Investigating the low-energy K^- multi-nucleon absorption processes with AMADEUS

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On the behalf of the AMADEUS collaboration

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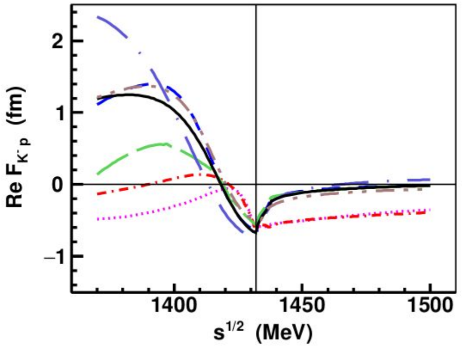
Motivation

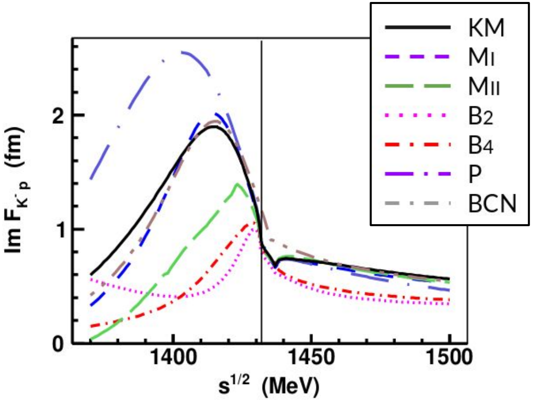
AMADEUS (**A**ntikaonic **M**atter **A**t **D**AΦNE: an **E**xperiment with **U**nravelling **S**pectroscopy) investigates **low-energy K^- absorption in nuclei** with the aim to extract information on:

- K^-N interaction above and below threshold
  - Λ(1405) nature
  - kaonic bound states
  - K^-N scattering amplitudes and cross sections
- **K^-NN, K^-NNN, K^-NNNN (multi-nucleon) interactions** → **THIS TALK**
  - **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

Motivation

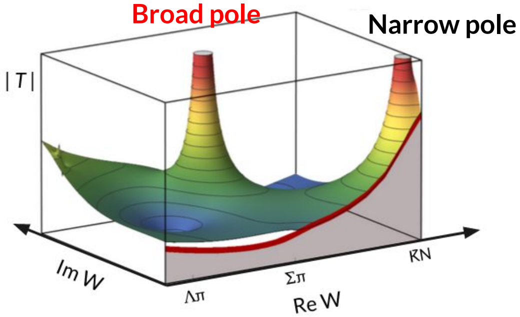
K^-p scattering amplitude

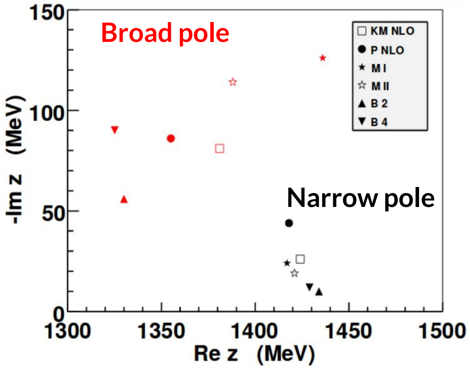


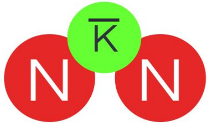


[from A. Cieply et al. Nucl.Phys. A954 (2016) 17-40]

Λ(1405) state: dynamical origin. Two poles of the scattering amplitude → pole positions is model dependent (relative contributions not measured experimentally)

