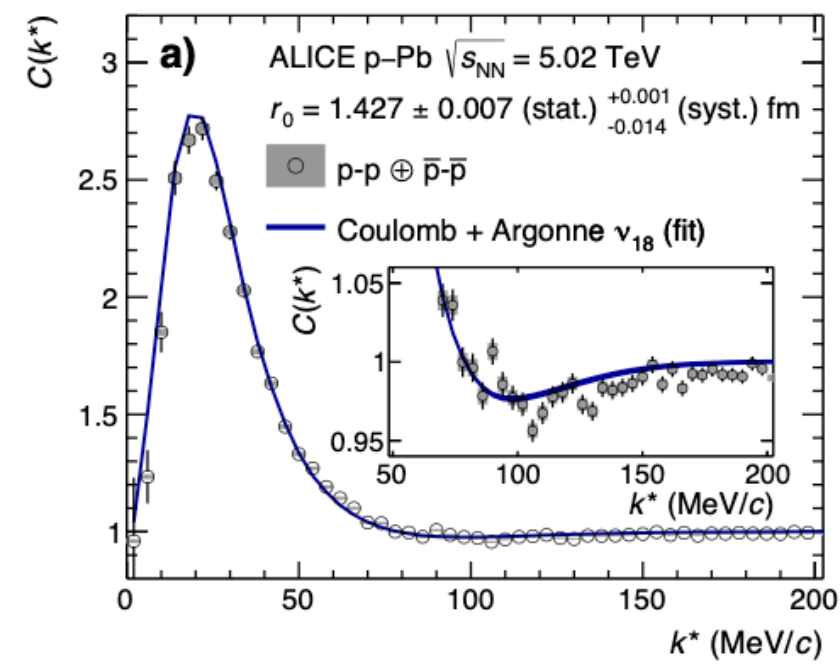
In the past



ALICE Collaboration, Nature 588, 232-238 (2020)



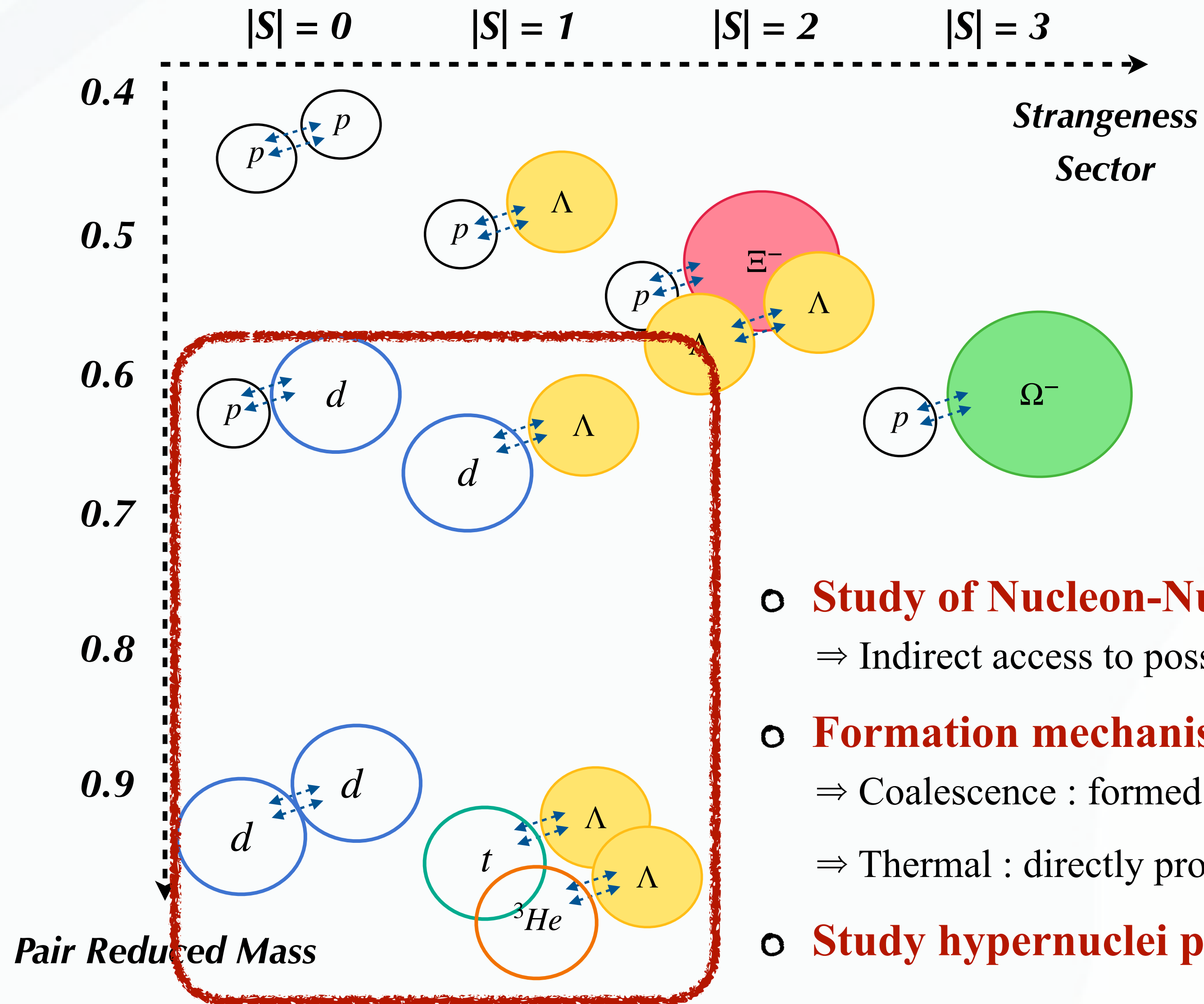
In the past



And more!

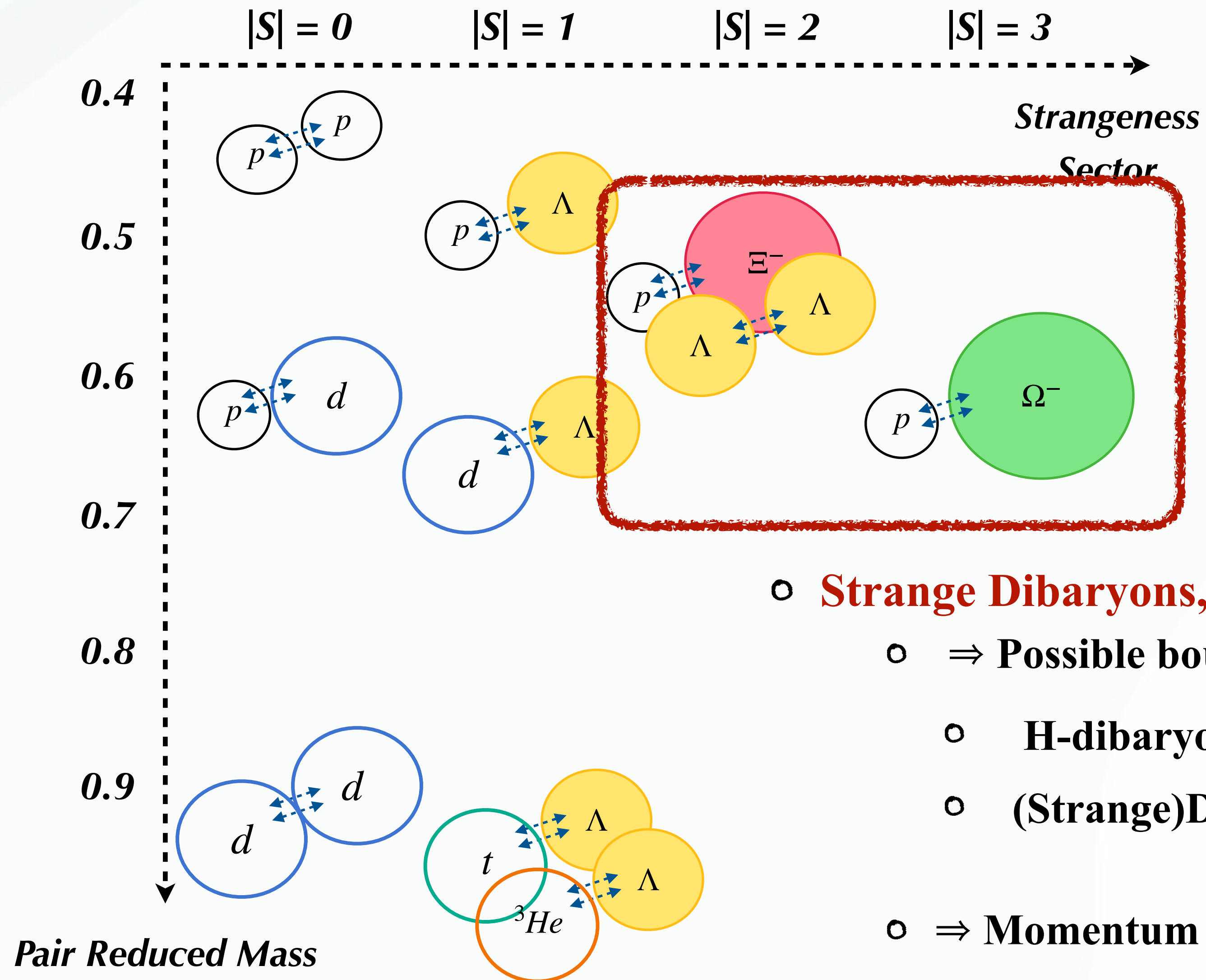
- Phys. Rev. Lett. 123, 112002 (2019)
- Phys. Rev. Lett. 124, 092301 (2020)
- Phys. Rev. Lett. 127, 172301 (2021)
- Phys. Rev. X 14 (2024) 031051
- Phys. Rev. Lett. 114, 022301 (2015)
- Phys. Rev. C 74, 064906 (2006)
- Phys. Lett. B 790, 490-497 (2019)

In this talk:



- **Study of Nucleon-Nucleon (NN) interactions in loosely bound systems**
 $\Rightarrow$ Indirect access to possible many-body effects
- **Formation mechanism of light nuclei remain under debate**
 $\Rightarrow$ Coalescence : formed via final-state interactions
 $\Rightarrow$ Thermal : directly produced from the fireball
- **Study hypernuclei properties via light nuclei - hyperons correlations**

In this talk:



- **Strange Dibaryons, have never been found experimentally**

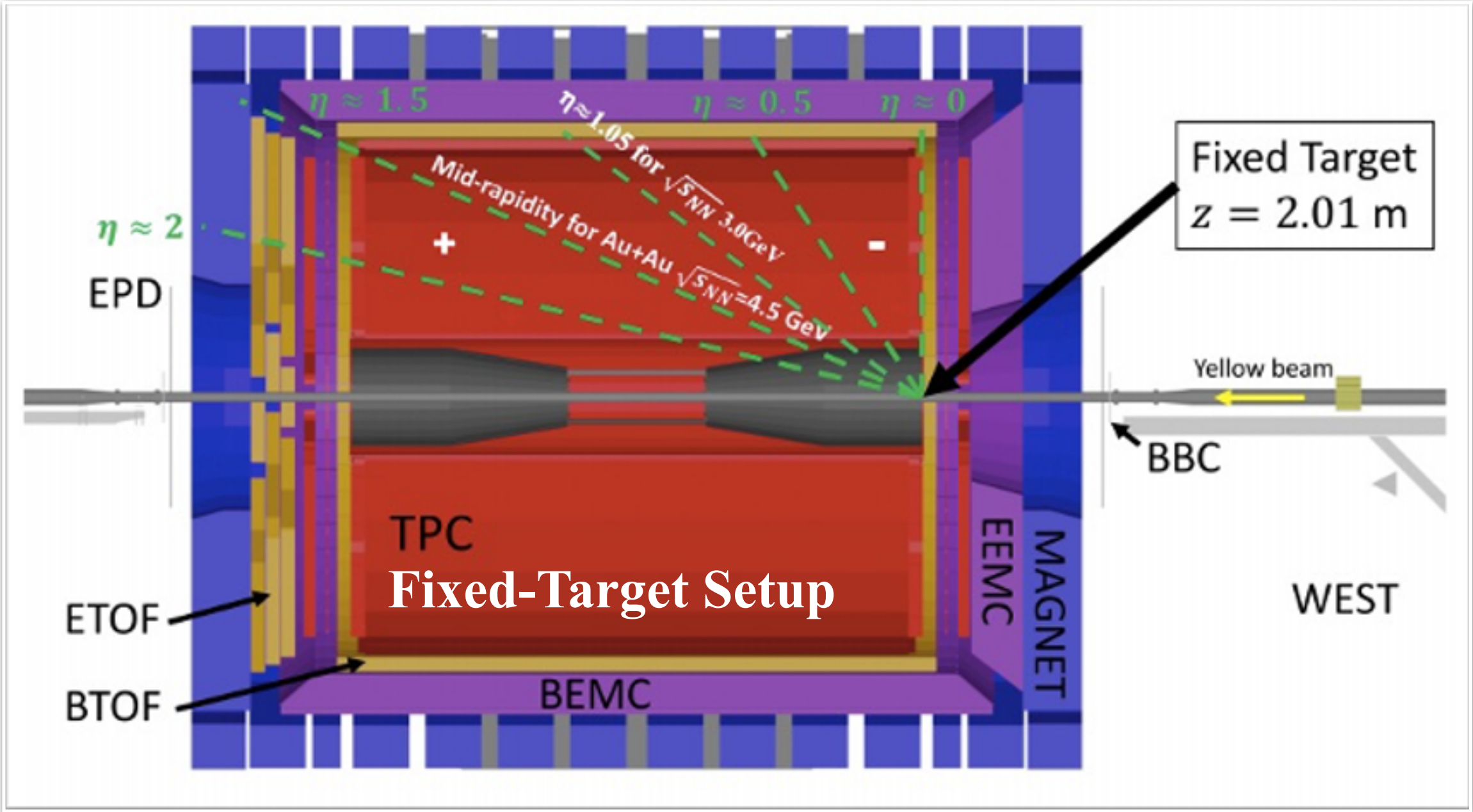
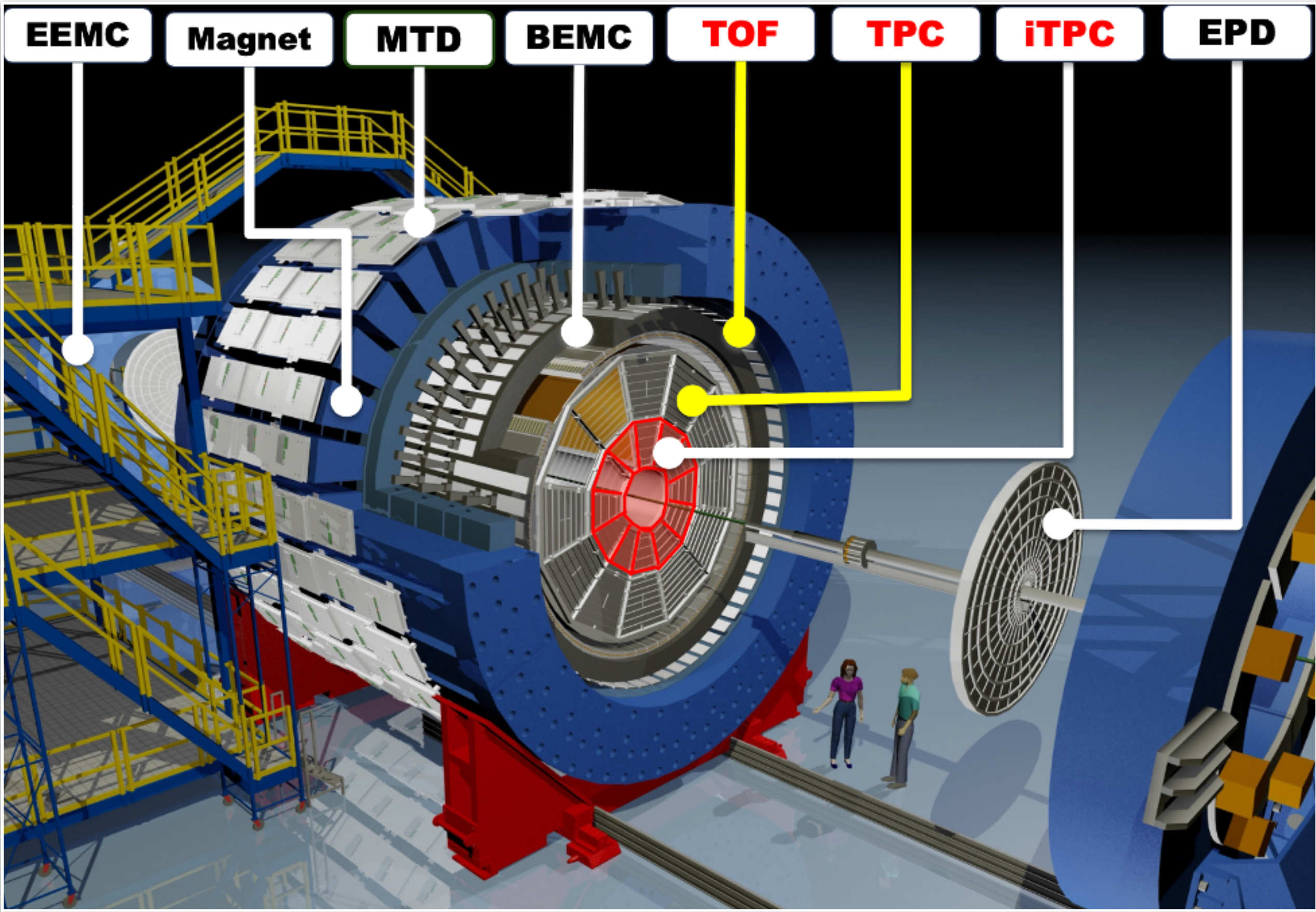
- $\Rightarrow$ Possible bound state:

