Updated experimental insight into the strong interaction between antikaons and nucleons

Otón Vázquez Doce (INFN Frascati)
HYP-2022, July 1st, 2022

FEMTO-STRONG
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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

KbarN interaction

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

The presence of the strange quark has dramatic consequences:
KN and KbarN interactions are very different and **with very different cross sections**

- excitation of resonances below threshold
- strong coupled channel dynamics
- absorption from one or more nucleons
- attractiveness in KbarN gives rise to bound states

Λ(1405) is an "old object" not fitting in the standard 3-quark picture

Theoretical framework

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Theoretical approaches:

- meson exchange
- phenomenological
- chiral SU(3) dynamical
- Lattice QCD (?)

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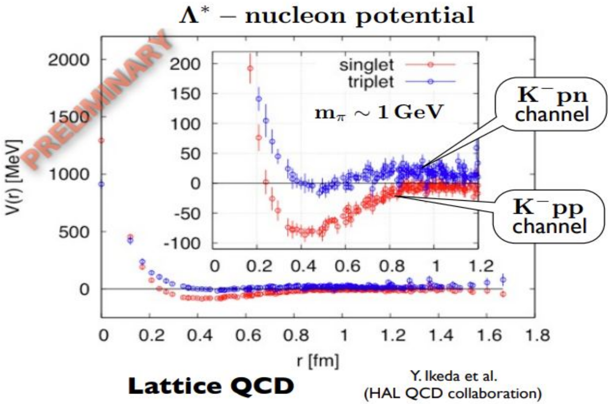
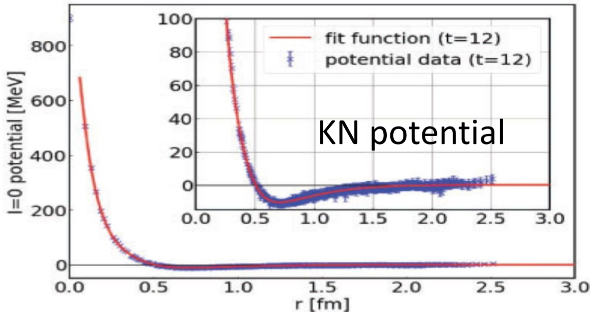
⇒ "Lattice QCD Evidence that the Λ(1405) Resonance is an Antikaon-Nucleon Molecule", Hall et al., PRL 114, 132002 (2015)





Murakami, Akahoshi, Aoki
PTEP 2020, 093B03 (2020)

⇒ MB systems with annihilation available K. Murakami arXiv:2111.15563v1 [hep-lat]

Theoretical framework

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Theoretical approaches:

- meson exchange
- phenomenological
- chiral SU(3) dynamical
- Lattice QCD (?)

Data is crucial to test (+feed) this approaches.

Theoretical frame

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

A. Feijoo @ HYP2022

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

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!

Theoretical approaches:

- meson exchange
- phenomenological
- chiral SU(3) dynamical
- Lattice QCD (?)

Data is crucial to test (+feed)

Data fitting by Chiral SU(3).

- Going to NLO (N^2LO?), s+p waves ⇒ more parameters to be fixed (by data)
- Adding **new data** helps to improve the model
- Adding **more precise data** helps to improve the model
- Adding **data at different energies** helps to improve the model

Available experimental data

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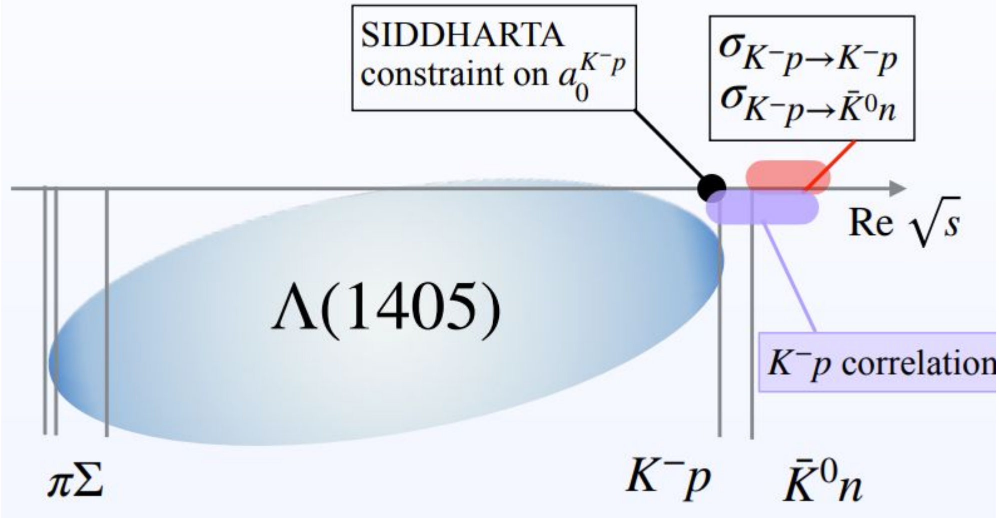
Y. Kamiya @ HYP2022

Antikaonic atoms

Scattering data



- **B and Γ of kaonic nuclear states**
- **Single vs Multi-nucleonic absorption rates**
- **K-pp three body femtoscopy**

Femtoscopy

Scattering amplitudes below threshold

Threshold branching ratios

Λ(1405) mass shape in different channels

Available experimental data

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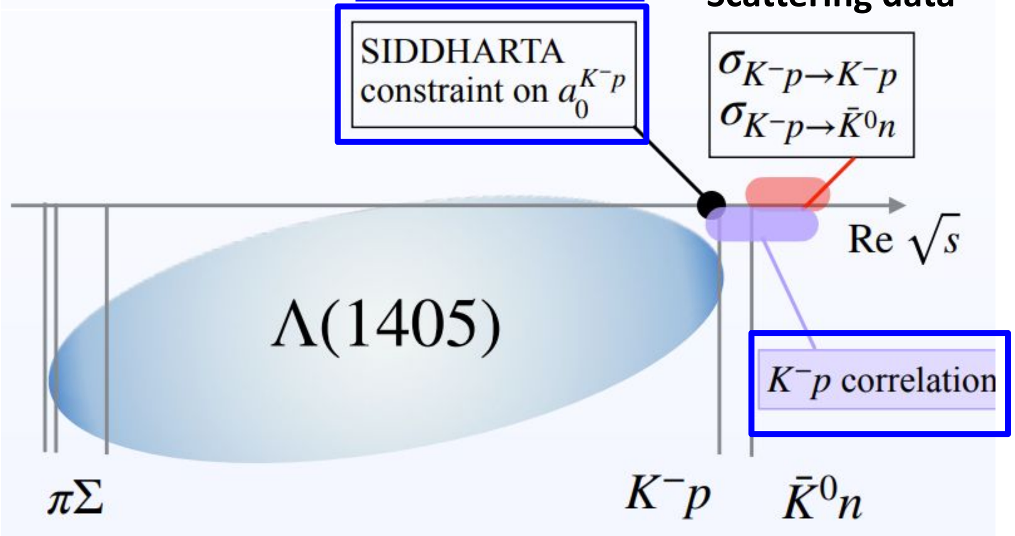

Femtoscopy

- B and Γ of kaonic nuclear states
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- K-pp three body femtoscopy

⇧ Scattering amplitudes below threshold

⇧ Threshold branching ratios

⇧ Λ(1405) mass shape in different channels

antikaonic hydrogen: SIDDHARTA

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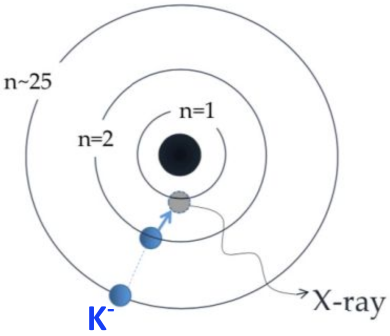

2p → 1s
K_α transition

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.

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

SIDDHARTA Coll., PLB 704 (2011) 113

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

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

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

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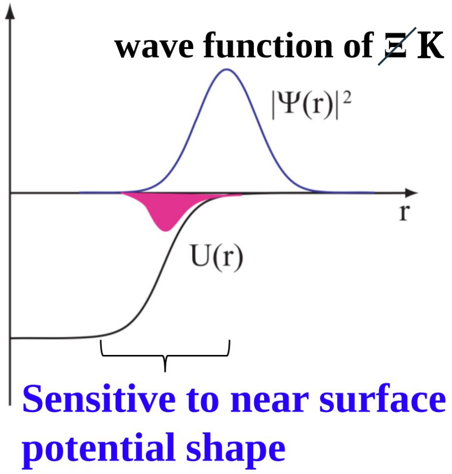
KbarN at threshold and low momentum

SIDDHARTA: antiKaonic Hydrogen



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

[T. O. Yamamoto @ HYP2022]

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

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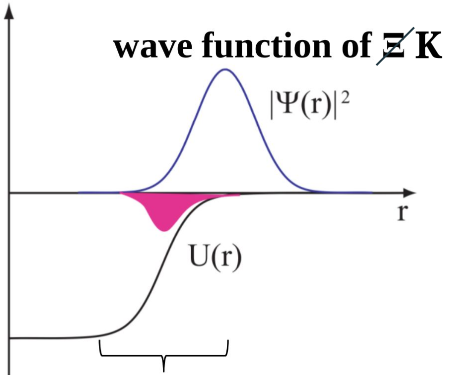
KbarN at threshold and low momentum

