Unveiling the antikaon/nucleon-nuclei strong interaction dynamics in the low energy regime with SIDDHARTA-2 and AMADEUS

Raffaele Del Grande*

On behalf of the SIDDHARTA-2 and AMADEUS collaborations

MESON 2021 – 16th International Workshop on Meson Physics

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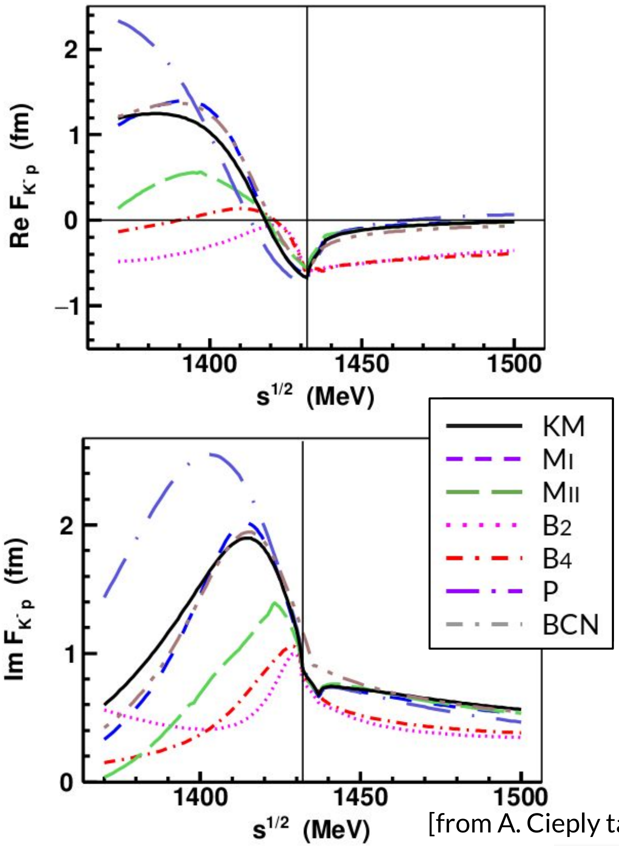
Motivation

Physics of kaonic atoms (**SIDDHARTA/SIDDHARTA-2**) and K^- absorption in nuclei (**AMADEUS**) at low-energy to extract information on:

- K^-N interaction in the energy region around the threshold
  - isospin dependent scattering amplitude
  - Λ(1405) nature
  - kaonic bound states
- K^-NN, K^-NNN, K^-NNNN (multi-nucleon) interactions
  - essential for the determination of K^--nuclei optical potential
- In medium modification of the KbarN interaction
  - partial restoration of chiral symmetry → hadrons mass origin
  - Equation of State of Neutron Stars
  - modification of Λ(1405) and Σ(1385) properties in nuclear medium

K^-p scattering amplitude



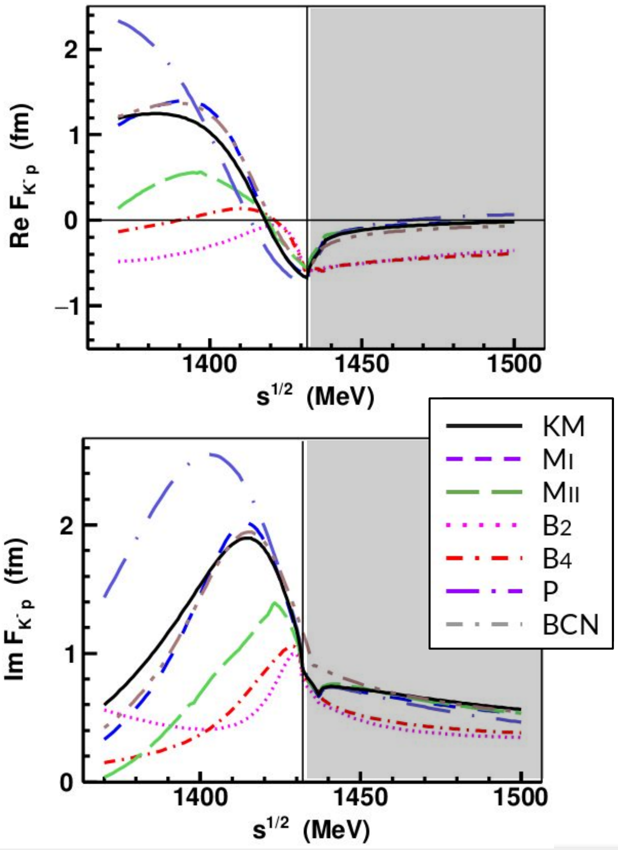
K^-p scattering amplitude in Chiral calculations

- Kyoto-Munich (KM)
  Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98
- Murcia (MI , MII)
  Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202
- Bonn (B2 , B4)
  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

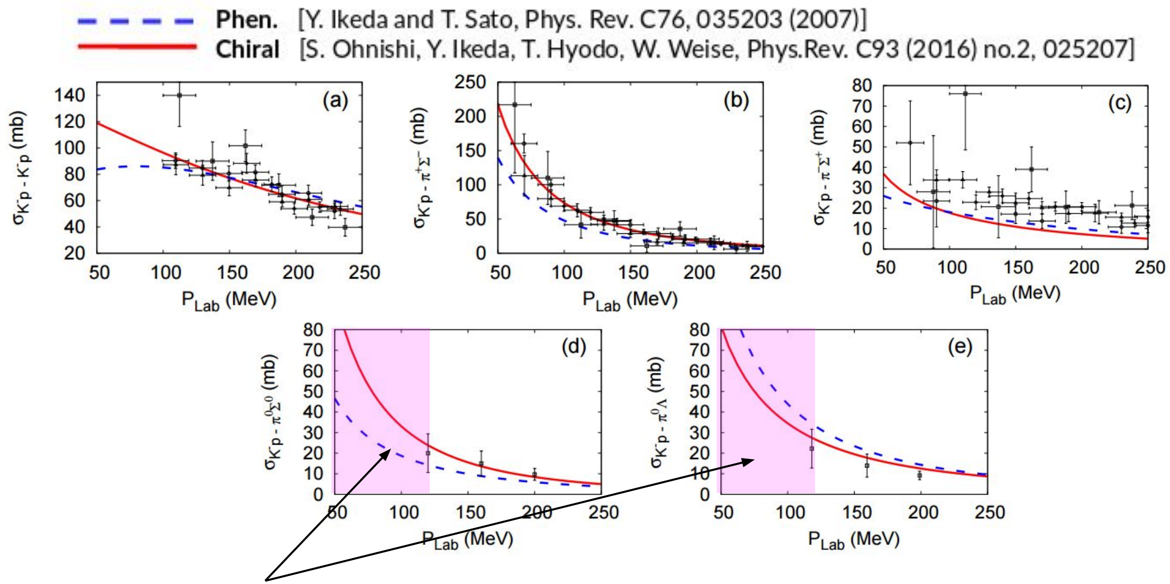
Large discrepancies in the region below threshold!

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

Experimental constraints above threshold

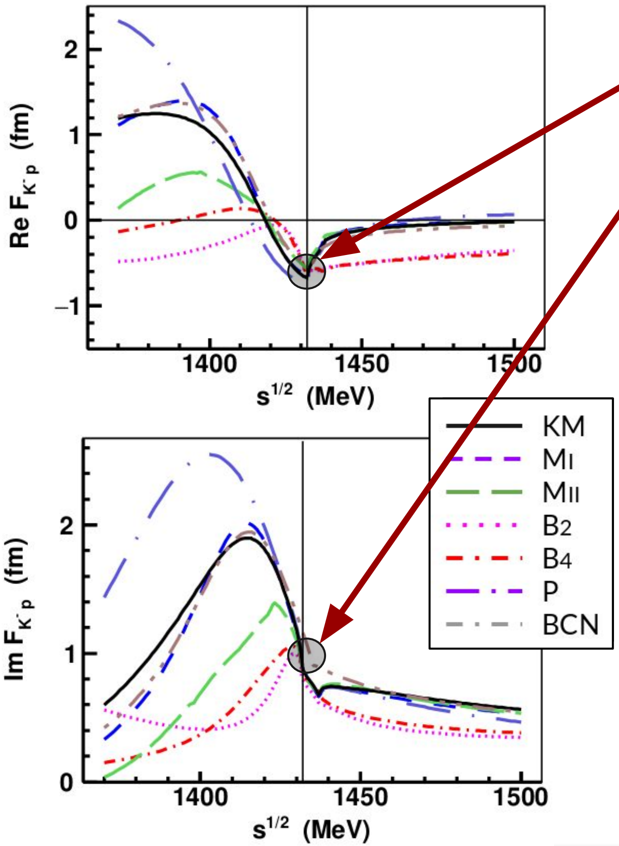


K^-p elastic and inelastic low-energy cross sections

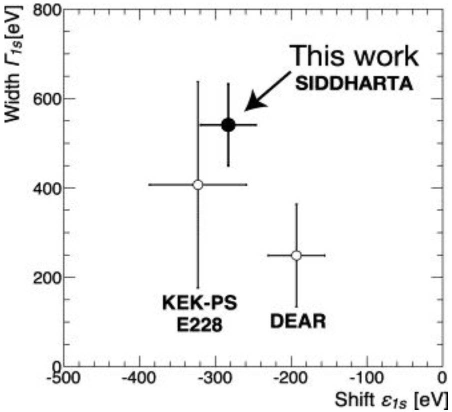


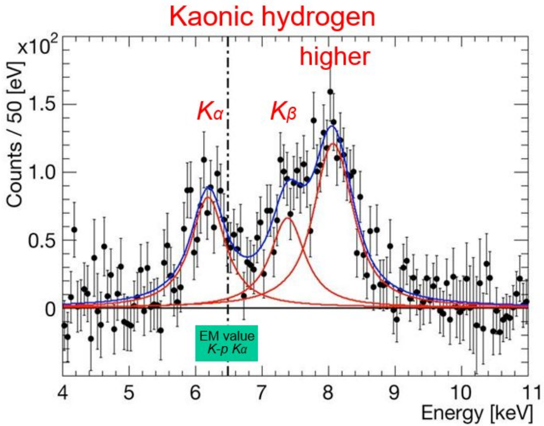
lack data for p_K < 120 MeV/c
AMADEUS can give this info

Experimental constraints at threshold



Precise SIDDHARTA measurement of kaonic hydrogen 1s level shift and width





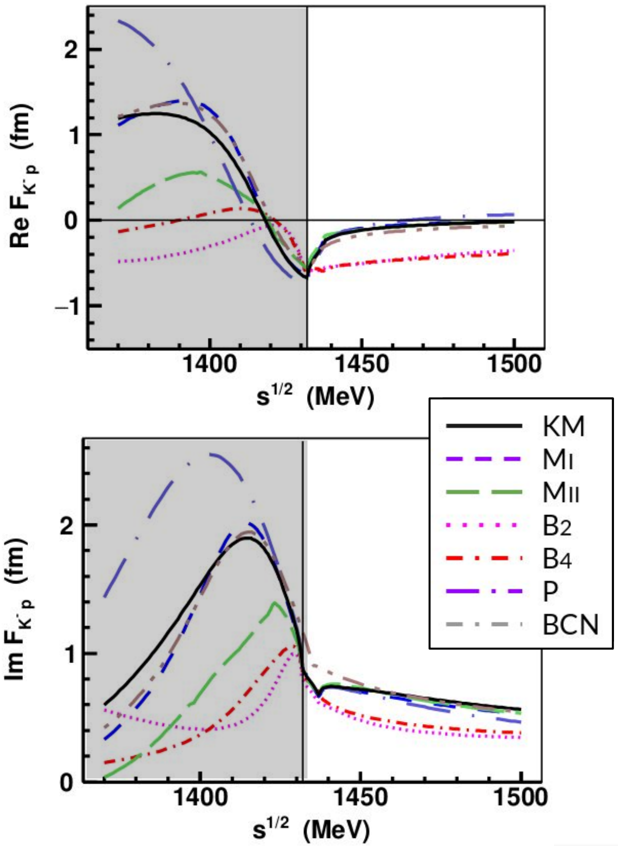
[M. Bazzi et al.. 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113]

$$\Delta E_N(1s) = 283 \pm 36(stat.) \pm 6(syst.)\ \text{eV}$$

$$\Gamma(1s) = 541 \pm 89(stat.) \pm 22(syst.)\ \text{eV}$$

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

Below threshold

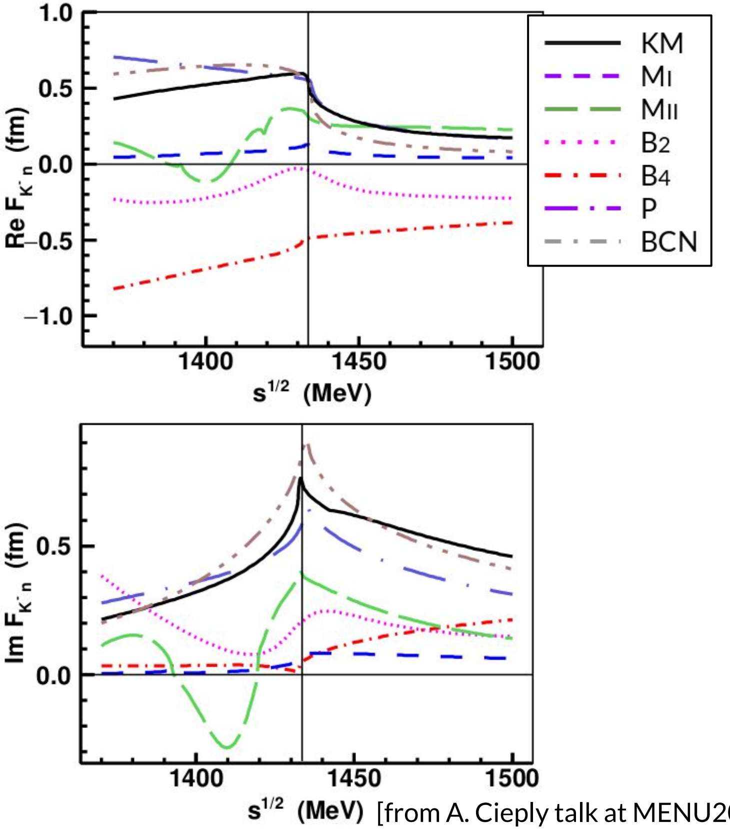


No direct amplitude measurements below threshold

...

