Femtoscopy analysis involving light nuclei at RHIC-STAR experiment

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Central China Normal University

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Spicy Gluons 2024: Workshop for Young Scientists on the quark-gluon matter in extreme conditions

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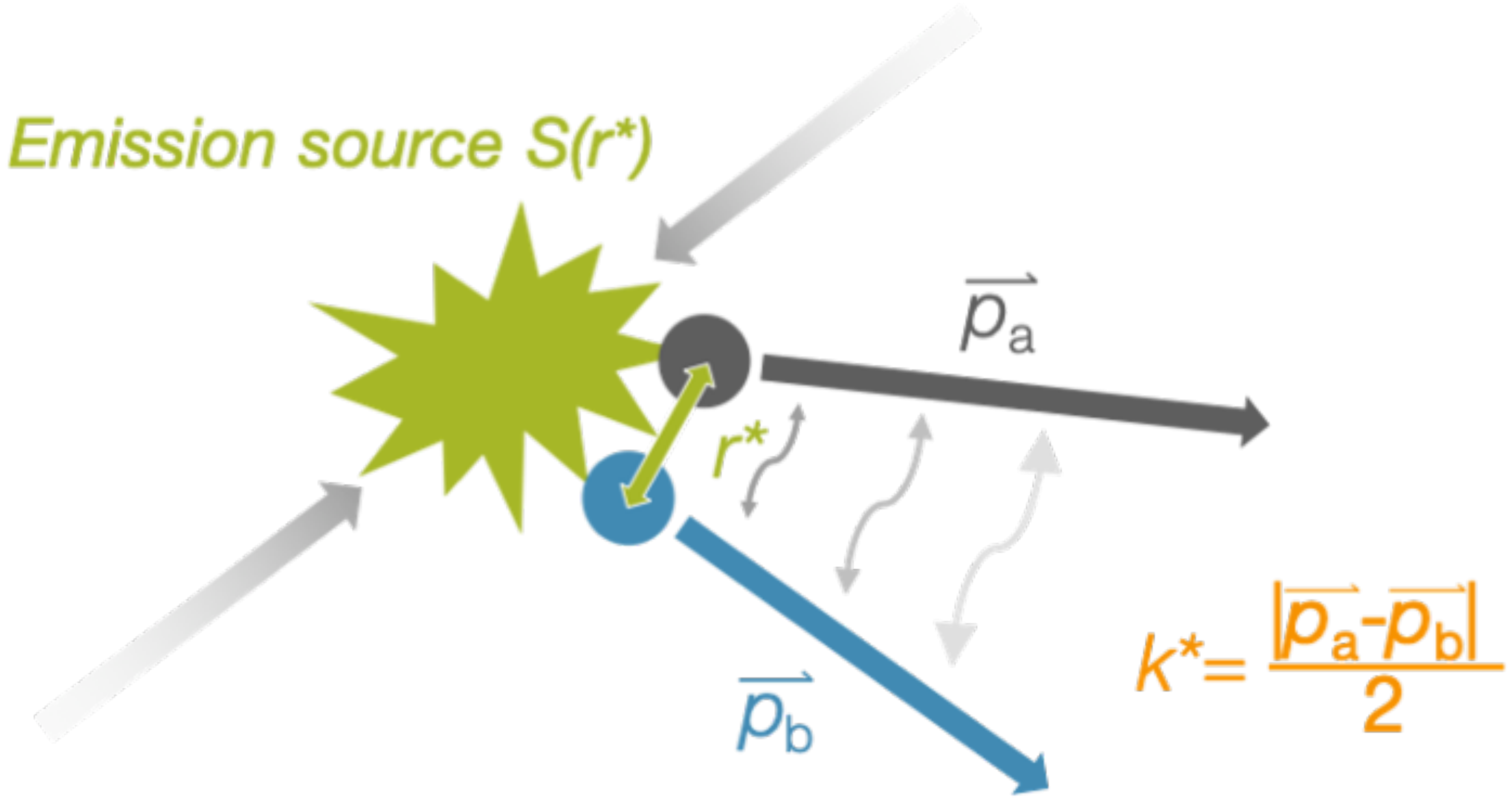
Femtoscopy



⇒ 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)

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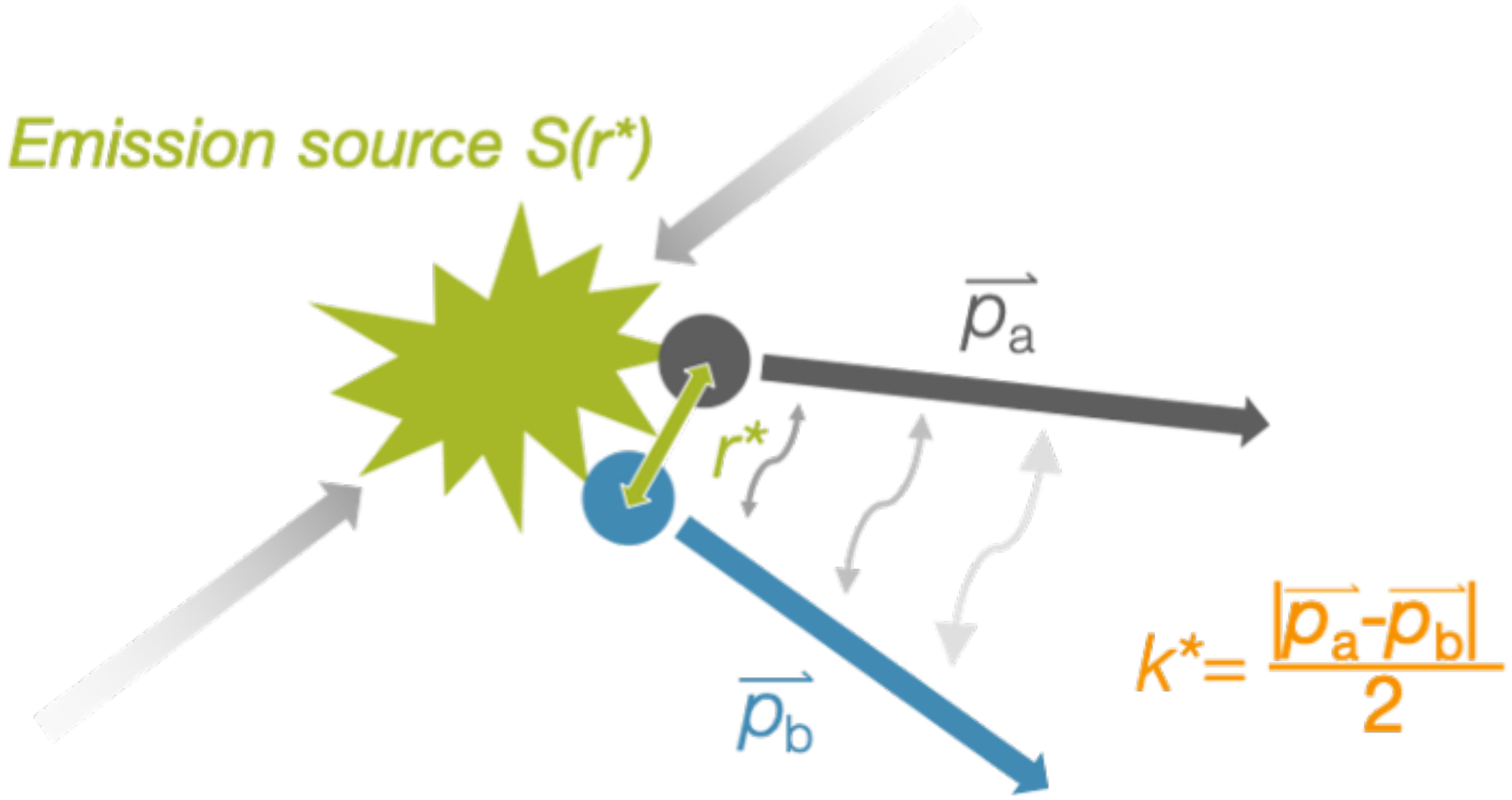

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✓ Two-particle correlation function:

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
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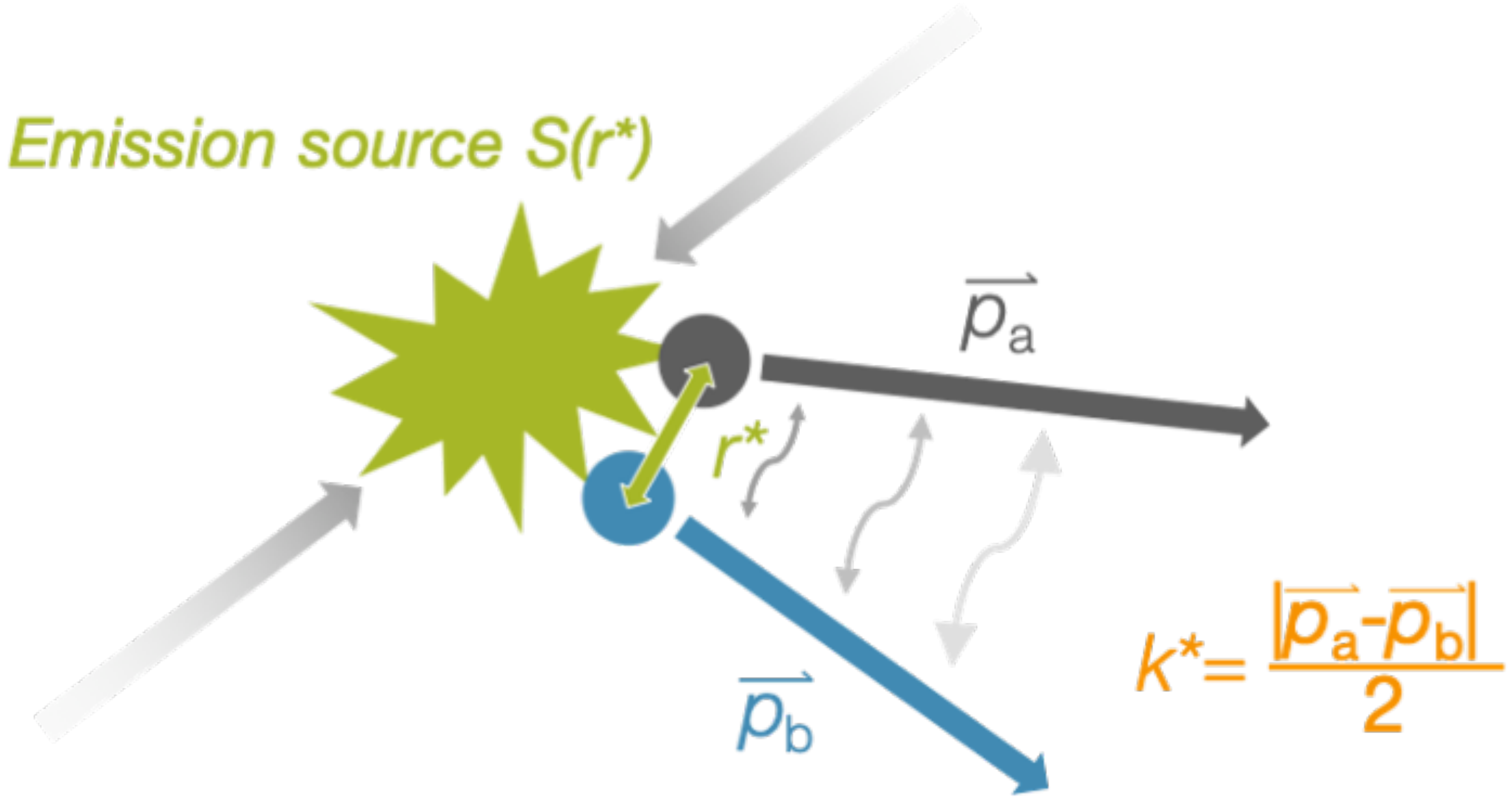

