Studies of low-energy kaons interactions in nuclear matter by AMADEUS

Magdalena Skurzok*

On the behalf of the AMADEUS collaboration

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

Jagiellonian University in Krakow

The 8th International Conference on Quarks and Nuclear Physics
14 November 2018

*magdalena.skurzok@lnf.infn.it

Plan

1. Motivation and scientific case
2. AMADEUS @ DAFNE experiment
3. Analysis results
4. Perspective

Motivation and Scientific Case

The investigation of the **in-medium modification of the $\bar{K}N$ interaction** is of **fundamental** for the low-energy QCD in the non perturbative regime.

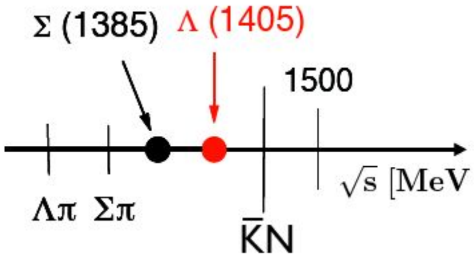
Chiral perturbation theory (ChPT): effective field theory where mesons and baryons represent the effective degrees of freedom instead of the fundamental quark and gluon fields.

$$\mathcal{L}_{eff} = \mathcal{L}_{mesons}(\Phi) + \mathcal{L}_B(\Phi, \Psi_B)$$

- The chiral symmetry is **spontaneously broken** → the existence of massless and spinless Nambu-Goldstone bosons which are identified with the pions. Explicitly broken by **q** masses.
- **Very successful** in describing the πN, ππ and NN interactions in the low-energy regime and is considered as the theory of the low-energy strong interaction **in the SU(2) flavour sector**.

The extension of the theory to the sector with the quark s turns out to be more problematic since it is not directly applicable to the $\bar{K}N$ channel.

The χPT is not applicable to the $\bar{K}N$ channel due to the emerging of the Λ(1405) and the Σ(1385) resonances just below the $\bar{K}N$ mass threshold



Λ(1405) I=0 $J^P = ½^-$

M = $(1405.1^{+1.3}_{-1.0})$ MeV Γ = (50.5 ± 2.0) MeV

decay modes: Σπ (I=0) 100%

Σ(1385) I=1 $J^P = 3/2^+$

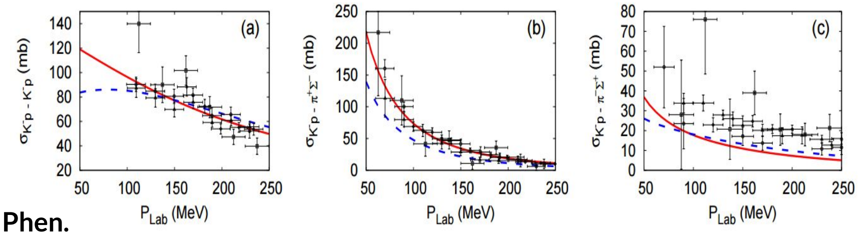
decay modes: Λ π (I=1) (87.0 ± 1.5) %

Σ π (I=1) (11.7 ± 1.5) %

Possible solutions:

- ➢ **Non-perturbative Coupled Channels approach: Chiral Unitary SU(3) Dynamics**
- ➢ **Phenomenological $\bar{K}N$ and NN potentials**

The parameters of the models are constrained by the existing scattering data

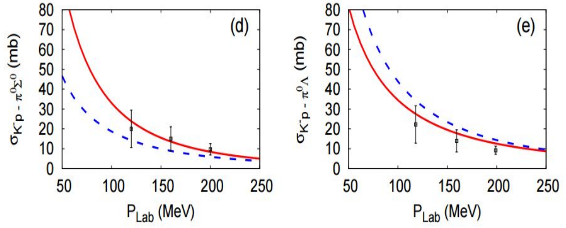


Phen.

Y. Ikeda and T. Sato, Phys. Rev. C76, 035203 (2007)

Chiral

S. Ohnishi, Y. Ikeda, T. Hyodo, W. Weise, Phys.Rev. C93 (2016) no.2, 025207



...but... large differences in the subthreshold extrapolations!

Significantly weaker attraction in chiral SU(3) models than in phenomenological potential models.

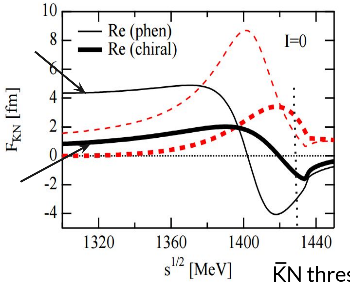
Re Im

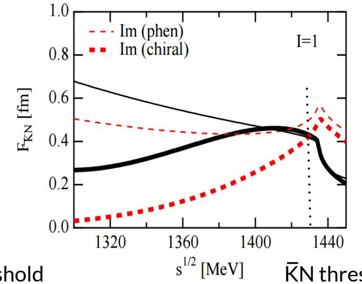
Phen. [Y. Akaishi, T. Yamazaki, Phys. Rev. C65, 044005 (2002)]

Chiral [Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B706, 63 (2011)]

Phenomenologic potential model

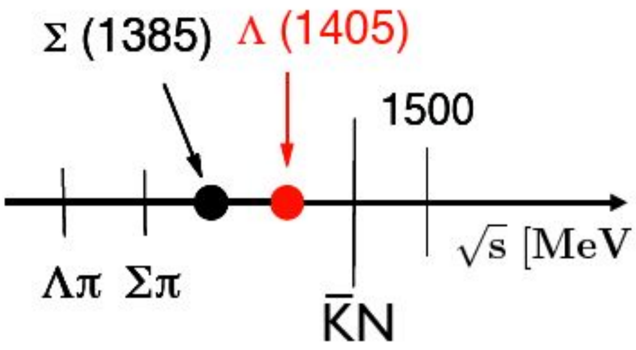
Chiral SU(3) dynamics





K̄N threshold K̄N threshold

The controversial nature of the Λ(1405)

