AntiKaon-deuteron measurements at Frascati. A new era of hadron-hadron interaction measurements.

Otón Vázquez Doce (Fellini fellow at LNF -INFN)
Supervisors: Alessandra Fantoni, ALICE
Catalina Curceanu, SIDDHARTA-2.

LNF General seminar,Frascati, January 12th, 2022

FEMTO-STRONG
Oton Vazquez Doce

Fellini
Fellowship for Innovation at INFN

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Study of the antiKaon-deuteron interaction

antiKaonic atoms spectroscopy
- **SIDDHARTA-2**
- DAΦNE e^+e^- collider
- Low energy kaons facility

Femtoscopy: two body correlations
- **ALICE**
- LHC
- Hadronic collisions

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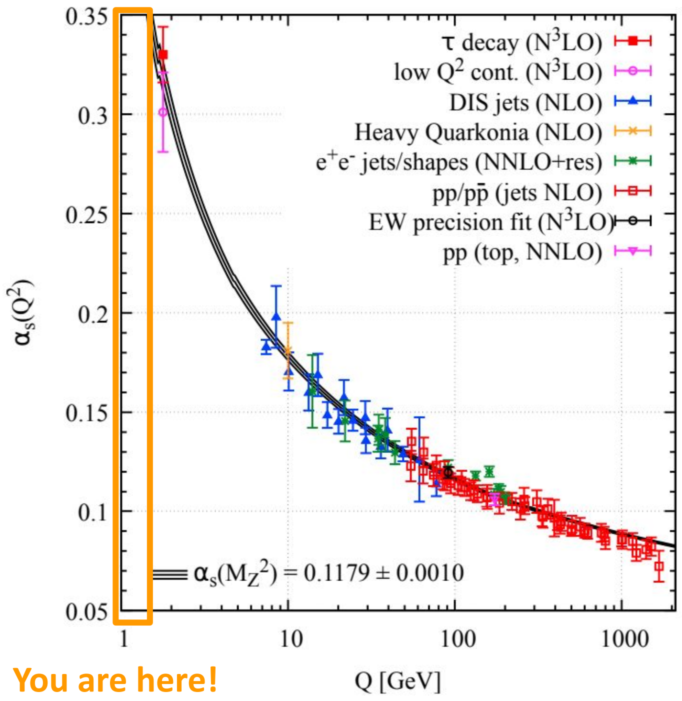
from high-energy physics to nuclear physics

Hadron-hadron strong interactions with strangeness

Hadron-hadron strong interactions

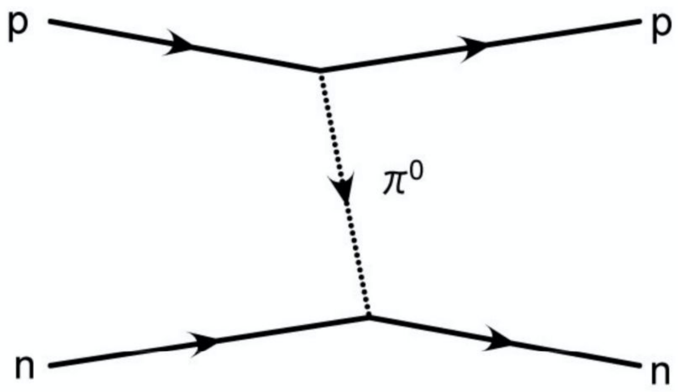


Running coupling constant defines the boundaries of "Low energy QCD"

- Q ~ 1 GeV, R ~ 1 fm
- Perturbative methods not applicable

Hadron-hadron strong interactions

Residual strong interaction among hadrons



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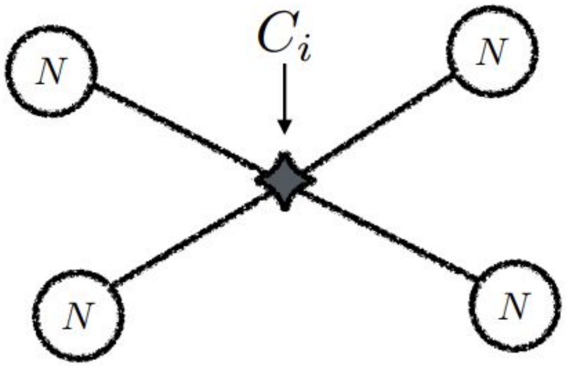


$$\mathcal{L}_{EFT}[\pi, N, \ldots; m_\pi, m_N, \ldots, C_i]$$

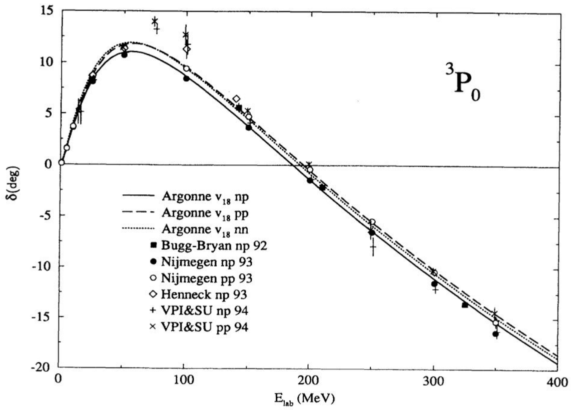
Effective theories (EFT)

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

Hadron-hadron interactions
(with strangeness)

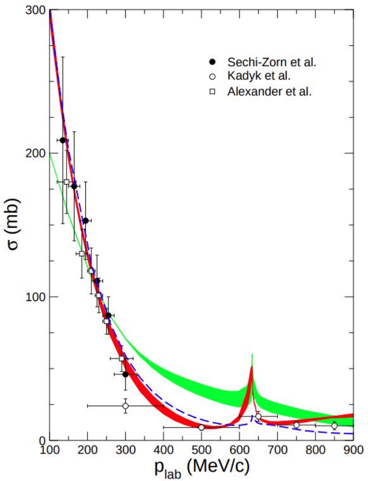
S=0 *S*=-1 *S*=-2

NN → NN



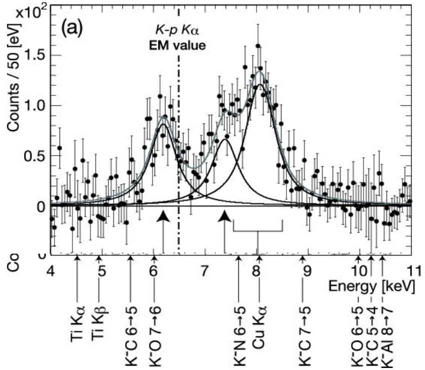
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla Phys. Rev. C 51, 38 (1995)

Λp → Λp



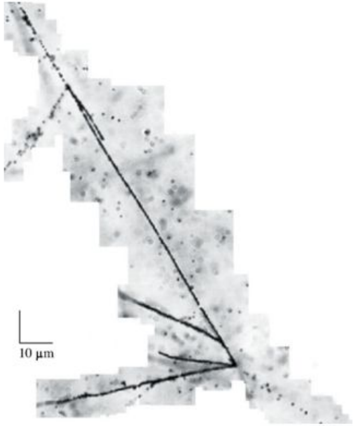
LO: H. Polinder, J. Haidenbauer, U. Meißner, Nucl. Phys. A779 (2006) 244.
NLO: J. Haidenbauer et al., Nucl. Phys. A915 (2013) 24.

Kaonic atoms



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

ΛΛ, Ξ hypernuclei

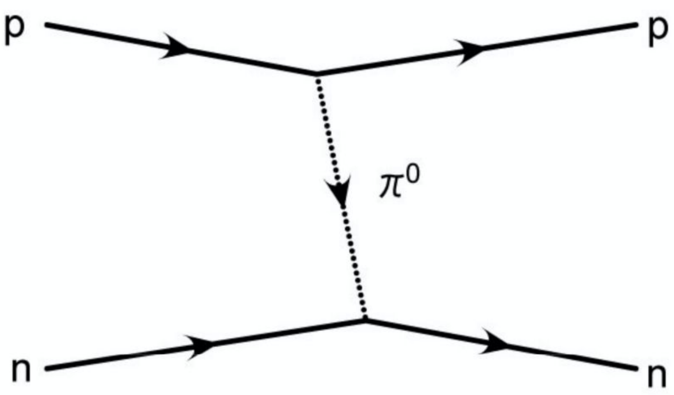


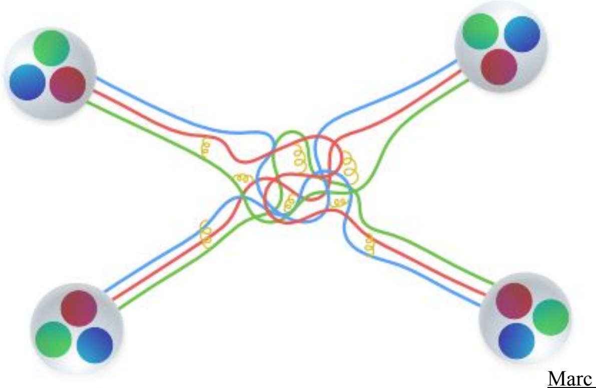
KISO event: K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015, 033D02
IBUKI event J-PARC E07 Coll., Phys. Rev. Lett. 126, 062501 (2021)

Experimental data

Hadron-hadron strong interactions

Residual strong interaction among hadrons





Marc Illa
THEIA-STRONG2020

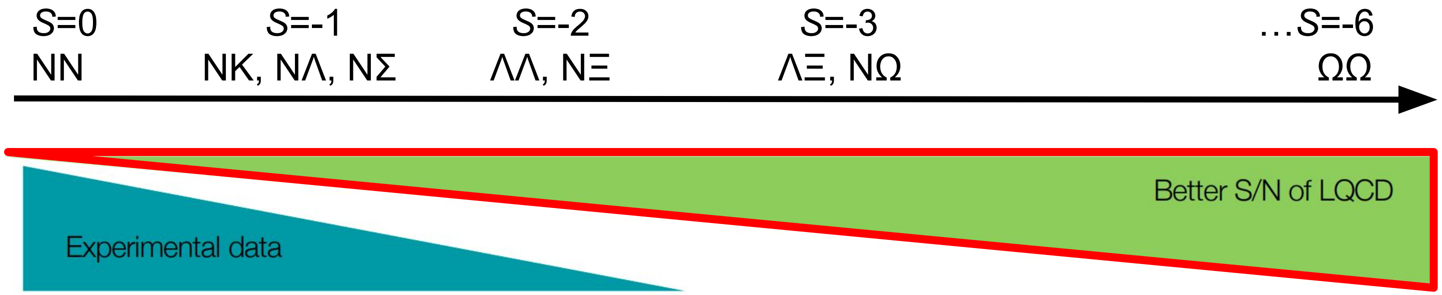
$$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$$

Lattice QCD

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

Hadron-hadron interactions

(with strangeness)



Hadron-hadron interactions

(with strangeness)

$m_\pi \approx 570$ MeV

Physics Letters B
Volume 681, Issue 5, 16 November 2009, Pages 439-443

A method to measure the antikaon–nucleon scattering length in lattice QCD ☆

Michael Lage ... Akaki Rusetsky

M. Lage et l., PLB 681 (2009) 439

S-wave kaon–nucleon potentials with all-to-all propagators in the HAL QCD method

HAL QCD Collaboration, Kotaro Murakami, Yutaro Akahoshi, Sinya Aoki

HAL QCD Coll. PTEP 2020 (2020) 9, 093B03

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

ELSEVIER

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NΩ dibaryon from lattice QCD near the physical point

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PHYSICAL REVIEW LETTERS

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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

Hadron-hadron interactions
(with strangeness)

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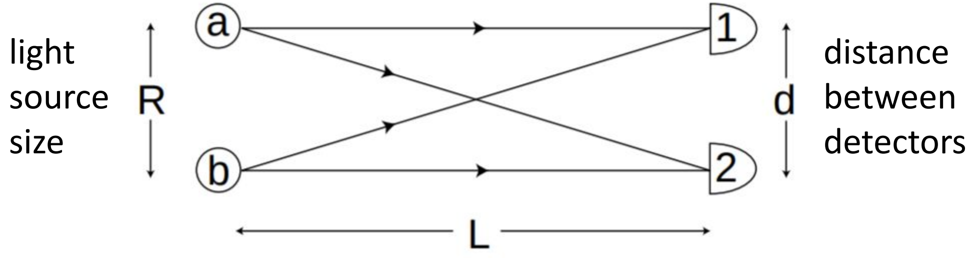
Femtoscopy

Femtoscopy method in nuclear collisions

Method defined by HBT interferometry

- based in the **measurement of the correlation function** $C(\vec{d}\,) = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$



Femtoscopy method in nuclear collisions

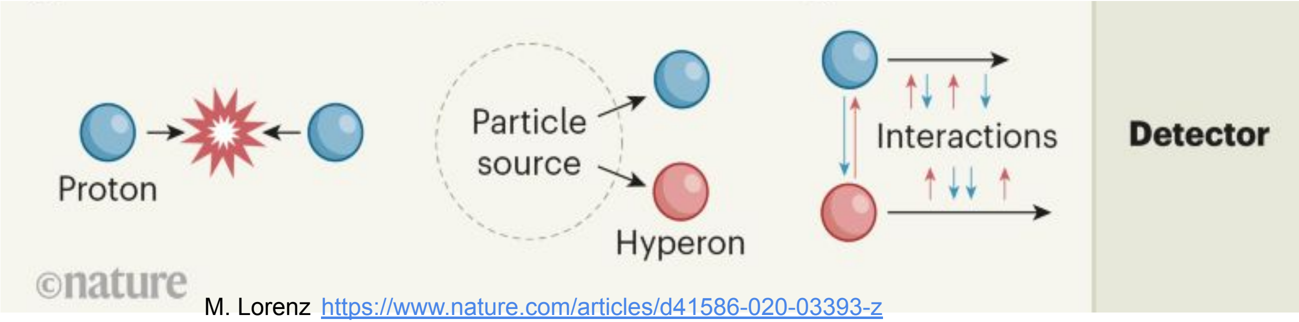
⇒ Application to Heavy Ion Collisions

Measurement of the particle source

- based on the correlation function of two particles emmited in the collision

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

⇒ Application to Small Systems



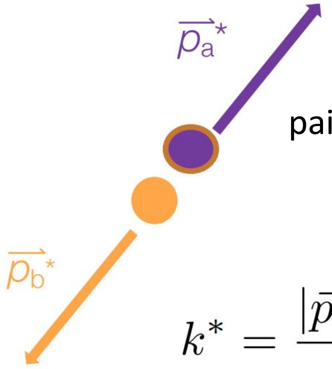
M. Lorenz https://www.nature.com/articles/d41586-020-03393-z

