Addressing hadron interactions and exotic states via femtoscopy

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INFN LNF Istituto Nazionale di Fisica Nucleare

Fundamental Physics with Exotic Atoms - June 23, 2025 Frascati

The femtoscopy method in nucleus nucleus collisions

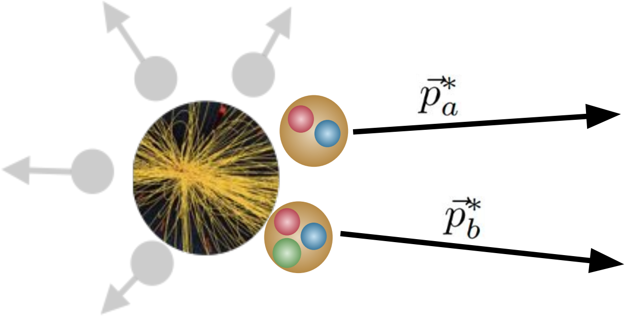
Accessing hadronic final-state interaction with correlation functions measured in pp collisions

M. Lisa, S. Pratt et al, Annu. Rev. Nucl. Part. Sci.. 55 (2005), 357-402, L. Fabbietti, V. Mantovani Sarti and O. Vazquez Doce Annu. Rev. Nucl. Part. Sci. 71 (2021), 377-402

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

particle source two-part. wave-function

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



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

* in pair rest frame

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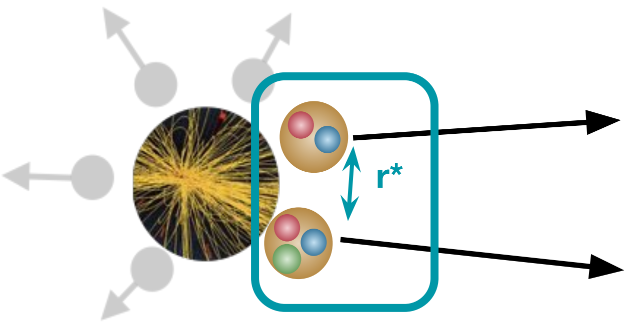


Particle-emitting source:

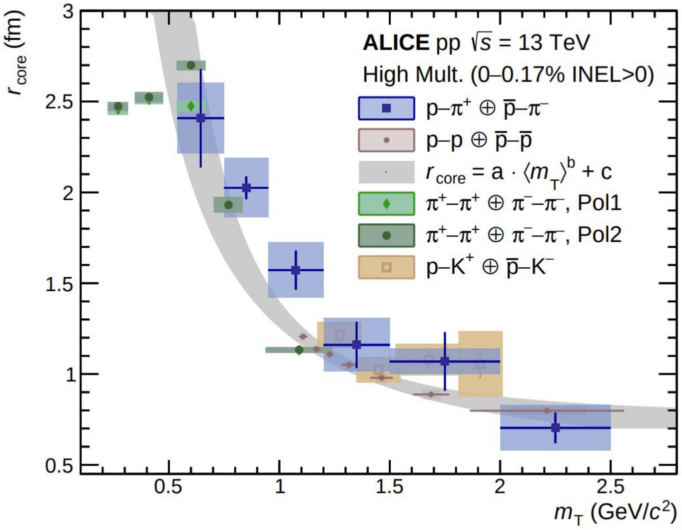
- pp: r* ~ 1fm
- HI: r* ~ 3-10 fm

ALICE Coll. Phys. Lett. B 811 (2020) 135849; Phys. Lett. B 861 (2025) 139233, Eur. Phys. J. C (2025) 85:198, arXiv:2502.20200 [nucl-ex]

Determination of the hadron-hadron source size in pp collisions →

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

* in pair rest frame



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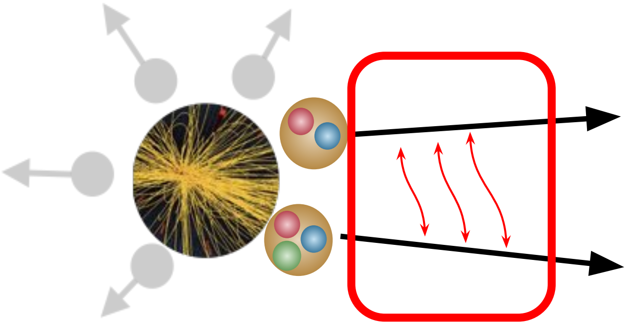


$$k^* = \frac{|\vec{p}_a^* - \vec{p}_b^*|}{2}$$

* in pair rest frame

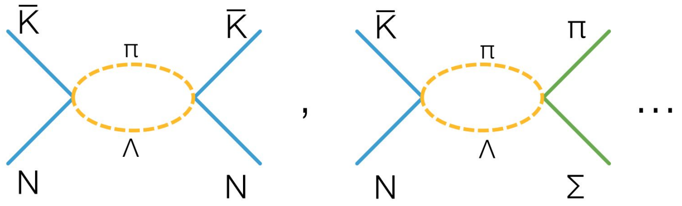
Two-particle wave function:
<u>For known source ⇒ Study the interaction</u>

We can test, for example, a local potential
⇒ **test Lattice QCD predictions of di-baryon bound states with strangeness!**

(Multi-)strange meson-baryon systems and exotic states

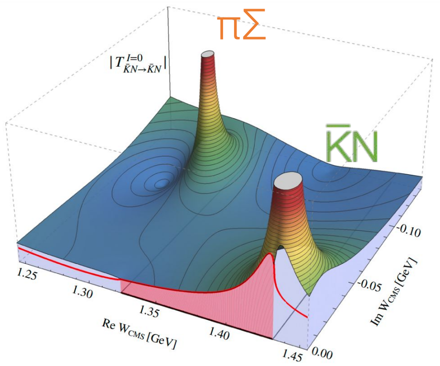
Interactions between mesons and baryons involving strangeness
→ Landmark for hadron-hadron interaction studies
→ Possibility to study nature and properties of exotic states

Presence of a **rich coupled-channel dynamics**
→ Systems sharing same quantum numbers (B,S,Q) relatively close in mass
→ On- and off-shell processes from one channel to the other



Several candidates for exotic states with **molecular nature**
→ Typically observed close to channel thresholds
→ Main example given by the **two-pole Λ(1405) state**

J. M.M. Hall et al. Phys. Rev. Lett. 114 (2015) 13
U. G. Meißner Symmetry 12 (2020) 6, 981



M. Mai Eur. Phys. J. Spec. Top. 230, 1593–1607 (2021)

S=-1 meson-baryon interaction

Large attractive interaction in isospin I=0 channel

→ Responsible for formation of Λ(1405) below $\bar{K}N$ threshold

Scarce statistics available from scattering data above $\bar{K}N$ threshold

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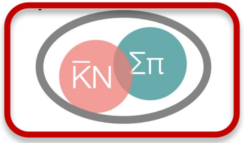
Photoproduction experiments

Λ(1405)



antiKaonic hydrogen

SIDDHARTA Coll. PLB 704 (2011)

Scattering experiments

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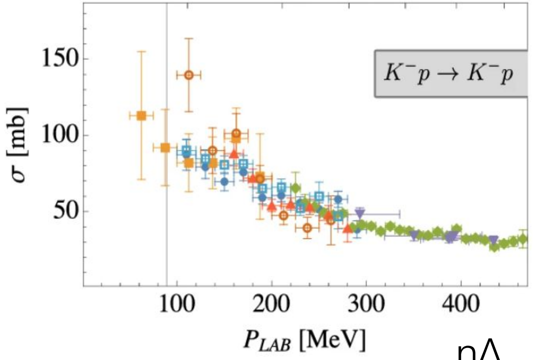


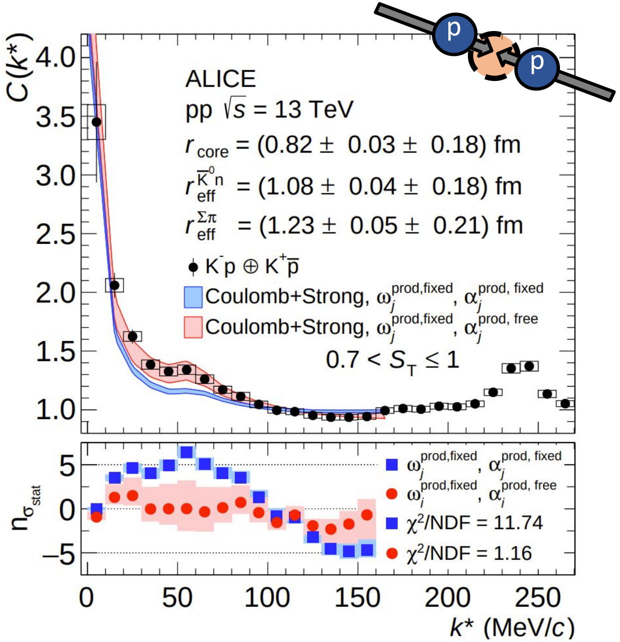
Λπ	Σπ	K̄N	ηΛ	ηΣ	KΞ	
1250-1255	1327-1337	1432-1437	1633	1740	1815	**Energy**

High-precision data on S=-1 sector above threshold

Femtoscopy delivers the **most precise data above K^{-}-p threshold**
→ Crucial input for low-energy chiral effective potentials
Provides a **quantitative test of coupled channels**

Data:
ALICE Coll. Phys. Rev. Lett. 124, 092301 (2020)
ALICE Coll. Eur. Phys. J. C 83, 340 (2023)

Strong interaction: Kyoto model
K. Miyahara et al., Phys. Rev. C98, 2, (2018) 025201



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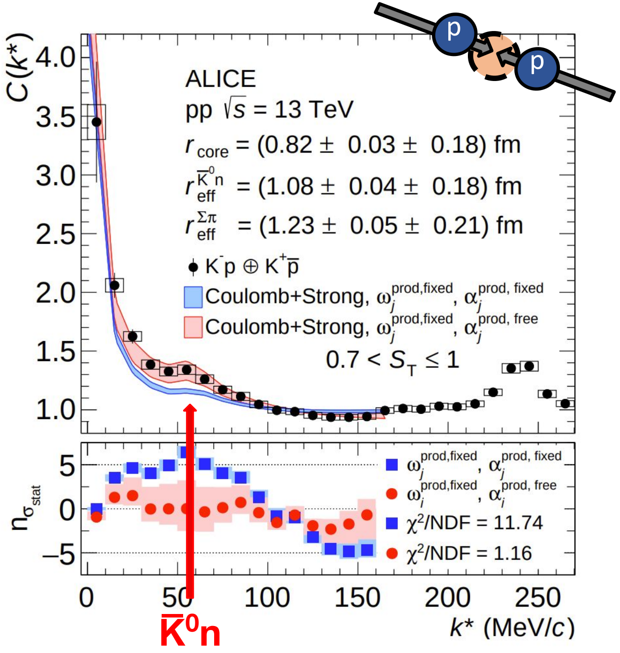