SIDDHARTA: antiKaonic Hydrogen



Sensitive to near surface potential shape

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

T. O. Yamamoto @ HYP2022

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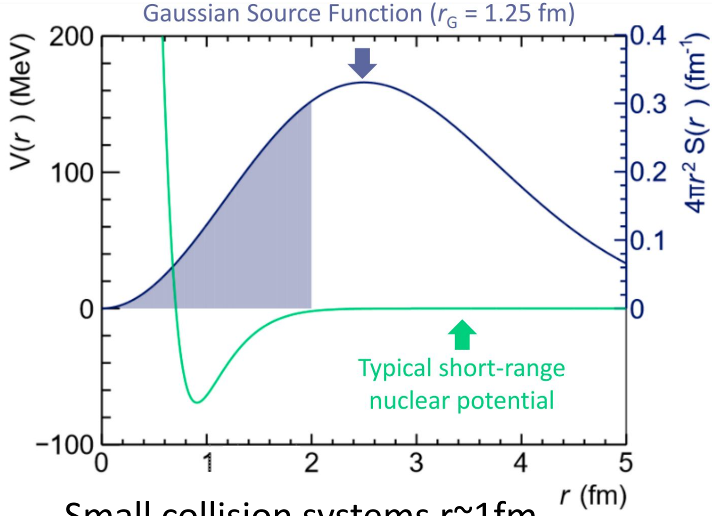
ALICE: K⁻p femtoscopy



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)

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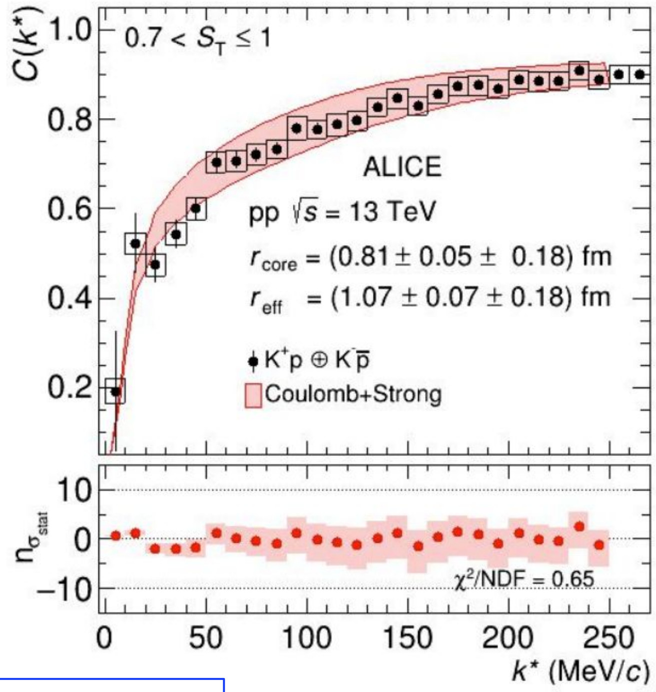
KbarN Femtoscopy with ALICE

An crucial PLUS: $K^{+}p$ interaction for crosscheck and **experimental determination of the radius**



R. Lea @ HYP2022

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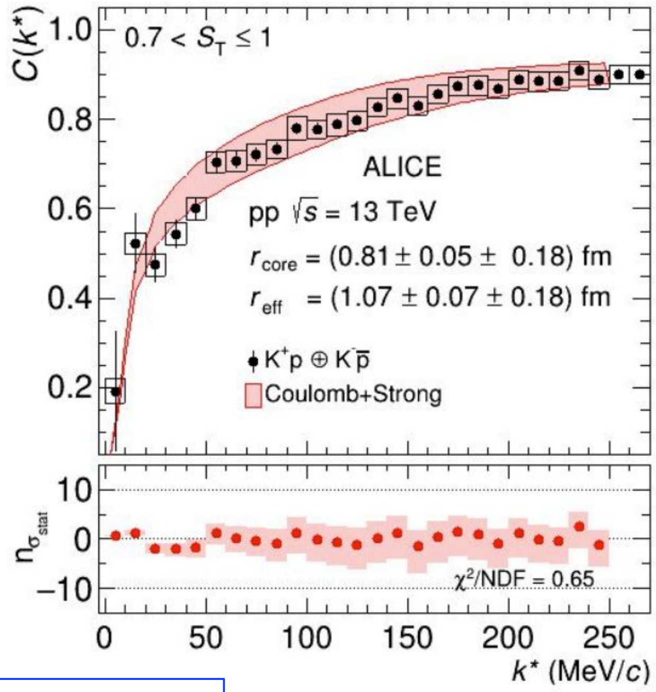

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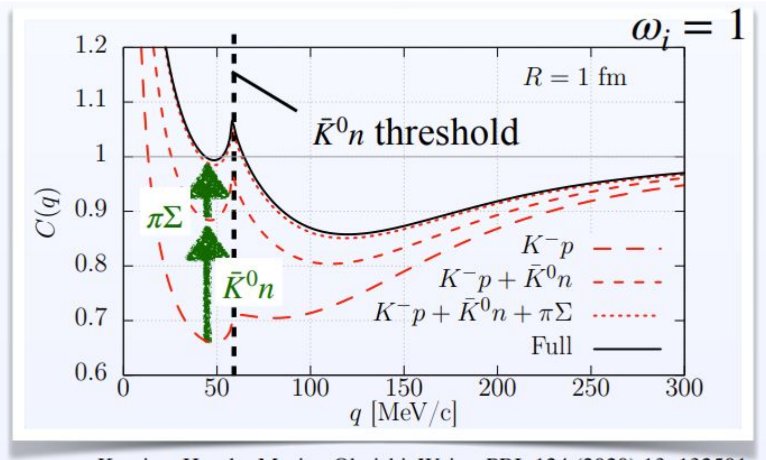
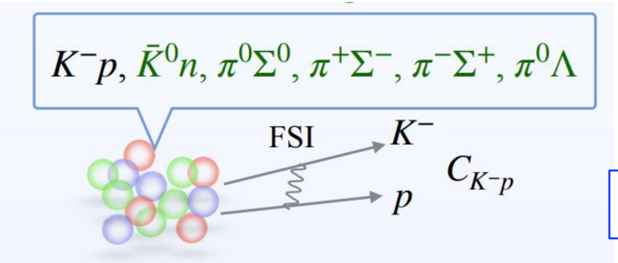
Effects of coupled channels enhanced by small source

- less important for large sources of HIC



Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501



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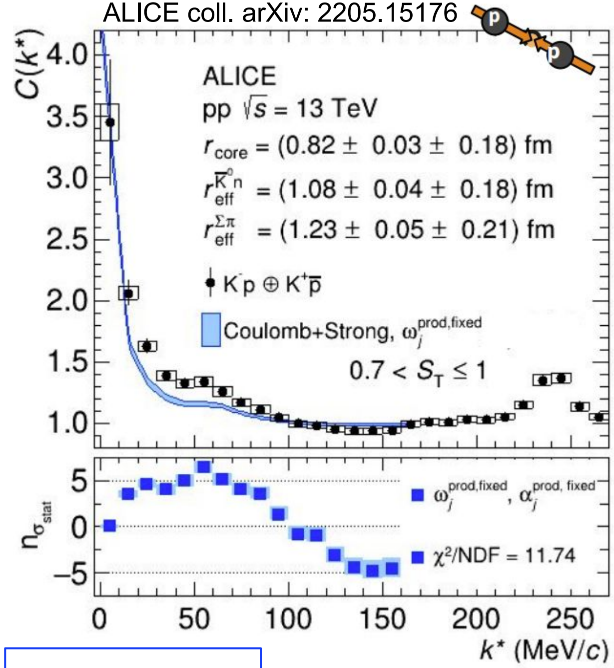
KbarN Femtoscopy with ALICE in pp collisions

ALICE coll. arXiv: 2205.15176



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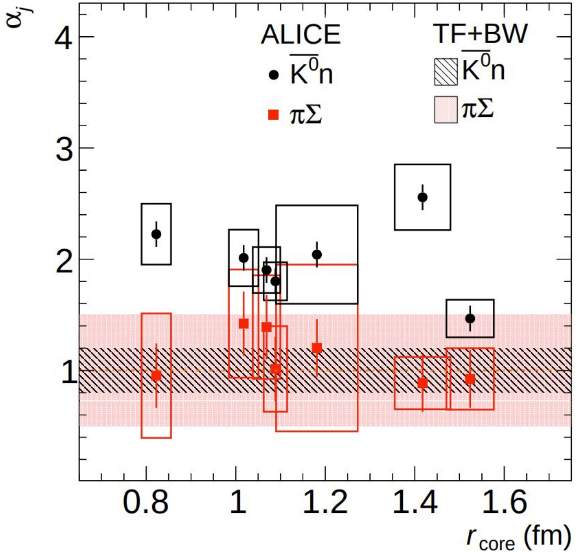
Small systems: pp collisions r~1fm

Coupled channels in the correlation function: production yields (thermal model) + production p_T spectrum (blast-wave) + pair kinematics

