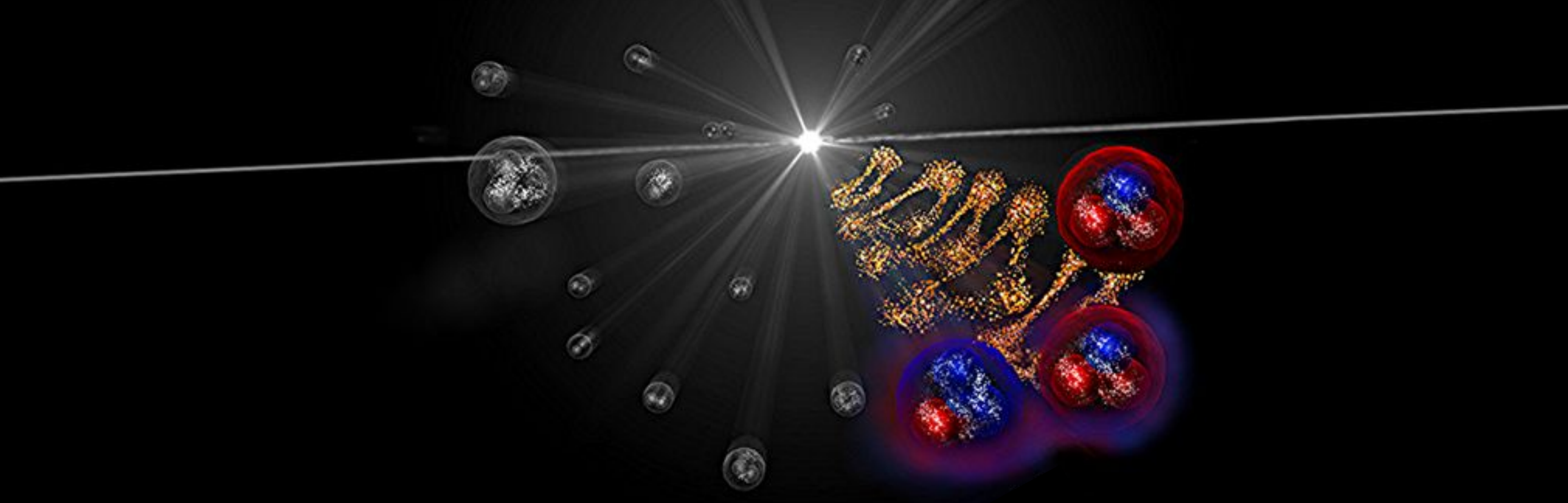
Study of the three-body dynamics at short range via femtoscopy by ALICE at the LHC

Otón Vázquez Doce (INFN - Frascati)



WPCF 2023 - XVI Workshop on Particle Correlations and Femtoscopy & IV Resonance Workshop.
Catania 6 - 10 Nov 2023.

Accessing three-body forces with femtoscopy

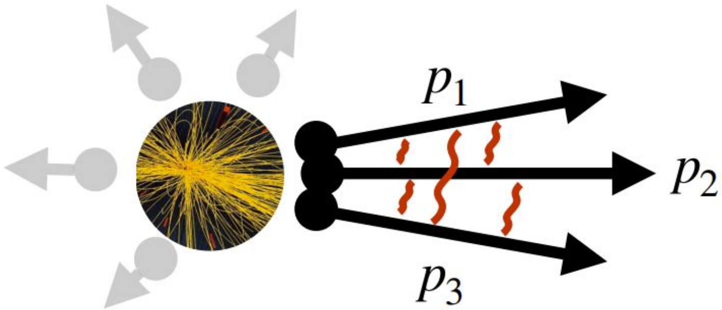
- Fundamental ingredient for the study of the nuclear structure
- Three-body forces necessary to describe properties of nuclei and hypernuclei

  S. C. Pieper, R. B. Wiringa, Ann. Rev. Nucl. Part. Sci. 51:53 (2001), K. Miyagawa et al., Phys. Rev. C 51, 2905 (1995)
- Relevant for dense nuclear matter and neutron stars

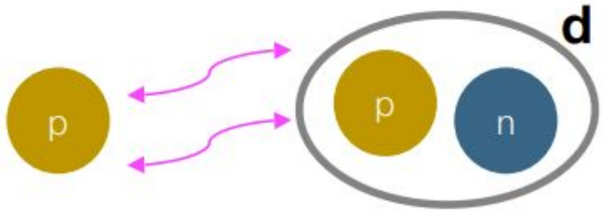
  D. Lonardoni et al., Phys. Rev. Lett. 114, 092301 (2015)
- Theory currently anchored to properties of nuclei, hypernuclei and scattering data

Femtoscopy studies can enable access to three-body systems:

three-body correlation function



hadron–deuteron correlation



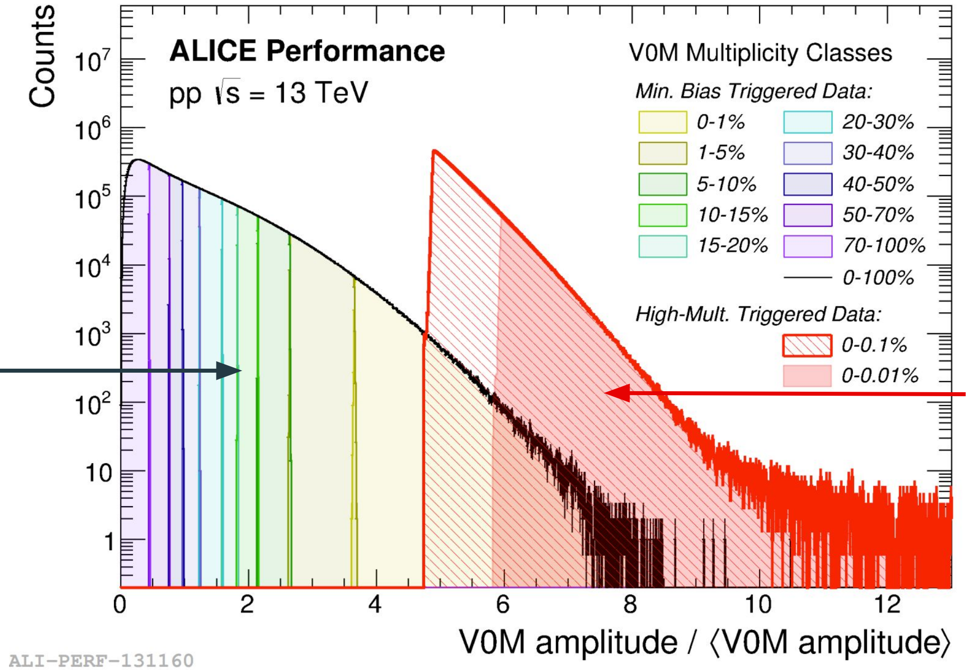
Femtoscopy in small systems with ALICE

Data sample from Run 2 (2015–2018)
- 1000 M events, **high-multiplicity (HM) pp collisions at 13 TeV**
- Strangeness production enhanced in HM events

