Measurements of hadronic interactions enter a new era

Otón Vázquez Doce, (ex) Fellini fellow at LNF -INFN

Supervisors: Alessandra Fantoni, ALICE
Catalina Curceanu, SIDDHARTA-2.

Fellini Seminar, December 13th, 2022

FEMTO-STRONG

Oton Vazquez Doce

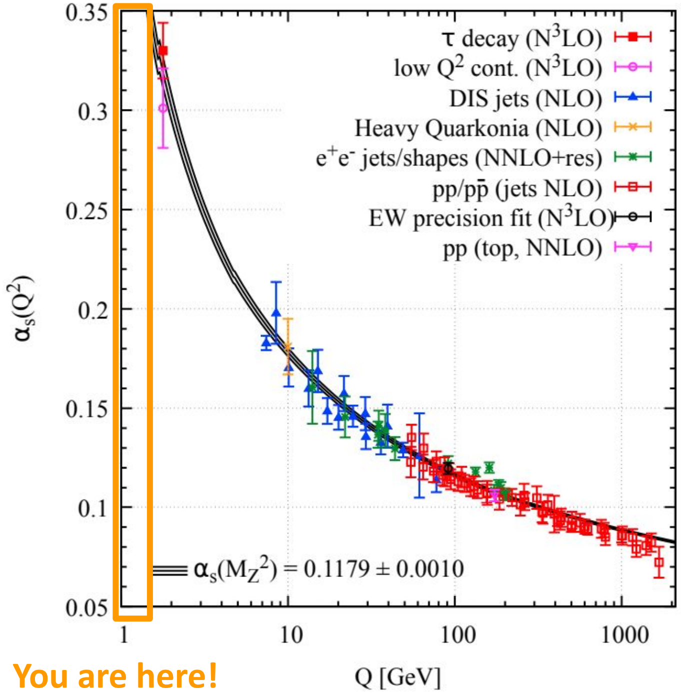
Fellini

Fellowship for Innovation at INFN

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 754496

Hadron-hadron strong interactions (with strangeness)

Hadron-hadron strong interactions

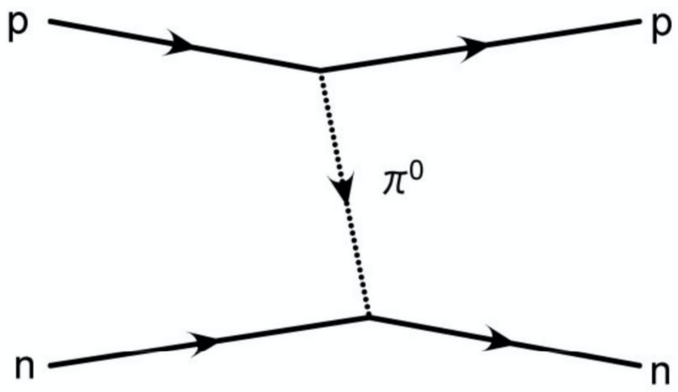


Running coupling constant defines the boundaries of "Low energy QCD"

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

Hadron-hadron strong interactions

Residual strong interaction among hadrons



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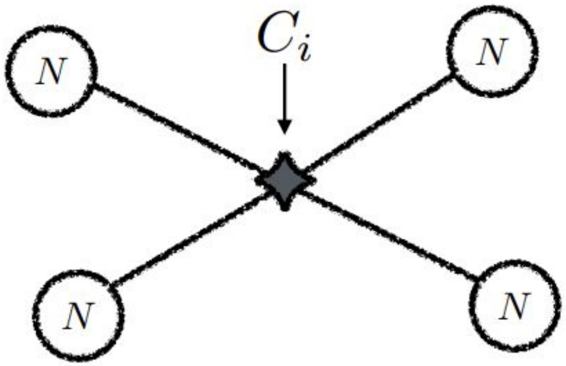


$$\mathcal{L}_{EFT}[\pi, N, \ldots; m_\pi, m_N, \ldots, C_i]$$

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

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

Parameter fixing by chiral SU(3) dynamical approaches for antiK-N interaction

- Going to NLO (N^{2}LO?), s+p waves ⇒ more parameters to be fixed (by data)

A. Feijoo @ HYP2022

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

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

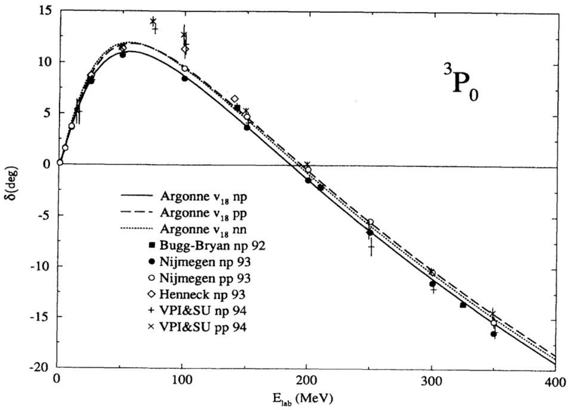
New terms taken into account (the g_1–g_4 and h_1–h_4 terms)

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

Hadron-hadron interactions
(with strangeness)

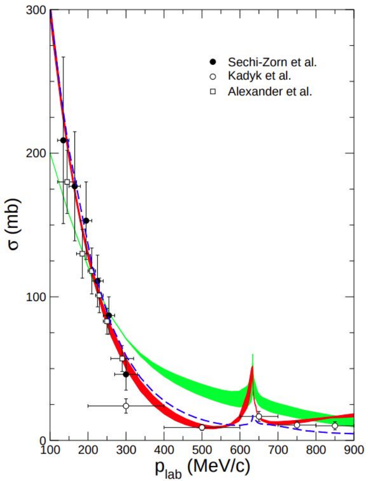
***S*=0** ***S*=-1** ***S*=-2**

NN → NN



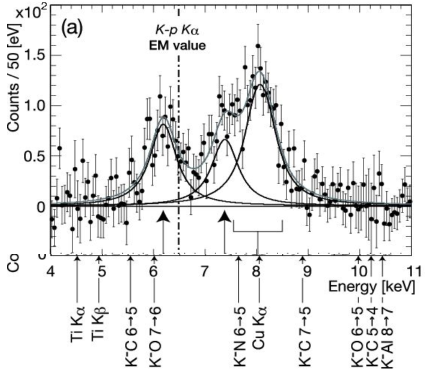
R. B. Wiringa, V. G. J. Stoks, R. Schiavilla Phys. Rev. C 51, 38 (1995)

Λp → Λp



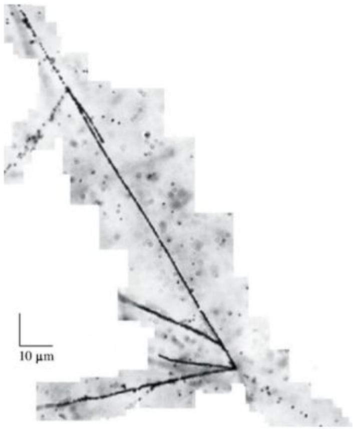
LO: H. Polinder, J. Haidenbauer, U. Meißner, Nucl. Phys. A779 (2006) 244.
NLO: J. Haidenbauer et al., Nucl. Phys. A915 (2013) 24.

Kaonic atoms



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

ΛΛ, Ξ hypernuclei

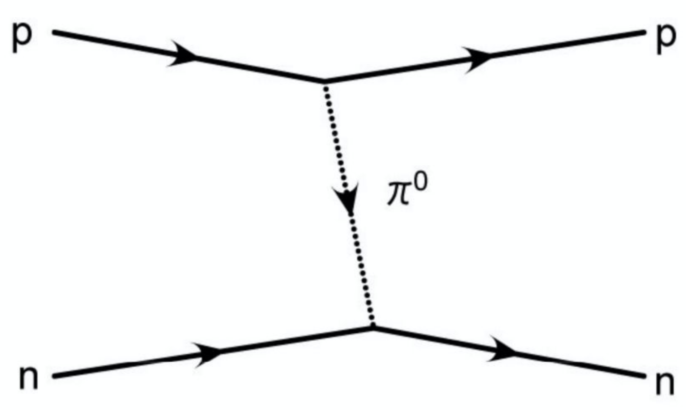


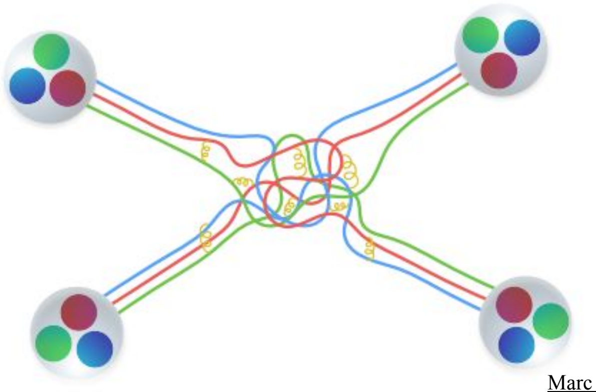
KISO event: K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015, 033D02
IBUKI event J-PARC E07 Coll., Phys. Rev. Lett. 126, 062501 (2021)

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**

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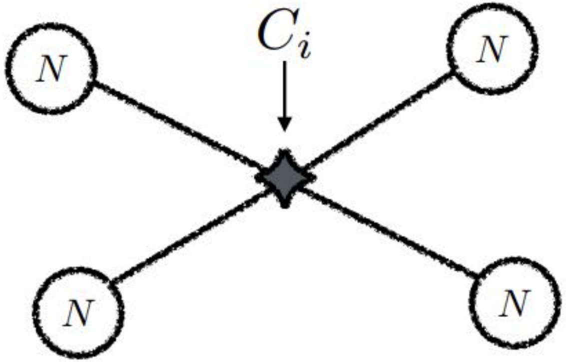

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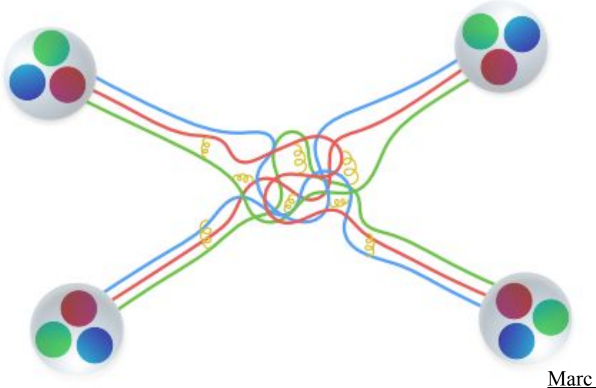

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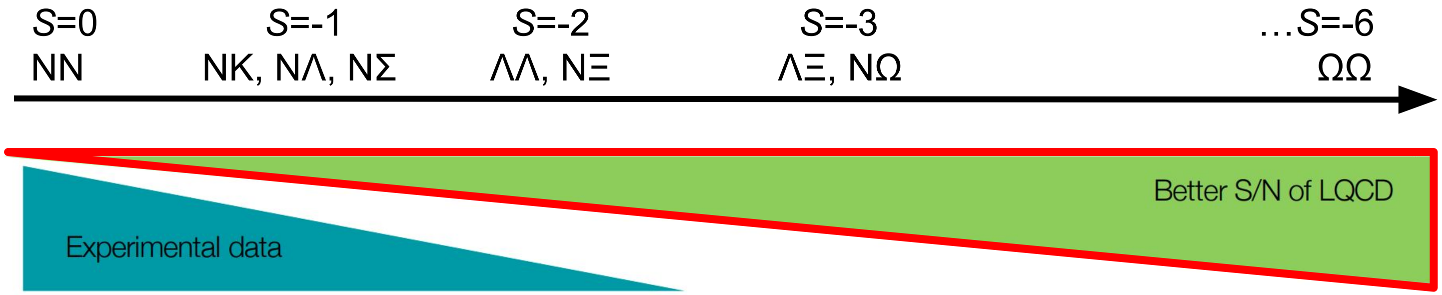

Hadron-hadron interactions
(with strangeness)

$m_\pi \approx 570$ 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

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

ELSEVIER

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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

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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

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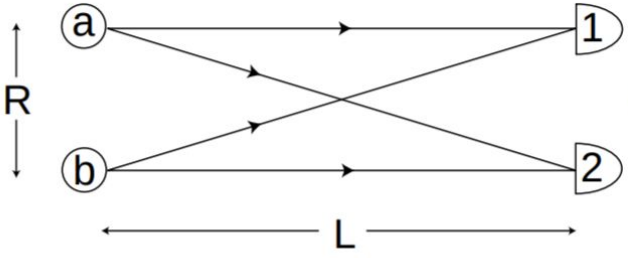
Femtoscopy

Femtoscopy method in nuclear collisions

Method defined by HBT interferometry

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

light source size



distance between detectors

Femtoscopy method in nuclear collisions

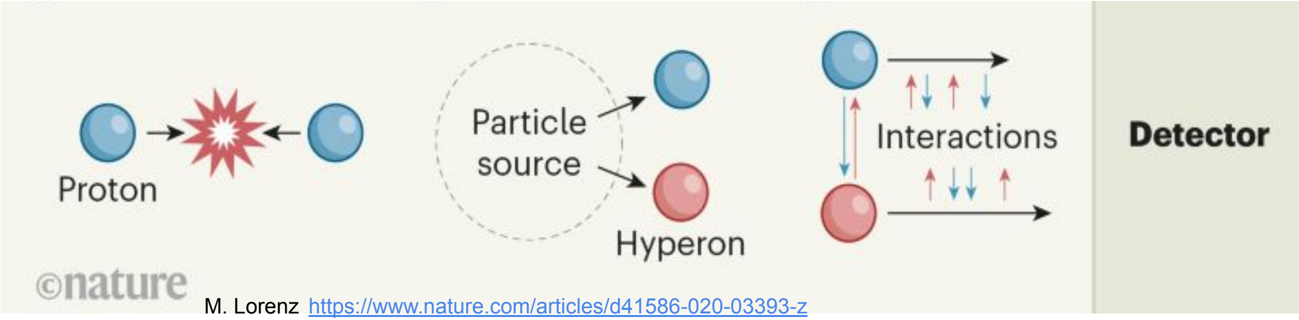
⇒ Application to Heavy Ion Collisions

Measurement of the particle source

- based on the <u>correlation function of two particles emitted in the collision</u>

