QPT 2025

Guilin, China

Two-Particle Correlations of Light Nuclei and Hyperons in Heavy-Ion Collisions at STAR

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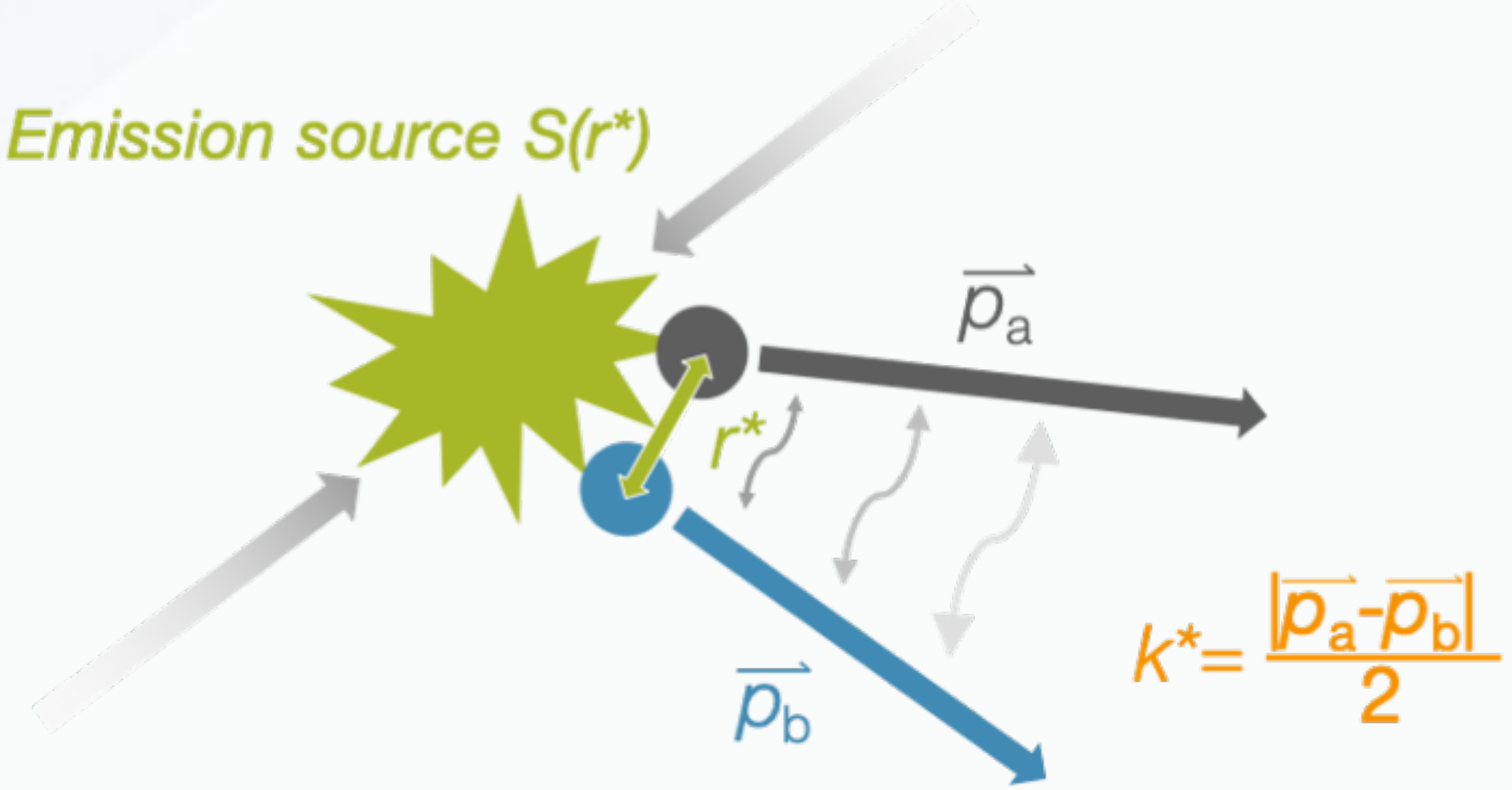
2025/10/27

Outline

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

- **Two-particle correlation function:**

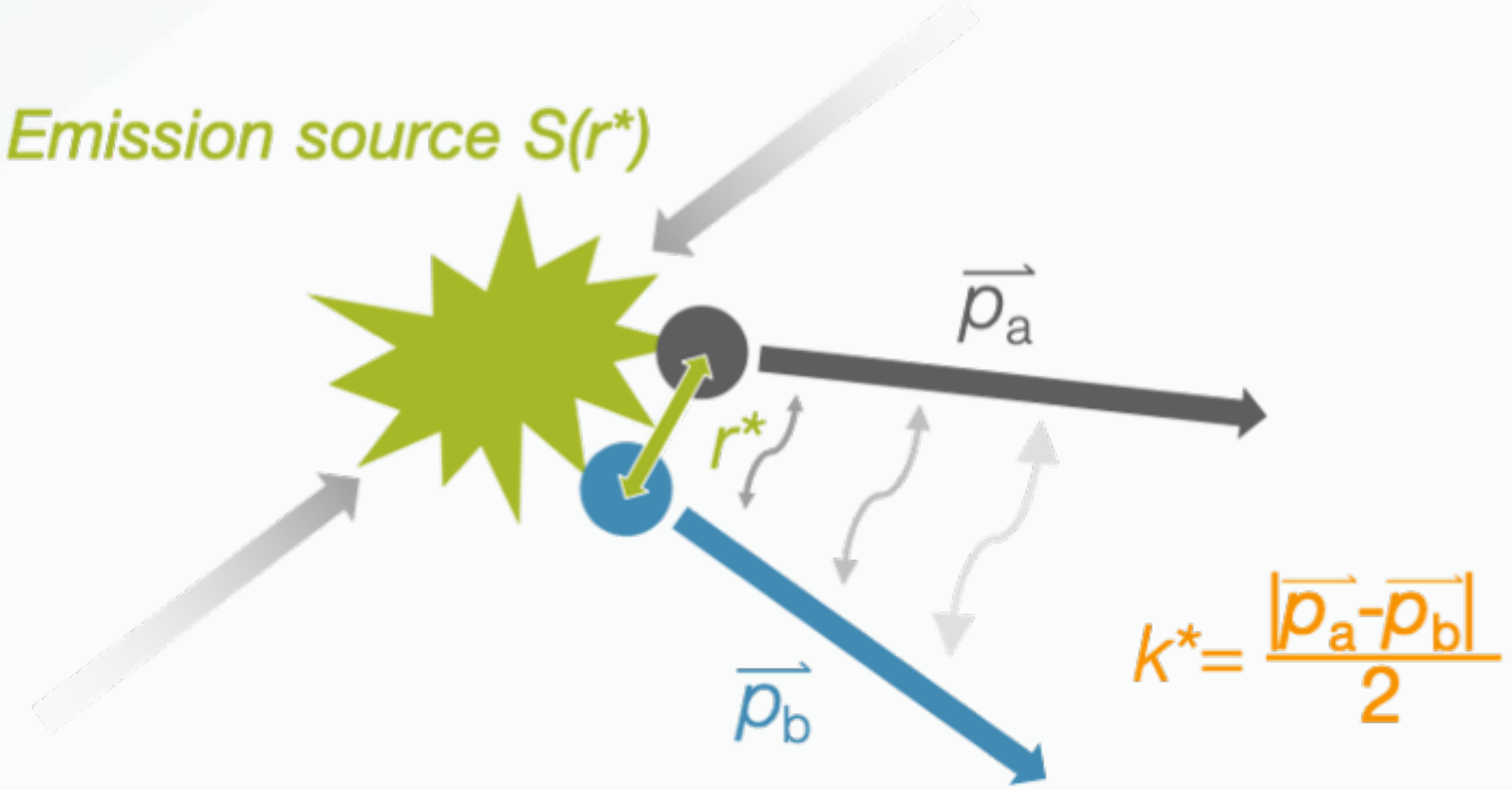
<u>*Model*</u>   <u>*Experimental*</u>

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

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

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

Femtoscopy



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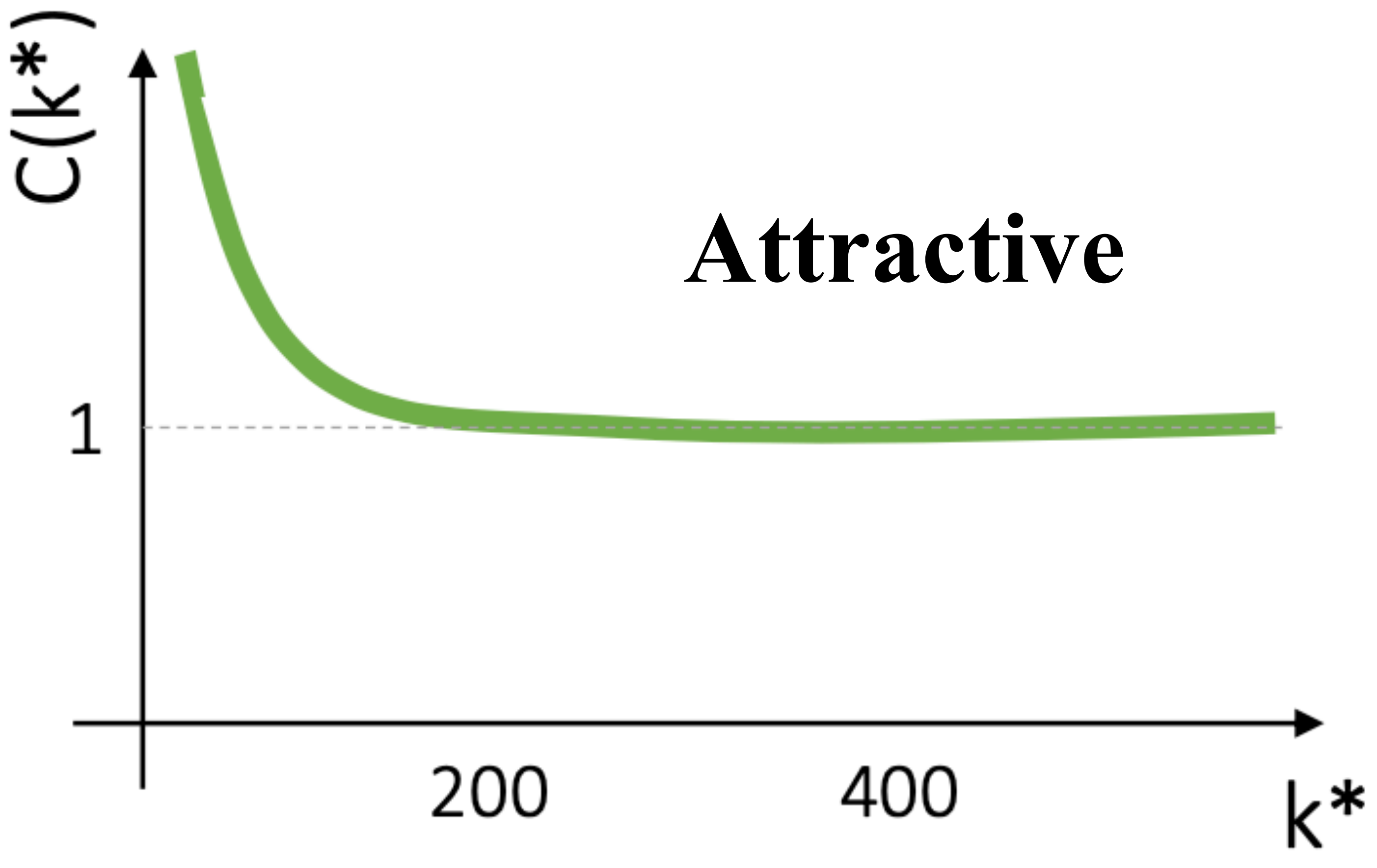

