# Hadronic interactions with $|S| = 1$

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**Catalina Curceanu, SIDDHARTA-2.**

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# Study of the antiKaon-deuteron interaction

**Femtoscopy**

- **ALICE experiment**
- LHC

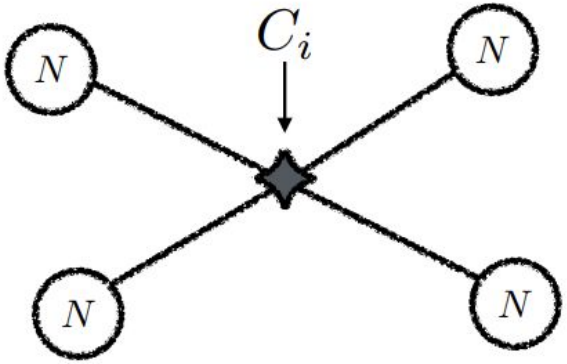
**from high-energy physics to nuclear physics**

**Kaonic atoms** spectroscopy

- **SIDDHARTA-2**
- DAΦNE $e^+e^-$ collider
- Low energy kaons facility

# Hadron-hadron strong interactions

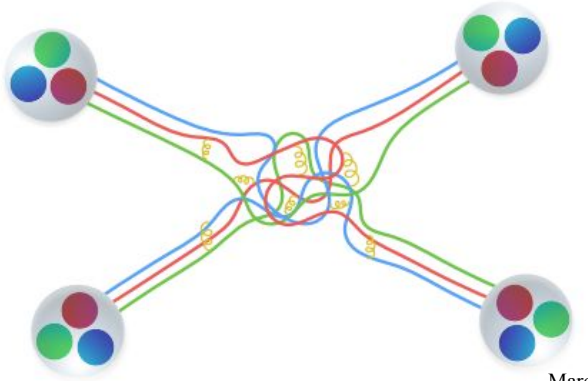
Residual strong interaction among hadrons




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

Effective theories (EFT)

- **Symmetries of underlying QCD…**
- **…but hadrons as degrees of freedom**
- **Low-energy EFT coefficients constraint by data**