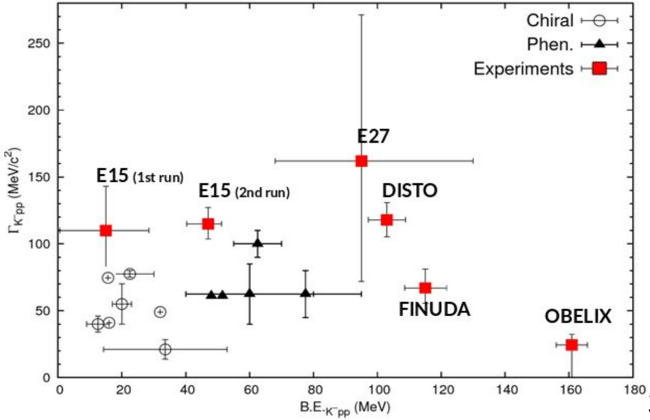






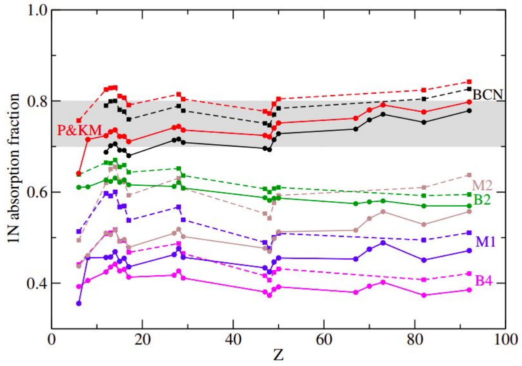
K^-pp bound state puzzle:

- K̄N input model is critical for the data interpretation
- different bound state production mechanisms give different predictions



K^- multi-nucleon absorptions

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



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

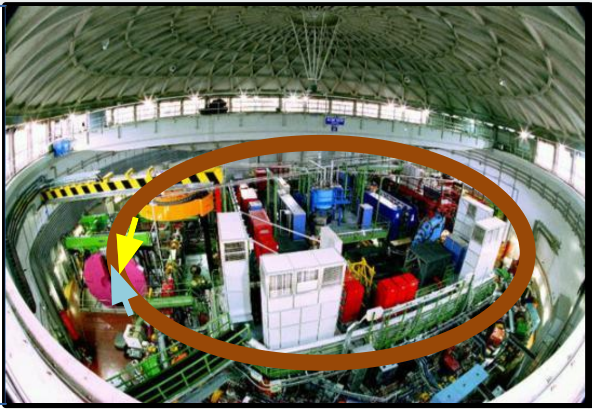
→ multi-N

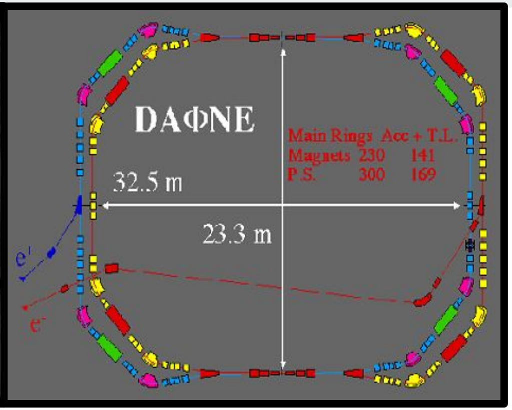
bound nucleons = "N", "NN", "NNN", "NNNN"
bound or unbound nucleons = (NN), (NNN)
Y = Λ, Σ

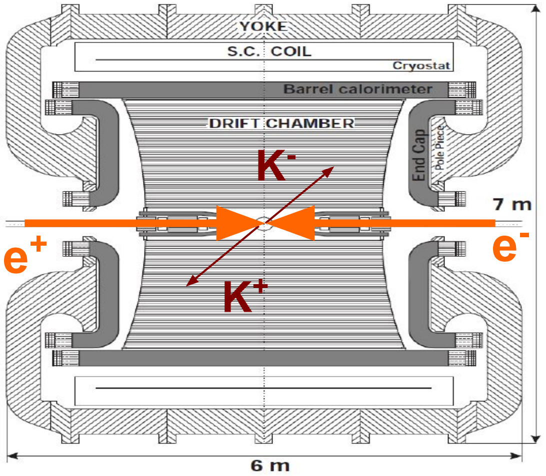
DAΦNE & AMADEUS

DAΦNE

- double ring $e^+ e^-$ collider working at C.M. energy of φ,
- producing ≈ **1000 φ /s**
  φ → $K^+ K^-$ (BR = (49.2 ± 0.6)%)
- **low momentum** Kaons ≈ 127 MeV/c
- **back to back** $K^+ K^-$ topology







