Studies of low-energy K- hadronic interactions with light nuclei by AMADEUS

Magdalena Skurzok*

On the behalf of the AMADEUS collaboration

Jagiellonian University in Krakow

INFN LNF
Istituto Nazionale di Fisica Nucleare

The 18th International Conference on
Strangeness in Quark Matter (SQM 2019)
10-15 June 2019, Bari (Italy)

*magdalena.skurzok@lnf.infn.it

Plan

1. Motivation and scientific case
2. AMADEUS @ DAΦNE
3. Analysis results
4. Conclusions & perspectives

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.

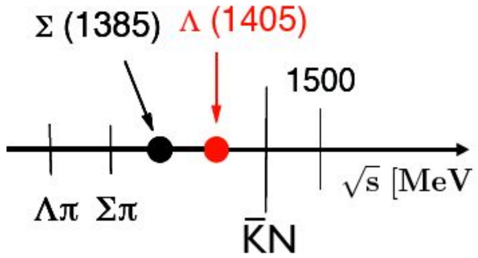
Chiral perturbation theory (ChPT): effective field theory where mesons and baryons represent the effective degrees of freedom instead of the fundamental quark and gluon fields.

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

- 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 $\overline{K}N$ channel due to the emerging of the Λ(1405) and the Σ(1385) resonances just below the $\overline{K}N$ 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 $J^P = 3/2^+$

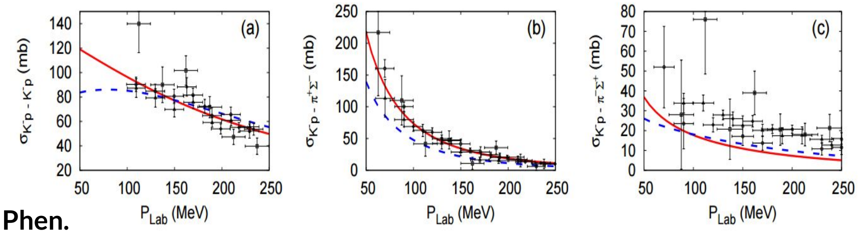
decay modes: Λ π (I=1) (87.0 ± 1.5) %

Σ π (I=1) (11.7 ± 1.5) %

Possible solutions:

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

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

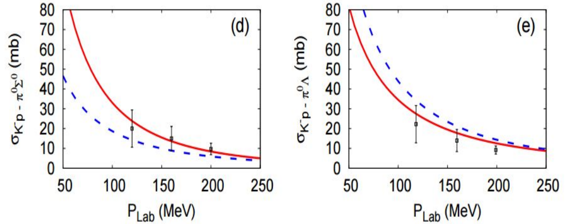


Phen.

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

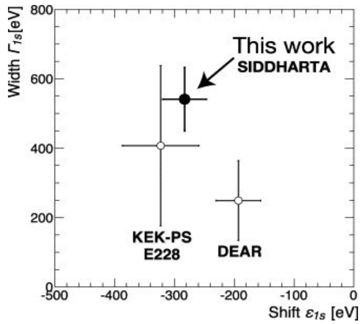
Chiral

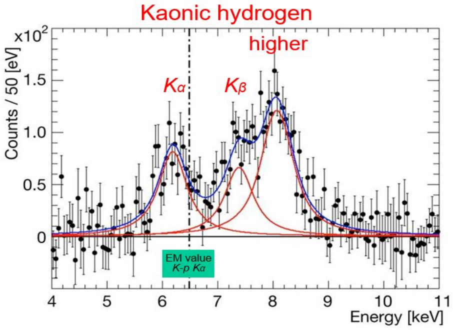
S. Ohnishi, Y. Ikeda, T. Hyodo, W. Weise, Phys.Rev. C93 (2016) no.2, 025207



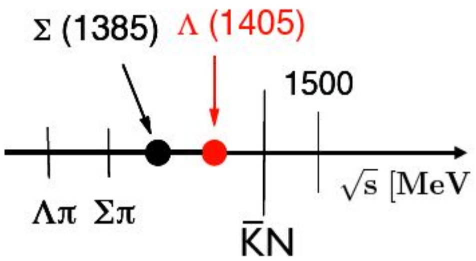
and by the SIDDHARTA measurement of K_α transition in Kaonic hydrogen at threshold

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





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:

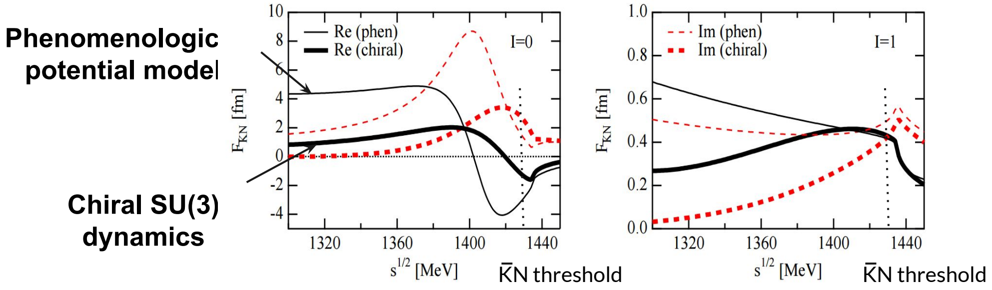
- **Non-perturbative Coupled Channels approach: Chiral Unitary SU(3) Dynamics**
- **Phenomenological $\bar{K}N$ and NN potentials**

...but... large differences in the subthreshold extrapolations! **Significantly weaker attraction in chiral SU(3) models** than in phenomenological potential models.

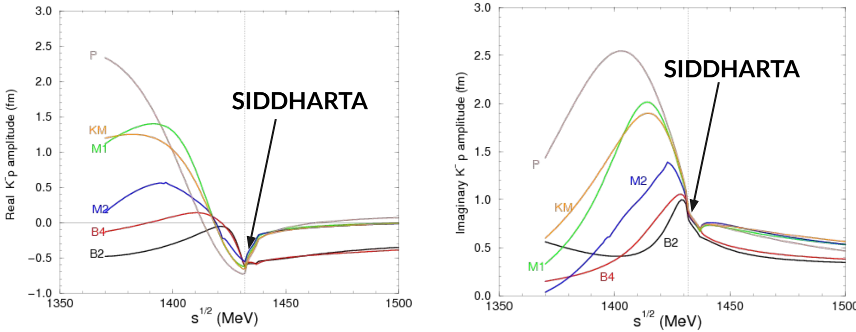
Re Im

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

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

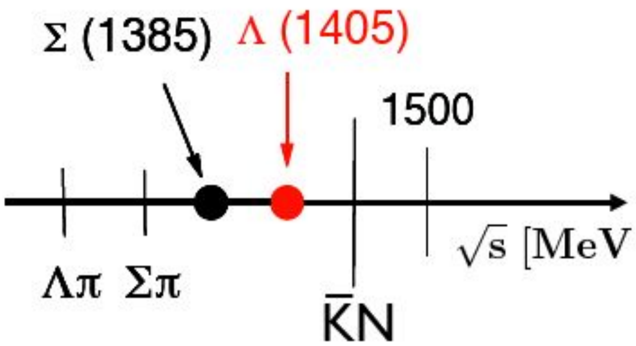


New experimental constraints!!!