Marc Illa
THEIA-STRONG2020

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

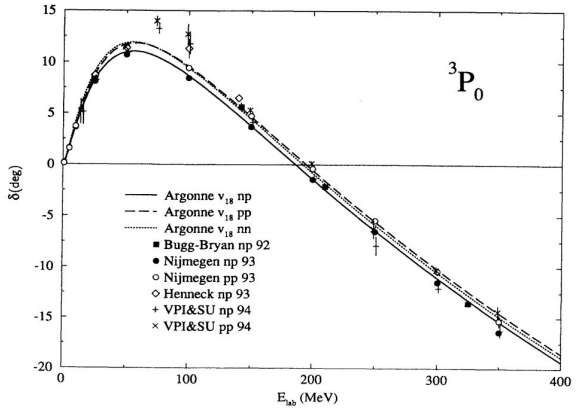
**Lattice QCD**

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

# Hadron-hadron interactions
# (with strangeness)

**S=0**

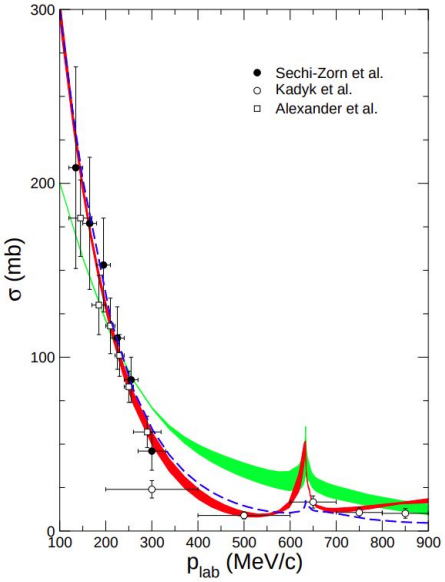
**NN → NN**




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

**S=-1**

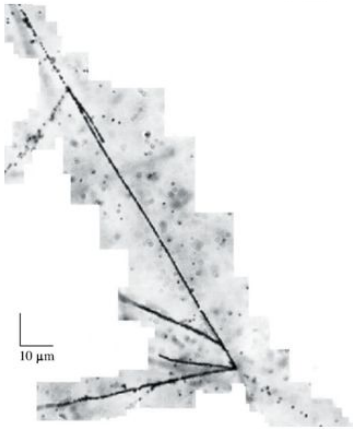
**Λp → Λp**




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

**S=-2**

**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 interactions
## (with strangeness)

$m_\pi \approx 570$ MeV

M. Lage et l., PLB 681 (2009) 439
HAL QCD Coll. PTEP 2020 (2020) 9, 093B03

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

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

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

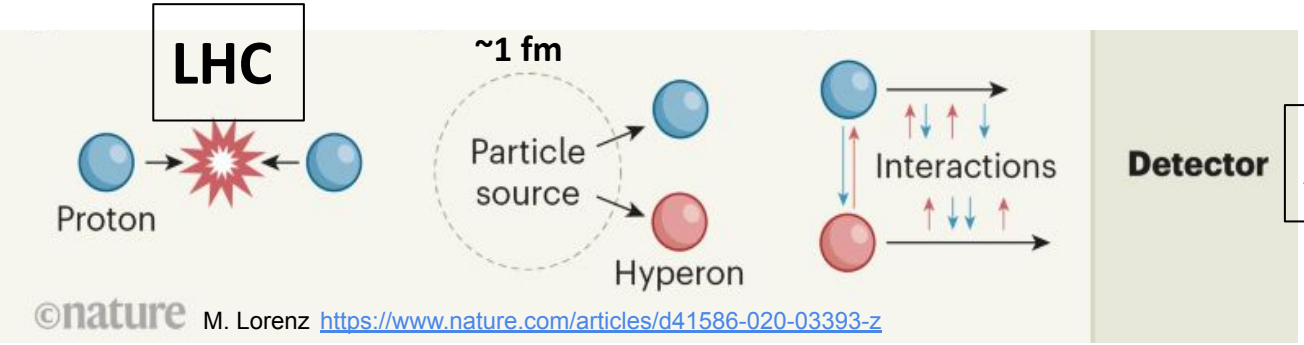
HAL QCD Coll. PRL 120, 212001 (2018)

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

# Femtoscopy

# Femtoscopy method in nuclear collisions

## ⇒ Application to Small Systems

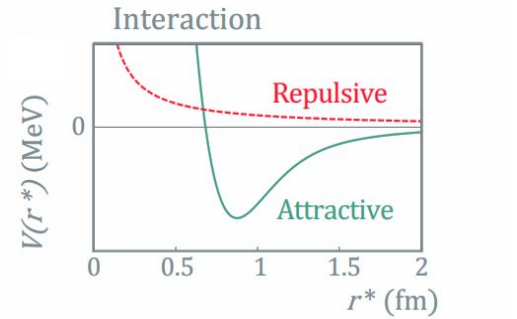



Based on the **measurement of the correlation function** of two particles emitted in the collision

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

# Theoretical correlation function

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




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

# Theoretical correlation function

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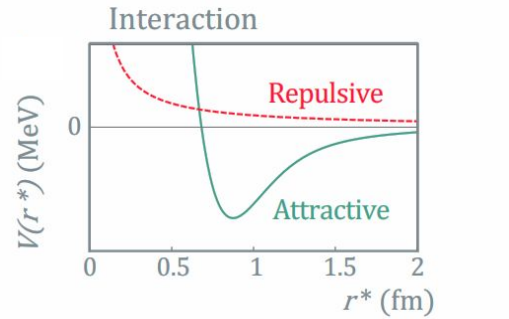