AMADEUS CAN GIVE THIS INFO

K^-n scattering amplitude



K^-n scattering amplitude (s-wave .. non resonant) in chiral calculations

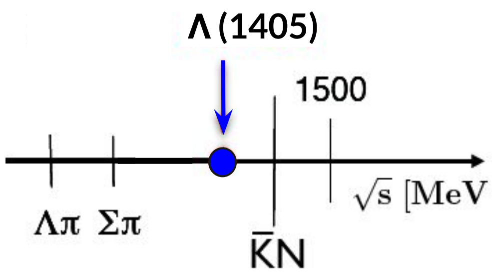
Even larger spread in I=1 channel

Experimental information is missing:

- **SIDDHARTA-2** → **first experimental constraint at threshold**
- **AMADEUS** → **first experimental constraint below threshold**

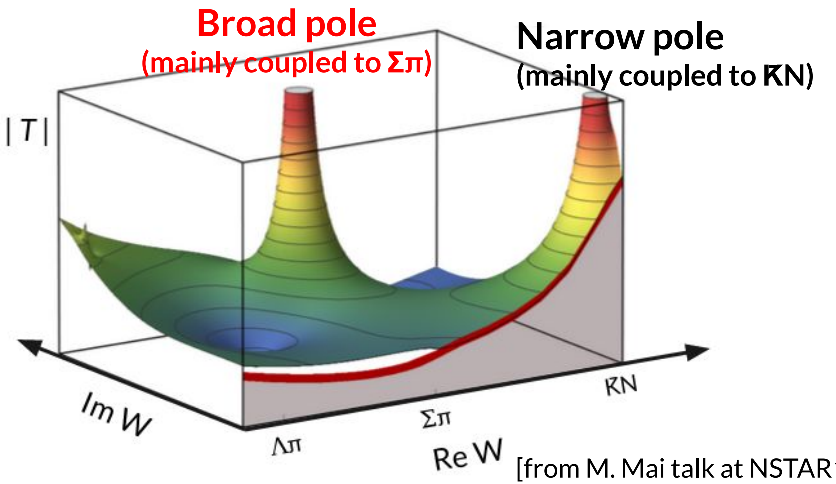
[from A. Cieply talk at MENU2019 conference, A. Cieply et al. Nucl.Phys. A954 (2016) 17-40]

Impact on Λ(1405) nature



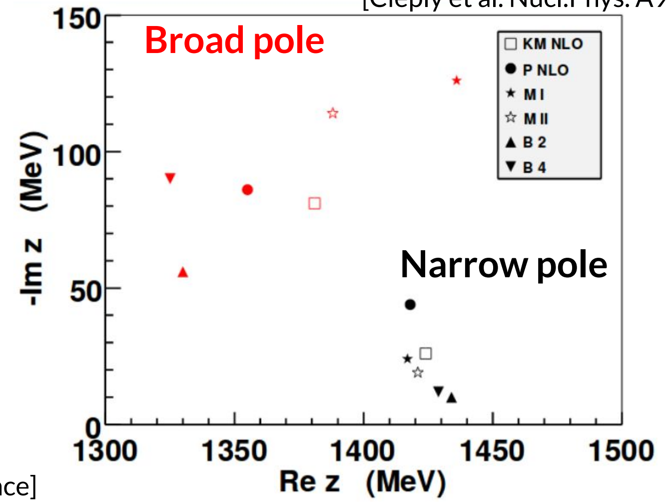
The Λ(1405) state does not fit with the simple three quarks model (*uds*) and it is commonly accepted to be **partially, a K̄N bound state.**
Decay channels: $\Sigma^{+}\pi^{-}$, $\Sigma^{-}\pi^{+}$, $\Sigma^{0}\pi^{0}$

Chiral models: dynamical origin. Two poles of the scattering amplitude → pole positions is model dependent (relative contributions not measured experimentally)



[from M. Mai talk at NSTAR19 conference]

[Cieply et al. Nucl.Phys. A954 (2016) 17-40]



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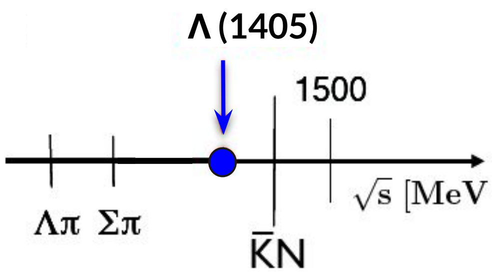

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Decay channels: $\Sigma^+\pi^-$, $\Sigma^-\pi^+$, $\Sigma^0\pi^0$

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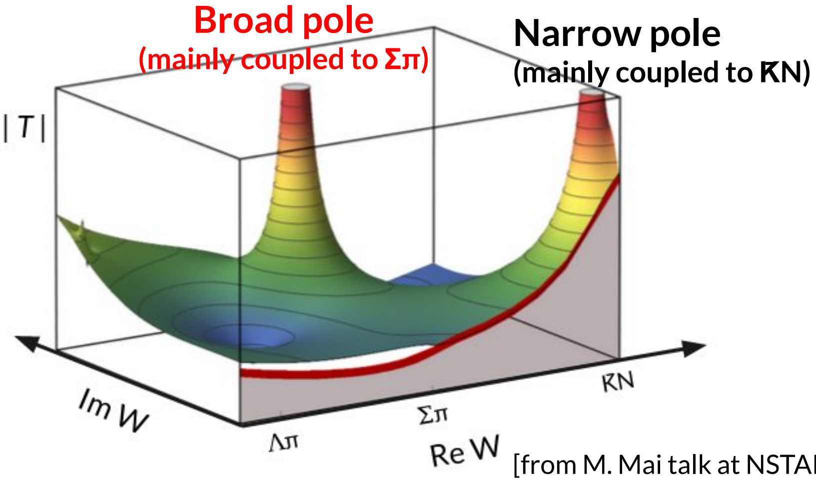

[from M. Mai talk at NSTAR19 conference]

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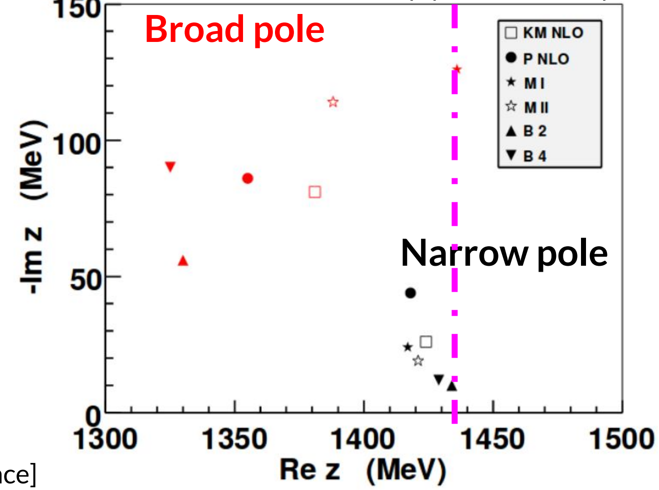
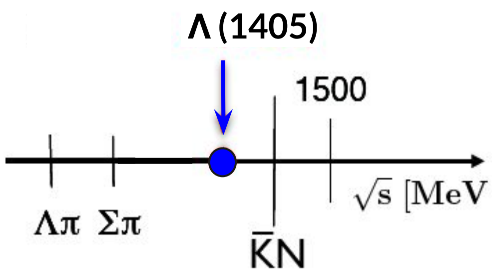
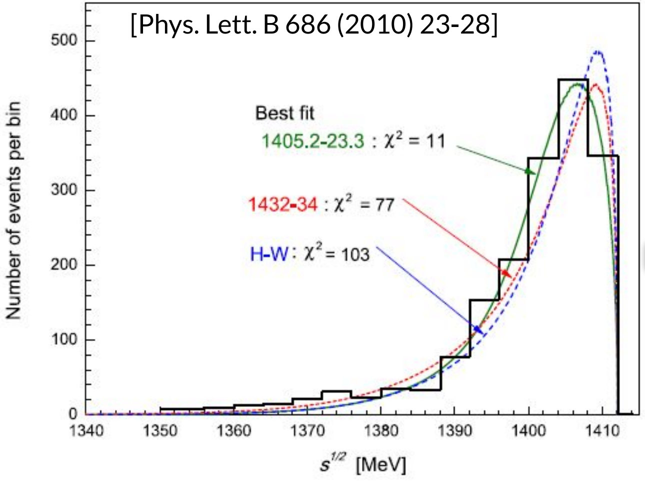


Impact on Λ(1405) nature

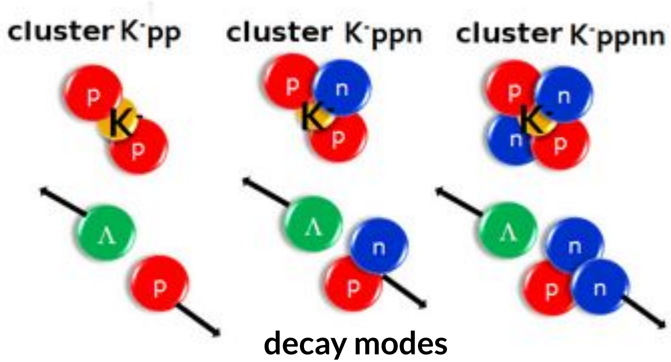


The Λ(1405) state does not fit with the simple three quarks model (*uds*) and it is commonly accepted to be **partially, a K̄N bound state**.

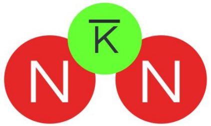
Single pole ansatz (Esmaili-Akaishi-Yamazaki phenomenological potentials model): Very strongly attractive K̄N (I = 0) interaction → existence of deeply bound kaonic bound states



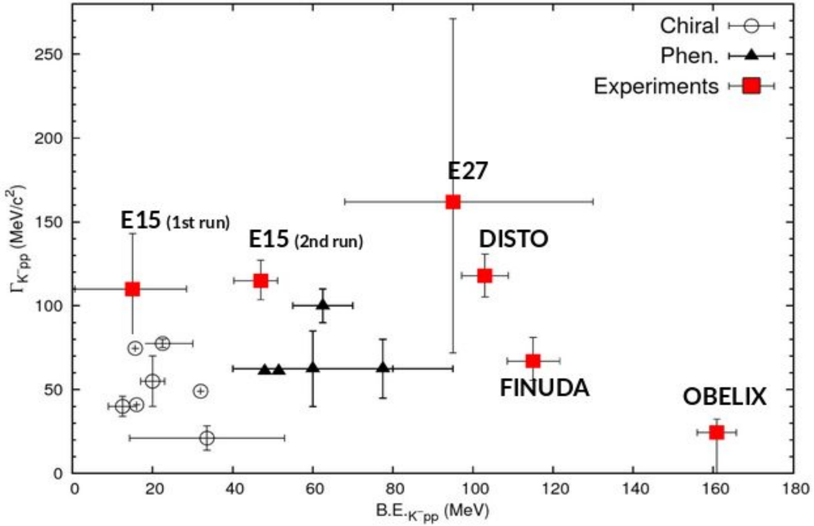
Kaonic Bound States



K^-pp bound state



- K̄N input model is critical for the theoretical interpretation
- different bound state production mechanisms give different predictions
- **E15 gives positive evidence in K^- induced reactions in flight** (theoretical interpretation by Sekihara, Oset, Ramos)



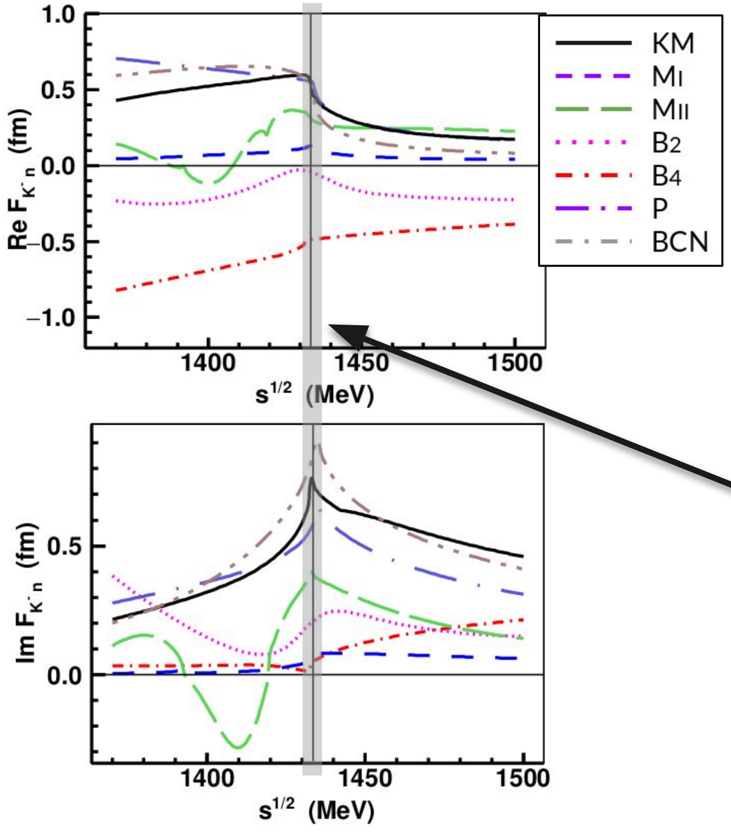
Theory

	BE (MeV)	Γ (MeV)	Reference
Dote, Hyodo, Weise	17-23	40-70	Phys.Rev.C79 (2009) 014003
Akaishi, Yamazaki	48	61	Phys.Rev.C65 (2002) 044005
Barnea, Gal, Liverts	16	41	Phys.Lett.B712 (2012) 132-137
Ikeda, Sato	60-95	45-80	Phys.Rev.C76 (2007) 035203
Ikeda, Kamano, Sato	9-16	34-46	Prog.Theor.Phys. (2010) 124(3): 533
Shevchenko, Gal, Mares	55-70	90-110	Phys.Rev.Lett.98 (2007) 082301
Revai, Shevchenko	32	49	Phys.Rev.C90 (2014) no.3, 034004
Maeda, Akaishi, Yamazaki	51.5	61	Proc.Jpn.Acad.B 89, (2013) 418
Bicudo	14.2-53	13.8-28.3	Phys.Rev.D76 (2007) 031502
Bayar, Oset	15-30	75-80	Nucl.Phys.A914 (2013) 349
Wycech, Green	40-80	40-85	Phys.Rev.C79 (2009) 014001
Sekihara, Oset, Ramos	16	72	Prog.Theor.Phys. (2016) no.12, 123D03
Sekihara, Oset, Ramos	20	80	E. Oset talk at UJ Symposium 2019

Experiments

Experiment	BE (MeV)	Γ (MeV)	Reference
FINUDA	115^{+6}_{-5} (stat.) $^{+3}_{-4}$ (syst.)	67^{+14}_{-11} (stat.) $^{+2}_{-3}$ (syst.)	PRL 94 (2005), 212303
OBELIX	160.9 ± 4.9	$< 24.4 \pm 8.0$	NPA 789 (2007), 222
E549	-	-	MPLA 23 (2008), 2520
DISTO	103 ± 3 (stat.) ± 5 (syst.)	118 ± 8 (stat.) ± 10 (syst.)	PRL 104 (2010), 132502
LEPS/SPring-8	Upper Limit		PLB 728 (2014), 616
HADES	Upper Limit		PLB 742 (2015), 242
E27	95^{+18}_{-17} (stat.) $^{+30}_{-21}$ (syst.)	162^{+87}_{-45} (stat.) $^{+66}_{-78}$ (syst.)	PTEP (2015), 021D01
AMADEUS	Upper Limit		PLB 758 (2016), 134
E15	15^{+6}_{-8} (stat.) ± 12 (syst.)	110^{+19}_{-17} (stat.) ± 27 (syst.)	PTEP (2016), 051D01
E15 (2nd run)	47 ± 3 (stat.) $^{+3}_{-6}$ (syst.)	115 ± 7 (stat.) $^{+10}_{-20}$ (syst.)	PLB 789 (2019), 620

K^-n scattering amplitude



K^-n scattering amplitude (s-wave .. non resonant)
in chiral calculations

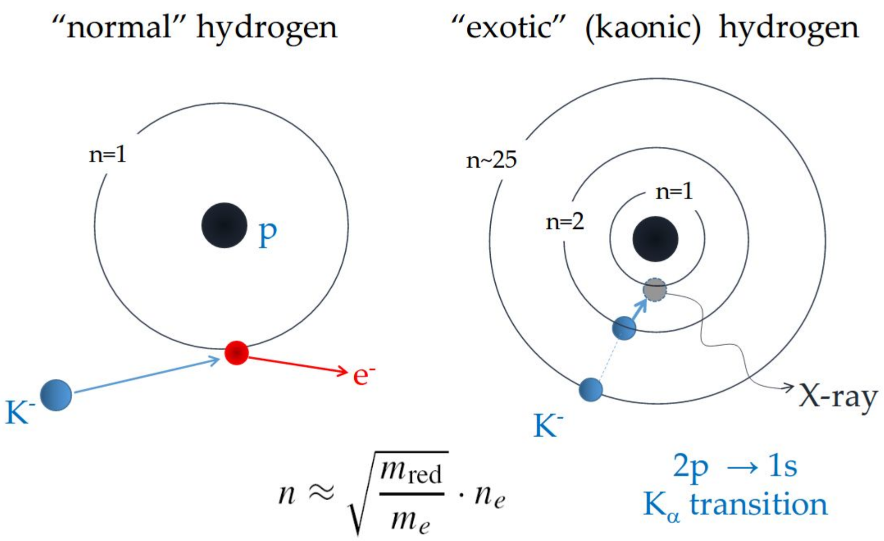
<u>Even larger spread in I=1 channel</u>

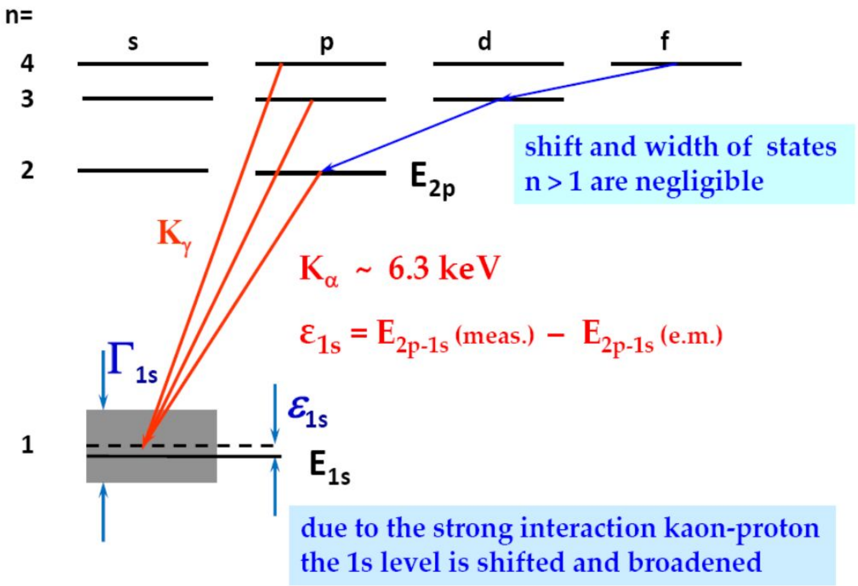
Experimental information is missing:

- **SIDDHARTA-2** → **first experimental constraint at threshold**
  - **KAONIC ATOMS**
    (kaonic deuterium + kaonic hydrogen)

- **AMADEUS** → **first experimental constraint below threshold**

Kaonic atoms





Strong interaction causes a **shifting of the energy (ε_{1s})** of the lowest atomic level from its purely electromagnetic value. Absorption reduces the lifetime of the state, so X-ray transitions to this final atomic level are **broadened (Γ_{1s})** .

