Extending the ALICE strong-interaction studies to nuclei: measurement of proton-deuteron correlations in pp collisions at $\sqrt{s}$ =13 TeV

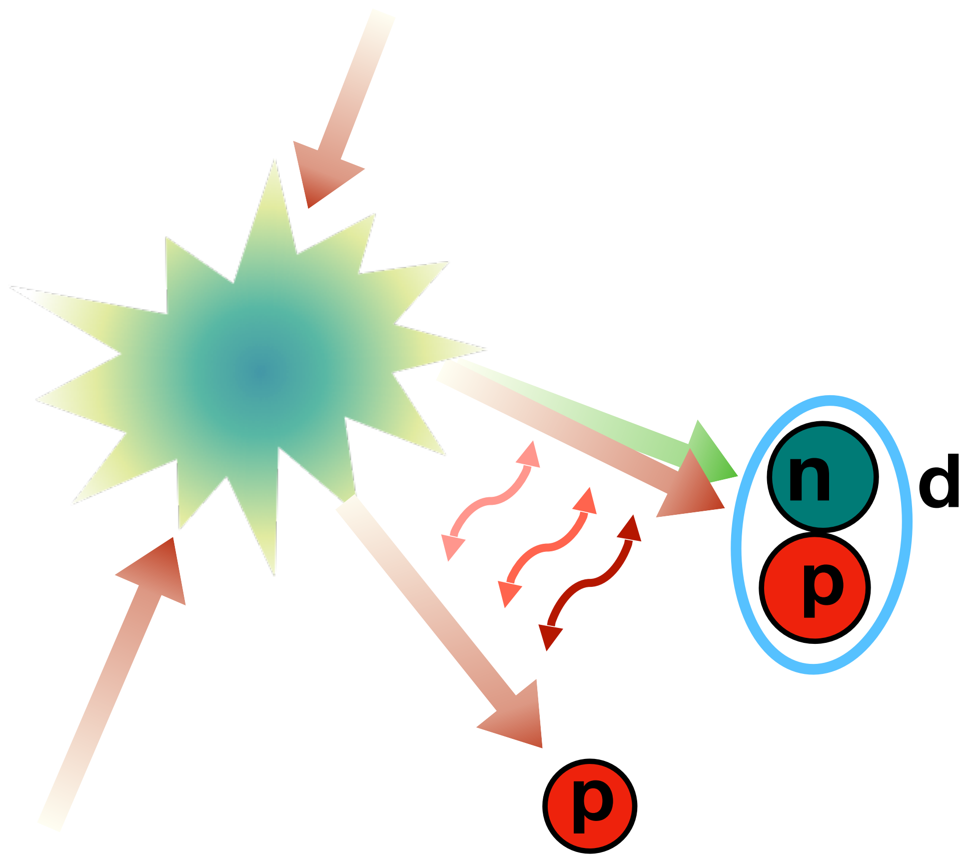
Bhawani Singh

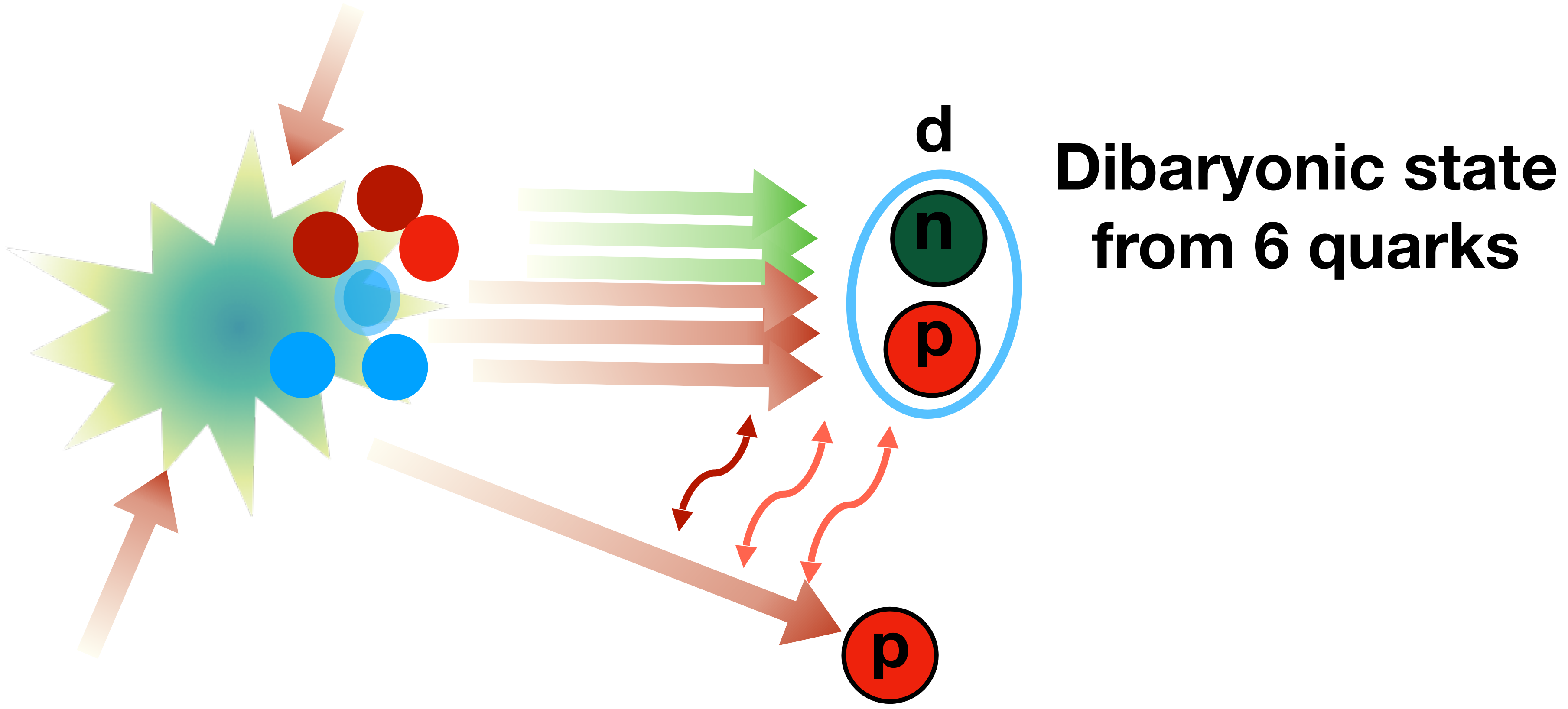
Technische Universität München

on behalf of the **ALICE Collaboration**

Motivation

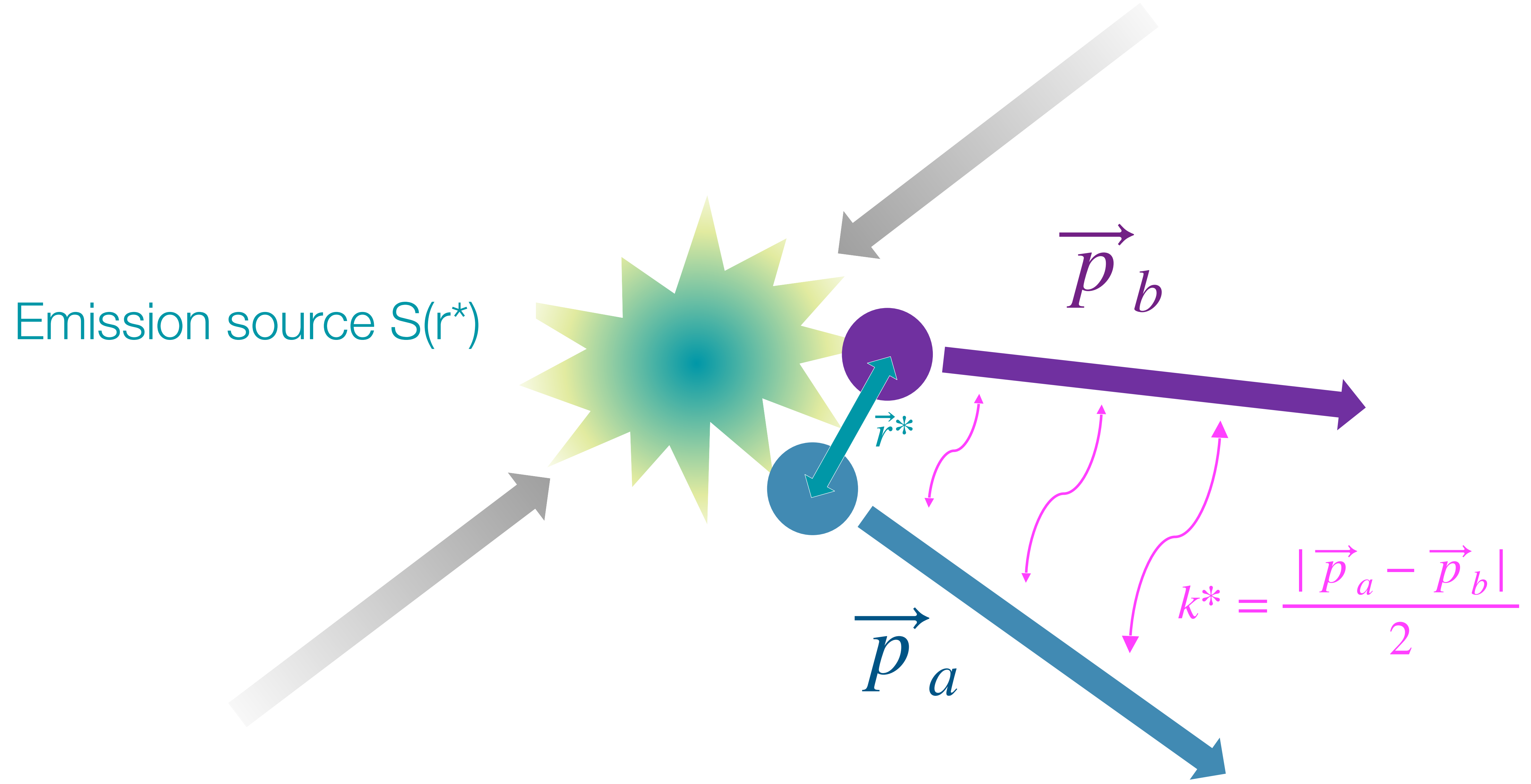
- **Proton-deuteron (p—d) interaction**
  - Three-nucleon force: doorway to probe short distances
  - p—d interaction is well constrained from the scattering experiments
- **Production mechanism of light nuclei not understood:**
  - Models: information on single particle, Statistical Hadronisation Model or Coalescence Model
  - Final-state interactions: probe the formation time of deuterons (anti-deuterons)





The femtoscopy technique at LHC

- Correlations in the relative momentum k^* distribution of a particle pair
- Traditionally used to study the geometry of the emission source with particles of known interaction
- Reversing the paradigm of femtoscopy
  - Study the interaction among the particles if emission source is known



Koonin-Pratt Equation

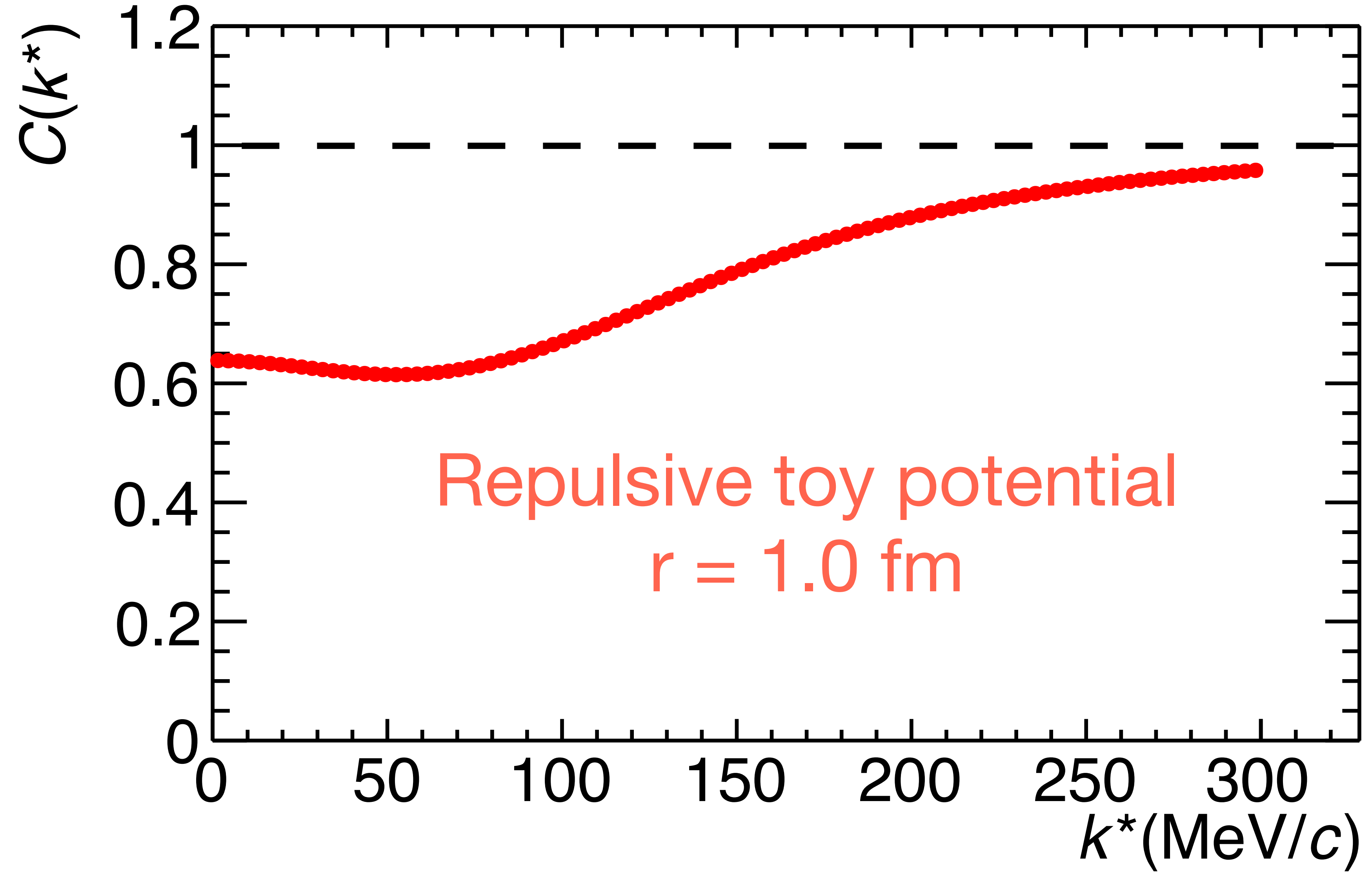
$$C(k^*) = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* = \mathcal{N} \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} \xrightarrow{k^* \to \infty} 1$$

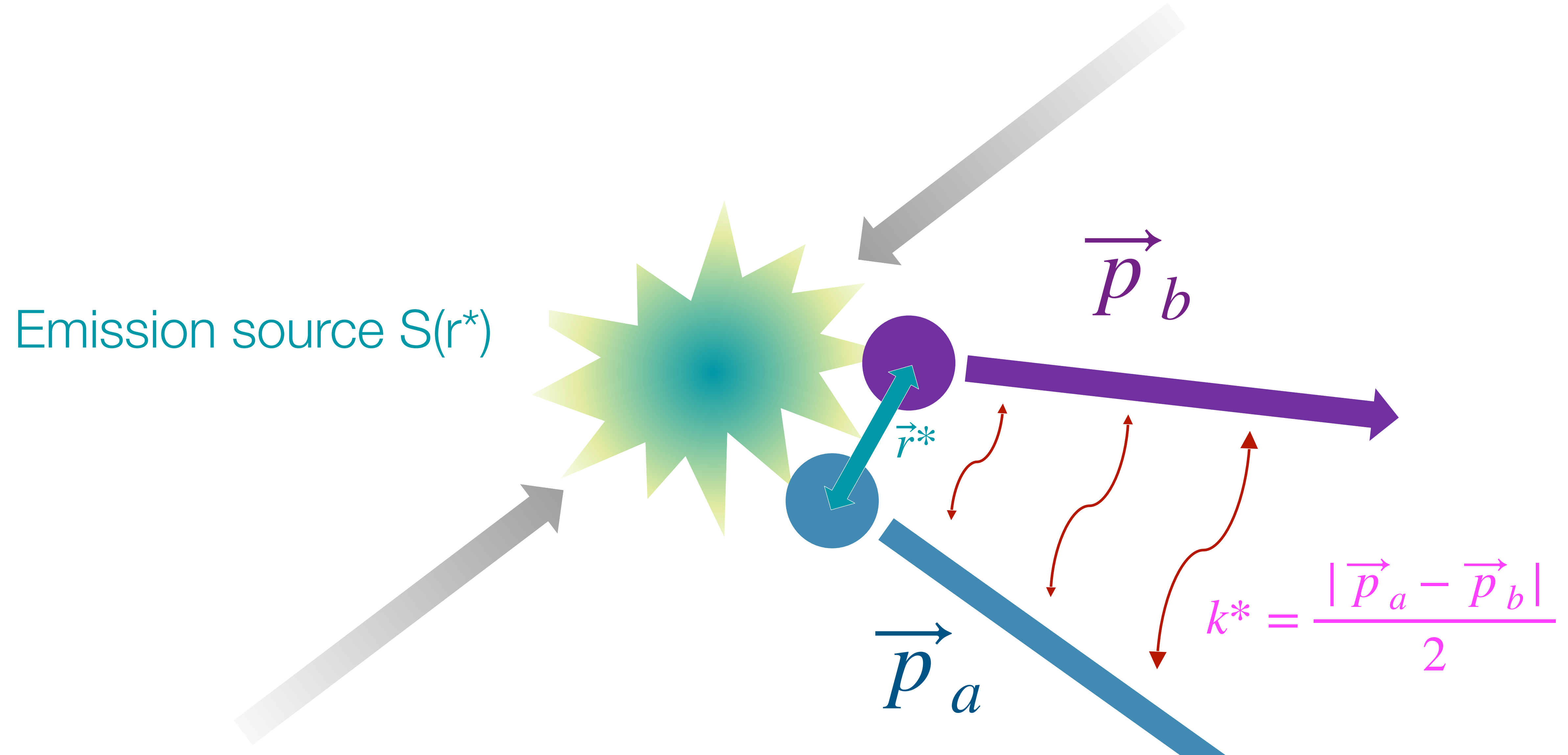
theoretical definition   experimental definition