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

⇒ Application to Small Systems



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

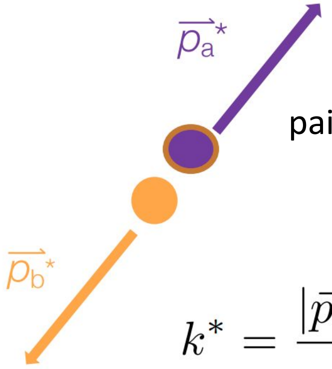
Experimental correlation function

Experimentally:

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

→ Pairs of particles from same collision

→ Particles produced in different collisions



pair reference frame

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

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→ Pairs of particles from same collision

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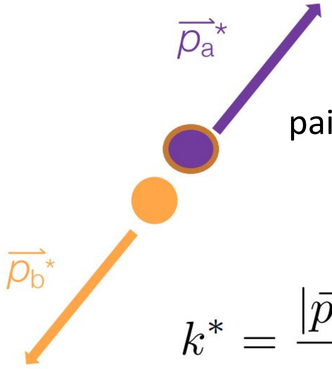
Corrections to the experimental measurement:

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



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

Theoretical correlation function

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

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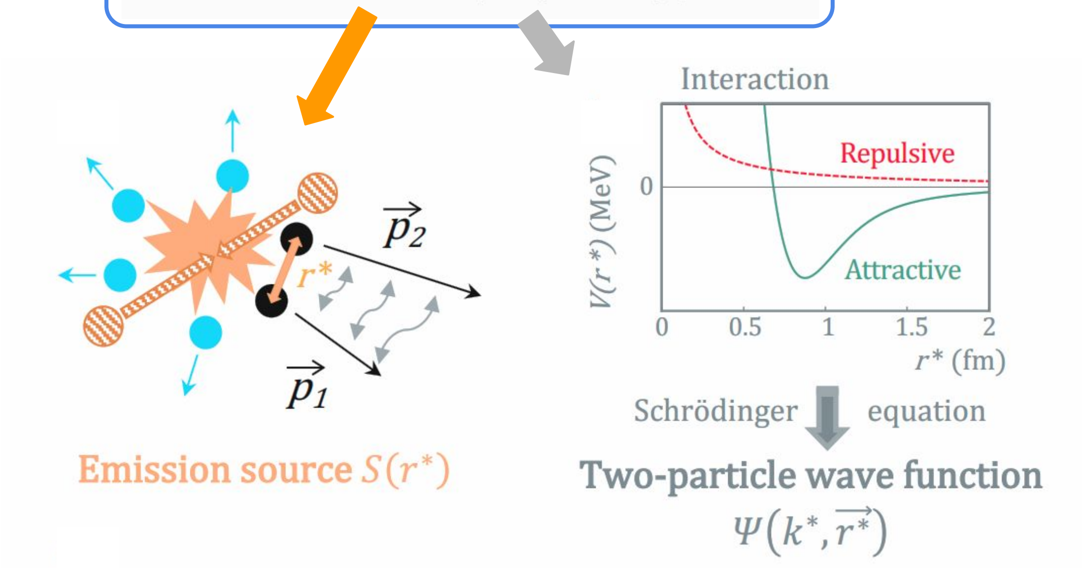

D.L.Mihaylov et al. Eur. Phys. J. C78 (2018) no.5,394

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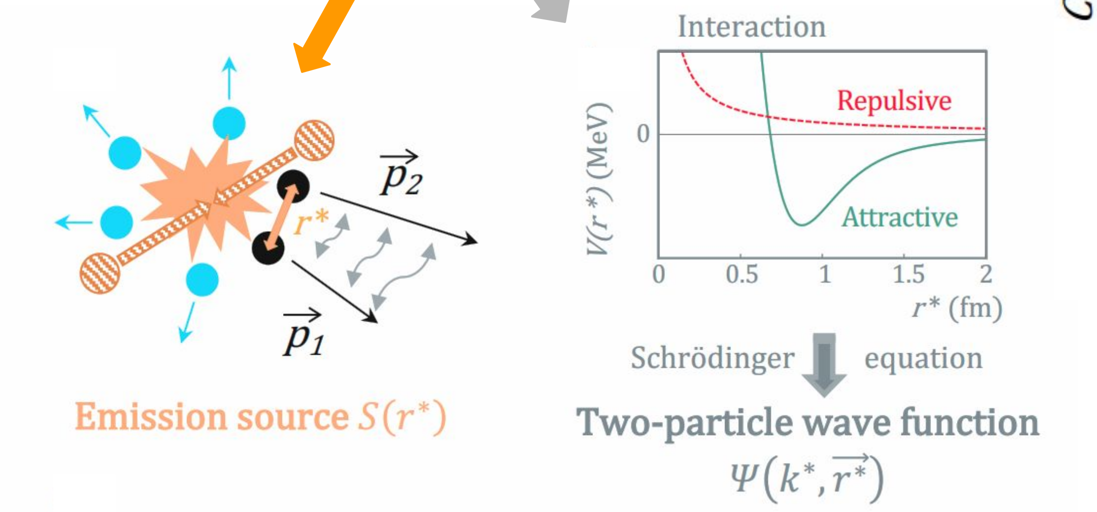

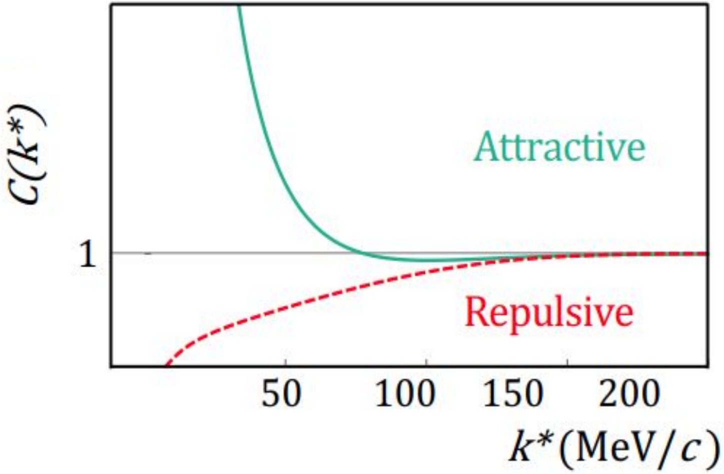

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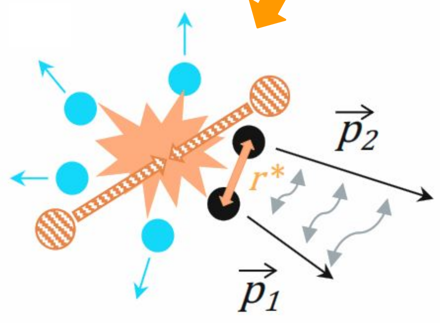

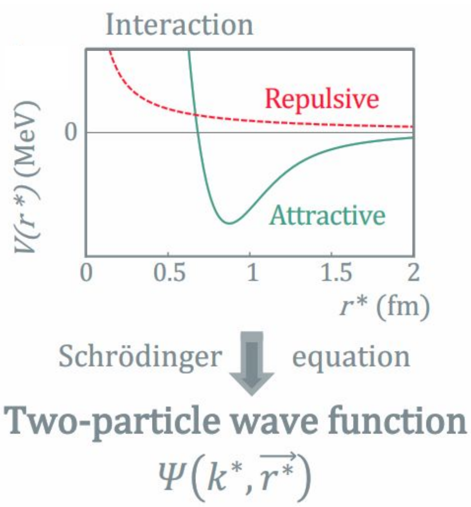

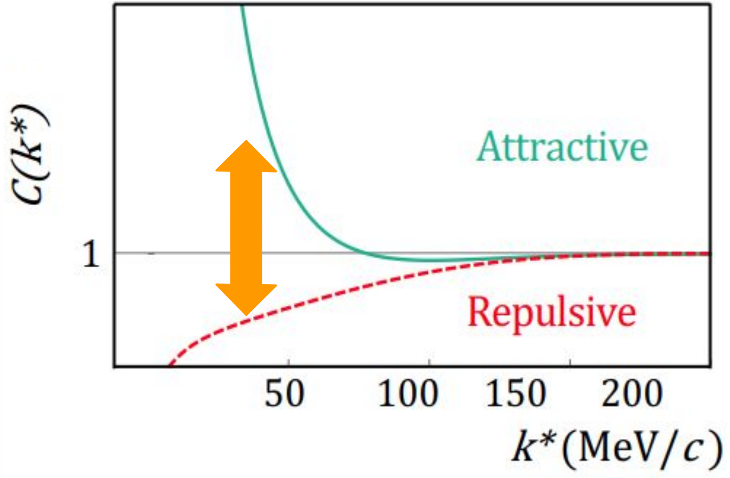

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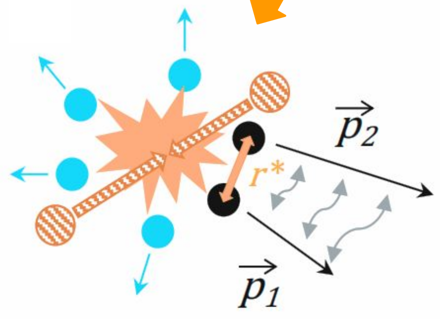
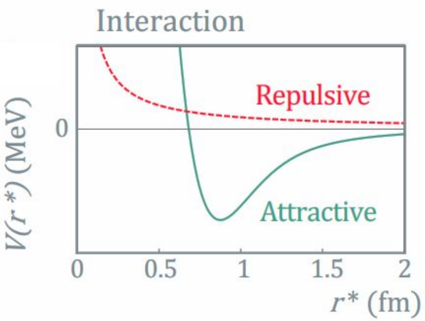


Emission source $S(r^*)$

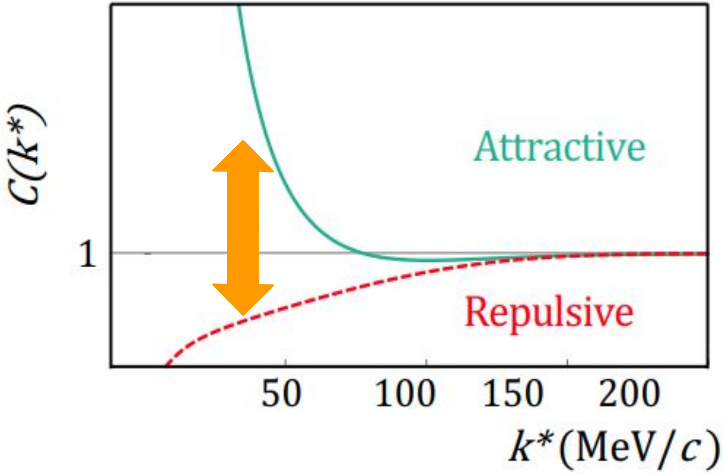


Schrödinger equation

Two-particle wave function

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

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



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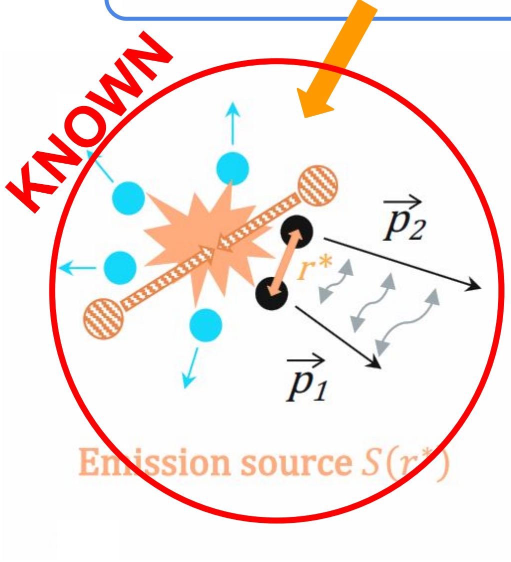

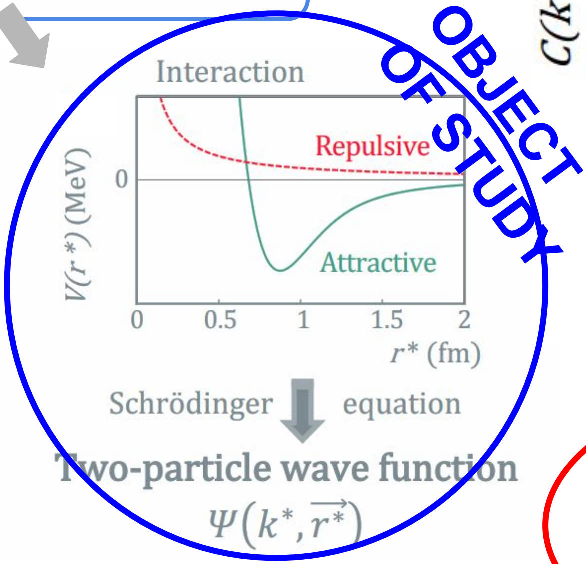

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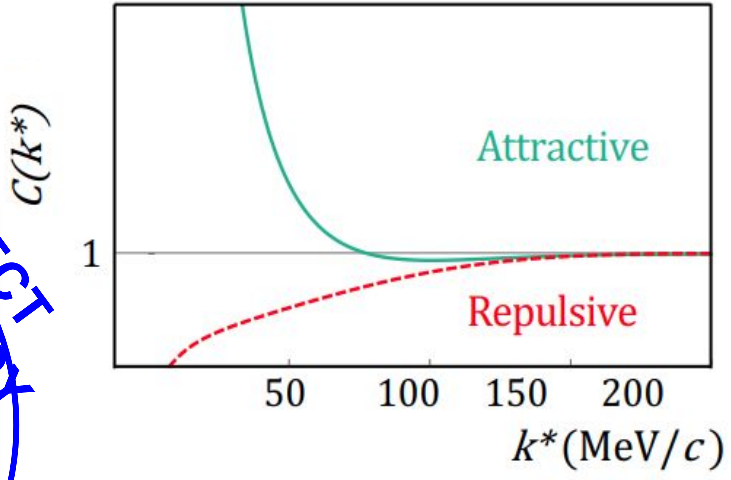

