Recent Results of Baryon Correlations at RHIC-STAR

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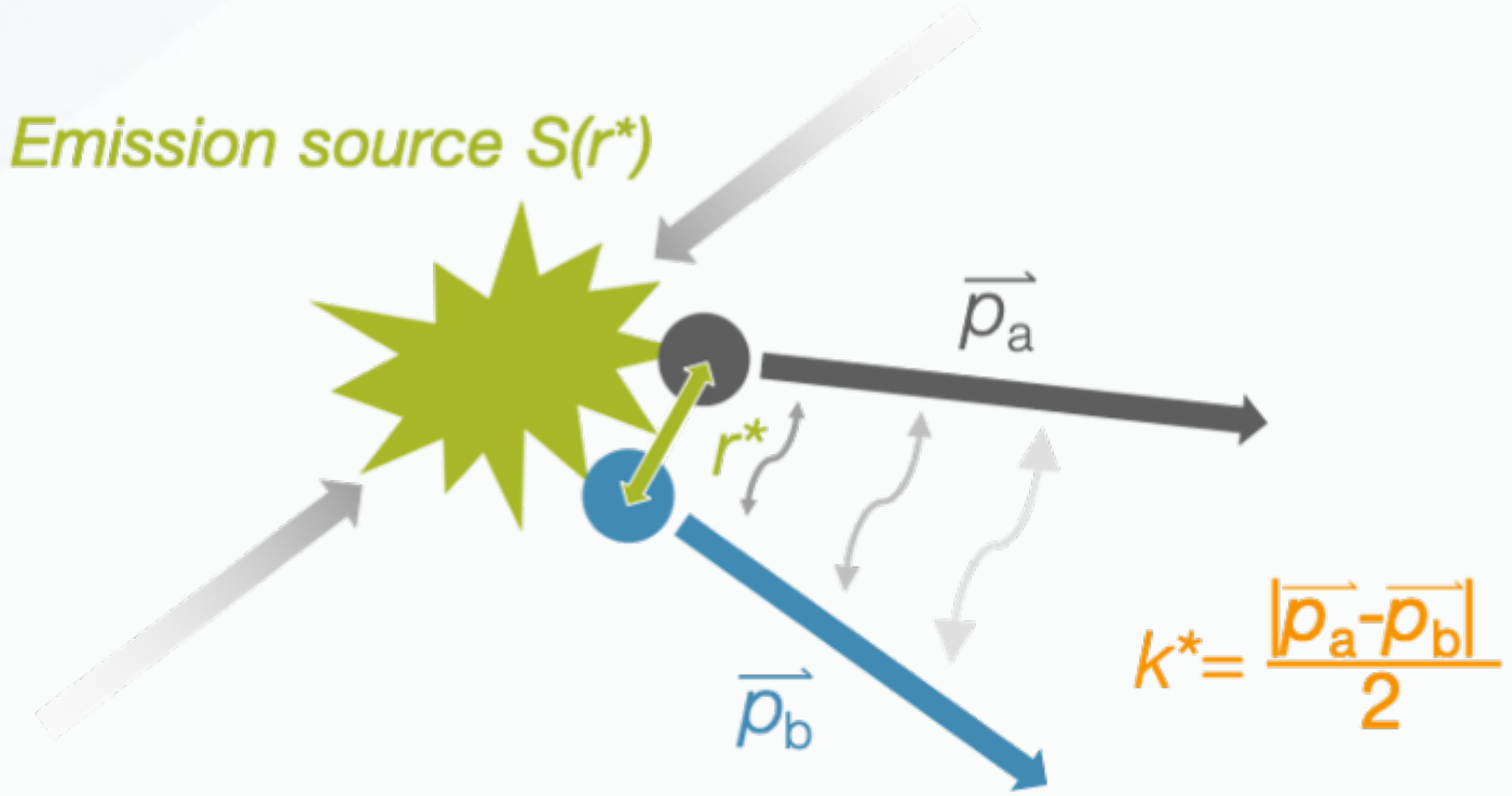
Central China Normal University

2025/04/17
XV Collaboration Meeting of the MPD Experiment at NICA — April 15-17 2025 — JINR

Outline

- Introduction
  - Femtoscopy
  - Lednicky-Lyuboshitz Approach
  - Motivation
  - STAR Detector
- Results
  - p-p, p-d and d-d Correlation
  - p-Λ, d-Λ, t-Λ and ^{3}He-Λ Correlation
  - p-Ξ^{-}, Λ-Λ and p-Ω^{-} Correlation
- Summary & Outlook

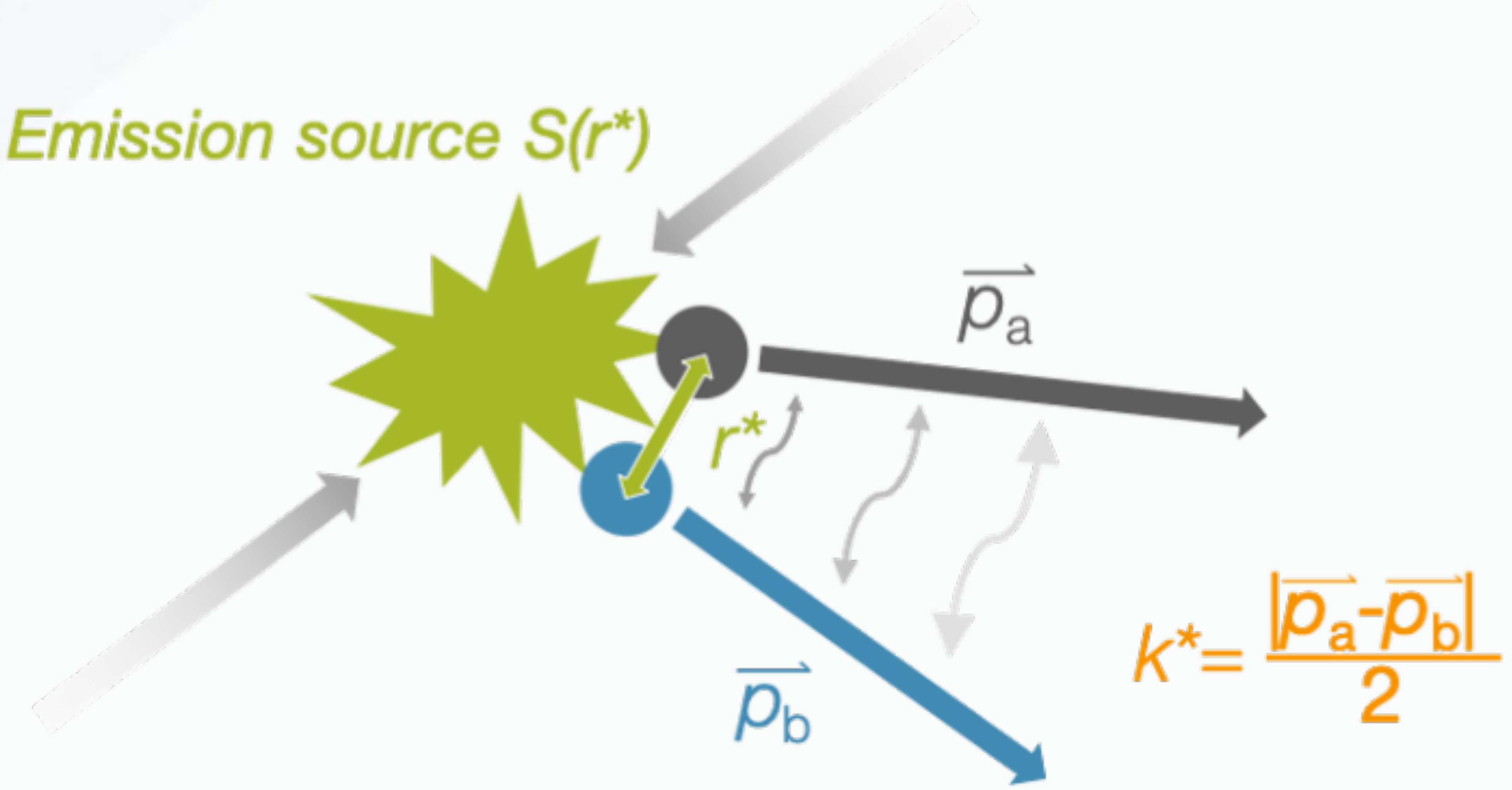
Femtoscopy



- **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)

Femtoscopy



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- **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*

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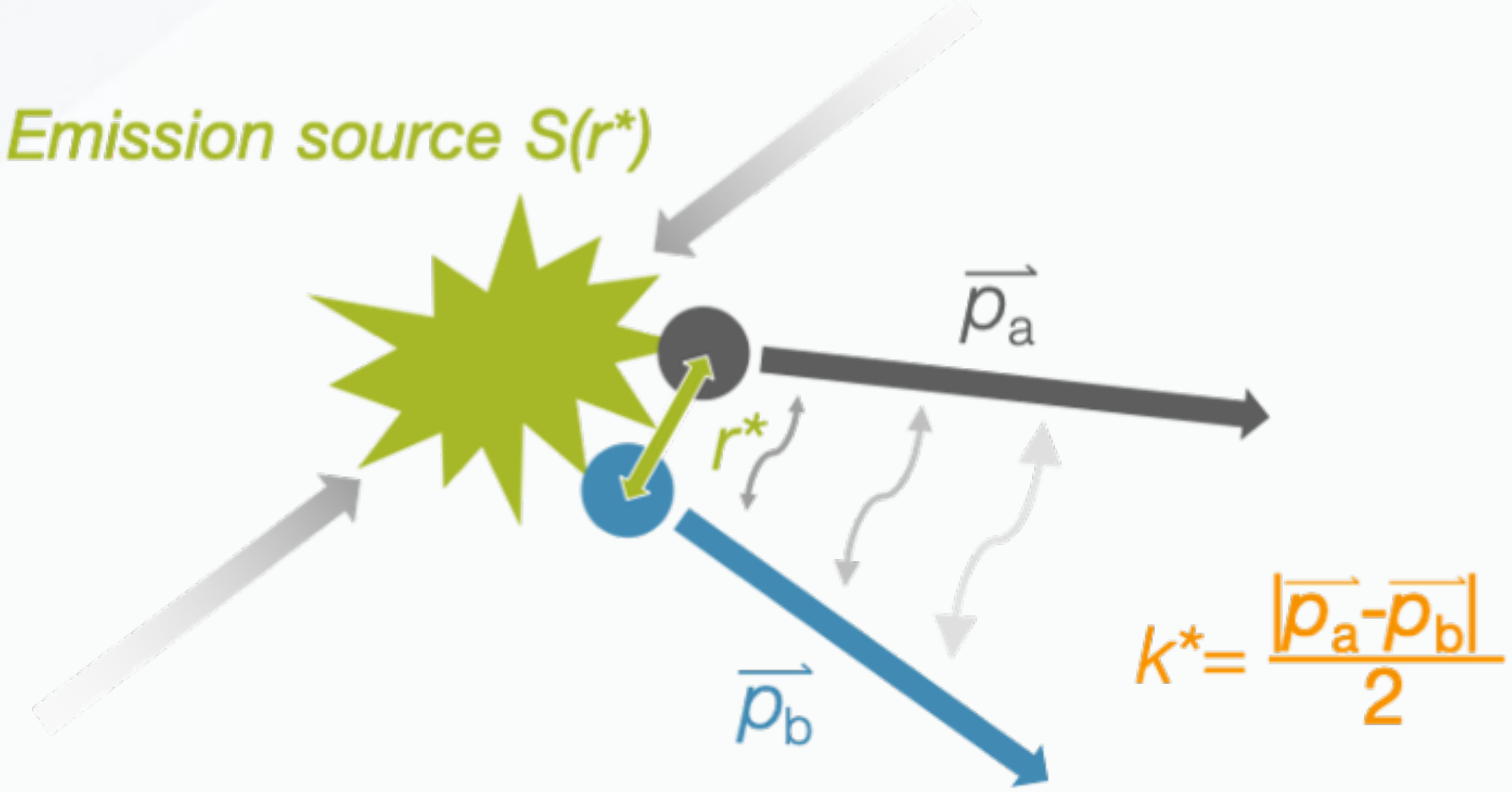

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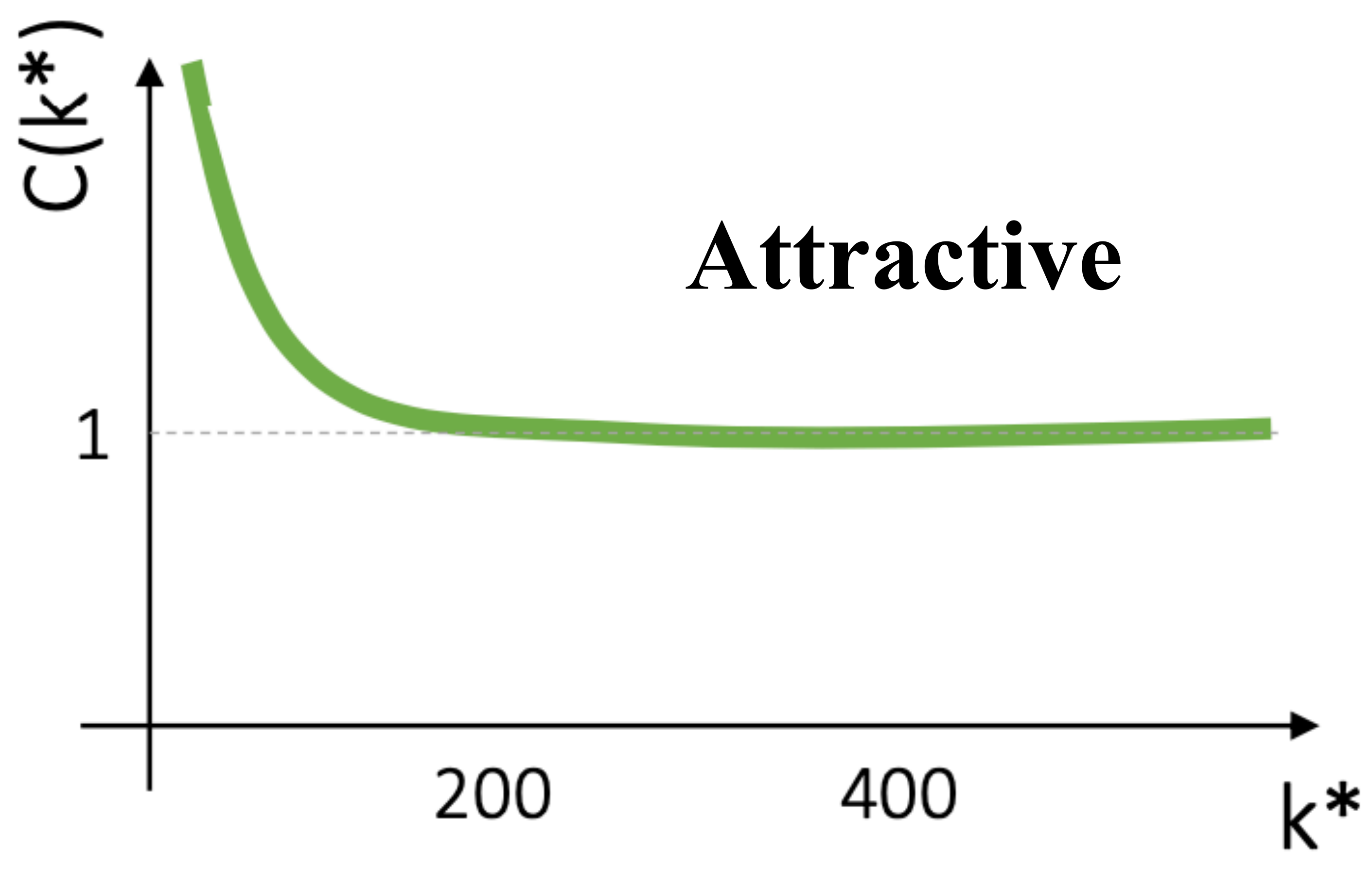

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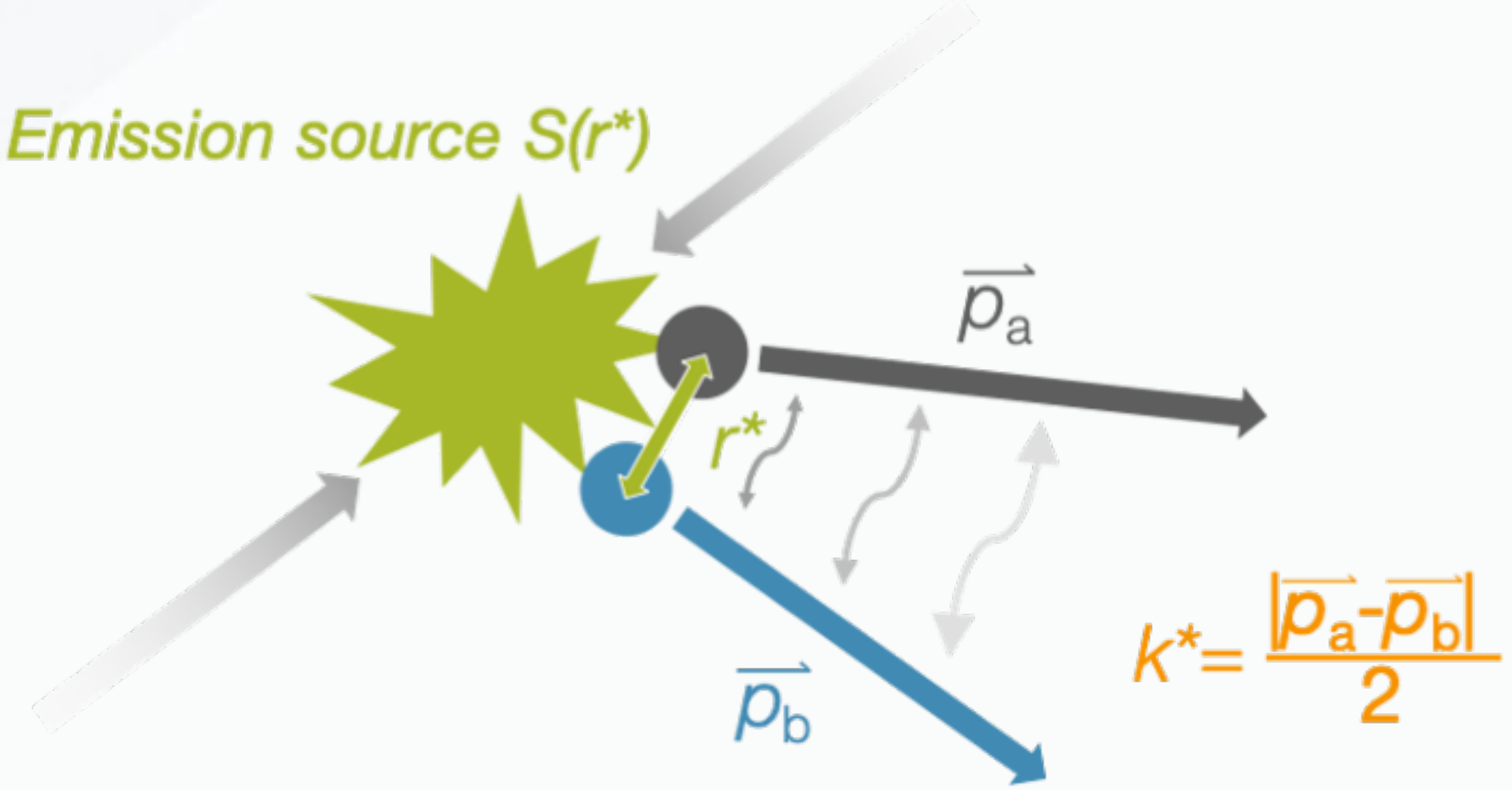

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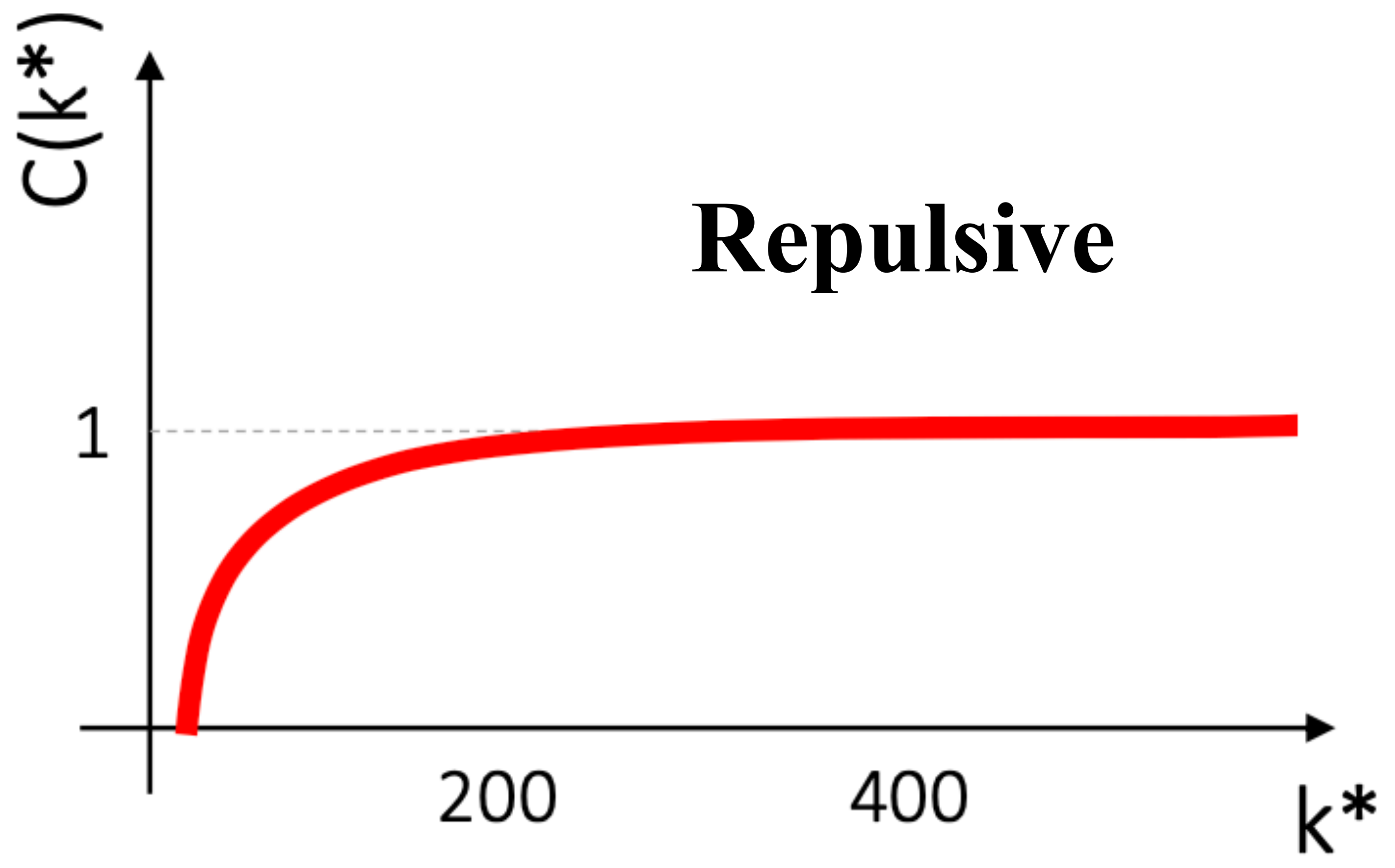