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



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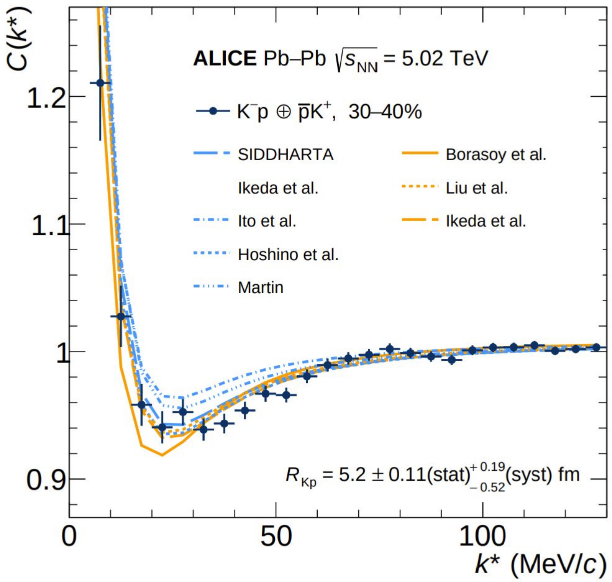
KbarN Femtoscopy with ALICE in PbPb collisions

ALICE Coll., PLB 822 (2021) 136708



Large systems (HIC): PbPb collisions, up to r~9fm

Strength of coupled channels significantly reduced

- Cyan line: Kyoto model with SIDDHARTA constraint
- Orange line: Fit to the scattering parameters (better χ^2)

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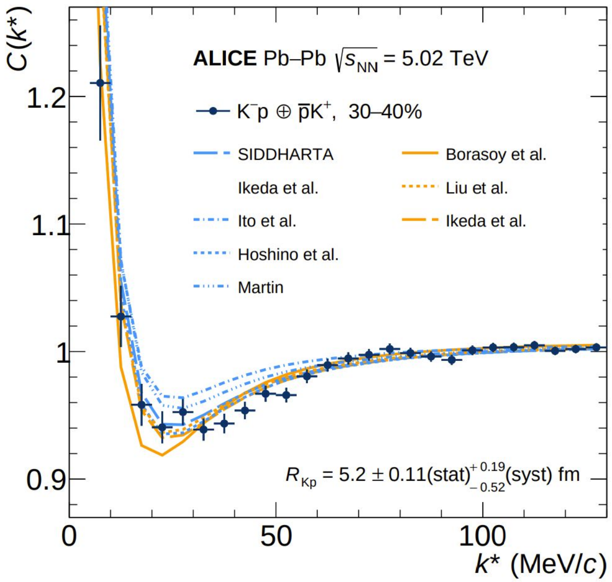
ALICE Coll., PLB 822 (2021) 136708



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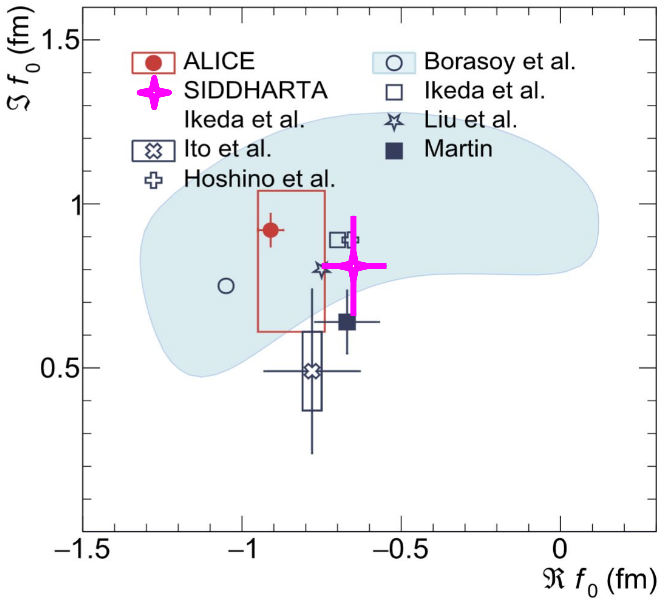

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Accessing KbarN I=1 interaction

Full isospin dependence needs K^-d interaction measurements:

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

A experimental constraint exists from pp→d K^0bar K^+ (COSY)
K^-d scatt. length |Re|≤1.3 fm, Im≤1.3 fm

V. Kleber et al., PRL 91 (2003) 172304
A. Sibirtsev et al PLB 601 (2004) 132

SIDDHARTA-2 with new experimental setup

→measurement of **antikaonic deuterium**

→very challenging! low yield of signal.

J. Zmeskal @ HYP2022

The interpretation of the SIDDHARTA-2 results will require some effort too:

- Deser type formulae with model dependence
- Better test potentials by **full three body calculations**

T. Hyodo@ HYP2022

Potential	$\Delta E - i\Gamma/2$ [eV]
$V^{1,\mathrm{SIDD}}_{\bar{K}N\text{-}\pi\Sigma}$	$767 - 464i$ [1]
$V^{2,\mathrm{SIDD}}_{\bar{K}N\text{-}\pi\Sigma}$	$782 - 469i$ [1]
$V^{\mathrm{chiral}}_{\bar{K}N\text{-}\pi\Sigma\text{-}\pi\Lambda}$	$835 - 502i$ [1]
Kyoto $\bar{K}N$	$670 - 508i$ [2]

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Accessing KbarN I=1 interaction with ALICE

- $K_S^0 p$ correlation

$$|K_S^0 p\rangle = [\,|\bar{K}^0 p\rangle - |K^0 p\rangle]/\sqrt{2}$$

$$C_{K_S^0 p} = [C_{\bar{K}^0 p} + C_{K^0 p}]/2$$

$\bar{K}N, I = 1$

- $I = 1$ component only
- Chiral amplitude

  Ikeda, Hyodo, Weise, NPA881 (2012)
- Effective potential

  Miyahara, Hyodo, Weise, PRC 98 (2018)

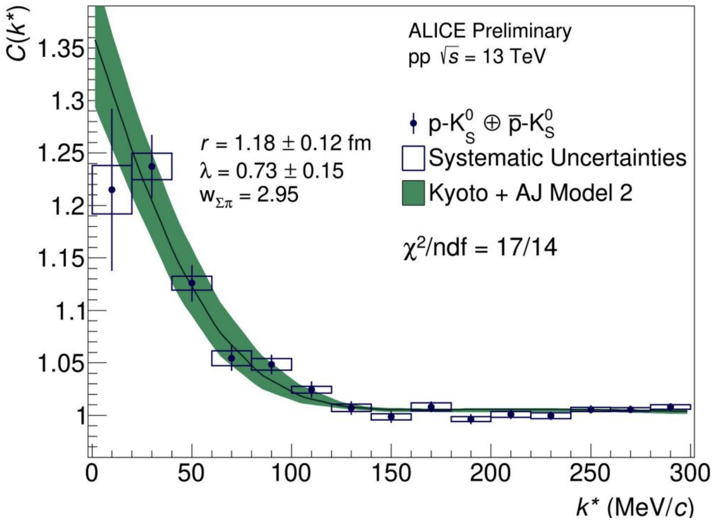
$KN, I = 0, 1$

- Well determined with scat. exp.
- Chiral amplitude

  K. Aoki and D. Jido, PTEP (2019)
- Effective potential

  Constructed from chiral amp.

⇒ Access to I=1 component of the KbarN interaction



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Accessing KbarN I=1 interaction with ALICE

- $K^0_S p$ correction

$$|K^0_S p\rangle = [|\bar{K}^0 p\rangle - |K^0 p\rangle]/\sqrt{2}$$

$$C_{K^0_S p} = [C_{\bar{K}^0 p} + C_{K^0 p}]/2$$

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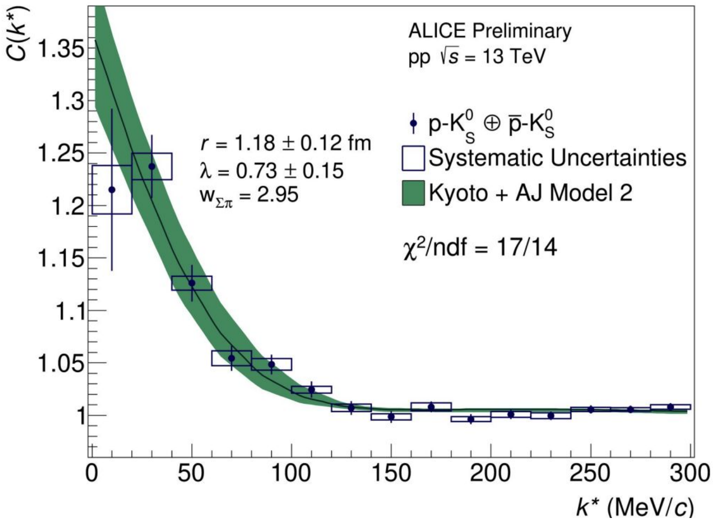

On the horizon by ALICE: K$^+$d, K$^-$d femtoscopy

For femtoscopy with deuterons (pd) by ALICE in small systems see B. Singh @ HYP2022 and by STAR in HIC: H. Zbroszczyk @ HYP2022

Kaonic nuclei

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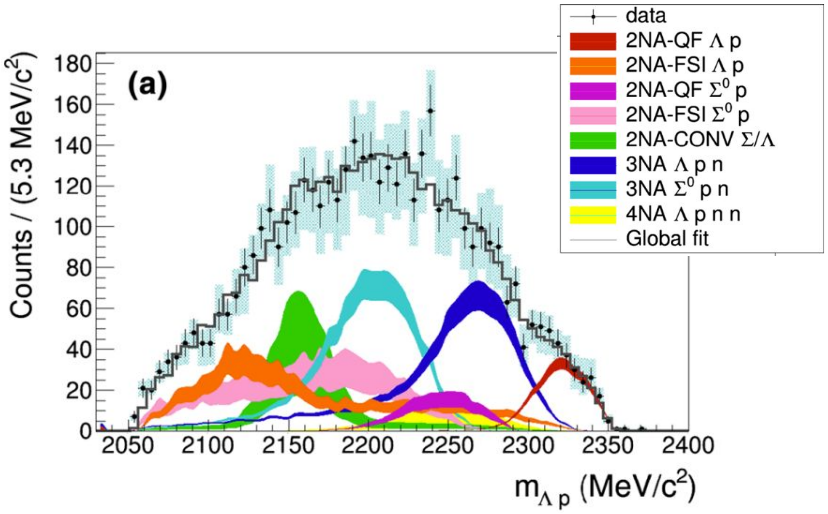
AMADEUS: K^- absorption in ^{4}He and ^{12}C



$K^- + A \rightarrow Yp + A'$

Multi-nucleon absorption processes dominate

AMADEUS Coll. PLB 758 (2016) 134
AMADEUS Coll. PLB 782 (2018) 339
AMADEUS Coll. FBS 62 (2021) 7.