S.E. Koonin PLB 70 43 (1977)
CATS Framework: D. Mihaylov et al., EPJ. C78 (2018) 394

The femtoscopy technique at LHC

- Repulsive interaction brings correlation below 1





Potential parameters from

K. Morita et al PRC 91, 024916 (2015)

Koonin-Pratt Equation

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theoretical definition — experimental definition

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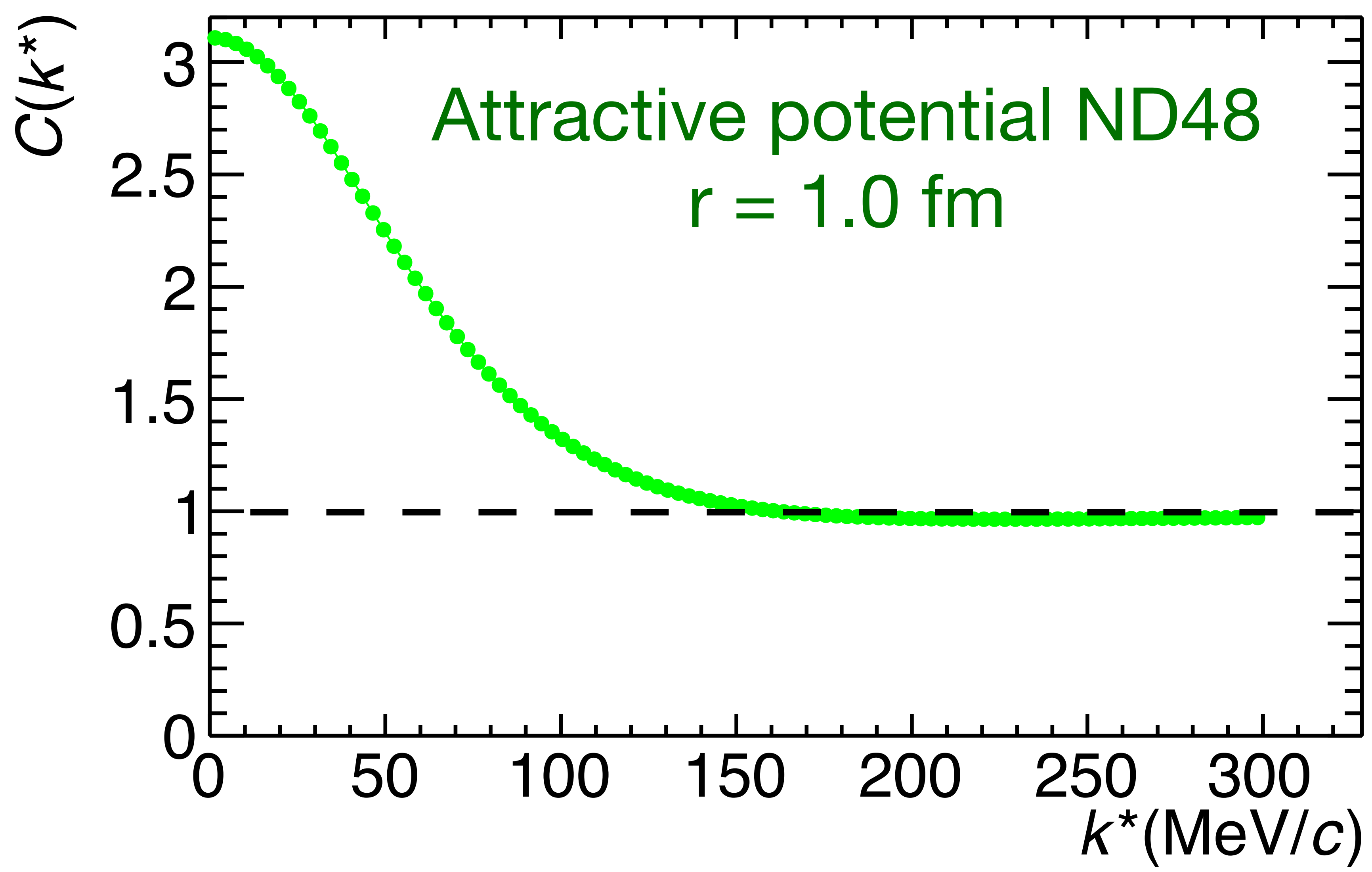
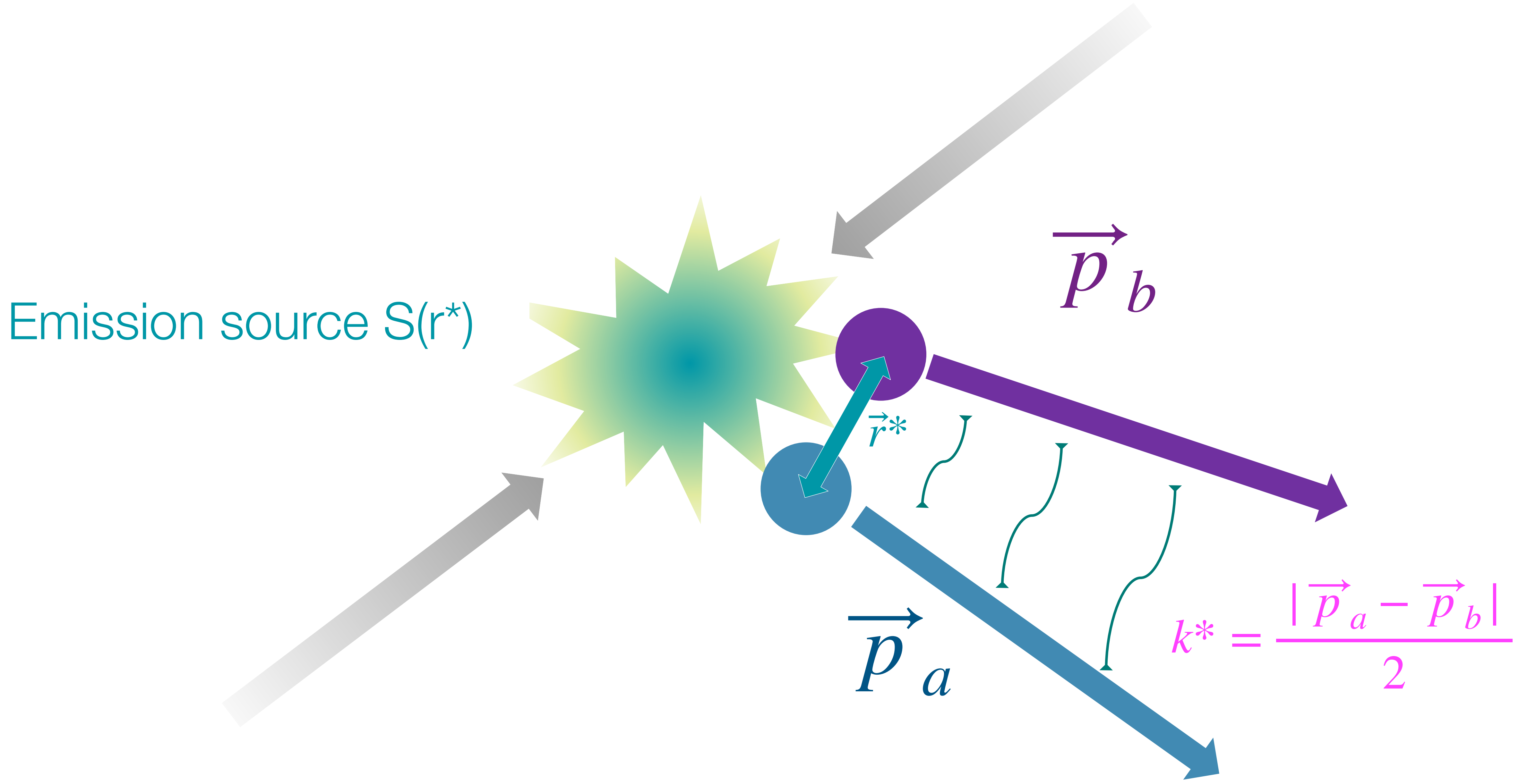
- Correlation rises above 1 for attractive potentials





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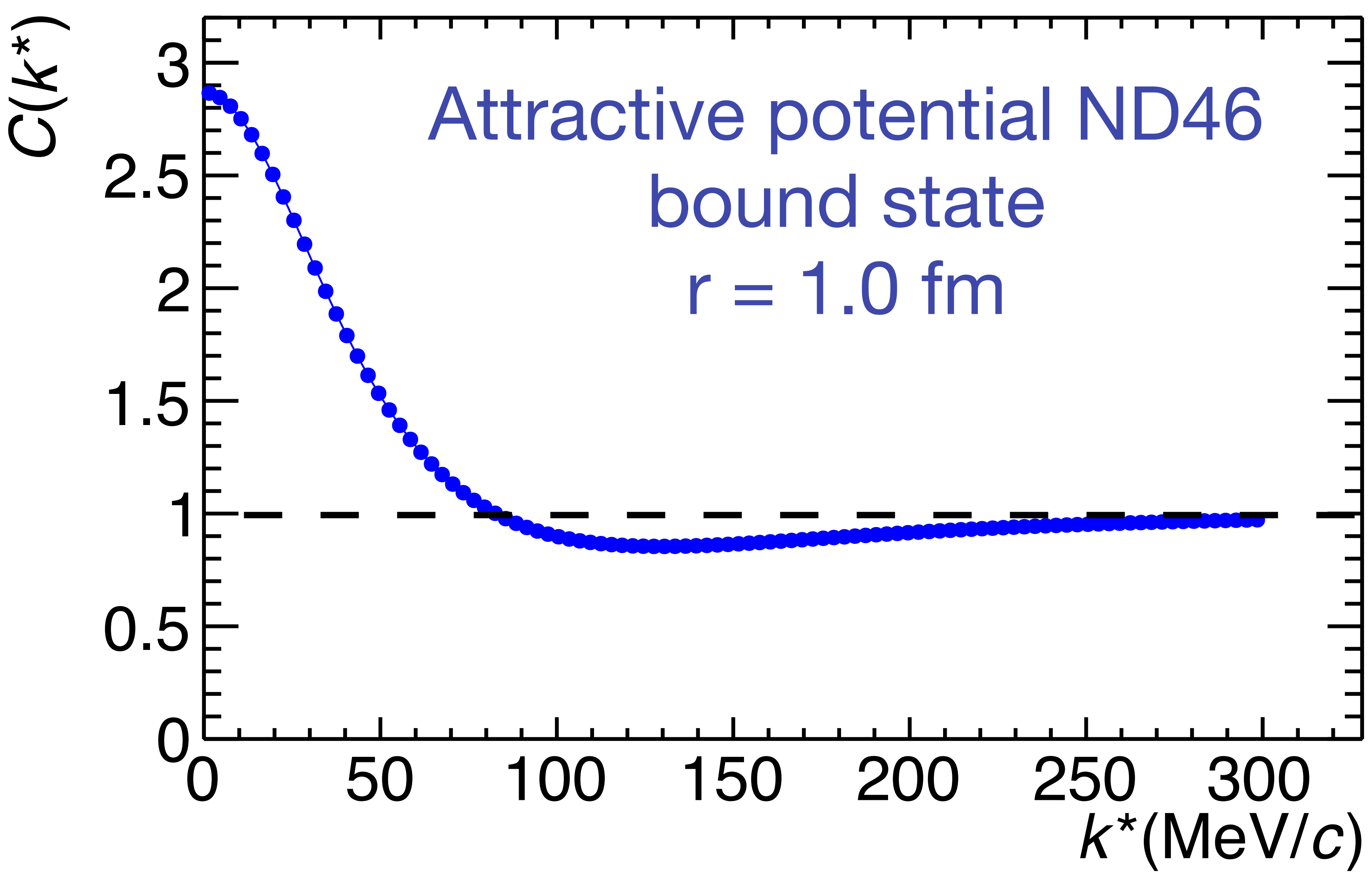
The femtoscopy technique at LHC

- Depletion due to the loss of particle pairs



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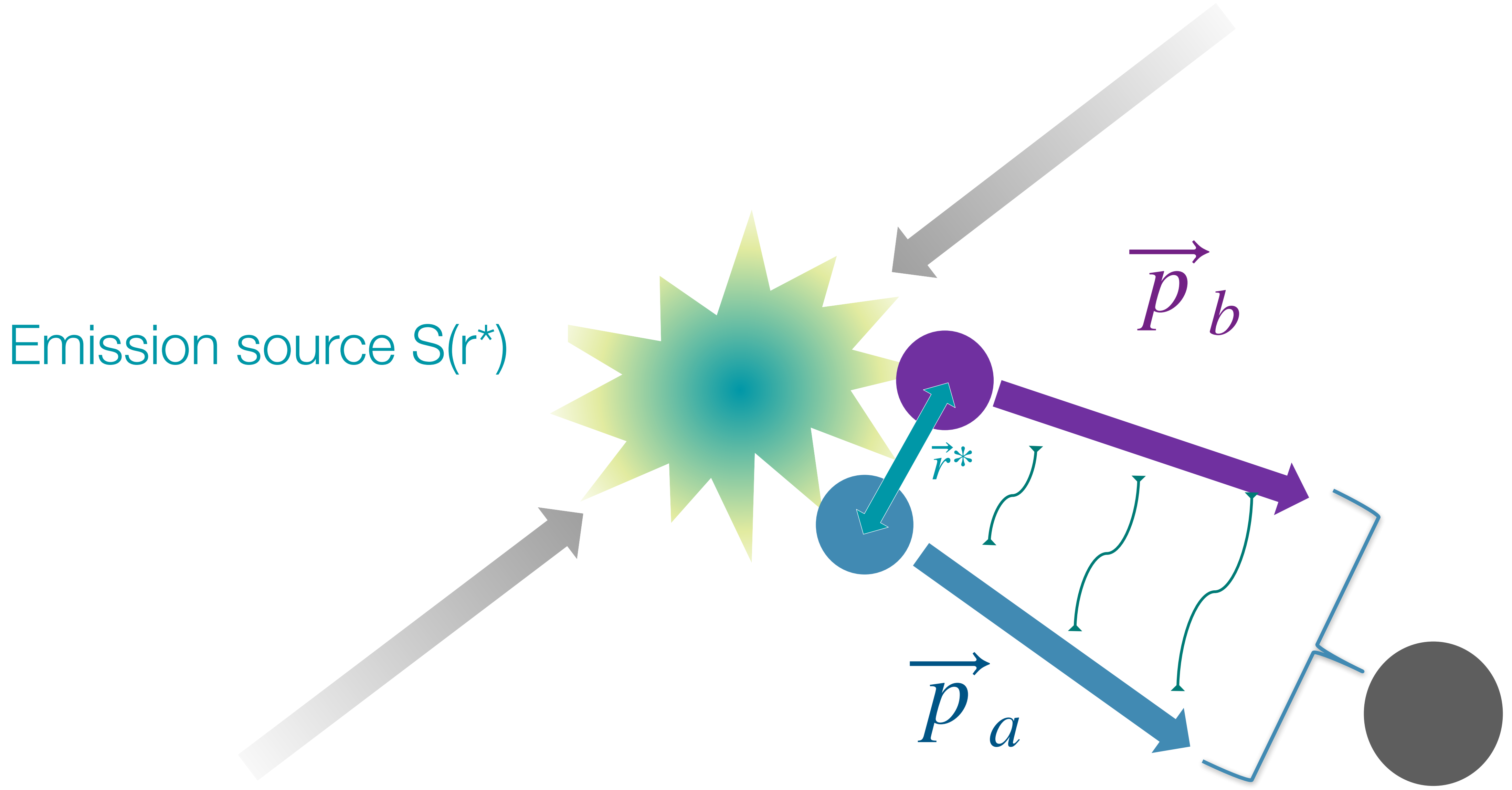

$$k^* = \frac{|\vec{p}_a - \vec{p}_b|}{2}$$

Koonin-Pratt Equation

$$C(k^*) = \underbrace{\int S(\vec{r}^*) \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^*}_{\text{theoretical definition}} = \underbrace{\mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}}_{\text{experimental definition}} < 1$$