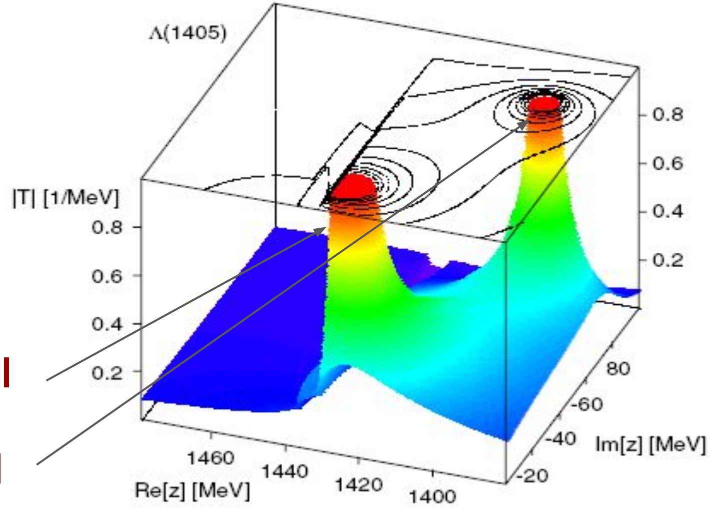


The Λ(1405) state does not fit with the simple three quarks model (*uds*) and it is commonly accepted that **it is, at least partially, a K̄N bound state**.

- **Chiral SU(3) coupled channel dynamics:**
  the state is given by the superpositions of **two poles of the K̄N scattering amplitude**.

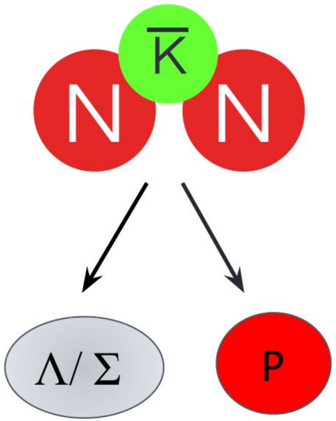
  M = 1425 MeV $\rightarrow$ **mainly coupled to the K̄N channel**

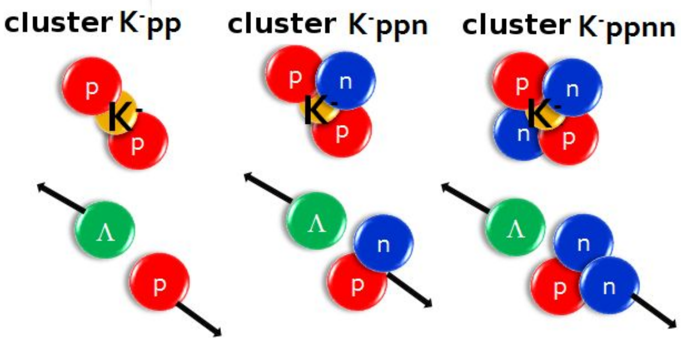
  M = 1380 MeV $\rightarrow$ **mainly coupled to the Σπ channel**



- **Phenomenological potentials models:** the **Λ(1405) is a pure K̄N bound state** with mass M=1405 MeV, binding energy BE = 27 MeV and width Γ=50 MeV.

Possible existence of kaonic bound states





$\Lambda + p$ / $\Sigma^0 + p$ — $\Lambda + d$ / $\Sigma^0 + d$ — $\Lambda + t$ / $\Sigma^0 + t$

Wycech (1986) - Akaishi & Yamazaki (2002)

Predicted in the **$\bar{K}$N interaction in the I=0** channel due to the strong interaction

Essential impact on the EoS of Neutron Stars

gravitational waves signal emitted by binary system of Neutron Stars

Theory

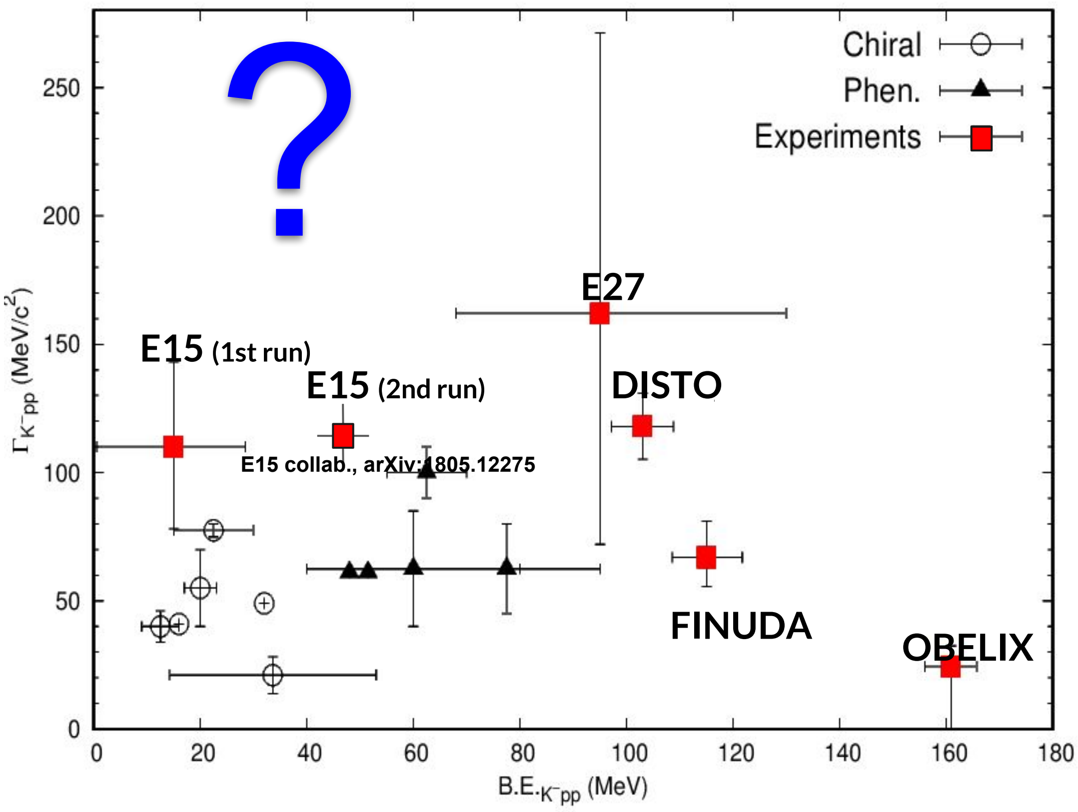
	BE (MeV)	Γ (MeV)	Reference
Dote, Hyodo, Weise	17-23	40-70	Phys.Rev.C79 (2009) 014003
Akaishi, Yamazaki	48	61	Phys.Rev.C65 (2002) 044005
Barnea, Gal, Liverts	16	41	Phys.Lett.B712 (2012) 132-137
Ikeda, Sato	60-95	45-80	Phys.Rev.C76 (2007) 035203
Ikeda, Kamano, Sato	9-16	34-46	Prog.Theor.Phys. (2010) 124(3): 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