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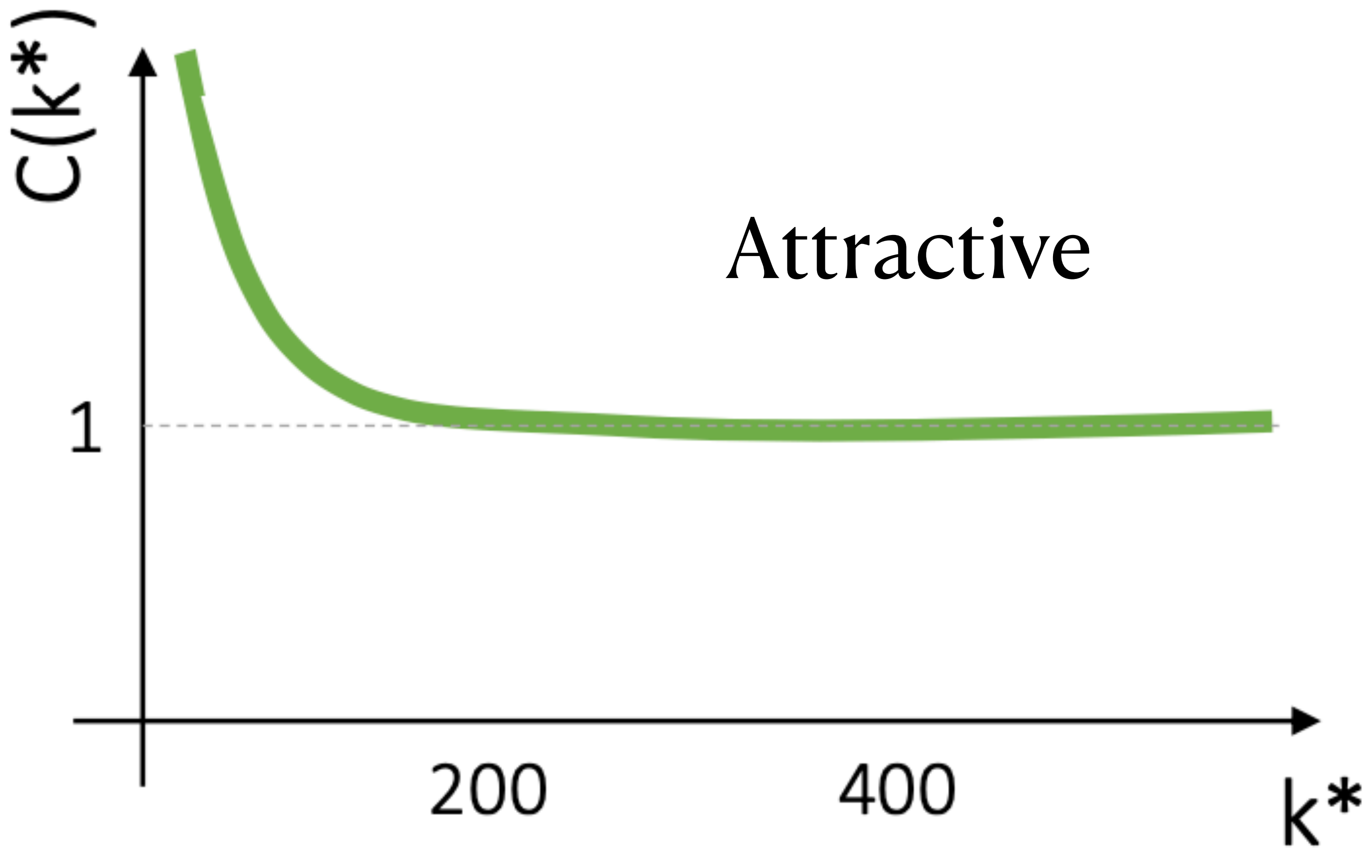

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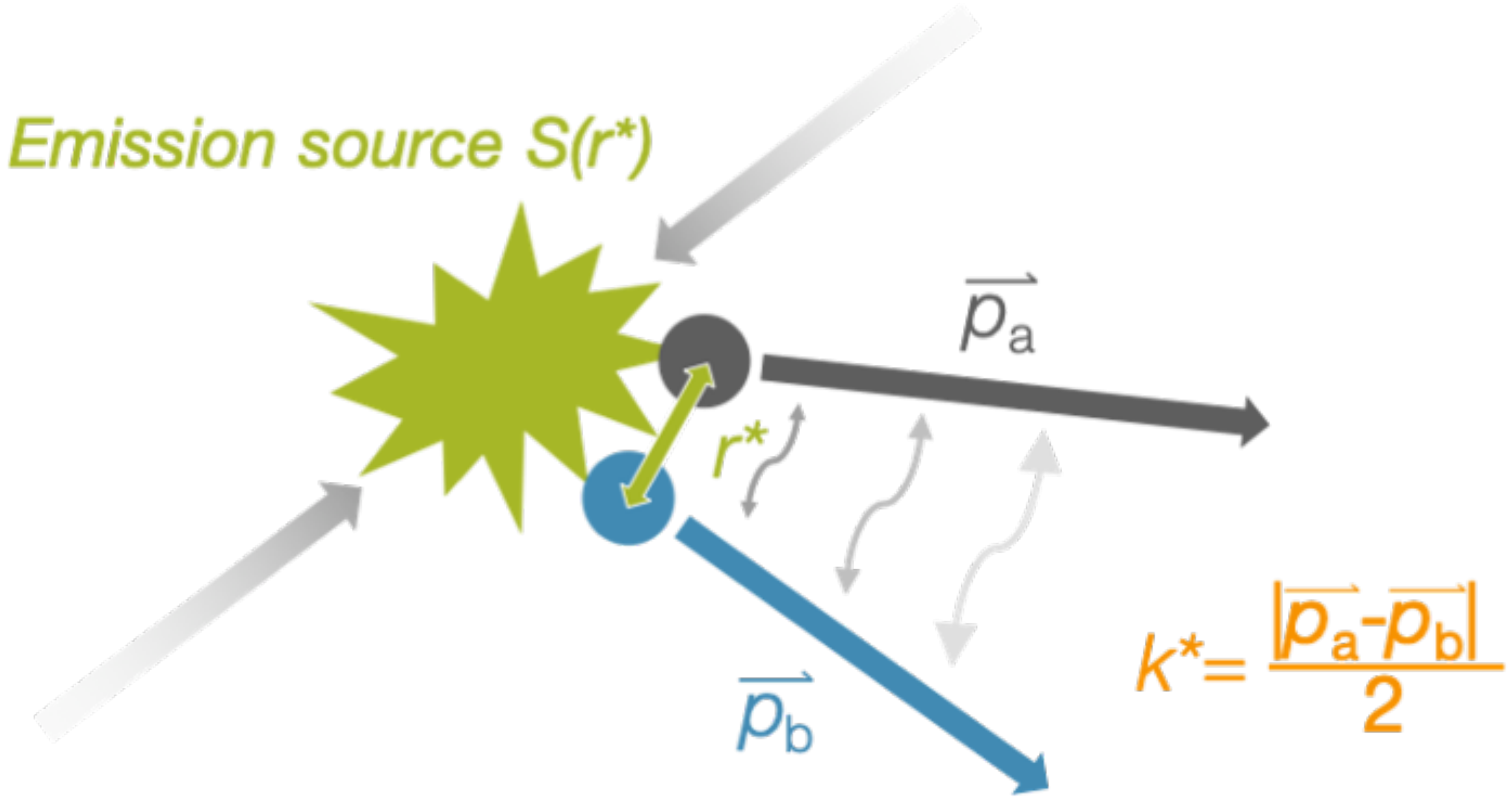