E. Friedman, A. Gal, Nucl. Phys. A959, 66 (2017)

The controversial nature of the Λ(1405)

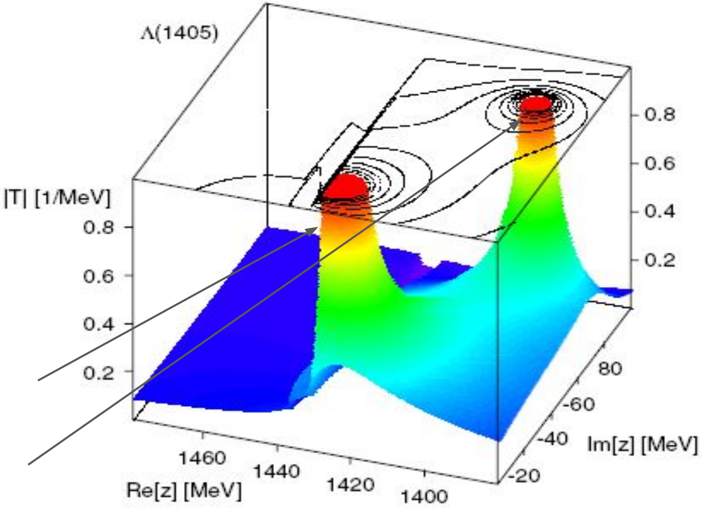


The Λ(1405) state does not fit with the simple three quarks model (*uds*) and it is commonly accepted that **it is, at least partially, a $\bar{K}N$ bound state**.

- **Chiral SU(3) coupled channel dynamics:**
  the state is given by the superpositions of **two poles of the $\bar{K}N$ scattering amplitude.**

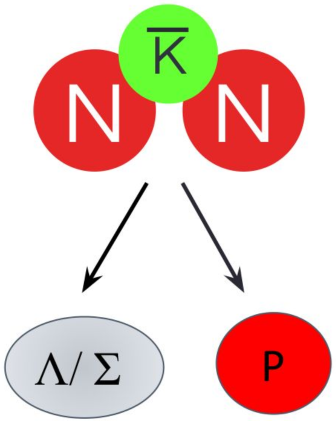
  M = 1425 MeV → **mainly coupled to the $\bar{K}N$ channel**

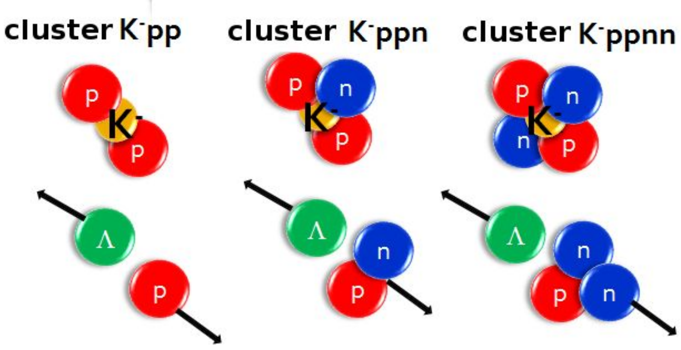
  M = 1380 MeV → **mainly coupled to the Σπ channel**



- **Phenomenological potentials models:** the **Λ(1405) is a pure $\bar{K}N$ bound state** with mass M=1405 MeV, binding energy BE = 27 MeV and width Γ=50 MeV.