Experiments

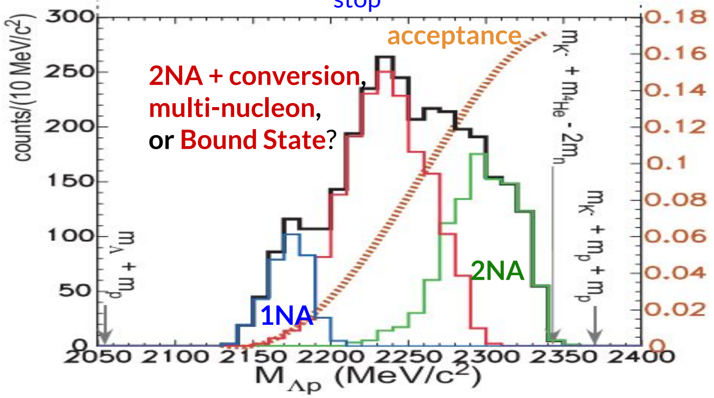
Experiment	BE (MeV)	Γ (MeV)	Reference
FINUDA	115^{+6}_{-5} (stat.) $^{+3}_{-4}$ (syst.)	67^{+14}_{-11} (stat.) $^{+2}_{-3}$ (syst.)	PRL 94 (2005), 212303
OBELIX	160.9 ± 4.9	$< 24.4 \pm 8.0$	NPA 789 (2007), 222
E549	-	-	MPLA 23 (2008), 2520
DISTO	103 ± 3 (stat.) ± 5 (syst.)	118 ± 8 (stat.) ± 10 (syst.)	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

Experimental search in K^- induced reactions

How deep can be bound antikaon in nucleus?

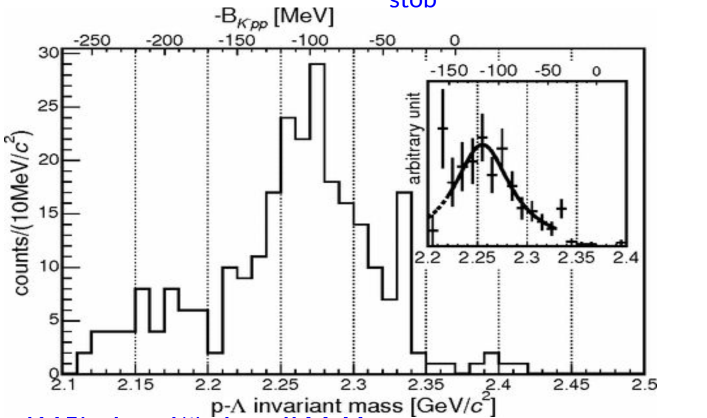


E549 at KEK: $K^-_{stop} + {}^4He \rightarrow \Lambda + p + X'$



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

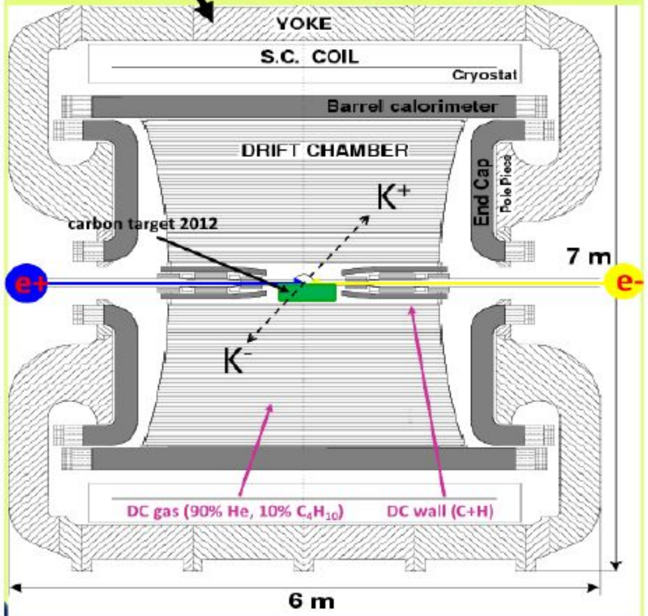
FINUDA at DAFNE: $K^-_{stop} + X \rightarrow \Lambda + p + X'$



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

Γ = (67^{+14}_{-11} (stat.)$^{+2}_{-3}$(syst.)) eV/c^2

AMADEUS @ DAFNE



DAFNE

- $\phi \rightarrow K^- K^+$ (49.2%), ≈1000 ϕ/s
- monochromatic **low momentum** Kaons ≈127 Mev/c
- **back to back** $K^- K^+$ topology
- **small hadronic background** due to the beam

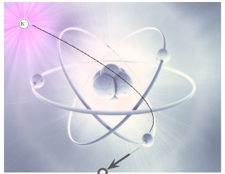
KLOE

- Cilindrical DC with **4π geometry** & electromagnetic calormeter
- **96% acceptance**
- **high efficiency and resolution** for charged and neutral particles

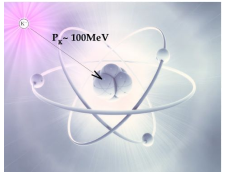
↓

- exclusive measurement of the considered

K^- absorption on light nuclei
AT REST & IN FLIGHT



K- absorbed from atomic orbit



AMADEUS step 0: KLOE 2004-2005 dataset analysis ($\mathcal{L}$ = 1.74 pb-1)

AMADEUS scientific case

- nature of Λ(1405) and K^-N amplitude below threshold

- K^- multiN absorption

- kaonic nuclear clusters

⇩

YN correlation studies
(Λp, Σ^0p, Λt)

- low-energy charged K cross section (for p=100MeV)

K⁻ N single nucleon absorption resonant and non-resonant amplitudes

Λ(1405) case

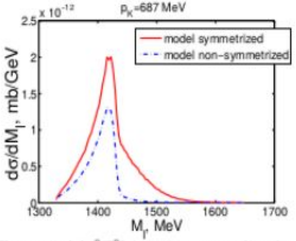


FIG. 4: Theoretical ($\pi^0\Sigma^0$) invariant mass distribution for an initial kaon lab momenta of 687 MeV. The non-symmetrized distribution also contains the factor 1/2 in the cross section.

