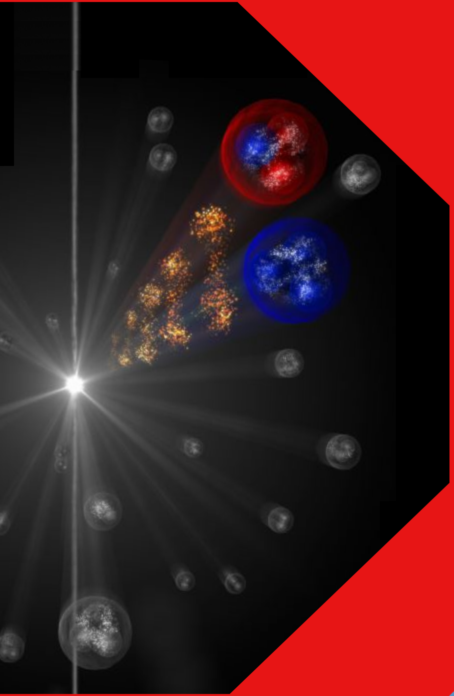


Femtoscopy as a tool to access the strong interaction among hadrons with ALICE

Oton Vazquez Doce (INFN - LNF)
on behalf of the ALICE Collaboration

INFN LNF
Istituto Nazionale di Fisica Nucleare

ALICE

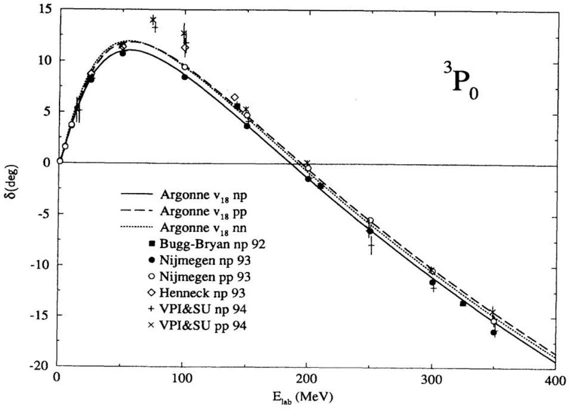
NSTAR 2026
15th International Workshop on the Physics of Excited Nucleons
Sevilla (Spain), September 8, 2026

Experimental input on hadron-hadron interactions

(with strangeness)

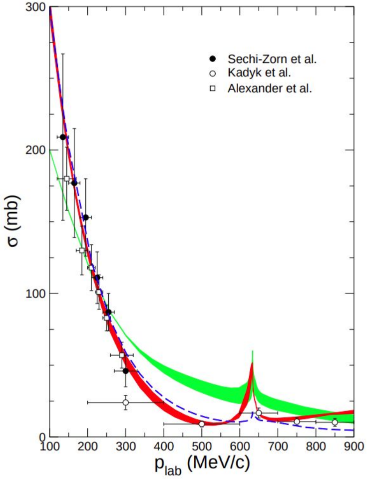
***S*=0** ***S*=-1** ***S*=-2**

NN → NN



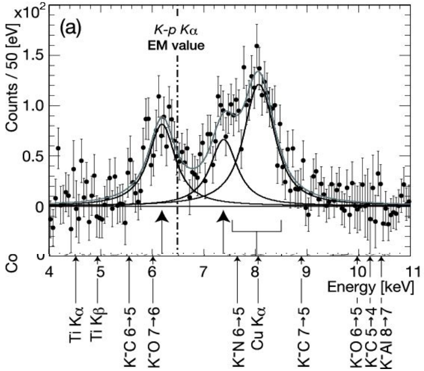
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla Phys. Rev. C 51, 38 (1995)

Λp → Λp



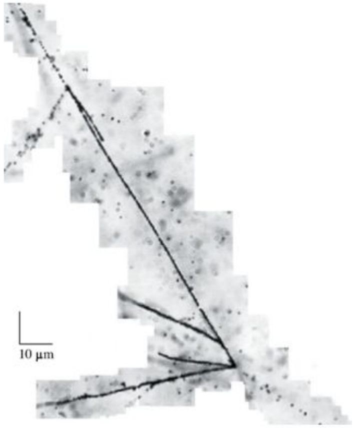
LO: H. Polinder, J. Haidenbauer, U. Meißner, Nucl. Phys. A779 (2006) 244.
NLO: J. Haidenbauer et al., Nucl. Phys. A915 (2013) 24.

Kaonic atoms



SIDDHARTA Coll. Phys.Lett.B 704 (2011) 113

ΛΛ, Ξ hypernuclei



KISO event: K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015, 033D02
IBUKI event J-PARC E07 Coll., Phys. Rev. Lett. 126, 062501 (2021)

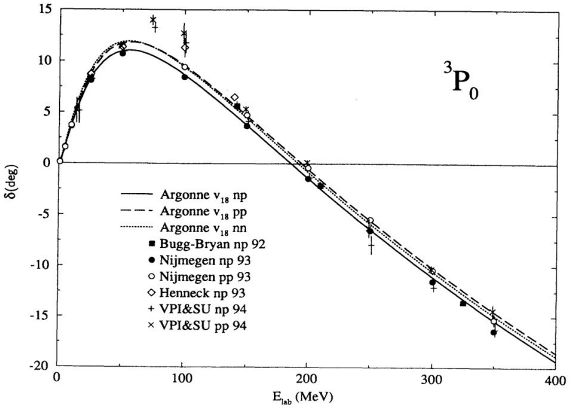
Experimental data

Experimental input on hadron-hadron interactions

(with strangeness)

S=0 *S*=-1 *S*=-2

NN → NN **Λp → Λp** **Kaonic atoms** **ΛΛ, Ξ hypernuclei**



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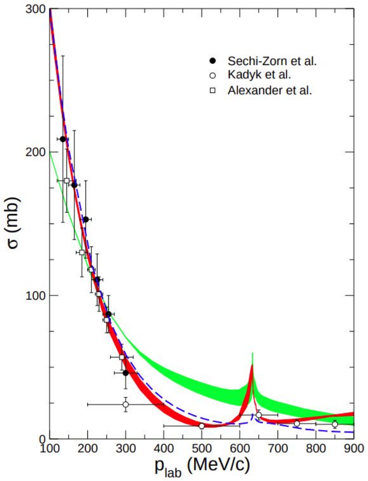

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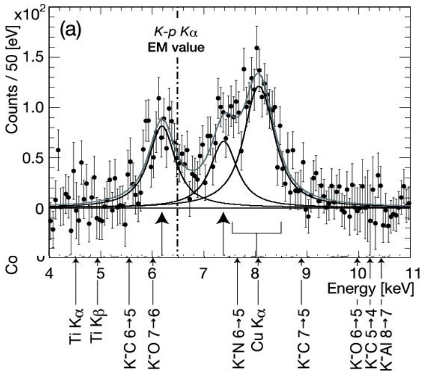
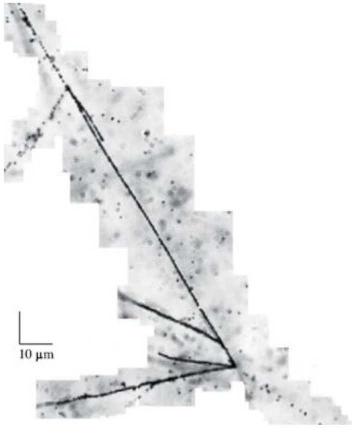


SIDDHARTA Coll. Phys.Lett.B 704 (2011) 113



KISO event: K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015, 033D02
IBUKI event J-PARC E07 Coll., Phys. Rev. Lett. 126, 062501 (2021)

Experimental data

The idea: exploit the copious production of (light, strange, charm…) particles in NN collisions at the LHC