ALICE Coll., Nature Physics, 13 535 (2017)

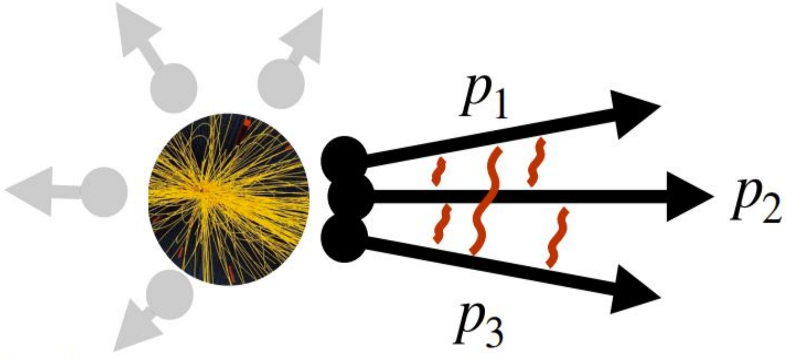
ALICE detector: Central barrel tracking and PID
- Reconstruction of **charged particles**: p, π, K, d
- **Hyperon reconstruction** through weak decays, purities >95%

minimum-bias events



high-multiplicity trigger trigger

Three-body femtoscopy



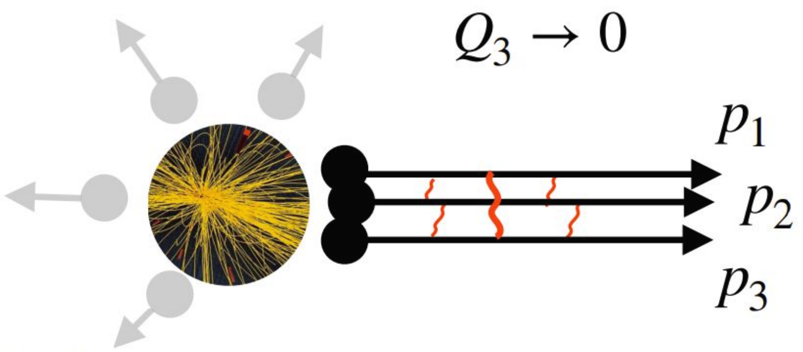
Three-particle correlation function:

$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1)\,P(\mathbf{p}_2)\,P(\mathbf{p}_3)} = \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

The Lorentz invariant Q_3 is defined as:

$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2} \qquad q_{ij}^{\mu} = (p_i - p_j)^{\mu} - \frac{(p_i - p_j)\cdot P_{ij}}{P_{ij}^2} P_{ij}^{\mu} \qquad P_{ij} \equiv p_i + p_j$$

Three-body femtoscopy



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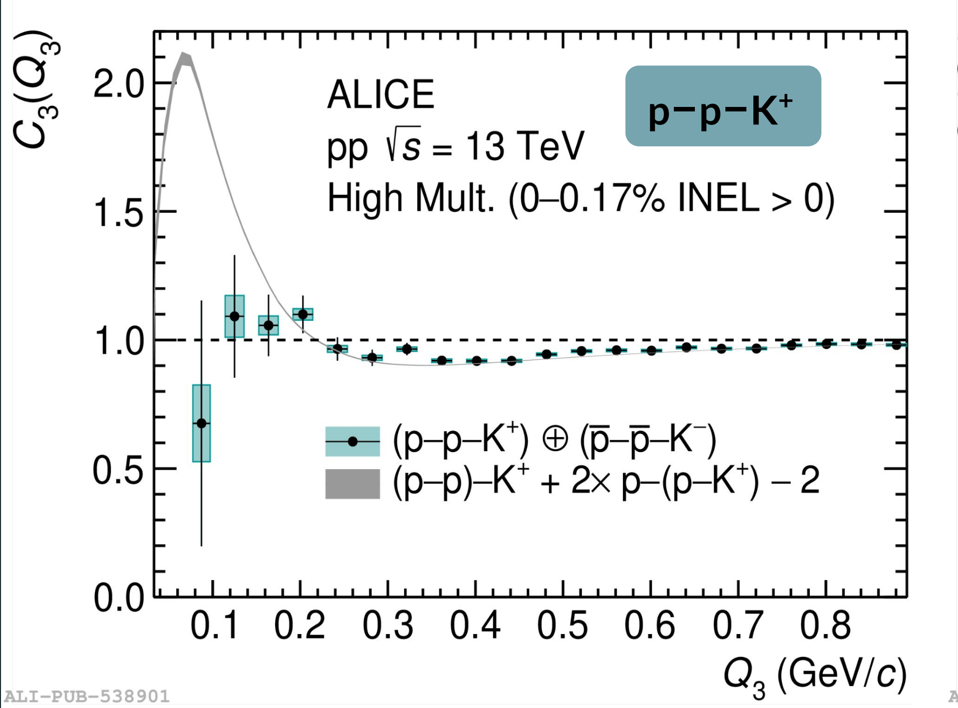
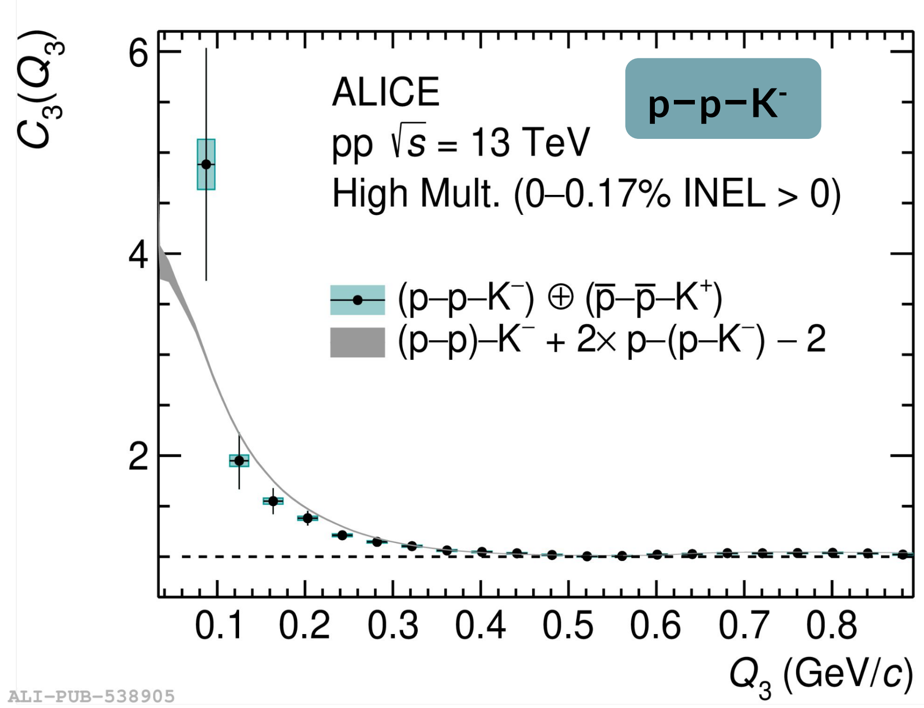
otonvd@cern.ch