- H-dibaryon $\Rightarrow \Lambda + \Lambda / p + \Xi^-$

- (Strange)Dibaryon $\Rightarrow p + \Omega^-$

- $\Rightarrow$ Momentum correlation provides a new way to explore

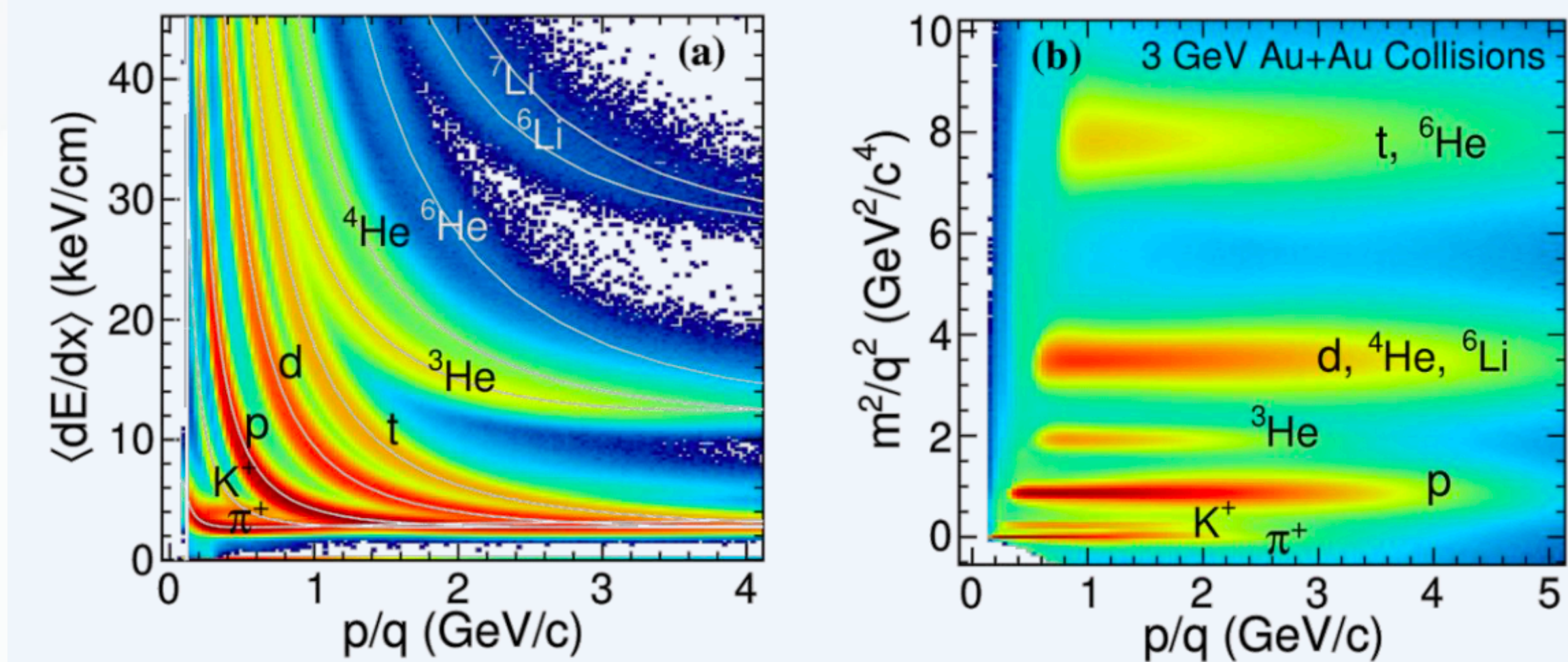
STAR Detector



- ⇒ Excellent particle identification
- ⇒ Large, uniform acceptance at mid-rapidity

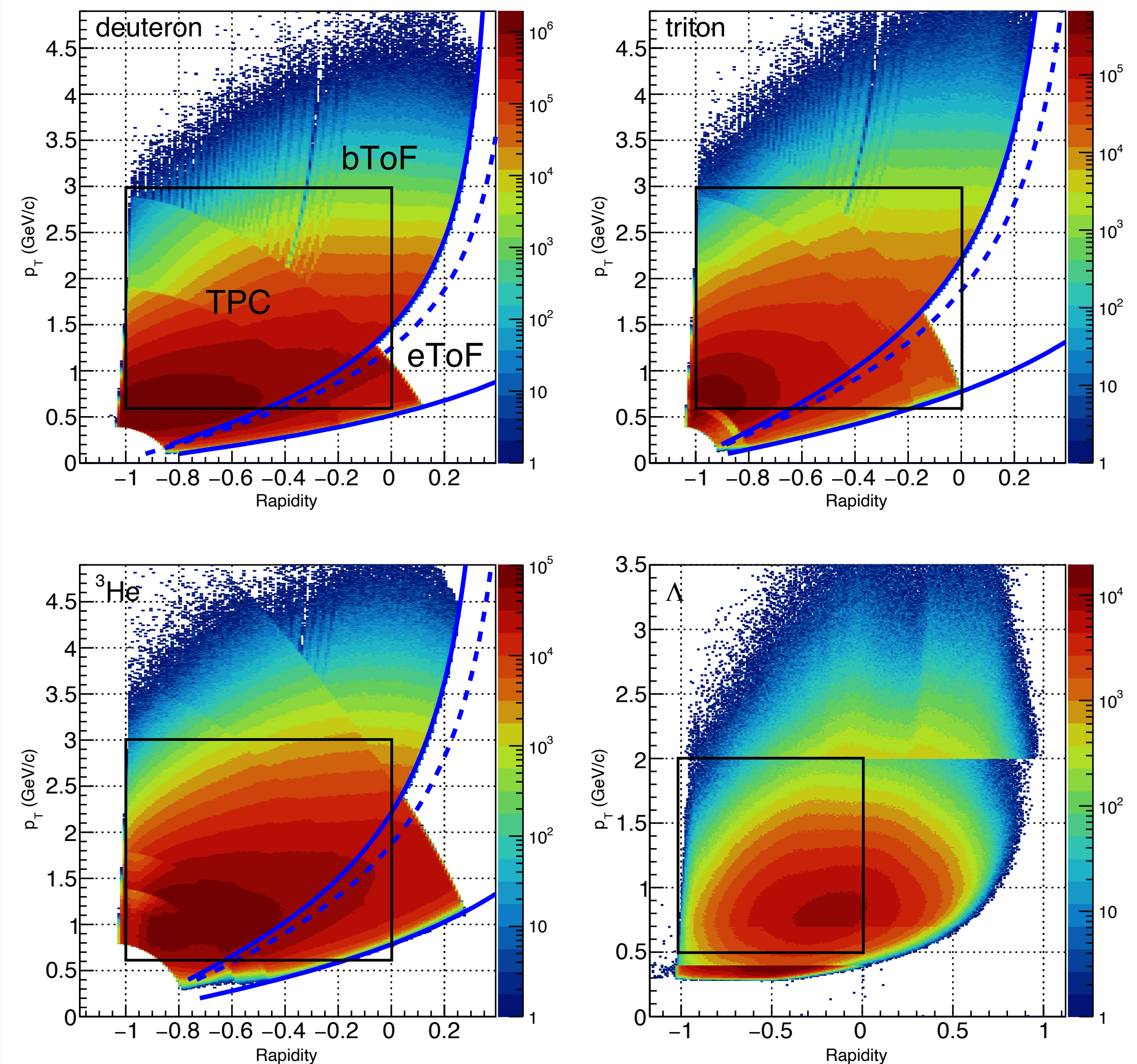
Center-of-Mass Energy	Collisions	Year	Mode	#Events
3 GeV	Au+Au	2018	FXT	260 M
3 GeV	Au+Au	2021	FXT	2000 M
200 GeV	Au+Au	2011/2014/2016	Collider	2000 M
200 GeV	Isobar (Ru+Ru/ Zr+Zr)	2018	Collider	4000 M