KLOE

- 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

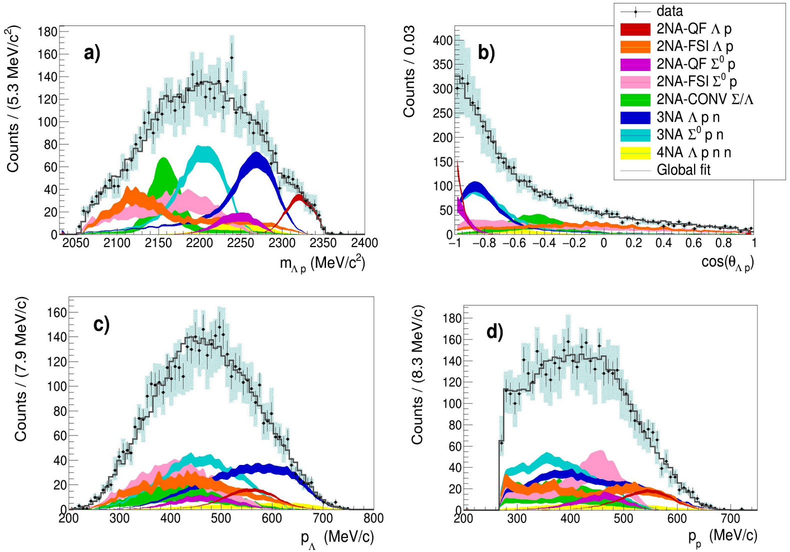
[M. Anelli et al., Nucl Inst. Meth. A 581, 368 (2007)]

KLOE is used as an active target: Carbon, Helium, Hydrogen

Two types of K- Nuclear absorptions:

-> AT-REST P_K = 0 MeV/c
-> IN FLIGHT P_K ~ 100 MeV/c

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



[R. Del Grande, K. Piscicchia, O. Vazquez Doce et al., Eur.Phys.J. C79 (2019) 190]
[R. Del Grande, K. Piscicchia, S. Wycech, Acta Phys. Pol. B 48 (2017) 1881]
[O. Vazquez Doce, L. Fabbietti et al., Phys. Lett. B 758 (2016) 134]
[R. Del Grande, K. Piscicchia et al., 2020 Phys. Scr.95 084012]

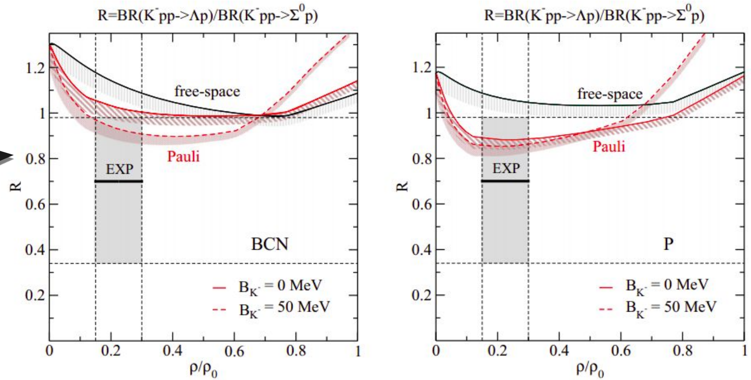
Process	Branching Ratio (%)	σ (mb)	@	p_K (MeV/c)
2NA-QF Λp	0.25 ± 0.02 (stat.) $^{+0.01}_{-0.02}$(syst.)	2.8 ± 0.3 (stat.) $^{+0.1}_{-0.2}$ (syst.)	@	128 ± 29
2NA-FSI Λp	6.2 ± 1.4(stat.) $^{+0.5}_{-0.6}$(syst.)	69 ± 15 (stat.) ± 6 (syst.)	@	128 ± 29
2NA-QF $\Sigma^0 p$	0.35 ± 0.09(stat.) $^{+0.13}_{-0.06}$(syst.)	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.) ± 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.)	-		