Three-body correlation function

ALICE Coll.. arXiv:2303.13448[nucl-ex] EPJA in press.





p−p−K⁻: Importance of three-body effects for Kaonic nuclear states?

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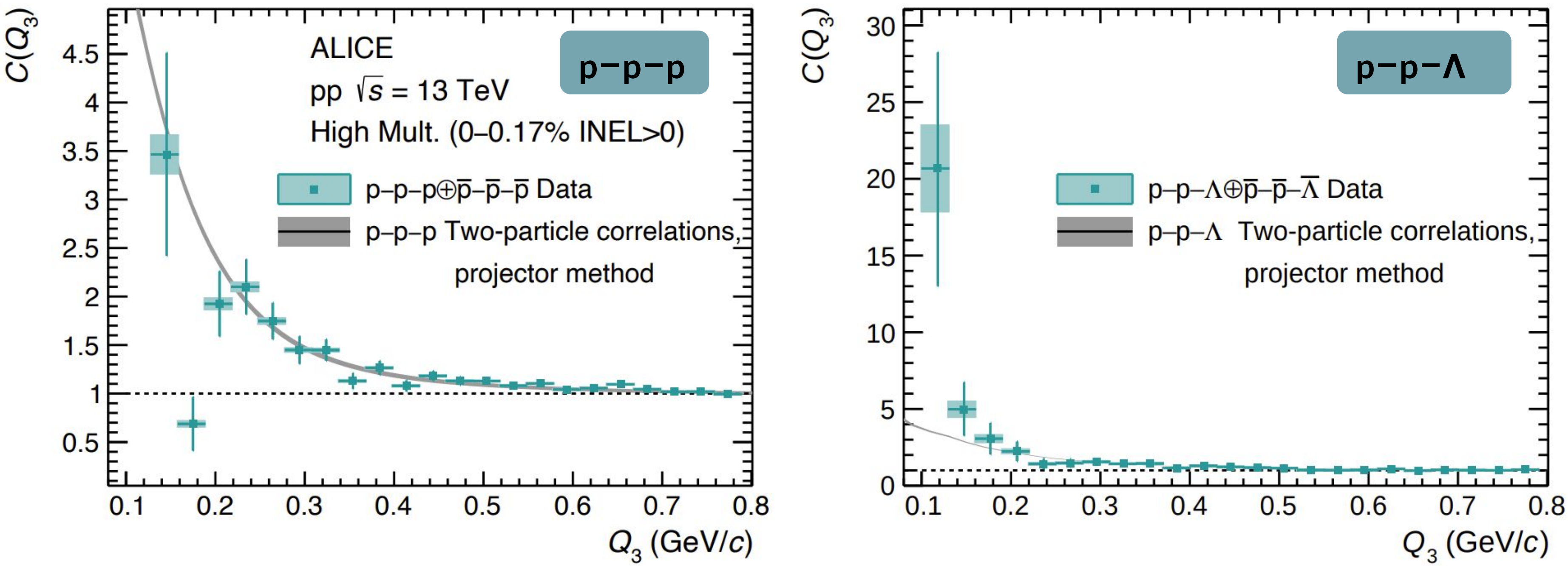
Three-body correlation function

ALICE Coll. Eur. Phys. J. A 59 (2023) 145



- Nuclear structure
- Neutron Stars and Equation of state

Gray band: projection of lower order (2-body) correlations

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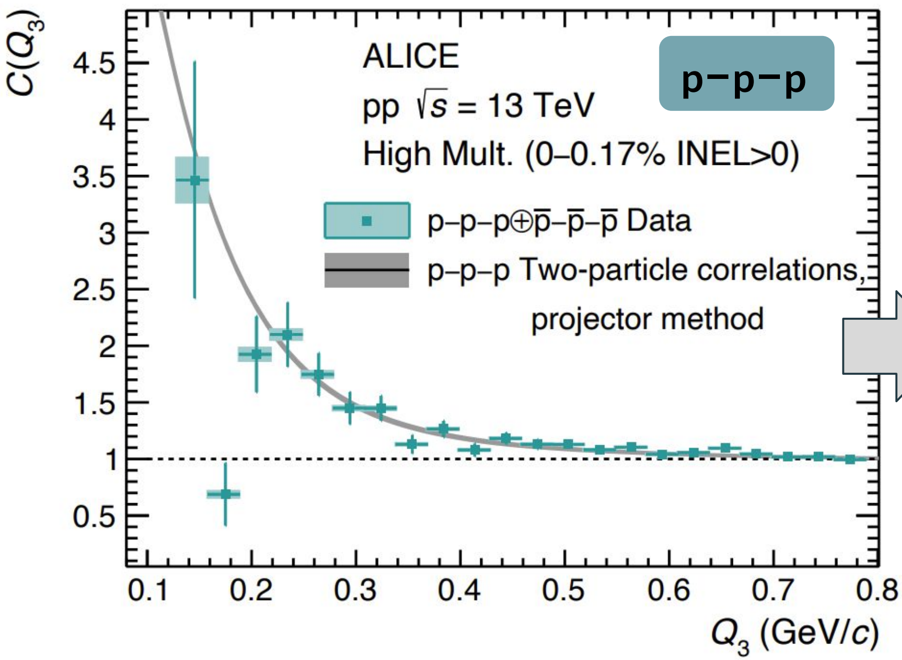
Three-body correlation function