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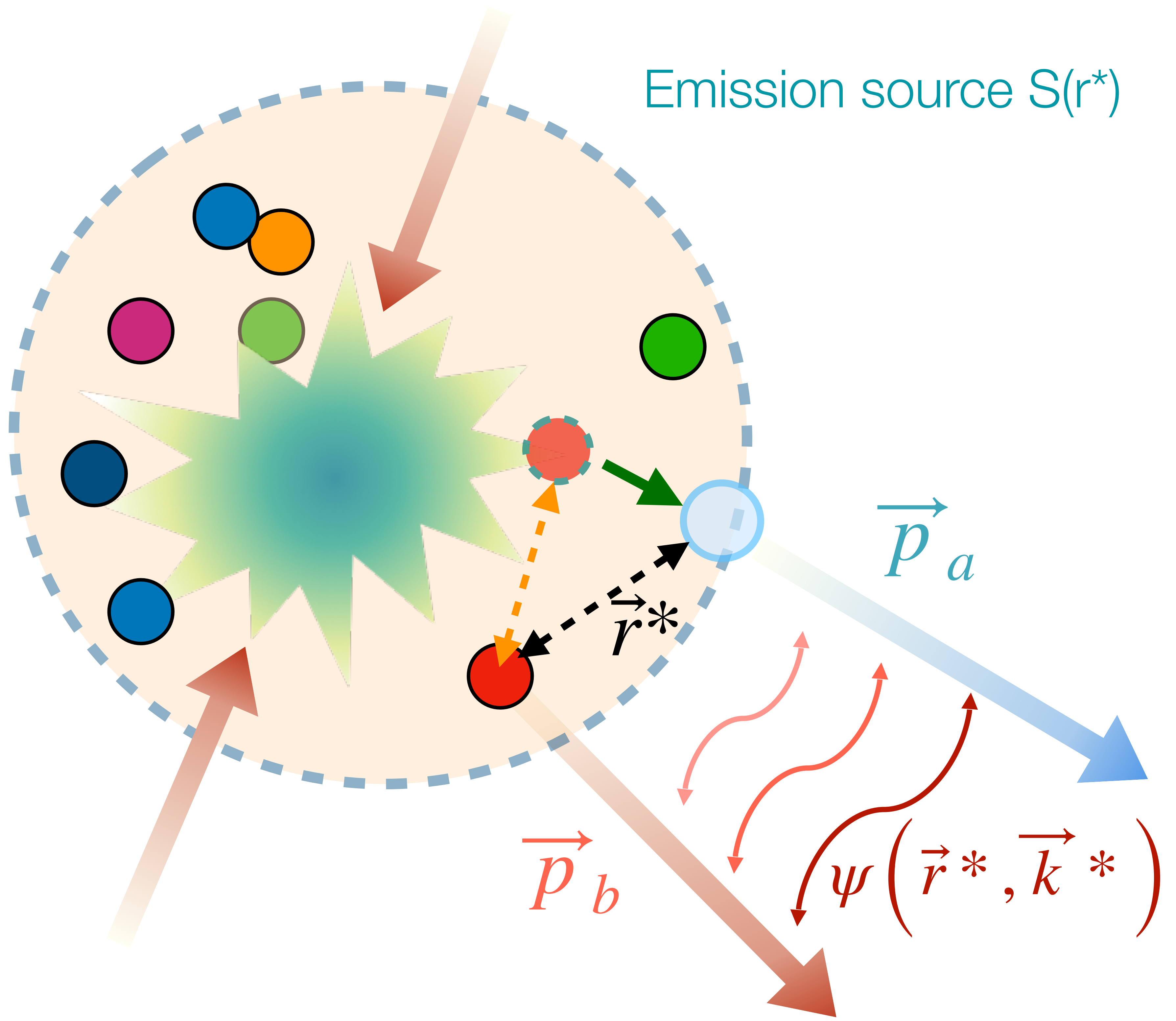
The source

- Short distances in pp and p—Pb collisions
- Particle emission from **Gaussian core** source
- The source radius is effectively increased by **short-lived strongly decaying resonances** ($c\tau \approx r_{core}$)

  e.g. Δ-resonances in case of protons

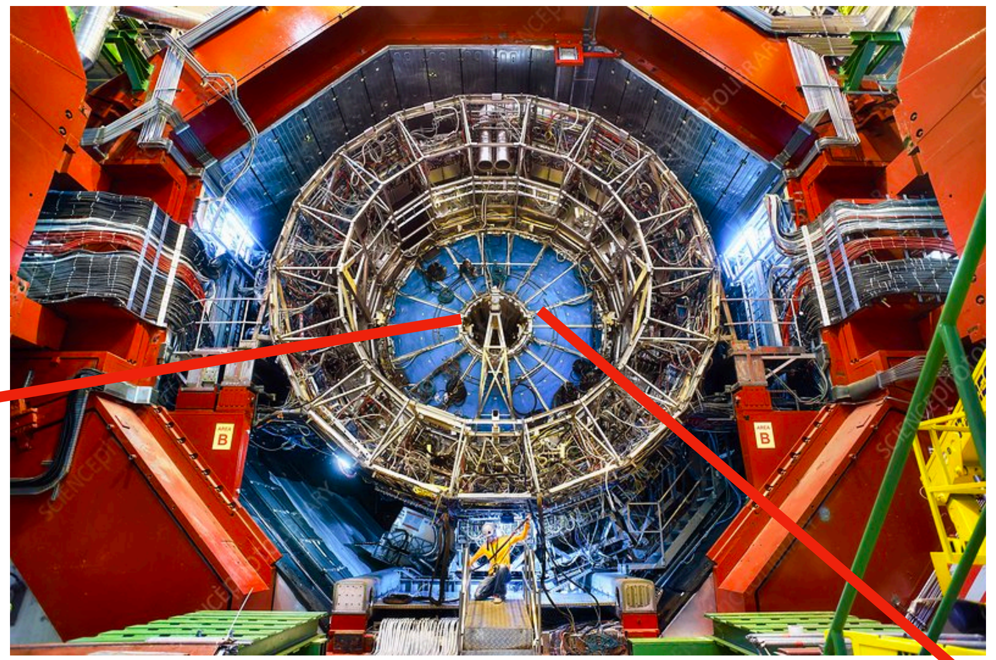
Source size	p-d
r_{core} [fm]	0.99±0.04
r_{eff} [fm]	1.07±0.04



ALICE Collab., *PLB*, 811(2020) 135849

Femtoscopy: fantastic results

- Experimental study of strong final-state interaction by ALICE Collaboration via correlation measurements



1. *PRC 99 (2019) 024001*
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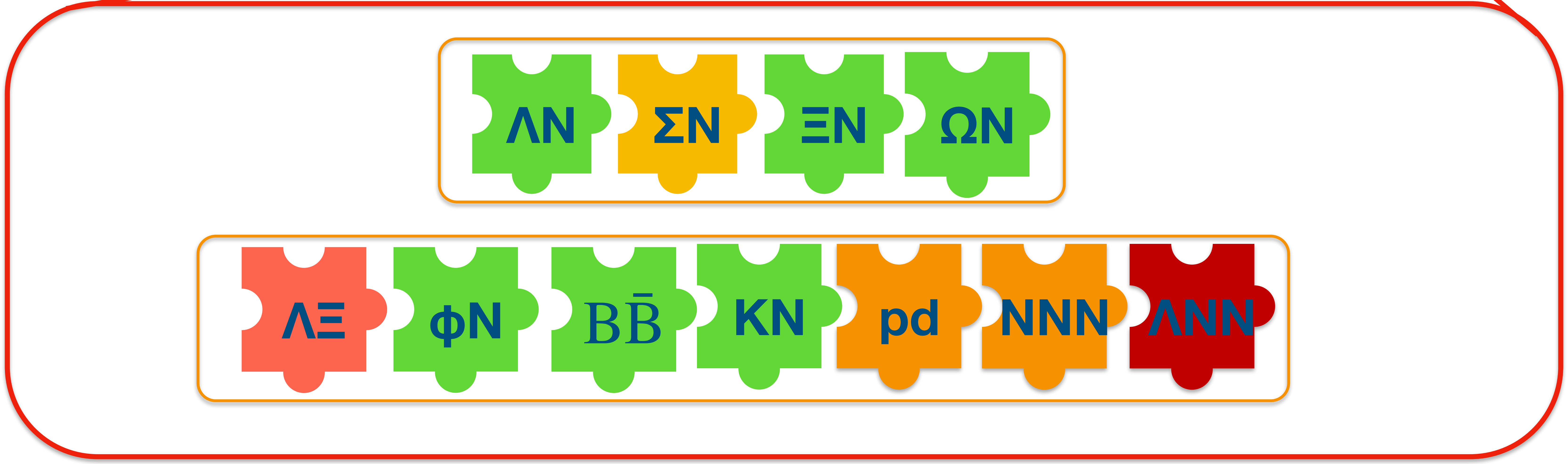
3. *PRL 123 (2019) 112002*
4. *PRL 124 (2020) 09230*
5. *PLB 805 (2020) 135419*
6. *PLB 811 (2020) 135849*
7. *Nature 588 (2020) 232-238*
8. *ALICE Coll. arXiv:2104.04427*
9. *ALICE Coll. arXiv:2105.05578*
10. *ALICE Coll. arXiv:2105.05683*
11. *ALICE Coll. arXiv:2105.05190*



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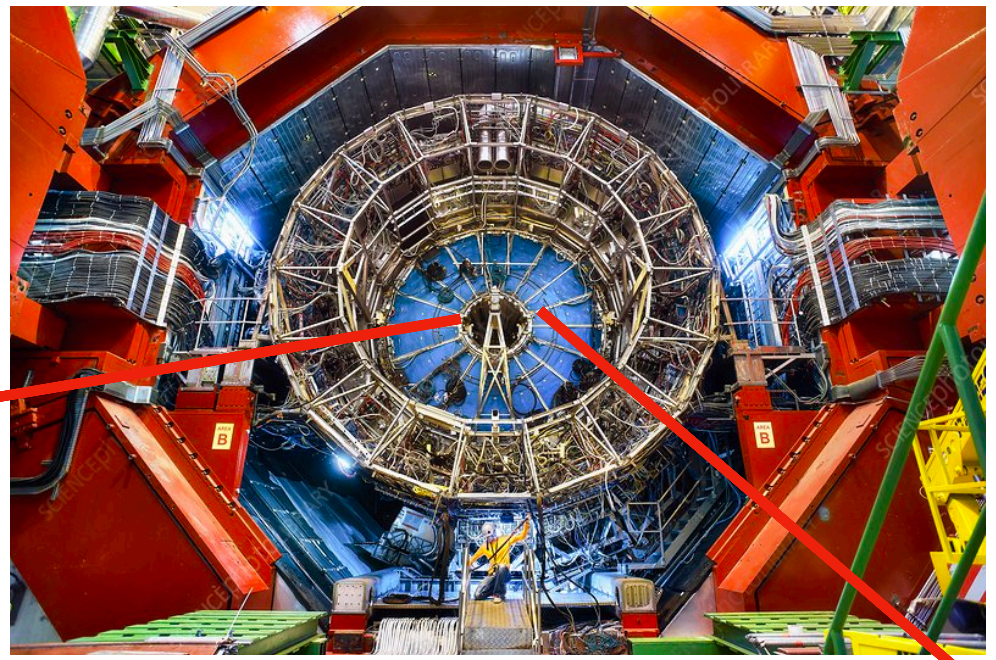
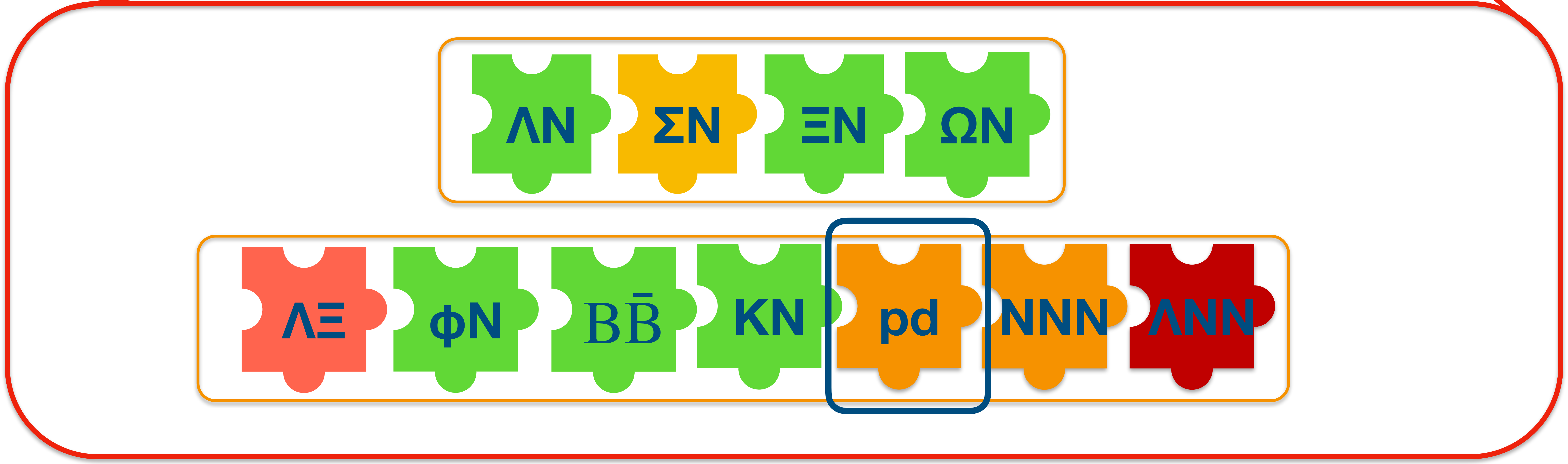
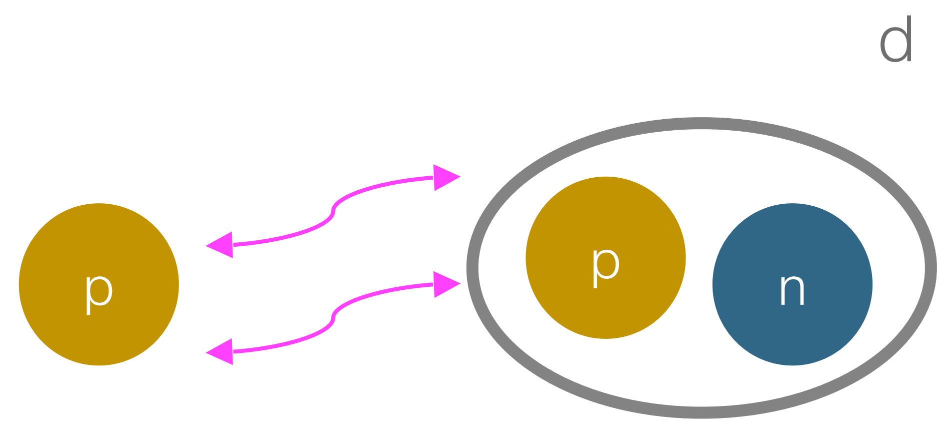


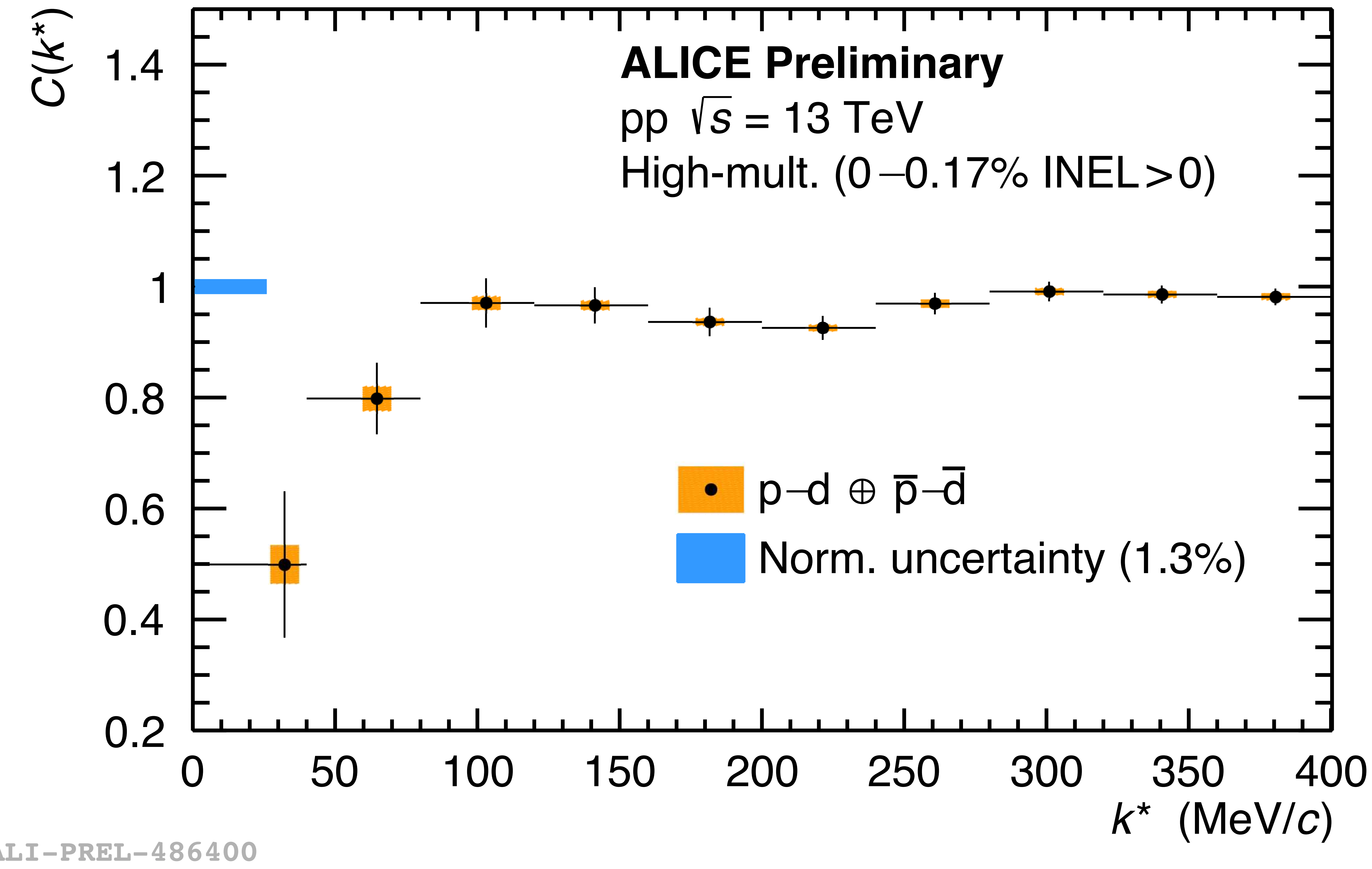


- First time: p—d interaction
- ALICE Run 2 data
- High-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV

First measurement of proton-deuteron

- p—d ⊕ $\bar{p}$—$\bar{d}$ correlation
  - Measured p-d correlation not flat, shows depletion at low *k**
  - Accessing spin-isospin dependence of NNN
- Particle selection
  - Average purity
    - p(anti-p) : **98.30% (98.76%)** in p_T [0.5,4.05]GeV/*c*
    - d(anti-d) : ~**100%** in p_T [0.5,1.4]GeV/*c*
  - Pairs below *k**< 200 MeV/*c*
    - p—d: 1747
    - $\bar{p}$—$\bar{d}$: 1250