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Lednicky-Lyuboshitz approach

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

- **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:**

W/O Coulomb:

$$f_c(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - ik^*]^{-1}$$

W/ Coulomb:

$$f_c(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta)]^{-1}$$

Physics Parameters:

R_G: Spherical Gaussian source

f_0 : Scattering length

d_0 : Effective range

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Physics Parameters:

R_G: Spherical Gaussian source

$\boxed{f_0 : \text{Scattering length}}$ $\xrightarrow{\text{Sign}}$

d_0 : Effective range

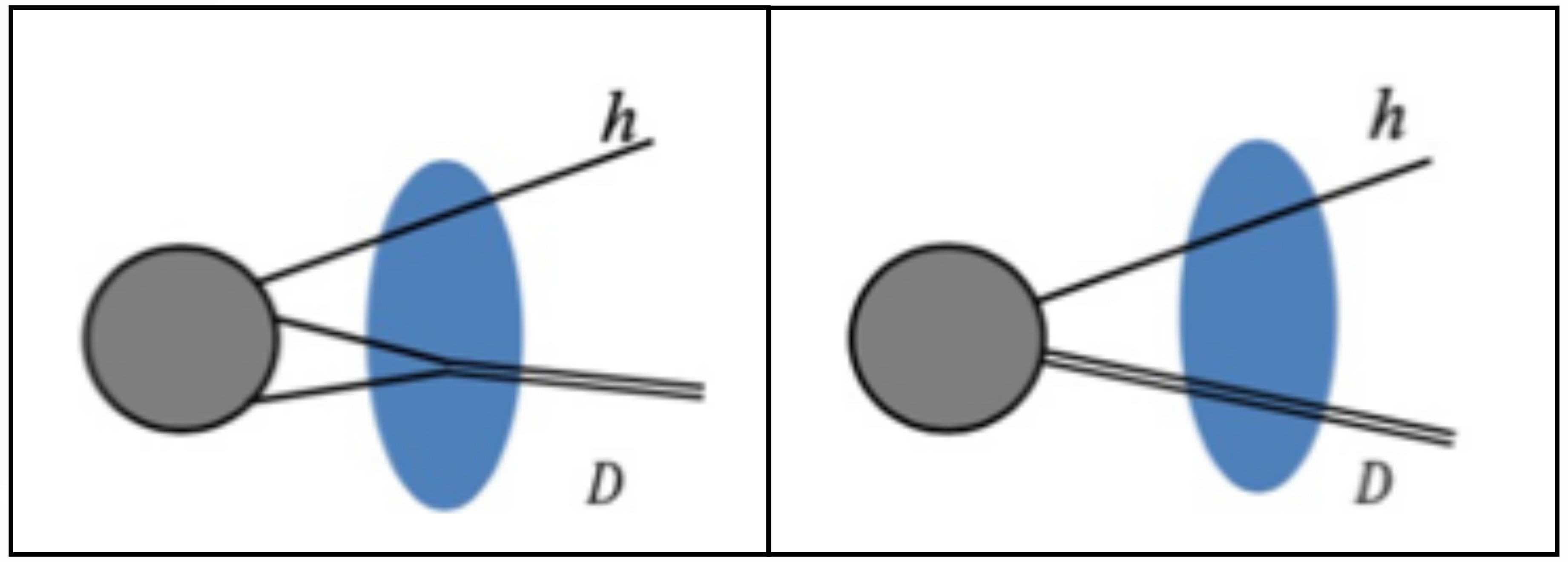
$f_0 > 0$: Attractive interaction

$f_0 < 0$: Repulsive interaction/ bound state

(distinguished by the relation between f_0 and d_0)

Motivation

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



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)

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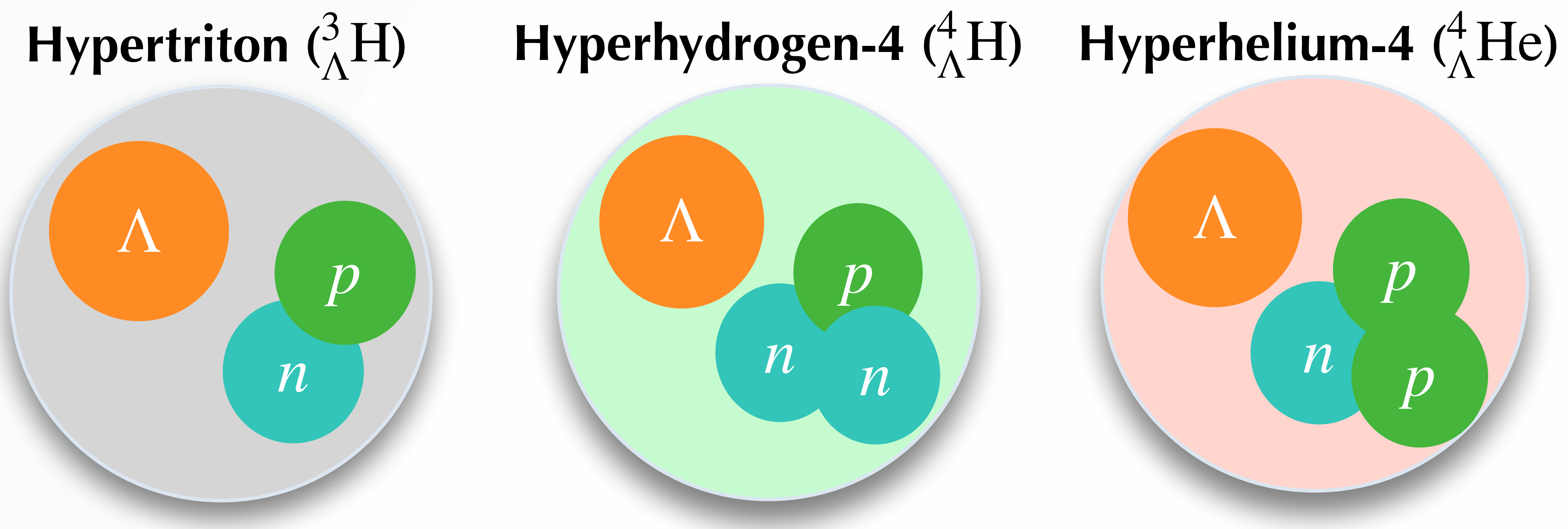
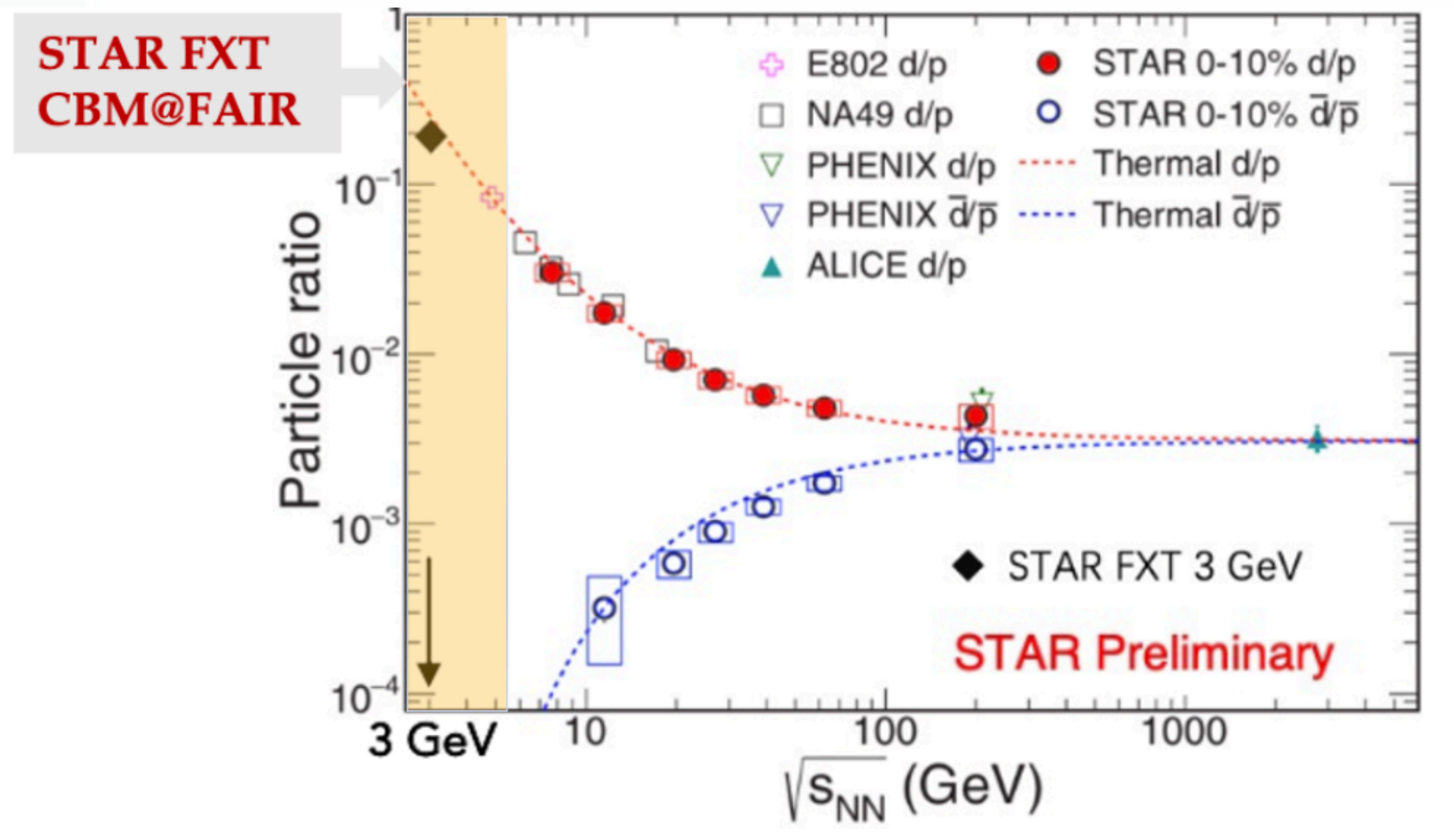
- **Light nuclei - Λ correlation: insights to hyper-nuclei structure and properties**





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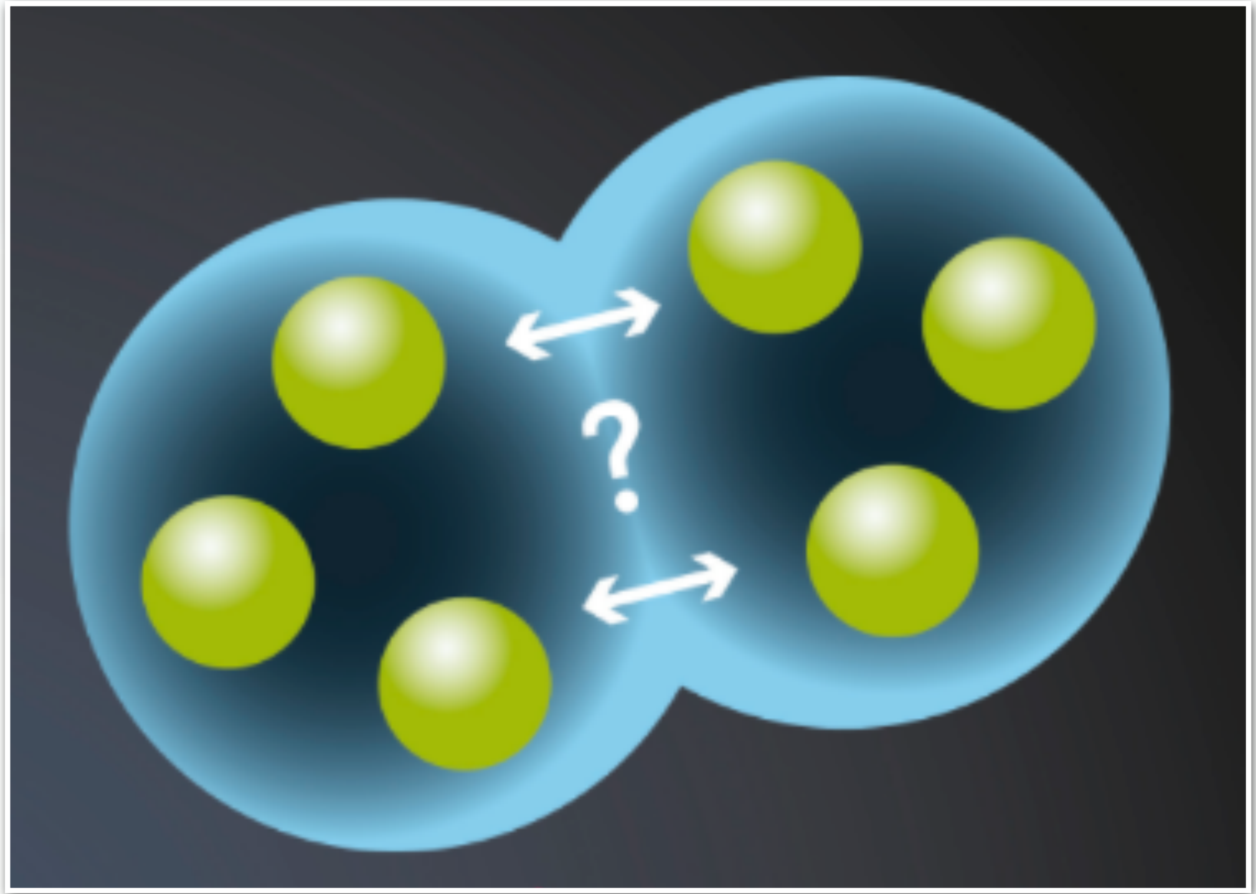
- Light nuclei - Λ correlation: insights to hyper-nuclei structure and properties

- **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**



Particle	Mass (MeV)	Quark composition	Decay mode
f_0	980	$q\bar{q}s\bar{s}$	$\pi\pi$
a_0	980	$q\bar{q}s\bar{s}$	$\pi\eta$
K(1460)	1460	$q\bar{q}q\bar{s}$	$K\pi\pi$
$\Lambda(1405)$	1405	$qqqs\bar{q}$	$\pi\Sigma$
$\Theta^+(1530)$	1530	$qqqq\bar{s}$	KN
H	2245	uuddss	$\Lambda\Lambda$
$N\Omega$	2573	qqqsss	$\Lambda\Xi$
$\Xi\Xi$	2627	qqssss	$\Lambda\Xi$
$\Omega\Omega$	3228	ssssss	$\Lambda K^- + \Lambda K^-$

Phys.Rev.C 99, 064905 (2019)
Phys.Rev.C 84, 064910 (2011)
Phys.Rev.C 83 (2011) 015202
Sungtae Cho, et al. (ExHIC), Phys. Rev. C 84, 064910 (2011)

Motivation

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  $\Rightarrow$ Coalescence : final-state interaction
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- Light nuclei - Λ correlation: insights to hyper-nuclei structure and properties

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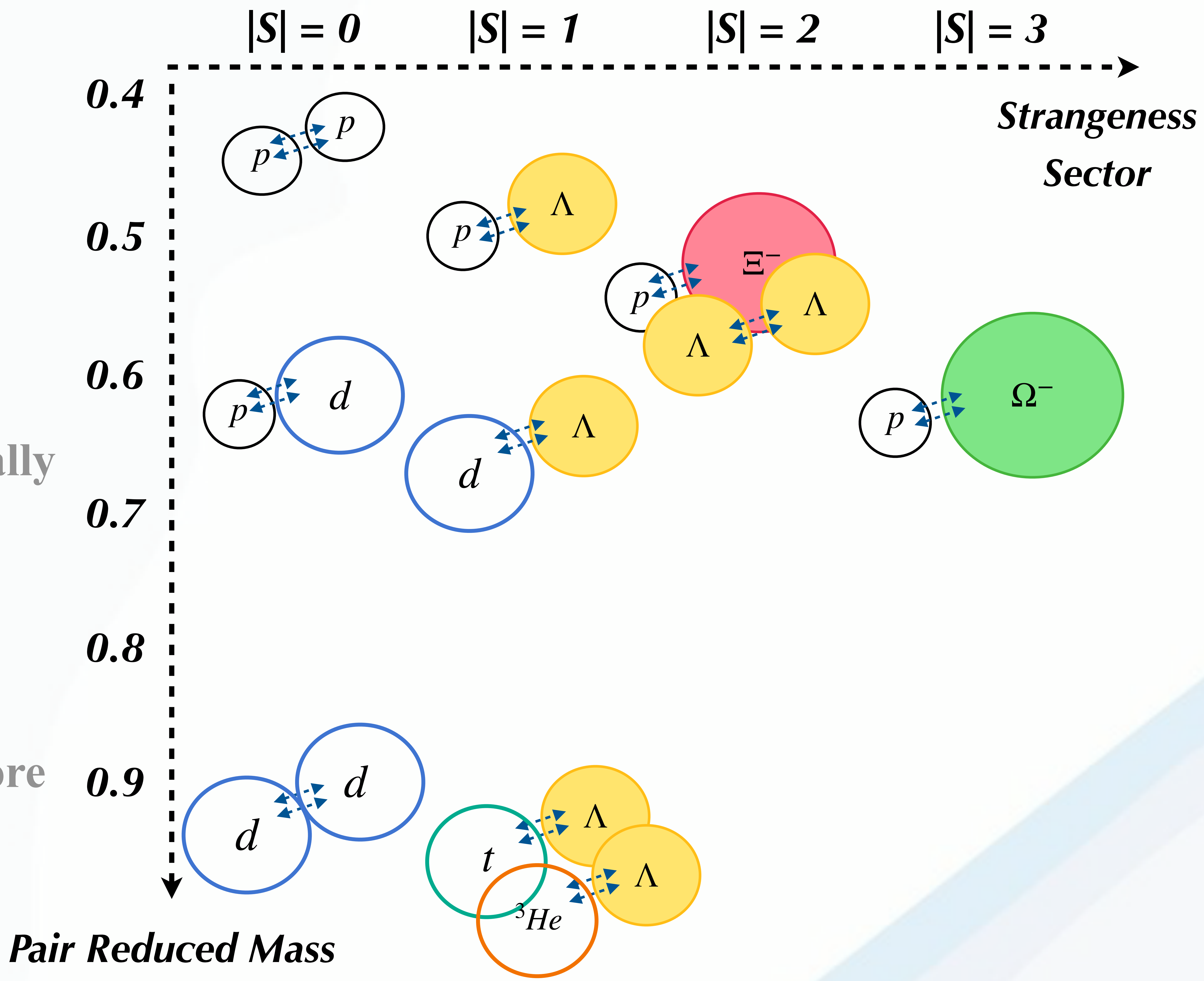
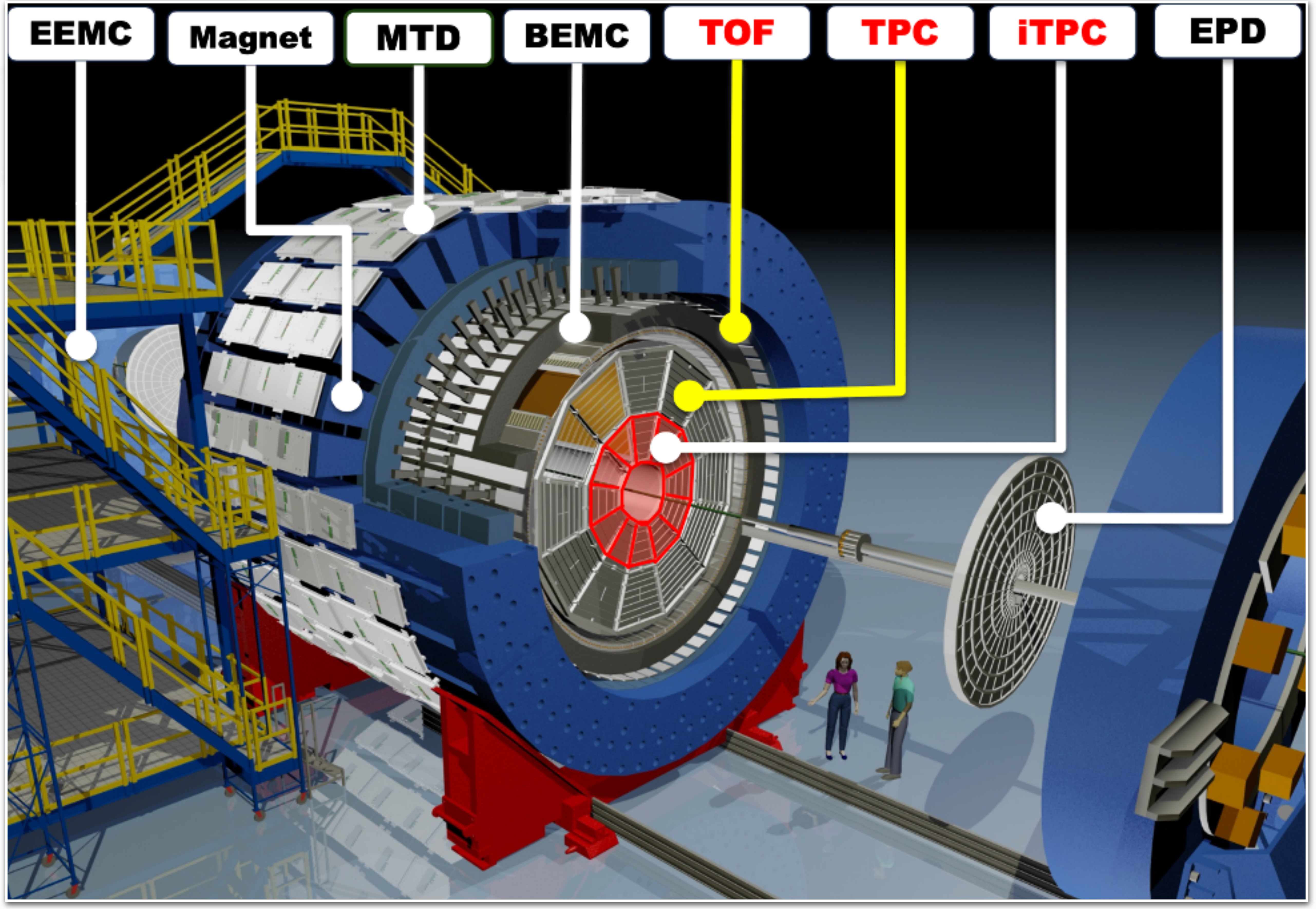
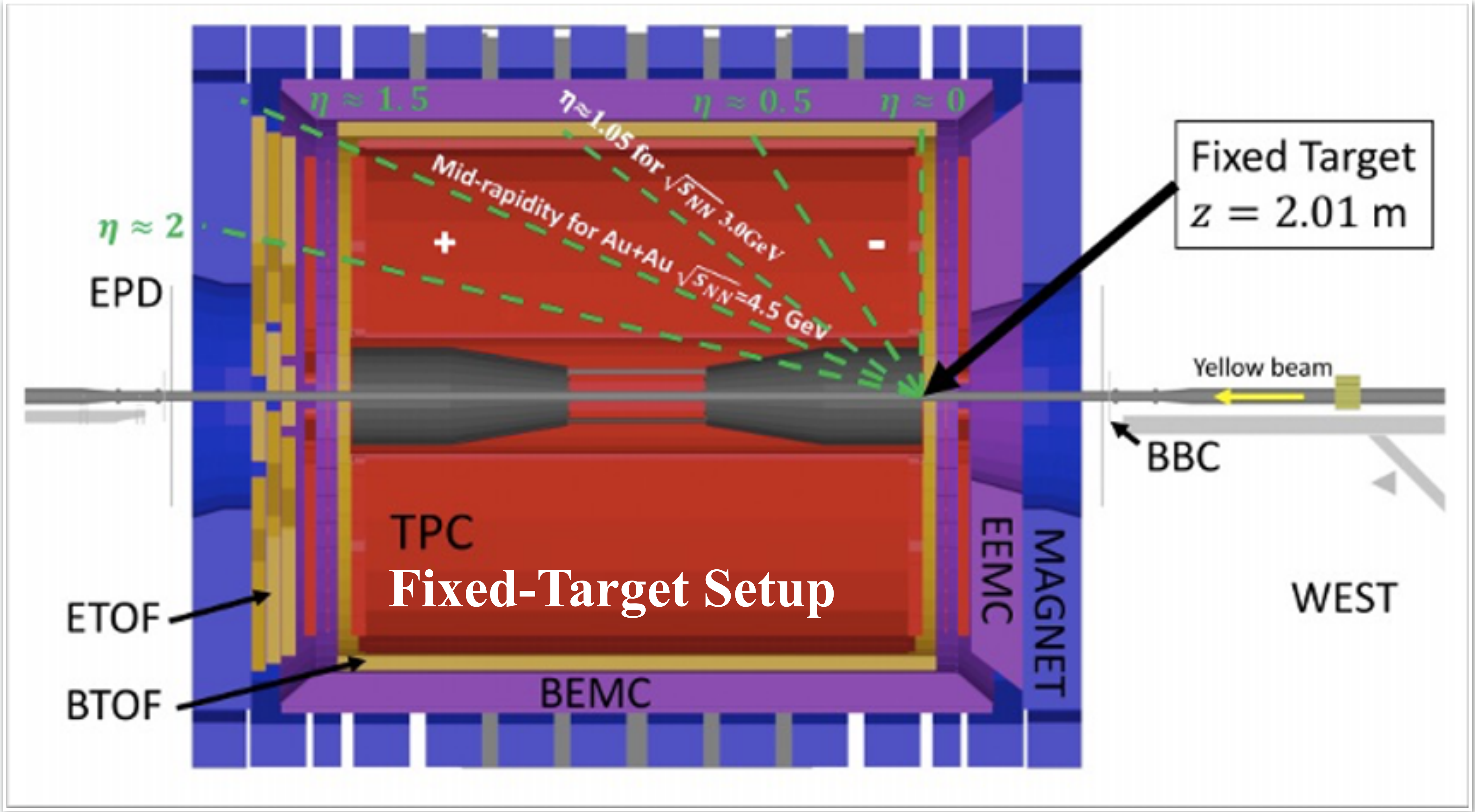
This talk covers:



STAR Detector



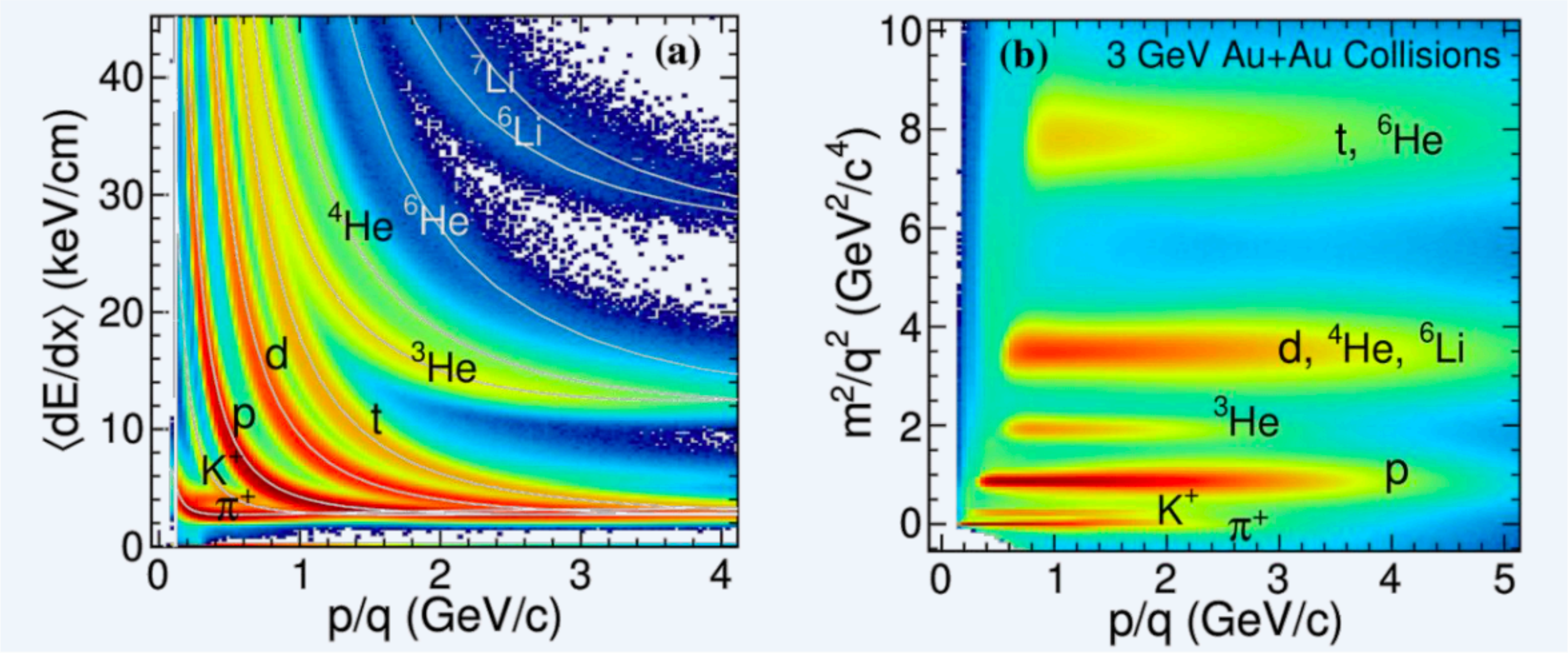


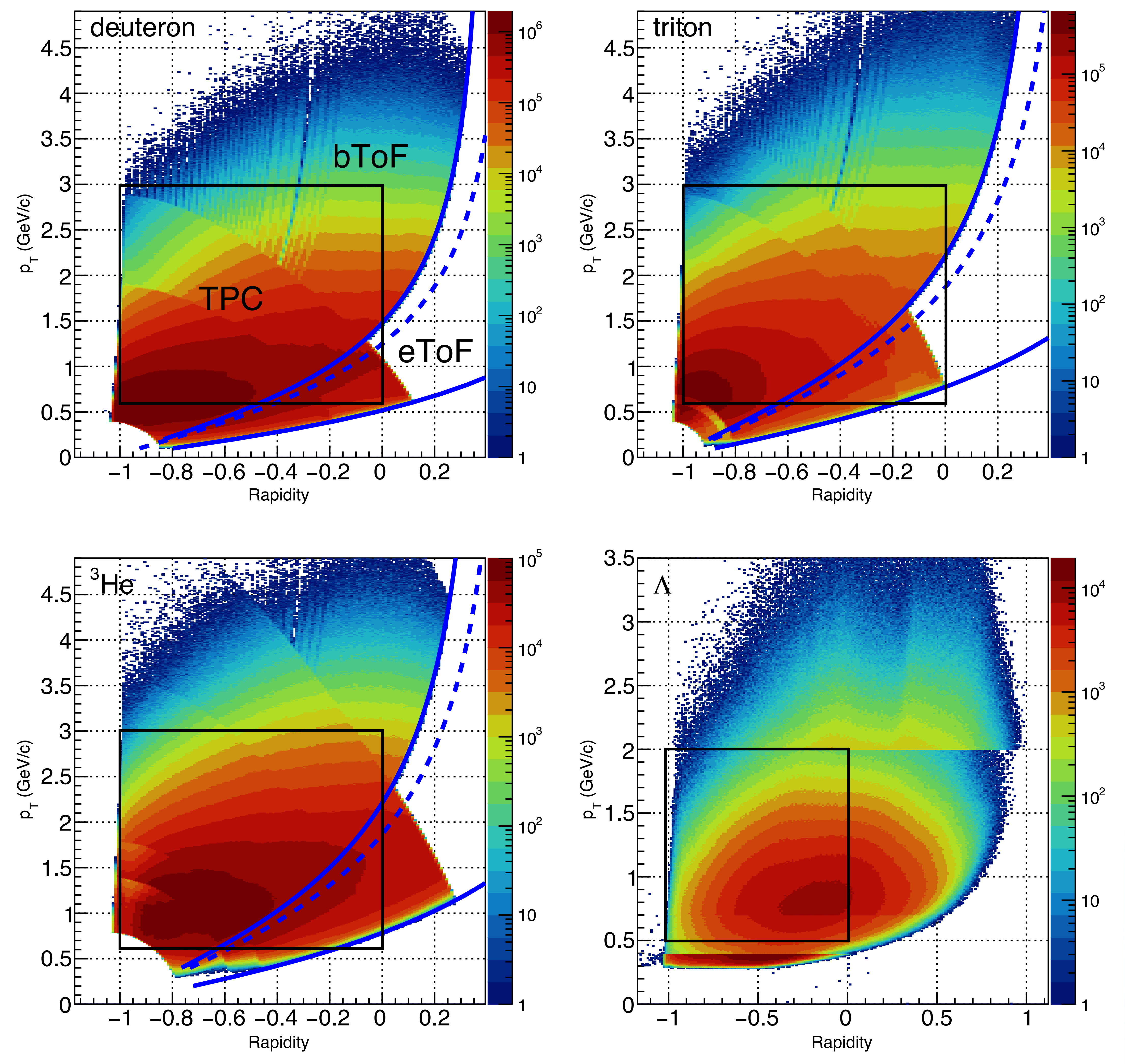
Center-of-Mass Energy	Collisions	Year	Mode	#Events
3 GeV	Au+Au	2018	FXT	260 M
3 GeV	Au+Au	2021	FXT	2000 M
200 GeV	Au+Au	2011/2014/2016	Collider	2000 M
200 GeV	Isobar (Ru+Ru/ Zr+Zr)	2018	Collider	4000 M

⇒ **Excellent particle identification**

⇒ **Large, uniform acceptance at mid-rapidity**

Particle Identification & Reconstruction



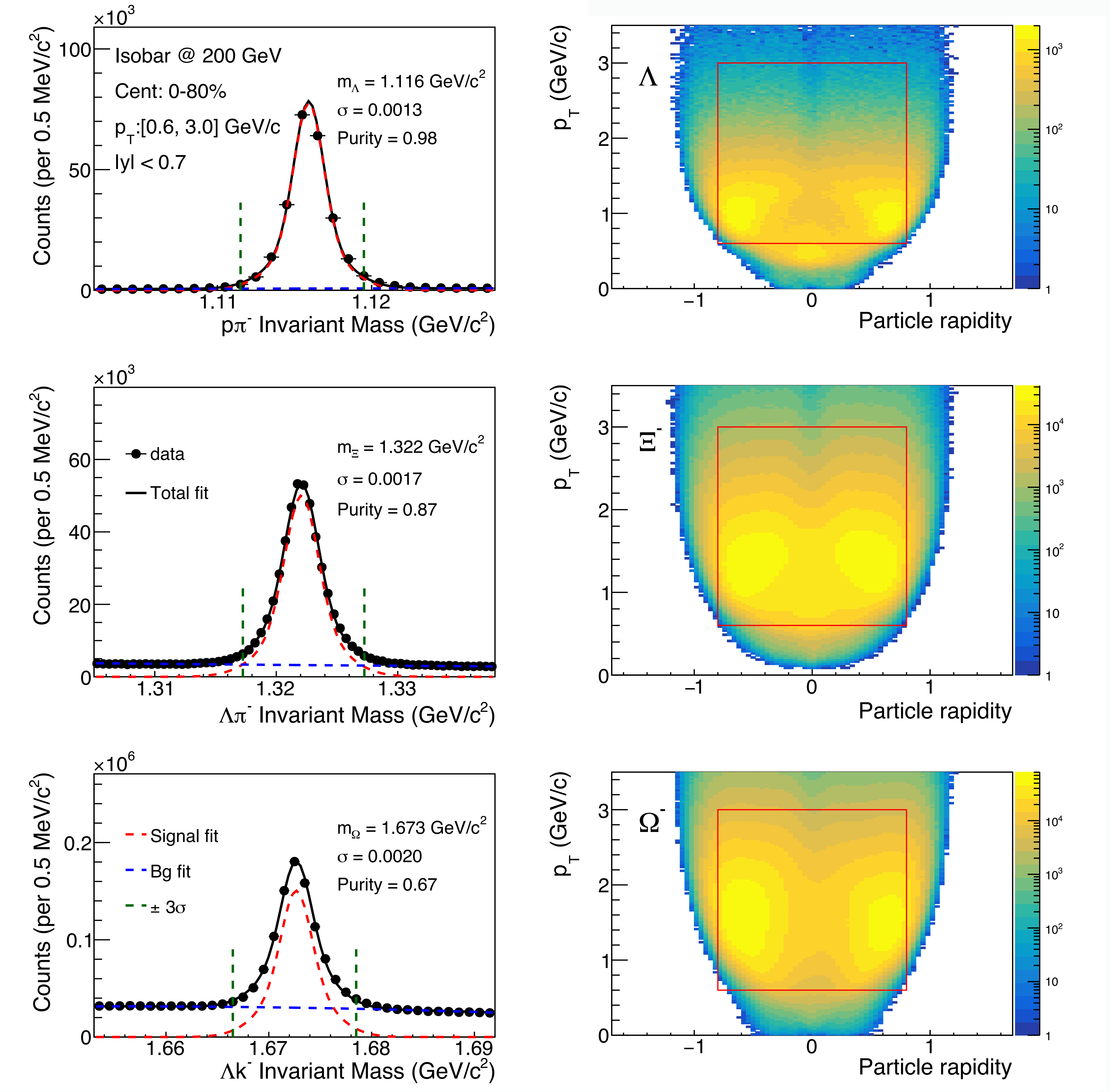


➡ **Protons, deuterons, tritons and helium3 are identified by TPC, TOF**

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

STAR, Phys. Lett. B 827 (2022) 136941

Particle Identification & Reconstruction



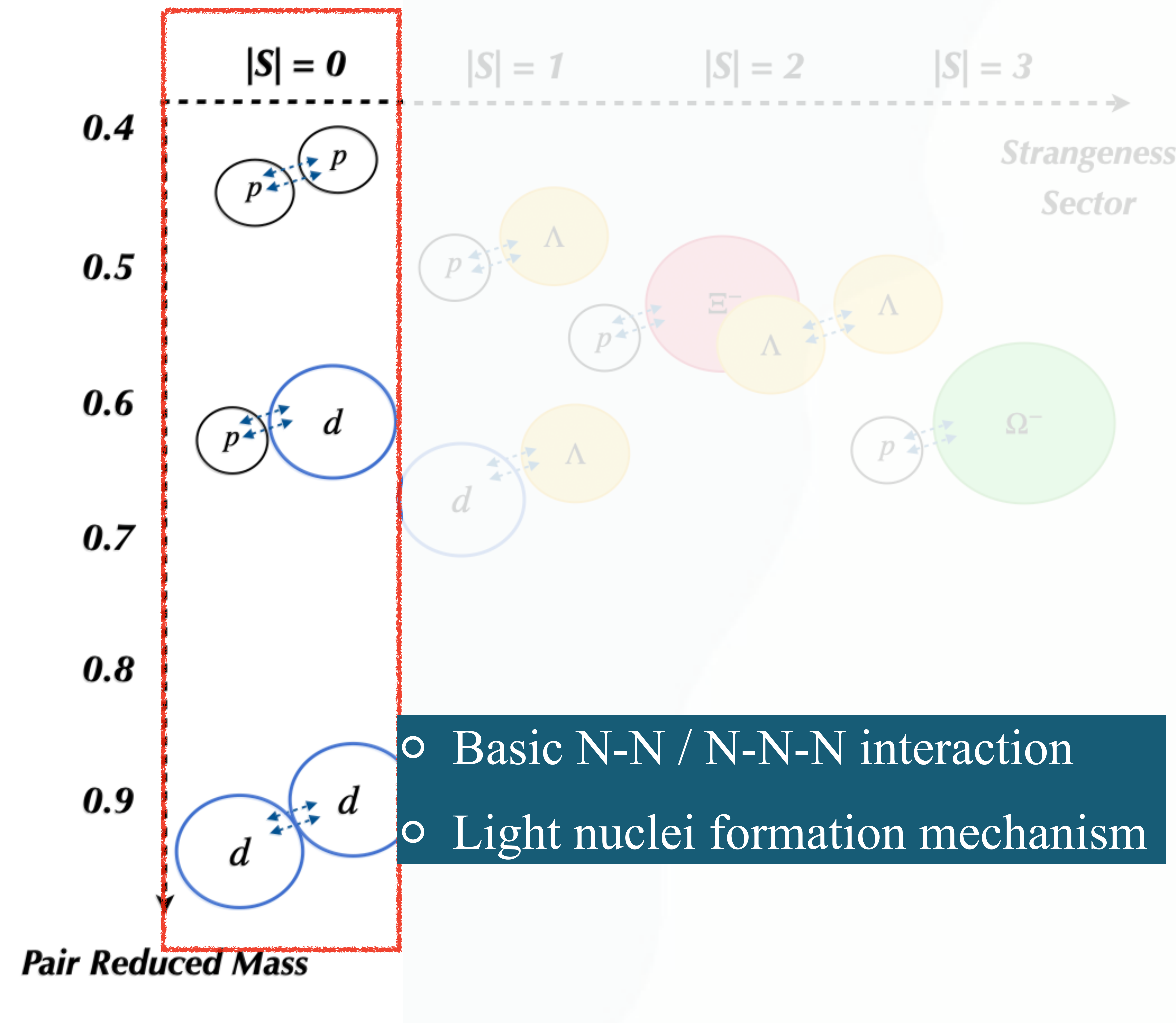
- Reconstruct hyperons (Λ, Ξ, Ω) with Helix-swimming method

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

- Fitting function:
  Double Gaussian + 2nd poly.