ALICE Coll. Eur. Phys. J. A 59 (2023) 145



- Nuclear structure
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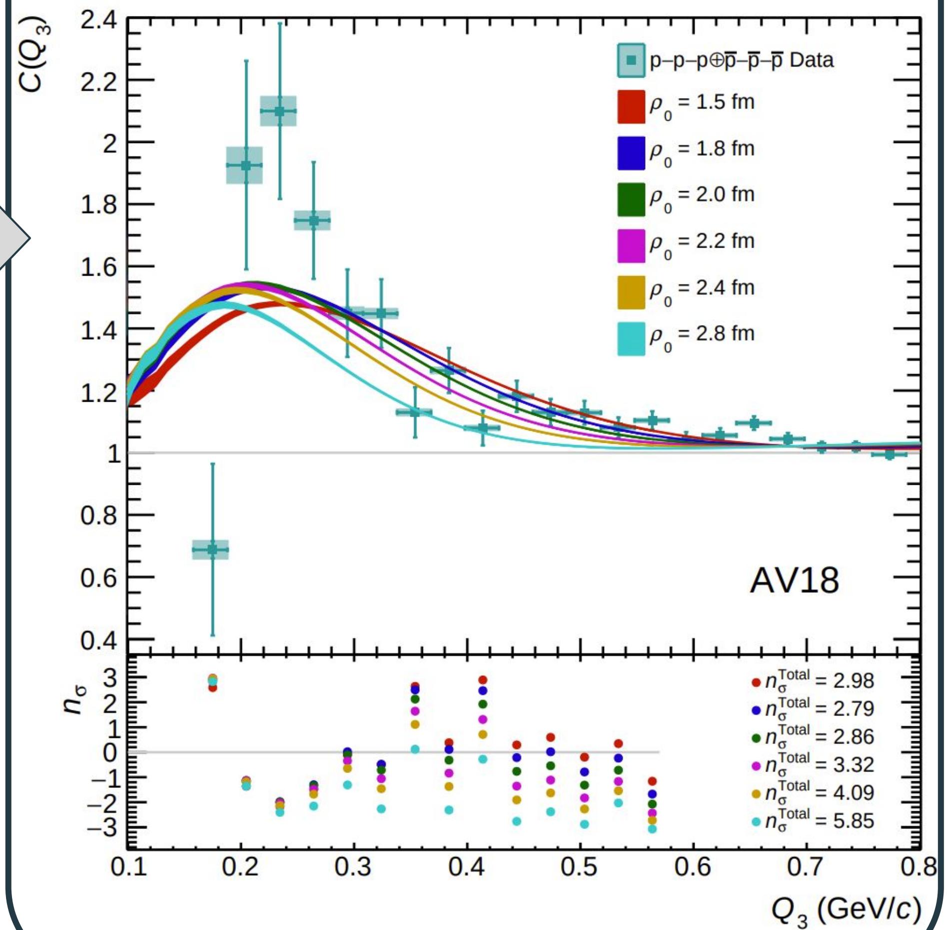
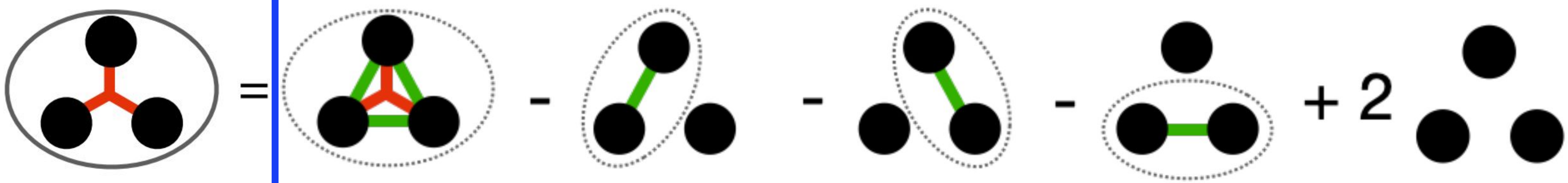
Gray band: projection of lower order (2-body) correlations

First calculation of the p-p-p correlation function

A. Kievsky et al., arXiv:2310.10428 [nucl-th]



Isolation of three-body effect: Cumulant



Cumulant

Measured: three-body correlation function

Lower-order correlations

R. Kubo, J. Phys. Soc. Jpn. 17, 1100 (1962)

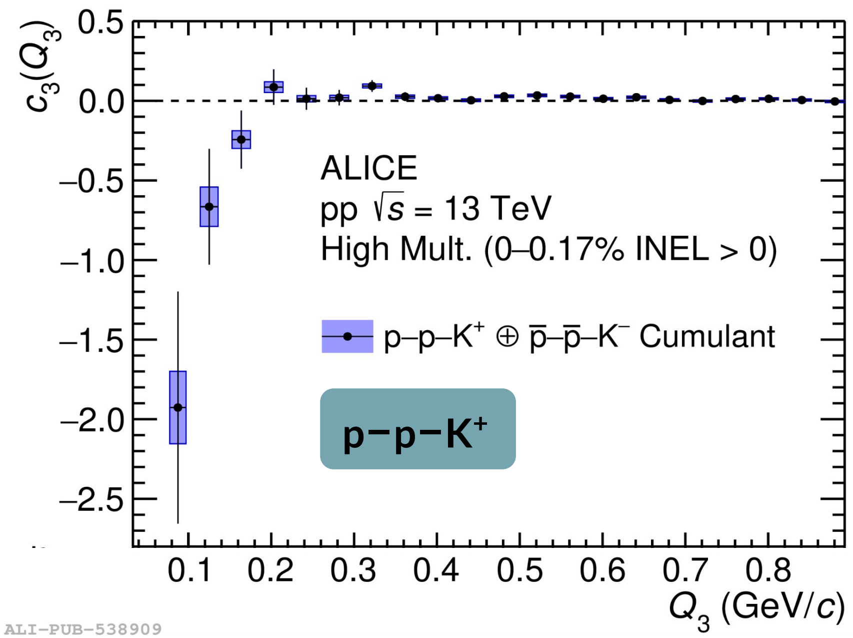
$$c_3(Q_3) = C(Q_3) - \left[C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2 \right]$$