Theoretical models and data

- Coulomb-corrected wave function for charged particles Lednický, R. *Phys. Part. Nuclei* 40, 307–352 (2009)
  - Coulomb + strong interaction (S = 1/2 and S = 3/2)
  - Only for s wave interaction
  - Theoretical models constrained to scattering p—d experiments

Ref	Quartet $^4S_{3/2}$	Doublet $^2S_{1/2}$
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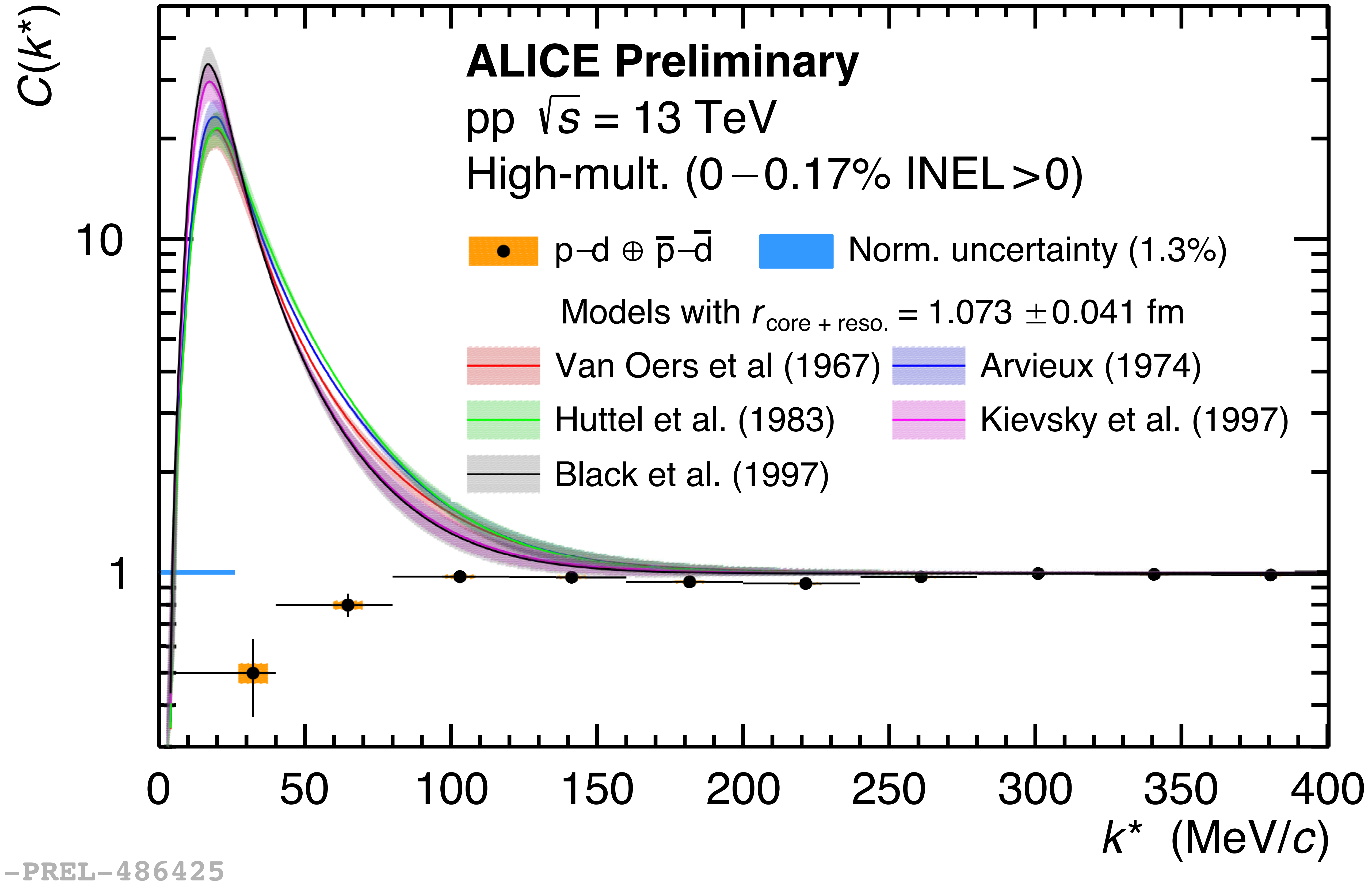
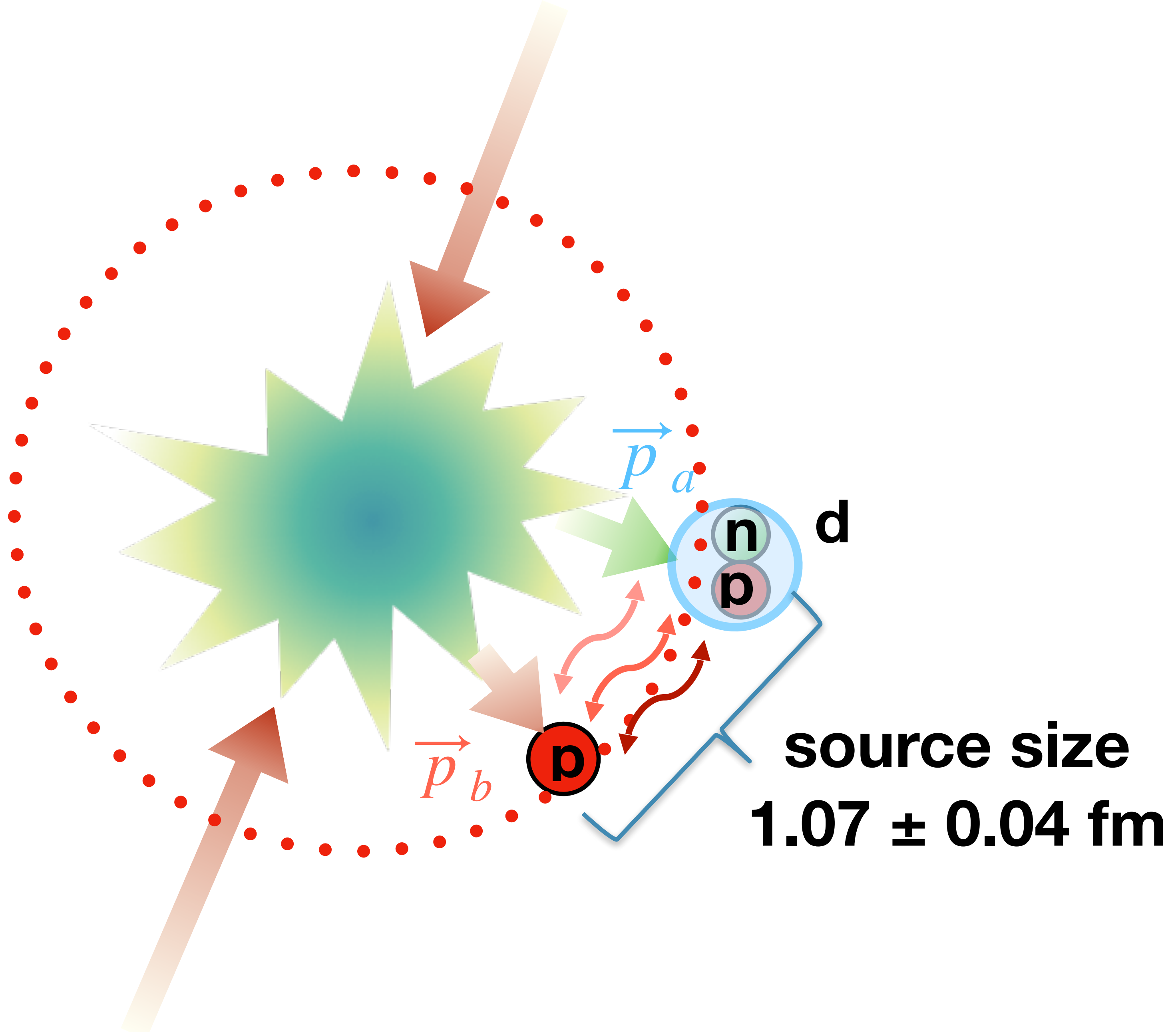


Oers,Brockmann et al. Nucl. Phys. A 561-583 (1967)
J.Arvieux et al. Nucl. Phys. A 221 253-268 (1973)
E.Huttel et al. Nucl. Phys. A 406 443-455 (1983)
A.Kievsky et al. PLB 406 292-296 (1997)
T.C.Black et al. PLB 471 103-107 (1999)

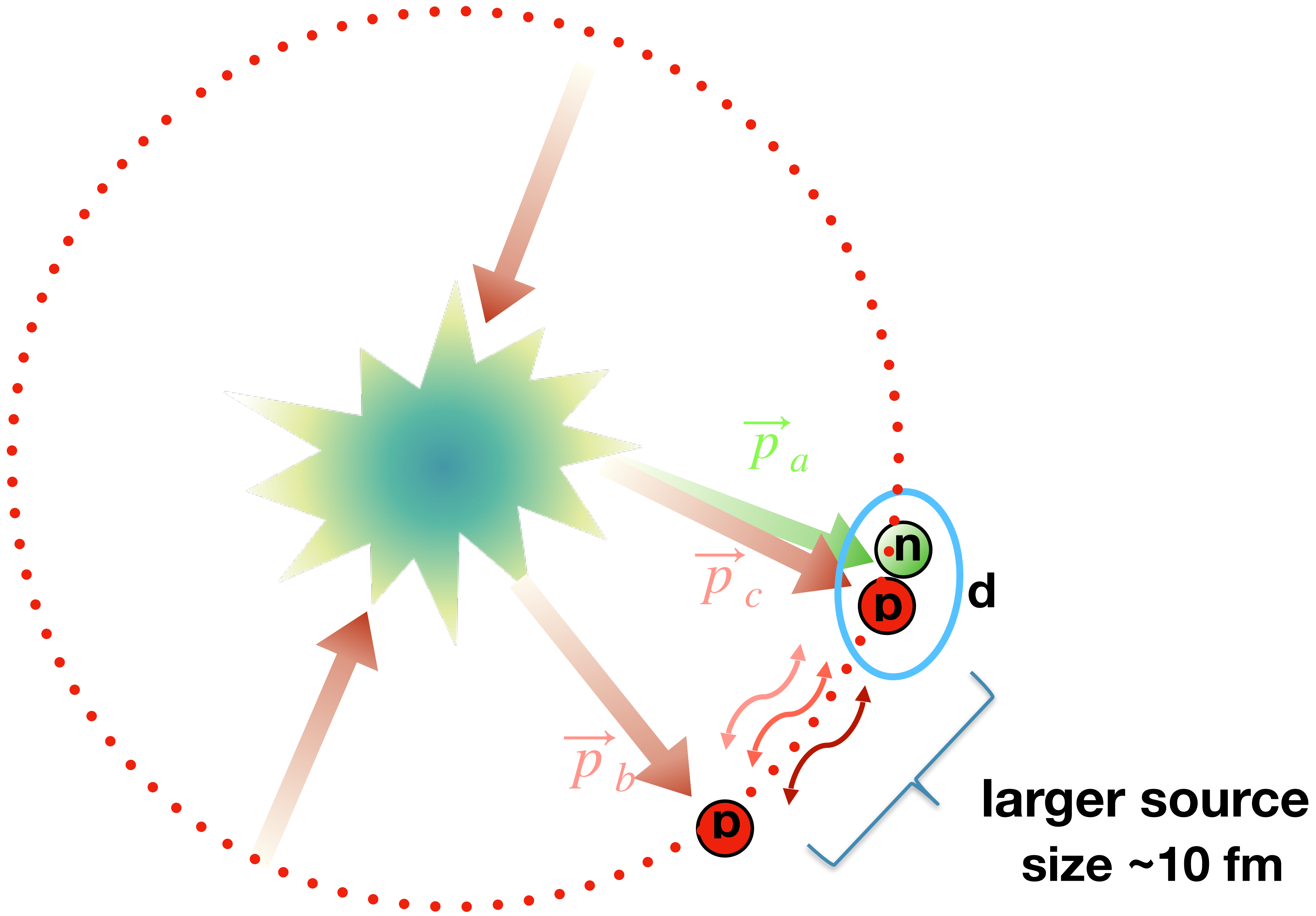
What if the deuteron is formed later?

- Source size increases due to **late formation** of deuteron
  - As a result the measured interaction between proton and deuteron weakens

Case I : p and d are formed at the same time



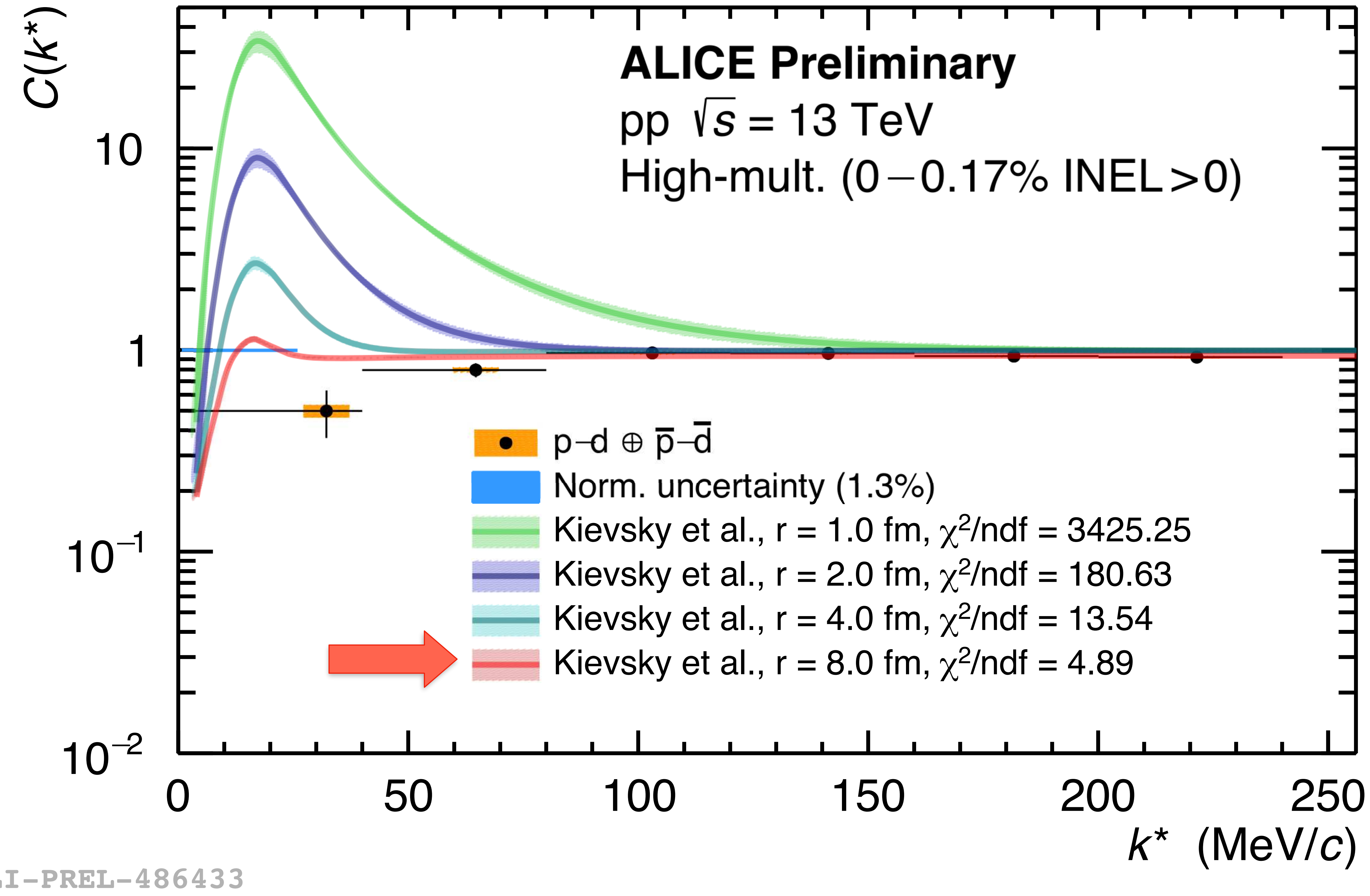
Case II : delayed formation of d



Delayed formation of deuteron(anti-deuteron)

- Improved agreement with larger source sizes
- CF becomes flat at larger source size
- The effect of attractive strong interaction in the CF is washed off

First time ever an indication of delayed formation of d(anti-d) in hadron-hadron collisions



A hint of ^{3}He formation?

