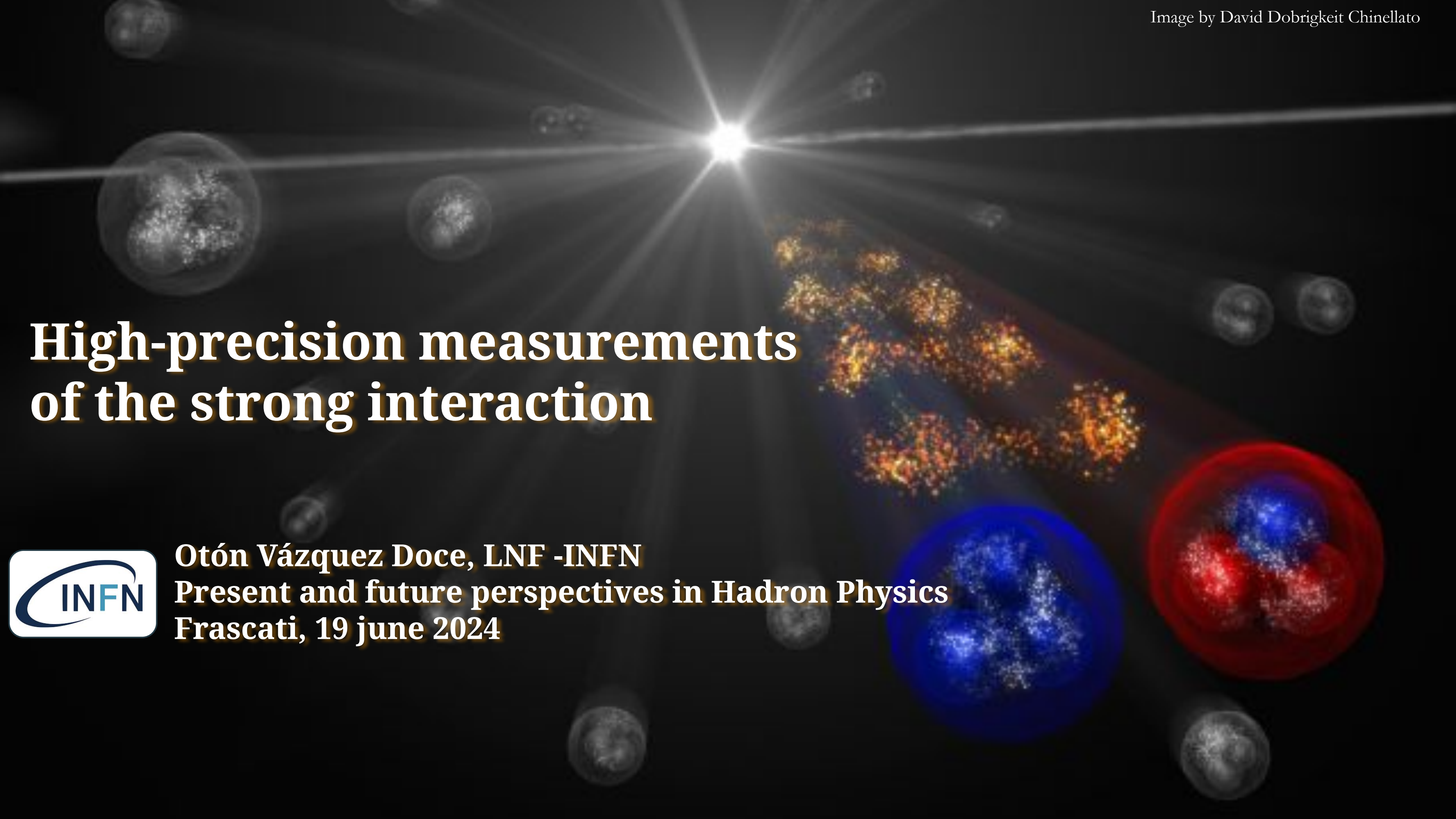


Image by David Dobrigkeit Chinellato

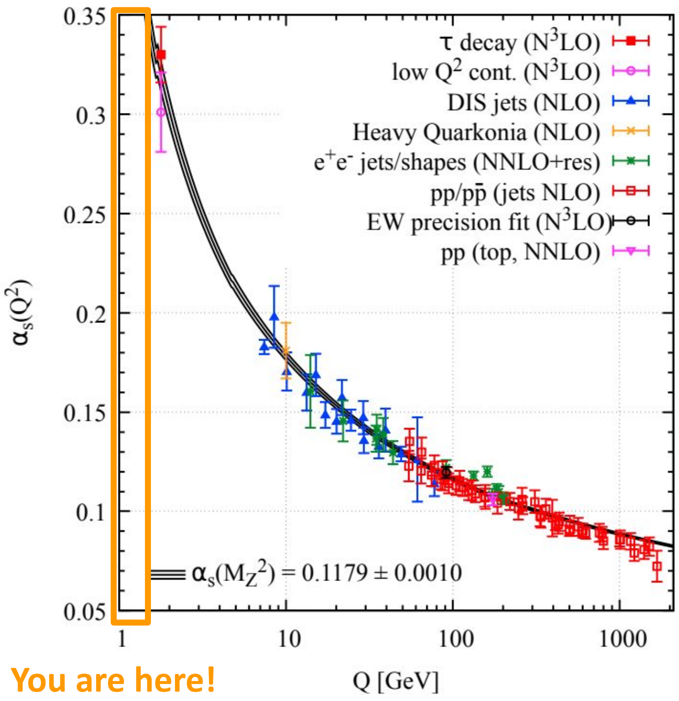
High-precision measurements of the strong interaction

Otón Vázquez Doce, LNF -INFN

Present and future perspectives in Hadron Physics

Frascati, 19 june 2024

Hadron-hadron strong interaction



You are here!

Running coupling constant defines the boundaries of "Low energy QCD"

- Q ~ 1 GeV, R ~ 1 fm
- Far away from the perturbative regime

High energy colliders data

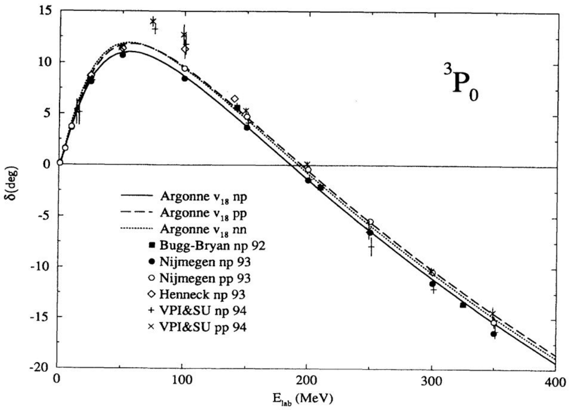
from high-energy physics facility to nuclear physics

Hadron-hadron interactions

(with strangeness)

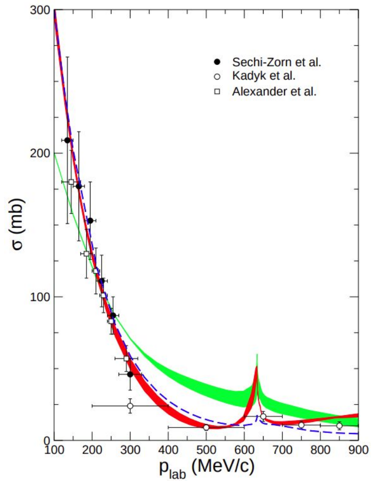
S=0 *S*=-1 *S*=-2

NN → NN



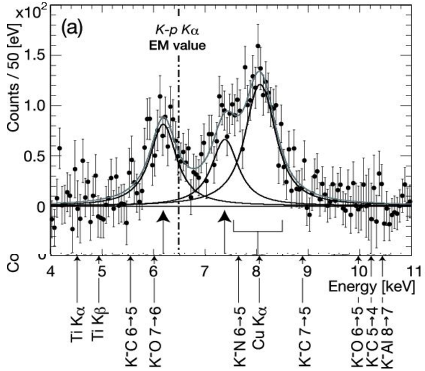
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla Phys. Rev. C 51, 38 (1995)

Λp → Λp



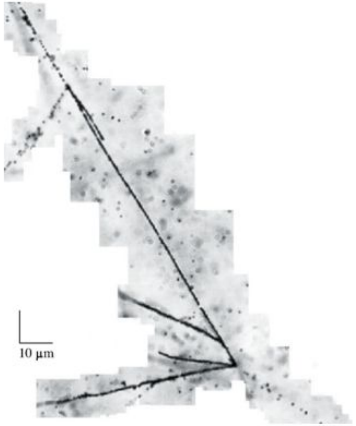
LO: H. Polinder, J. Haidenbauer, U. Meißner, Nucl. Phys. A779 (2006) 244.
NLO: J. Haidenbauer et al., Nucl. Phys. A915 (2013) 24.

Kaonic atoms



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

ΛΛ, Ξ hypernuclei

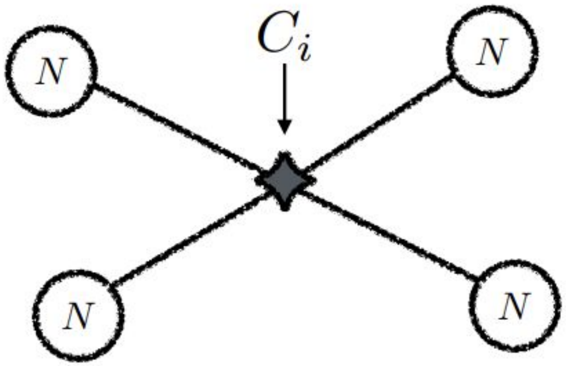


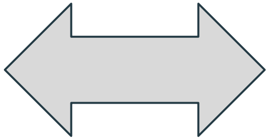
KISO event: K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015, 033D02
IBUKI event J-PARC E07 Coll., Phys. Rev. Lett. 126, 062501 (2021)

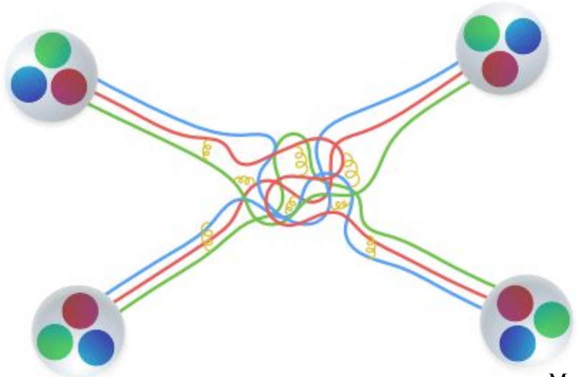
Experimental data

Hadron-hadron strong interactions

Residual strong interaction among hadrons







Marc Illa THEIA-STRONG2020

$$\mathcal{L}_{EFT}[\pi, N, \ldots; m_\pi, m_N, \ldots, C_i]$$

$$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$$

<u>Effective theories (EFT)</u>

- **Hadrons as degrees of freedom**
- **Low-energy EFT coefficients constraint by data**