Particle Identification & Reconstruction

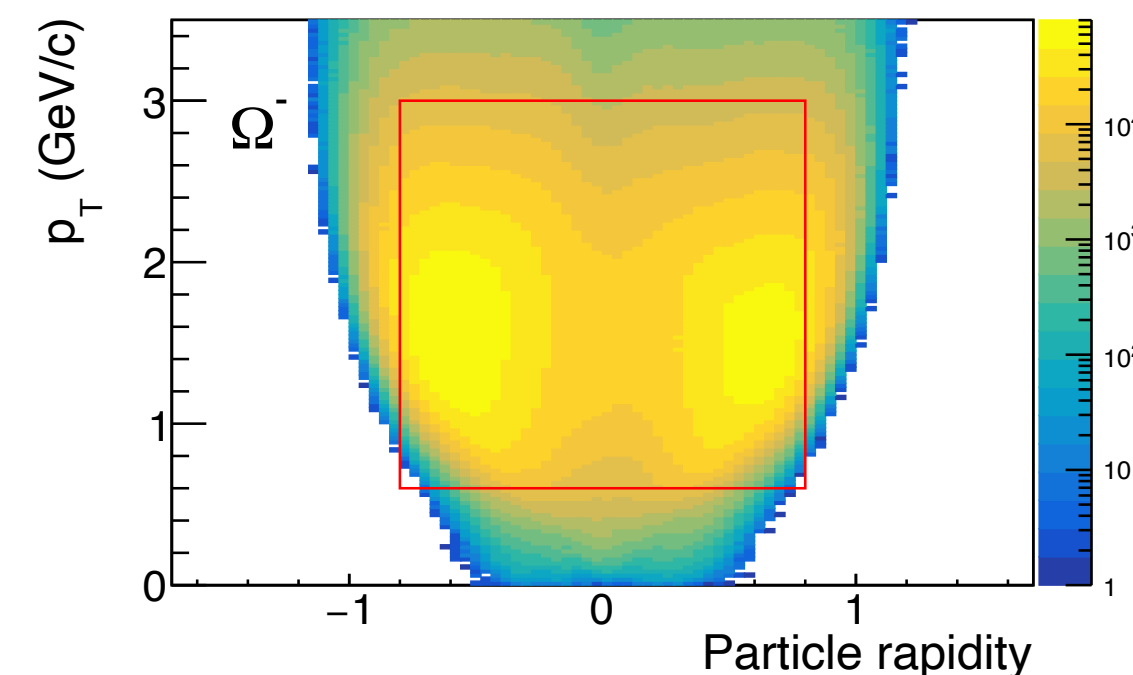
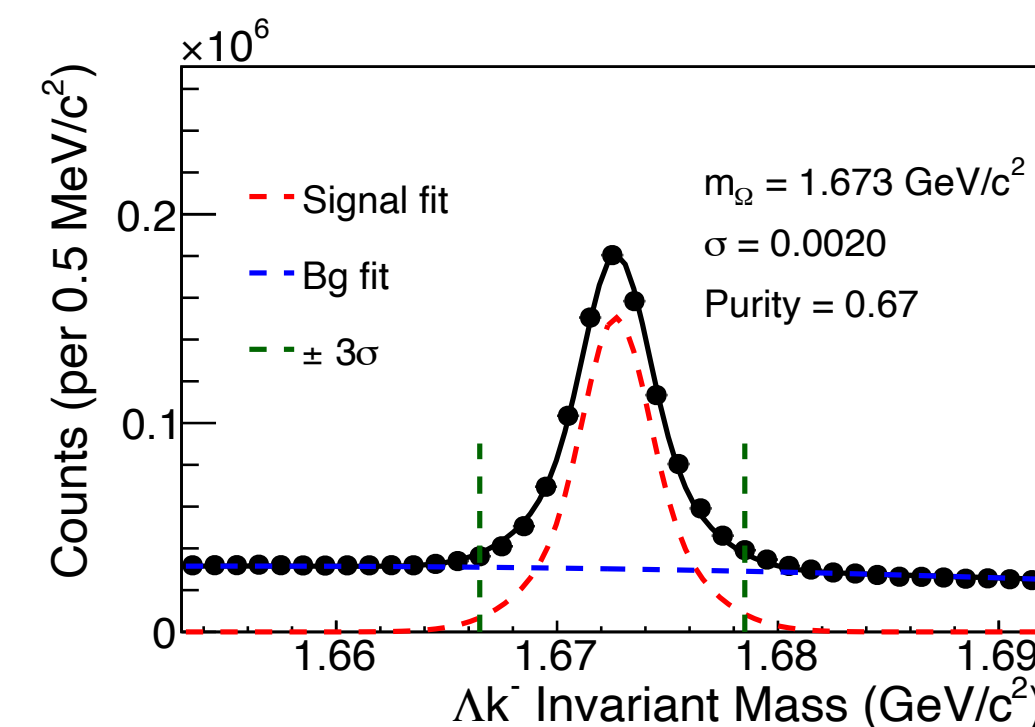
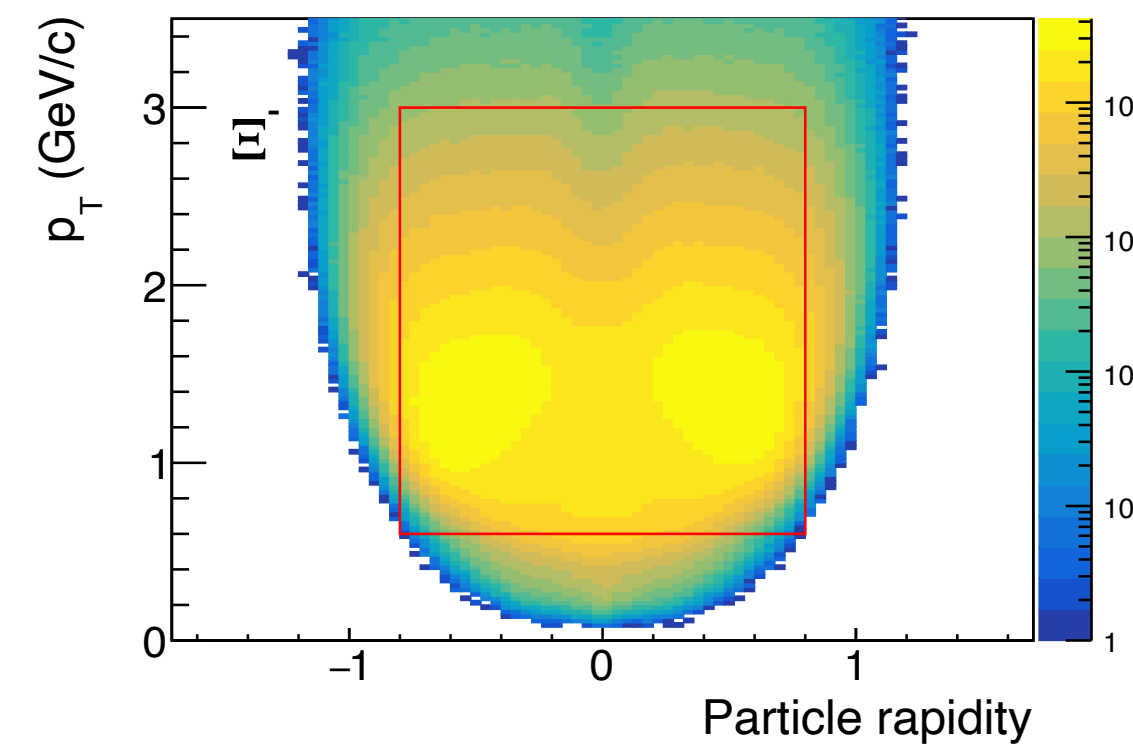
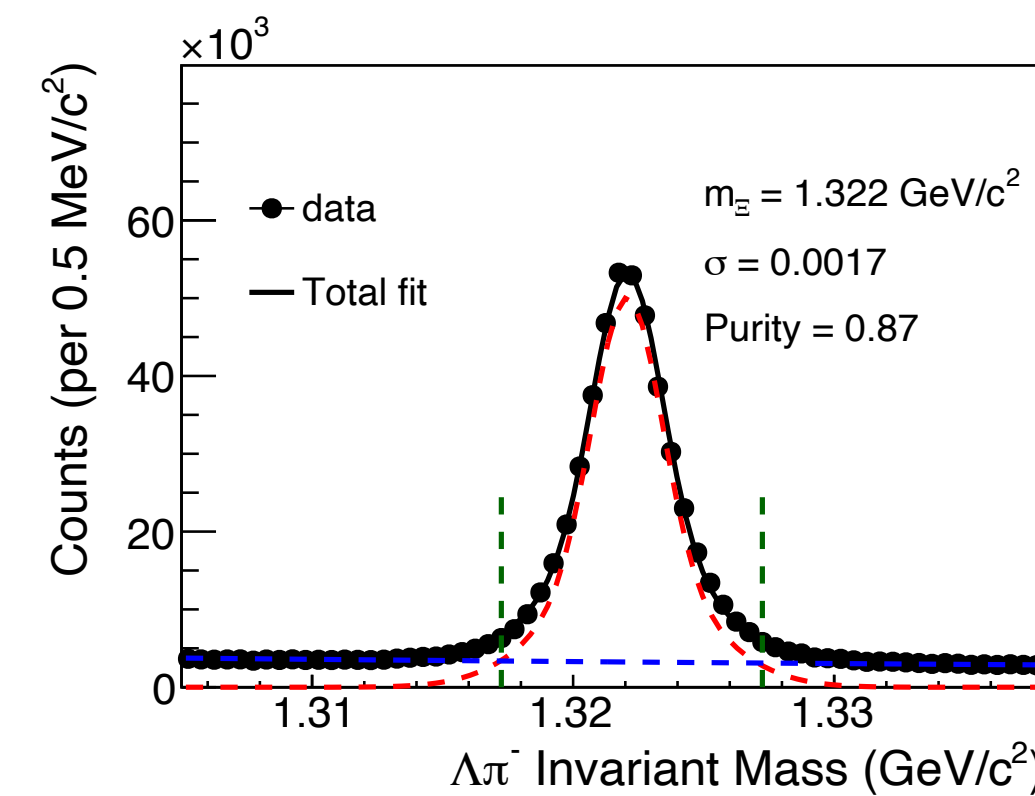
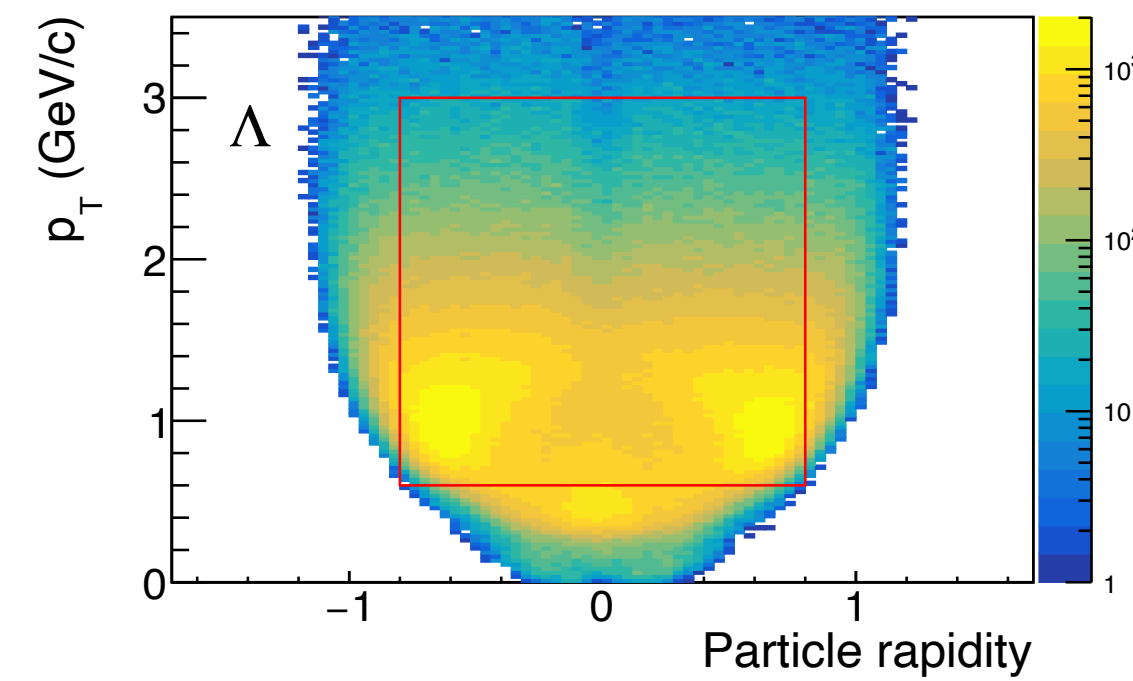
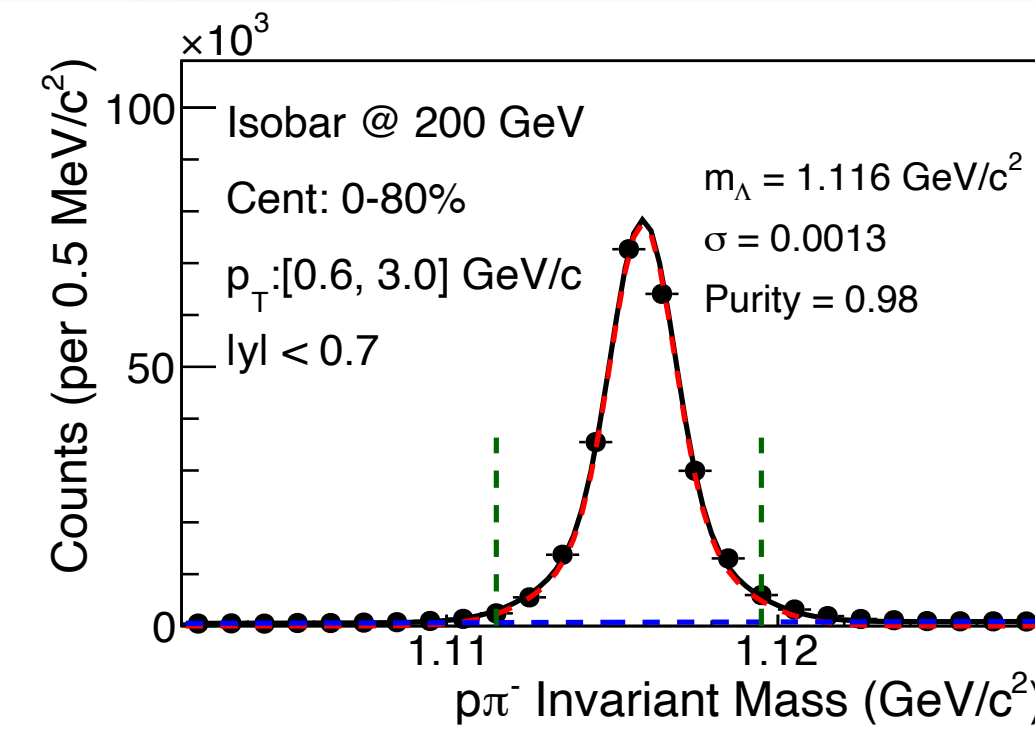


➡ Protons, deuterons, tritons and helium3 are identified by TPC, TOF

- Low p_T : TPC
- High p_T : TPC + TOF
- Purity > 95%



Particle Identification & Reconstruction



○ Reconstruct hyperons (Λ , Ξ , Ω) with Helix-swimming method

$$\Lambda \rightarrow p + \pi^-$$

$$\Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + \pi^- + \pi^-$$

$$\Omega^- \rightarrow \Lambda + K^- \rightarrow p + \pi^- + K^-$$

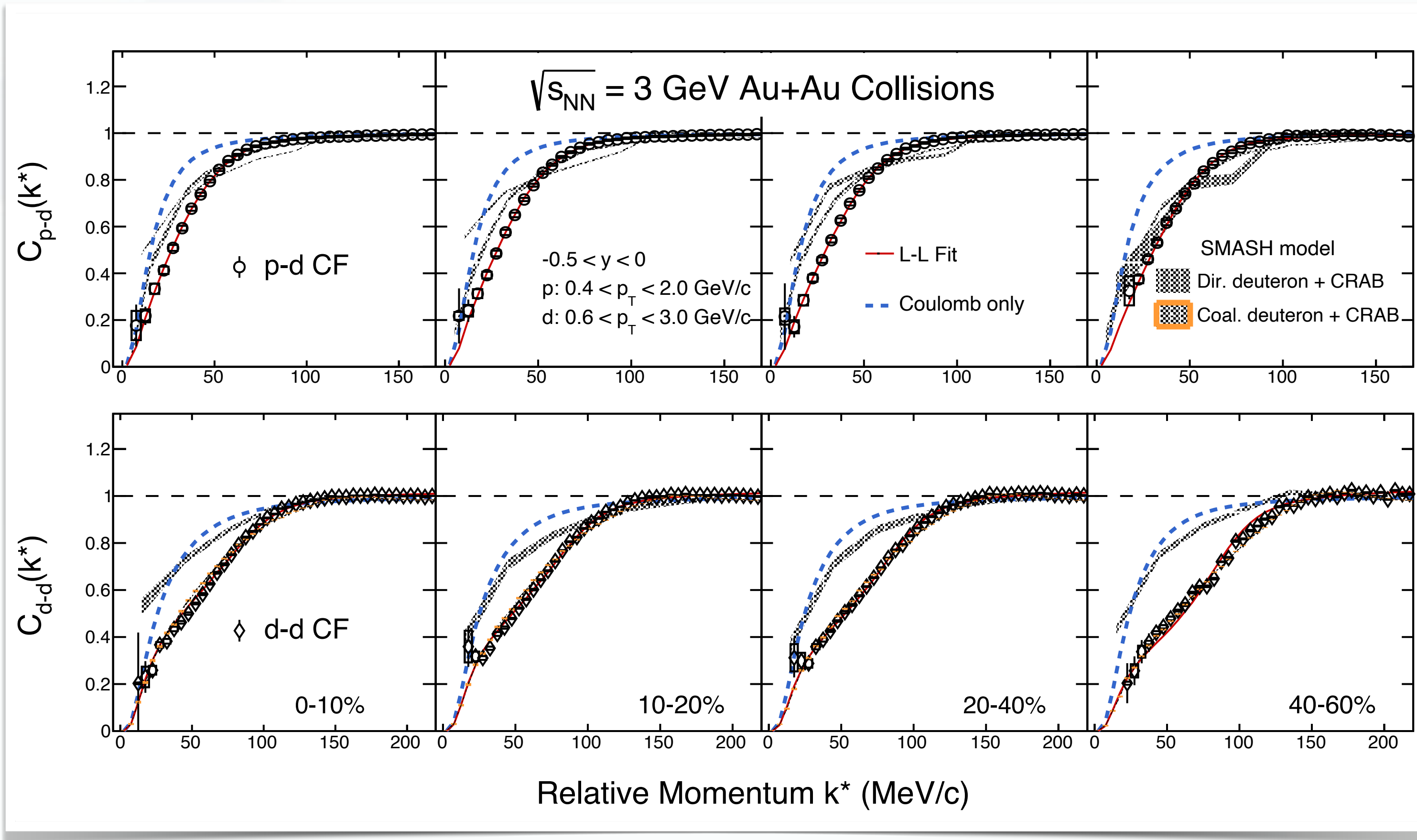
○ Fitting function:

Double Gaussian + 2nd poly.

○ High purity achieved

Results

p-d / d-d Correlation @ 3 GeV



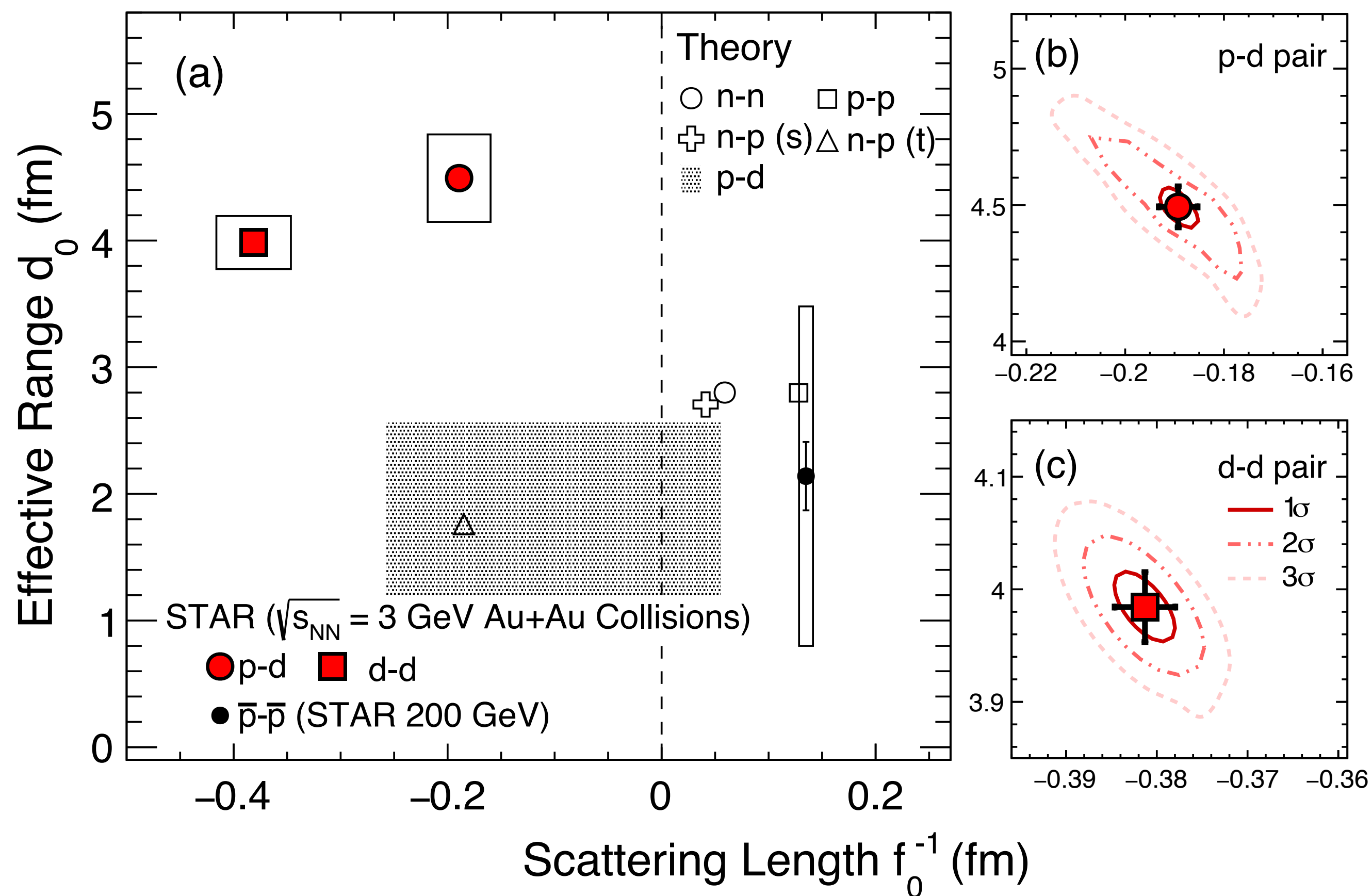
- First measurements of p-d/d-d correlation functions in HIC
- Clear depletion in low k^*
 - Coulomb repulsive & strong interaction
- Fitted with L-L model simultaneously, assuming in different centrality:
 - Different R_G with common f_0 and d_0
- Simulated with SMASH model, consider two deuteron formation 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