- Improved agreement with larger source sizes
- CF becomes flat at larger source size
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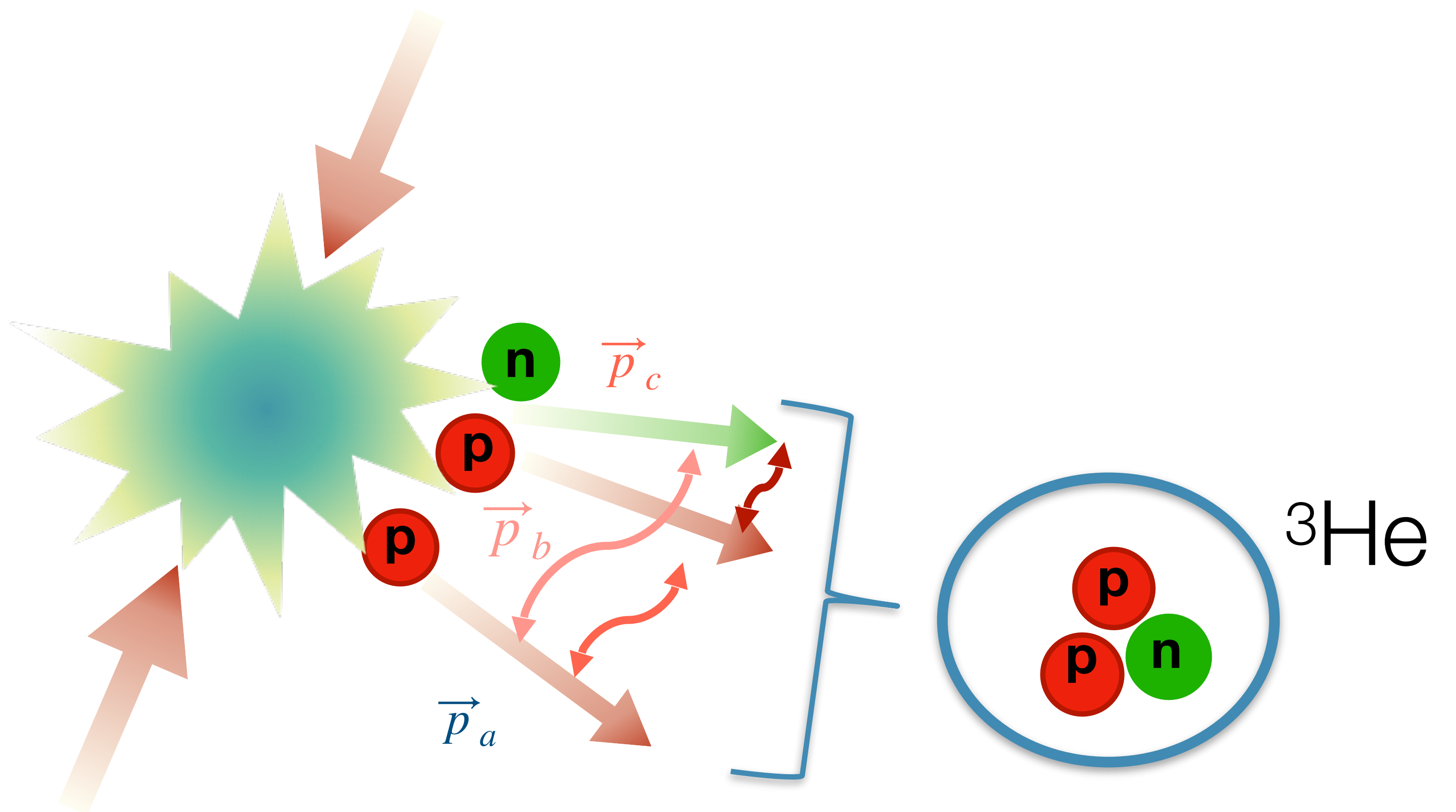
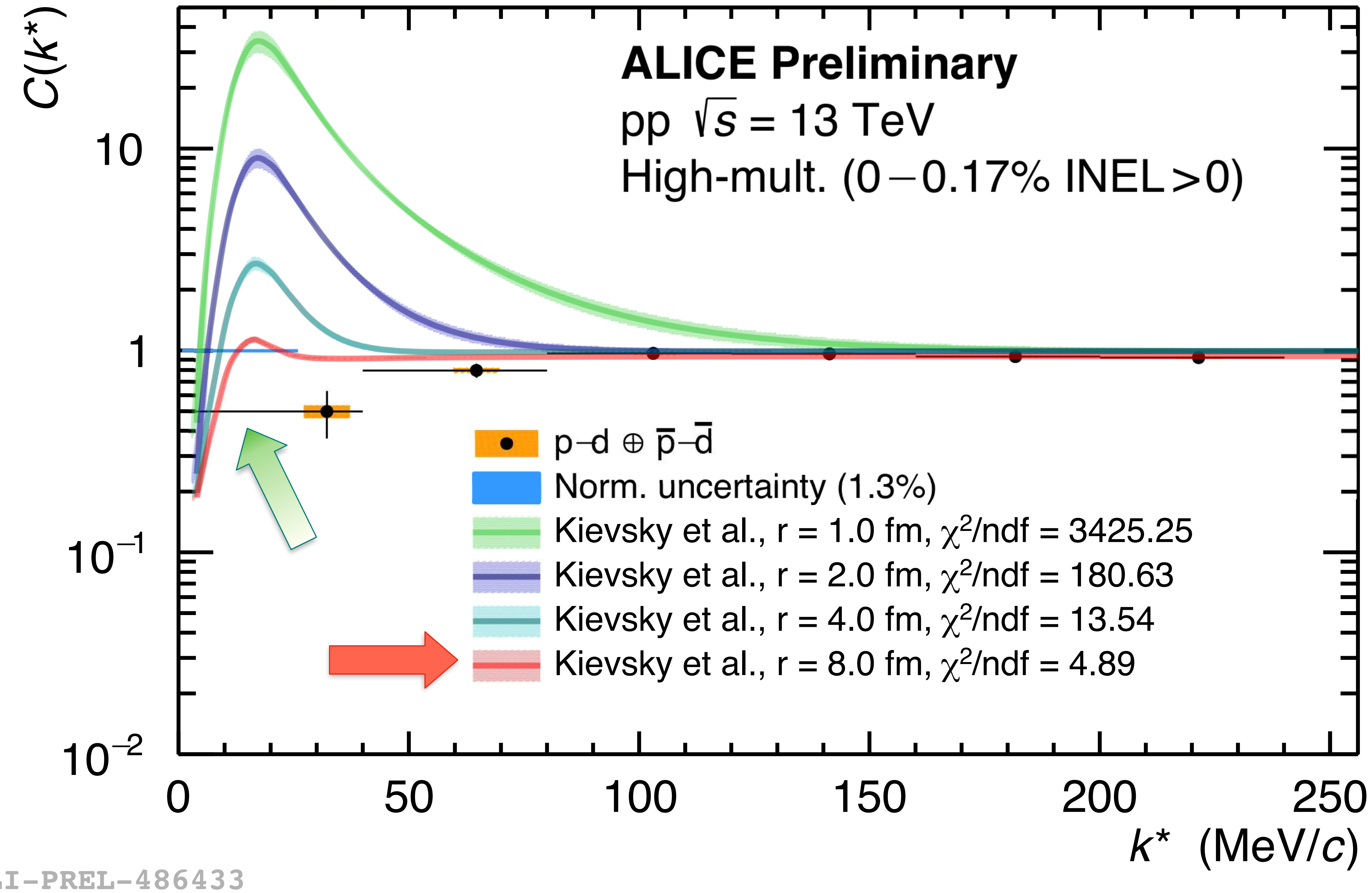
First time ever an indication of delayed formation of d(anti-d) in hadron-hadron collisions

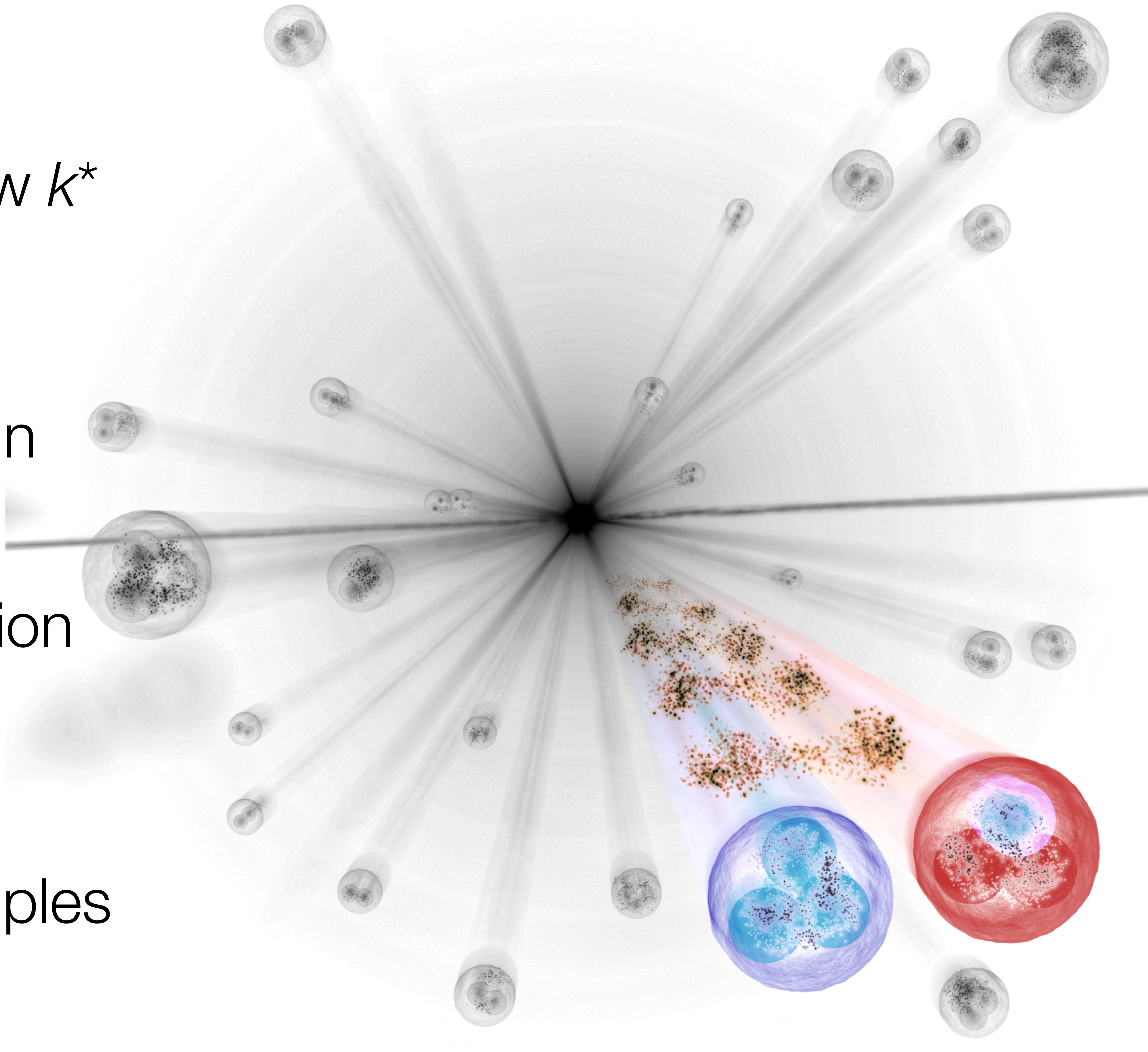
- Depletion at low k^*
  - Can be connected to ^{3}He formation





Summary & Outlook

- Summary:
  - First measurement of proton-deuteron correlations in high multiplicity pp collisions at $\sqrt{s}$ = 13 TeV
  - In contrast to the data, the models show a huge peak at low k^*
- Interpretation:
  - Demonstration of the late formation time of (anti)deuterons in hadron-hadron collisions
  - The observed depletion in CF could be a hint of ^{3}He formation
- Run 3 & Run 4:
  - More precision studies within reach with the large data samples



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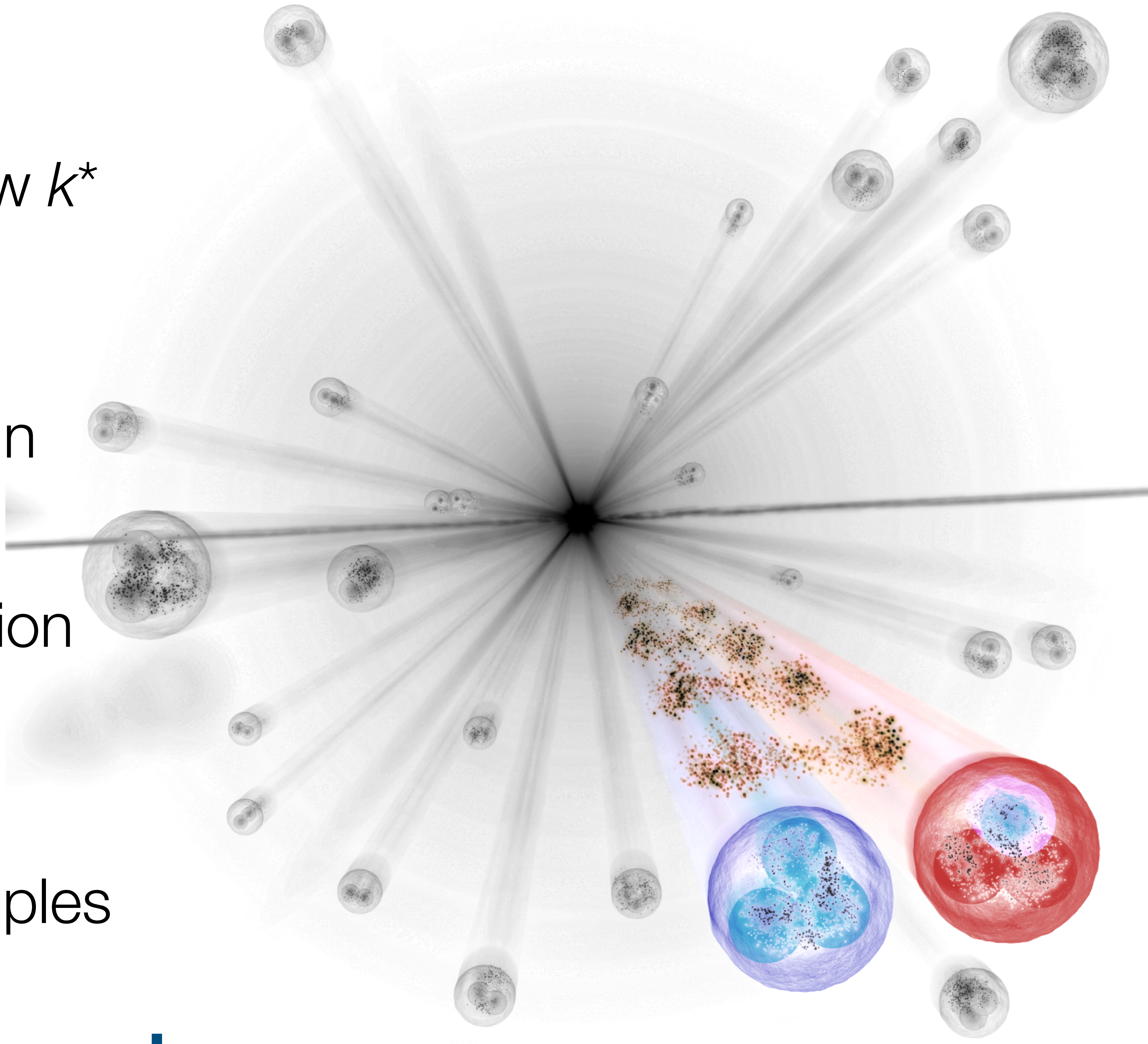


Thanks for your time!

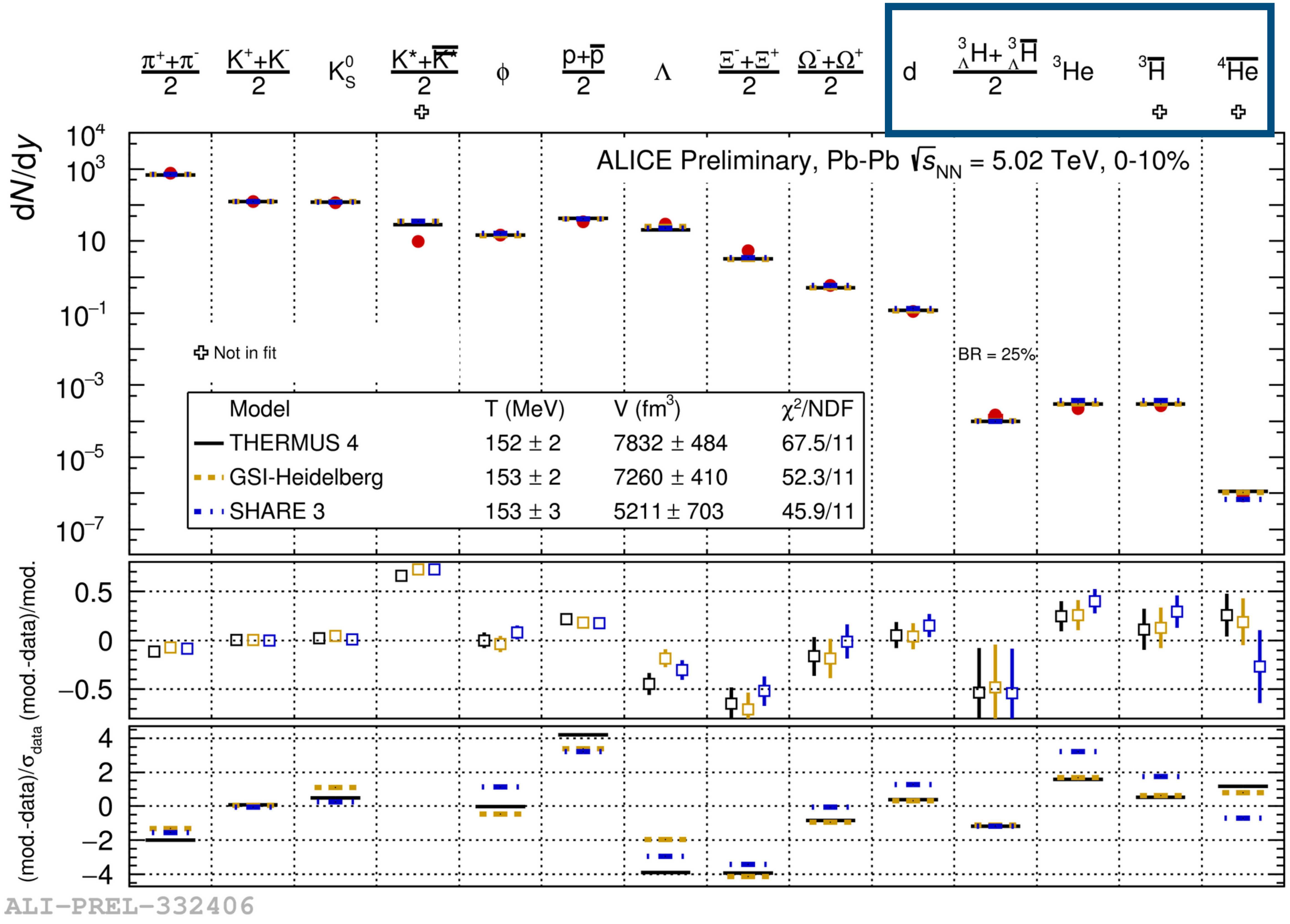
Additional slides

The Statistical Hadronisation Model (SHM)