Femtoscopy with ALICE

what we measure:

$$C(k^*) = \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

k^*: relative momentum

r^*: relative distance

Femtoscopy with ALICE

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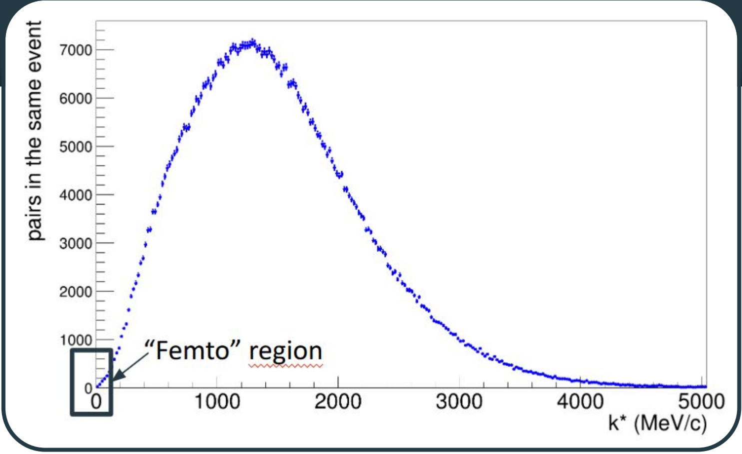


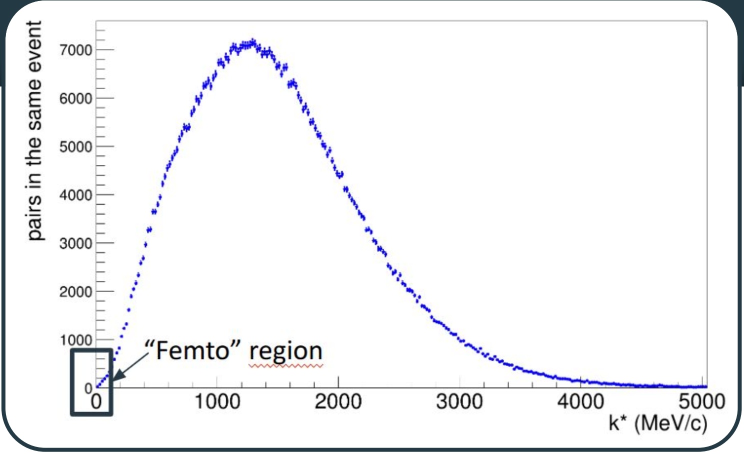
⇒ In the low relative momentum region of the correlation function the femtoscopic signal arises influenced by both the characteristics of the particle source and the final state interaction

k^*: relative momentum
r^*: relative distance

Femtoscopy with ALICE

what we measure:

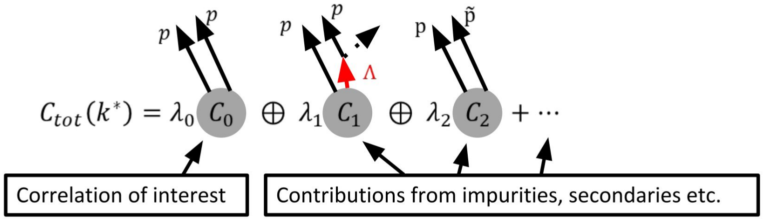
$$C(k^*) = \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$



⇒ In the low relative momentum region of the correlation function the femtoscopic signal arises influenced by both the <u>characteristics of the particle source</u> and the <u>final state interaction</u>

<u>Behind the scenes:</u>

- Data-driven approaches for feed-down corrections
- Corrections for mini-jet background correlations
- Machine learning approaches for particle identification
- Finite momentum resolution effects …and more!



k^*: relative momentum
r^*: relative distance

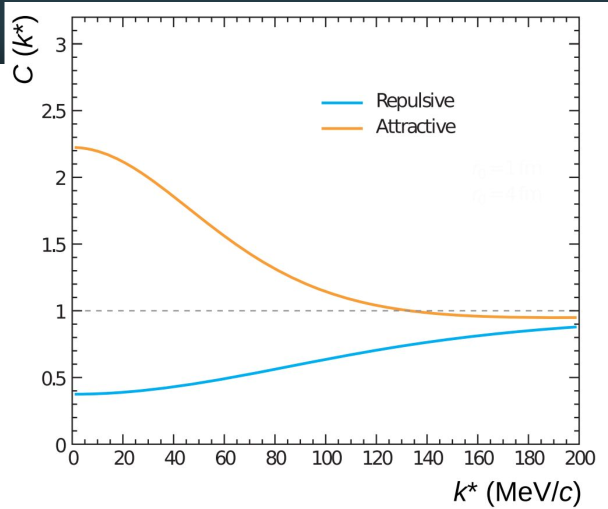
Femtoscopy with ALICE

what we measure:

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

theoretical expectation:

Source **Interaction**



$$S(r) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp\left(-\frac{r^2}{4r_0^2}\right)$$

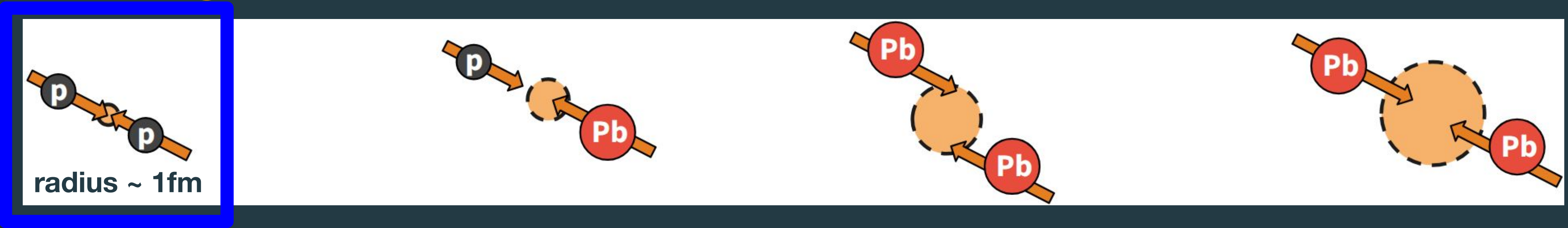
- Gaussian distr. of relative distances (r)
- Width of the gaussian (r_0) → source size

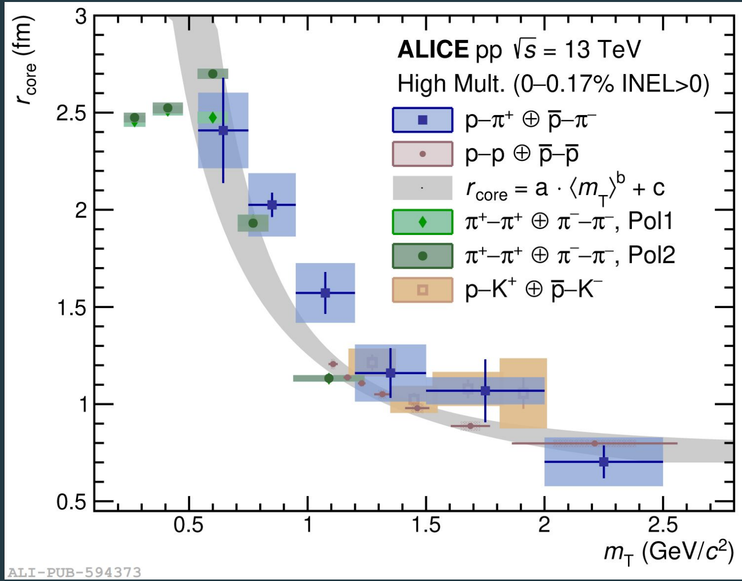
- **Two-particle wave function**
- Can also be obtained via:
  - Interaction potential D.L.Mihaylov et al. Eur. Phys. J. C78 (2018) no.5,394
  - Scattering parameters R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53 (1982) 770
  - Other methods