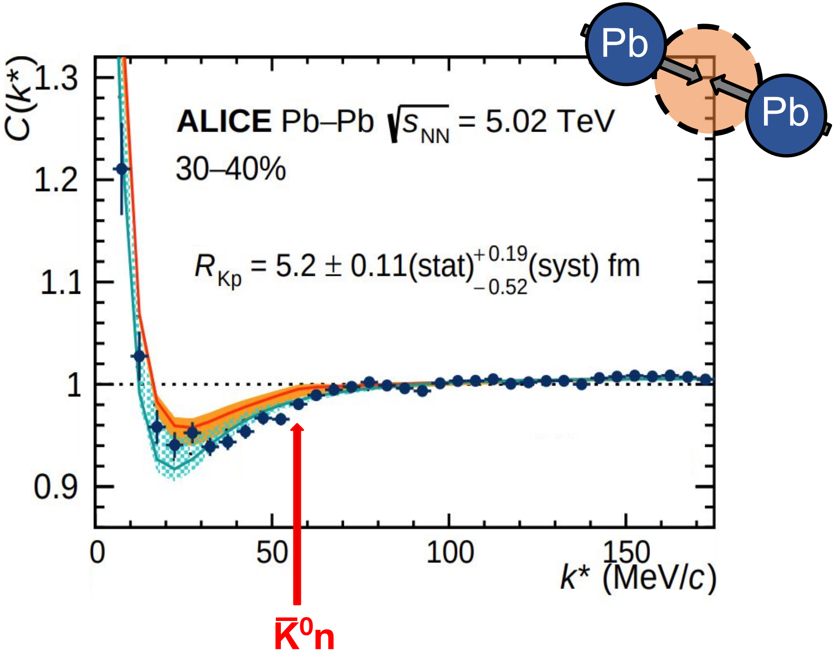

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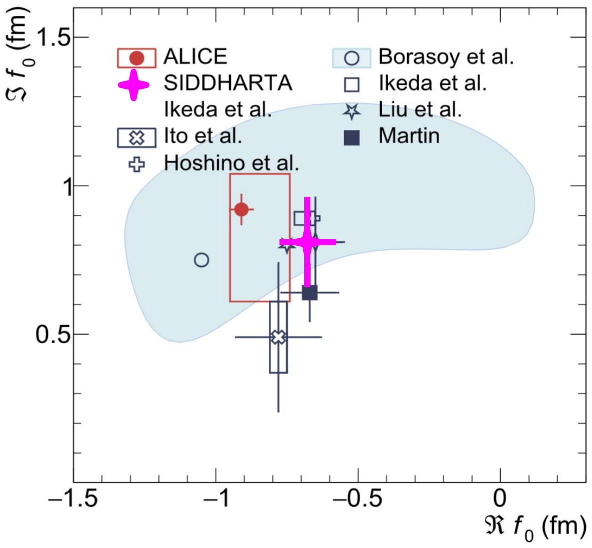
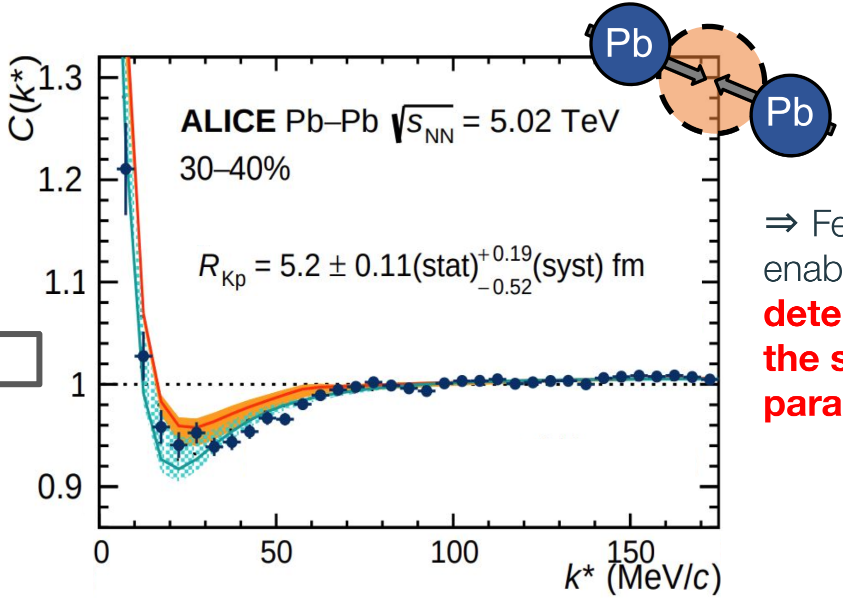
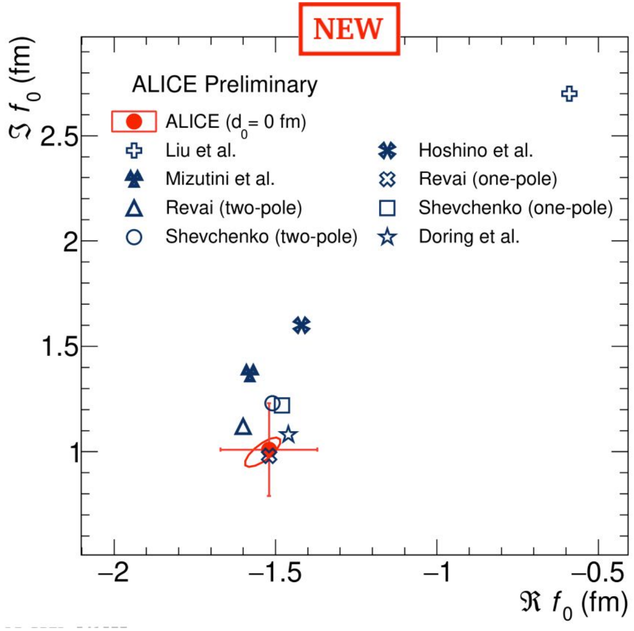




⇒ Femtoscopy data enables the **determination of the scattering parameters**

K^-d Femtoscopy with ALICE in Pb-Pb collisions

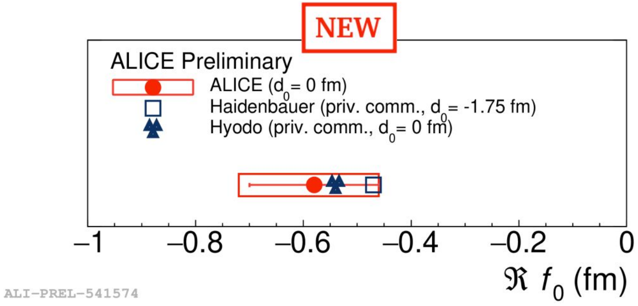


W. Resza @ Hadron 2023

Fit to K^-d correlation function:

Simultaneous fit with 6 free parameters with Lednicky wave function

- Re. K^+d scatt. length
- Re., Im. K^-d scatt. length
- r_0 x3 centralities



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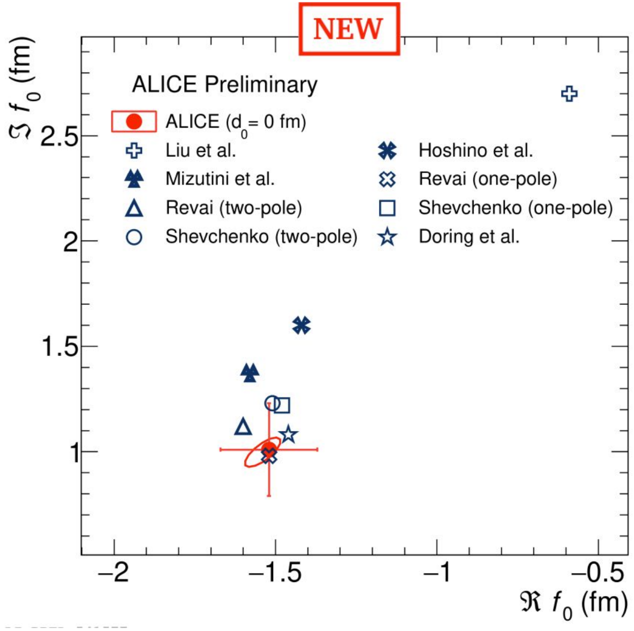

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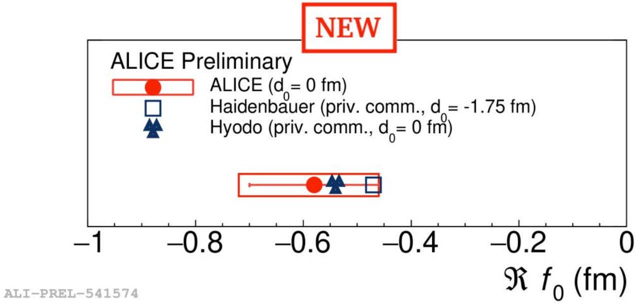


What other data can help?

Parameter fixing in EFTs

- KbarN interaction: Chiral SU(3) dynamical approach.
- **From LO to NLO, N²LO… from s to s+p, s+p+d waves**

  ⇒ more parameters to be fixed (by data)

A. Feijoo @ HYP2022

- **Next to leading order (NLO),** just considering the **contact term**

$$\begin{aligned}\mathcal{L}_{\phi B}^{(2)} &= b_D\langle\bar{B}\{\chi_+,B\}\rangle + b_F\langle\bar{B}[\chi_+,B]\rangle + b_0\langle\bar{B}B\rangle\langle\chi_+\rangle + d_1\langle\bar{B}\{u_\mu,[u^\mu,B]\}\rangle \\ &+d_2\langle\bar{B}[u_\mu,[u^\mu,B]]\rangle + d_3\langle\bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle\bar{B}B\rangle\langle u^\mu u_\mu\rangle \\ &-\frac{g_1}{8M_N^2}\langle\bar{B}\{u_\mu,[u_\nu,\{D^\mu,D^\nu\}B]\}\rangle - \frac{g_2}{8M_N^2}\langle\bar{B}[u_\mu,[u_\nu,\{D^\mu,D^\nu\}B]]\rangle \\ &-\frac{g_3}{8M_N^2}\langle\bar{B}u_\mu\rangle\langle[u_\nu,\{D^\mu,D^\nu\}B]\rangle - \frac{g_4}{8M_N^2}\langle\bar{B}\{D^\mu,D^\nu\}B\rangle\langle u_\mu u_\nu\rangle \\ &-\frac{h_1}{4}\langle\bar{B}[\gamma^\mu,\gamma^\nu]Bu_\mu u_\nu\rangle - \frac{h_2}{4}\langle\bar{B}[\gamma^\mu,\gamma^\nu]u_\mu[u_\nu,B]\rangle - \frac{h_3}{4}\langle\bar{B}[\gamma^\mu,\gamma^\nu]u_\mu\{u_\nu,B\}\rangle \\ &-\frac{h_4}{4}\langle\bar{B}[\gamma^\mu,\gamma^\nu]u_\mu\rangle\langle u_\nu,B\rangle + h.c.\end{aligned}$$

New terms taken into account (the g_1–g_4 and h_1–h_4 terms)

- $b_0, b_D, b_F, d_1, d_2, d_3, d_4, g_1, g_2, g_4, h_1, h_2, h_3, h_4$ are not well established, so they should be treated as parameters of the model!

S=-1 meson-baryon interaction

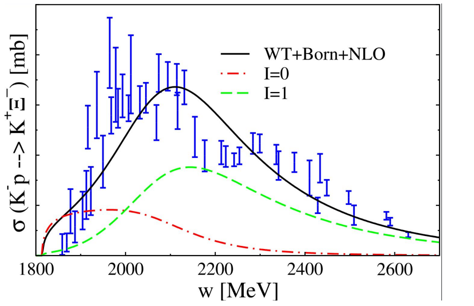
Large attractive interaction in isospin I=0 channel

→ Responsible for formation of Λ(1405) below K̅N threshold

Scarce statistics available from scattering data above K̅N threshold

Sensitivity to I=1 component

A. Feijoo et al., Phys. Rev. C99, 035211 (2019)



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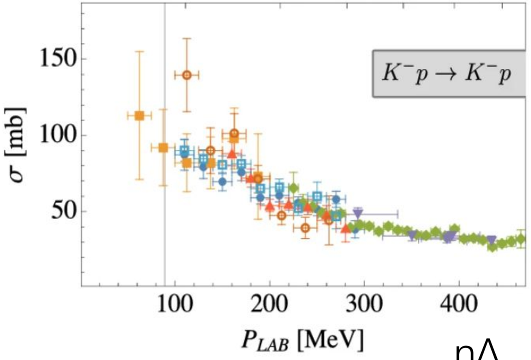
M. Mai Eur. Phys. J. Spec. Top. 230, 1593 (2021)



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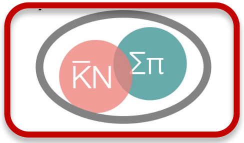


Λπ — 1250-1255

Σπ — 1327-1337

K̅N — 1432-1437

ηΛ — 1633

ηΣ — 1740

KΞ — 1815

Energy

Femtoscopy delivers high-precision data close to threshold and on several inelastic channels

Accessing the Ξ^-K^+ system with femtoscopy

Most precise data at low momenta on the interaction between Ξ and kaons

→ Important constraints for **I=1 channel** of S=-1 meson-baryon interaction

Modeled assuming Lednický-Lyuboshits wavefunction with Coulomb (S-wave only)

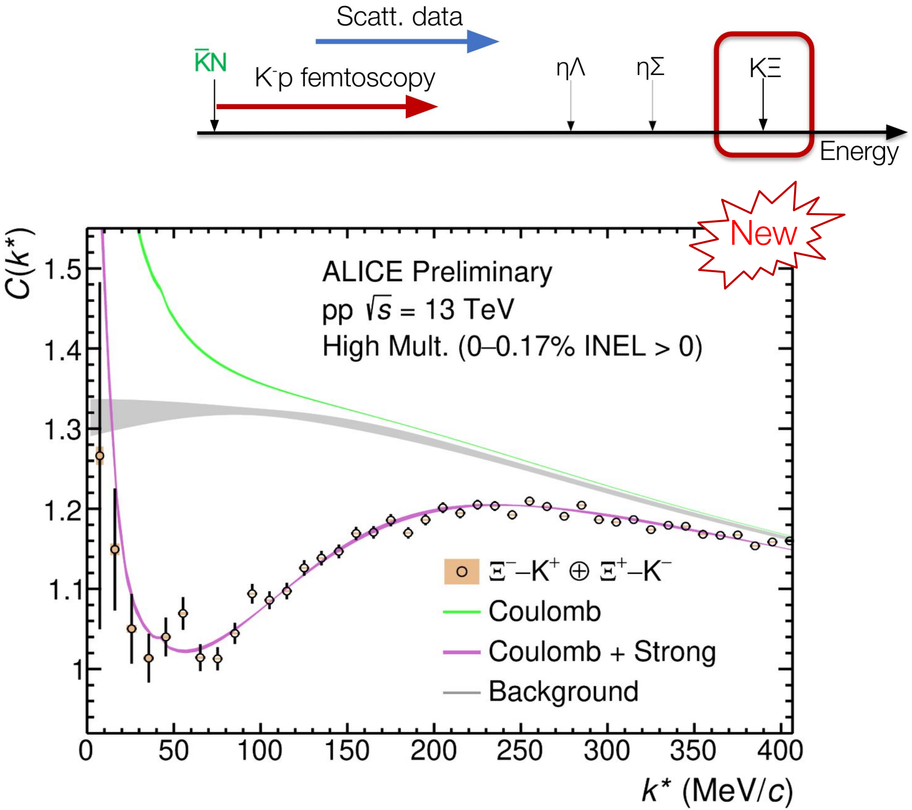
R. Lednický, Phys. Part. Nucl. 40: 307-352 (2009)