Information on the in-medium dynamics

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

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

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

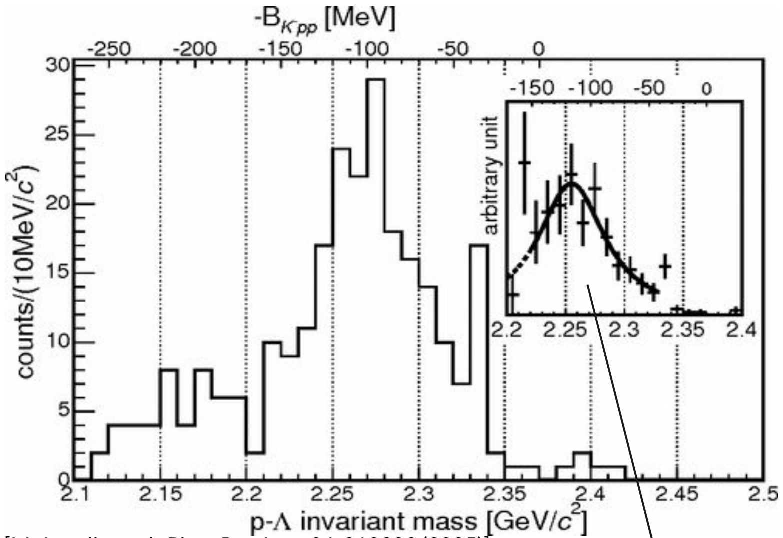


and the ratio between the corresponding phase spaces is $\mathcal{R}' \simeq 1.22$.

Experimental search in K$^-$ induced reactions

FINUDA at DAΦNE: $K^-_{stop} + X \rightarrow \Lambda + p + X'$

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



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

Interpreted as the signal of:
$K^-pp \rightarrow \Lambda + p$

extracted parameters:

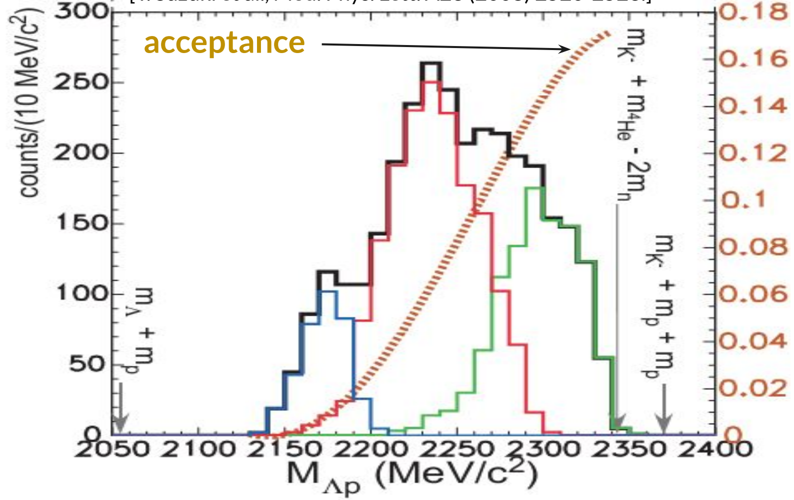
BE = $(115^{+6}_{-5}\,(\text{stat.})^{+3}_{-4}\,(\text{syst.}))$ MeV

$\Gamma = (67^{+14}_{-11}(\text{stat.})^{+2}_{-3}(\text{syst.}))$ MeV/c^2

E549 at KEK: $K^-_{stop} + {}^4He \rightarrow \Lambda + p + X'$

detected particles

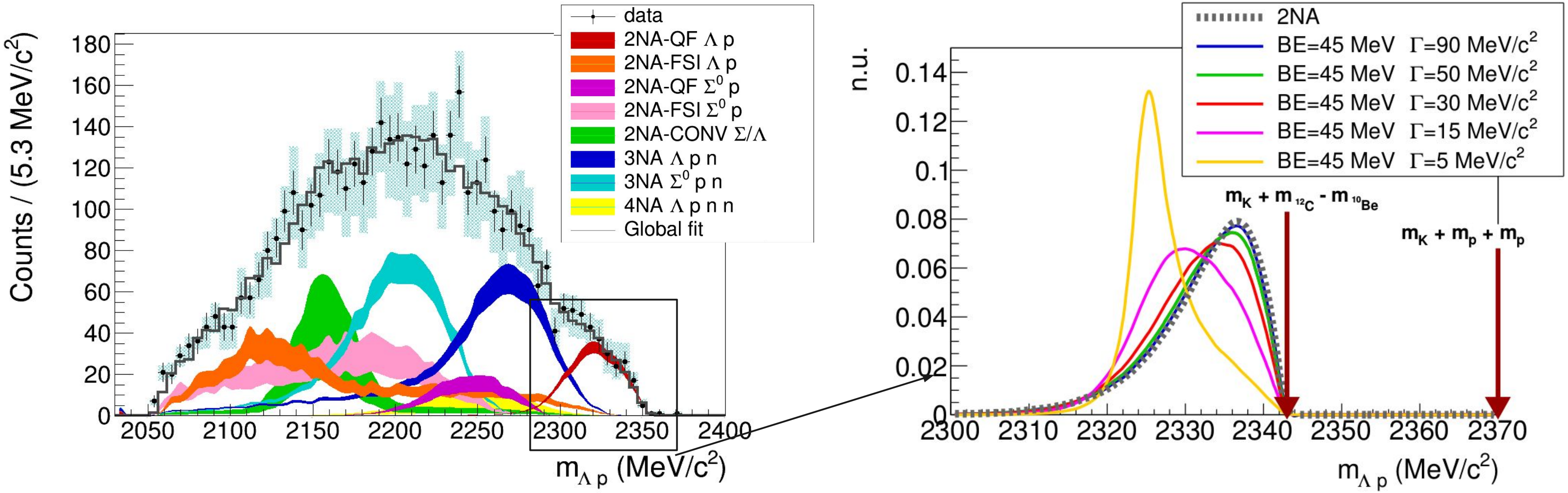
[T. Suzuki et al., Mod. Phys. Lett. A23 (2008) 2520-2523.]