k^*: relative momentum

r^*: relative distance

Getting to know the source in **pp collisions at the LHC**



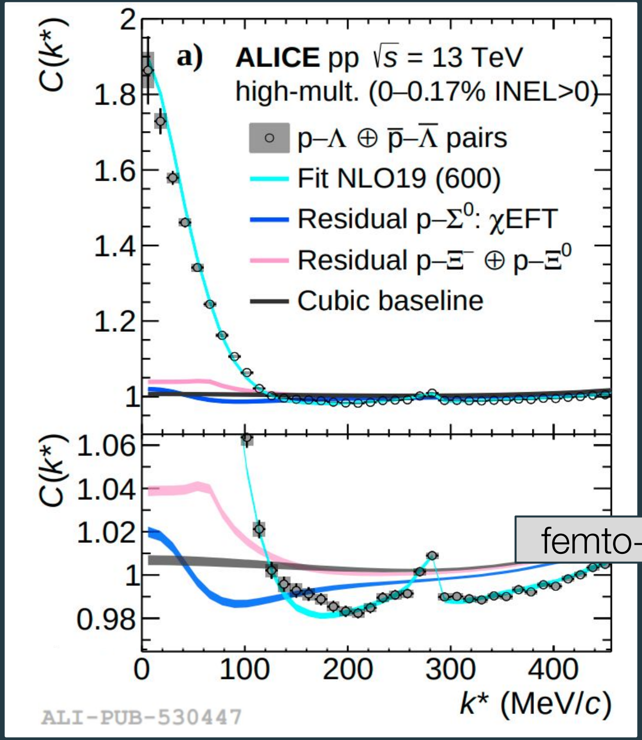


Source in high-multiplicity (HM) pp collisions constrained by studying proton-proton pair correlations

- Well constrained interactions ⇒ Source size determined from data
- Effect of strong decaying resonances taken into account
- **Different pairs deliver similar size and m_T dependence**
  - p-p
  - p-$\pi^{\pm}$
  - $\pi^{\pm}$-$\pi^{\pm}$
  - p-K^{+}

ALICE Coll. Eur. Phys. J. A 61, 194 (2025)

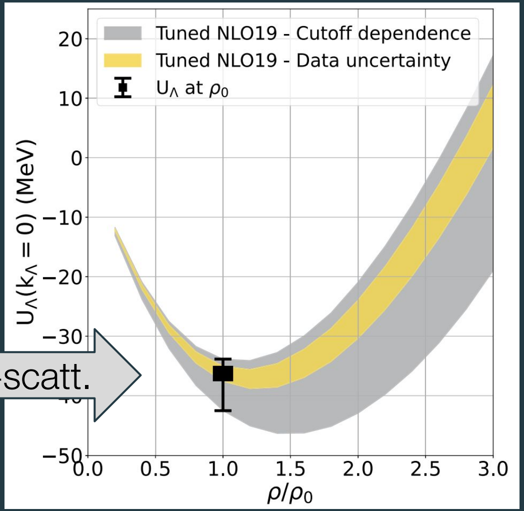
Theory constraints using femtoscopy data



ALICE Coll. Phys.Lett.B 833 (2022) 137272

Λp femtoscopy in HM pp collisions

→ Clear signal of the cusp due to ΛN-ΣN coupling



$$U_\Lambda(\rho_0) = -36.3 \pm 1.3(\mathrm{stat})^{+2.5}_{-6.2}(\mathrm{syst})\ \mathrm{MeV}$$

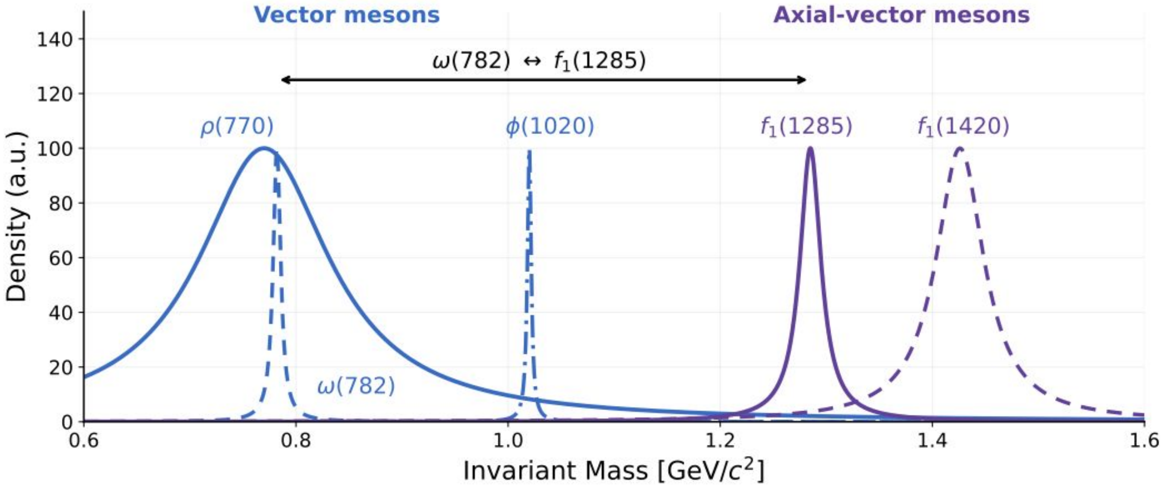
Ultimate goal: provide data to constrain hyperon potential at high baryon densities

⇐ Constraining the pΛ interaction with scattering data + femtoscopy

D. Mihaylov et al., Phys. Lett. B 850 (2024) 138550

Vector and axial-vector meson - nucleus interaction

(Axial-)vector meson-nucleon interactions crucial for interpretation of chiral symmetry restoration signals



Vector and axial-vector meson - nucleus interaction

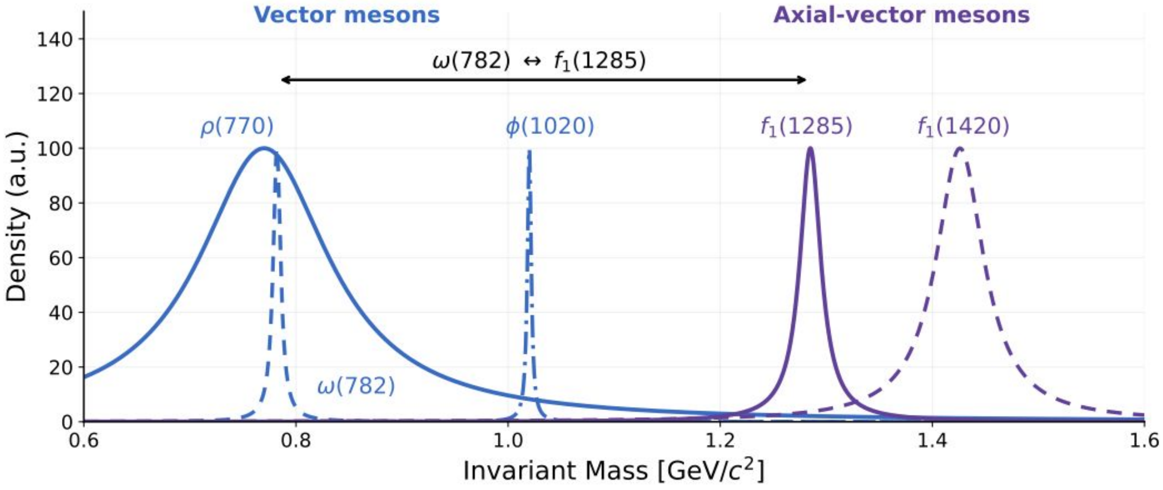
(Axial-)vector meson-nucleon interactions crucial for interpretation of chiral symmetry restoration signals