- It assumes hadron abundances from **statistical equilibrium** at the **chemical freeze-out**
- The chemical freeze-out temperature (***T_{ch}***) is a key parameter:

$$\mathrm{d}N/\mathrm{d}y \propto \exp\left(-\frac{m}{T_{ch}}\right)$$

- Large reaction volume ($VT^3 > 1$) in Pb-Pb collisions
  - **grand canonical ensemble**
- Production yields **d*N*/dy** in central Pb-Pb collisions described over a wide range of d*N*/dy (**7 orders of magnitude**), including nuclei
- In **small systems** ($VT^3 < 1$) a local conservation of quantum numbers (*S*, *Q* and *B*) is necessary
  - **canonical ensemble**



The coalescence model

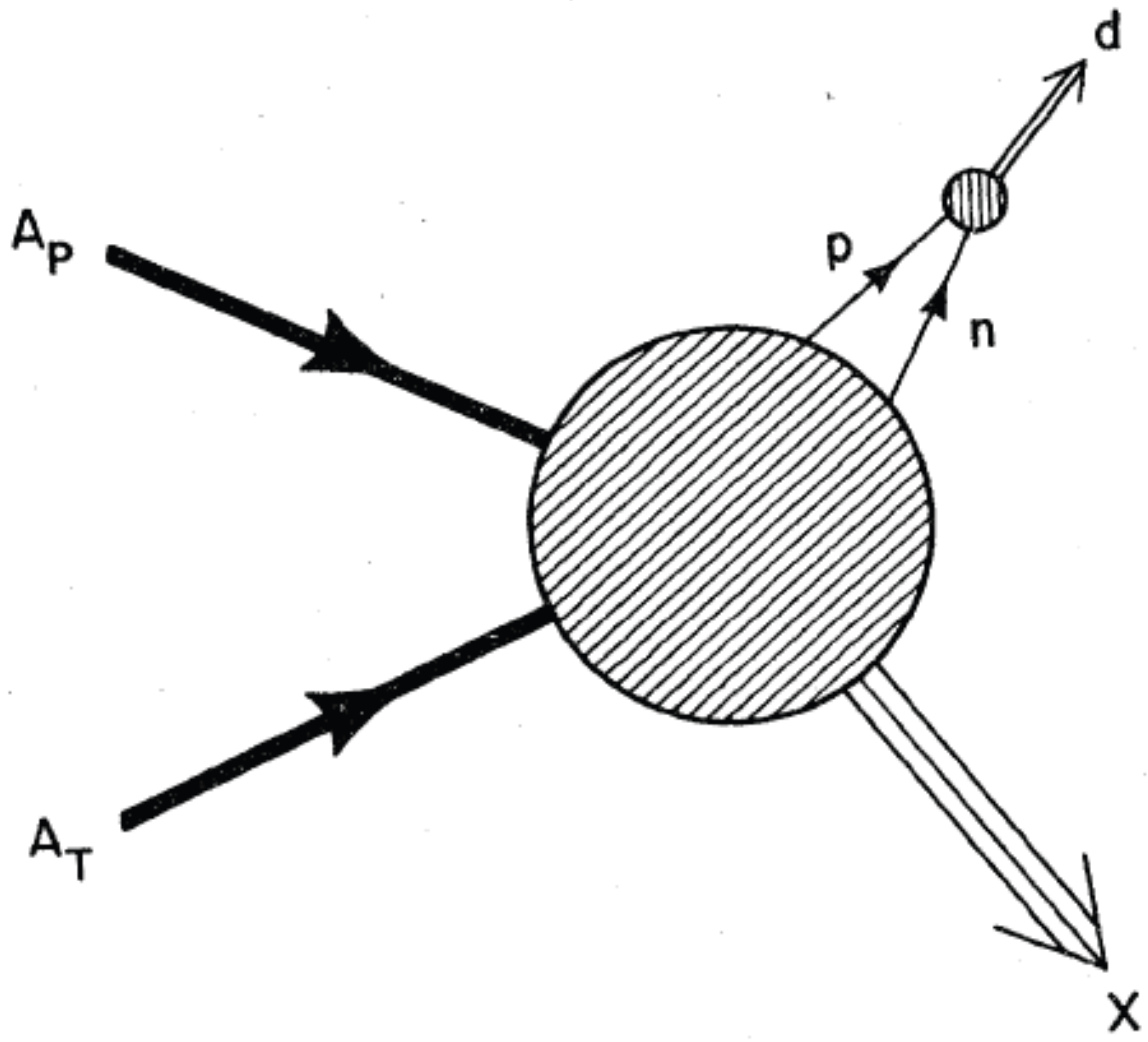
- Nucleons that are **close in the phase space** at the **freeze-out** can form a nucleus via **coalescence**
- The key concept is the overlap between the **nucleus wave-function** and the **phase space** of the **nucleons**
- The main parameter of the coalescence is the $\boldsymbol{B_A}$, defined as:

$$B_A = \frac{E_A \frac{d^3 N_A}{d^3 p_A}}{\left(E_p \frac{d^3 N_p}{d^3 p_p} \right)^A}$$

where:

- A is the mass number of the nucleus
- $p_p = p_A / A$

- $\boldsymbol{B_A}$ is related to the **probability** to form a nucleus via coalescence



J. I. Kapusta, Phys. Rev. C21, 1301 (1980)

The ALICE experiment

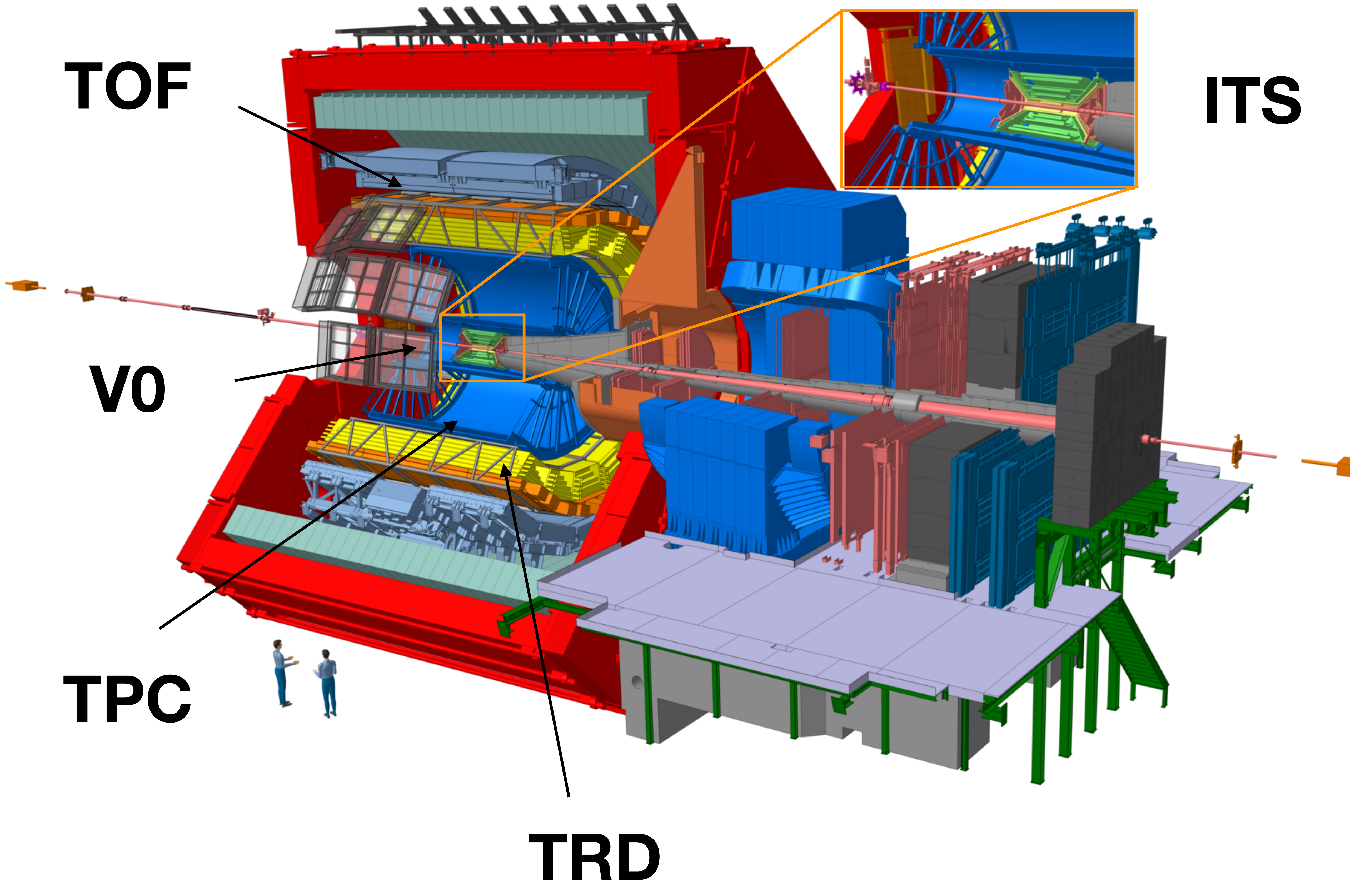
- General purpose heavy-ion experiment
  - 19 different sub-systems
  - Excellent particle identification (**PID**)
  - Most suited LHC experiment for studying the production of nuclei

Inner **T**racking **S**ystem

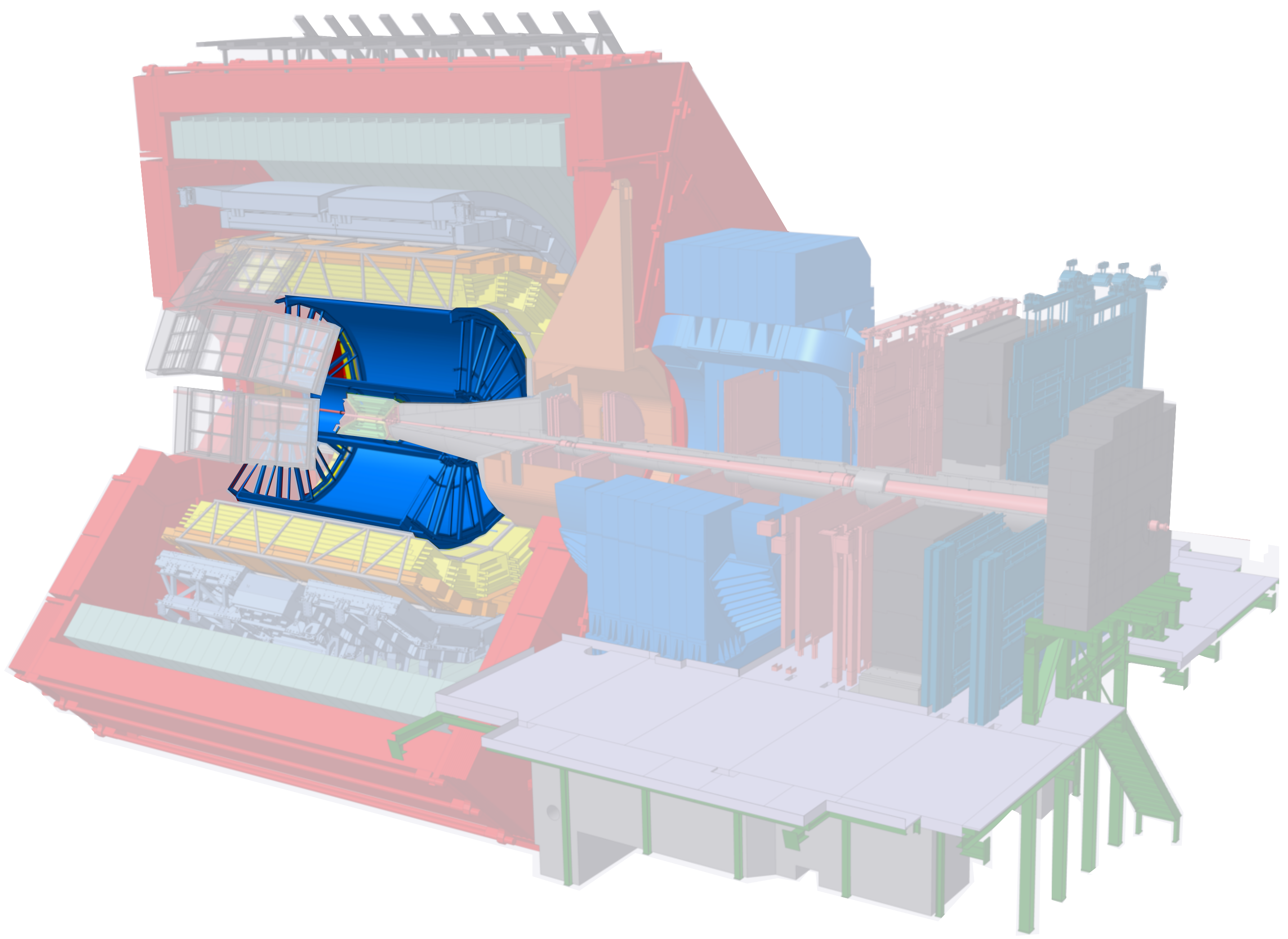
- **Tracking** and **Vertex** reconstruction
- $\boldsymbol{\sigma_{DCA_{xy}}}$ **< 100 µm** for p_{T} > 0.5 GeV/c in p-p
  - Separation of **primary** and **secondary nuclei** (coming from material knock-out)
  - Separation of **primary** and **secondary vertices**

V0

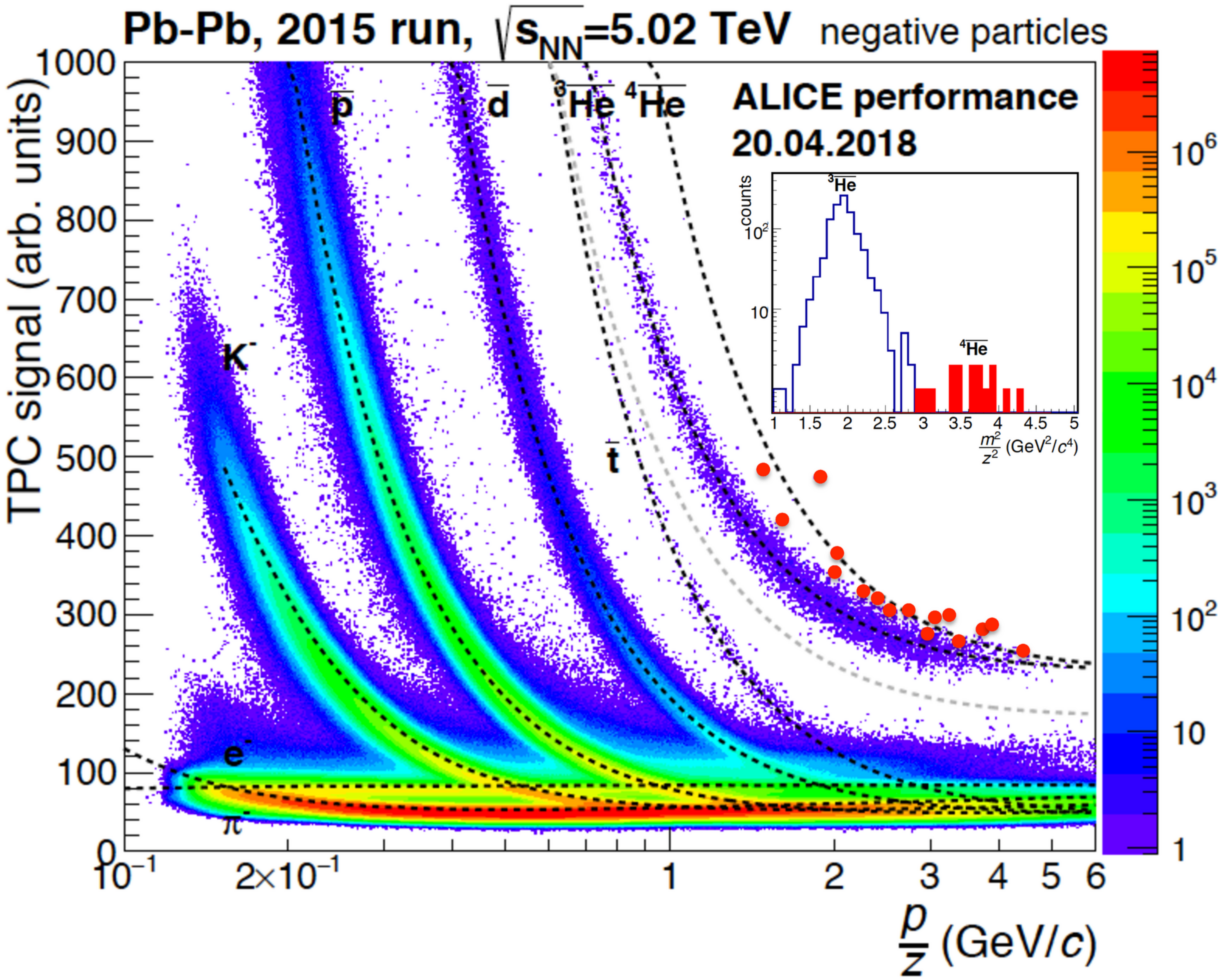
- **Multiplicity/centrality** determination