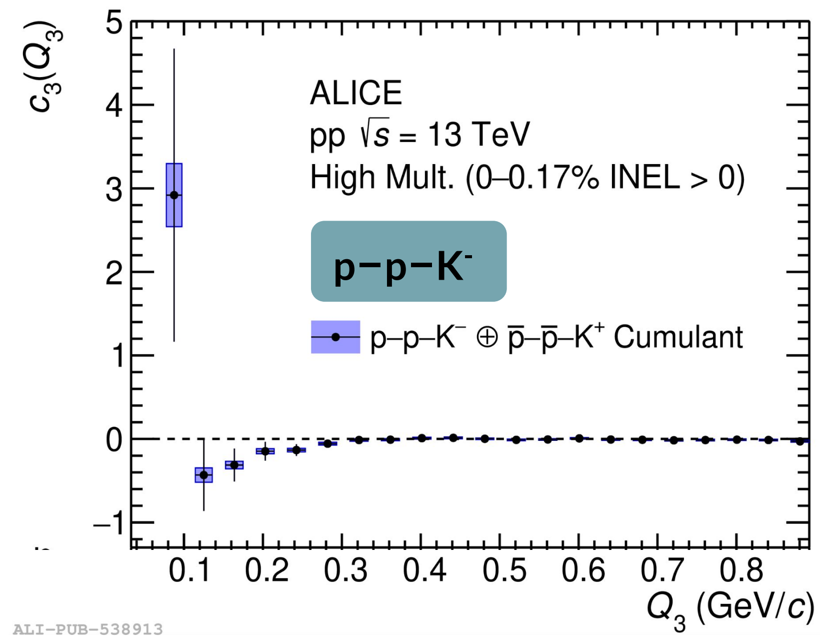
Two alternative methods to **obtain the lower-order correlations**

- Projector method: Project the measured two-particle correlation function on Q_3 using the kinematic transformation Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244
- Data-driven approach with mixed events

Three-body cumulant

ALICE Coll.. arXiv:2303.13448[nucl-ex] EPJA in press.



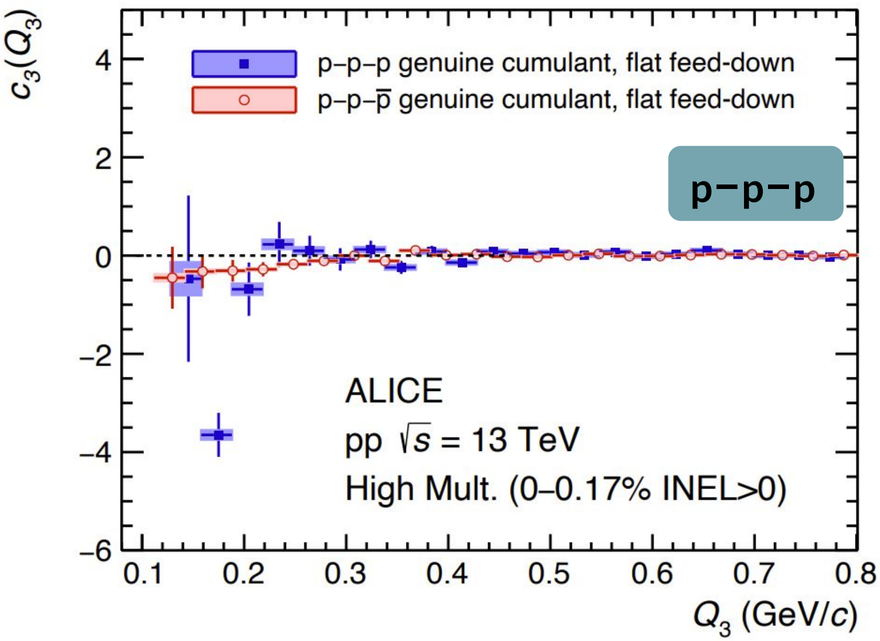


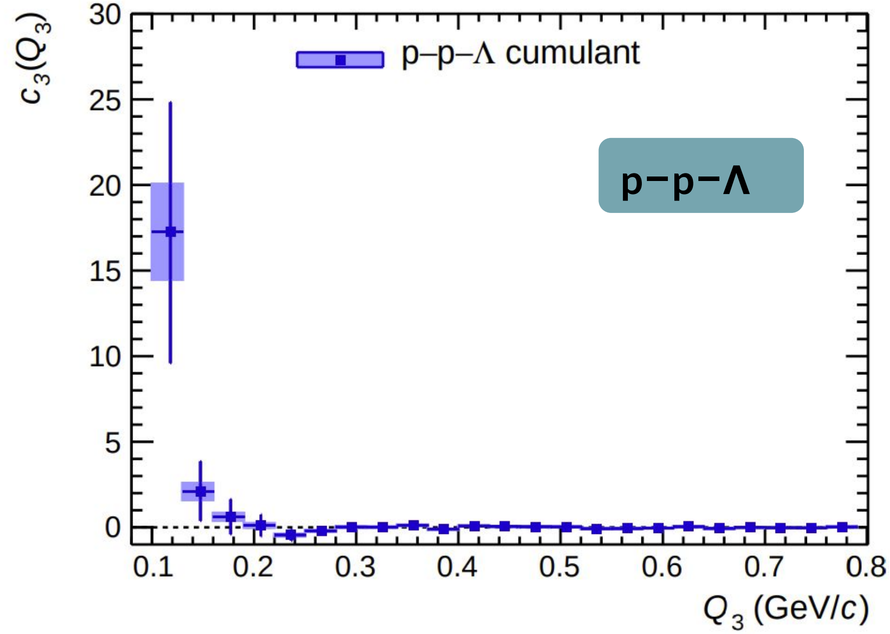
p−p−K$^+$ and p−p−K$^-$:

- No visible effect beyond 2-body interaction
- **p−p−K$^-$** measurement suggests negligible 3-body effects in the formation of kaonic clusters

