Updated experimental insight into the $\bar{K}N$ interaction.

Otón Vázquez Doce (INFN Frascati)

EMMI Workshop: Bound states and particle interactions in the 21st century, 3-6 julio 2023, Trieste, Italy

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KbarN interaction

KN and KbarN strong interactions are very different

⇒ **Strong attractiveness of KbarN interaction**

Meson-Baryon interaction in S=-1 sector: building block of non-perturbative regime of QCD

- Strong coupled channel dynamics + Bound/resonant/molecular states
- Fundamental to accommodate/rule-out a meson condensate with strangeness content in the interior of NS

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

- Chiral SU(3) EFT ⇒ Molecular state with **two poles KbarN-Σπ**
- PDG 2020: lower pole as **new state Λ(1380)**

⇒ Nature of **Λ(1405): playground for new charm Pentaquark/molecular states**

⇒New Belle-ALICE data: "**Analogous" behaviour repeated in the S=-2 sector!**

- Ξ(1620)-Ξ(1690): coupled to Kbar-Λ, Kbar-Σ, Ξπ.

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Theoretical framework

Theoretical approaches:

- meson exchange
- phenomenological
- Chiral SU(3) EFT
- Lattice QCD

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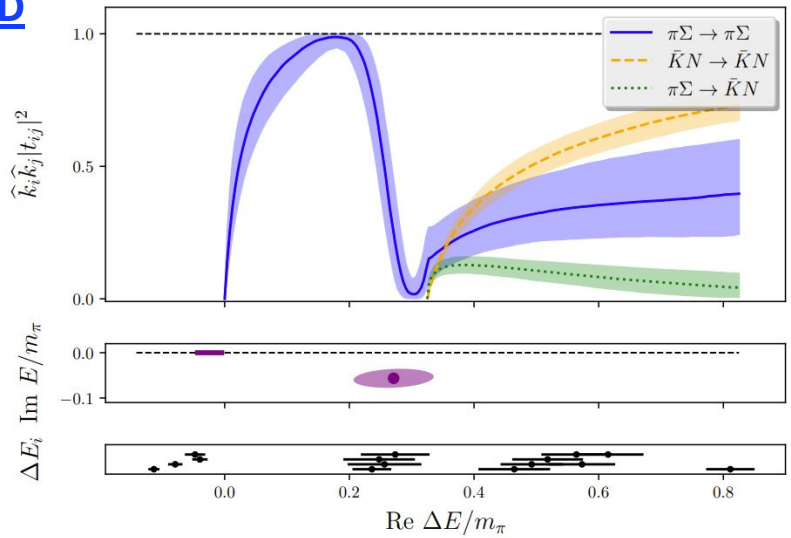
Daniel Mohler @ Meson 2023



- Scattering calculation on the lattice.
- Coupled channel analysis find 2 poles.
- Still not physical masses.

a [fm]	$T \times L^3$	m_π [MeV]	m_K [MeV]	$m_\pi L$	N_{cnfg}
0.0633(4)(6)	128×64^3	200	480	4.3	2000

- Our (preliminary) result for the poles is

$$\text{Pole II} \quad 1395(9)_{\text{stat}}(2)_{\text{model}}(16)_{\text{a}}\ \text{MeV}$$
$$\text{Pole I} \quad 1456(14)_{\text{stat}}(2)_{\text{model}}(16)_{\text{a}}\ \text{MeV} - i \times 11.7(4.3)_{\text{stat}}(4)_{\text{model}}(0.1)_{\text{a}}\ \text{MeV}$$

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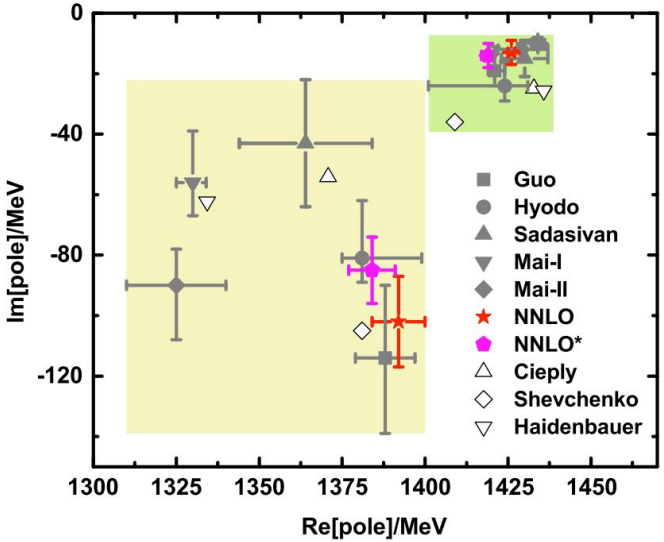
NNLO in SU(3) ChiEFT using S=0, S=1, S=-1 data

Cross-Channel Constraints on Resonant Antikaon-Nucleon Scattering

Lu, Geng, Doering, Mai Phys. Rev. Lett. 130, 071902 (2023)



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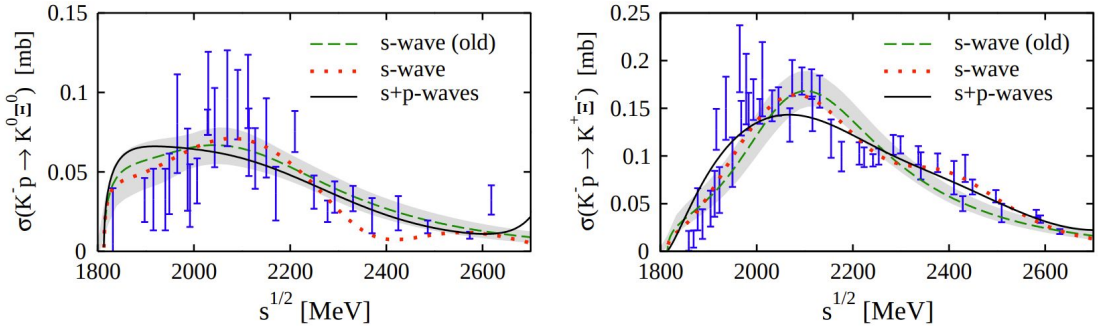
Meson-baryon S=-1 interaction, NLO chiral SU(3) Lagrangian including s- and p-waves.

The $\bar{K}N$ Interaction in Higher Partial Waves

A. Feijoo, D. Gazda, V. Magas, A. Ramos, Symmetry 13 (2021) 8, 1434



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

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

Theoretical frame

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- Lattice QCD

Data is crucial to test (+feed)

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

A. Feijoo @ Meson 2023

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

New terms taken into account

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

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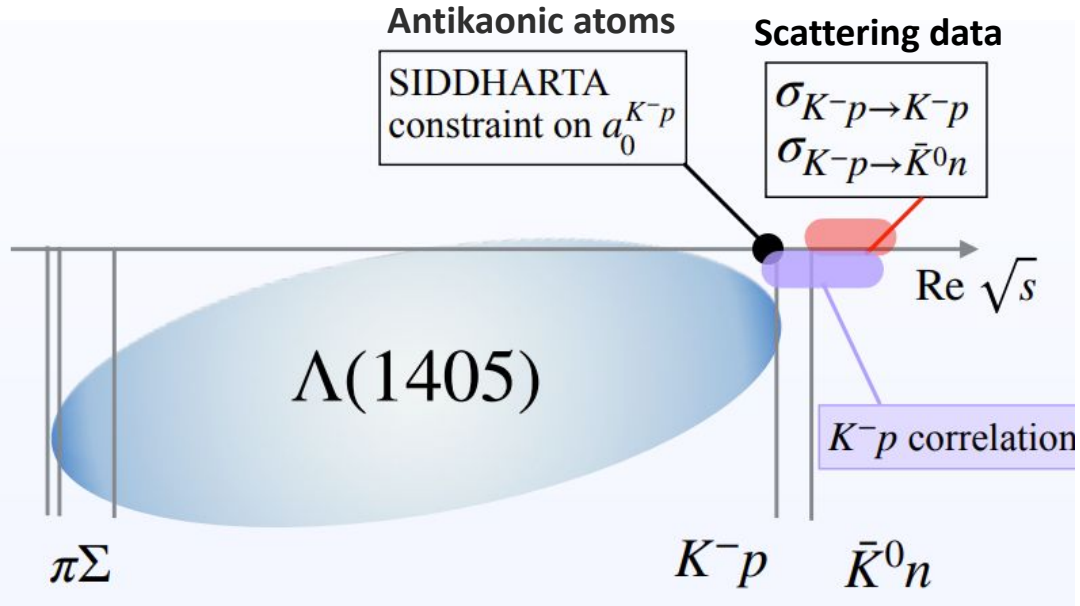
Available experimental data



Femtoscopy

Scattering amplitudes below threshold

Threshold branching ratios

Λ(1405) mass shape in different channels

image courtesy of Y. Kamiya

More relevant data:

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

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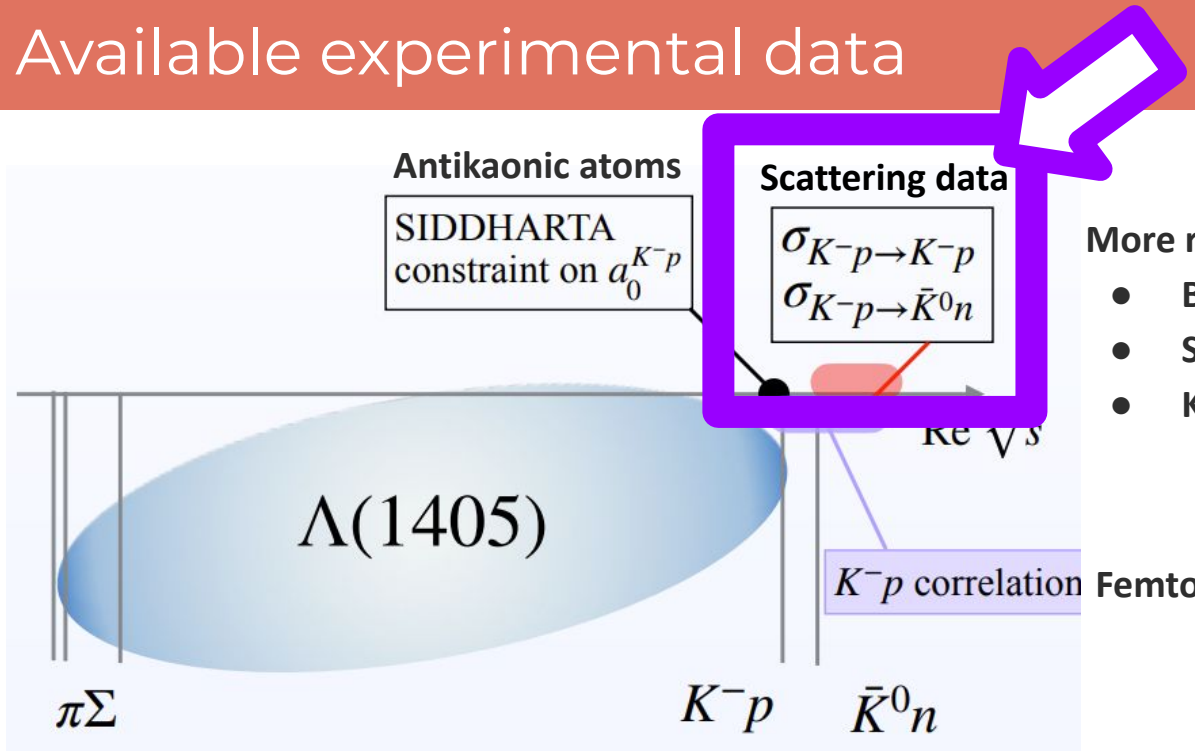

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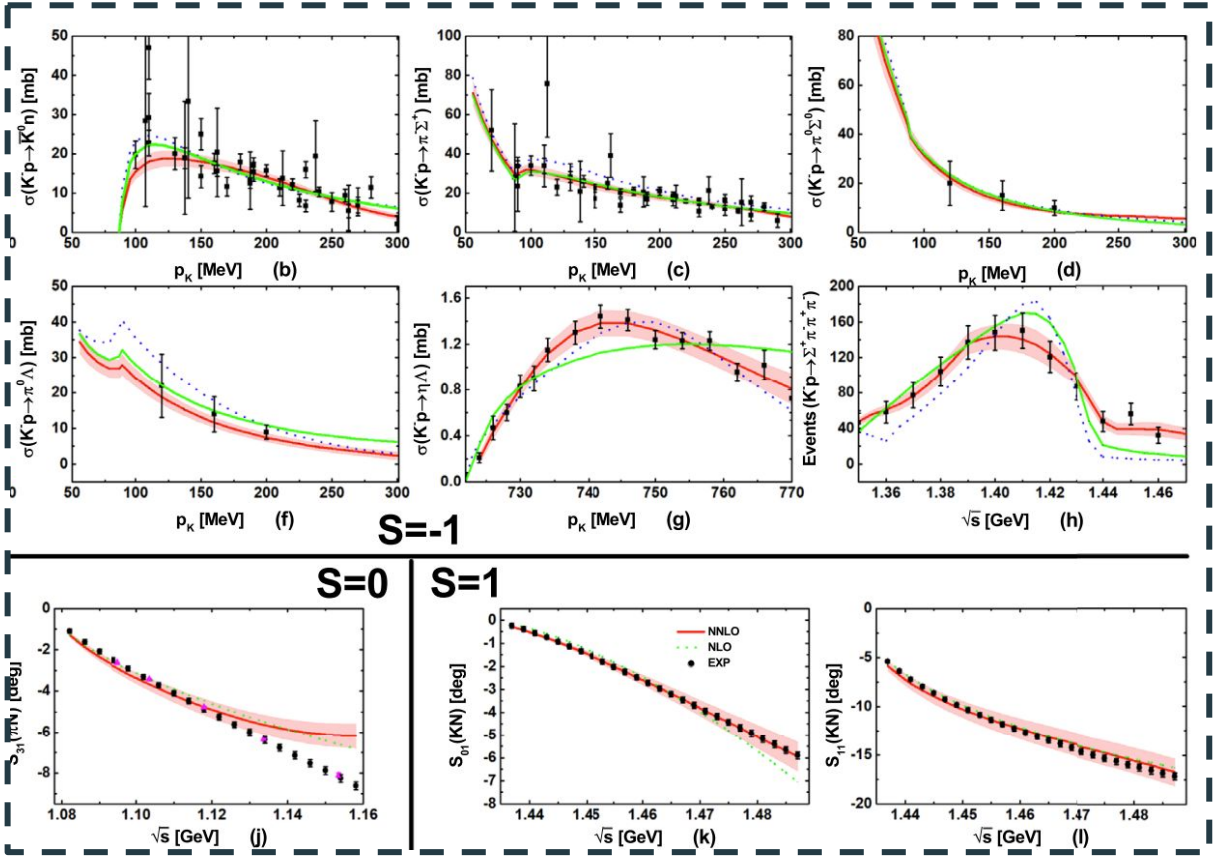

Lu, Geng, Doering, Mai Phys. Rev. Lett. 130, 071902 (2023)

- The present knowledge of total and differential cross sections of low energy kaon-nucleon reactions is very limited.
- Below 150 MeV/c the experimental data are very scarce and with large errors.