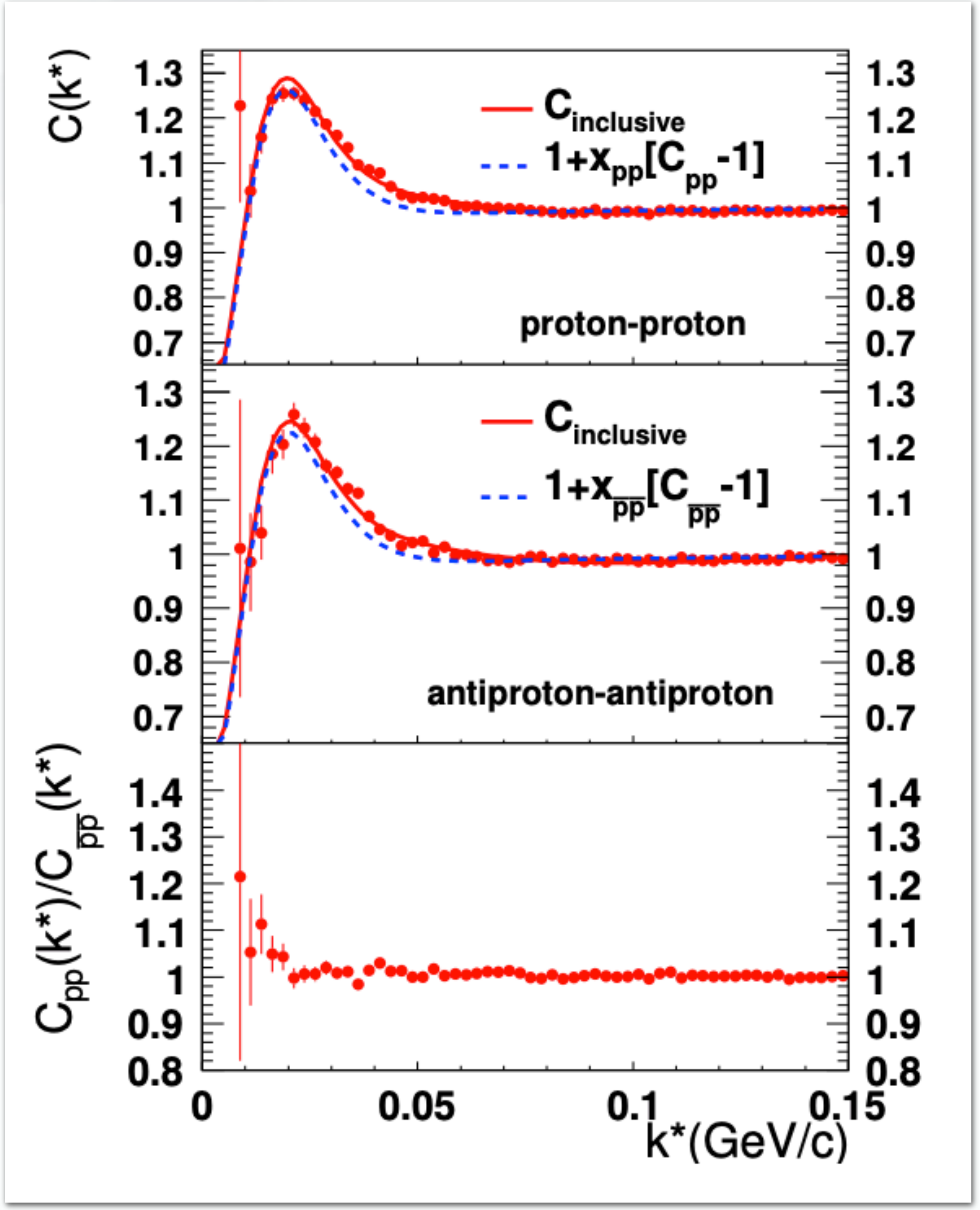
- High purity achieved

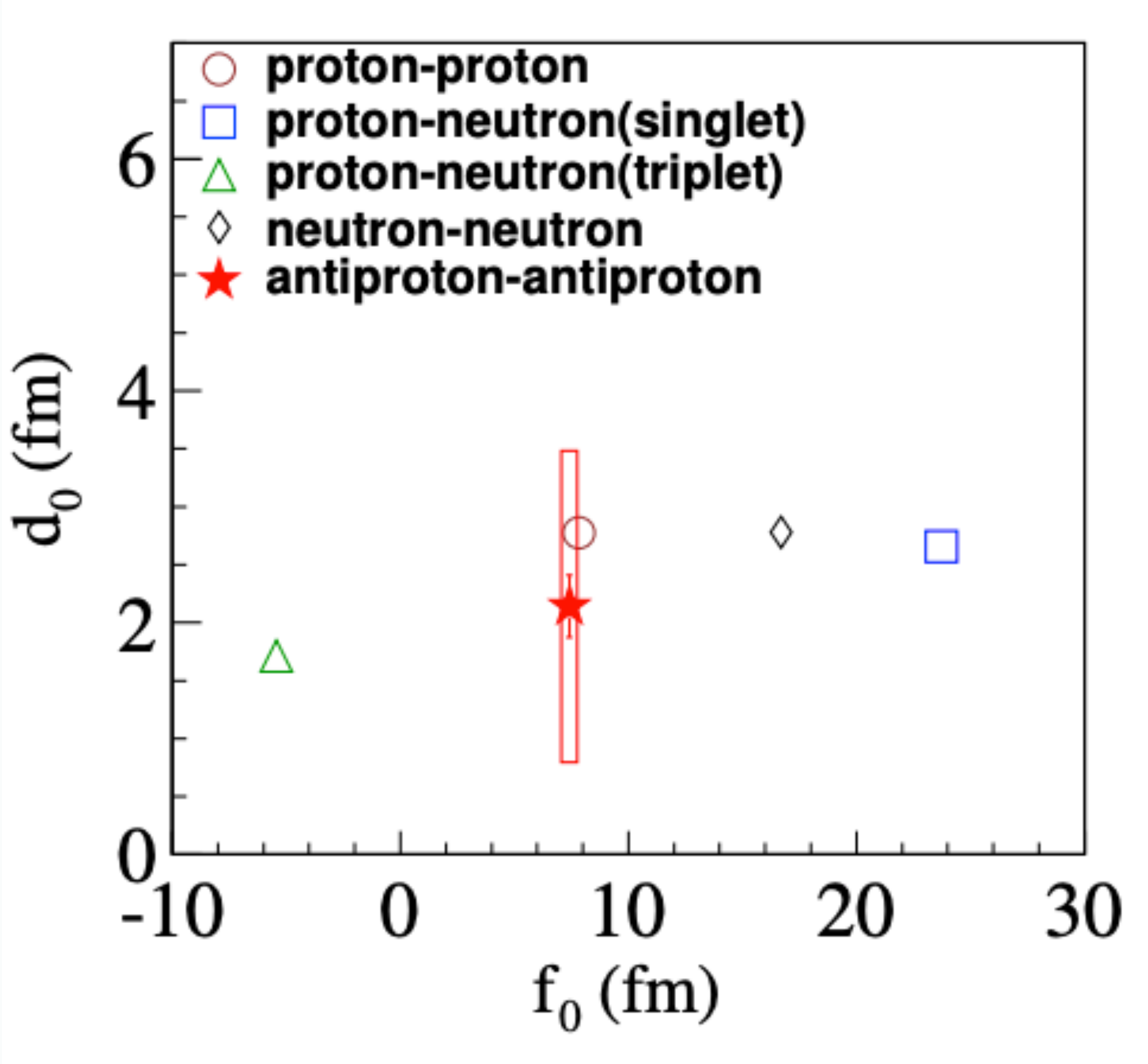
Results I

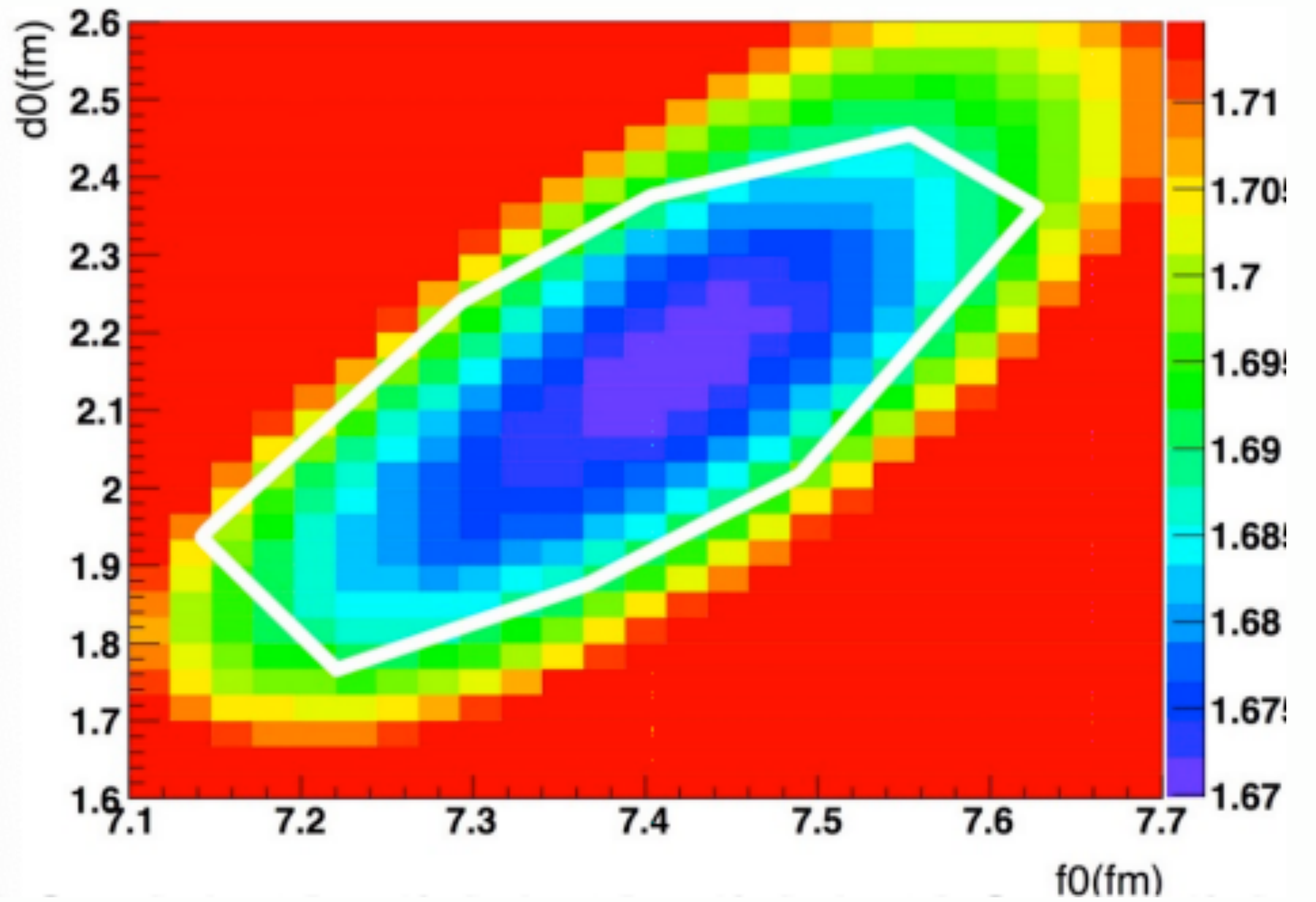


- Basic N-N / N-N-N interaction
- Light nuclei formation mechanism

p-p and p̄-p̄ Correlation

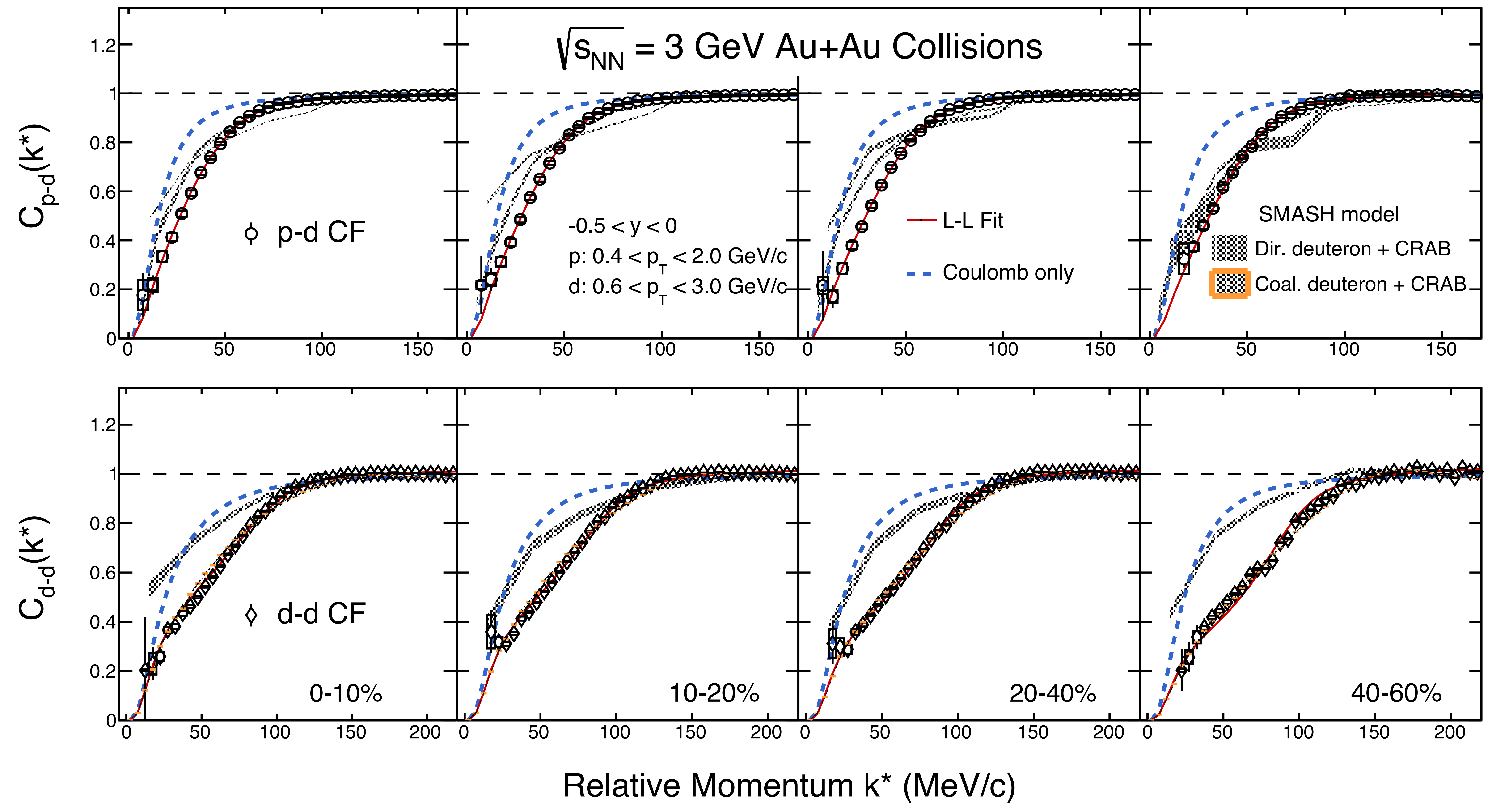






- Measured p-p and p̄-p̄ correlation at 200 GeV Au+Au collisions
- Fitted with LL model:
  - The force in p-p and p̄-p̄ is found to be attractive
  - Within errors, the f_0 and d_0 are consistent in p-p and p̄-p̄ pairs
  - The result provides a quantitative verification of CPT symmetry from a new aspect

p-d / d-d Correlation @ 3 GeV (run18)



- **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: Phys. Lett. B (2025) 139412
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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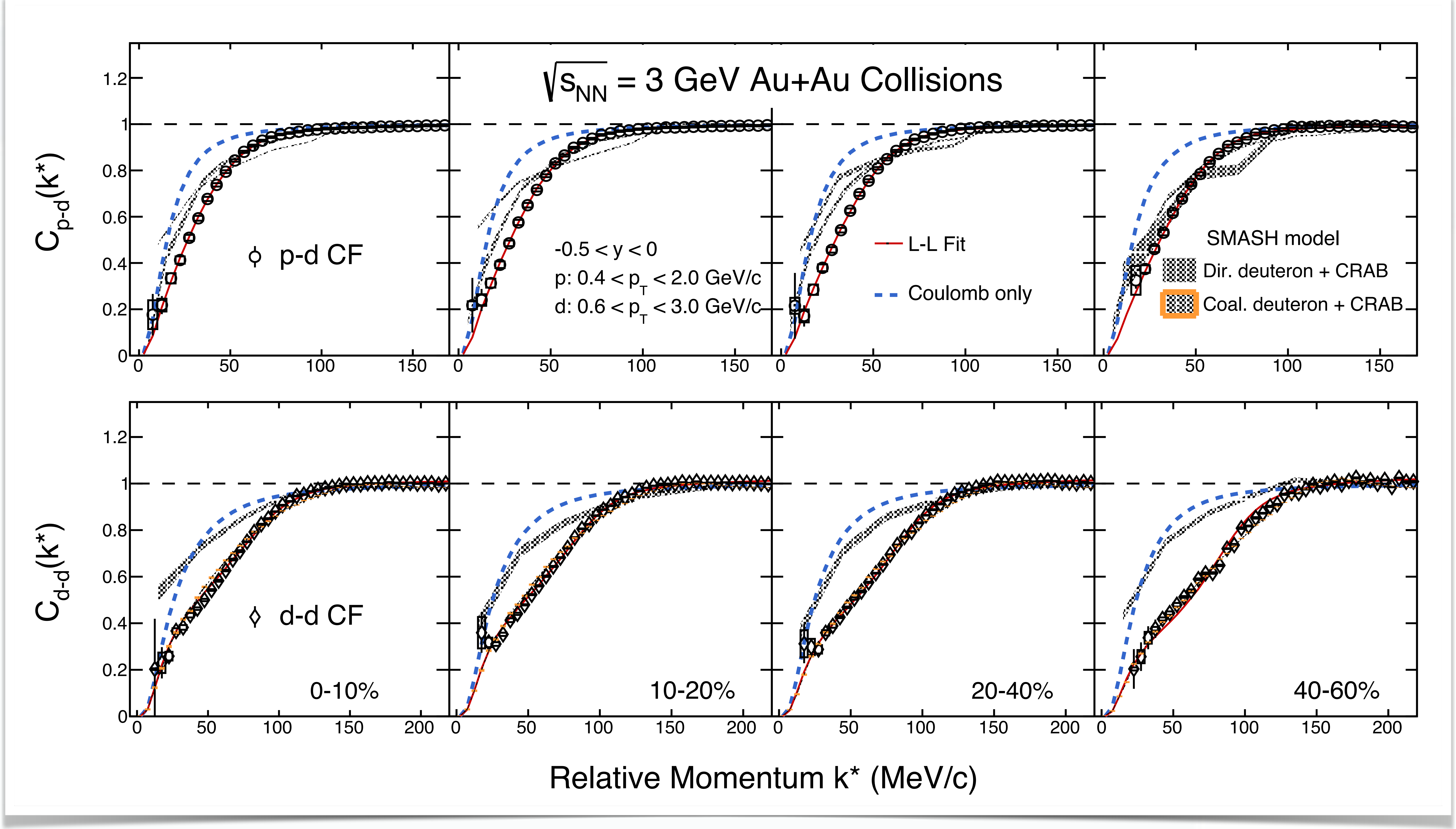

- **Simulated with SMASH model, consider two deuteron formation mechanism:**
  - **Direct production**
    - **Hadronic scattering**
    - **Fail to describe data at certain k***
  - **Coalescence production**
    - **Wigner function**
    - **Well description to data**
    - **Coalescence is the dominant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

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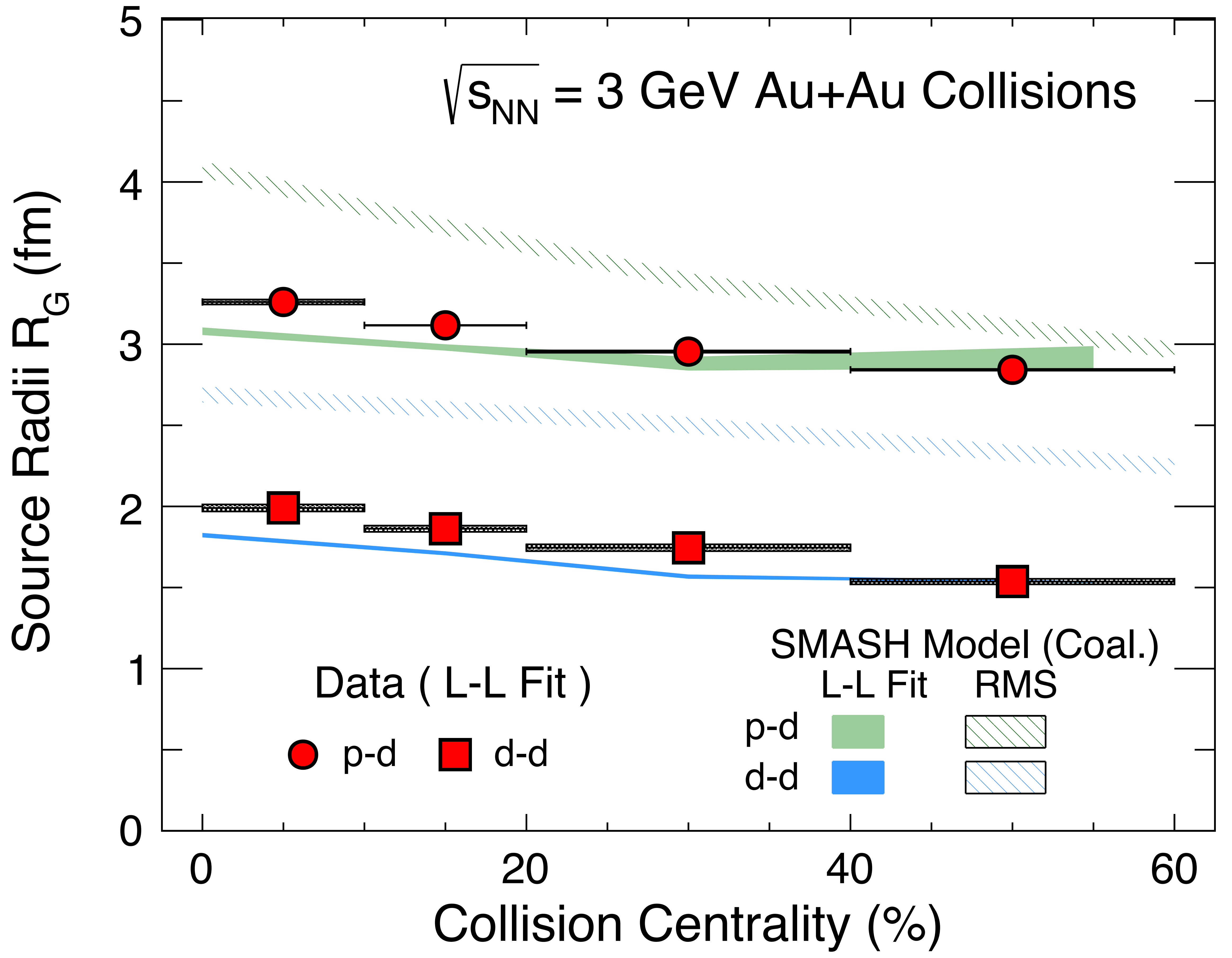
p-d / d-d Source Size



- 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}) is closely match the data
- The root mean square (RMS) values from SMASH are larger than R_G
  - Dynamical expansion of the system