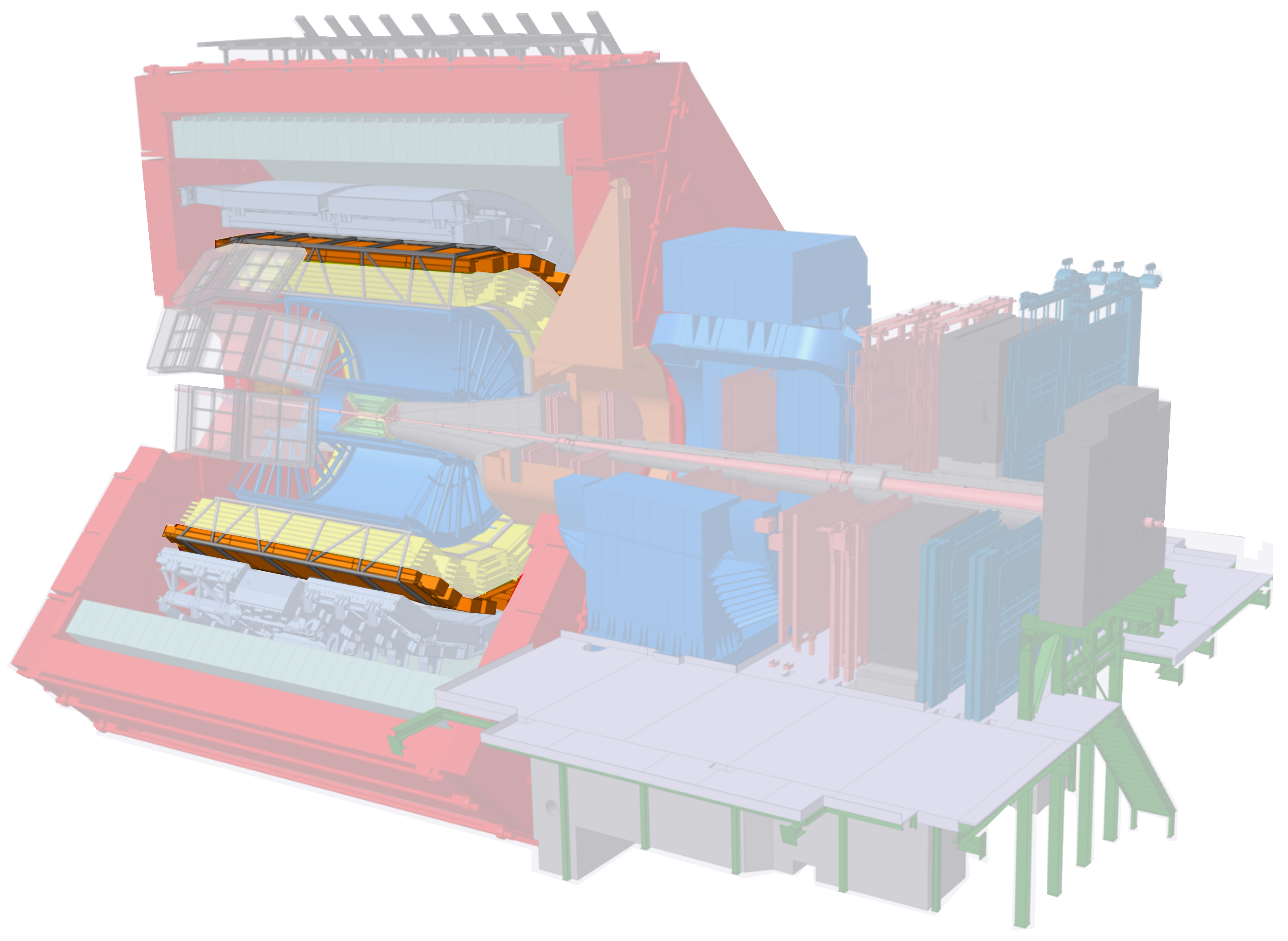
PID with the Time Projection Chamber

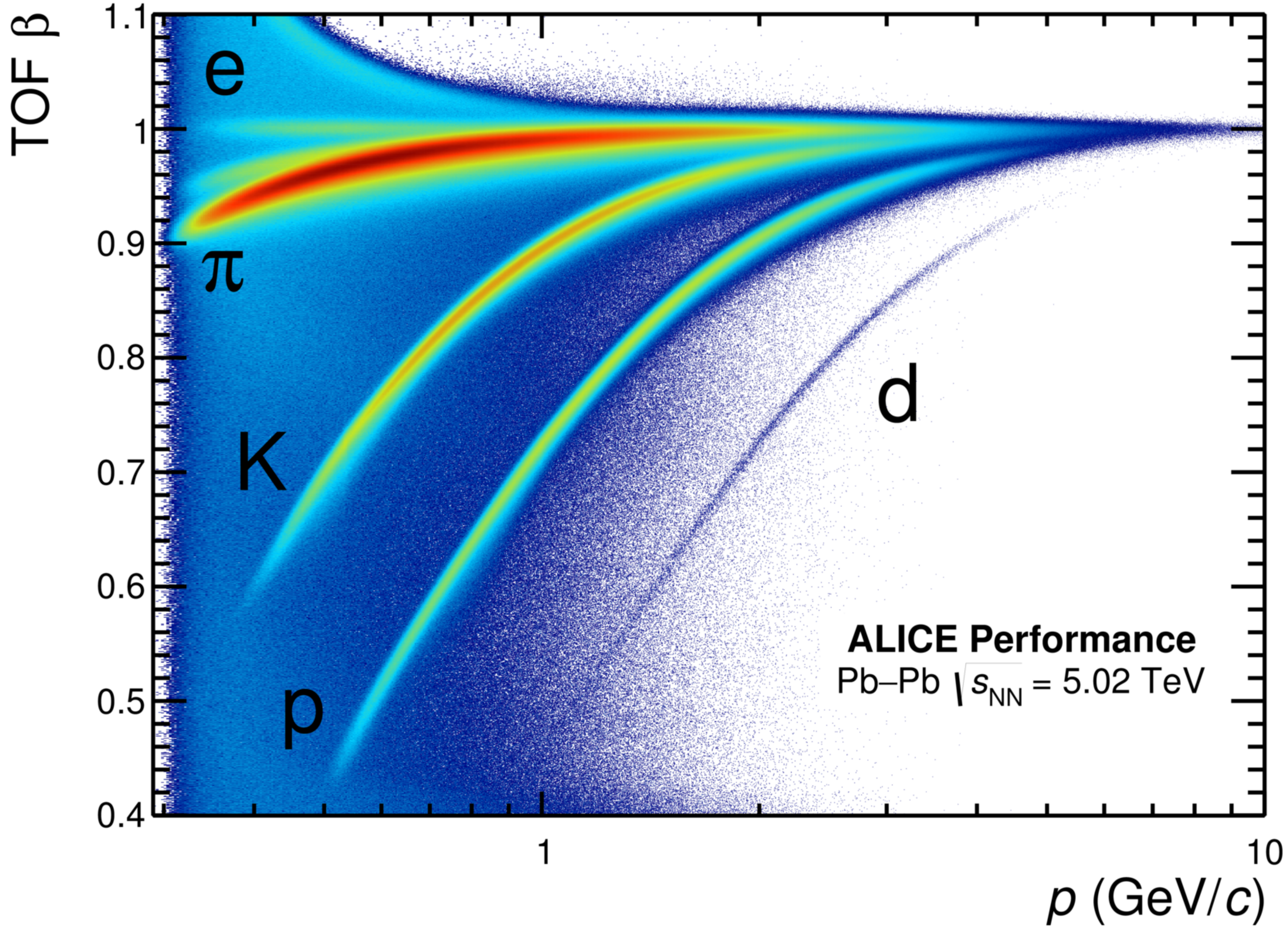


- **Tracking**
- **PID** via **d*E*/dx** measurement
  - $\sigma_{dE/dx}$ ~ **5.5%** (in pp collisions)
  - $\sigma_{dE/dx}$ ~ **7%** (in Pb-Pb collisions)
- deuteron and p are well separated



PID with the Time Of Flight





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- **PID** via **β** measurement
  - **$\sigma_{TOF\text{-}PID}$ ~ 60 ps** in **Pb-Pb** collisions
  - **$\sigma_{TOF\text{-}PID}$ ~ 70 ps** in **pp** collisions (lower precision on event collision time)

Femtoscopic correlation

- The femtoscopic correlation may have background/contributions from
  - Particles from weak decays
  - Particles from material knock-outs
  - Misidentifications

$$C_{femto}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \ldots$$

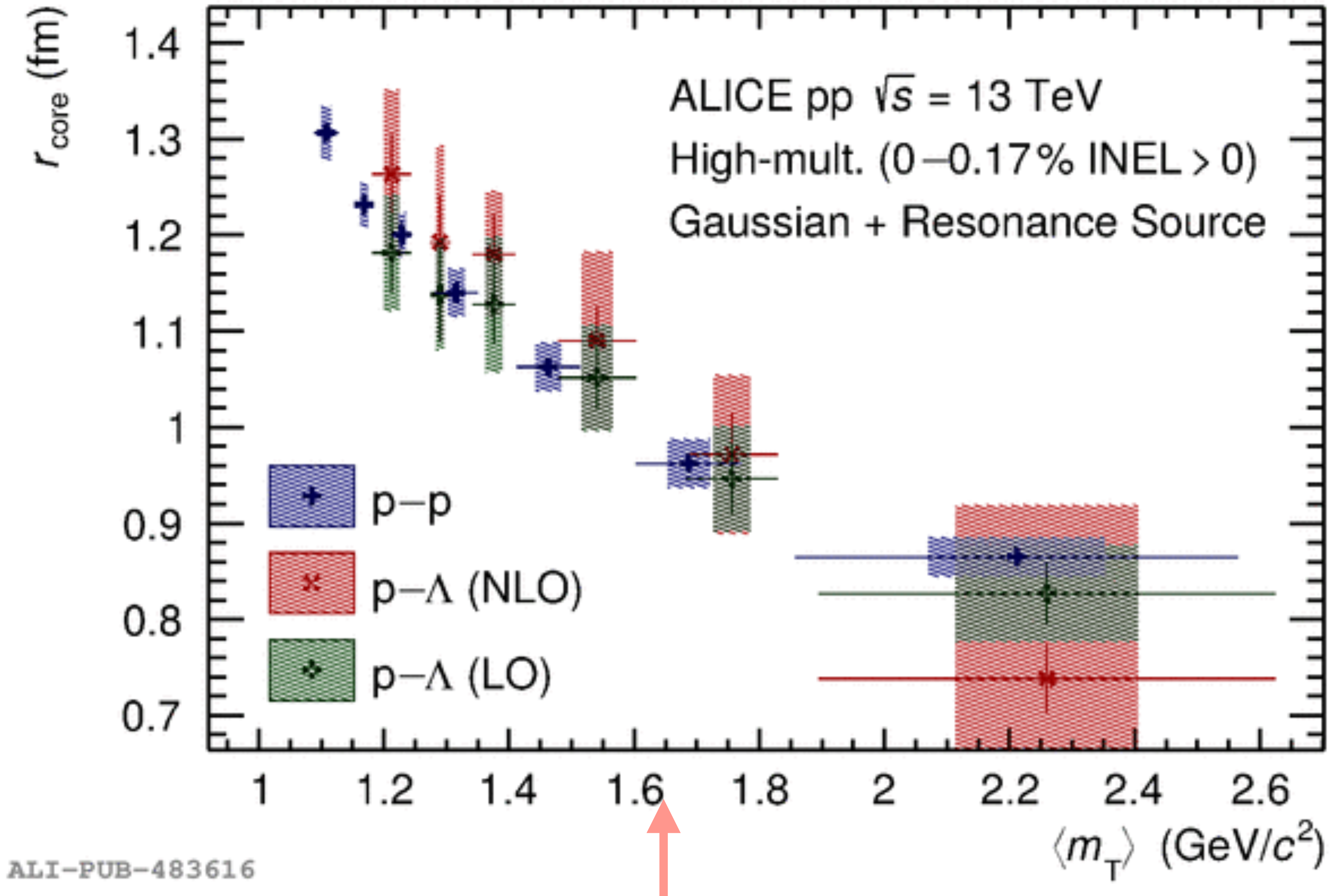
Contributions from: genuine feed-down misidentifications

- Quantification of the contributions to the pairs done by the lambda parameters $\lambda_{ij} = \mathscr{P}_i . f_i \times \mathscr{P}_j . f_j$
  - Purity of the individual particles ($\mathscr{P}_i$)
  - Feed-down fractions (f_i)

The source

- Particle emission from **Gaussian core** source
- Short-lived strongly decaying resonances ($c\tau \approx r_{core}$) effectively increase the source radius
- e.g. Δ-resonances in case of protons
- Universal source model*
  - $\boldsymbol{r_{core}}$ fixed for each pair based on $\langle m_T \rangle$
  - Particle-specific resonances are added to the core
- Small effective source gives rise to pronounced correlation signal

Source size	p-d
r_{core} [fm]	0.99±0.04
r_{eff} [fm]	1.07±0.04

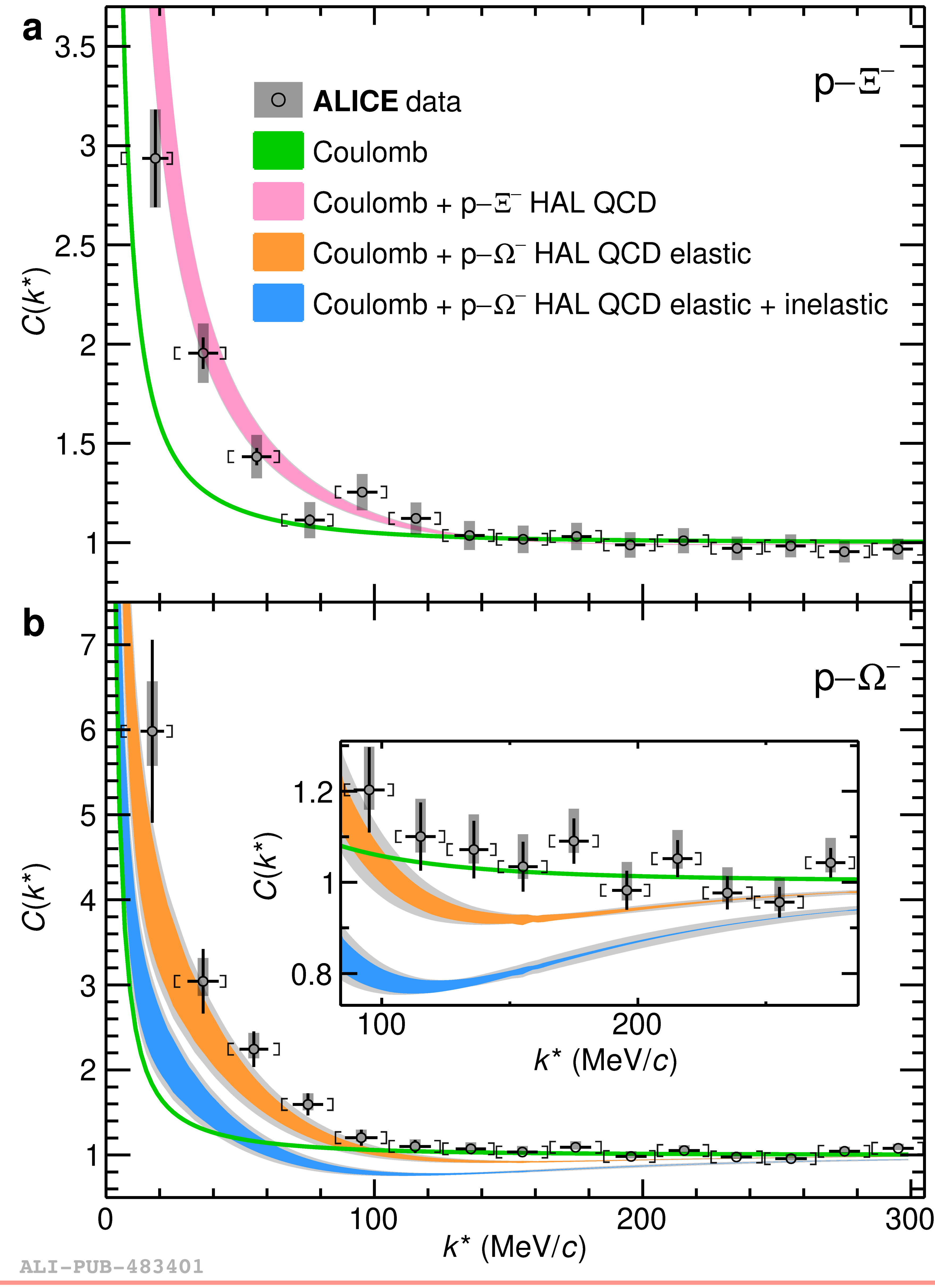


$\langle m_{T,\mathbf{p\text{-}d}} \rangle$ = 1.651 GeV/c²

(*) ALICE Collab., *Physics Letters B*, 811(2020) 135849

|S|=2,3 sector: p-Ξ^- and p-Ω interaction and first test of LQCD

- Observation of the strong interaction beyond Coulomb
- Agreement with lattice calculations confirmed in pp and p-Pb colliding systems
- **At finite density HAL QCD potentials predict in PNM a slightly repulsive U_Ξ ~+6 MeV(*) → stiffening of the EoS**