KNOWN

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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 $\sqrt{s}$ = 13 TeV

⇒ size of particle source ~1 fm

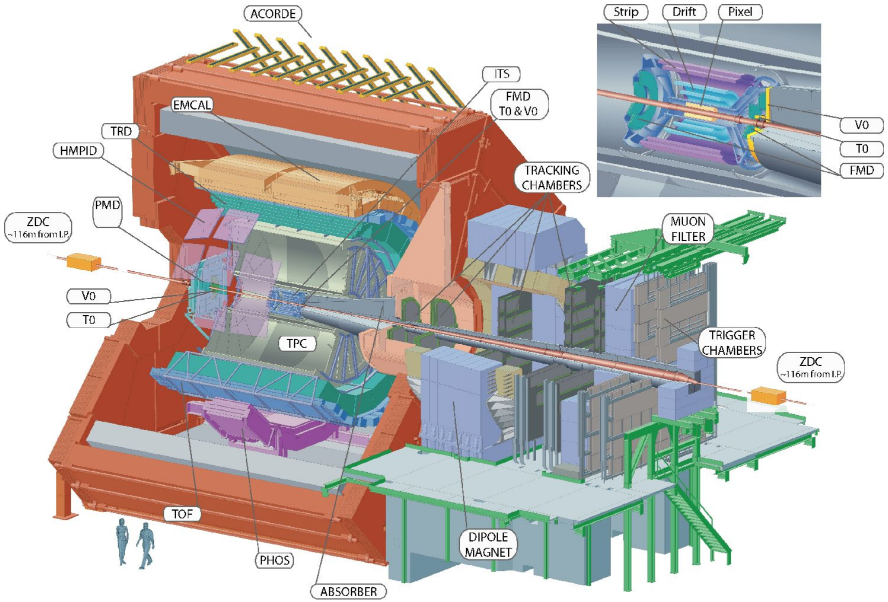
Femtoscopy at the LHC with ALICE

LHC

ALICE

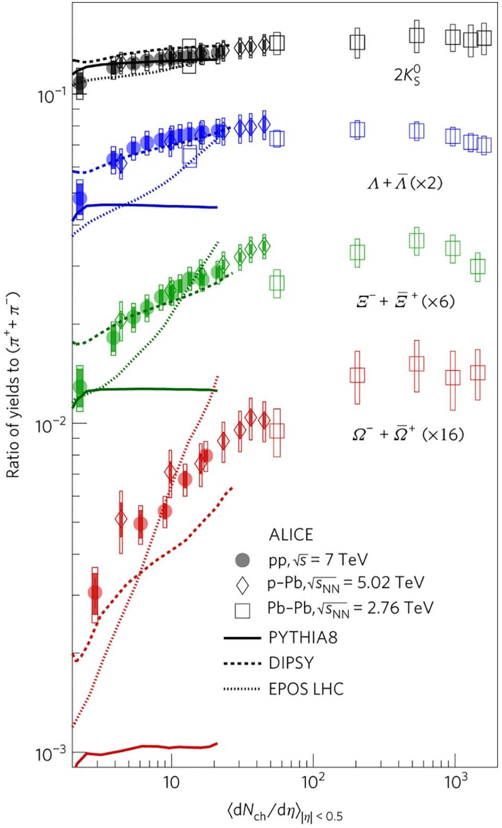
Central barrel **tracking and PID**:

- 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

ALICE High-Multiplicity pp data

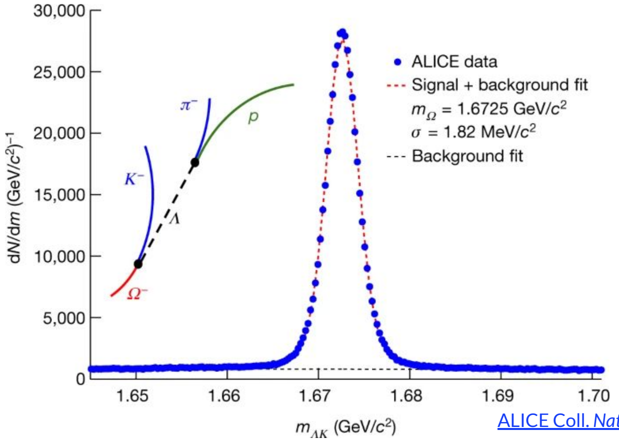


Data sample:

- pp 13 TeV (1000 M **high multiplicity** events)

Tracking and PID:

- Hyperon reconstruction with purities >95%

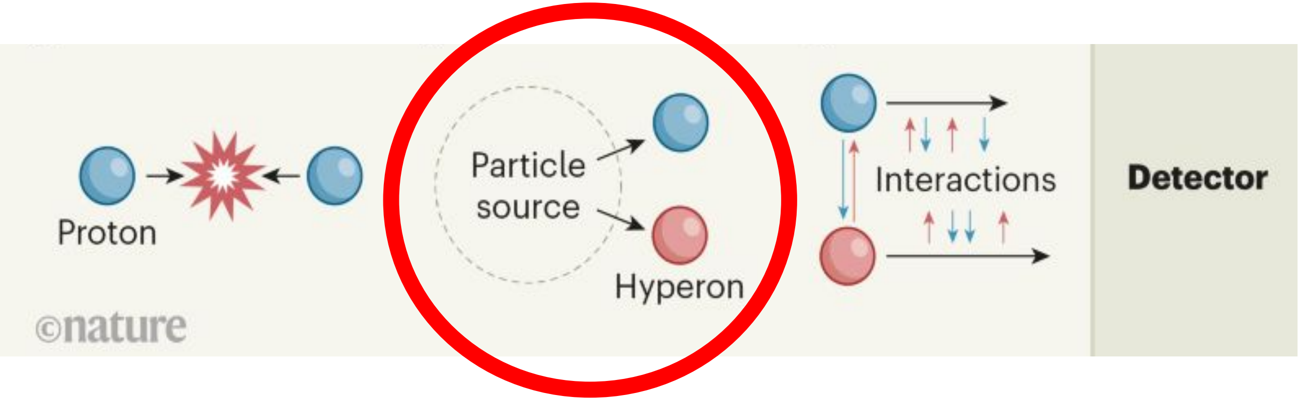


ALICE Coll. *Nature* **588**, 232 (2020)

⇒ Enhanced strangeness production!

Nature Physics volume 13, 535–539(2017)

1st step: Setting the source



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

Ansatz: similar source for all baryon-baryon (hadron-hadron?) 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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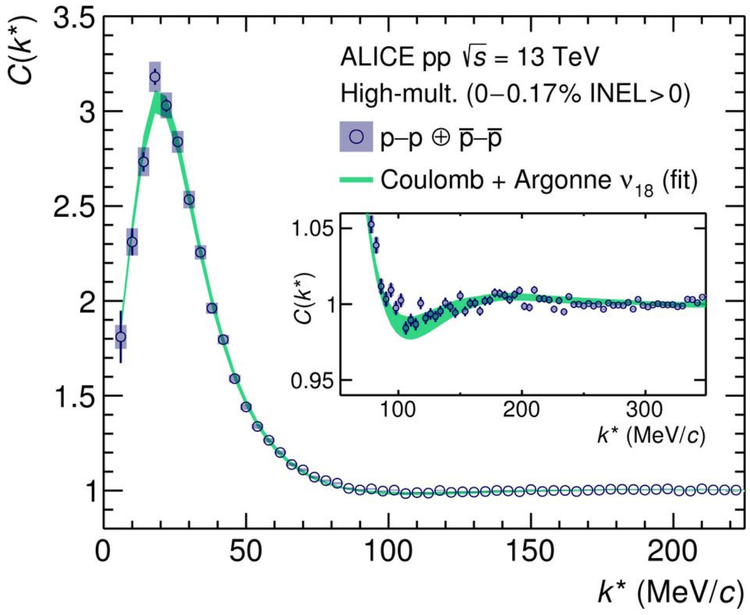

⇒ **Fit of the radius of the source of p-p pairs in p-p collisions.**

The source size (gaussian width) 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

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Determine **gaussian "core" radius as a function of pair <m_T>**
- Common to all hadron-hadron pairs

✖

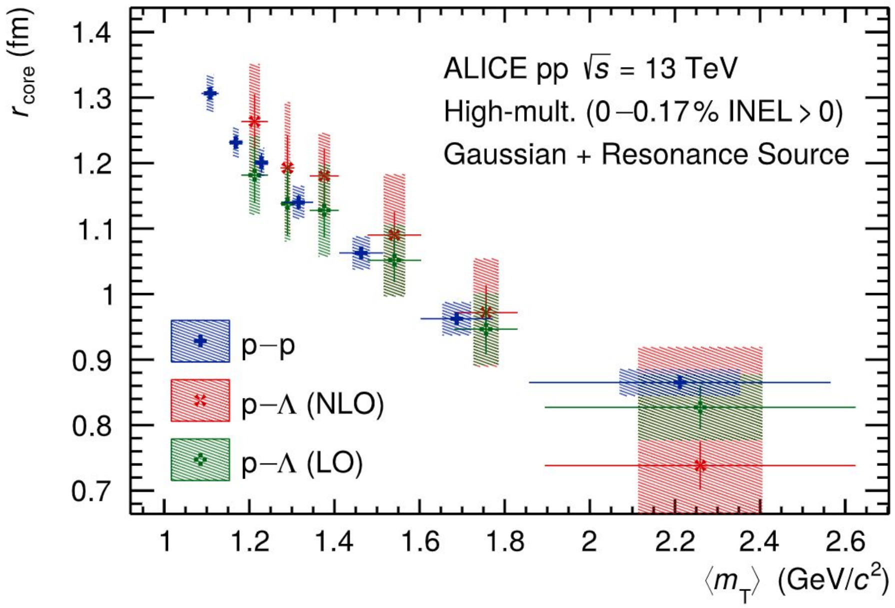
Effect of strong short-lived resonances
Adds **exponential tail** to the source profile
→ Angular distributions from EPOS

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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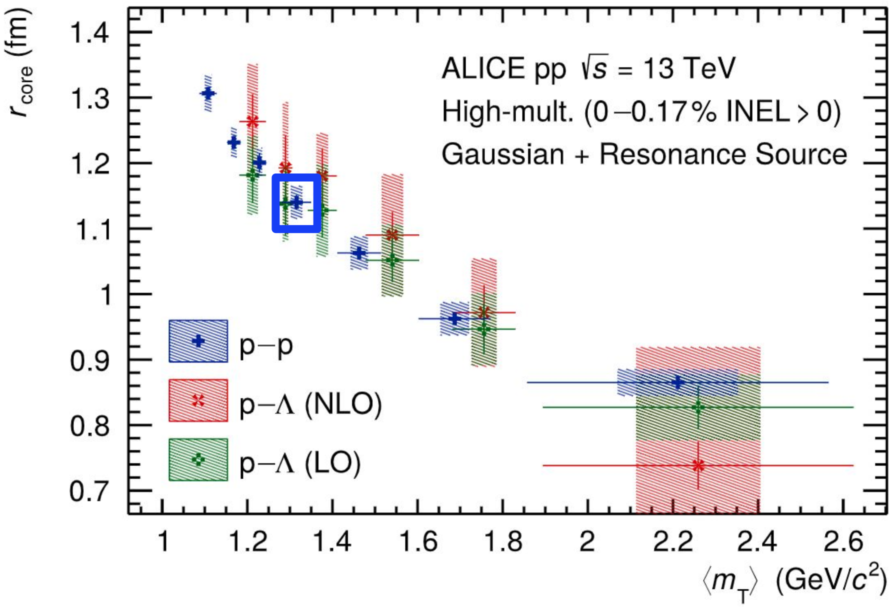