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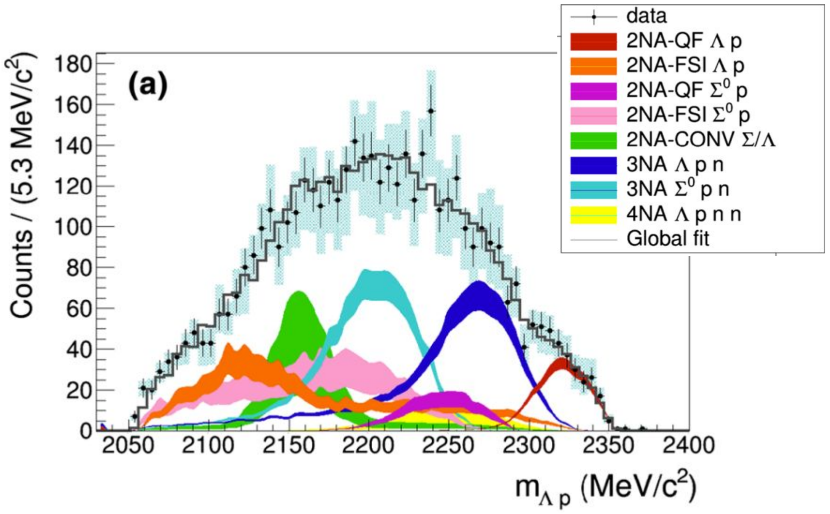
AMADEUS: K$^-$ absorption in ^{4}He and ^{12}C



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AMADEUS Coll. PLB 758 (2016) 134
AMADEUS Coll. PLB 782 (2018) 339
AMADEUS Coll. FBS 62 (2021) 7.

K. Piscicchial @ HYP2022

Below threshold (-33 MeV)

$K^-n \rightarrow \pi^-\Lambda$ (I=1 non resonant)

$$|A_{K^-n\rightarrow\Lambda\pi^-}| = (0.334 \pm 0.018\,\text{stat}^{+0.034}_{-0.058}\text{syst})\ \text{fm}.$$

AMADEUS Coll., PLB 782 (2018) 339-345]

Avobe threshold

$K^-p \rightarrow \pi^0\Lambda$, $\pi^0\Sigma^0$ cross sections (preliminary)

- $\sigma_{K^-p\rightarrow\Sigma^0\pi^0} = 42.8 \pm 1.5(stat.)^{+2.4}_{-2.0}(syst.)\ \text{mb}$
- $\sigma_{K^-p\rightarrow\Lambda\pi^0} = 31.0 \pm 0.5(stat.)^{+1.2}_{-1.2}(syst.)\ \text{mb}\,,$

J-PARC E15

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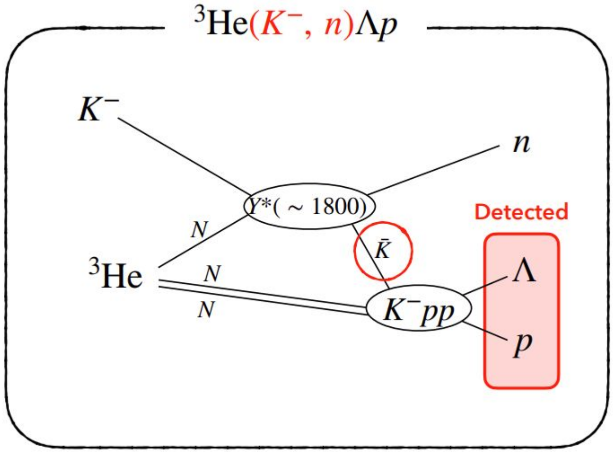
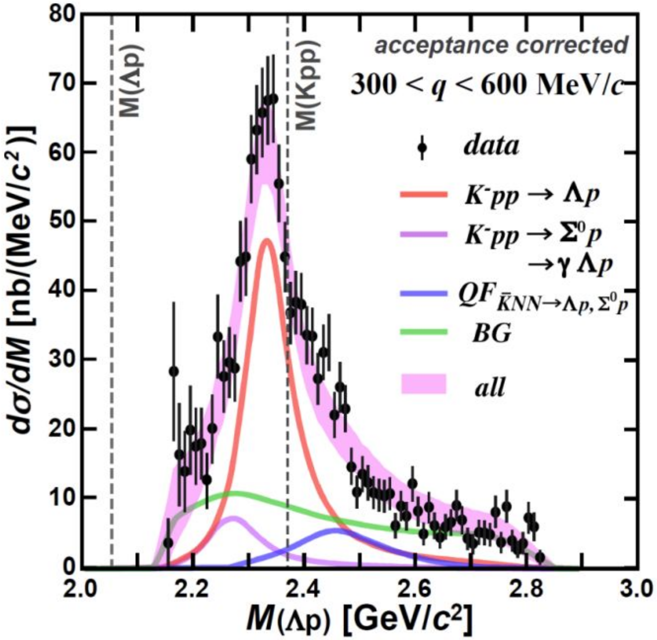
In-flight ^{3}**He(K^{-} ,n)Λp** reaction @ 1.0 GeV/c



$$B_K = 42 \pm 3(\text{stat.})^{+3}_{-4}(\text{syst.})\ \text{MeV}$$

$$\Gamma_K = 100 \pm 7(\text{stat.})^{+19}_{-9}(\text{syst.})\ \text{MeV}$$

J-PARC E15 Coll. PRC 102, 044002 (2020)



Similar interpretation by Sekihara, Oset, Ramos

JPS Conf. Proc. 26, 023009 (2019)

PTEP 2016, 12, 123D03

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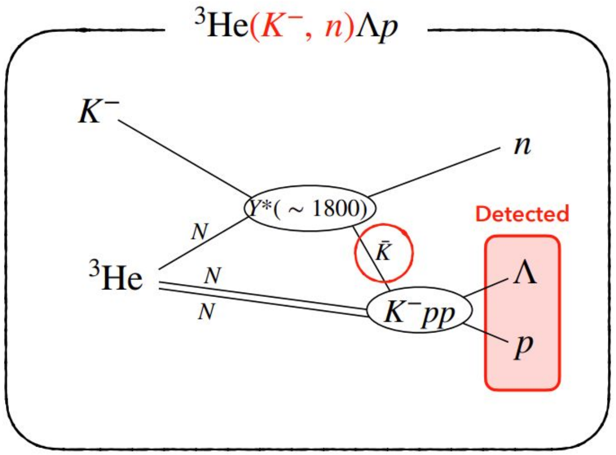
J-PARC E15

In-flight ^{3}**He(K$^-$,n)Λp** reaction @ 1.0 GeV/c



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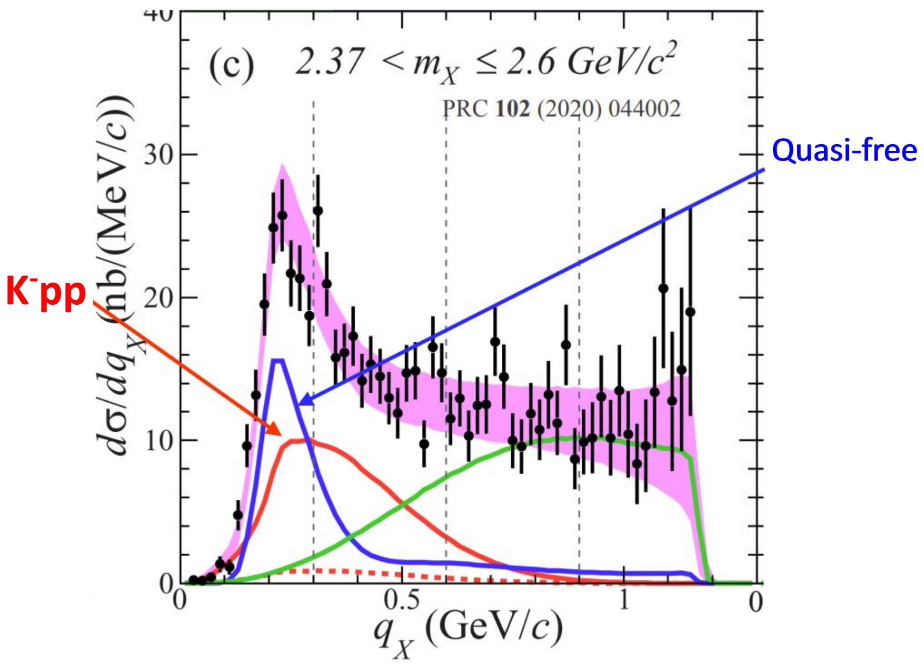
J-PARC E15 Coll. PRC 102, 044002 (2020)