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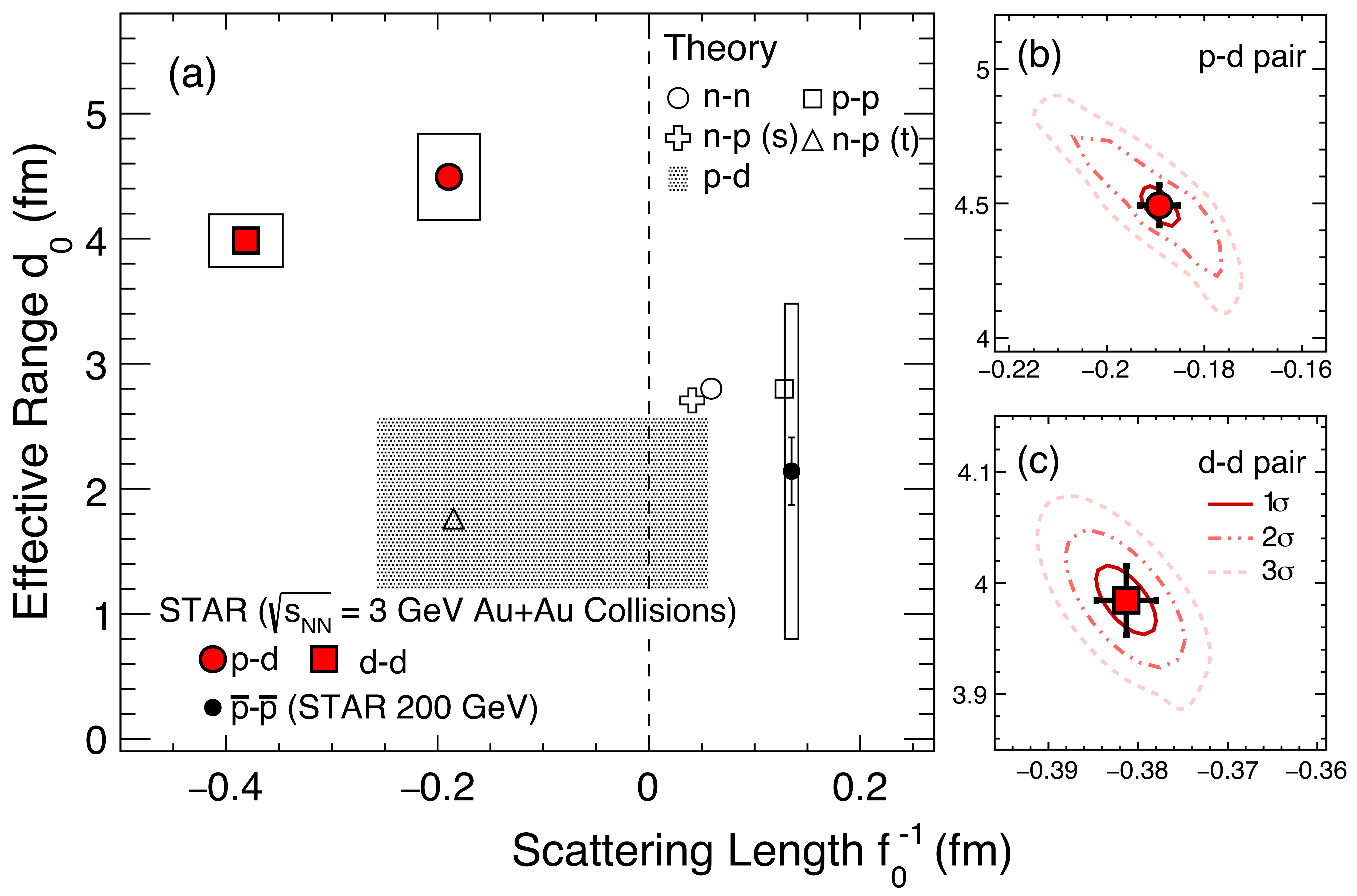
Coalescence: W.Zhao et al. Phys. Rev. C.98 (2018) 5,054905

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 (^{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**

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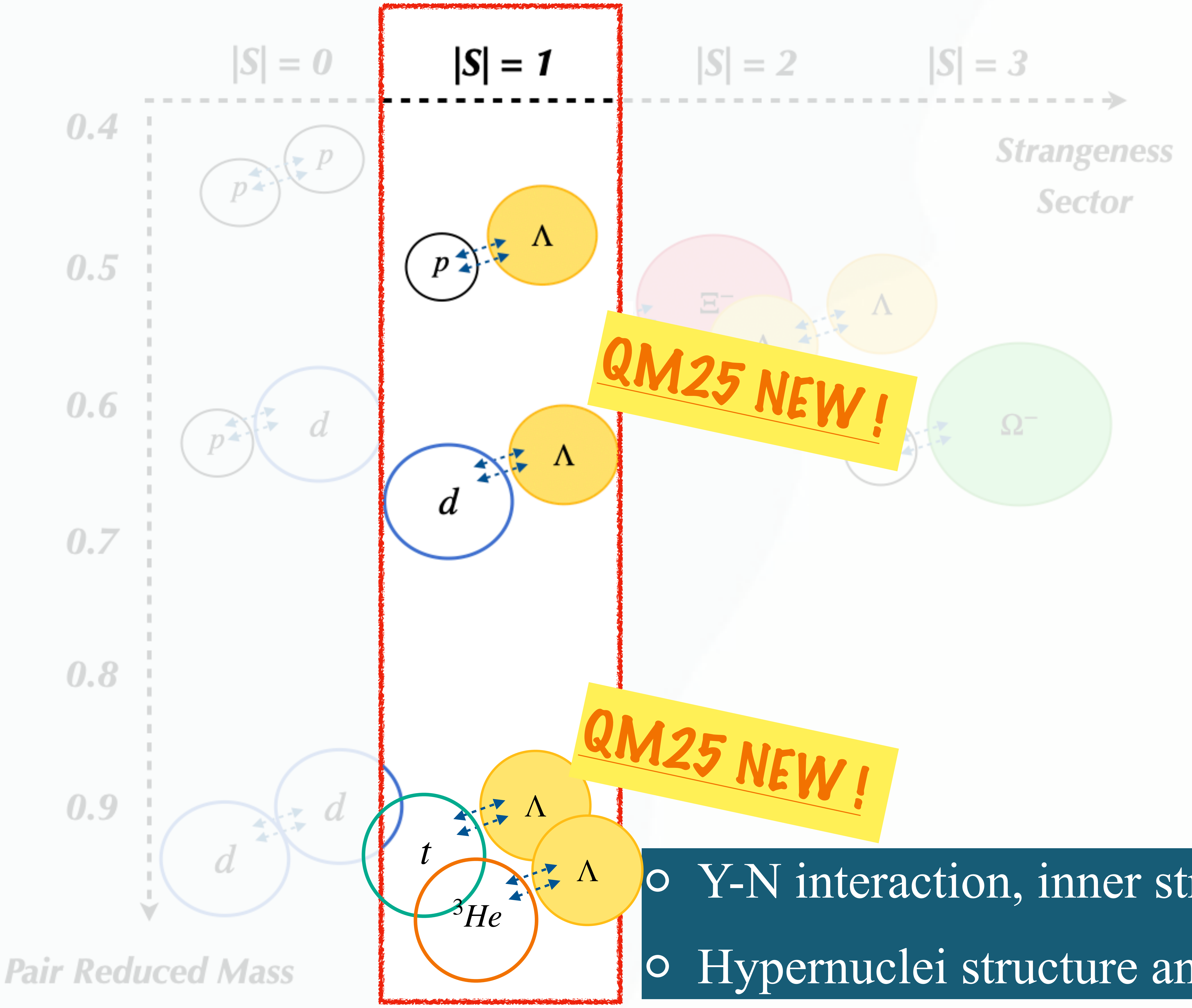
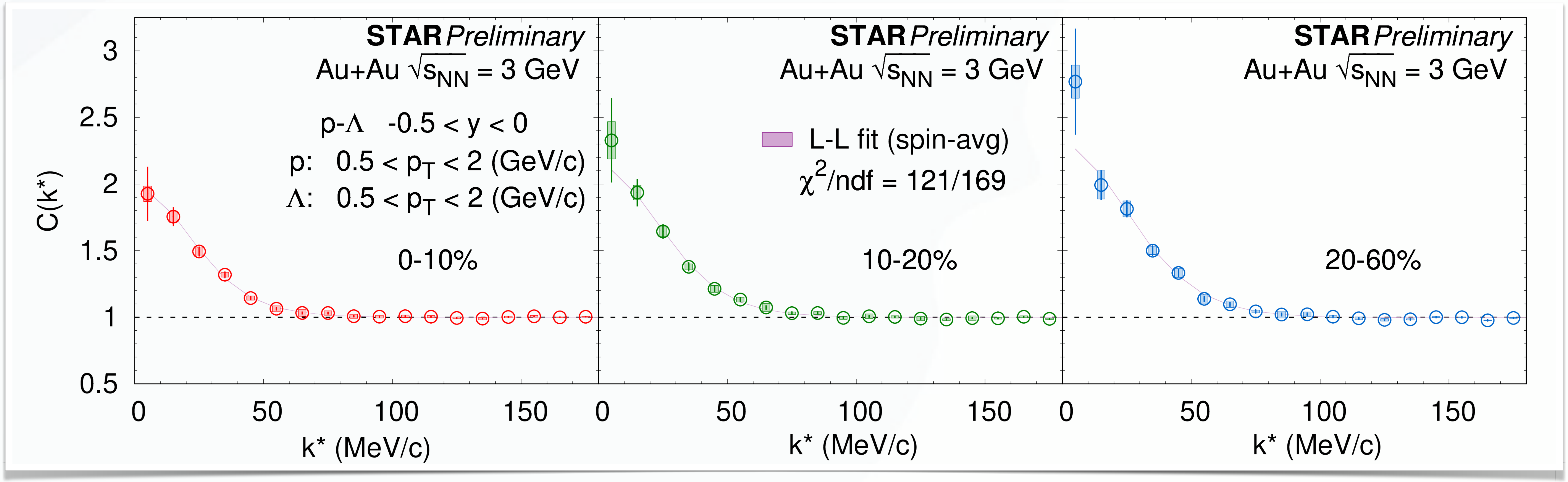
Results II



- Y-N interaction, inner structure of compact stars
- Hypernuclei structure and properties

p-Λ / d-Λ Correlation @ 3 GeV (run18)

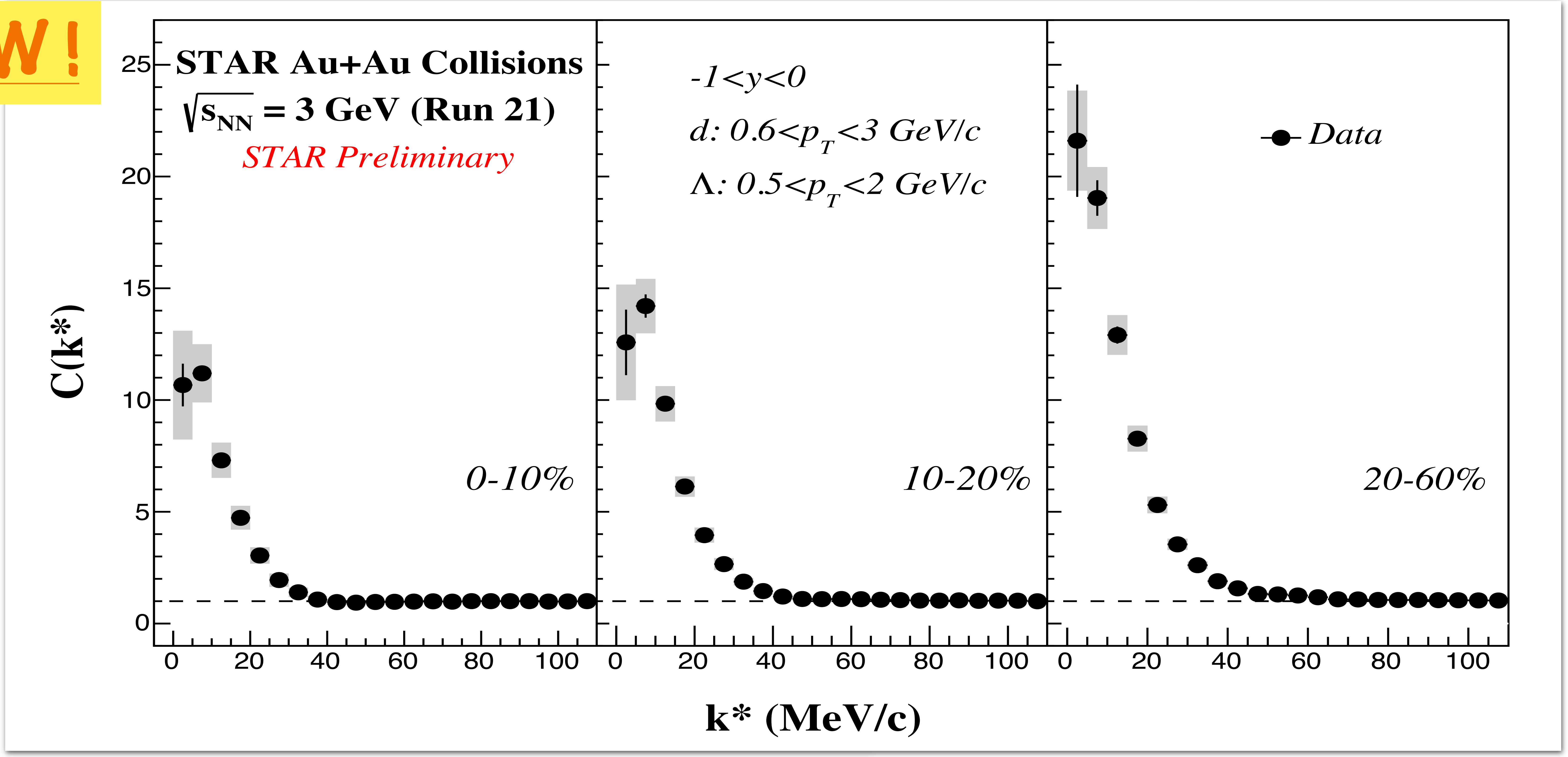


- Strong enhancements at small k* : Attractive interactions
- Simultaneously fit to data in different centralities with LL approach
  - Spin averaged scattering length (f_0) and effective range (d_0)

f_0 (ave) $= 2.32\,^{+0.12}_{-0.11}$ fm, d_0 (ave) $= 3.5\,^{+2.7}_{-1.3}$ fm

p-Λ / d-Λ Correlation @ 3 GeV (run21)

QM25 NEW !

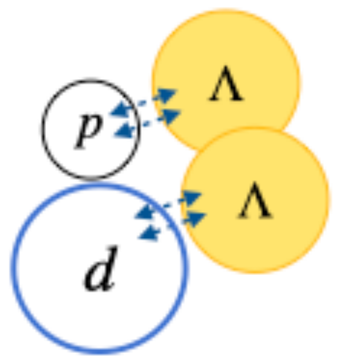


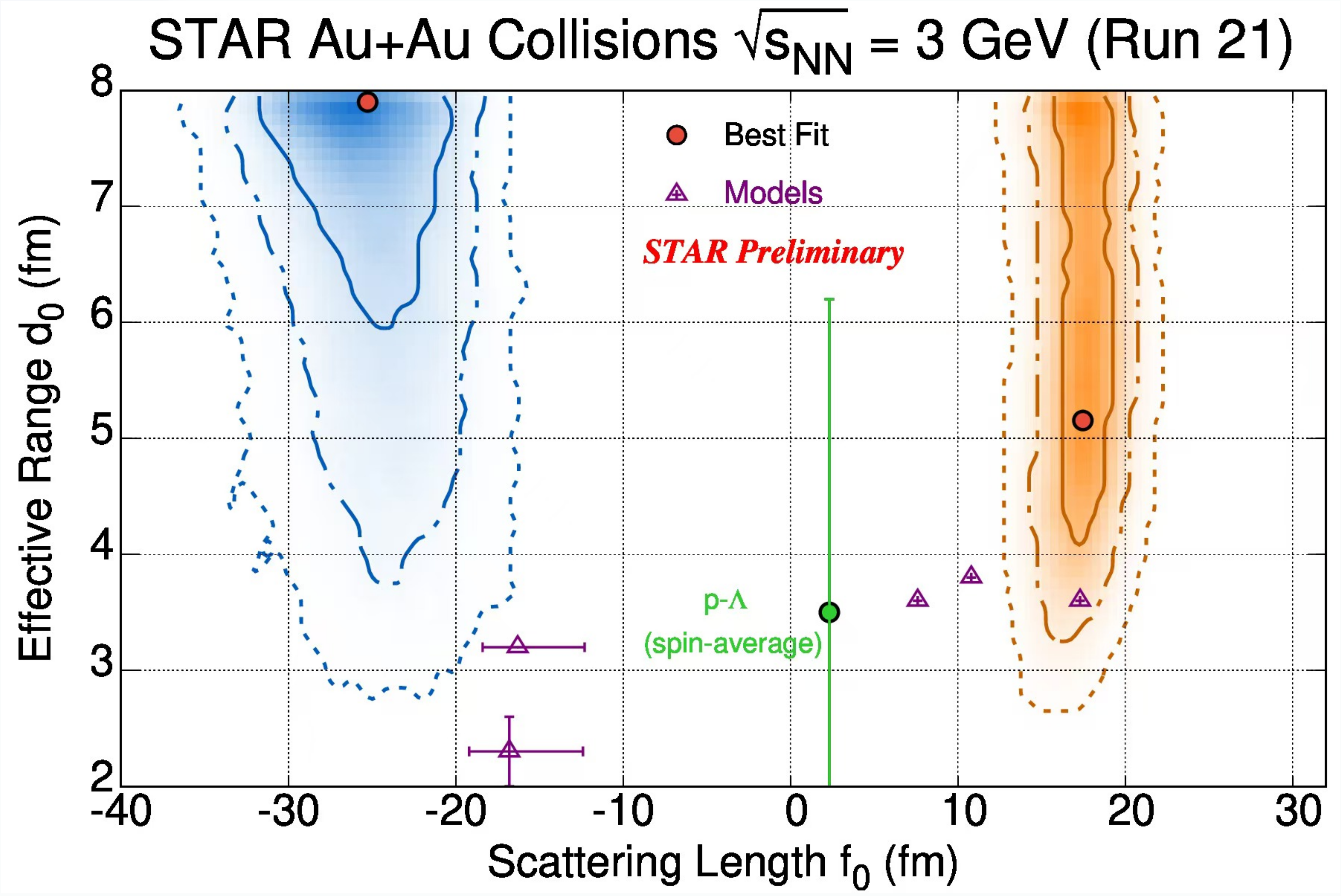
- More precise measurements of d-Λ correlation function using 2 billion events at $\sqrt{s_{NN}}$ = 3 GeV
- Strong enhancements at small k* => Attractive interactions
- Consistent results between run18 and run21, improving the accuracy of extracted parameters

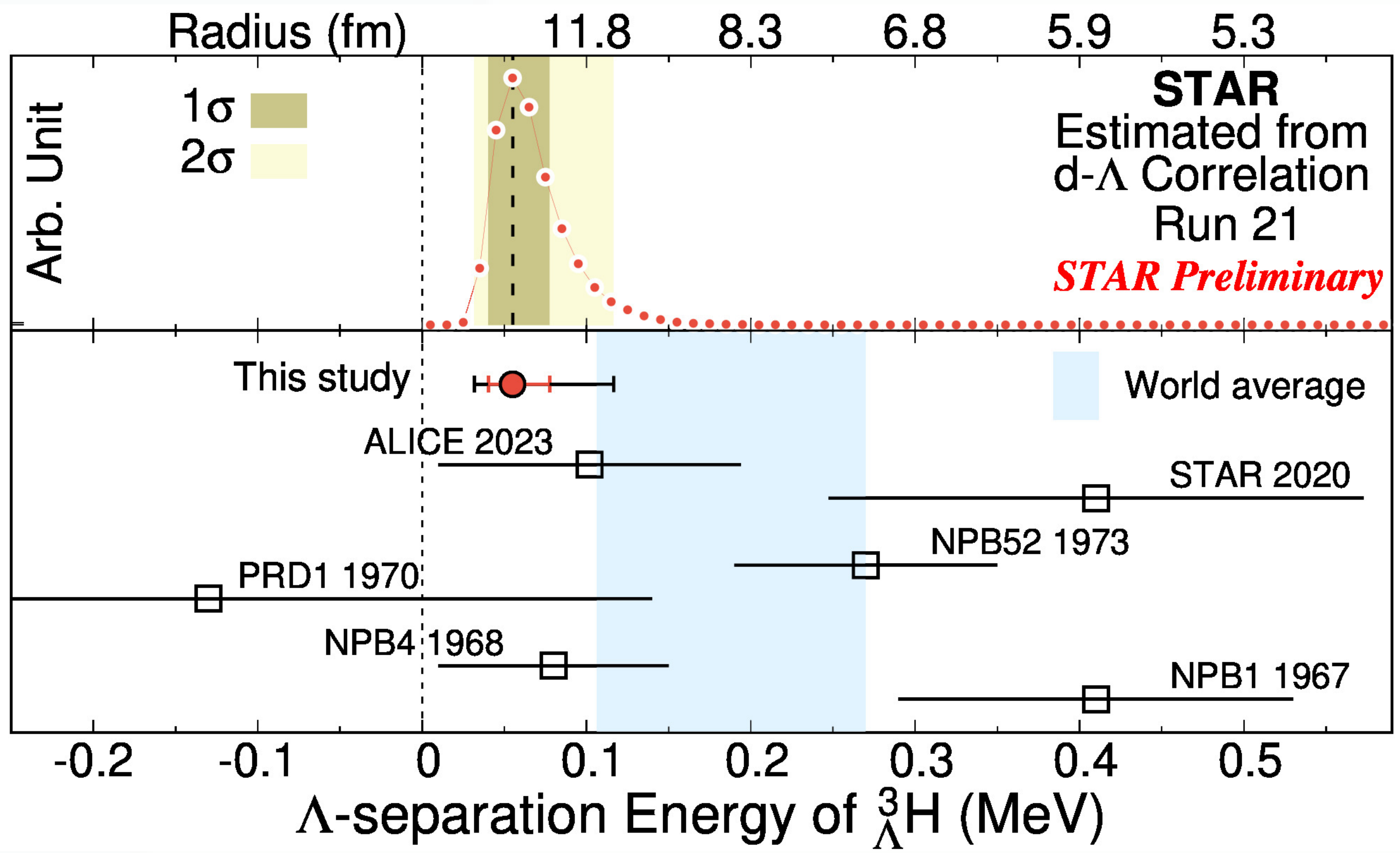
$$f_0\,(D) = -25.3^{+3.3}_{-3.3}\ \text{fm},\quad f_0\,(Q) = 17.5^{+1.6}_{-1.6}\ \text{fm}$$

p-Λ / d-Λ Interaction

QM25 NEW !