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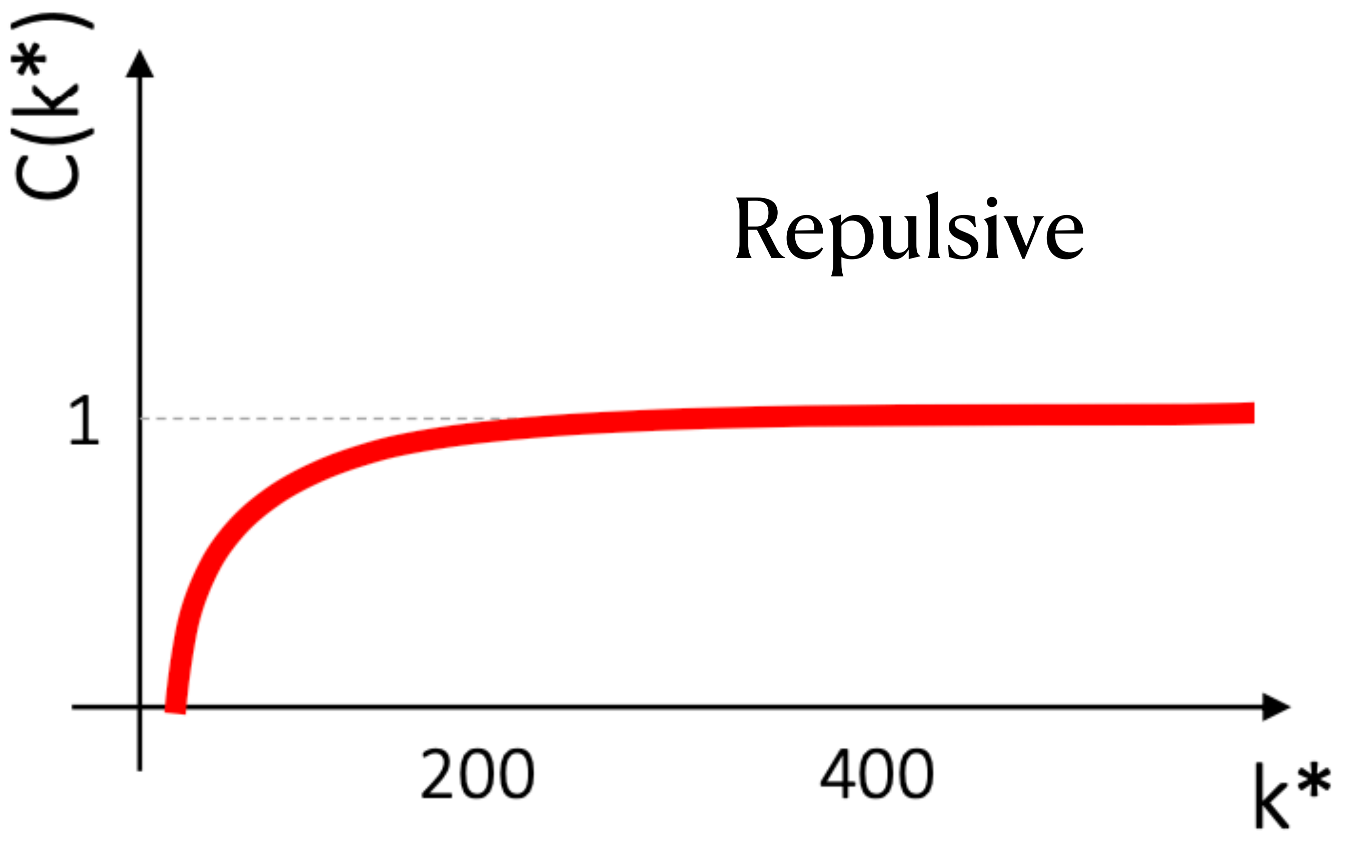

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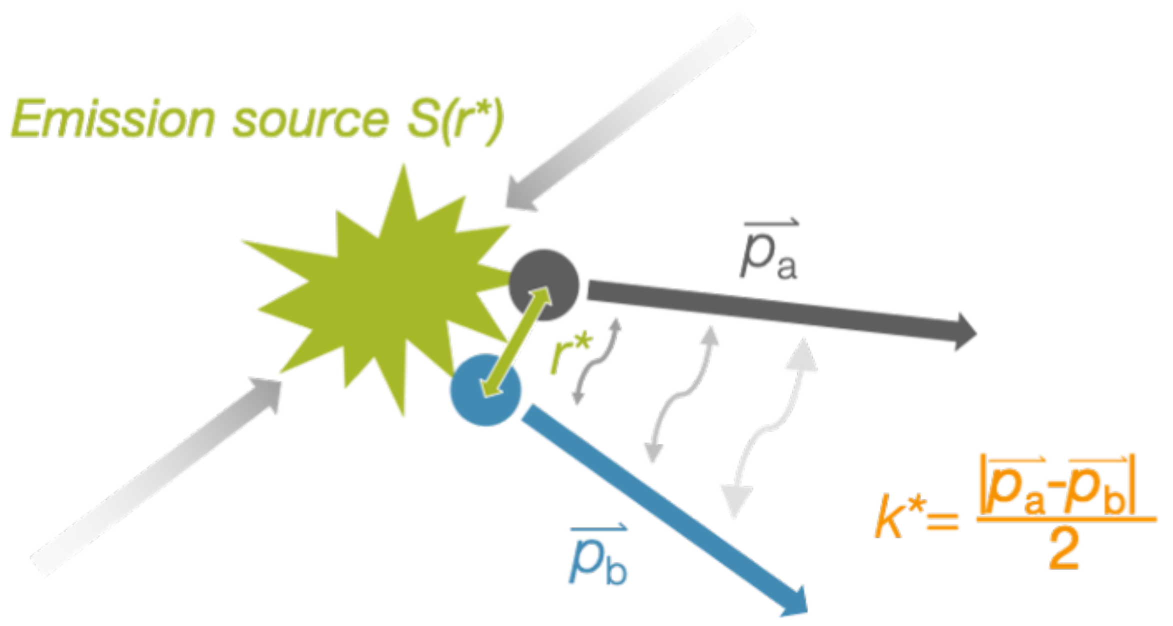
Femtoscopy — Lednicky-Lyuboshitz approach



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⇒ Formalism with Lednicky-Lyuboshitz (L-L) approach

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

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

Femtoscopy — Lednicky-Lyuboshitz approach

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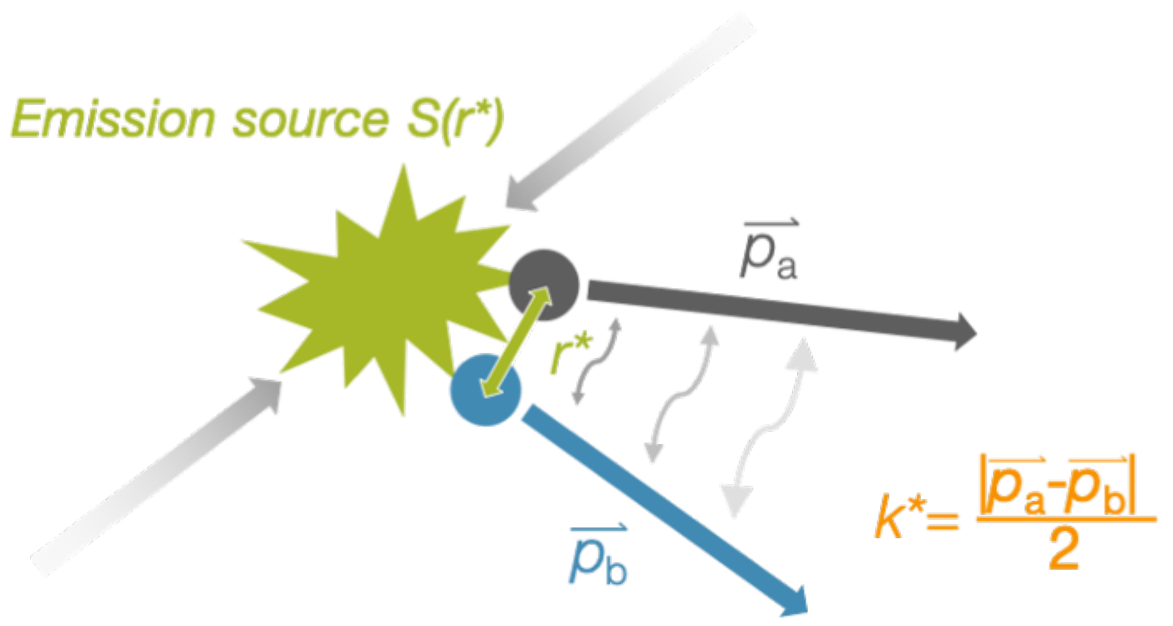

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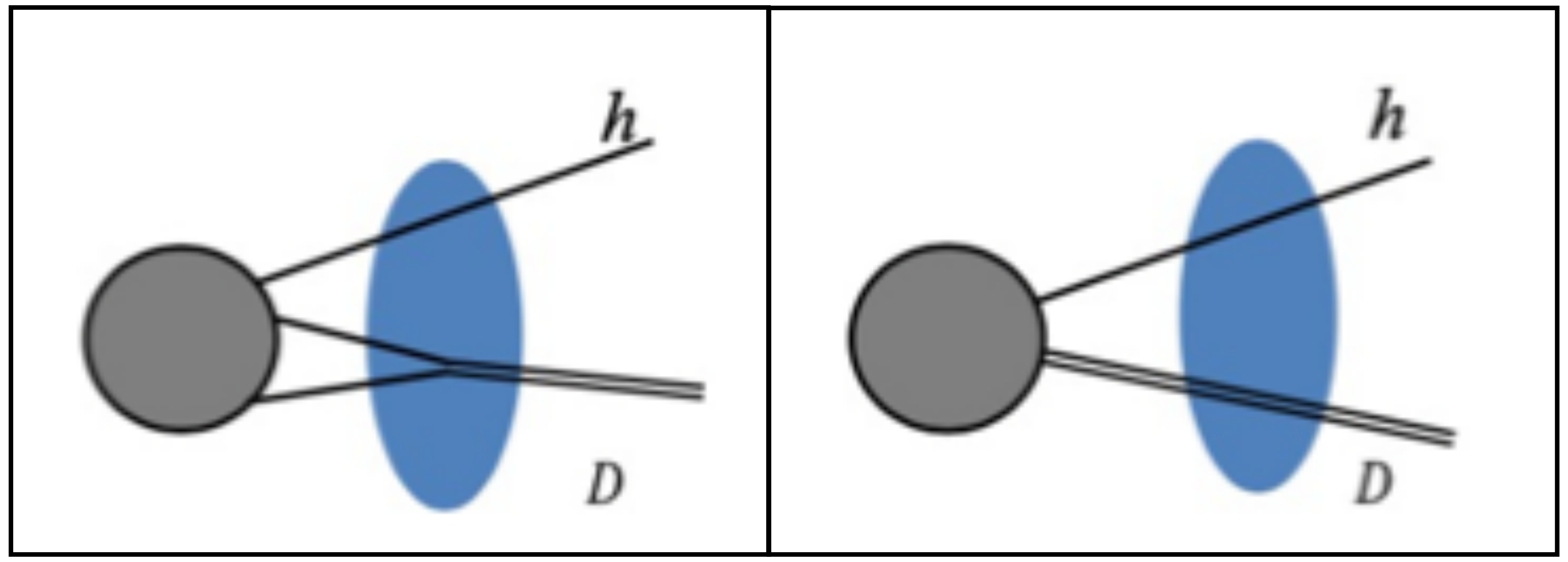
Physics quantity:

1. R_G: Spherical Gaussian source size
2. f_0: Scattering length
3. d_0: Effective range

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

Light Nuclei correlation

- 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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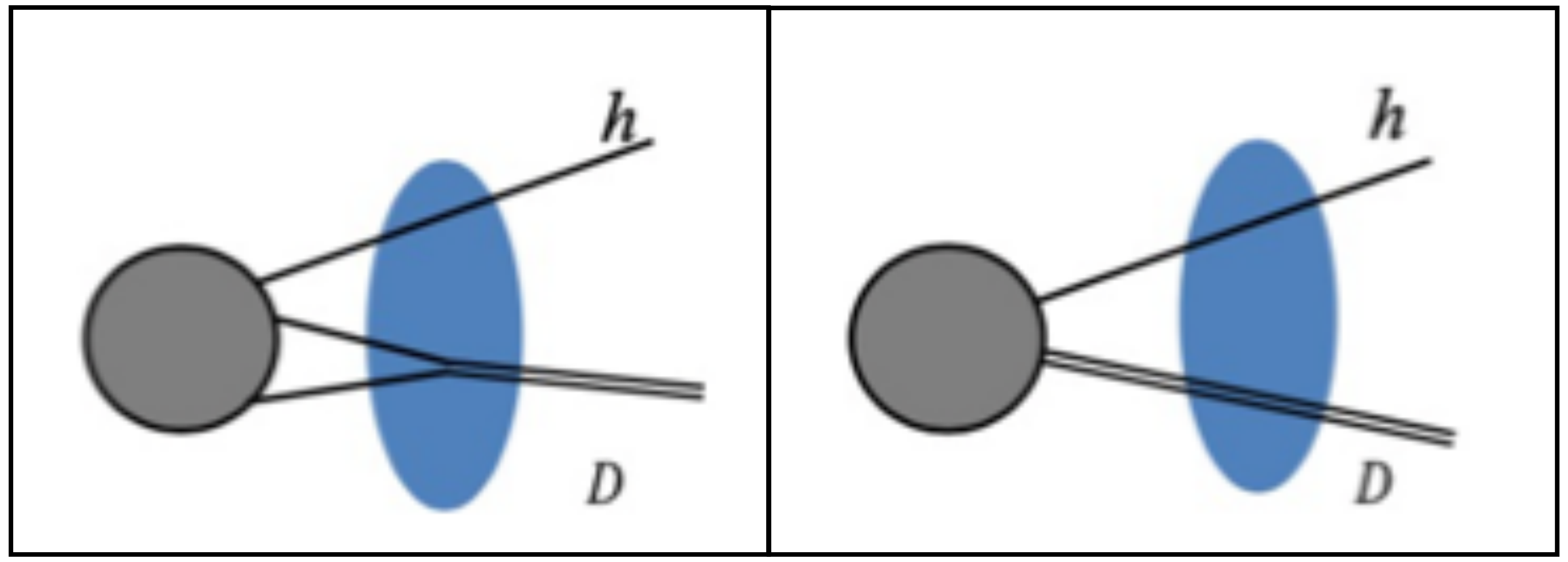
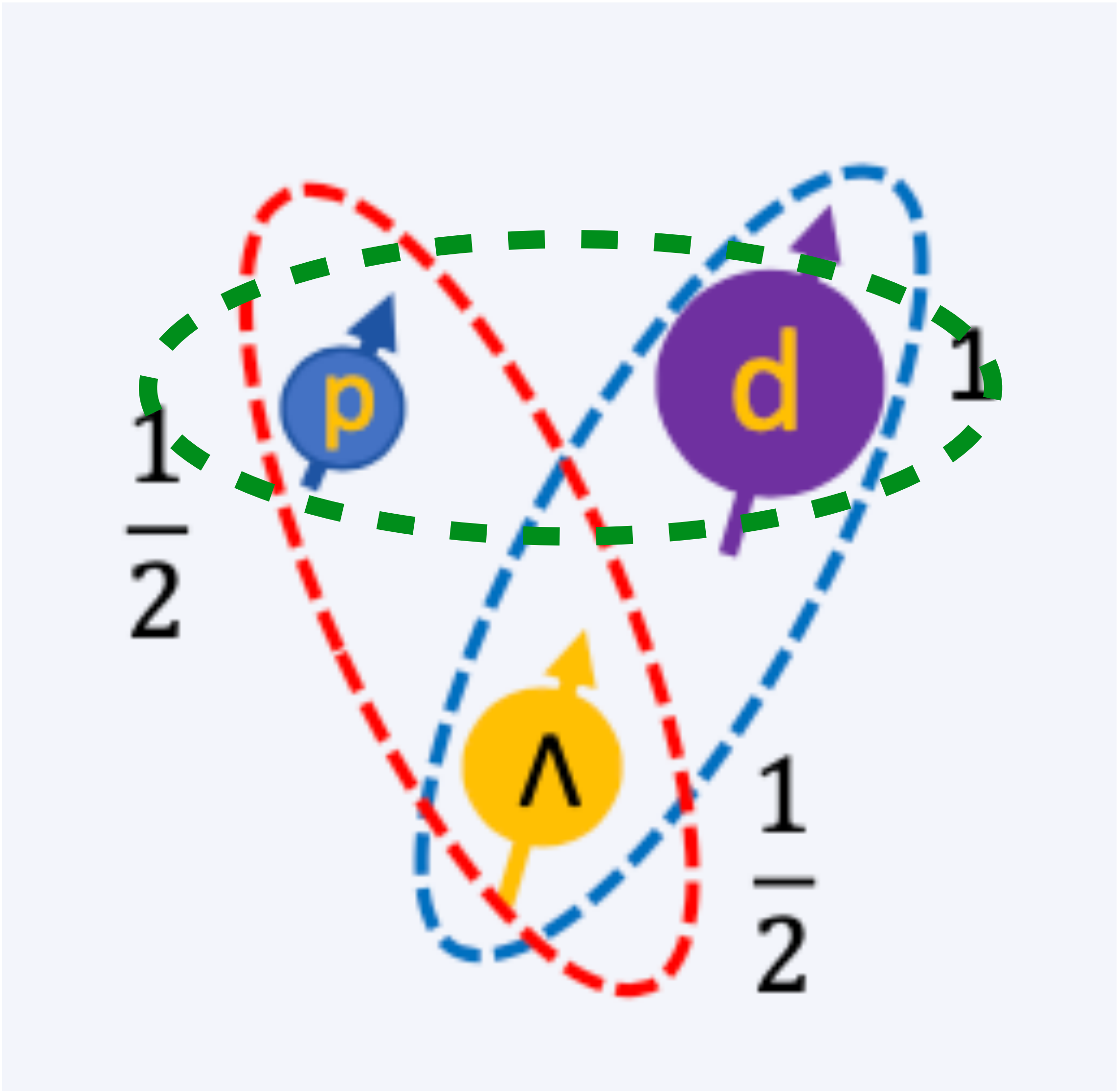


Coalescence Direct production

- Role of Nucleon-Nucleon (N-N) and Hyperon-Nucleon (Y-N) interactions in the Equation-of-State
  - ⇒ Inner structures of neutron star