Using the missing mass information, three components to the invariant mass spectrum are found:

- **1NA**: K$^-$ single nucleon absorption
- **2NA**: K$^-$ two nucleon absorption
- **2NA + conversion**, **multi-nucleon**, **or Bound State**?

Λp analysis: no K⁻ pp bound state evidence



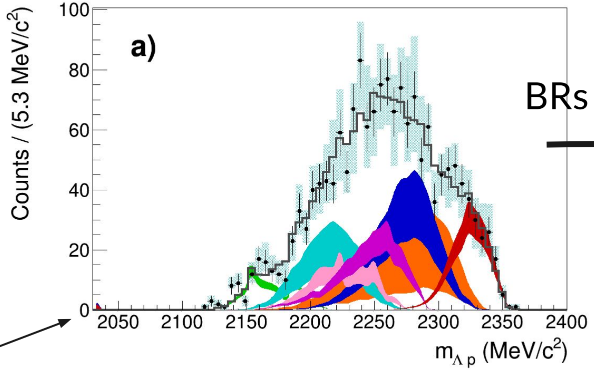
[R. Del Grande, K. Piscicchia, O. Vazquez Doce et al., Eur.Phys.J. C79 (2019) no.3, 190]

No K^-pp bound state contribution emerges

K^-pp completely overlaps with the K^-2NA

Λp analysis: no K⁻ pp bound state evidence

AMADEUS at DAΦNE

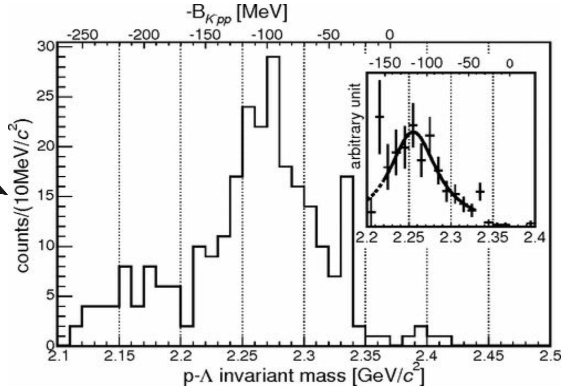


BRs evaluation

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 $\Sigma^0 p$	$0.54 \pm 0.20(\text{stat.})\ ^{+0.20}_{-0.16}(\text{syst.})$
2NA-FSI $\Sigma^0 p$	$5.4 \pm 1.5(\text{stat.})\ ^{+1.0}_{-2.7}(\text{syst.})$
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 $\Sigma^0 pn$	$1.9 \pm 0.7(\text{stat.})\ ^{+0.8}_{-0.4}(\text{syst.})$

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

FINUDA at DAΦNE



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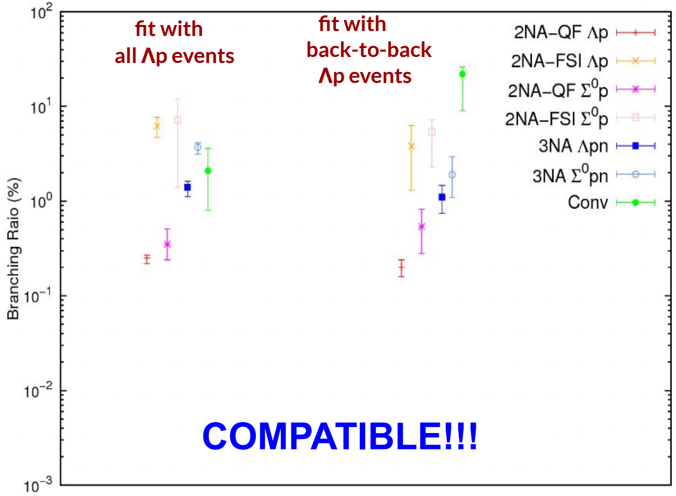


