# Femtoscopy of Light Nuclei in Au+Au Collisions at RHIC-STAR

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EXOTICO: EXOTIc atoms meet nuclei COllisions for a new frontier precision era in low-energy strangeness nuclear physics

# Outline

# Introduction

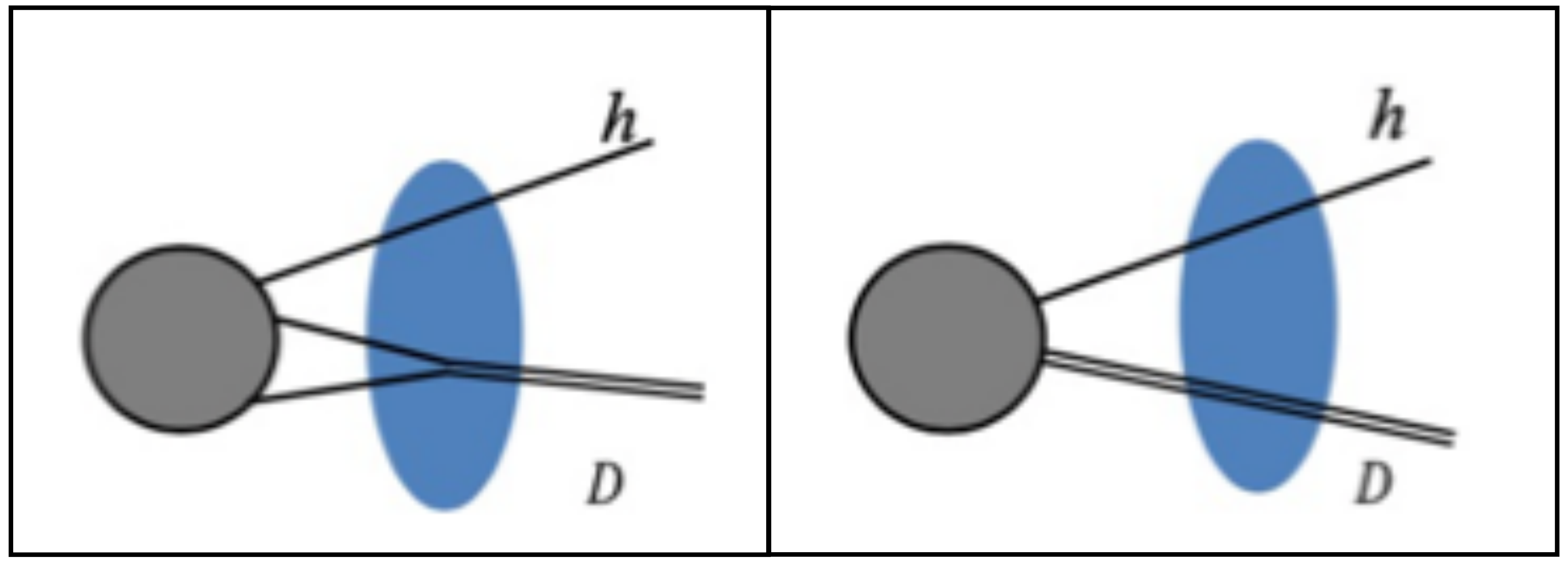
Two-particle correlations at small relative momenta contain information about the space-time characteristics of the emitting source and final-state interactions effects