Experimental correlation function

Experimentally:

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

- $N_{\text{same}}(k^*)$ → Pairs of particles from same collision
- $N_{\text{mixed}}(k^*)$ → Particles produced in different collisions



pair reference frame

$$k^* = \frac{|\vec{p_a^*} - \vec{p_b^*}|}{2}$$

Experimental correlation function

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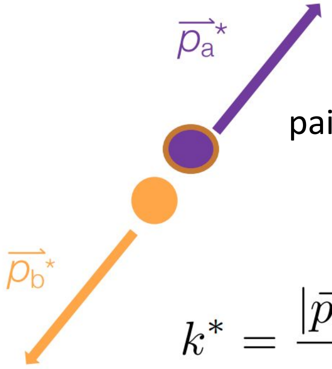
$$C(k^*) = \xi(k^*) \otimes \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

- $N_{\text{same}}(k^*)$ → Pairs of particles from same collision
- $N_{\text{mixed}}(k^*)$ → Particles produced in different collisions

$\xi(k^*)$ → Corrections to the experimental measurement:

- Normalization
- Resolution effects
- **Residual correlations**



pair reference frame

$$k^* = \frac{|\vec{p_a^*} - \vec{p_b^*}|}{2}$$

Theoretical correlation function

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

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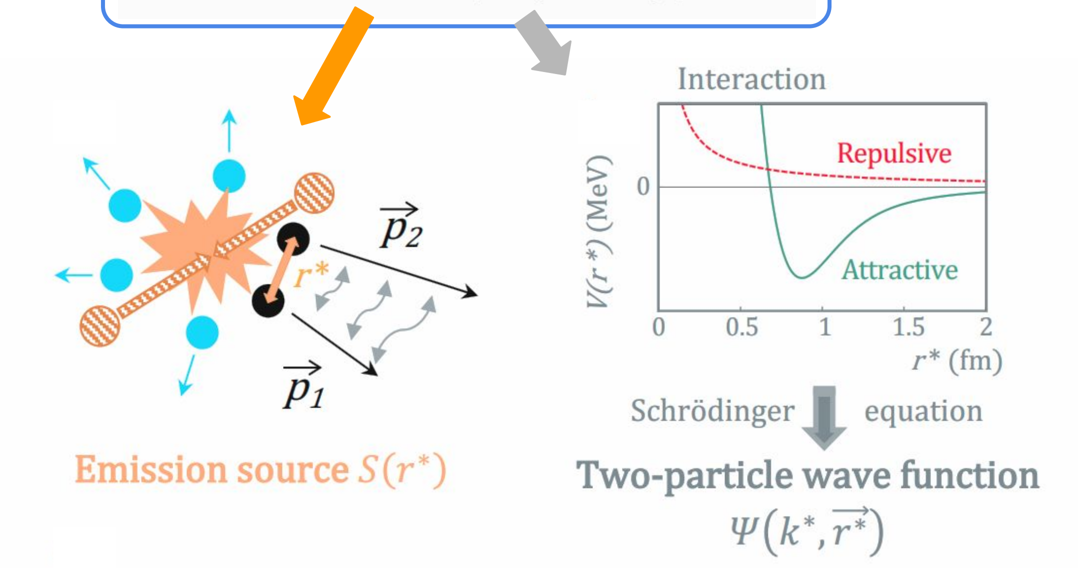

D.L.Mihaylov et al. Eur. Phys. J. C78 (2018) no.5,394

Theoretical correlation function

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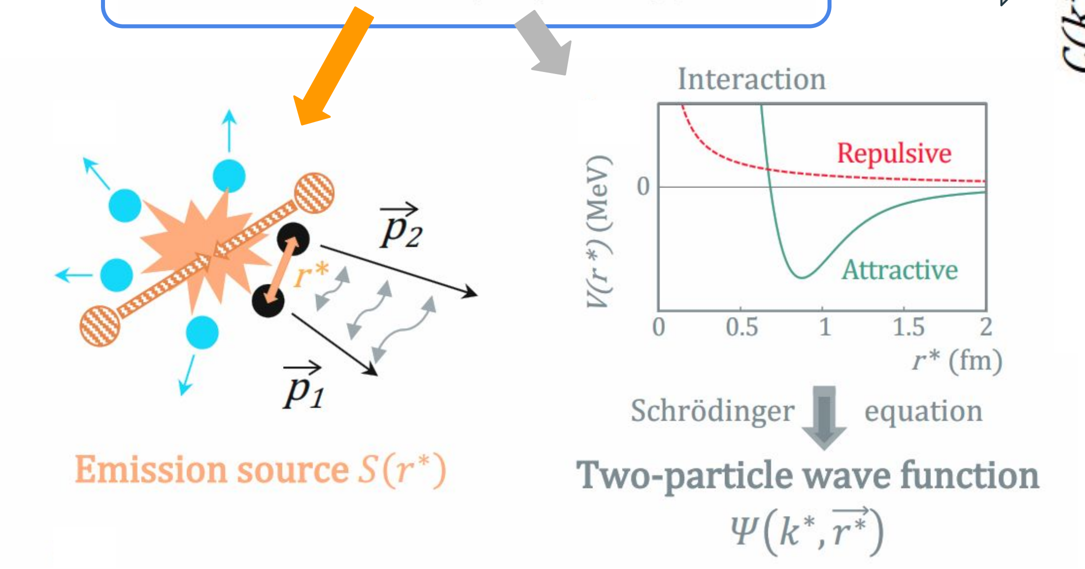

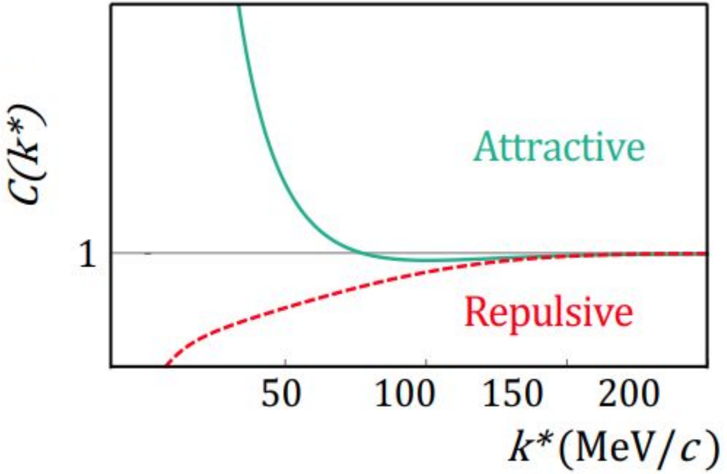

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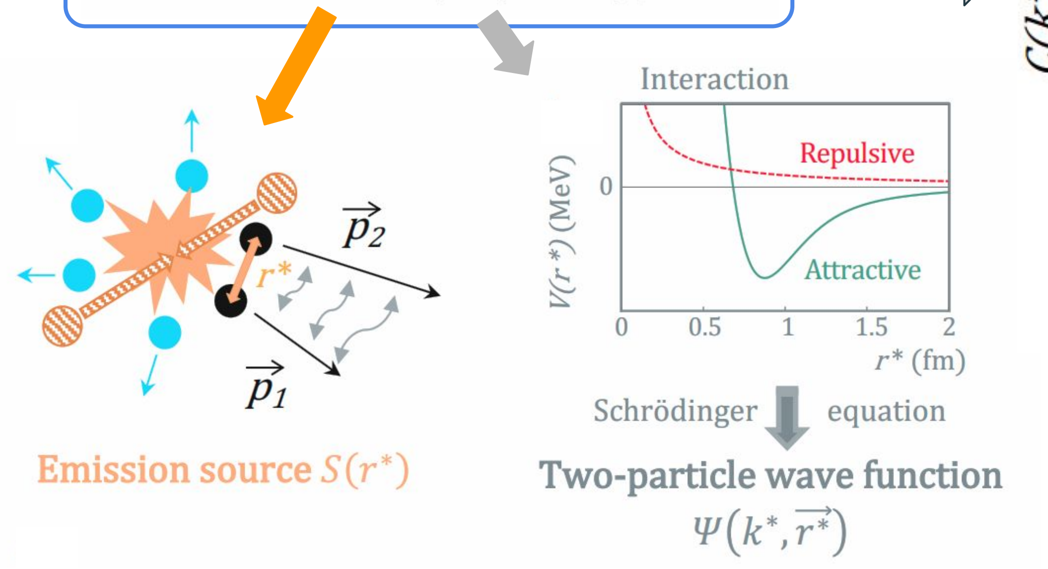

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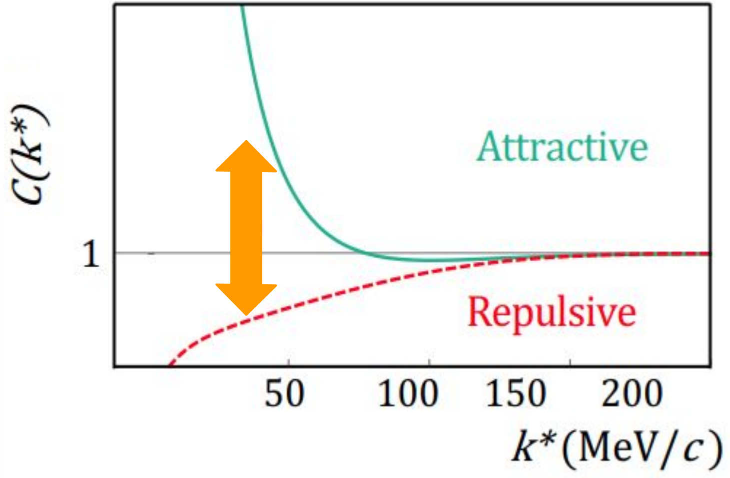

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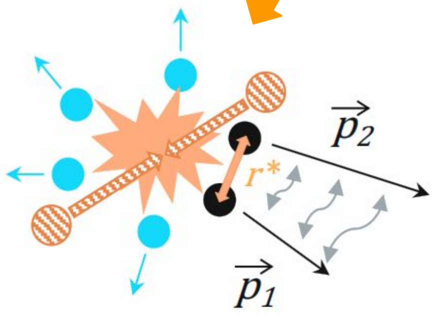

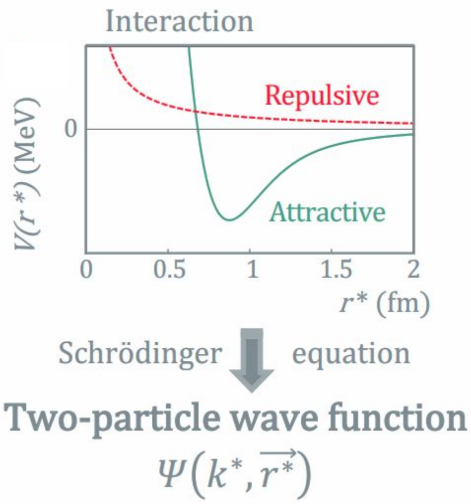

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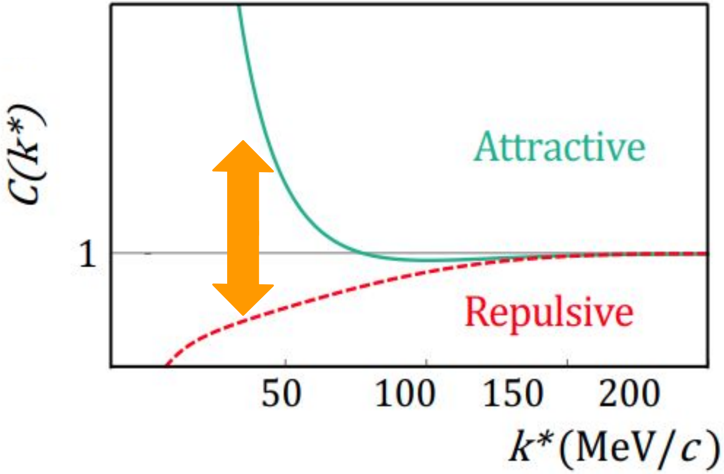

Experimentally:

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

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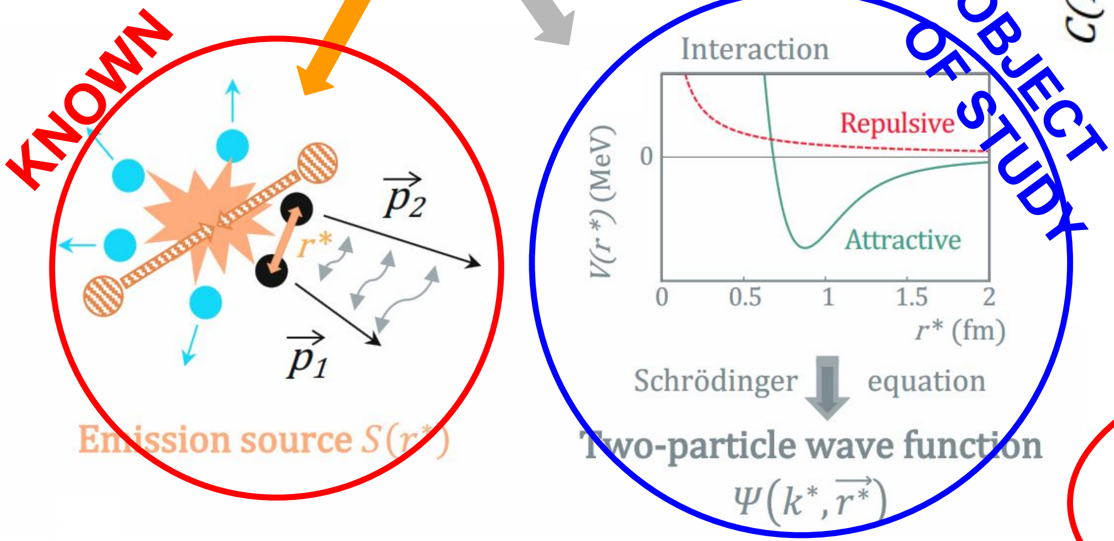

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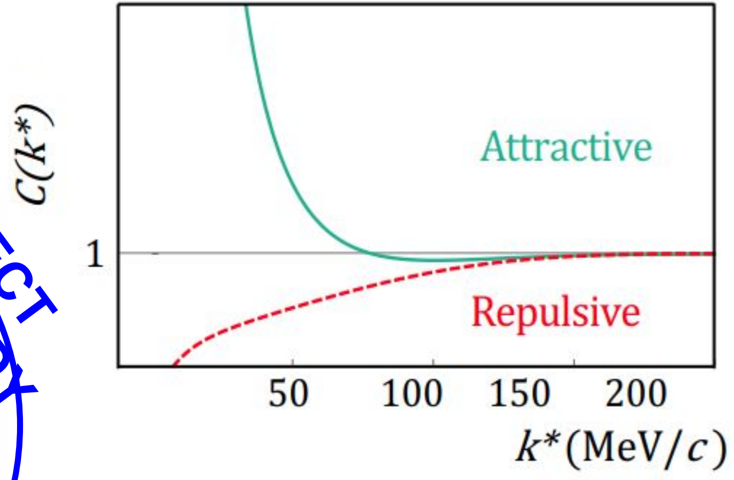


Experimentally: KNOWN

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

Femtoscopy method in small systems

“Traditional” femtoscopy analyses in Heavy Ions Collisions:

Study pairs of particles with “known” interaction

⇒ **Determine the characteristics of the source (sizes 3-10 fm)**

“Non-traditional” femtoscopy

⇒ **Study the interaction** given a known source

Applied to small collision systems **~1fm**

Femtoscopy in small systems with ALICE

Femtoscopy at the LHC with ALICE

LHC

Small collision systems:
- pp $\sqrt{s}$ = 7, 13 TeV

⇒ size of particle source ~1 fm

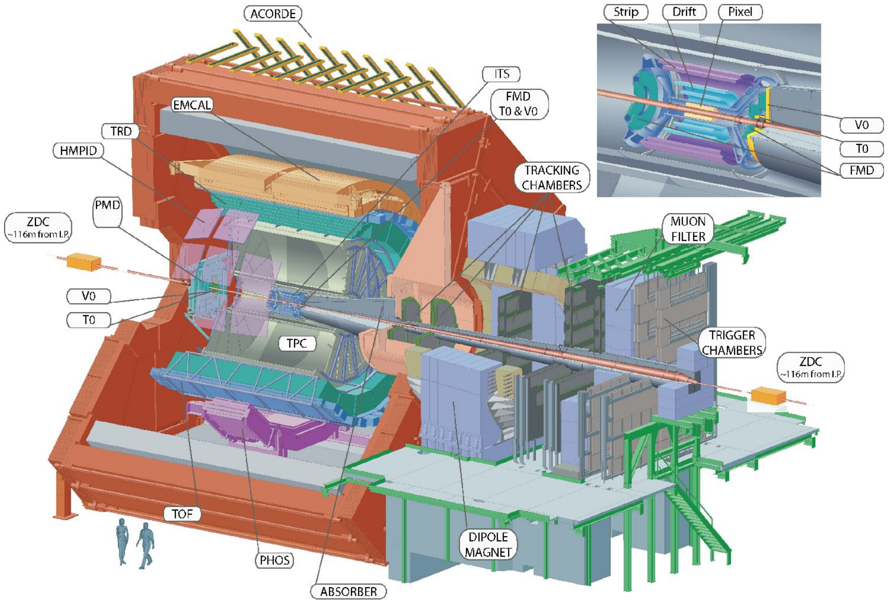
Femtoscopy at the LHC with ALICE

LHC

ALICE

Central barrel **tracking and PID**:

- Reconstruction of charged particles: p, π, K.
- **Hyperon reconstruction** through weak decays
  $\Lambda \rightarrow p\pi$, $\Xi \rightarrow \Lambda\pi$, $\Omega \rightarrow \Lambda K$



ALICE in Run 1 & 2

Femtoscopy at the LHC with ALICE

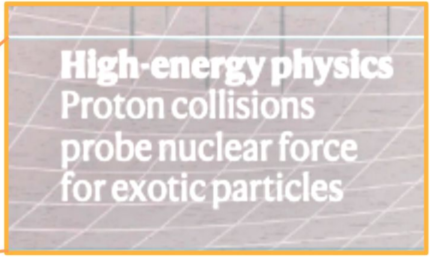
LHC

ALICE

Study of hadron strong interactions

Femtoscopy: Precise data in the low momentum range, hardly accessible with other approaches

ALICE Coll. *Nature* **588**, 232 (2020)



1st step: Setting the source [ALICE Coll., Phys. Lett. B 811 (2020) 135849]

Ansatz: similar source for all baryon-baryon pairs in small collision systems

The first step is “traditional” femtoscopy: known interaction → determine source size

- p–p interaction: Argonne v18 potential

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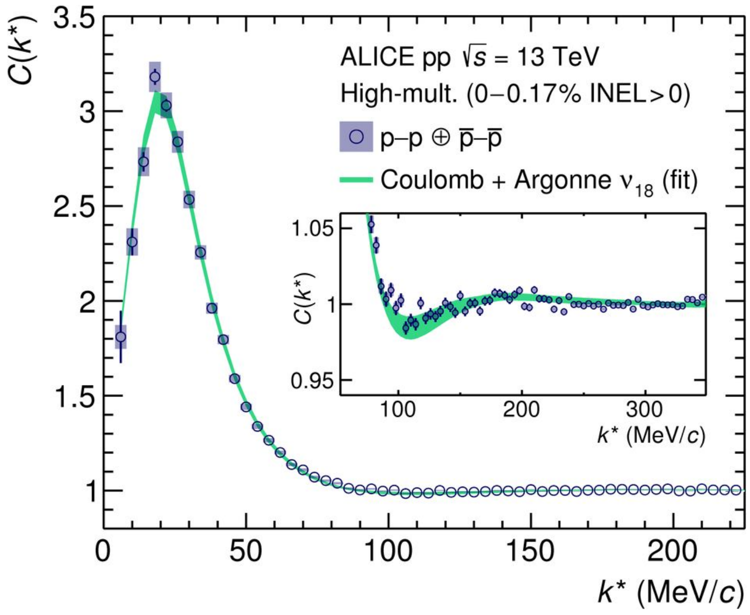


⇒ Fit of the radius of the source of p-p pairs in p-p collisions.

The size source here is the only fit parameter

1st step: Setting the source

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

Ansatz: similar source for all baryon-baryon pairs in small collision systems

The first step is "traditional" femtoscopy: known interaction → determine source size

- p−p interaction: Argonne v18 potential

Determine **gaussian "core" radius as a function of pair $\langle m_T \rangle$**
- Common to all hadron-hadron pairs

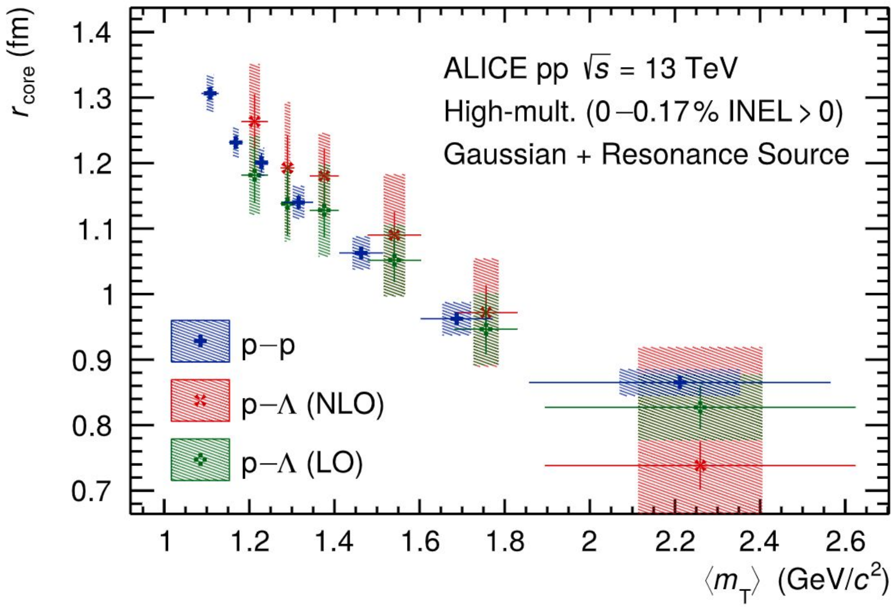
✖

Effect of strong short-lived resonances
Adds **exponential tail** to the source profile
→ Angular distributions from EPOS

Input:
→ Production fraction/lifetimes (Statistical Hadronization Model)
F. Becattini and G. Passaleva Eur.Phys.J.C 23 (2002) 551-583

→ Angular distributions (EPOS event generator)
T. Pierog et al.m PRC 92 (2015) 3, 034906

1st step: Setting the source [ALICE Coll., Phys. Lett. B 811 (2020) 135849]



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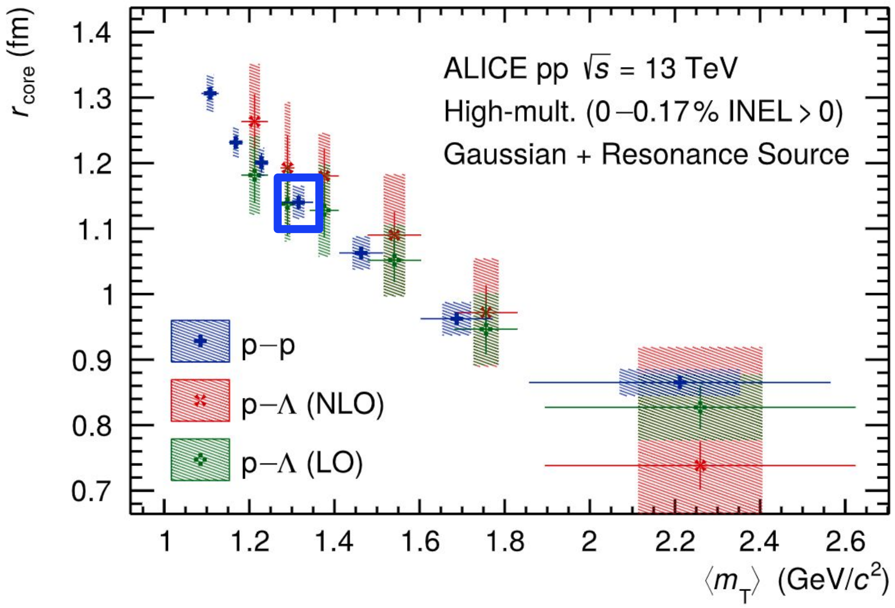

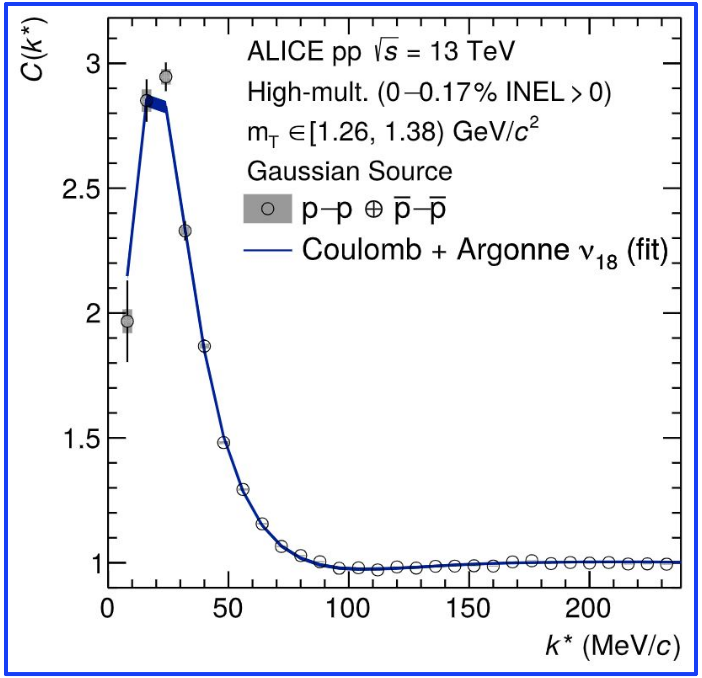

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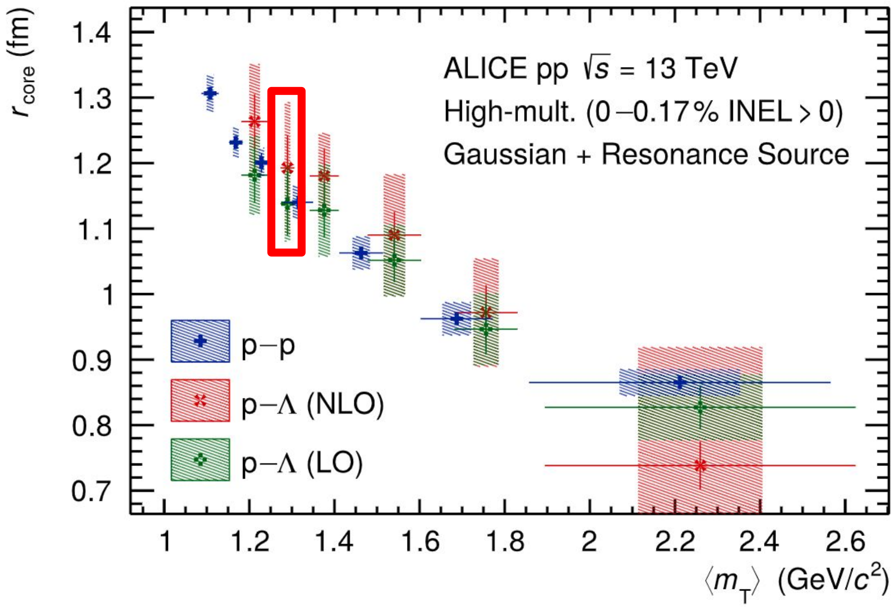