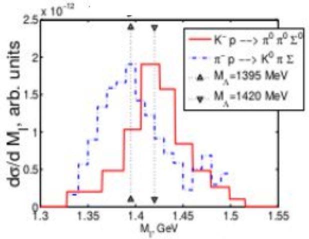
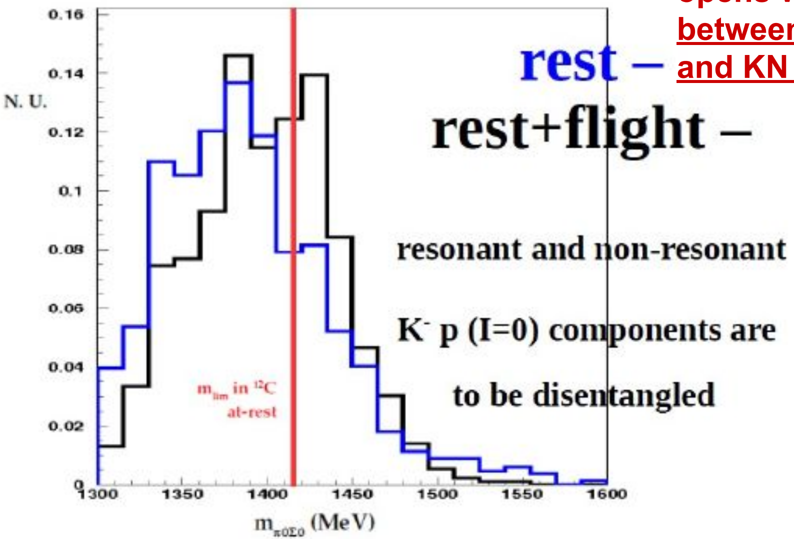
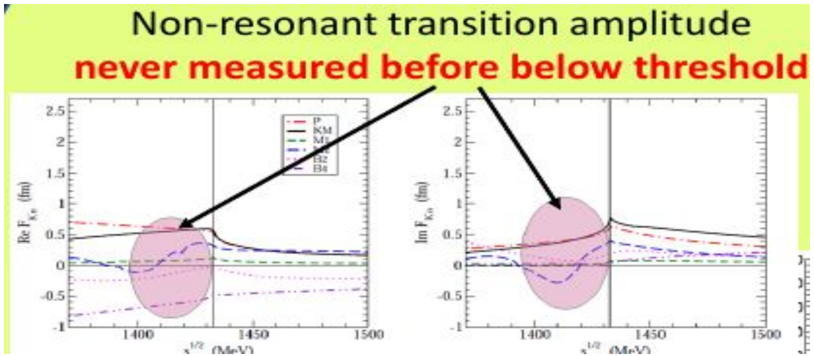


FIG. 5: Two experimental shapes of Λ(1405) resonance. See text for more details.

IN FLIGHT K^- ^{12}C opens window <u>**between 1416 MeV and KN threshold**</u>

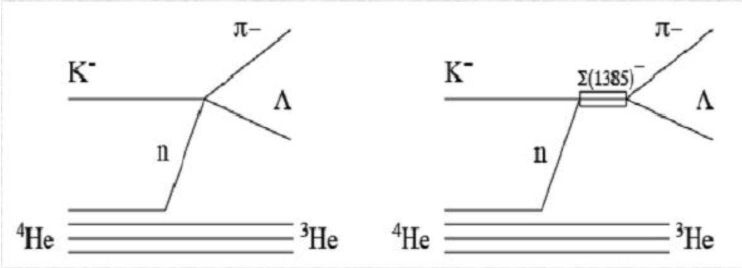


Goal: how much comes from resonance in **$K^-N \rightarrow Y\pi$**



J. Hrtankova, J. Mares, Phys. Rev. C96, 015205 (2017)
A. Cieply et al, Nycl. Phys. A 954, 17 (2016)

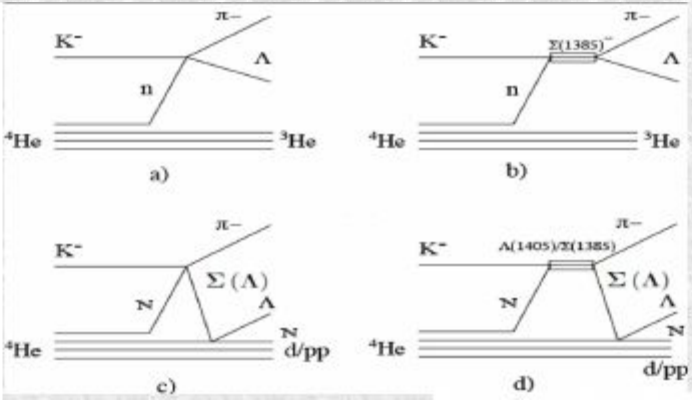
K^-"n" → $\Lambda\pi^-$ direct formation in **^{4}He**



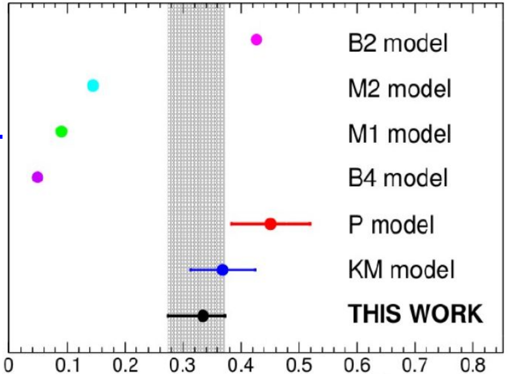
$|f^{N-R}_{\Lambda\pi}(I=1)|$ ⇒ $|f^{N-R}_{\Sigma\pi}(I=0)|$