Three-body cumulant

ALICE Coll. arXiv:2206.03344 EPJA in press (2022)





p−p−p: **Negative cumulant**. Statistical significance: n_σ=6.7 for Q_3< 0.4 GeV/c

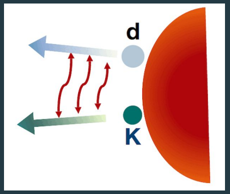
- Pauli blocking?
- **Test with mixed-charged particles, cumulant negligible**

p−p−Λ: No visible effects beyond 2-body interaction

Three-body correlation function analyses is statistics hungry

- **Run 3 and Run 4 (2022–2030): On-line trigger for ppΛ detected triplets**

Hadron-deuteron correlation function as a two-body system



K^+–d, p–d correlations measured by ALICE in pp HM collisions compared with theoretical expectation **considering deuteron as a point-like particle**

$$C(k^*) = \int \underbrace{S(\boldsymbol{r}^*)}_{\text{source}} \underbrace{|\psi(\boldsymbol{k}^*, \boldsymbol{r}^*)|^2}_{\text{wave function}} \, \mathrm{d}^3\boldsymbol{r}^*$$

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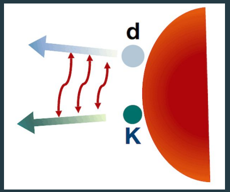

K⁺–d, p–d correlations measured by ALICE in pp HM collisions compared with theoretical expectation **considering deuteron as a point-like particle**

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→ Lednický **s-wave asymptotic wave function from scattering parameters** R. Lednický, Phys. Part. Nucl. 40, 307 (2009)

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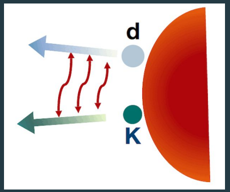

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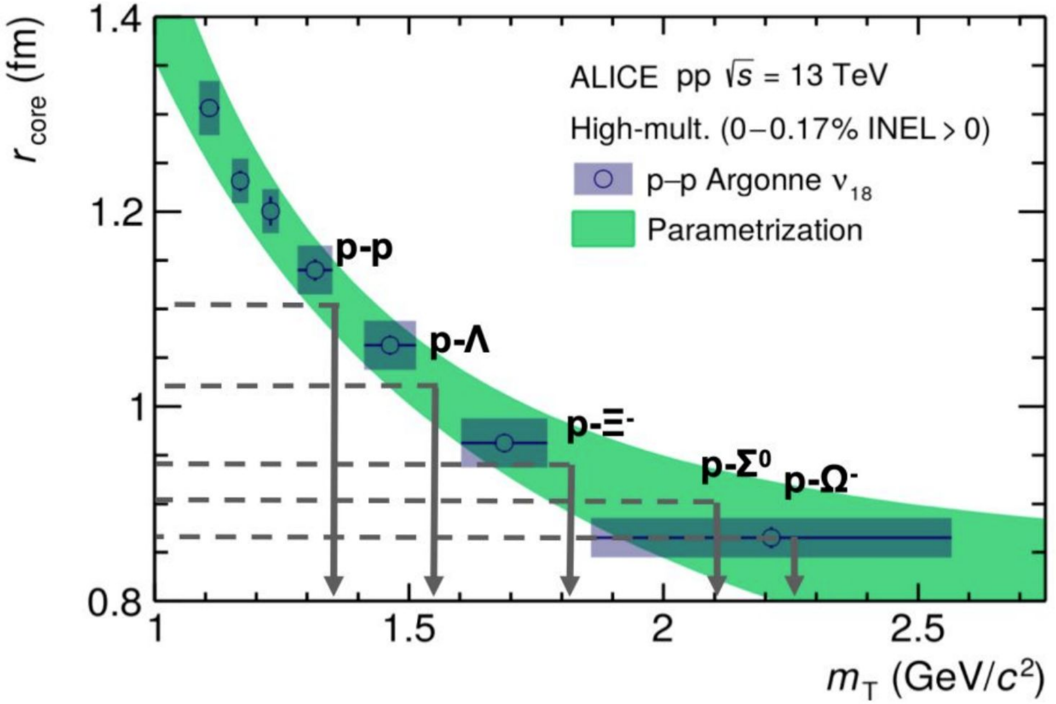
Lednický **s-wave asymptotic wave function from scattering parameters** R. Lednický, Phys. Part. Nucl. 40, 307 (2009)

Source size for hadron−hadron pairs determined in pp HM events

[ALICE Coll., Phys. Lett. B 811 (2020) 135849](#)



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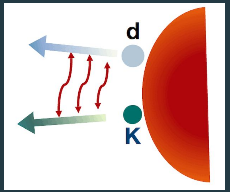
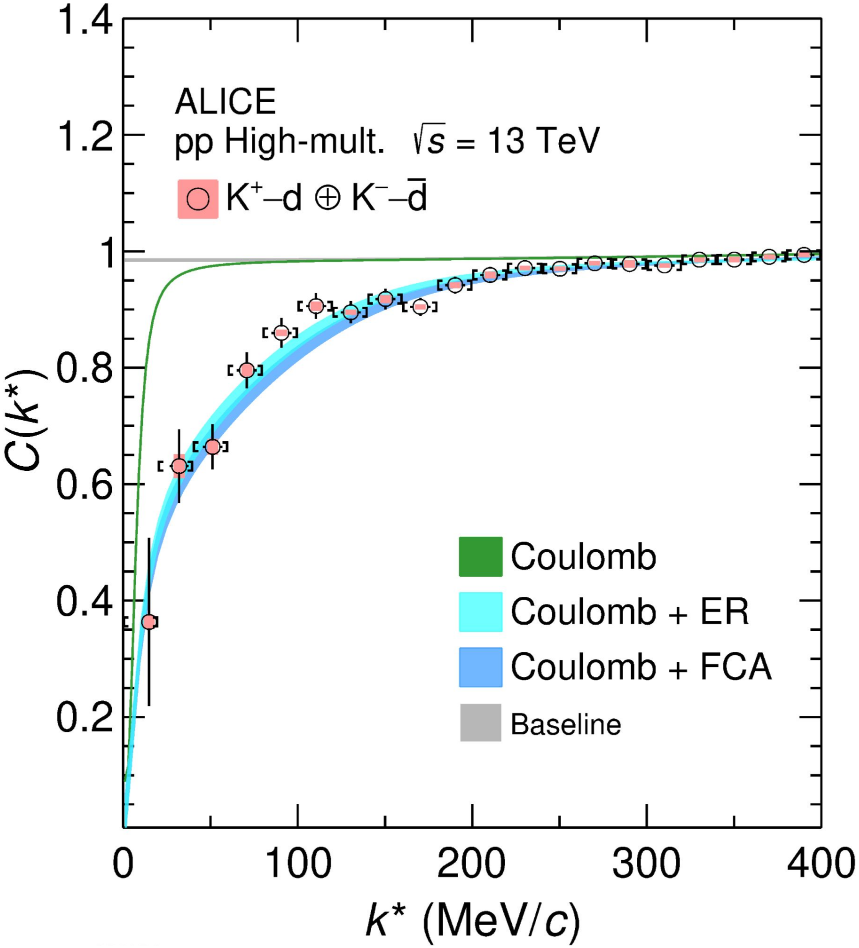