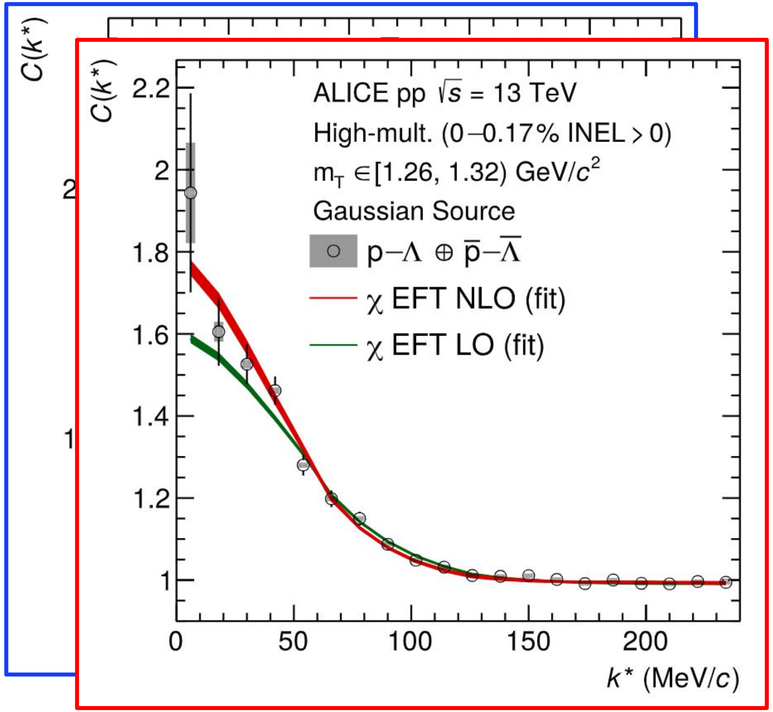

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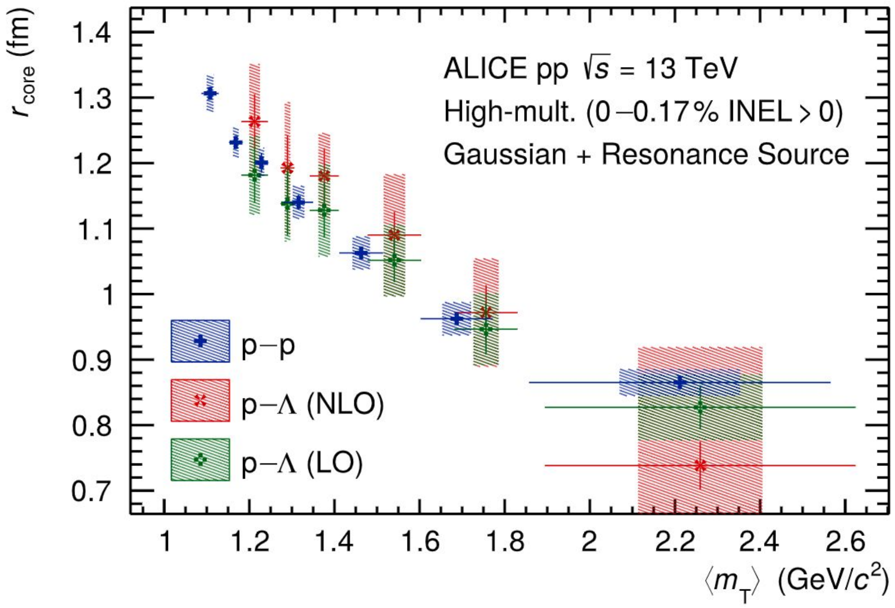


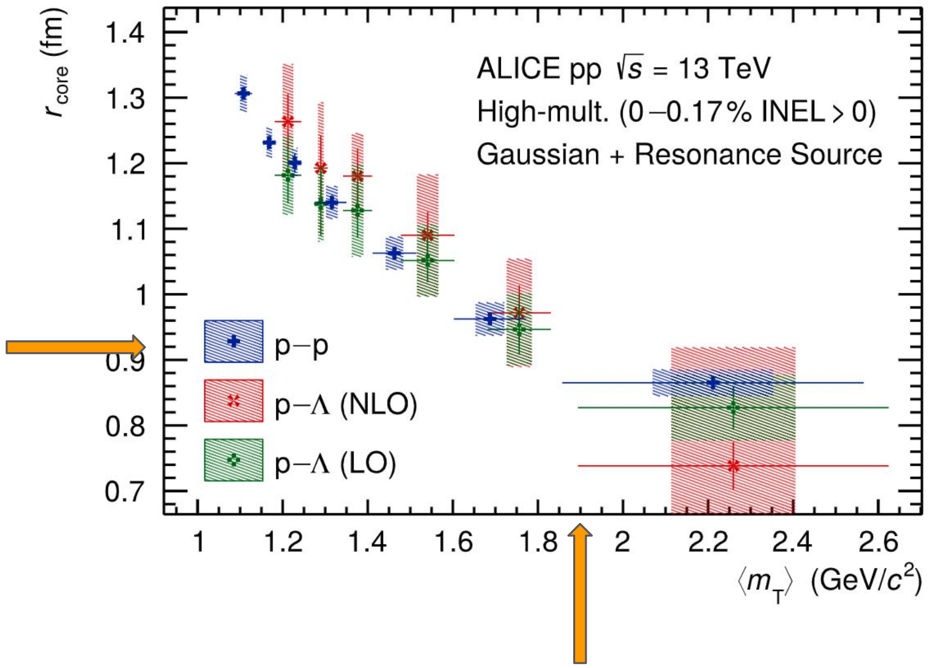
Dependence of the source size with **$\langle m_T \rangle$ related to collective phenomena**

“HIC”-like features being observed now in small systems:

- strangeness enhancement
- collective flow

1st step: Setting the source

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



Source **size determined given the pair <m_T>** and **considering the effect of strong resonances** for the particles of the pair of interest

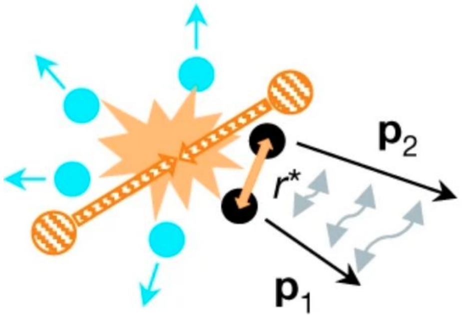
Example:

p–Ξ⁻: <m_T> = 1.9 GeV/c ⇒ r_{core} = 0.92 ± 0.05 fm

strong resonances effect

⇒ r_{gauss} = 1.02 ± 0.05 fm

Femtoscopy for hadron-hadron interactions: **What can we do this tool?**



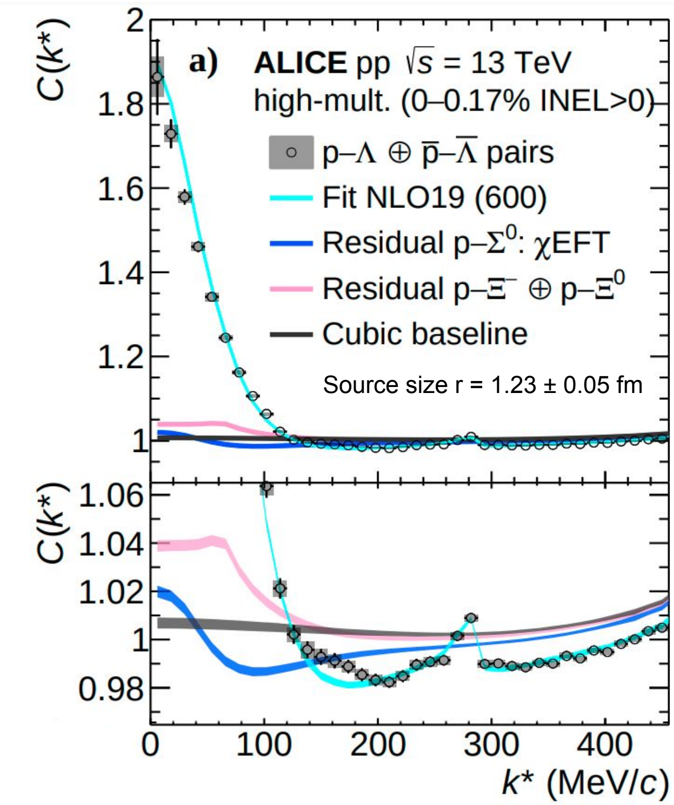
Precise data in the low momentum range to hadron-hadron interaction with unprecedented precision

Test of first principle calculations (and other models) and...

- Study **coupled-channel systems**
- **Equation of State** of neutron stars
- **Search for new bound states** beyond the deuteron

Coupled-channels: p–Λ correlation function

S = -1



[ALICE Coll. arXiv:2104.04427 (submitted to PRL)](https://arxiv.org/abs/2104.04427)

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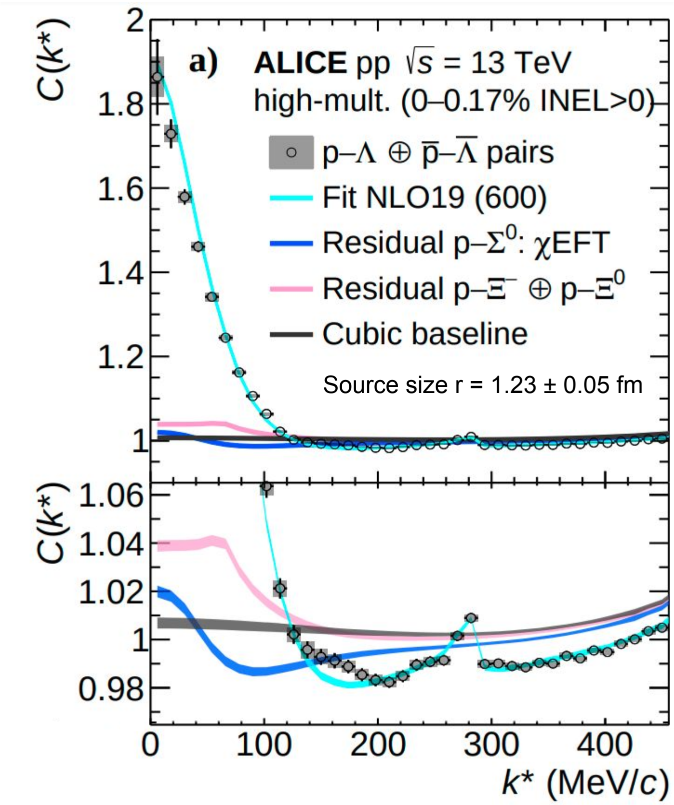

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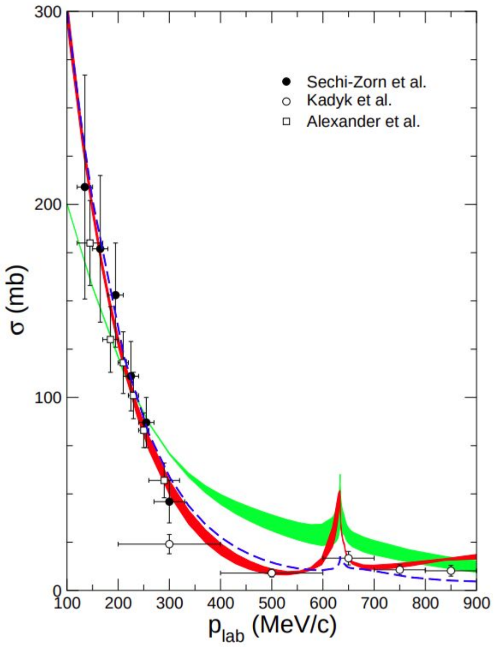

Coupled-channels: p–Λ correlation function

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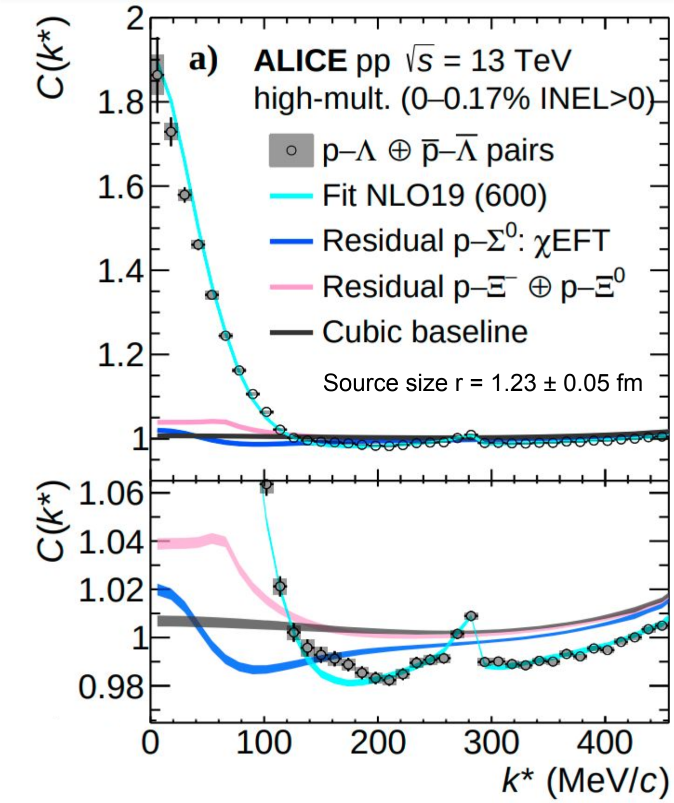