✓ Formation mechanism of light nuclei are under debate

⇒ Coalescence : final-state interaction

⇒ Thermal : produced directly from fireball

⇒ A systematic measurements of light nuclei femtoscopy may help to investigate




Coalescence Direct production

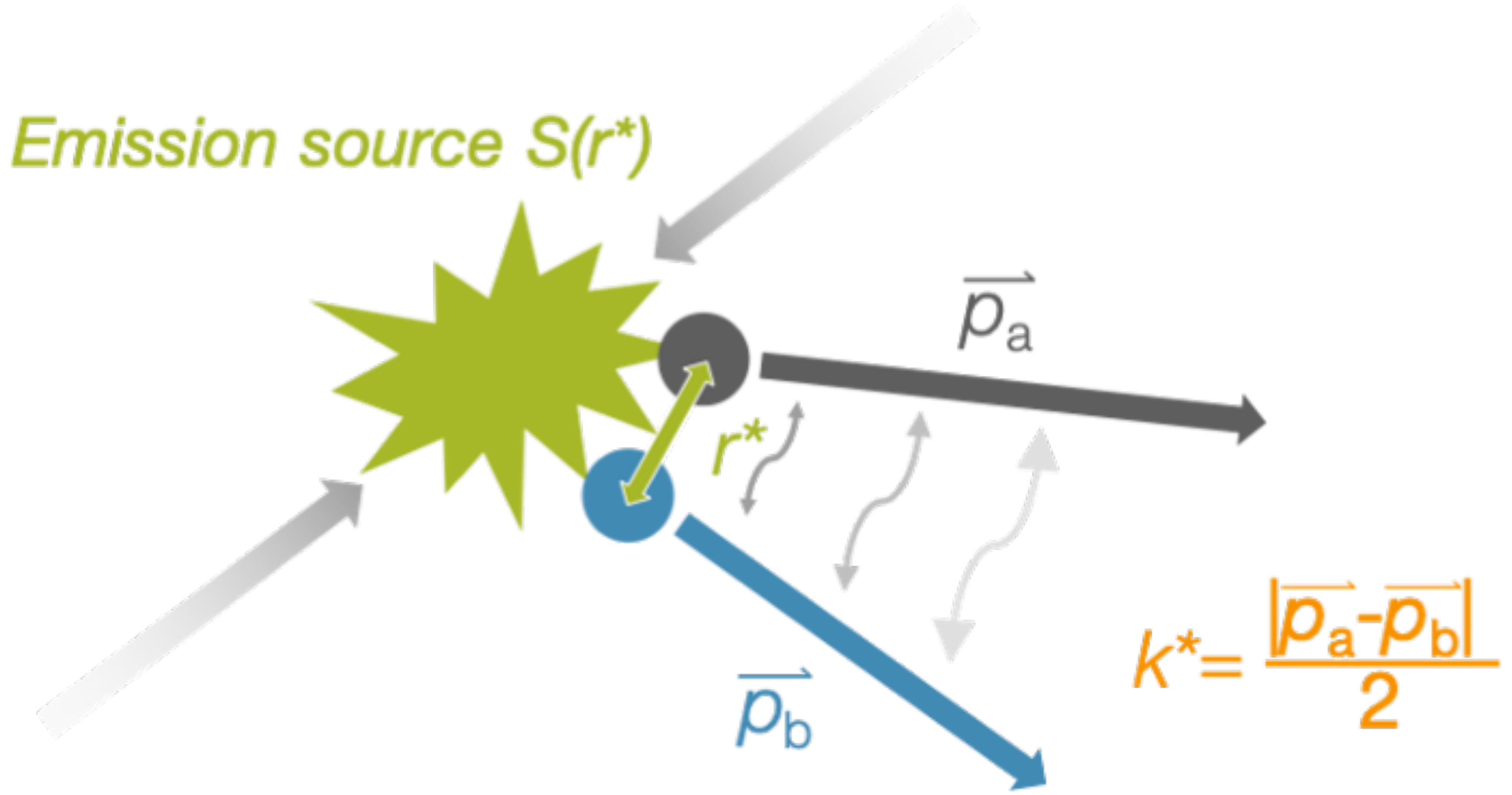
✓ A large amount of light nuclei produced at $\sqrt{s_{NN}}$ = 3 GeV

⇒ Allowing precision measurements of various light nuclei correlations(p-d, d-d, p-$^3He$, p-$\alpha$, etc ....)

J. Cleymans et al, Phys. Rev. C 74, 034903 (2006)

K. Blum et al, Phys. Rev. C 99, 04491(2019)