→ Coulomb + strong repulsive interaction assumption agrees with the data

Determination of scattering length from best fit

$$\Re f_0 = -0.61^{\pm 0.02(stat)}_{\pm 0.07(syst)}$$

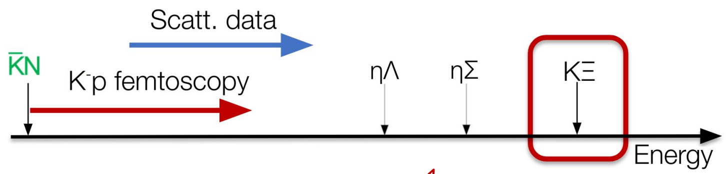
$$\Im f_0 = \mathbf{0.41}^{\pm \mathbf{0.04}(stat)}_{\pm \mathbf{0.11}(syst)}$$



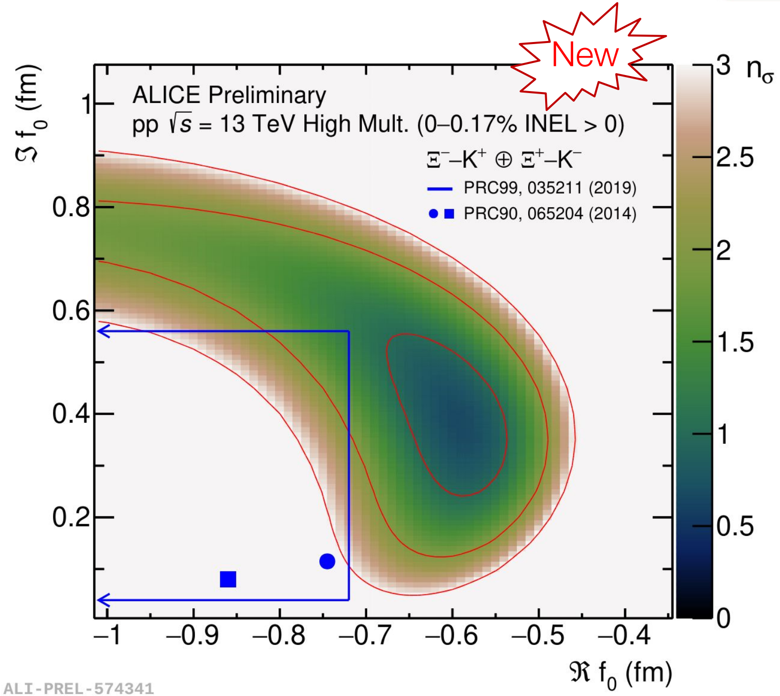
Constraining the Ξ^-K^+ scattering parameters

Comparison of data with modeling assuming different values of ($\Re f_0$, $\Im f_0$)

→ Delivered in terms of number of standard deviations (n_σ) in $k^* \in [0,250]$ MeV/c



Allowed values for f_0 from **state-of-the-art chiral calculations** at next-to-leading order and phenomenological potentials **constrained** to **available scattering data**



Higher precision constraints can be delivered with correlation data

Moving to the S=-2 sector

Scattering experiments challenging with increasing strangeness

→ $\Xi(1620)$ lying across the $\bar{K}\Lambda$ threshold as molecular candidate, poorly known

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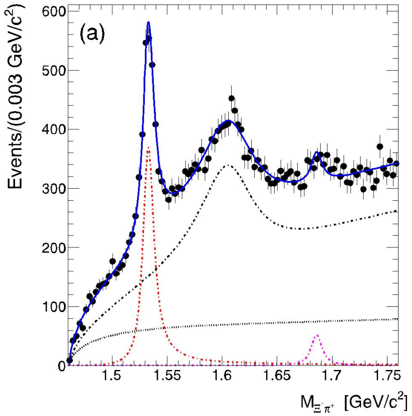
Scattering experiments challenging with increasing strangeness

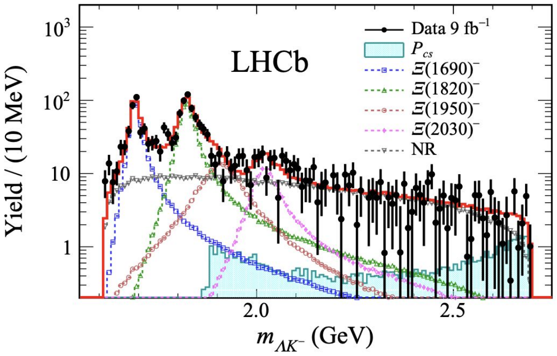
→ Ξ(1620) lying across the $\bar{K}\Lambda$ threshold as molecular candidate, poorly known

Intensive searches via spectroscopy measurements

→ Combine different production mechanisms/decay channels to reveal the nature of the state

Ξ(1620)
Belle Coll.,
Phys. Rev. Lett 122 (2019)





Ξ(1690)
LHCb Coll.
Sci. Bull. 66 (2021)

Ξπ	$\bar{K}\Lambda$	$\bar{K}\Sigma$	ηΞ	
1449-1461	1609-1613	1683-1691	1870	**Energy**

Moving to the S=-2 sector

Scattering experiments challenging with increasing strangeness

→ Ξ(1620) lying across the K̄Λ threshold as molecular candidate, poorly known

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Belle Coll.,
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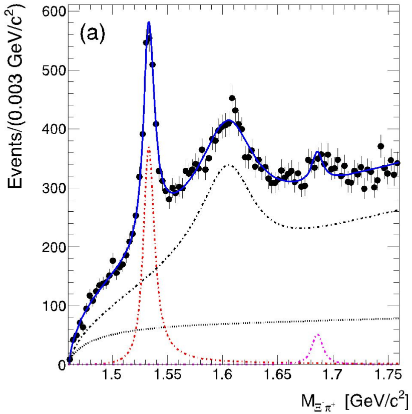

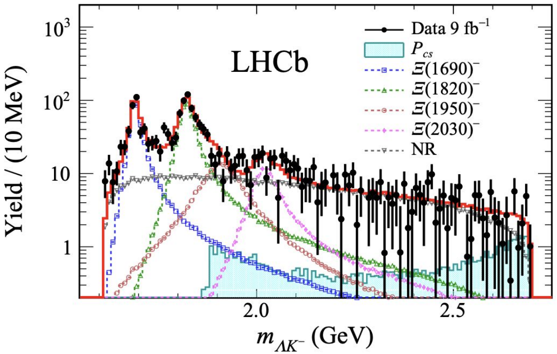

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Ξπ	K̄Λ	K̄Σ	ηΞ	
1449-1461	1609-1613	1683-1691	1870	**Energy**

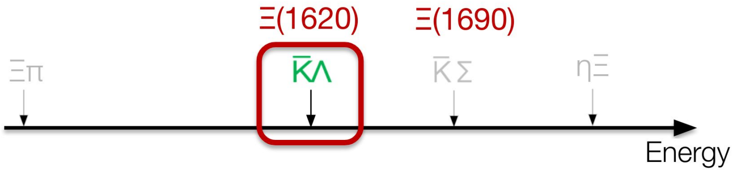
Femtoscopy approach: accessing the interaction between the constituents

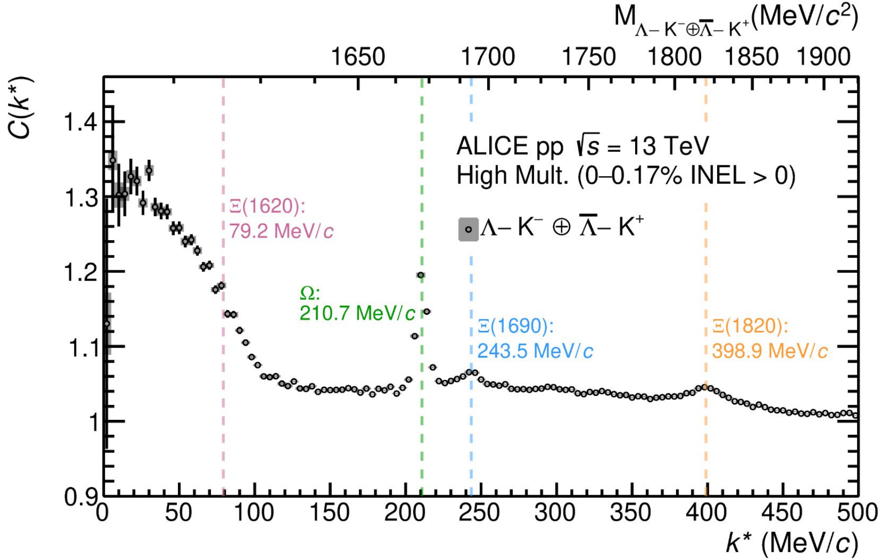
Accessing the S=-2 meson-baryon interaction

Extending previous Pb–Pb femtoscopic measurements to pp collisions

Pb–Pb: ALICE Coll. Phys. Rev. C 103 (2021)
pp: ALICE Coll. Phys. Lett. B 845 (2023) 138145

Several structures present in the measured correlation





ALI-PUB-562688

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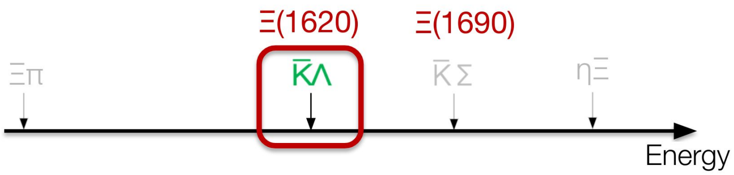
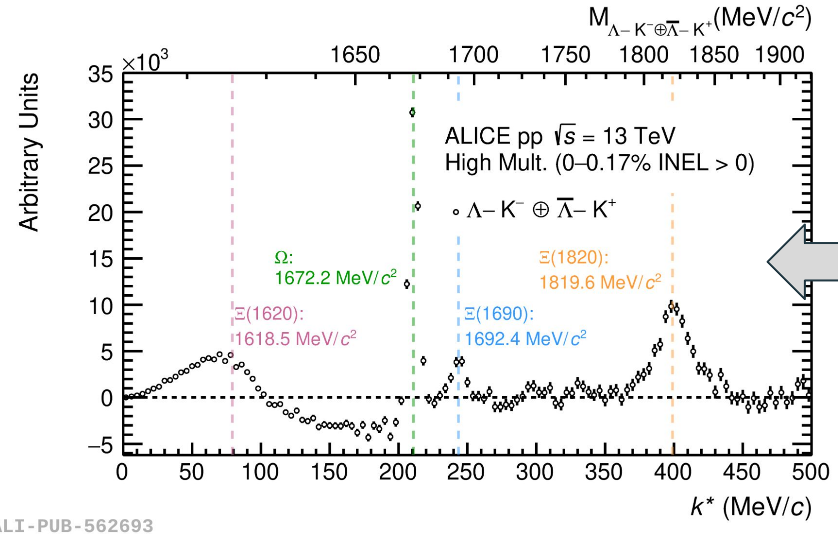


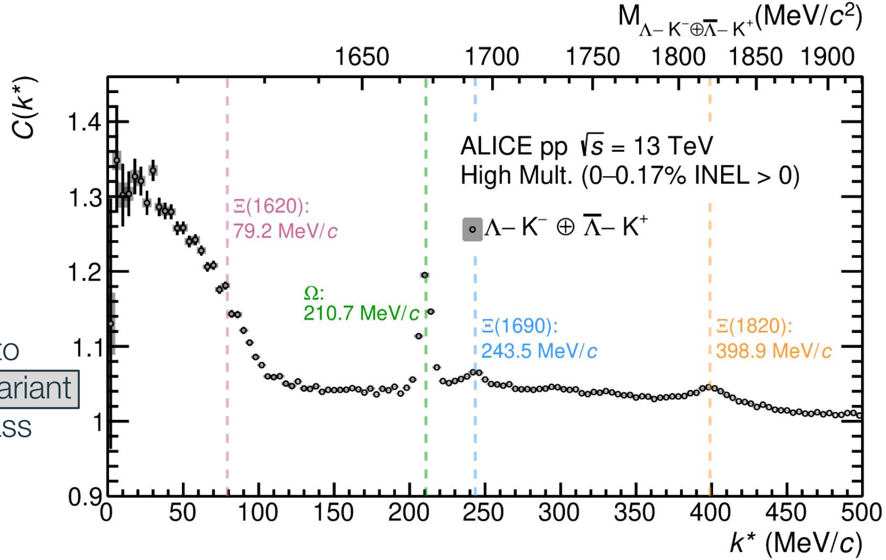
Several structures present in the measured correlation