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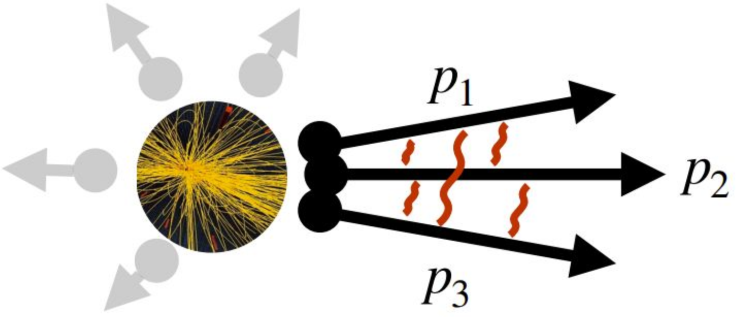
3-Body femtoscopy



L. Serksnyte@ HYP2022

Three-particle correlation function:

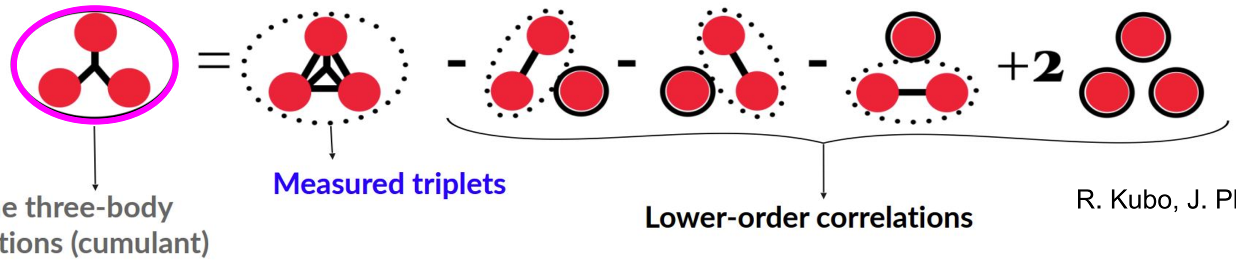
$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1)\, P(\mathbf{p}_2)\, P(\mathbf{p}_3)} = \mathcal{N} \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

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

<u>Isolation</u> <u>of the</u> **<u>three-body effects</u>** <u>in the correlation function:</u>

$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$

2-body correlations experimentally determined



R. Kubo, J. Phys. Soc. Jpn. 17, 1100 (1962)

ppK⁻ cumulant

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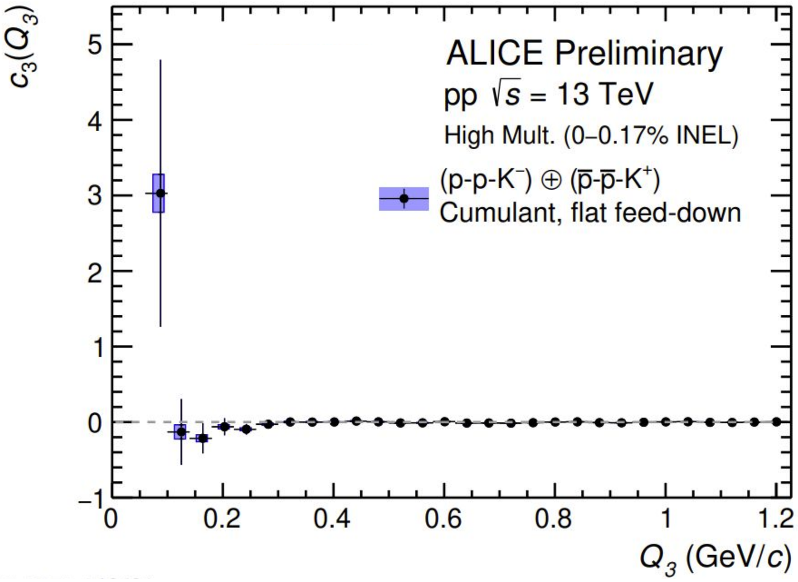

⇒ **ppK⁻ cumulant** is **compatible with zero.**

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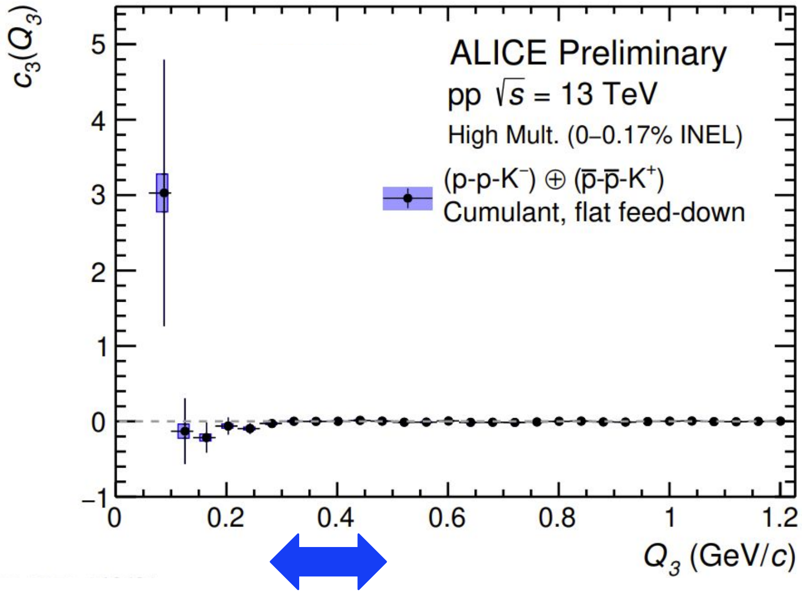
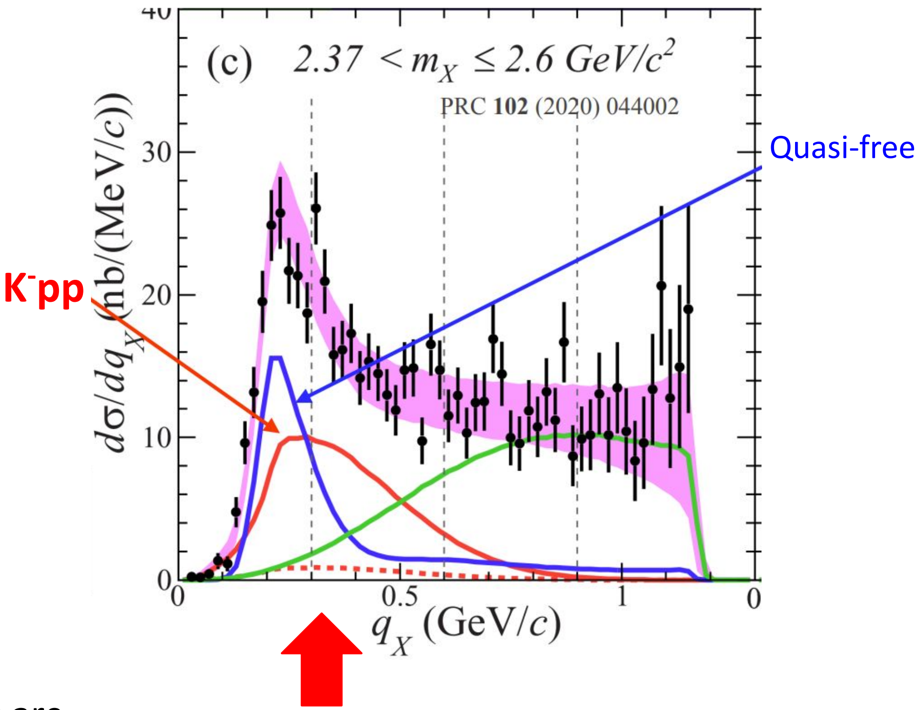
ppK⁻ cumulant





⇒ **ppK⁻ cumulant** is **compatible with zero.**

⇒ The measurement suggest that **three-body effects** are **not relevant for the description of the K⁻pp system**

p-p-p cumulant

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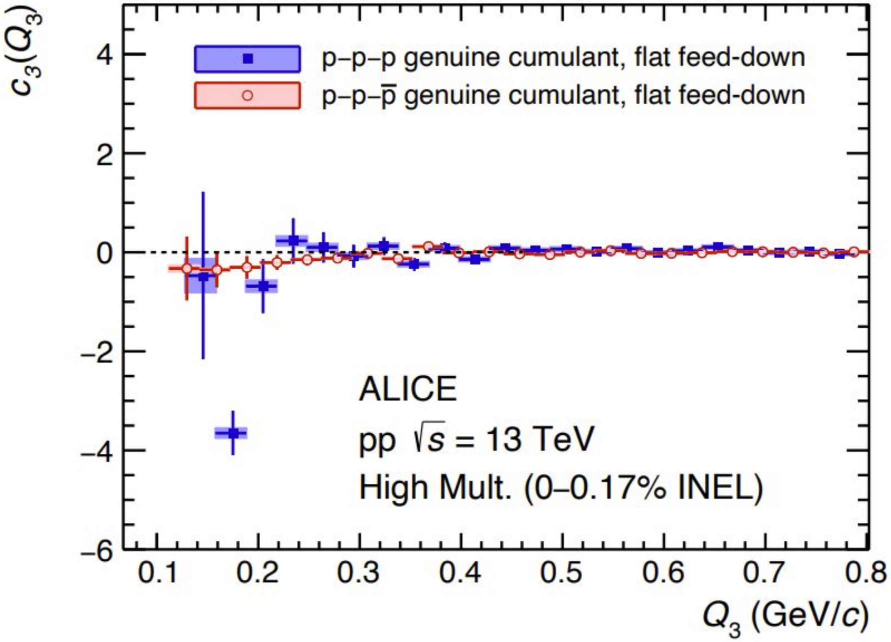

Statistical significance: $n_\sigma = 6.7$ for $Q_3 < 0.4$ GeV/c
Origin of the 3-body effect?