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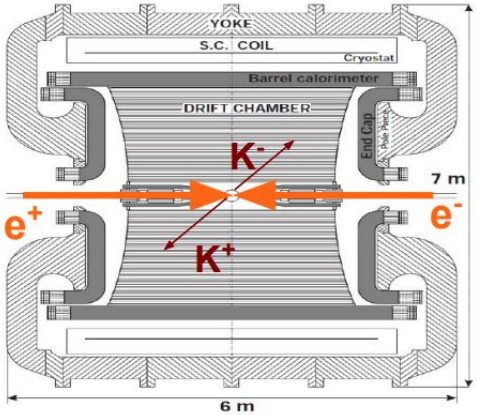
AMADEUS: Inelastic cross sections at p=98 MeV



- KLOE at Daφne e^+e^- collider: φ factory ⇒ Kaon beam of ~120MeV
- Drift chamber of KLOE used as active target (90% ^{4}He, 10% C_4H_{10})

First Simultaneous $K^- p \rightarrow (\Sigma^0/\Lambda)\,\pi^0$ Cross Sections Measurements at 98 MeV/c

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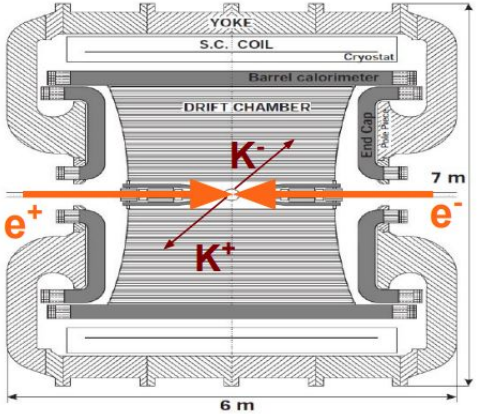

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AMADEUS Collaboration, arXiv:2210.10342 [nucl-ex]. Submitted to PRL.

- $\sigma_{K^-p\to\Sigma^0\pi^0} = 42.8 \pm 1.5(stat.)^{+2.4}_{-2.0}(syst.)$ mb
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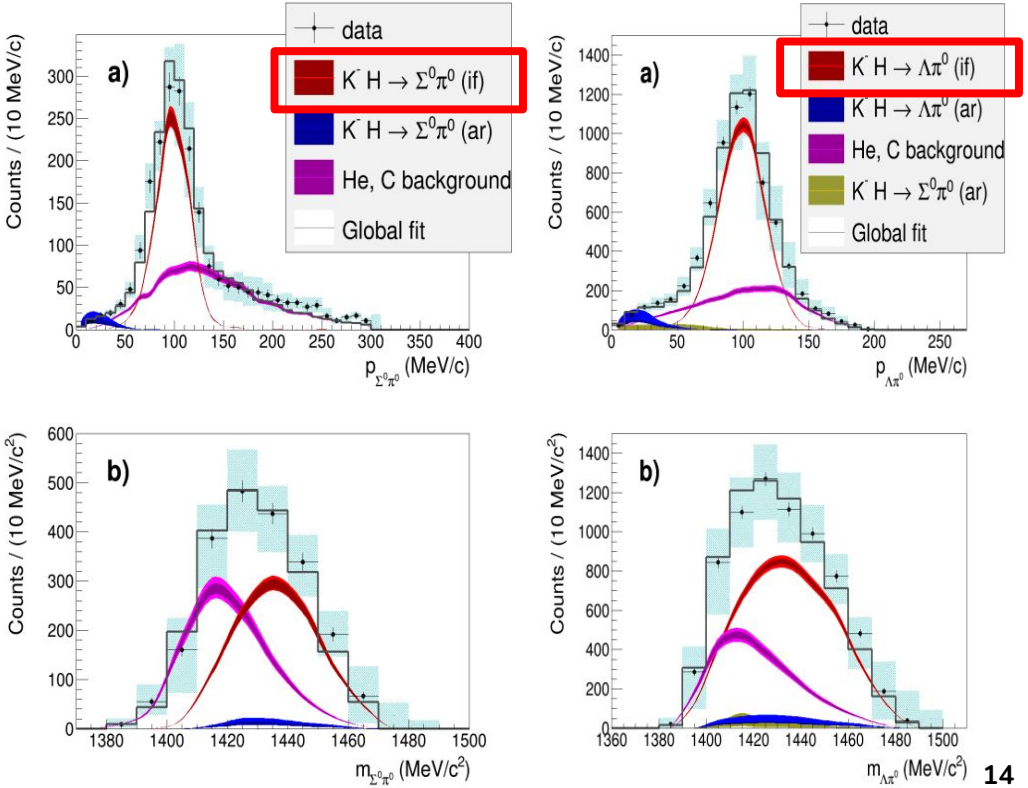

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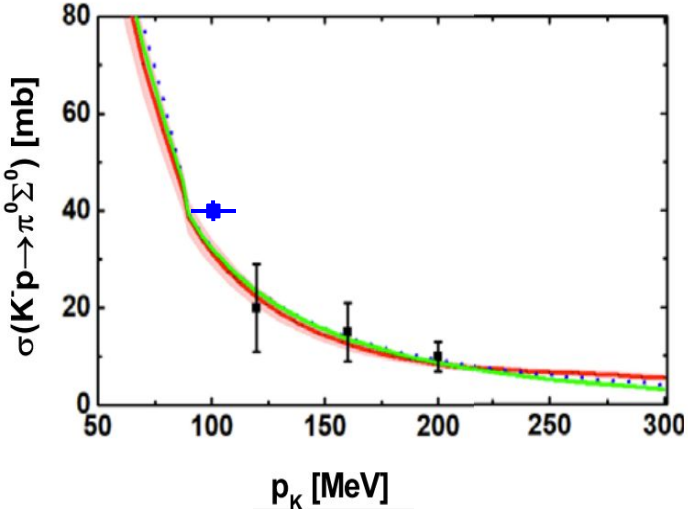

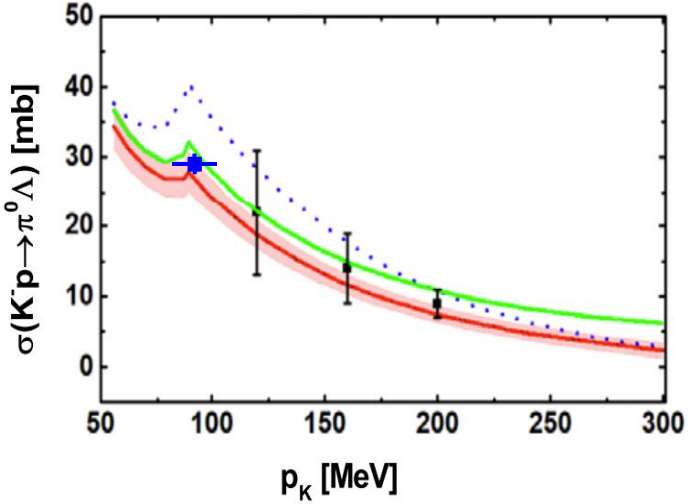

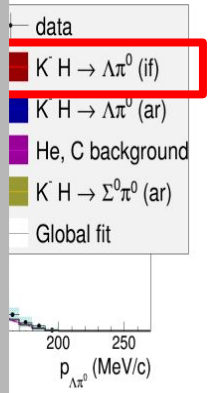

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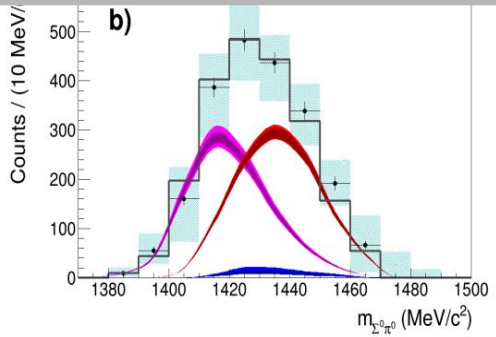

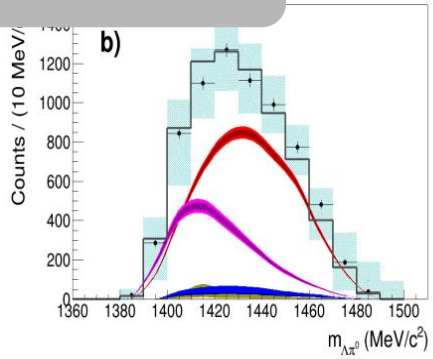

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011)

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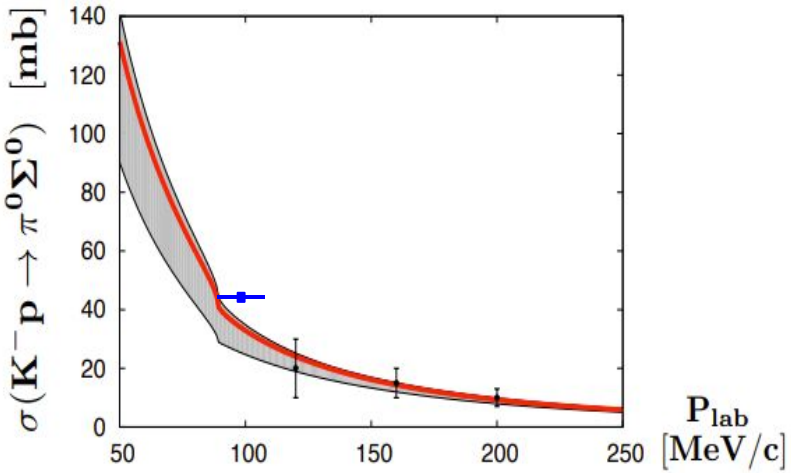

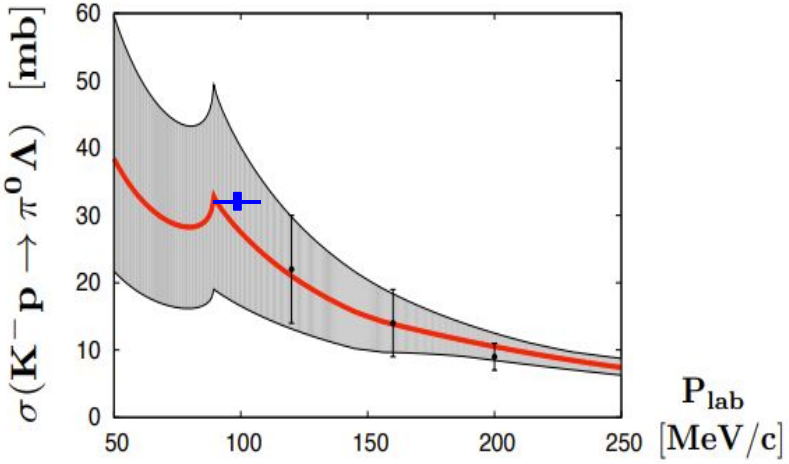

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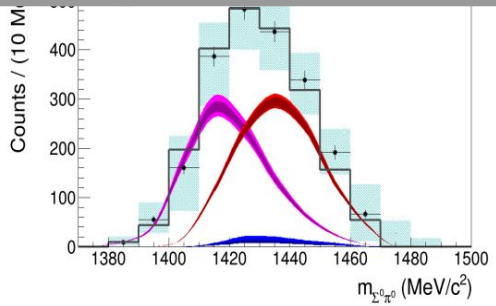

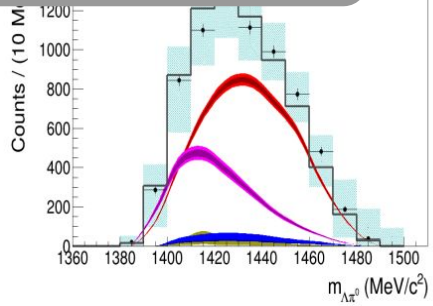

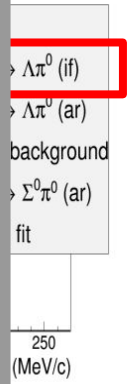

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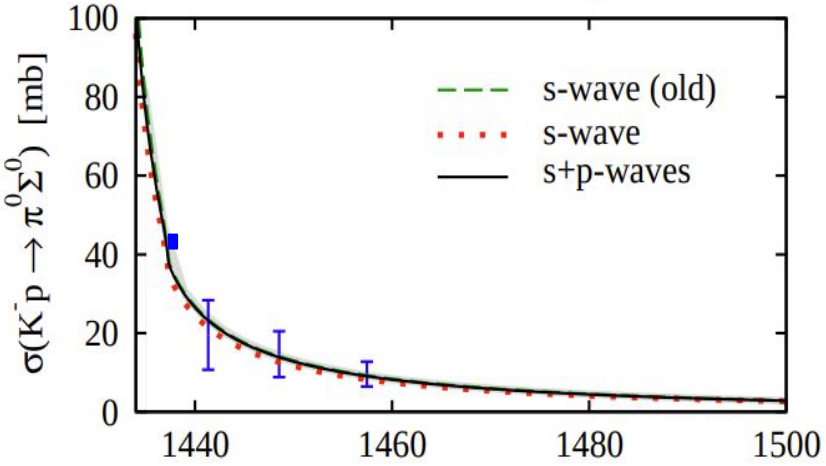

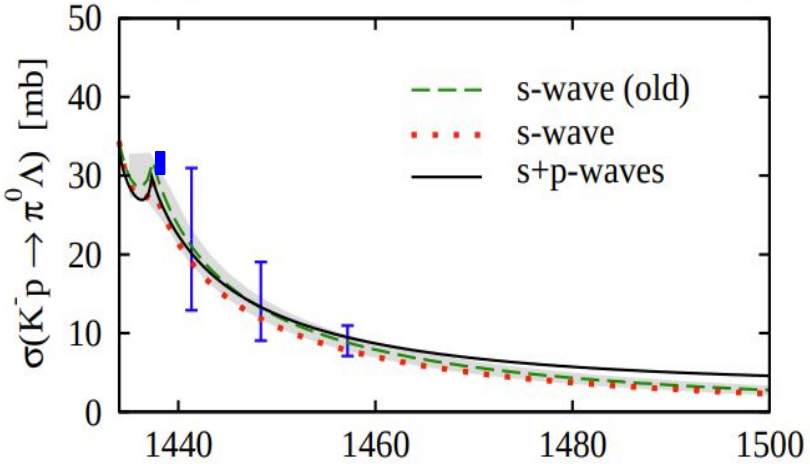

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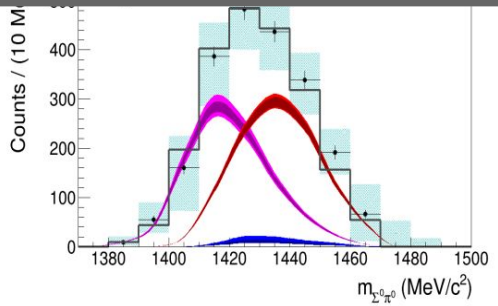