⇒ First experimental evidence of Ξ(1620)⟶ΛK⁻



ALI-PUB-562693

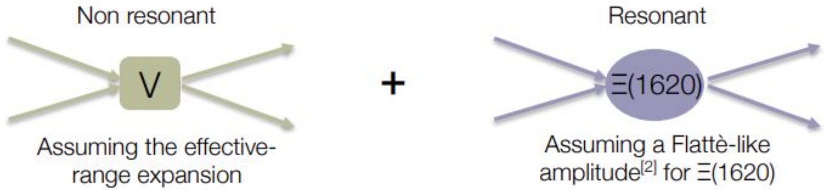
k* to invariant mass

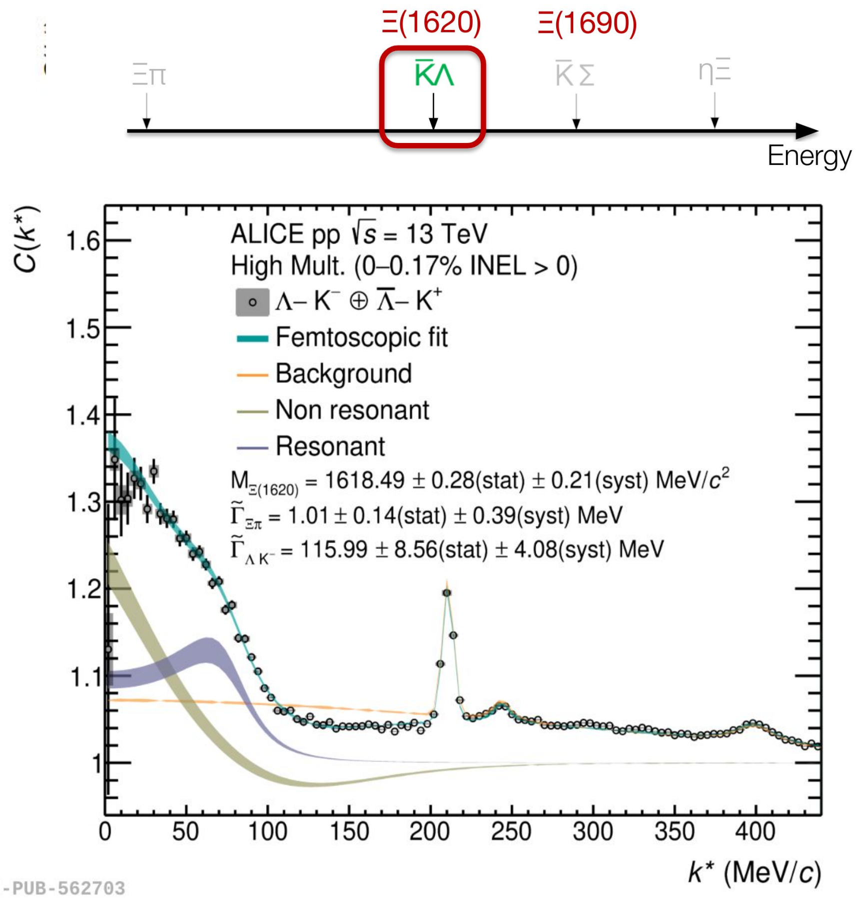


ALI-PUB-562688

K⁻Λ correlations and the S=-2 meson-baryon sector

- Data modeled with the Lednicky-Lyuboshits formula[1]





$K^-\Lambda$ correlations and the S=-2 meson-baryon sector

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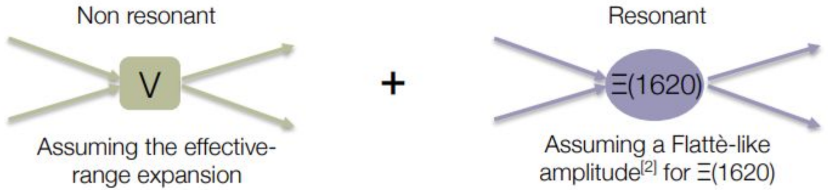
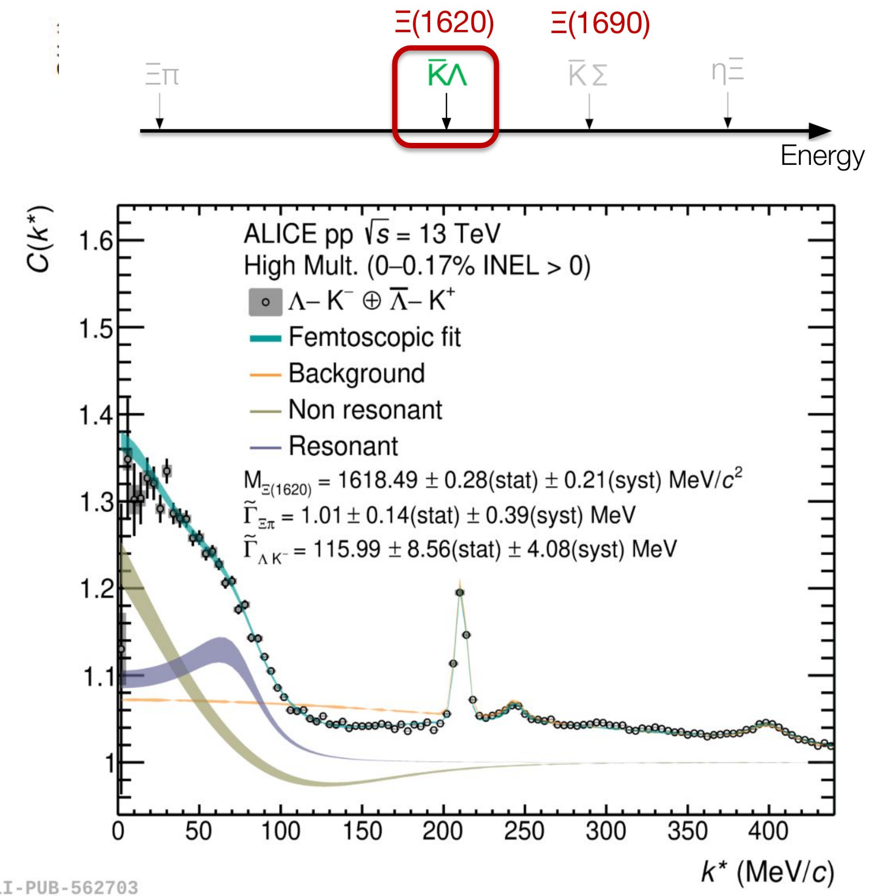


- **Ξ(1620) properties** and scattering parameters
  → Mass in agreement with Belle[3]

$$M_{\Xi(1620)} = 1618.49^{\pm 0.28(stat)}_{\pm 0.21(syst)}$$

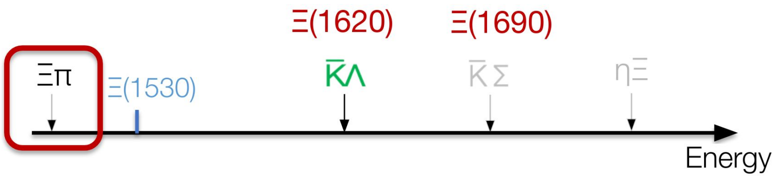
  → Indication of a large coupling of Ξ(1620) to ΛK^-
  → Non-resonant scattering parameters in agreement wit ALICE Pb-Pb results[4]

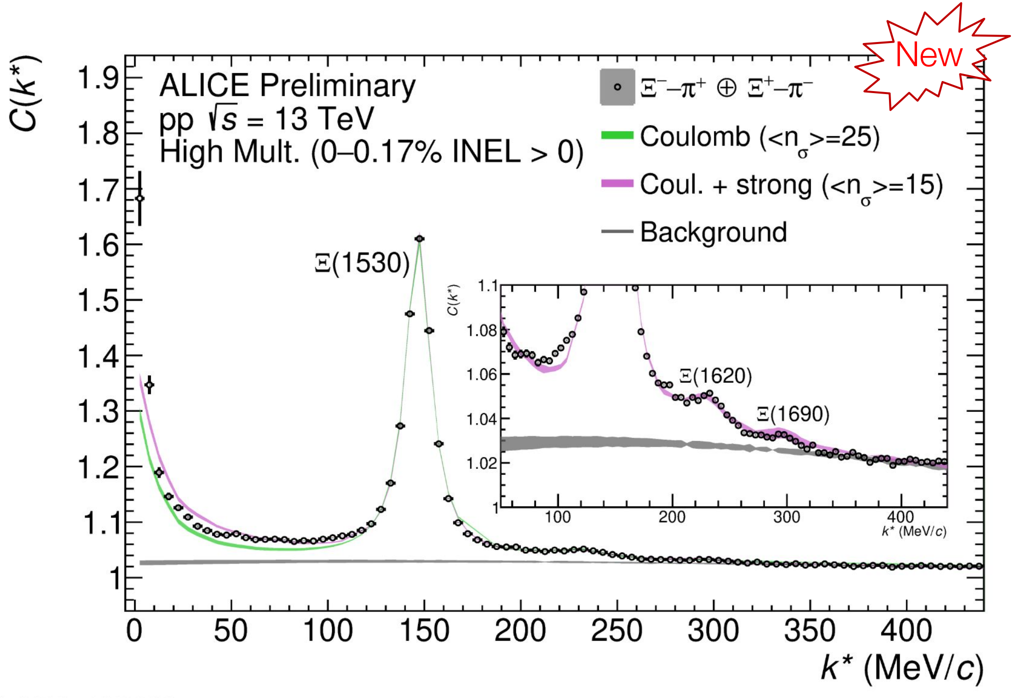
- High-precision data to constrain effective chiral theories and to understand the Ξ(1620) nature[5,6]



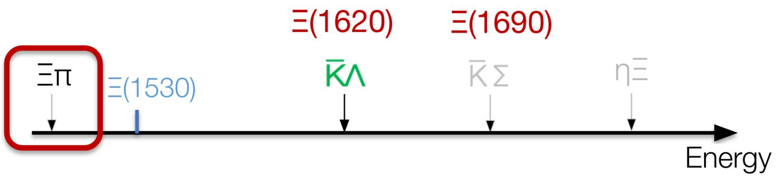
The $\Xi^{-}\,\pi^{+}$ correlation in pp collisions

Femto **data for $\Xi^{-}\pi^{+}$ down to threshold**





The $\Xi^- \pi^+$ correlation in pp collisions



Femto **data for $\Xi^-\pi^+$ down to threshold**

Several states visible in the measured correlation

- $\Xi(1530)^0 \rightarrow \Xi^-\pi^+$ (B.R. 100%)
- Ξ(1620) and Ξ(1690) as observed by Belle

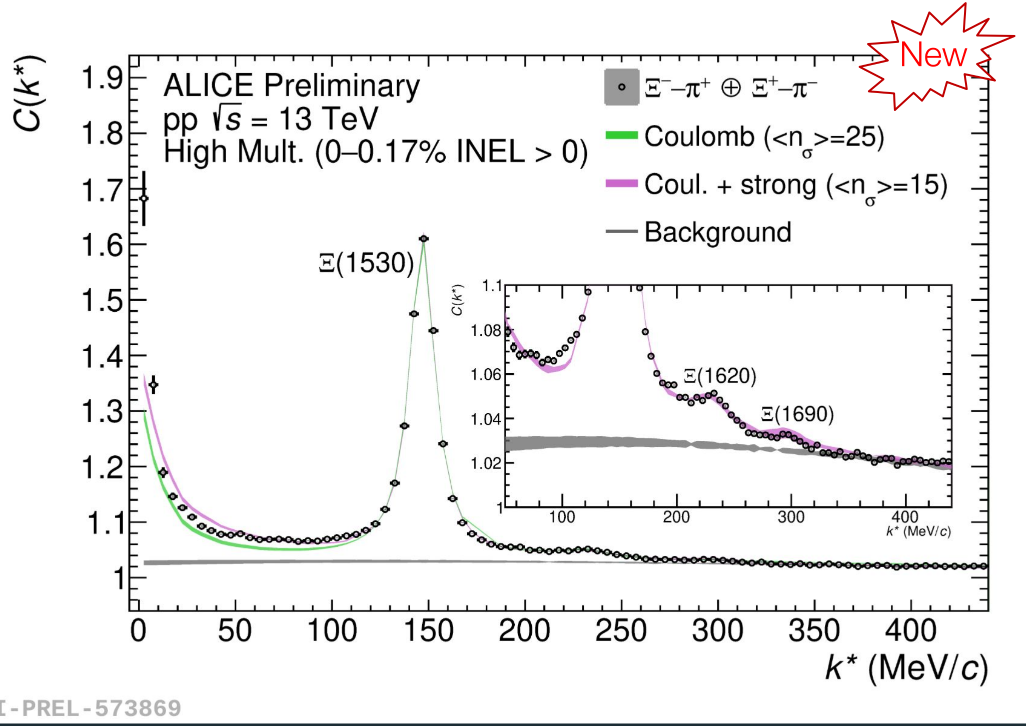
Same modeling as in Ξ^-K^+

R. Lednický, Phys. Part. Nucl. 40: 307-352 (2009)

- Evidence of strong attractive interaction

Breit-Wigner for Ξ(1620) and Ξ(1690) :