ALICE Coll. arXiv:2104.04427 (submitted to PRL)

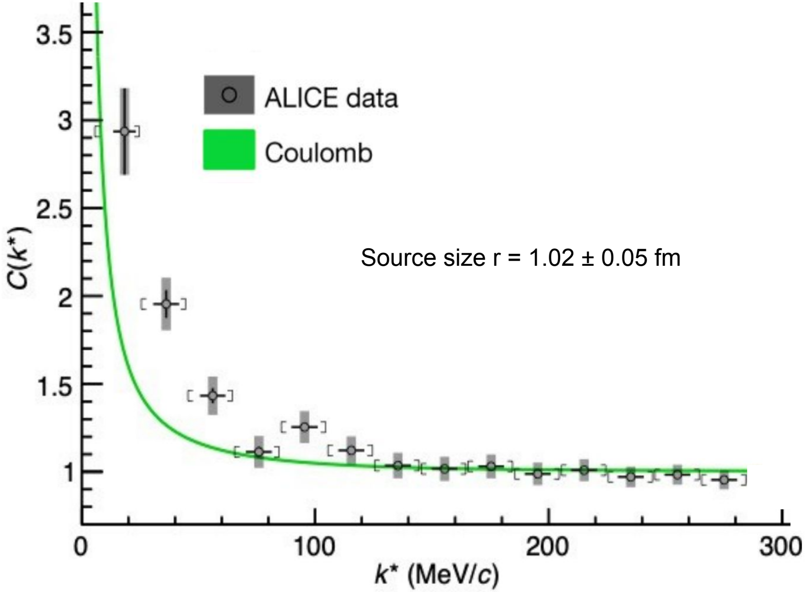
- Most precise measurements on the p–Λ interaction
- **Test strengths of the NΣ ↔ NΛ transition**
- Hyperons in NS?: Exact composition strongly depends on constituent interactions and couplings

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

Hyperons in NS: p–Ξ^- correlation function

$S = -2$

ALICE Coll. *Nature* **588**, 232 (2020)

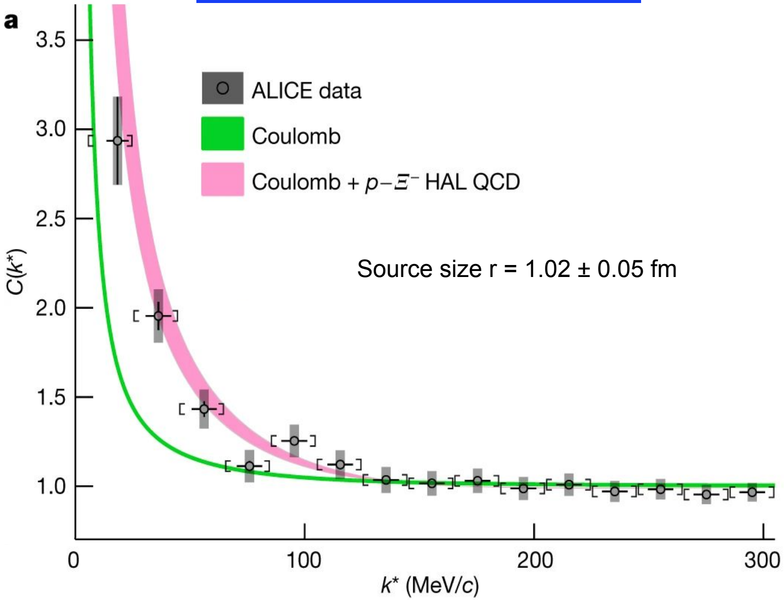


Enhancement above Coulomb-only prediction
⇒ Observation of the **attractive strong interaction**

<u>**Hyperons in NS**</u>: p–Ξ⁻ correlation function

S = -2

[ALICE Coll. *Nature* **588**, 232 (2020)](#)



Enhancement above Coulomb-only prediction
⇒ Observation of the **attractive strong interaction**

Theory: HAL QCD Coll., Nucl. Phys. A 998, 121737 (2020).

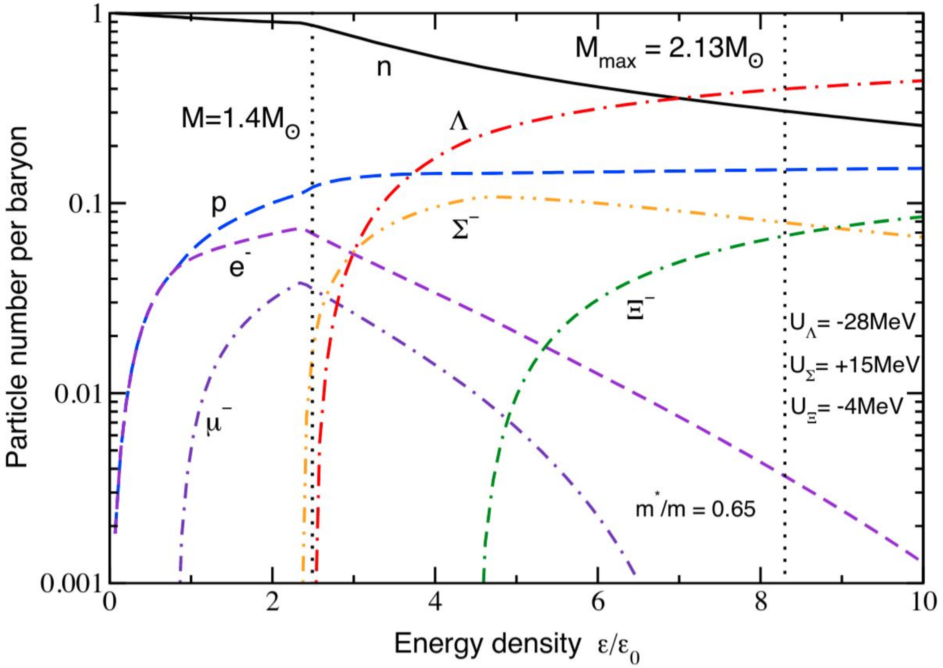
Excellent agreement with lattice predictions
⇒ Effect of validated Lattice QCD pΞ interaction for the **Equation of State of Neutron Stars**

Hyperons in NS

Lattice: slightly repulsive single particle potential in PNM for Ξ

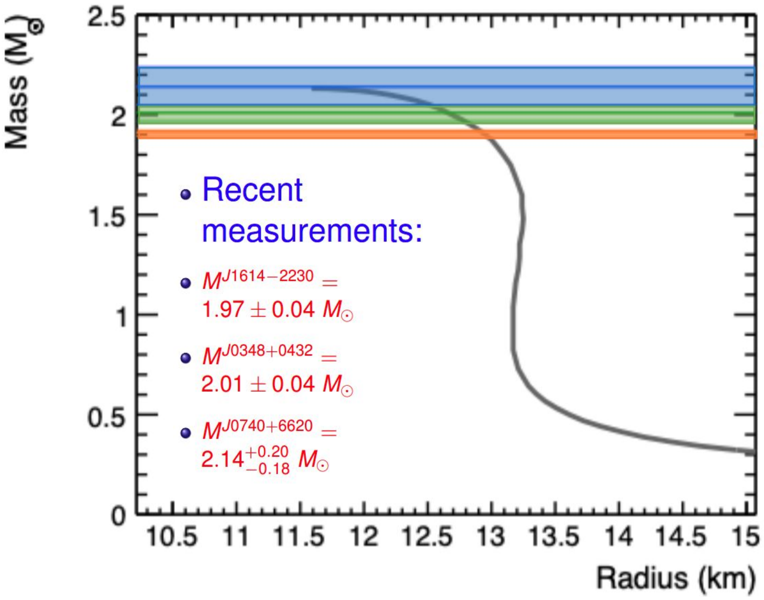
⇒ **Ξ appears at larger densities** in NS

⇒ **Stiffer EoS**



Recent constraints from NICER & GW

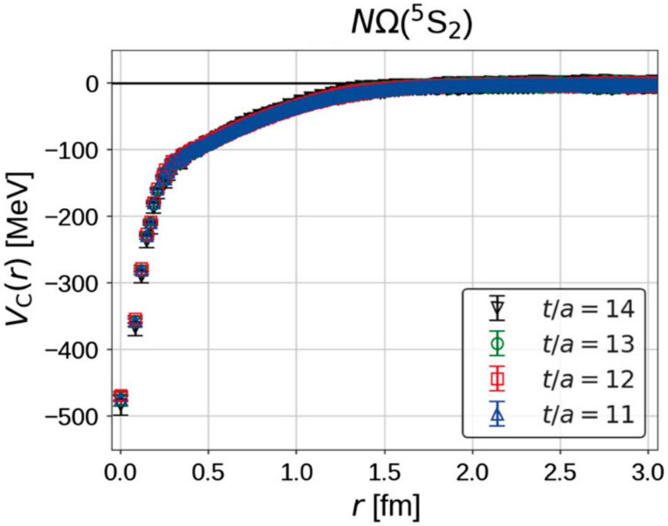
G. Raaijmakers et al., AJL 918 (2021), L29



Courtesy J. Schaffner-Bielich (2021)

Di-baryon states: p–Ω⁻ correlation function

S = -3



T. Iritani et al. (HAL QCD Coll.) Phys. Lett. B792 (2019) 284

Interaction of p–Ω^- pairs in $^5S_2$ state by HAL QCD

Predicts the formation of a p–Ω^- di-baryon

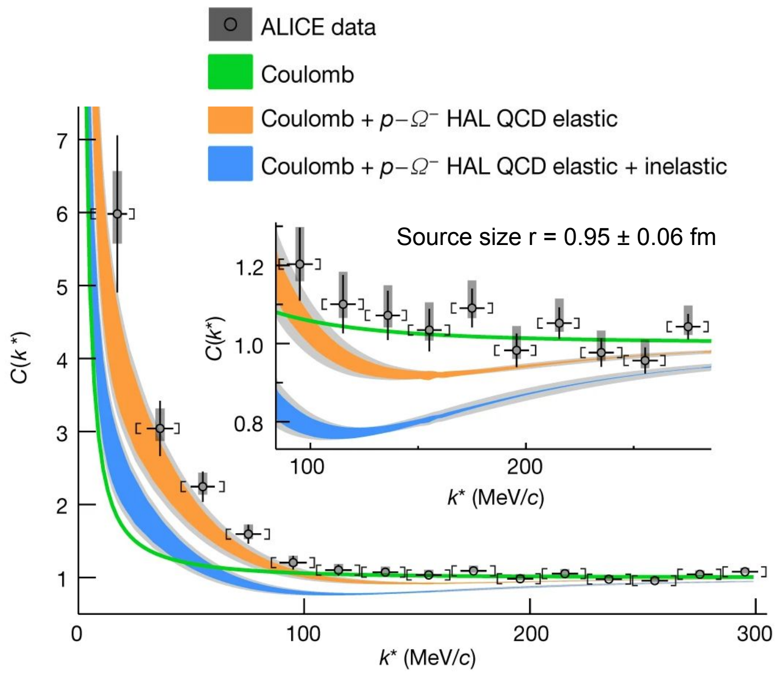
⇒ Binding Energy = 2.5 MeV

Meson exchange models predict smaller binding

T. Sekihara et al., Phys. Rev. C 98, 015205 (2018)

Di-baryon states: p–Ω⁻ correlation function

S = -3



Theory: HAL QCD Coll., Phys. Lett. B792 (2019) 284

ALICE Coll. *Nature* **588**, 232 (2020)

- **Data more precise** than lattice calculations
  ⇒ First constraints in the S=-3 sector
- So far, **no indication of a bound state**
  No visible depletion of C(k*)
- Uncertainty of calculations dominated by inelastic channels

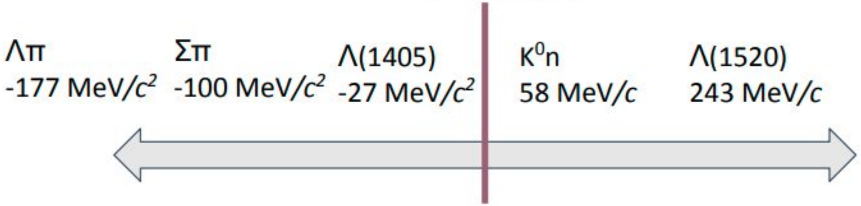
The case of the antiKaon-Nucleon interaction

The case of the antiKaon-Nucleon interaction

Kaon and antiKaon interactions with nucleons are <u>totally different</u>

<u>antiKaon-Nucleon interaction:</u> Chiral Perturbation Theory (Weinberg, Gasser, Leutwyler) is not applicable

- mass of the strange quark: **$m_s > m_u, m_d$**
- appearance of the **Λ(1405) below** (and close to) **threshold**



Approaches: Chiral SU(3) unitary, meson exchange and phenomenological models should:

- make <u>predictions below threshold</u>
- <u>describe</u> (the nature of) <u>the Λ(1405)</u>

