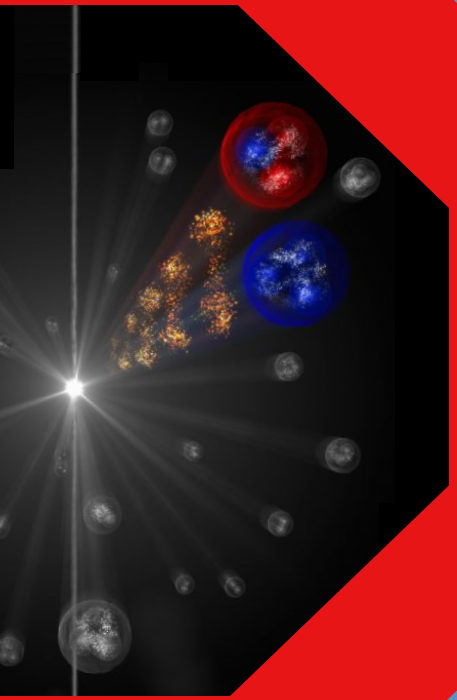


Femtoscopy with ALICE: Accessing hadronic interactions and nuclei formation

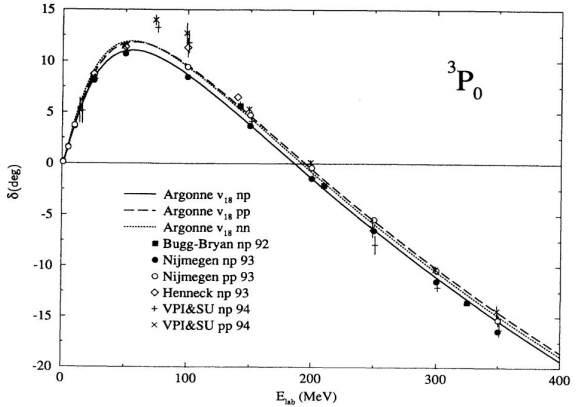
Oton Vazquez Doce (INFN - LNF)
on behalf of the ALICE Collaboration

ZIMÁNYI SCHOOL
2 December 2025
Budapest

Experimental input on hadron-hadron interactions (with strangeness)

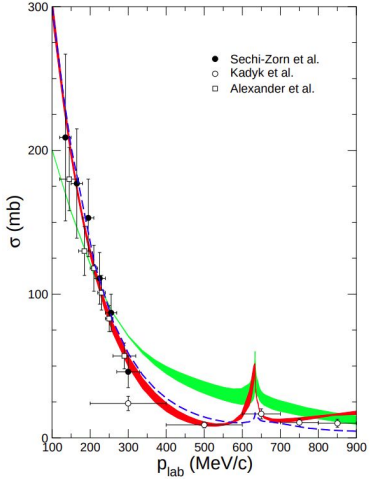
S=0 **S=-1** **S=-2**

NN → NN



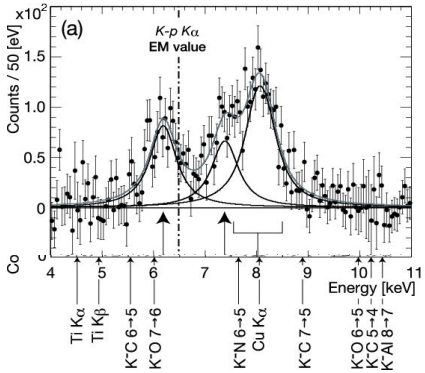
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla Phys. Rev. C 51, 38 (1995)

Λp → Λp



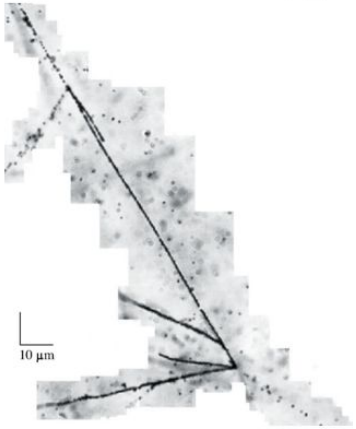
LO: H. Polinder, J. Haidenbauer, U. Meißner, Nucl. Phys. A779 (2006) 244.
NLO: J. Haidenbauer et al., Nucl. Phys. A915 (2013) 24.

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)

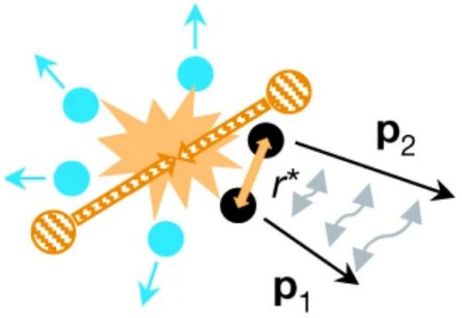
Experimental data

Study hadronic interactions with femtoscopy at the LHC

Copious production of (strange) particles in NN collisions at the LHC

- **Correlation function in momentum** space gives **access to the strong interaction** effects in systems difficult to measure otherwise

$$C(\overrightarrow{p_a}, \overrightarrow{p_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})}$$



Test and constraint theoretical approaches…

- **Effective theories (EFT)**
  - Needs data as input for fixing low-energy constants
- **Lattice QCD**
  - Important to test it in the strangeness sector
- Meson exchanges models
- Quark constituents models

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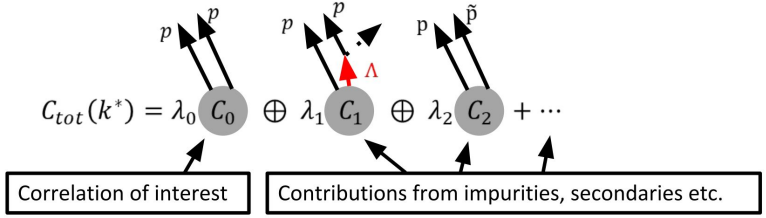
$$C(k^*) = \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

Behind the scenes:

- 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!



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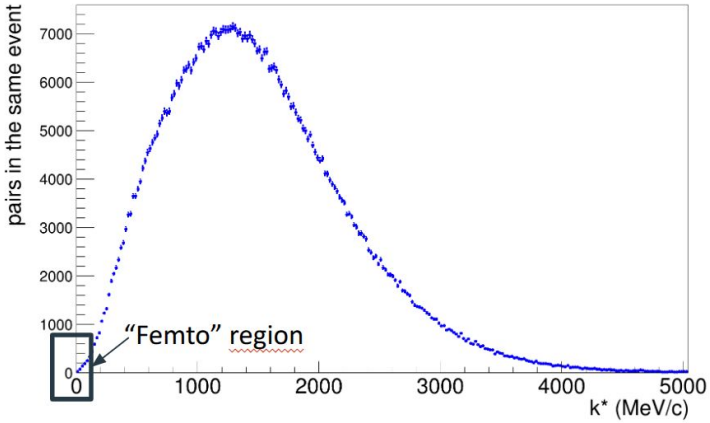

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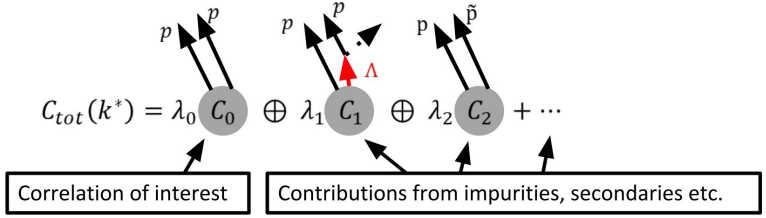

⇒ In the low relative momentum region of the correlation function the femtoscopic signal arises influenced by both the characteristics of the particle source and the final state interaction

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

Femtoscopy with ALICE

what we measure:

theoretical expectation:

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

Source **Interaction**

S.E. Koonin, Phys. Lett. B 70, 43 (1977)
S. Pratt and M.B. Tsang, Phys. Rev. C 36, 2390 (1987)

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Femtoscopy with ALICE

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

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

k^*: relative momentum
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Femtoscopy with ALICE