- Mass and widths compatible with previous spectroscopic measurements



Scattering parameters for the $\Xi^- \pi^+$ interaction

Rather shallow attractive interaction

$$\Re f_0 = 0.089^{\pm 0.007(stat)}_{\pm 0.009(syst)}$$

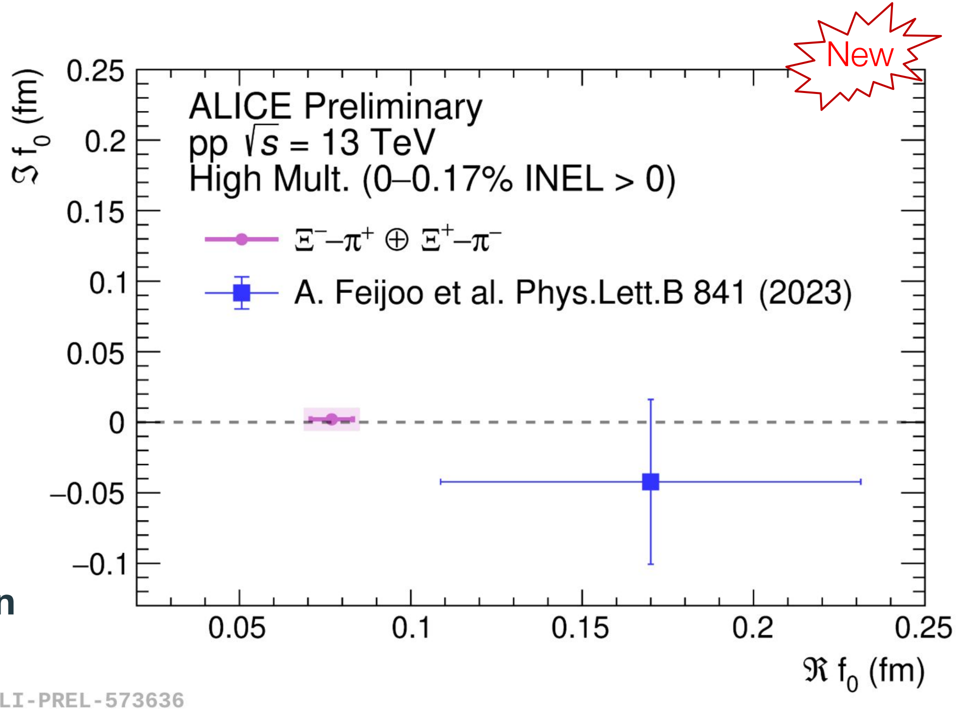
$$\Im f_0 = \mathbf{0.007}^{\pm 0.003(stat)}_{\pm 0.005(syst)}$$

Available predictions from NLO chiral potentials constrained to S=-1 data

A. Feijoo et al. Phys. Lett. B 841 (2023), 137927, Phys. Lett. B 853 (2024) 138660

- Affected by large uncertainties
- Overall compatible with our results

Novel high-precision data available to constrain this multi-strange meson-baryon sector!



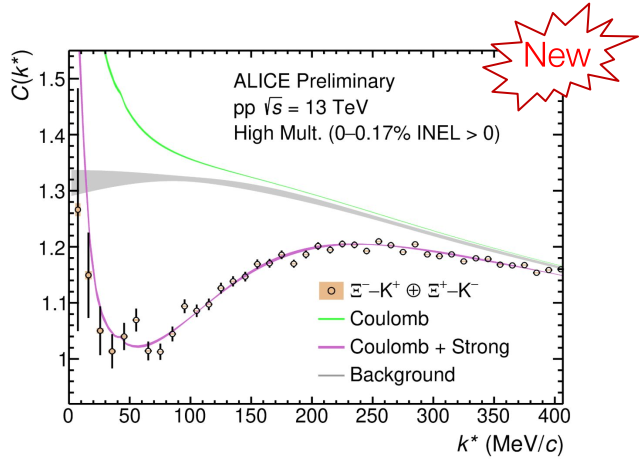
Conclusions and outlook

Most precise data on ΞK and Ξπ at low momenta available

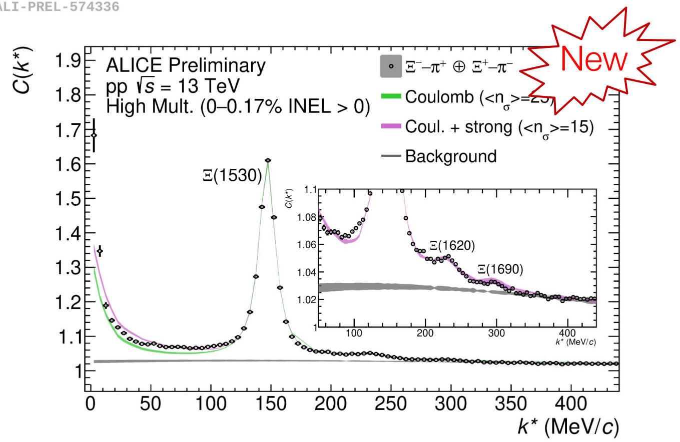
- Novel high-precision constraints on S=-1 and S=-2 baryon interactions available with correlation data
- Input for low-energy effective chiral lagrangians

Femtoscopy is a **complementary tool** to provide precision data on hadron-hadron interactions to **study exotic states**

⇒ Possibility to explore other relevant systems in these sectors with **ongoing Run 3!**

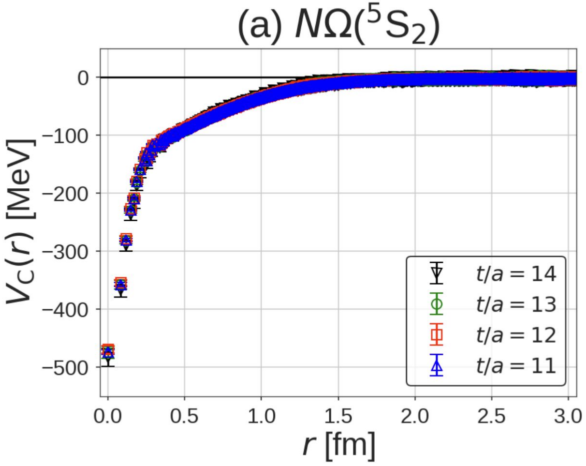


ALI-PREL-574336



ALI-PREL-573869

Test of the N-Ω HAL-QCD potential



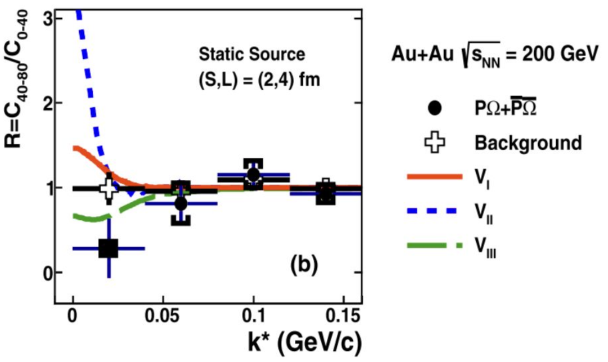
HAL-QCD N-Ω potential

T. Iritani et al., Phys. Lett. B792 (2019) 284.

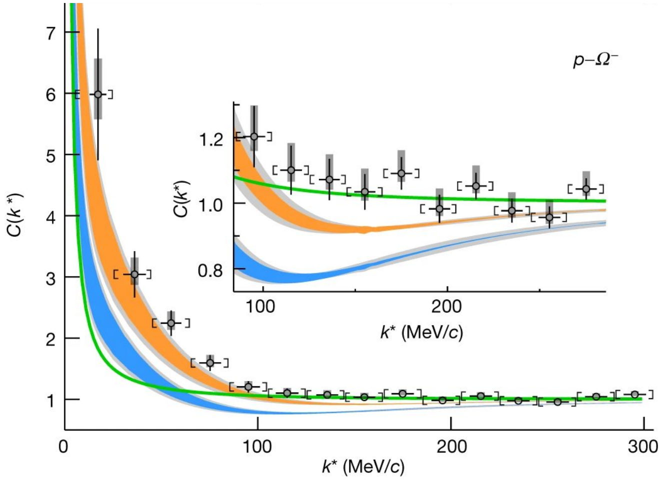
⇒ Very attractive N-Ω interaction at all distances

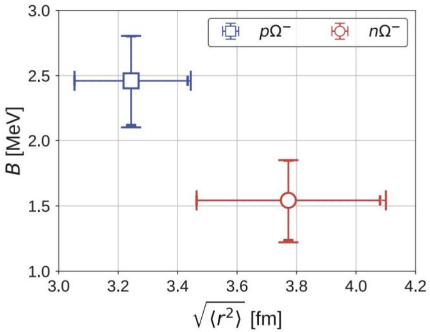
Tested by STAR and ALICE

STAR Coll. Phys.Lett.B 790 (2019) 490-497



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





⇒ Bound state in J = 2 channel N-Ω di-baryon

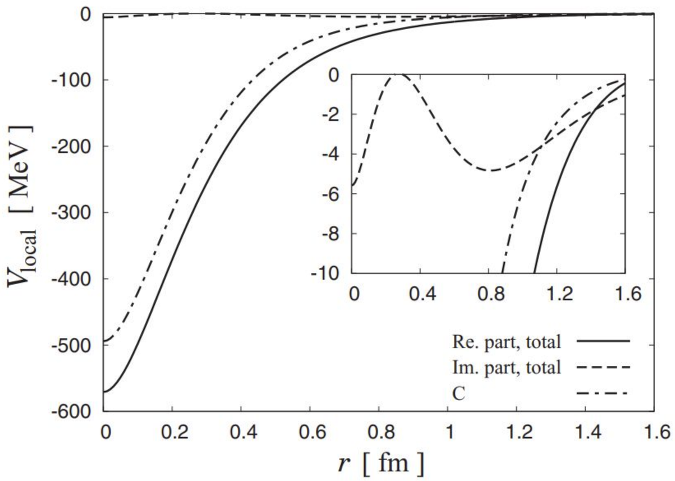
J = 1 channel unknown

Two assumptions

- **Same attraction as J =2**
- **Total absorption**

N-Ω meson-exchange potential

Other approaches [**meson-exchange** T. Sekihara et al., Phys. Rev. C 98, 015205 (2019), M. Piquer i Méndez et al., arXiv:2409.16747 [nucl-th] (2024); quark model H Huang et al., Phys. Rev. C 92, 065202 (2015)] predict as well a J = 2 N-Ω bound state



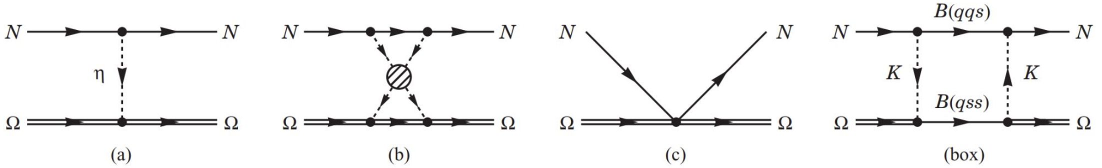


FIG. 1. Feynman diagrams for the $N\Omega$ interaction. The dashed lines represent the pseudoscalar mesons, while the solid and double lines indicate baryons. Shaded circle denotes the correlation of two mesons, and $B(qqs)B(qss)$ represents $\Lambda\Xi$, $\Sigma\Xi$, and $\Lambda\Xi(1530)$.

$$V = V_A + V_B + c\, V'_C + \sum_{j=2}^{6} V_{box(j)}$$

Long-range: meson-exchange (a),(b)

N-Ω meson-exchange potential

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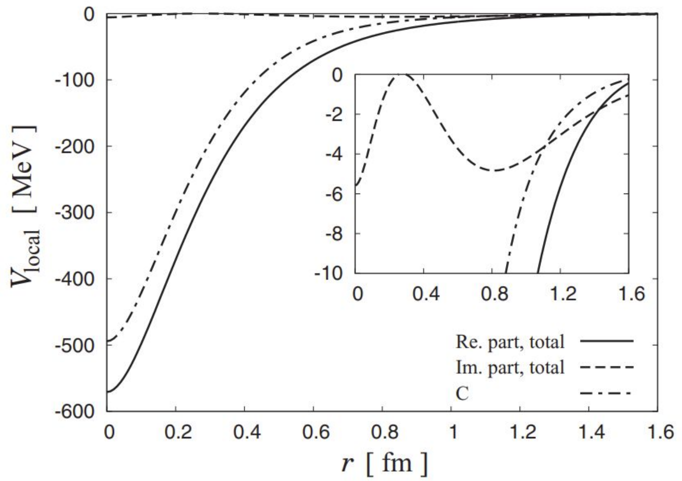

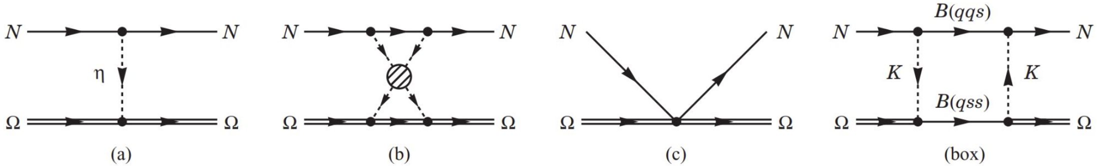

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Short range: contact term, coupled through **constant *c***