- **Spin-averaged f_0 and d_0 in p-Λ pair -> Attractive interaction**
  - $f_0(ave) = 2.32^{+0.12}_{-0.11}$ **fm**, $d_0(ave) = 3.5^{+2.7}_{-1.3}$ **fm**
- **Successfully separate two spin components in d-Λ pair**
  - f_0 **(D) = -25.3** $^{+3.3}_{-3.3}$ **fm -> Related to** ${}^{3}_{\Lambda}\mathrm{H}$
  - f_0 **(Q) = 17.5** $^{+1.6}_{-1.6}$ **fm -> Attractive interaction**

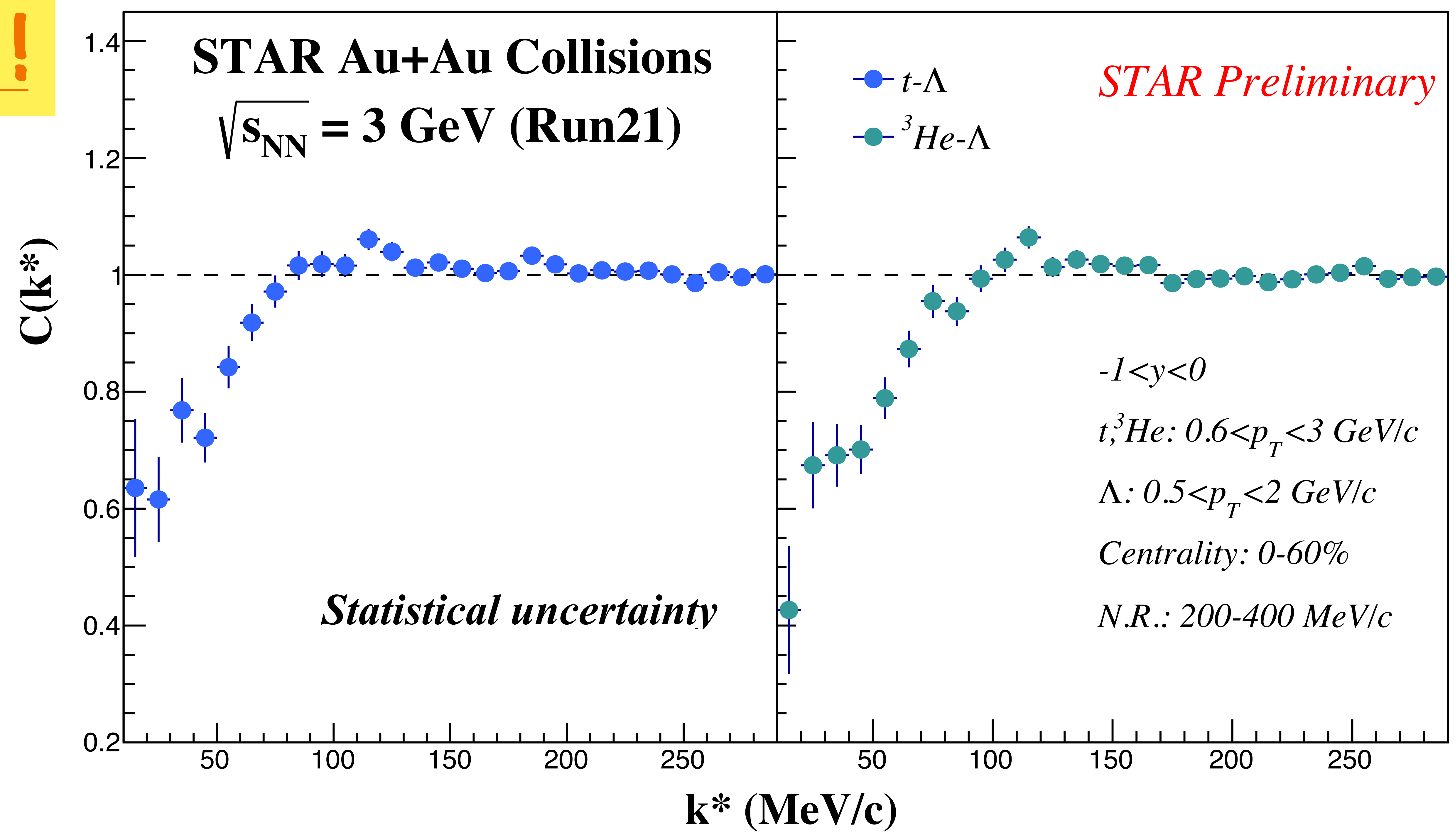
- **Extract the most accurate results of binding energy and radius of** ${}^{3}_{\Lambda}\mathrm{H}$
  - $B_\Lambda = 0.06^{+0.06}_{-0.03}$ **(MeV) @ 95% CL**
  - **r** $({}^{3}_{\Lambda}\mathrm{H}) = 16^{+5}_{-5}$ **(fm) @ 95% CL**
- **Open a new way to constrain** ${}^{3}_{\Lambda}\mathrm{H}$ **properties**

Xialei Jiang: https://indico.cern.ch/event/1334113/contributions/6369528/attachments/3048344/5386855/QuarkMatter_v18_xialei.pdf

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}He-Λ Correlation @ 3 GeV (run21)

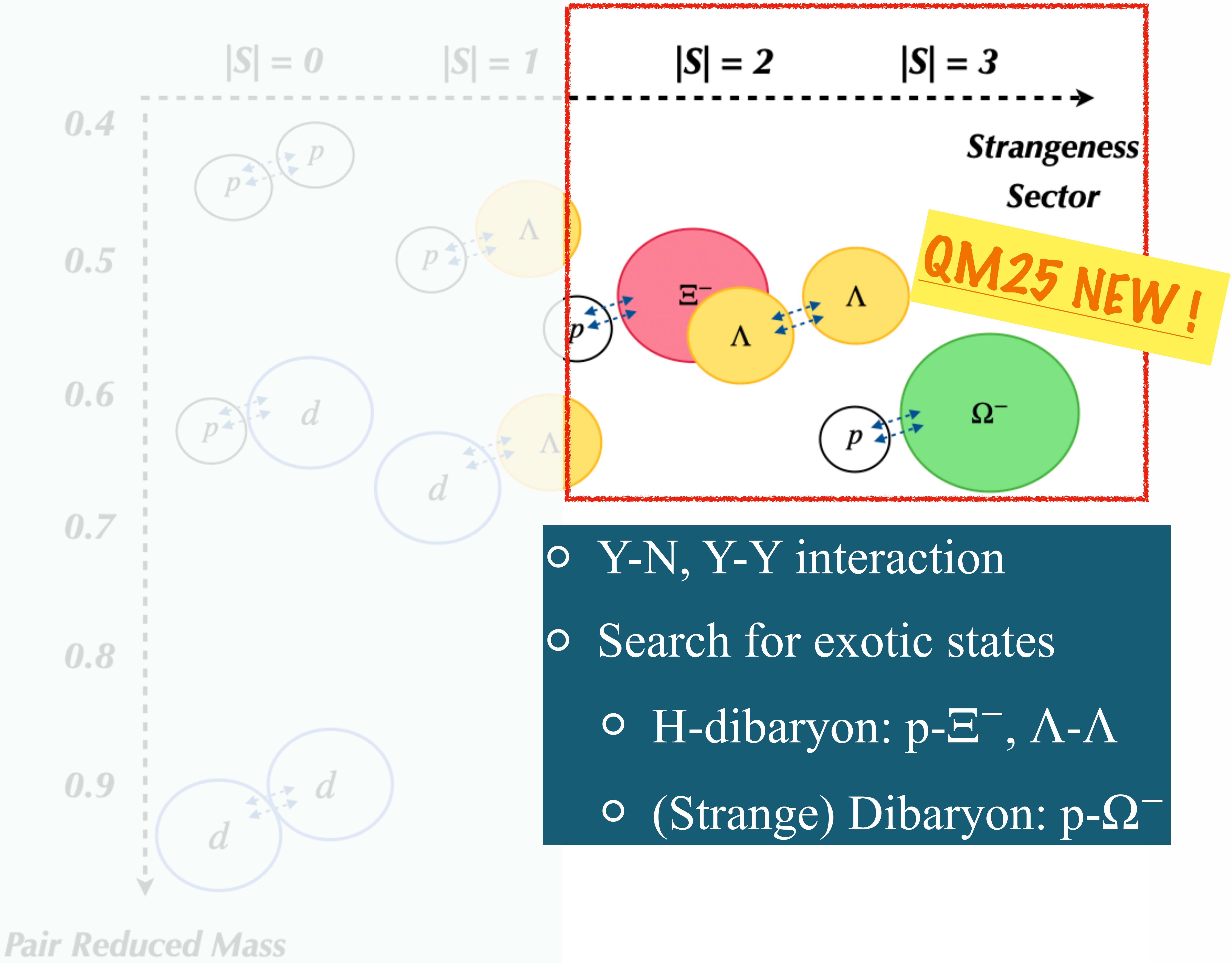
QM25 NEW !



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

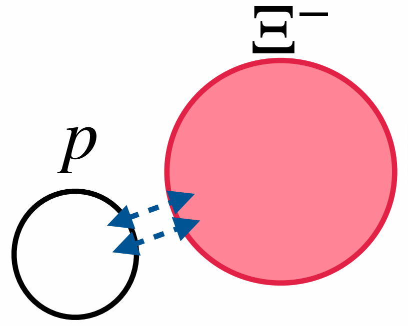
Xialei Jiang: https://indico.cern.ch/event/1334113/contributions/6369528/attachments/3048344/5386855/QuarkMatter_v18_xialei.pdf

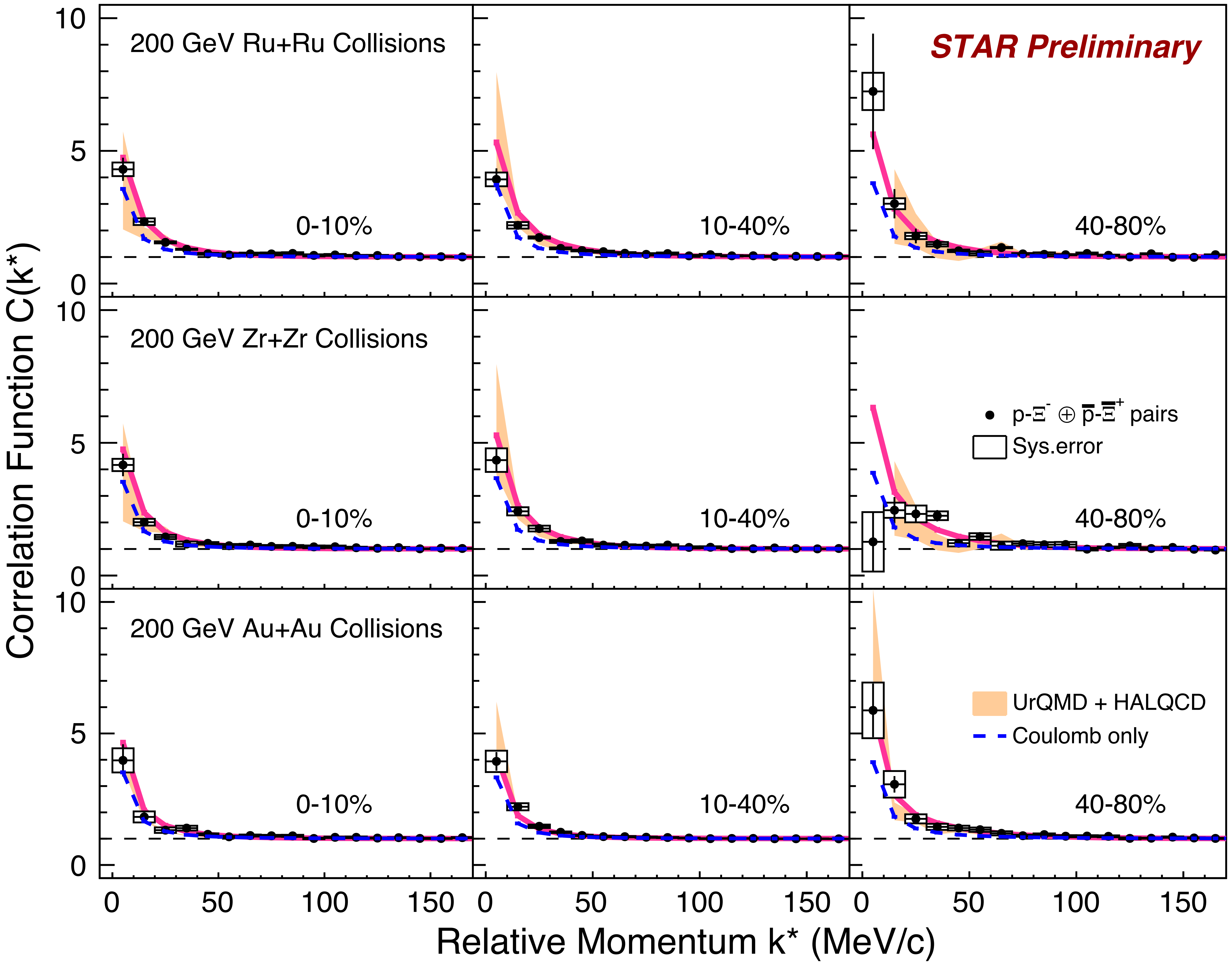
Results III

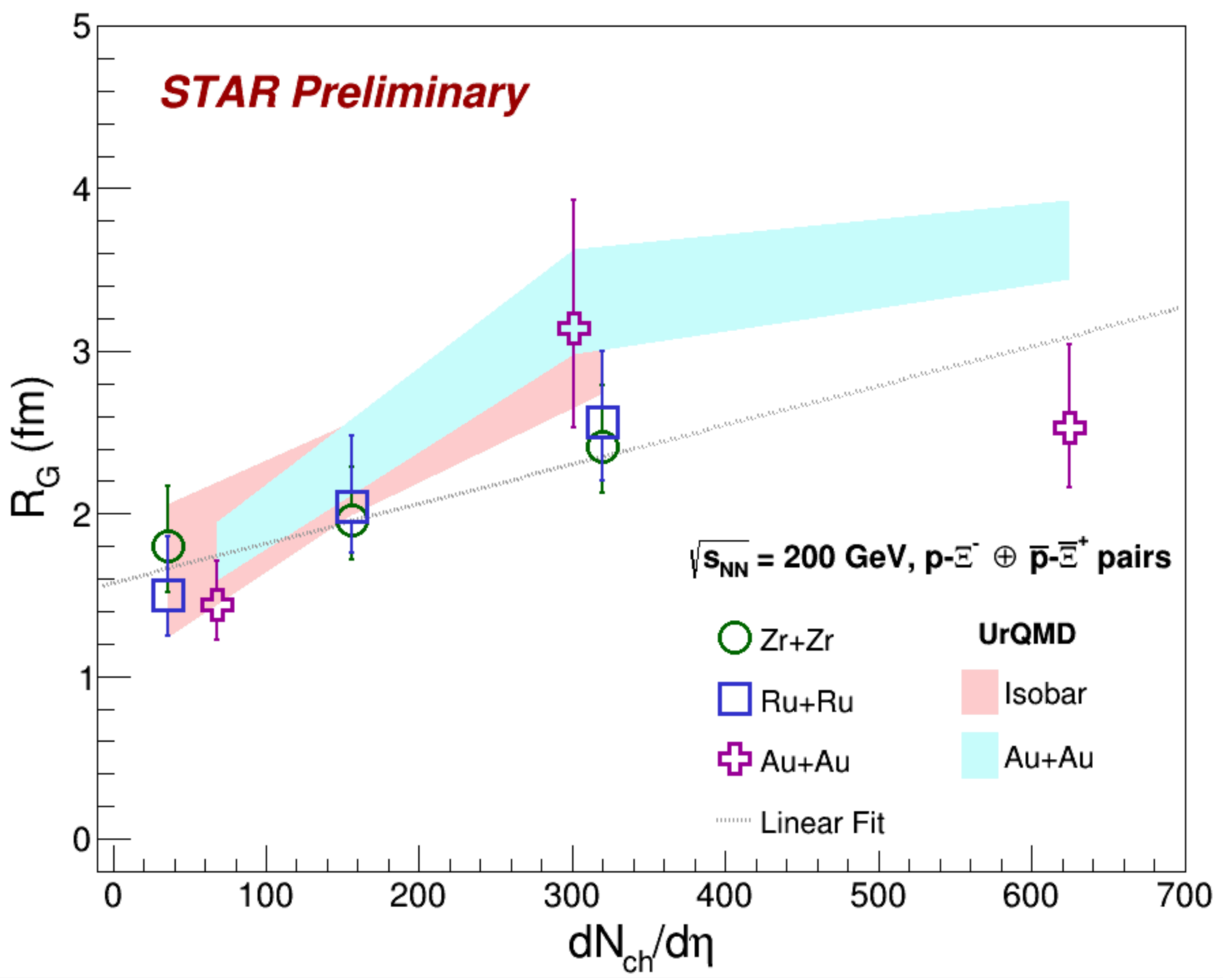


- Y-N, Y-Y interaction
- Search for exotic states
  - H-dibaryon: p-Ξ^-, Λ-Λ
  - (Strange) Dibaryon: p-Ω^-

p-Ξ^- Correlation @ 200 GeV



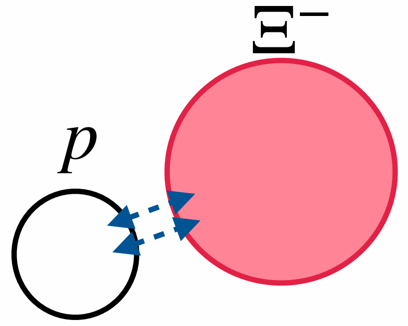


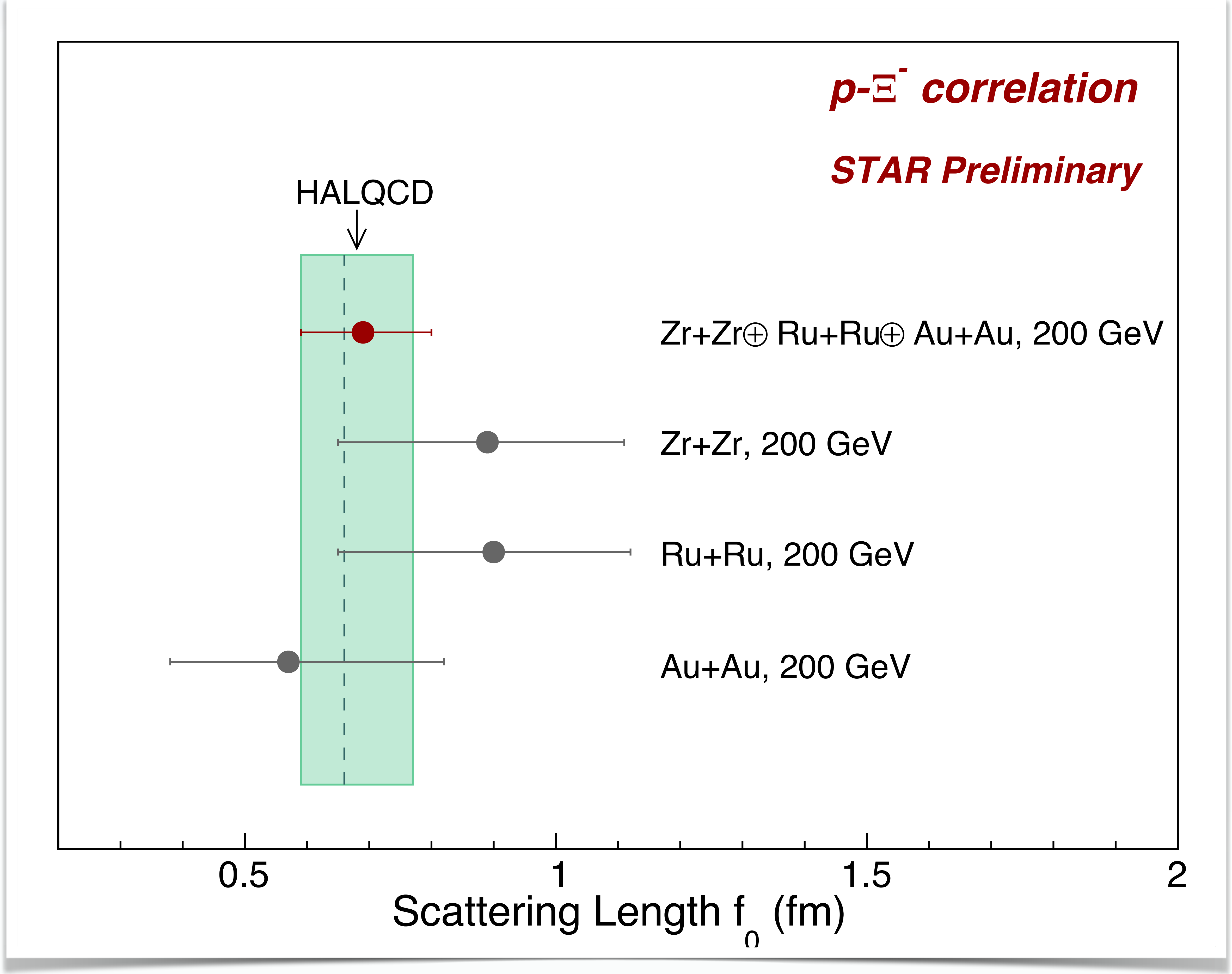


- **p-Ξ^- CFs show enhancement at low k*: Coulomb attraction and strong interaction**
- **Simultaneously fit to Isobar and AuAu data**
  - 9 centralities + f_0 + d_0
- **UrQMD + HALQCD results are consistent with data**
- **Source size shows centrality dependence and follow a similar trend in different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

B. Fu, SQM2024, EPJ Web Conf.316 (2025) 03010
Y. Kamiya, et al., Phys. Rev. C 105, 014915 (2022)

p-Ξ⁻ Interaction



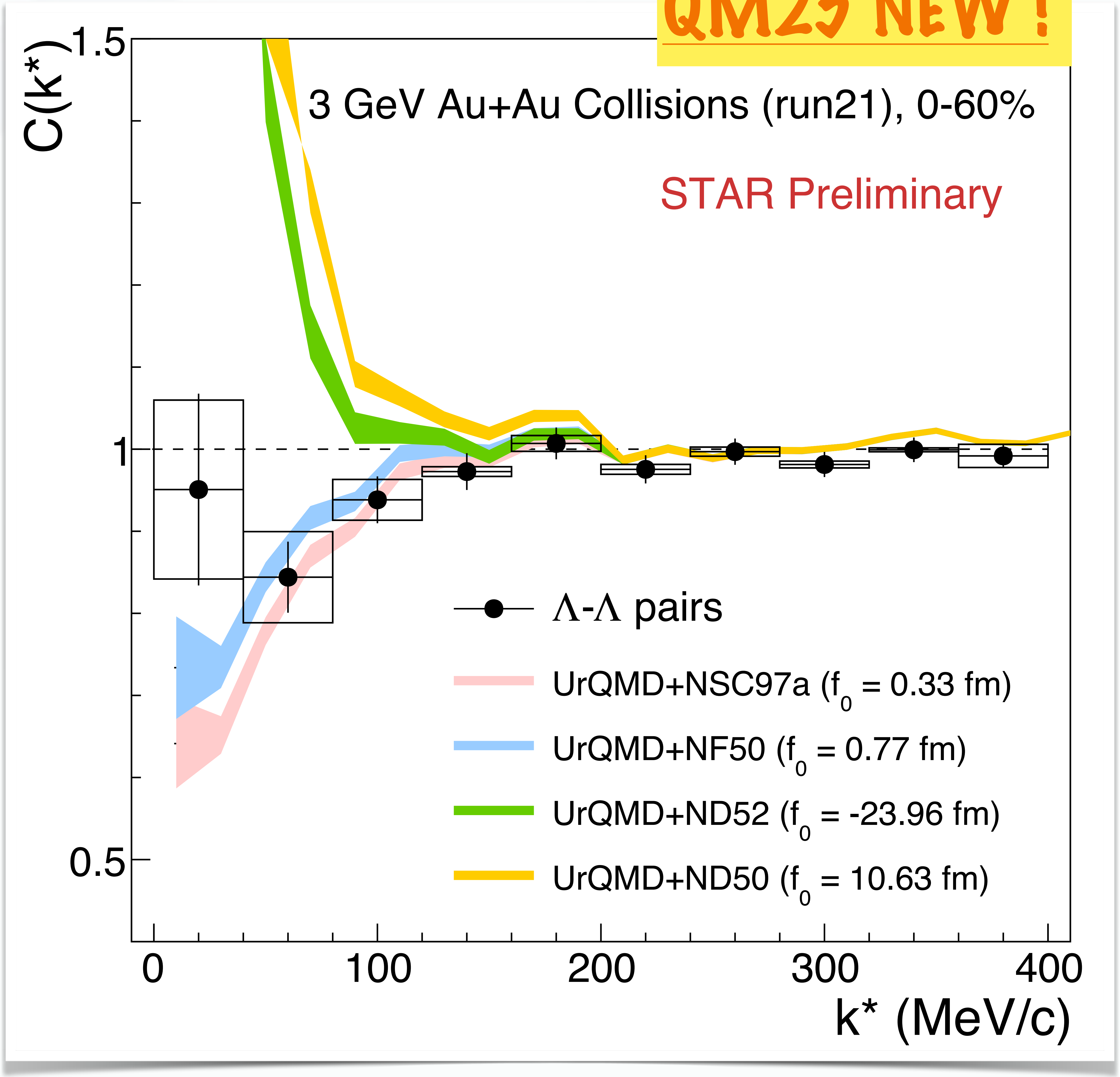


- **First experimental extraction of strong interaction parameters in p-Ξ^- pairs**
- **Extracted *positive* $f_0 = 0.69^{+0.11}_{-0.10}$ fm**
  - ***Attractive* strong interaction in p-Ξ^- pair**
  - **Shallow interaction compared to p-p interaction**
  - **Consistent with Lattice predictions**

B. Fu, SQM2024, EPJ Web Conf.316 (2025) 03010

Λ-Λ Correlation @ 3 GeV

QM25 NEW !