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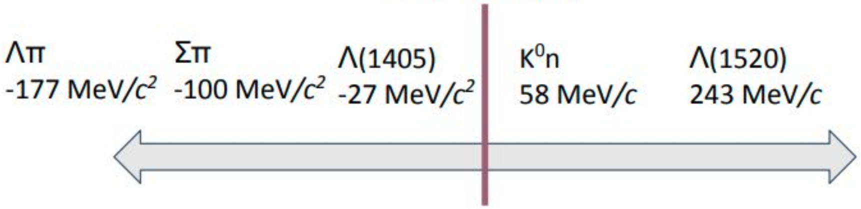

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Connected to the main issues :

- Strong coupled channel dynamics $\bar{K}N$-Σπ
  Y. Kamiya et al., Phys. Rev. Lett. 124, 132501 (2020)
- Kaonic bound states (case of $\bar{K}NN$)
  JPARC E15, PLB 789 (2019) 620
- Enhanced production of strangeness with multiplicity T. Song @ SQM2021
- Strangeness in NS: kaon condensate
  D.Logoteta Universe 2021, 7(11), 408

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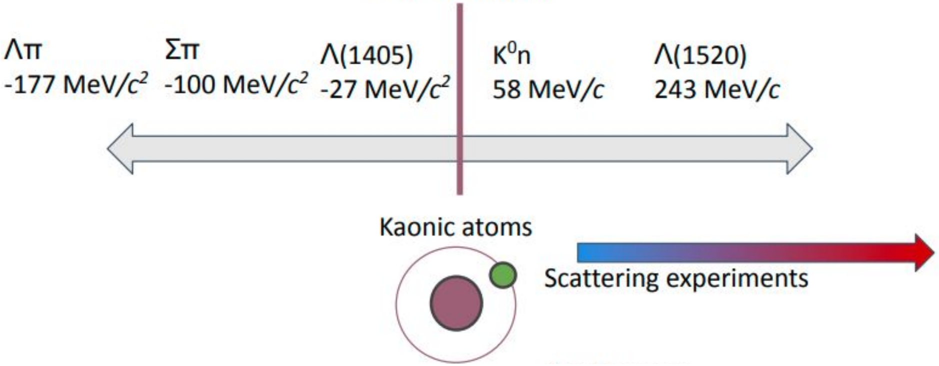

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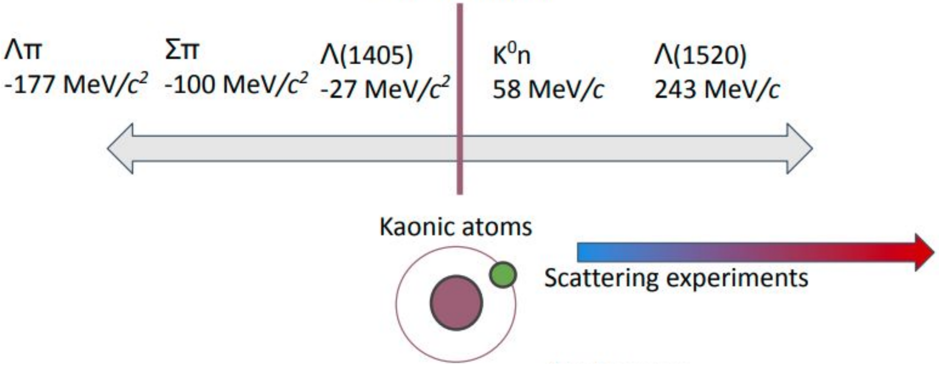

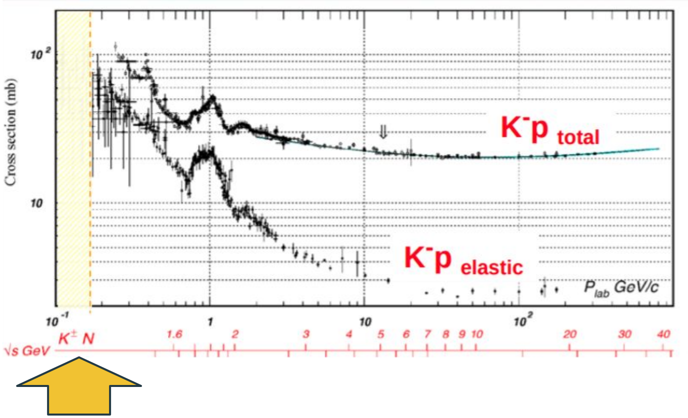

DAΦNE

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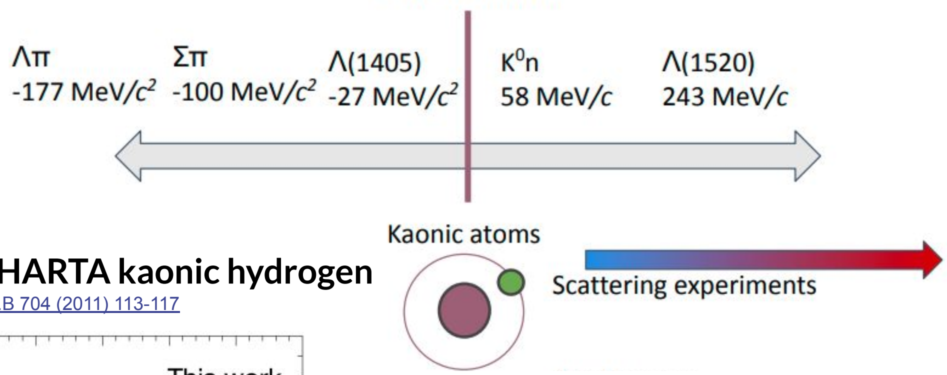
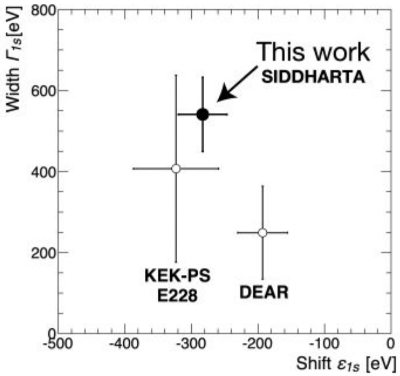


SIDDHARTA kaonic hydrogen

Phys.Lett.B 704 (2011) 113-117



K^-p scattering parameters through Deser-type formula

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-p} = 412\,\tfrac{eV}{fm}\,a_{K^-p}$$

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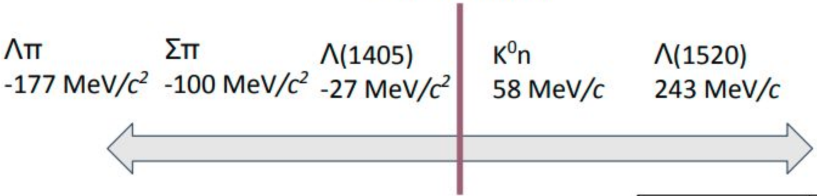
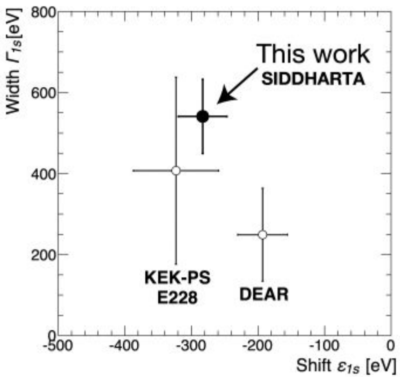


Kaonic atoms

SIDDHARTA kaonic hydrogen

[Phys.Lett.B 704 (2011) 113-117]



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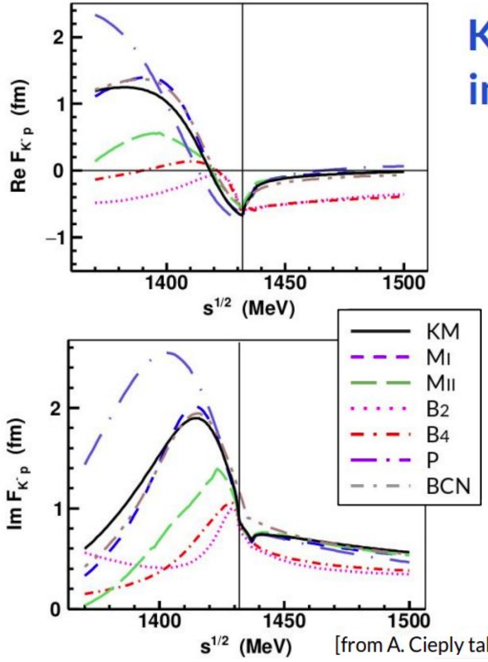

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Kyoto-Munich (KM)
Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98

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Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202

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A. Feijoo, V. Magas, À. Ramos, Phys. Rev. C 99 (2019) 035211

[from A. Cieply talk at MENU2019 conference, A. Cieply et al. Nucl.Phys. A954 (2016) 17-40]

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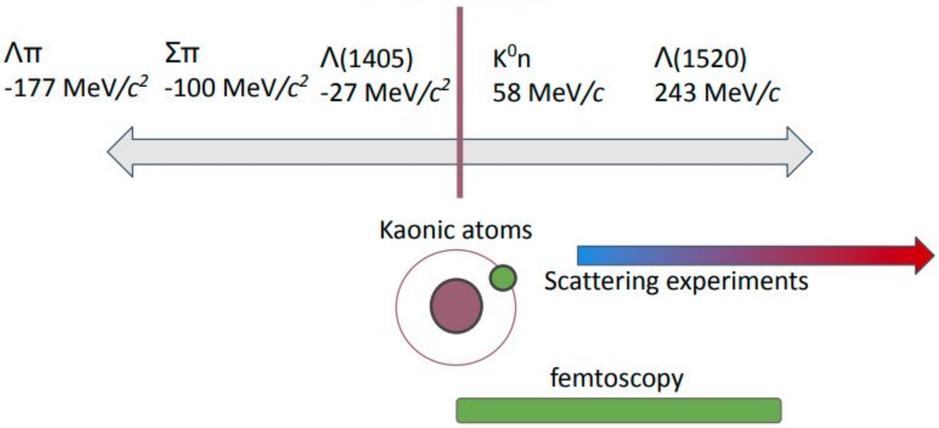
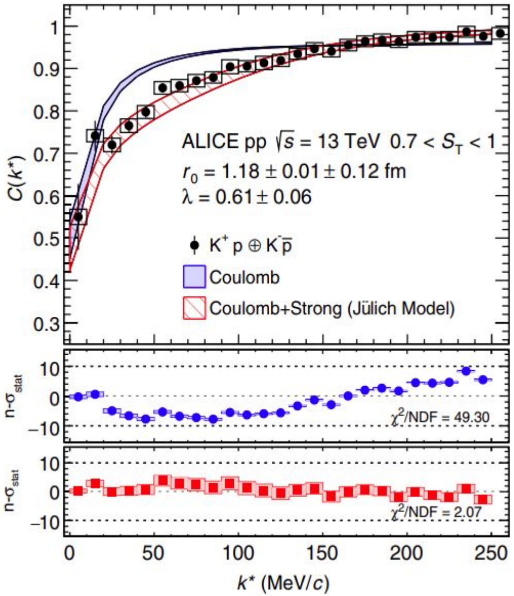


$K^{-}p$ correlation function [ALICE Coll. Phys. Rev. Lett. 124 (2020) 092301]

Well known K^{+}–p interaction

C(k*)<1 → Repulsive interaction



Jülich meson exchange model Eur. Phys. J. A47, 18 (2011)

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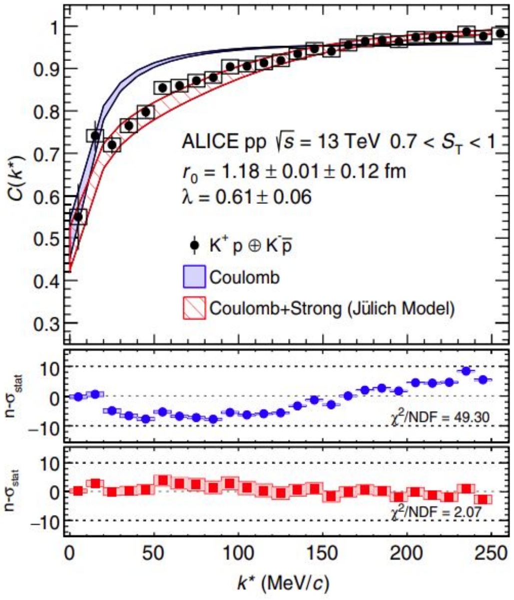

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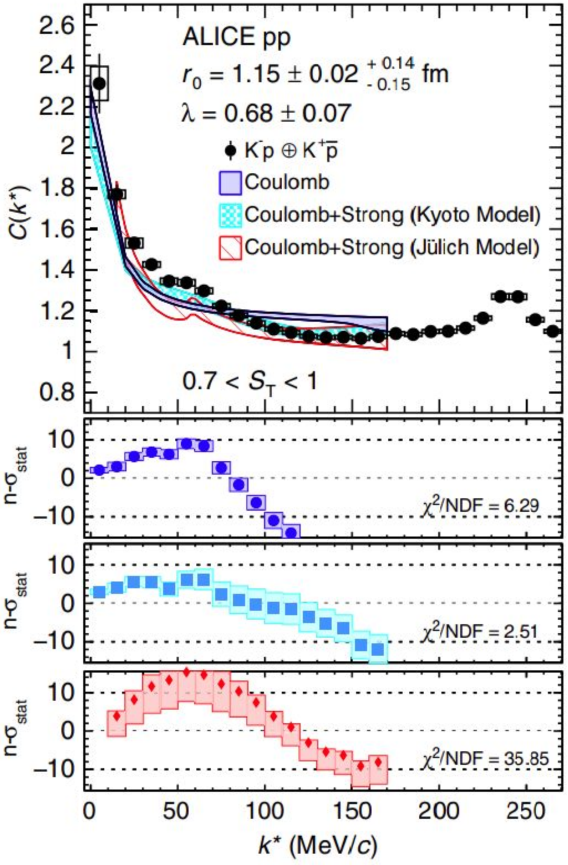