- c = -22.1 GeV^{-1} fixed by **fit to Lattice QCD potential**

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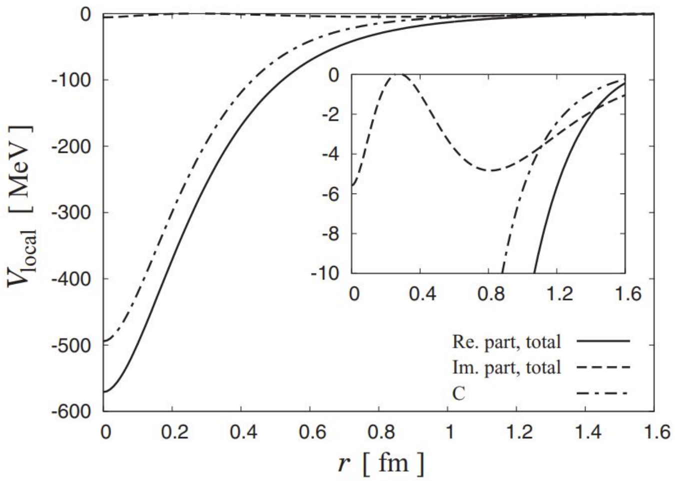


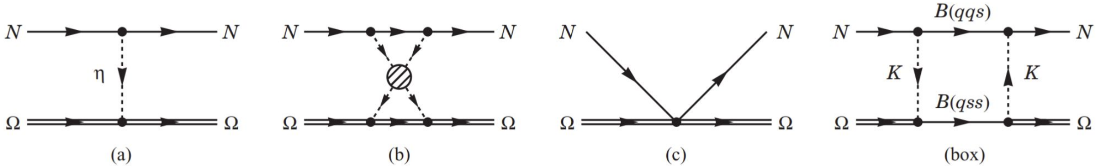


FIG. 1. Feynman diagrams for the $N\Omega$ interaction. The dashed lines represent the pseudoscalar mesons, while the solid and double lines indicate baryons. Shaded circle denotes the correlation of two mesons, and $B(qqs)B(qss)$ represents ΛΞ, ΣΞ, and ΛΞ(1530).

$$V = V_A + V_B + c\,V'_C + \sum_{j=2}^{6} V_{box(j)} \Rightarrow V = V_A + V_B + \beta\,c\,V'_C + \sum_{j=2}^{6} V_{box(j)}$$

Long-range: meson-exchange (a),(b)

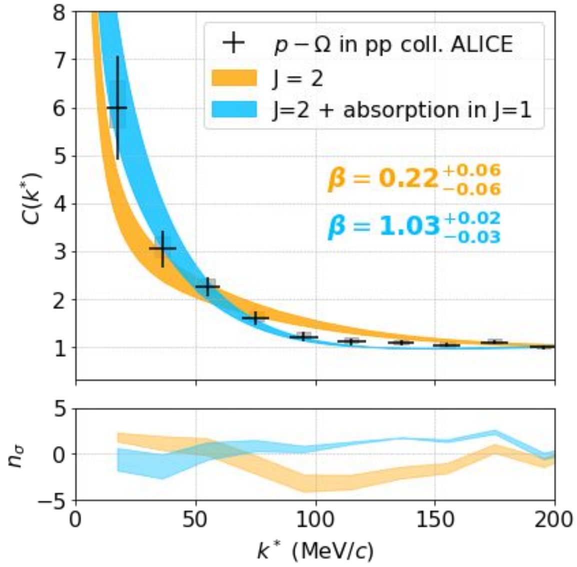
Short range: contact term, coupled through constant *c*

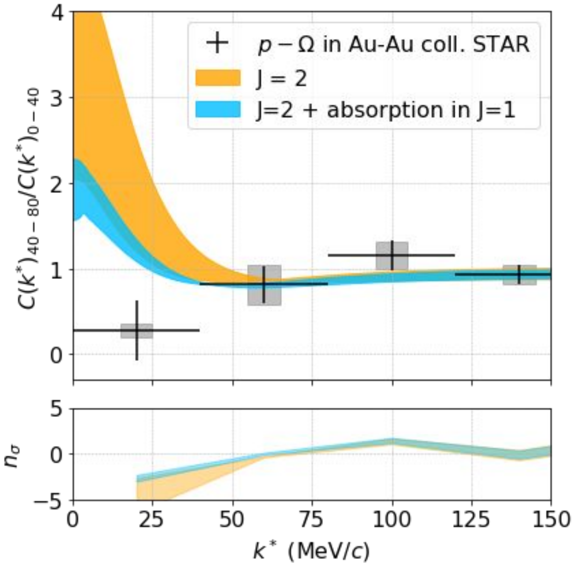
- c = -22.1 GeV^{-1} fixed by **fit to Lattice QCD potential**

⇒ **Tuning of the short-range part using femtoscopy data:**

- **Multiplicative parameter β weights the contact term**
- Starting point β=1 (original potential fitted to Lattice)

Tuning the p-Ω potential with femtoscopy data



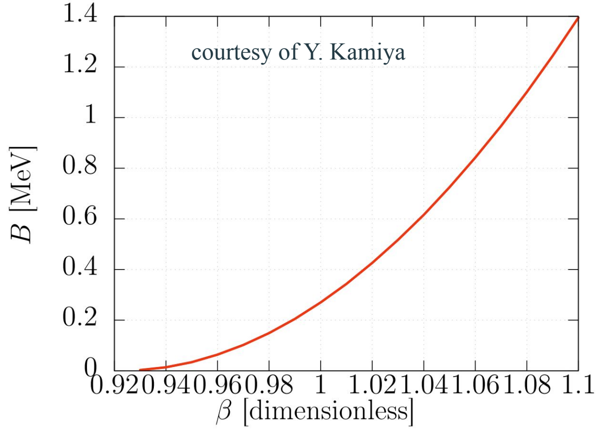


M. Piscitelli @ ALICE Italy 2024

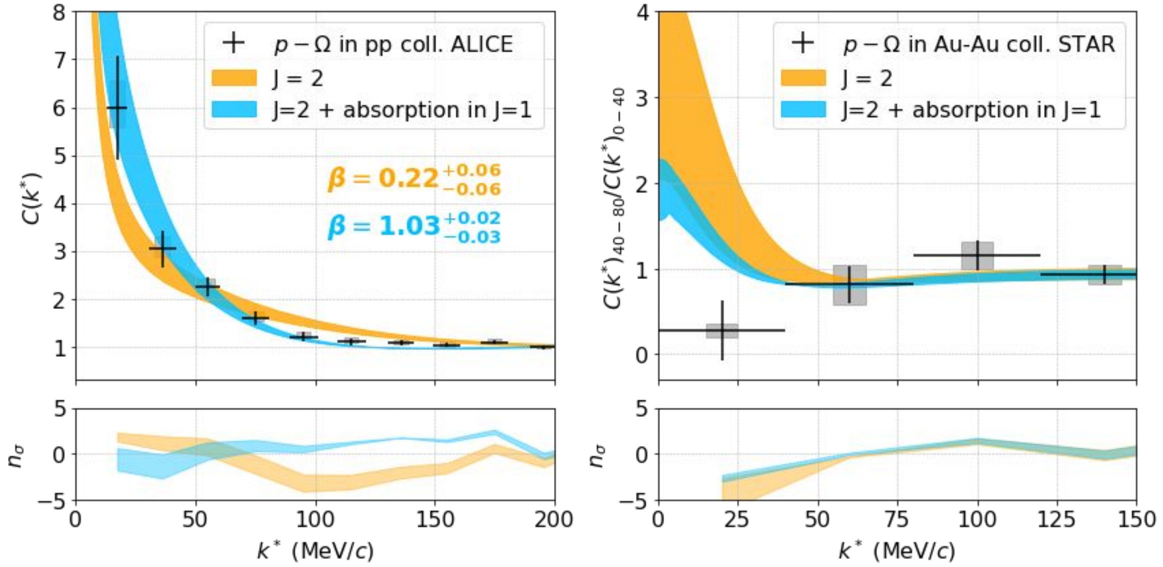
- J=2 only: large χ^2 values
- Indetermination on J=1: large variation in β values

β = 0.22 (J=2) ⇒ no bound st.

β = 1.03 (J=1+abs.) ⇒ B~0.5 MeV



Tuning the p-Ω potential with femtoscopy data



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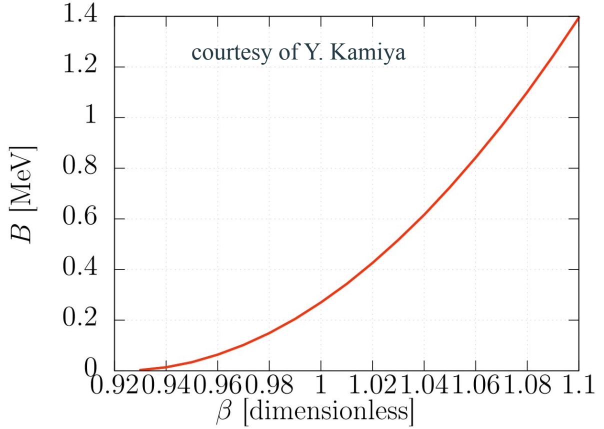


Pin down the presence and characteristics of NΩ state:

⇒ Experimental info on **coupled channels**: ΞΛ ALICE Coll. PLB844 (2023) 137223

⇒ Different collision systems → **scan different source sizes**

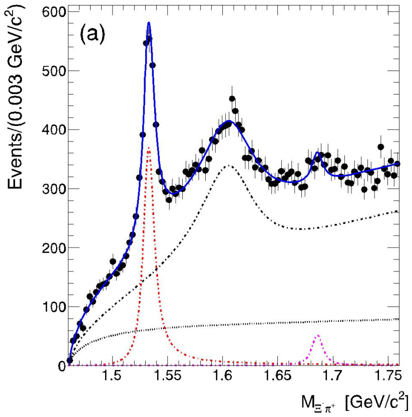
⇒ ML approaches for **multivariate analysis** L. Wang, JSPC 3 (2025) 100024

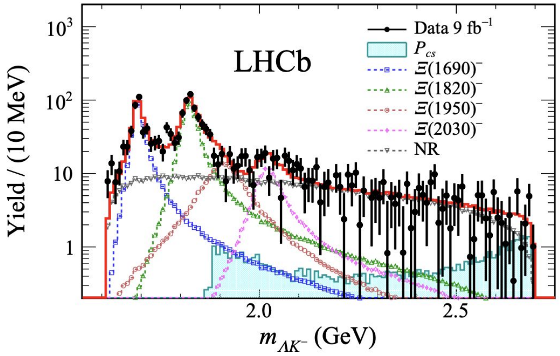
Studying molecular states

Intensive searches via spectroscopy measurements: Ξ(1620), Ξ(1690) states in the S=-2 sector

→ **Ξ(1620) lying across the K̅Λ threshold as molecular candidate, poorly known**

Ξ(1620)
Belle Coll.,
Phys. Rev. Lett 122 (2019)





Ξ(1690)
LHCb Coll.
Sci. Bull. 66 (2021)

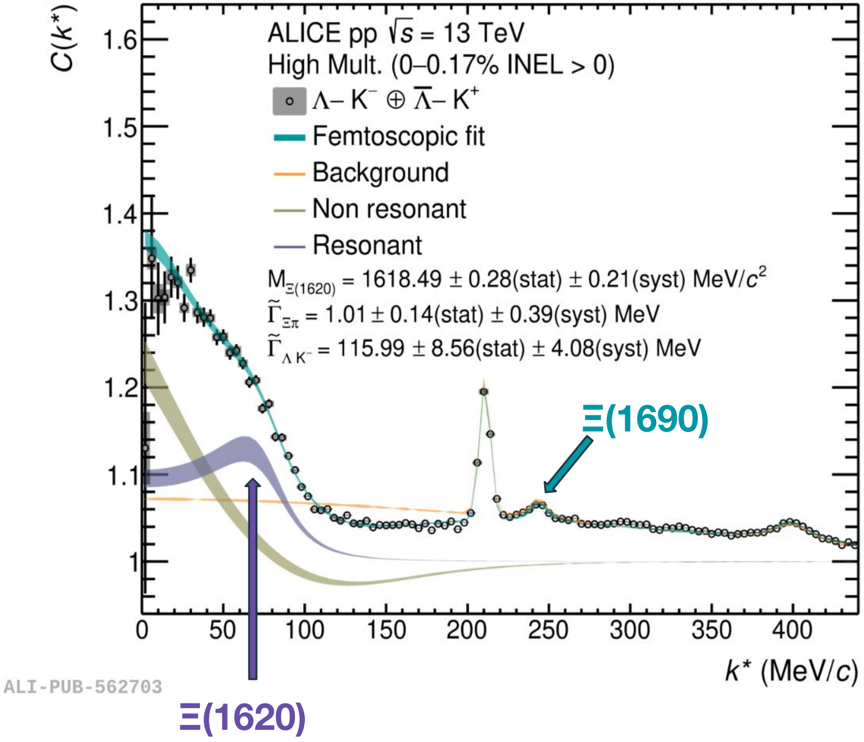
Ξπ	K̅Λ	K̅Σ	ηΞ	
1449-1461	1609-1613	1683-1691	1870	**Energy**