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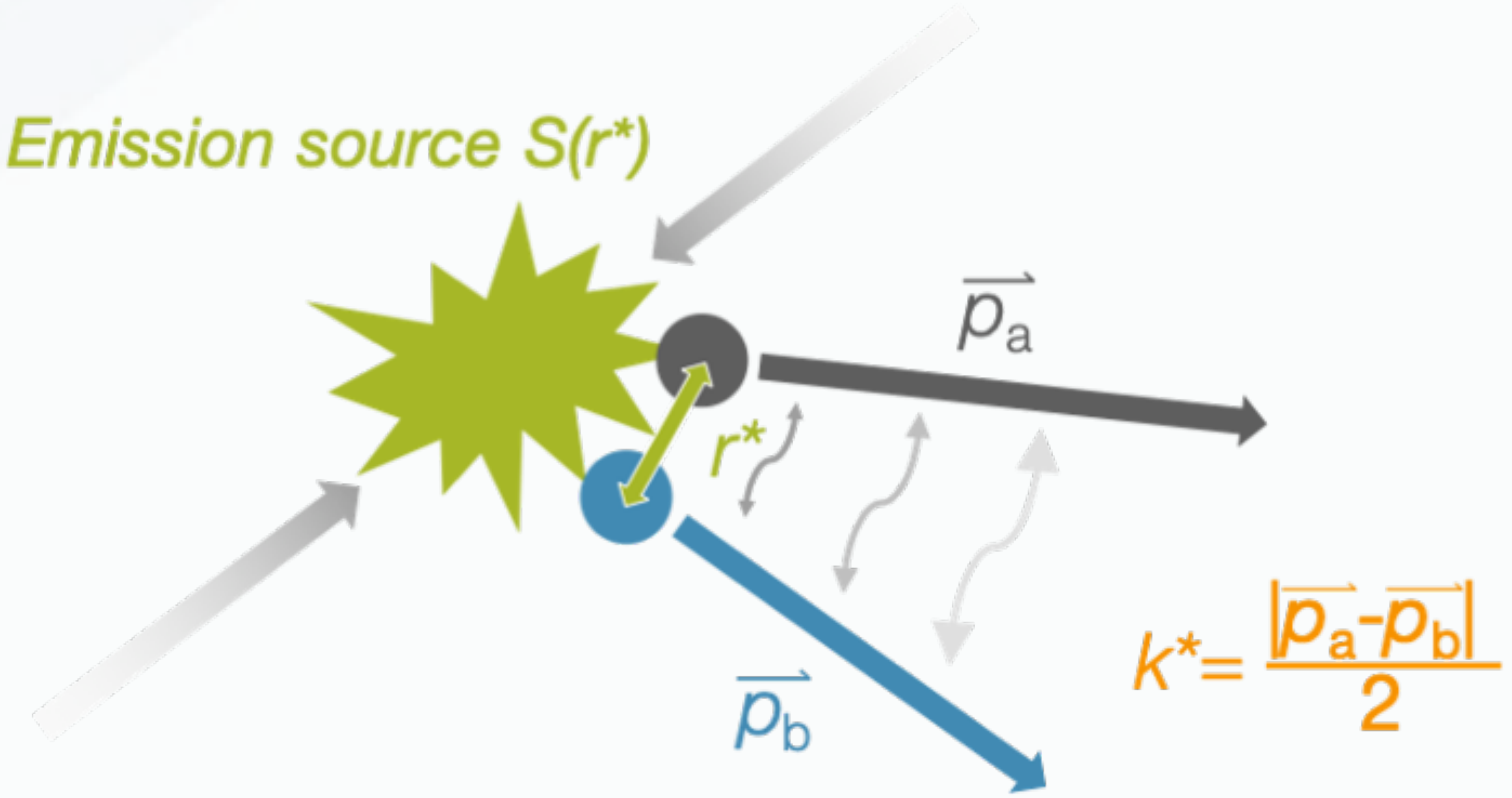

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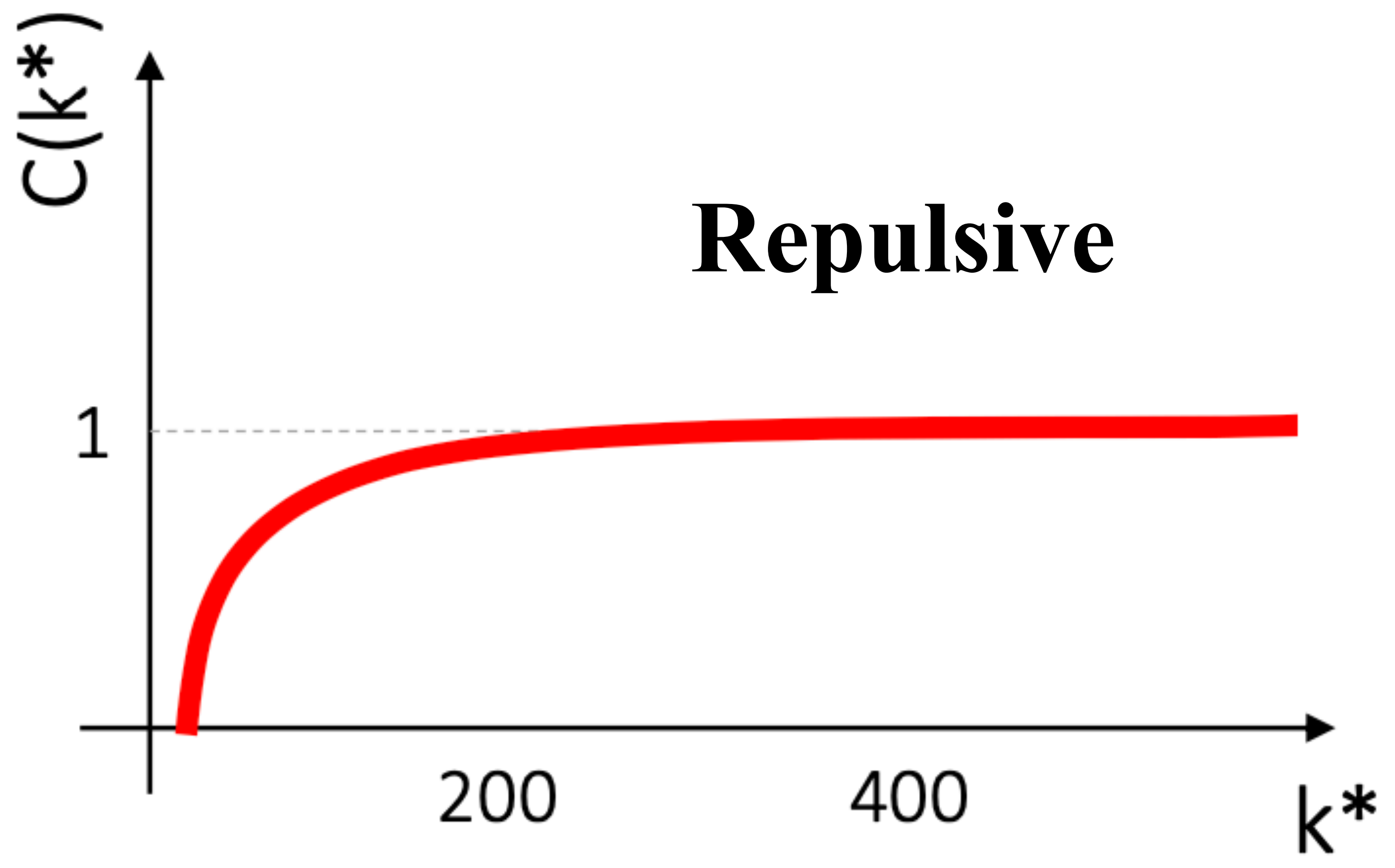

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Lednicky-Lyuboshitz approach

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

- **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:

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d_0 : Effective range

Sign

$f_0 > 0$: Attractive interaction

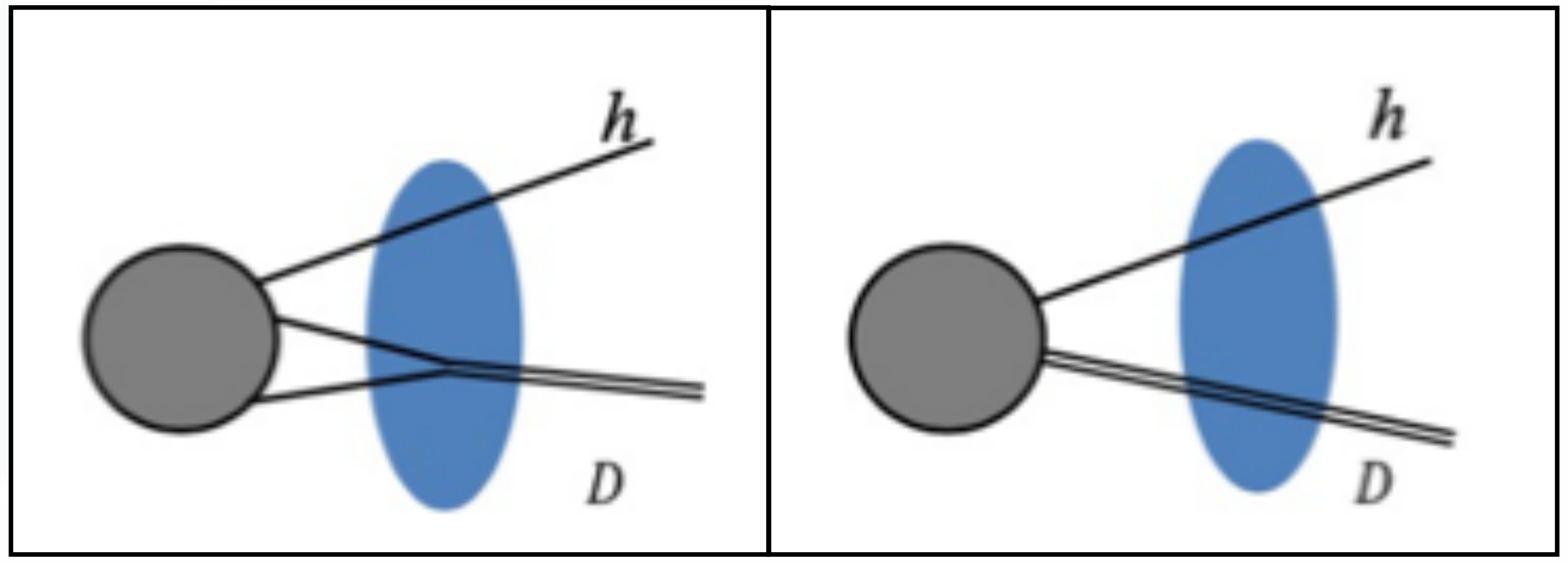
$f_0 < 0$: Repulsive interaction/ bound state

(distinguished by the relation between f_0 and d_0)

Motivation

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

- **Indirect approach to study three-body interaction**



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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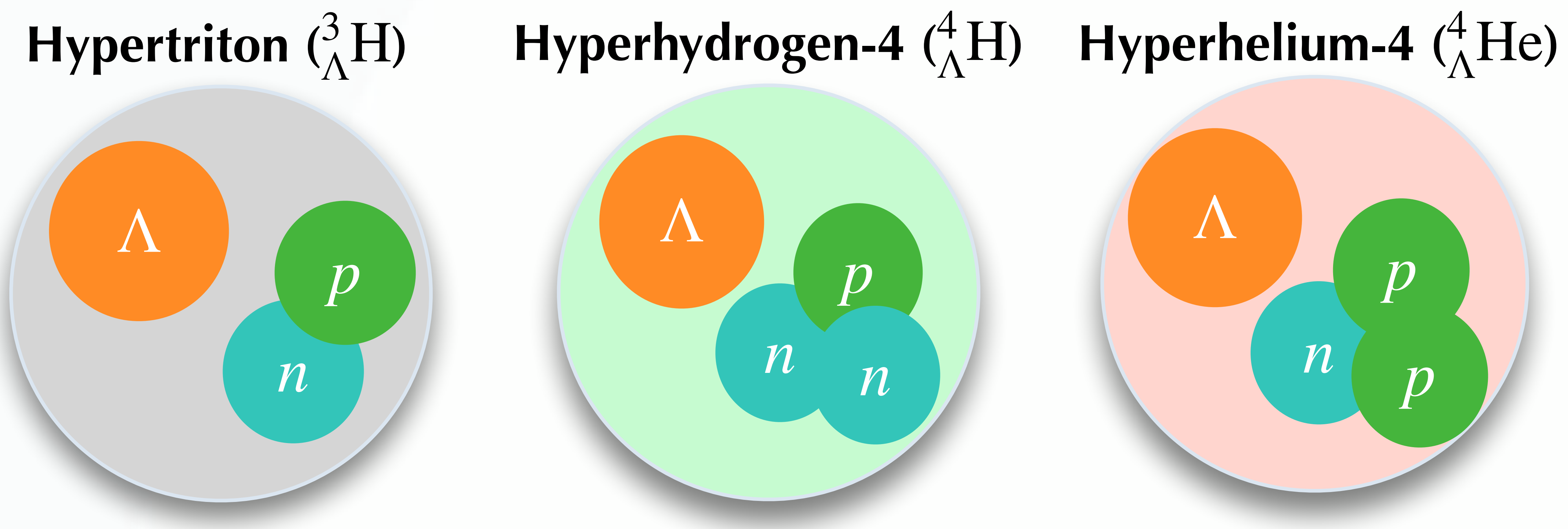
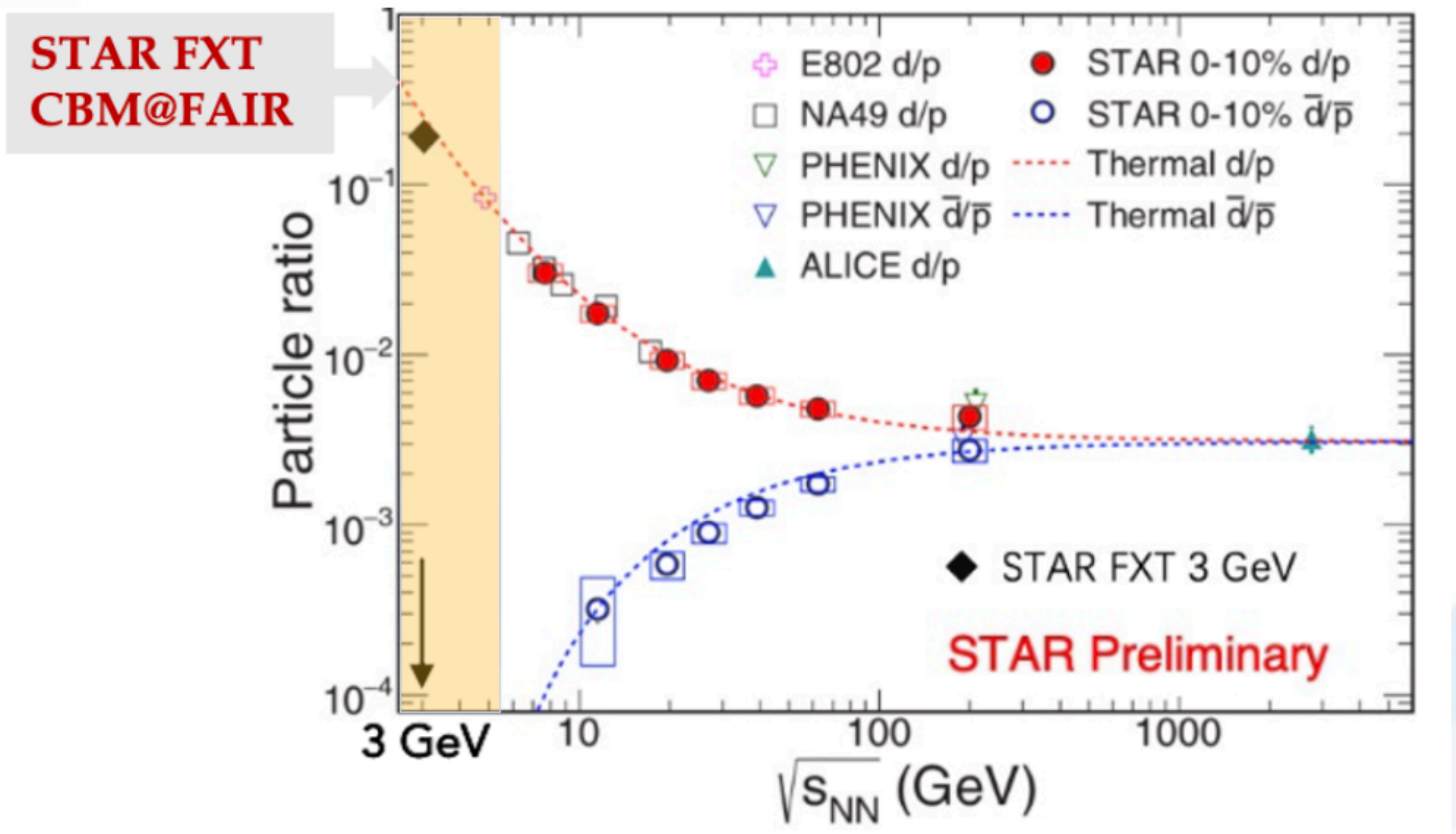
- **Light nuclei - Λ correlation: insights to hyper-nuclei structure and properties**
  - $^{3}_{\Lambda}$H: **Deuteron (n+p) - Λ**
  - $^{4}_{\Lambda}$H: **Triton (n+n+p) -Λ**
  - $^{4}_{\Lambda}$He: **Helium3 (n+p+p) - Λ**