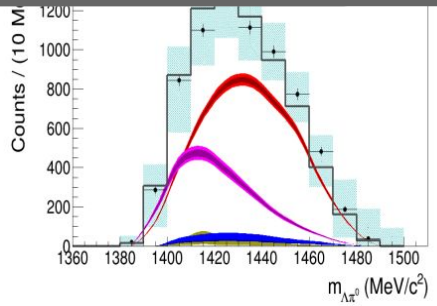

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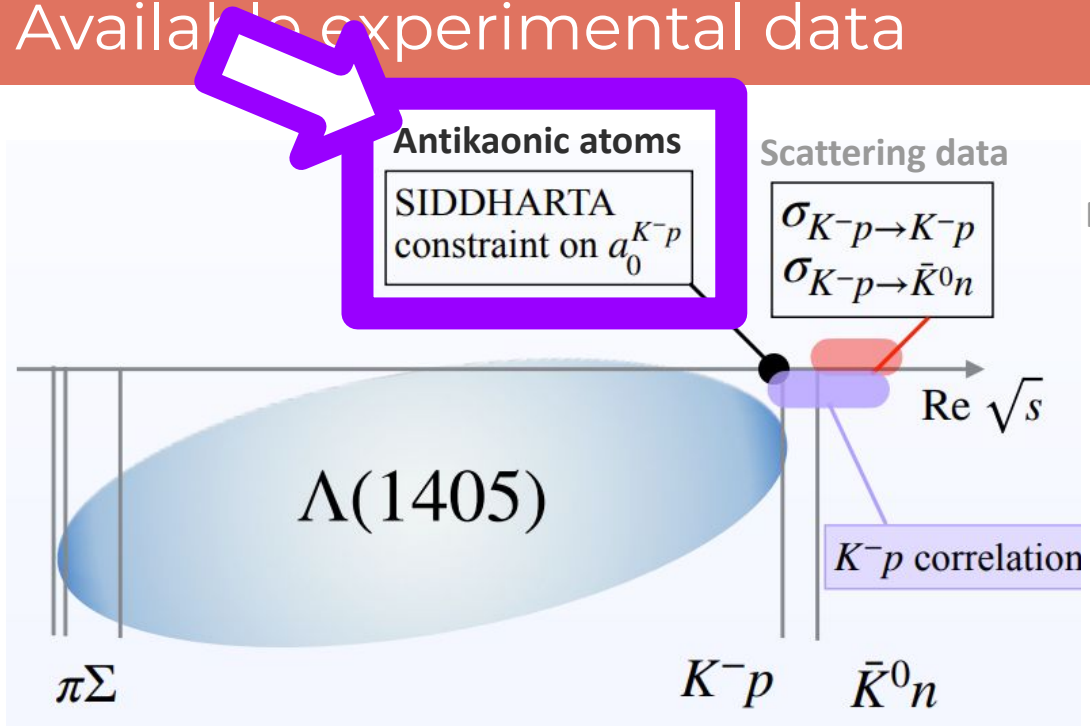

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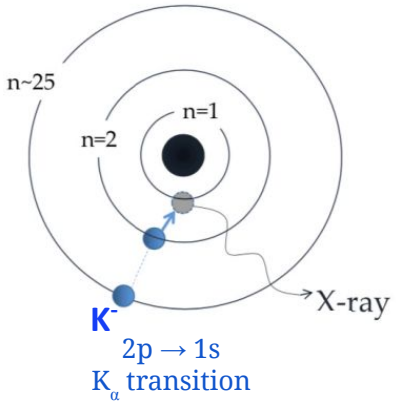
antikaonic hydrogen: SIDDHARTA



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.

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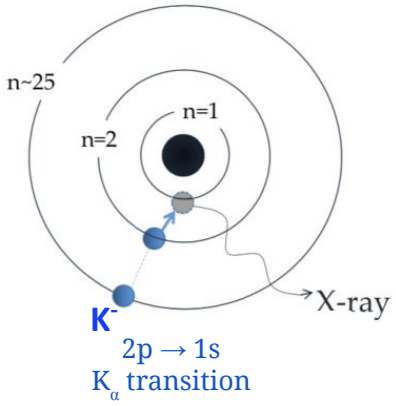

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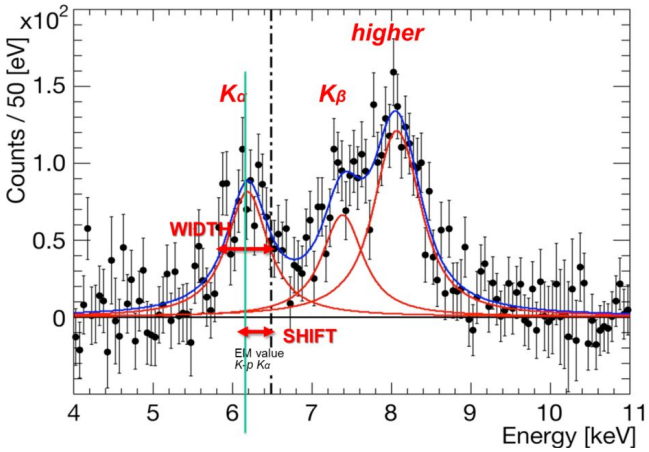

SIDDHARTA Coll., PLB 704 (2011) 113

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

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

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

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

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antiKaonic-deuterium SIDDHARTA-2

AntiKaonic-deuterium scattering lengths more sensitive to the I=1 channel

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

Deser-type relation
for antikaonic deuterium

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<u>SIDDHARTA-2 measurement is a challenging one:</u>

- **Yield of antiKaonic deuterium smaller than antiKaonic hydrogen**
- Width of the signal higher than in hydrogen

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

- Deser type formula with model dependence
- Recoil corrections to the multiple scattering
- **Requires full three-body calculations**

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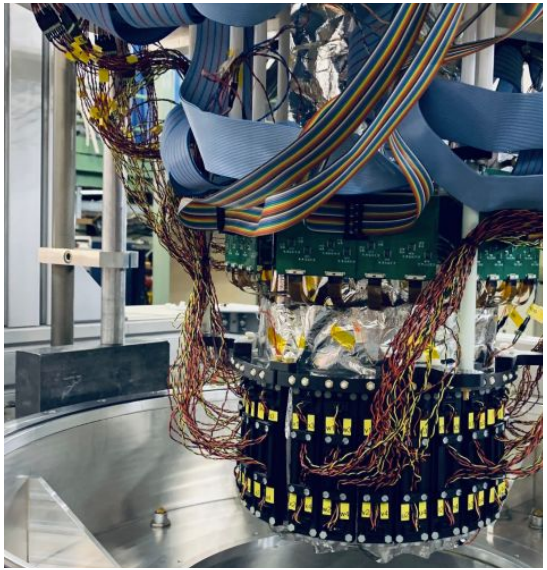
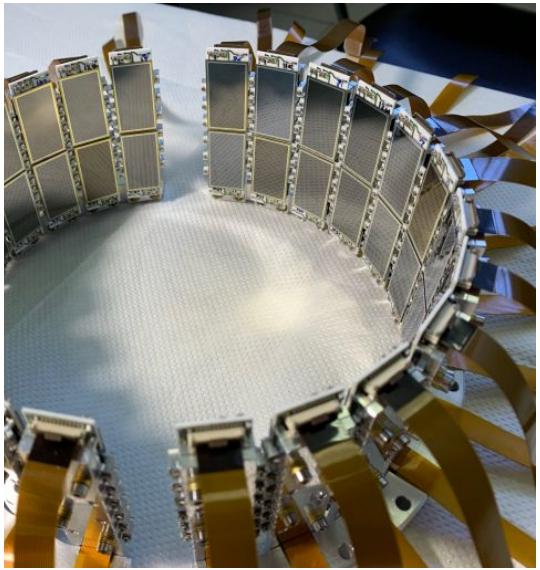
antiKaonic-deuterium SIDDHARTA-2

SIDDHARTA-2 with new experimental setup

→New (and more! 384) SDD's: timing resolution 450 ns @ -140 °C, thickness 450 µm, area 0.64 cm^2

→New Target





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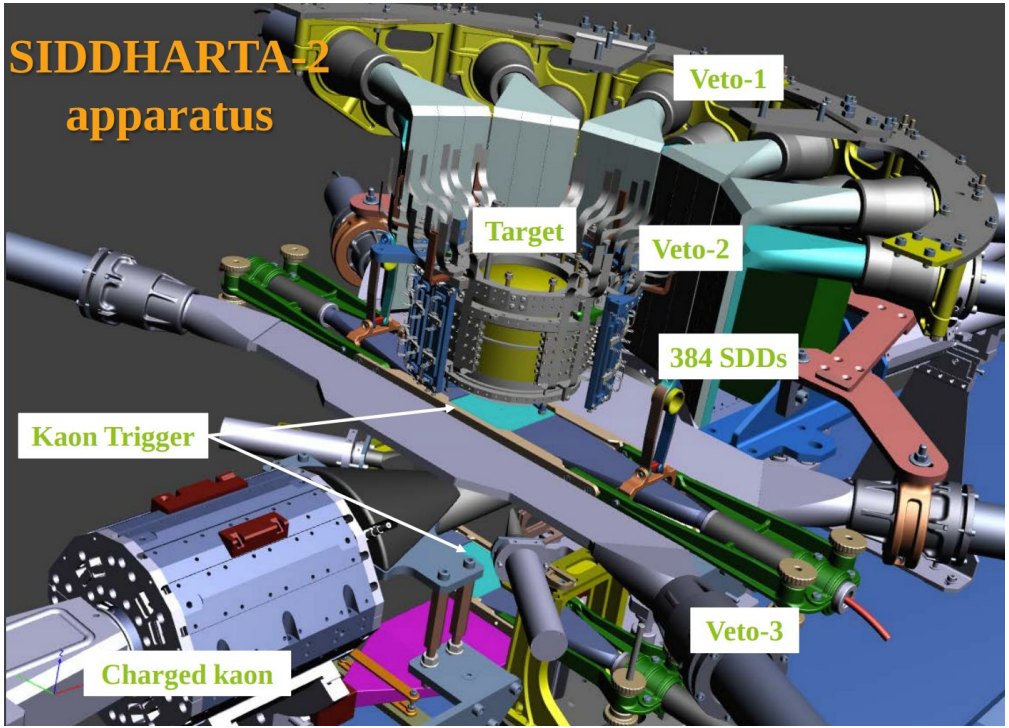
→New Target

→**New setup configuration closer to IR**

→**New Veto systems**

⇒ Full setup ready, deuterium data taking started in june!



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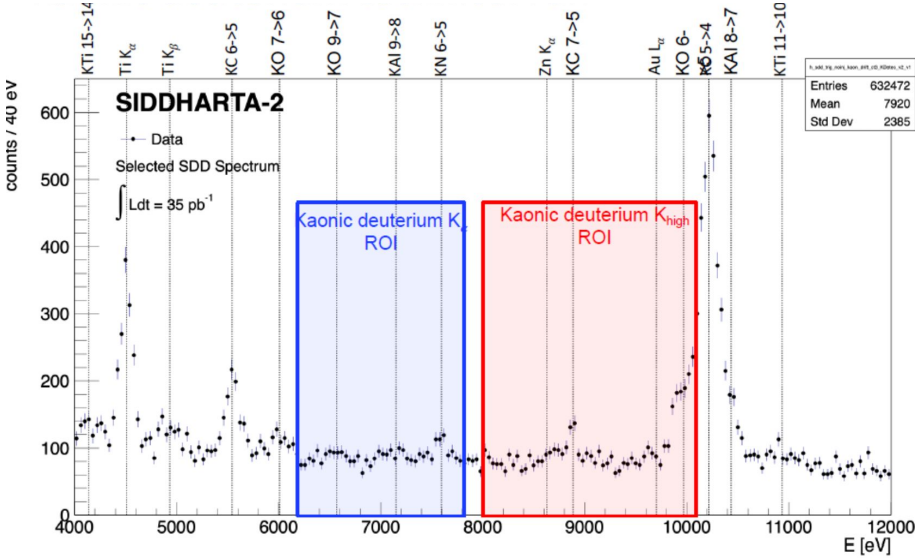
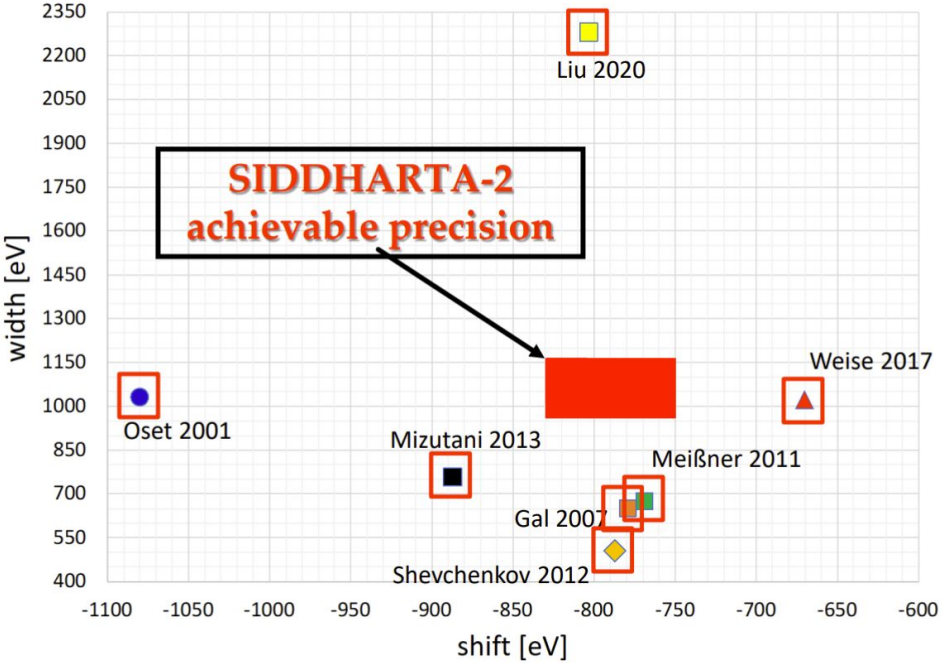
antiKaonic-deuterium SIDDHARTA-2

800 pb^{-1} to be acquired by 2024 ⇒ Expected <u>precision</u> better than SIDDHARTA measurement of antiKaon-hydrogen

Technical Run with Deuterium Target 2022:





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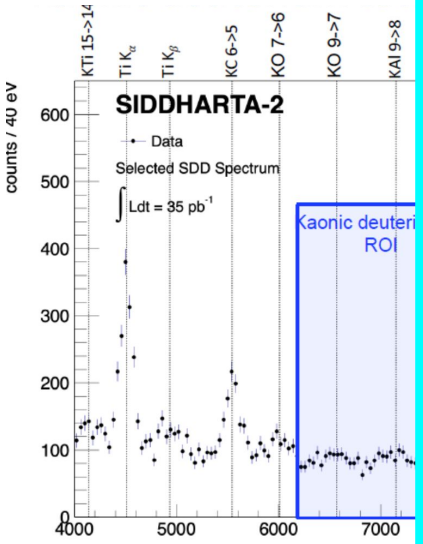
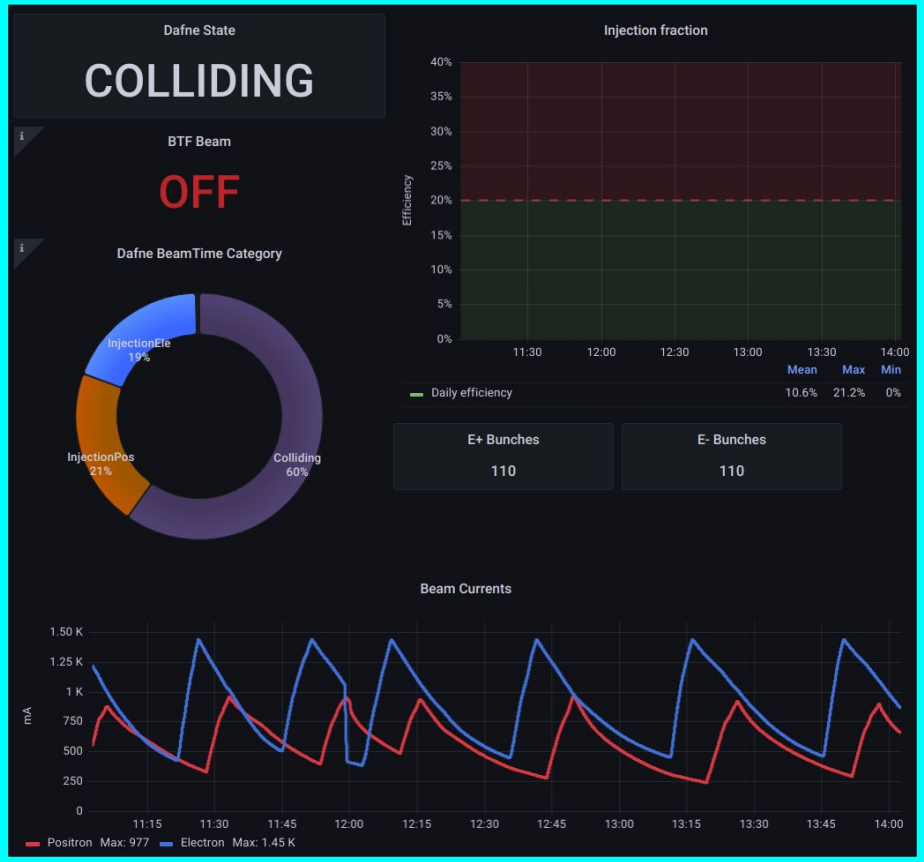
antiKaonic-deuterium SIDDHARTA-2

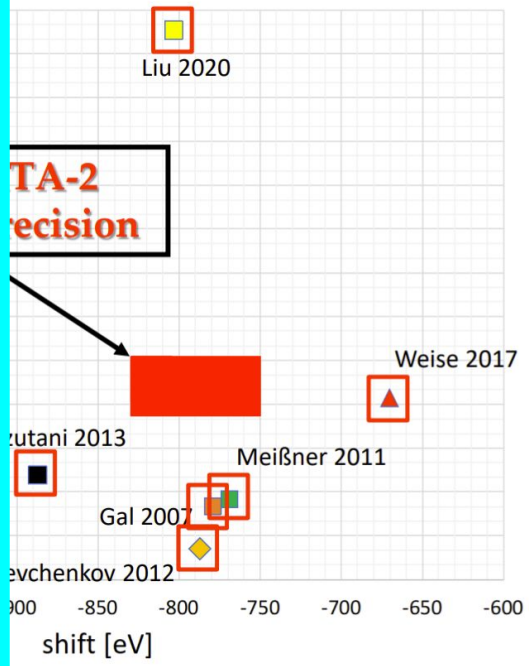
800 pb^{-1} to be acquired by
than SIDDHARTA measur

Technical Run with Deuter



Daphne collisions today July 3rd 2023





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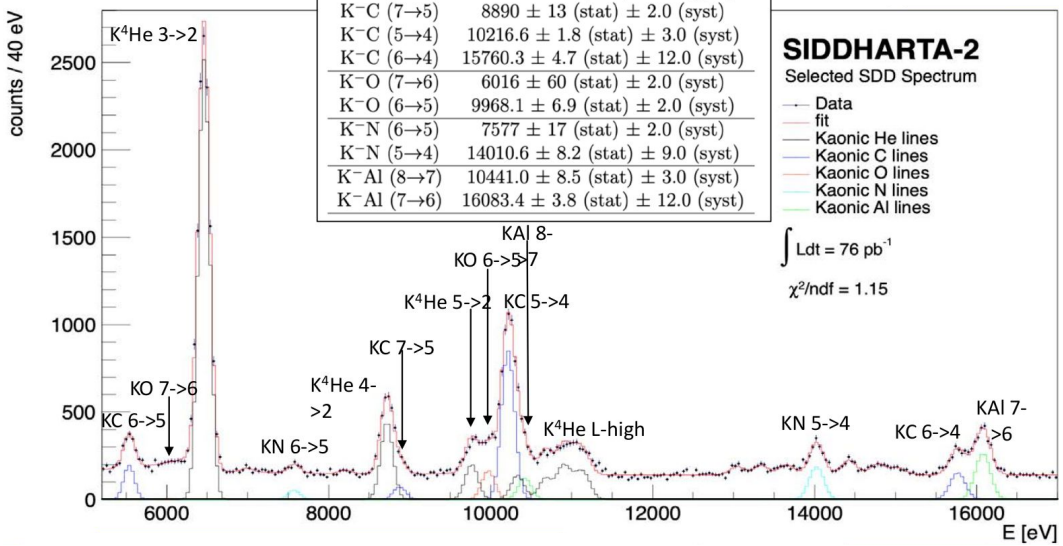
SIDDHARTA-2 antikaonic atoms results

Transition	Energy (eV)
K^4He (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (stat) ± 2.0 (syst)
K^-C (5→4)	10216.6 ± 1.8 (stat) ± 3.0 (syst)
K^-C (6→4)	15760.3 ± 4.7 (stat) ± 12.0 (syst)
K^-O (7→6)	6016 ± 60 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-N (6→5)	7577 ± 17 (stat) ± 2.0 (syst)
K^-N (5→4)	14010.6 ± 8.2 (stat) ± 9.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-Al (7→6)	16083.4 ± 3.8 (stat) ± 12.0 (syst)



AntiKaonic ^{4}He 3d->2p $L\alpha$ measurement
SIDDHARTA Coll. 2022 J. Phys. G: Nucl. Part. Phys. 49 055106

Yield of antiKaonic ^{4}He yield at 0.75% liquid helium density
SIDDHARTA Coll., Nuclear Physics A 1029 (2023) 122567

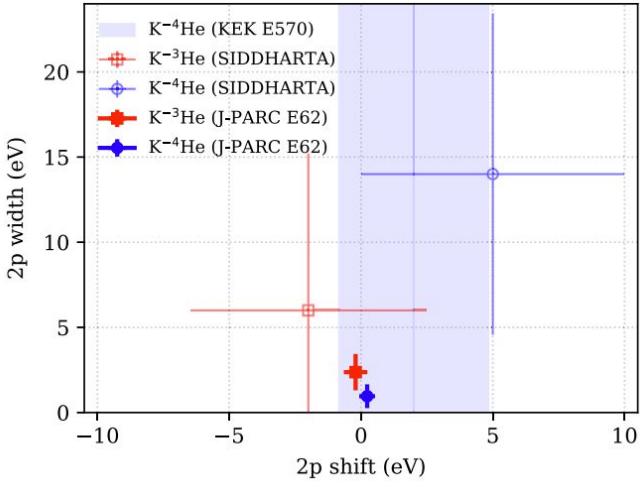
⇐ **Measurements of high-n transitions in intermediate mass antikaonic atoms**
SIDDHARTA Coll., Eur. Phys. J. A 59, 56 (2023)

In the pipeline ⇒ First measurement of **antiKaonic-Neon** AND **M-type transitions** on antiK-^{4}He

J. Obertova talk Wednesday
Microscopic model for multincleonic K^- absorptions applied in calculations of kaonic atoms

oton.vazquez.doce@cern.ch

eV precision measurements by J-PARC E62



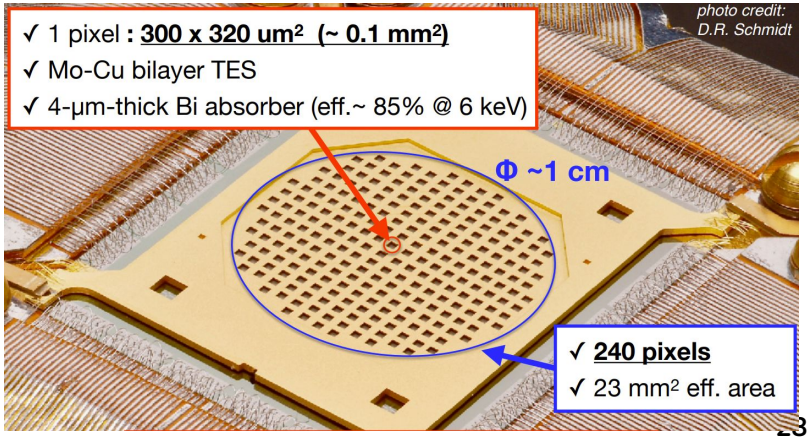
JPARC E62 Coll, Phys. Rev. Lett. 128, 112503 (2022)

eV precision measurements **2p shift and width for kaonic ^{3}He and ^{4}He**

- Relevant information for the description p-wave kaonic bound states and 4-body systems
- Precise calculations with the most recent potentials on the horizon (require 3-, 4-body calculations)

⇒ **First application of microcalorimeter spectrometer, superconducting transition edge sensor (TES) for antikaonic atoms**

Total collection area	23 mm²
ΔE (FWHM)	5 eV @ 6 keV



⇒ Future of hardware for intermediate and high-Z kaonic atoms, also: High-purity germanium detectors, 1mm thick SDD's, others.

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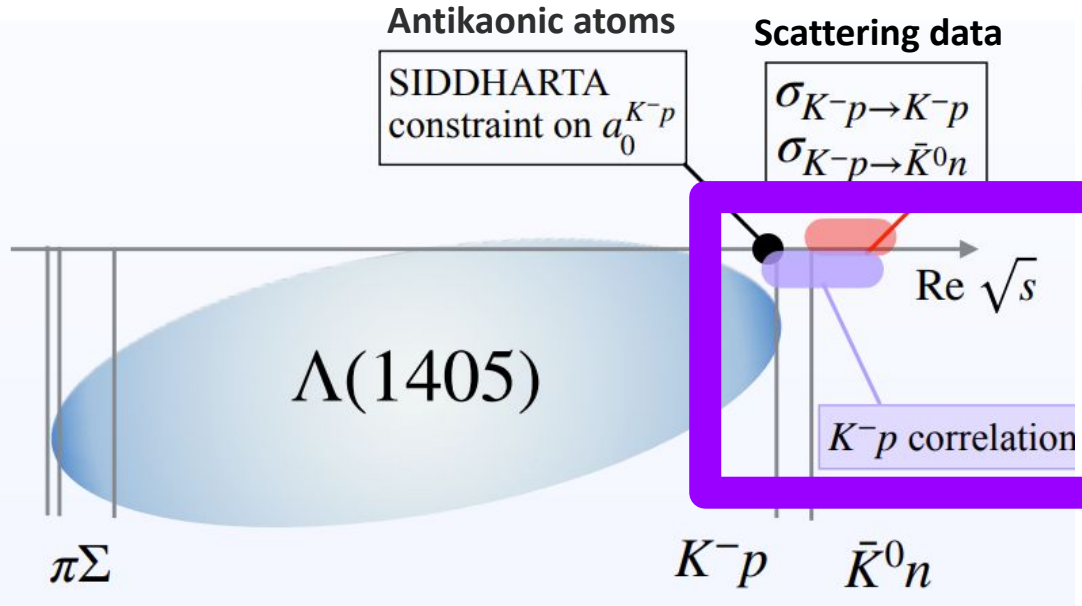
Available experimental data



More relevant data:

- B and Γ of kaonic nuclear states
- Single/multi-nucleonic absorption rates
- K-pp three body femtoscopy

Femtoscopy

Scattering amplitudes below threshold

Threshold branching ratios

Λ(1405) mass shape in different channels

image courtesy of Y. Kamiya

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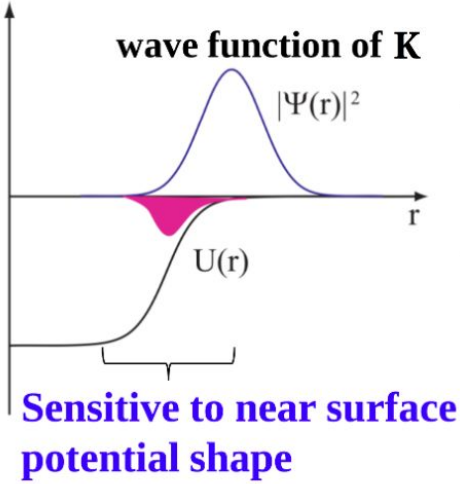
Digression: KbarN at threshold and low momentum

SIDDHARTA: antiKaonic Hydrogen



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

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

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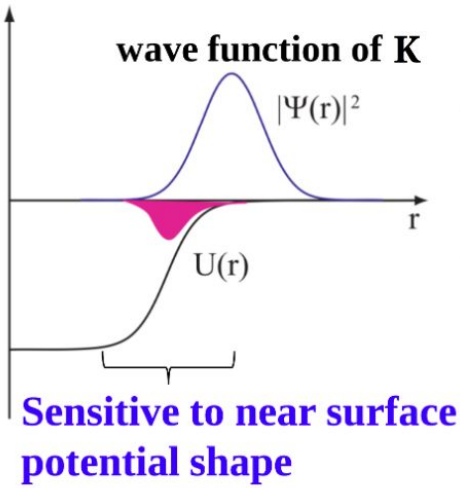