STAR: Phys. Lett. B 864, 139412 (2025)

SMASH: J. Weil et al. PRC 94 (2016) 5, 054905

Coalescence: W.Zhao et al. PRC.98 (2018) 5,054905

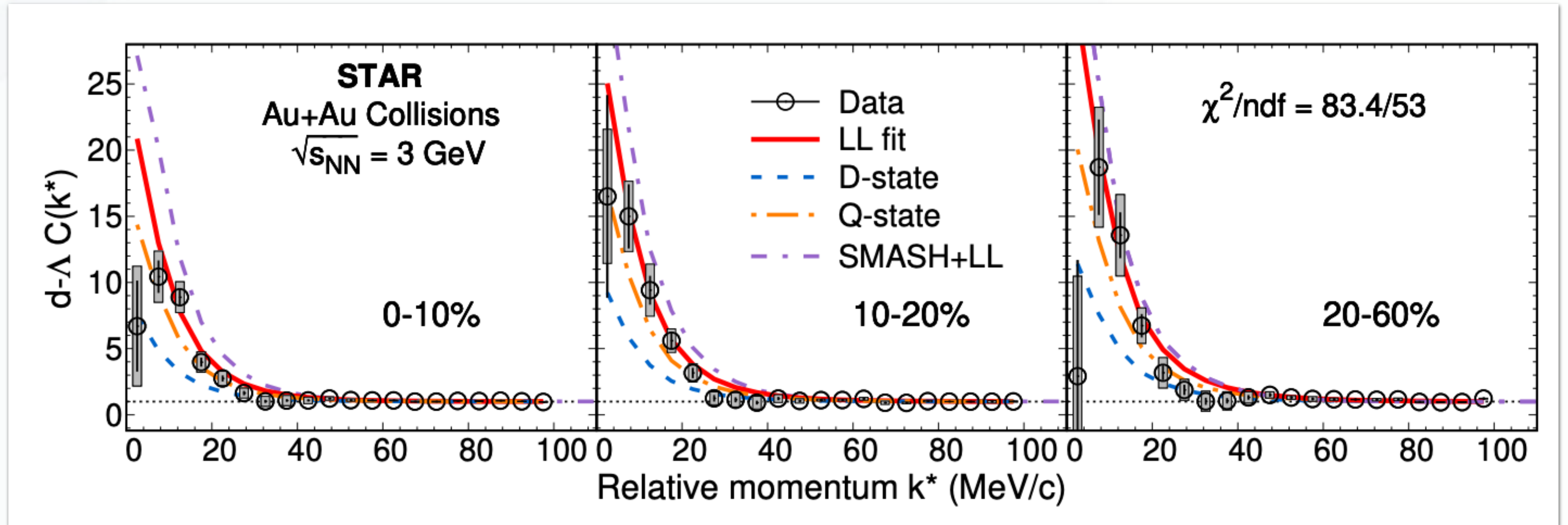
p-d / d-d Interaction



- **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 (^3He for p-d and ^4He 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: Phys. Lett. B 864, 139412 (2025)

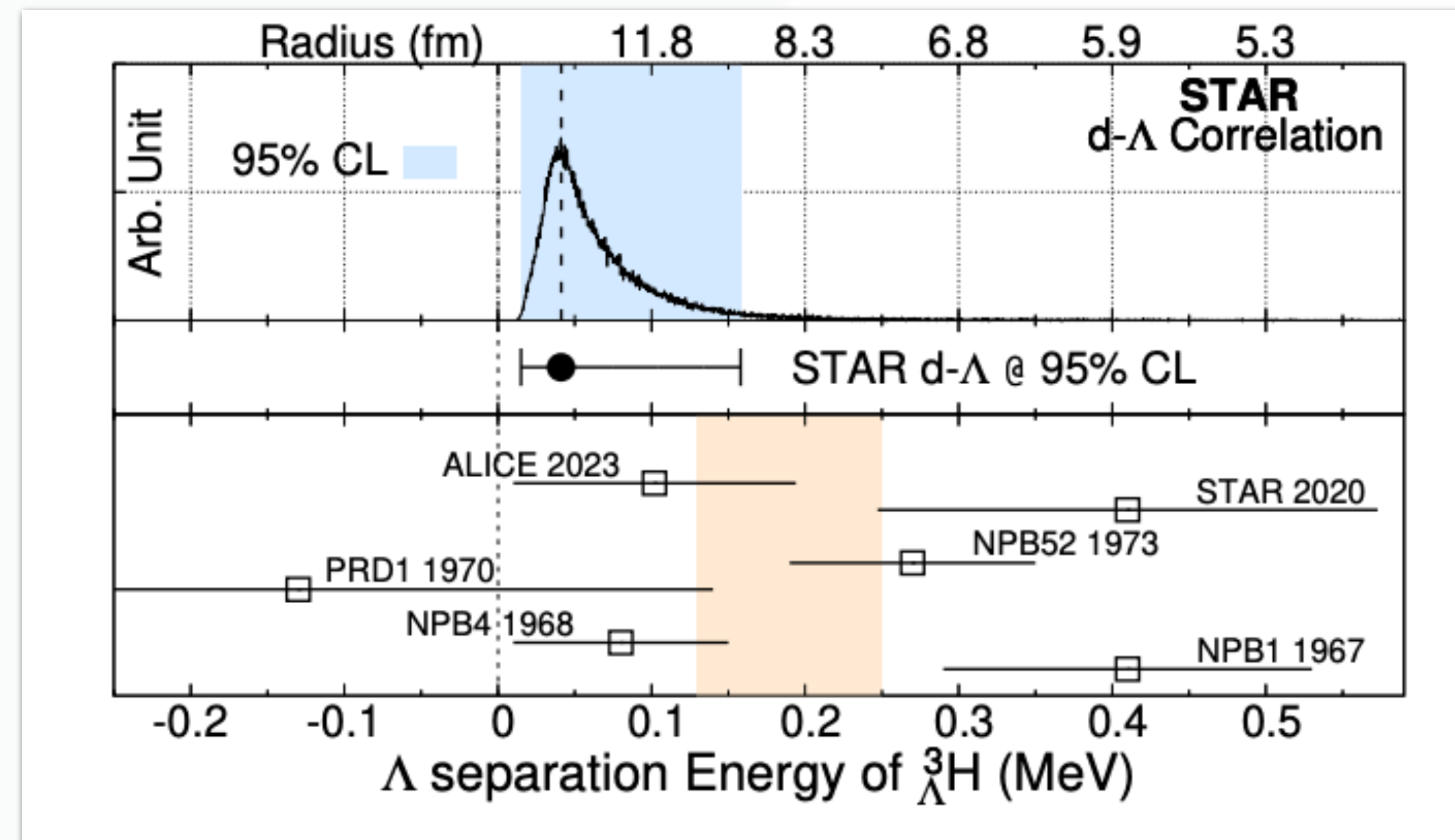
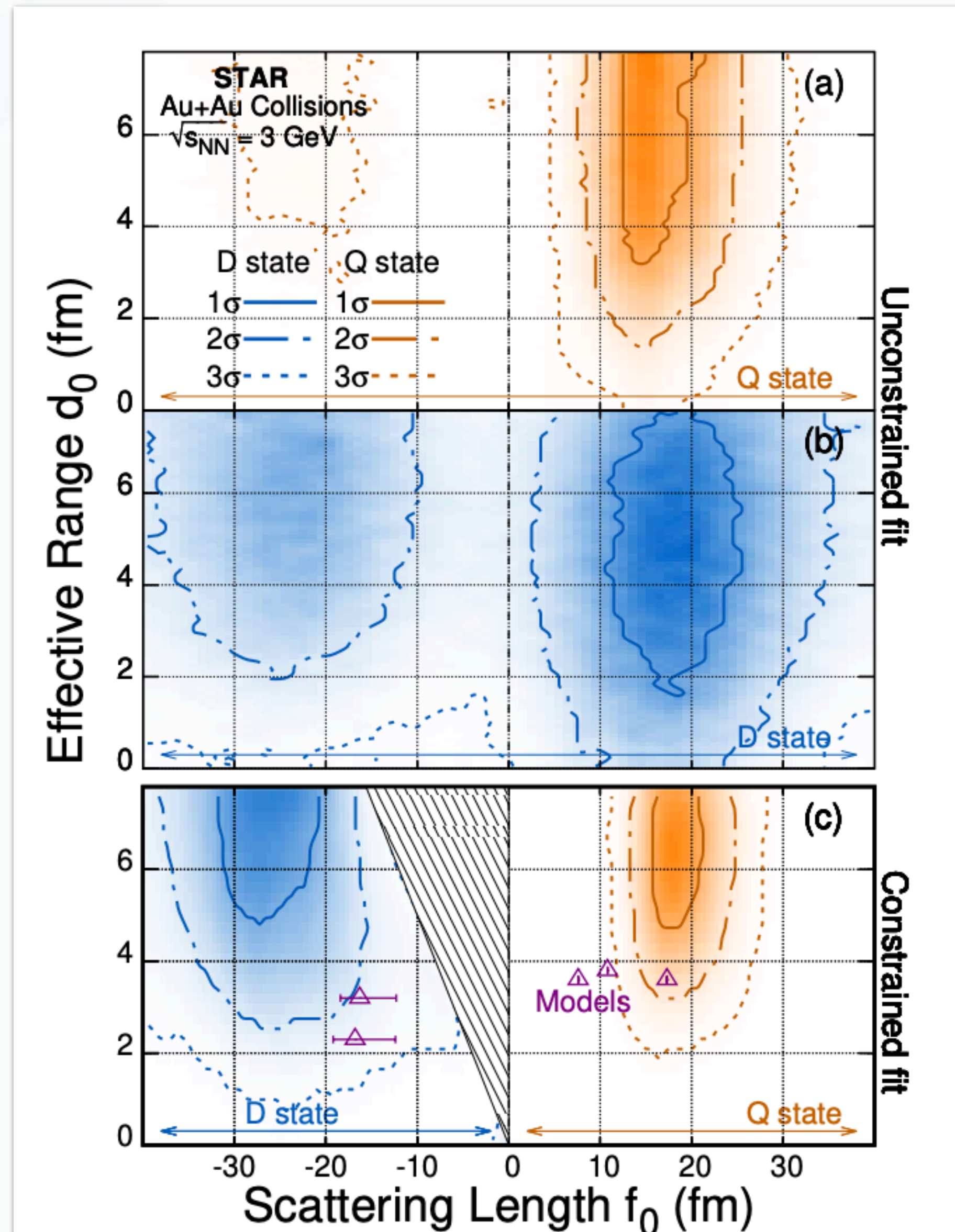
d- Λ Correlation @ 3 GeV



- First d- Λ correlation measurements in the heavy-ion collision experiment
- Strong enhancements at small k^* => **Attractive interactions**
- **Perform spin-separate fitting ($f_0(D)$, $d_0(D)$, $f_0(Q)$ and $d_0(Q)$ with LL approach**

$$f_0(D) = -26.1^{+5.6}_{-5.6} \text{ fm}, \quad f_0(Q) = 18.7^{+2.8}_{-2.8} \text{ fm}$$

d- Λ Interaction



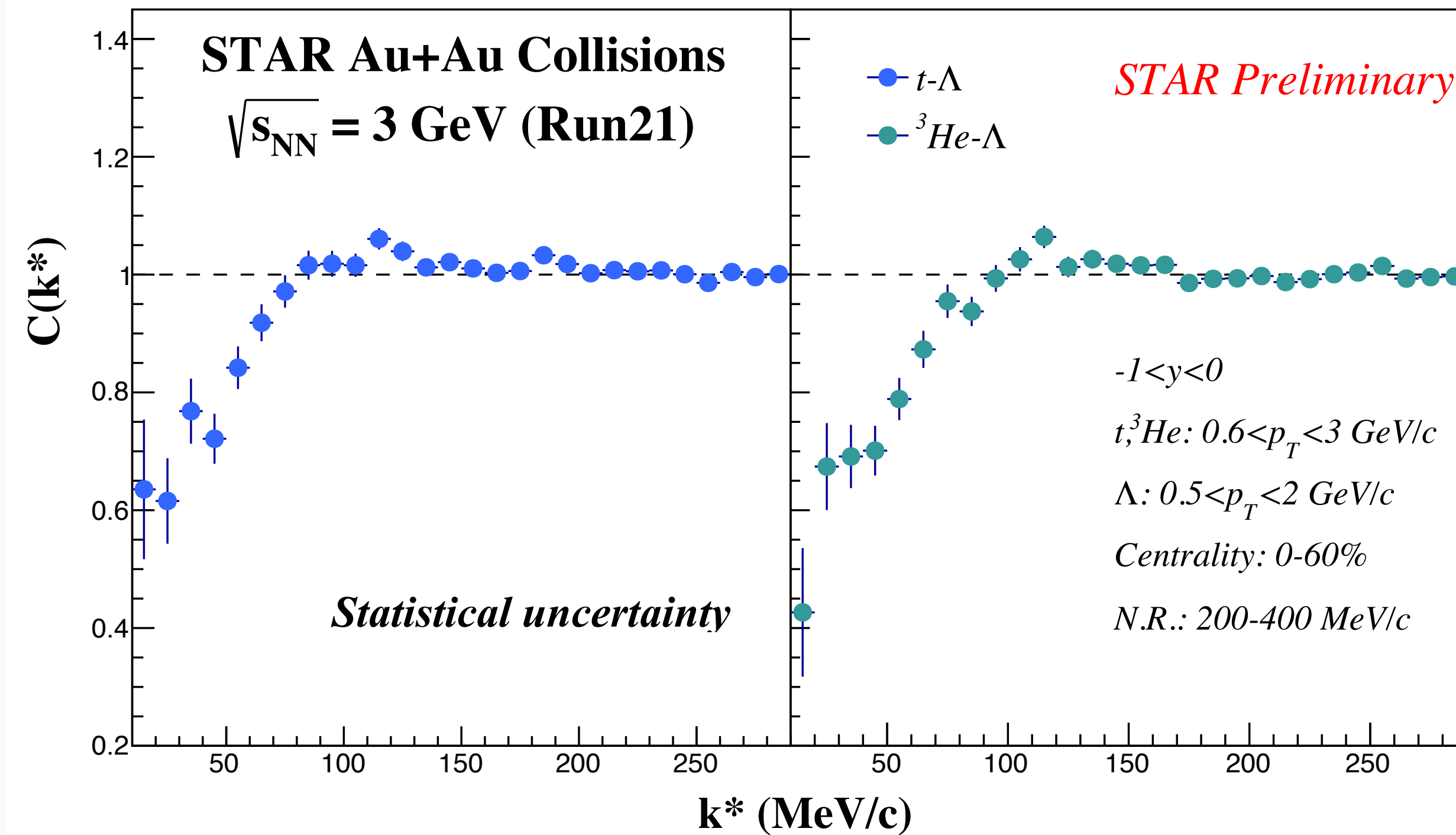
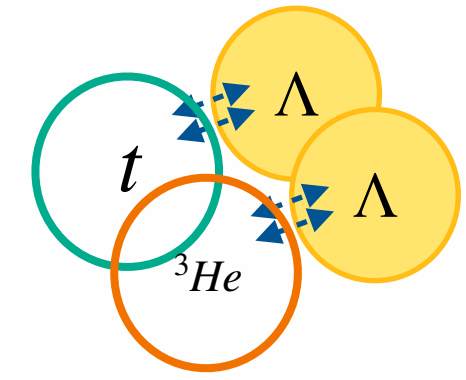
- Successfully separate two spin components in **d- Λ** pair
- Extract the most accurate results of binding energy and radius of ${}^3_\Lambda\text{H}$
 - $B_\Lambda = 0.06^{+0.06}_{-0.03}$ (MeV) @ 95% CL
 - $r({}^3_\Lambda\text{H}) = 16^{+5}_{-5}$ (fm) @ 95% CL
- Open a new way to constrain ${}^3_\Lambda\text{H}$ properties