Antikaon-nucleon scattering lengths

Deser-type relation connects shift ε_{1s} and width Γ_{1s} to the real and imaginary part of a_{K^-p} and a_{K^-d}:

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

done by SIDDHARTA

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

aim of SIDDHARTA-2

one can obtain the isospin dependent antikaon-nucleon scattering lengths

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

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

→ Fundamental inputs of low-energy QCD effective field theories

SIDDHARTA-2 Collaboration

SIlicon **D**rift **D**etector for **H**adronic **A**tom **R**esearch by **T**iming **A**pplications

HadronPhysics2 — Study of Strongly Interacting Matter

HadronPhysics I3 — Study of Strongly Interacting Matter

Farnesina — Ministero degli Affari Esteri e della Cooperazione Internazionale

LNF- INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
Politecnico di Milano, Italy
IFIN – HH, Bucharest, Romania
TUM, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada
Univ. Zagreb, Croatia
Helmholtz Inst. Mainz, Germany
Univ. Jagiellonian Krakow, Poland
Research Center for Electron Photon Science (ELPH), Tohoku University

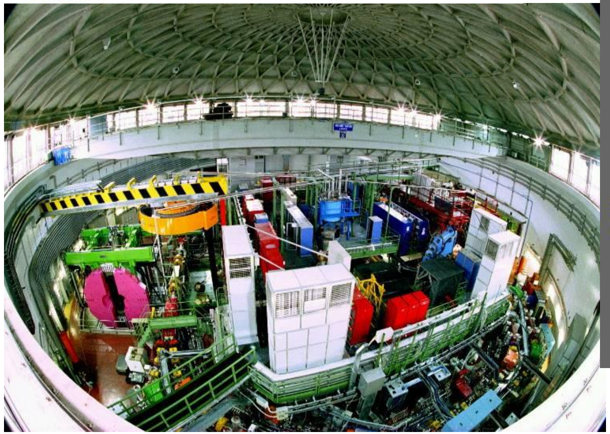
STRONG-2020

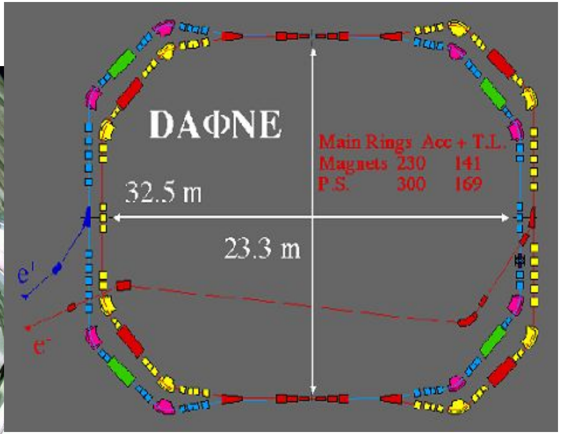
Croatian Science Foundation, research project 8570

FWF Der Wissenschaftsfonds.

DAΦNE the Φ factory

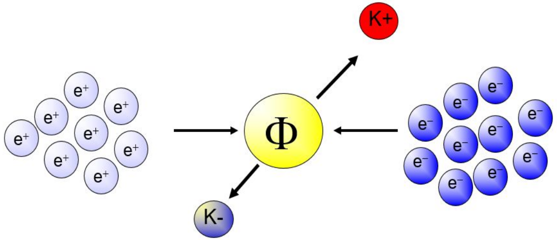
INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI





- $e^+ e^-$ at 510 MeV
- φ resonance decays at 49.2 % in $K^+ K^-$ back to back pair
- Very low momentum (≈ 127 MeV) K^- beam
- Flux of produced kaons: about 1000/second

Best low momentum K^- factory in the world

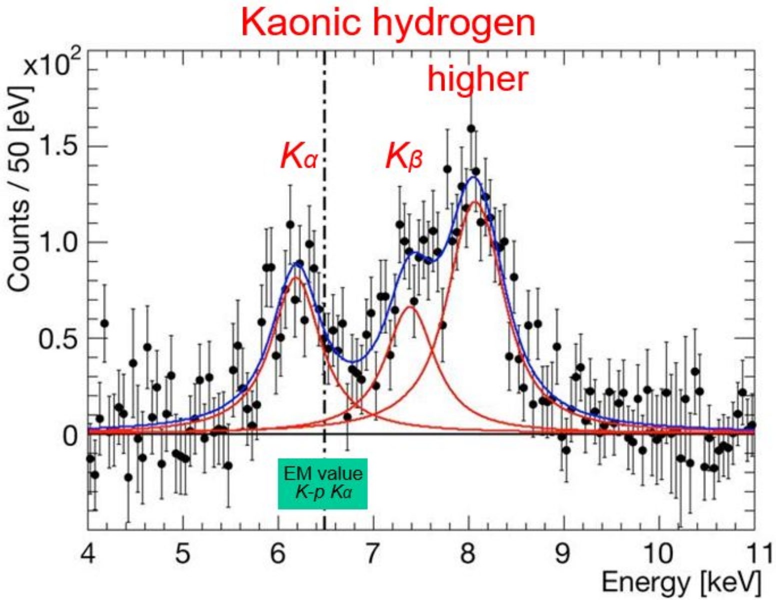


Suitable for low-energy kaon physics:
→ **Kaonic atoms** (**SIDDHARTA-2**)
→ **Kaon-nucleons/nuclei interaction** studies (**AMADEUS**)

SIDDHARTA outcomes

1. Kaonic Hydrogen

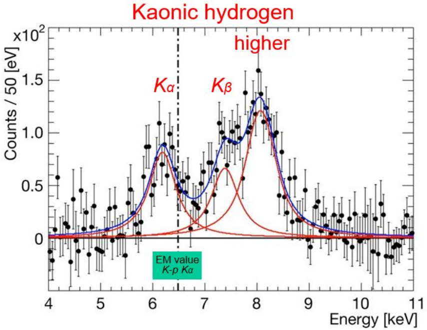
Residuals of K-p x-ray spectrum after subtraction of fitted background



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

M. Bazzi et al.. 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113

SIDDHARTA outcomes



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Residuals of K-p x-ray spectrum after subtraction of fitted background

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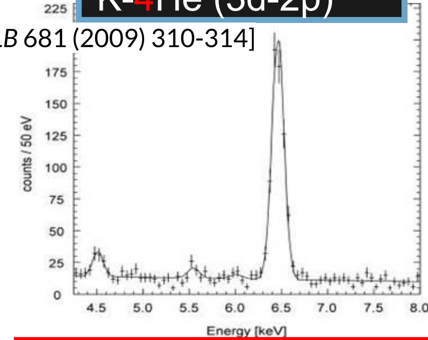
M. Bazzi et al.. 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113

2. Kaonic 4-Helium

K-4He (3d-2p)

[*PLB* 681 (2009) 310-314]

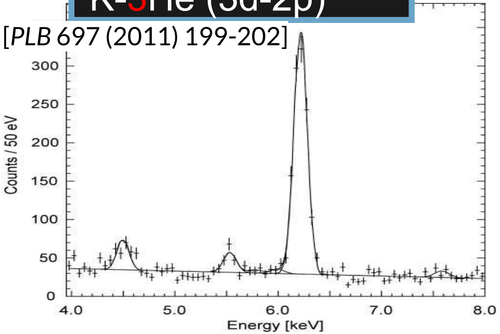


$$\Delta E_{2p} = +5 \pm 3(sta) \pm 4(sys)\ \mathrm{eV}$$

3. Kaonic 3-Helium

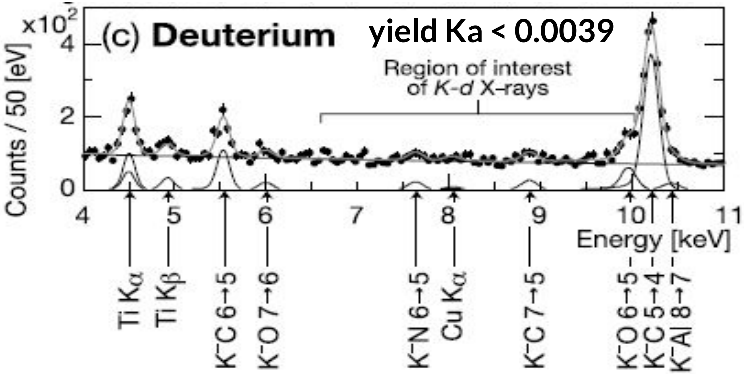
K-3He (3d-2p)

[*PLB* 697 (2011) 199-202]

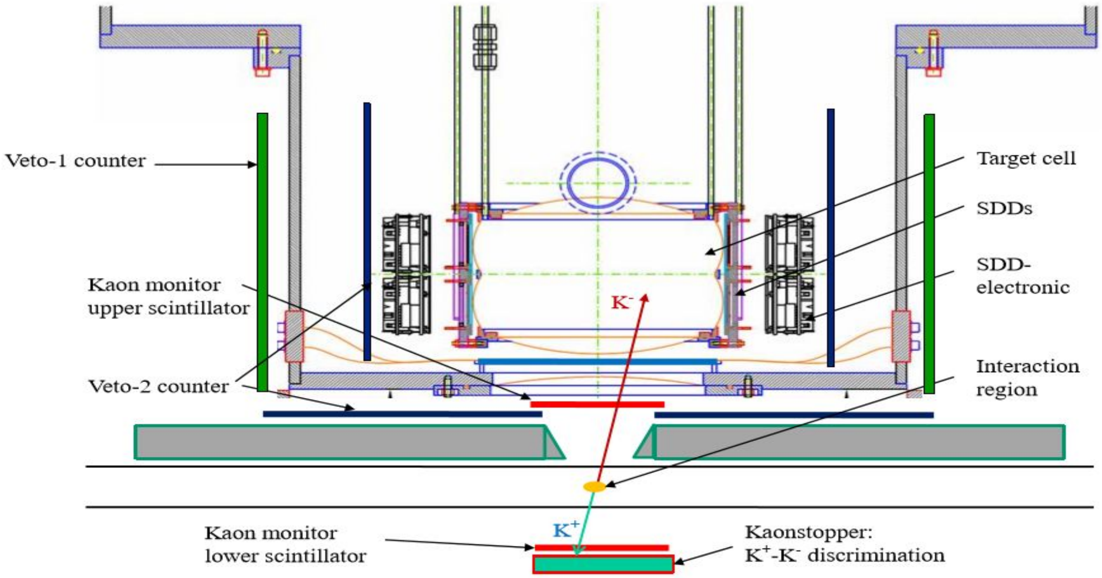


$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \mathrm{eV}$$

4. Exploratory measurement for Kd, no measured ε, Γ values



From SIDDHARTA to SIDDHARTA-2

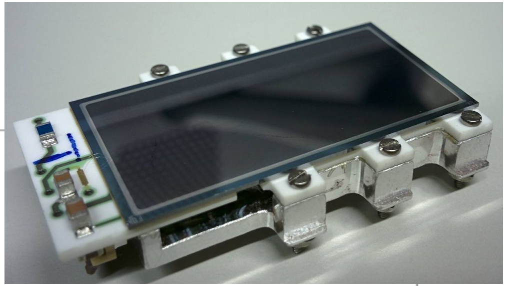


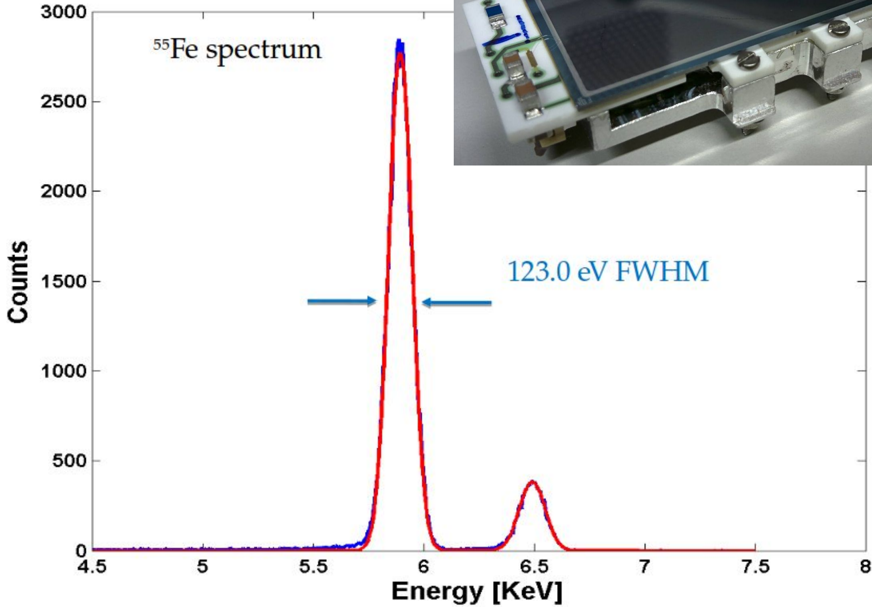
- new target cell
- new vacuum chamber
- new cooling system
- new kaon monitor/trigger
- two veto systems
- K^+ induced backg. discriminator
- new shielding structure
- new SDD detectors

With the new S/B : 3/1,
Kd measurement will be possible

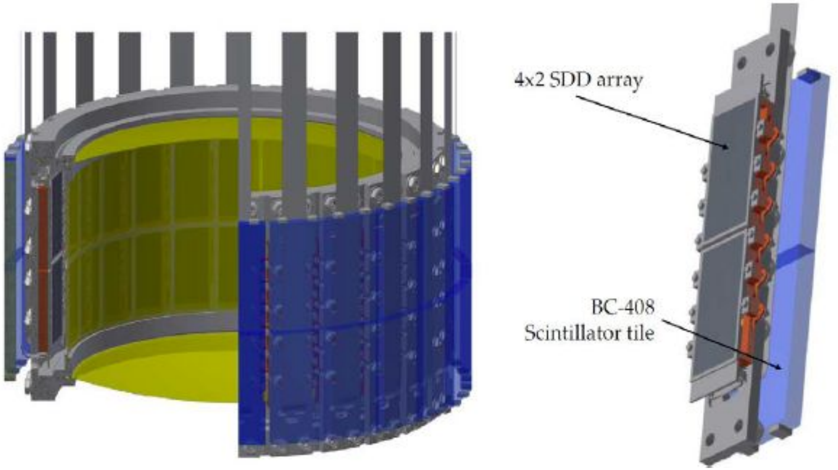
SIDDHARTA-2 new X-rays SDD detectors

new X-rays SDD detectors

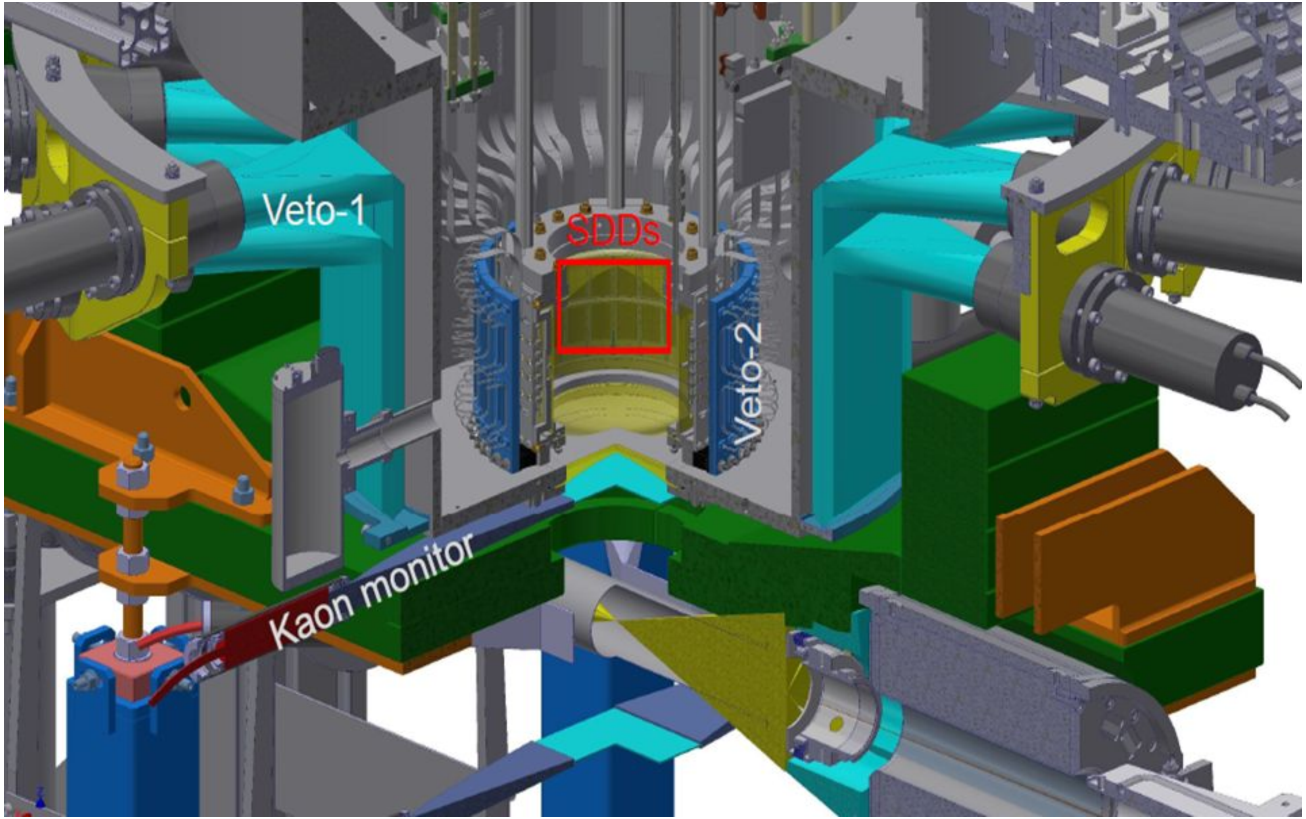




48 monolithic SDD arrays will be around the **target** with a total area of about 246 cm^2