ρ^0-p femtoscopy

- Vector meson-nucleon interactions usually probed by Vector Meson Dominance model
- Help understanding dynamically generated N* states

f_1(1285)-p femtoscopy

- No previous measurement available for axial-vector-meson interactions with nucleons
- Help understanding the nature of the f_1(1285)



ρ^0–p femtoscopy in HM pp collisions

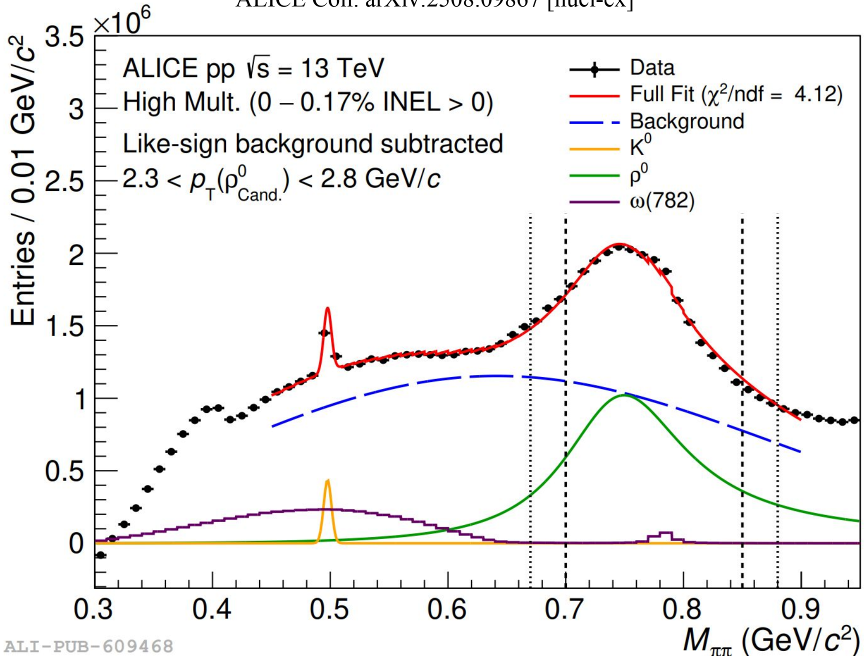
Run 2 data

Femtoscopy data offers the possibility to **access directly the ρ^0-p strong interaction**

…but not an easy task:

- **Demonstration that femtoscopy can be applied to hadrons with lifetimes of order 1 fm/c.**
- ρ^0 **purity of identification 3%** (inclusive p_T)
- Analysis of invariant mass sidebands useful: account for the mini-jet background

ALICE Coll. arXiv:2508.09867 [nucl-ex]



ρ^0–p femtoscopy in HM pp collisions

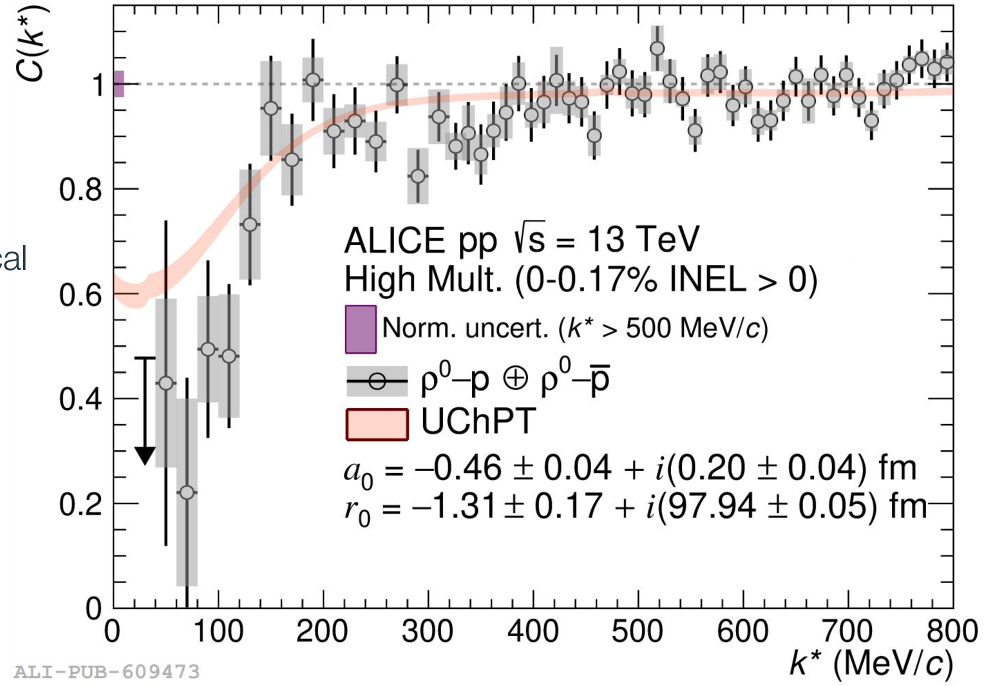
Run 2 data

Correlation function shows evidence of strong interaction

Comparison with a UχPT model:

- Simultaneous fit including ϕ–p correlation function
  ALICE, Phys. Rev. Lett. 127 (2021) 172301
  A. Feijoo et al., Phys. Rev. D 111 (2025) 014009
- Model includes coupled-channel dynamics and dynamical N*(1700) and N*(2000) states

⇒ Femtoscopy data provide **unique constraint on N*(1700) pole position** and shows the **relevance of coupled-channel dynamics** in vector-meson–baryon interactions



ALICE Coll. arXiv:2508.09867 [nucl-ex]

f_1(1285)-p femtoscopy in pp collisions

Data from the **recently finished LHC Run 3** with an upgraded ALICE apparatus enables many new studies

Femtoscopy data can help clarify the debated internal structure of the f_1(1285)

- Conventional diquark?
- Tetraquark? Unfavoured by analyses of B decays and production yields
  LHCb, Phys. Rev. Lett. 112 (2014) 091802, ALICE, Phys. Lett. B 866 (2025) 139562
- Kbar-K* molecule?

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  LHCb, Phys. Rev. Lett. 112 (2014) 091802, ALICE, Phys. Lett. B 866 (2025) 139562
- Kbar-K* molecule?

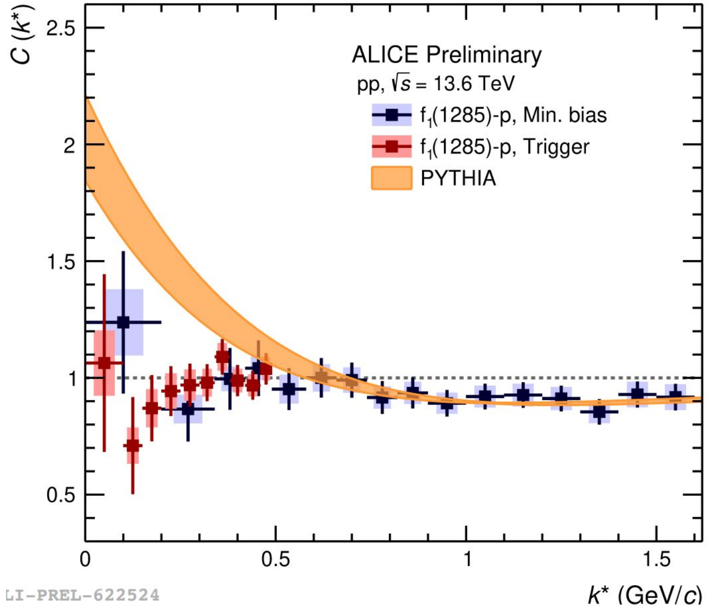
f_1(1285)-p correlation function in pp collisions