$K^- \, {}^4He \rightarrow \Lambda p^- \, {}^3He$ resonant and non-resonant processes

K. P., S. Wycech and C. Curceanu, Nucl. Phys. A954 (2016) 75-93
R. Del Grande, K. P., S. Wycech, Acta Phys. Pol. B 48 (2017) 1881

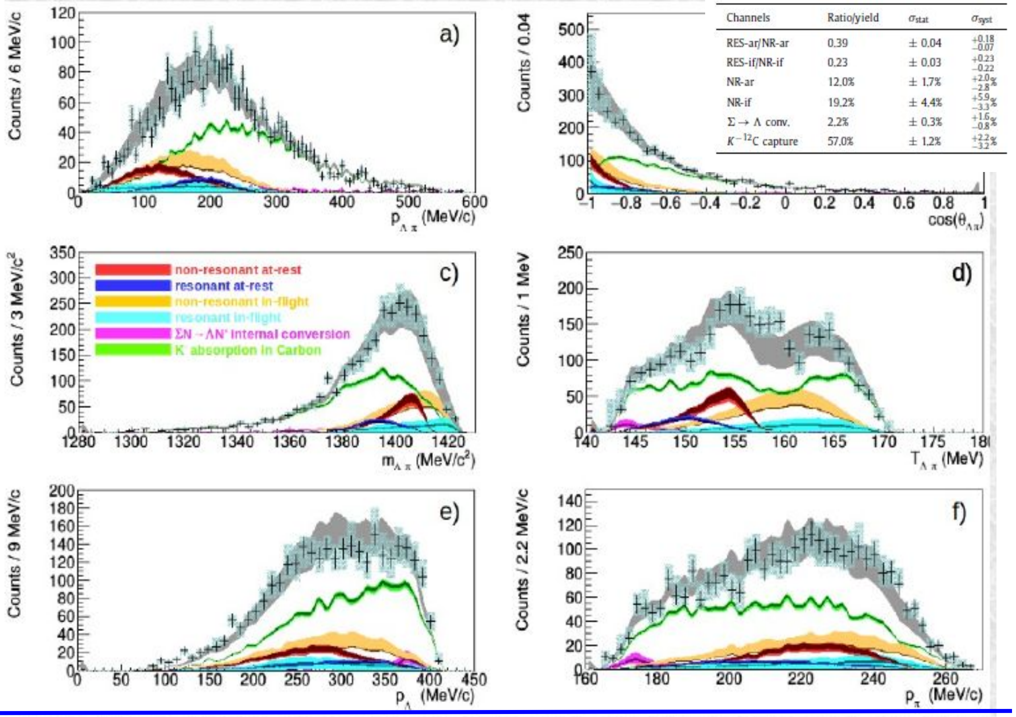


Simulations for resonant and non-resonant processes performed based on calculations for both S-state and P-state K- capture AT REST and IN FLIGHT



K. Piscicchia, et. al., Phys. Lett. B782, 339 (2018)

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



Channels	Ratio/yield	σ_{stat}	σ_{syst}
RES-ar/NR-ar	0.39	± 0.04	$^{+0.18}_{-0.07}$
RES-if/NR-if	0.23	± 0.03	$^{+0.23}_{-0.22}$
NR-ar	12.0%	± 1.7%	$^{+2.0}_{-2.8}$%
NR-if	19.2%	± 4.4%	$^{+5.9}_{-3.3}$%
$\Sigma \rightarrow \Lambda$ conv.	2.2%	± 0.3%	$^{+1.6}_{-0.8}$%
$K^{-\,12}C$ capture	57.0%	± 1.2%	$^{+2.2}_{-3.2}$%

From the well known Σ* transition probability:

$$\frac{\mathrm{NR-ar}}{\mathrm{RES-ar}} = \frac{\int_0^{pmax} P_{ar}^{nr}(p_{\Lambda\pi})\, dp_{\Lambda\pi}}{\int_0^{pmax} P_{ar}^{res}(p_{\Lambda\pi})\, dp_{\Lambda\pi}} =$$

$$= |f_{ar}^{s}|^2 \cdot 8,94 \cdot 10^5 \mathrm{MeV}^2$$

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

1) extract the amplitude for each model .. $A_{K\text{-}n} = (\mathrm{Re}F^2_{K\text{-}n} + \mathrm{Im}F^2_{K\text{-}n})^{1/2}$
2) scale the amplitudes for the K^-n couplings to the $\Sigma^-\pi^0$ and $\Sigma^0\pi^-$ channels:

$$\frac{Prob_{K^-n\rightarrow\Lambda\pi^-}}{Prob_{K^-n\rightarrow\Sigma^-\pi^0}} = \frac{Ph_{K^-n\rightarrow\Lambda\pi^-}}{c_1 Ph_{K^-n\rightarrow\Sigma^-\pi^0}}$$

Isospin (I, I_z) = = (1 , -1) component

Phase spaces ratios

$$\frac{Prob_{K^-n\rightarrow\Lambda\pi^-}}{Prob_{K^-n\rightarrow\Sigma^0\pi^-}} = \frac{Ph_{K^-n\rightarrow\Lambda\pi^-}}{c_2 Ph_{K^-n\rightarrow\Sigma^0\pi^-}}$$