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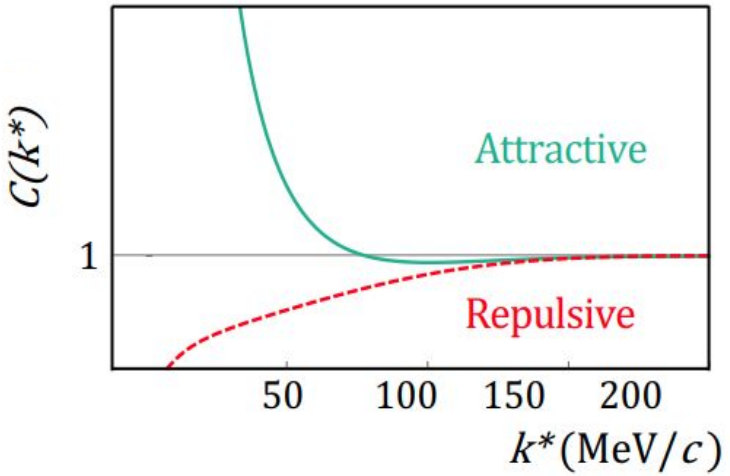

# Femtoscopy for hadron-hadron interactions: **What can we do this tool?**

**Test of potentials and first principle calculations** and…

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

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

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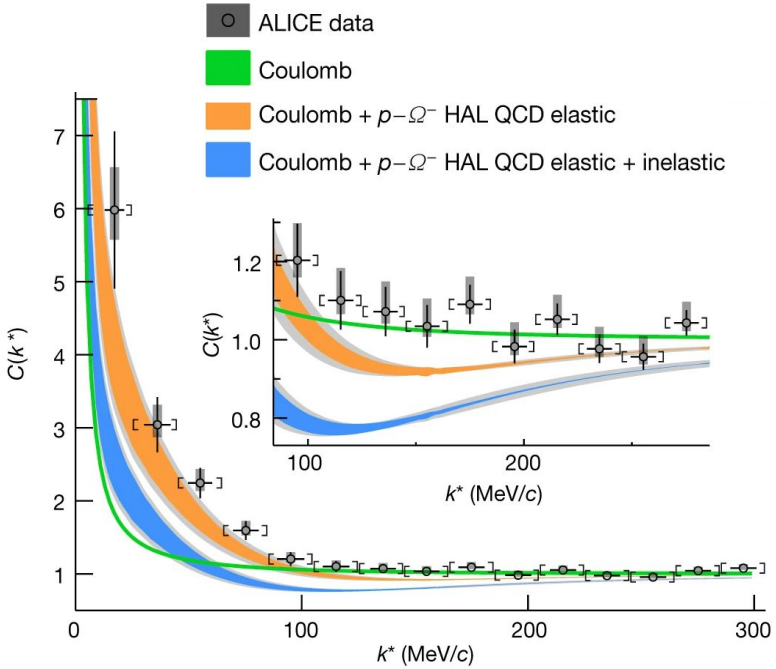
**⇒ p–Ω⁻ correlation function**
by ALICE Collaboration in pp collisions

*Nature* **588**, 232 (2020)




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

# The case of the antiKaon-Nucleon interaction

# The case of the antiKaon-Nucleon interaction

**antiKaon-Nucleon interaction:** 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**


Theoretical description should:

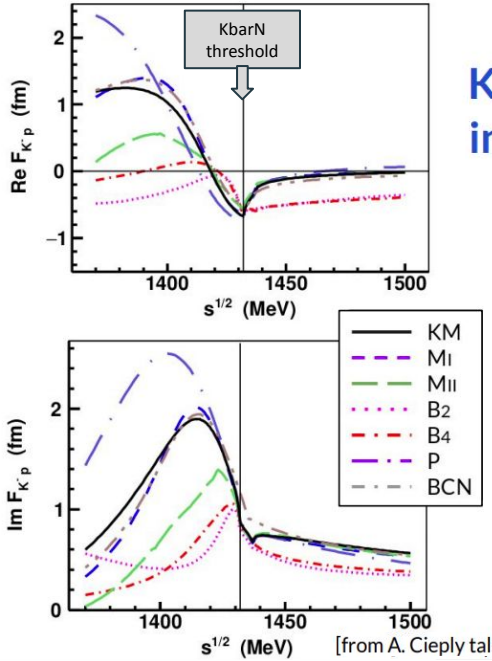
- make predictions below threshold
- **describe (the nature of) the Λ(1405)**