K^+–d correlation in pp HM collisions

- Source size: r = $1.35^{+0.04}_{-0.05}$ fm from m_T scaling
- K^+–d scattering parameters from
  - Effective-Range approximation (ER):
    a_0 = −0.47 fm, d_0 = −1.75 fm.
  - Fixed-Center Approximation (FCA):
    a_0 = −0.54 fm, d_0 = 0 fm.

Calculation using Coulomb + strong interaction and source size from m_T scaling describes the data ⇒ **deuterons are produced at very short distances w.r.t. other hadrons**

ALICE Coll., arXiv:2308.16120 [nucl-ex]



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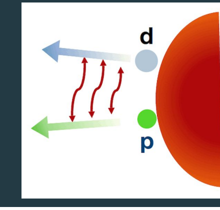


p–d correlation in pp HM collisions

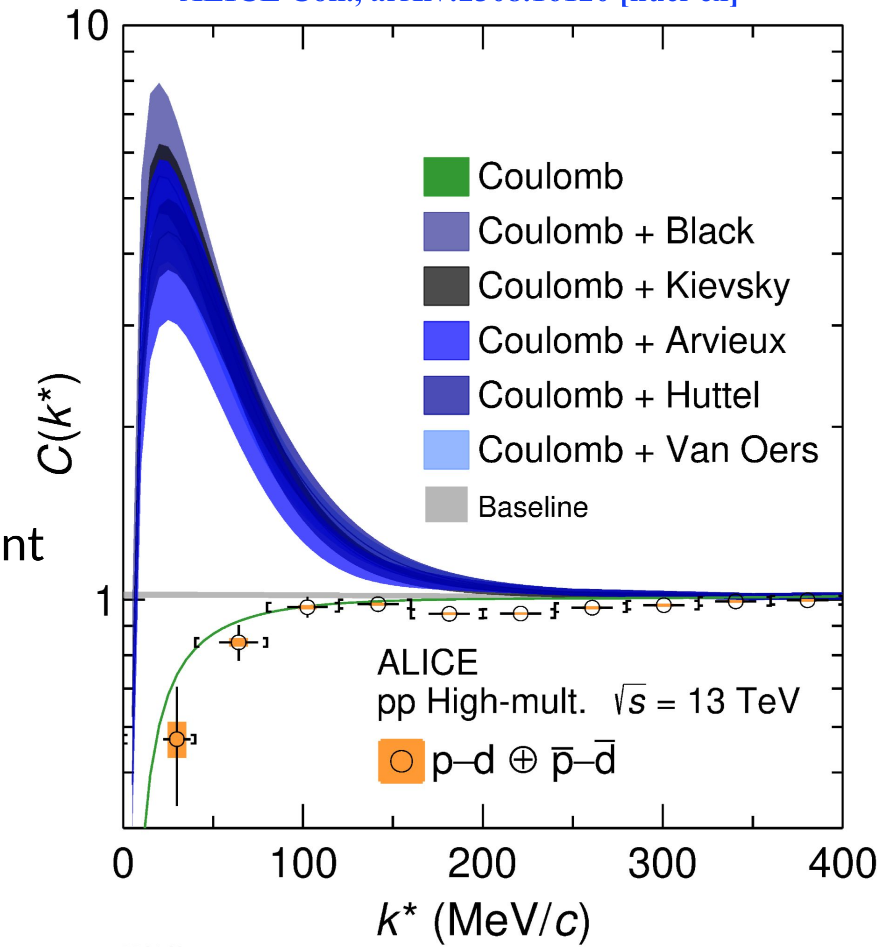
- Source size: r = $1.08^{+0.06}_{-0.06}$ fm from m_T scaling
- Strong interaction constrained from the scattering measurements

For p–d, calculations with two point-like particles fail to reproduce the data:

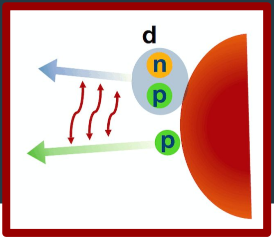
- Pauli blocking for p–(pn) at short distances
- Asymptotic strong interaction not sufficient for small distances

⇒ Need for three-body calculations accounting for p-pn dynamics

ALICE Coll., arXiv:2308.16120 [nucl-ex]



p-d correlation function including three-body dynamics



First formulation of the p–d correlation function starting from p–(pn) dynamics that forms the p–d state

$$C_{pd}(k^*) = \frac{1}{16\,A_d} \sum_{m_2,m_1} \int \rho^5 d\rho\, d\Omega \left| \Psi_{m_2,m_1\vec{k}^*} \right|^2 \frac{e^{-\rho^2/4R_M^2}}{(4\pi R_M^2)^3}$$

with: $\Psi_{m_2,m_1\vec{k}^*}$ three-nucleon wave function, p–(pn) to p–d state asymptotically