STAR: arXiv: 2511, 15493

EF. 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

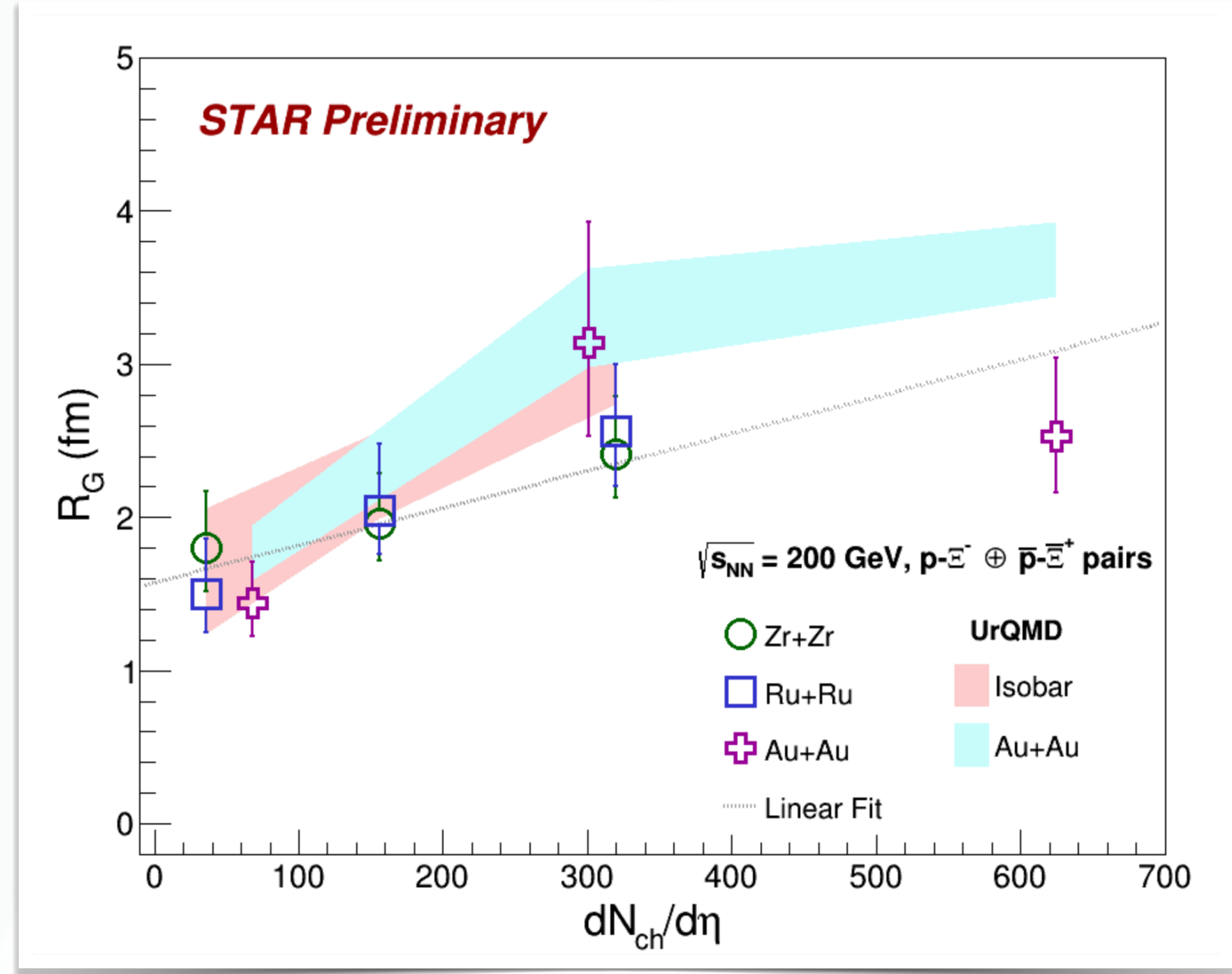
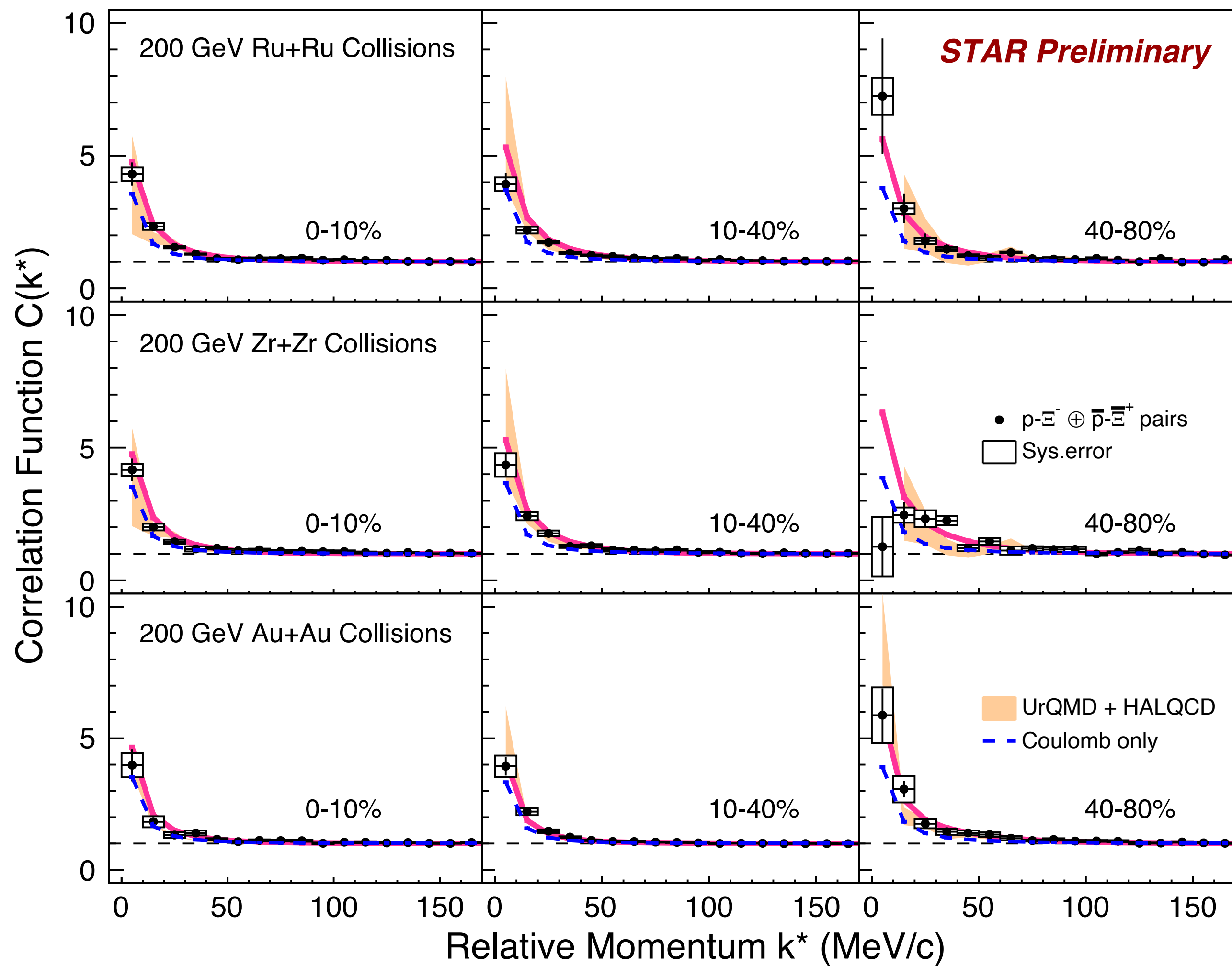
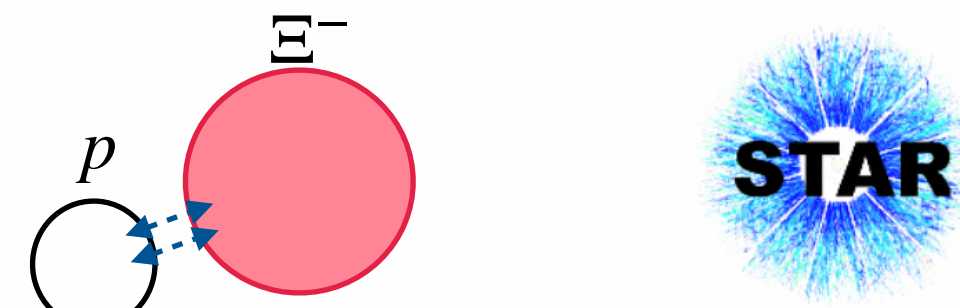
J. Haidenbauer, et al. Nucl. Phys. A 915 (2013) 24
H. W. Hammer, Nucl. Phys. A 805 (2002) 173
Cobis, et al. J. Phys. G 23 (1997) 401
J. Haidenbauer, Phys. Rev. C 102 (2020) 3, 034001
H. Bethe, Phys. Rev. 76. 38 (1949)

t - Λ / ${}^3\text{He}$ - Λ Correlation @ 3 GeV



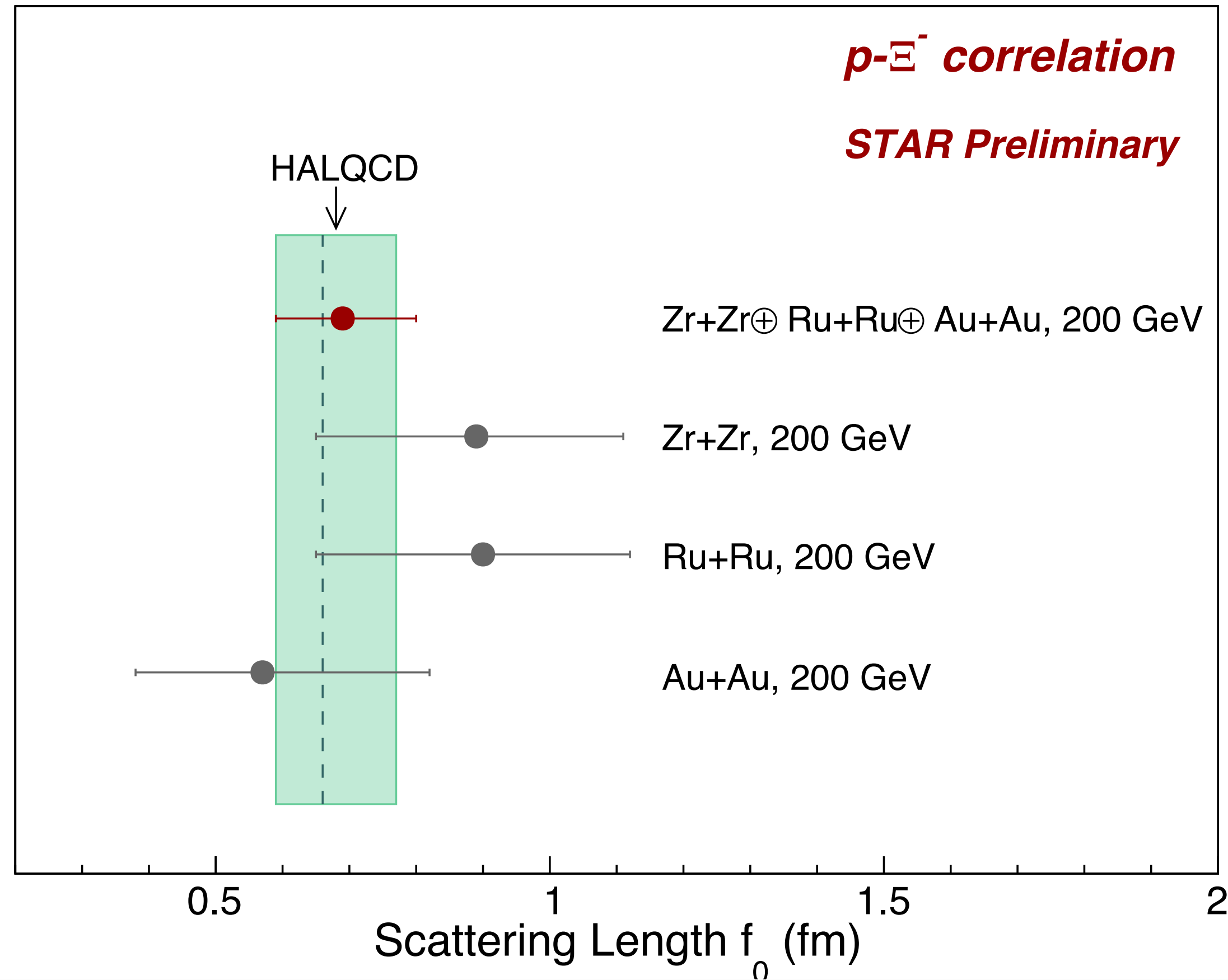
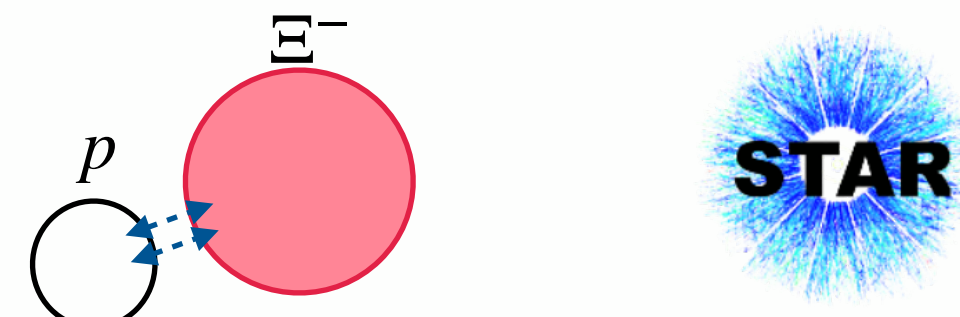
- First t - Λ and ${}^3\text{He}$ - Λ correlation function measurements in the heavy-ion collisions
- t - Λ and ${}^3\text{He}$ - Λ exhibit similar correlation structures
 - Depletion at low k^*
 - Cusp structure at $k^* \sim 100$ MeV
 - Particle decay?
 - Final-state interaction?