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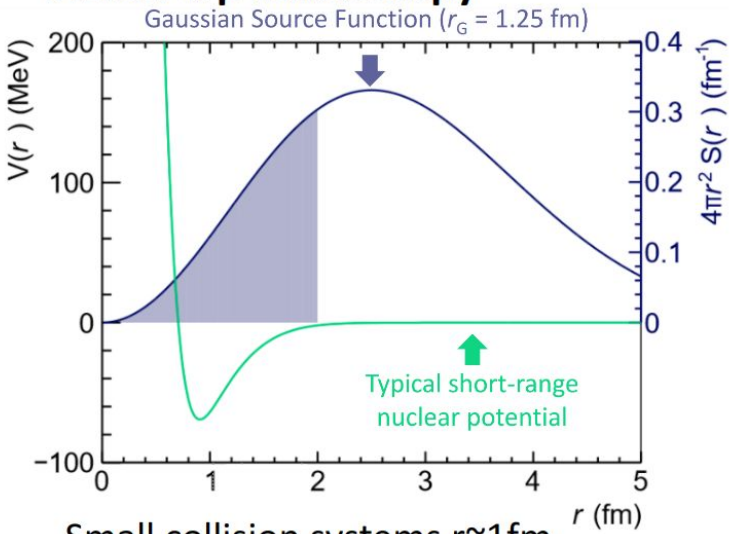
ALICE: K⁻p femtoscopy



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)

K^-p Femtoscopy with ALICE

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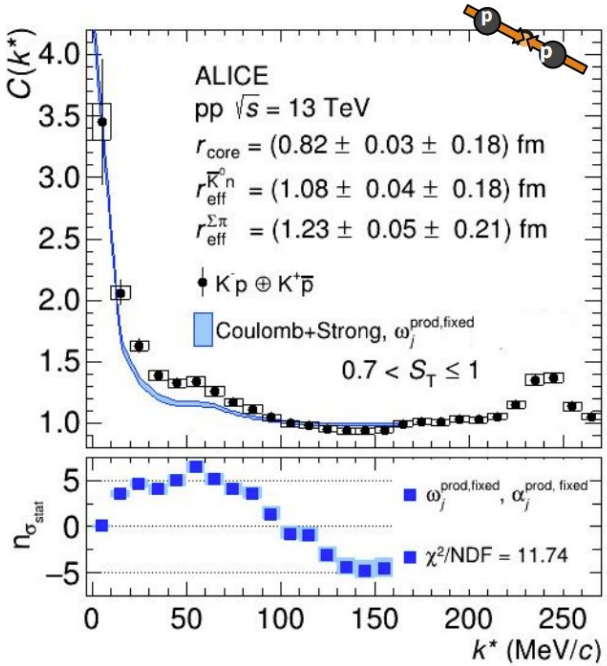
ALICE coll. Eur.Phys.J.C 83 (2023) 4, 340
ALICE coll. Phys. Rev. Lett. 124, 092301 (2020)



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

<u>K^-p femtoscopy</u>: most precise **test of the interaction model at small relative momentum**

⇒ Test of **Kyoto model** anchored to SIDDHARTA result

K⁻p Femtoscopy with ALICE

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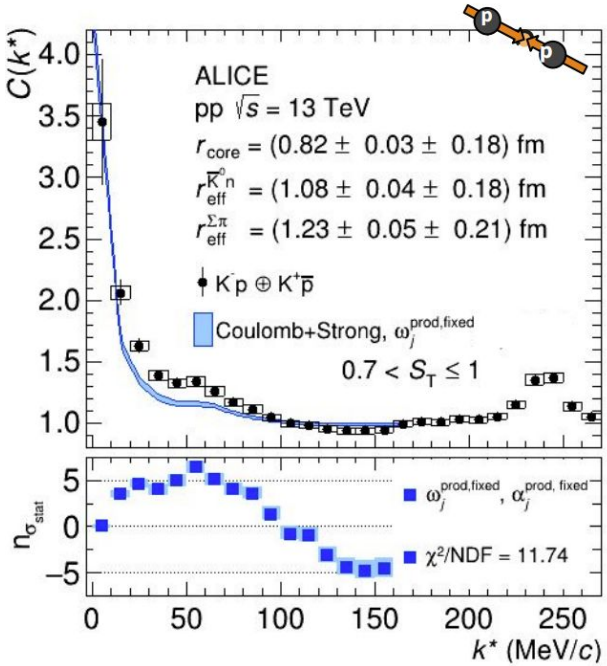

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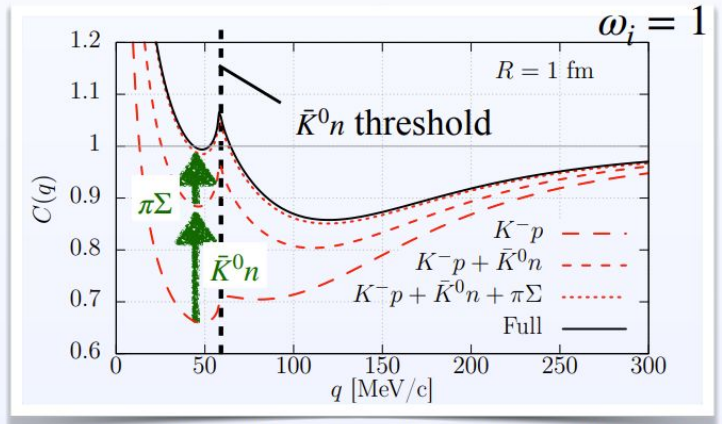
Small systems: pp collisions r~1fm, p-Pb, peripheral p-Pb r~1.5fm
Effects of coupled channels enhanced by small source



Y. Kamiya et al., Phys. Rev. Lett. 124, 132501 (2020)

K⁻p Femtoscopy with ALICE

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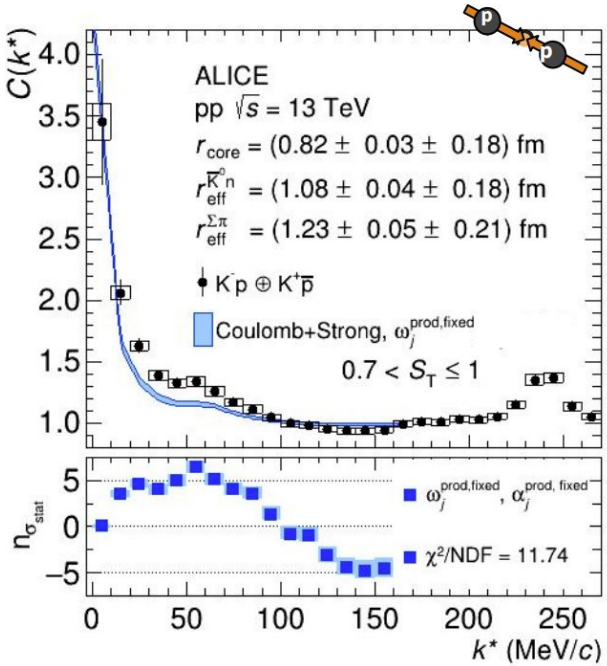
ALICE coll. Eur.Phys.J.C 83 (2023) 4, 340



Correlation function with coupled channels:

$$C_{\mathrm{K^-p}}(k^*) = \int d^3r^* S_{\mathrm{K^-p}}(r^*)|\psi_{\mathrm{K^-p}}(k^*,r^*)|^2 + \sum_j \omega_j \int d^3r^* S_j(r^*)|\psi_j(k^*,r^*)|^2$$

$$\omega_j = \omega_j^{\mathrm{prod}}$$

ω_j^{prod} = production yields (thermal model)
+ production p_T spectrum (blast-wave)
+ pair kinematics

K⁻p Femtoscopy with ALICE

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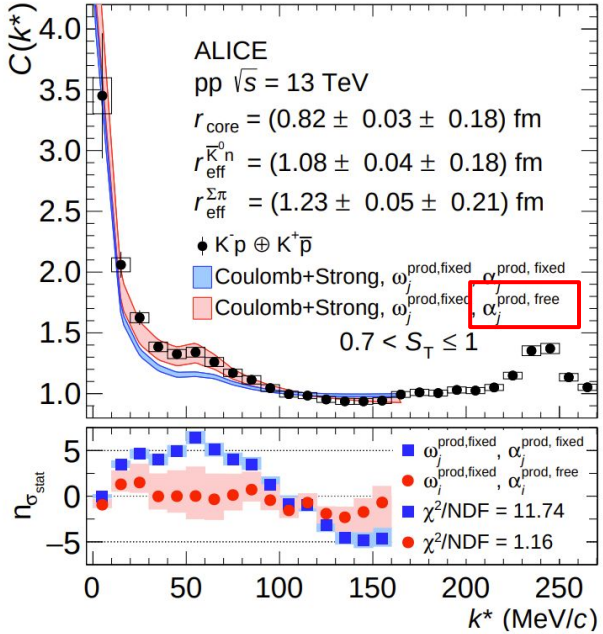
ALICE coll. Eur.Phys.J.C 83 (2023) 4, 340



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⇒ **Quantitative test of coupled channels in the theory**

K⁻p Femtoscopy with ALICE

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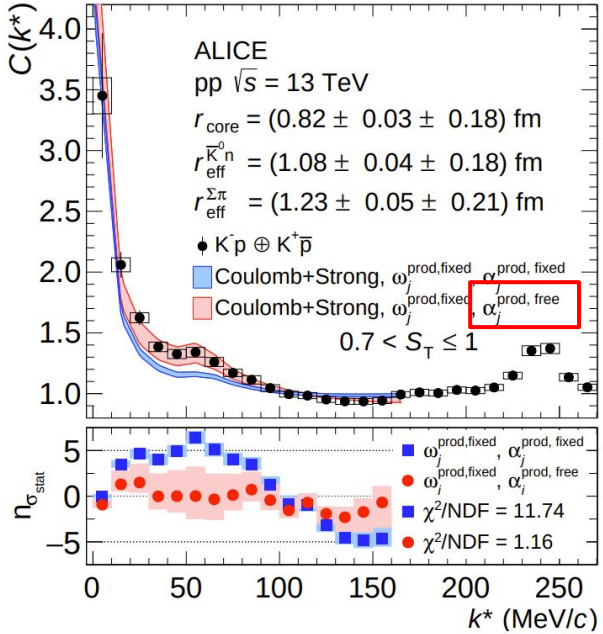
ALICE coll. Eur.Phys.J.C 83 (2023) 4, 340



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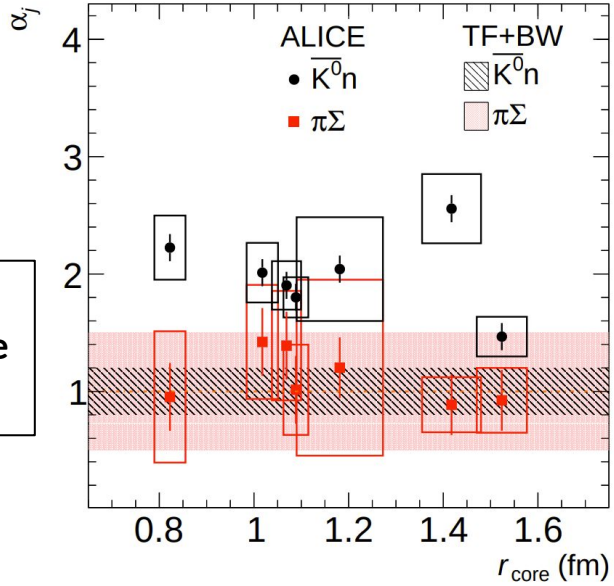
⇒ **Quantitative test of coupled channels in the theory**

The model does not reproduce the strength of the antiK⁰-n channel! ⇒



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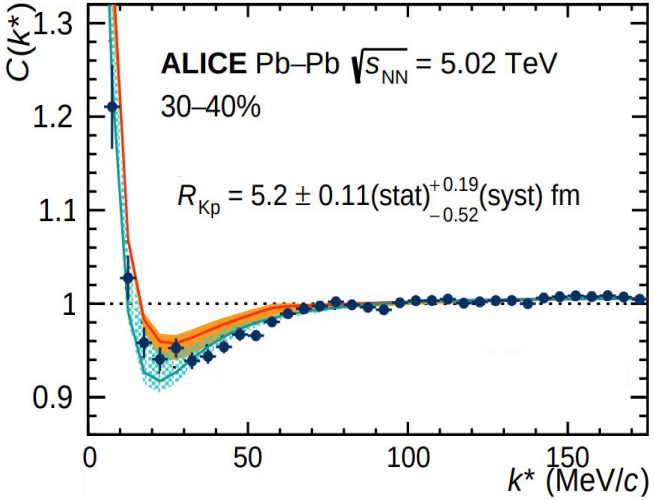
K⁻p Femtoscopy with ALICE in Pb-Pb collisions