- **At high baryon density like 3 GeV, the production of light nuclei reaches its highest yield -> precise measurements**





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- Light nuclei - Λ correlation: insights to hyper-nuclei structure and properties
  - ${}^{3}_{\Lambda}H$: Deuteron (n+p) - Λ
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  - ${}^{4}_{\Lambda}He$: Helium3 (n+p+p) - Λ

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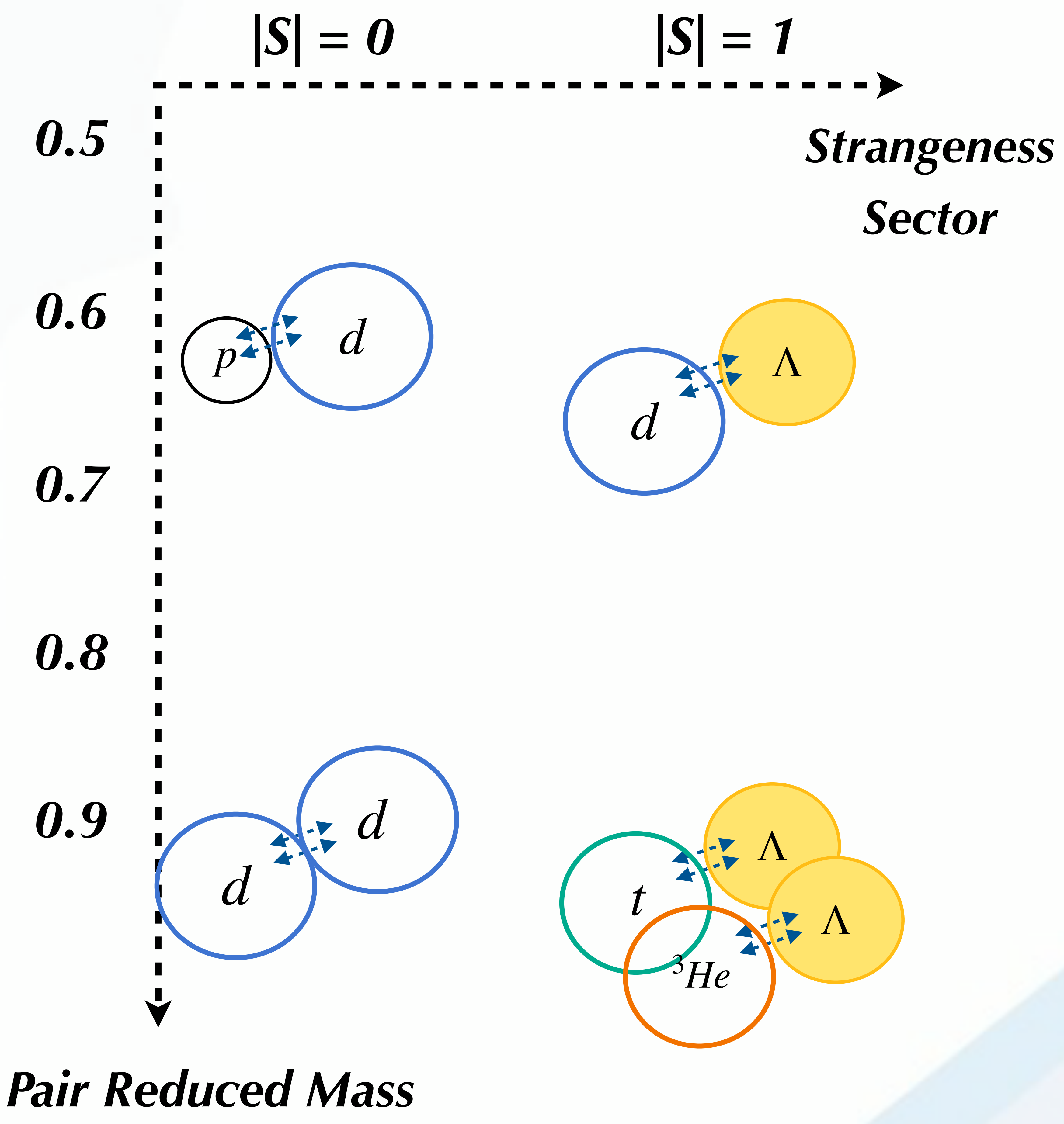
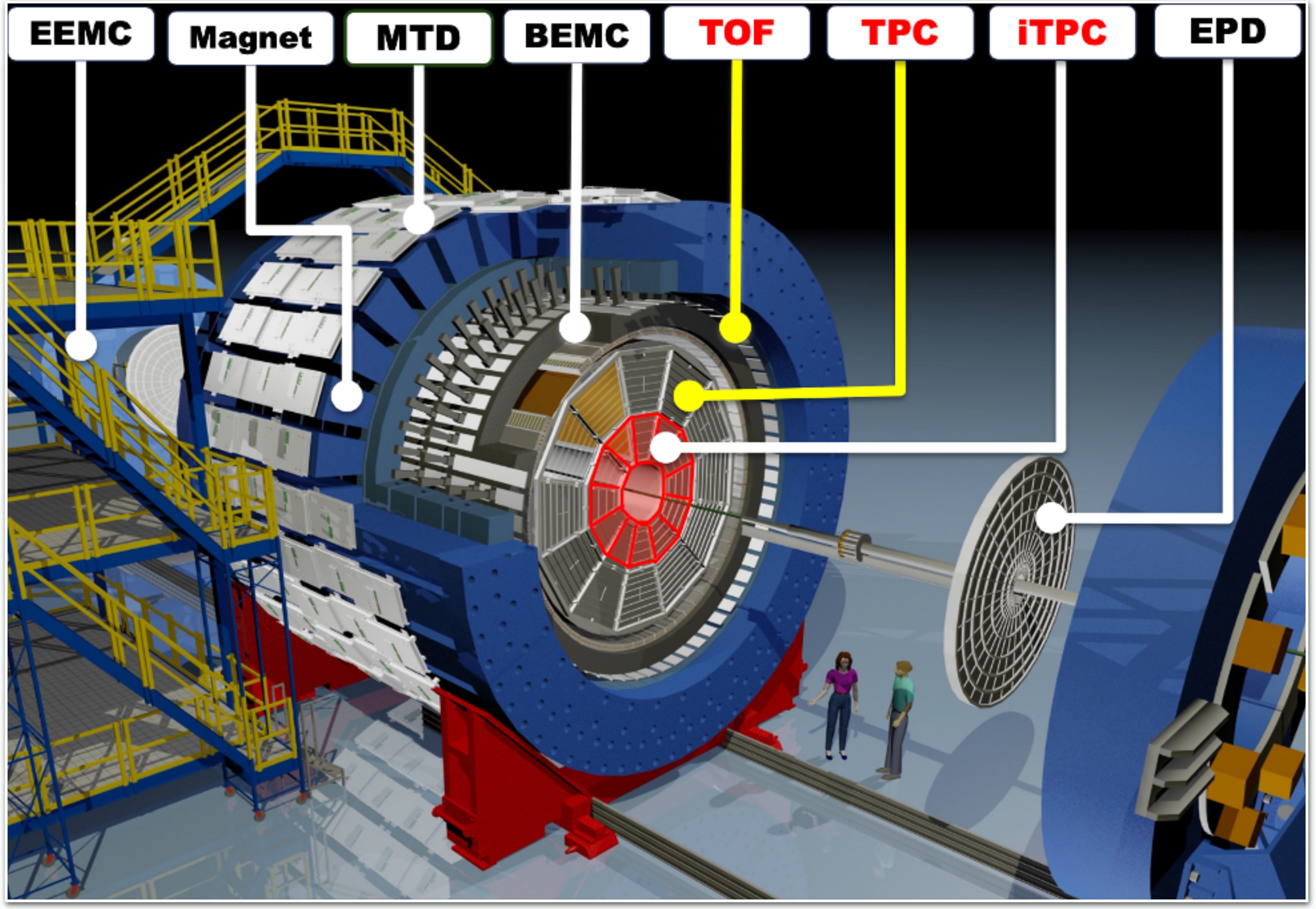
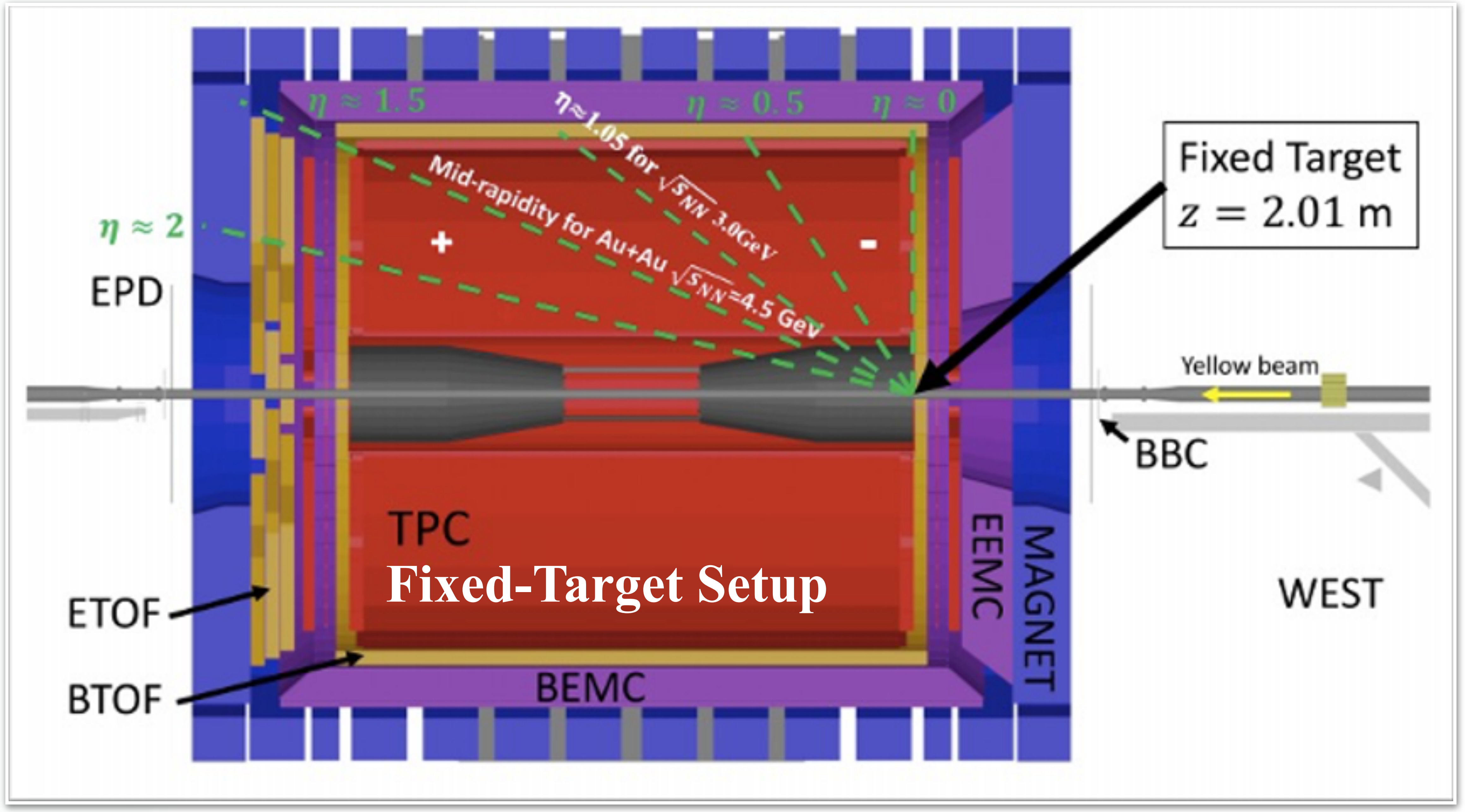
This talk covers:



STAR Detector



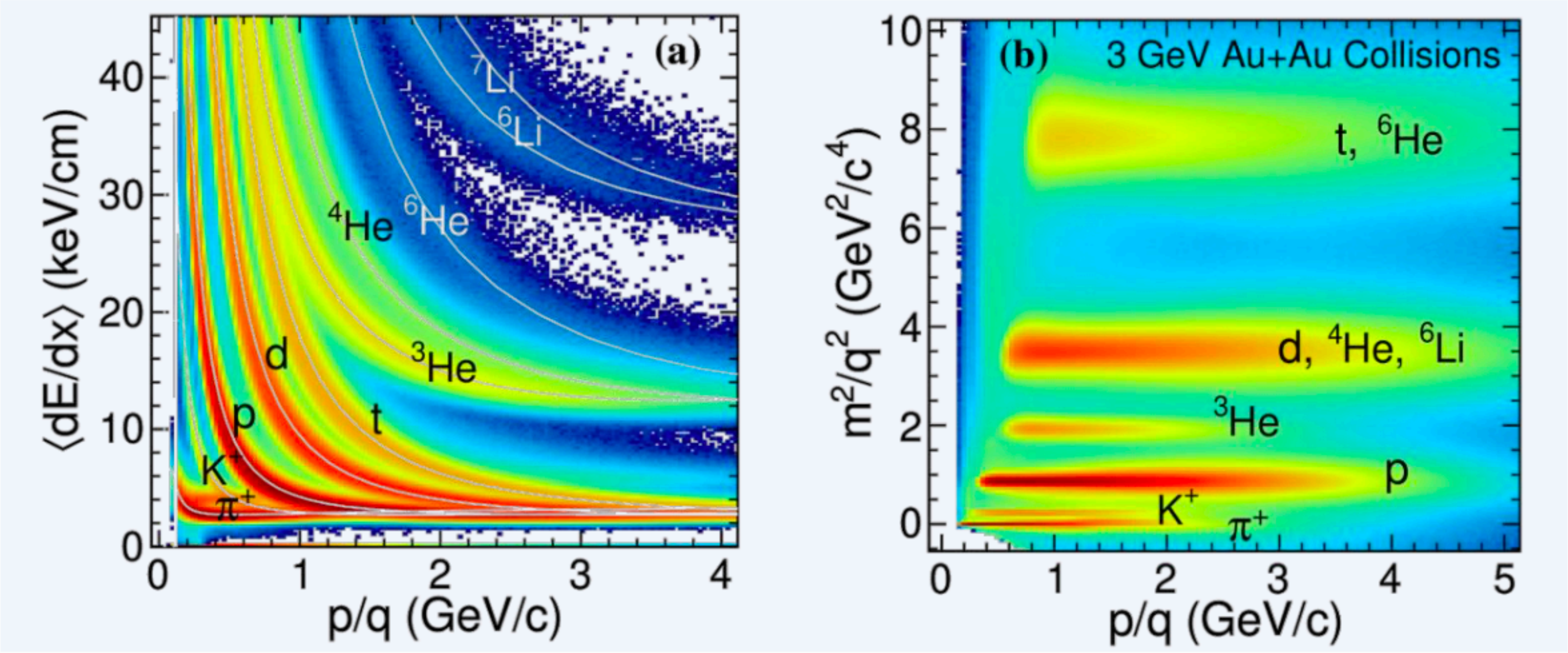


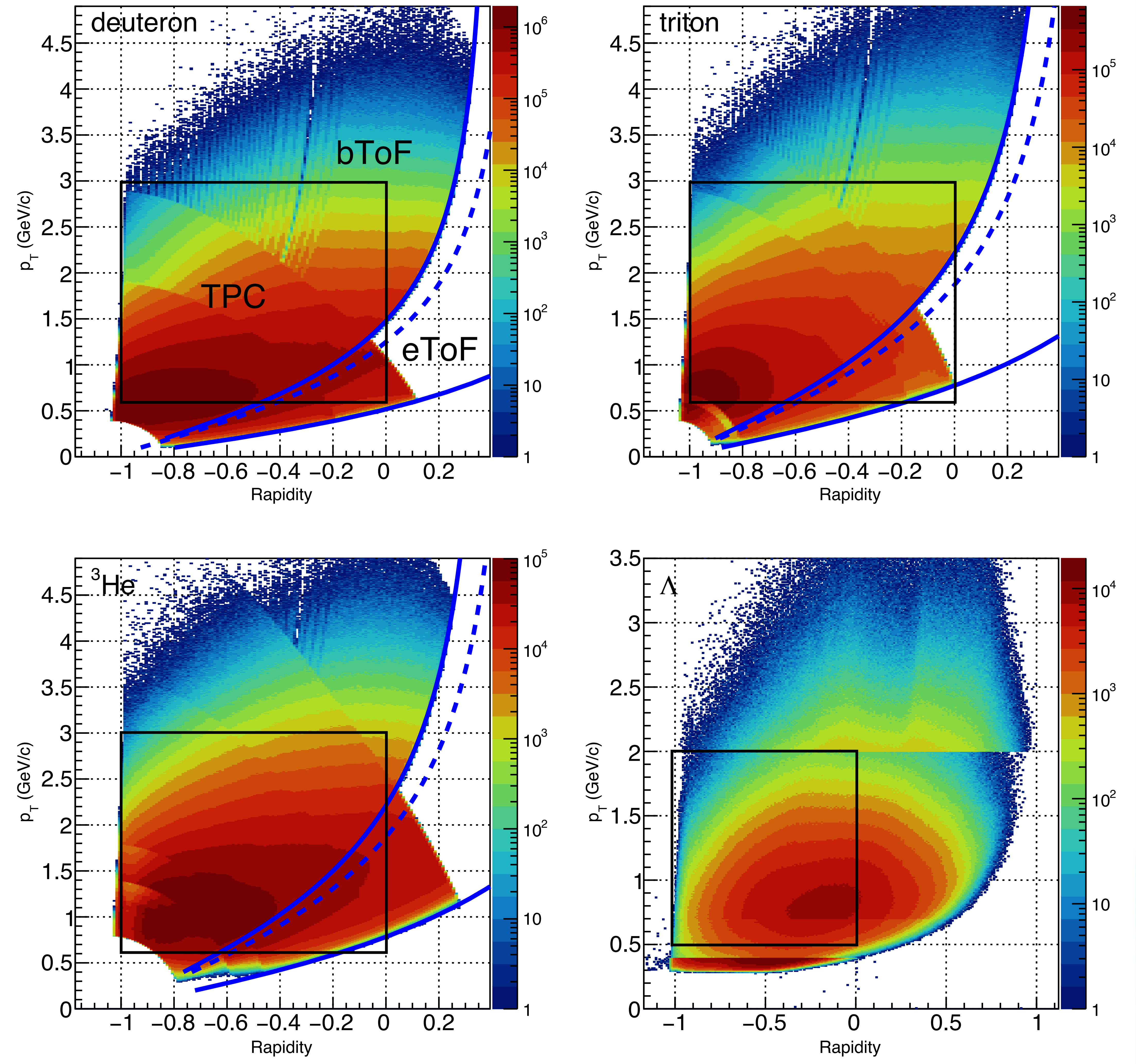
Center-of-Mass Energy	Collisions	Year	Mode	#Events
3 GeV	Au+Au	2018	FXT	260 M
3 GeV	Au+Au	2021	FXT	2000 M

⇒ **Excellent particle identification**

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

Particle Identification & Reconstruction

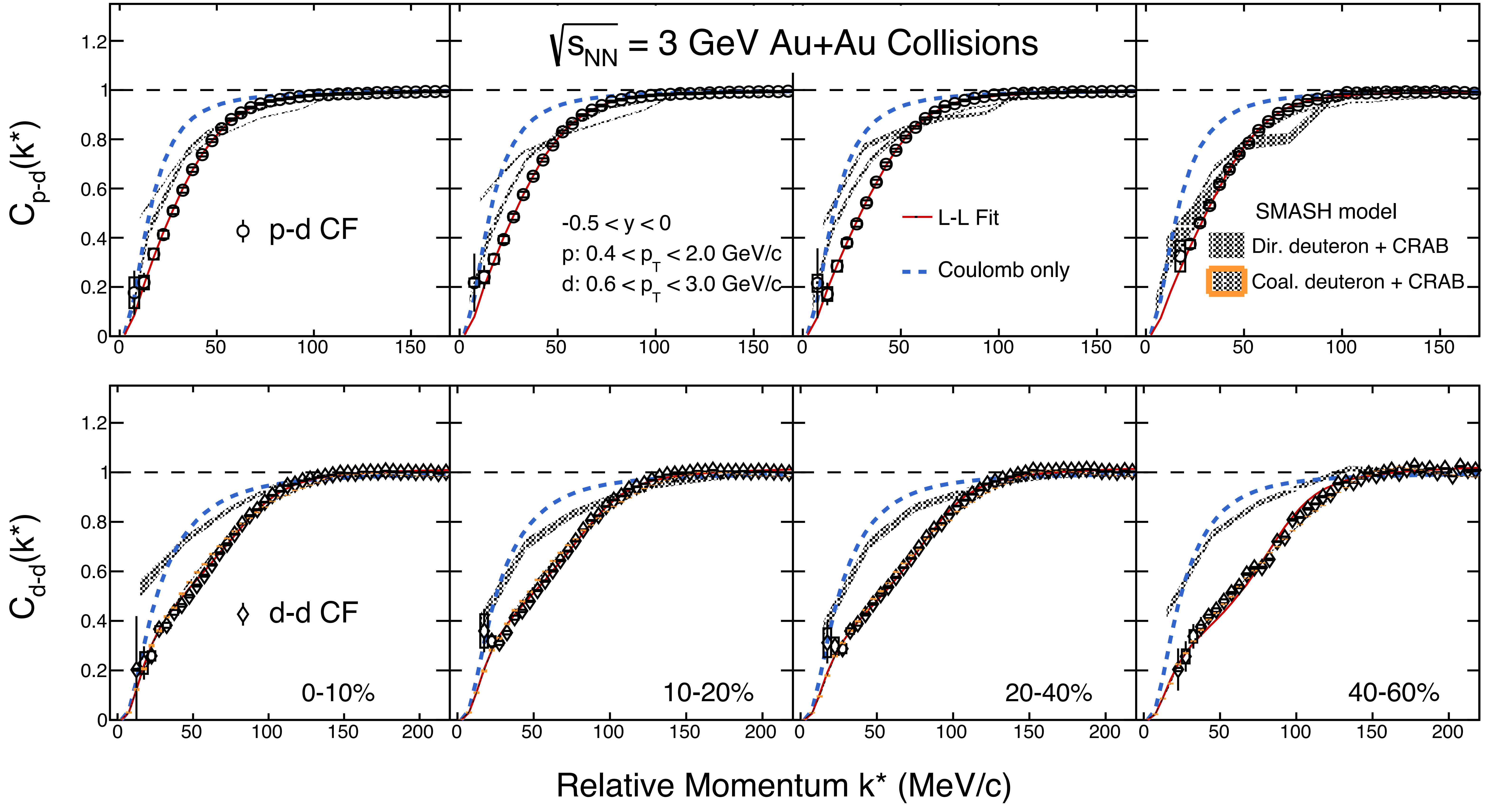




- ➡ **Protons, deuterons, tritons and helium3 are identified by TPC, TOF**
  - **Low p_T : TPC**
  - **High p_T : TPC + TOF**
  - **Purity > 95%**
- ➡ **Reconstruct Λ hyperons using KFParticle finder**

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

p-d / d-d Correlation (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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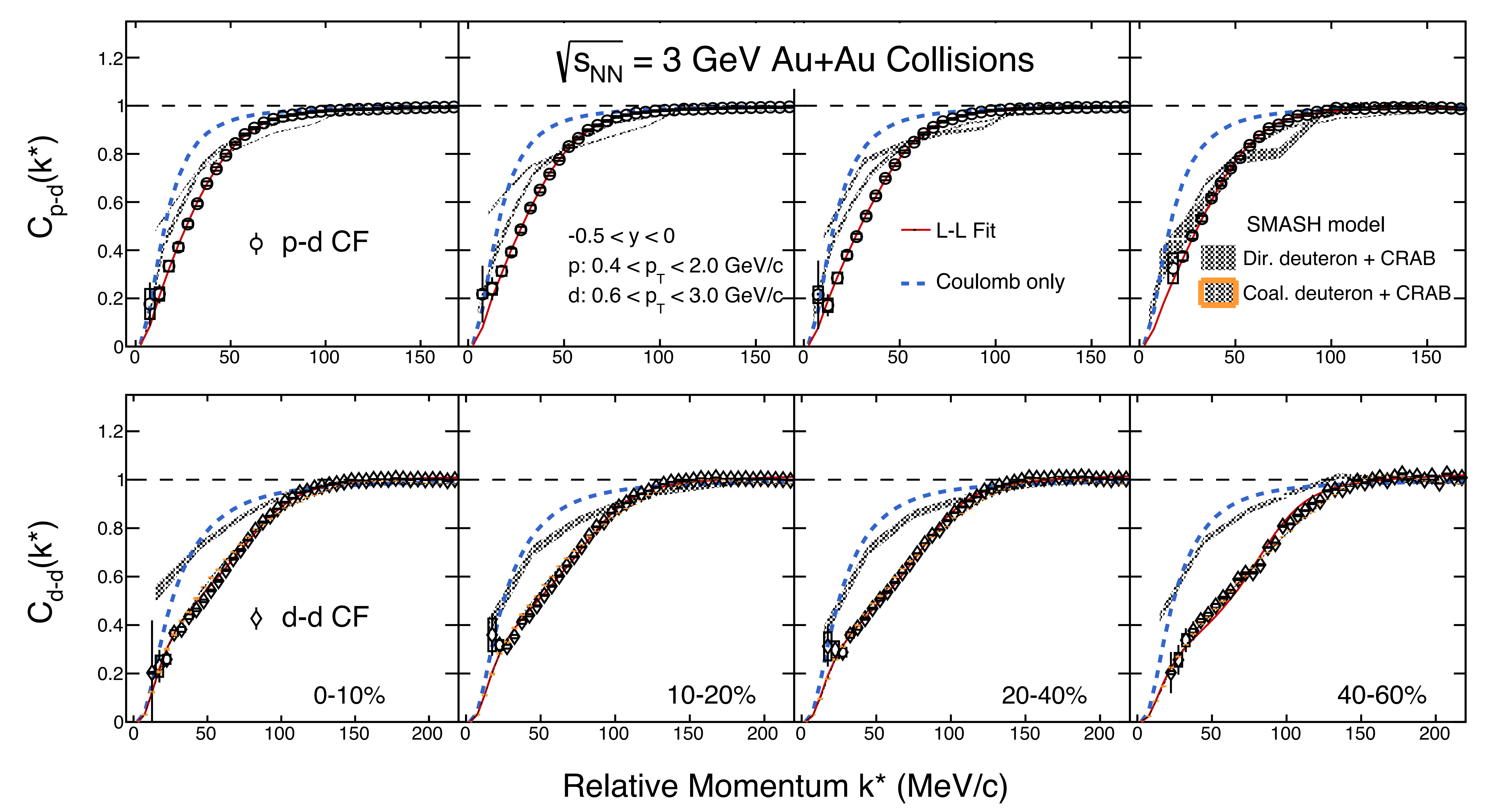