- Indirect approach of three-body and four-body interactions



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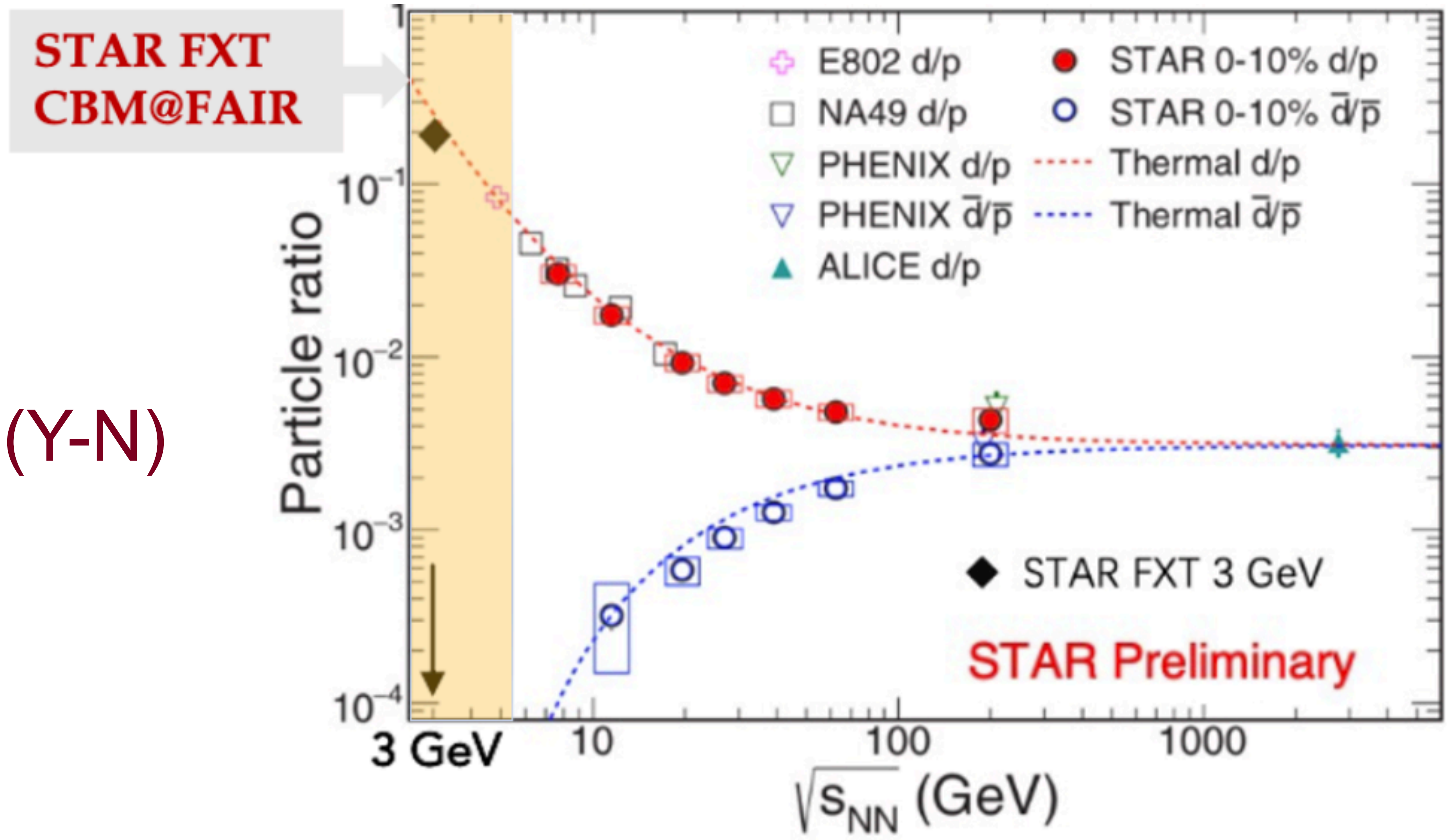
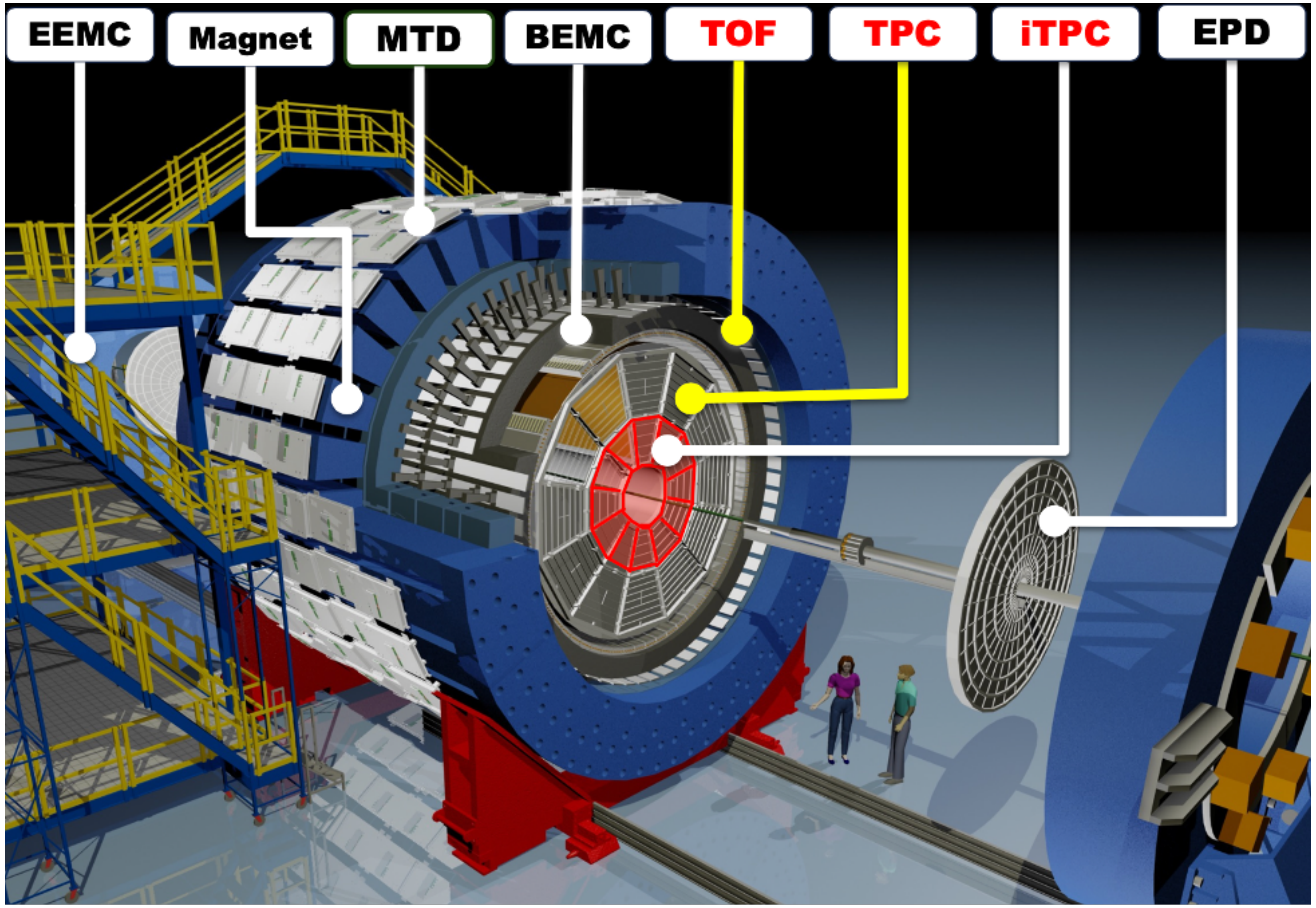


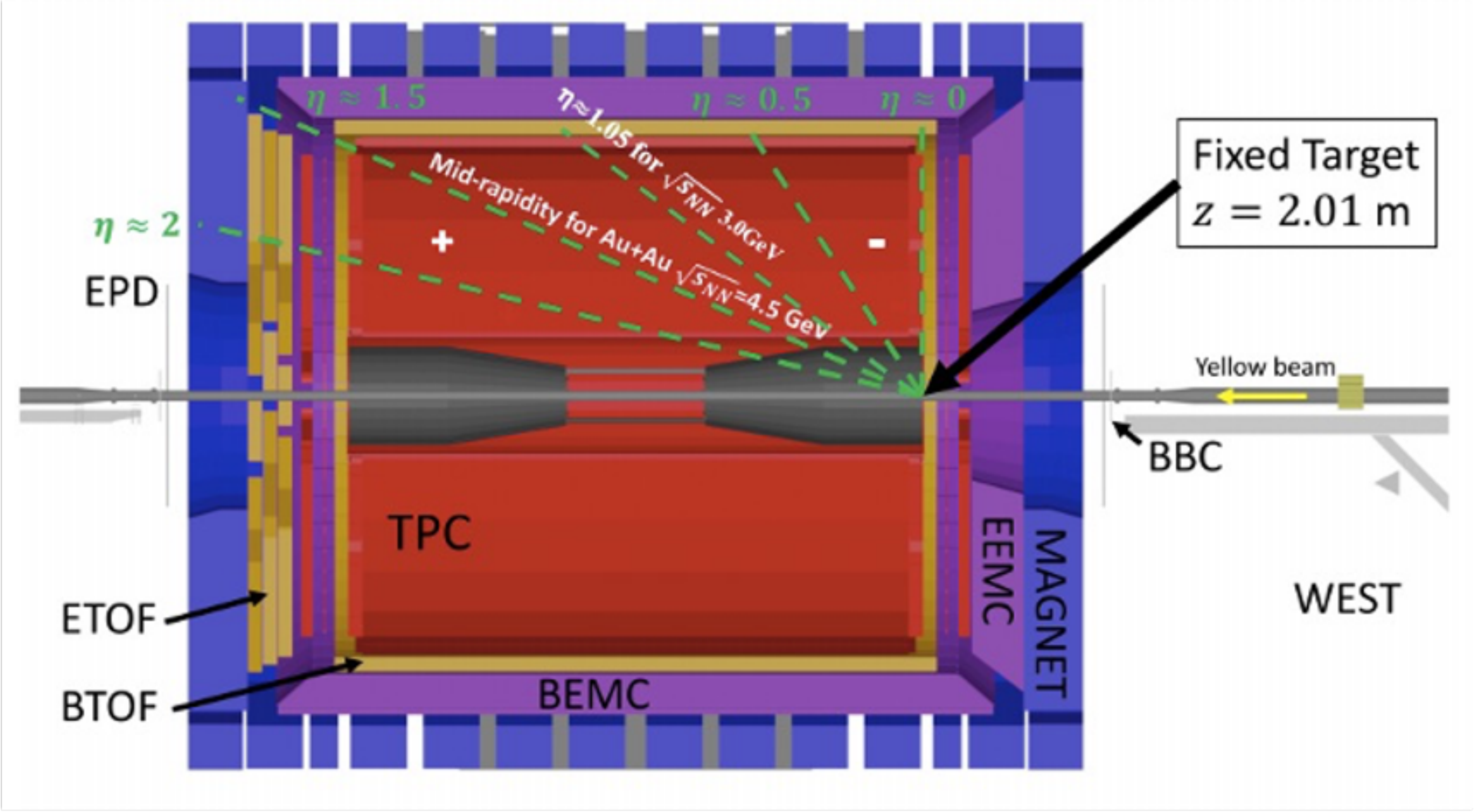
Phys.Rev.C 99, 064905 (2019)

Large amount of light nuclei produced at 3 GeV, allowing precision measurements

In this talk: p-d, d-d, d-Λ correlation at 3 GeV in Au+Au collisions

STAR Detector and Datasets





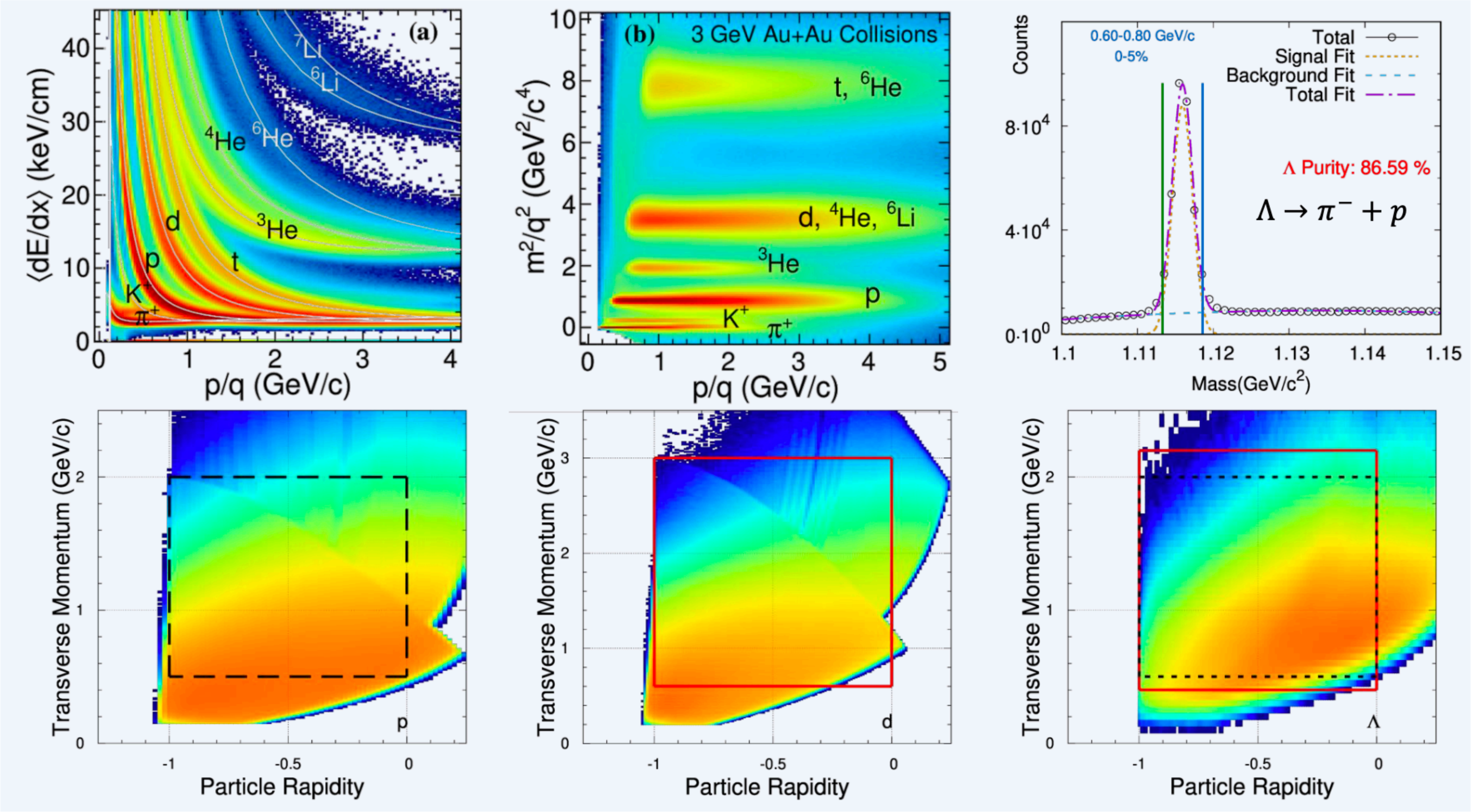
⇒ 3 GeV Au+Au collisions -> μ_B ~ 720 MeV