→ Reconstructed decay $f_1(1285) \rightarrow K\pi K_s^0$

→ Use of offline software trigger

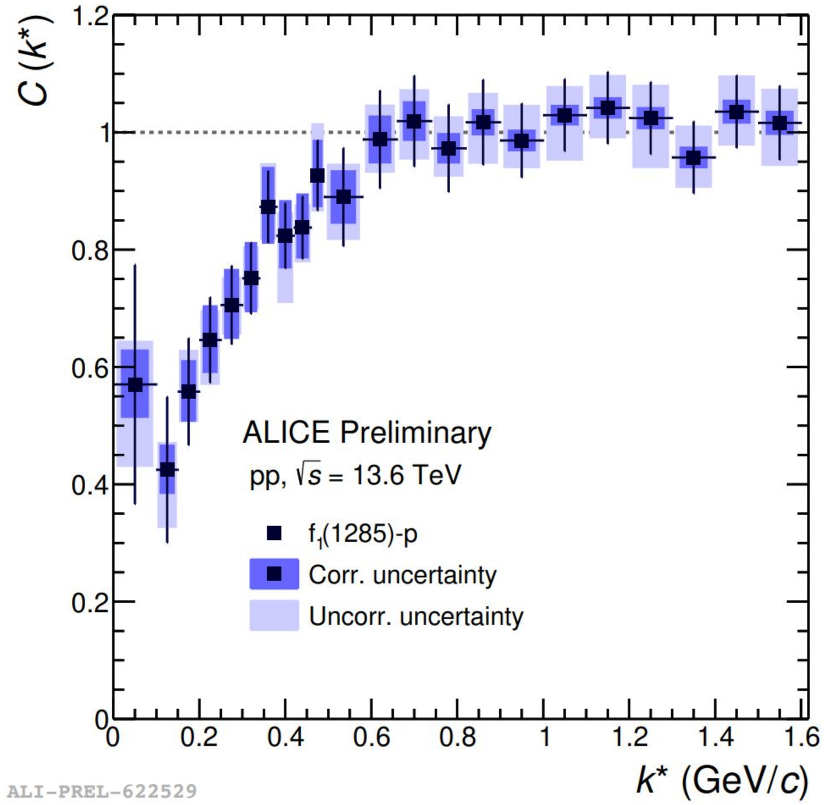
→ mini-jet background modelled with **pythia simulations**

Run 3 prelim.



f_1(1285)-p femtoscopy in pp collisions

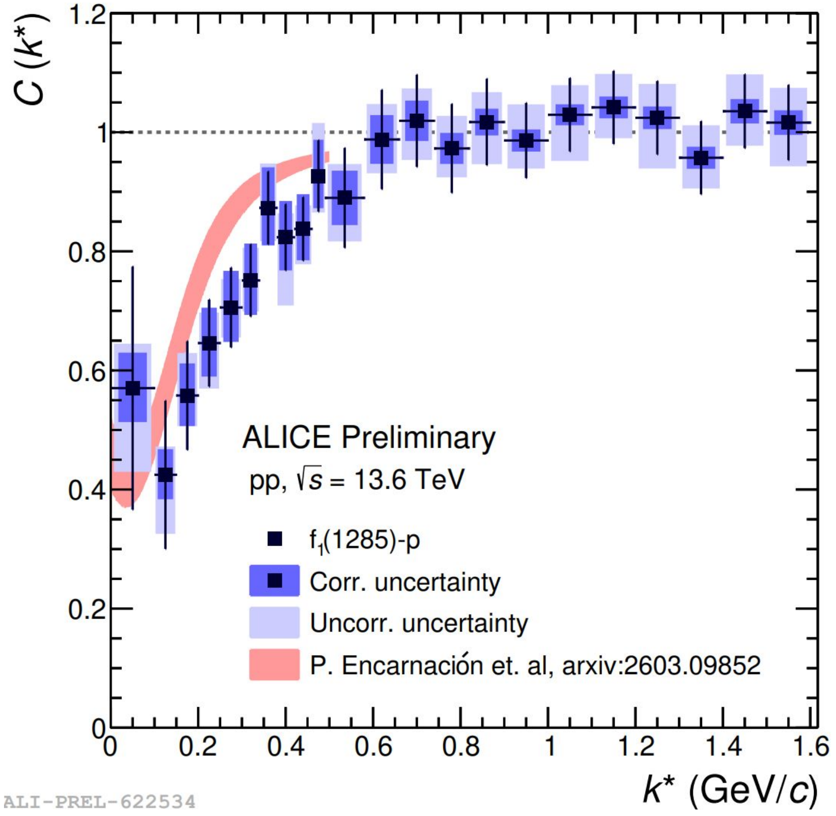
Run 3 prelim.



First experimental evidence of strong interaction between axial-vector meson and nucleon

f_1(1285)-p femtoscopy in pp collisions

Run 3 prelim.



First experimental evidence of strong interaction between axial-vector meson and nucleon

Model comparison P. Encarnación et al., Phys. Rev. D 111(2025) 114023

- Signal qualitatively consistent with strong interaction when f_1(1285) is <u>treated as K*Kbar molecular cluster</u>
- The observed interaction emerges from proton scattering off the cluster constituents through three-body rescattering
- Theory predicts a bound state below f_1(1285) -p threshold

Charm sector: p-D femtoscopy in pp collisions

Femtoscopy in the charm sector can help unveiling the nature of exotic charm states

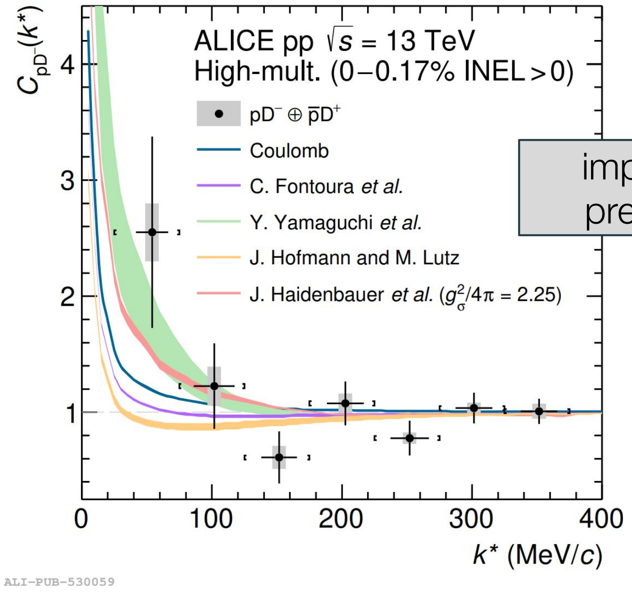
Run 3 data delivers a better insight for p-D^- correlations

Charm sector: p-D femtoscopy in pp collisions

Femtoscopy in the charm sector can help unveiling the nature of exotic charm states

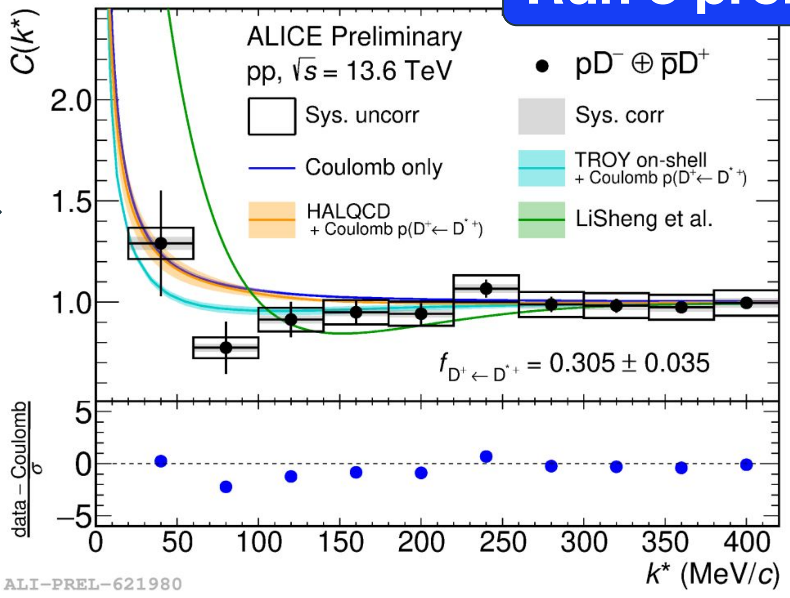
Run 3 data delivers a better insight for p-D⁻ correlations