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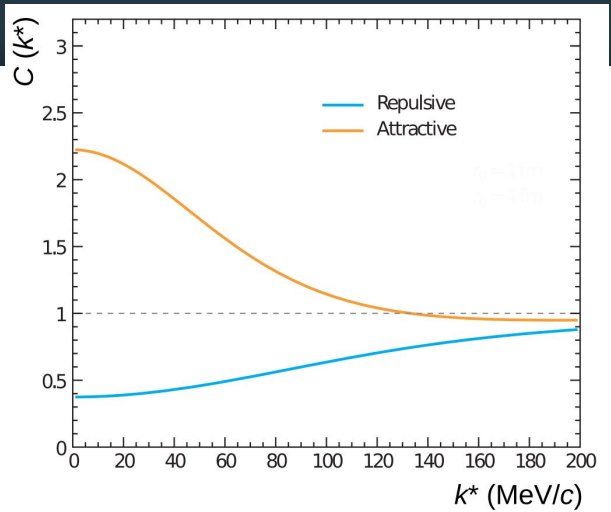

- **Two-particle wave function**
- Can also be obtained via:
  - Interaction potential D.L.Mihaylov et al. Eur. Phys. J. C78 (2018) no.5,394
  - Scattering parameters R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53 (1982) 770

k^*: relative momentum
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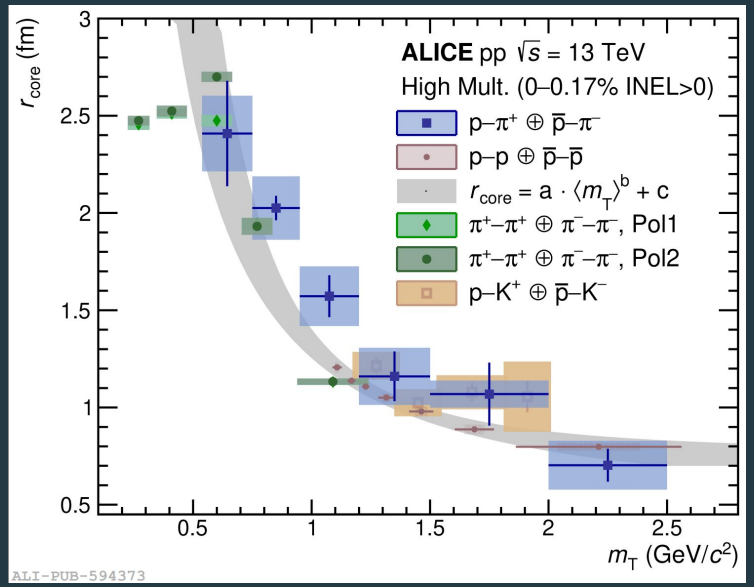
Getting to know the source

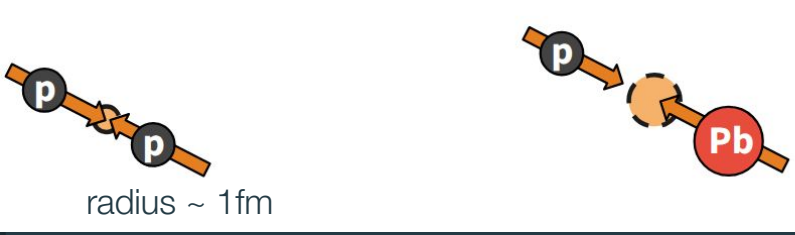


Source in high-multiplicity (HM) pp collisions constrained by studying proton-proton pair correlations

- 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)

Getting to know the source



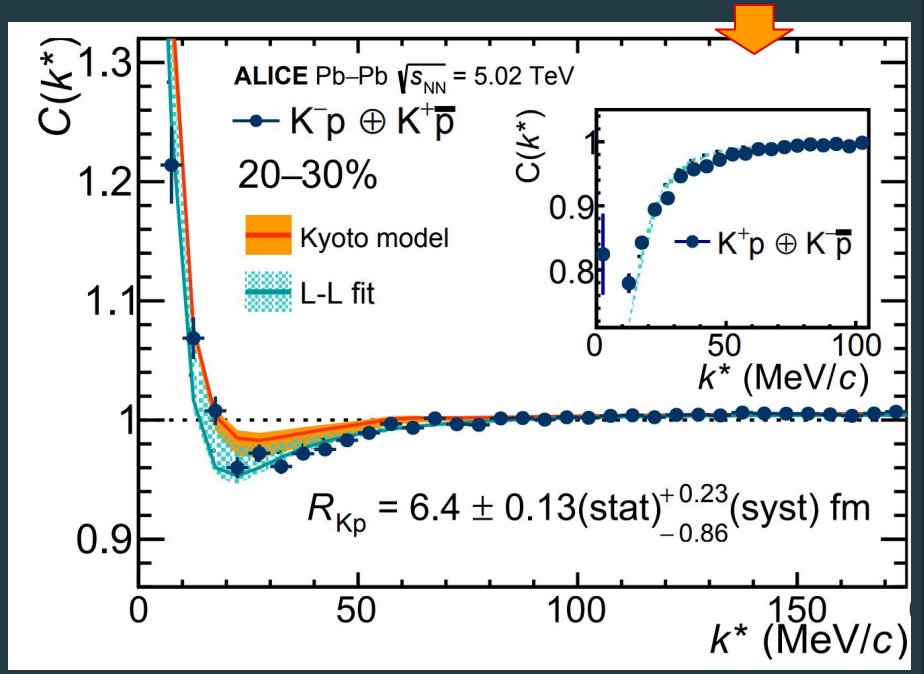
radius ~ 1fm

radius up to 10fm

Alternative methods to constrain the source size with "known" interactions:

- E. g. in Pb-Pb analysis of Kaon-proton pairs, source constrained by a simultaneous fit to the K^+p and K^-p correlation functions

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



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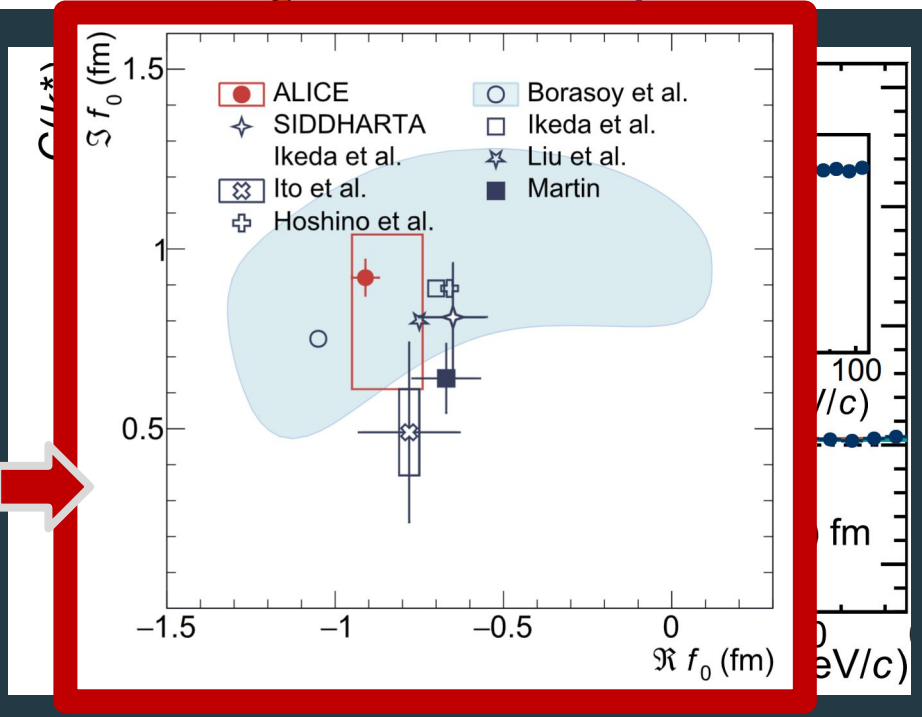
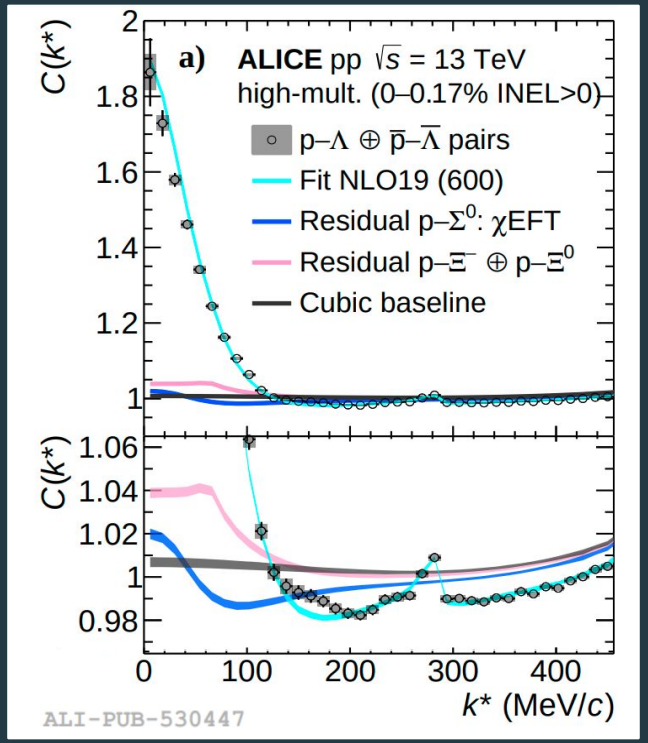
ALICE Coll. Phys. Lett. B 822 (2021) 136708