Lattice QCD

- Understanding of the interaction starting from **quark and gluons**

Hadron-hadron interactions

(with strangeness)

$m_\pi \approx 200$ MeV

PHYSICAL REVIEW D **109,** 014511 (2024)

Lattice QCD study of $\pi\Sigma - \bar{K}N$ scattering and the $\Lambda(1405)$

BaSc Coll. Phys. Rev. D 109, 014511 (2024)

$$m_\pi = 146 \text{ MeV}/c^2$$
$$m_K = 525 \text{ MeV}/c^2$$

Physics Letters B
Volume 792, 10 May 2019, Pages 284-289

NΩ dibaryon from lattice QCD near the physical point

HAL QCD Coll.) Phys. Lett. B792 (2019) 284

$$m_\pi = 146 \text{ MeV}/c^2$$
$$m_K = 525 \text{ MeV}/c^2$$

PHYSICAL REVIEW LETTERS **120,** 212001 (2018)

Most Strange Dibaryon from Lattice QCD

HAL QCD Coll. PRL 120, 212001 (2018)

S=0	S=-1	S=-2	S=-3	…S=-6
NN	NK, NΛ, NΣ	ΛΛ, NΞ	ΛΞ, NΩ	ΩΩ

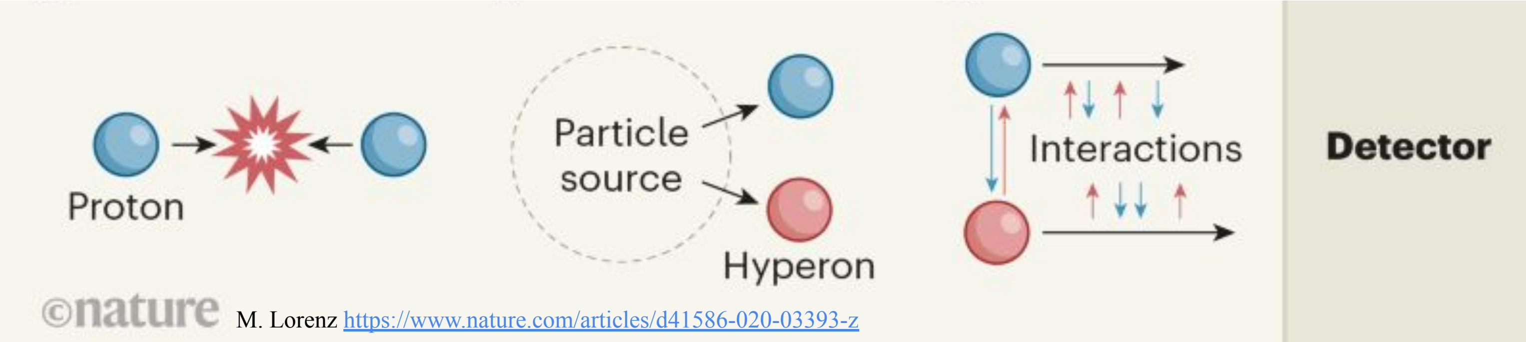
Better S/N of LQCD

Experimental data

Femtoscopy method in nucleus-nucleus collisions

Measurement of **the correlation function of two particles emitted a nucleus-nucleus collision**

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



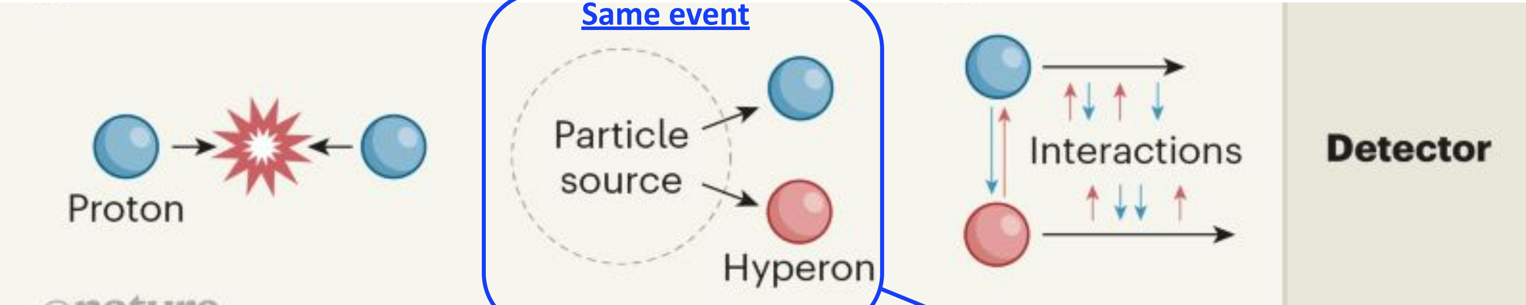
M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

Femtoscopy method in nucleus-nucleus collisions

Measurement of **the <u>correlation function</u>**
<u>of two particles emitted a nucleus-nucleus collision</u>

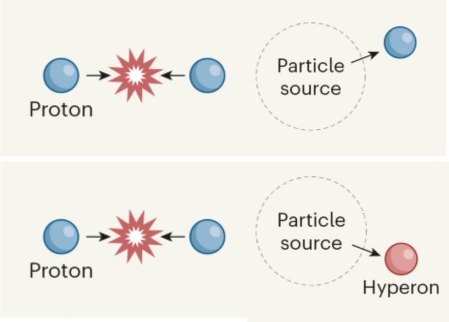
$$C(\overrightarrow{p_a}, \overrightarrow{p_b}) = \frac{P(\overrightarrow{p_a}, \overrightarrow{p_b})}{P(\overrightarrow{p_a})P(\overrightarrow{p_b})}$$

<u>Same event</u>



M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

<u>Mixed events</u>



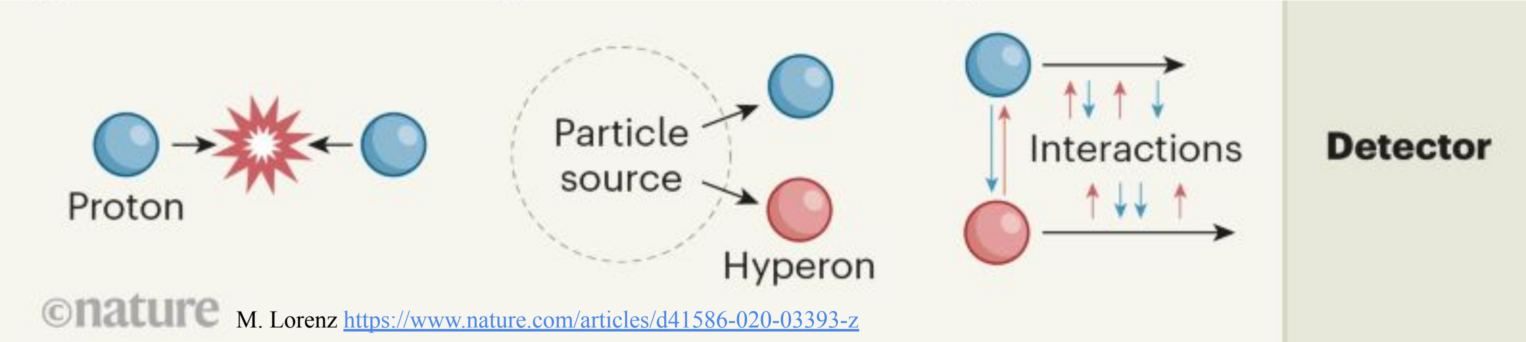
Experiment:

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

Femtoscopy method in nucleus-nucleus collisions

Measurement of **the correlation function of two particles emitted a nucleus-nucleus collision**

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



M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

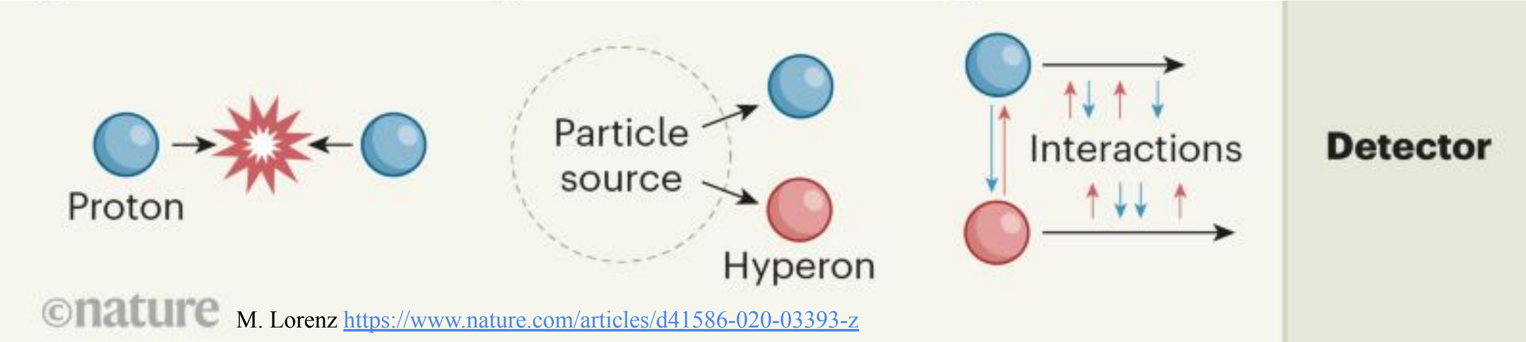
Traditional femtoscopy in heavy-ion collisions

- Study pairs of bosons (typically ππ, KK)
  - Correlation produced by quantum statistics effect + known interaction (Coulomb)
- Source sizes ~ **3-10 fm**

Femtoscopy method in nucleus-nucleus collisions

Measurement of **the correlation function of two particles emitted a nucleus-nucleus collision**

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



M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

“Non-traditional” femtoscopy

- **Study the interaction** given a **known source**
- Applied to small collision systems, pp ⇒ Source size **~1fm**

L. Fabbietti, V. Mantovani, O. Vázquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377

Theoretical correlation function

$$C(k^*) = \int S(r^*)\ |\Psi(k^*, \vec{r^*})|^2\ d^3r^*$$

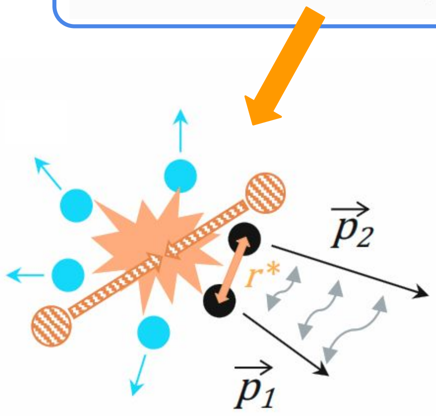
S. E. Koonin, *Physics Letters B* **70** (1977) 43-47
S. Pratt, *Phys. Rev. C* **42** (1990) 2646-2652

Relative momentum $\vec{k}^* = \frac{1}{2} | \vec{p}_1^* - \vec{p}_2^* |$ and $\vec{p}_1^* + \vec{p}_2^* = 0$

Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

Theoretical correlation function

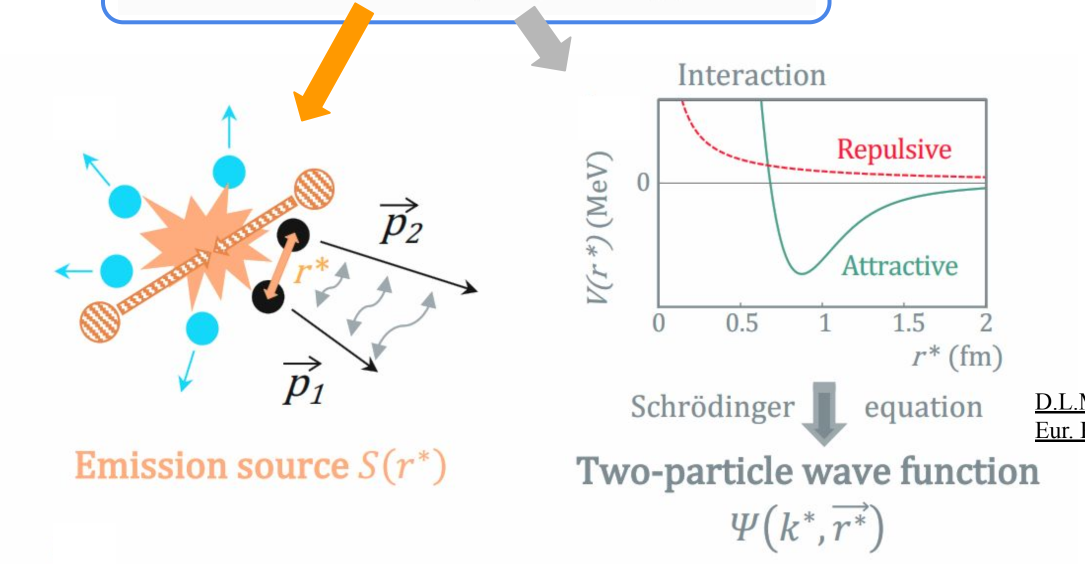
$$C(k^*) = \int S(r^*) \, \left|\Psi(k^*, \vec{r^*})\right|^2 d^3r^*$$



Emission source $S(r^*)$

Theoretical correlation function

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



D.L.Mihaylov et al.
Eur. Phys. J. C78 (2018) no.5,394

Theoretical correlation function

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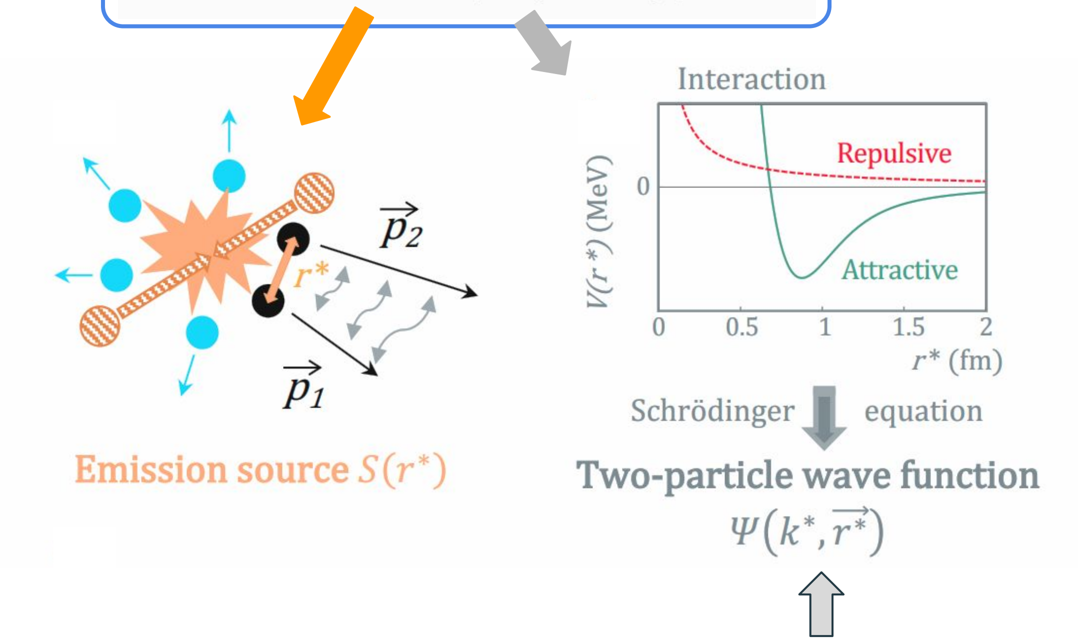
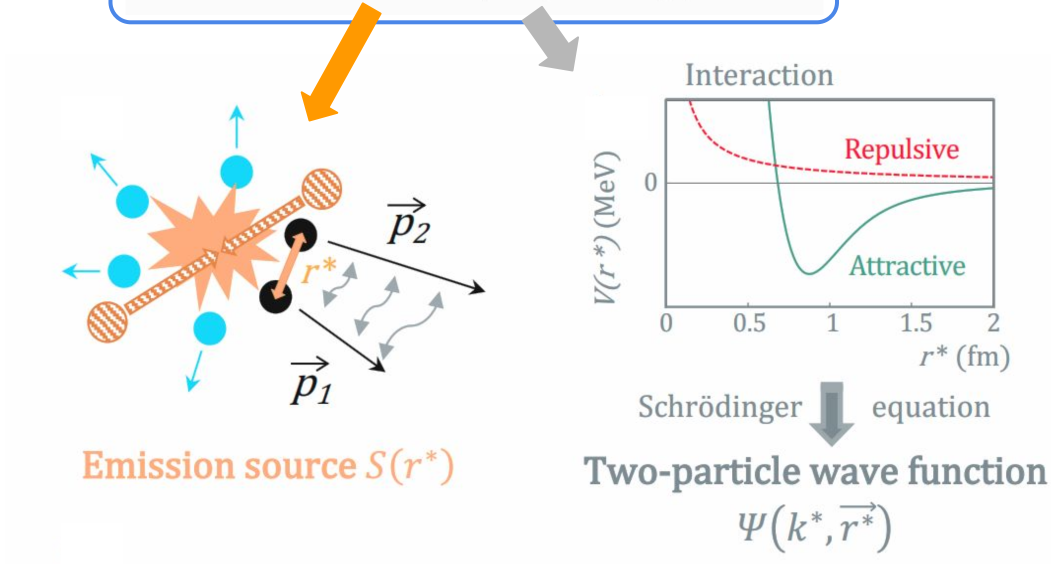


Scattering parameters

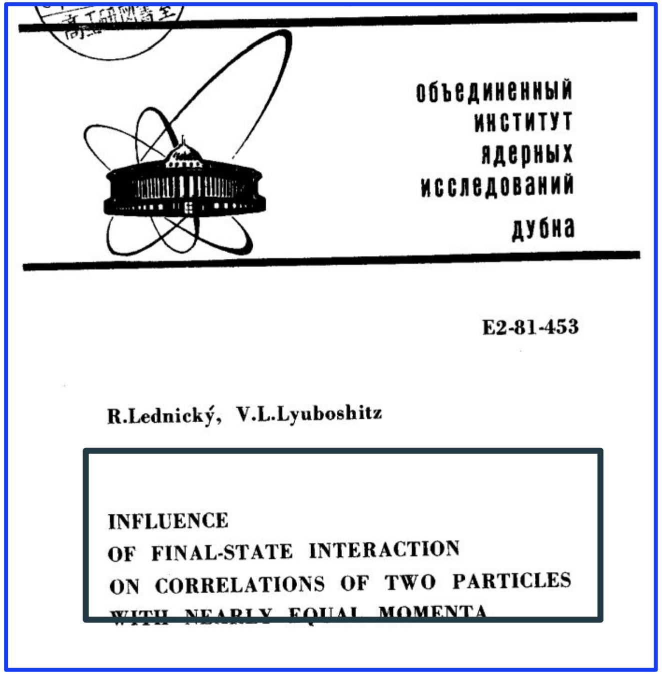
Theoretical correlation function

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



Scattering parameters

s-wave asymptotic wave function from scattering parameters



ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

ДУБНА

E2-81-453

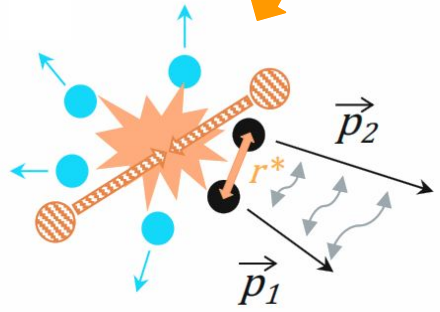
R.Lednický, V.L.Lyuboshitz

INFLUENCE OF FINAL-STATE INTERACTION ON CORRELATIONS OF TWO PARTICLES WITH NEARLY EQUAL MOMENTA

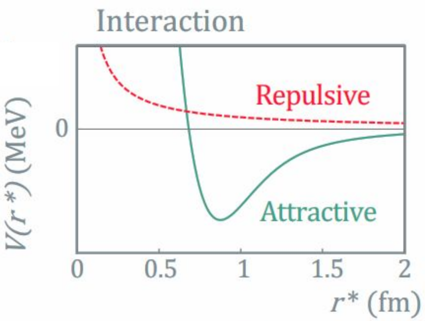
[R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 53 (1982) 770]