⇒ 0-60% centrality

⇒ Excellent Particle Identification

⇒ Large, Uniform Acceptance at mid-rapidity

Particle Identification and Reconstruction

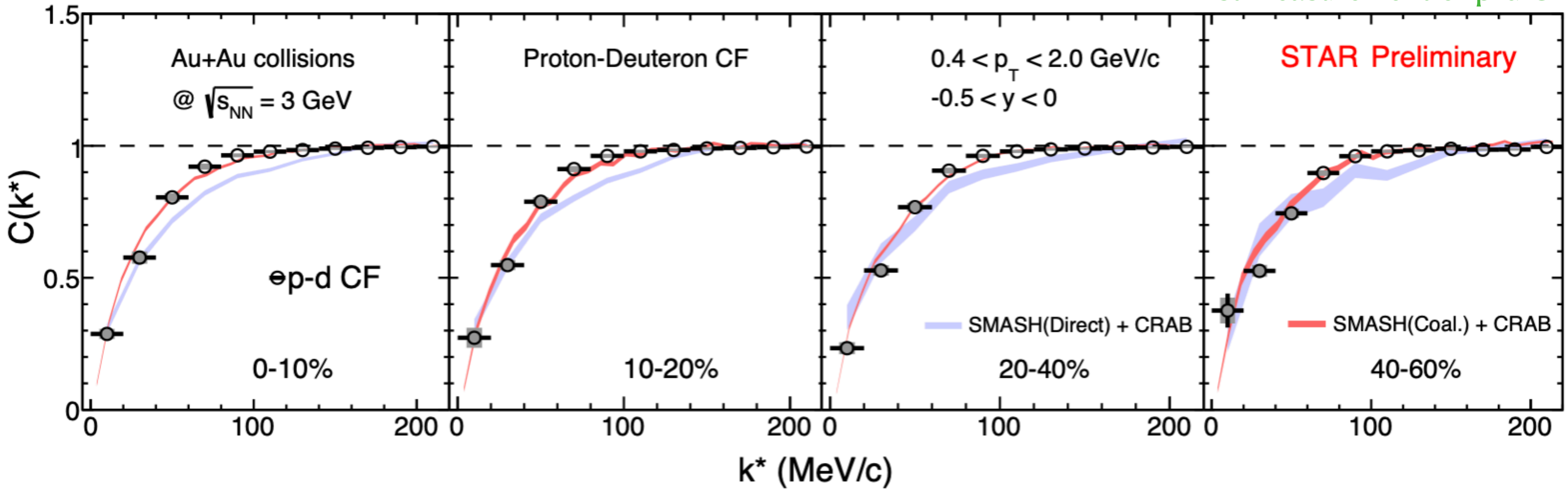


⇒ π^-, p and d are identified by Time Projection Chamber (TPC) and Time-Of-Flight (TOF)

⇒ Reconstruct Λ candidates with KF-Particle package -> Improve significance *STAR. Phys. Lett. B 827 (2022) 136941*

Results — Proton-Deuteron Femtoscopy

First measurement of p-d CF at STAR



⇒ Clear depletion at small k^* range seen in data

⇒ Compared with SMASH + Correlation After burner (CRAB) model

- Two deuteron formation mechanism: Direct (hadronic scattering) vs. Coal (Wigner fund.)
- CF calculated with coalescence of deuterons is in better agreement with data

arXiv:2208.05722

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

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

Results — Deuteron-Deuteron Femtoscopy

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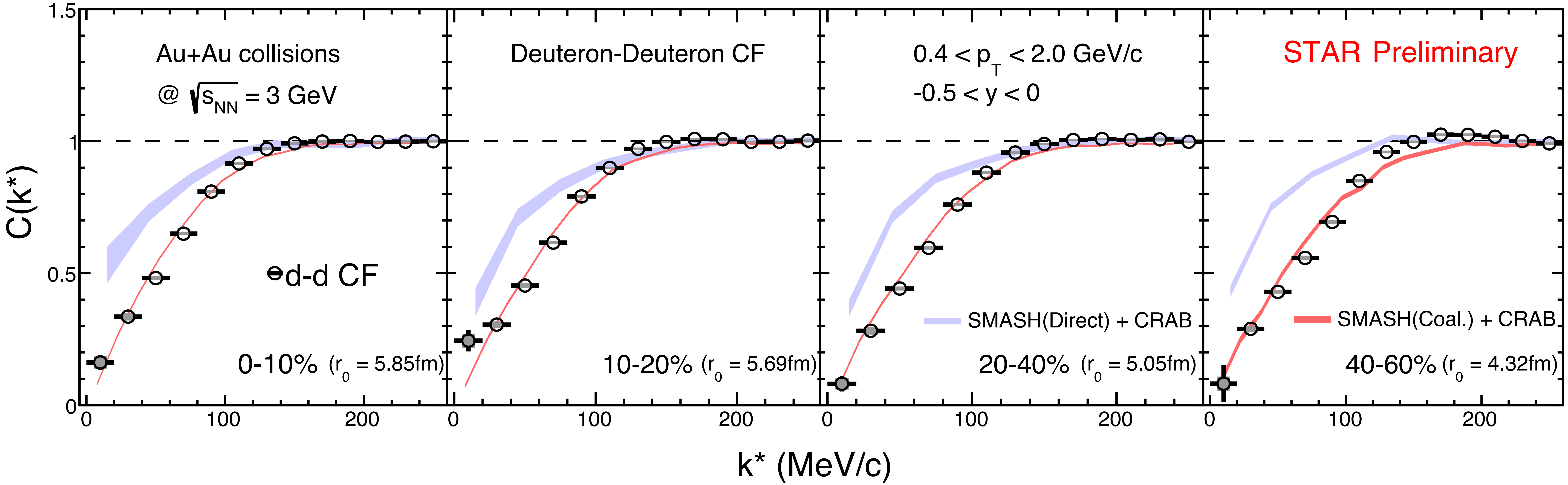
First measurement of d-d CF at STAR



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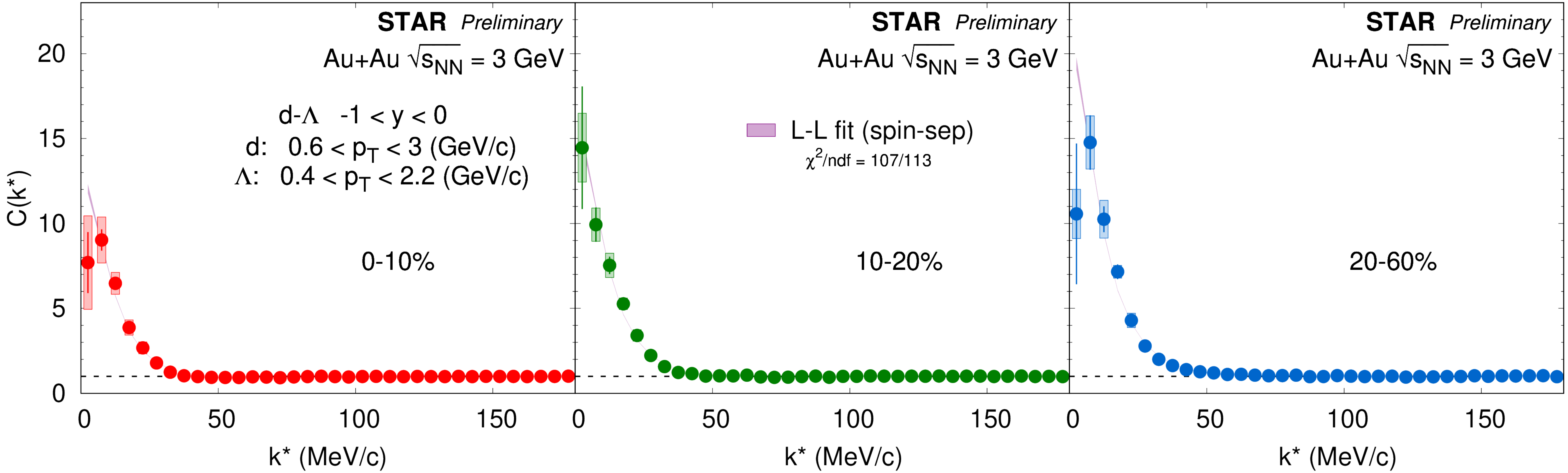
Results — Deuteron-Lambda Femtoscopy