⇒ **Measurement of K^-p scattering lengths**



From femtoscopy data…to neutron stars

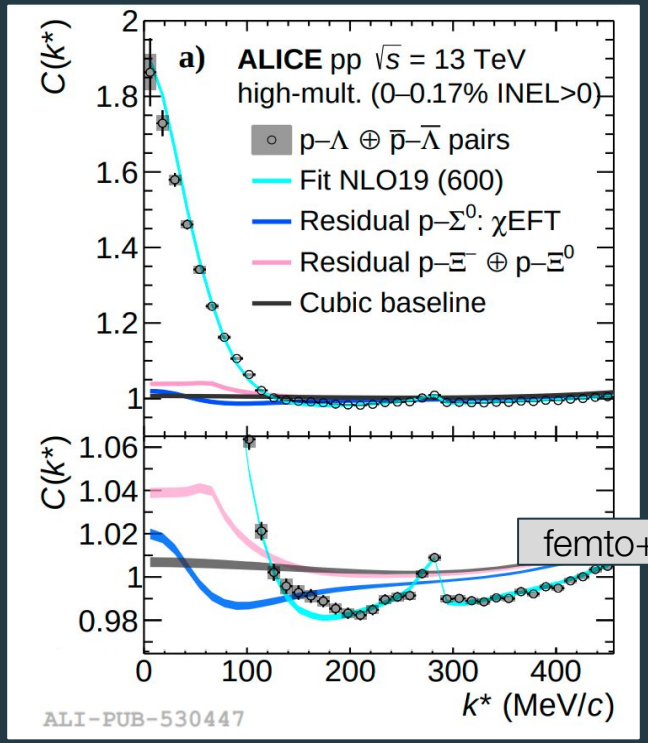


Λp femtoscopy in HM pp collisions

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

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

From femtoscopy data…to neutron stars



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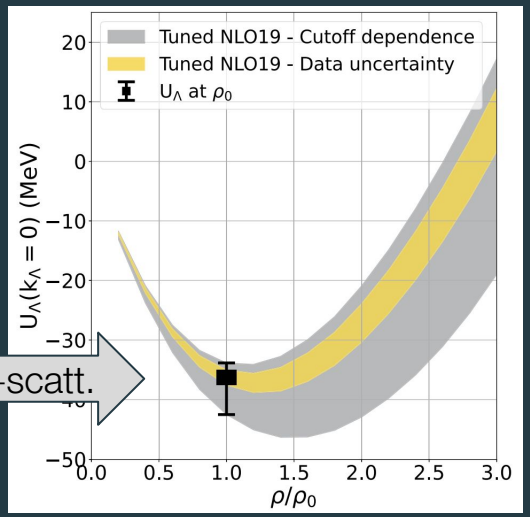
femto+scatt.



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

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

EoS of hypernuclear matter via chiral hyperon-nucleon interactions constrained by femtoscopic data and Lattice QCD
I. Vidaña et al., arXiv:2412.12729 [nucl-th]

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

New **Run 2 (2015-2018)** results: **Σ^+p femtoscopy in HM pp coll.**

New **Run 2 (2015-2018)** results: **Σ^+p femtoscopy in HM pp coll.**

First measurement of Σ^+p correlation function

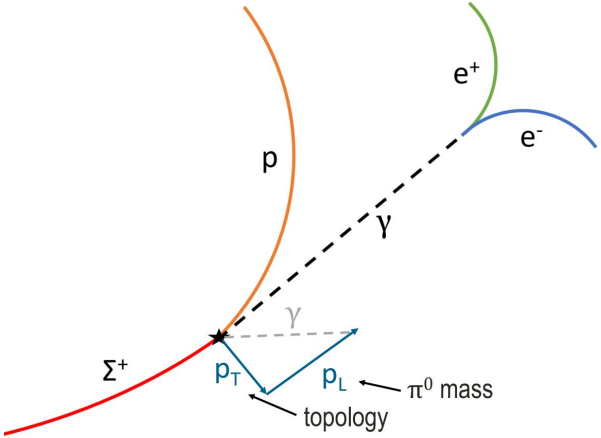
- $^1S_0$ channel of pΣ^+ interaction rather well known through NN (I=1) interaction
- $^3S_1$ not accessible through NN or ΛN interactions

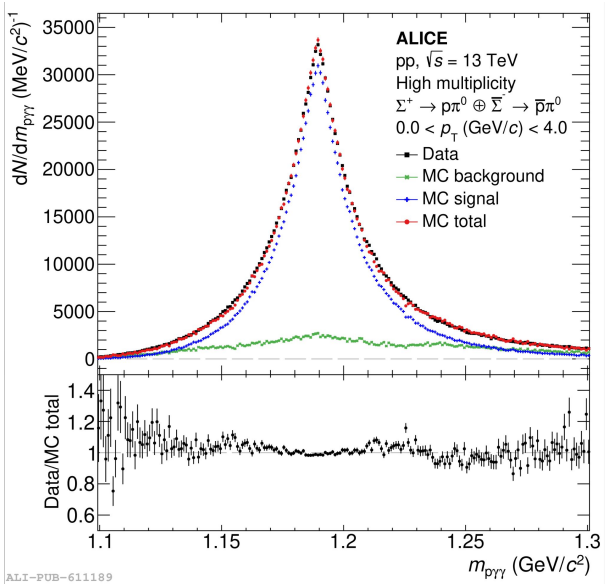
Reconstruction of $\Sigma^+ \rightarrow p\pi^0$ in ALICE Run 2 data

Identify only one photon and calculate missing momentum from topology and π^0 mass

⇒ Reconstruction efficiency improved by one order of magnitude

⇒ keeping a good momentum resolution →



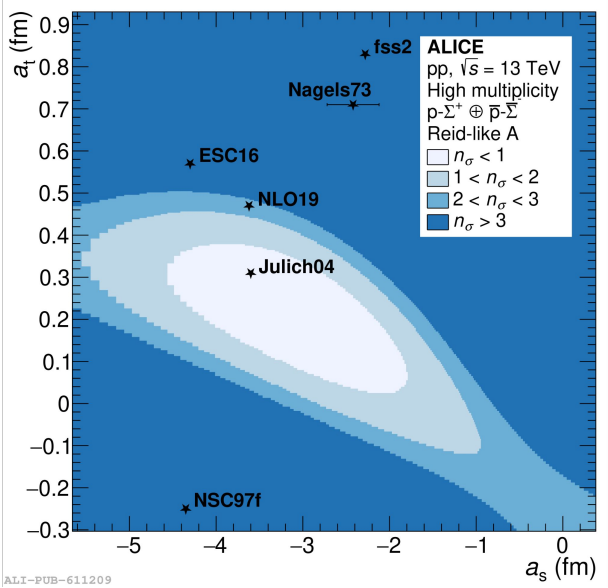


Σ^+p femtoscopy in pp HM collisions

χEFT YN interactions: Large spread in predictions
→ $^3S_1$ range from strong repulsion to moderate attraction