**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

# Knowledge on antiKaon-Nucleon interaction

**$K^-p$ interaction from experiments:** ⇒ Kaonic hydrogen
⇒ Femtoscopy
⇒ Scattering experiments




## $K^-p$ scattering amplitude in Chiral calculations

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

Murcia ($M_I$ , $M_{II}$ )
Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202

Bonn ($B_2$ , $B_4$ )
M. Mai, U.-G. Meißner - Eur. Phys. J. A 51 (2015) 30

Prague (P)
A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115

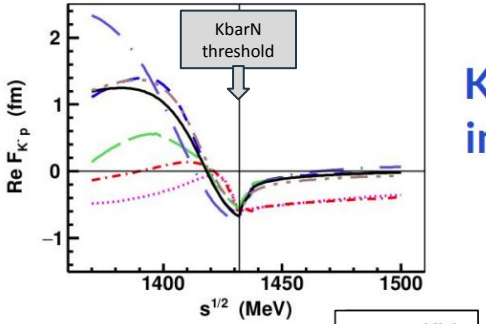
Barcelona (BCN)
A. Feijoo, V. Magas, À. Ramos, Phys. Rev. C 99 (2019) 035211

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

# Knowledge on antiKaon-Nucleon interaction

**$K^-p$ interaction from experiments:** ⇒ Kaonic hydrogen
⇒ Femtoscopy
⇒ Scattering experiments

**$K^-n$ interaction from experiments:**

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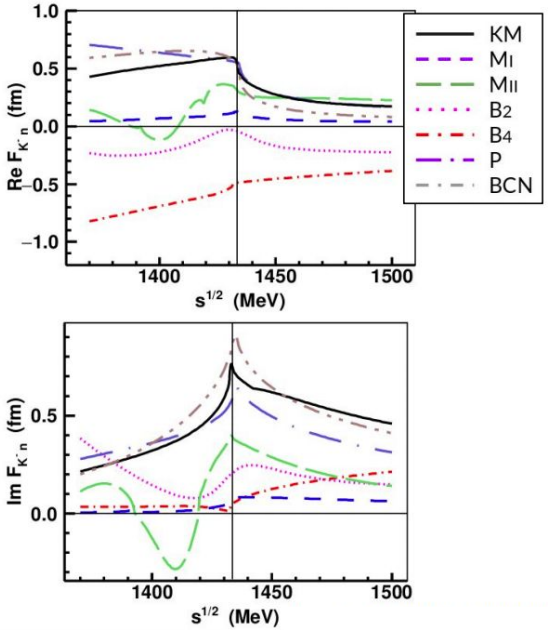
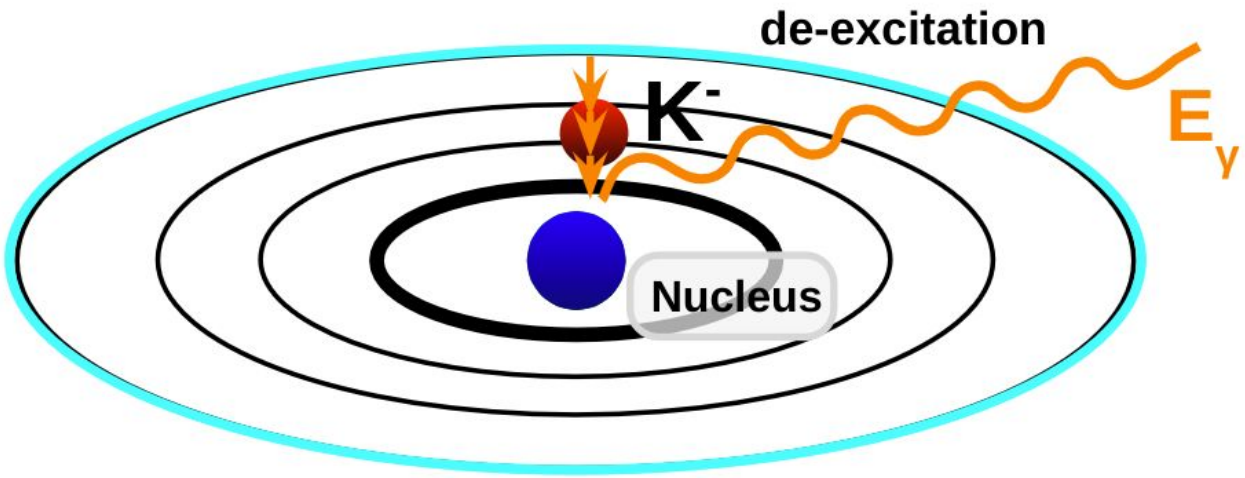