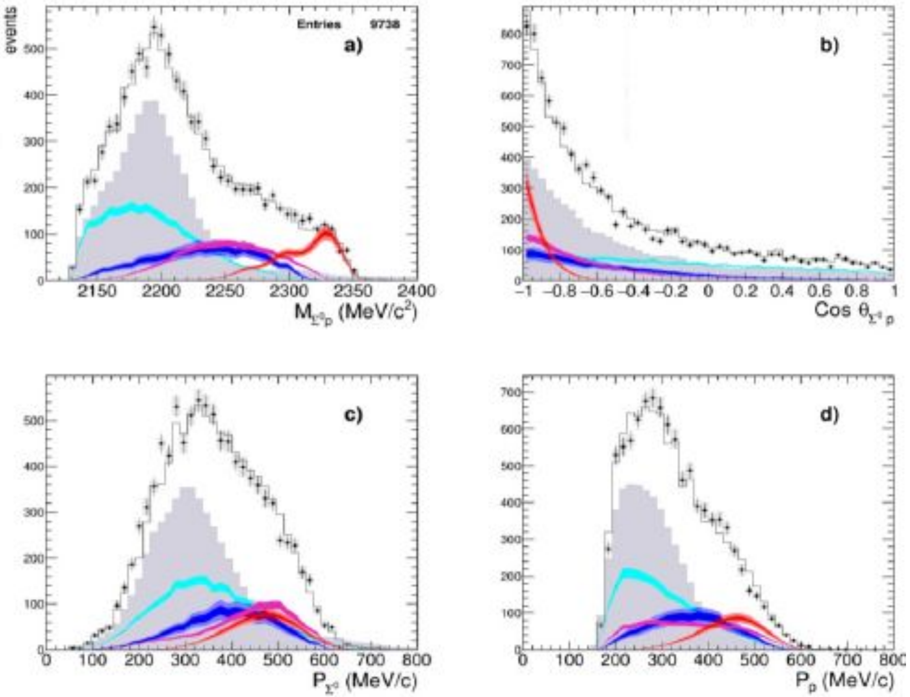
Low-energy $K^{-}\,^{12}C$ absorption $\Sigma^0 p/\Lambda p$ final states

Final fit

- data
- π^0 background
- 4NA+Uncorr.
- 3NA
- 2NA FSI
- 2NA QF
- Total fit

$$\chi^2 = 0.85$$

2NA-QF clearly separated From other processes



O. Vazquez Doce, et. al., Phys. Lett. B758, 134 (2016)

	yield / $K^-_{stop} \cdot 10^{-2}$	$\sigma_{stat} \cdot 10^{-2}$	$\sigma_{syst} \cdot 10^{-2}$
2NA-QF	0.127	± 0.019	+0.004 −0.008
2NA-FSI	0.272	± 0.028	+0.022 −0.023
Tot 2NA	0.376	± 0.033	+0.023 −0.032
3NA	0.274	± 0.069	+0.044 −0.021
Tot 3body	0.546	± 0.074	+0.048 −0.033
4NA + bkg.	0.773	± 0.053	+0.025 −0.076

No statistically significant bound state emerges at 2σ level

- **Λp** analysis finalized
- K multiN BRs and cross sections for kaon mom ~100MeV/c determined

Contribution from eventual K^-pp bound state overlaps with 2NA-QF contribution

its absolute yield remains indistinguishable

Cross section and BR for 4NA in $K^- \, ^4He \rightarrow \Lambda t$ process

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**

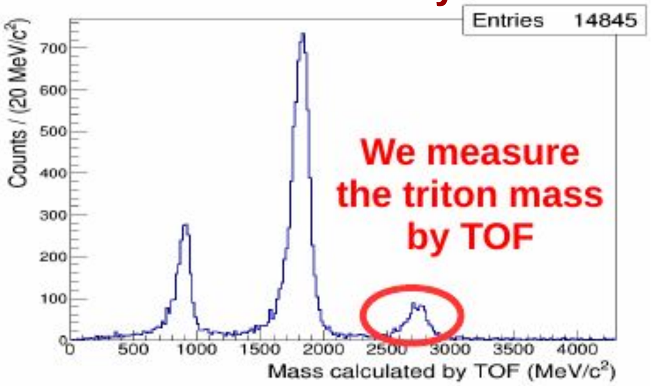
- in **solid targets:** ^{6,7}**Li,** ^{9}**Be** (FINUDA)

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

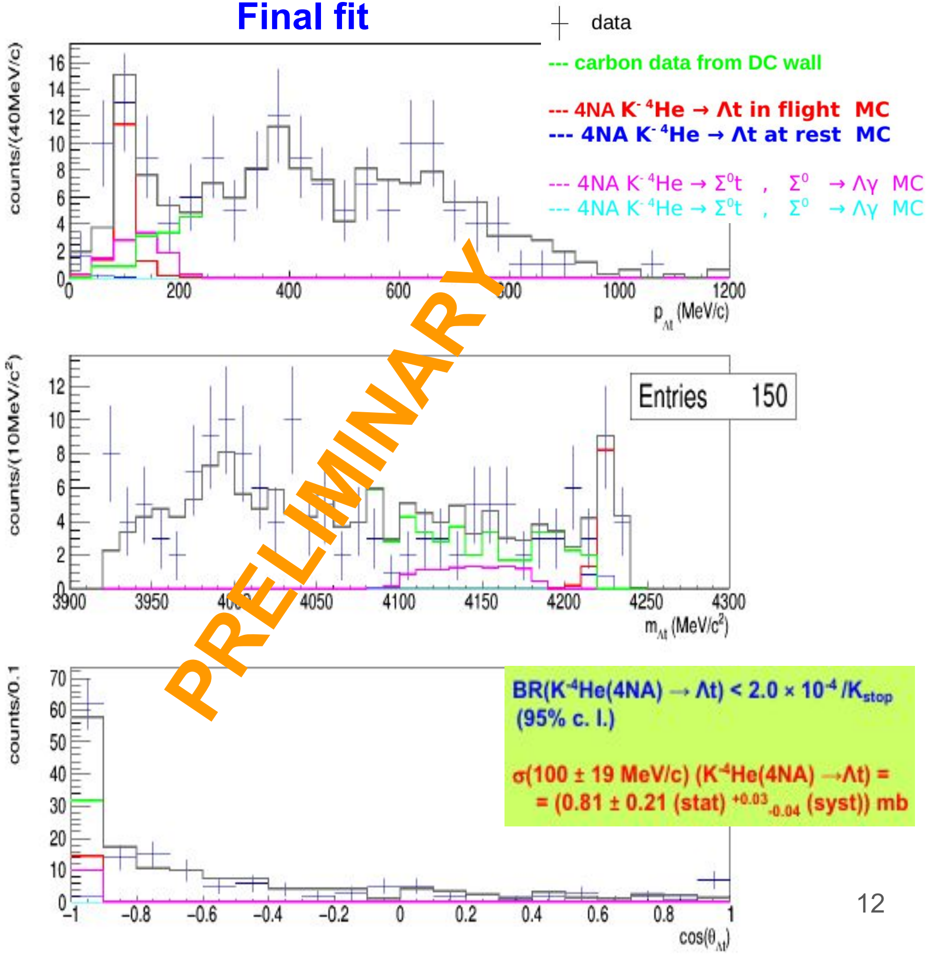
40 events, only **back-to-back data**

Λt emission yield $\rightarrow 10^{-3} - 10^{-4} / K^-_{stop}$ → **global, no 4NA**