Theoretical correlation function

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



Emission source $S(r^*)$

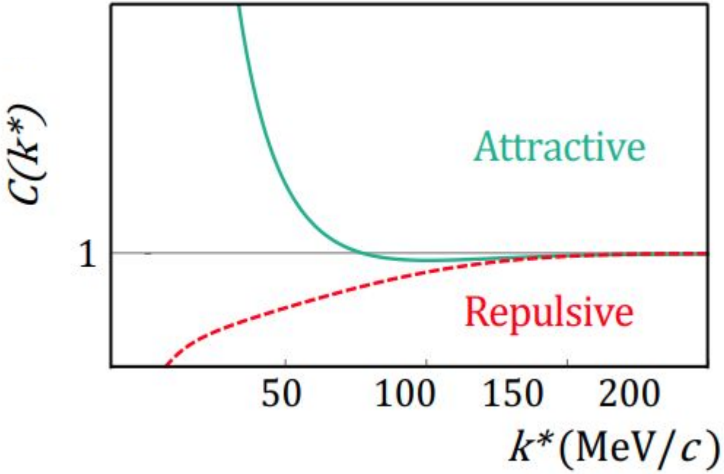


Schrödinger equation

Two-particle wave function

$\Psi(k^*, \vec{r^*})$

Scattering parameters



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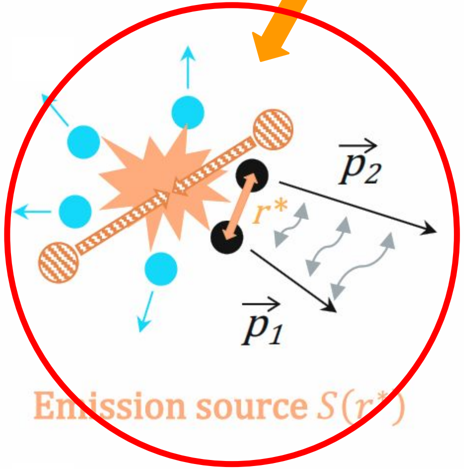
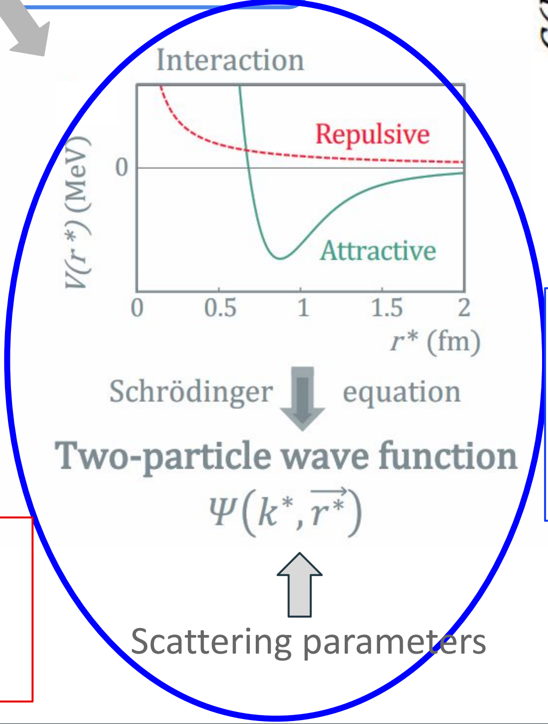
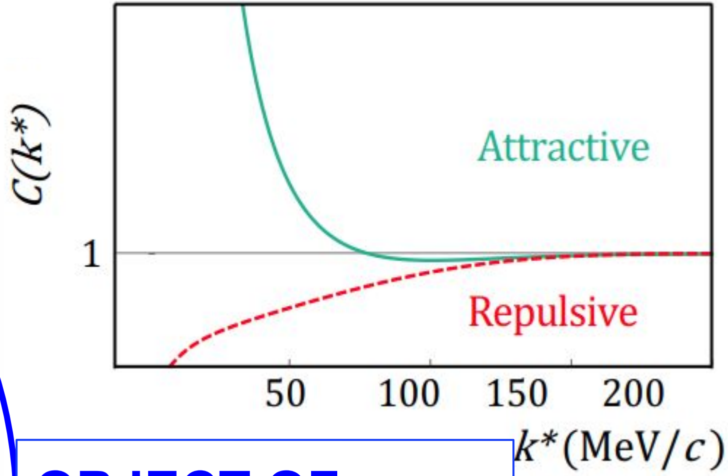


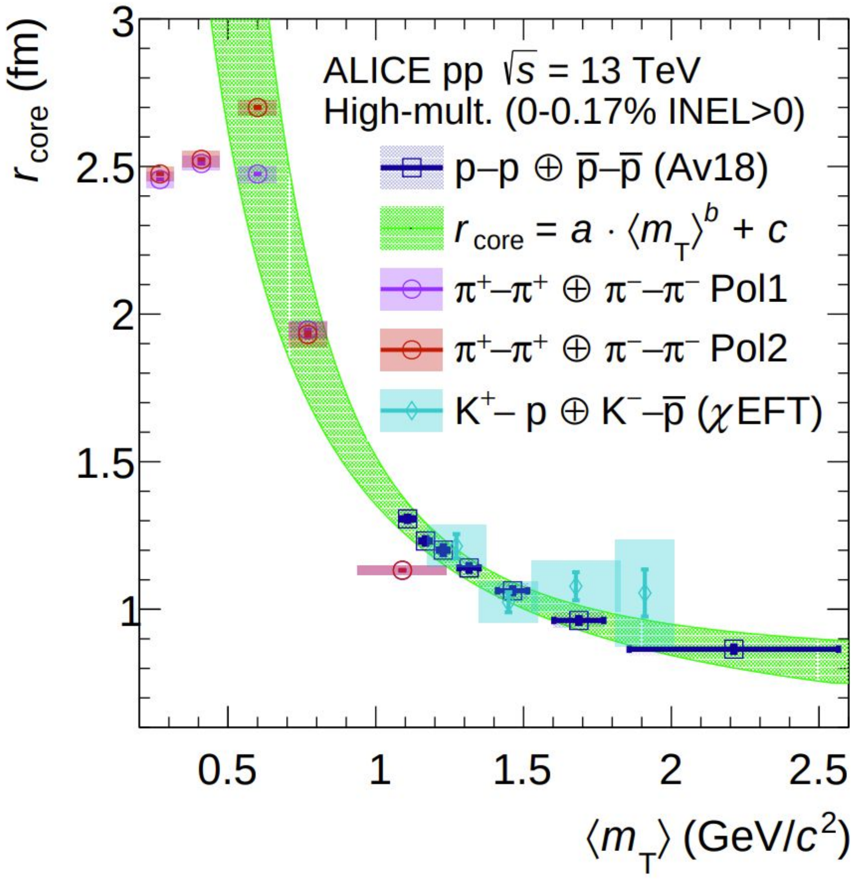
⇒ **Simple gaussian description**
⇒ **Size determined a-priori**





OBJECT OF STUDY IN SMALL SYSTEMS

A necessary first step: Setting the source



"Universal" dependence of the source size with pair transverse mass $<m_T>$

- related to hydrodinamics /collective phenomena ?

newst results:

[ALICE Coll.,arXiv:2311.14527 [hep-ph] EPJC in press](https://arxiv.org/abs/2311.14527)

Source size $<m_T>$ scaling in pp collisions confirmed as well with π-π and K-p pairs

$$m_T = \sqrt{k_T^2 + m^2} \qquad k_T = \frac{1}{2}|p_{T,1} + p_{T,2}|$$

Kbar-N interaction

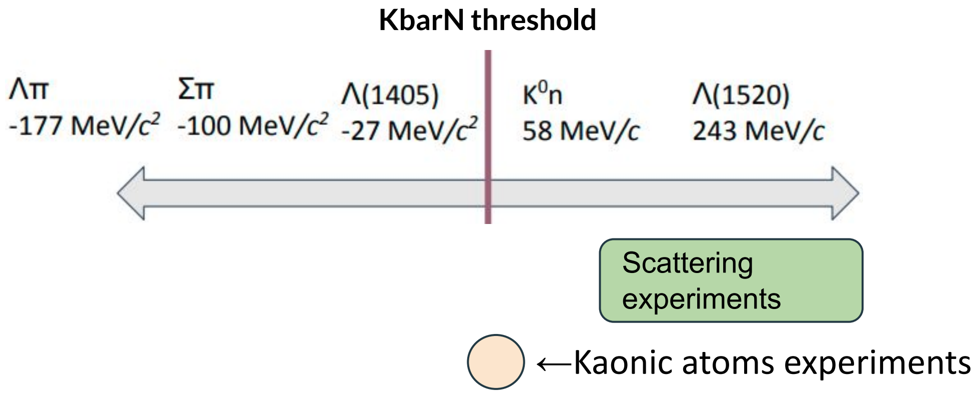
***S* = -1**

Kaon and antiKaon interactions with nucleons are totally different

KN interaction: mild and repulsive, perfectly constraint by scattering data

KbarN interaction:

- appearance of the **Λ(1405) below** (and close to) **threshold**
- **Strong coupled channel dynamics** KbarN-Σπ



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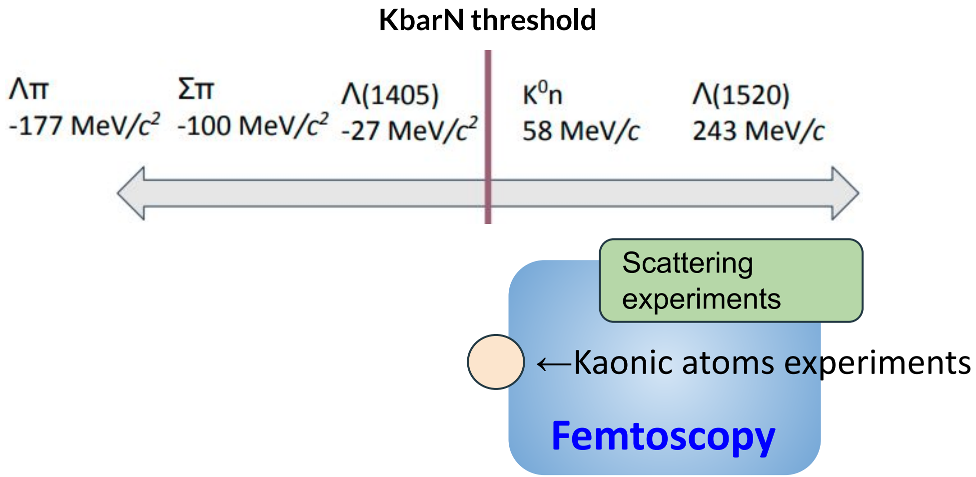
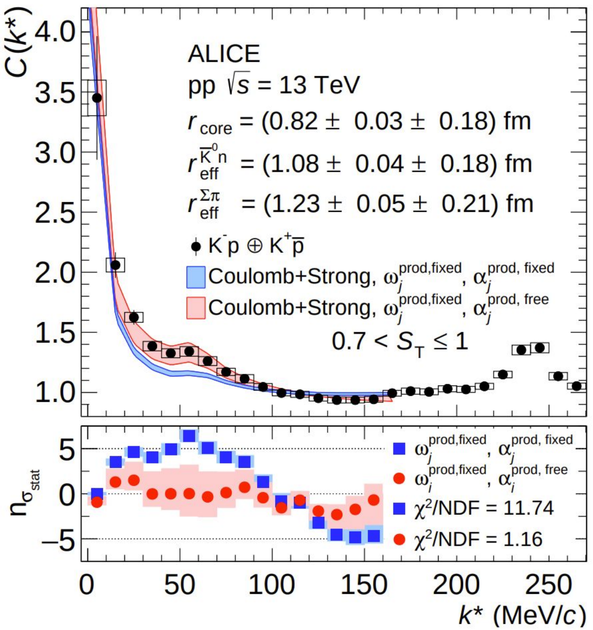


Kbar-N interaction

S = -1

K^-p femtoscopy in pp collsions

ALICE Coll. Phys. Rev. Lett. 124, 092301 (2020)
ALICE Coll. arXiv:2205.15176, EPJC in press (2022)



Strong interaction: Kyoto model
K. Miyahara, T. Hyodo, W. Weise, Phys. Rev. C98, 2, (2018) 025201

⇒ Provides a **quantitative test of coupled channels in the theory**
Effects of coupled channels enhanced by small source

Kbar-N interaction

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K⁻p femtoscopy in pp collsions