ALICE Collaboration PRD 106 (2022) 052010



improved precision

Run 3 prelim.



p-D⁻ femtoscopy in pp collisions

Femtoscopy in the charm sector can help unveiling the nature of exotic charm states

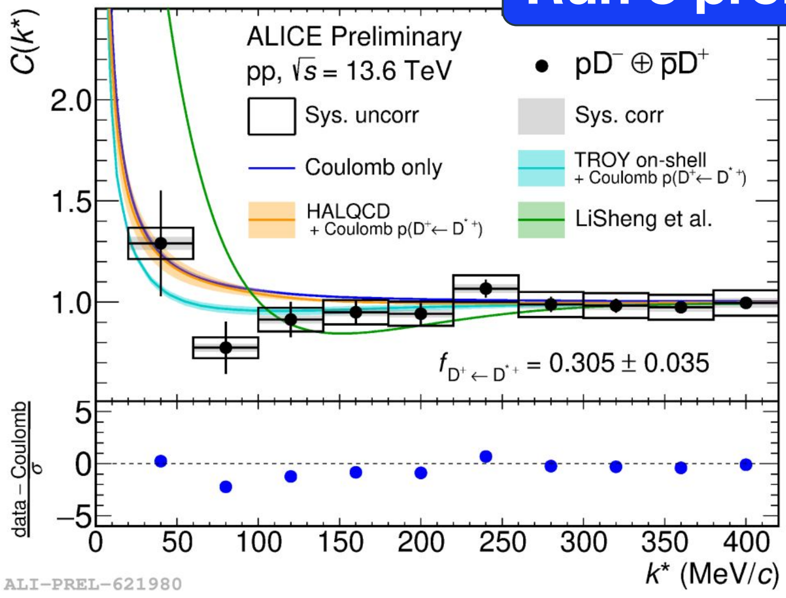
Run 3 data delivers a better insight for p-D⁻ correlations

Preliminary Run 3 p-D⁻ femtoscopy data:

- Unveils a slight deviation wrt Coulomb expectation
- Models with a repulsive strong component give better qualitative description

TROY: M. F. Barbat and J. M. Torres-Rincon, arXiv:2507.07864 (2025)
HalQCD: W. Yamada and Y. Lyu, arXiv:2603.12251 (2026)
LiSheng: B. Wang, L. Meng, S.-L. Zhu, Phys. Rev. D 101 (2020) 094035
LiSheng: M. Altenbuchinger and L.-S. Geng, Phys. Rev. D 89 (2014) 014026

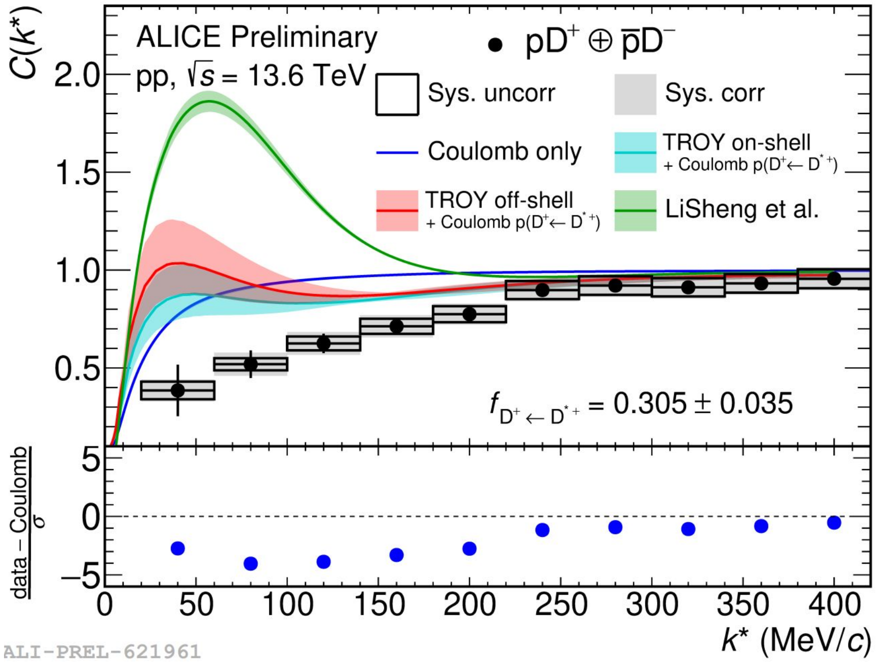
Run 3 prelim.



p-D⁺ femtoscopy in pp collisions

Preliminary Run 3 **p-D⁺ femtoscopy** data

- Significant deviation from Coulomb-only: evidence of **residual strong interaction in the charm sector**



Run 3 prelim.

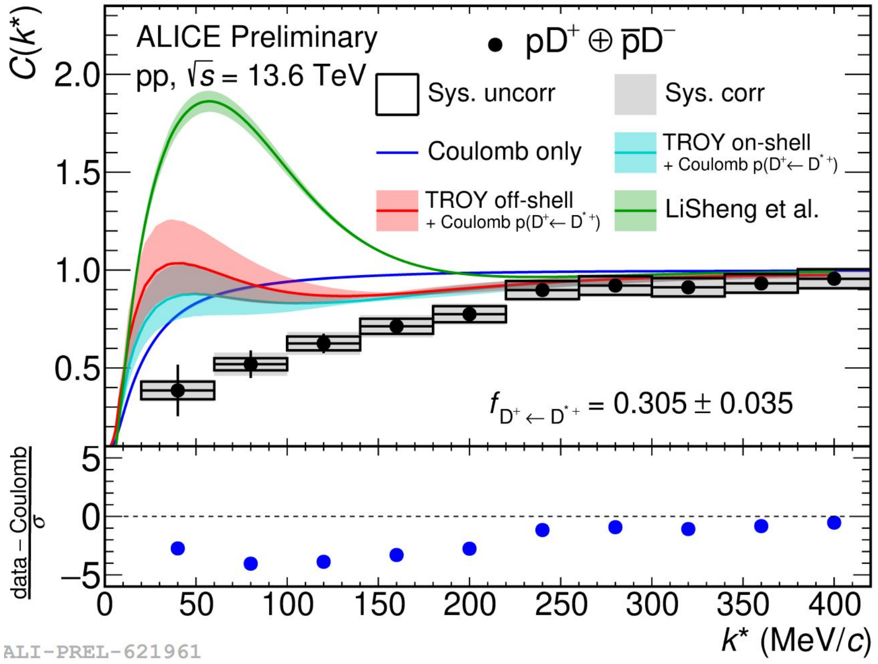
p-D$^+$ femtoscopy in pp collisions

Preliminary Run 3 **p-D$^+$ femtoscopy** data

- Significant deviation from Coulomb-only: evidence of **residual strong interaction in the charm sector**

<u>Theory comparison:</u>

- Models do not describe the data
- Low-k* structure arises from the interplay of strong and Coulomb interactions
- Strong-interaction shape reflect coupled channels and the sub-threshold dynamically generated **Σ_c(2800) resonance**
- Importance of D* feed-down: all theoretical calculations include Coulomb p-D*, only LiSheng model incorporates strong interaction



Run 3 prelim.