p- Ξ^- Correlation @ 200 GeV



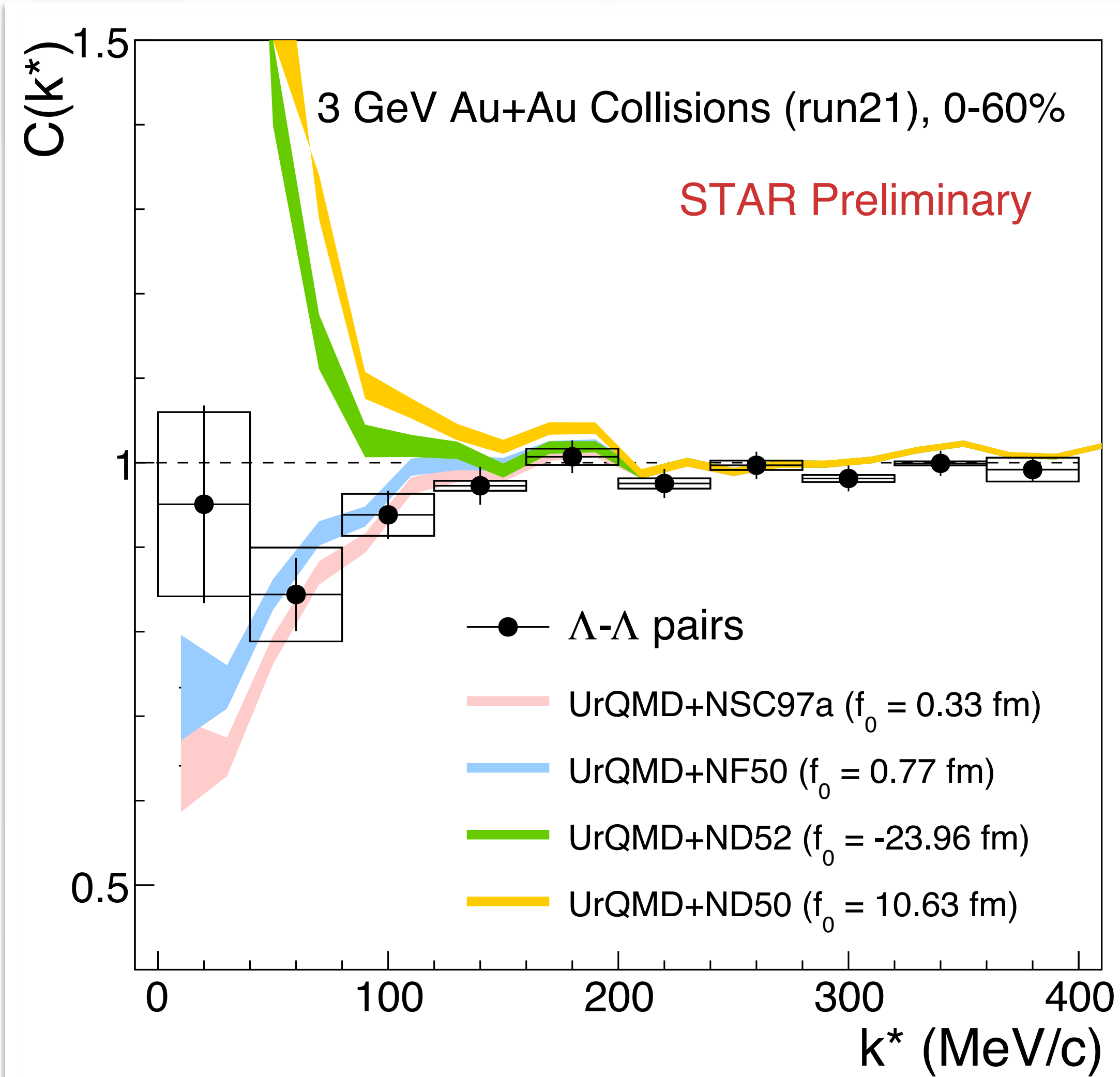
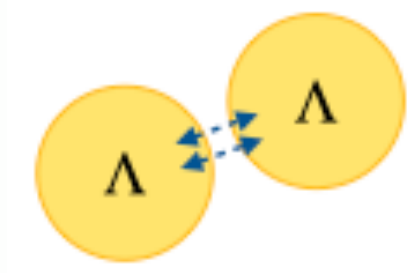
- p- Ξ^- CFs show enhancement at low k^* : Coulomb attraction and strong interaction
- Simultaneously fit to Isobar and AuAu data
 - 9 centralities + $f_0 + d_0$
- UrQMD + HALQCD results are consistent with data
- Source size shows centrality dependence and follow a similar trend in different collision system

p- Ξ^- Interaction



- First experimental extraction of strong interaction parameters in p- Ξ^- pairs
- Extracted *positive* $f_0 = 0.69^{+0.11}_{-0.10}$ fm
 - *Attractive* strong interaction in p- Ξ^- pair
 - Shallow interaction compared to p-p interaction
 - Consistent with Lattice predictions

Λ - Λ Correlation @ 3 GeV



- Λ - Λ correlation function shows suppression at small k^*
- Compared with UrQMD + potential, it is found that the simulation with positive f_0 is in better agreement with data
 $\Rightarrow$ Hints at an attractive interaction in Λ - Λ pairs
- Need more precise data to confirm
 $\Rightarrow$ High statistics Isobar and Au+Au collisions

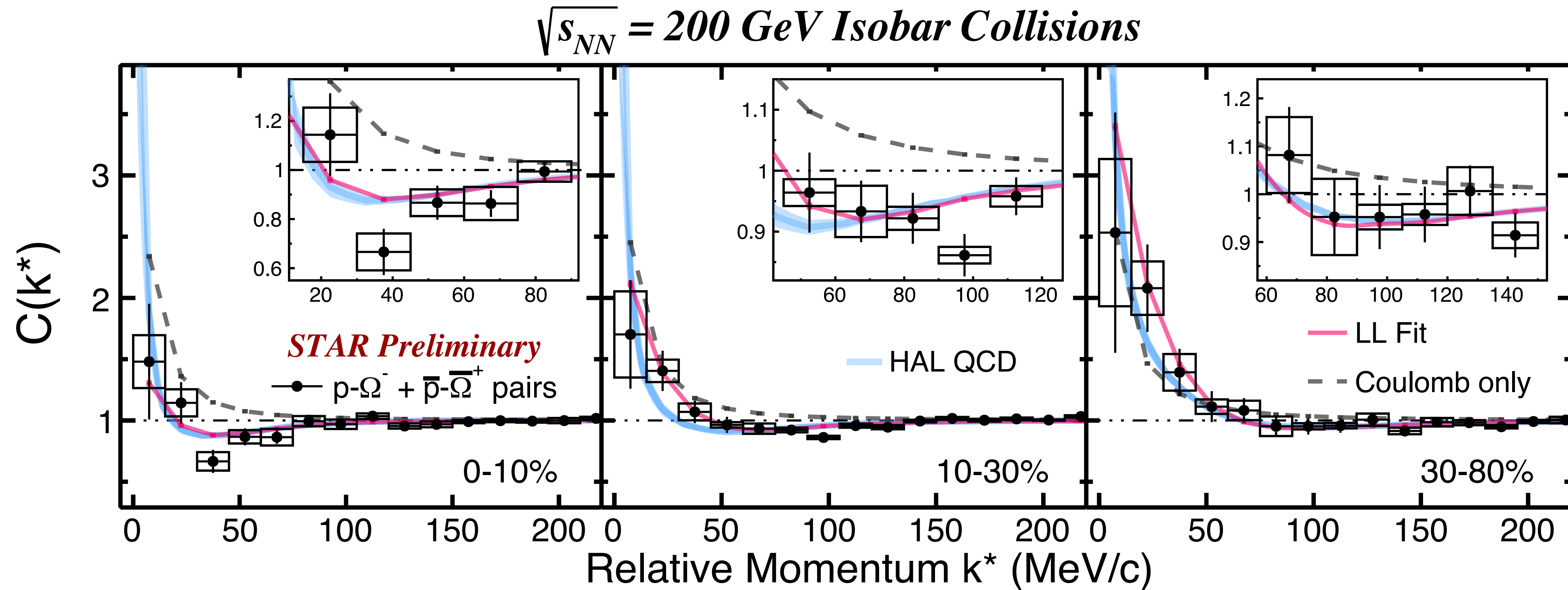
Potential	f_0 (fm)	d_0 (fm)	Chi2/NDF
NSC97a [1]	0.33	12.37	1.53
NF50 [2]	0.77	4.27	1.61
ND52 [3]	-23.96	2.59	2.24
ND50 [3]	10.63	2.04	4.02

[1] P. M. M. Maessen, et al, Phys. Rev. C 40 (1989) 2226

[2] M. M. Nagels, et al, Phys. Rev. D 20 (1979) 1633

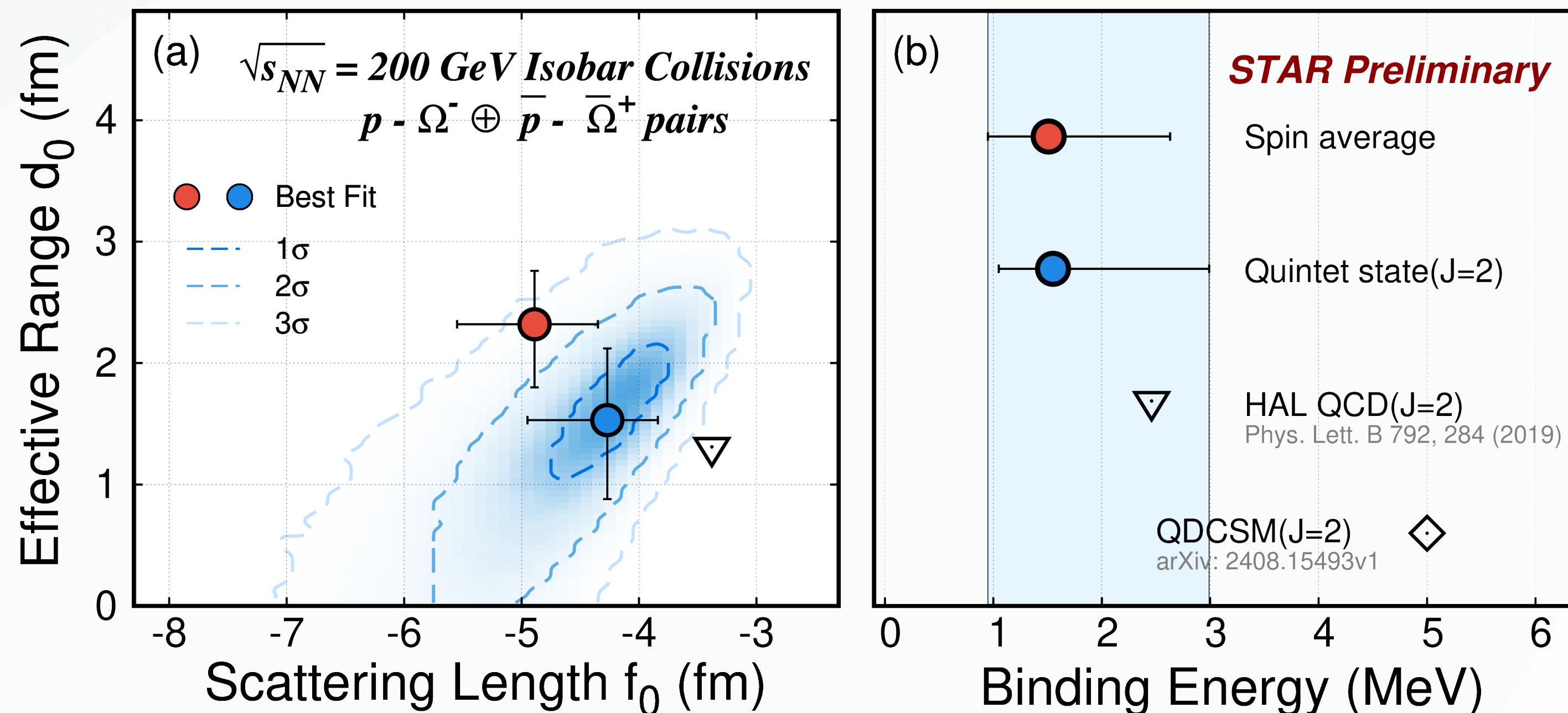
[3] M. M. Nagels, et al, Phys. Rev. D 15 (1997) 2547

p- Ω^- Correlation @ 200 GeV (Isobar)



- Precise measurements of p- Ω^- and $\bar{p}$ - $\bar{\Omega}^+$ correlation functions in Isobar collisions
 - CFs show enhancement at low k^* -> mainly due to Coulomb attraction
 - CFs show depletion at $k^* \sim 30\text{-}100\text{MeV/c}$ -> mainly due to the strong interaction
- Simultaneously fit with LL function for 3 centralities to extract R_G, f_0 and d_0 by Bayesian method
- CFs obtained by HAL QCD with extract R_G by LL model is consistent with the data.

p- Ω^- Correlation @ 200 GeV (Isobar)



- First experimental constraints in heavy-ion collisions of strong interaction parameters in p- Ω^- pair
- Extracted negative f_0 ($|f_0| > 2d_0$) by Spin average method and Quintet method
 - **First experimental evidence of Strange Dibaryon!**
- Calculate binding energy (BE) via Betha formula
 - $\text{BE} = 1.6^{+1.4}_{-0.5} \text{ MeV}$

	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.89^{+0.54}_{-0.66}$	$-4.27^{+0.43}_{-0.68}$	-3.38
d_0 (fm)	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	1.31
BE (MeV)	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	2.27