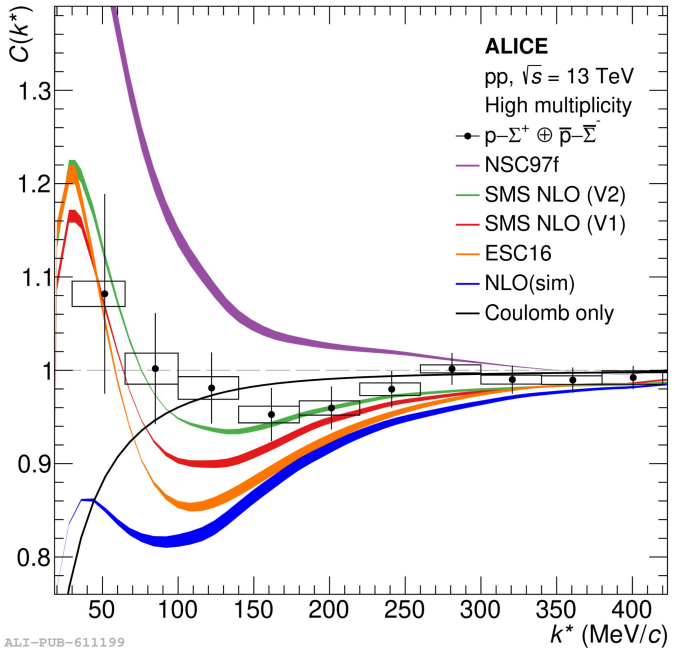
⇒ **Data constraining despite statistical uncertainties**
- Data very sensitive to triplet strength at high k*

➢ **Agreement with $^3S_1$ very shallow repulsion**



← Determination of scattering lengths from the correlation function via fitting of parameters from Reid-like potential

ALICE Coll. arXiv:2510.14448 [nucl-ex]

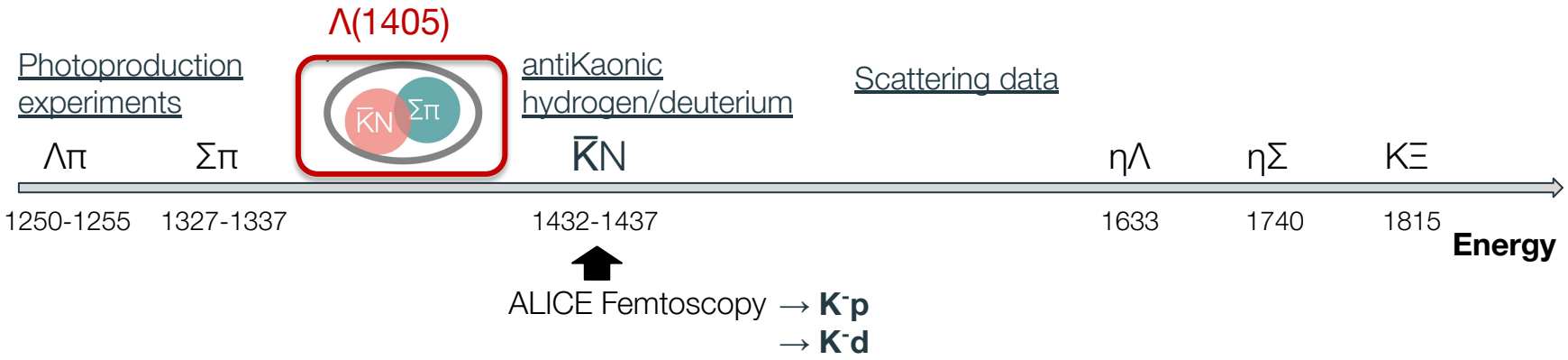


SMS NLO: J. Haidenbauer et al., Eur. Phys. J. A 56 (2020) 91
NSC97f: T. Rijken et al., Phys. Rev. C 59 (1999) 21
ESC16: M. Nagels et al., Phys. Rev. C 99 (2019) 044003
NLO(sim): J. Haidenbauer et al., Phys. Lett. B 829 (2022) 137074

S=-1 meson-baryon interaction

Meson-baryon interactions S =-1 ⇒ Presence of a **rich coupled-channel dynamics**

- Large attractive interaction in isospin I=0 channel → formation of Λ(1405)
- Chiral SU(3) EFT and calculations on the lattice: Molecular state with two poles $\bar{K}$N-Σπ



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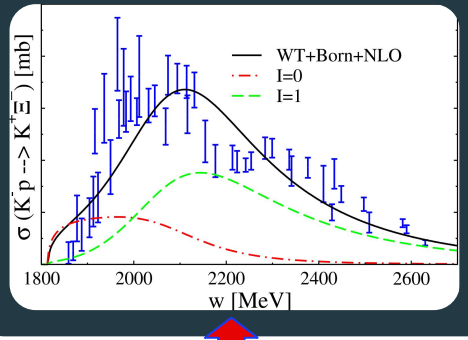
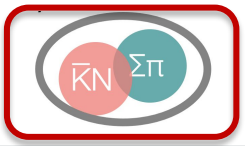
Incorporation of data up to KΞ energies A. Feijoo et al., PRC99, 035211 (2019)
→ Help on fixing of the NLO constants
→ Incorporate channels sensitive to the I=1 component



Λ(1405)



Photoproduction experiments

antiKaonic hydrogen/deuterium

Scattering data

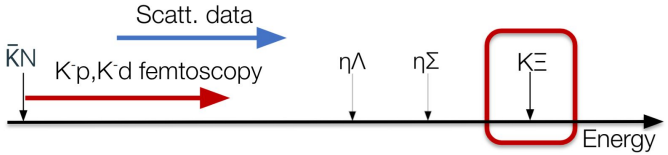
Λπ Σπ $\bar{K}N$ ηΛ ηΣ KΞ

1250-1255 1327-1337 1432-1437 1633 1740 1815 **Energy**

ALICE Femtoscopy → K^-p
→ K^-d

NEW Femtoscopy

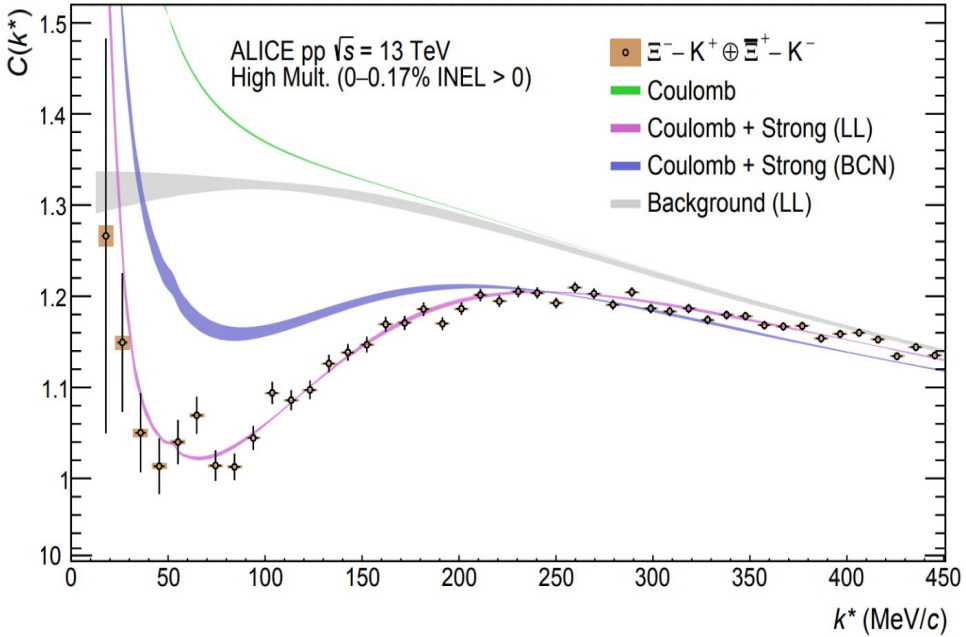
Ξ^-K^+ femtoscopy in HM pp collisions



Ξ^-K^+ correlation function

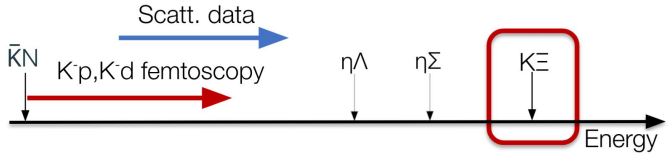
First ever data down to threshold in the Ξ^-K^+ channel

ALICE Coll. arXiv:2509.24519 [nucl-ex]