SIDDHARTA-2



SIDDHARTA-2

Phase 1: SIDDHARTINO

We are presently in Phase 1 with SIDDHARTINO:

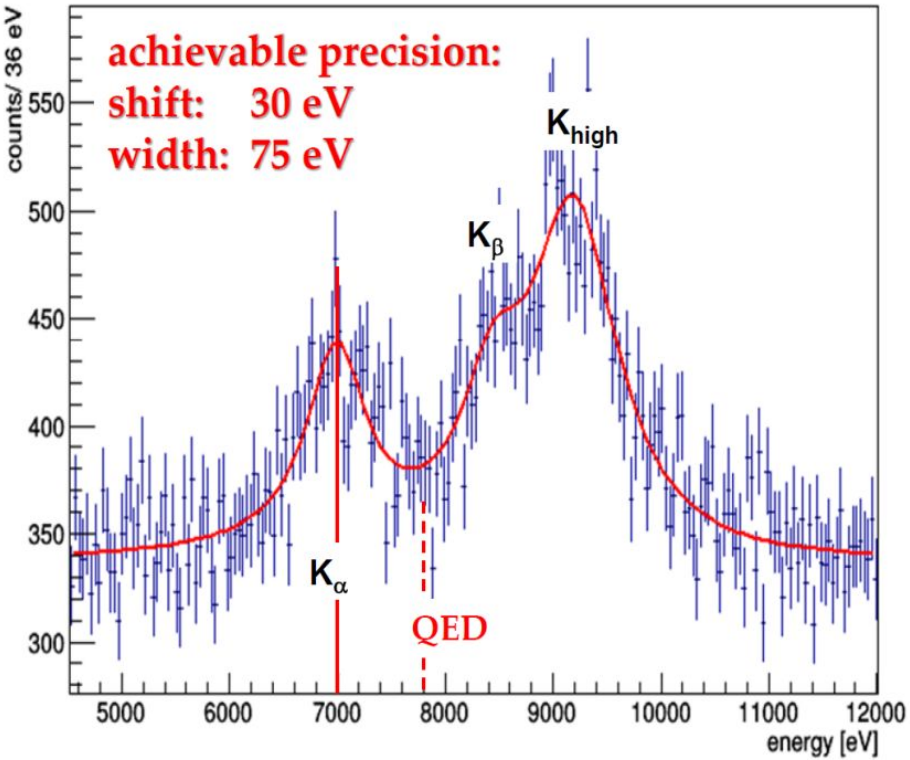
during the commissioning of DAΦNE optimization with the SIDDHARTINO setup for the K^{-}-^{4}He measurement (with 8 SDD arrays)

Aim: confirm when DAΦNE background conditions are similar to those in SIDDHARTA 2009

(Phase 2: Kd measurement)

Phase 2: SIDDHARTA-2 Kd measurement

Geant4 simulated $K^{-}d$ X-ray spectrum for 800 pb^{-1}



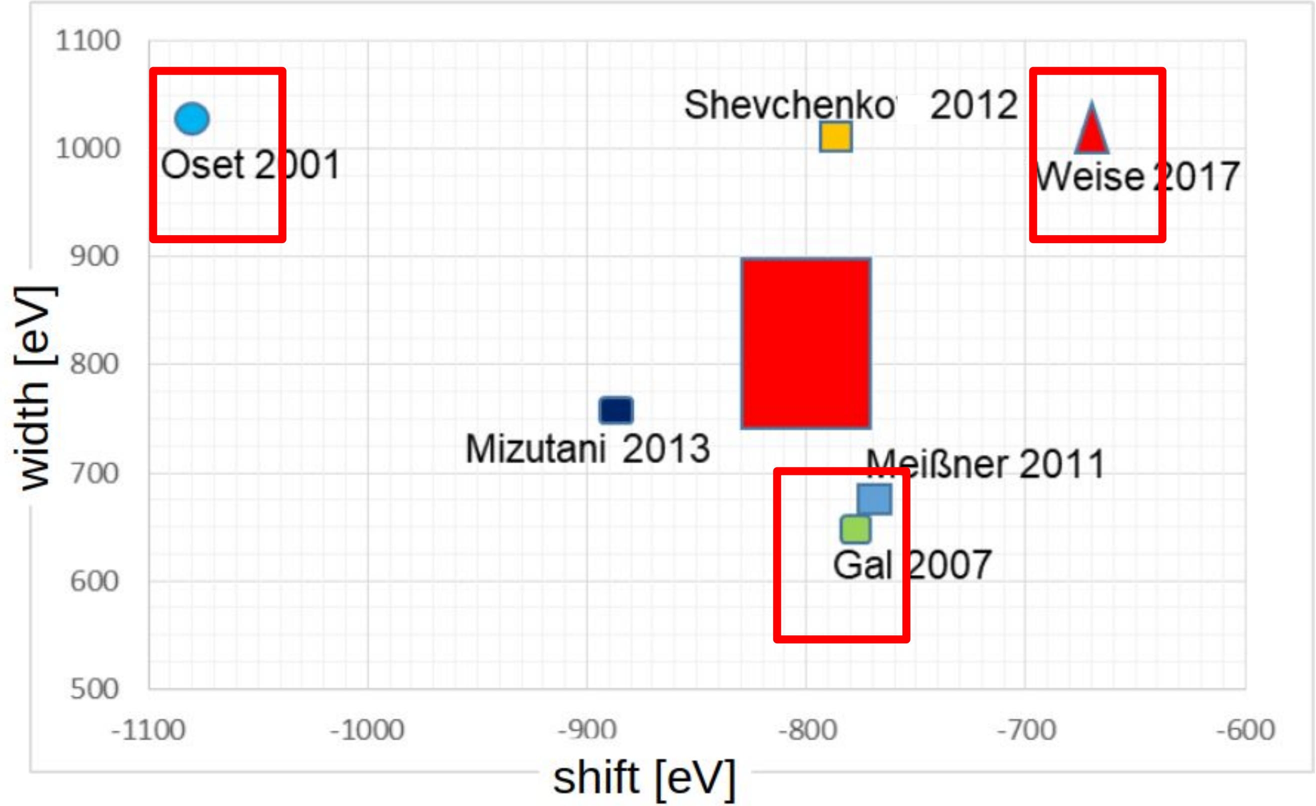
Kaonic deuterium run: 2021/2

for S/B as 1/3:

for an integrated luminosity of 800 pb^{-1}

to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as $K^{-}p$) !

Kaonic deuterium puzzle



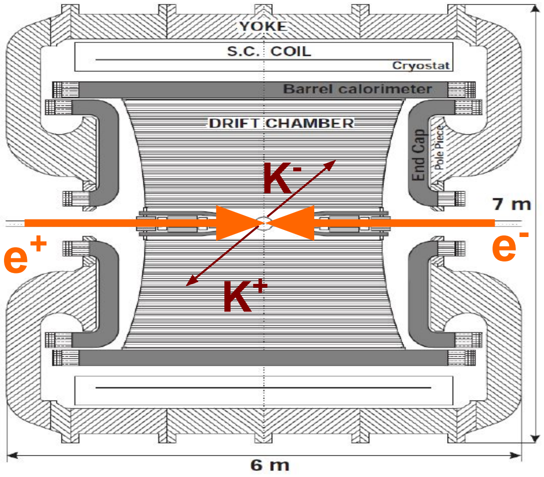
AMADEUS

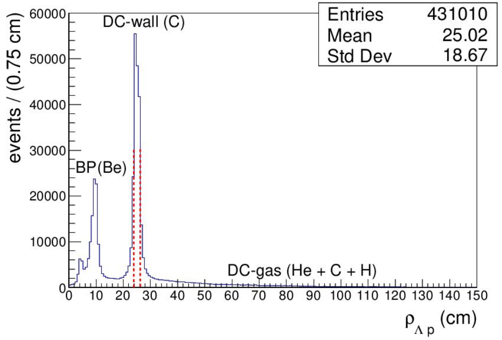
Antikaonic Matter At DAΦNE: an Experiment with Unraveling Spectroscopy

Low-energy charged kaons absorptions in light nuclei (H, ^{4}He, ^{8}Be, ^{12}C) in order to obtain unique quality information on:

1. Controversial **nature of the Λ(1405)** and **$\bar{K}$N amplitude below threshold** → **Yπ CORRELATION STUDIES** (i.e. Λπ and Σπ and final states)
2. **Low-energy** charged kaon **cross sections** for momenta of 100 MeV/c → **Yπ CORRELATION STUDIES** and **YN CORRELATION STUDIES**
3. a) Interaction of K^- with one and more nucleons (**single and multi–nucleon K^- absorption**) → **YN CORRELATION STUDIES** (i.e. Λ p, Σ^0 p, and Λ t final states)

   b) possible existence of **kaonic bound states** → **YN CORRELATION STUDIES**
4. **YN scattering** → extremely **poor experimental information** from scattering data (helpful to understand the EoS of Neutron Stars)





The KLOE detector

- Cylindrical drift chamber with a **4π geometry** and electromagnetic calorimeter
- **96% acceptance**
- optimized in the energy range of all **charged particles** involved
- **good performance** in detecting **photons and neutrons** checked by kloNe group

[M. Anelli et al., Nucl Inst. Meth. A 581, 368 (2007)]

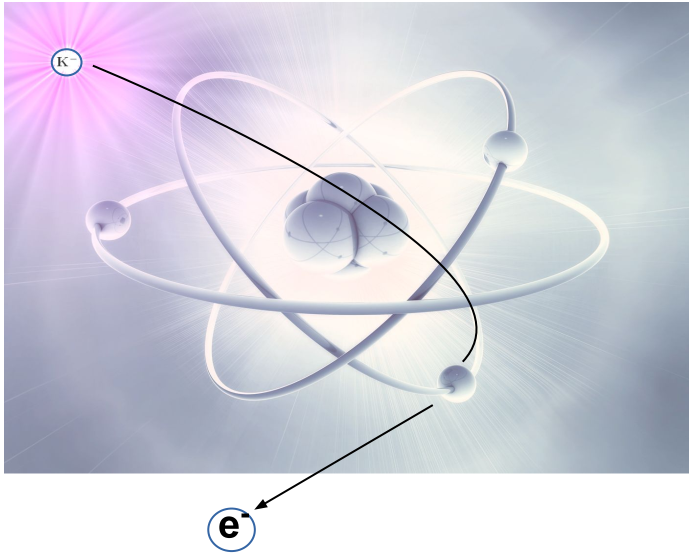
Possibility to use KLOE materials as an active target
- DC wall (750 μm C foil , 150 μm Al foil);
- DC gas (90% He, 10% C_4H_{10}).

K^- absorptions at-rest and in-flight

AT-REST

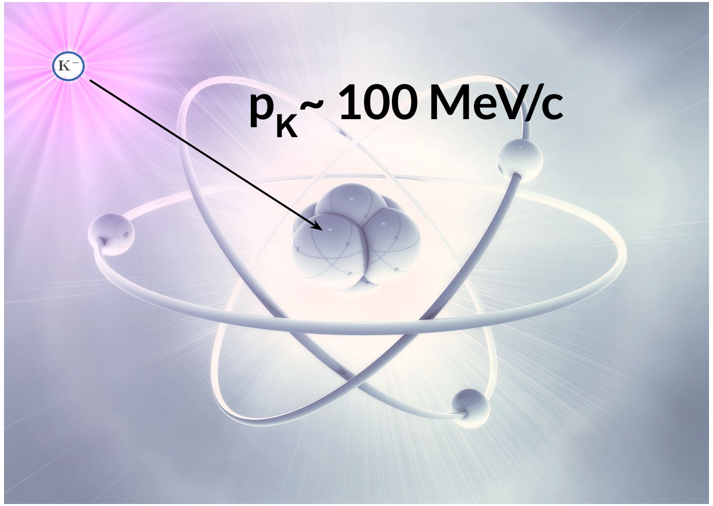
K^- absorbed from atomic orbitals

(p_K ~ 0 MeV/c)

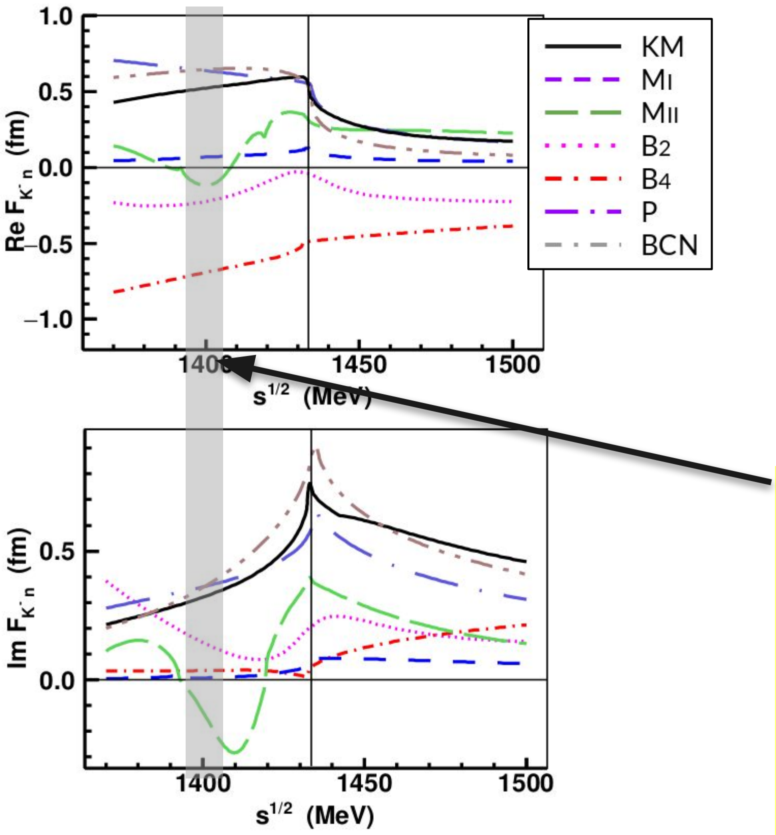


IN-FLIGHT

(p_K~ 100 MeV/c)



Experimental constraints at threshold



K^-n scattering amplitude with Chiral models

Large spread in I=1 channel

Experimental information is totally missing:

- **SIDDHARTA-2** → **first experimental constraint at threshold**

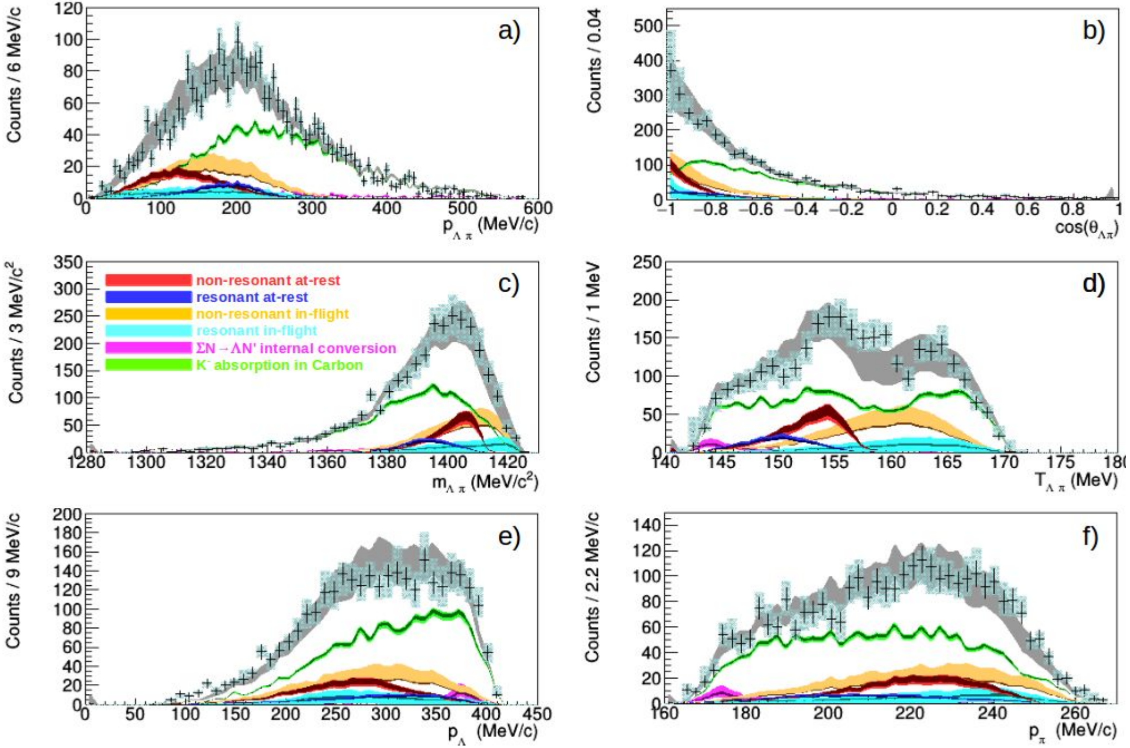
- **AMADEUS** → **First determination of the non-resonant (s-wave) transition amplitude below threshold**

  Investigated using:

  K^- "n" → $\Lambda\pi^-$ to extract **$|f^{N-R}_{\Lambda\pi}(I=1)|$**

  below threshold

Simultaneous fit : ($p_{\Lambda\pi^-}$ - $m_{\Lambda\pi^-}$ - $\cos(\theta_{\Lambda\pi^-})$)



Investigated using:

K^- "n" ^{3}He $\rightarrow$ $\Lambda\pi^-$ ^{3}He

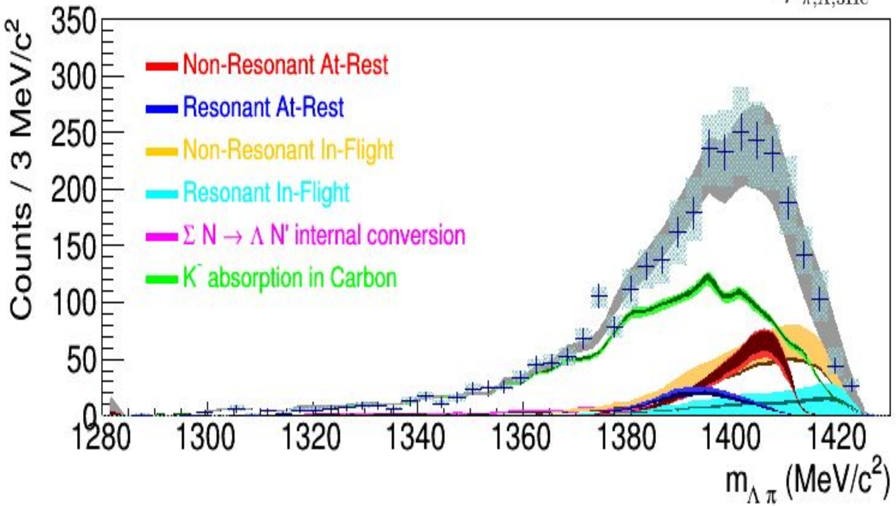
$$E_{Kn} \sim -B_n - < \frac{p^2_{\Lambda\pi}}{2\mu_{\pi,\Lambda,3He}} >$$

[K. Piscicchia, S. Wycech, L. Fabbietti et al. Phys.Lett. B782 (2018) 339-345]
[K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A 954 (2016) 75-93]

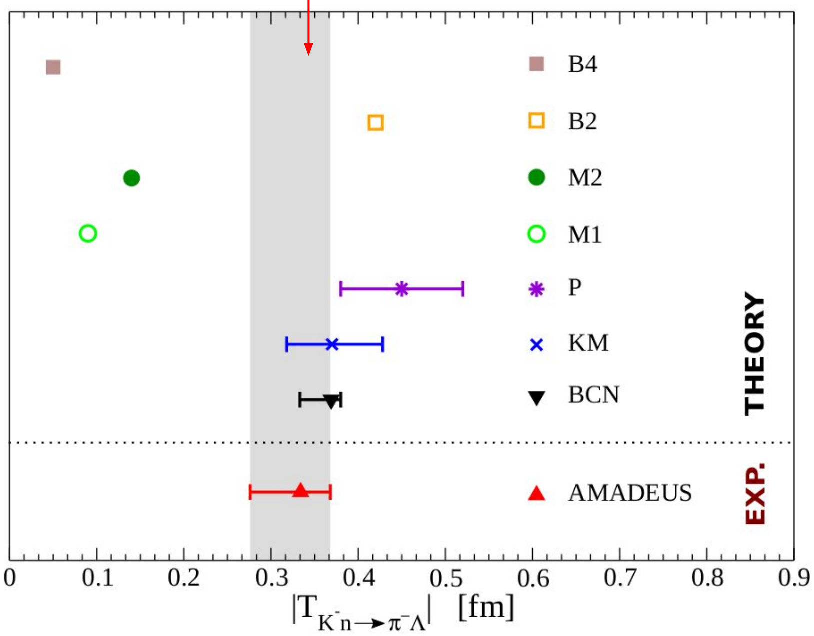
Outcome of the measurement

Investigated using: **K$^-$ "n"** ^{3}He → **Λπ$^-$** ^{3}He

$$E_{Kn} \sim -B_n - < \frac{p^2_{\Lambda\pi}}{2\mu_{\pi,\Lambda,3He}} >$$



$$|f^s_{ar}| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst})\ \mathrm{fm}\,.$$



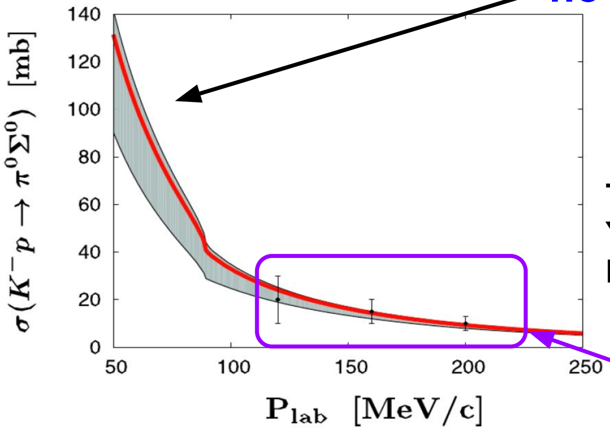
[K. Piscicchia, S. Wycech, L. Fabbietti et al. Phys.Lett. B782 (2018) 339-345]
[K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A 954 (2016) 75-93]

$K^- p \rightarrow \Sigma^0 \pi^0$ cross section at p_K~100 MeV/c

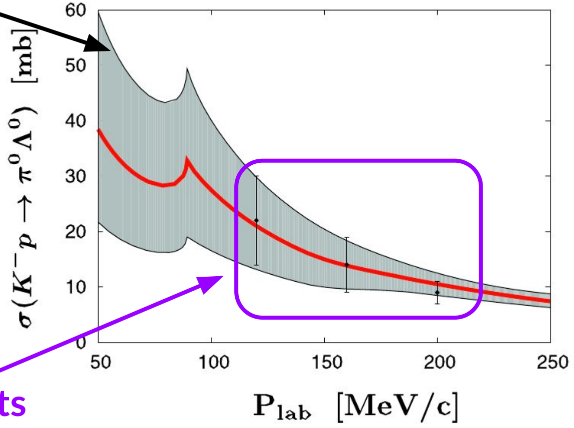
- three points in the p_K=120-200 MeV/c range (bubble chamber experiments),
- uncertainties larger than 30%,
- the $K^- p \rightarrow \Sigma^0 \pi^0$ cross sections are obtained **not directly but** on the basis of the isospin symmetry argument, from the measurement of $K^- p \rightarrow \Lambda\pi^0$ events

[W. E. Humphrey and R. R. Ross, Phys. Rev. 127 (1962) 1305]
[J. K. Kim, Columbia University Report No. NEVIS-149 (1966)]

no experimental data

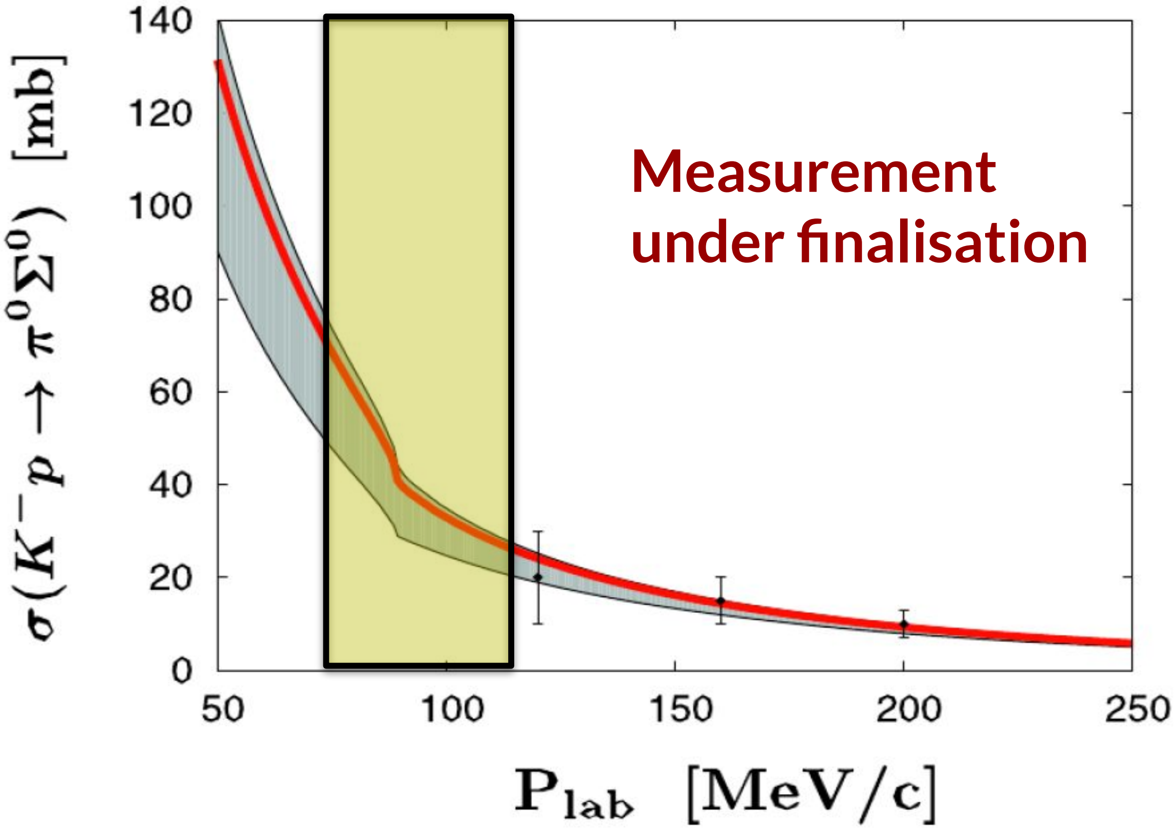


Theoretical calculation:
Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98.



bubble chamber experiments

$K^- p \to \Sigma^0 \pi^0$ cross section



Measurement under finalisation

K^- multi-nucleon absorptions

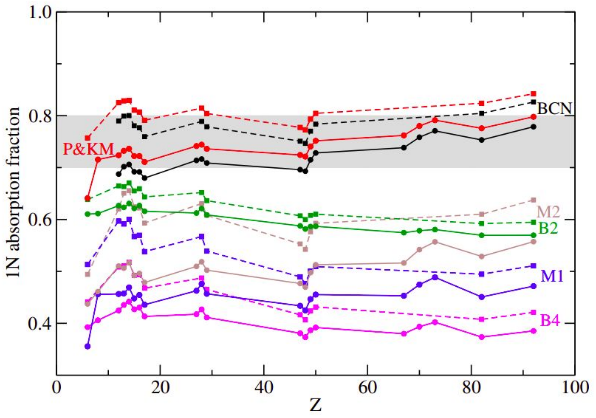
In order to fit the kaonic atoms data a K^- multi-nucleon absorption term is necessary in the K^--nuclei optical potential:

$$V_{K^-}(\rho) = V_{K^-}^{(1)}(\rho) + V_{K^-}^{(2)}(\rho)$$

→ phen. multi-nucleon term

[E. Friedman, A. Gal, Nucl. Phys. A 959, 66 (2017)]
[Hrtánková, J. & Mareš, J. Phys. Rev. C96, 015205 (2017)]

single nucleon term from chiral models



- **Single nucleon absorption (1NA):** K^- "N" → Y π
- **Two nucleon absorption (2NA):** K^- "NN" → Y N
- **Three nucleon absorption (3NA):** K^- "NNN" → Y (NN)
- **Four nucleon absorption (4NA):** K^- "NNNN" → Y (NNN)

→ multi-N processes

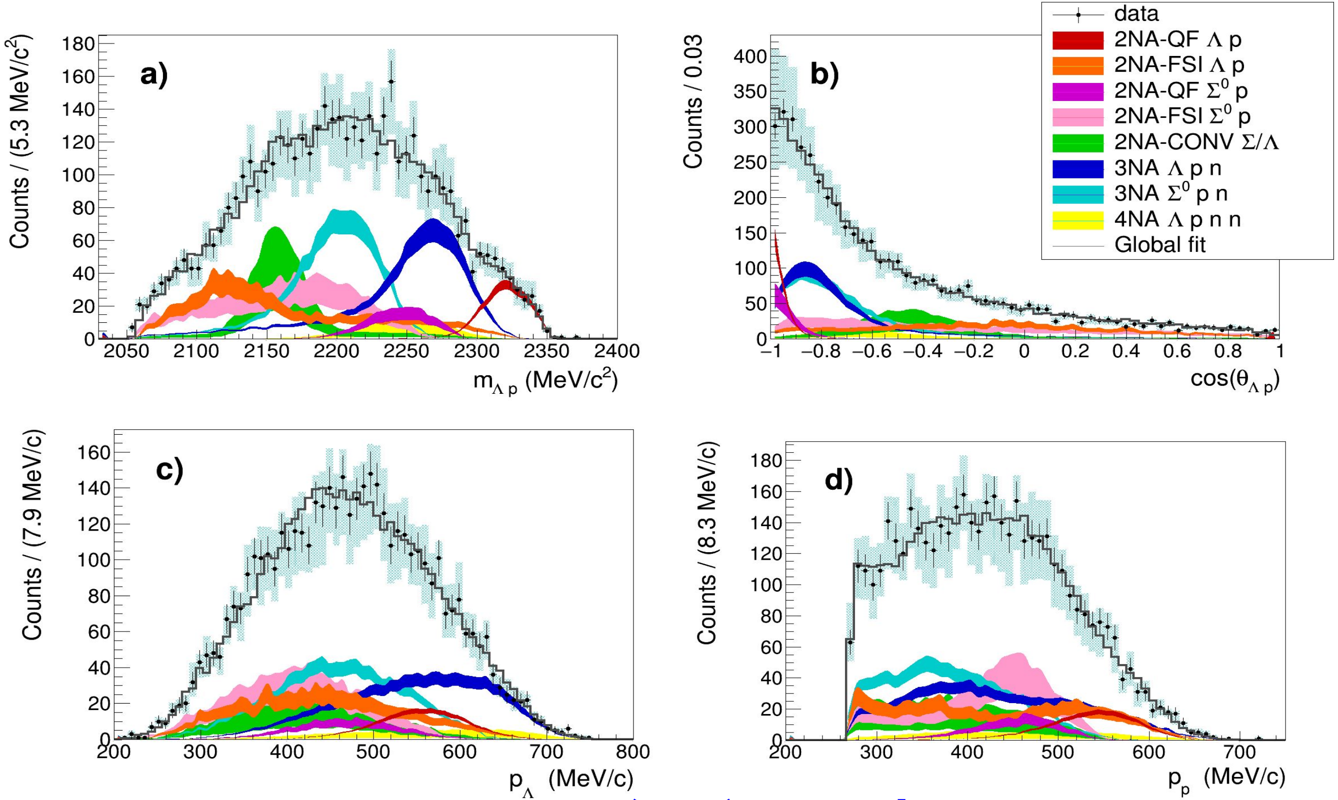
bound nucleons = "N", "NN", "NNN", "NNNN"
bound or unbound nucleons = (NN), (NNN)   Y = Λ, Σ

Λp analysis: $K^- + {}^{12}C \rightarrow \Lambda + p + R$

Simultaneous fit of:

- Λp invariant mass;
- angular correlation;
- proton momentum;
- Λ momentum.