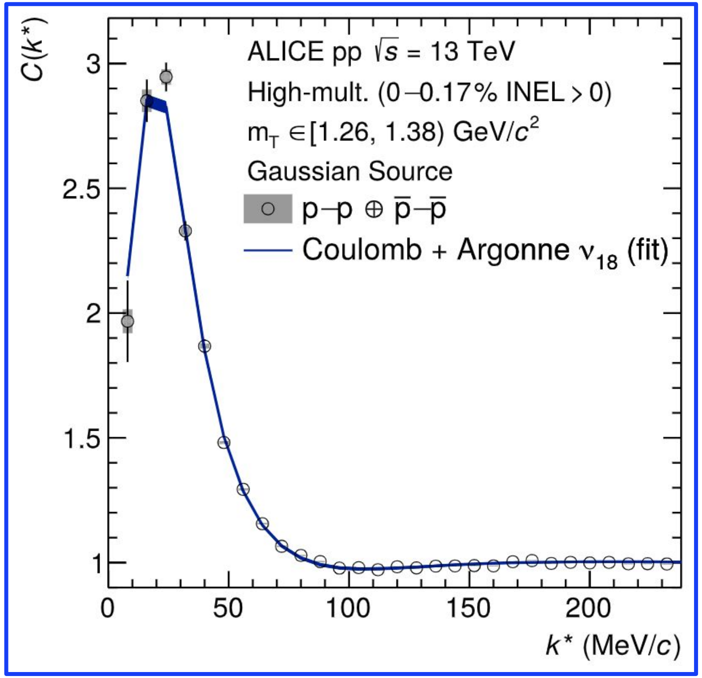

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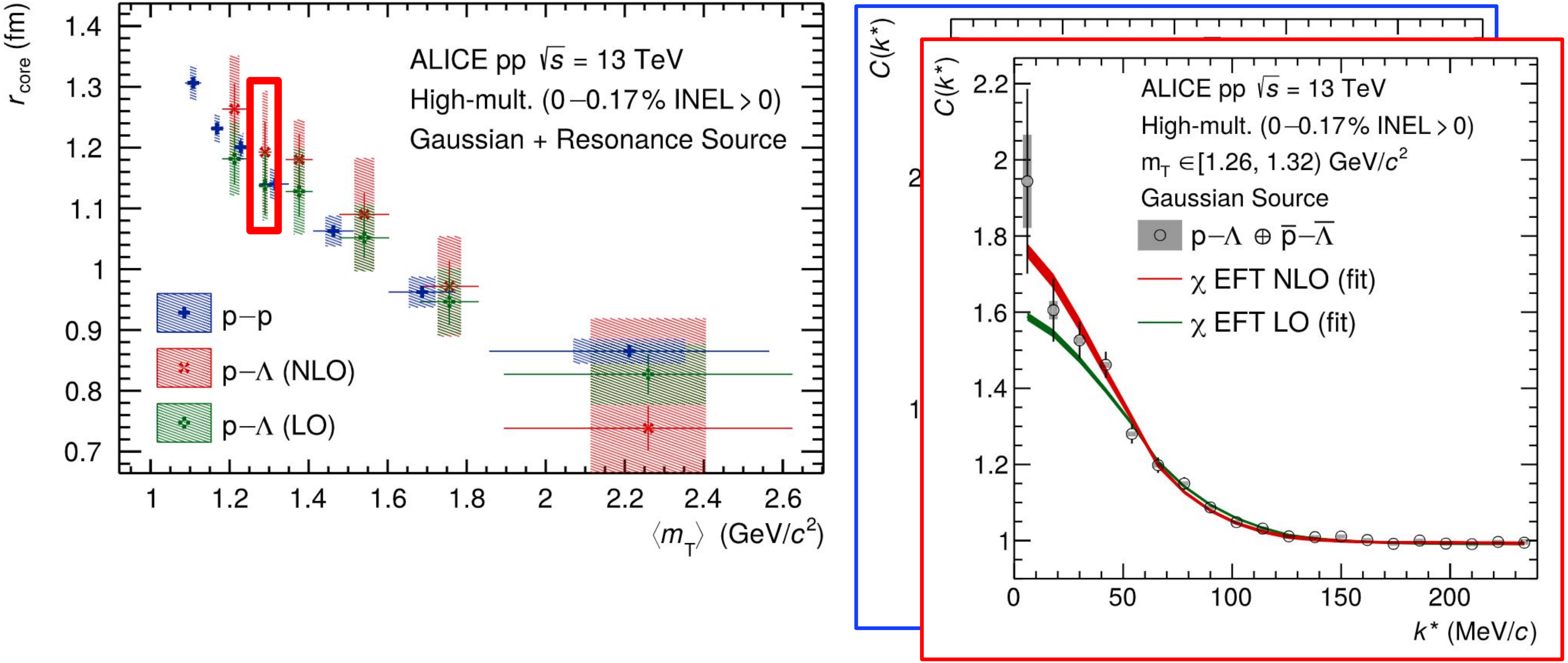

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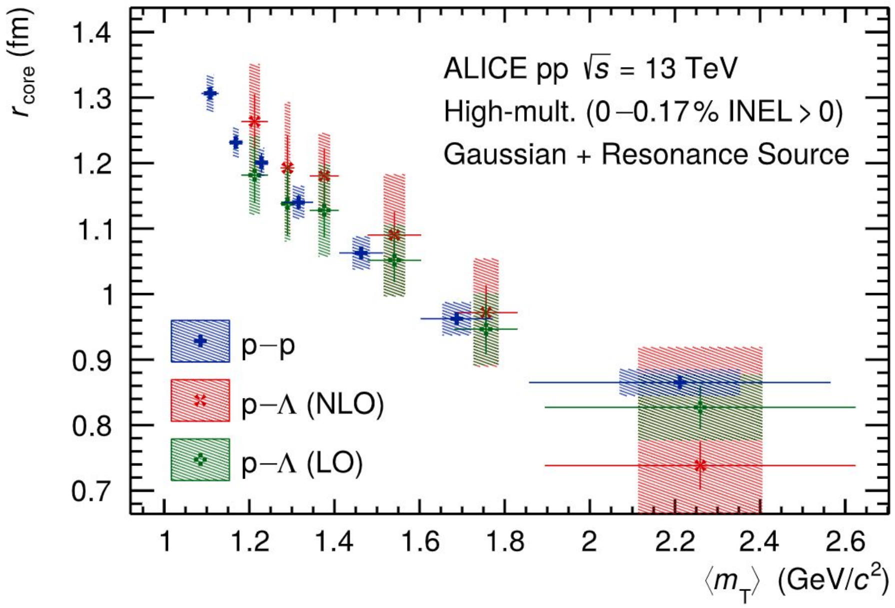
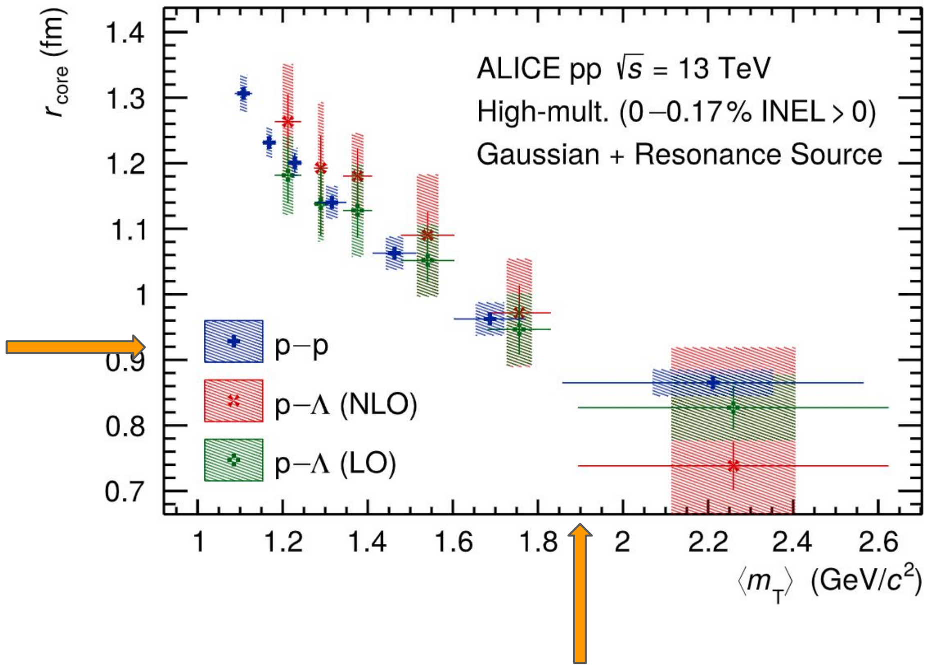


Dependence of the source size with **$\langle m_T \rangle$ related to collective phenomena**

“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 $\langle m_T \rangle$** and **considering the effect of strong resonances** for the particles of the pair of interest

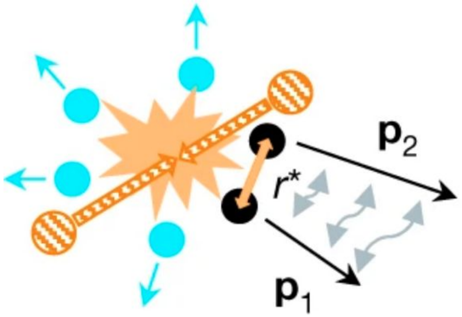
Example:

p–Ξ⁻: $\langle m_T \rangle$ = 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

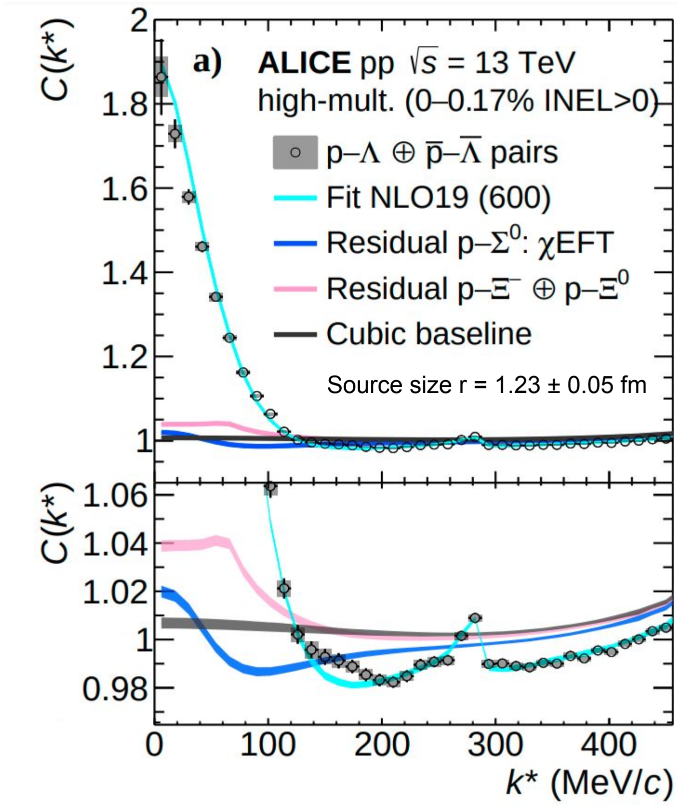
Test of first principle calculations (and other models) and...

- 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. Phys.Lett.B 833 (2022) 137272



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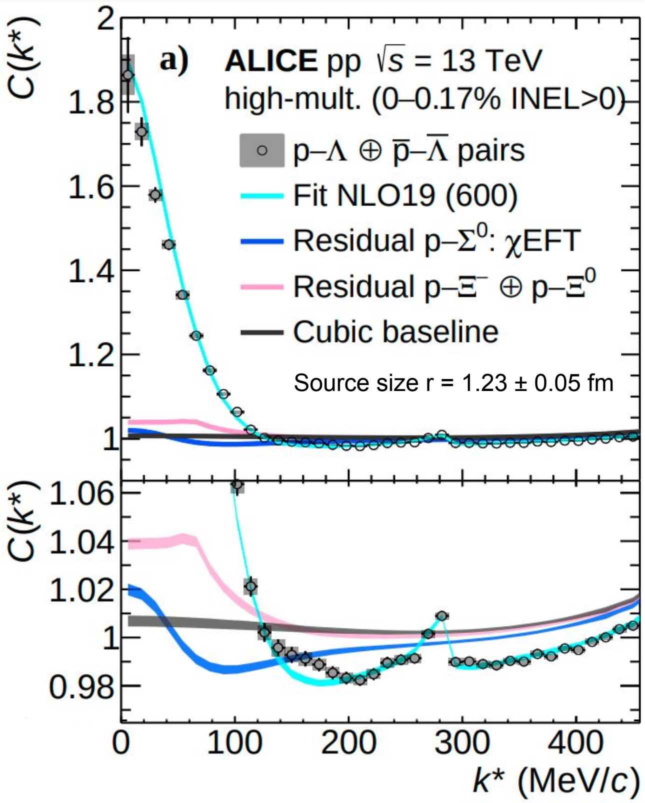
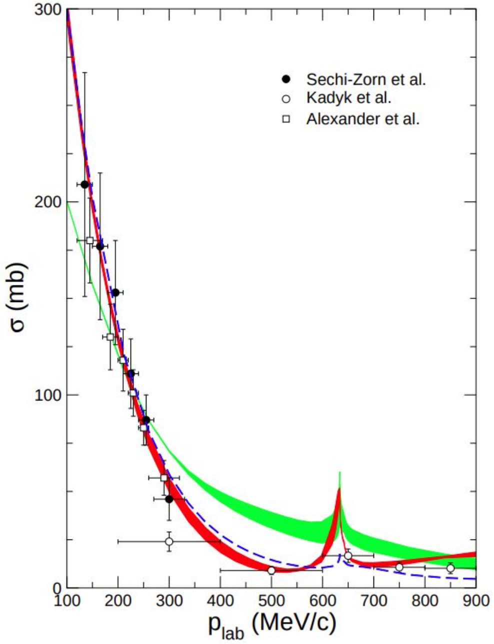


ALICE Coll. Phys.Lett.B 833 (2022) 137272



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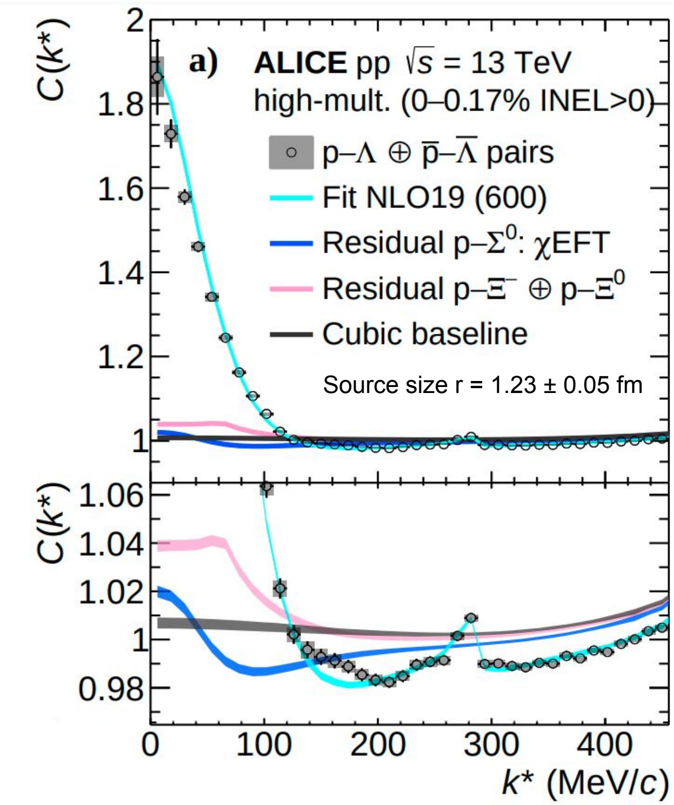