Possible existence of **kaonic bound states**





$\Lambda + p$ $\Lambda + d$ $\Lambda + t$

$\Sigma^0 + p$ $\Sigma^0 + d$ $\Sigma^0 + t$

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

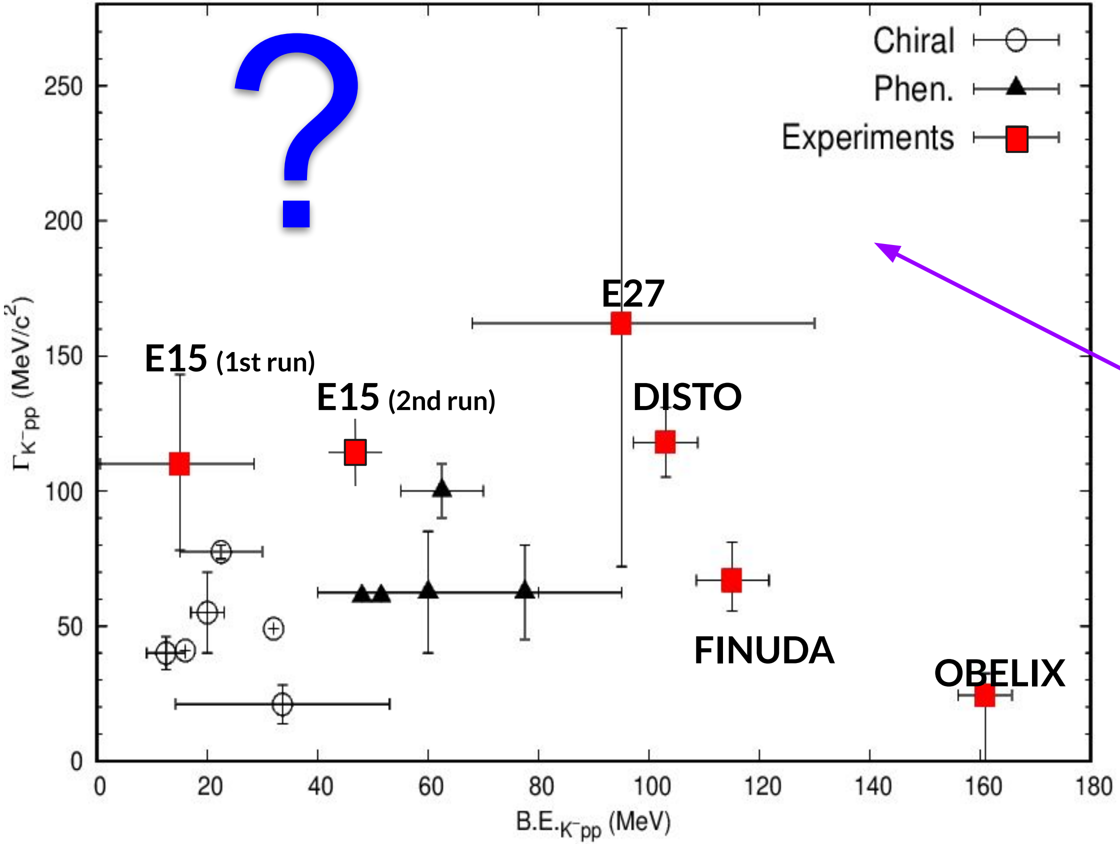
Theory

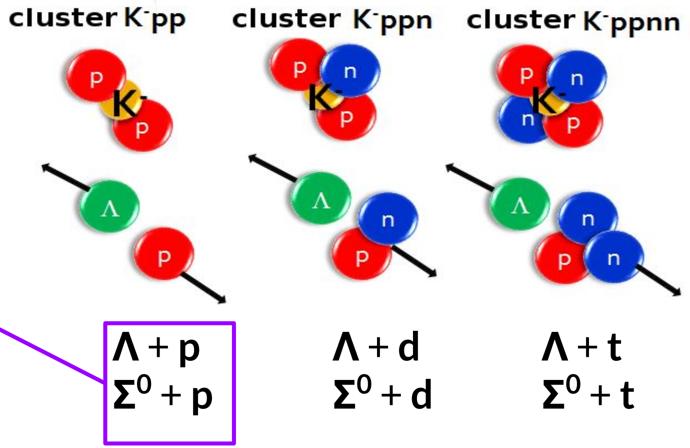
Chiral models	BE [MeV]	Γ [MeV]	Reference
Dote, Hyodo, Weise	17 - 23	40 - 70	Phys. Rev. C 79 (2009) 014003
Barnea, Gal, Liverts	16	41	Phys. Lett. B 712 (2012) 132
Ikeda, Kamano, Sato	9 - 16	34 - 46	Prog. Theor. Phys. (2010) 124 (3)
Bicudo	14.2 - 53	13.8 - 28.3	Phys. Rev. D 76 (2007) 031502
Bayar, Oset	15 - 30	75 - 80	Nucl. Phys. A 914 (2013) 349
Dote, Inoue, Myo	21.2 - 32.2	9 - 31.7	Prog. Theor. Exp. Phys. 2015 (2015) 043D02
Sekihara, Oset, Ramos	16	72	Prog. Theor. Exp. Phys. 2016 (2016) 123D03
Phen. approach	**BE [MeV]**	**Γ [MeV]**	**Reference**
Akaishi, Yamazaki	48	61	Phys. Rev. C 65 (2002) 044005
Ikeda, Sato	60 - 95	45 - 90	Phys. Rev. C 76 (2007) 035203
Shevchenko, Gal, Mares	55 - 70	90 - 110	Phys. Rev. Lett. 98 (2007) 082301
Revai, Shevchenko	32	49	Phys. Rev. C 90 no. 3 (2014) 034004
Maeda, Akaishi, Yamazaki	51.5	61	Proc. Jpn. Acad. B 89 (2013) 418
Wycech, Green	40 - 80	40 - 85	Phys. Rev. C 79 (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±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 1st run	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), 612

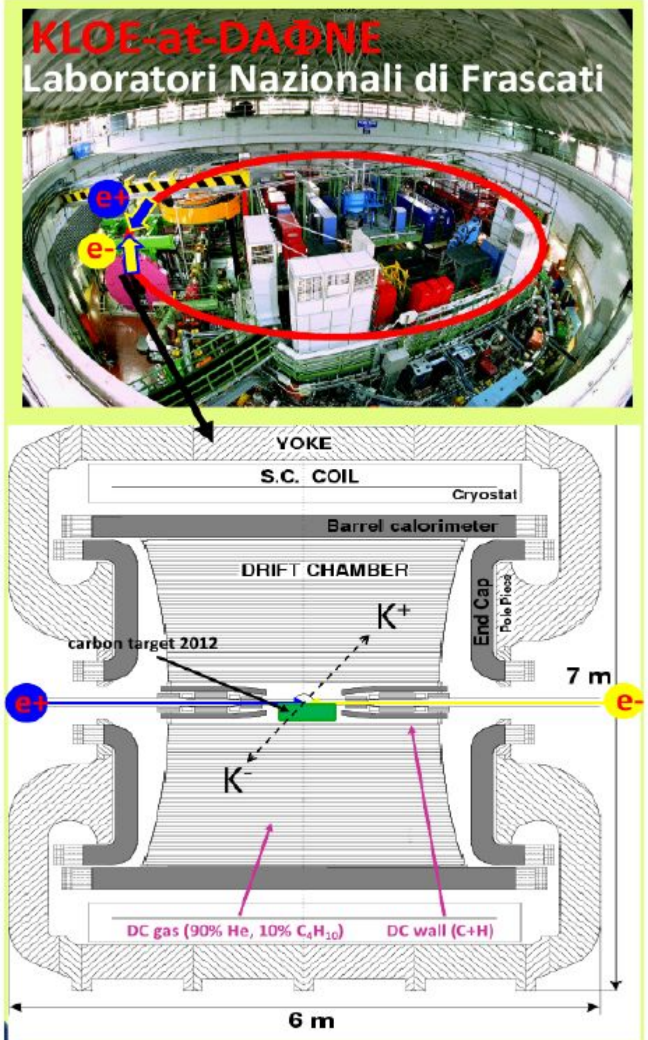
Possible existence of kaonic bound states





FINUDA, E549, E15, AMADEUS: K^- induced reactions
DISTO, HADES: p-p collisions
OBELIX: anti-p annihilations
E27: π induced reactions
LEPS/SPring-8: photoproduction

AMADEUS @ DAΦNE



DAΦNE

- $\phi \rightarrow K^- K^+$ (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

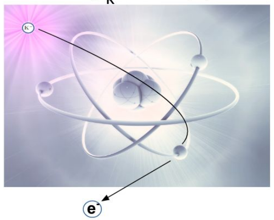
KLOE

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

AT-REST

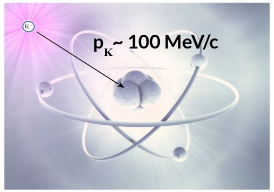
K^- absorbed from atomic orbitals

(p_K ~ 0 MeV/c)



IN-FLIGHT

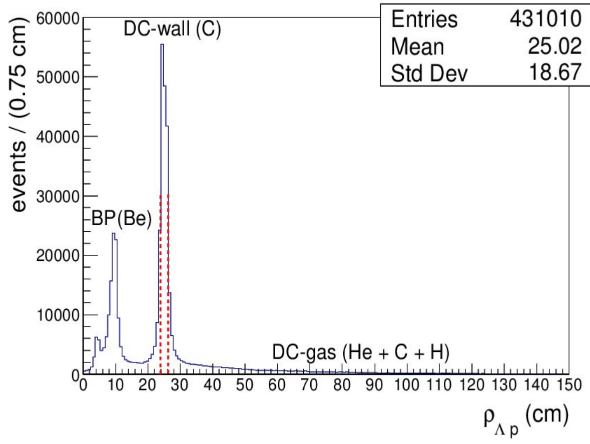
(p_K ~ 100 MeV/c)



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

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}).



$\Lambda\pi^-$ analysis: K^-n non-resonant transition amplitude

$\Lambda(1405)$ case

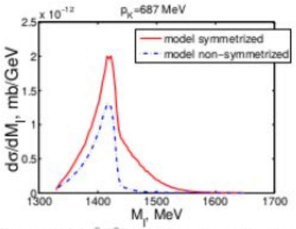


FIG. 4: Theoretical ($\pi^0\Sigma^0$) invariant mass distribution for an initial kaon lab momenta of 687 MeV. The non-symmetrized distribution also contains the factor 1/2 in the cross section.

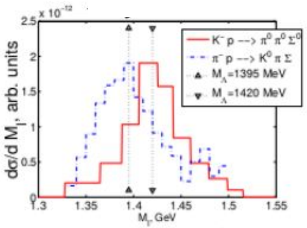
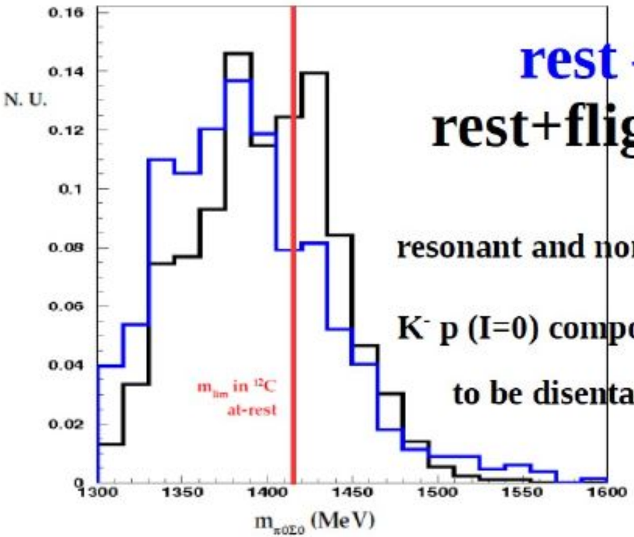


FIG. 5: Two experimental shapes of $\Lambda(1405)$ resonance. See text for more details.