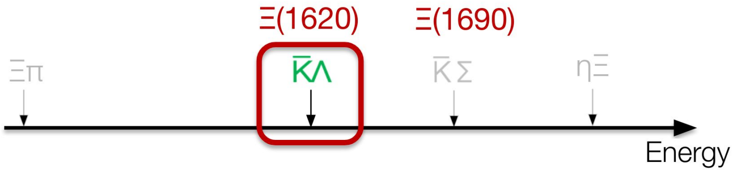
Femtoscopy approach: accessing the interaction between the constituents

Accessing the S=-2 meson-baryon interaction

Femtoscopy: most precise data for ΛK^- down to threshold

ALICE Coll. Phys. Lett. B 845 (2023) 138145





Model: Interplay between **resonant (Flatté-like)** and **non-resonant** interaction

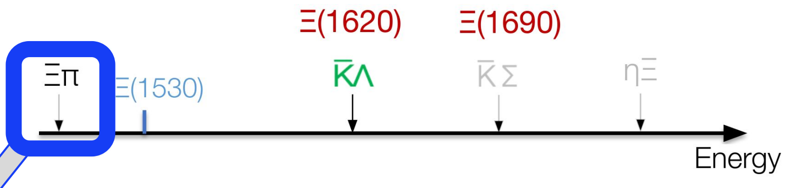
- First experimental evidence of Ξ(1620)→ΛK^-

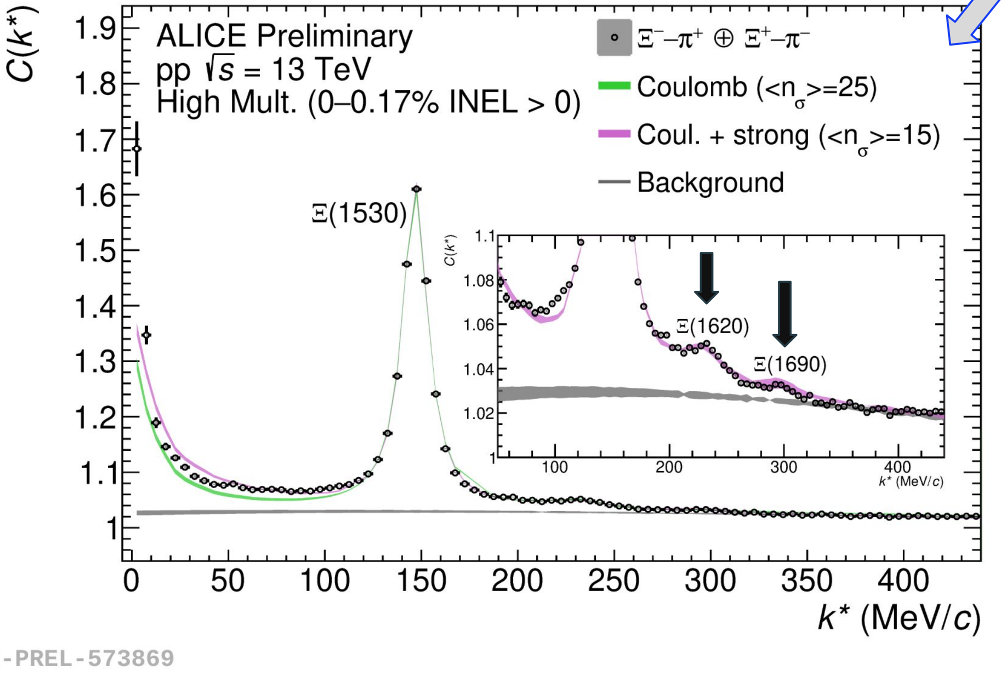
⇒ **Ξ(1620) and Ξ(1690) properties**

- Overall compatible with previous Belle and LHCb results
- Indication of a large coupling of Ξ(1620) to ΛK^-

Accessing the S=-2 meson-baryon interaction

Femtoscopy also delivers the most precise data down to threshold in the $\Xi\pi^-$ channel!





Ξ(1620) and **Ξ(1690)** with Breit-Wigner distribution

- Mass and widths compatible with previous spectroscopic measurements

Coulomb interaction at low k* underestimates data
⇒ attractive Ξπ strong interaction

Femtoscopy coupled-channel analysis + studies on production mechanisms/decay channels complement to reveal the nature of the states!

Deuteron femtoscopy: test the emission time

New femtoscopy results available utilizing **deuteron femtoscopy**

- p-d and d-d correlation functions in Au+Au collisions ⇒ **test coalesence afterburners** STAR Coll. 2410.03436 [nucl-ex]
- p-d and K^+-d femtoscopy in pp collisions ⇒ **access dynamics of three-body systems** ALICE Coll. Phys. Rev. X 14, 031051 (2024)

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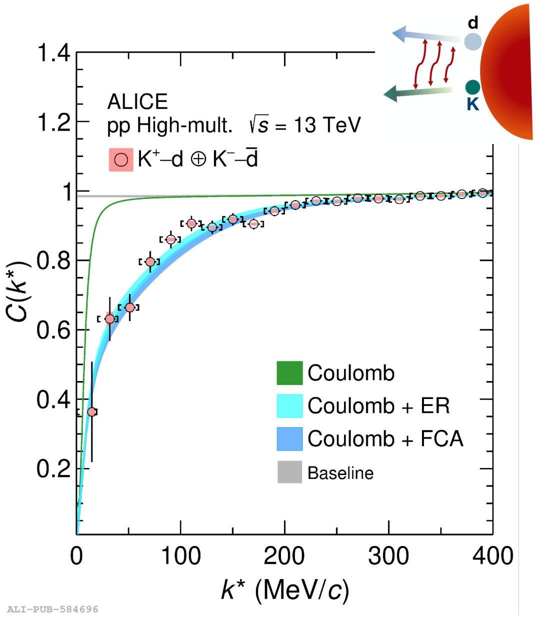

K^+-d correlation function in pp collisions:

Interaction: with Lednicky model using K^+-d known scattering parameters

- ER (effective-range approximation): $a_0 = -0.47$ fm, $d_0 = -1.75$ fm
- FCA (fixed-center approximation): $a_0 = -0.54$ fm, $d_0 = 0$ fm

Source: Gaussian + effects of short lived resonances from p-p m_T scaling

⇒ **Coulomb + strong interaction + small radius** describes the data

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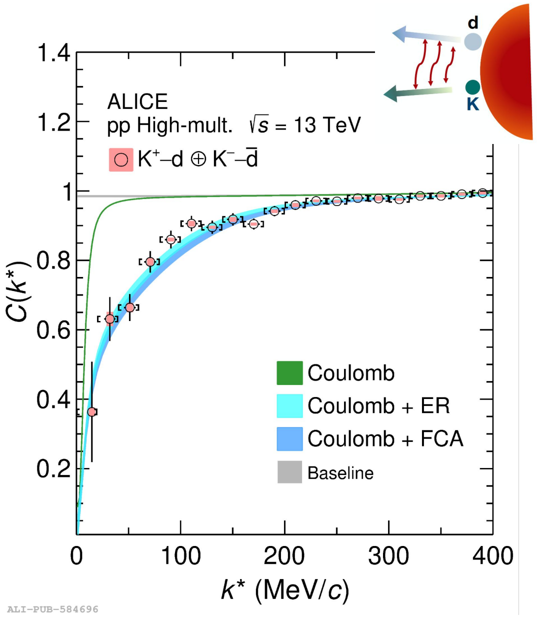

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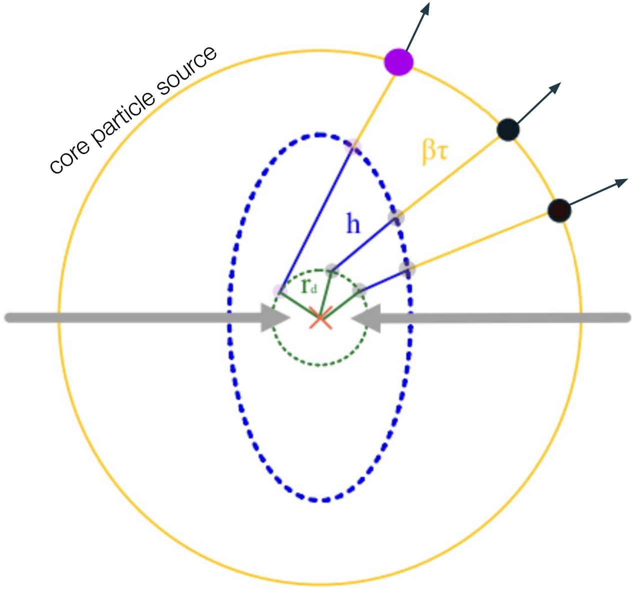
Source: Gaussian + effects of short lived resonances from p-p m_T scaling

⇒ **Coulomb + strong interaction + small radius** describes the data

In the following: **determine the upper limit for the delayed emission of deuterons with new source model**

→Does the data allow for a “developing time” for deuterons?

CECA model for particle emission in small coll. systems



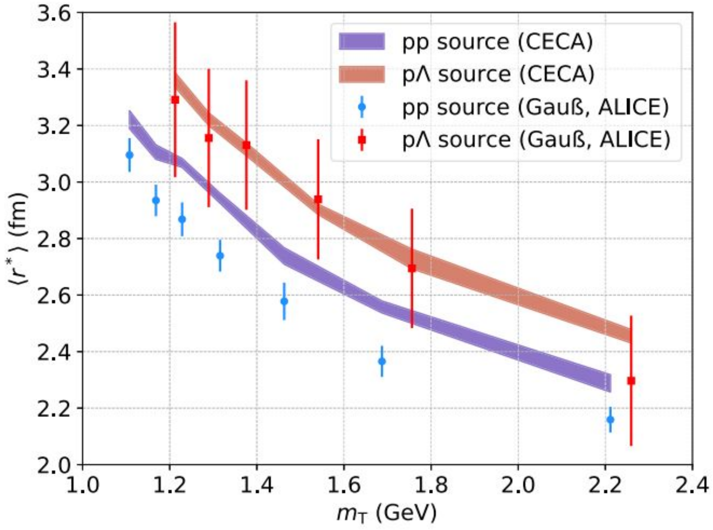
CECA free parameters:

- r_d ~0.3 fm → Position of initial scattering
- h ~3 fm → Hadronisation parameter
- τ ~3 fm/c → Decoupling time

CECA: MC simulation of single particles and resonances

D. Mihaylov, J. González, Eur.Phys.J.C 83 (2023) 7, 590

- Assume a common ellipsoidal 'hadronization surface' ⇒ serves as a source of spatial-momentum correlations
- Effects of short-lived resonances decay taken into account
- **Reproduces m_T scaling of source size**. Parameters fixed by p-p, p-Λ femtoscopy data in pp coll. ALICE

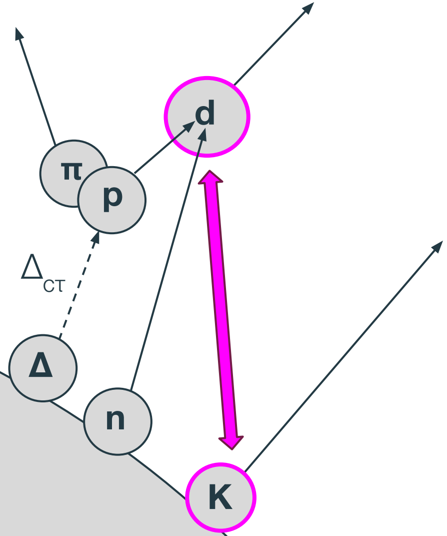


Deuteron emission time in CECA

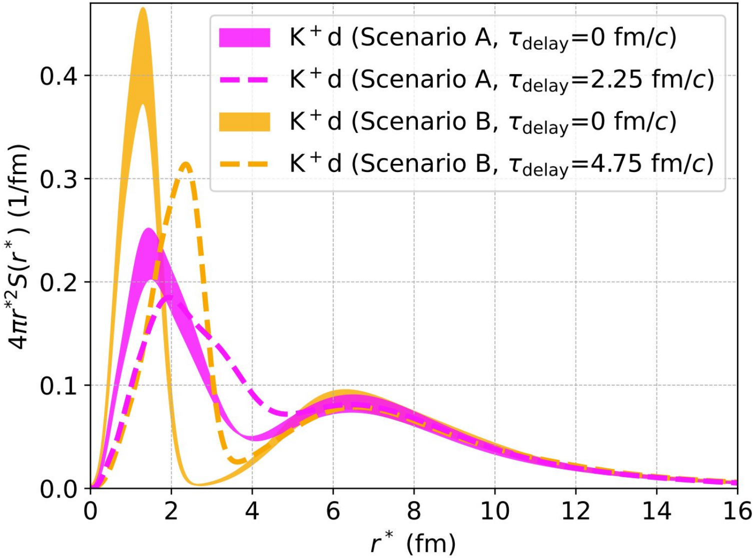
Test two scenarios for deuteron production in CECA **adding a deuteron delay τ_{delay}**