- Simulated with SMASH model, consider two deuteron formation mechanism:
  - **Direct production**
    - Hadronic scattering
    - Fail to describe data at certain k*
  - **Coalescence production**
    - Wigner function
    - Well description to data
    - Coalescence is the dominant process for deuteron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

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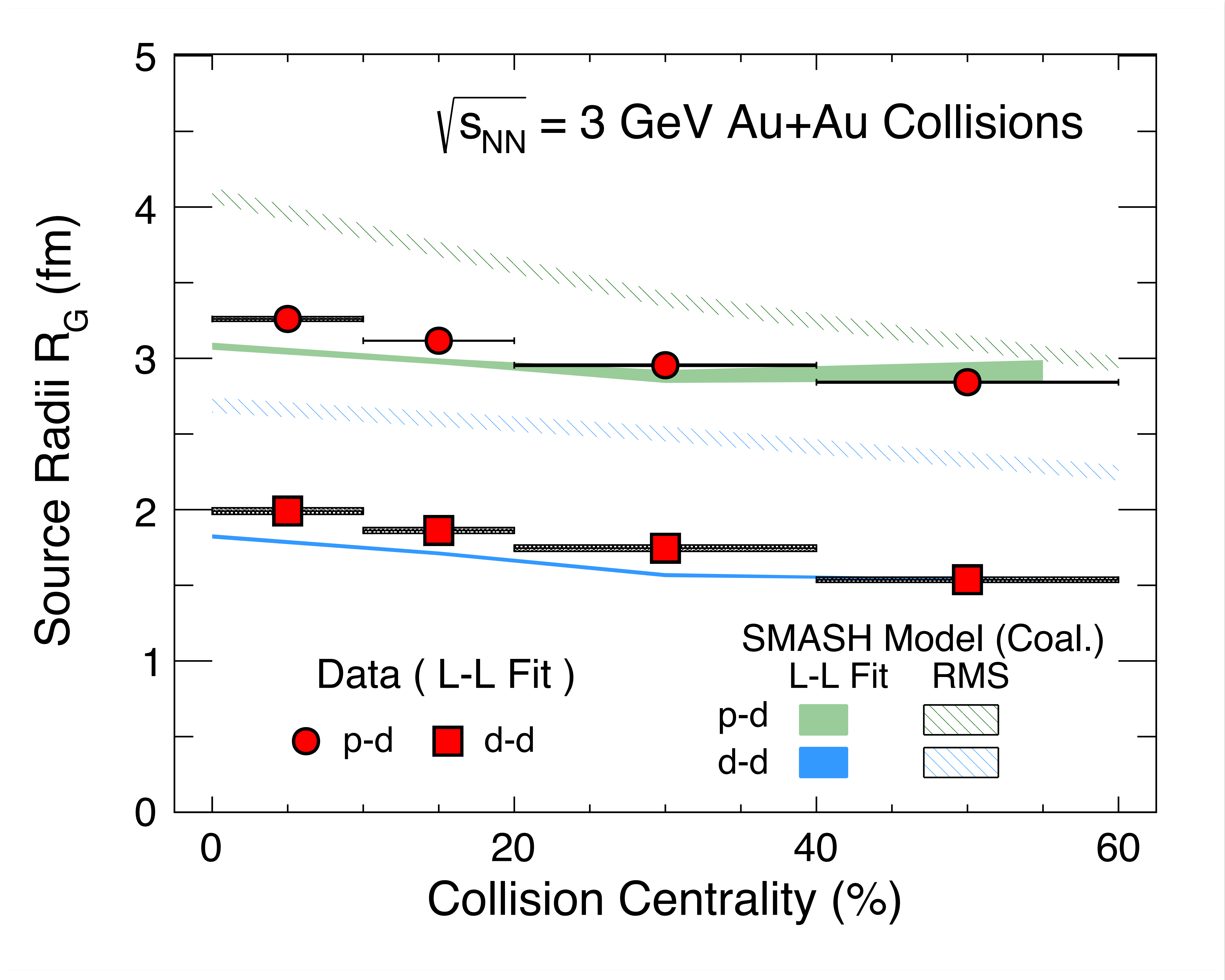
p-d / d-d Source Size



- **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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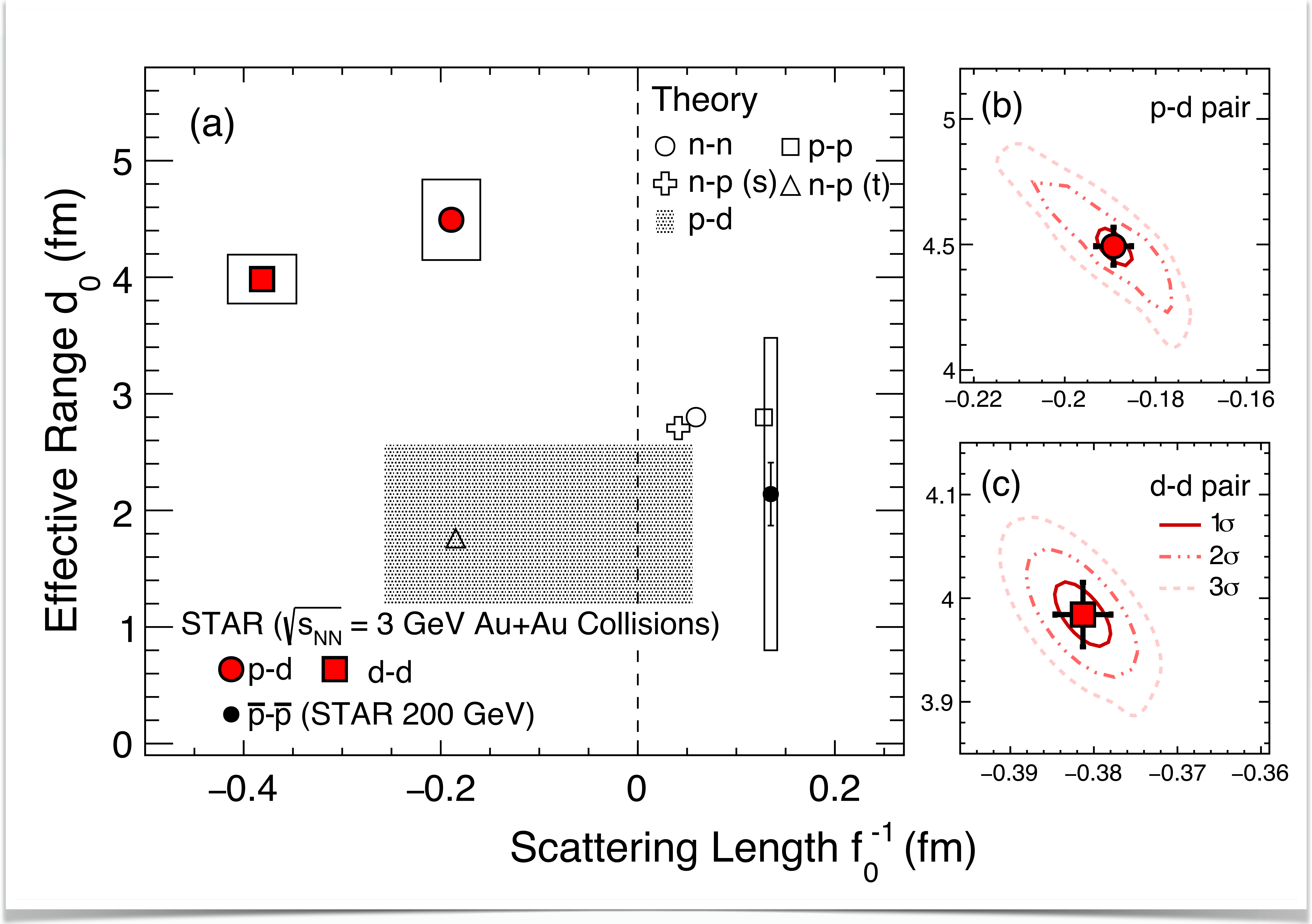
p-d / d-d Interaction



- **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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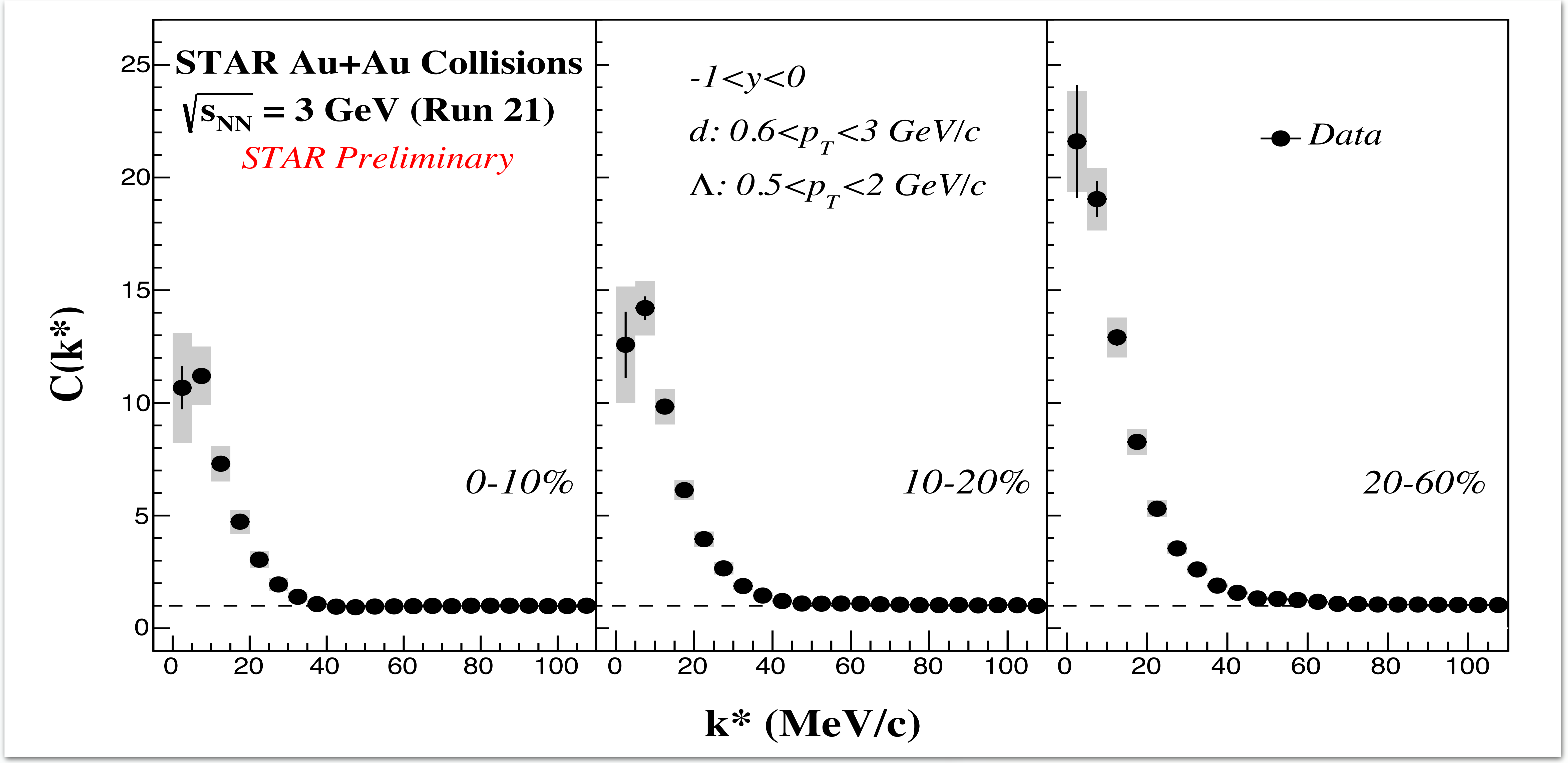
d-Λ Correlation (run21)