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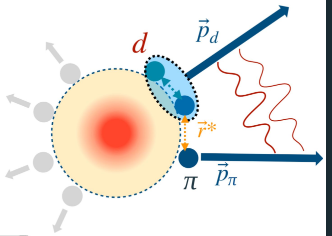
Femtoscopy with bound systems: **$\pi^{\pm}$d correlations**

π±d femtoscopy in HM pp coll. at 13 TeV

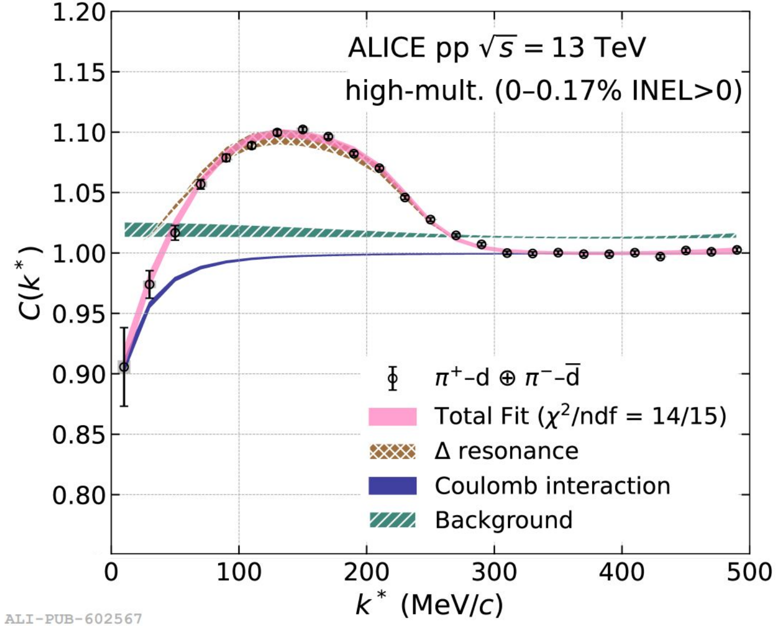
Recent femtoscopy results utilizing deuteron femtoscopy in HIC addressing production of light (anti)nuclei and deuteron sources ALICE Coll. 2504.02333 [nucl-ex], 2505.01061 [nucl-ex] STAR Coll. 2410.03436 [nucl-ex]

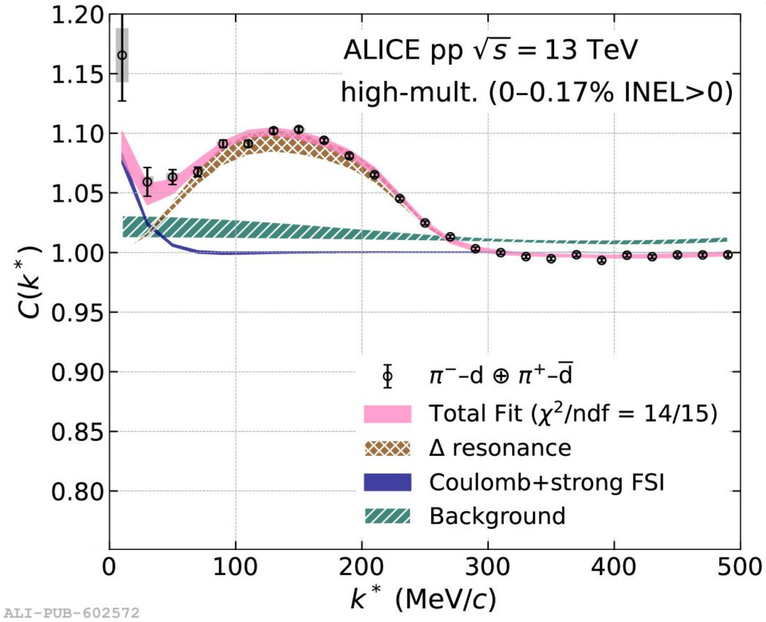


Correlation function of π±d pairs in pp collisions:

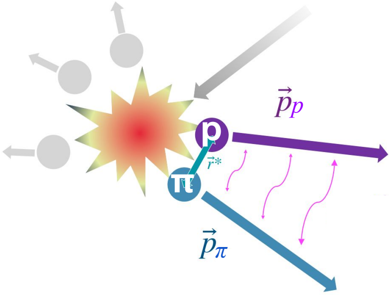
- dominated by Coulomb (+strong FSI) at low k*
- **large bump about 150 MeV/c**

ALICE Coll. Nature 648 (2025) 8093, 306-311





Features of **π±-proton femtoscopy** in HM pp coll. at 13 TeV

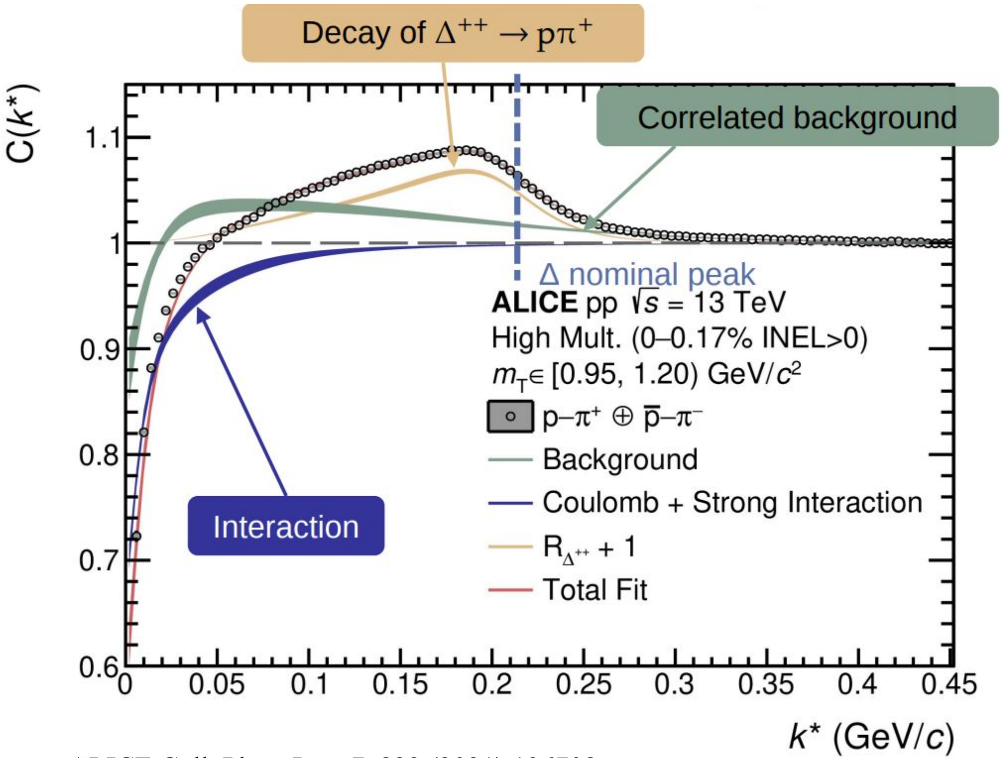


A step back…

…fitting the **π±-p correlation function:**

- **Large contribution from Δ→πp decay**
- Δ spectral shape modeled with a Flatté-like distribution distorted due to rescattering of daughter particles by a phase-space factor (PS)

$$PS\,(p_{\mathrm{T}},T) \propto \frac{m}{\sqrt{m^2+p_{\mathrm{T}}^2}} \times \exp\left(-\frac{\sqrt{m^2+p_{\mathrm{T}}^2}}{T}\right)$$



ALICE Coll. Phys. Lett. B 822 (2021) 136708

Simulations for the π±d correlation function in pp

Which process can explain the bump in πd correlation?