First measurement of d-Λ CF at STAR



⇒ Strong enhancements at small k^* range -> Attractive interactions

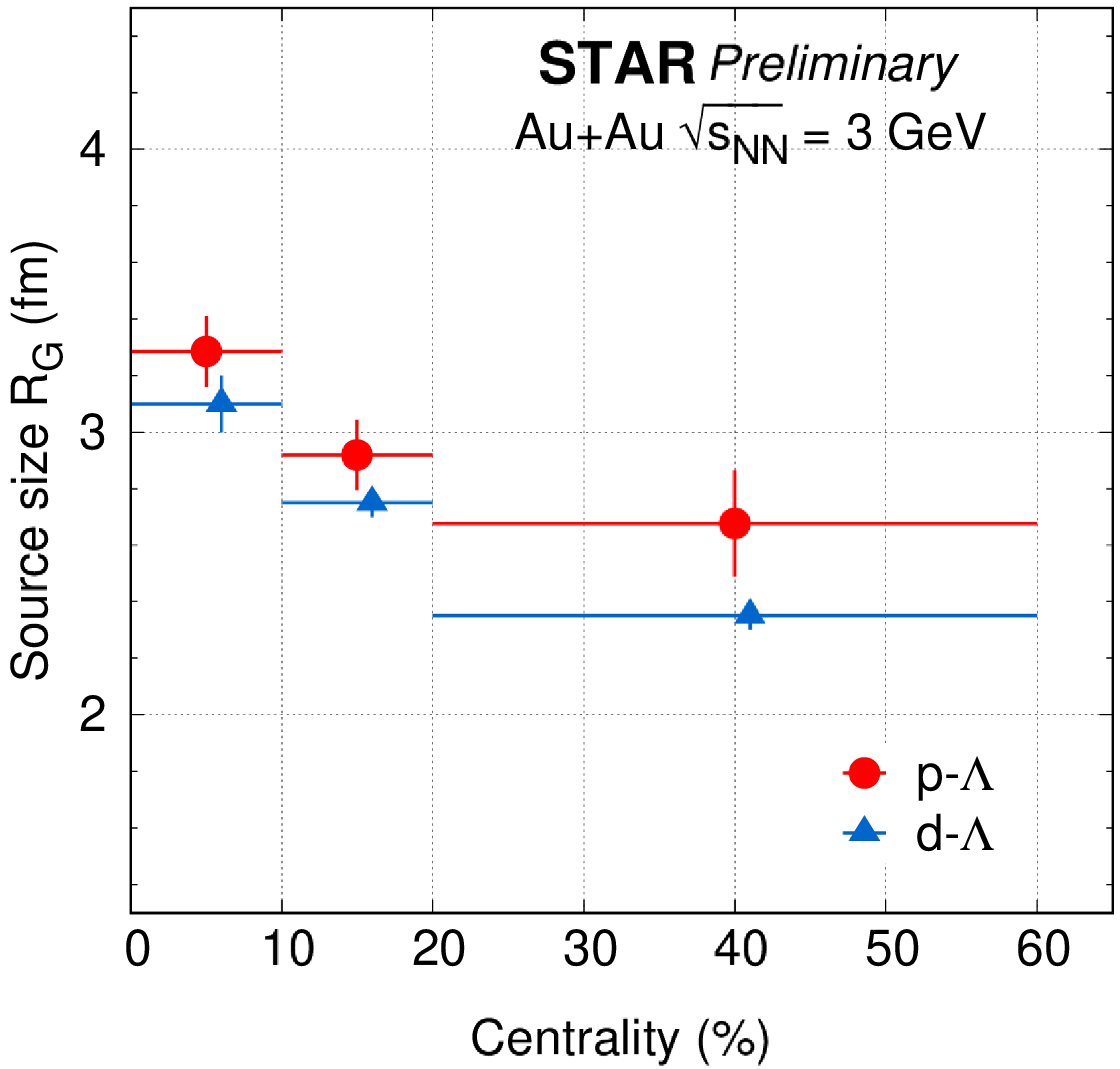
⇒ Simultaneously fit to data in different centralities with L-L approach

- Consider two-spin components: D (doublet, S = 1/2), Q (quartet, S=3/2)

$$f_0\,(D) = -20\,^{+3}_{-3}\ \text{fm},\ \ d_0\,(D) = 3\,^{+2}_{-1}\ \text{fm}$$
$$f_0\,(Q) = 16\,^{+2}_{-1}\ \text{fm},\ \ d_0\,(Q) = 2\,^{+1}_{-1}\ \text{fm}$$

* Λ feed-down correction not applied

Results — Deuteron-Lambda Femtoscopy



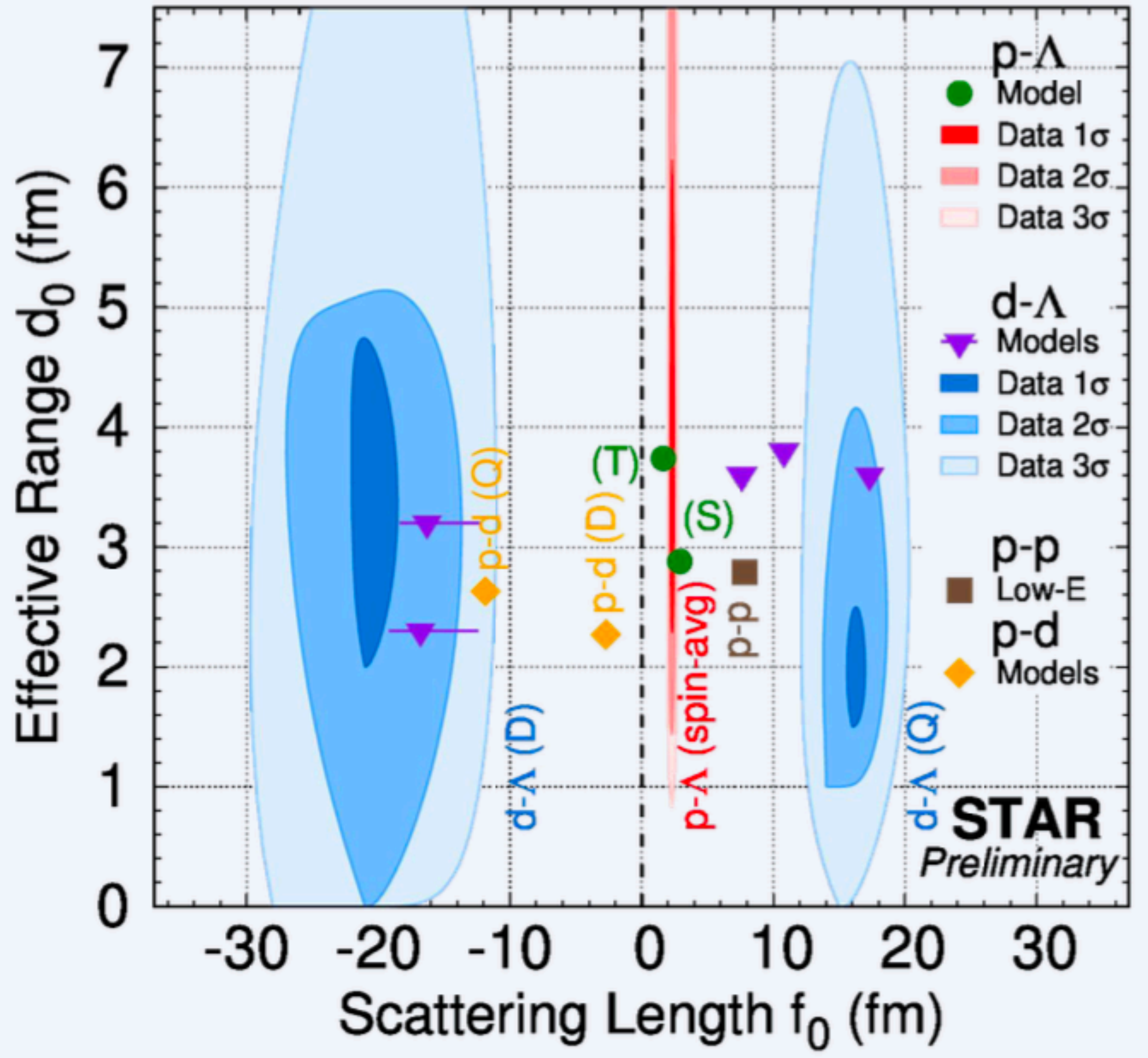
⇒ R_G: spherical Gaussian source extracted with L-L approach

⇒ Collision dynamics as expected

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

$p-\Lambda$ correlation at 3 GeV: backup

Results — Deuteron-Lambda Femtoscopy



$p-\Lambda$ correlation at 3 GeV: backup

⇒ 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 -> ${}^{3}_{\Lambda}\mathrm{H}$ bound state
- Positive f_0 in quartet state -> Attractive interaction

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
F. 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

Results — ${}^{3}_{\Lambda}$H binding energy

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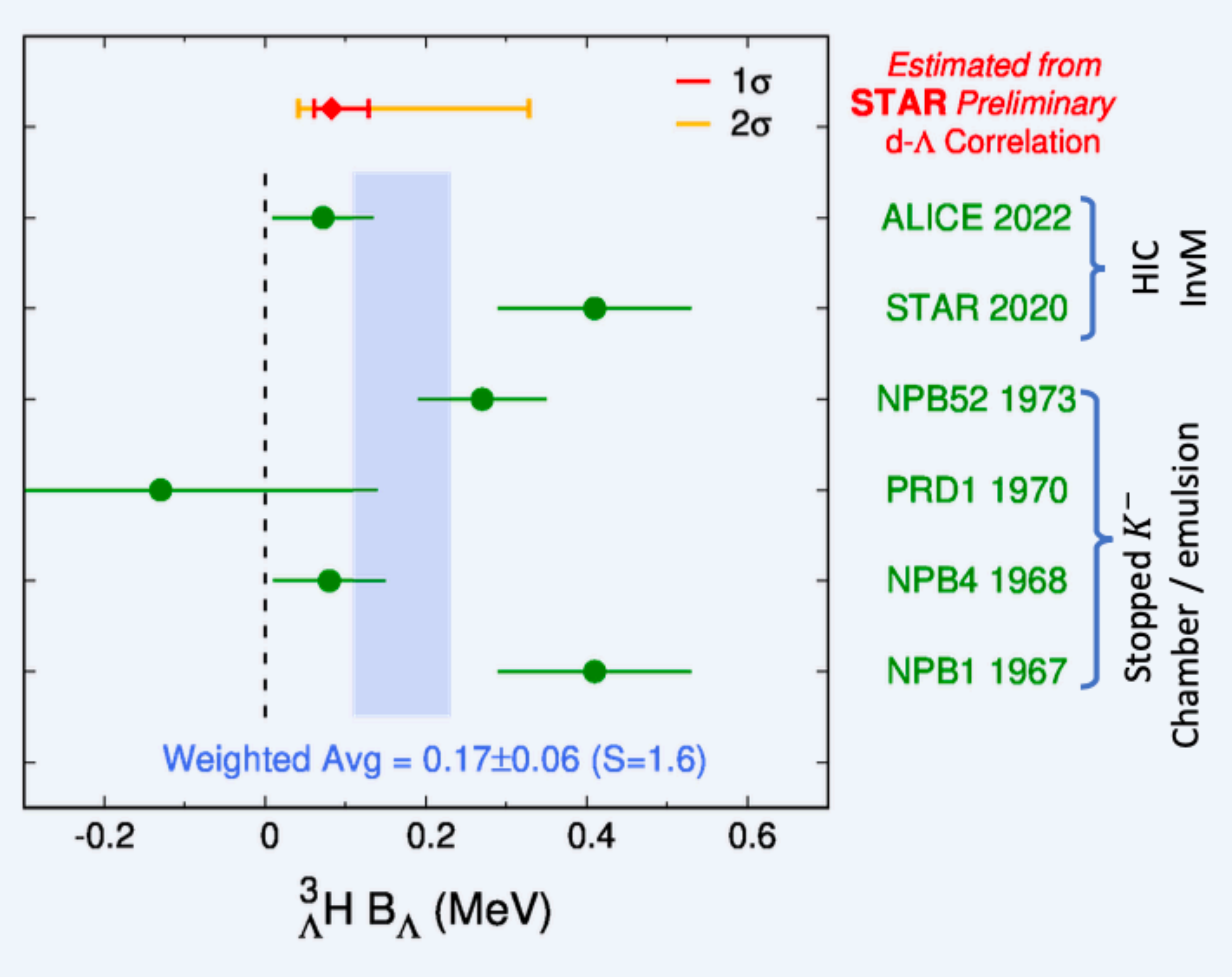