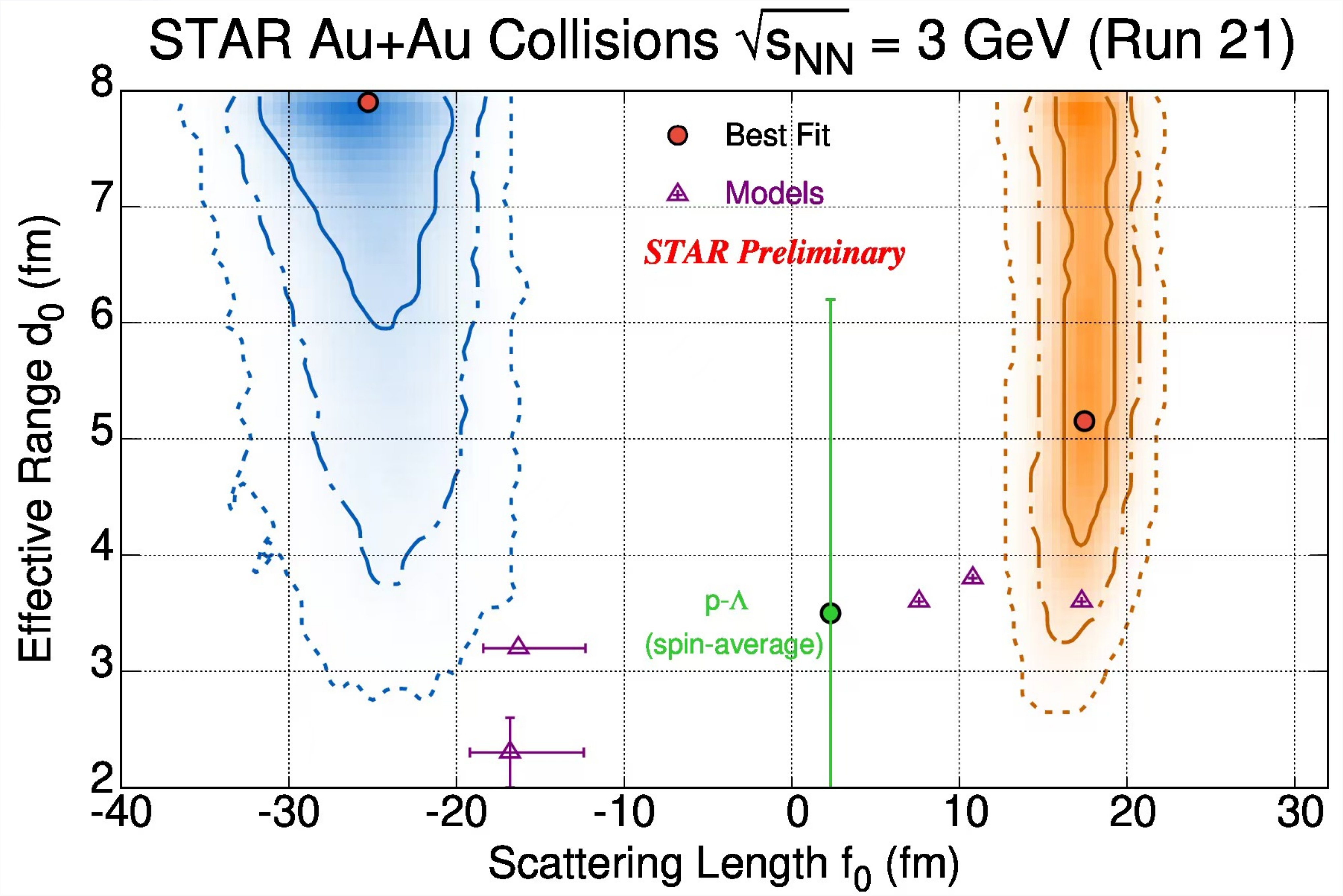


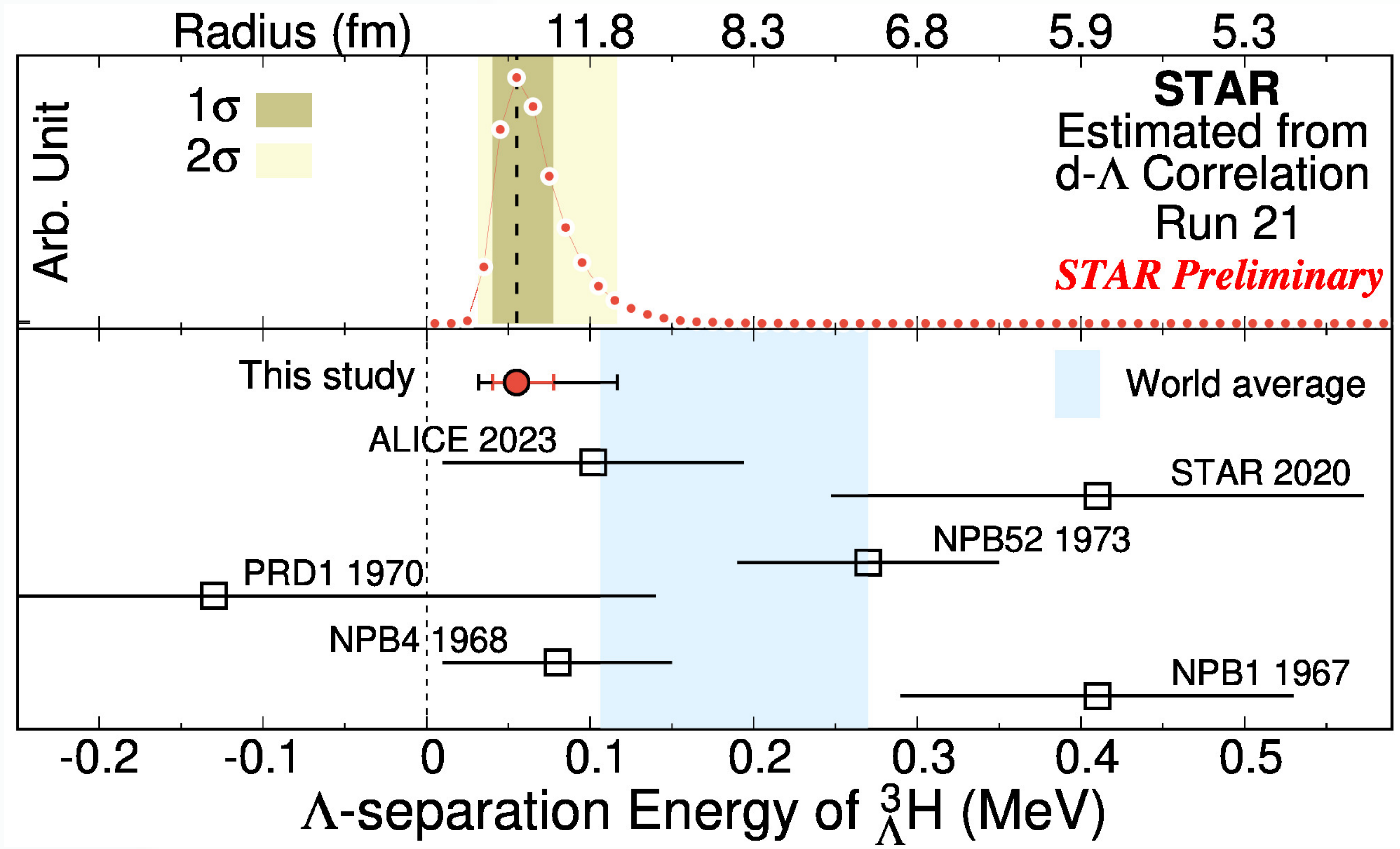
- Strong enhancements at small k* => Attractive interactions
- More precise measurements of d-Λ correlation functions using 2 billion events with run 21
  - Consistent results between run18 and run21, improving the accuracy of extracted parameters

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

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

d-Λ Interaction (run21)



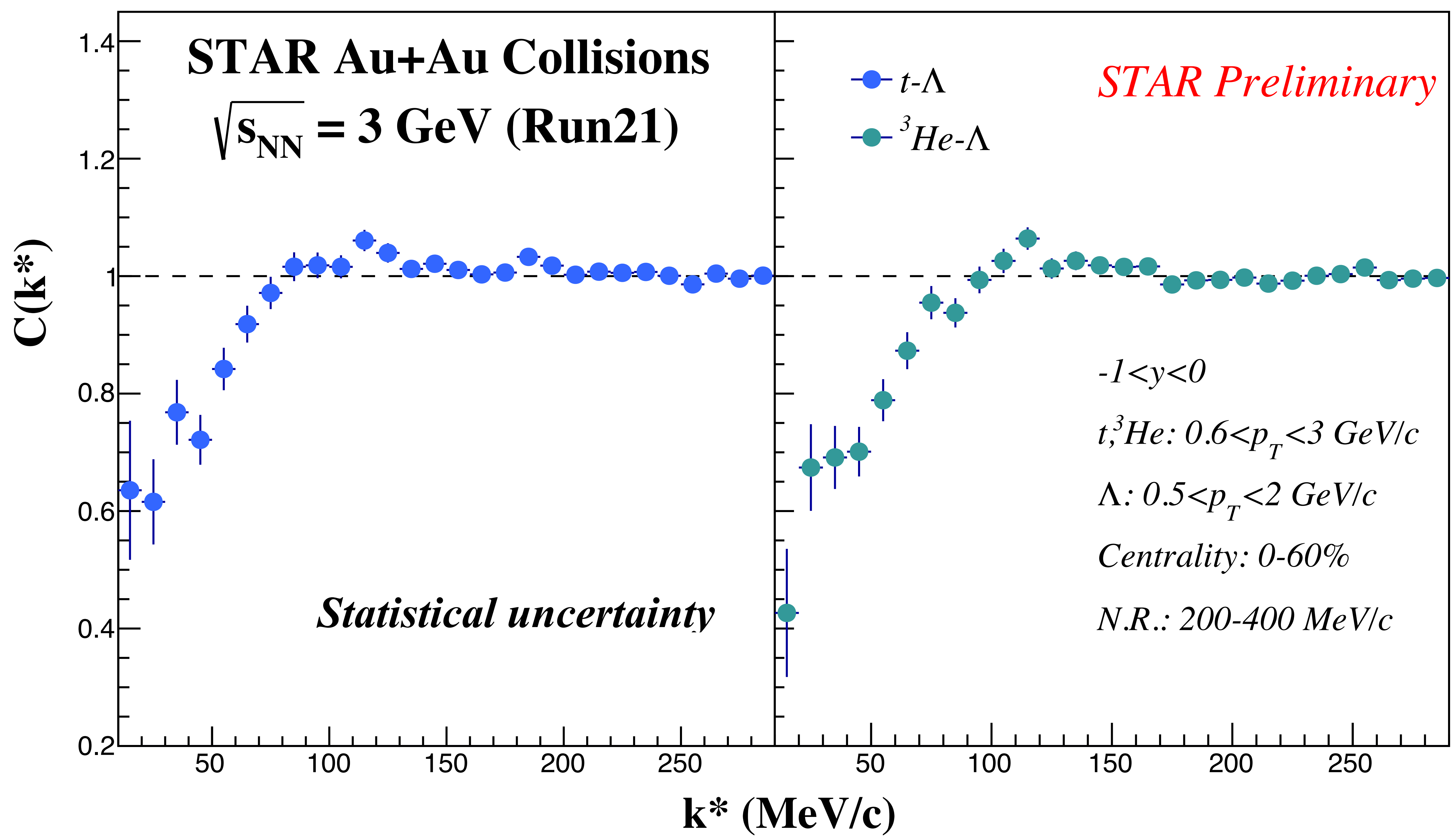


- **Successfully separate two spin components in d-Λ pair**
  - f_0 **(D) = -25.3** $^{+3.3}_{-3.3}$ **fm -> Related to** $^3_\Lambda$H
  - f_0 **(Q) = 17.5** $^{+1.6}_{-1.6}$ **fm -> Attractive interaction**

- **Extract the most accurate results of binding energy and radius of** $^3_\Lambda$H
  - B_Λ **= 0.06** $^{+0.06}_{-0.03}$ **(MeV) @ 95% CL**
  - **r (**$^3_\Lambda$H**) = 16**$^{+5}_{-5}$ **(fm) @ 95% CL**
- **Open a new way to constrain** $^3_\Lambda$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 (run21)



- **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?**

Summary

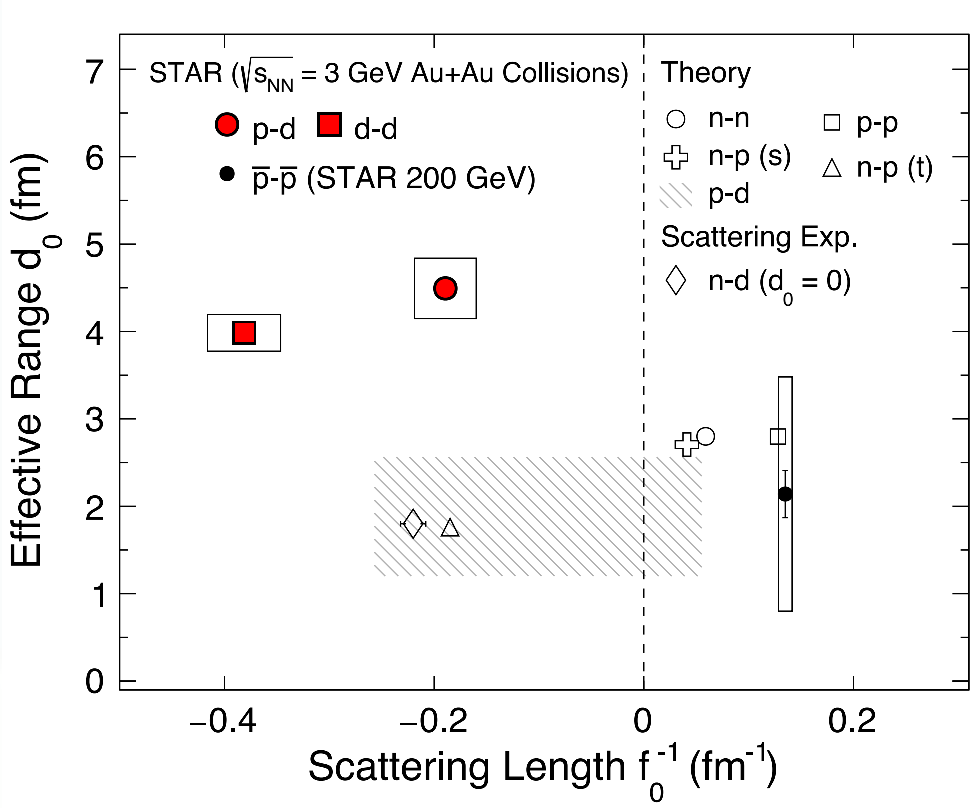
⇒ **Femtoscopy measurements from HIC provides a unique tool to explore strong interactions and evolution dynamics**