ALICE Coll. Phys.Lett.B 833 (2022) 137272

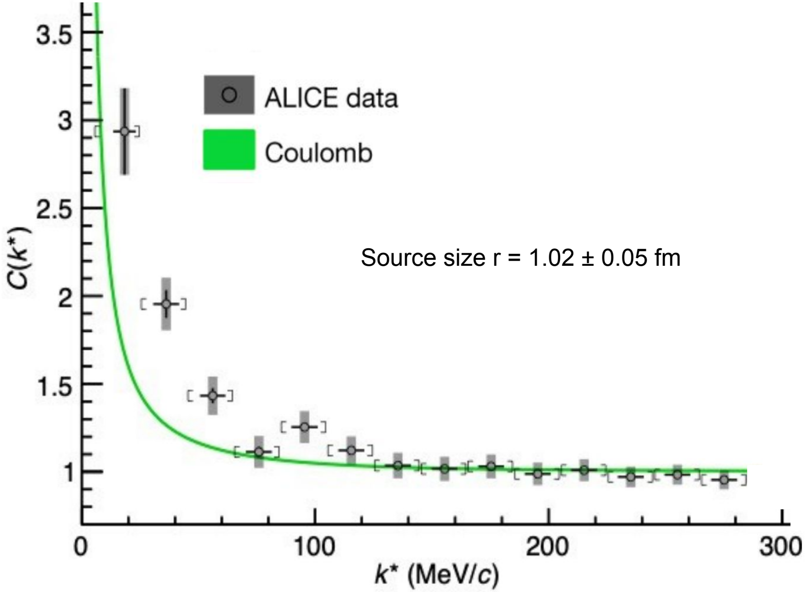
- Most precise measurements on the p–Λ interaction
- **Test strengths of the NΣ ↔ NΛ transition**
- Hyperons in NS?: Exact composition strongly depends on constituent interactions and couplings

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)](#)

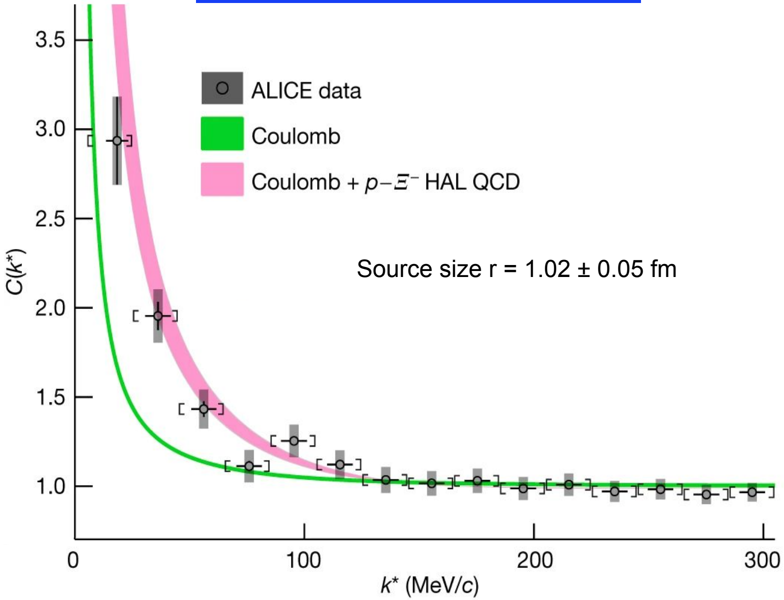


Enhancement above Coulomb-only prediction
⇒ Observation of the **attractive strong interaction**

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**

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**

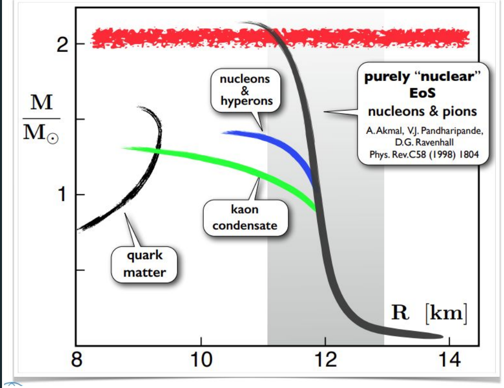
EoS of dense symmetric nuclear matter

W. Weise @ HYP 2022

CONSTRAINTS on EQUATION-of-STATE

- from observations of $2\,M_\odot$ neutron stars

Mass-Radius Relation



Tolman - **O**ppenheimer - **V**olkov Equations

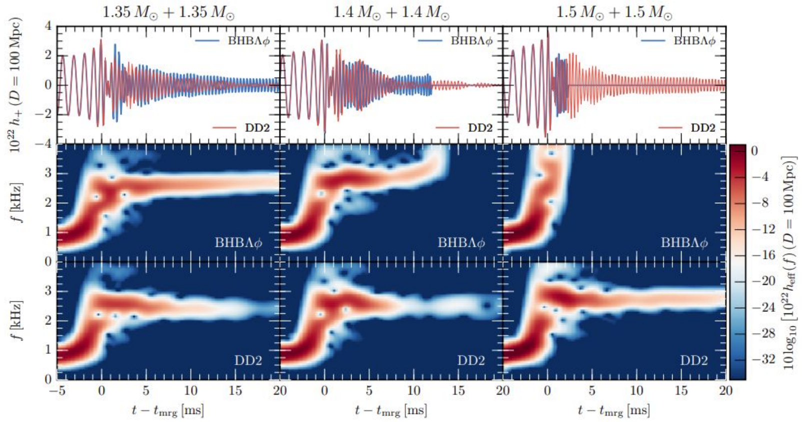
$$\frac{dP}{dr} = -\frac{G}{c^2}\frac{(\mathcal{E}+P)(M+4\pi P r^3)}{r(r-2GM/c^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \frac{\mathcal{E}}{c^2}$$

- **Stiff equation-of-state $P(\mathcal{E})$ required**
- **Simple forms of exotic matter** (kaon condensate, quark matter, …) **ruled out**

D. Logoteta @ EXOTICO 2022

GWs spectrum with hyperons and without



D. Radice et al. ApJL 842 L10 (2017)

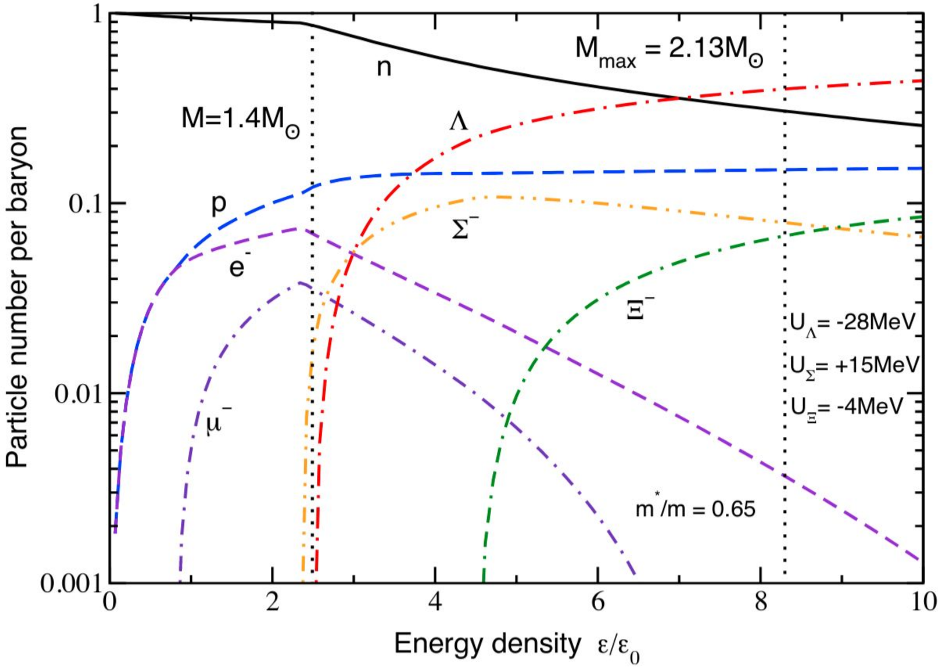
Domenico Logoteta | Equation of state for neutron stars and binary neutron star mergers

Hyperons in NS

Lattice: slightly repulsive single particle potential in PNM for Ξ

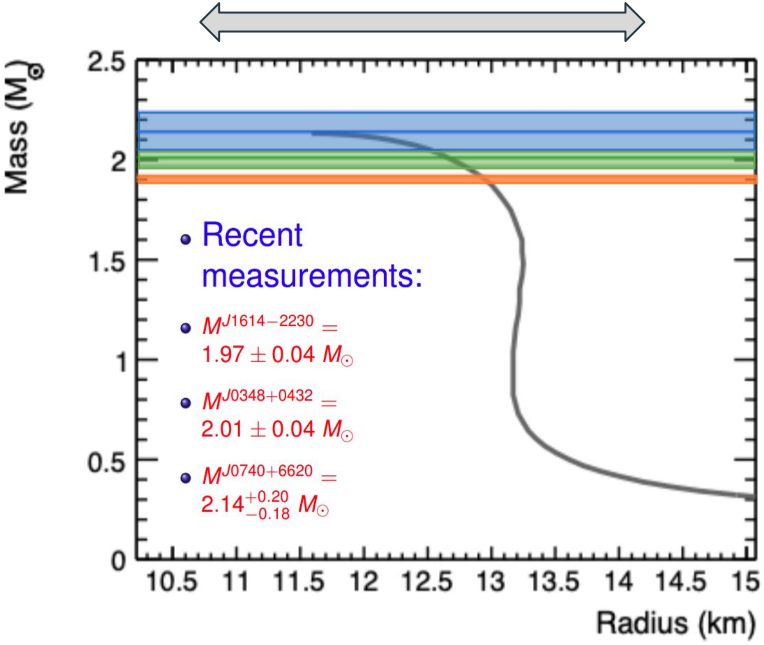
⇒ Ξ appears at larger densities in NS

⇒ **Stiffer EoS**



Constraints from NICER

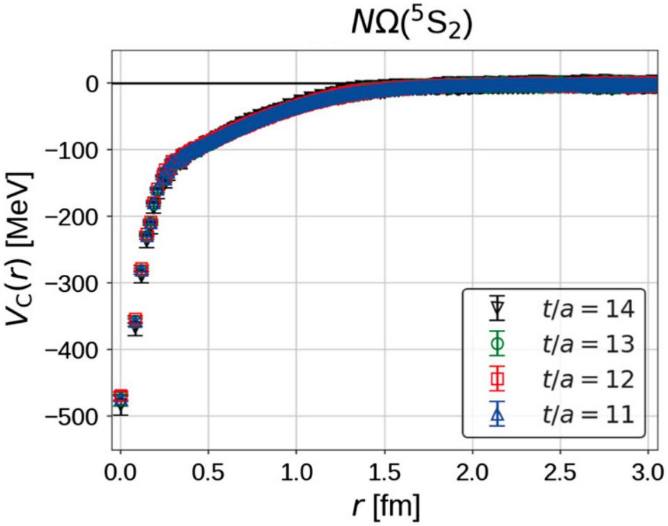
G. Raaijmakers et al., AJL 918 (2021), L29



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

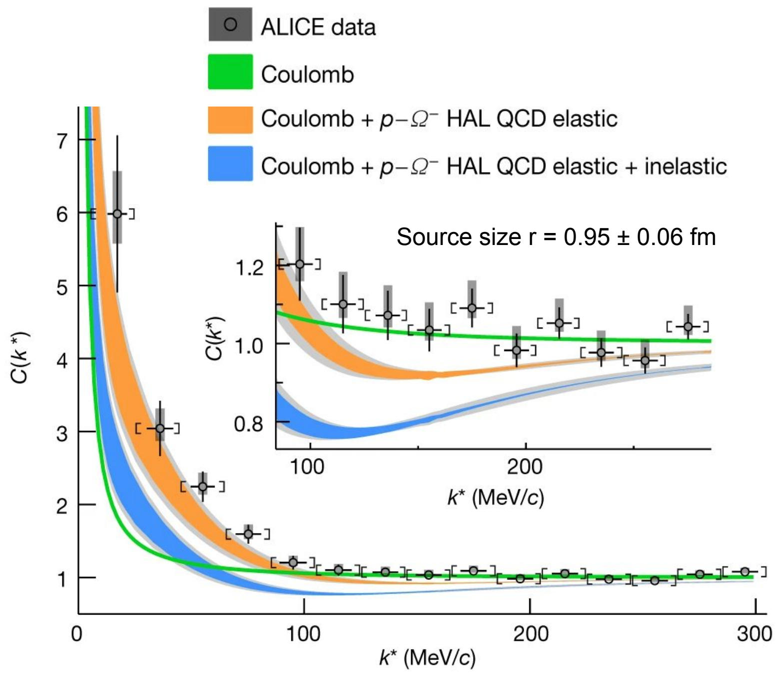
⇒ Binding Energy = 2.5 MeV

Meson exchange models predict smaller binding

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

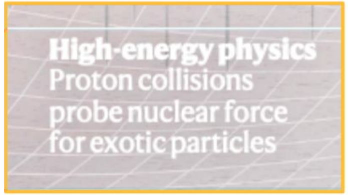
Di-baryon states: p–Ω⁻ correlation function

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

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

The case of the antiKaon-Nucleon interaction

- KbarN interaction: building block of non-perturbative regime of QCD

- **KN and KbarN strong interactions are very different**
  - The presence of the strange quark has dramatic consequences
  - Strong attractiveness in KbarN gives rise to bound states

- Sub-threshold: **Λ(1405) is an “old object” not fitting in the standard 3-quark picture**
  - Molecular state with two poles KbarN-Σπ
  - Strong coupled channel dynamics