Baseline due to mini-jet induced correlations

Ξ^-K^+ femtoscopy in HM pp collisions



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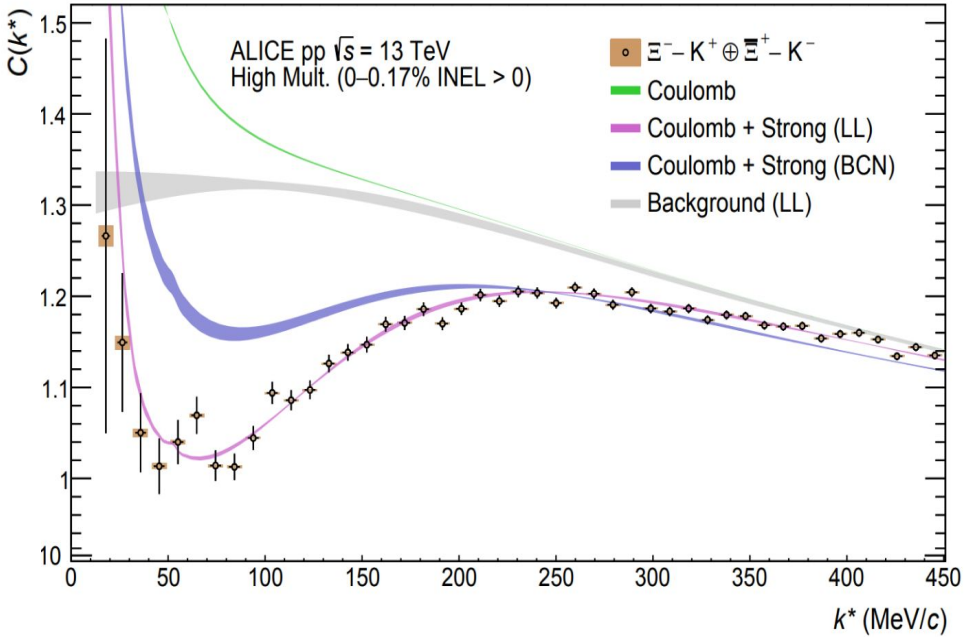

Baseline due to mini-jet induced correlations

Best fit: **Coulomb+repulsive strong interaction (LL)**

$$\Re f_0 = -0.61 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.}) \text{ fm}$$
$$\Im f_0 = 0.41 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.}) \text{ fm}$$

BCN model: NLO chiral Lagrangian constrained to scattering data **including Kp→ΞK reactions**

P. Encarnación et al., aXiv:2412.20880 [hep-ph]

Other models anchored to the same scattering data also deliver shallower repulsive strong interaction

H. Kamano et al., Phys. Rev. C 90, 065204 (2014)

Preliminary **Run 3 (2022-2026)** results

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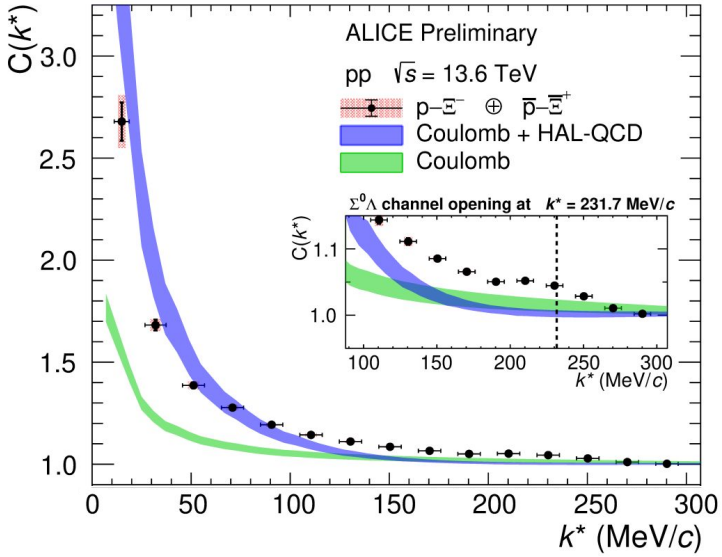


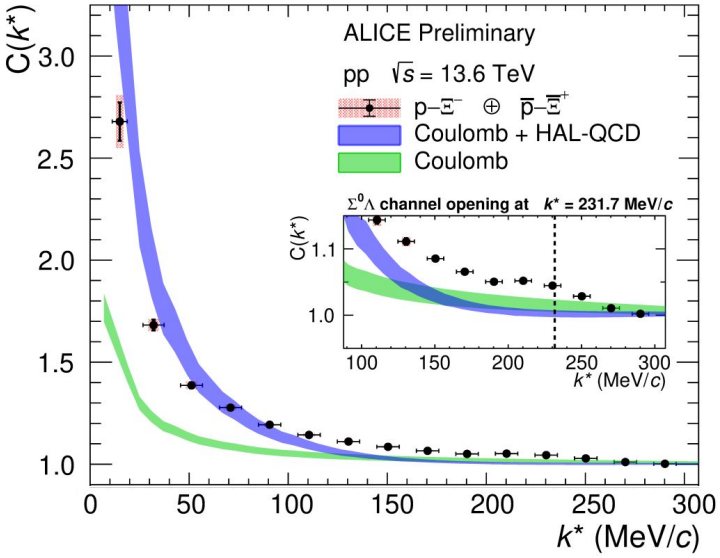
ALI-PREL-603893

➡ **pΞ⁻ femtoscopy in pp collisions at 13.6 TeV**

Larger statistics with respect to Run 2 enable resolving **cusp at the $\Sigma^0\Lambda$ channel** opening and poses stringent test to Lattice QCD

- Coupling in I=1 channel, measuring helps constraining the isospin dependence

Preliminary **Run 3 (2022-2026)** results



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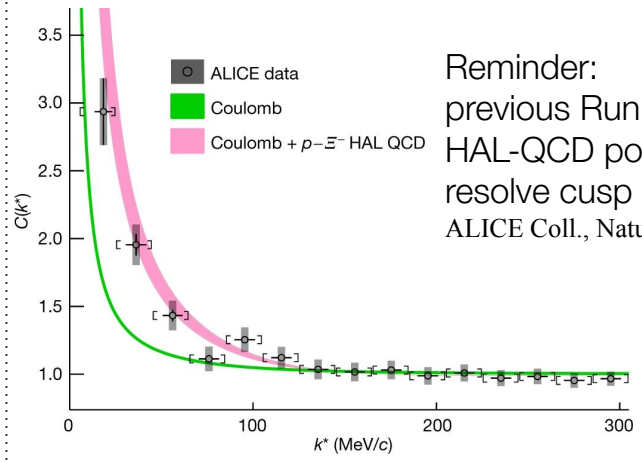
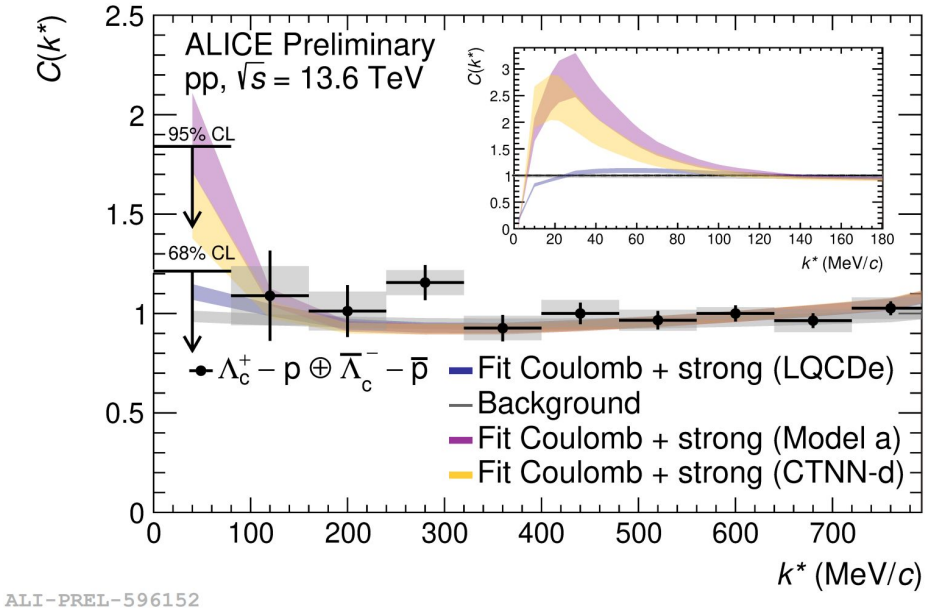


Reminder:
previous Run 2 result validated HAL-QCD potential but does not resolve cusp
ALICE Coll., Nature 588, 232 (2020)

Preliminary **Run 3 (2022-2026)** results



ALI-PREL-596152

➡ Λ_c^+p femtoscopy in pp coll. at 13.6 TeV

Accessing (the lightest) charmed hypernuclei:

- c-deuteron can only exist if charm baryon-nucleus strong interaction is attractive enough

⇒ So far data favors slight attraction

LQCDe: Haidenbauer, Krein, EPJA 56 (2020) 7, 184
Haidenbauer, Krein, EPJA 54, 199 (2018)
Model a: Vidaña, Ramos, Jimenez-Tejero, PRC 99, 045208 (2019)
CTNN-d: Maeda, Oka, Yokota, Hiyama, Liu, PTEP 2016, 023D02 (2016)

Upcoming: analysis of triggered data collected since 2023

Special guest: **$\pi^{\pm}$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]

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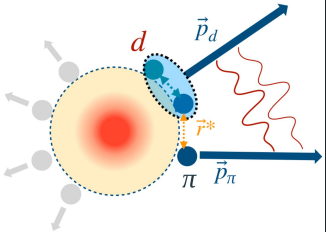
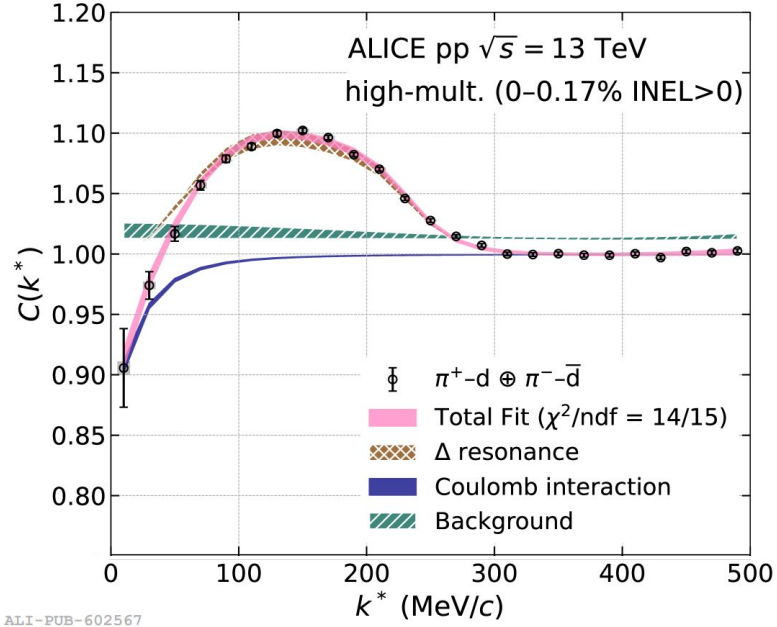
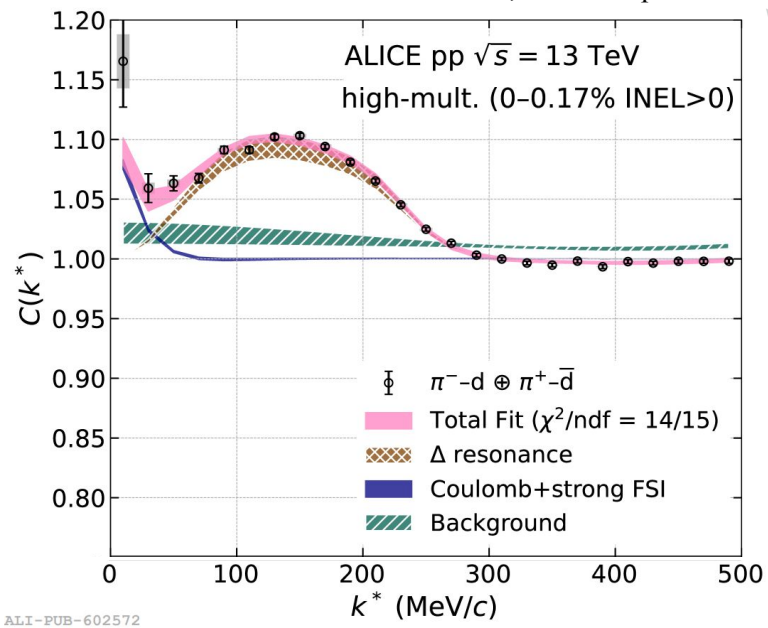
Correlation function of π±d pairs in pp collisions:

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

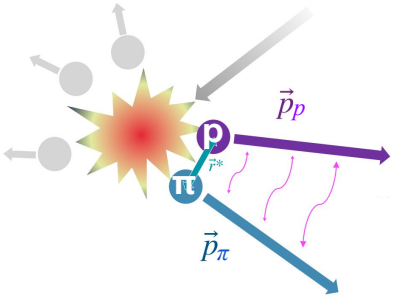


ALICE Coll. arXiv:2504.02393, Nature in press.





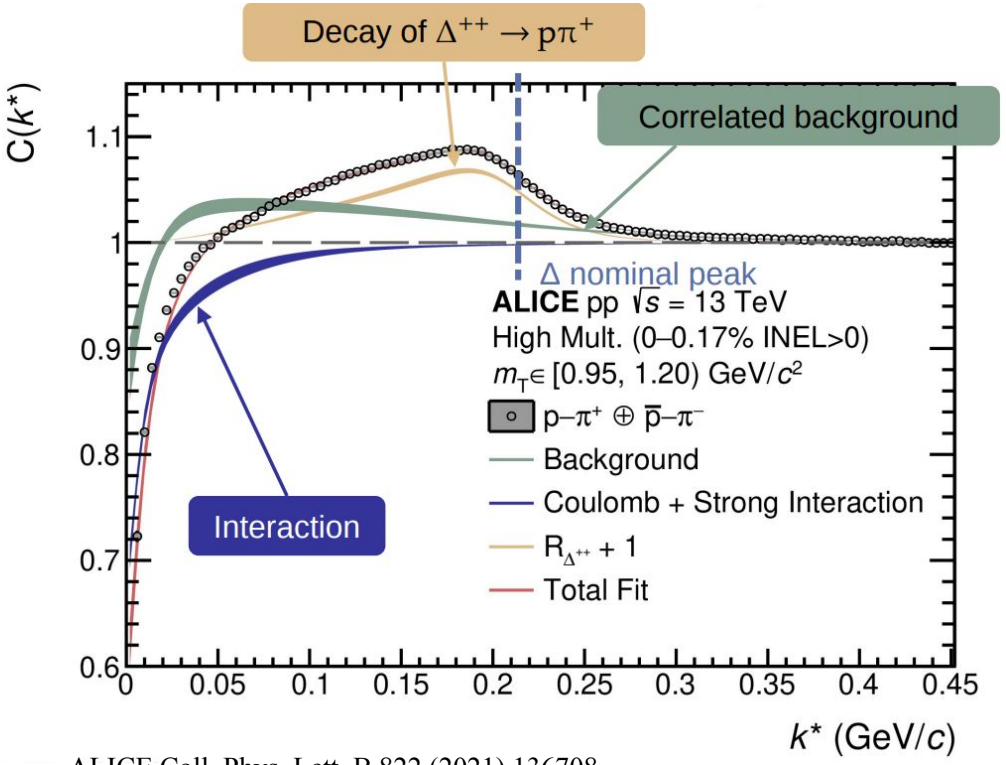
Features of **π±-proton femtoscopy** in HM pp coll. at 13 TeV



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)

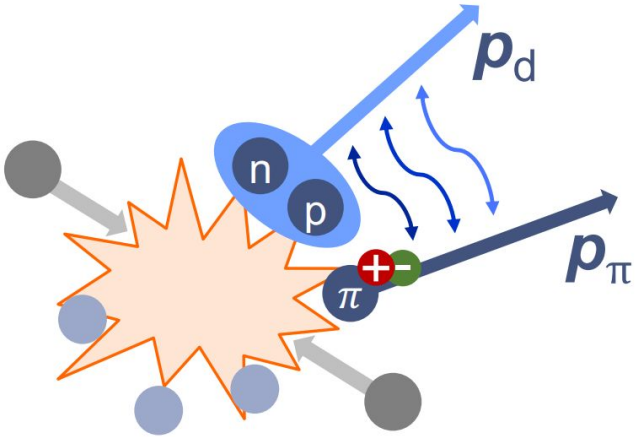
$$PS(p_T, T) \propto \frac{m}{\sqrt{m^2+p_T^2}} \times \exp\left(-\frac{\sqrt{m^2+p_T^2}}{T}\right)$$