- Pauli blocking at the three-particle level
- FSI

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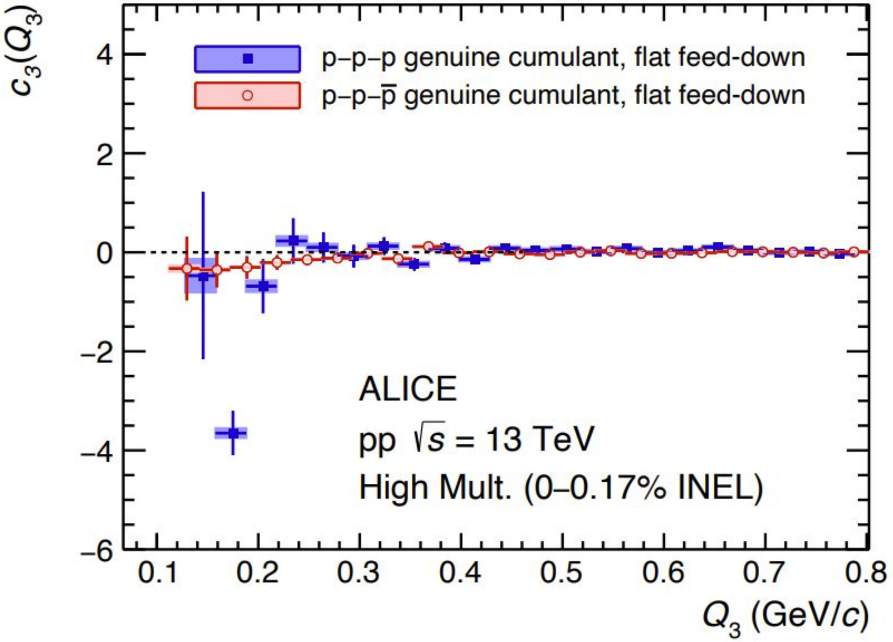
p-p-p cumulant



N. Shevchenko@ HYP2022

$K^-ppn - \bar{K}^0nnp$ system:

$\bar{K}NNN$ with $I^{(4)} = 0, S^{(4)} = 1/2, L^{(4)} = 0$

	$V_{NN}^{\mathrm{TSA-A}}$		$V_{NN}^{\mathrm{TSA-B}}$		V_{NN}^{TSN}	
	B	Γ	B	Γ	B	Γ
$V_{\bar{K}N}^{1,\mathrm{SIDD}}$	52.0	50.4	50.3	49.6	51.2	50.8
$V_{\bar{K}N}^{2,\mathrm{SIDD}}$	47.0	39.6	46.4	38.2	46.4	39.9
$V_{\bar{K}N}^{\mathrm{Chiral}}$	32.6	39.7	34.5	50.9	30.5	42.8

Statistical significance: n_σ = 6.7 for Q_3 < 0.4 GeV/c
Origin of the 3-body effect?

- Pauli blocking at the three-particle level
- FSI

⇒ relevant for the description of the K^-NNN system?

Data is coming

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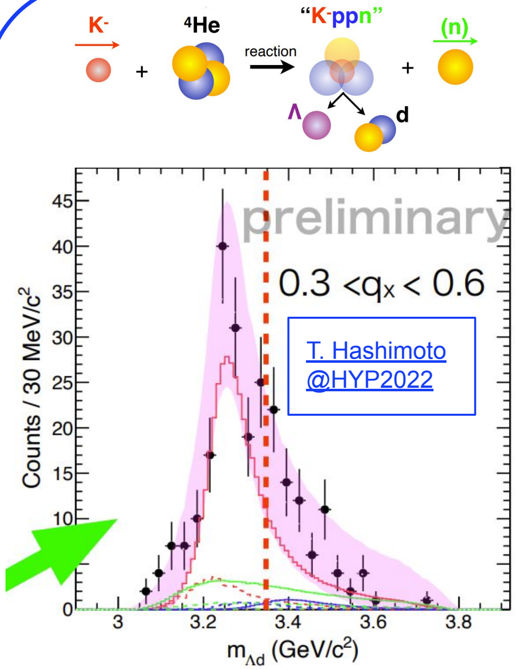
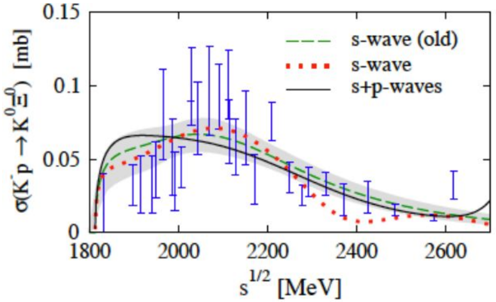


T. Hashimoto @HYP2022

- Extended J-PARC program for kaonic nuclei studies

T. Yamaga@ HYP2022

Calculations in p-wave with fitting higher mass channels



A. Feijoo @ HYP2022

⇒ J-Lab proposal for the secondary K_L beam

GLUEX:

Λ(1405) photoproduction

$$\gamma p \to K^+ \Lambda^*$$

N. Wickramaarachchi @ HYP2022

New approaches proposed:

fusion reaction $K^- d \to p\Sigma^-$

⇒ can deliver information on the lower pole of Λ(1405)

E. Oset @ HYP2022

Outlook

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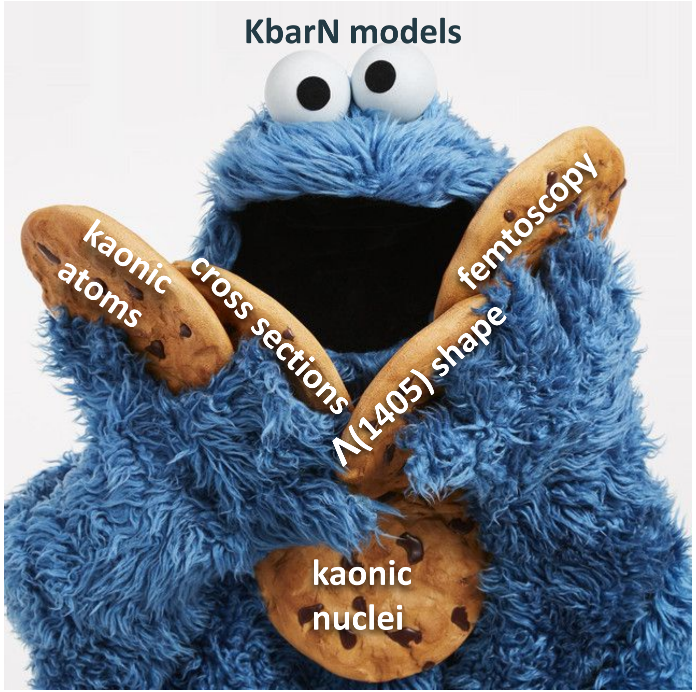
We are collecting new data (e.g. ALICE run 3 with ≥ x100 stats and improved tracking, SIDDHARTA2 running)
In the near future:
- **new experimental apparatus**
- **new facilities**

In the KbarN field a boost similar to the precise measurement of kaonic hydrogen is expected

On the search for a description of the KbarN interaction that can accommodate all the data from above to below threshold



you really need to eat ALL the cookies!