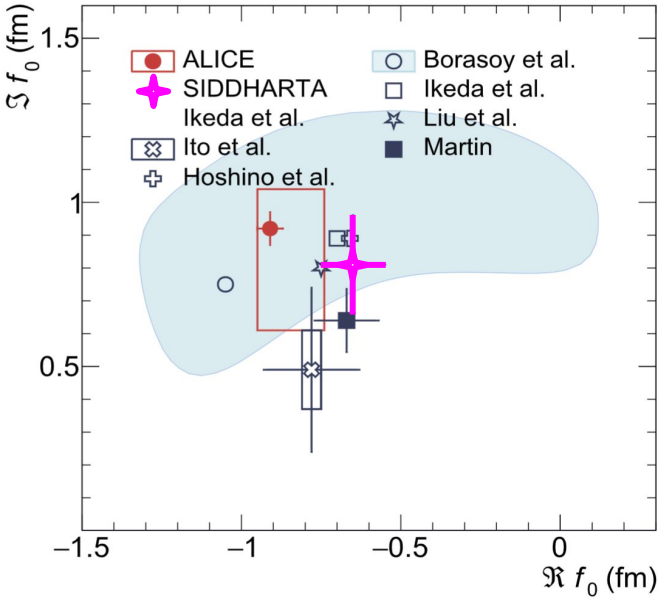
ALICE Coll., PLB 822 (2021) 136708



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

Strength of coupled channels significantly reduced

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



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

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

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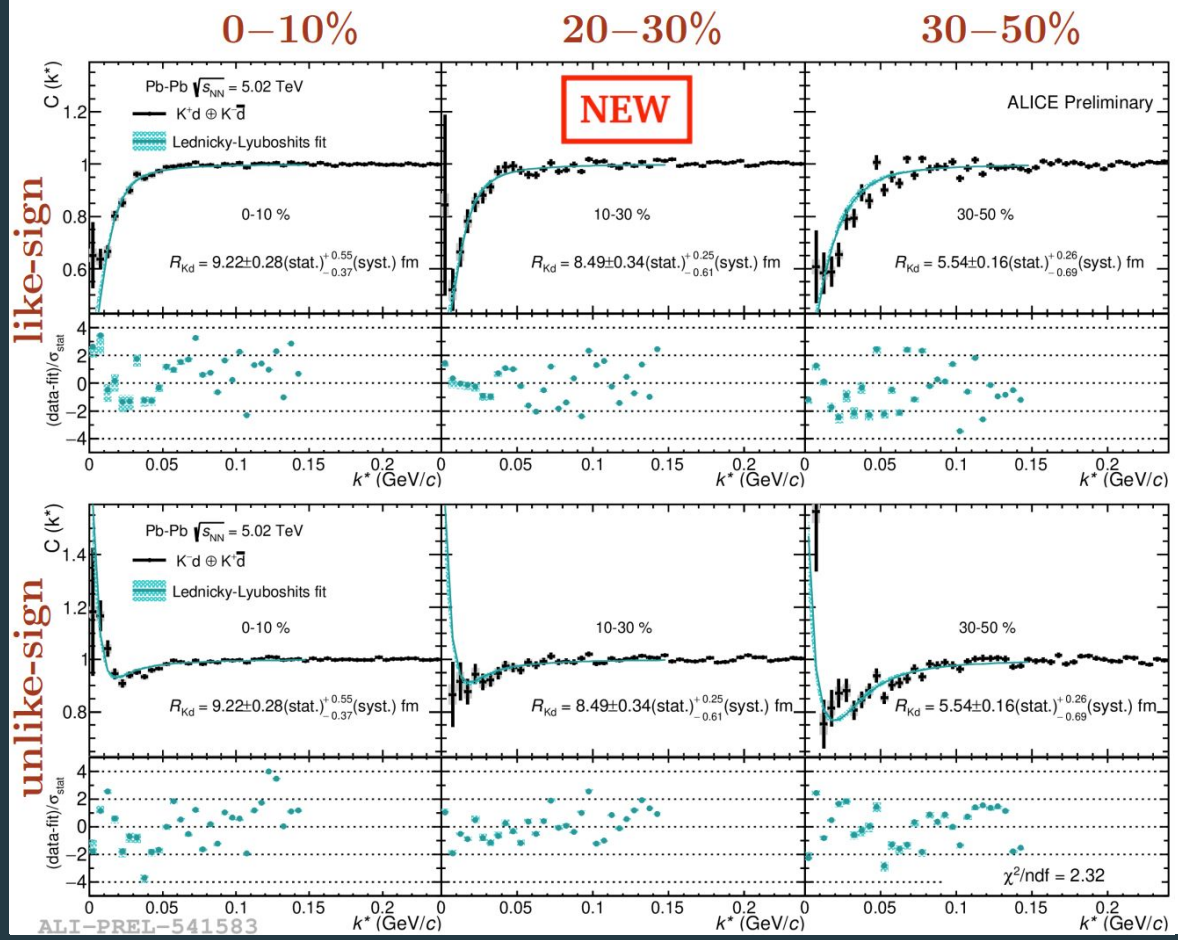
K⁻d Femtoscopy with ALICE in Pb-Pb collisions

W. Resza @ Hadron 2023



Fit to K⁻d correlation function:

Simultaneous fit with 6 free parameters with Lednicky wave function

- Re. K^+d scatt. length
- Re., Im. K^-d scatt. length
- r_0 x3 centralities

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K⁻d Femtoscopy with ALICE in Pb-Pb collisions

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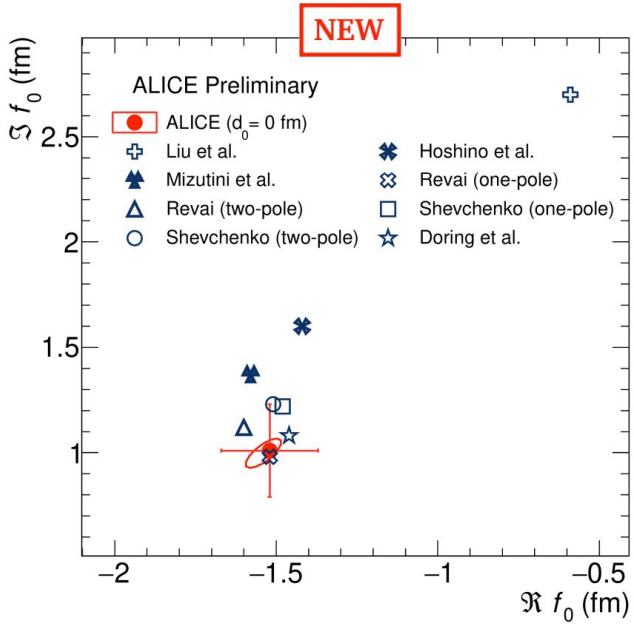

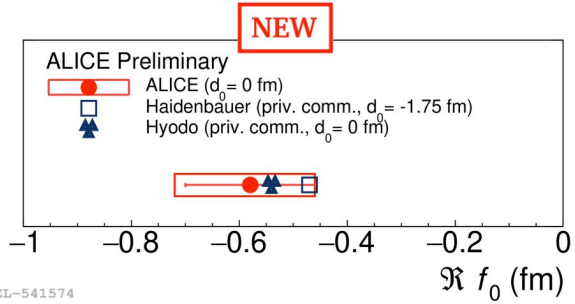

ALI-PREL-541574

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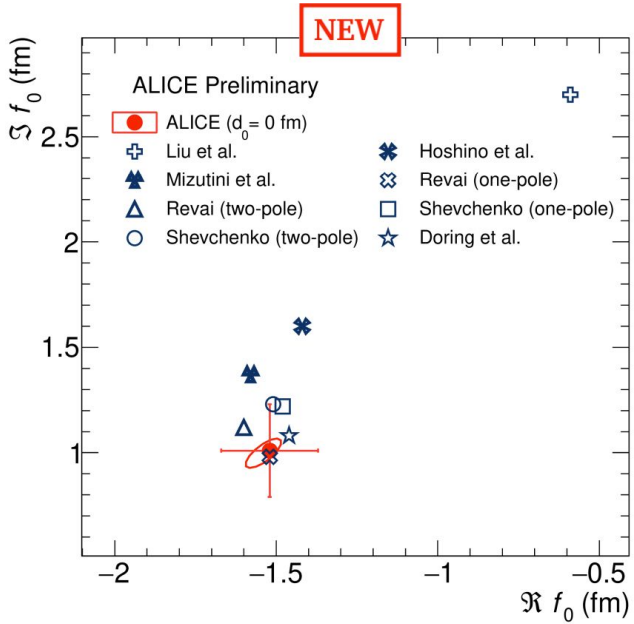
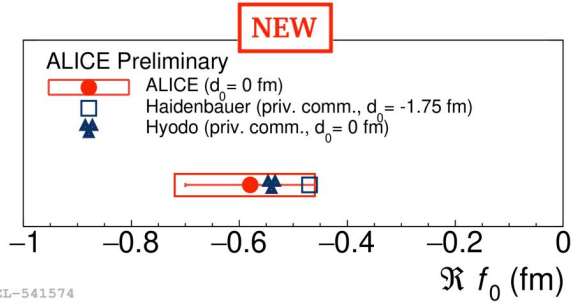
W. Resza @ Hadron 2023





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- Re. K^+d scatt. length
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- r_0 x3 centralities

⇒ K^+d scatt. length well constrained by scattering data and KN interaction

See also pp data in L. Serksnyte talk

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Available experimental data

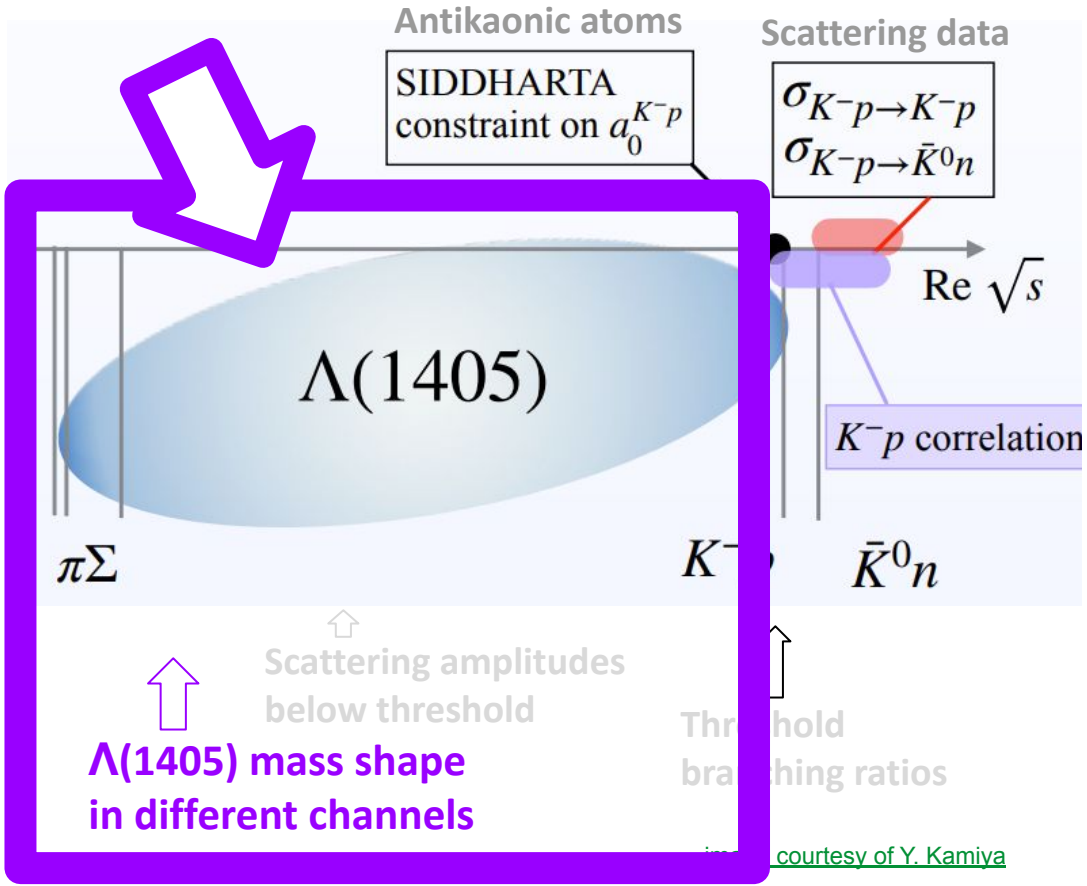

image courtesy of Y. Kamiya

More relevant data:

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

Femtoscopy

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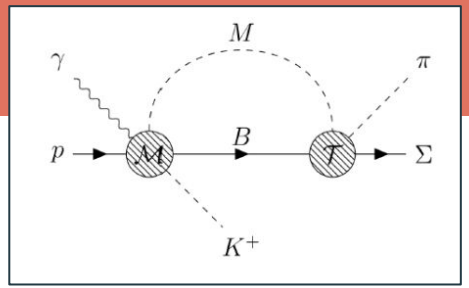
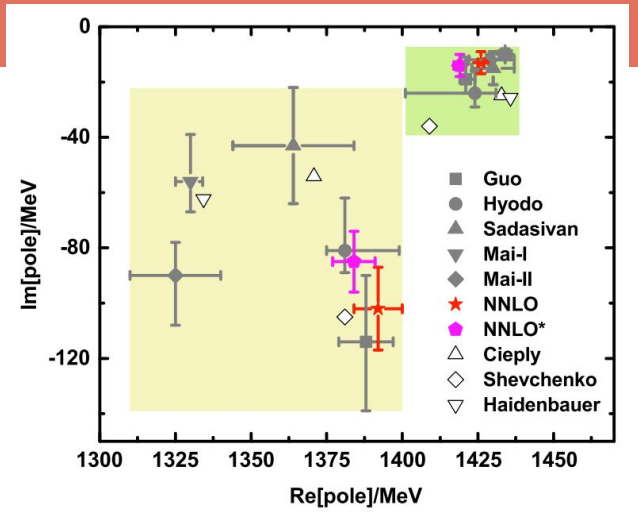
Λ(1405) → $\Sigma^0\pi^0$ data



Some of the "Classic data":

- **photo(electro)-production: CLAS**
  CLAS Collaboration, Phys. Rev. C 87, 035206 (2013)
  (CLAS Collaboration) Phys. Rev. C 88, 045202 (2013))
- pp collisions: ANKE
  I. Zychor et al., Phys. Lett. B660, 167-171 (2008)
- pp collisions: HADES
  HADES Collaboration Phys. Rev. C 87, 025201

Consistent with two pole scenario ⇒



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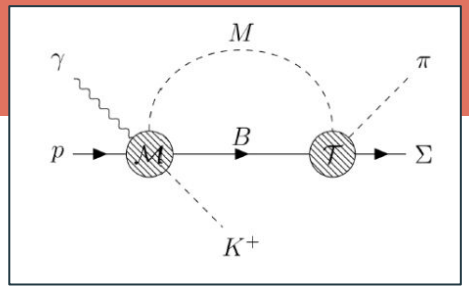

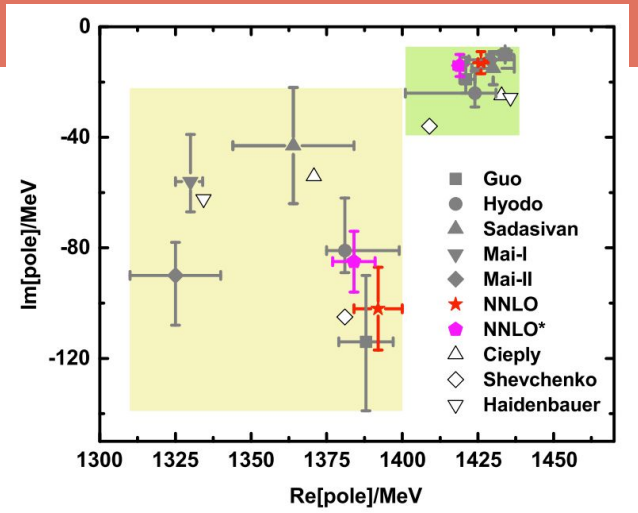

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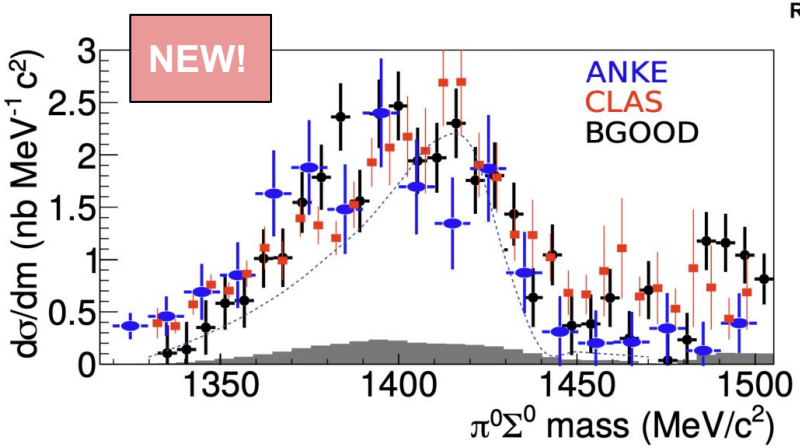
  HADES Collaboration Phys. Rev. C 87, 025201

Consistent with two pole scenario ⇒

New data:

- photo-production: BGOOD ⇒
  G. Scheluchin et al., Phys. Lett. B833, 137375 (2022)
- J-PARC E31: d(K⁻,n)π reaction
  J-PARC E31 Coll. Phys Lett B 837 137687 (2023)
  (Preliminary) GlueX photoproduction
  arXiv:2209.06230v1 [nucl-ex]



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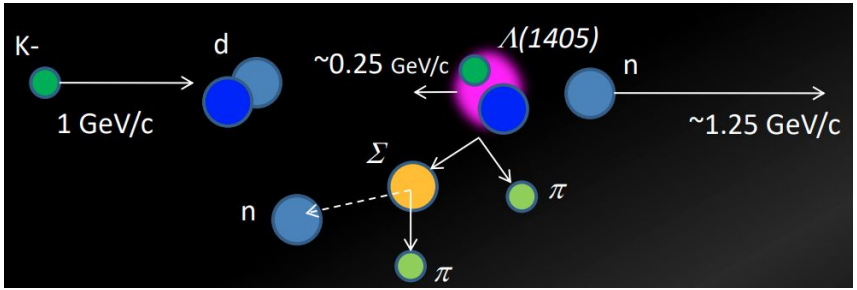
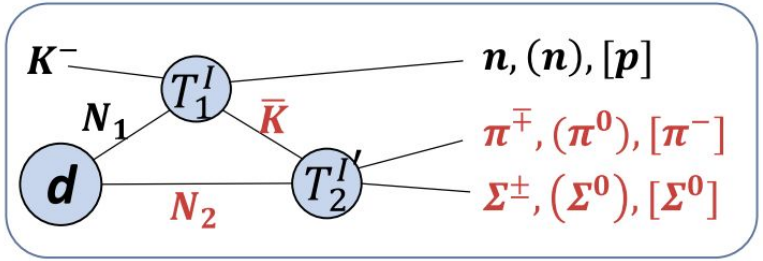
Λ(1405) with J-PARC E31 data

Pole position of Λ(1405) measured in d(K⁻,n)π reactions





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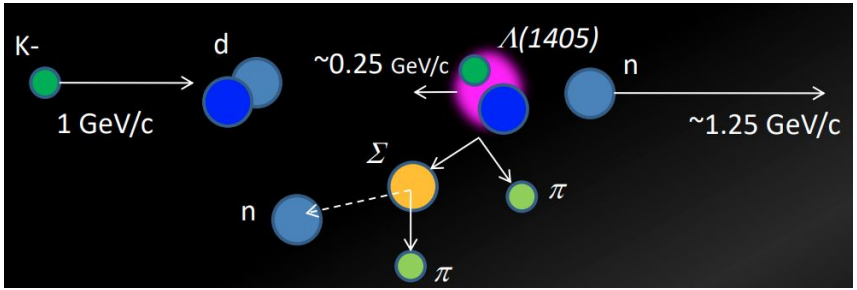

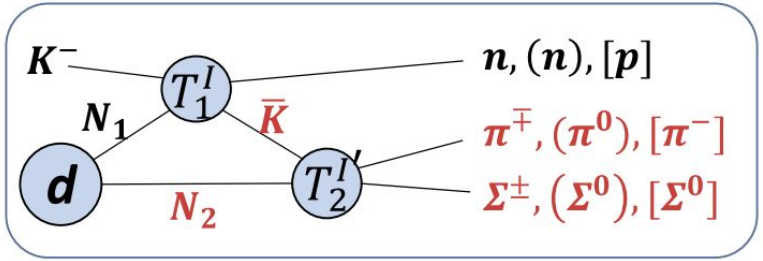

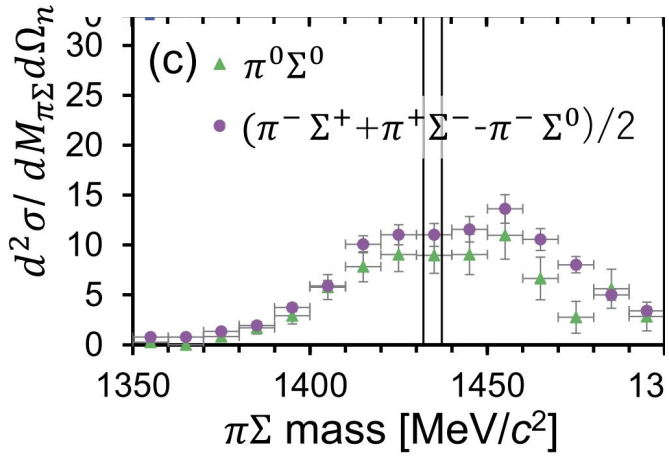

J-PARC E31 Coll. Phys Lett B 837 137687 (2023)

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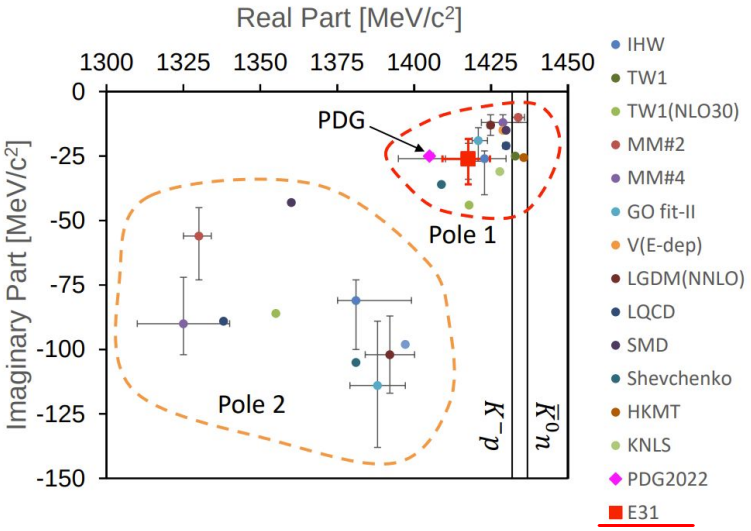
Λ(1405) with J-PARC E31 data



⇒ Higher pole ~1420 MeV well constrained
Lower pole: large differences in predictions.

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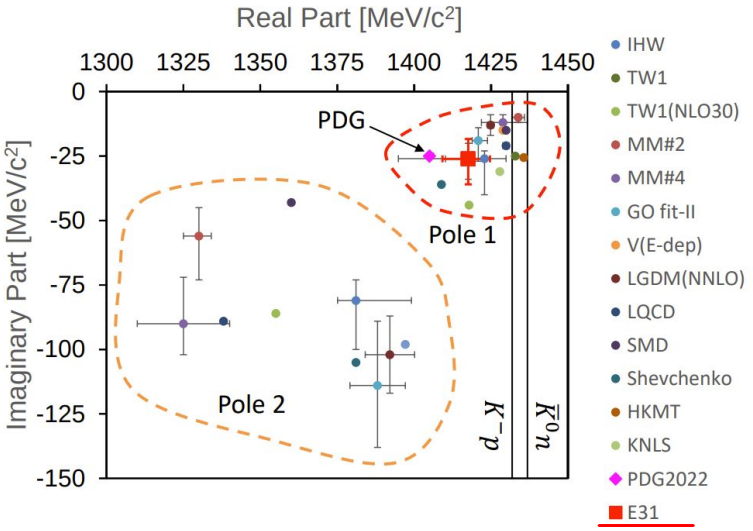
Λ(1405) with J-PARC E31 data

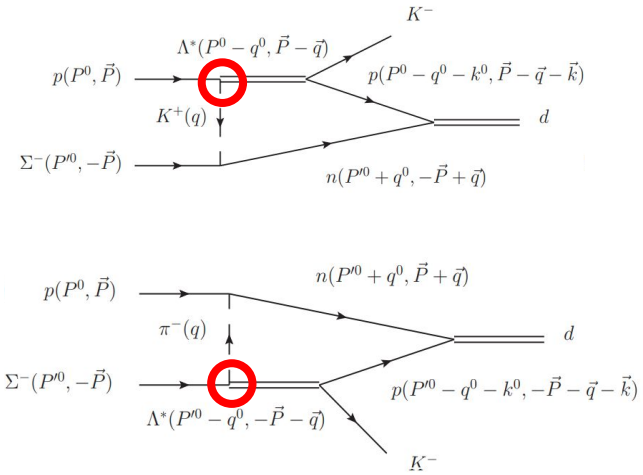


⇒ Higher pole ~1420 MeV well constrained
Lower pole: large differences in predictions.

<u>Proposed:</u> Fusion reaction through triangle singularity sensible also to the lower pole contribution to the scattering

E. Oset et al., EPJ WoC 271, 07006 (2022)

$K^- + d \rightarrow \Sigma p$ reaction



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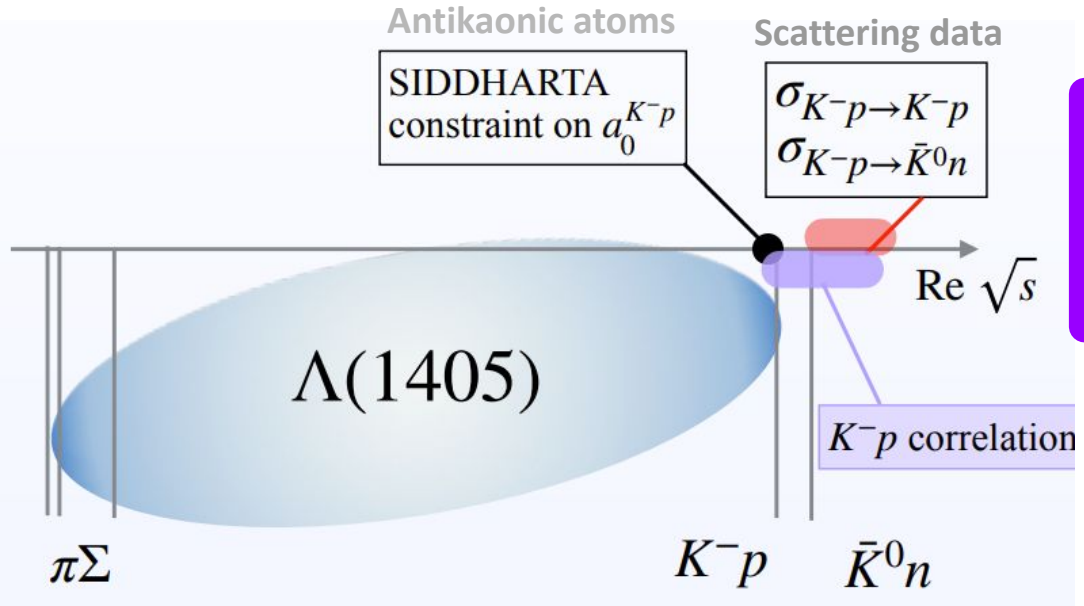
Available experimental data



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

Scattering amplitudes below threshold

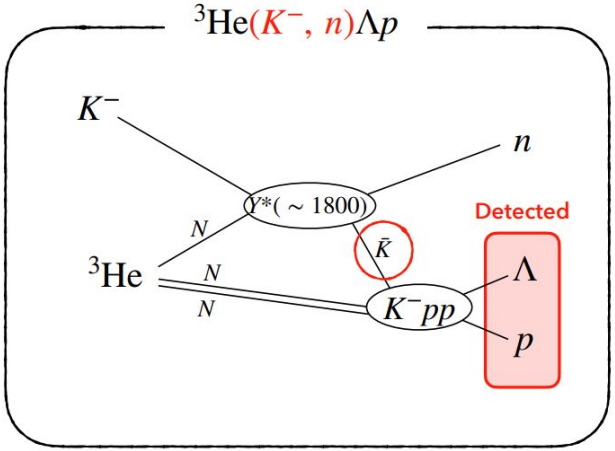
Threshold branching ratios

Λ(1405) mass shape in different channels

image courtesy of Y. Kamiya

J-PARC E15

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



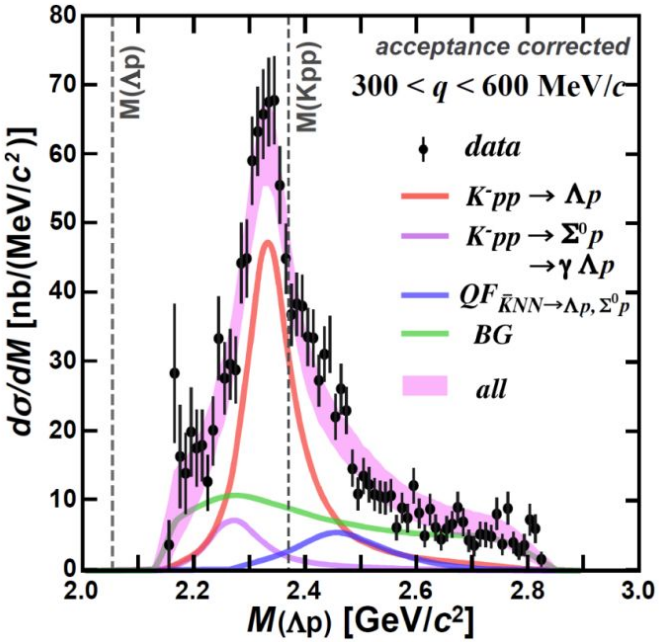
$$B_K = 42 \pm 3(\text{stat.})^{+3}_{-4}(\text{syst.})\ \text{MeV}$$

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

We observed a signal of

$$\bar{K}NN^{(I_z=+1/2)} \rightarrow \Lambda p$$

J-PARC E15 Coll. Phys. Rev. C 102, 044002 (2020)



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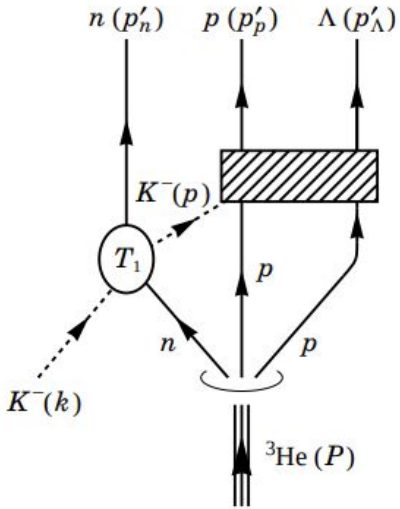
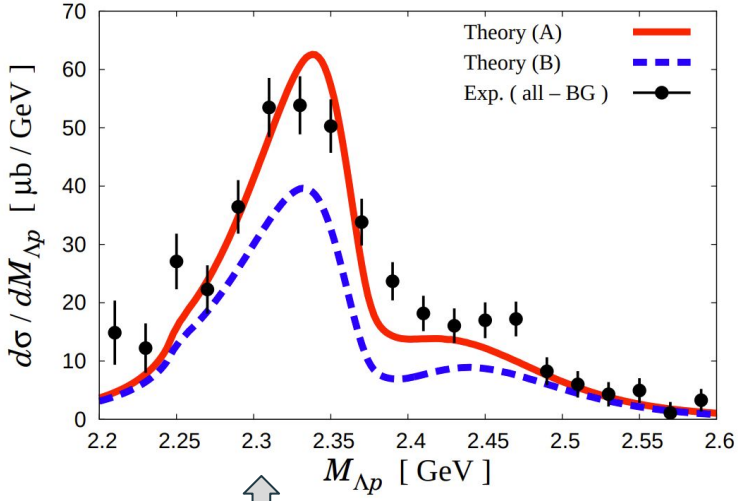
E15 data interpretation