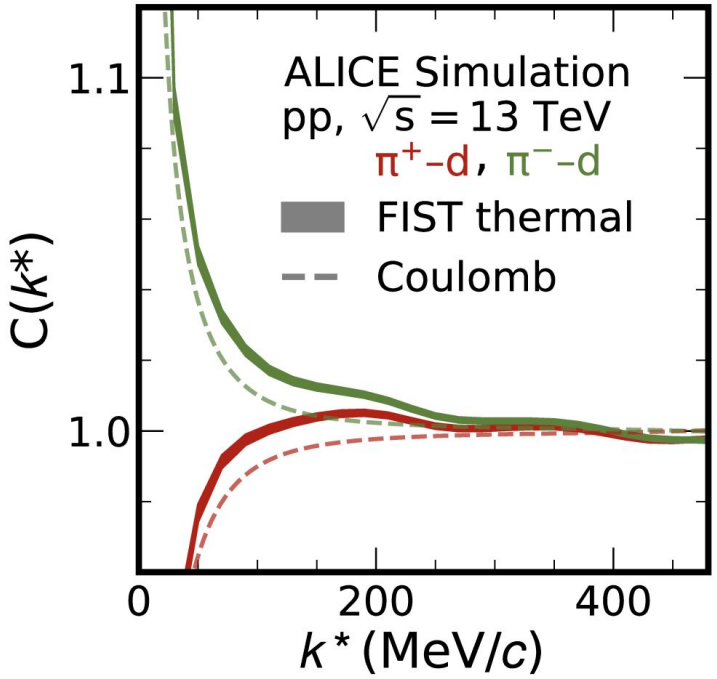


ALICE Coll. Phys. Lett. B 822 (2021) 136708

Simulations for the **$\pi^{\pm}$d correlation function** in pp

➡ **Thermal FIST + Coulomb gives FSI-only baseline**



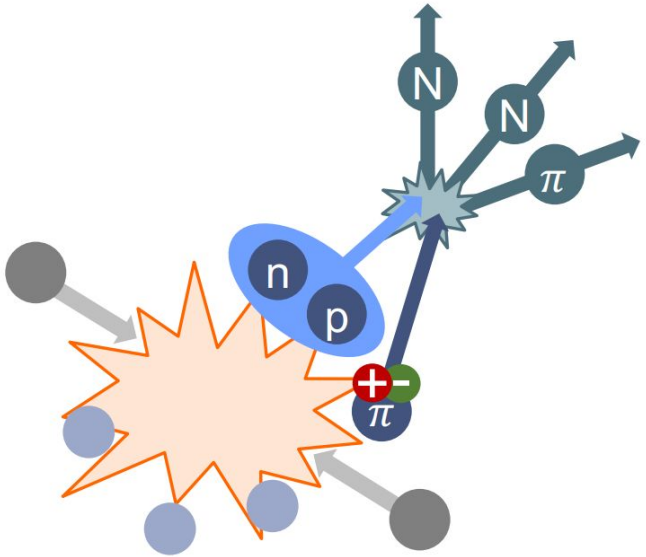


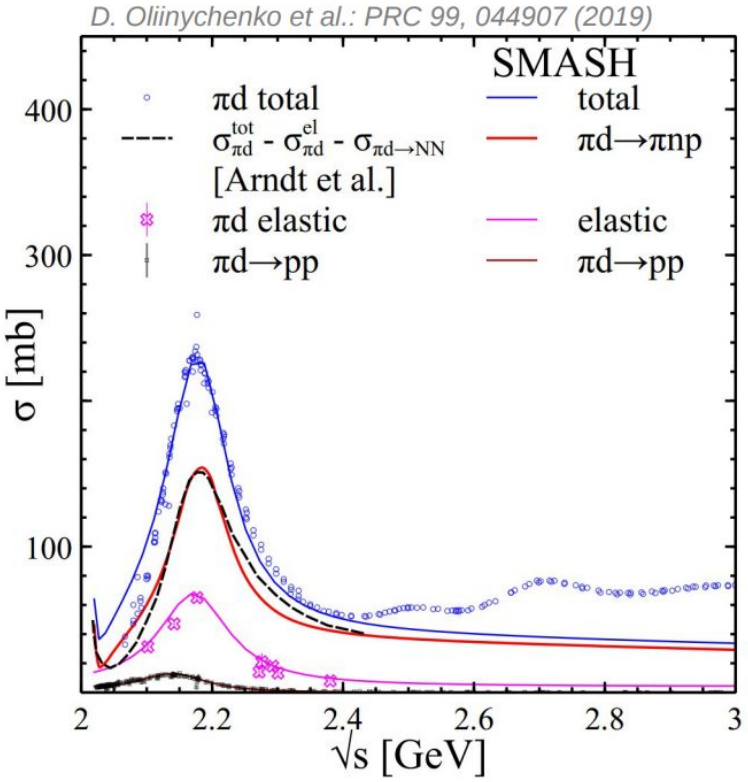
Simulations for the **$\pi^{\pm}$d correlation function** in pp

Thermal FIST + Coulomb gives FSI-only baseline

Coulomb + elastic + inelastic interaction

- Inelastic channel dominant
- FIST + SMASH: reduction due to deuteron destruction



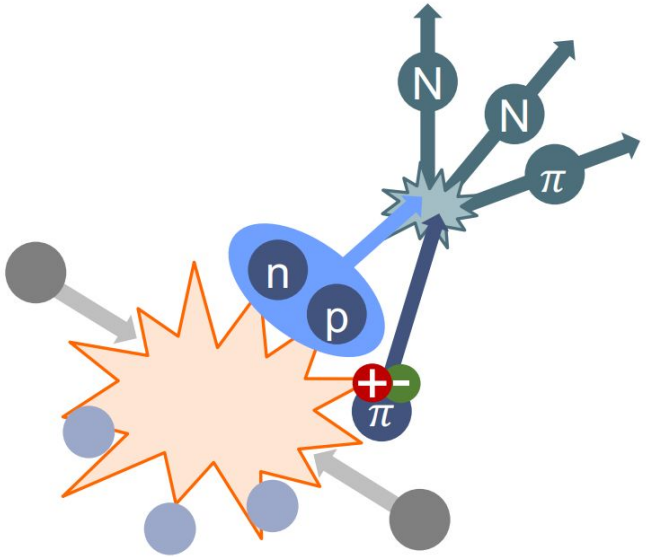


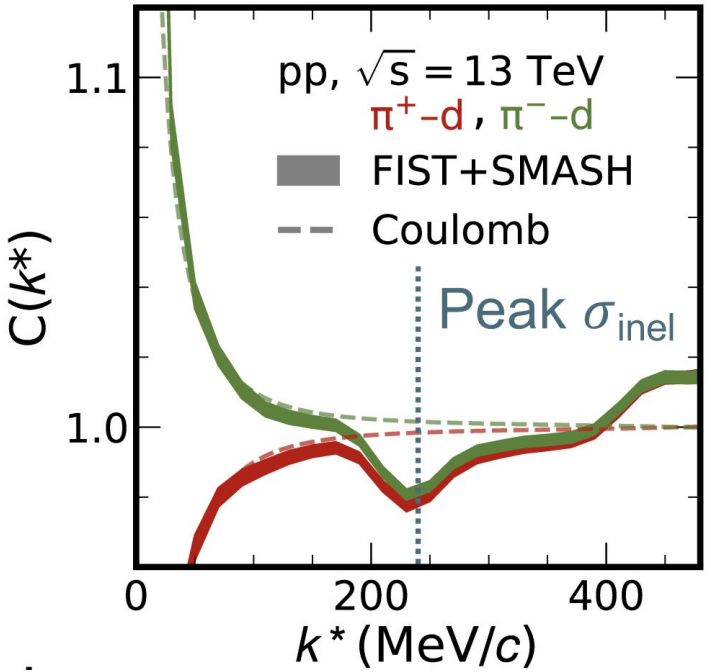
Simulations for the **$\pi^{\pm}$d correlation function** in pp

Thermal FIST + Coulomb gives FSI-only baseline

Coulomb + elastic + inelastic interaction ⇒ **depletion**

- Inelastic channel dominant
- FIST + SMASH: reduction due to deuteron destruction