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



rest –

rest+flight –

resonant and non-resonant

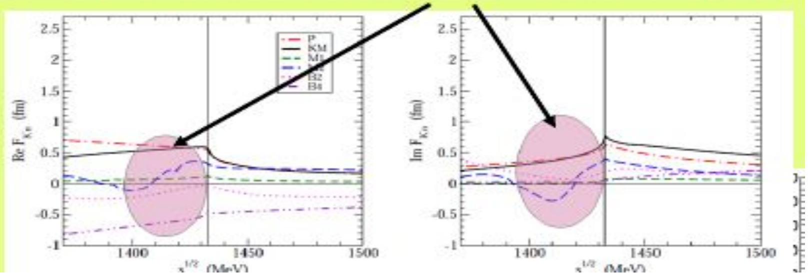
K^- p (I=0) components are

to be disentangled

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

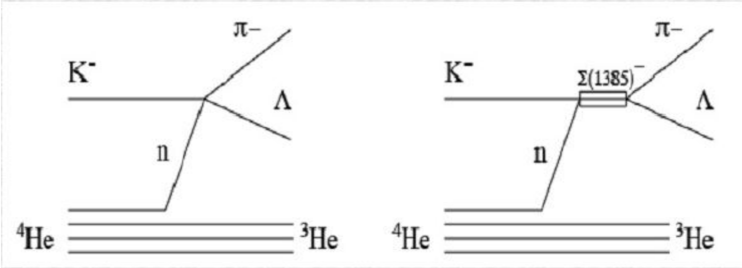
Non-resonant transition amplitude

never measured before below threshold



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

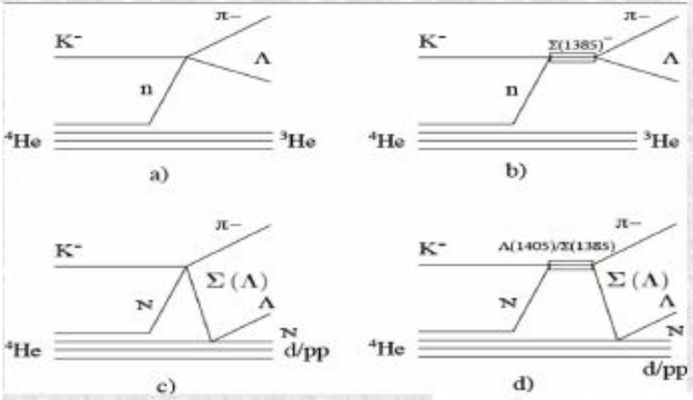
K^-"n" $\to$ $\Lambda\pi^-$ direct formation in **^{4}He**



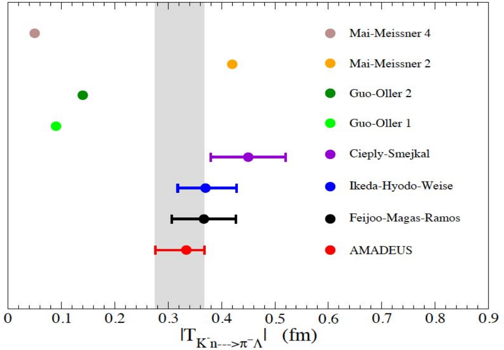
$$|f^{N-R}_{\Lambda\pi}(I=1)| \Rightarrow |f^{N-R}_{\Sigma\pi}(I=0)|$$

$K^- \, {}^4He \rightarrow \Lambda p^- \, {}^3He$ 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

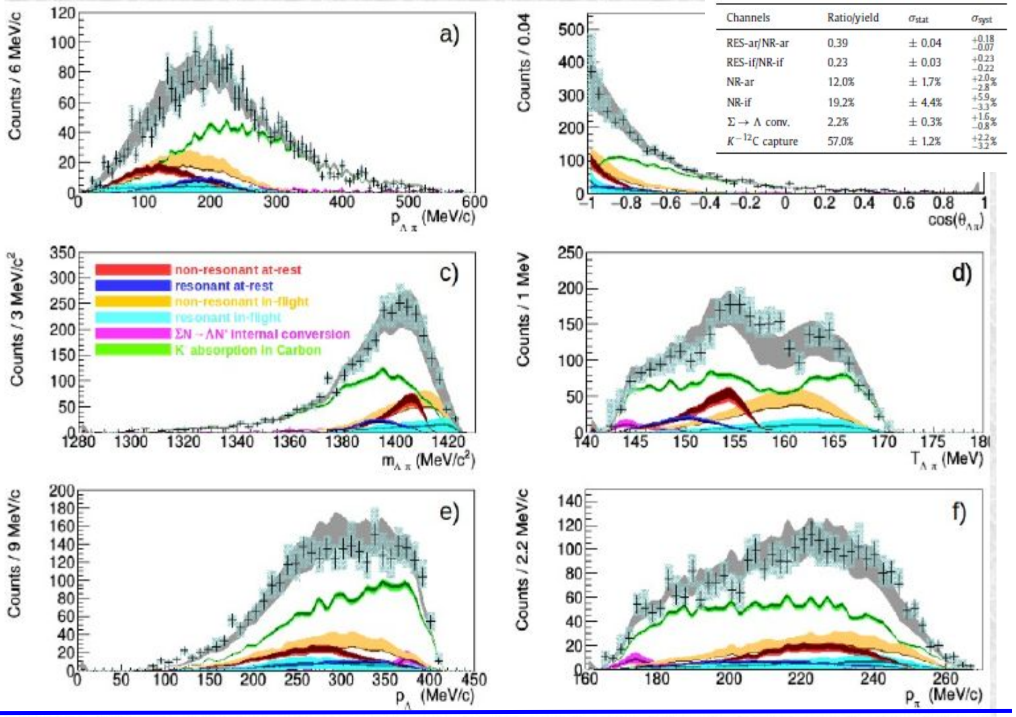


Simulations for resonant and non-resonant processes performed based on calculations for both S-state and P-state K- capture AT REST and IN FLIGHT



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:

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

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

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

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:

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

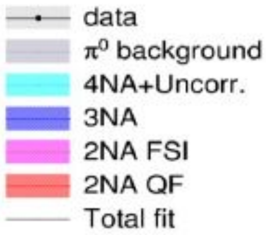
Isospin (I , I_z) = = (1 , -1) component