# Analysis Method: Femtoscopy




⇒ Femtoscopy (HIC) is inspired by Hanbury Brown and Twiss interferometry method (Astronomy)[1]

⇒ Study the spatial and temporal extent of emission source

→ Quantum Statistics (Fermi-Dirac, Bose-Einstein)

→ Final-state Interactions (Coulomb, Strong interaction)

→ Collision Dynamics

✓ Two-particle correlation function:

| Statistical | Model | Experimental |
|---|---|---|

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

- >1: Attraction
- =1: No Correlation
- <1: Replusion

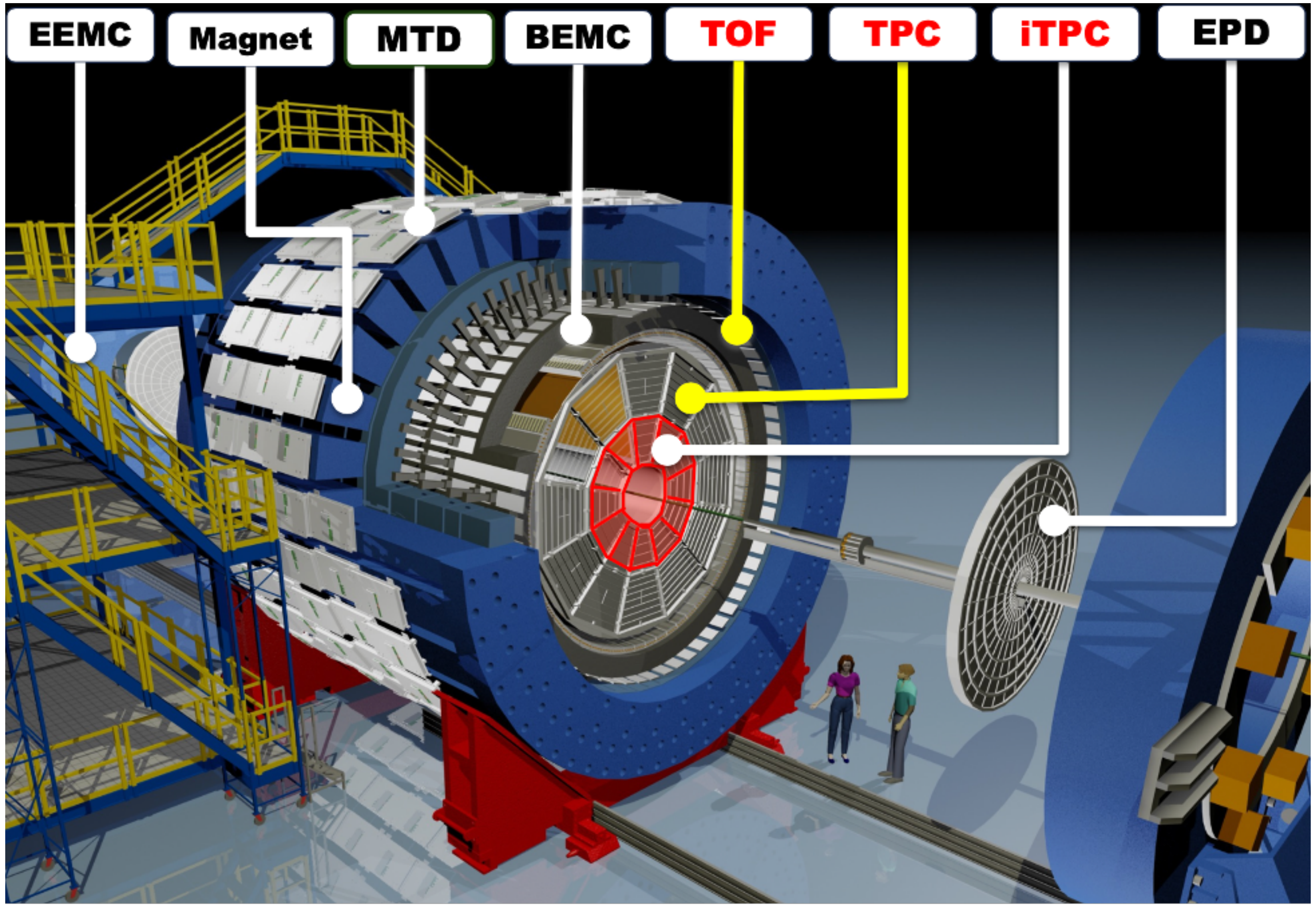
$\vec{p}_a$, $\vec{p}_b$: Single-particle momentum