Scenario A
deuteron formed via coalesence of nucleons produced after resonance decay

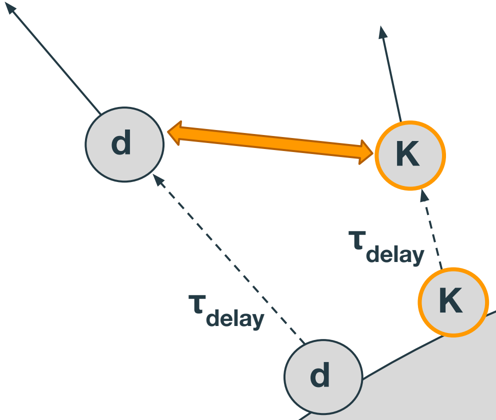
Scenario B
primary production of deuterons



Resulting two-particle source size:



O. Vazquez Doce, D. Mihaylov, L. Fabbietti, Eur. Phys. J. A 61, 53 (2025)



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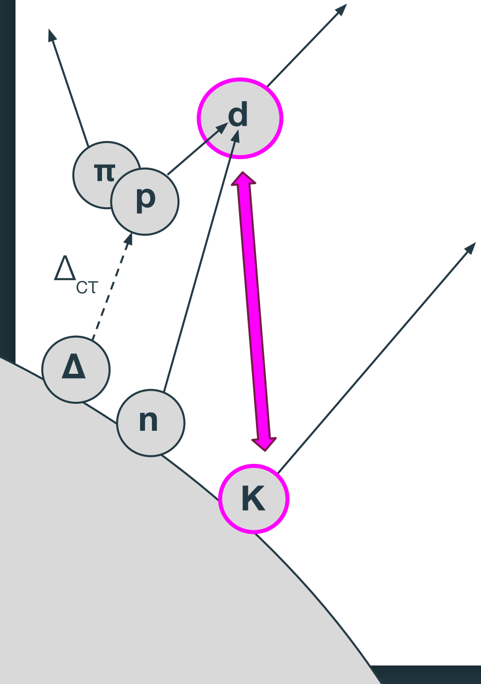

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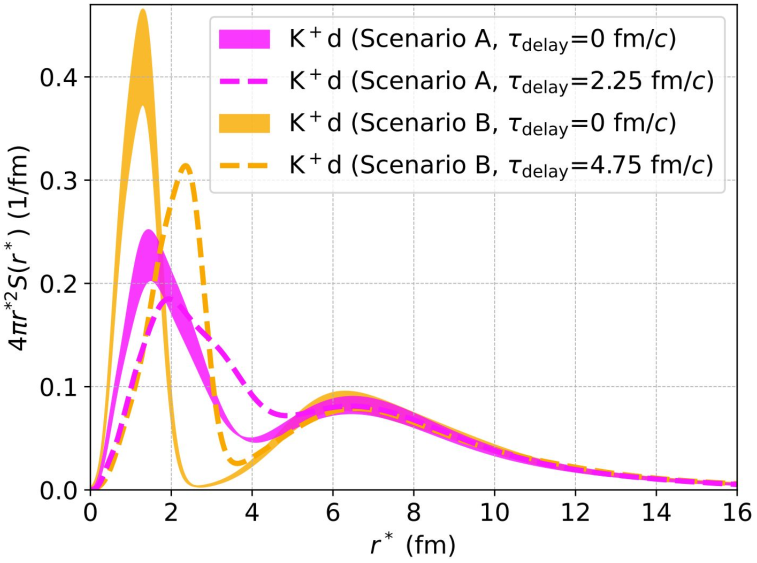
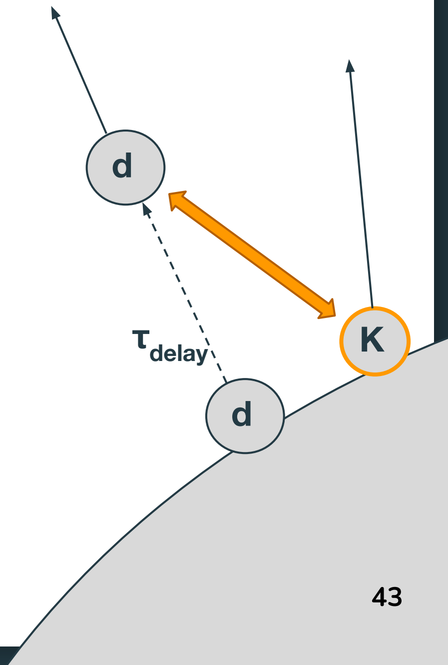
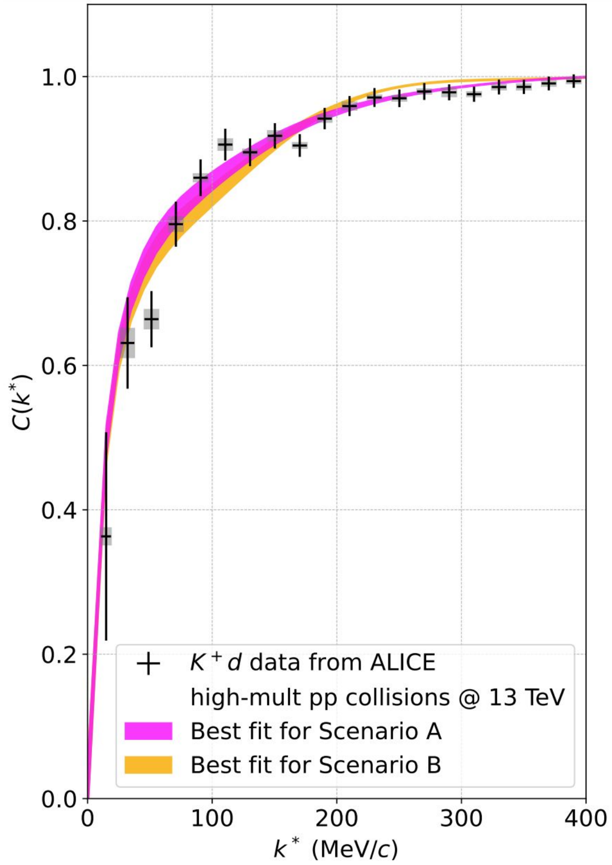


O. Vazquez Doce, D. Mihaylov, L. Fabbietti, Eur. Phys. J. A 61, 53 (2025)



Maximum allowed deuteron emission time

O. Vazquez Doce, D. Mihaylov, L. Fabbietti, Eur. Phys. J. A 61, 53 (2025)



Extract τ_{delay} by fitting K^+-d data with
Coulomb+strong interaction + CECA source

Scenario A: deuteron after resonances

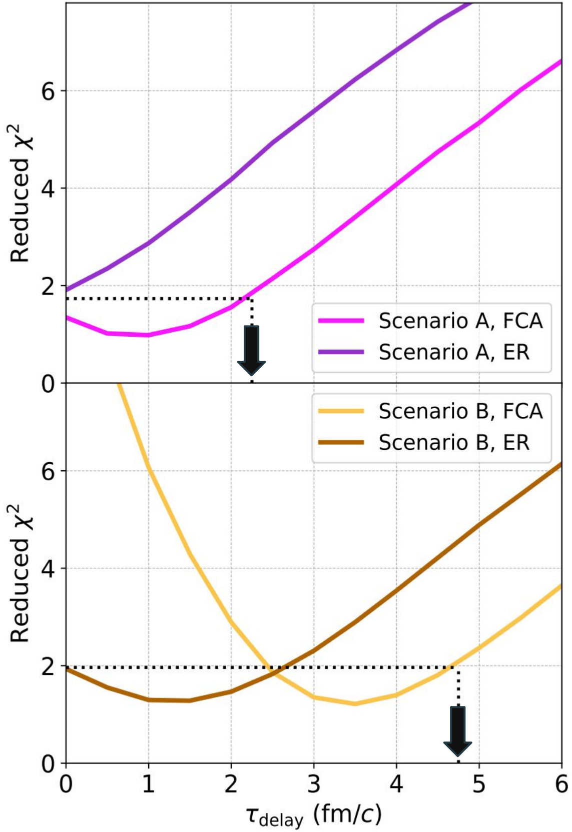
- **Best fit: τ_{delay} = 1 fm/c**
- Maximum allowed (3σ) τ_{delay} = 2.25 fm/c

Scenario B: primary produced deuterons

- **Best fit: τ_{delay} = 3.5 fm/c**
- Maximum allowed (3σ) τ_{delay} = 4.75 fm/c

Maximum allowed deuteron emission time

O. Vazquez Doce, D. Mihaylov, L. Fabbietti, Eur. Phys. J. A 61, 53 (2025)



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⇒ Favor early formation of deuteron as extended, weakly bound composite object in pp collisions at the LHC

⇒ Disfavor a compact doorway state reaching proper size and binding energy after a time > 5 fm/c

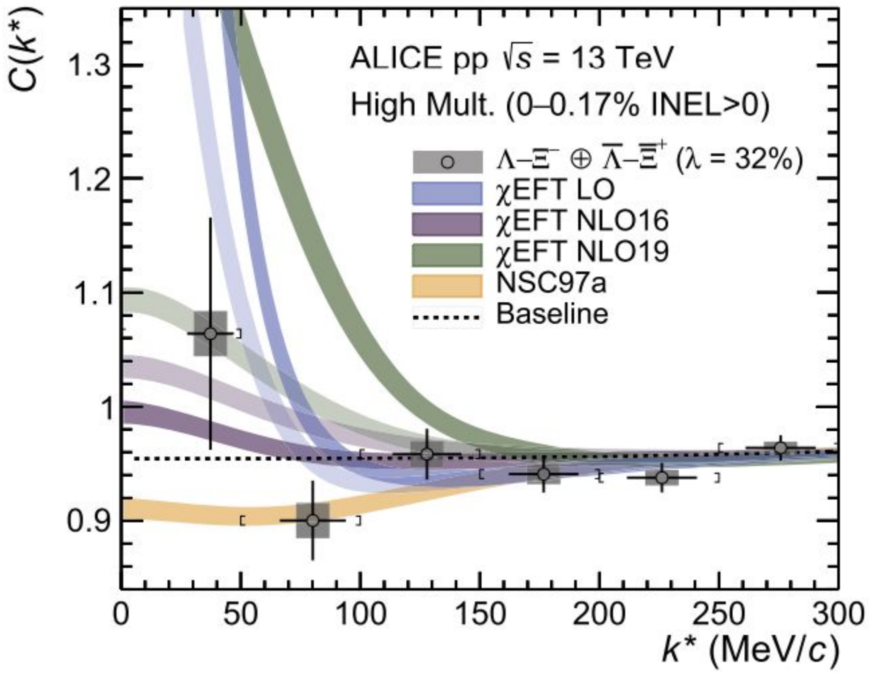
Femtoscopy addressing key challenges in Hadron Physics

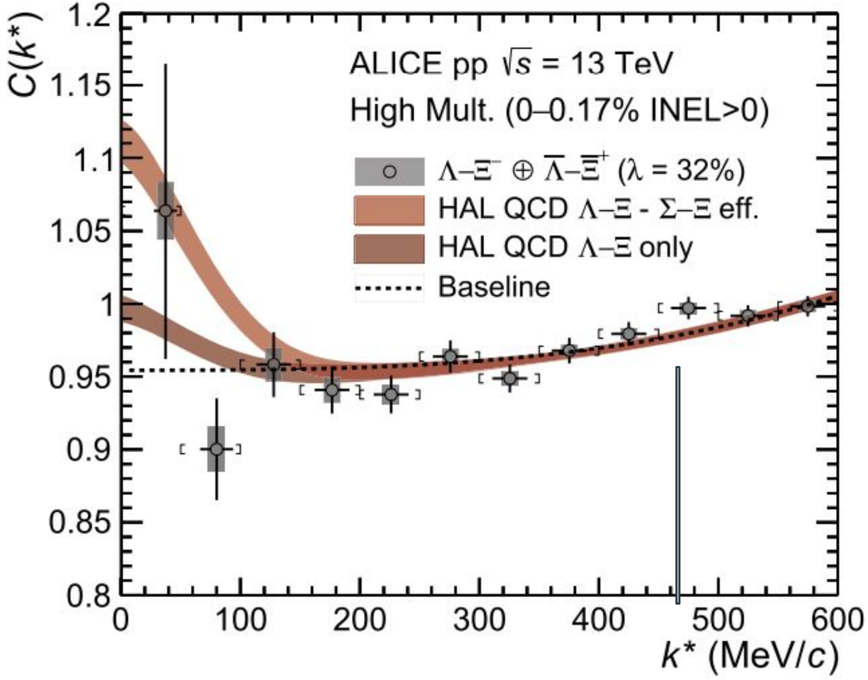
Checklist

- Test hadron-hadron interactions ✓
  ⇒ study the formation of bound states
- Complement spectroscopy ✓
  ⇒ study molecular states
- Reveal the signatures of formation mechanisms of light nuclei ✓

thank you for your attention!

ΞΛ femtoscopy in pp collisions





Physics Letters B 844 (2023) 137223 ALICE Coll.

room for larger delay?

6.5 fm delay ≥ 5σ