[R. Del Grande, K. Piscicchia, O. Vazquez Doce et al., Eur.Phys.J. C79 (2019) no.3, 190]

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)

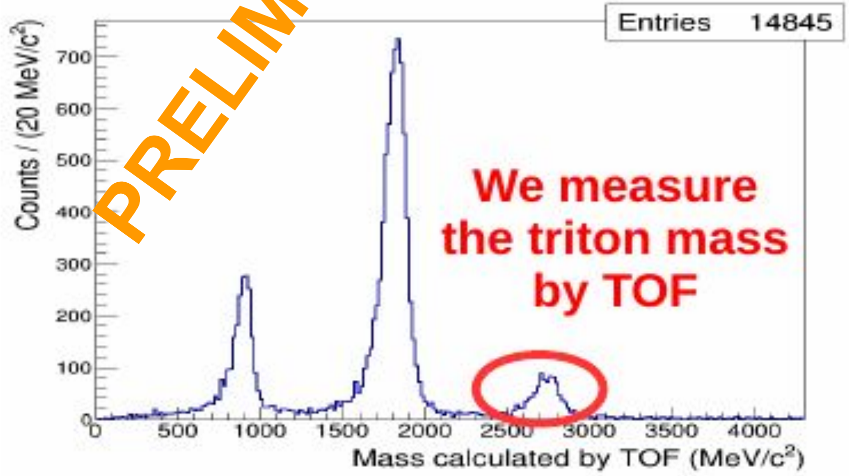
/Phys. Lett. B, 229 (2008)/

40 events, only **back-to-back data**

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

→ global, no 4NA

AMADEUS analysis



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

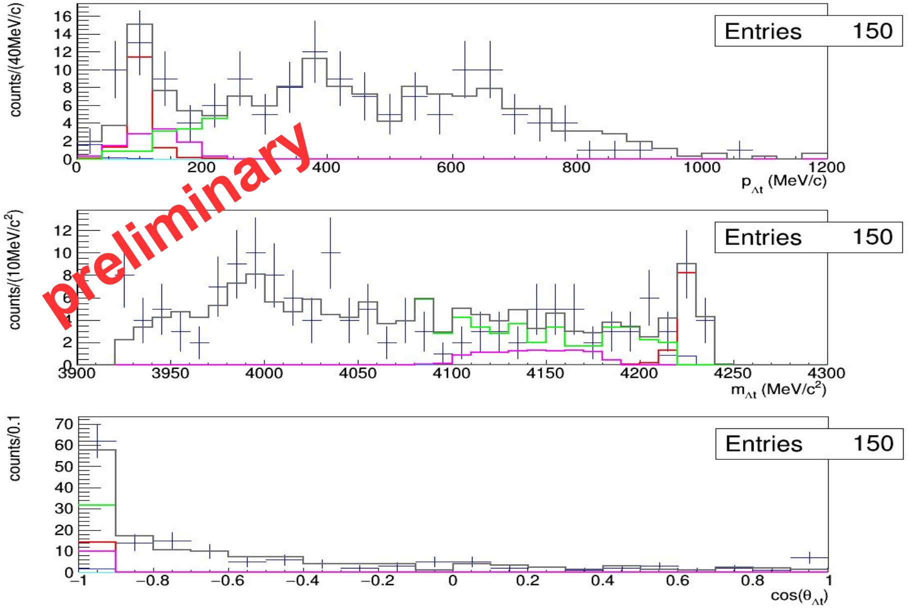
BR($K^{-4}He(4NA) \rightarrow \Lambda t$) **< 2.0 × 10^{-4} /K_{stop} (95% c. l.)**