Summary



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

⇒ p-d, d-d correlation

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

⇒ d- Λ correlation

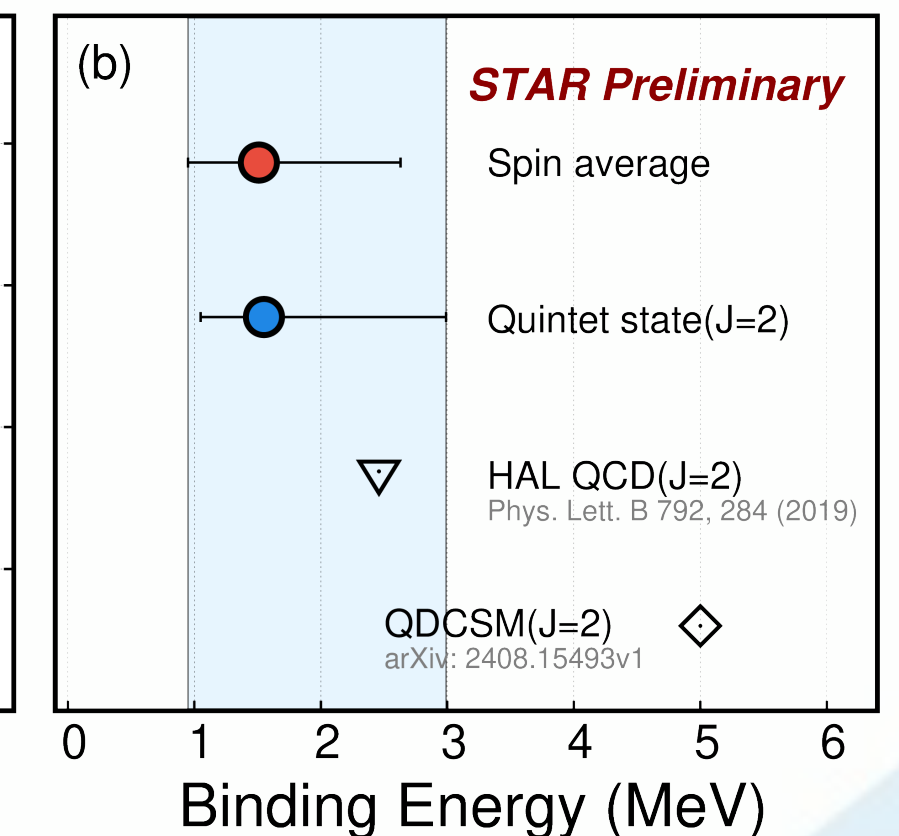
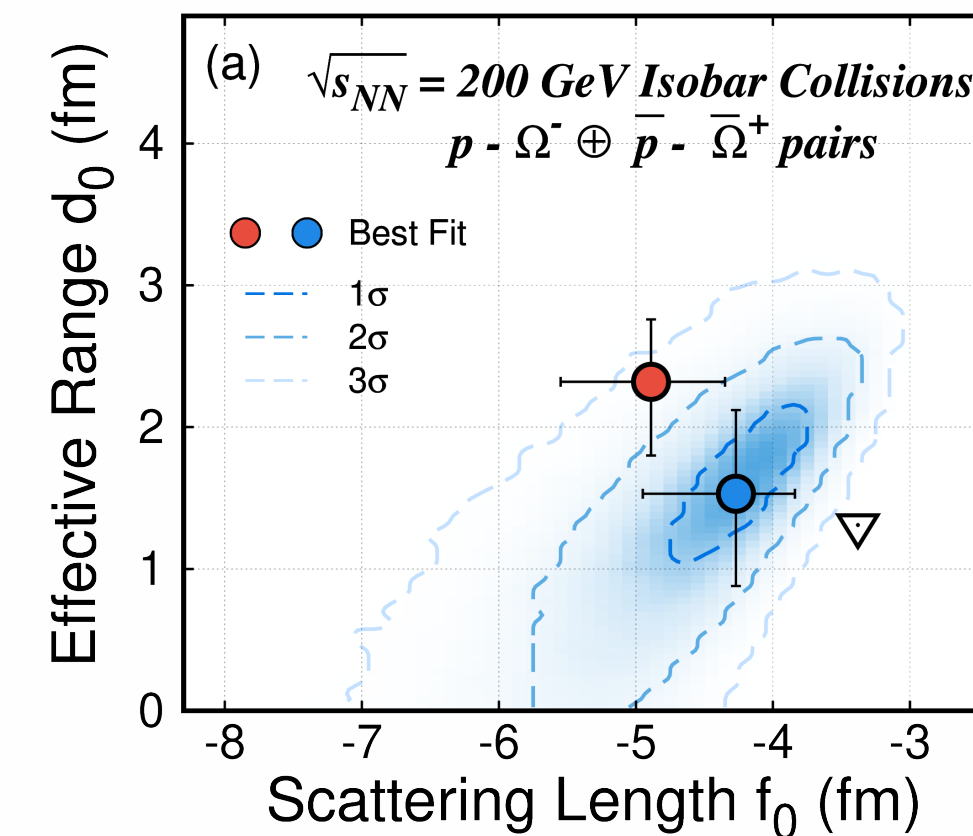
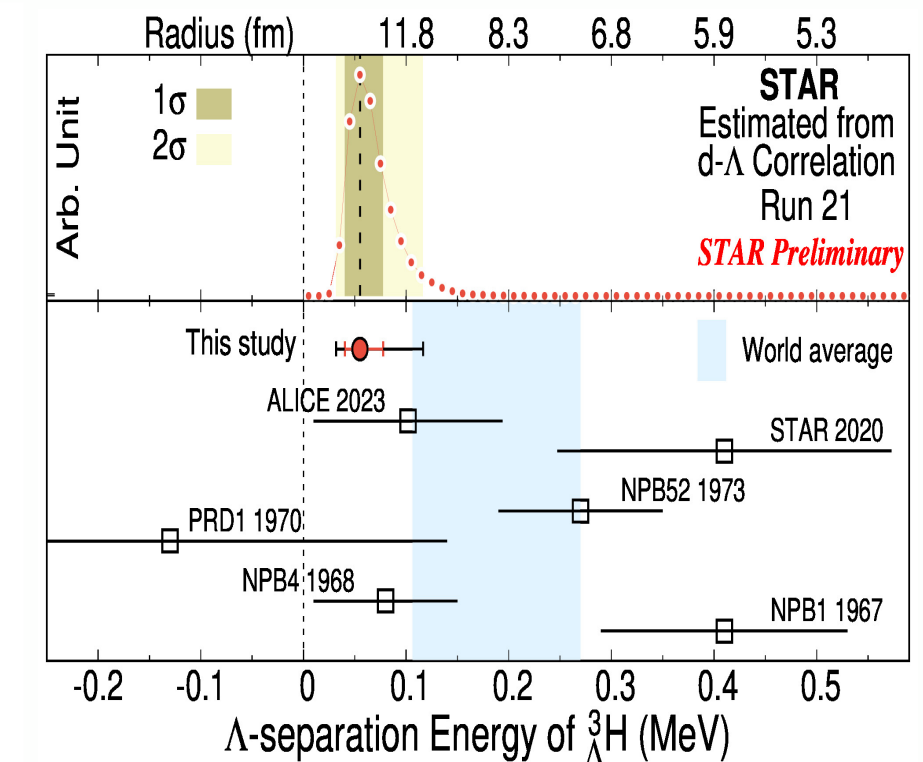
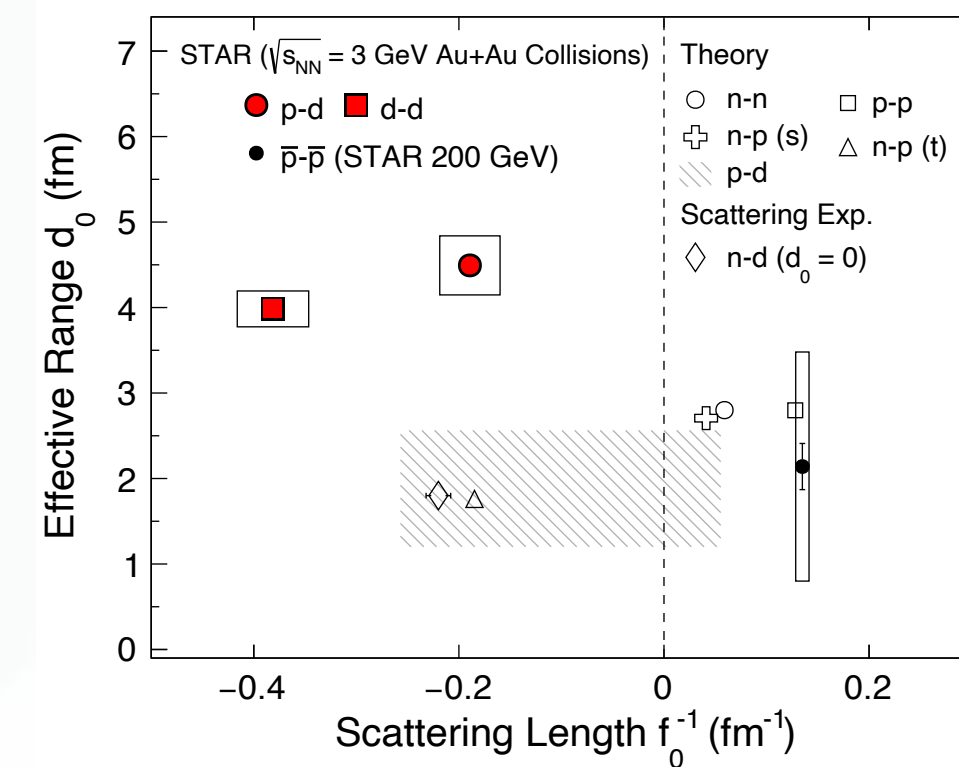
- **Most accurate results of binding energy and radius of $^3_\Lambda\text{H}$**
- Provide a new way to explore hypernuclei properties

⇒ p- Ω correlation

- **First experiment evidence of Strange-Dibaryon in p- Ω^- channel !**

* **More interesting results are on the way!**

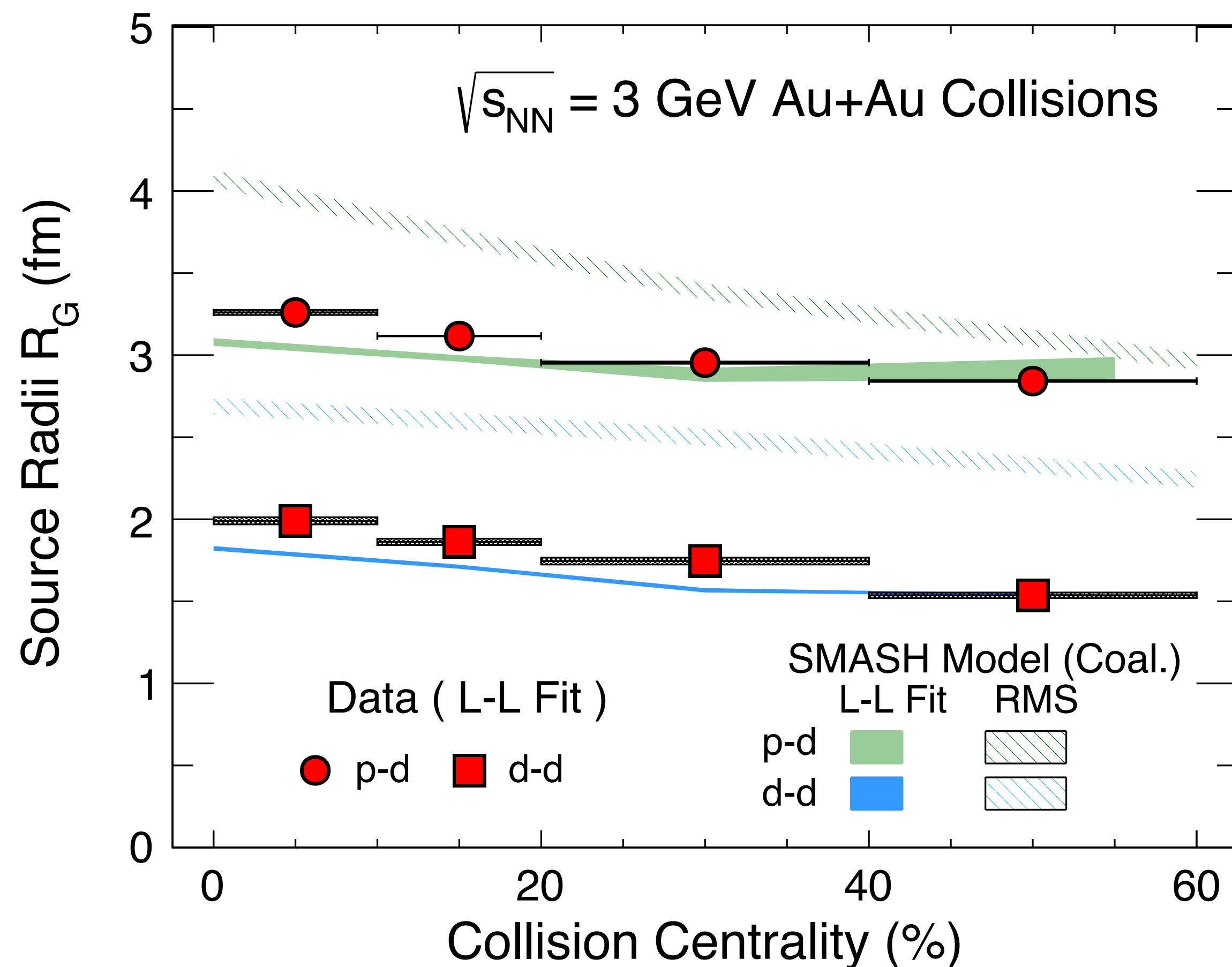
- * Di-baryon search: p- Ξ^- , Λ - Λ ..
- * Hyper-nuclei properties: t- Λ , ^3He - Λ ...
- * Triplets correlation: p-p-p, p-p- Λ , p- Λ - Λ ..



Thank you ! 25 YEARS

Backup

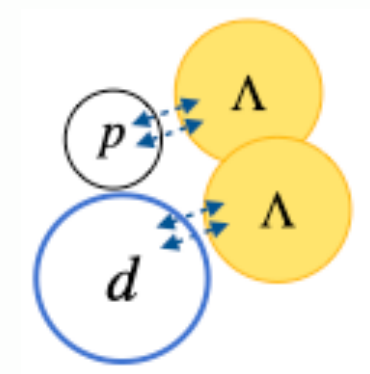
p-d / d-d Source Size



- **Extracted source size (R_G) with LL model**
 - **Centrality dependence:** $R_G^{\text{central}} > R_G^{\text{peripheral}}$
 - **$\langle m_T \rangle$ 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: Phys. Lett. B 864, 139412 (2025)