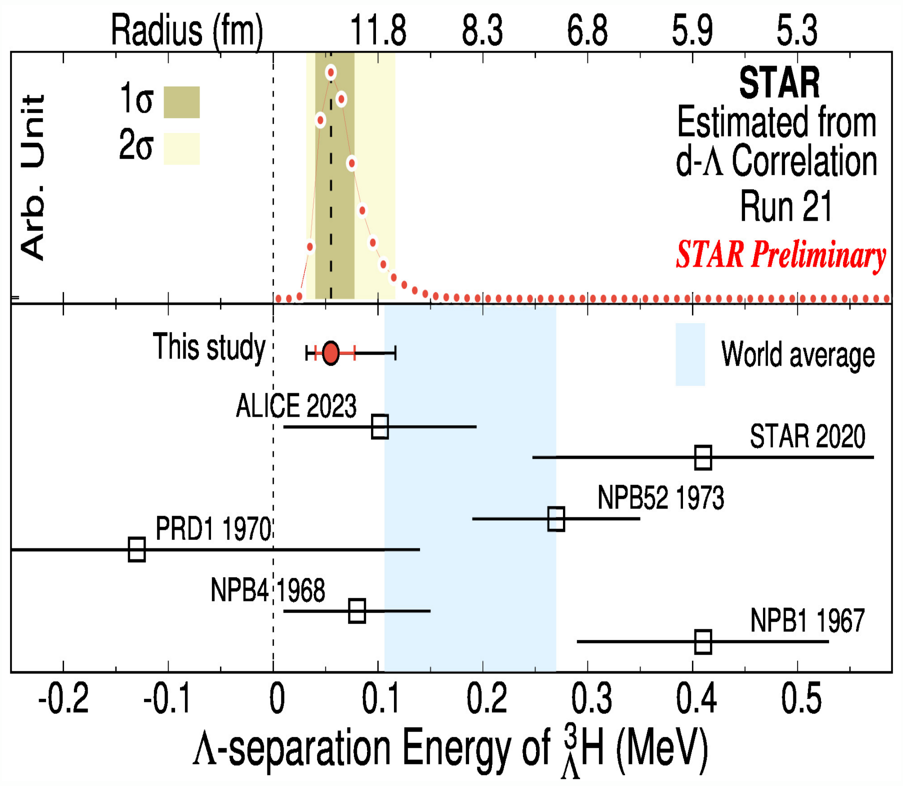
⇒ **p-d, d-d correlation**

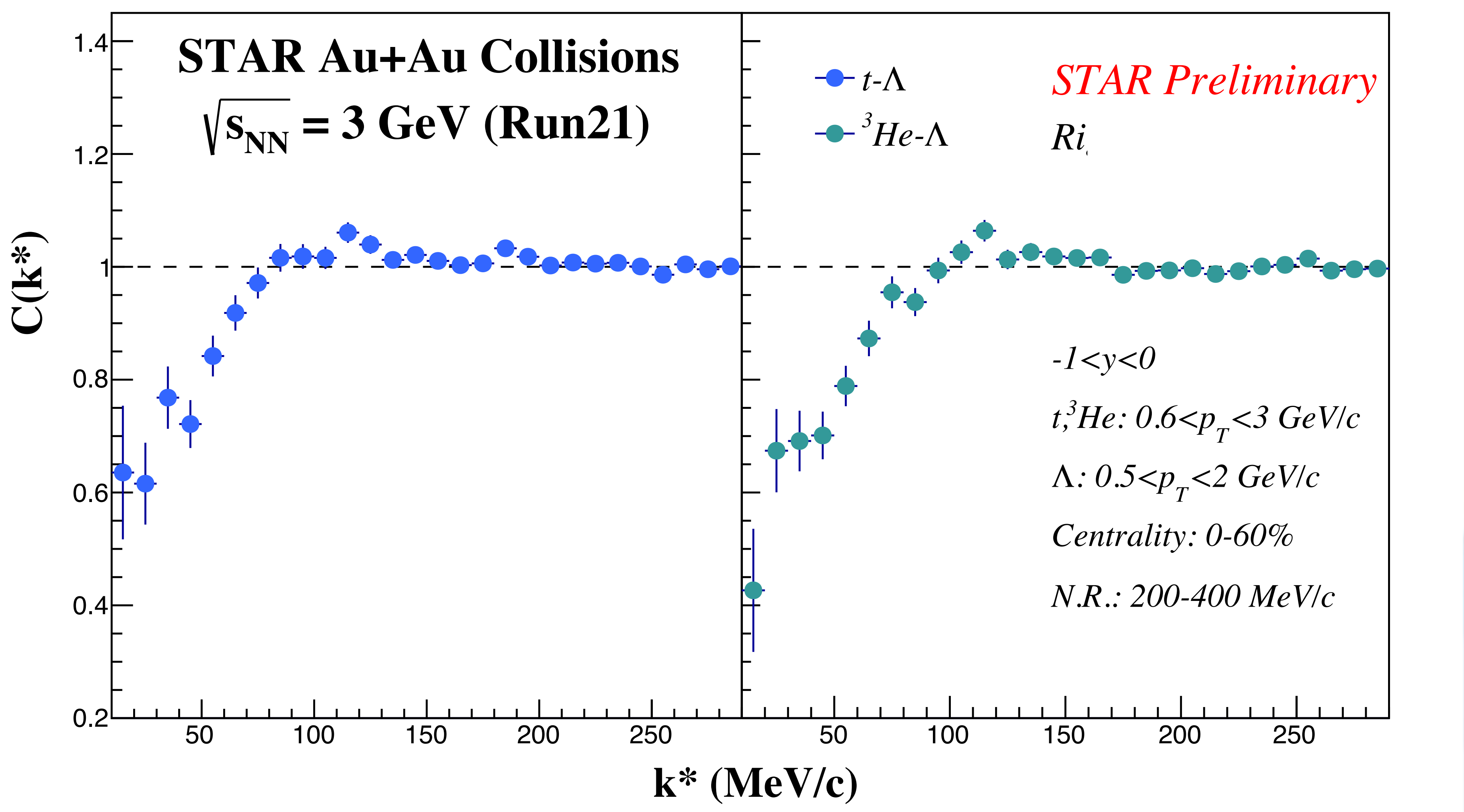
- **First extraction of p-d / d-d interaction parameters in HIC**
- ***Coalescence* is the dominant process for deuteron formation in the high-energy collisions**

⇒ **d-Λ, 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**





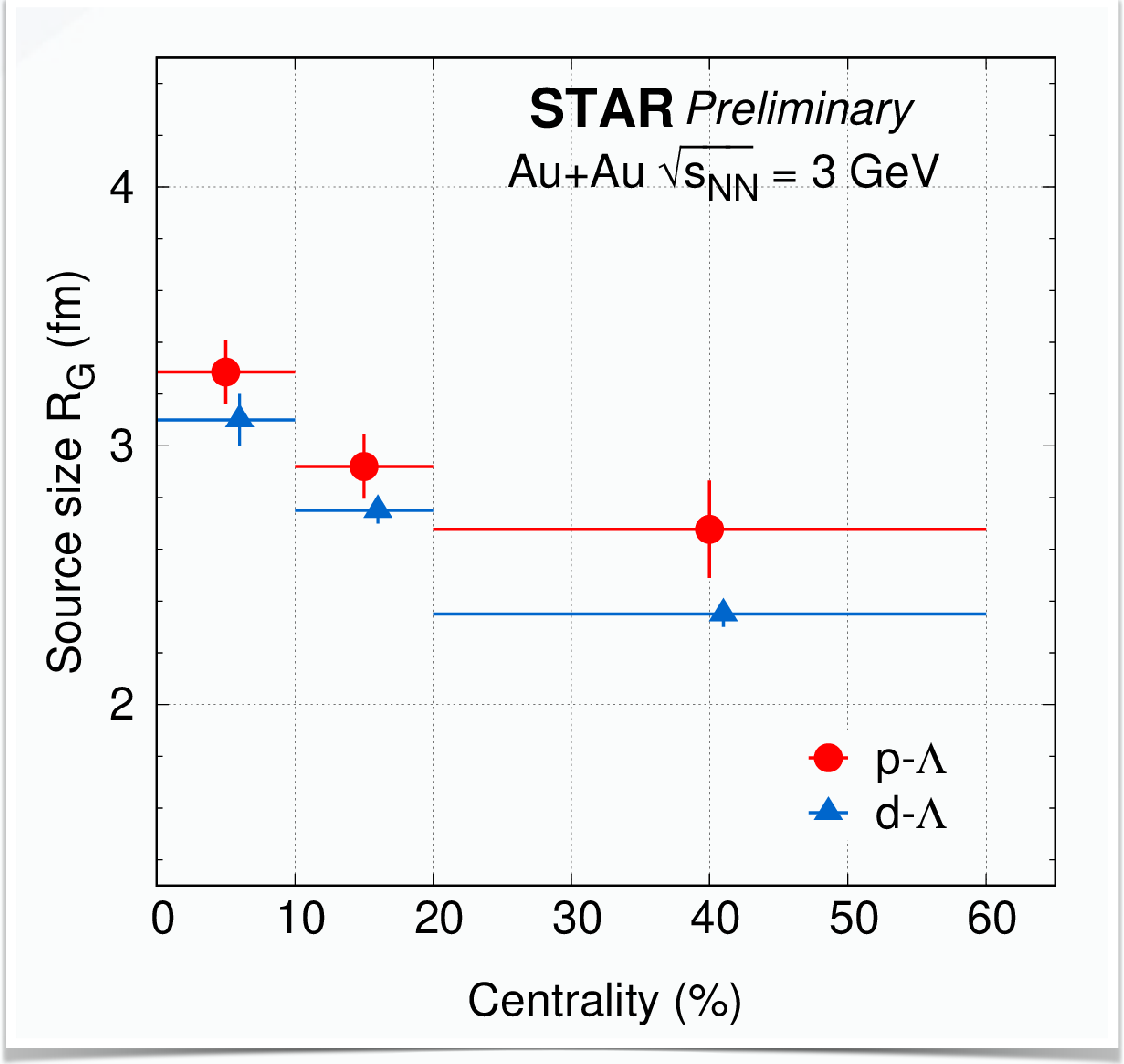


* **More than 10 times statistics from BES-II program, making it possible to study:**

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

Thank you !