$S(\vec{r})$: 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

$N_{same}(k^*)$: same event
$N_{mixed}(k^*)$: mixed event

[1] *Nature 178 1046-1048(1956)*
[2] *ALICE Coll. Nature 588, 232–238 (2020)*

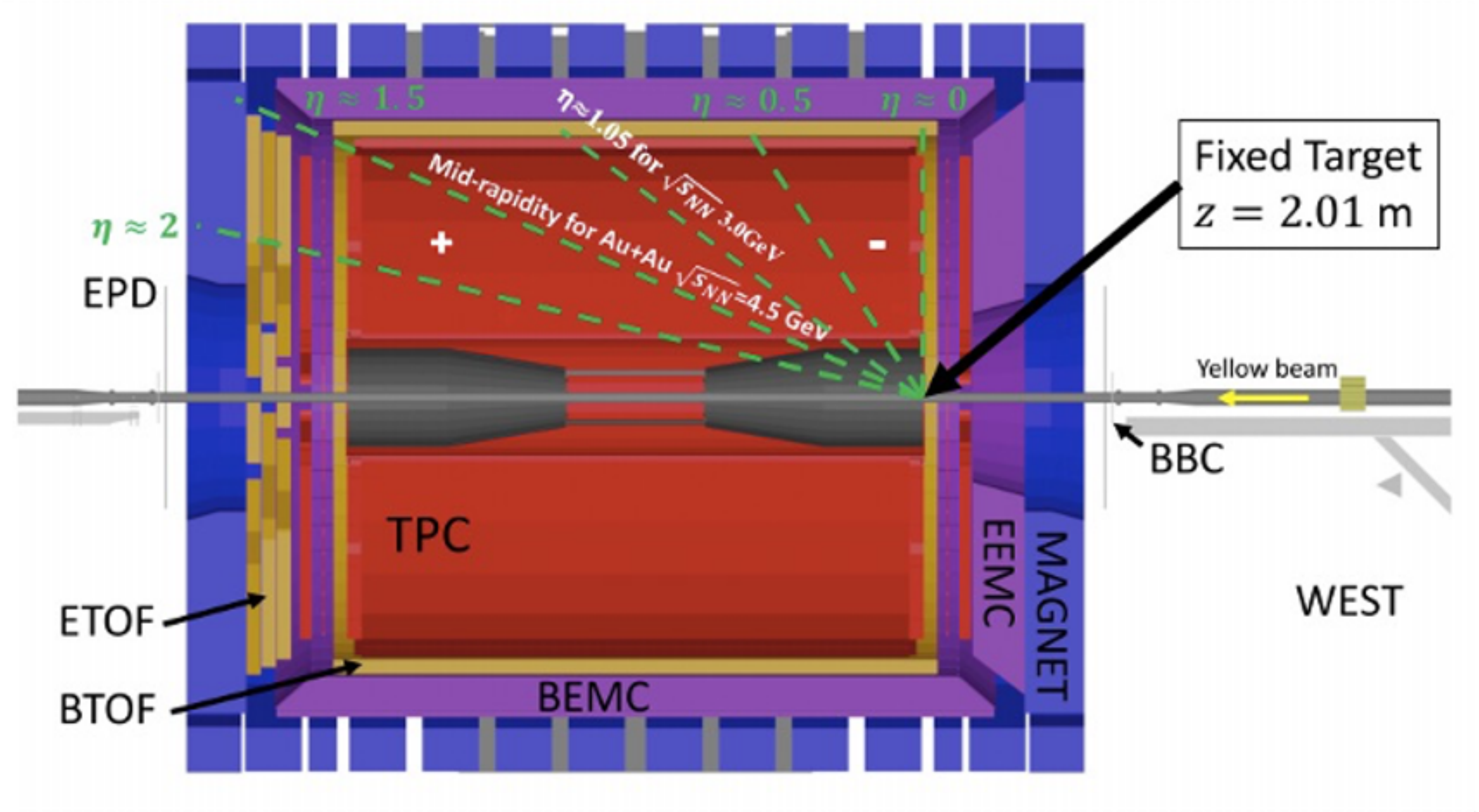
# STAR Detector




→ Excellent Particle Identification

→ Large, Uniform Acceptance at Mid-rapidity

**STAR Fixed-target Experiment Setup**

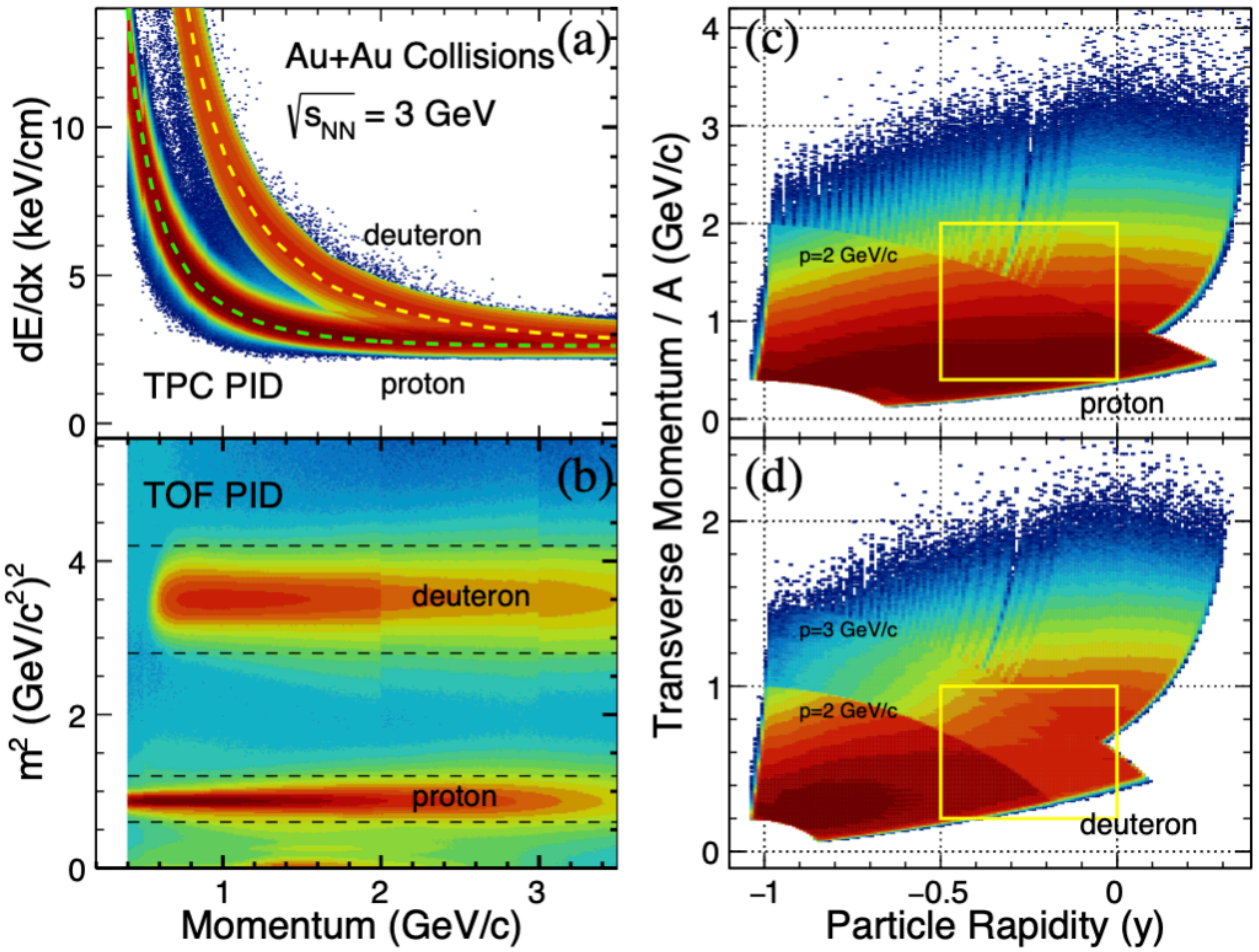



→ Dataset

$\sqrt{s_{NN}}$ = 3 GeV, Au+Au Collisions, Fixed-target mode

~260 millions minimum bias triggered event

# Particle Identification




⇒ PID using TPC (low momentum)and TOF (high momentum)