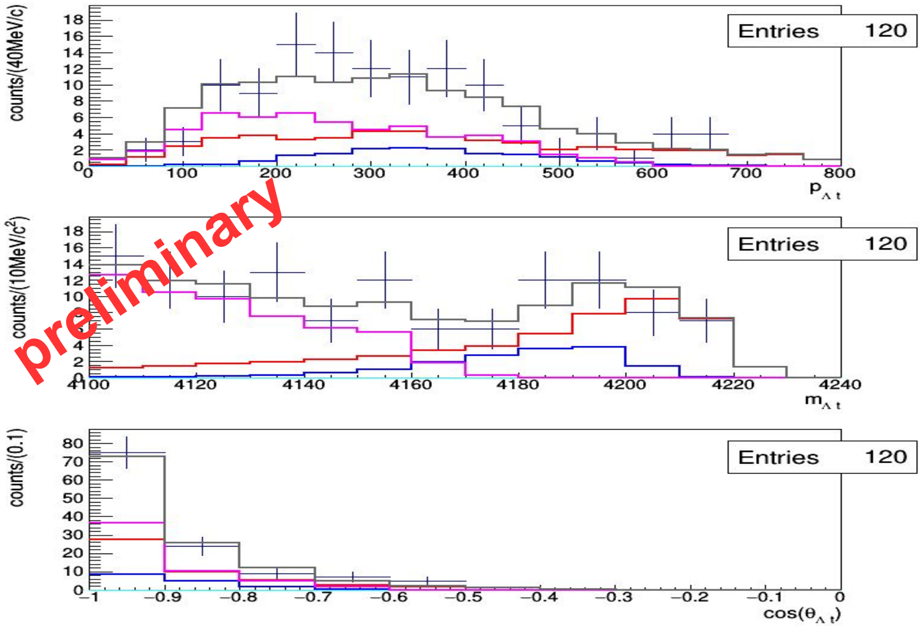
σ(100 ± **19** MeV/c) ($K^{-4}He(4NA) \rightarrow \Lambda t$) =
= (0.81 ± 0.21 (stat) $^{+0.03}_{-0.04}$ (syst)) mb

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

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

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





Paper in preparation

Summary

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
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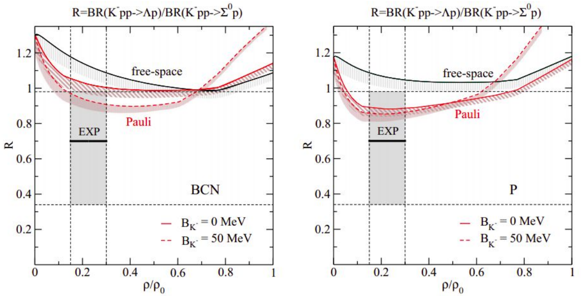
Global $\Lambda(\Sigma^0)$p	21 ± 3(stat.) $^{+5}_{-6}$(syst.)	-		

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



Λ t channel: 4NA BRs and σ

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

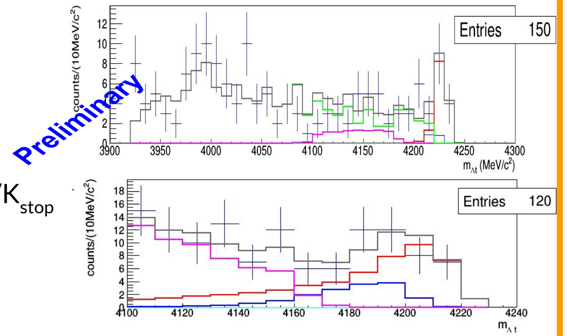
$\sigma(100 \pm 19$ MeV/c$)$ $(K^{-4}He(4NA) \to \Lambda t) =$

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

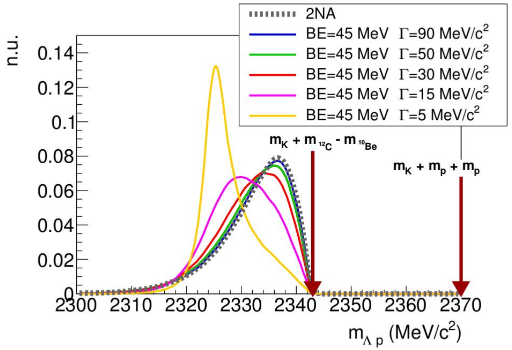
$BR(K^{-12}C(4NA) \to \Lambda t\ {}^8Be) = 1.5 \pm 0.5 \times 10^{-4}$ (stat) $/K_{stop}$

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

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



K⁻pp bound state



Thank You