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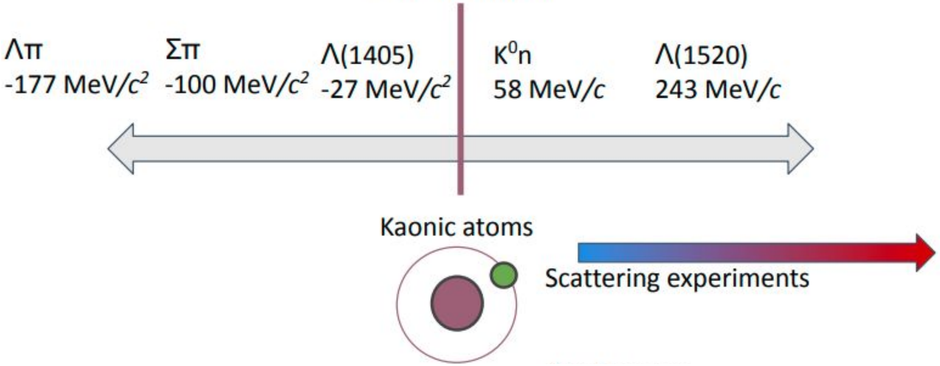
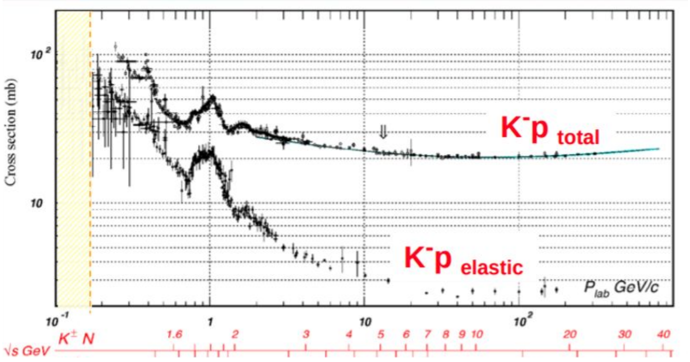
Connected to the main topics:

- 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
- Strangeness in NS: kaon condensate
  D.Logoteta Universe 2021, 7(11), 408
- Enhanced production of strangeness with multiplicity T. Song @ SQM2021

The case of the antiKaon-Nucleon interaction





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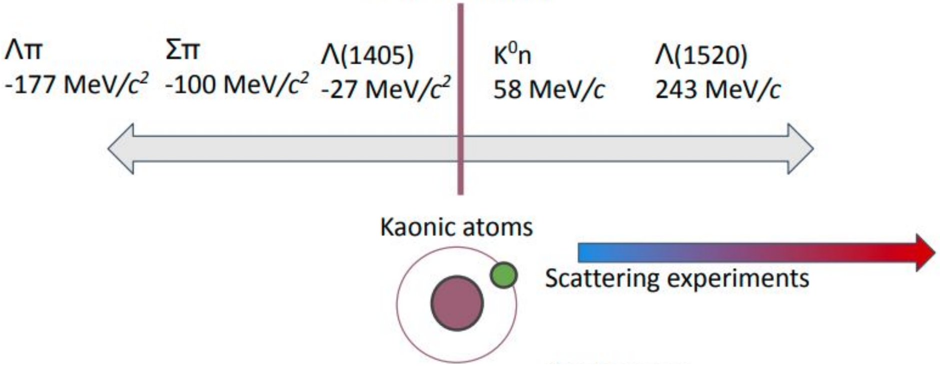
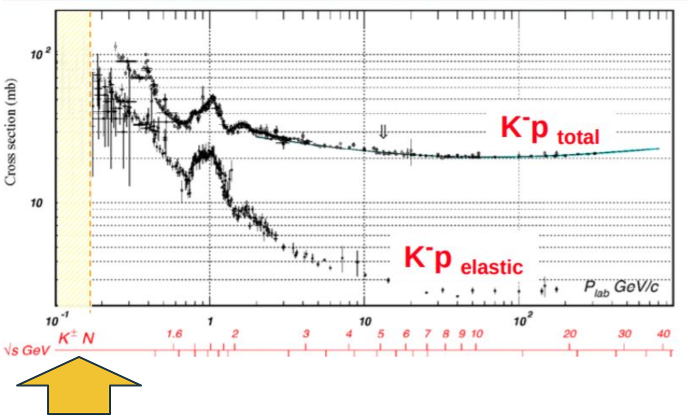
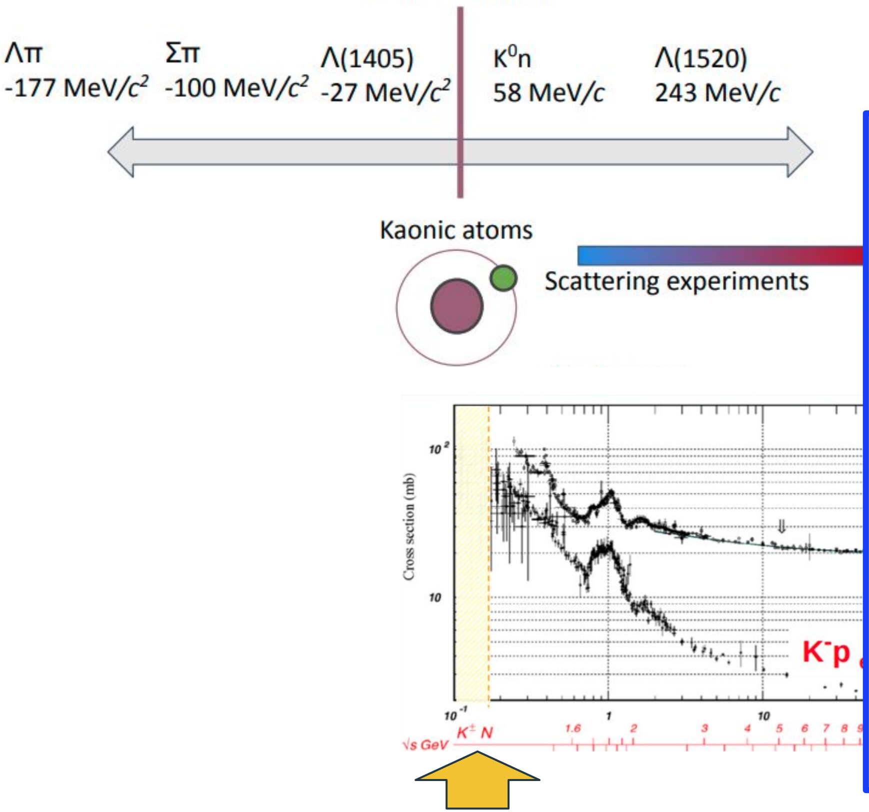
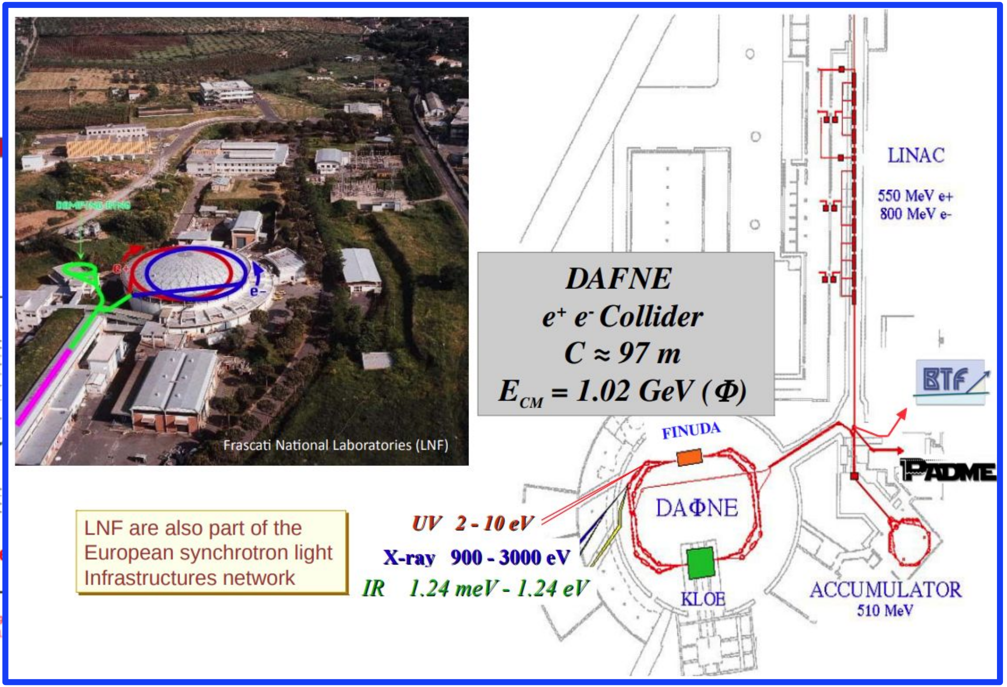




DAΦNE: e^+e^- collider @1GeV ⇒ Production of Φ meson at rest ⇒ low E. kaon beam!

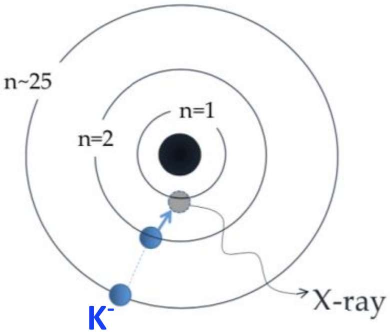
The case of the antiKaon-Nucleon interaction





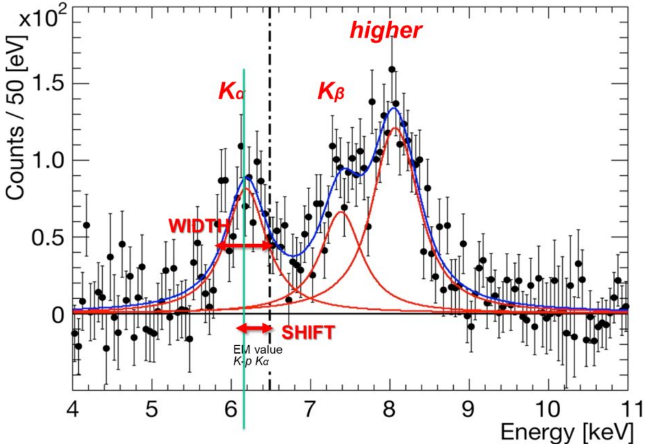
DAΦNE: e^+e^- collider @1GeV ⇒ Production of Φ meson at rest ⇒ low E. kaon beam!

antikaonic hydrogen: SIDDHARTA



shift(ε), width(Γ) with respect to e.m. value caused by attractive/repulsive strong interaction and the presence of inelastic channels

Measurement of the **shift(ε) and width(Γ) induced by the strong interaction** in the lowest level atomic transition.



SIDDHARTA Coll., PLB 704 (2011) 113

$$\epsilon_{1s} = -283 \pm 36(\mathrm{stat}) \pm 6(\mathrm{syst})\ \mathrm{eV}$$
$$\Gamma_{1s} = 541 \pm 89(\mathrm{stat}) \pm 22(\mathrm{syst})\ \mathrm{eV},$$

Translated via Desser-type Formula into a **K^-p scattering length** that is an average of the KbarN scattering lengths for I=0 and I=1

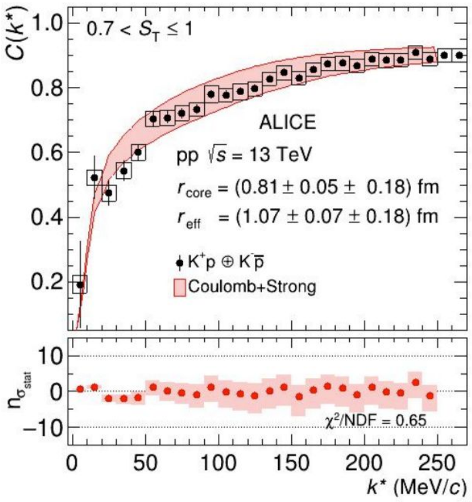
$$\epsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_p\left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_p\right)$$

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

KbarN Femtoscopy with ALICE

Well known K^+p interaction

⇒ experimental determination of the source size



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

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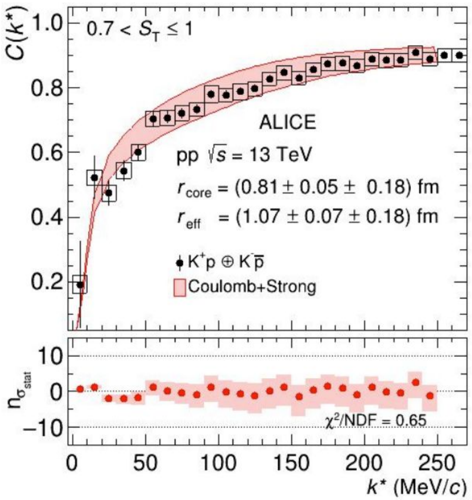

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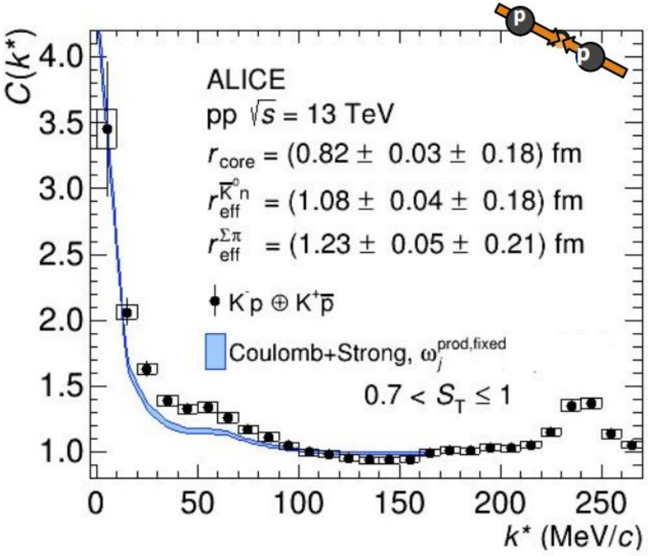
K^-p femtoscopy:

Test of Kyoto potential anchored to SIDDHARTA result



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

Small systems: pp collisions r~1fm

⇒ Provides a **quantitative test of coupled channels in the theory**

Effects of coupled channels enhanced by small source

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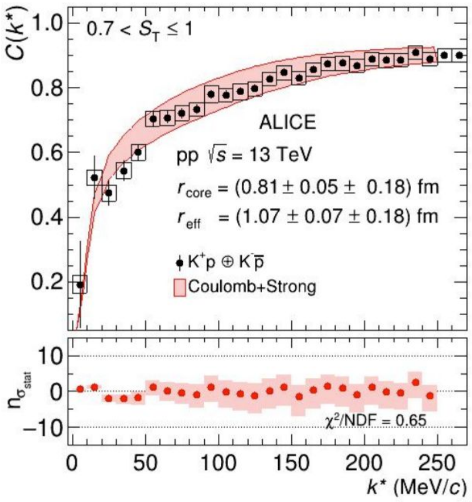