Phase spaces ratios

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

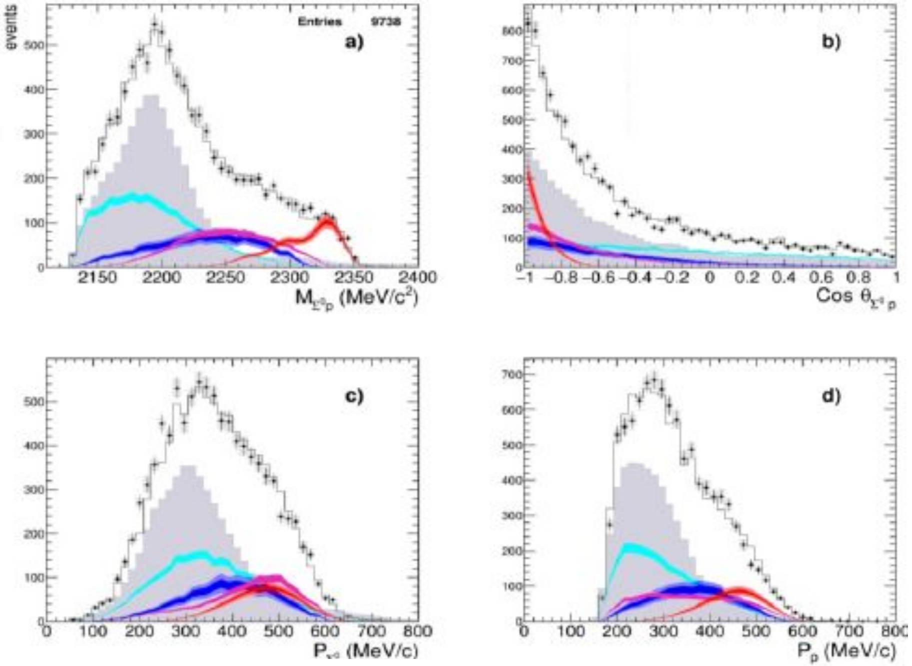
Σ^0p analysis: K^- multi-nucleon absorptions in ^{12}C

Final fit



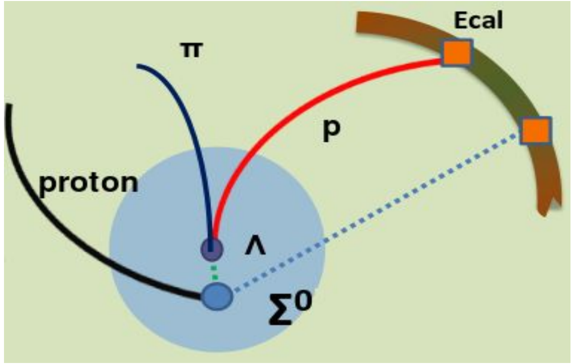
$$\chi^2 = 0.85$$

2NA-QF clearly separated From other processes



$K^-\ ^{12}C \to \Sigma^0\ p\ R \to (p\ \pi^-)\ \gamma\ p\ R$

detected particles



No statistically significant bound state emerges at 2σ level

	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	$^{+0.025}_{-0.076}$

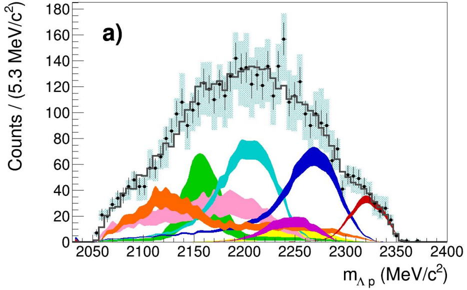
O. Vazquez Doce, et. al., Phys. Lett. B758, 134 (2016)

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

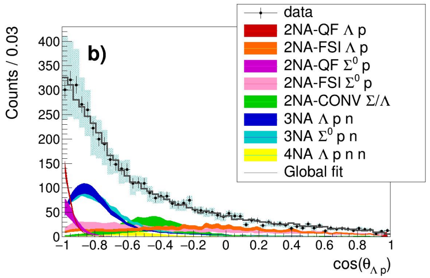
Simultaneous fit of:

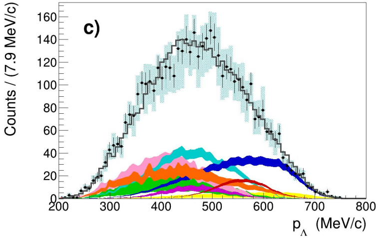
- Λp invariant mass;
- angular correlation;
- proton momentum;
- Λ momentum.

Total reduced χ^2: χ^2/dof = 0.94

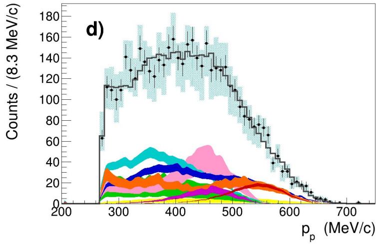


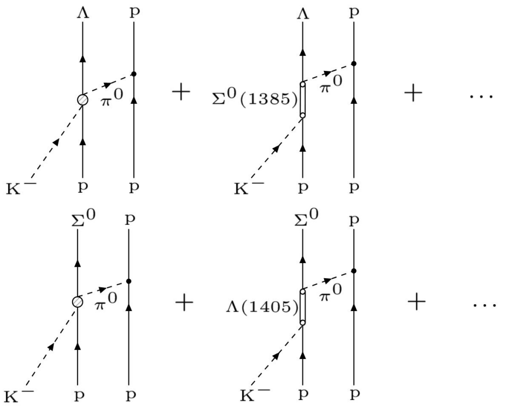
R. Del Grande et al., Eur.Phys.J. C79 (2019) no.3, 190





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 Λ(Σ^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 $\mathcal{R}' \simeq 1.22$.

According to the pion exchange model:

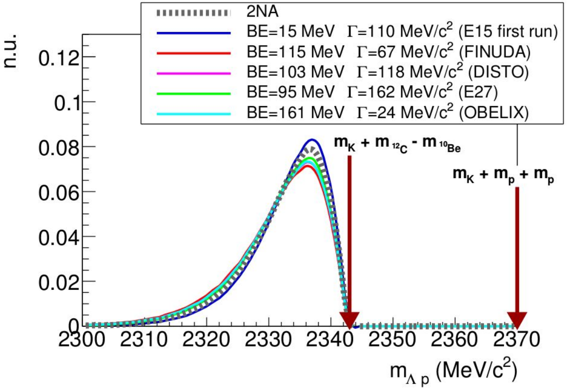
$$\frac{BR(K^-pp \to \Lambda p)}{BR(K^-pp \to \Sigma^0 p)} = \frac{BR(K^-p \to \Lambda \pi^0)}{BR(K^-p \to \Sigma^0 \pi^0)}$$

[E. Oset and H. Toki, Phys. Rev. C 74 (2006) 015207]

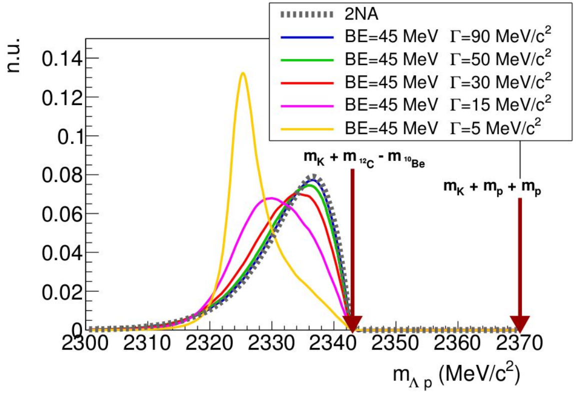
information on the in-medium properties of the Λ (1405).