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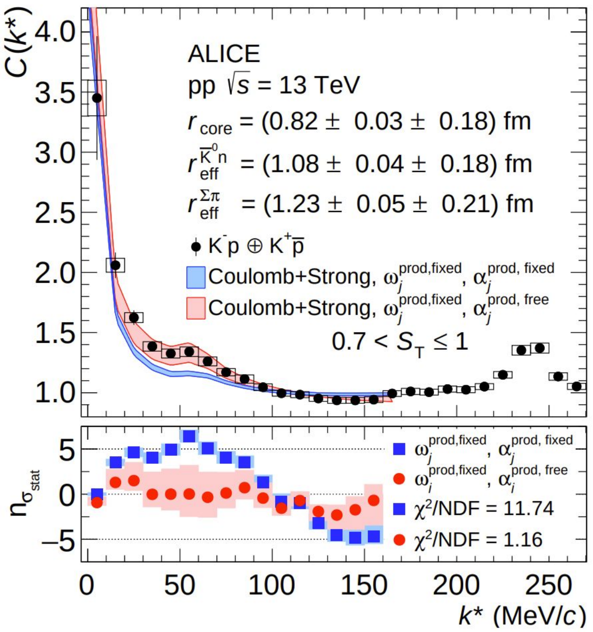

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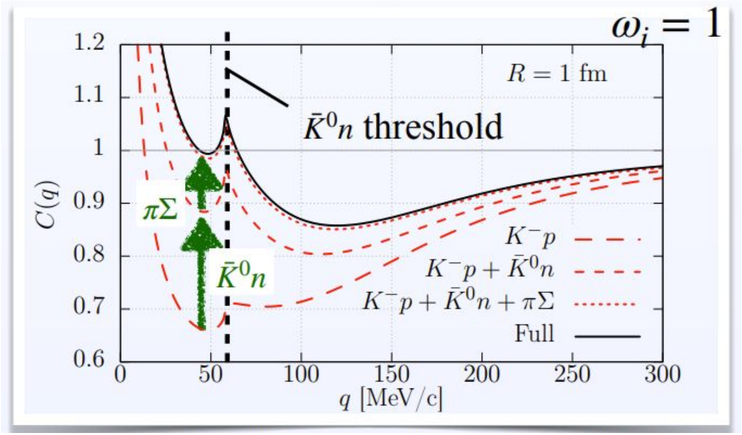
⇒ Provides a **quantitative test of coupled channels in the theory**
Effects of coupled channels enhanced by small source

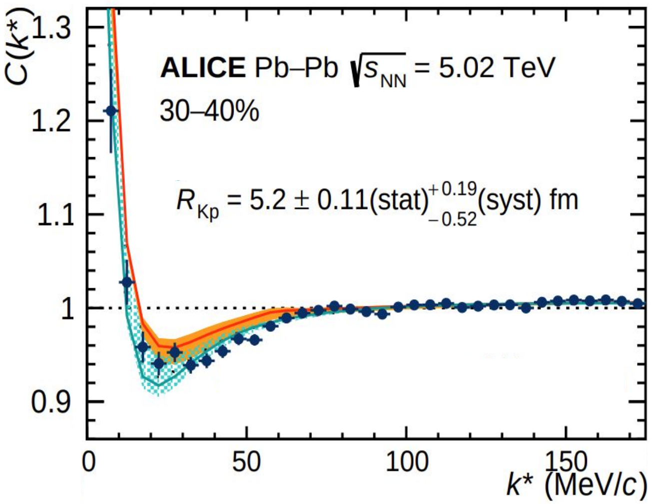
Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501
⇒ Predicted to be negligible in larger sources



Kbar-N interaction

S = -1

ALICE Coll., PLB 822 (2021) 136708

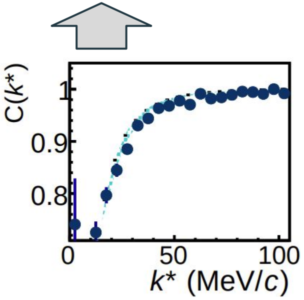


Large systems (HIC): **Pb-Pb collisions, up to r~9fm**

Strength of coupled channels significantly reduced

- Kyoto model
- Fit to the scattering parameters R. Lednický Phys. Atom. Nucl. 67 (2004) 72

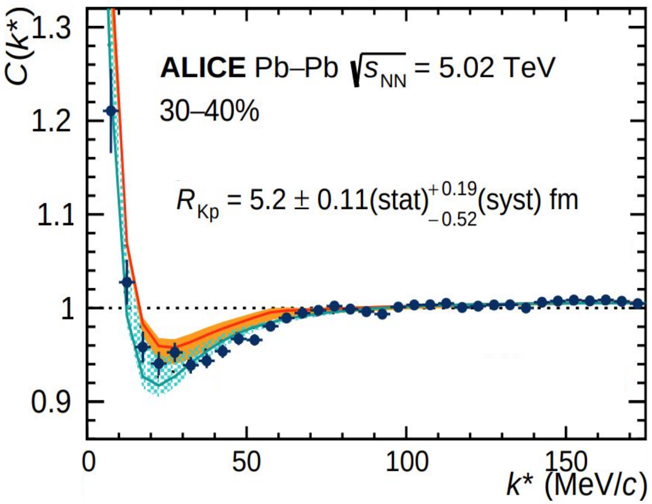
HIC: size determined by simultaneous analysis of K+p corr. func:



Kbar-N interaction

S = -1

ALICE Coll., PLB 822 (2021) 136708



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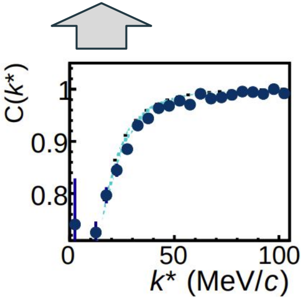

<u>Large systems (HIC):</u> Pb-Pb collisions, up to r~9fm

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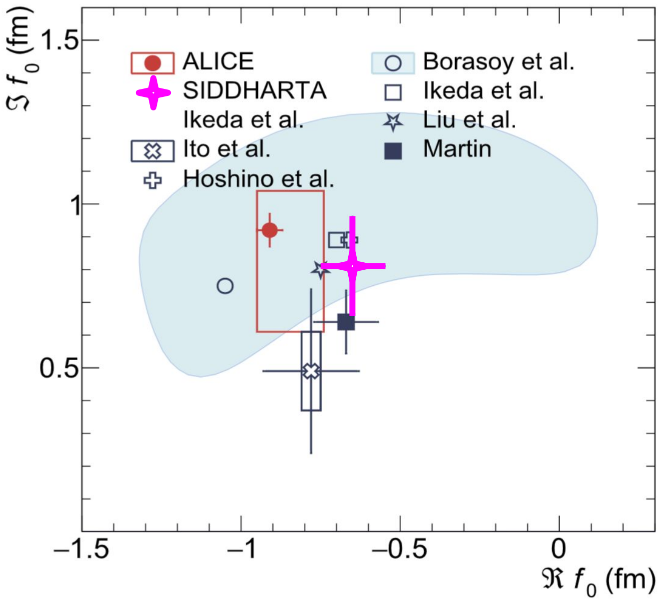
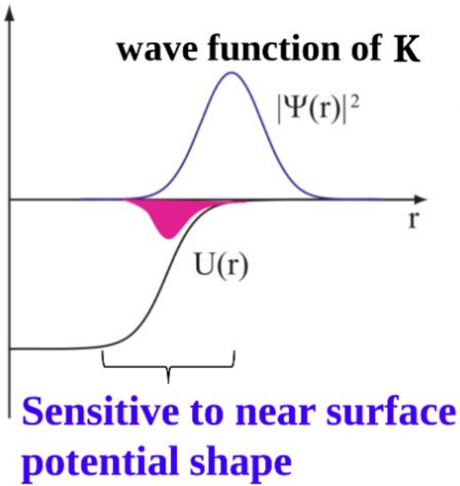


⇒ Antikaonic-hydrogen and K-p femtoscopy scattering parameters compatible

Digression: KbarN at threshold and low momentum

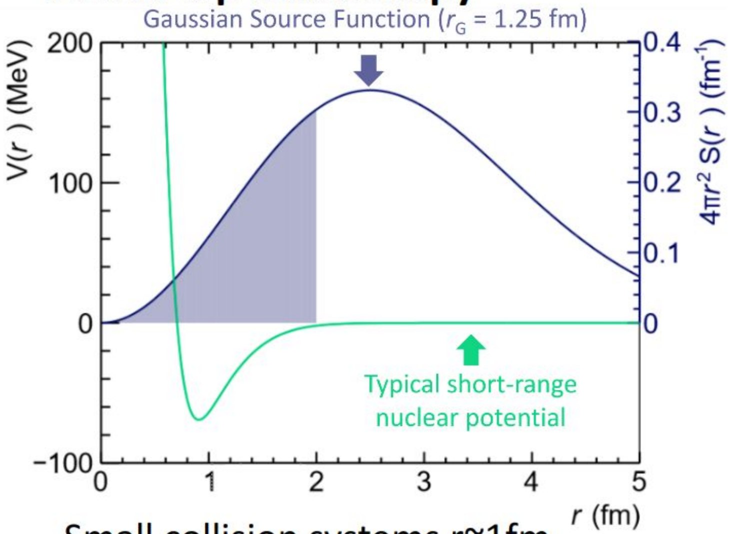
SIDDHARTA: antiKaonic Hydrogen



For antikaonic hydrogen (deuterium) the Bohr radius is ~84 (70) fm.`

The overlap of the kaon wavefunction with the nucleon delivers insight into the effects of the strong interaction, competing with Coulomb effects

ALICE: K⁻p femtoscopy



Small collision systems r~1fm

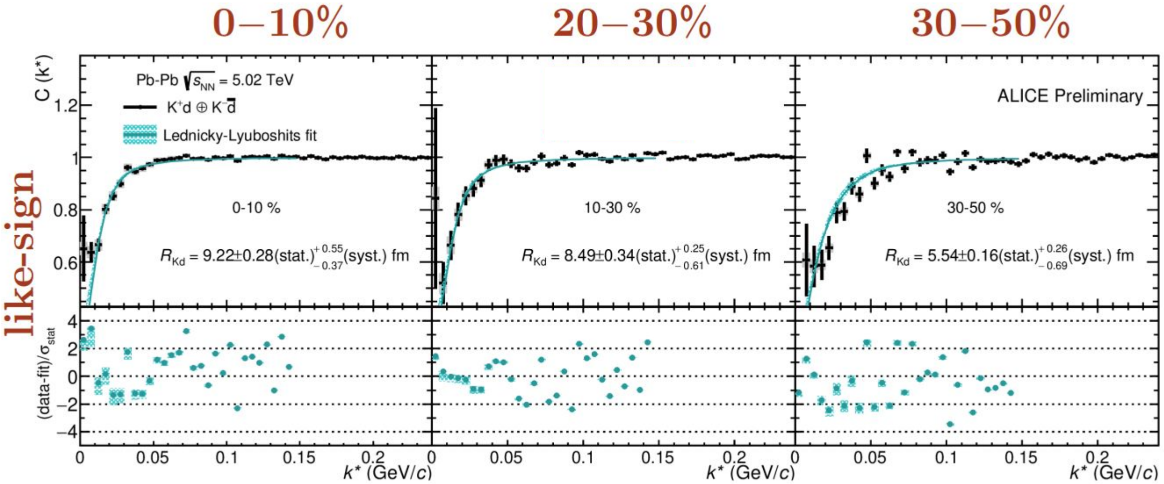
⇒ effect of the interaction is enhanced

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

Deliver different observables ⟺ **scattering lengths can be obtained** from both (via Deser-type and Lednický–Lyuboshitz formulae)