Total reduced χ^2: $\chi^2/dof = 0.94$



[R. Del Grande, K. Piscicchia, O. Vazquez Doce et al., Eur.Phys.J. C79 (2019) no.3, 190]
[R. Del Grande, K. Piscicchia, S. Wycech, Acta Phys. Pol. B 48 (2017) 1881]

Λp analysis: K⁻ multi-nucleon absorption BRs and σ

[R. Del Grande, K. Piscicchia, O. Vazquez Doce et al., Eur.Phys.J. C79 (2019) no.3, 190]

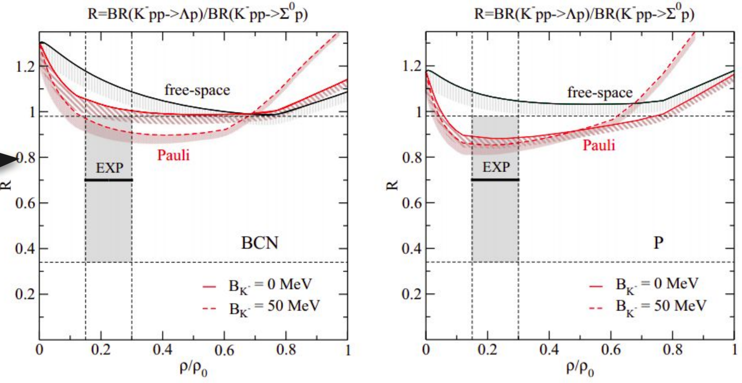
Process	Branching Ratio (%)	σ (mb)	@	p_K (MeV/c)
2NA-QF Λp	0.25 ± 0.02 (stat.) $^{+0.01}_{-0.02}$(syst.)	2.8 ± 0.3 (stat.) $^{+0.1}_{-0.2}$ (syst.)	@	128 ± 29
2NA-FSI Λp	6.2 ± 1.4(stat.) $^{+0.5}_{-0.6}$(syst.)	69 ± 15 (stat.) ± 6 (syst.)	@	128 ± 29
2NA-QF Σ^0p	0.35 ± 0.09(stat.) $^{+0.13}_{-0.06}$(syst.)	3.9 ± 1.0 (stat.) $^{+1.4}_{-0.7}$ (syst.)	@	128 ± 29
2NA-FSI Σ^0p	7.2 ± 2.2(stat.) $^{+4.2}_{-5.4}$(syst.)	80 ± 25 (stat.) $^{+46}_{-60}$ (syst.)	@	128 ± 29
2NA-CONV Σ/Λ	2.1 ± 1.2(stat.) $^{+0.9}_{-0.5}$(syst.)	-		
3NA Λpn	1.4 ± 0.2(stat.) $^{+0.1}_{-0.2}$(syst.)	15 ± 2 (stat.) ± 2 (syst.)	@	117 ± 23
3NA Σ^0pn	3.7 ± 0.4(stat.) $^{+0.2}_{-0.4}$(syst.)	41 ± 4 (stat.) $^{+2}_{-5}$ (syst.)	@	117 ± 23
4NA Λpnn	0.13 ± 0.09(stat.) $^{+0.08}_{-0.07}$(syst.)	-		
Global $\Lambda(\Sigma^0)$p	21 ± 3(stat.) $^{+5}_{-6}$(syst.)	-		

The ratio between the branching ratios of the 2NA-QF in the Λp channel and in the Σ^0p is measured to be:

$$\mathcal{R} = \frac{BR(K^- pp \to \Lambda p)}{BR(K^- pp \to \Sigma^0 p)} = 0.7 \pm 0.2(stat.)^{+0.2}_{-0.3}(syst.)$$

and the ratio between the corresponding phase spaces is $\mathcal{R}' \simeq 1.22$.

Information on the in-medium dynamics



[J. Hrtánková and A. Ramos. Phys. Rev. C, 101(3):035204, 2020]

Total BR of the K^- 2NA process in ^{12}C

Hyperon-nucleon pairs produced in K^-2NA process: **Λp Λn Σ^0p Σ^0n Σ^+n Σ^-p Σ^-n**

BCN calculation at 0.3 ρ_0 (baryon density in ^{12}C) → BR(K^-2NA → YN) = (15.4 ± 2.2) %
[J. Hrtánková and A. Ramos. Phys. Rev. C, 101(3):035204, 2020]

Process	Branching Ratio (%)
2NA-QF Λp	$0.25 \pm 0.02\,(\text{stat.})\,^{+0.01}_{-0.02}(\text{syst.})$
2NA-FSI Λp	$6.2 \pm 1.4(\text{stat.})\,^{+0.5}_{-0.6}(\text{syst.})$
2NA-QF Σ^0p	$0.35 \pm 0.09(\text{stat.})\,^{+0.13}_{-0.06}(\text{syst.})$
2NA-FSI Σ^0p	$7.2 \pm 2.2(\text{stat.})\,^{+4.2}_{-5.4}(\text{syst.})$
2NA-CONV Σ/Λ	$2.1 \pm 1.2(\text{stat.})\,^{+0.9}_{-0.5}(\text{syst.})$
3NA Λpn	$1.4 \pm 0.2(\text{stat.})\,^{+0.1}_{-0.2}(\text{syst.})$
3NA Σ^0pn	$3.7 \pm 0.4(\text{stat.})\,^{+0.2}_{-0.4}(\text{syst.})$
4NA Λpnn	$0.13 \pm 0.09(\text{stat.})\,^{+0.08}_{-0.07}(\text{syst.})$
Global Λ(Σ^0)p	$21 \pm 3(\text{stat.})\,^{+5}_{-6}(\text{syst.})$

We measure a total K^-2NA BR in ^{12}C

→ $(16.1 \pm 2.9(\text{stat.})\,^{+4.3}_{-5.5}(\text{syst.}))\%$,

Λp and Σ^0p pairs in the final state....

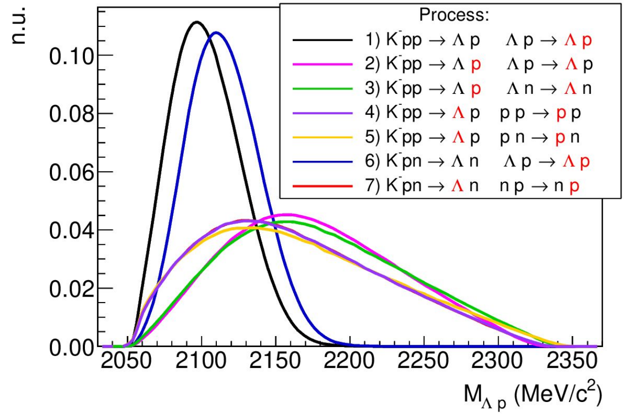
....information on the remaining YN pairs provided by FSI e Conversion reactions

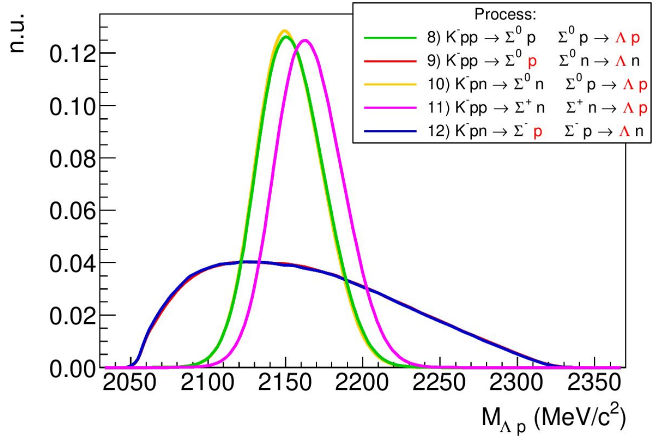
[R. Del Grande, K. Piscicchia et al., 2020 Phys. Scr.95 084012]
[R. Del Grande, K. Piscicchia et al., Few Body Syst. 62 (2021) 1, 7]

Total BR of the K^- 2NA process in ^{12}C

FSI and Conversion reactions contributing to the measured BRs

	primary interaction	secondary interaction
2NA-FSI Λp	$K^-pn \to \Lambda n$	$\Lambda p \to \Lambda p$
	$K^-pn \to \Lambda n$	$np \to np$
	$K^-pp \to \Lambda p$	$\Lambda N \to \Lambda N$
	$K^-pp \to \Lambda p$	$pN \to pN$
2NA-FSI $\Sigma^0 p$	$K^-pn \to \Sigma^0 n$	$\Sigma^0 p \to \Sigma^0 p$
	$K^-pn \to \Sigma^0 n$	$np \to np$
	$K^-pp \to \Sigma^0 p$	$\Sigma^0 N \to \Sigma^0 N$
	$K^-pp \to \Sigma^0 p$	$pN \to pN$
2NA-Conv.	$K^-pn \to \Sigma^0 n$	$\Sigma^0 p \to \Lambda p$
	$K^-pp \to \Sigma^0 p$	$\Sigma^0 p \to \Lambda p$
	$K^-pp \to \Sigma^0 p$	$\Sigma^0 n \to \Lambda n$
	$K^-pn \to \Sigma^- p$	$\Sigma^- p \to \Lambda n$
	$K^-pp \to \Sigma^+ n$	$\Sigma^+ n \to \Lambda p$





red = detected Λp pair

Total BR of the K^- 2NA process in ^{12}C

the only missing components are:

- BR($\Sigma^- n$) = (0.12 ± 0.01(syst.))%
- BR(QF-Λn + QF-$\Sigma^0 n$) = $(0.76 \pm 0.09(\text{stat.})\ ^{+0.13}_{-0.06}\ (\text{syst.}))\%$
- BR(FSI-Λn + FSI-$\Sigma^0 n$) = $(1.62 \pm 0.04(\text{stat.})\ ^{+0.22}_{-0.21}\ (\text{syst.}))\%$
- BR(no conv Σ^+ and Σ^-) = (3.04 ± 0.03(stat.) ± 0.92(syst.))%

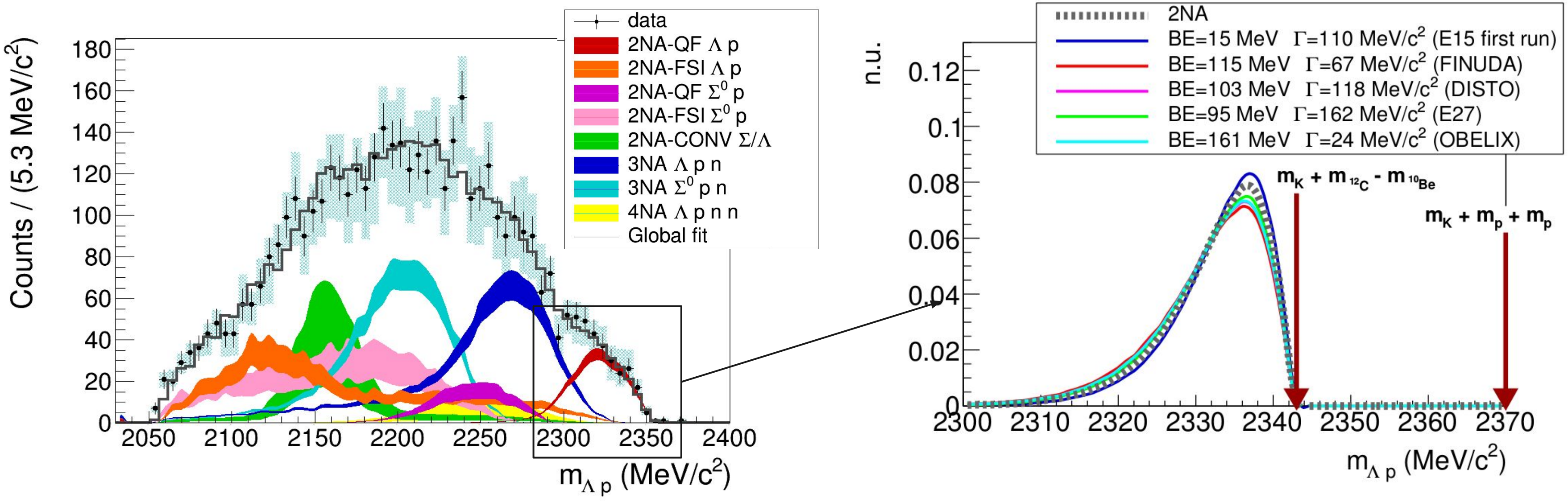
→ $(5.5 \pm 0.1(\text{stat.})\ ^{+1.0}_{-0.9}\ (\text{syst.}))\%$

[R. Del Grande, K. Piscicchia et al., 2020 Phys. Scr.95 084012]
[R. Del Grande, K. Piscicchia et al., Few Body Syst. 62 (2021) 1, 7]

Including the missing components the total BR of the K^-2NA is:

$$\mathrm{BR}(\mathrm{K^-2NA} \rightarrow \mathrm{YN}) = (21.6 \pm 2.9(\mathrm{stat.})^{+4.4}_{-5.6}(\mathrm{syst.}))\%$$

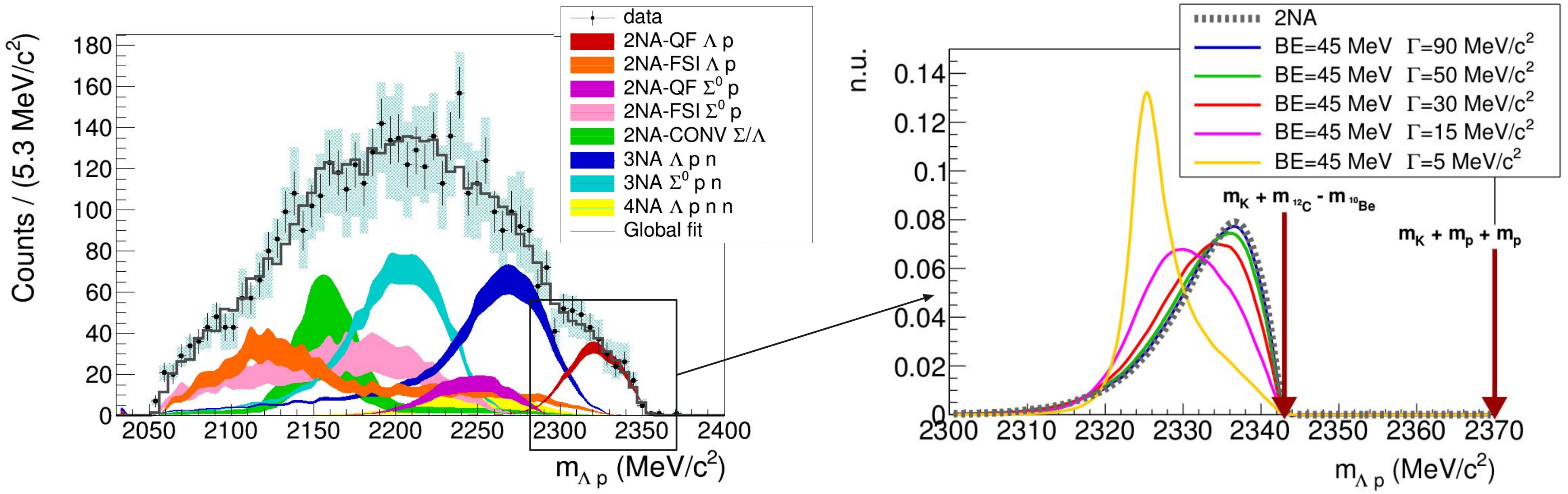
Λp analysis: K⁻ pp bound state



K^-pp bound state contribution **completely overlaps** with the K^-2NA

[R. Del Grande, K. Piscicchia, O. Vazquez Doce et al., Eur.Phys.J. C79 (2019) no.3, 190]
[R. Del Grande, K. Piscicchia, S. Wycech, Acta Phys. Pol. B 48 (2017) 1881]