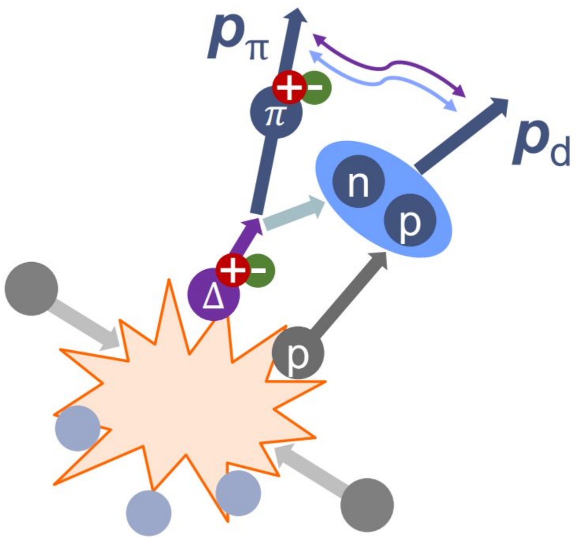
1- **Thermal** production? **No:** Thermal FIST + Coulomb **gives FSI-only baseline**

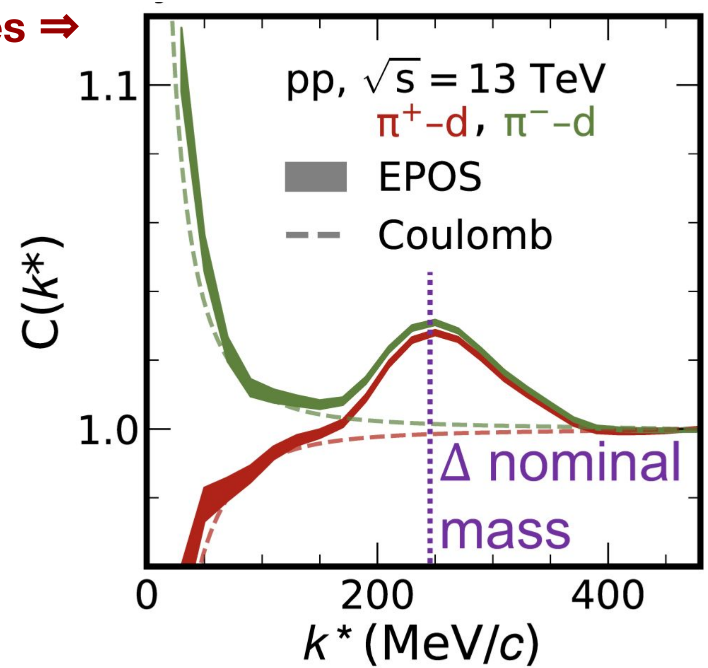
2- Coulomb + **elastic + inelastic interaction? No: introduces depletion instead**

3- Nuclear fusion after Δ decay? Yes ⇒

EPOS 3 generator + coalescence afterburner

M. Mahlein et al.,EPJC 83 (2023) 804





Other exotic explanations like the decay from a ΔN dibaryon state are also excluded by the data

Interpretation $\pi^{\pm}$d correlation function in HM pp

Enhancement caused by Δ decay inherited during fusion process

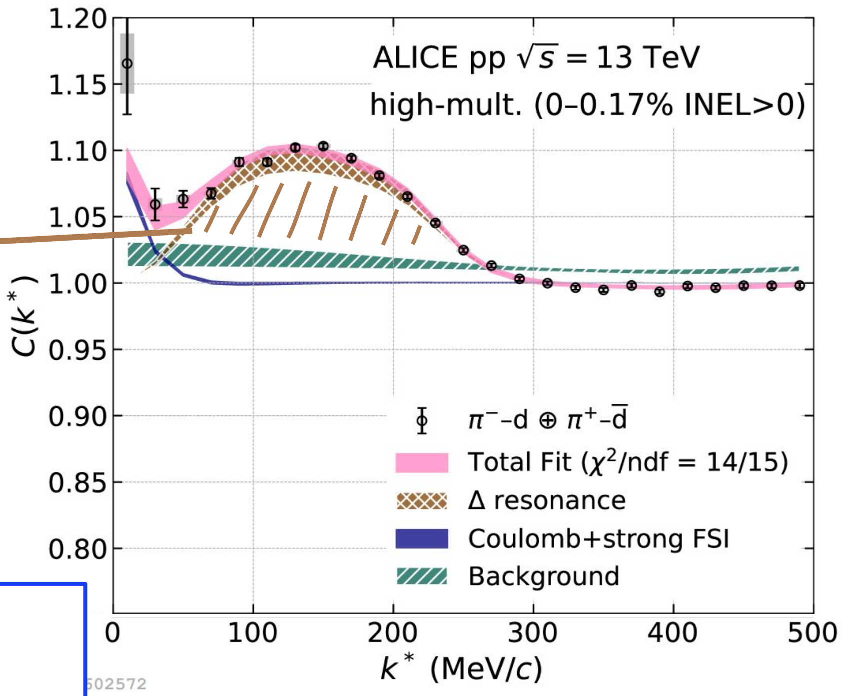
Fraction of deuterons from Δ decay from bump yield:

$F_{\Delta\to d} = 60.6 \pm 4.1\ \%$

Extrapolation considering all possible resonances decays:

$F_{R\to d} = 88.9 \pm 6.3\%$

to be compared with EPOS: $F_{R\to d} = 89.3 \pm 1.6\%$



"Observation of deuteron and antideuteron formation from resonance decay nucleons" ALICE Coll. Nature 648 (2025) 8093, 306-311

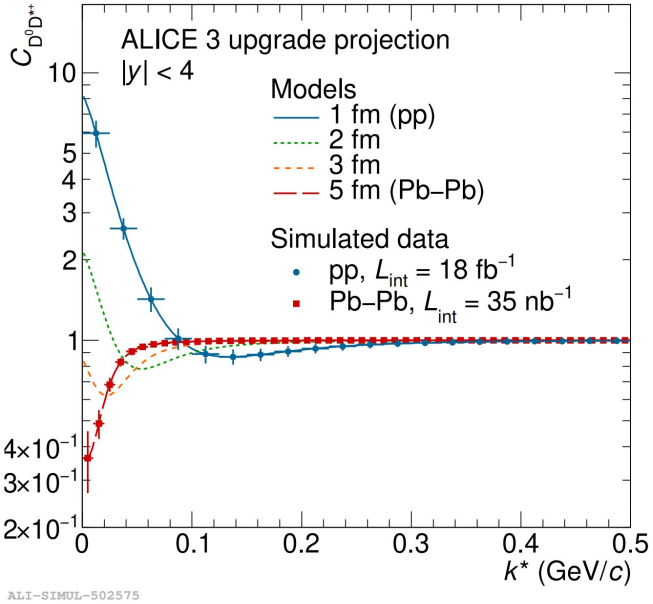
- ➡ The only scenario compatible with the data is **nuclear formation by fusion process**
- ➡ The obtained **fraction of deuterons from resonances compatible with coalescence model prediction**

Conclusions and outlook

Femtoscopy at the LHC provides an unique opportunity for precise testing of the strong interaction among hadrons at short distances

ALICE is delivering high-precision constraints, often the most precise data at low momenta in many complementary channels, in some cases the only data!
→ Run 3 large statistics enables high precision in two-body and of three-body systems

The future looks bright:
ALICE 3: the next-generation heavy-ion experiment at the LHC…
…will enable precision studies in the charm sector ⇒



Thank you for your attention!