⇒Excellent acceptance within middle rapidity window

⇒ High purity particle sample

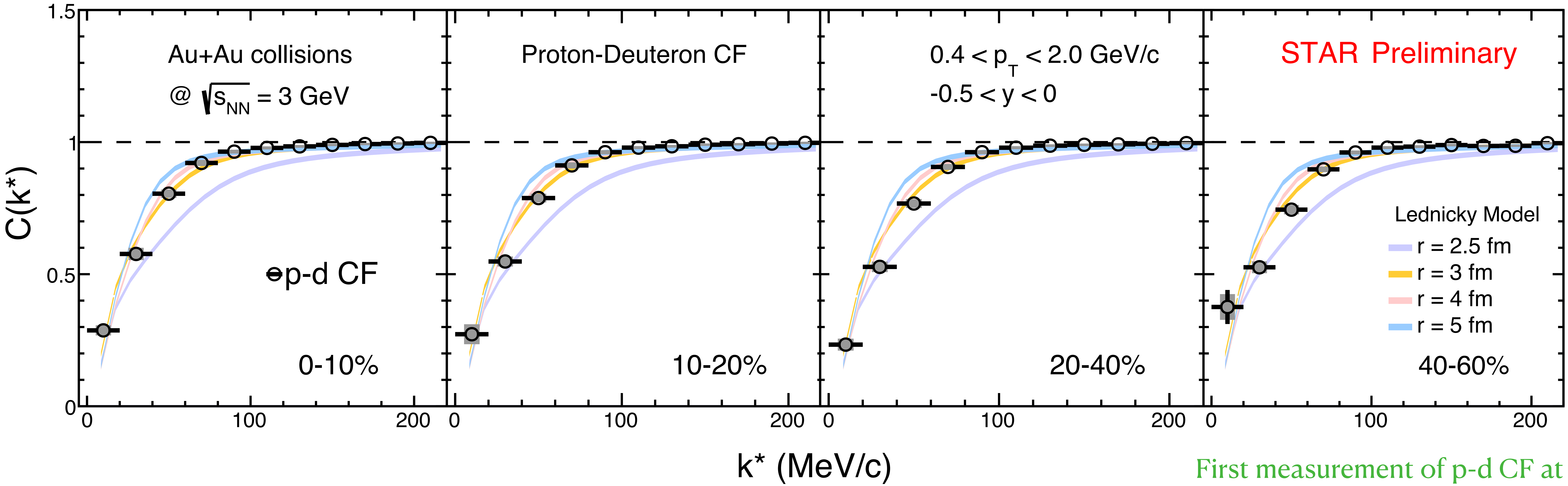
Proton purity > 99%

Deuteron purity > 97%

Pair purity: > 96% (pd) , >95% (dd)

# Proton-Deuteron Femtoscopy

QM2022




First measurement of p-d CF at STAR

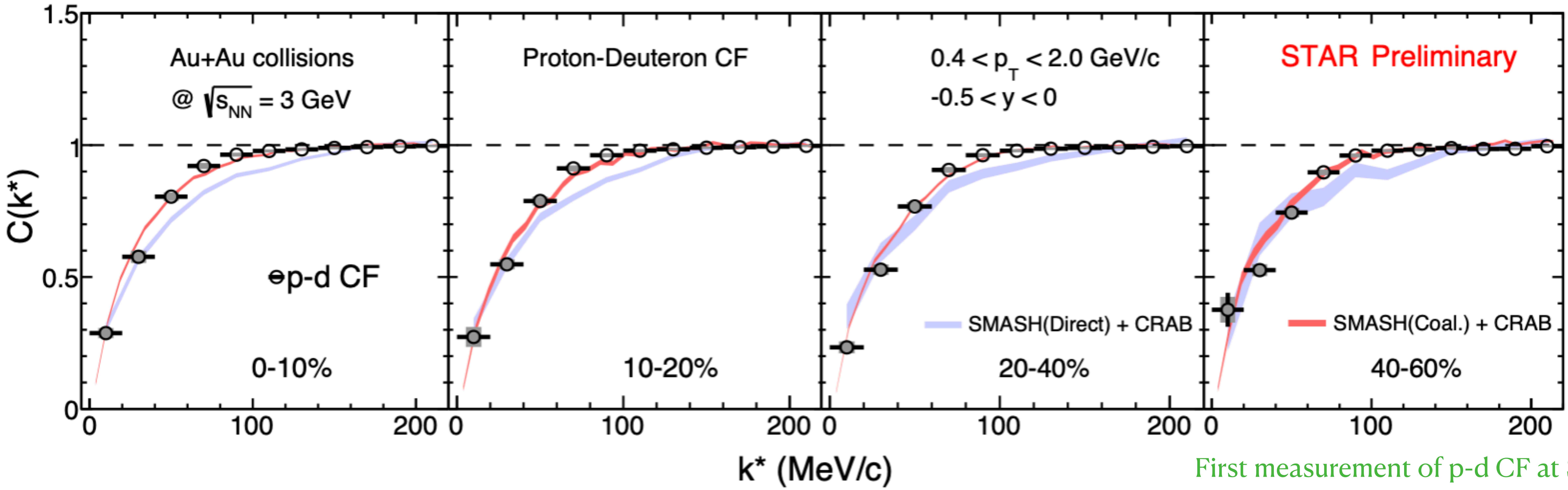
⇒ Clear depletion at small $k^*$ range seen in data