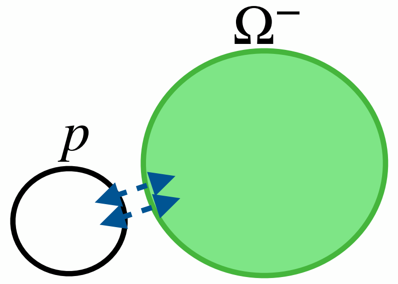


- **Λ-Λ correlation function shows suppression at small k***
- **Compared with UrQMD + potential, it is found that the simulation with positive f_0 is in better agreement with data**
  => Hints at an attractive interaction in Λ-Λ pairs
- **Need more precise data to confirm**
  => High statistics Isobar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

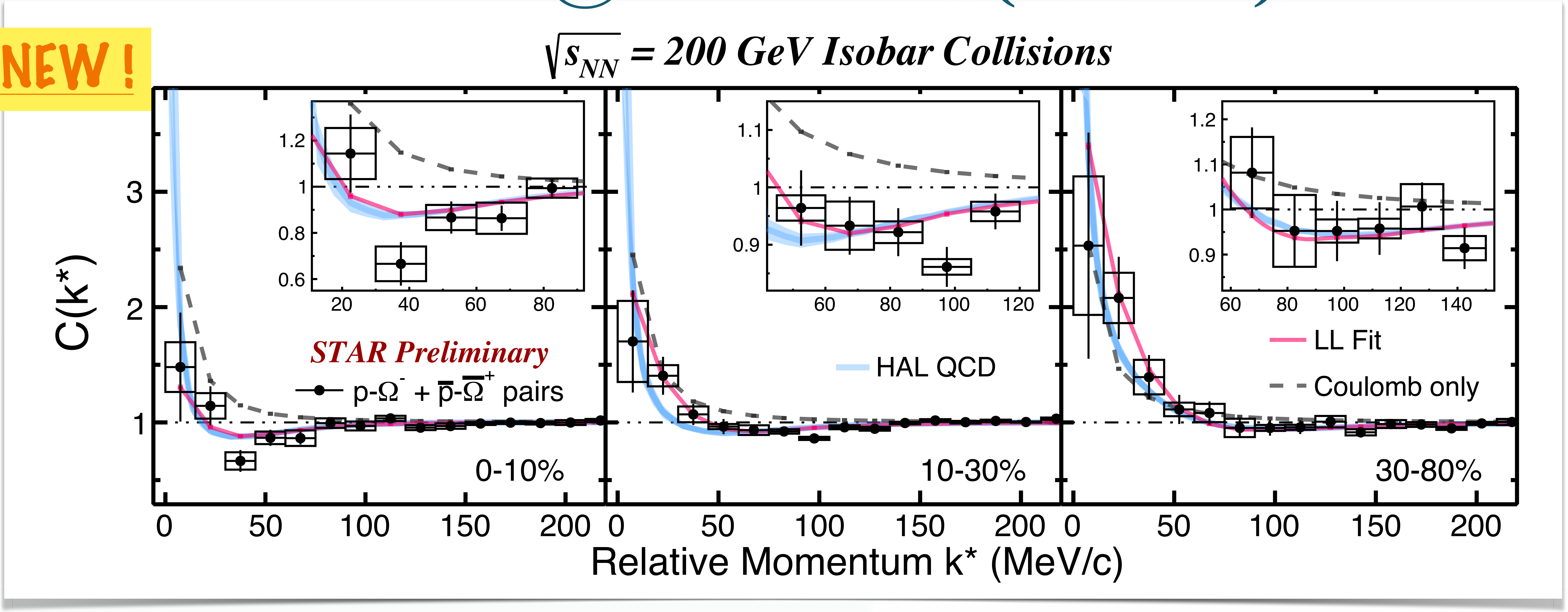
Potential	f0 (fm)	d0 (fm)	Chi2/NDF
NSC97a [1]	0.33	12.37	1.53
NF50 [2]	0.77	4.27	1.61
ND52 [3]	-23.96	2.59	2.24
ND50 [3]	10.63	2.04	4.02

[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)

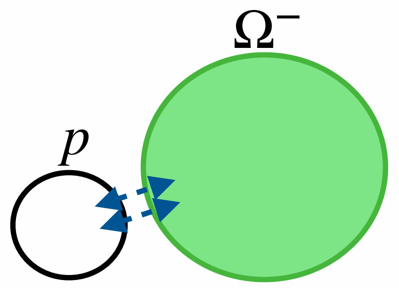


QM25 NEW !

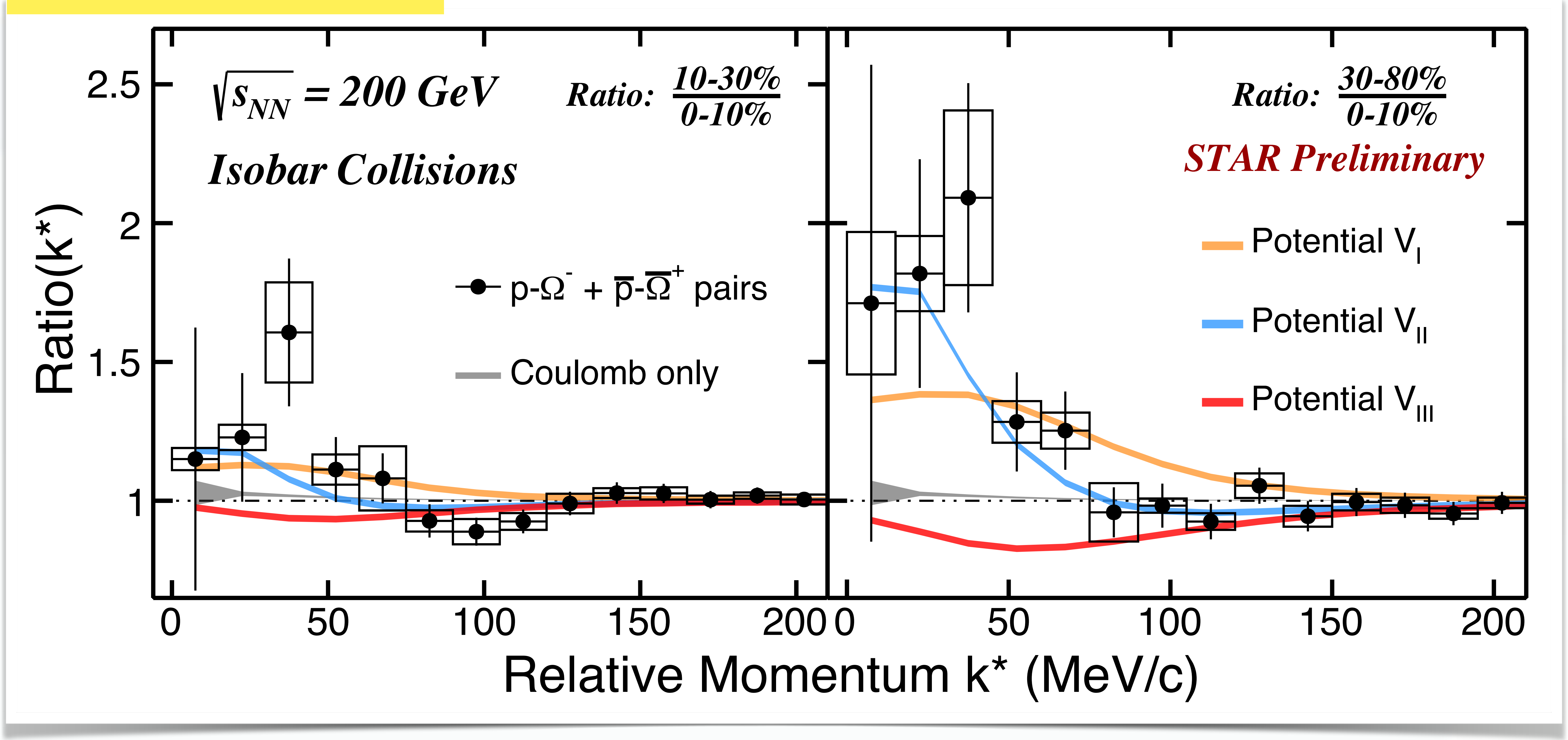


- **Precise measurements of p-Ω^- and $\bar{p}$-$\overline{\Omega}^+$ correlation functions in Isobar collisions**
  - **CFs show enhancement at low k* -> mainly due to Coulomb attraction**
  - **CFs show depletion at k* ~ 30-100MeV/c -> mainly due to the strong interaction**
- **Simultaneously fit with 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)



QM25 NEW !

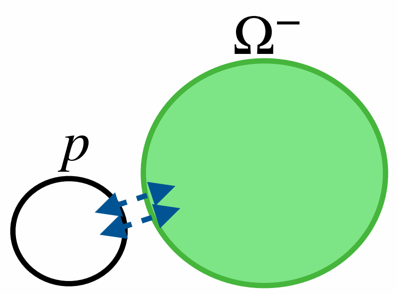


Type	f_0 (fm)	d_0 (fm)	BE (MeV)	χ^2/ndf	p-value	
V_I [1]	1.12	1.16	--	48.2/29	0.014	No Bound
V_II [2]	-3.38	1.31	2.15	22.2/29	0.812	Shallow Bound
V_III [1]	-1.29	0.65	26.9	58.7/29	0.001	Deeply Bound

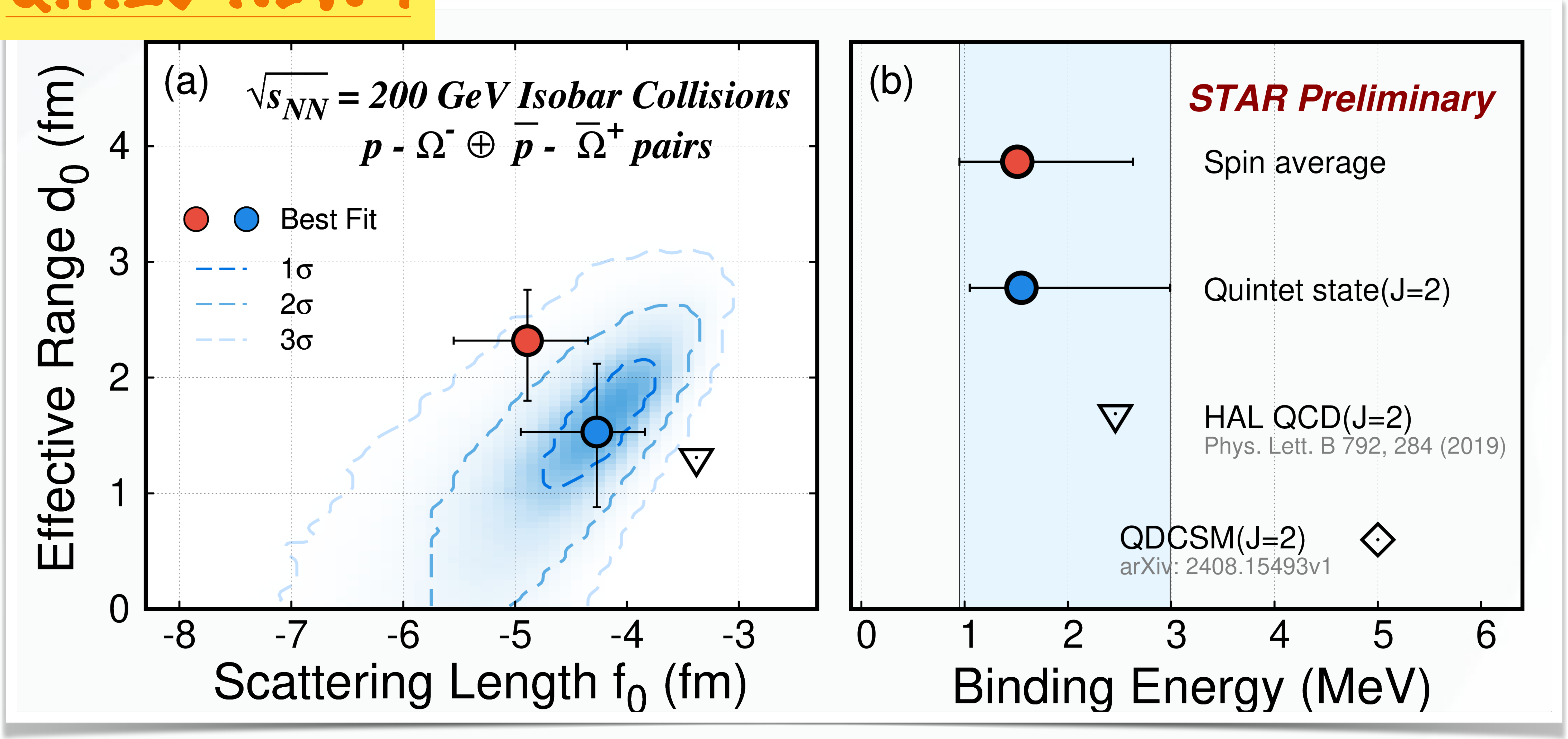
- **By taking the CF ratio, Coulomb effect can be largely canceled**
- **CF ratio shows enhancement at low k* and depletion around k* ~ 100 MeV/c**
  - **Due to the presence of shallow bound state**
- **The potential VII (shallow bound), with a p-value of 0.812, provides a better description of the data**

[1] Kenji Morita, et al,. Phys. Rev. C 94, 031901 (2016)
[2] Kenji Morita, et al,. Phys. Rev. C 101, 015201 (2020)

p-Ω^- Correlation @ 200 GeV (Isobar)



QM25 NEW !



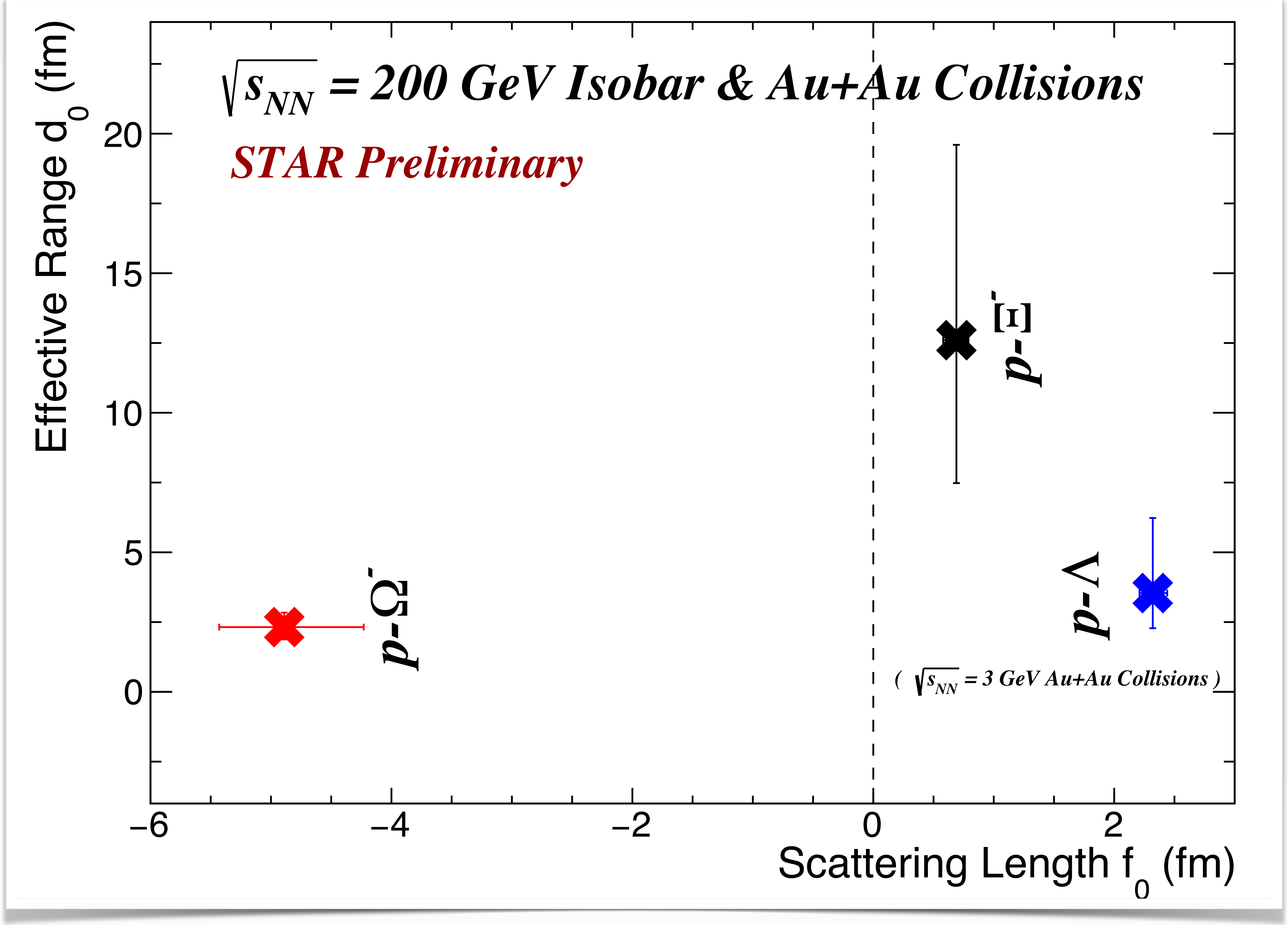
	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.89^{+0.54}_{-0.66}$	$-4.27^{+0.43}_{-0.68}$	-3.38
d_0 (fm)	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	1.31
BE (MeV)	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	2.27

- **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**
  - **BE = $1.6^{+1.4}_{-0.5}$ MeV**

Kehao Zhang: https://indico.cern.ch/event/1334113/contributions/6369557/attachments/3047284/5384623/QM2025_StrangeDibaryon_ZKH.pdf

Strong Interaction Parameters

QM25 NEW !