[from A. Cieply talk at MENU2019 conference, A. Cieply et al. Nucl.Phys. A954 (2016) 17-40]

# SIDDHARTA2: Kaonic deuterium



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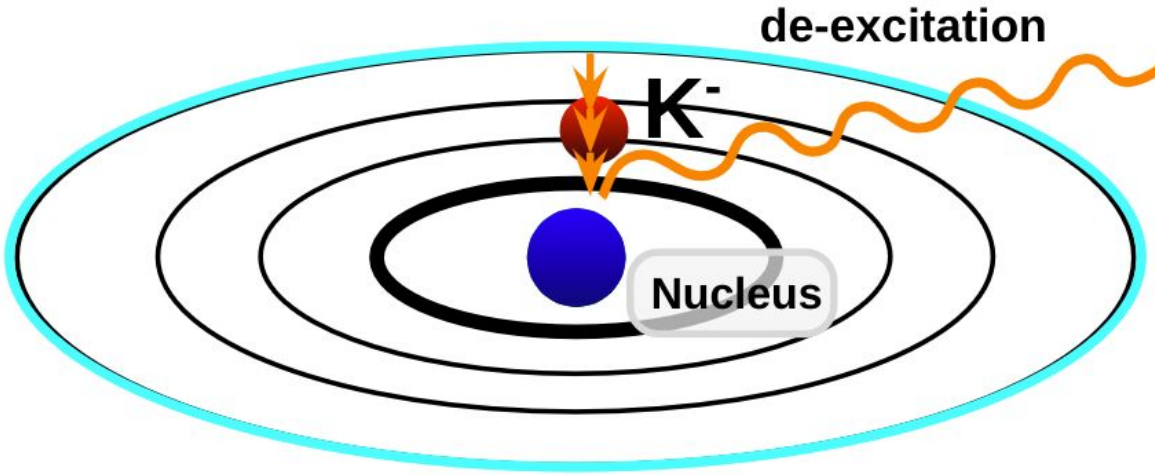


⇒ E.M. value modified by strong interaction

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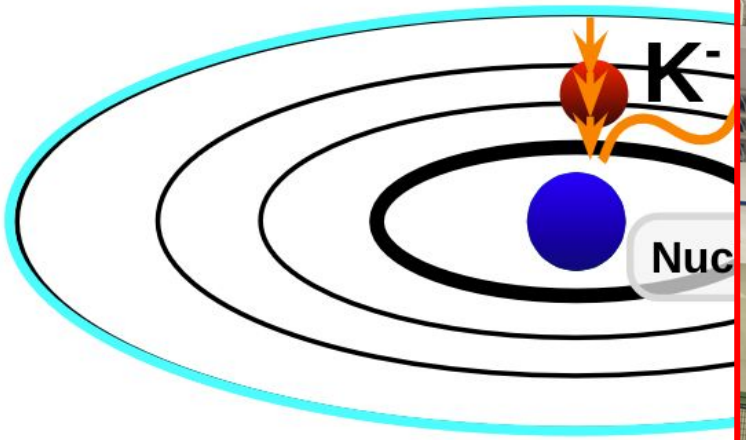



⇒ DAΦNE $e^+e^-$ collider provides a beam of low momentum (~120 MeV/c) kaons

⇒ SIDDHARTA2 setup: Deuterium target surrounded by SDD detectors

# 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, test coalesence picture)

**THANK YOU VERY MUCH!**