Λp analysis: K⁻pp bound state search

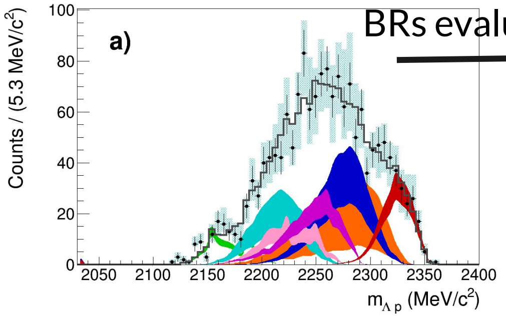
Using BE and Γ from experiments:



Fixing BE and moving Γ:



AMADEUS at DAΦNE

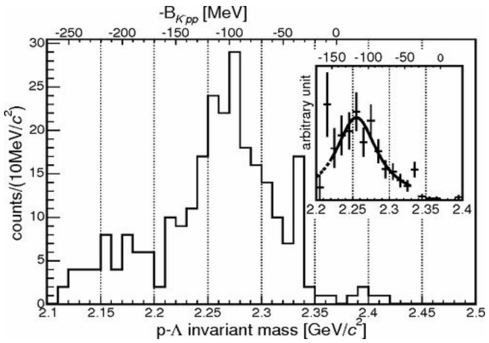


BRs evaluation

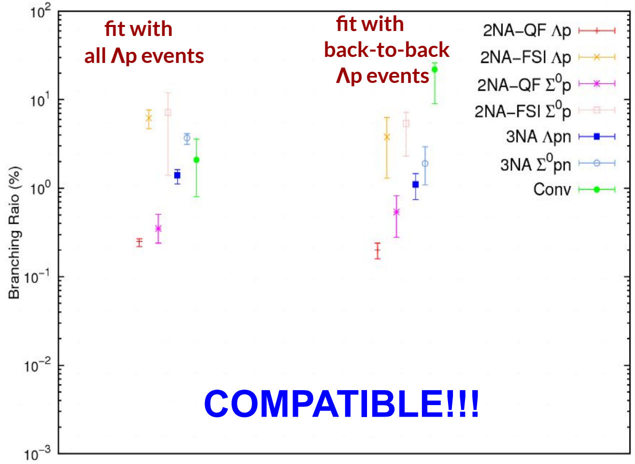
R. Del Grande et al., Eur.Phys.J. C79 (2019) no.3, 190

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	$1.9 \pm 0.7(\text{stat.})\,^{+0.8}_{-0.4}(\text{syst.})$

FINUDA at DAΦNE



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



<u>Λt analysis</u>: Cross section and BR for 4NA in $K^{-}\,{}^{4}He \to \Lambda t$ process

<u>Previous data:</u>

- 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

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

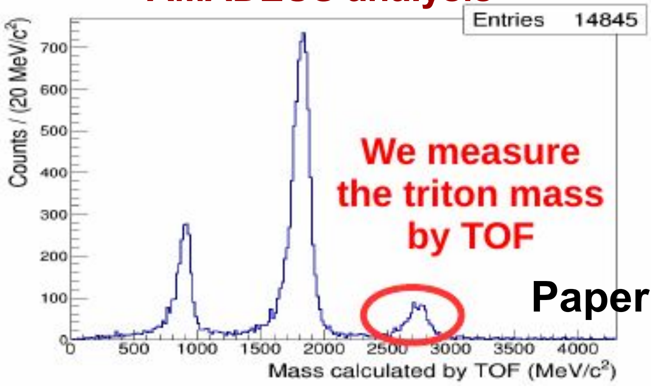
- in **solid targets:** ^{6,7}**Li**, ^{9}**Be** (FINUDA)

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

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

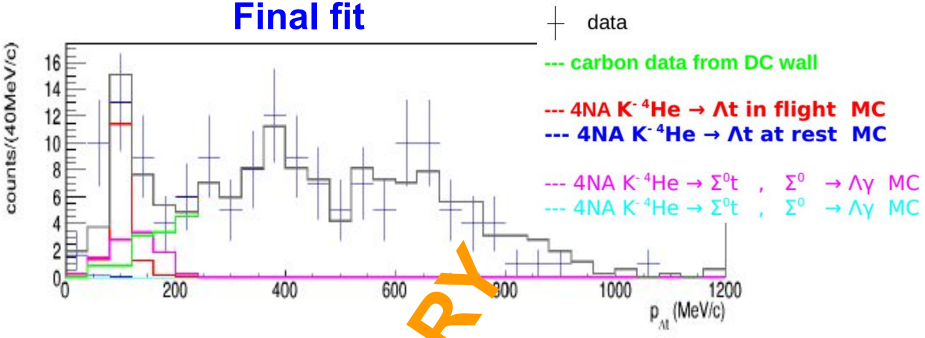
Λt emission yield → $10^{-3} - 10^{-4} / K^{-}_{stop}$ → **global, no 4NA**

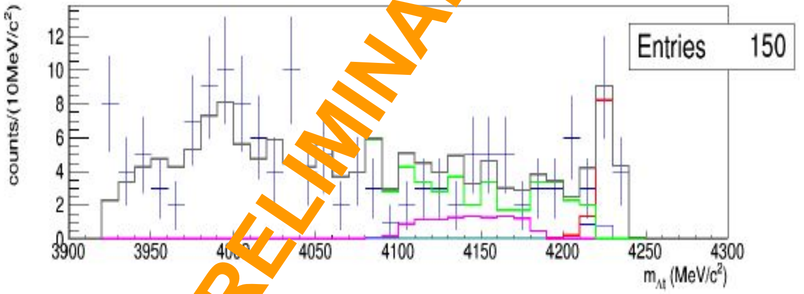
AMADEUS analysis

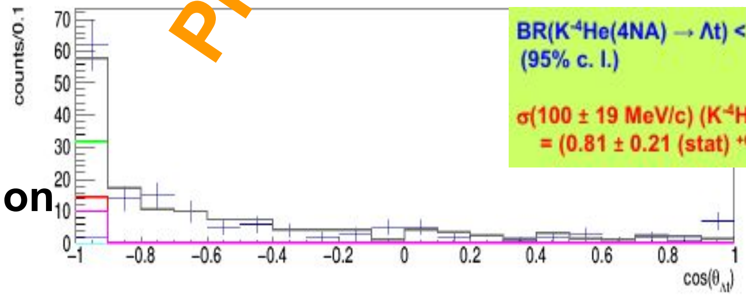


Paper in preparation

Final fit





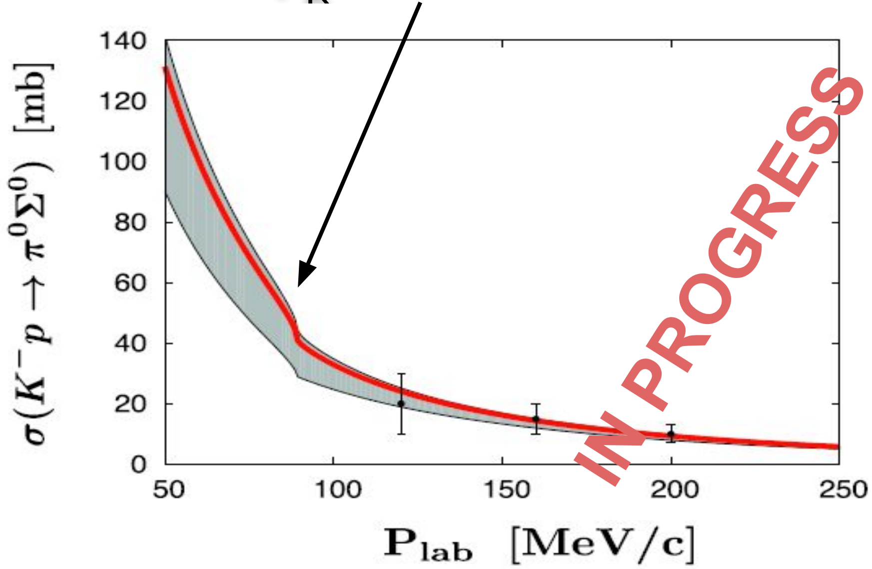


$BR(K^{-}\,{}^{4}He(4NA) \to \Lambda t) < 2.0 \times 10^{-4} / K_{stop}$ (95% c. l.)