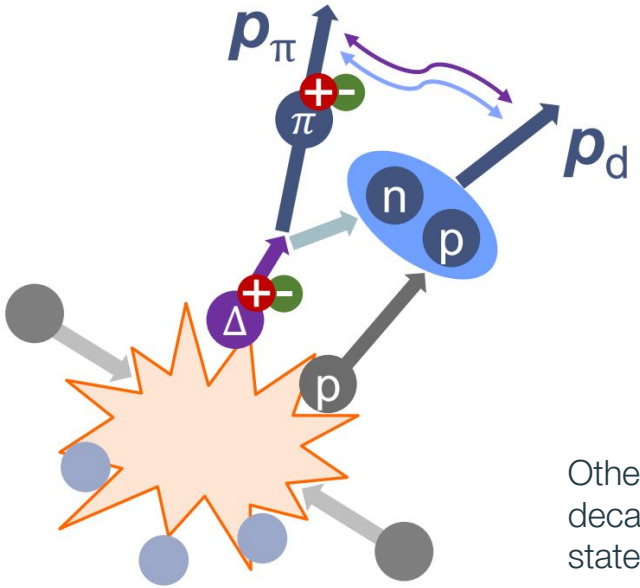
Simulations for the **$\pi^{\pm}$d correlation function** in pp

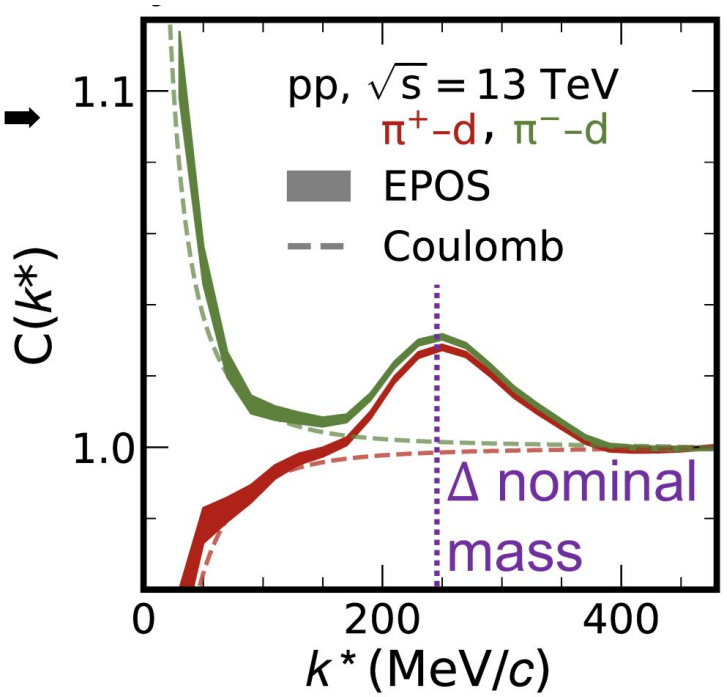
Thermal FIST + Coulomb gives FSI-only baseline
Coulomb + elastic + inelastic interaction ⇒ depletion

- **<u>Nuclear fusion after Δ decay explains the bump</u>** ➡

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

Enhancement caused by Δ decay inherited during fusion process

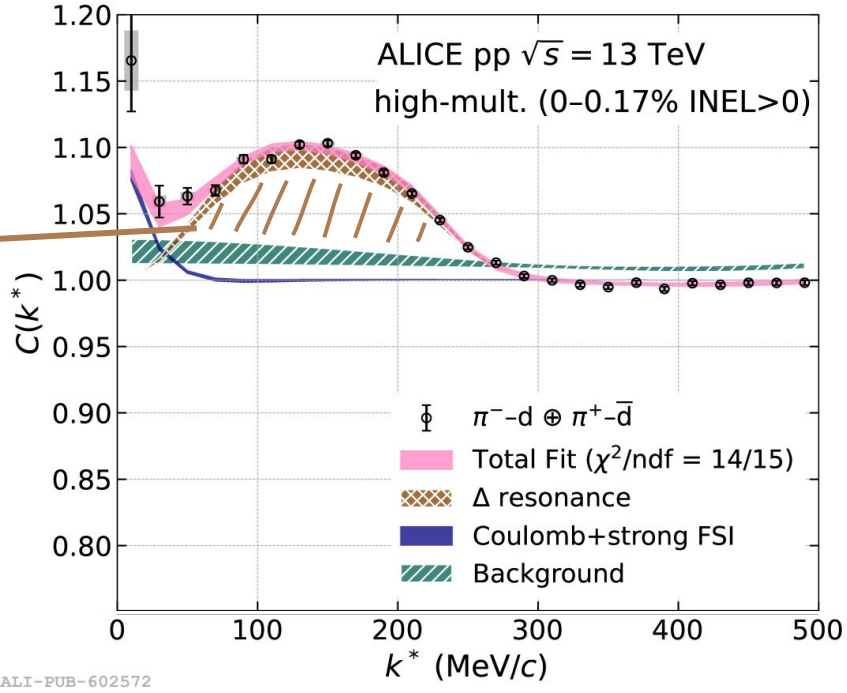
Fraction of deuterons from Δ decay from bump yield

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

Extrapolation considering all possible resonances decays:

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

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



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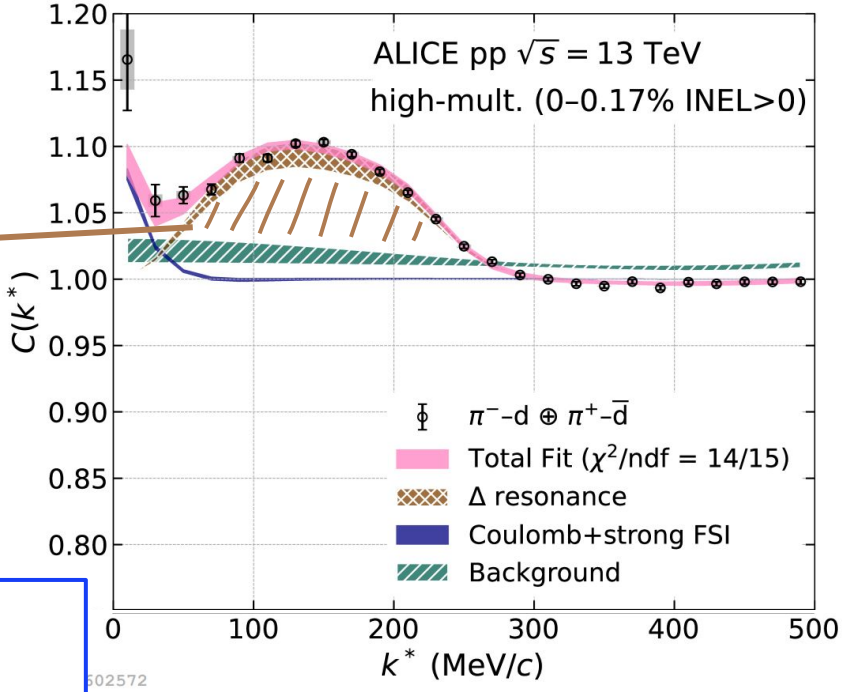


"Observation of deuteron and antideuteron formation from resonance decay nucleons" ALICE Coll. arXiv:2504.02393 Nature in press (11-Dec-2025)

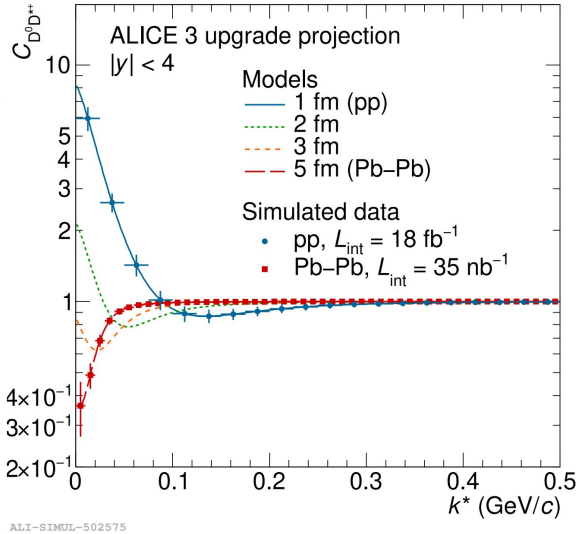
- ➡ The only scenario compatible with the data is **nuclear formation by fusion process**
- ➡ The obtained **fraction of deuterons from resonances compatible with coalescence model prediction**

Conclusions and outlook

Femtoscopy is 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 moving to charm! ⇒

Thank you for your attention!