p-Λ / d-Λ Source Size

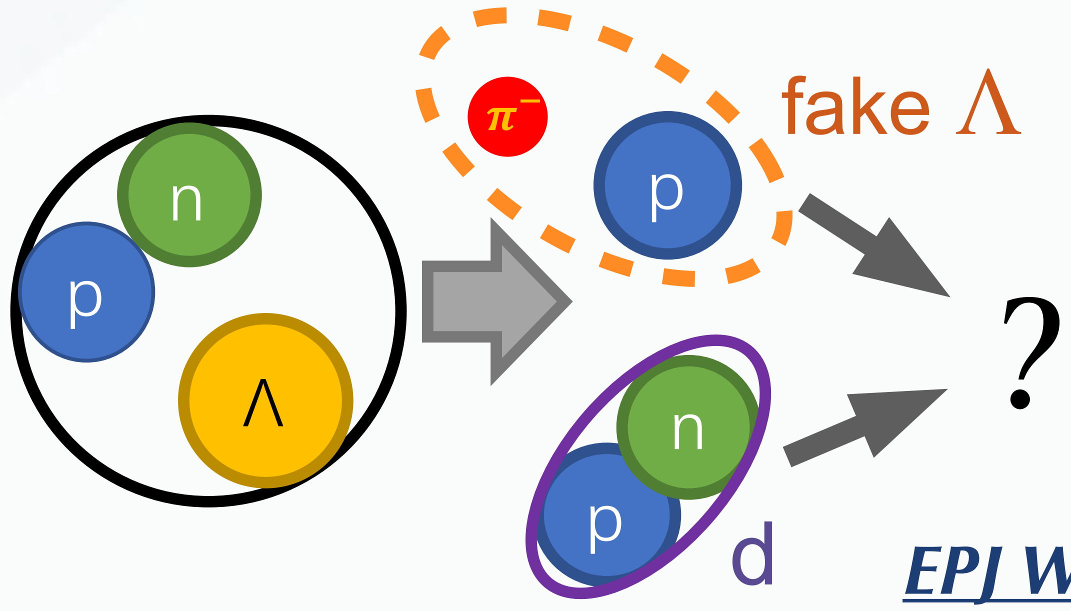


⇒ R_G: **spherical Gaussian source size**

⇒ **Collision dynamics as expected**

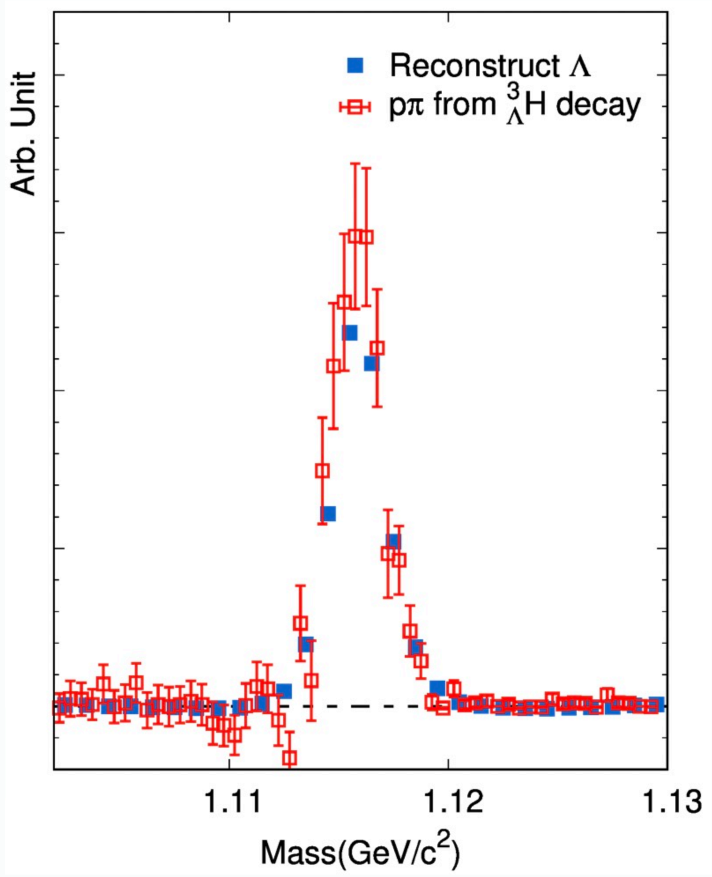
- **Centrality dependence:** $R_G^{central} > R_G^{peripheral}$
- $\langle m_T \rangle$ **dependence:** $R_G(p-\Lambda) > R_G(d-\Lambda)$

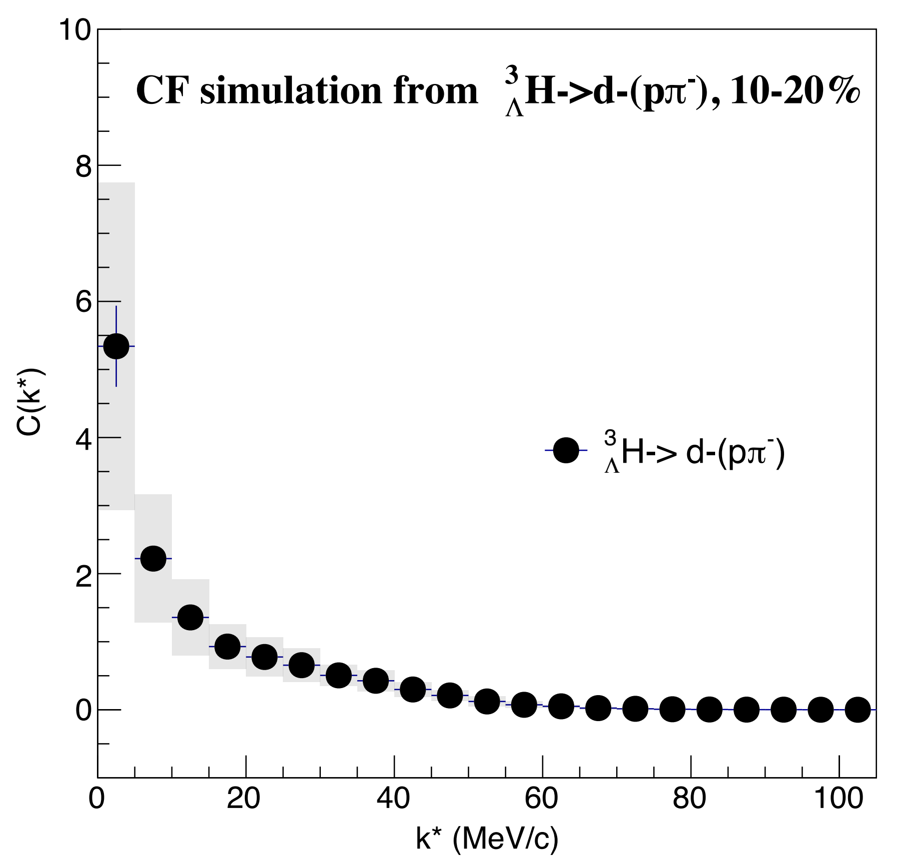
Contamination from Hyper-nuclei Decay

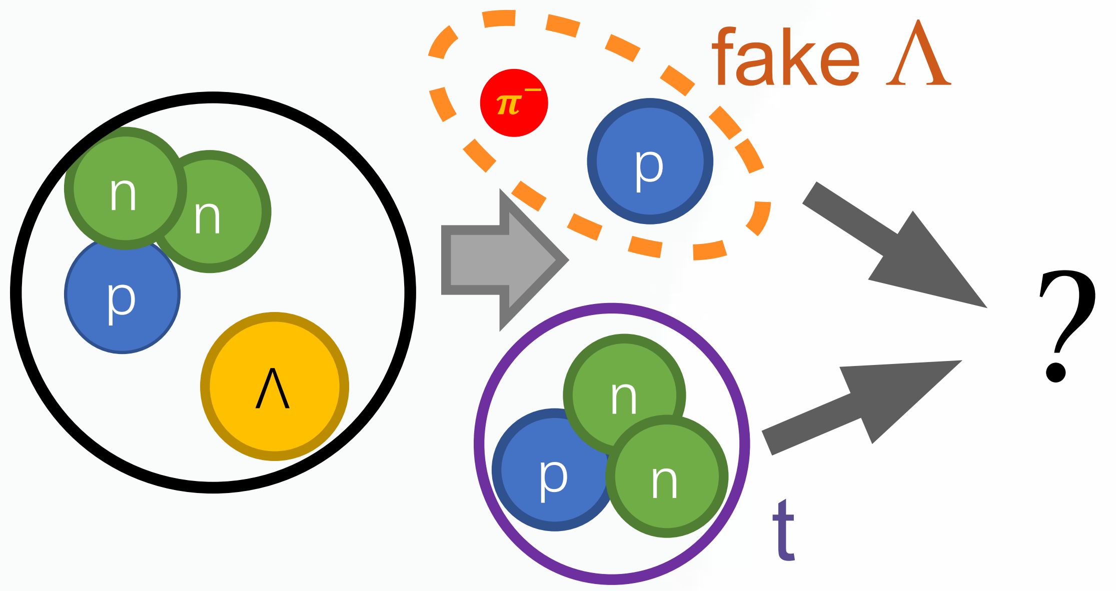


$^3_\Lambda H -> d + p + \pi^-$

EPJ Web Conf. 296 (2024) 14010





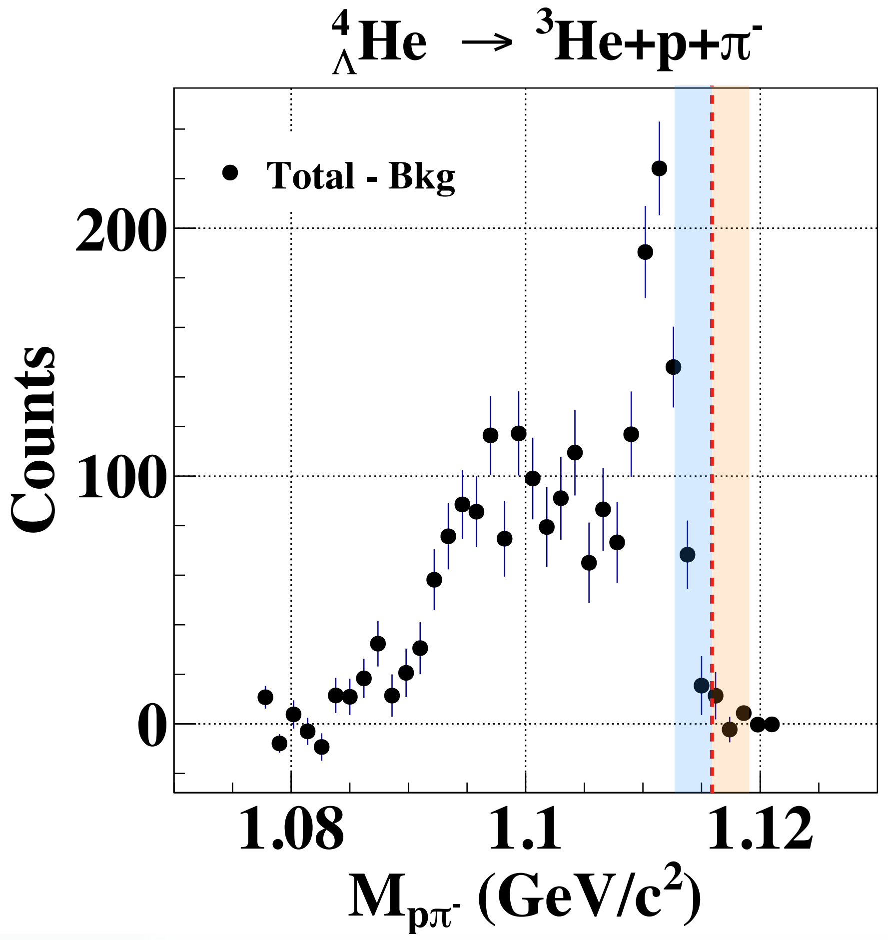


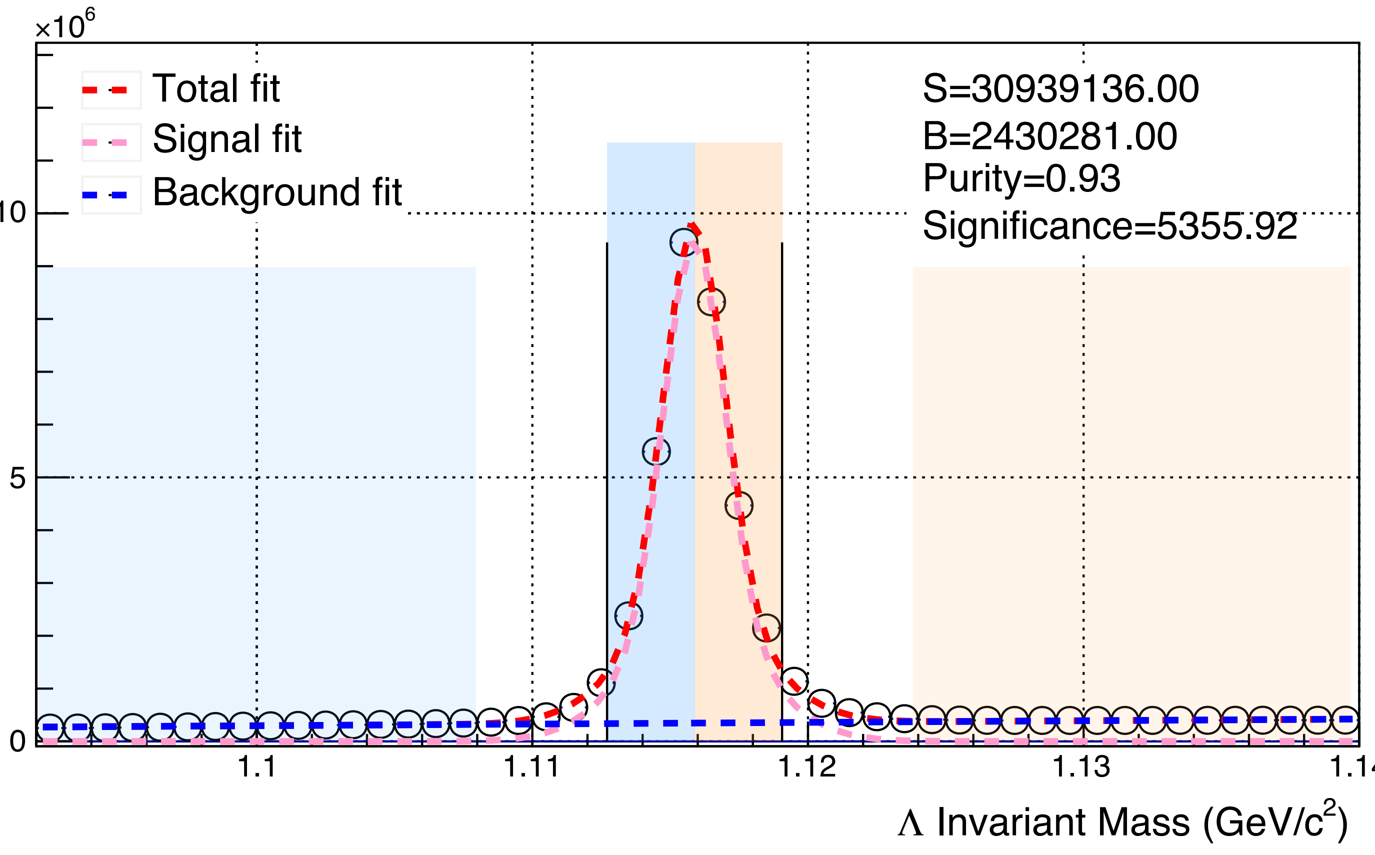
$^4_\Lambda H -> t + p + \pi^-$

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

Left signal: 1.11271~1.11589 GeV/c^2

Right signal: 1.11589~1.11906 GeV/c^2





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