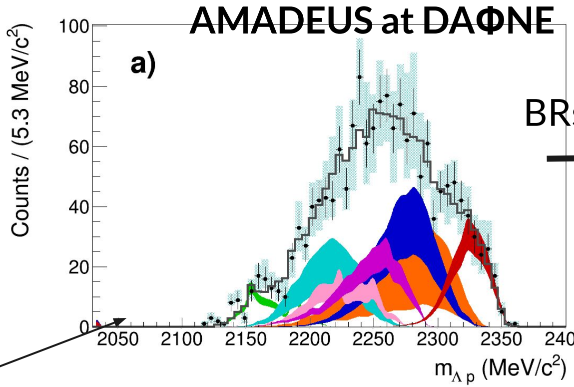
Λp analysis: K^- pp bound state



K^-pp bound state contribution **completely overlaps** with the K^-2NA

[R. Del Grande, K. Piscicchia, O. Vazquez Doce et al., Eur.Phys.J. C79 (2019) no.3, 190]
[R. Del Grande, K. Piscicchia, S. Wycech, Acta Phys. Pol. B 48 (2017) 1881]

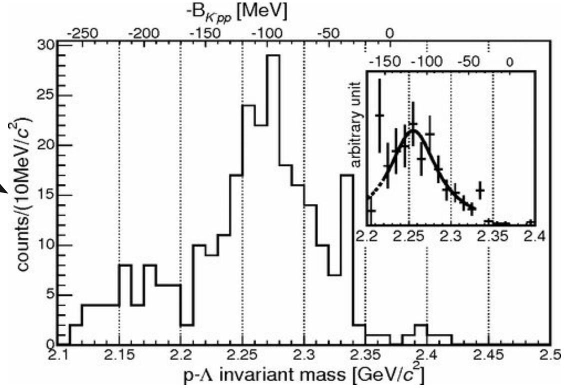
Λp analysis: K^-pp bound state search



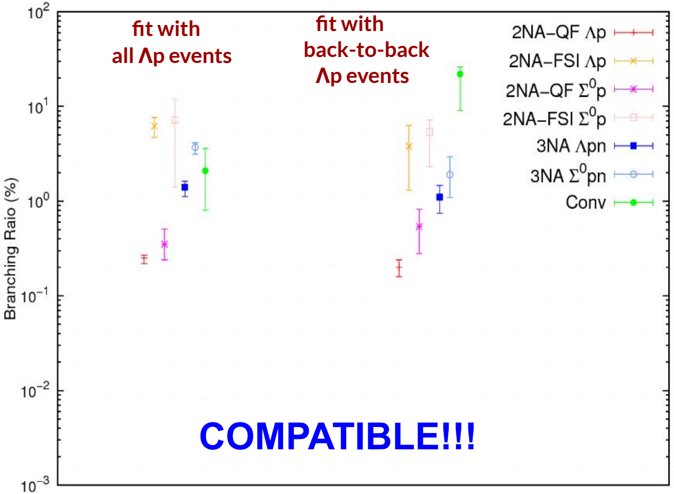
BRs evaluation

Process	Branching Ratio (%)
2NA-QF Λp	$0.20 \pm 0.04(\text{stat.}) \pm 0.02(\text{syst.})$
2NA-FSI Λp	$3.8 \pm 2.3(\text{stat.}) \pm 1.1(\text{syst.})$
2NA-QF Σ^0p	$0.54 \pm 0.20(\text{stat.}) {}^{+0.20}_{-0.16}(\text{syst.})$
2NA-FSI Σ^0p	$5.4 \pm 1.5(\text{stat.}) {}^{+1.0}_{-2.7}(\text{syst.})$
2NA-CONV Σ/Λ	$22 \pm 4(\text{stat.}) {}^{+1}_{-12}(\text{syst.})$
3NA Λpn	$1.1 \pm 0.3(\text{stat.}) \pm 0.2(\text{syst.})$
3NA Σ^0pn	$1.9 \pm 0.7(\text{stat.}) {}^{+0.8}_{-0.4}(\text{syst.})$

only **back-to-back** Λp pairs ($\cos\theta_{\Lambda p} < -0.8$)



[M. Agnello et al., Phys. Rev. Lett. 94, 212303 (2005)]



Λt analysis: Cross section and BR for 4NA

GOLDEN CHANNEL to extrapolate the K^- 4NA

$$K^- + \text{“ppnn”} \rightarrow \Lambda + t$$

Previous data:

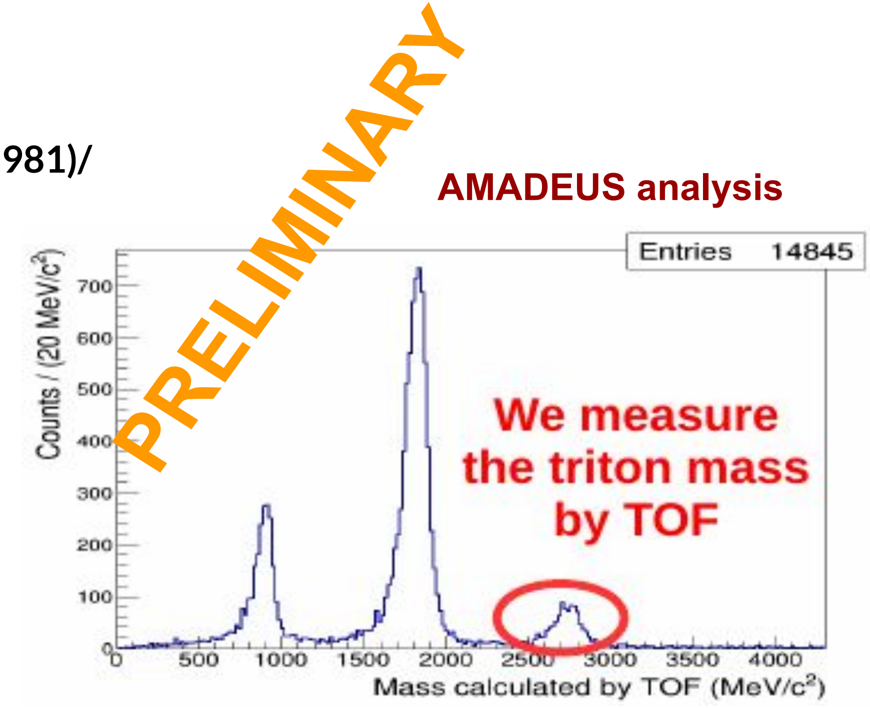
- in ^{4}**He:** bubble chamber experiment
/M. Roosen, J. H. Wickens, Il Nuovo Cimento 66, 101 (1981)/
only **3 events** compatibile with Λt kinematics found

BR$(K^- {}^4He \rightarrow \Lambda t) = (3 \pm 2) \times 10^{-4} / K^-_{stop}$ → global, no 4NA

- in **solid targets:** ^{6,7}**Li,** ^{9}**Be** (FINUDA)
/Phys. Lett. B, 229 (2008)/
40 events, only **back-to-back data**

Λt emission yield → $10^{-3} - 10^{-4} / K^-_{stop}$

→ global, no 4NA



Λt analysis: Cross section and BR for 4NA in $K^{-}\,{}^{4}He \rightarrow \Lambda t$ process

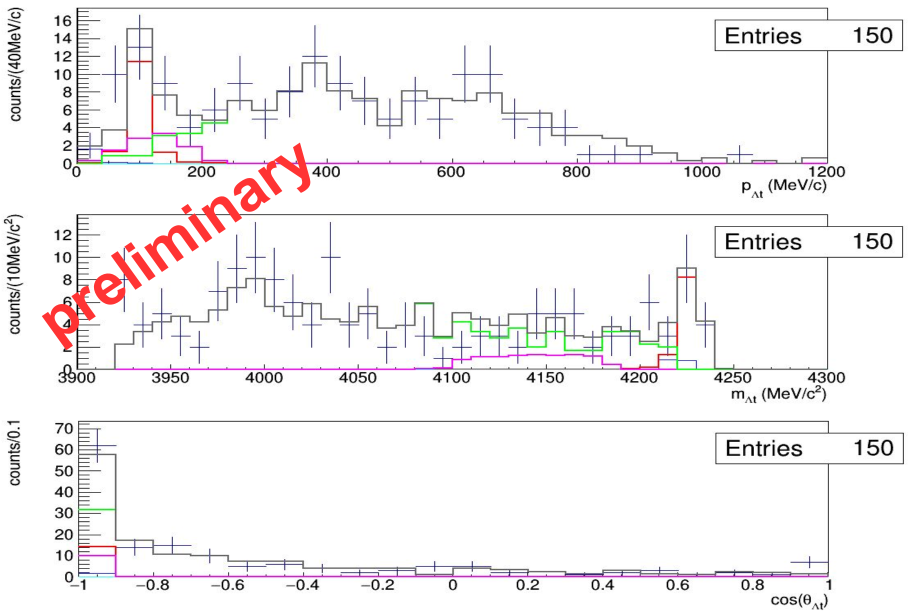
BR($K^{-}\,{}^{4}He(4NA) \rightarrow \Lambda t$) **< 2.0 × 10^-4 /K_stop (95% c. l.)**

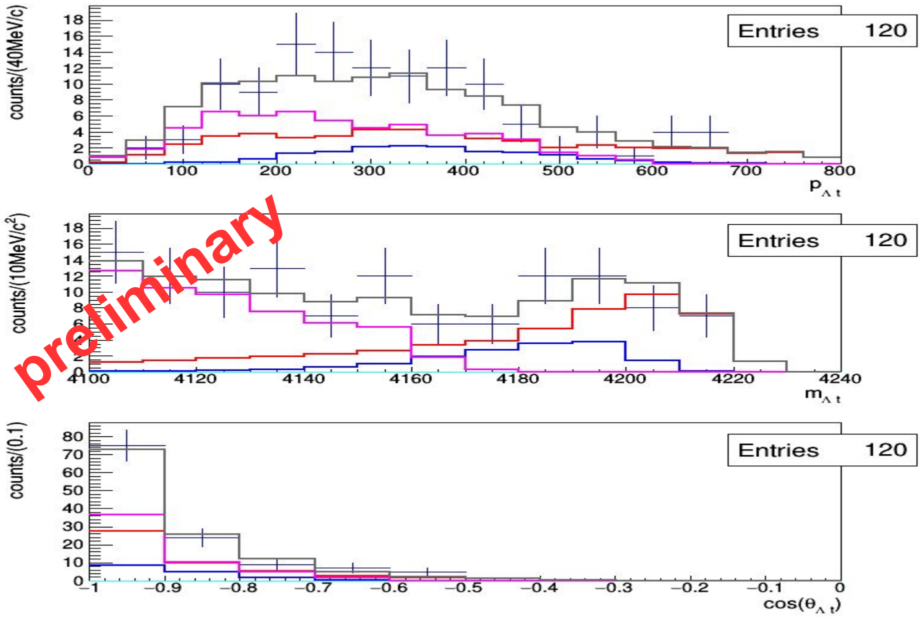
σ(100 ± 19 MeV/c) ($K^{-}\,{}^{4}He(4NA) \rightarrow \Lambda t$) =
= (0.81 ± 0.21 (stat) $^{+0.03}_{-0.04}$ **(syst)) mb**

BR($K^{-}\,{}^{12}C(4NA) \rightarrow \Lambda t\,{}^{8}Be$) **= 1.5 ± 0.5 × 10^-4 (stat) /K_stop**

σ($K^{-}\,{}^{12}C$ (4NA) $\rightarrow \Lambda t\,{}^{8}Be$) **= 0.58 ± 0.11 (stat) mb**

σ($K^{-}\,{}^{12}C$ (4NA) $\rightarrow \Sigma^{0} t\,{}^{8}Be$) **= 1.88 ± 0.35 (stat) mb**

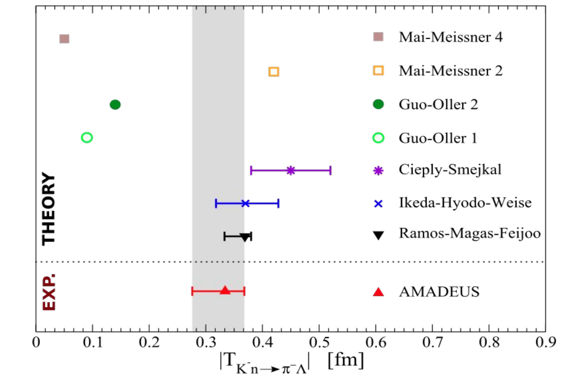




AMADEUS: Summary of the results

K^-n amplitude below threshold

$$|f^s_{ar}| = (0.334 \pm 0.018\,\text{stat}^{+0.034}_{-0.058}\text{syst})\ \text{fm}\,.$$

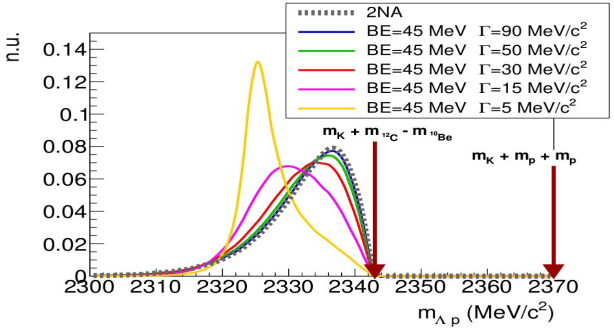


Λ p channel: 2NA, 3NA and 4NA BRs and σ

Process	Branching Ratio (%)	σ (mb)	@	p_K (MeV/c)
2NA-QF Λp	0.25 ± 0.02 (stat.) $^{+0.01}_{-0.02}$(syst.)	2.8 ± 0.3 (stat.) $^{+0.1}_{-0.2}$ (syst.)	@	128 ± 29
2NA-FSI Λp	6.2 ± 1.4(stat.) $^{+0.5}_{-0.6}$(syst.)	69 ± 15 (stat.) $\pm$ 6 (syst.)	@	128 ± 29
2NA-QF $\Sigma^0 p$	0.35 ± 0.09(stat.) $^{+0.13}_{-0.06}$(syst.)	3.9 ± 1.0 (stat.) $^{+1.4}_{-0.7}$ (syst.)	@	128 ± 29
2NA-FSI $\Sigma^0 p$	7.2 ± 2.2(stat.) $^{+4.2}_{-5.4}$(syst.)	80 ± 25 (stat.) $^{+46}_{-60}$ (syst.)	@	128 ± 29
2NA-CONV Σ/Λ	2.1 ± 1.2(stat.) $^{+0.9}_{-0.5}$(syst.)	-		
3NA Λpn	1.4 ± 0.2(stat.) $^{+0.1}_{-0.2}$(syst.)	15 ± 2 (stat.) $\pm$ 2 (syst.)	@	117 ± 23
3NA $\Sigma^0 pn$	3.7 ± 0.4(stat.) $^{+0.2}_{-0.4}$(syst.)	41 ± 4 (stat.) $^{+2}_{-5}$ (syst.)	@	117 ± 23
4NA Λpnn	0.13 ± 0.09(stat.) $^{+0.08}_{-0.07}$(syst.)	-		
Global $\Lambda(\Sigma^0)p$	21 ± 3(stat.) $^{+5}_{-6}$(syst.)	-		

Total 2NA in ^{12}C: $\mathrm{BR}(K^-2NA \to YN) = (21.6 \pm 2.9(\text{stat.})^{+4.4}_{-5.6}(\text{syst.}))\%$

K^-pp bound state

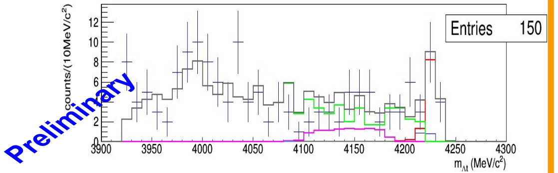


Λ t channel: 4NA BRs and σ

$\mathrm{BR}(K^-\,^4He(4NA) \to \Lambda t) < 2.0 \times 10^{-4}/K_{stop}$ (95% c. l.)