⇒ ${}^{3}_{\Lambda}$H binding energy (B_{Λ}):

Bethe formula from Effective Range Expansion (ERE)

$$B_{\Lambda} = \frac{\gamma^2}{2\mu_{d\Lambda}}$$

$$\frac{1}{-f_0} = \gamma - \frac{1}{2}d_0\gamma^2$$

$\mu_{d\Lambda}$: 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

$p - \Lambda$ correlation at 3 GeV: backup

H.Bethe, Phys.Rev 76, 38 (1949)

Summary and Outlook

⇒ Femtoscopy measurements from heavy-ion collisions provides a unique tool to explore strong interactions and evolution dynamics

⇒ N-N interaction (p-d && d-d)

- First measurements of p-d and d-d correlation functions in STAR
- Deuterons are likely to be formed via Coalescence at 3 GeV

⇒ Y-N interaction (d-Λ)

- First measurements of d-Λ in heavy-ion collisions
- First experimental measurements of strong interaction parameters (f_0, d_0) in two spin components
- Provide a new way to constrain ${}^{3}_{\Lambda}\mathrm{H}$ properties

More precise femtoscopy results with large statistics in BES-II program coming soon !
(light nuclei, many body, exotica ...)

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Thank you for your attention !

Backup

p—p, p—Λ correlation functions @ 3 GeV

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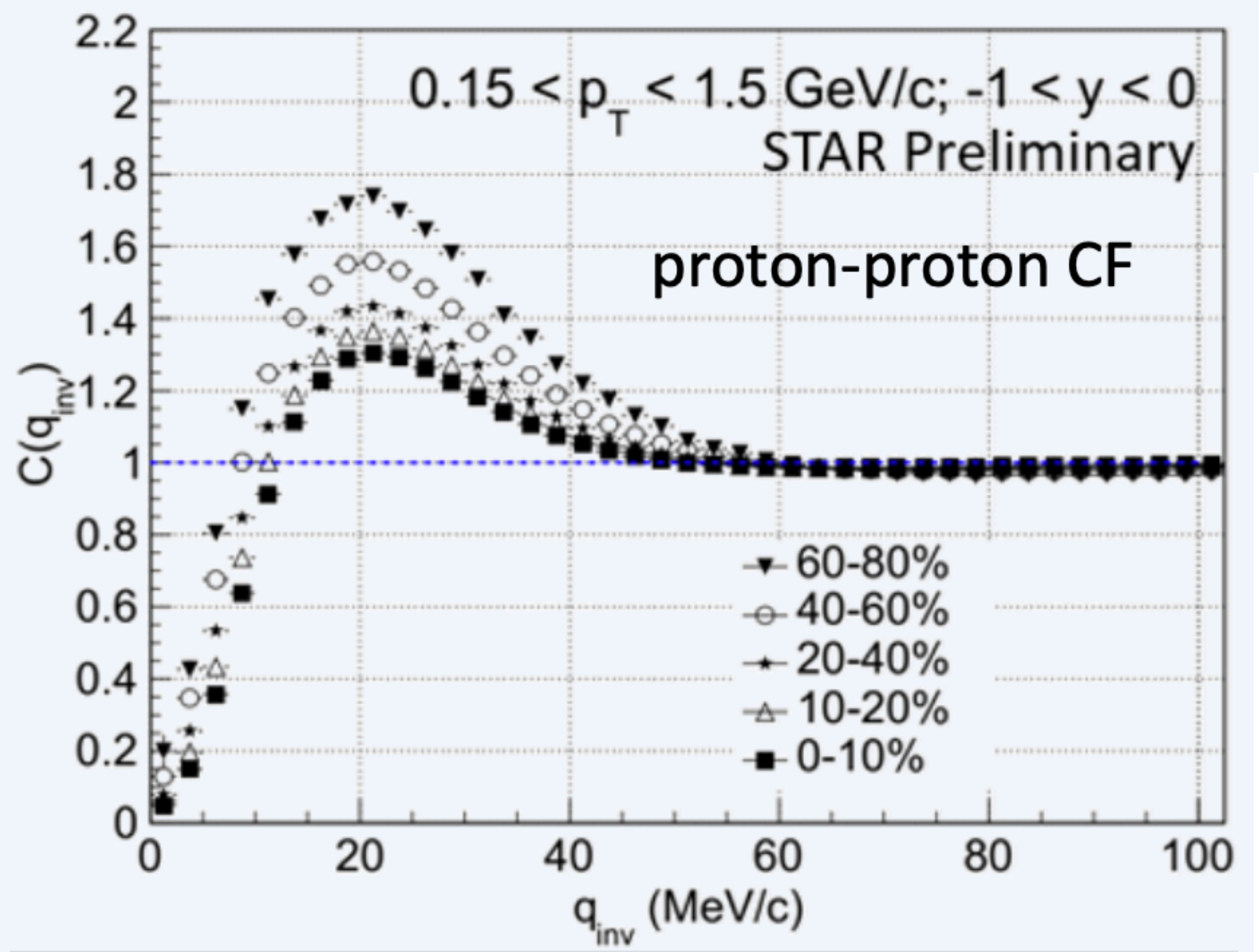
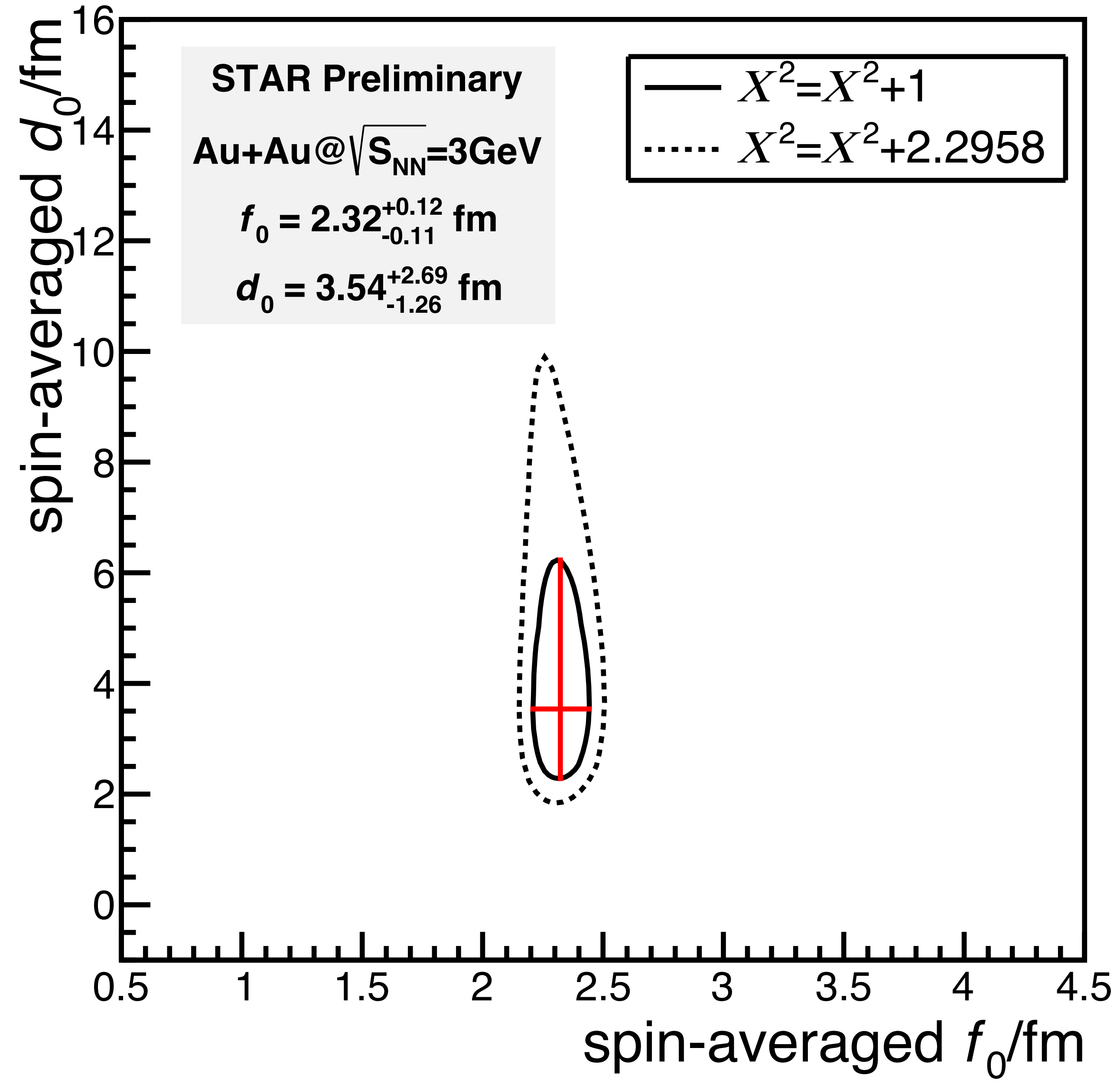


X^2 contour of spin-averaged d_0 and f_0 for $p\Lambda$ (-1<y<0)



QM2022/ QM2023

$p\Lambda$ Correlation Function with Lednicky-Lyuboshit Fitting

STAR Preliminary

Au+Au@$\sqrt{S_{NN}}$=3GeV