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K$^-$n, K$^-$d experimental constraints

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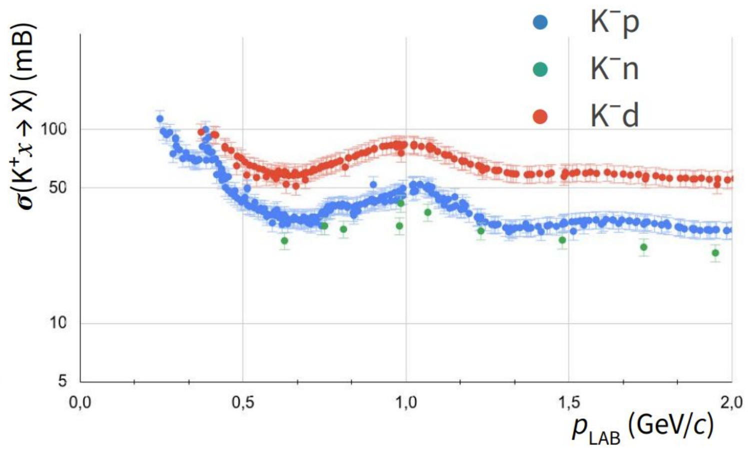
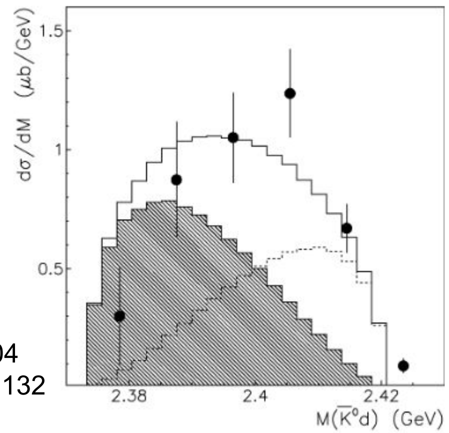
- K$^-$n, K$^-$d scattering data



- COSY at Jülich:
  pp→d K^{0}bar K$^+$



K$^-$d scattering length constraints:
|Re a|≤1.3 fm, Im a ≤1.3 fm

V. Kleber et al., PRL 91 (2003) 172304
A. Sibirtsev et al PLB 601 (2004), p. 132

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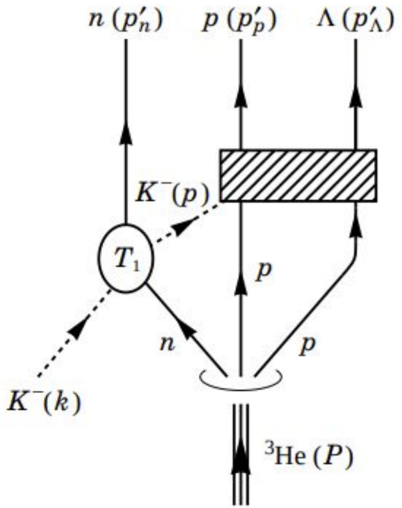
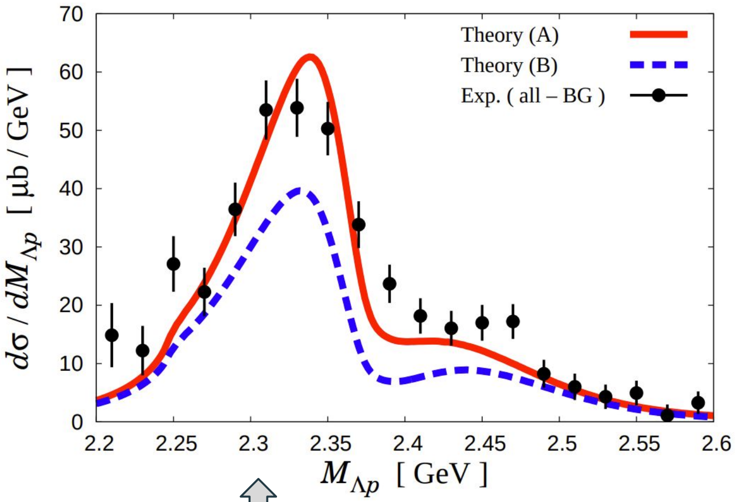
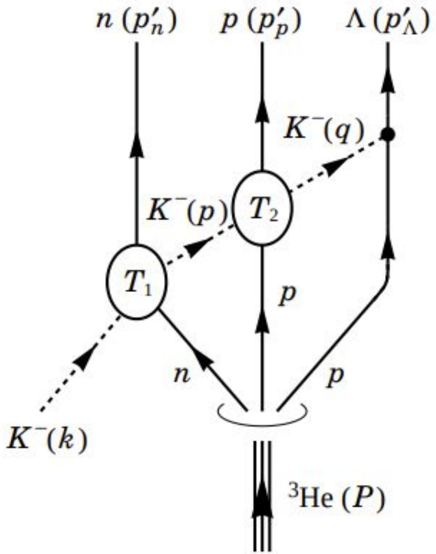
Sekihara, Oset, Ramos
JPS Conf. Proc. 26, 023009 (2019)
PTEP 2016, 12, 123D03

bound state





quasi-elastic scattering via Λ(1405) formation



SIDDHARTA-2: antikaonic deuterium

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K-atom experiments @ J-PARC K1.8BR

		K-d (E57)	$K^{-3/4}He$ (E62)
Physics		$K^{bar}N$ (I=1)	K^{bar}-nucleus potential
X-ray transition		2p → 1s	3d → 2p
	Energy	~ 8 keV	~ 6 keV
	Width	**~ 1000 eV**	**~ 2 eV**
	Yield (per stopped K-)	**~ 0.1 %** **(0.04% of liquid D2 density)**	~ 7 % (Liquid He)
X-ray detector		**Silicon Drift Detector**	**TES microcalorimeter**
	FWHM resolution	~ 150 eV	**~ 5 eV**
	Effective area	**~ 200 cm²**	~ 0.2 cm²
		High sensitivity	**High resolution**

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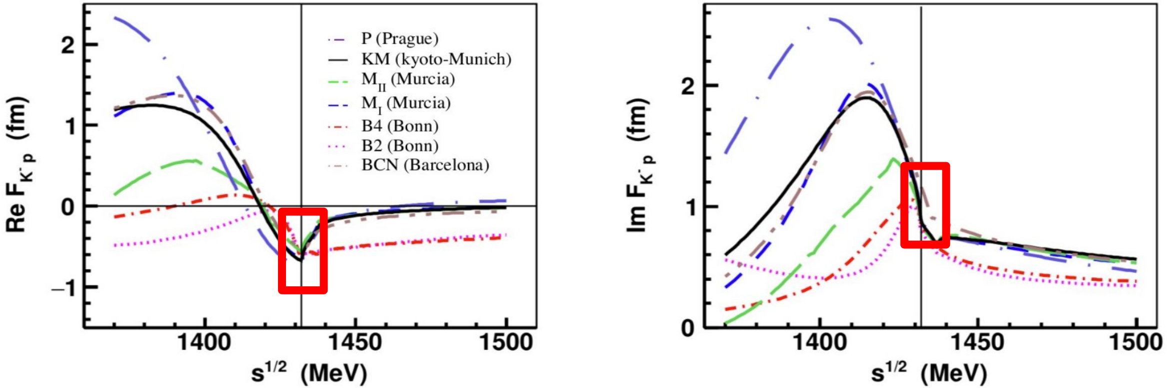
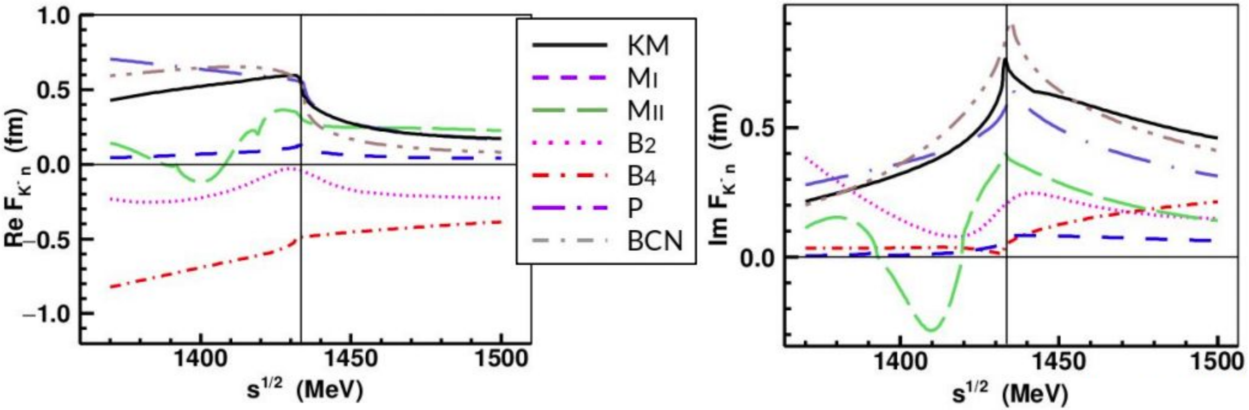
antikaonic hydrogen: SIDDHARTA



A. Cieply, J. Hrtánková, J. Mareš, E. Friedman, A. Gal and A. Ramos, AIP Conf. Proc. 2249, no.1, 030014 (2020).

⇒ **Kaonic hydrogen SIDDHARTA constraint**



⇒ **Lack of experimental K-n constraint**

Femtoscopy

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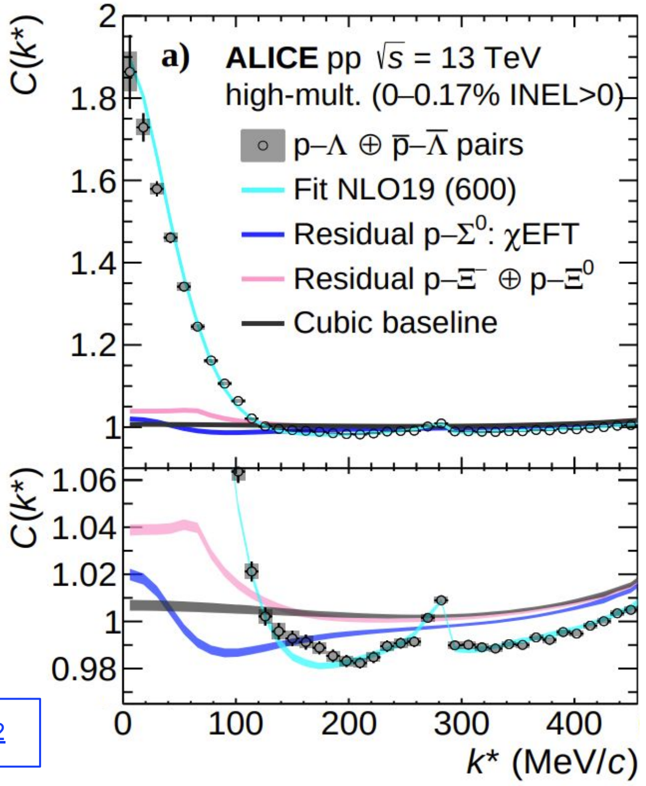
KbarN is also the ideal playground for femtoscopy studies
Connected to the main issues addressed using femtoscopy:

- **Coupled channel dynamics**
- **Strangeness in NS**
- Bound states

ALICE Coll., arXiv:2104.04427 [nucl-ex]. PLB in press.