$\sigma(100 \pm 19\ \mathrm{MeV/c})\ (K^-\,^4He(4NA) \to \Lambda t) =$

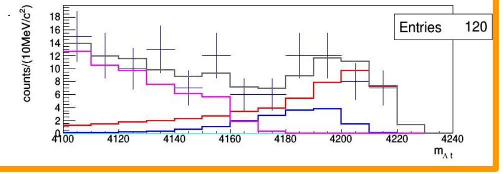
$= (0.81 \pm 0.21\ (\text{stat})\ ^{+0.03}_{-0.04}\ (\text{syst}))$ mb



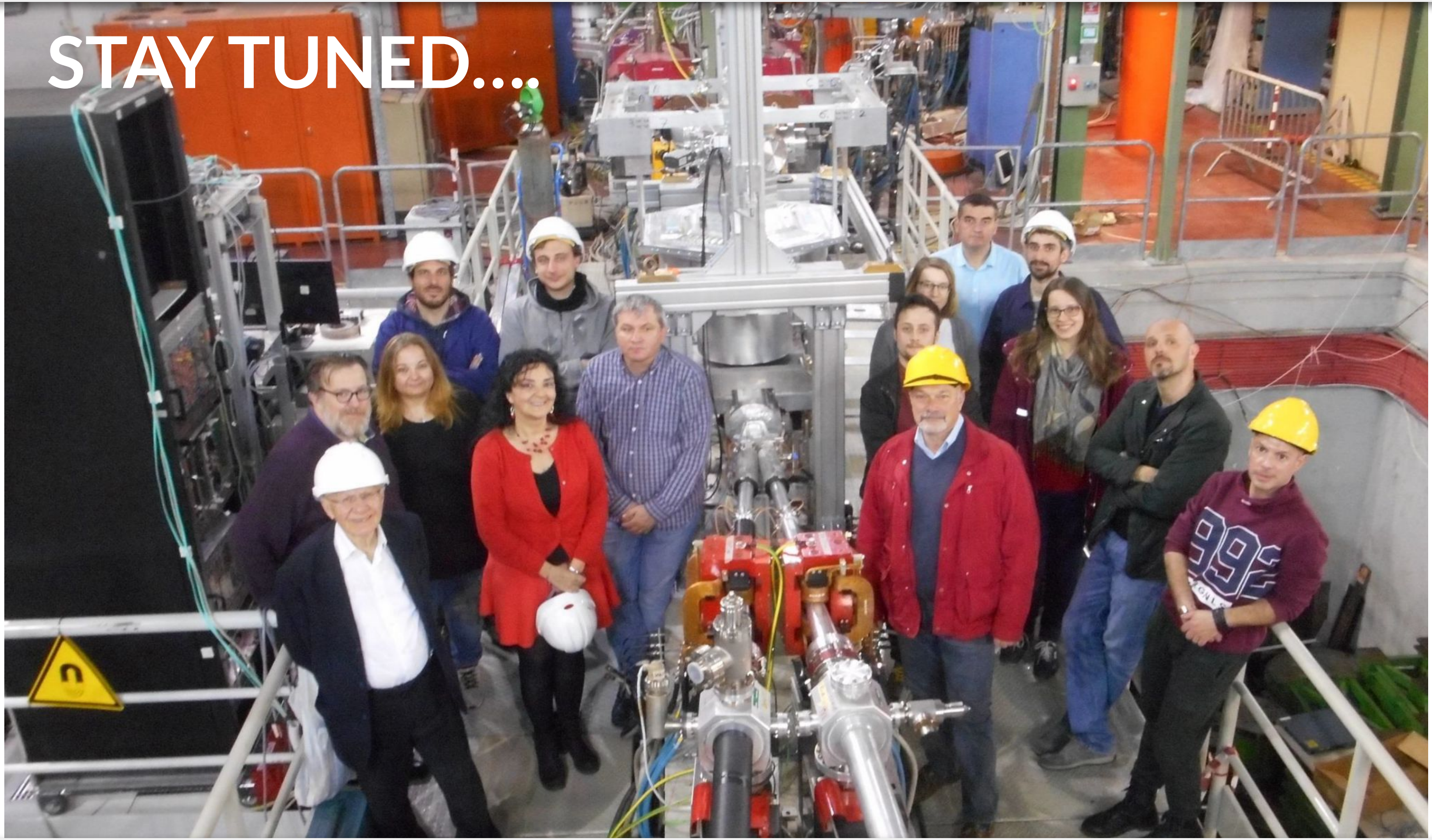
$\mathrm{BR}(K^-\,^{12}C(4NA) \to \Lambda t\,^8Be) = 1.5 \pm 0.5 \times 10^{-4}$ (stat) $/K_{stop}$

$\sigma(K^-\,^{12}C\ (4NA) \to \Lambda t\,^8Be) = 0.58 \pm 0.11$ (stat) mb

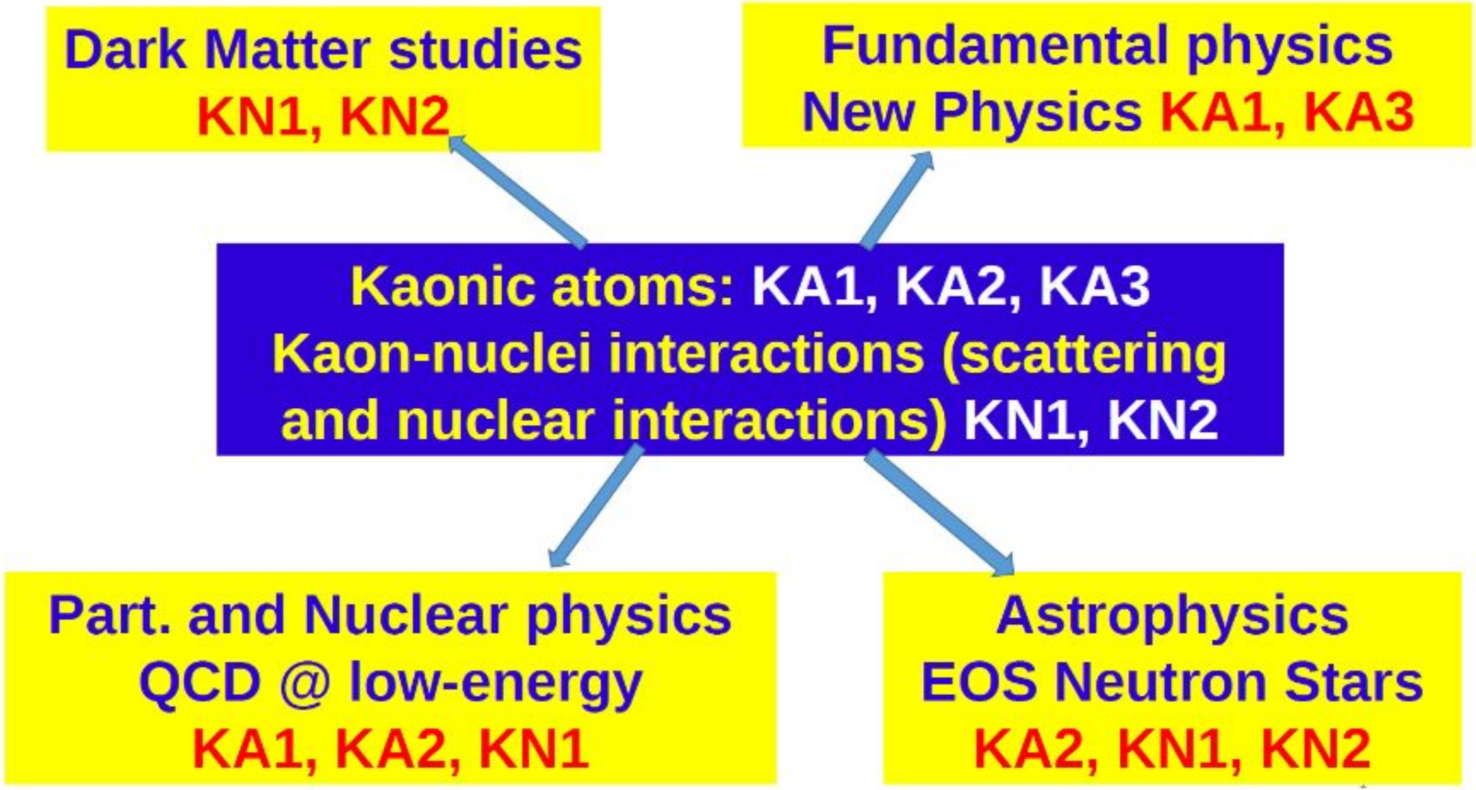
$\sigma(K^-\,^{12}C\ (4NA) \to \Sigma^0 t\,^8Be) = 1.88 \pm 0.35$ (stat) mb



SIDDHARTA-2



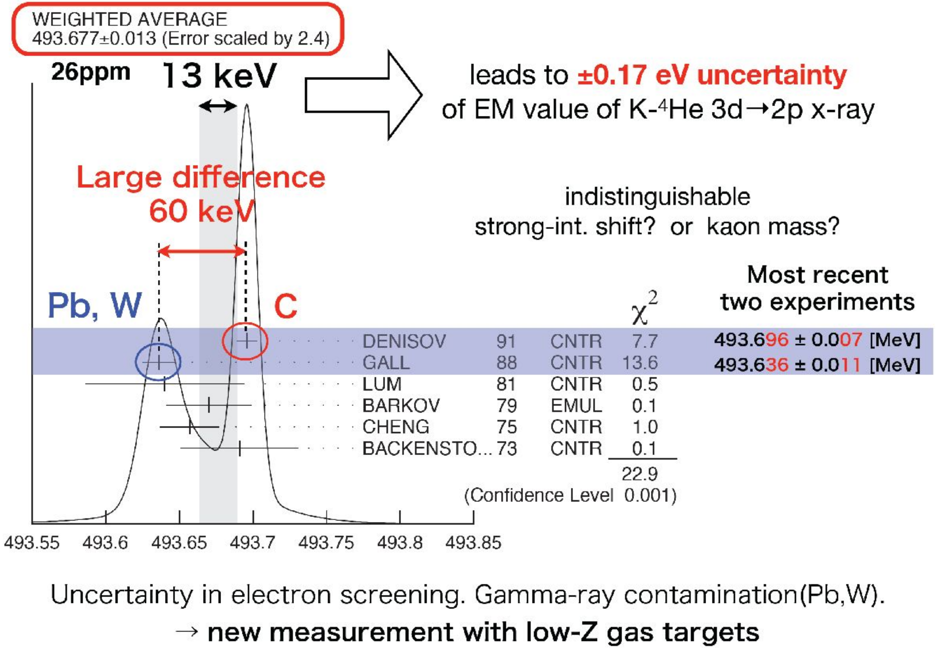
Future at DAΦNE



Kaon mass discrepancy – impact on kaonic atoms; CPT, all physics where kaon mass is important such for charmed meson studies and searches beyond standard model

- a new measurement is strongly required – PDG...

The best D0 mass relies, and is limited by the K- mass (Claude Amsler; Simon Eydelman)



Future at DAΦNE

For kaon mass: kaonic Carbon 4-->3 transition = 22 keV

For test of QCD antikaon-nucleon scattering lengths from KH and Kd: kaonic Helium-3 2-->1 transition = 33 keV kaonic Helium-4 2-->1 transition = 35 keV

QCD (Lambda(1405), multi-nucleon…):

Kaonic Lithium-6 3-->2 transition = 15.08 keV kaonic Lithium-6 4-->3 transition = 5.28 keV

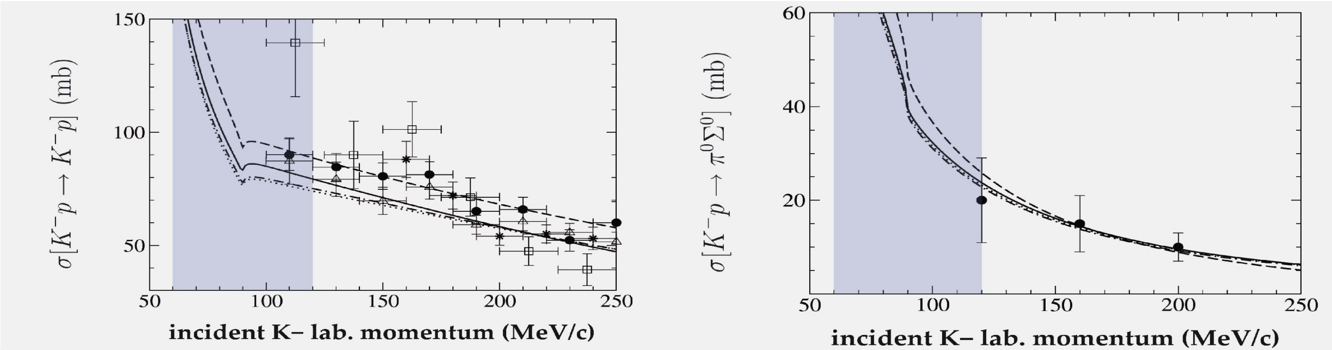
Kaonic Lithium-7 3-->2 transition = 15.3 keV kaonic Lithium-7 4-->3 transition = 5.34 keV

Kaonic Boron-9 3-->2 transition = 43.04 keV kaonic Boron-9 4-->3 transition = 15.07 keV

Kaonic Beryllium-9 is similar to kaonic Boron 9.

KAON-NUCLEI SCATTERING and INTERACTION

- The present knowledge of total and differential cross sections of low energy kaon-nucleon reactions is very limited.
- Below 150 MeV/c there is a “desert” - the experimental data are very scarce and with large errors and practically no data exist below 100 MeV/c.
- **Studies of Hyperon-nucleon, Hyeron-multinucleon (AMADEUS experience)**
- **Kaon-nucleon scattering/interaction data are fundamental to validate theories: chiral symmetries; lattice calculations; potential models etc.**



Priorities and readiness:

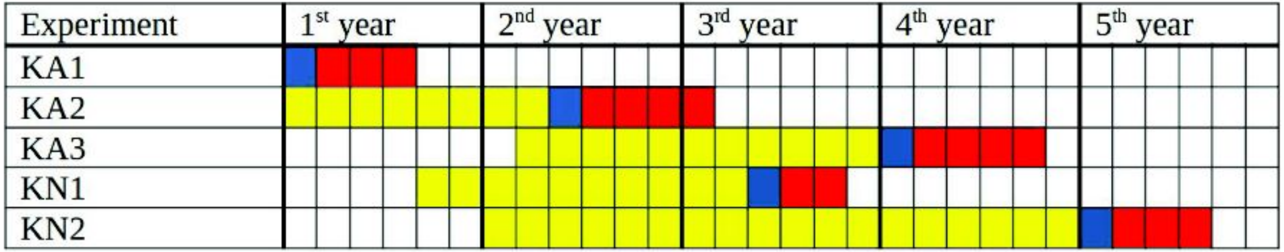


Fig. 1. Schematic Gantt Chart for Fundamental physics at the Strangeness Frontier at the DAΦNE Proposal: KA1 (see Sec. 2.1), KA2 (see Sec. 2.2), KA3 (see Sec. 2.3), KN1 (see Sec. 3.2), KN2 (see Sec. 3.3). Yellow: preparation phase. Blue: installation phase. Red: data taking.

Future at DAΦNE

Fundamental physics at the strangeness frontier at DAΦNE.
Outline of a proposal for future measurements.

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The DAΦNE collider at INFN-LNF is a unique source of low-energy kaons, which was used by the DEAR, SIDDHARTA and AMADEUS collaborations for unique measurements of kaonic atoms and kaon-nuclei interactions. Presently, the SIDDHARTA-2 collaboration is underway to measure the kaonic deuterium exotic atom. With this document we outline a proposal for fundamental physics at the strangeness frontier for future measurements of kaonic atoms and kaon-nuclei interactions at DAΦNE, which is intended to stimulate discussions within the broad scientific community performing research directly or indirectly related to this field.

PACS numbers: 13.75.Jz, 36.10.-k, 36.10.Gv, 14.40.-n, 25.80.Nv, 29.30.-h, 29.90.+r, 87.64.Gb, 07.85.Fv, 29.40.-n, 29.40.Gx, 29.40.Wk

https://arxiv.org/pdf/2104.06076.pdf

Towards a LOI

(authors: Editorial Board only)

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- Igor Strakovsky, SAID INS The George Washington University, USA
- INFN (LNF + more), Italy
- SMI, Vienna, Austria

11 countries

LOI/Technical Design Report in preparation

We strongly believe that this is an opportunity which cannot be missed, since we propose to measure fundamental interaction processes which could not be measured till now, and which will have a huge and concrete impact, "now and here", in particle and nuclear physics, astrophysics, cosmology and foundational Issues, supported by a strong international collaboration.

Our proposed measurements have a huge potential of producing a consistent number of high-impact publications in high-impact factor journals, which will guide the developments of physics at strangeness frontier in the next 10-20 years, setting DAΦNE and LNF on the forefront of fundamental physics studies.

Thank You