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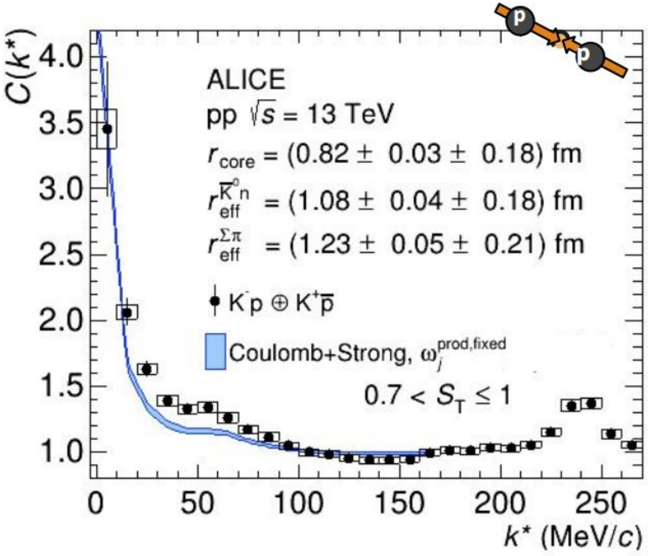

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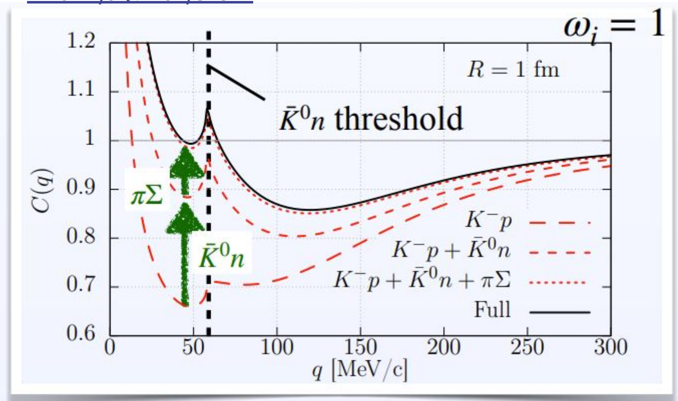
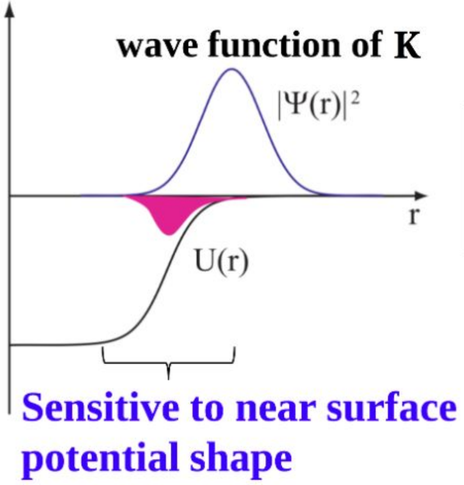
Y. Kamiya @ Baryons22



KbarN at threshold and low momentum

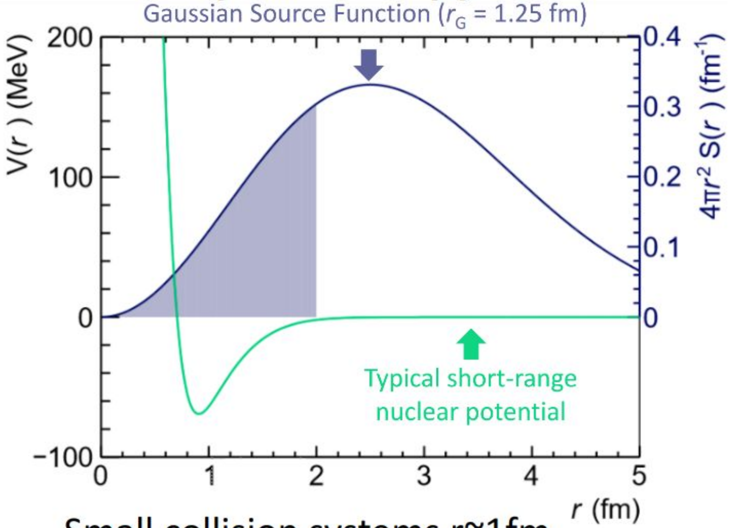
SIDDHARTA: antiKaonic Hydrogen



* for antikaonic hydrogen the K- p distance is ~100 times the Bohr radius

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

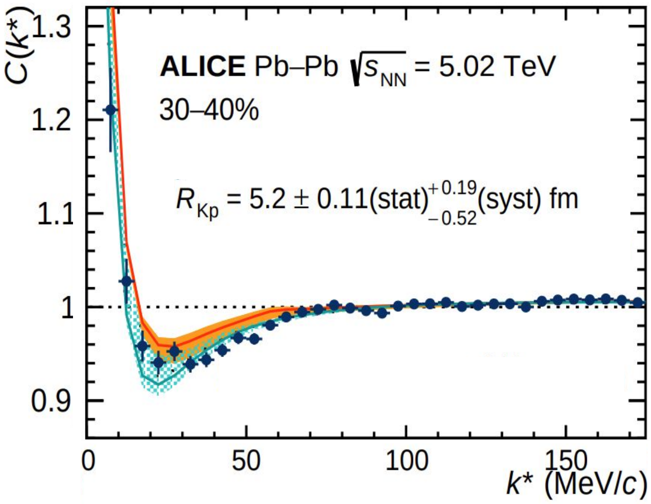
$$C(k^*) = \int S(r^*) \left|\Psi(k^*,\vec{r^*})\right|^2 d^3r^*$$

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

ıts

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

ALICE Coll., PLB 822 (2021) 136708



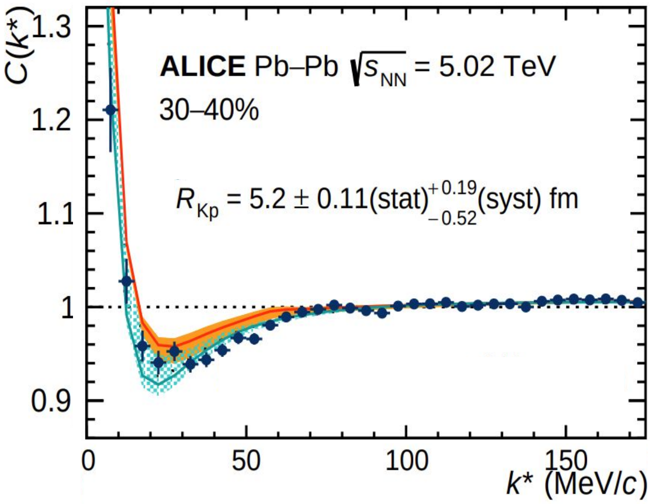
<u>Large systems (HIC):</u> Pb-Pb collisions, up to r~9fm

Strength of coupled channels significantly reduced

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

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

ALICE Coll., PLB 822 (2021) 136708



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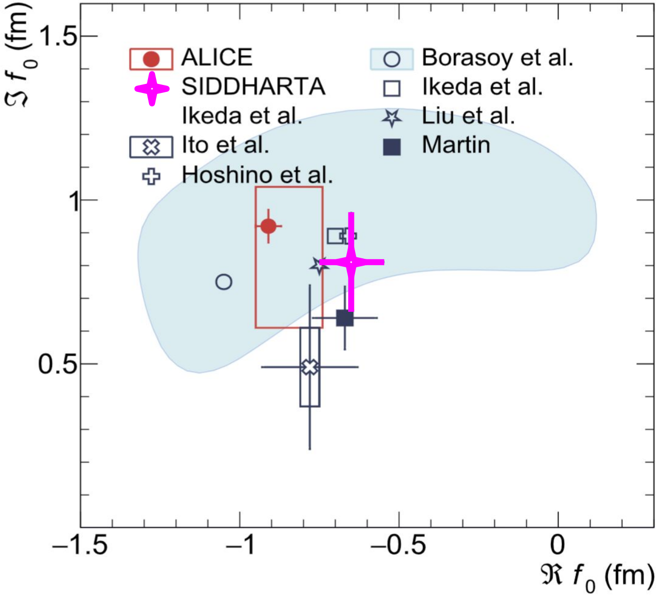
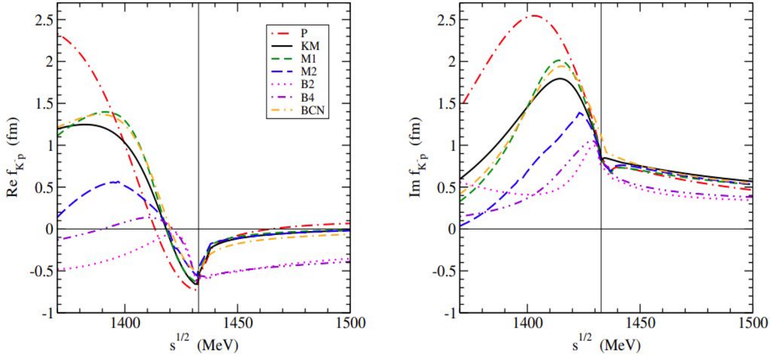


⇒ Antikaonic-hydrogen and K-p femtoscopy scattering parameters compatible

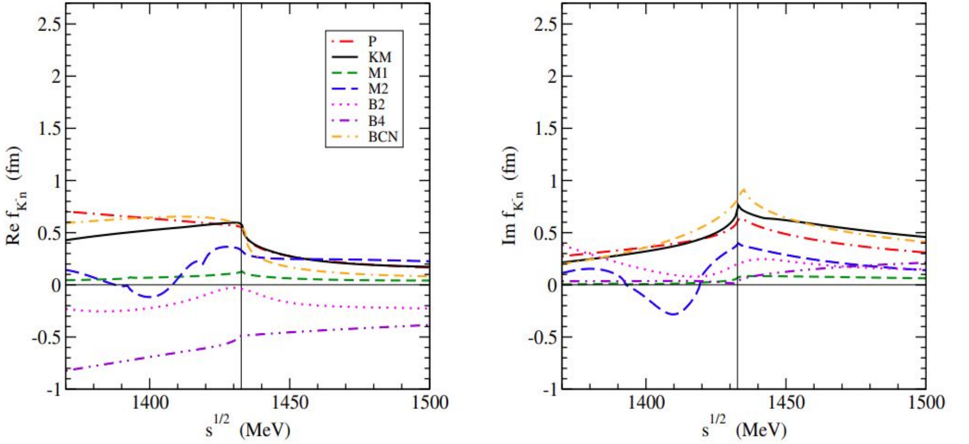
Upcoming: Accessing KbarN I=1 interaction

Free-space K^-p amplitudes in various chiral models



Prague (P)	*A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115*
Kyoto-Munich (KM)	*Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98*
Murcia (M1 and M2)	*Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202*
Bonn (B2 and B4)	*M. Mai, U.-G. Meißner, Nucl. Phys. A 900 (2013) 51*
Barcelona (BCN)	*A. Feijoo, V. Magas, A. Ramos, Phys. Rev. C 99 (2019) 035211*

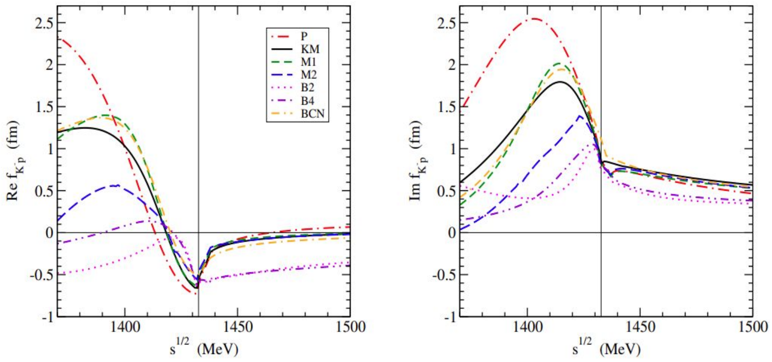
Free-space K^-n amplitudes



J. Obertova @ EXOTICO 2022

Upcoming: Accessing KbarN I=1 interaction

Free-space $K^{-}p$ amplitudes in various chiral models



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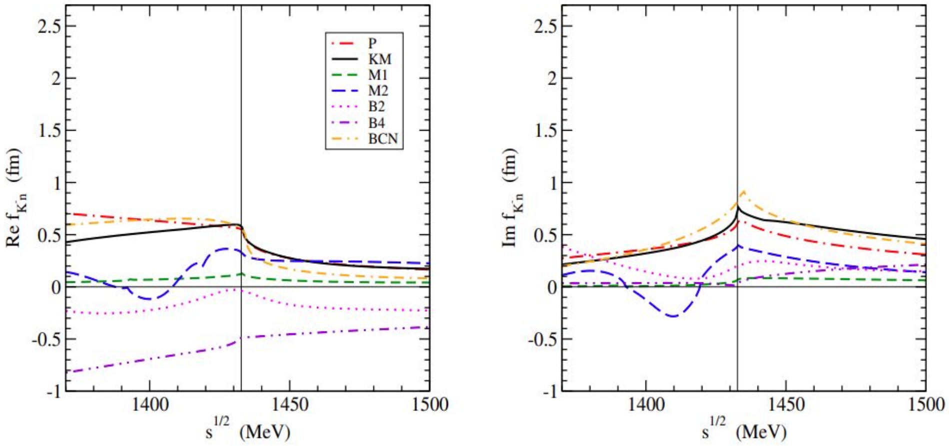


J. Obertova @ EXOTICO 2022

⇒ **Full isospin dependence** needs K^-d interaction measurements:

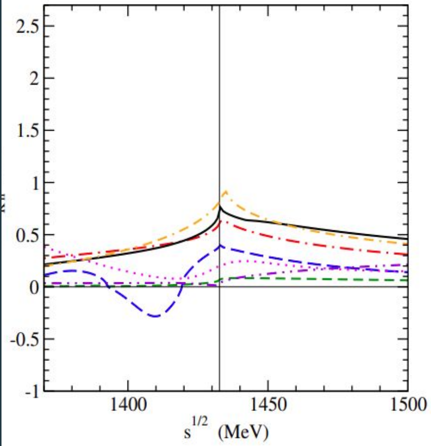
SIDDHARTA2: $a_{K^-d} = \frac{1}{2}\frac{m_N + m_K}{m_N + \frac{m_K}{2}}(3a_1 + a_0) + C$

Upcoming: Accessing KbarN I=1 interaction

Free-sp

800 pb-1 to be acquired during 2002
⇒ Expected precision similar to SIDDHARTA measurement of antiKaon-hydrogen

Prague
Kyoto-M
Murcia
Bonn (E
Barcelon



J. Obertova @ EXOTICO 2022

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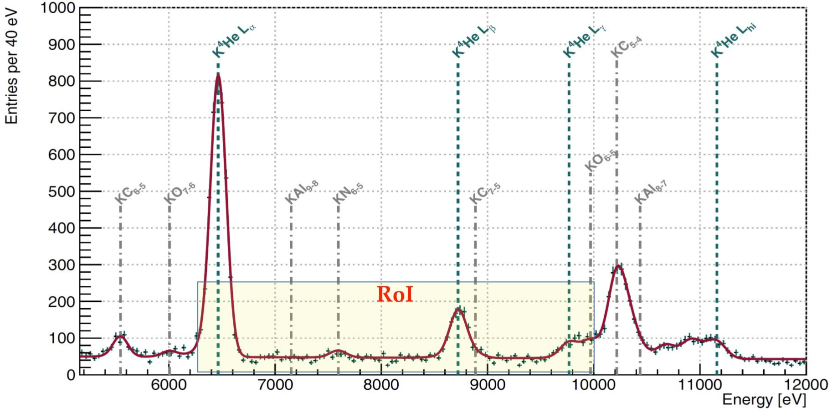
SIDDHARTA-2 with new experimental setup

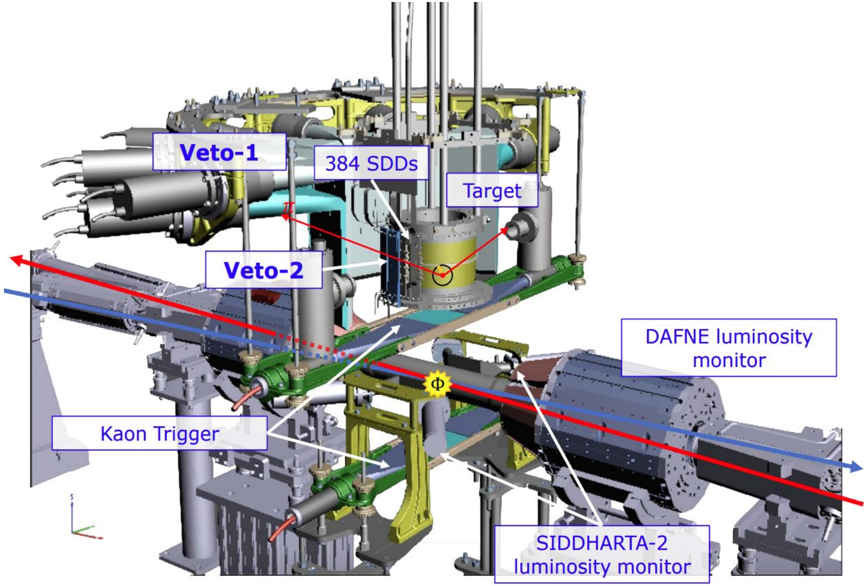
→measurement of **antikaonic deuterium**

→very challenging! low yield of signal.

→Complete upgrade of SIDDHARTA setup

Beam tuning April – May 2022, He measurement





➢ *Deuterium measurement started begin of June 2022 at DAΦNE*

Upcoming: Accessing KbarN I=1 interaction

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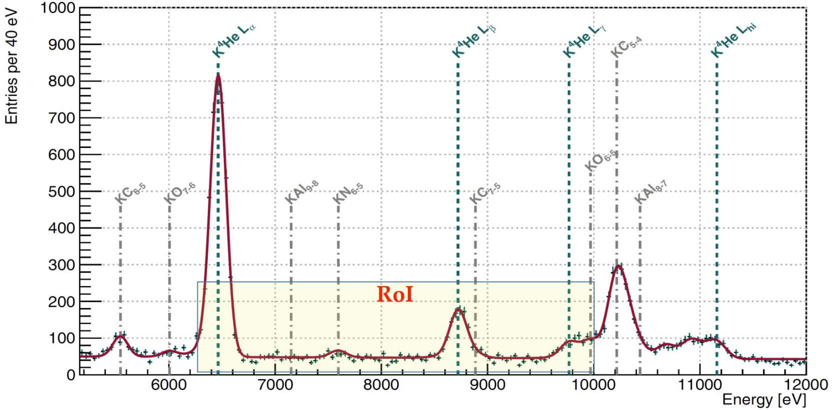
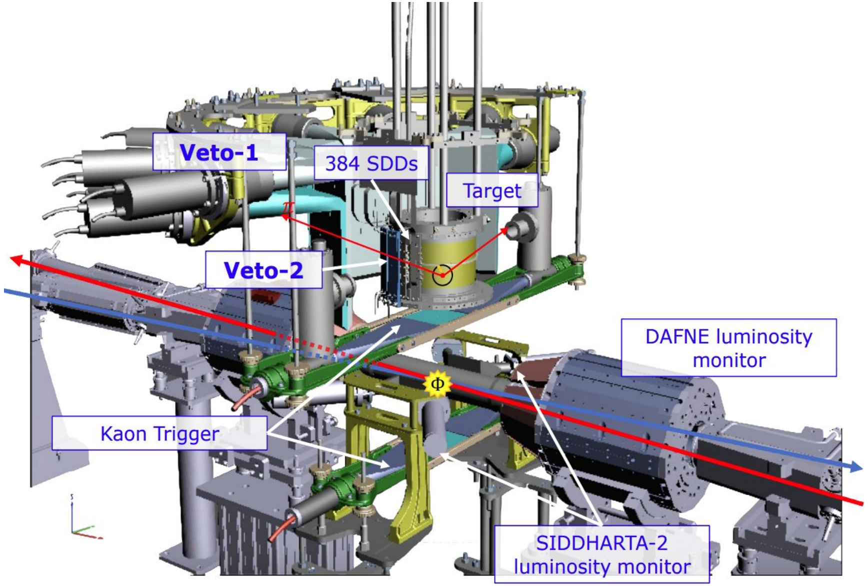
→Complete upgrade of SIDDHARTA setup

Beam tuning April – May 2022, He measurement





➢ *Deuterium measurement started begin of June 2022 at DAΦNE*

… and femtoscopy with deuterons with ALICE

K^-d femtoscopy with ALICE

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

- deuterons are expensive… penalty factor of 1/1000 w.r.t. protons
- K^+d correlation function to be used as reference

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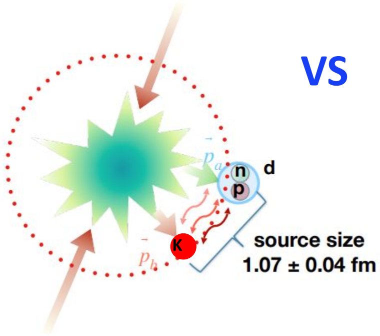
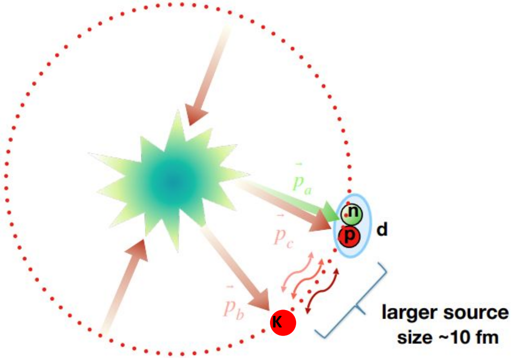
Thermal emission



VS

Coalesence



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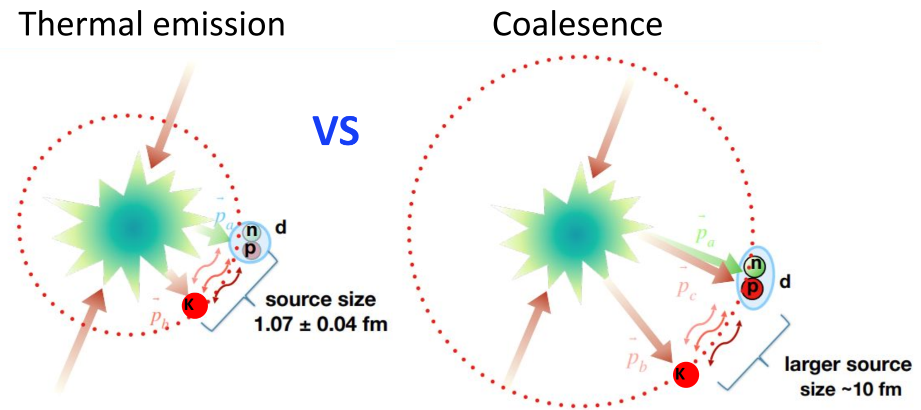

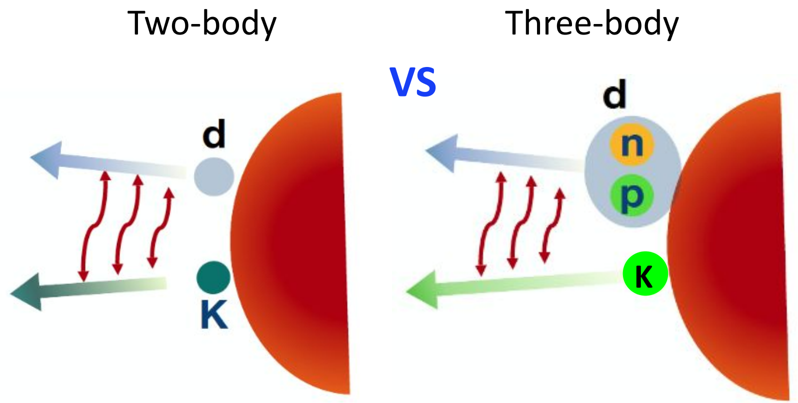

PISA theory group (M. Viviani, A. Kievsky, L. Marcucci) developing three-body calculations for the correlation function

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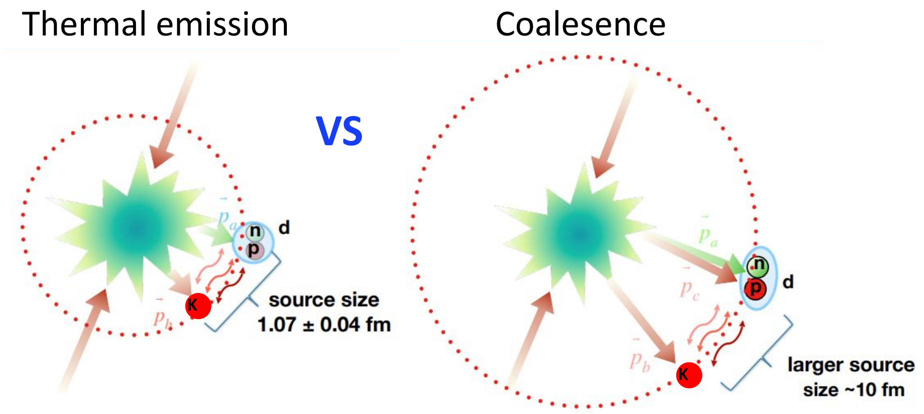
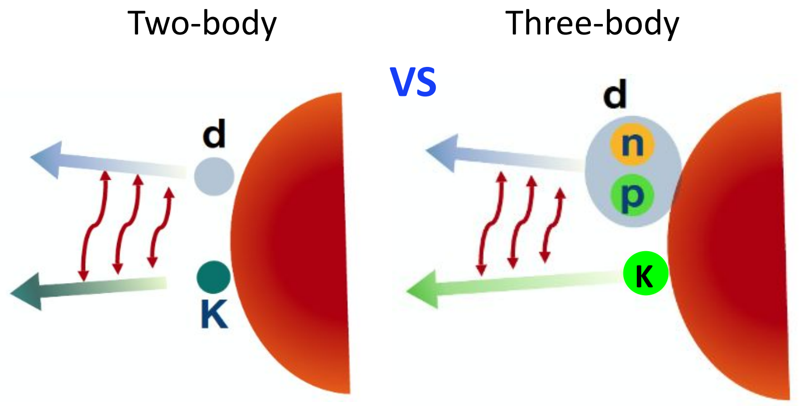
⇒ Currently being studied also via three-body femtoscopy!!!





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Outlook

Precision studies of the strong interaction between hadrons at the LNF

⇒ **Exotic atoms experiment**s enter a **new era** with SIDDHARTA-2

⇒ **Femtoscopy** studies at the LHC **update the experimental studies** on hadron-hadron interactions

What we do now:

- Test lattice calculations
- Study bound states
- Provide important constraints to the EoS of NS

What we are going to do:

More precision studies within reach with the large data samples to be collected in LHC Run 3 & 4

- Direct measurements of **three-body interactions** for the first time
- Study the **formation of light nuclei**
- And then we **move to charmed hadrons**…

... and **thank you very much**!

I only spent ~**1.5 years as Fellini fellow**...

... however this time helped me to focus my career and move to the next step!

Most of the items in my Career Plan Development have been reached or initiated:

- Get a tenure track position, eventually in Italy ✅
- Reach a new level in my status as a researcher ✅
- Boost my profile as an independent researcher (be able to decide “what to do next”) ✅
- Increase the visibility of my research ✅
- Improve my skills: machine learning, hardware items, etc ✅
- Get a better theoretical understanding of the field ✅
- In my case: learn from two supervisors in different “energy regimes” ✅
- First steps for dissemination out of the scientific community ✅
- Management of funds ✅
- Improve my written italian ✅