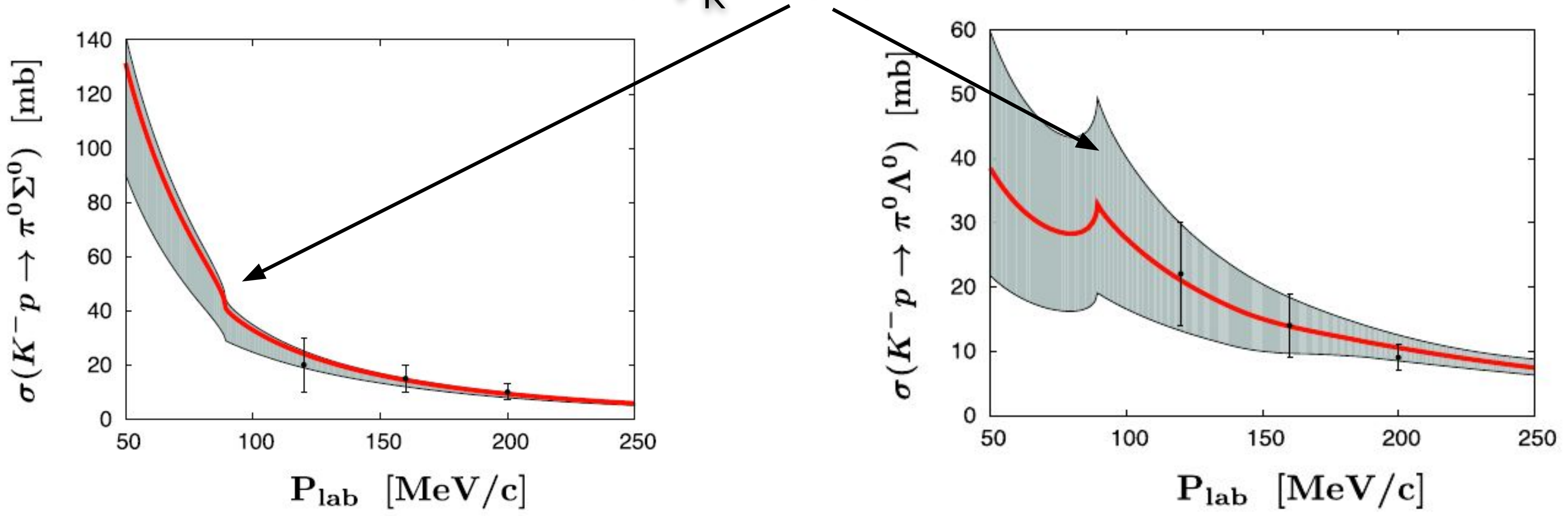
AMADEUS analysis



Final fit



Perspective: measurement of the $K^- H \rightarrow \Sigma^0\pi^0/\Lambda\pi^0$ cross sections for p_K = 98±10 MeV/c

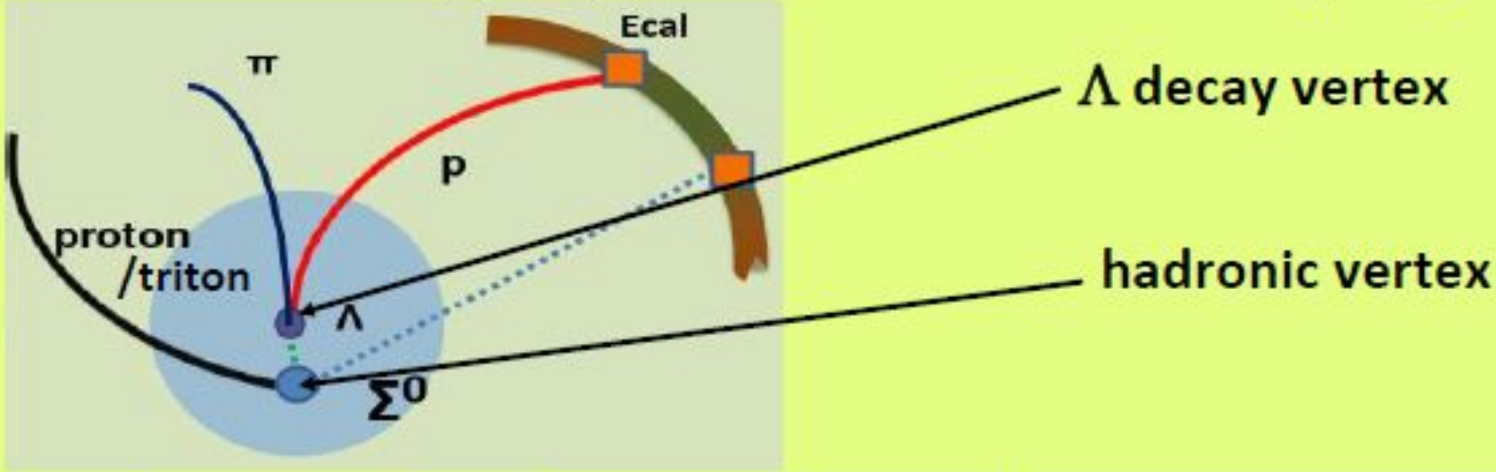


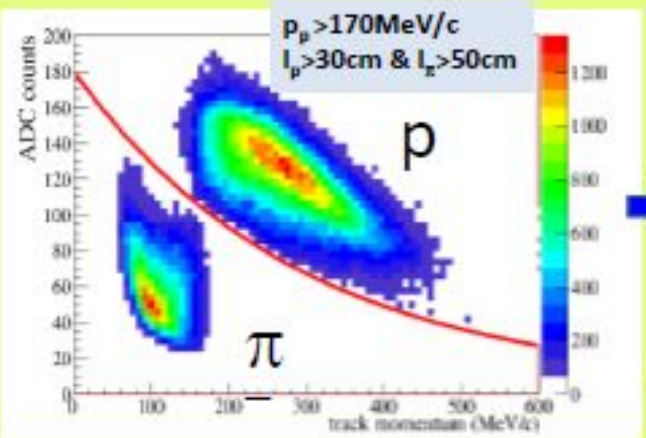
Y. Ikeda, T Hyodo, W. Weise, et. al., Phys. Lett. B706, 63 (2011); Nucl. Phys. A881, 98 (2012)