⇒ Data compared with Lednicky&Lyuboshitz model

A spherical source size with $r_g$ = 3 -4 fm is consistent with data

# Proton-Deuteron Femtoscopy

QM2022



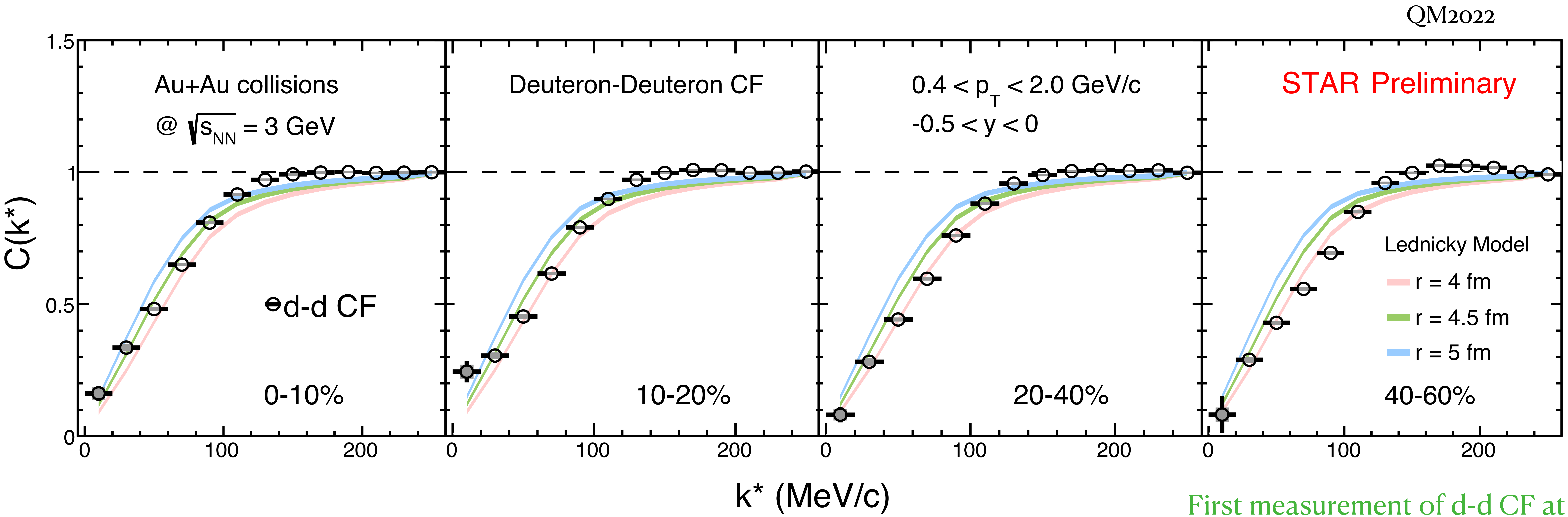

First measurement of p-d CF at STAR

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

CF calculated with coalescence of deuterons is in better agreement with data

Support the deuteron formation at 3 GeV is dominated by coalescence

# Deuteron-Deuteron Femtoscopy




First measurement of d-d CF at STAR

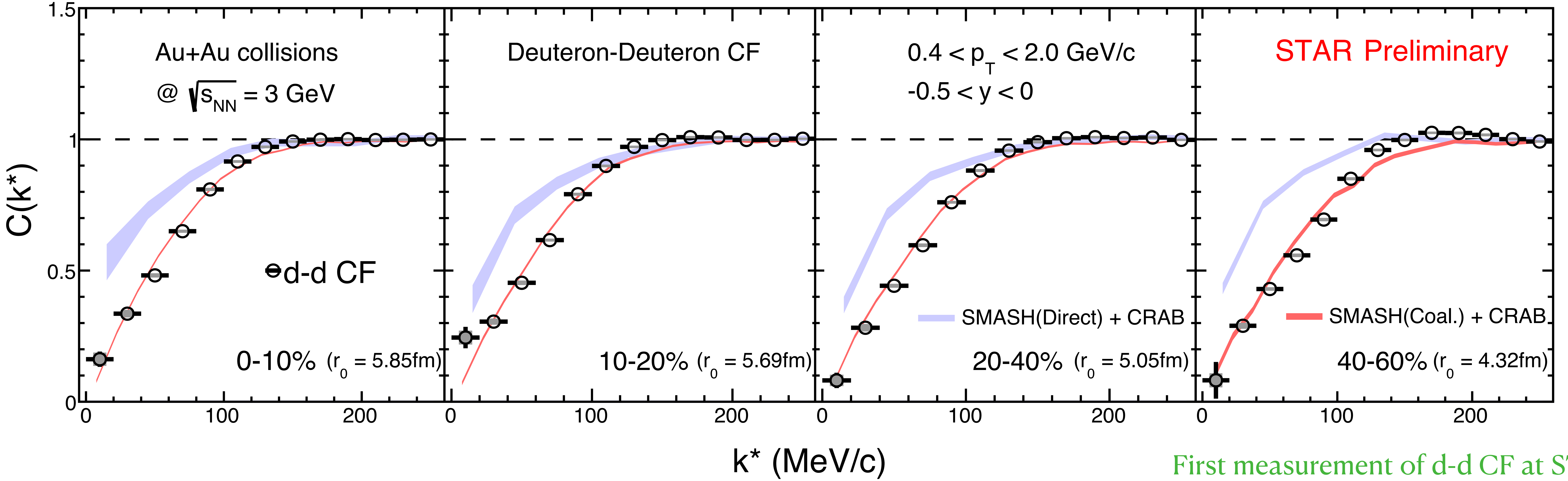
⇒ Clear depletion at small $k^*$ range seen in data

⇒ Data compared with Lednicky & Lyuboshitz model

A spherical source size with $r_g$ = 4-5 fm is consistent with data

# Deuteron-Deuteron Femtoscopy

QM2022




First measurement of d-d CF at STAR

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

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# Summary

✓ First measurement of p-d and d-d correlation functions with good precision from STAR

✓ p-d and d-d correlation functions qualitatively described by L&L model

✓ p-d and d-d CF described better by the model including coalescence

⇒ Light nuclei are likely to be formed via coalescence at $\sqrt{s_{NN}} = 3$ GeV

⇒ With high precision data, the properties of strong interactions among light nuclei pairs is achievable

⇒ More inputs from theory are needed

⇒ In the 2nd phase of BES, STAR has collected 10-20 times more data in Au+Au collisions at the energy range $\sqrt{s_{NN}} = 3 - 19.6$ GeV. These data allow us to perform precision light nuclei femtoscopy analysis !

*Stay tuned for the RHIC BES-II !*

Thank you for your attention !