A_d deuteron formation probability using deuteron wave function

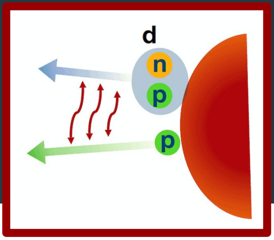
$R_M = 1.43 \pm 0.16$ fm nucleon-nucleon source size in the p–d system from universal m_T scaling

arXiv:2306.02478 [nucl-th] (2023) Phys. Rev. C in press

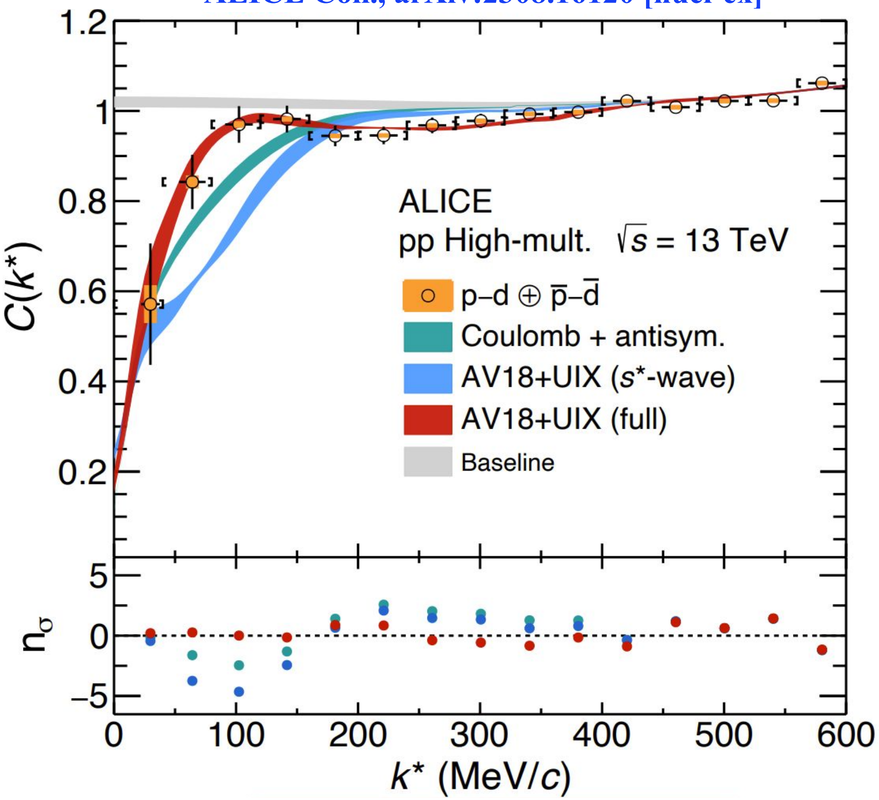
Role of three-body dynamics in nucleon-deuteron correlation functions

M. Viviani,[1,*] S. König,[2,†] A. Kievsky,[1,‡] L. E. Marcucci,[3,1,§] B. Singh,[4,¶] and O. Vázquez Doce[5]

p-d correlation function including three-body dynamics



ALICE Coll., arXiv:2308.16120 [nucl-ex]



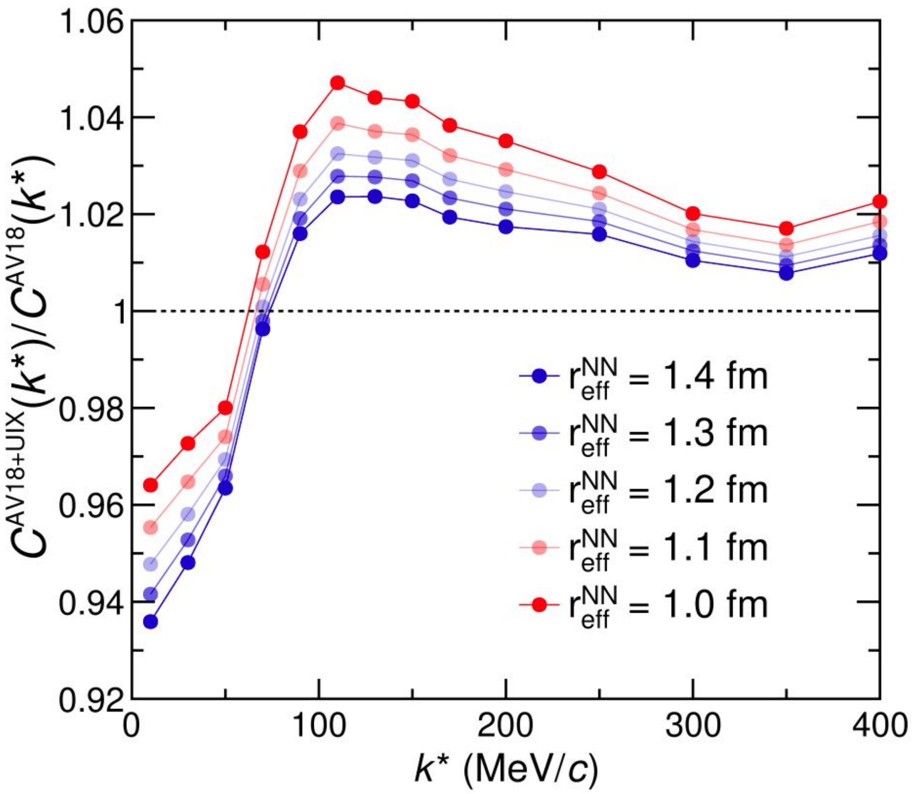
- **Full-fledged three-body calculation describes the data** by including:
  - AV18, two-nucleon potential
  - Urbana IX, three-nucleon force
  - Calculation up to d-wave
- s-wave only and Coulomb only calculations disagree with data
- additional π-less EFT NLO (s+p+d waves) three-body calculation also in agreement

ALICE measurement of the p-d correlation function sensitive to dynamics of the three-body p–(pn) system at short distances

Open possibilities for the future

Computed correlation function with and without three-nucleon force (Urbana IX) ⇒

- Up to 5% effect of genuine three-body interaction
- Run 2 statistics does not allow to see the effect in the measurement



• Run 3 data will enable m_T differential analysis ⇒ scan in radius

Avenue for the study of hadron–deuteron systems, including charm and strange hadrons!

Summary and outlook

Femtoscopy technique has been proved to provide unprecedented constraints on hadron-hadron interactions …

Now ALICE has **access to the three-body dynamics** via measurements of:

- three-body correlation function
- hadron-deuteron correlations

More data = more fun:

- New studies within reach with the current **Run 3: Stats Run 2 x100!**
- A completely new **ALICE3 detector** in the future
  ⇒ Studies of systems with strangeness and charm will be accessible