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

$\Sigma^0\pi^0$ analysis

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

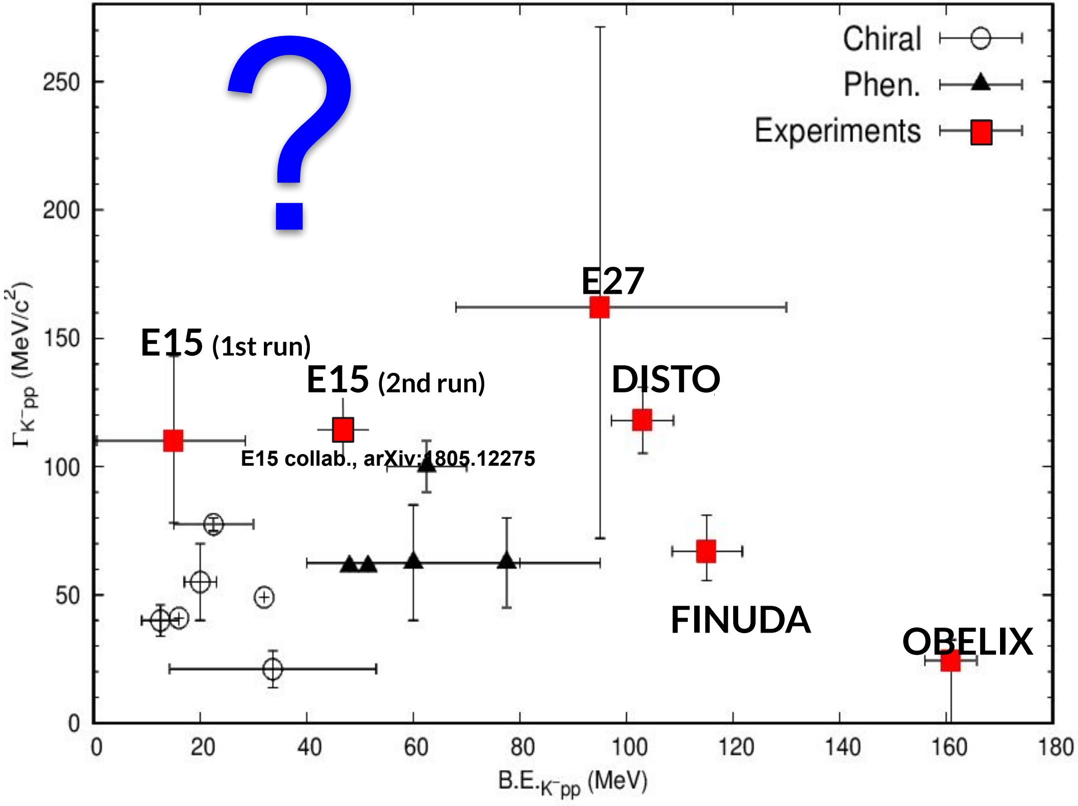


Y. Ikeda, T Hyodo, W. Weise, et. al., Phys. Lett. B706, 63 (2011); Nucl. Phys. A881, 98 (2012)

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

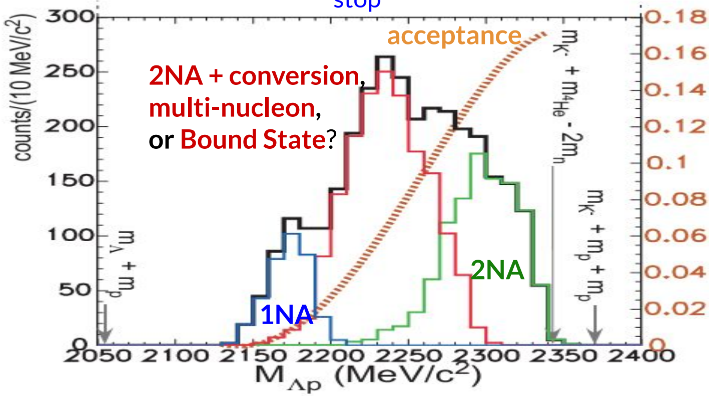

Thank you for attention!

How deep can be bound antikaon in nucleus?



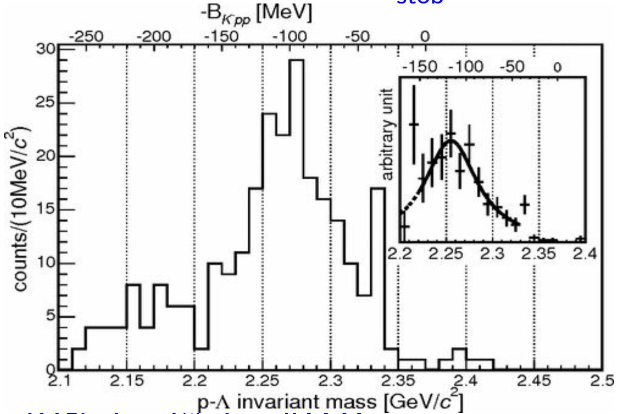
Experimental search in K^- induced reactions

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



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

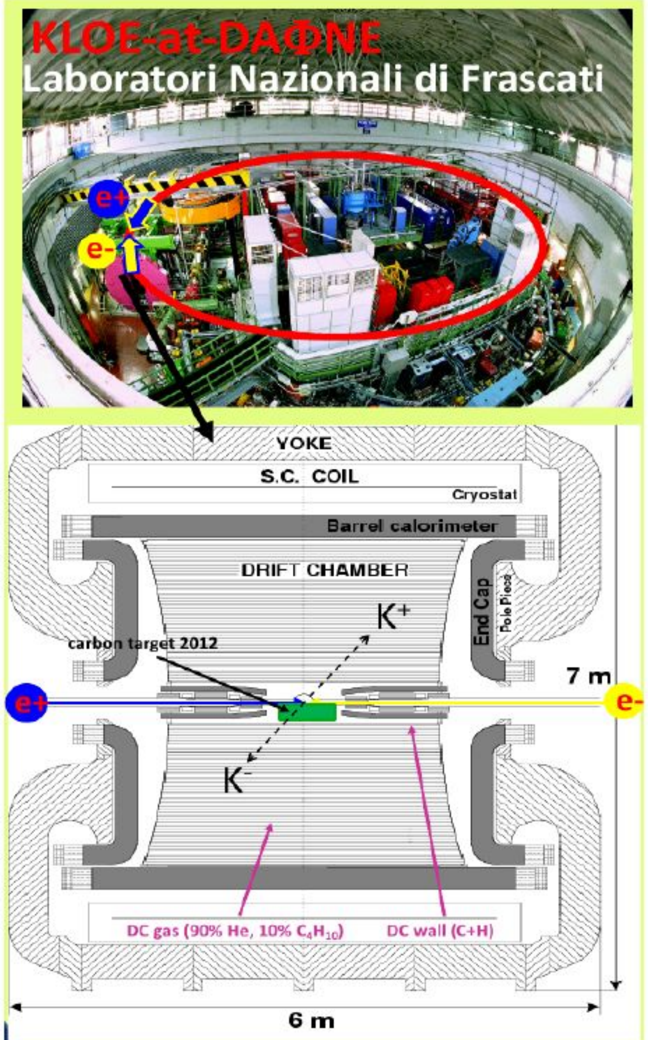
FINUDA at DAΦNE: $K^-_{stop} + X \rightarrow \mathbf{\Lambda} + \mathbf{p} + X'$