# Back up slides

# SMASH + CRAB

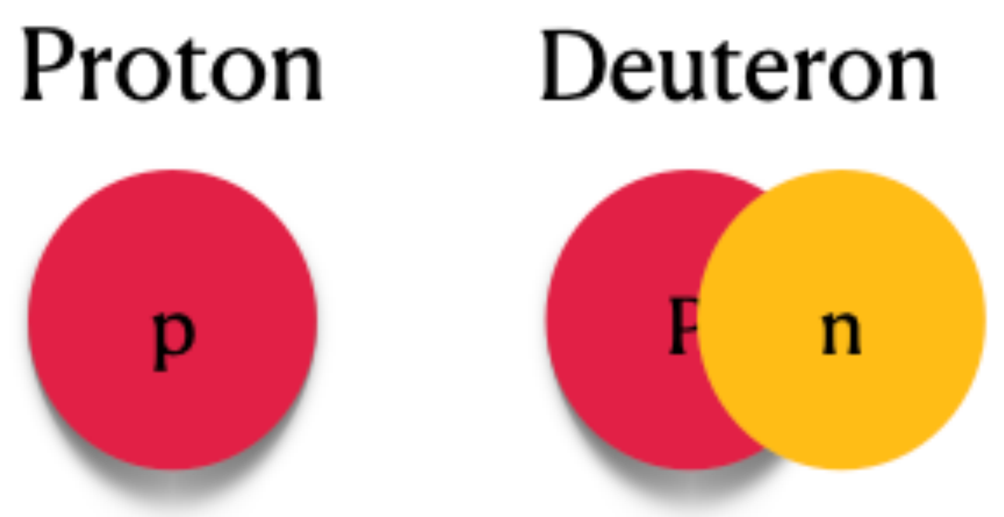
⇒ Phase Space of proton / neutron /deuteron is produced via SMASH transport model

⇒ Coalescence ( p + n -> d):

⇒Formation probability calculated via Wigner Function

$$f_2(\boldsymbol{\rho}, \mathbf{p}_\rho) = 8g_2 \exp\left[-\frac{\boldsymbol{\rho}^2}{\sigma_\rho^2} - \mathbf{p}_\rho^2\sigma_\rho^2\right],$$

$$\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{x}'_1 - \mathbf{x}'_2), \quad \mathbf{p}_\rho = \sqrt{2}\,\frac{m_2\mathbf{p}'_1 - m_1\mathbf{p}'_2}{m_1 + m_2},$$




⇒ Related to the relative coordinate and relative momentum of proton and neutron

⇒ Interaction

⇒ SMASH does not contain FSI interaction between two particles

⇒ All of Coulomb, QS and SI potentials are introduced via CRAB

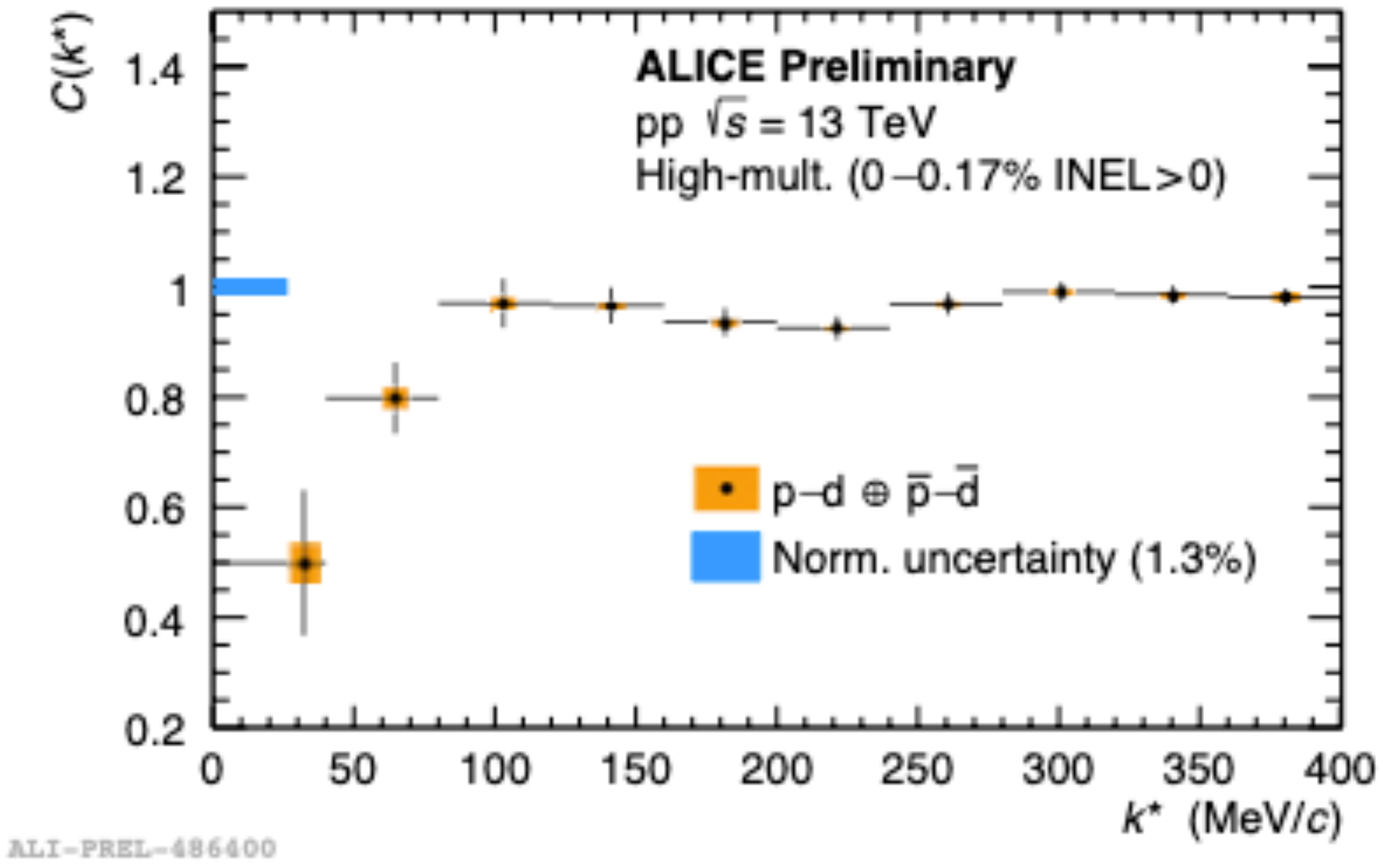
SMASH: J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905