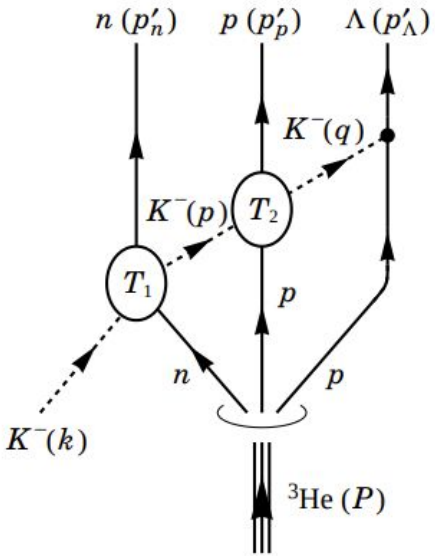
Structure in the in-flight ^{3}He(K$^-$,Λp)n reaction well reproduced by the assumption that a ppK$^-$bound state is formed T. Sekihara, E. Oset, A. Ramos PTEP 2016, 12, 123D03

Bound state





quasi-elastic scattering via Λ(1405) formation



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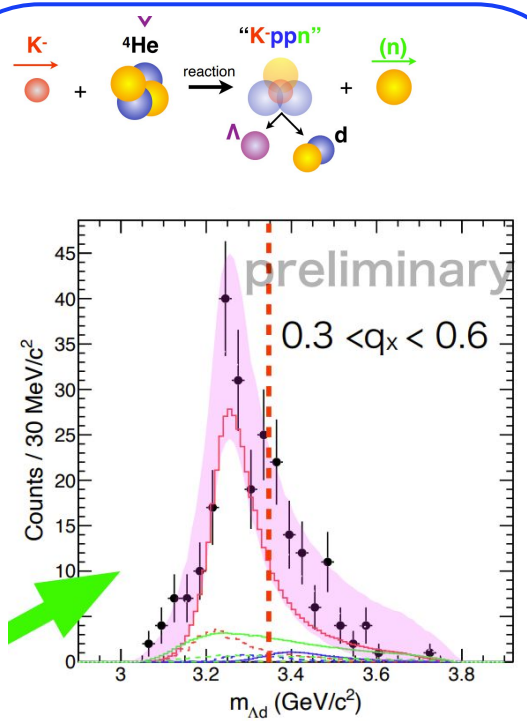
Systematic studies of kaonic nuclear states

Extended J-PARC program for kaonic nuclei studies to be realized

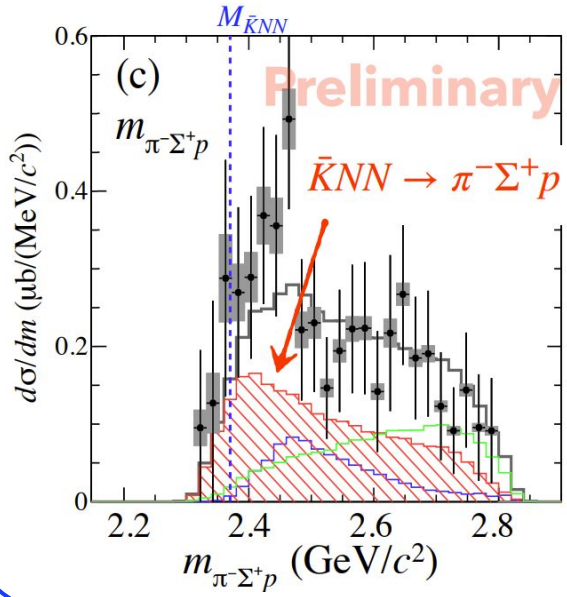
…in the meantime, new results on the pipeline ⇒



T. Hashimoto @ QNP2022

T. Yamaga @ Exotico2022

$\pi^-\Sigma^+p + n_{miss}$



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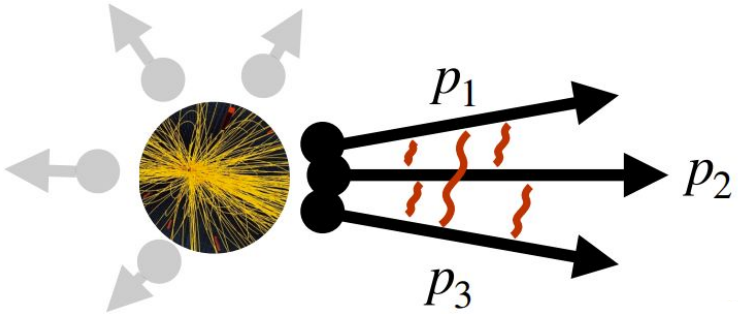
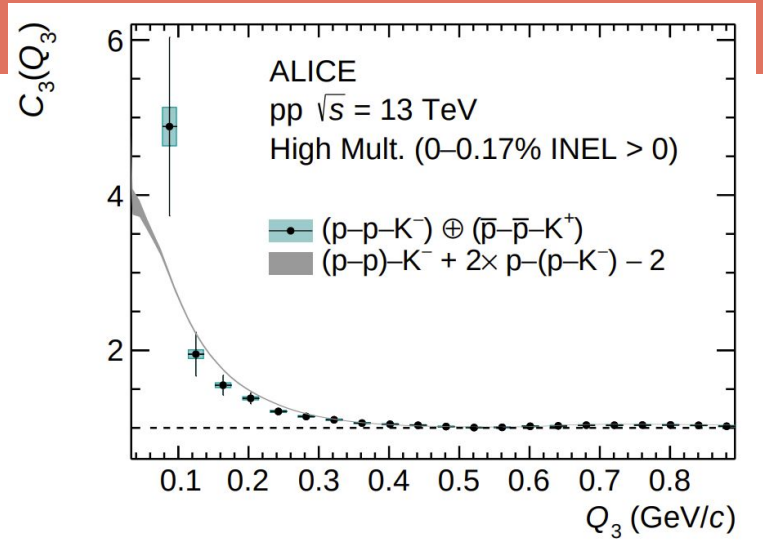
3-Body femtoscopy by ALICE



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



ALICE Coll., arXiv:2303.13448 [nucl-ex], submitted to EPJA

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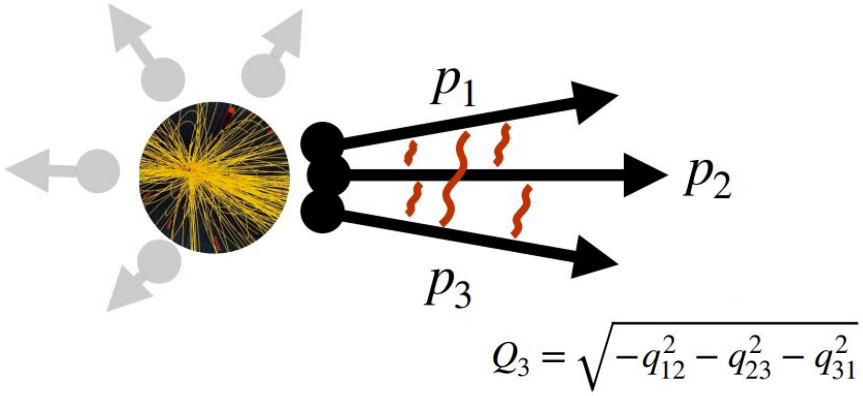
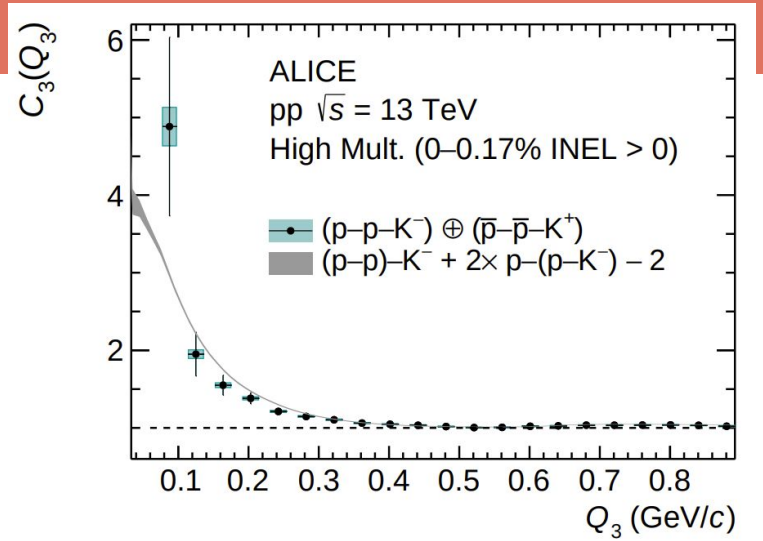
3-Body femtoscopy by ALICE





ALICE Coll., arXiv:2303.13448 [nucl-ex], submitted to EPJA

The effect of the **2-body correlations** are also experimentally determined

⇒ can be "**removed**" obtaining the three-particle cumulant. R. Kubo, J. Phys. Soc. Jpn. 17, 1100 (1962)

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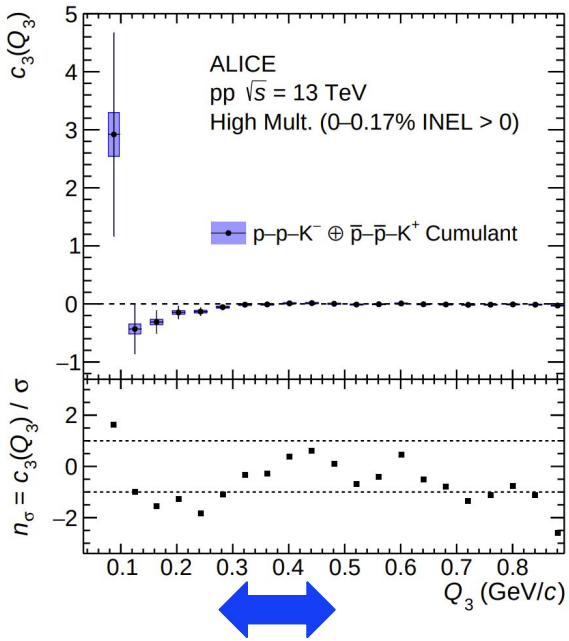
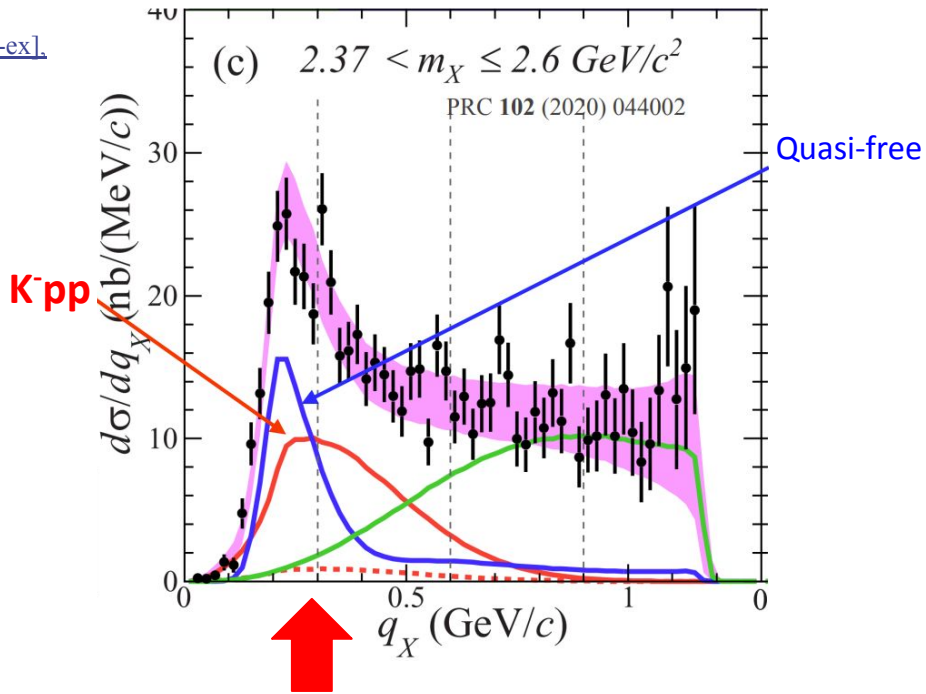
ppK$^-$ cumulant



ALICE Coll., arXiv:2303.13448 [nucl-ex], submitted to EPJA



ppK$^-$ cumulant is compatible with zero.

Explored Q_3 region overlaps with the relevant momentum region for **the K$^-$pp system**

more in L. Serksnyte talk

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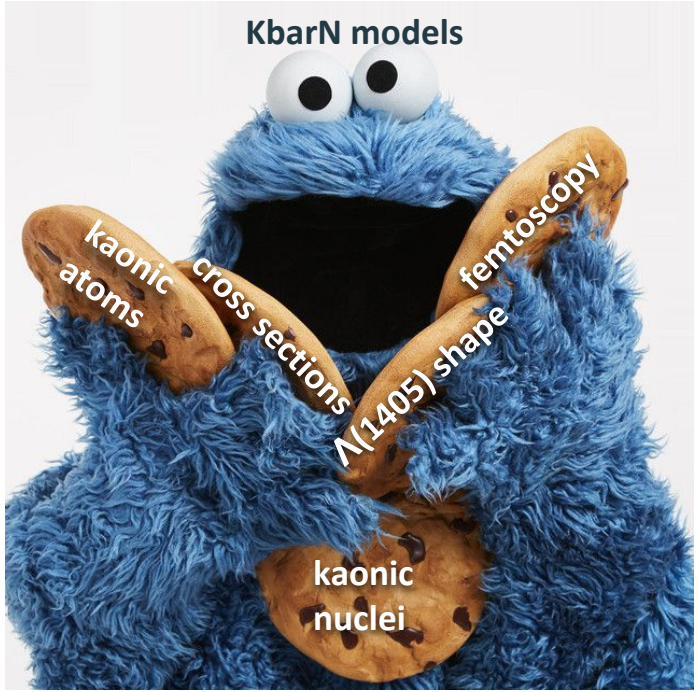
Outlook: Everything everywhere all at once

New facilities (K-Long@ J-Lab), apparati (extensive J-PARC hadron physics plan) **in the near future**

Currently collecting new data: e.g. SIDDHARTA-2 running, ALICE run 3 with more than x500 in stats.

Data will arrive from everywhere (below and above threshold!)
⇒ boost similar to the precise measurement of antiKaonic hydrogen is expected

…still on the search for a <u>description of the KbarN interaction</u> that can accommodate all the data from above to below threshold and predict how kaons behave in nuclear matter in a reliable way



you really need to eat ALL the cookies!