K⁻d Femtoscopy with ALICE in Pb-Pb collisions

W. Resza @ Hadron 2023

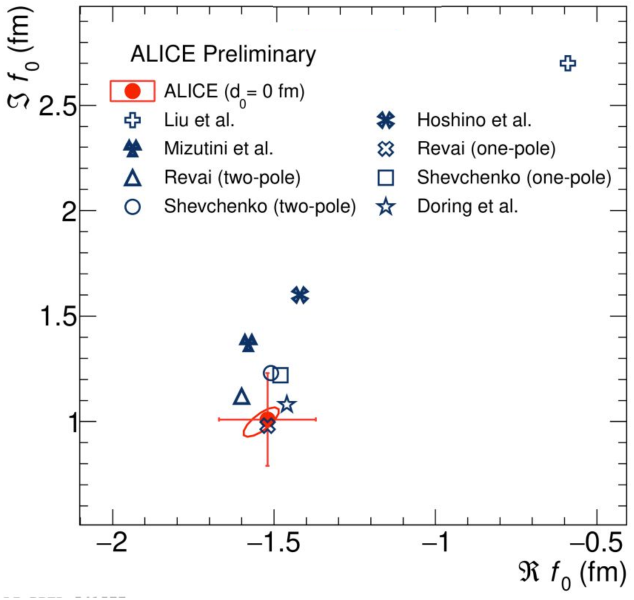


Fit to K⁻d correlation function:

Simultaneous fit with 6 free parameters with Lednicky wave function

- Re. K⁺d scatt. length
- Re., Im. K⁻d scatt. length
- radius size x3 centralities

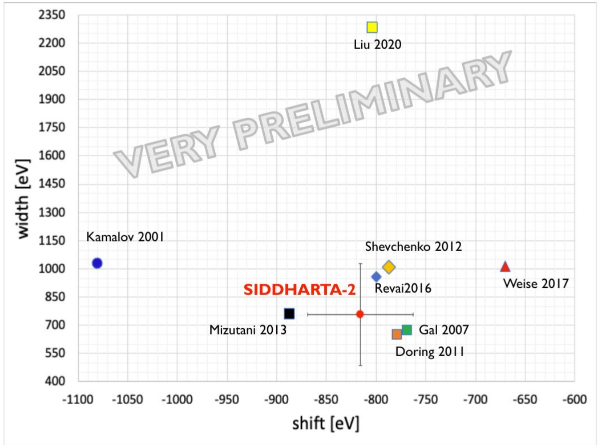
K^-d Femtoscopy with ALICE in Pb-Pb collisions



W. Resza @ Hadron 2023

Fit to K^-d correlation function:

⇒ Real and imaginary part of K^-d scattering length via Lednicky model

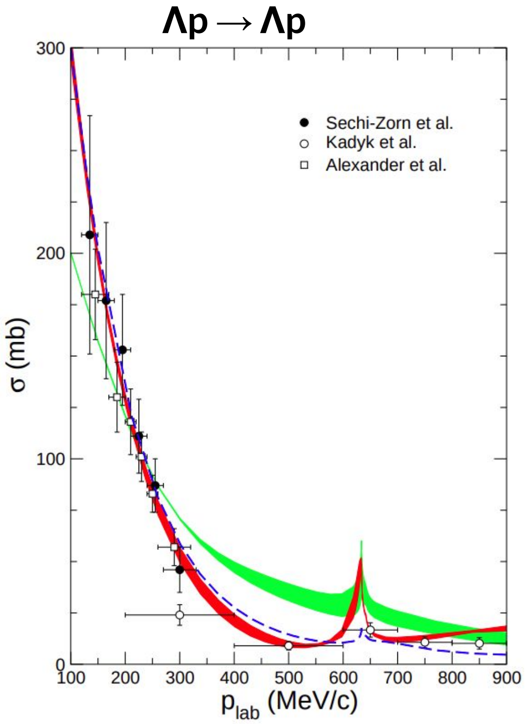


F. Sgaramella SIDDHARTA-2

otonvd@cern.ch

p–Λ interaction

S = -1



→ Chiral SU(3) EFT vs scattering data

LO: H. Polinder, J. Haidenbauer, U. Meißner, Nucl. Phys. A779 (2006) 244.

NLO: J. Haidenbauer et al., Nucl. Phys. A915 (2013) 24.

p–Λ interaction

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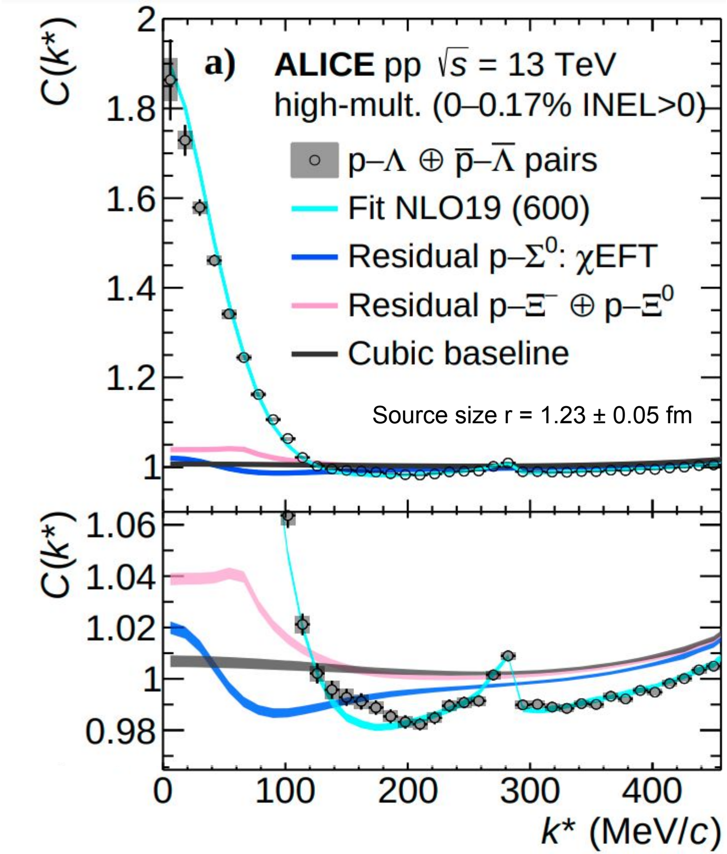
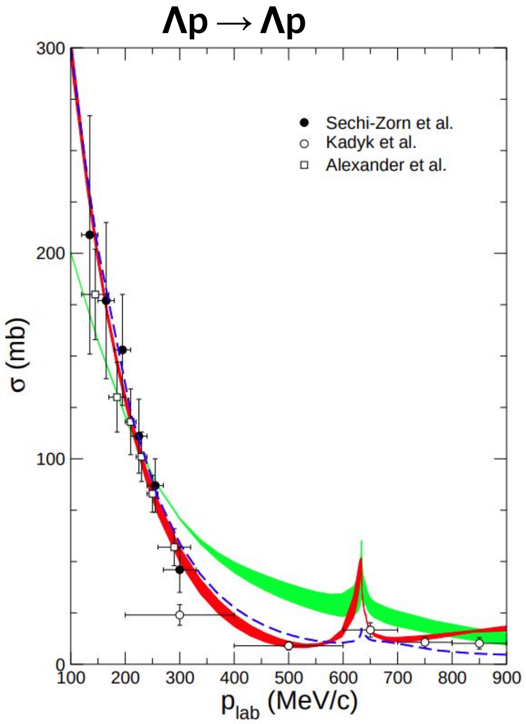




→ Chiral SU(3) EFT vs scattering data

LO: H. Polinder, J. Haidenbauer, U. Meißner, Nucl. Phys. A779 (2006) 244.

NLO: J. Haidenbauer et al., Nucl. Phys. A915 (2013) 24.

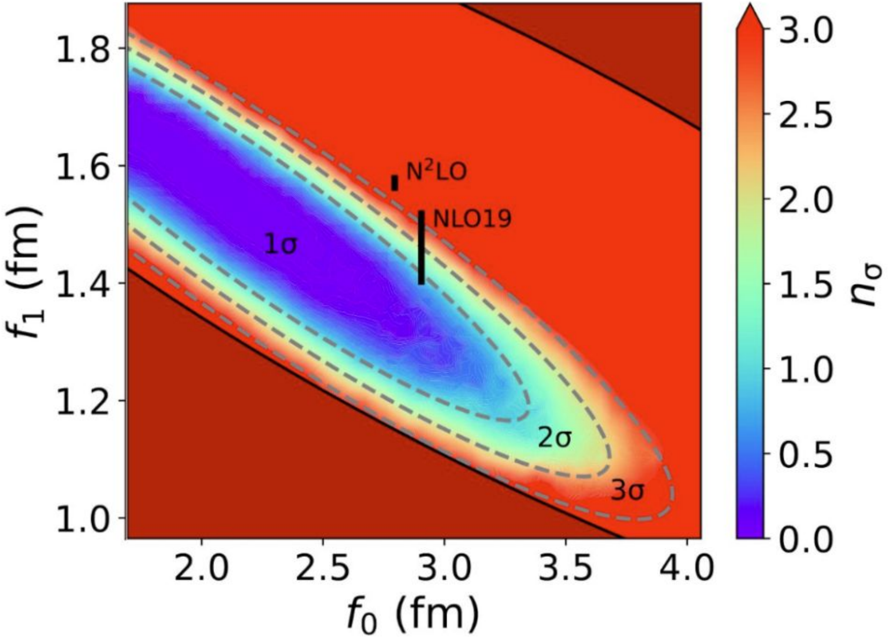
ALICE Coll. Phys.Lett.B 833 (2022) 137272`