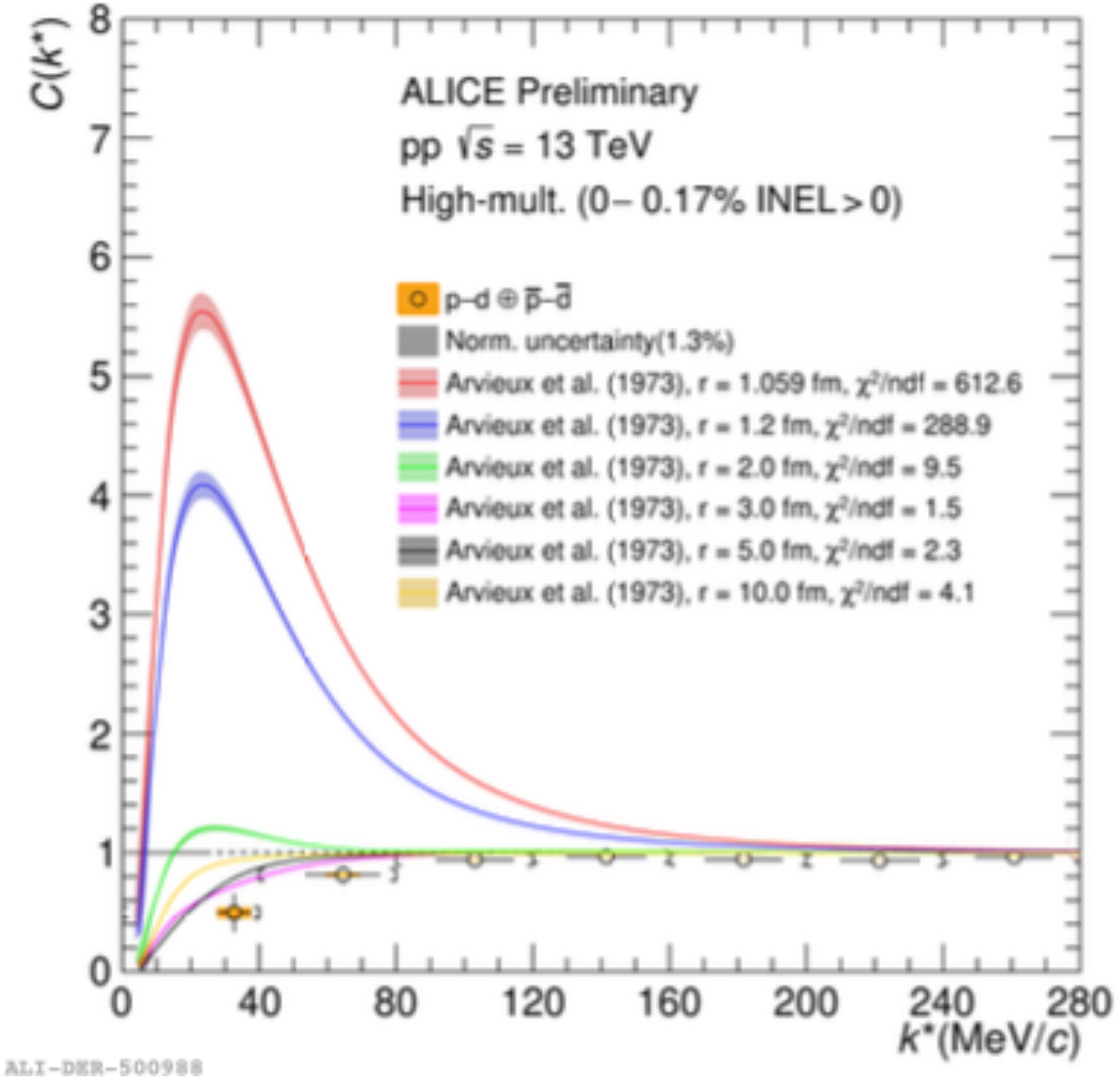
Coalescence: W.Zhao et al. Phys. Rev. C.98 (2018) 5,054905

CRAB (p-d): Private conversations with Prof.Scott Pratt

# Proton-Deuteron CF from ALICE

QM2022




Interpretation:

⇒ Improved agreement with larger source sizes

⇒ CF becomes flat at large source size

⇒ The effect of attractive strong interaction in the CF is diluted

# Proton-Cluster CF from HADES

M.Stefaniak, WPCF 2022

Ag+Ag @ 1.58A GeV