- Extracted negative f_0 in p-Ω^- pair => **Support the formation of bound state**
- Interaction section is proportional to f_0^2, the observation implies that the strength of the interaction depends on strangeness
- Hierarchy of strangeness content:
  $f_0(|s| = 0) > f_0(|s| = 1) > f_0(|s| = 2) > 0$

Summary

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

⇒ **p-p, p-d, d-d correlation**

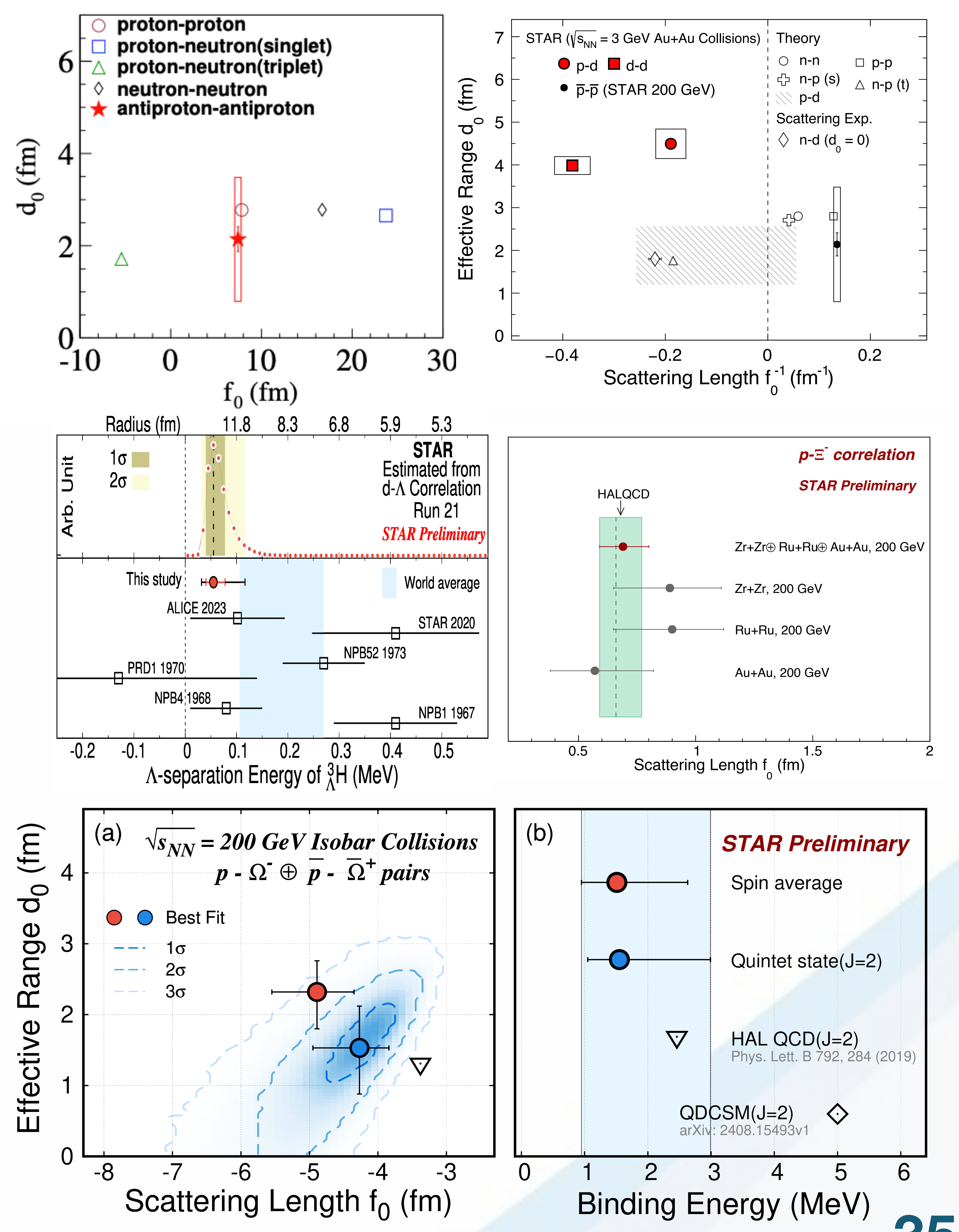
- **Consistent interaction parameters between p-p and $\bar{p}$-$\bar{p}$**
- **First extraction of p-d / d-d interaction parameters in HIC**
- ***Coalescence* is the dominant process for deuteron formation in the high-energy collisions**

⇒ **p-Λ, d-Λ, t-Λ, ^{3}He-Λ correlation**

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

⇒ **p-Ξ, Λ-Λ, p-Ω correlation**

- **First experimental results of p-Ξ^{-} interaction**
- **Λ-Λ hints at shallow attractive interaction**
- **First experiment evidence of Strange-Dibaryon in p-Ω^{-} channel !**

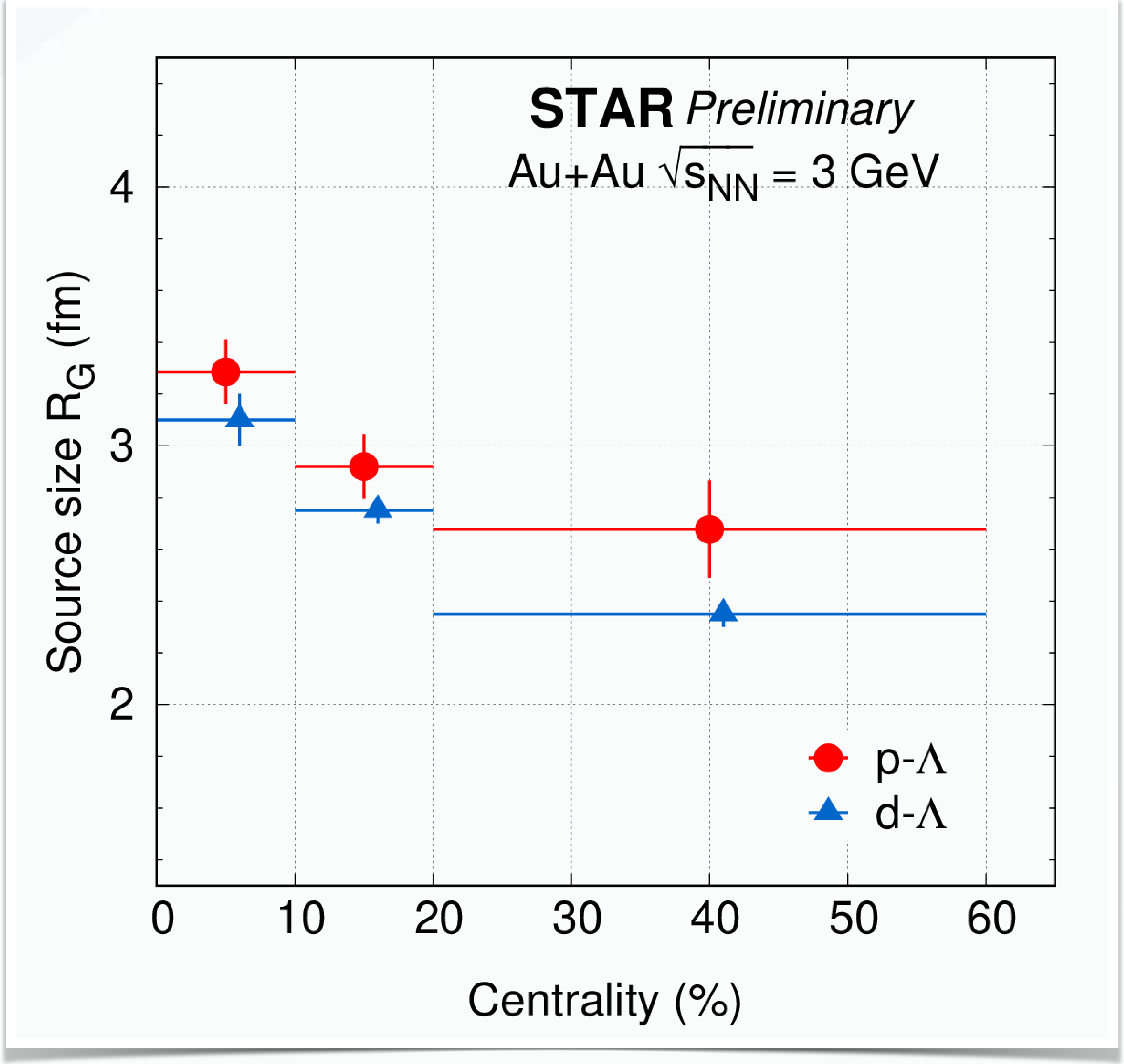


Outlook

* More than 10 times statistics from BES-II program, making it possible to study:
  - Emission source size vs. energy, rapidity…
  - Baryon-baryon, baryon-meson, meson-meson correlations with different species

Thank you !

p-Λ / d-Λ Source Size

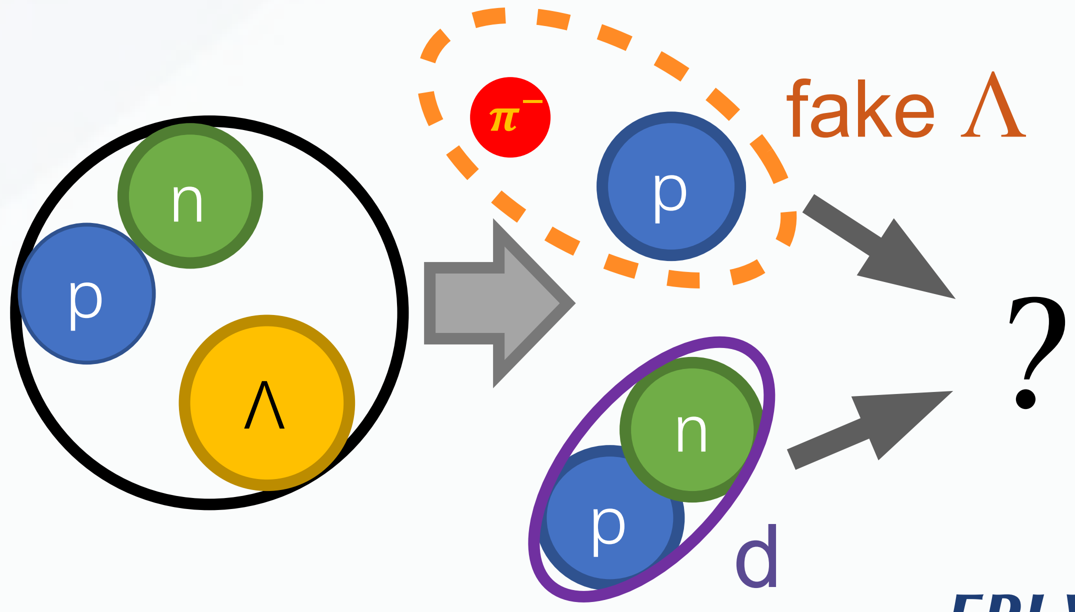


⇒ R_G: **spherical Gaussian source size**

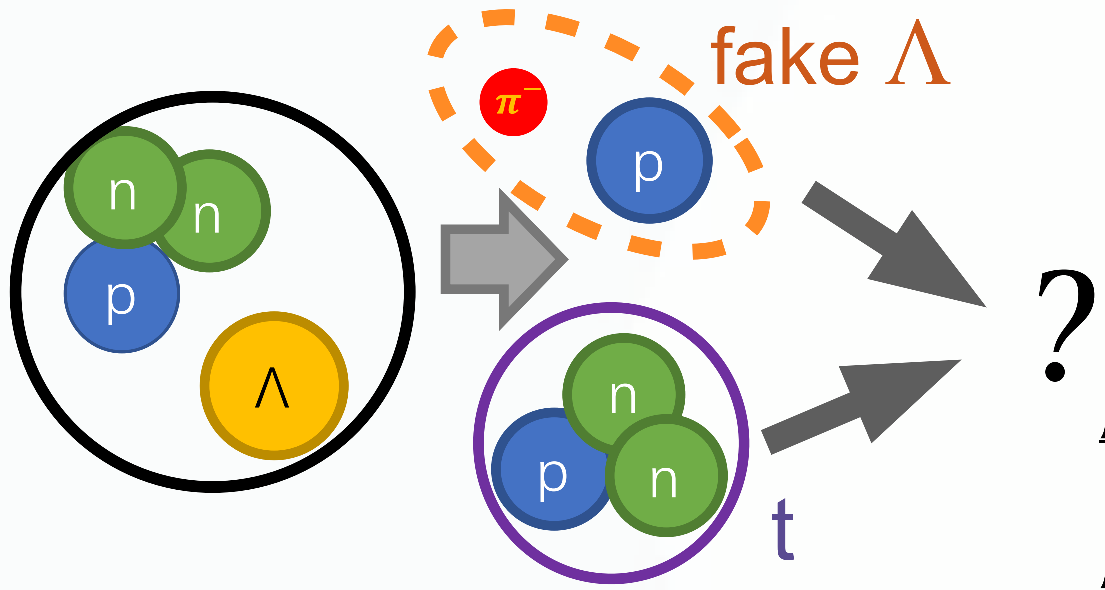
⇒ **Collision dynamics as expected**

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

Contamination from Hyper-nuclei Decay



$${}^{3}_{\Lambda}\mathrm{H} -> \mathrm{d} + \mathrm{p} + \pi^-$$



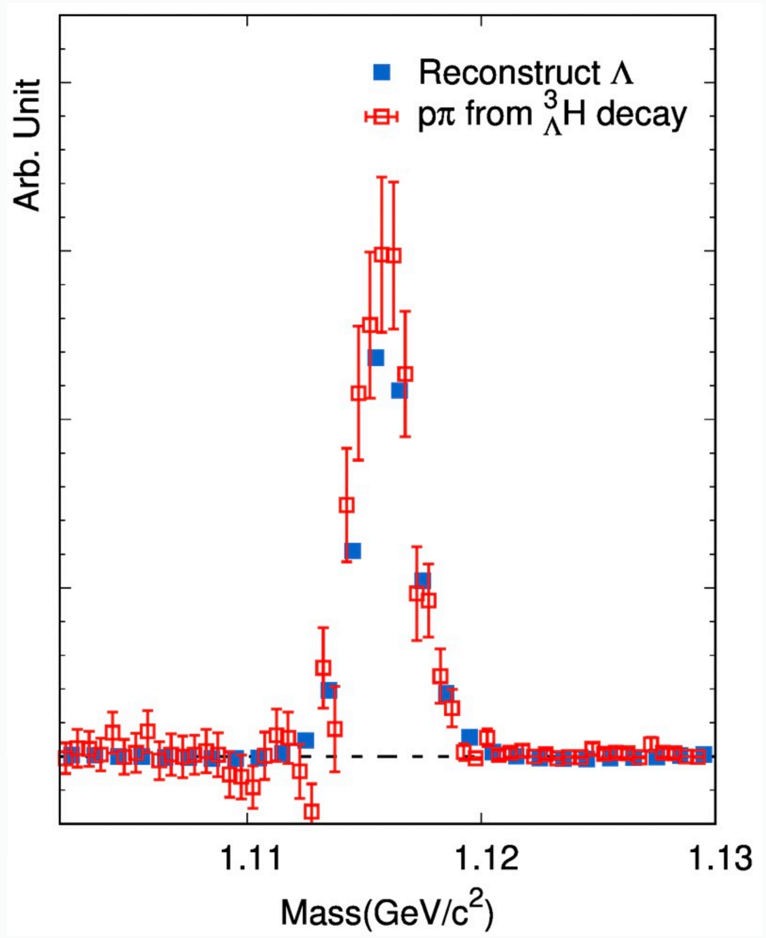
$${}^{4}_{\Lambda}\mathrm{H} -> \mathrm{t} + \mathrm{p} + \pi^-$$

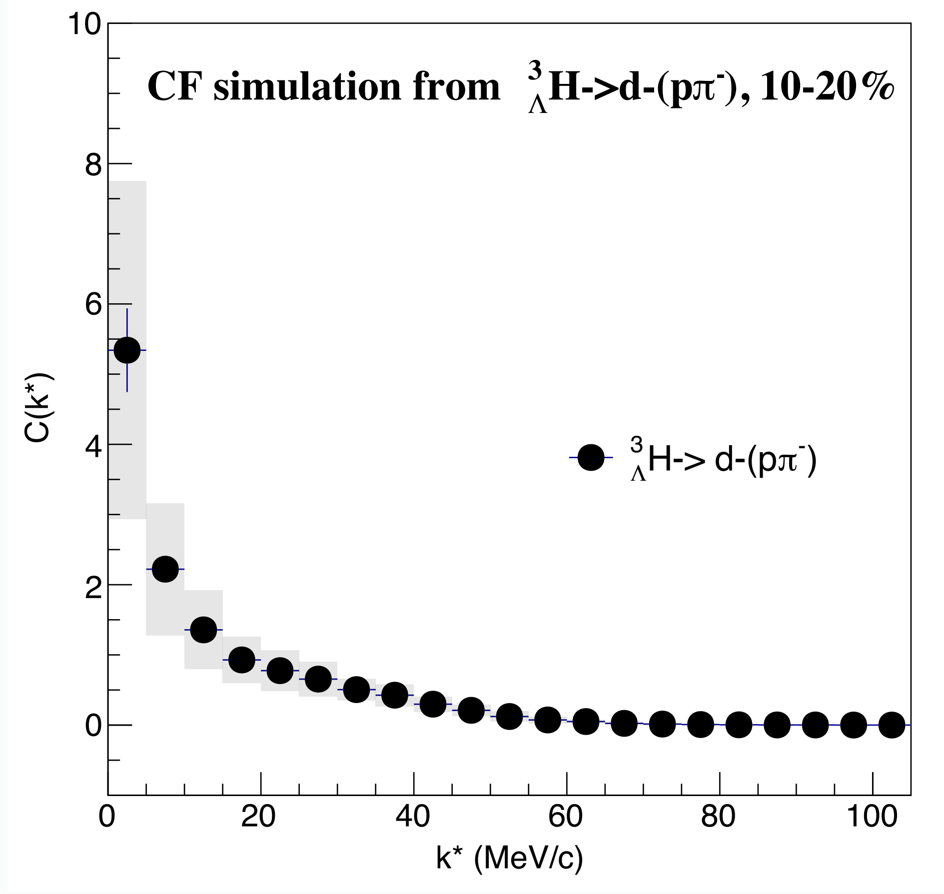
$${}^{4}_{\Lambda}\mathrm{He} -> {}^{3}\mathrm{He} + \mathrm{p} + \pi^-$$

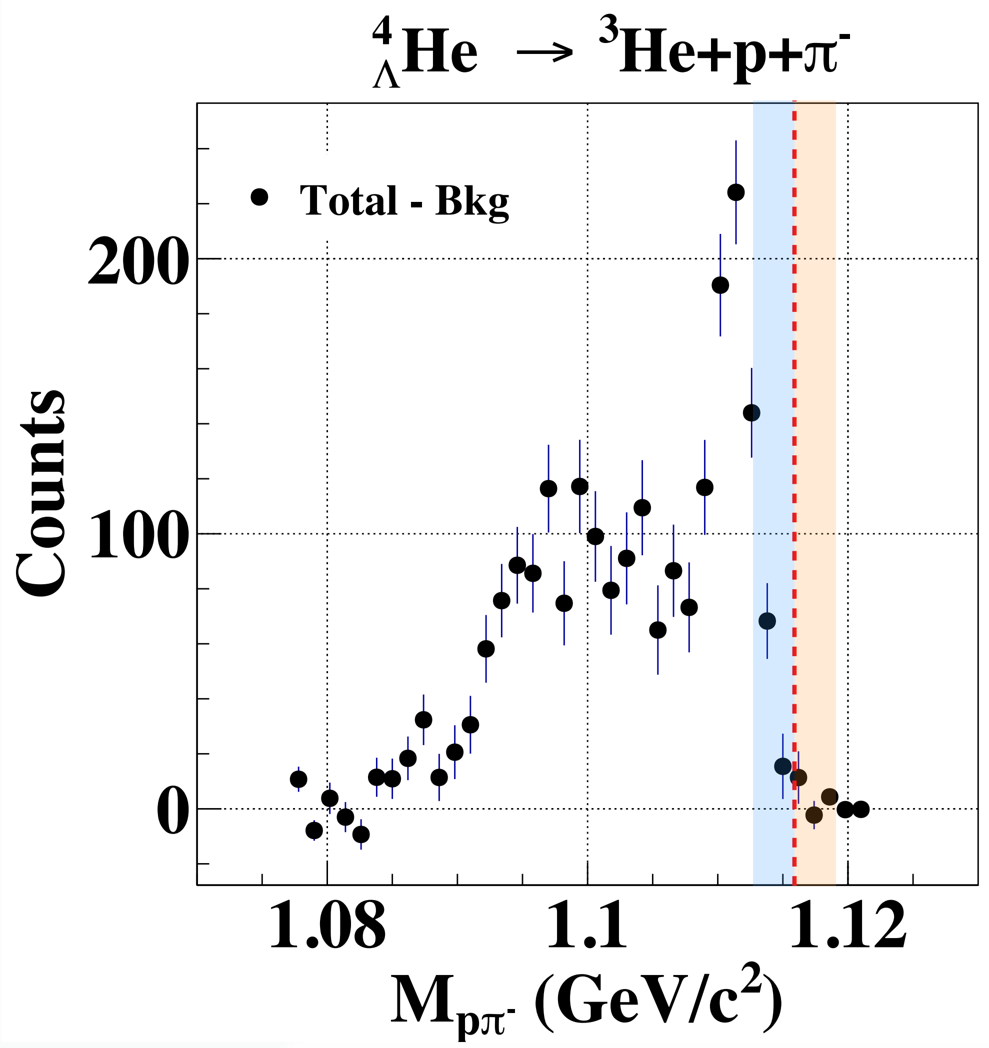
Left signal: 1.11271~1.11589 GeV/c^2

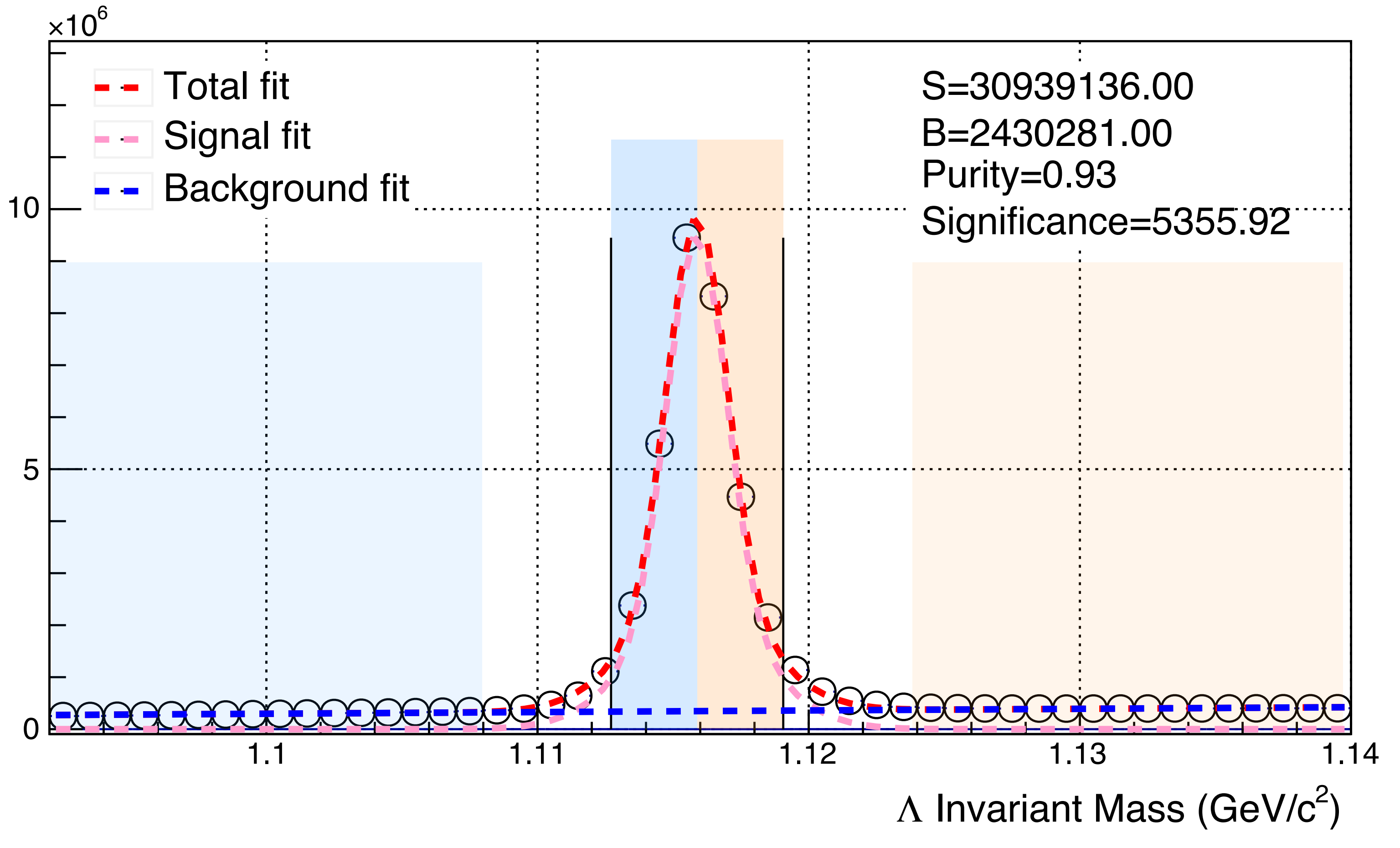
Right signal: 1.11589~1.11906 GeV/c^2

EPJ Web Conf. 296 (2024) 14010









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