D. Mihaylov @ HYP2022

Femtoscopy

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KbarN is also the ideal playground for femtoscopy studies
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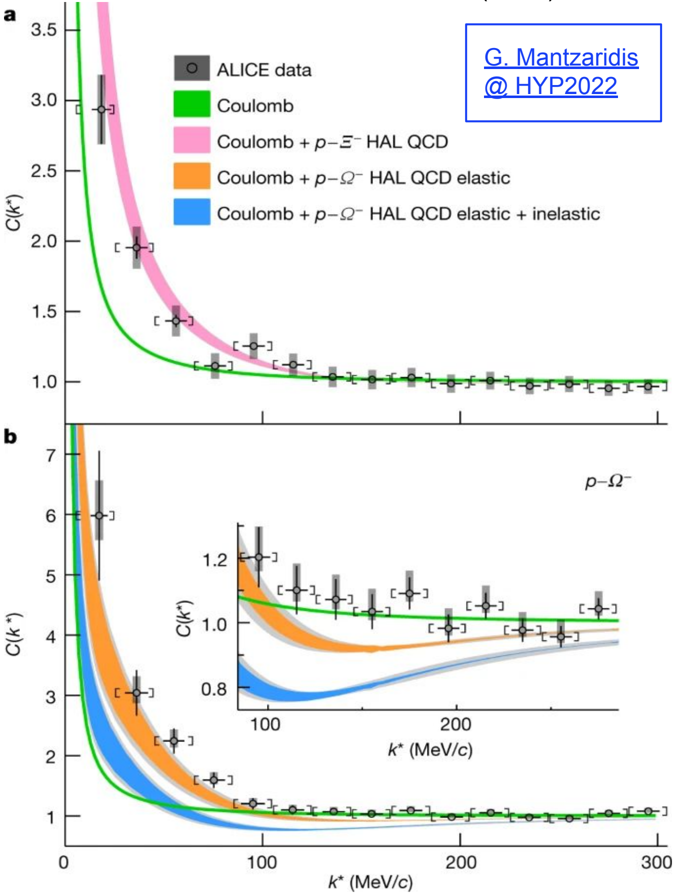
- Coupled channel dynamics
- **Strangeness in NS**
- **Bound states**

ALICE Coll., Nature 588, 232 (2020)



G. Mantzaridis @ HYP2022

Single and Multi-Nucleonic absorptions

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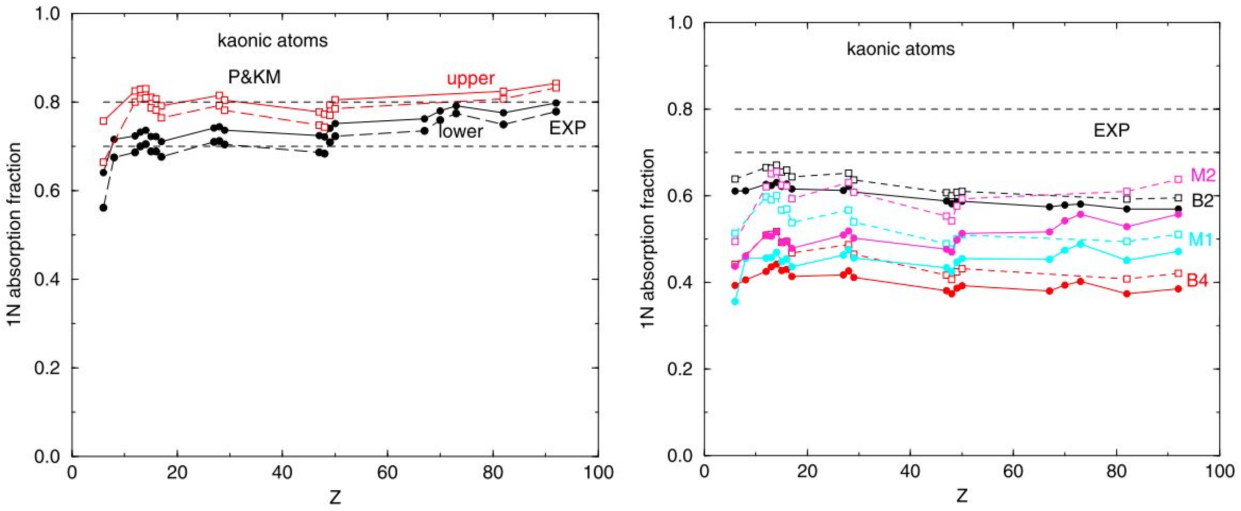
Nuclear Physics A 959 (2017) 66–82

Multinucleonic absorption contributes between 20-30% constant in Z

Main background for kaonic nuclear states

KbarN potentials need to set constraints for such 1NA, 2NA, 3NA, etc

Chiral models tested in the framework of antikaonic atoms up to high Z:



⇒ to be incorporated to few-body calculations in order to predict BE vs Width for KNN,KNNN, …

AMADEUS avobe and below threshold

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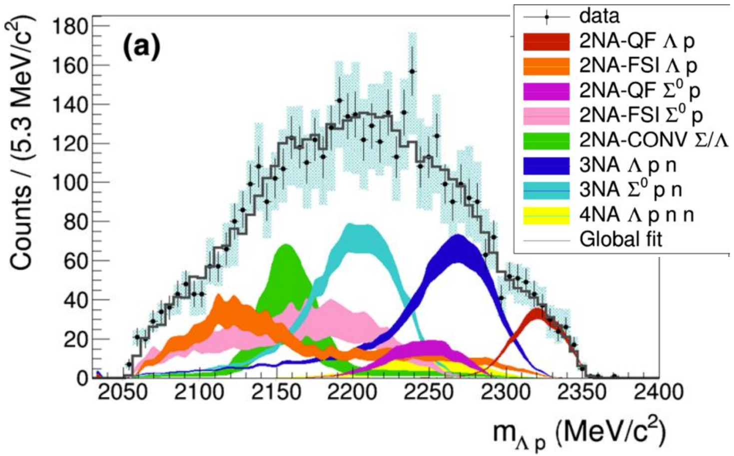
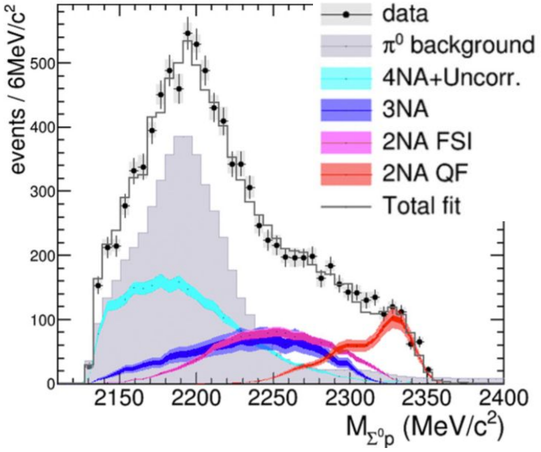


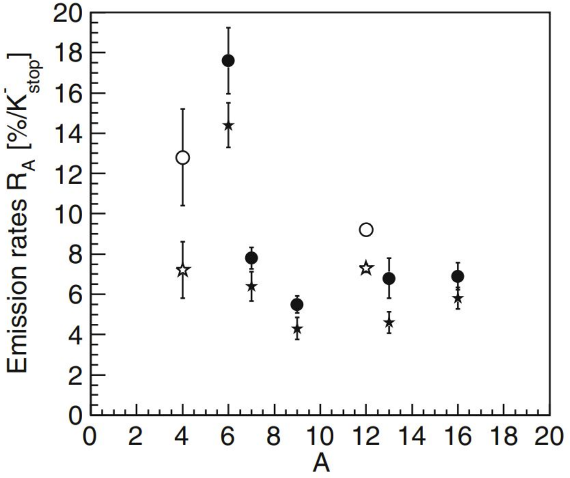


AMADEUS Coll. PLB 758 (2016) 134, PLB 782 (2018) 339, FBS 62 (2021) 7.

$$(K^-2NA \to YN) = \left(21.6 \pm 2.9(\text{stat.})^{+4.4}_{-5.6}(\text{syst.})\right)\ \%$$

FINUDA Coll. Hyperfine Interact (2012) 210:97–101

Sigma-p emission rates from A 6 to 16



emission rates of $K^-_{\text{stop}} + A \to \Sigma^+ + \pi^- + A'$, circles, and $K^-_{\text{stop}} + A \to \Sigma^- + \pi^+ + A'$,