p- Λ / d- Λ Source Size



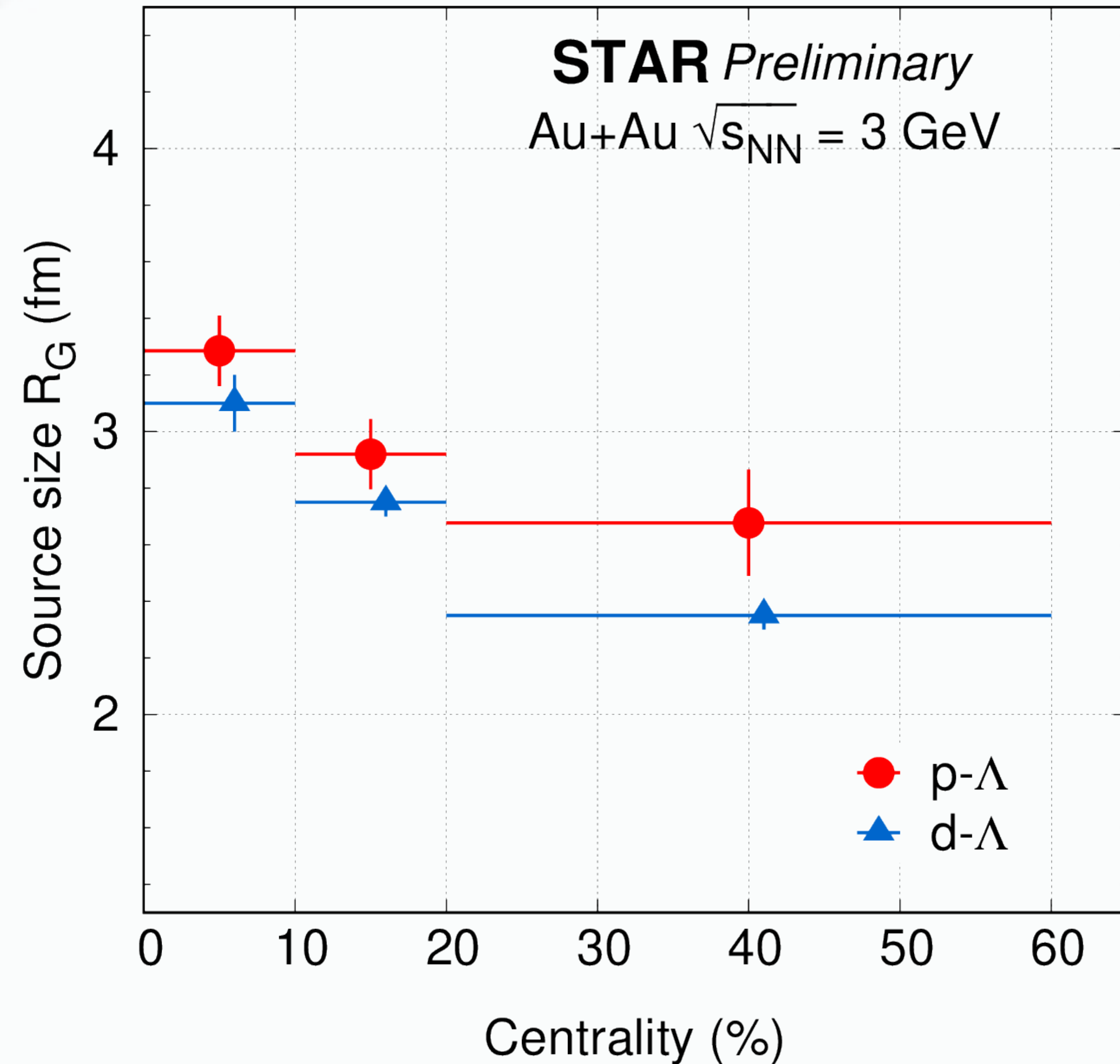
STAR

⇒ R_G : spherical Gaussian source size

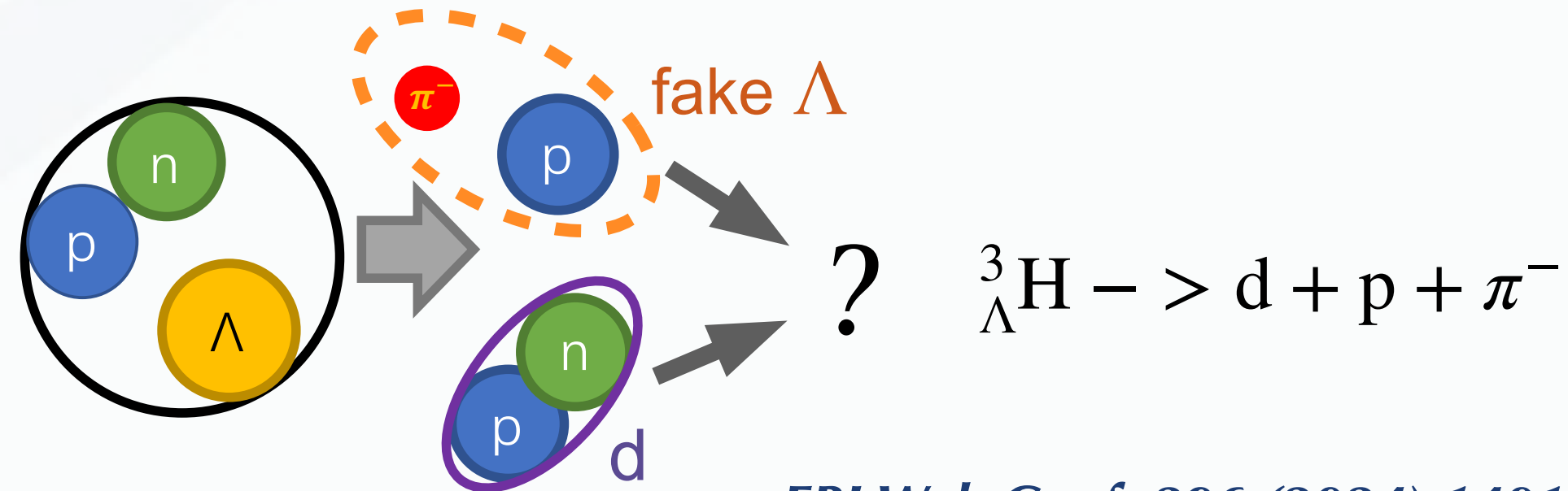
⇒ Collision dynamics as expected

○ Centrality dependence: $R_G^{\text{central}} > R_G^{\text{peripheral}}$

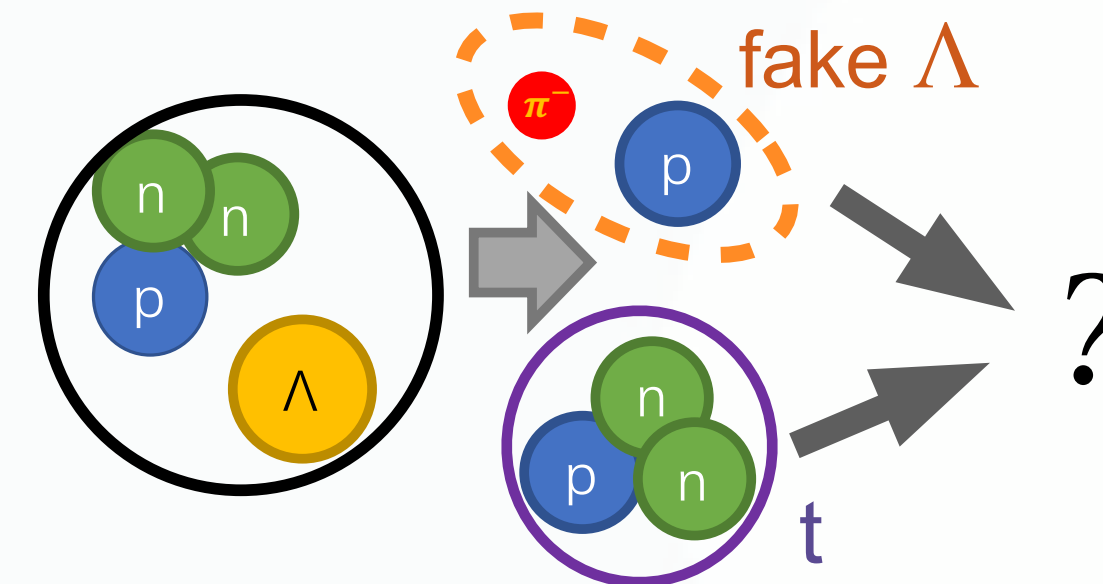
○ $\langle m_T \rangle$ dependence: $R_G(p - \Lambda) > R_G(d - \Lambda)$



Contamination from Hyper-nuclei Decay



EPJ Web Conf. 296 (2024) 14010

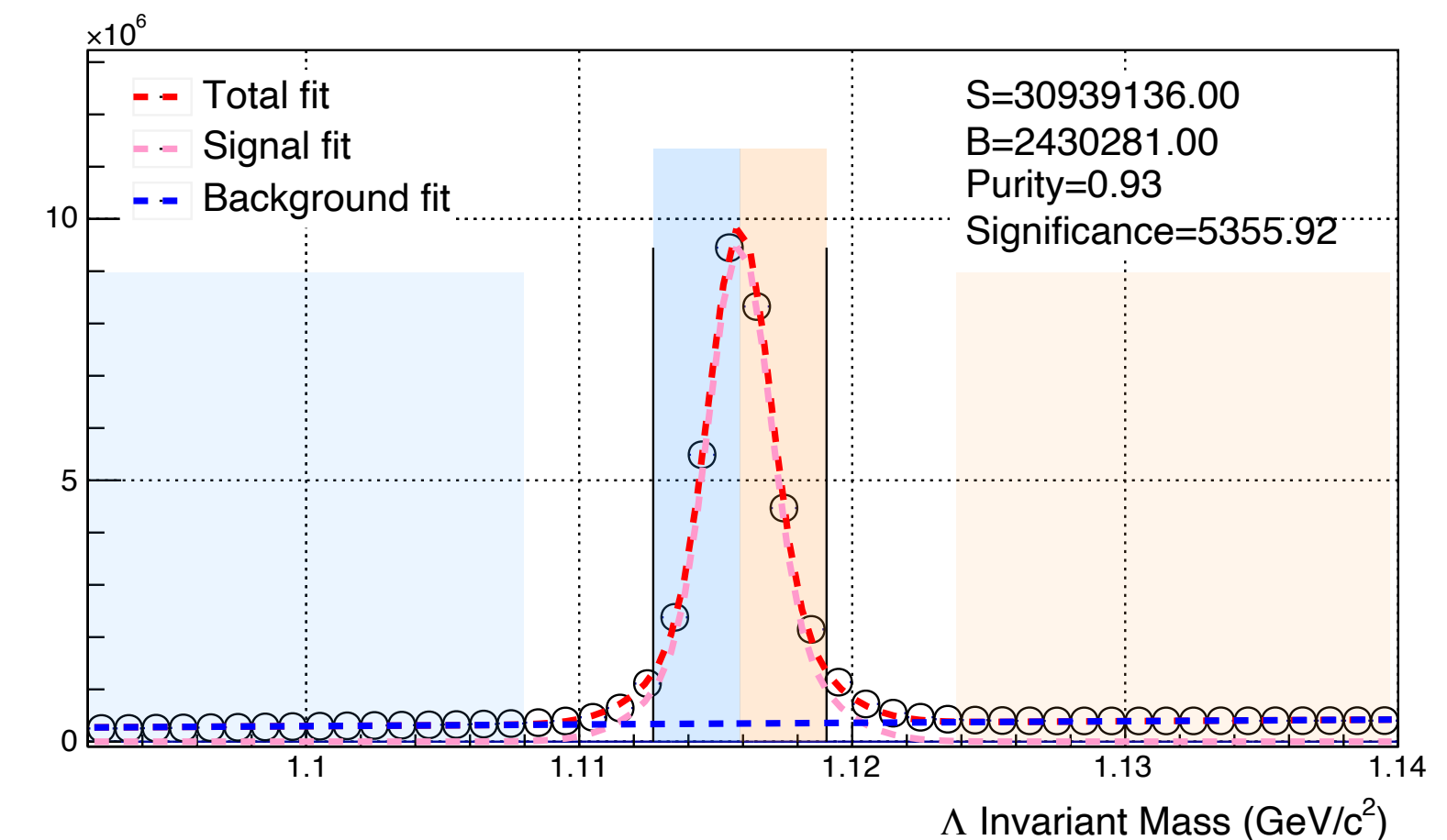
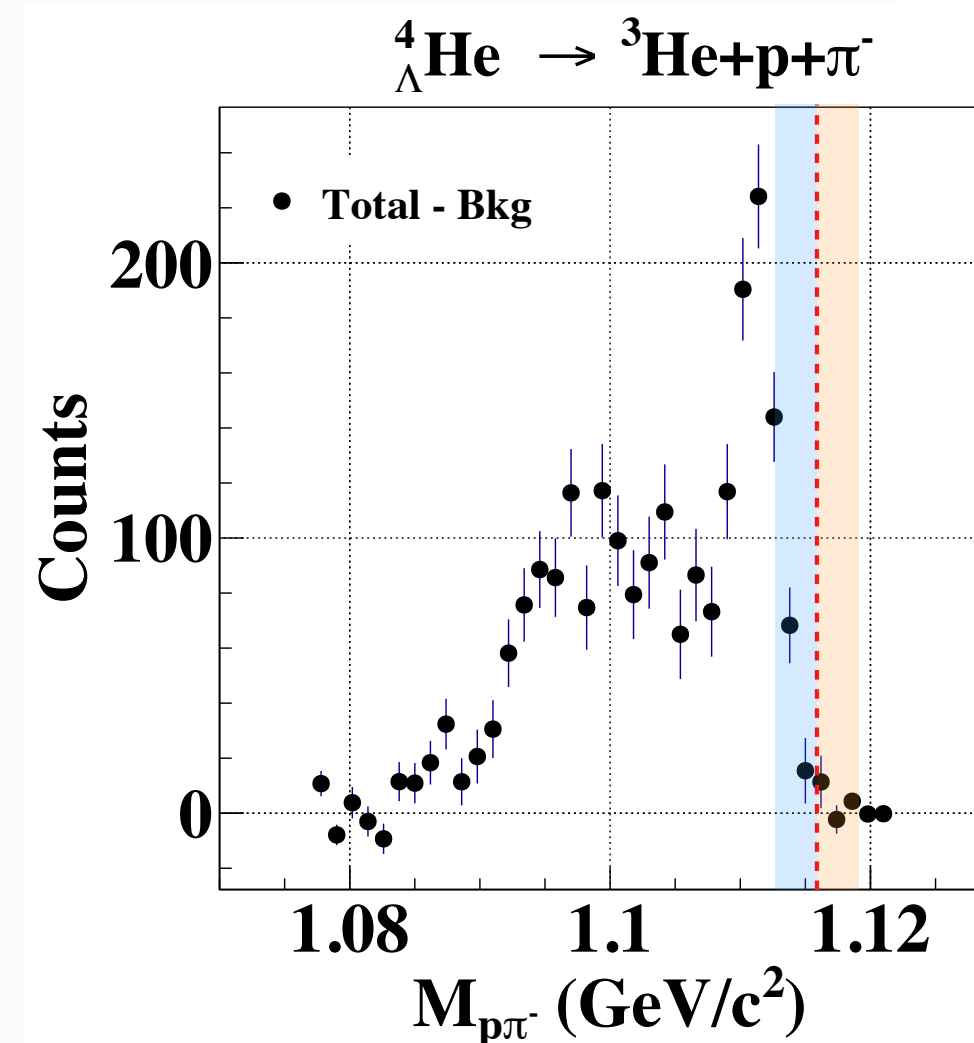
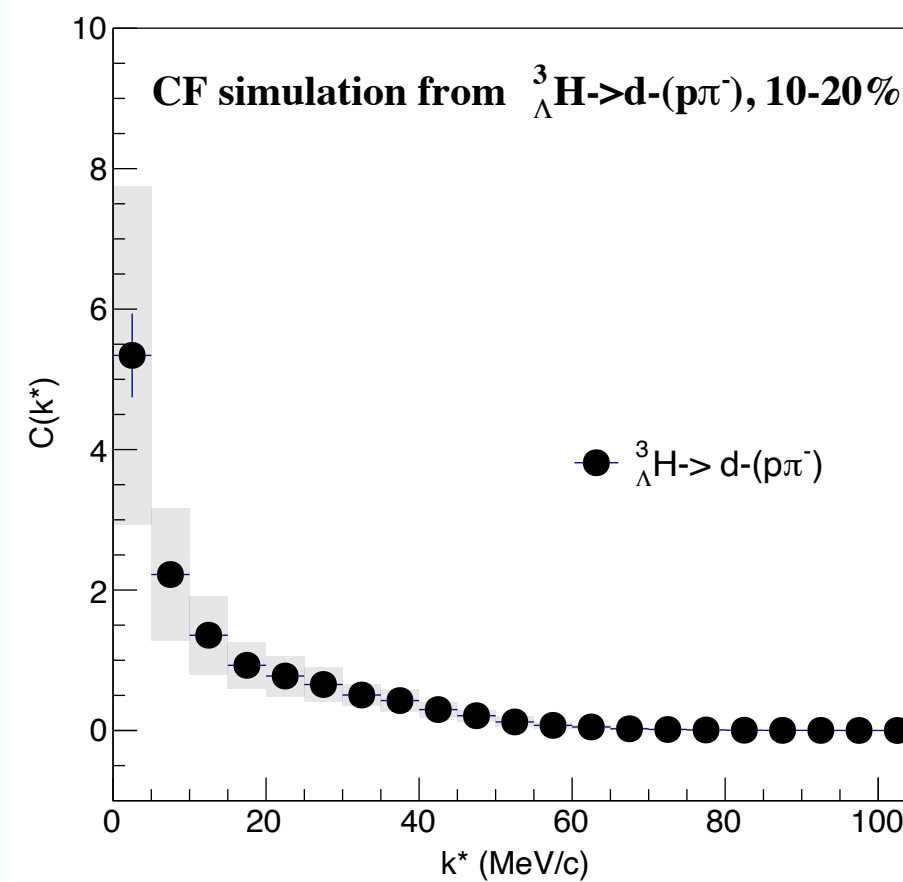
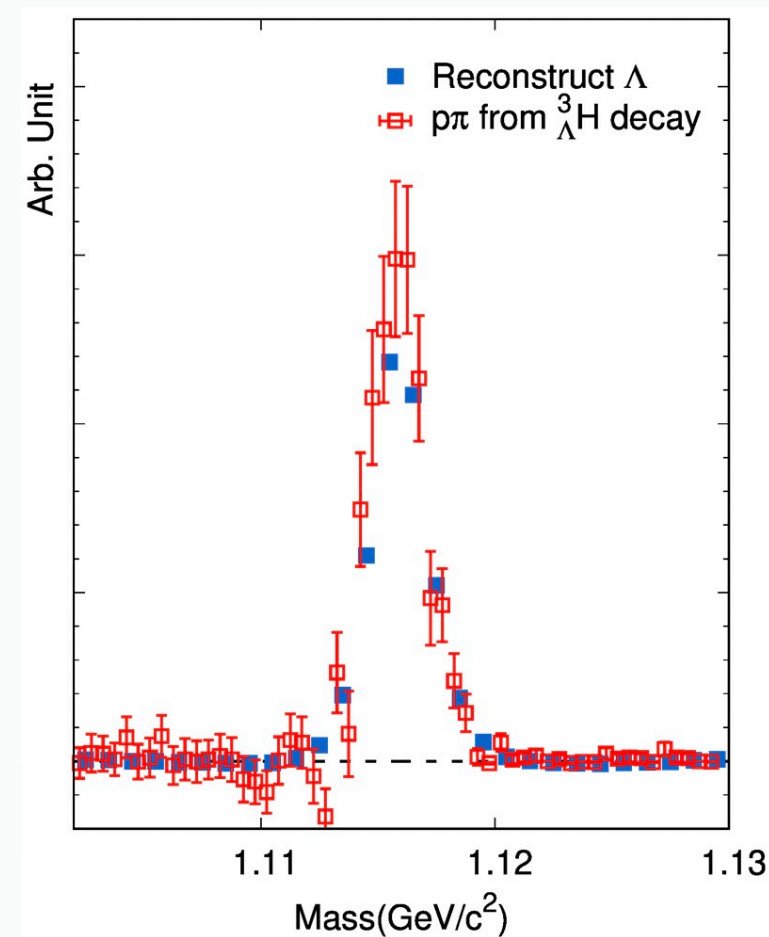


$${}^4_{\Lambda}\text{H} \rightarrow t + p + \pi^-$$

$${}^4_{\Lambda}\text{He} \rightarrow {}^3\text{He} + p + \pi^-$$

Left signal: 1.11271~1.11589 GeV/c²

Right signal: 1.11589~1.11906 GeV/c²



- The ${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ decayed $p + \pi^-$ are not experimentally distinguishable with the reconstructed Λ .
- $(p\pi^-) - d$ from ${}^3_{\Lambda}\text{H}$ will affect CF at small k^* region, as same with $(p\pi^-) - t$ and $(p\pi^-) - {}^3\text{He}$.
- For $d - \Lambda$, since we cannot separate them experimentally, we need to estimate their contribution and remove it from the CF.
- For $t - \Lambda$ and ${}^3\text{He} - \Lambda$, we can experimentally remove the contribution by selecting the right side of the Λ invariant mass peak.