K⁻–p correlation function

C(k*)>1→ attractive interaction

Coulomb potential only

Coulomb + Chiral Kyoto model

Phys. Rev. C93 no. 1, 015201 (2016)

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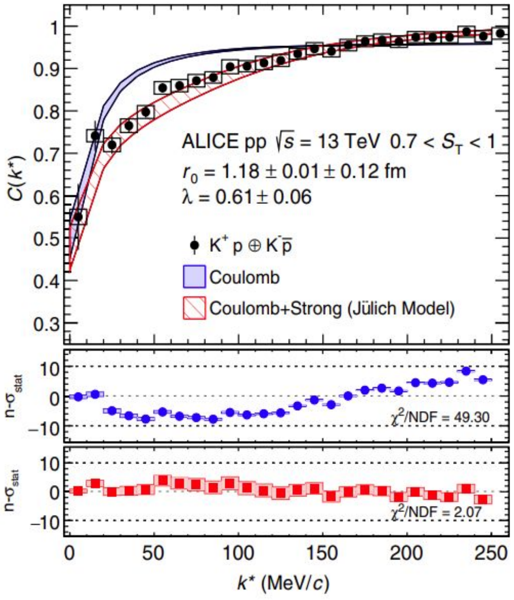

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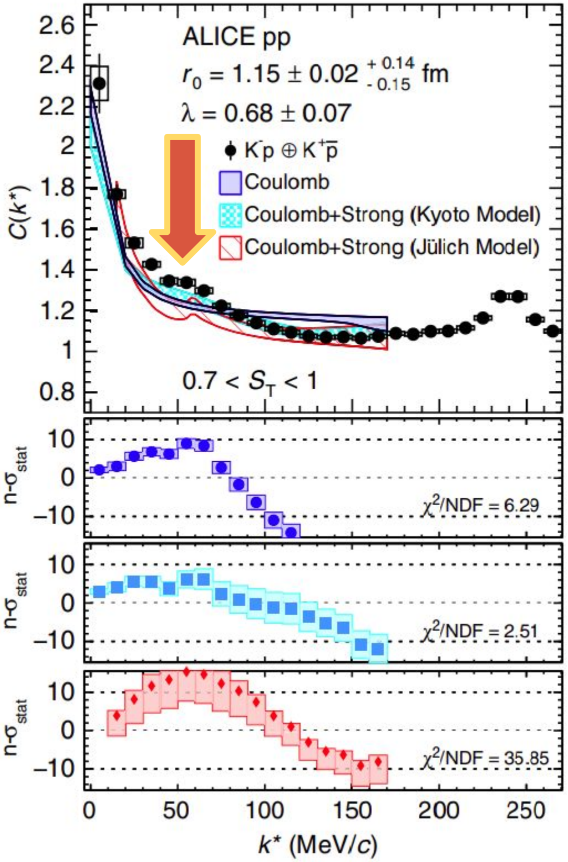

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⇒ Evidence of the opening of the $\bar{K}^0$n isospin breaking channel

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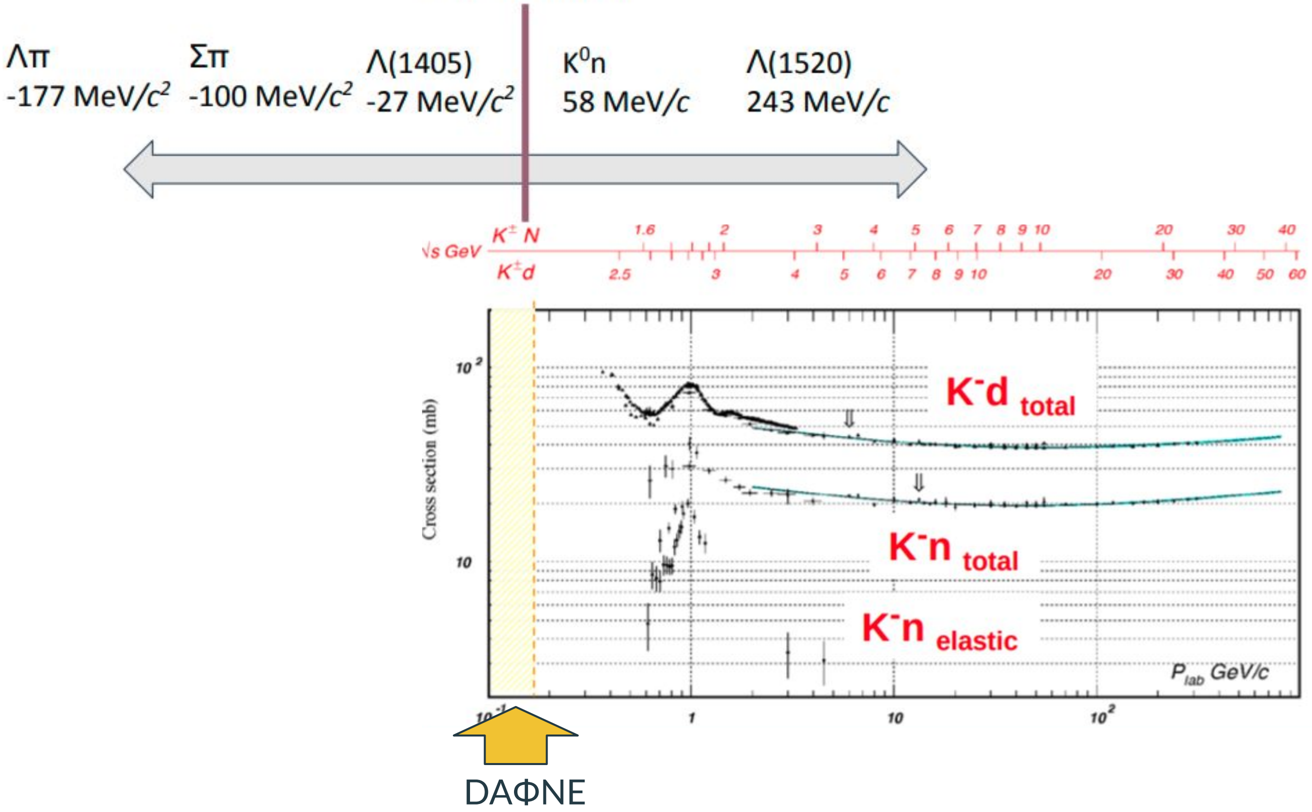

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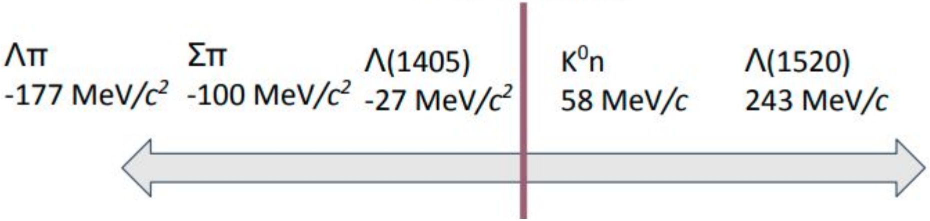

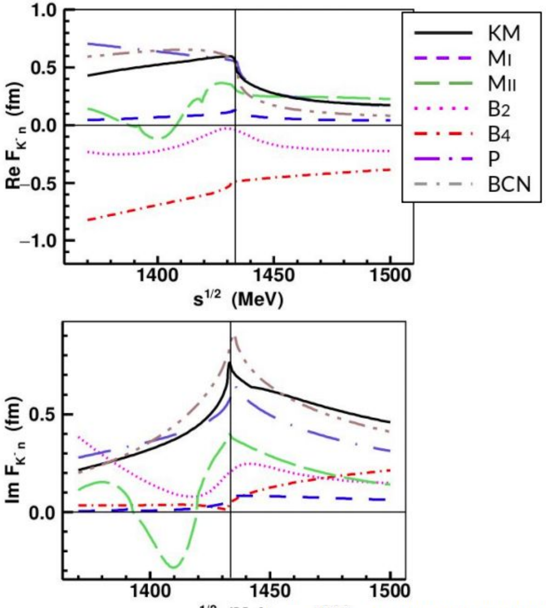

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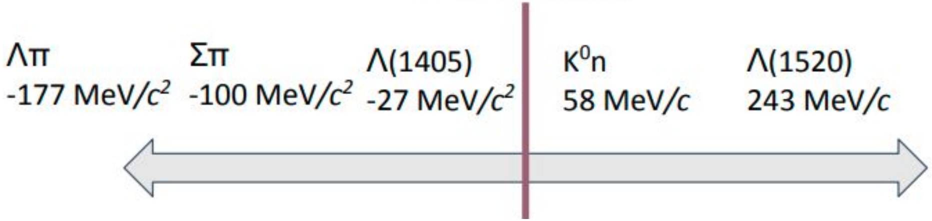
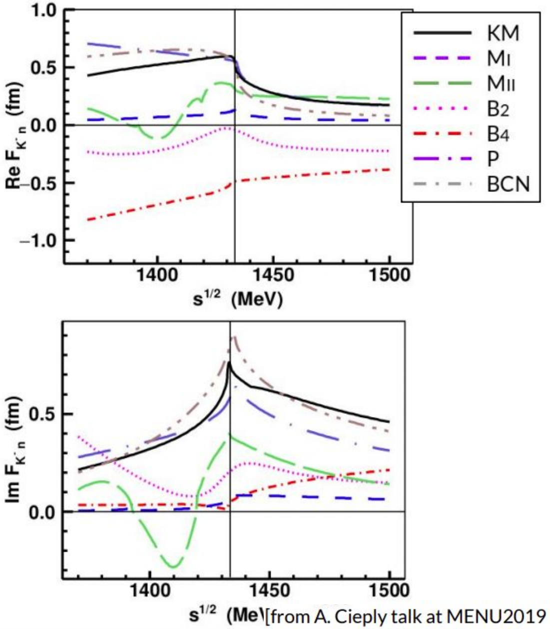


Data needed:

Constraints at <u>threshold</u>
⇒ **SIDDHARTA-2**

Constraints at small relative momentum
⇒ **ALICE femtoscopy**



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SIDDHARTA-2

Deser-type relation **connects shift and width** of the spectral lines of antiKaonic atoms to the antiKaon-nucleon **scattering lengths**

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-p} = 412\,\tfrac{eV}{fm}\, a_{K^-p}$$

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-d} = 601\,\tfrac{eV}{fm}\, a_{K^-d}$$

Full isospin dependence can be disentangled

$$a_{K^-p} = \frac{a_0(I=0) + a_1(I=1)}{2}$$

$$a_{K^-d} = \frac{1}{2}\frac{m_N + m_K}{m_N + \frac{m_K}{2}}(3a_1 + a_0) + C$$

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SIDDHARTA-2 measurement is a **challenging** one:

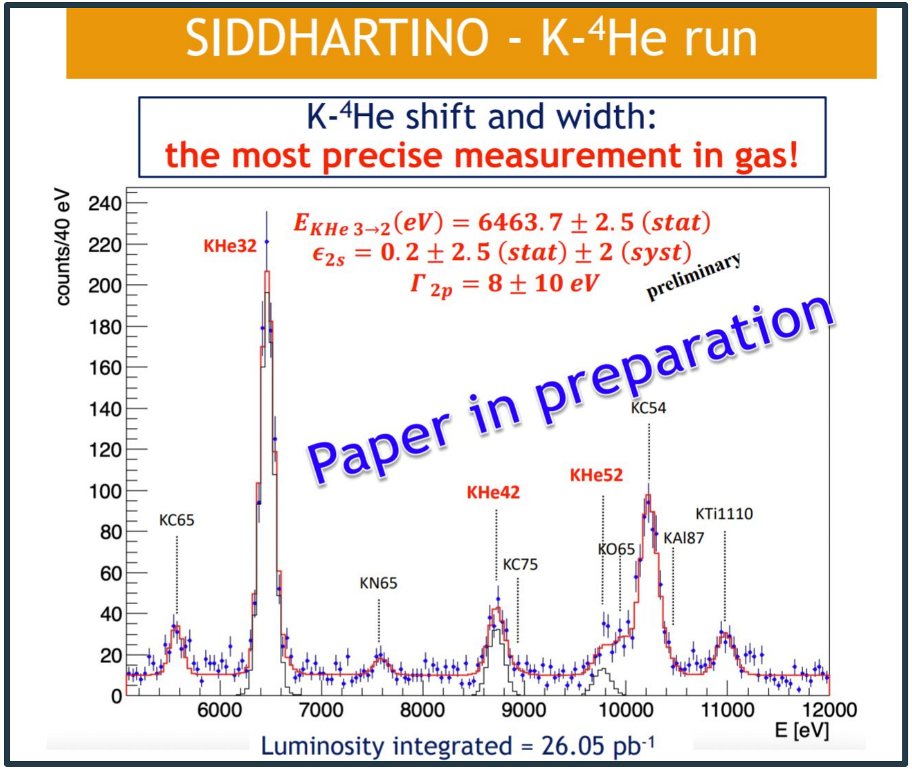
- **Yield** of antiKaonic deuterium smaller than antiKaonic hydrogen
- Complete **upgrade** of SIDDHARTA setup
  - S/B improved

The **interpretation** of the SIDDHARTA-2 results will be **challenging** as well:

- Deser type formula with model dependence
- Effect of three-body forces

SIDDHARTA-2

From F. Sgaramella at the 62nd LNF Scientific Commitee Meeting



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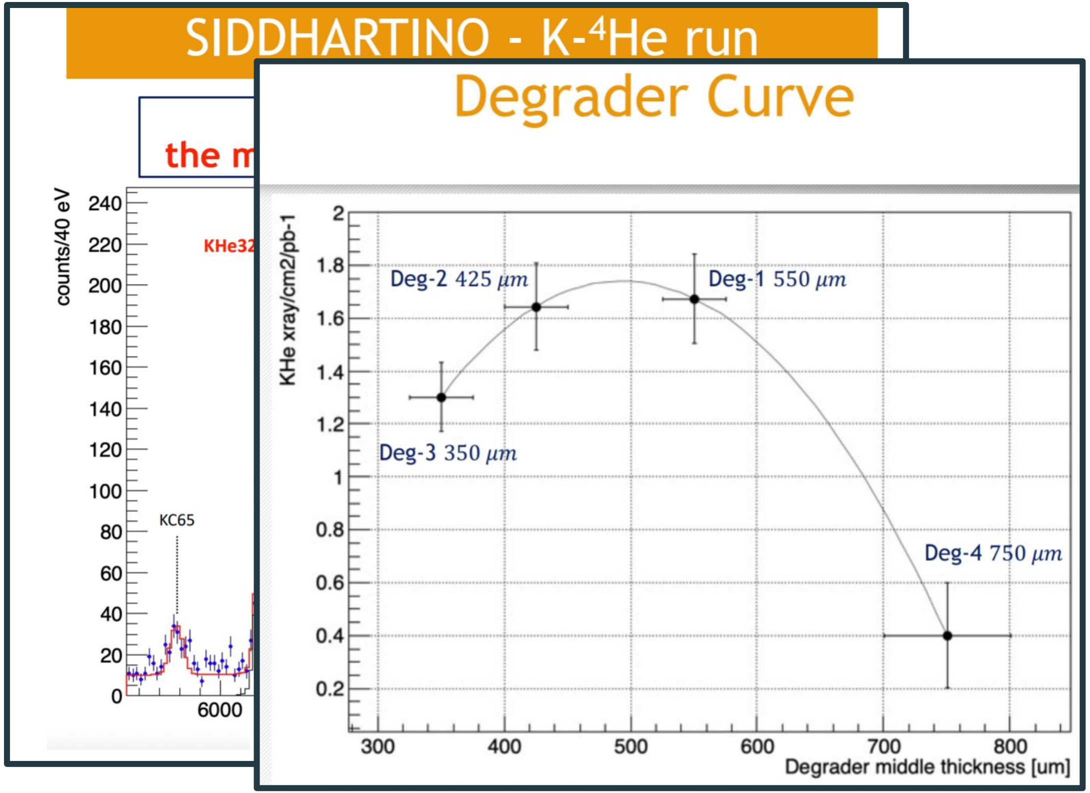

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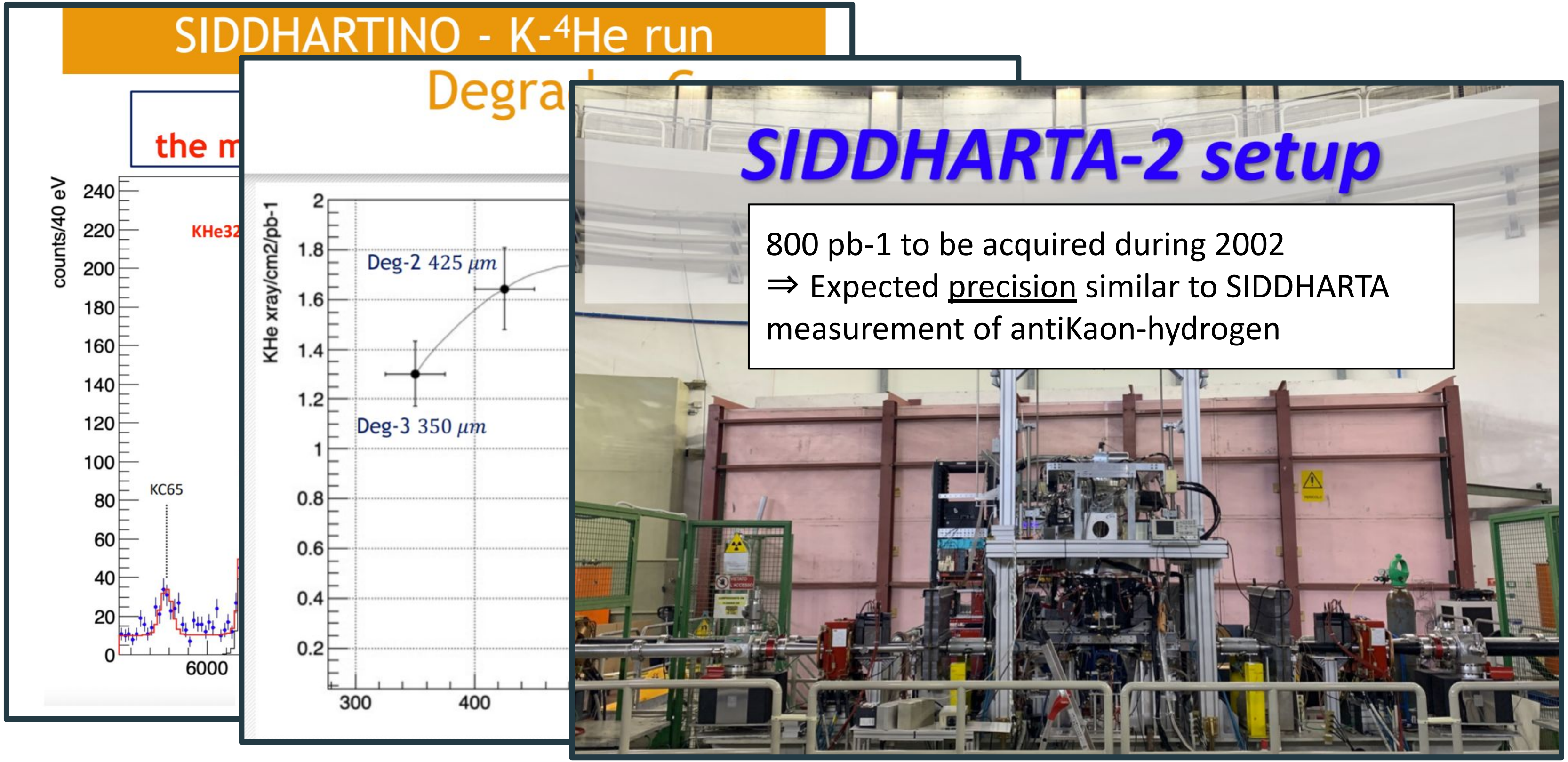

K^-d femtoscopy

Femtoscopy measurements with deuterons are indeed very **challenging**

- K^+d correlation function to be used as reference
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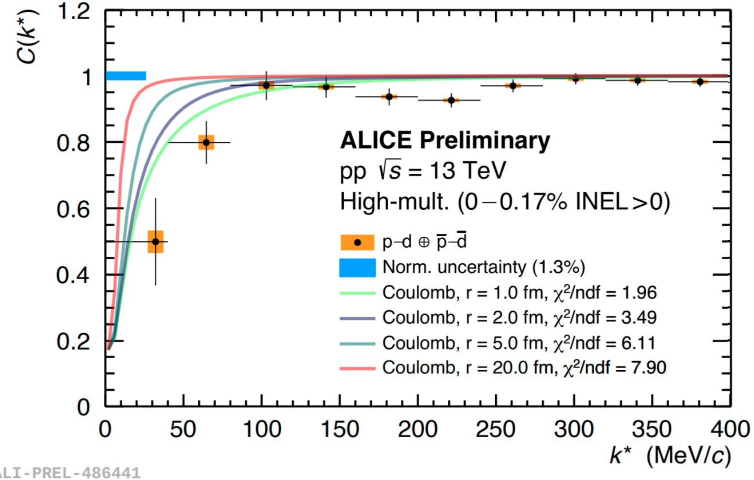
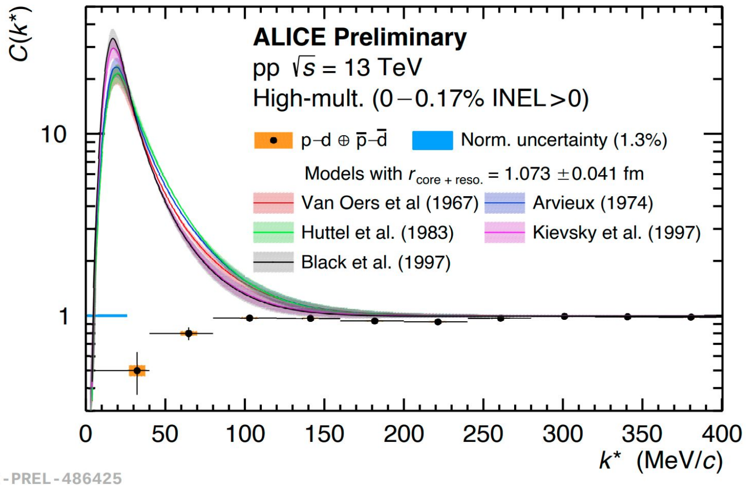
p-d femtoscopy with ALICE (preliminary):



ALI-PREL-486441



ALI-PREL-486425

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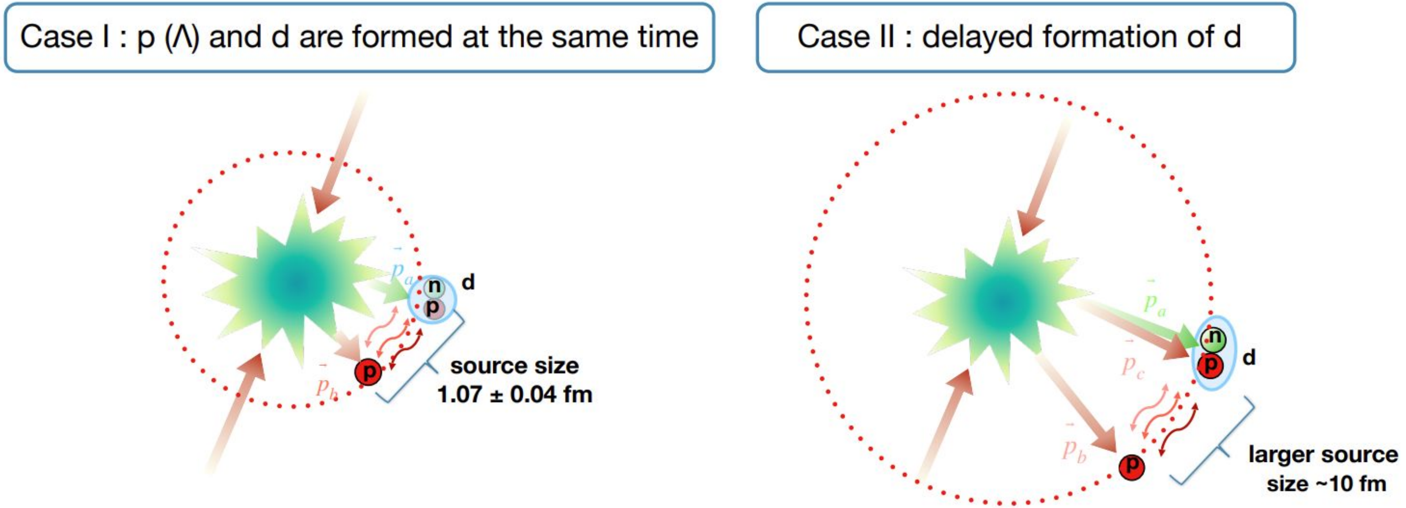

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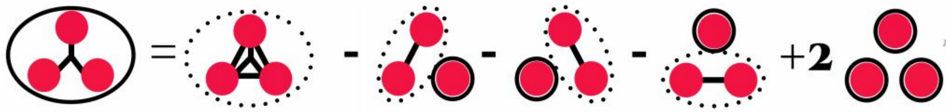
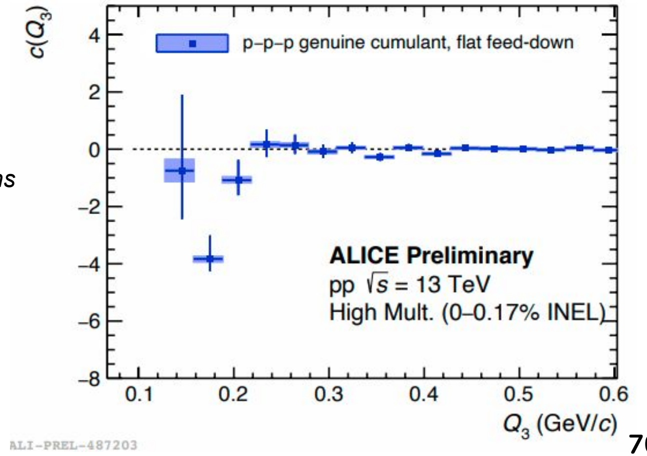
ALICE femtoscopy → **<u>First measurement of genuine three-body p-p-p correlation function</u>**



A method to remove lower order contributions in multi-particle femtoscopic correlation functions
R. del Grande et al., arXiv:2107.10227 [nucl-th]



Outlook

Precision studies of the strong interaction between hadrons at the LNF

- **Exotic atoms** experiments enter a **new era** with SIDDHARTA-2
- **Femtoscopy** studies at the LHC **updates the scenario of the experimental studies** on hadron-hadron interactions

⇒ The measurement of the antiKaon-deuteron interaction faces many challenges

- Very different experimental techniques will provide **complementary approaches**
- The expected results will **deliver a difficult test to the theoretical approaches**
- **The project is evolving and can be extended** (e. g. direct measurements of three-body interactions for the first time)

THANK YOU VERY MUCH!

FONDAZIONE BRUNO KESSLER
ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

OCTOBER
17-21.10 EXOTICO: EXOTIc Atoms Meet Nuclear COllisions for a New Frontier Precision Era in Low-Energy Strangeness Nuclear Physics*
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