Theory: Haidenbauer et al., Eur. Phys. J. A 56 (2020) 91

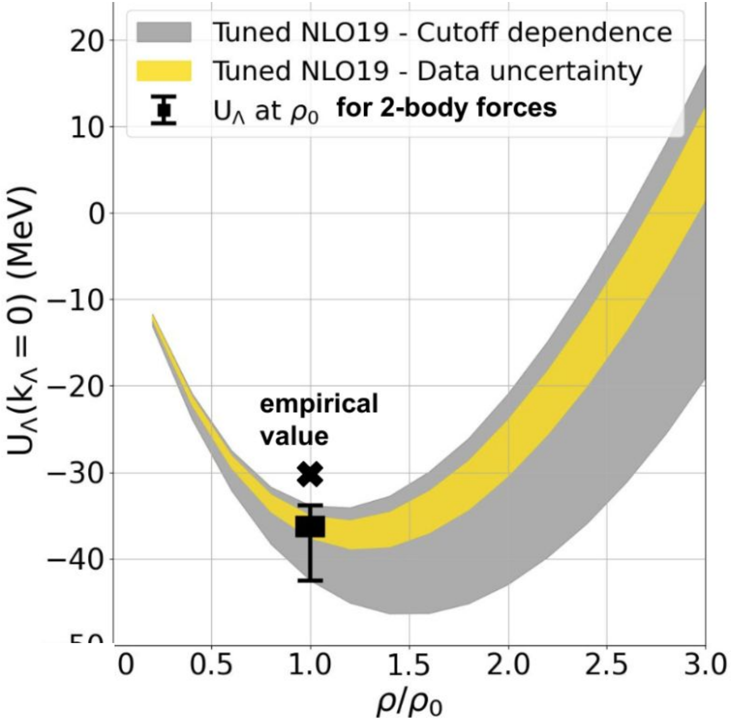
p–Λ interaction

$S = -1$

⇒ Combined analysis of femtoscopy and scattering data



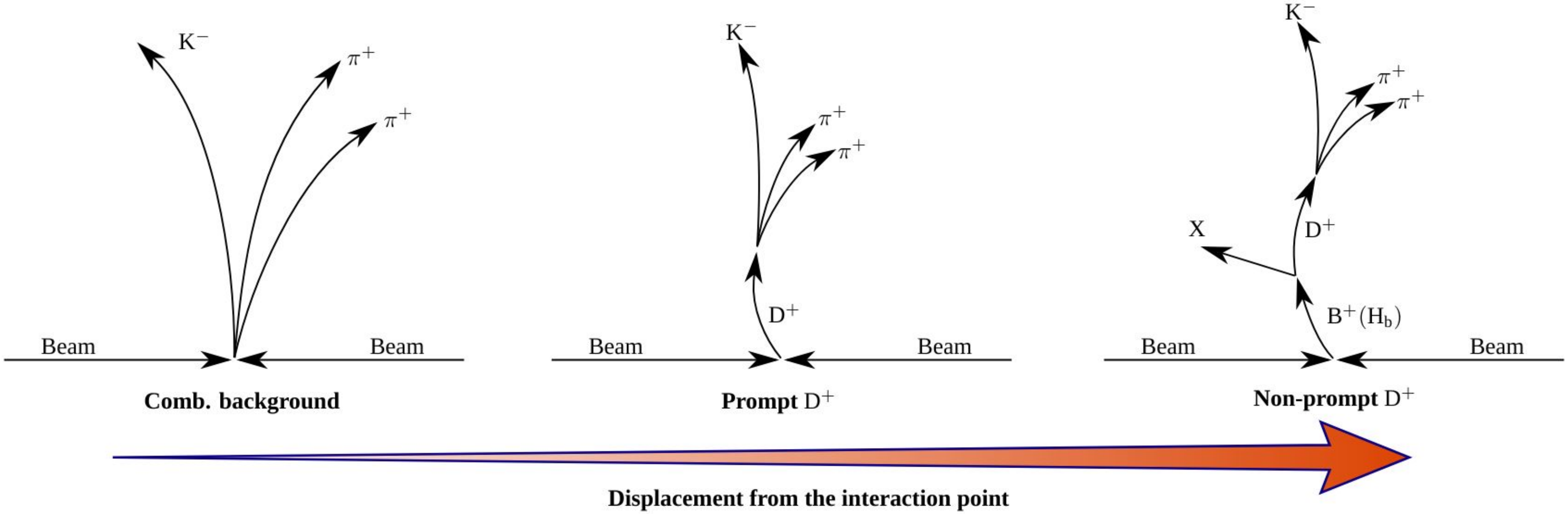
⇒ New parameterization of χEFT
Compatible with repulsive 3-body forces



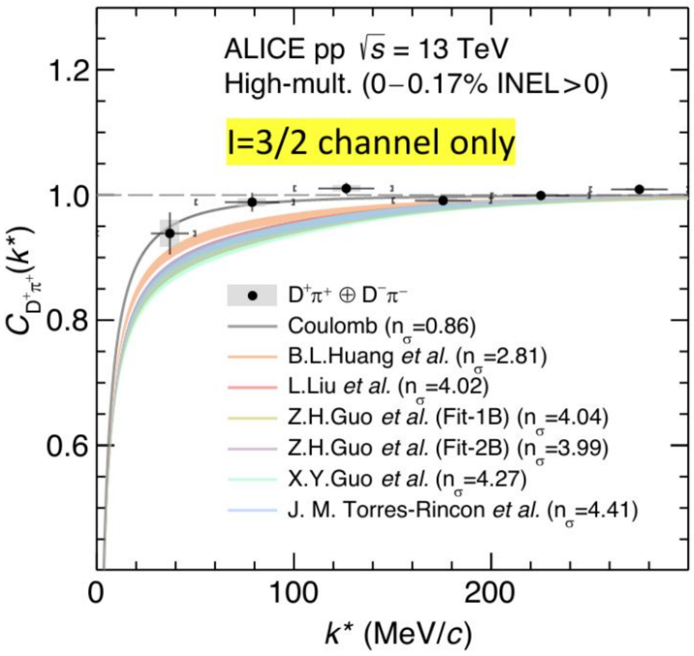
D. Mihaylov, J. Haidenbauer, V. Mantovani Sarti Phys. Lett. B 850 (2024) 138550

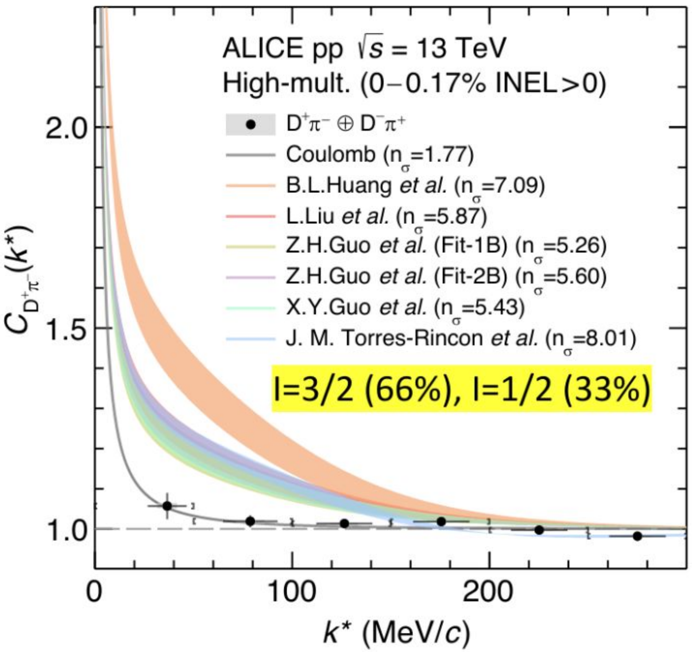
$D^{(*)}$–π/K femtoscopy

- Exploit the decay vertex topology for identification
- Machine learning algorithm based on boosted decision trees
- Account for uncorrelated backgrounds: D mesons from beauty-hadron decays



D$^{(*)}$–π femtoscopy

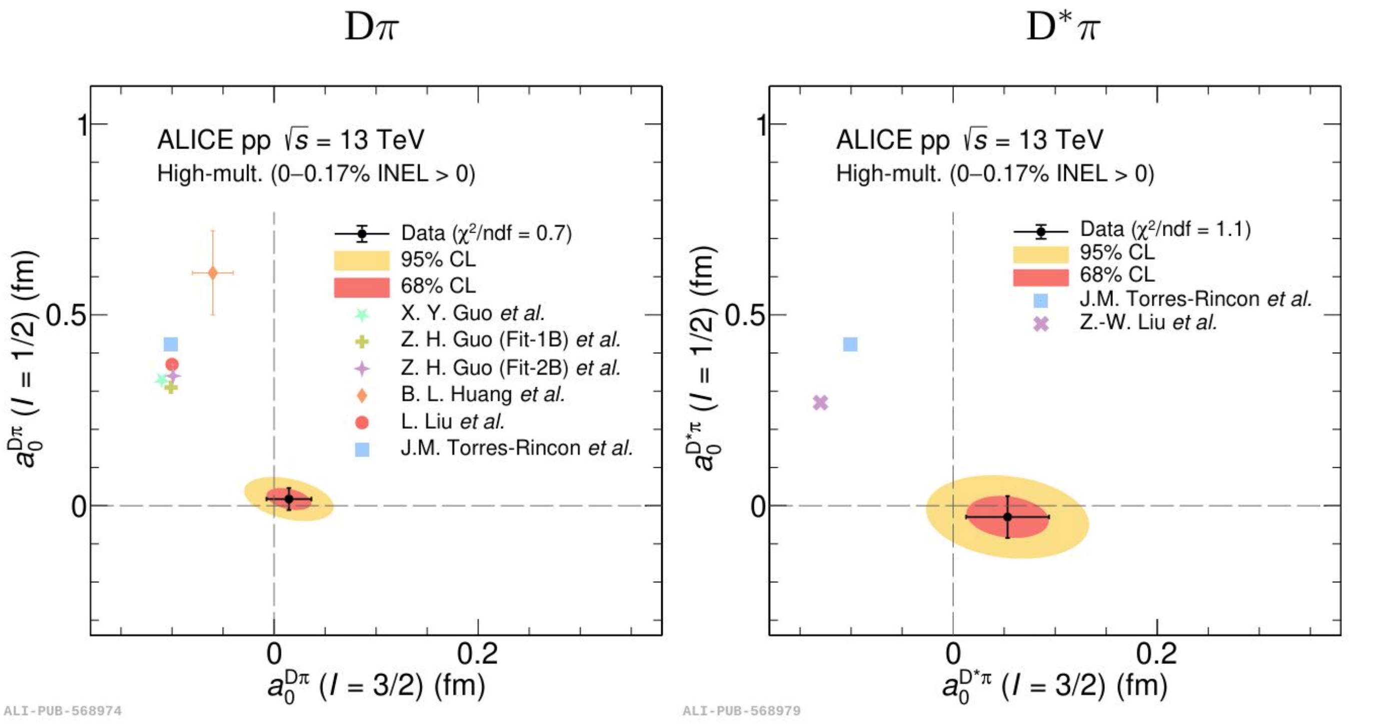




L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
J. M. Torres-Rincon et al, Phys. Rev. D 108 (2023) 096008

D$^{(*)}$–π interaction

ALICE Coll. arXiv:2401.13541 [nucl-ex]



Small scattering lengths:

- compatible with Coulomb-only assumption
- theory overestimates interaction strength

Scattering lengths similar for Dπ and D*π:

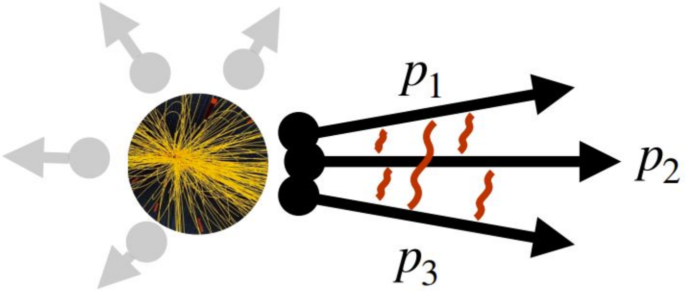
- heavy-quark spin symmetry

- DK data so far not precise enough

Three-body femtoscopy

Three-particle correlation function:

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

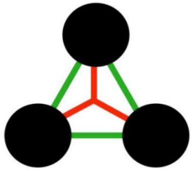


The Lorentz invariant Q_3 is defined as:

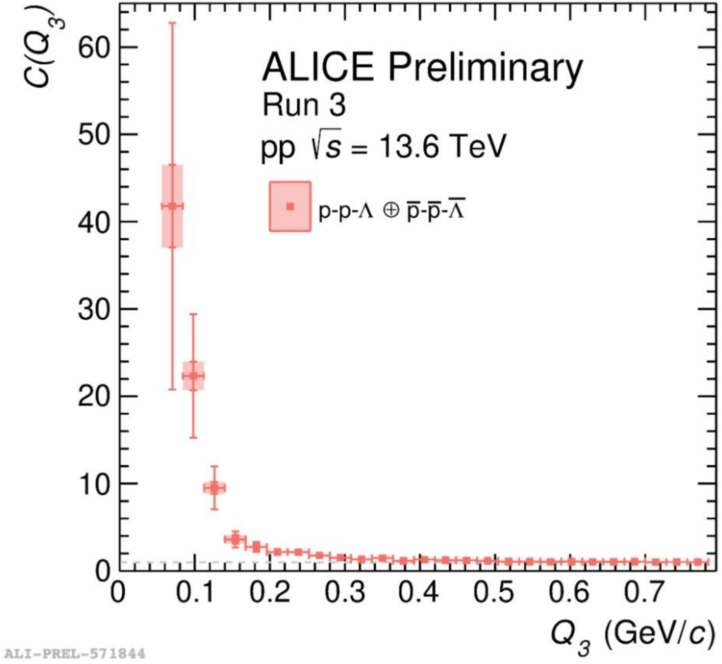
$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

Three-particle correlation function function incorporates:

- Two body interactions
- Three body interactions

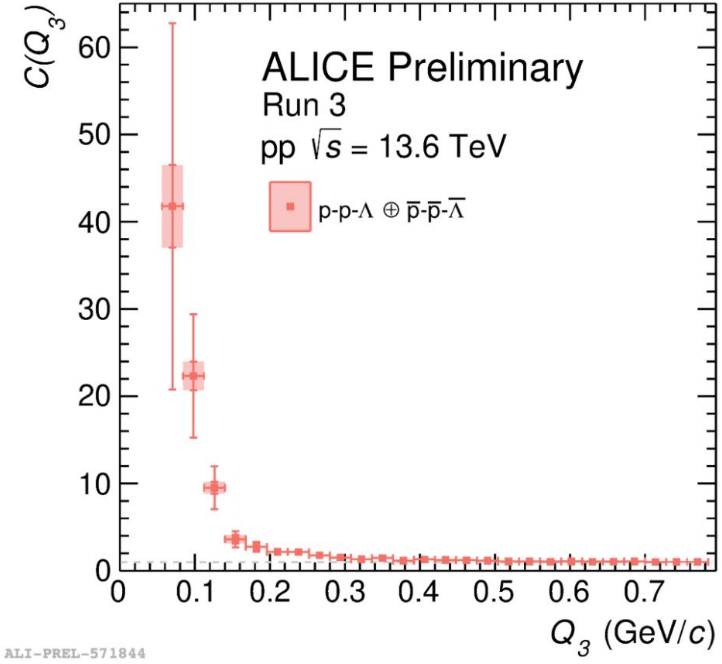


p-p-Λ correlation function



⇒ Exploiting current LHC run and new detectors

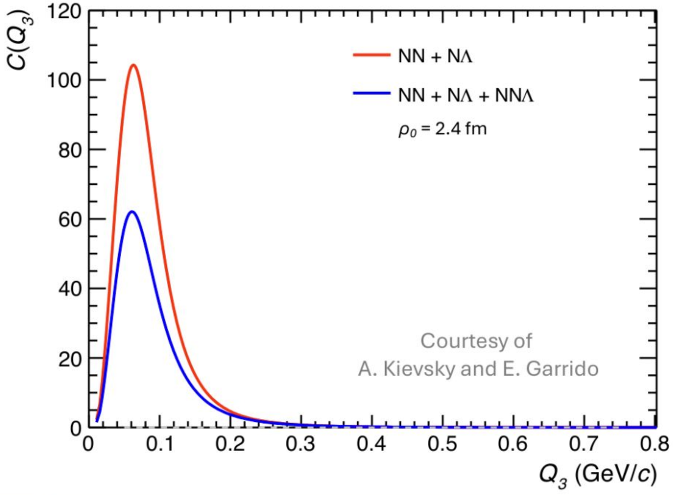
p-p-Λ correlation function



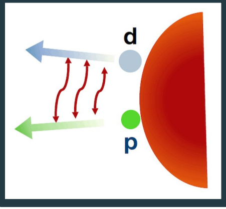
⇒ Exploiting current LHC run and new detectors

First theoretical predictions:

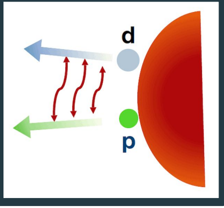
- NΛ interaction from χEFT NLO19
- NNΛ interaction fixed to hypertriton BE



proton-deuteron correlation function



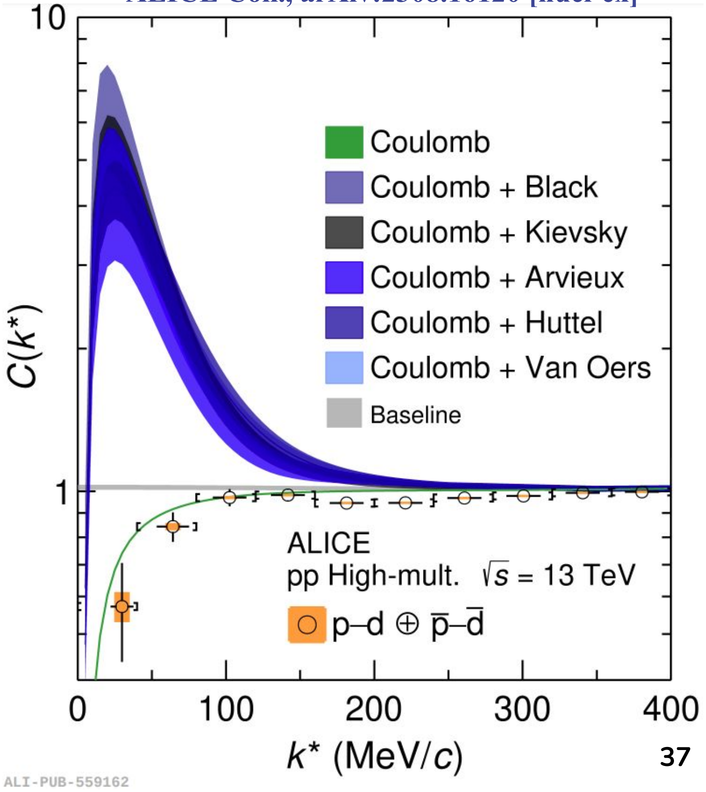
proton-deuteron correlation function as a two-body system



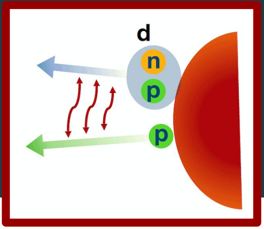
ALICE data in pp HM collisions compared with theoretical correlation function **considering deuteron as a point-like particle**

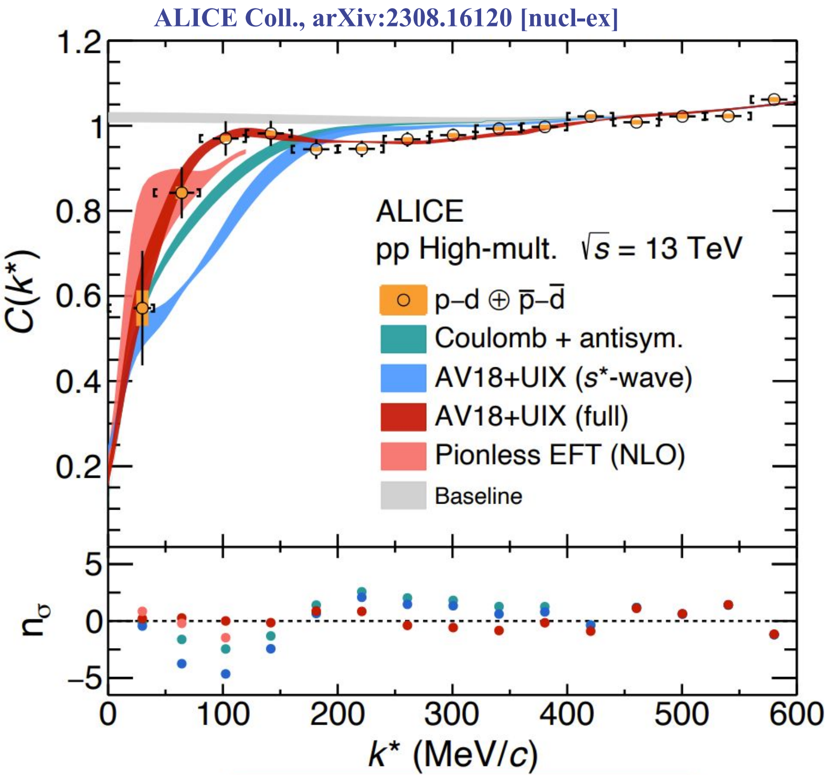
- Lednický model:
  - s-wave asymptotic wave function from scattering parameters R. Lednický, Phys. Part. Nucl. 40, 307 (2009)
- Strong interaction constrained from the scattering measurements

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



p-d correlation function **including three-body dynamics**





Red curve: **full-fledged three-body calculation describes the data** by including:

- **2N** force (AV18 potential) **+ 3N** force (UIX potential)
- Calculation up to d-wav

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

Summary and outlook

Femtoscopy technique can be used to provide **unprecedented constraints on hadron-hadron interactions…**

- We are **testing lattice calculations** and **EFT** approaches
- We study **bound states** and **channel couplings**
- We provide important constraints to the **equation of state of neutron stars**
- Direct measurements of **three-body dynamics**
- Access to **D meson interactions**

- More data, more people, more experiments… more fun
  - **STAR**: S= -4 $\Xi\Xi$ femtoscopy, deuteron femtoscopy: coalesence vs thermal models
  - **CMS** ΛK femtoscopy
  - **HADES** proton-cluster femtoscopy
  - **ALICE** with current LHC data x100 stats… and DD femtoscopy with ALICE 3

… stay tuned for more!!!