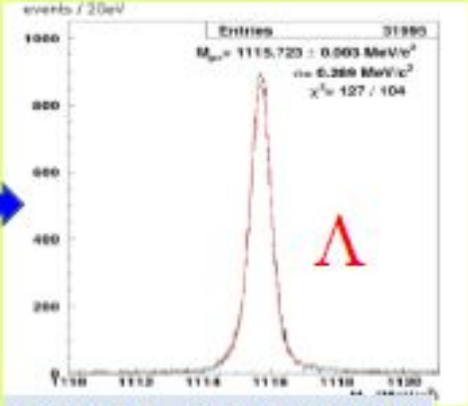
Low momentum K^- scattering cross sections in this Isospin I = 0 channel represent a fundamental input for the non-perturbative low energy QCD models

Thank you for attention!

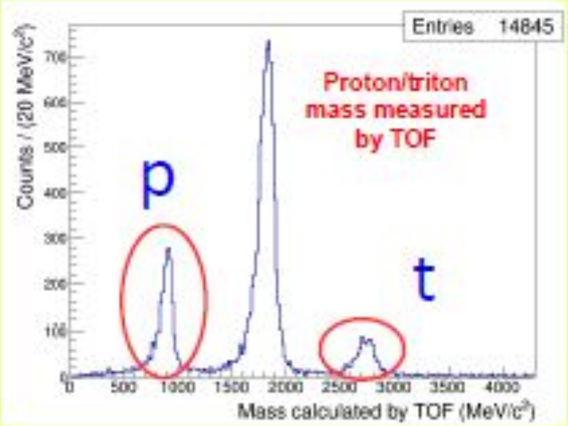
$K^- \, {}^{12}C \rightarrow \Lambda/\Sigma^0 \; p$ (2NA) $\qquad$ $K^- \, {}^{4}He \rightarrow \Lambda/\Sigma^0 \; t$ (4NA)







1112<$M_{p\pi}$< 1118 MeV/c²



$K^- \, {}^{12}C \rightarrow \Lambda/\Sigma^0 \; p$ (2NA)

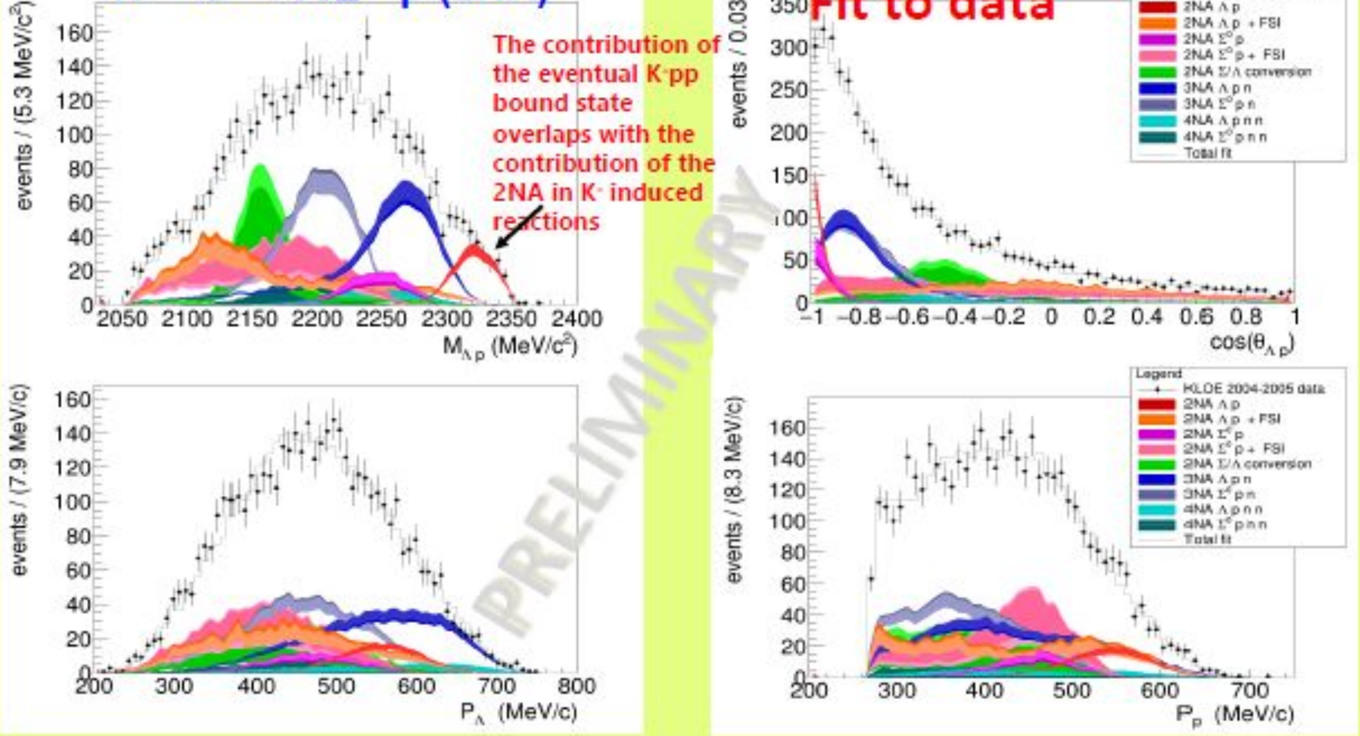


Table 1 Branching ratios and cross sections of the K^- multi-nucleon absorption processes. The statistical and systematic errors are also shown.

Process	Banching 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
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.)			
2NA-Σ/Λconv.	2.1 ± 1.2(stat.) $^{+0.9}_{-0.5}$(syst.)			

$$BR(K^{-\,12}C \rightarrow \Lambda(\Sigma^0)pR) = 0.177 \pm 0.024(stat.)^{+0.027}_{-0.032}(syst.$$