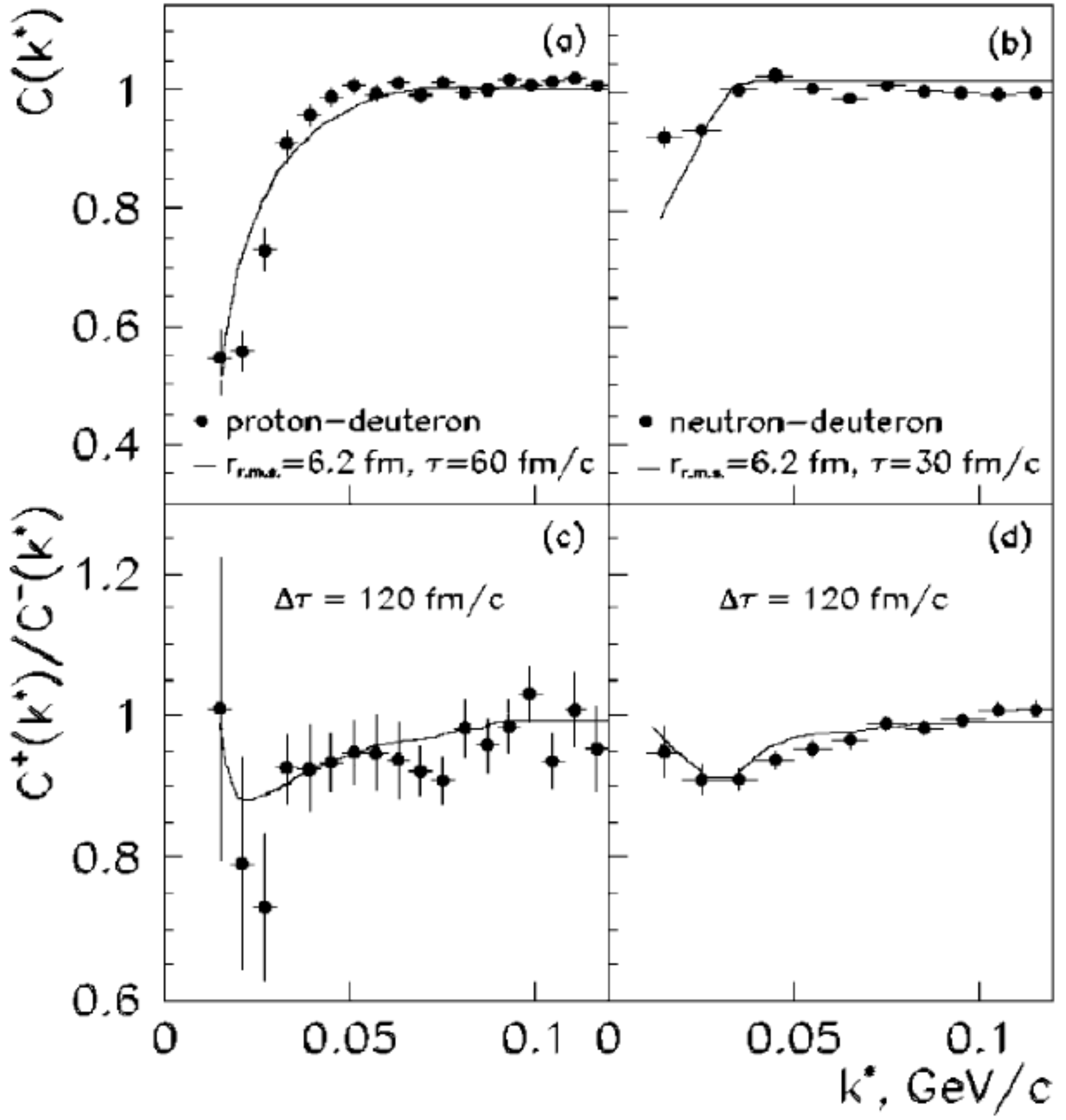


(*) HAL QCD Coll., PoS INPC2016 (2016)

277 ALICE Coll. Nature 588, 232–238 (2020)

proton-deuteron correlation measurement so far

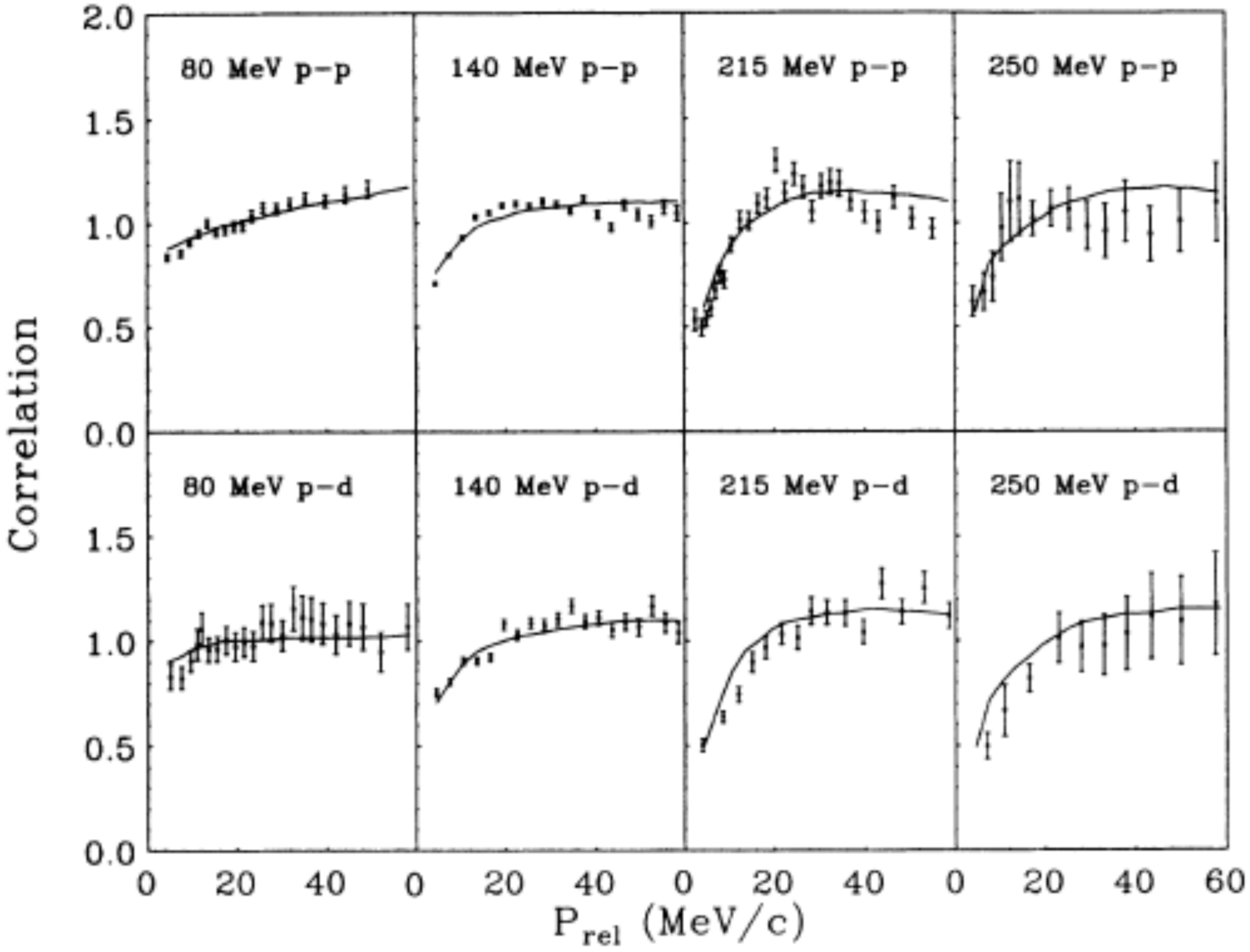
- **Status**:
  - p-d correlation function from 2006
  - GANIL(Grand Accélérateur National d'Ions Lourds):
    - ^{40}Ar-^{58}Ni reaction at 77 MeV/u
    - Show a clear depletion
    - Only unto 100 MeV/c in relative momentum



[1] Wosińska, K., Pluta, J., Hanappe, F. *et al. Eur. Phys. J. A* 32, 55–59 (2007)

proton-deuteron correlation measurement so far

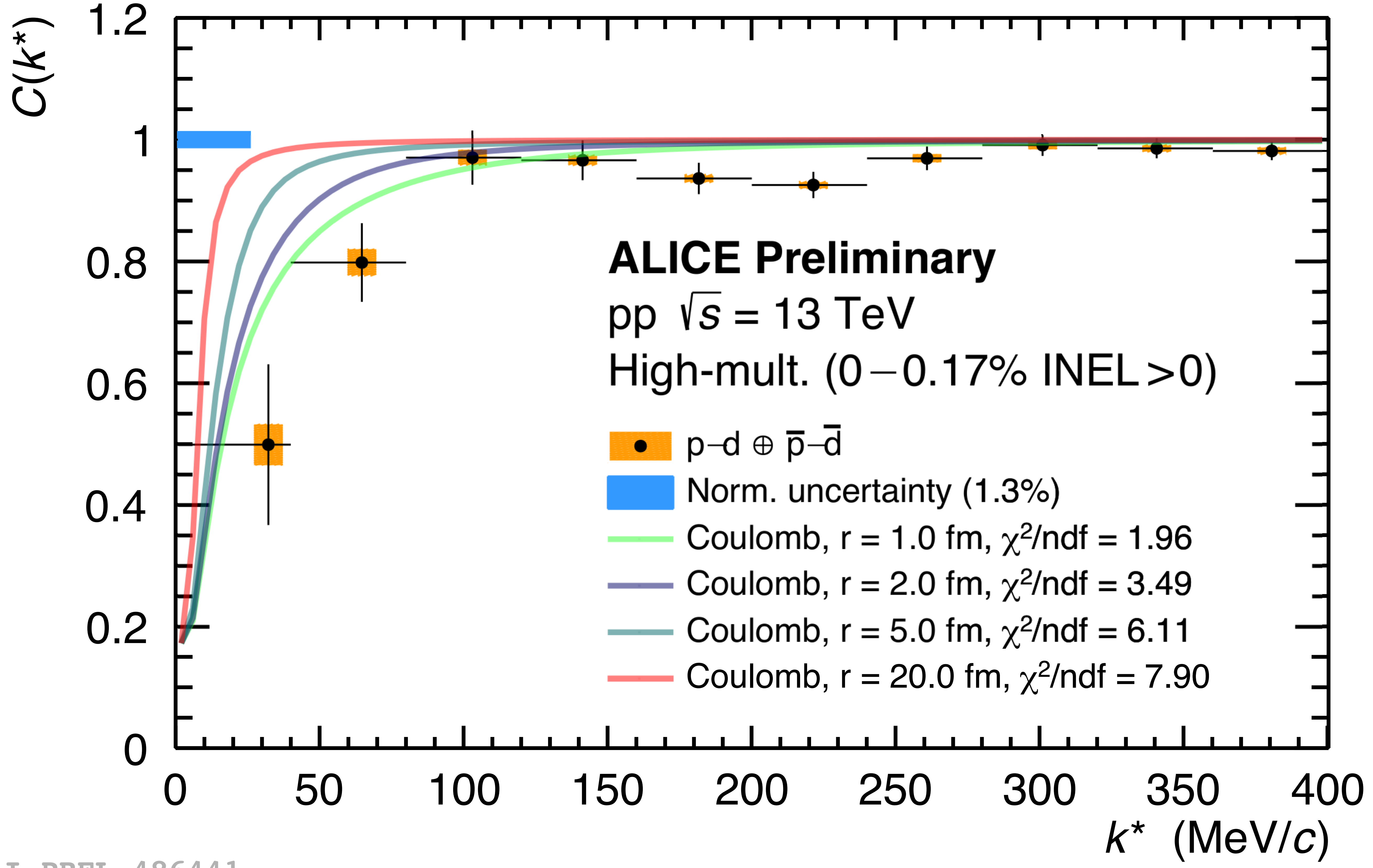
- **Status**: Measurement by *P. A. DeYoung et al* in 1990
  - Measurements for 80 and 140 MeV/c ^{16}O - ^{27}Al reaction were performed at the Stony Brook Linac
  - Measurements for 215 and 250 MeV/c ^{16}O - ^{27}Al reaction were performed at the ATLAS facility of the Argonne National Laboratory.
  - In the relative momentum range [0-60] MeV/c
  - Show a clear depletion
  - Solid line coulomb prediction from Koonin model



P. A. DeYoung et al. PRC ***41,*** *R1885* (1990)

Theoretical models and data

- Coulomb-corrected wave function for charged particles Lednický, R. *Phys. Part. Nuclei* 40, 307–352 (2009)
  - Coulomb + strong interaction (S = 1/2 and S = 3/2)
  - Only for s wave interaction
  - Theoretical models constrained to scattering p—d experiments
  - Coulomb-interaction only does not describe the data



ALI-PREL-486441

Proton-deuteron correlation

- Proton-deuteron correlations using Coulomb-corrected wave functions:
  - Source size: 1.073 fm
  - Published scattering lengths for p-d listed in the table

Ref	Quartet $^4S_{3/2}$	Doublet $^2S_{1/2}$
Oers, Brockmann et al.(1967)	$11.4^{+1.8}_{-1.2}$	$1.2^{+0.2}_{-0.2}$
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Kievsky et al.(1997)	13.8	0.024
Black et al. (1999)	$14.7^{+2.3}_{-2.3}$	$-0.13^{+0.04}_{-0.04}$

  - The contributions from quartet and doublet channel are added with ⅔ and ⅓ spin weights
  - The calculation shows a very strong signature of attractive interaction in p-d system

Lednický model

- Coulomb-corrected wave function for final-state interactions (Lednický): arxiv.org/abs/nucl-th/0501065

$$\psi_{-k^*}(r^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-ik^*r^*}F\left(-i\eta,1,i\zeta\right)+f_c(k^*)\frac{\tilde{G}(\rho,\eta)}{r^*}\right]$$

  - f_c is the Coulomb-corrected strong scattering amplitude
  - $F(-i\eta,1,i\zeta)$ is the confluent hypergeometric function and $\tilde{G}(\rho,\eta)$ is the regular Coulomb function

- It is an approximated wave function for two near-threshold charged particles:

- The two-particle correlation: we can use Koonian-Pratt formula

$$C(k) = \int S(\mathbf{r}) \mid \psi_k(\mathbf{r}) \mid^2 \mathrm{d}^3 r, \quad \text{with source function} \quad S(r) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp\left(-\frac{r^2}{4r_0^2}\right)$$

Another calculation at hand

- Hadron-Deuteron Correlations and Production of Light Nuclei in Relativistic Heavy-Ion Collisions: arxiv.org/abs/1904.08320
  - hadron-deuteron correlation function which carries information about the source of the deuterons
  - Allows one to determine whether a deuteron is directly emitted from the fireball or if it is formed afterwards
  - Conclusion:
    - The theoretical p-d correlation function is strongly dependent on the source size

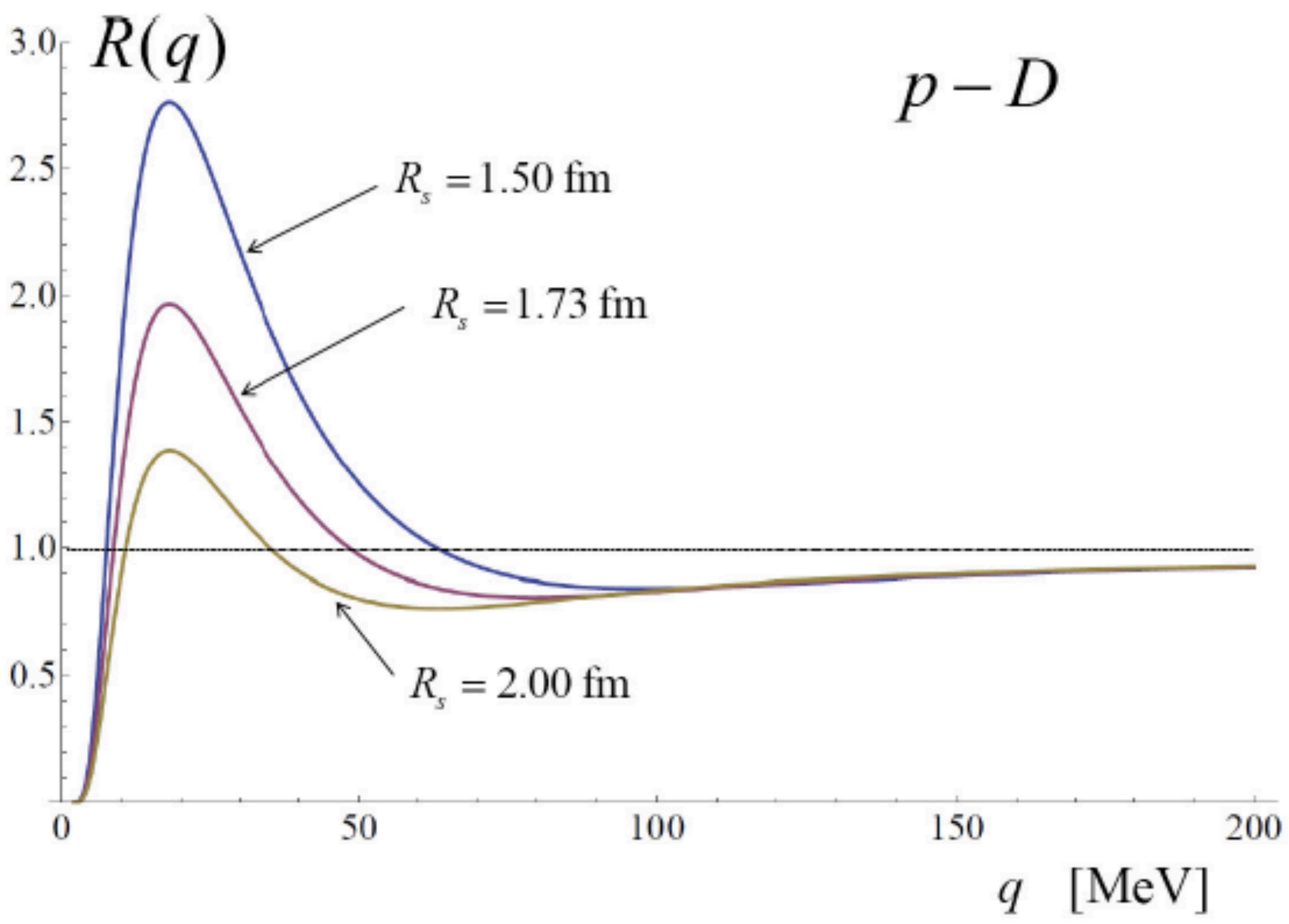

Fig. 2. $p-D$ correlation function