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

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

AMADEUS @ DAΦNE



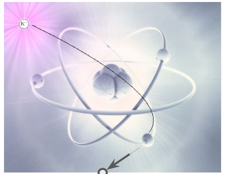
DAΦNE

- $\phi \rightarrow K^- K^+$ (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

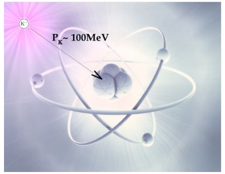
KLOE

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

AMADEUS scientific case

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

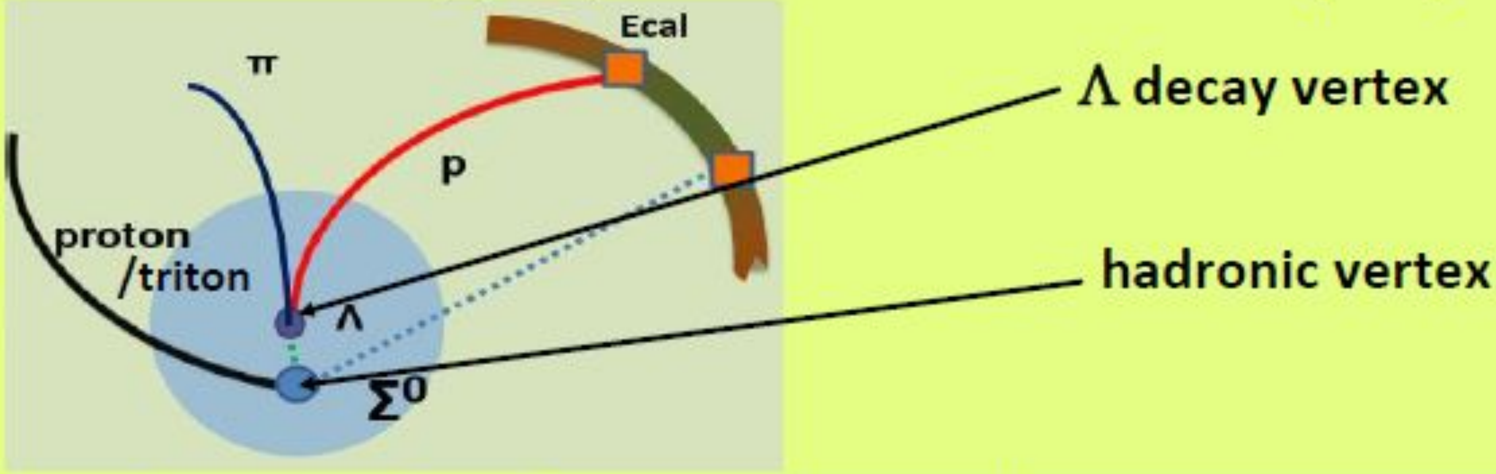
- K^- multiN absorption

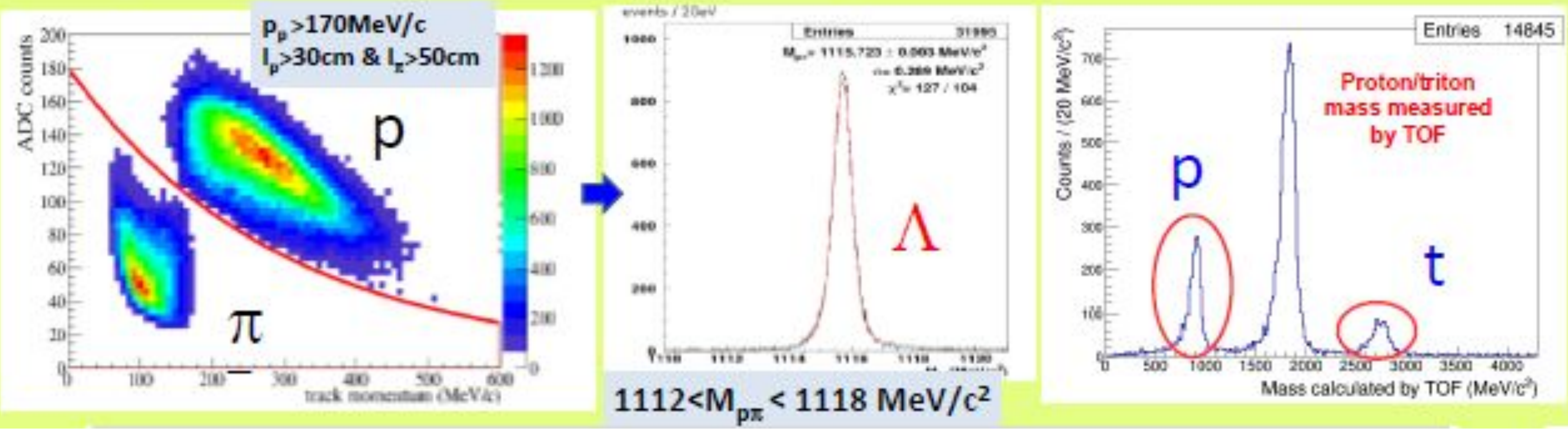
- kaonic nuclear clusters

YN correlation studies (Λp, Σ^0p, Λt)

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

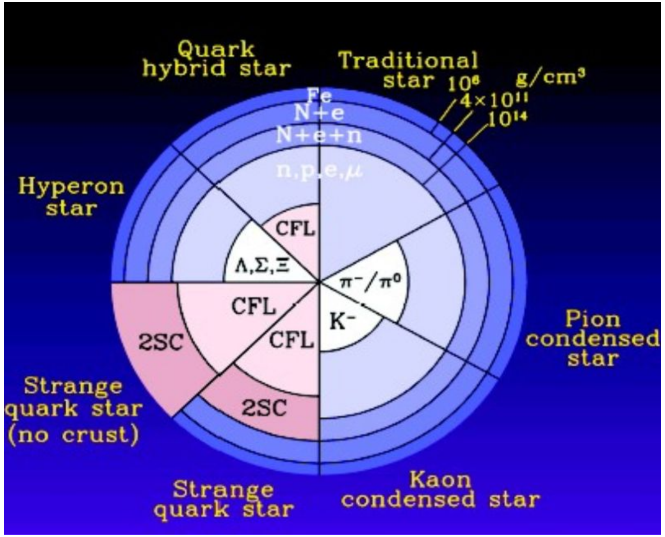
$K^- \, ^{12}C \rightarrow \Lambda/\Sigma^0 \; p$ (2NA) $\qquad$ $K^- \, ^{4}He \rightarrow \Lambda/\Sigma^0 \; t$ (4NA)





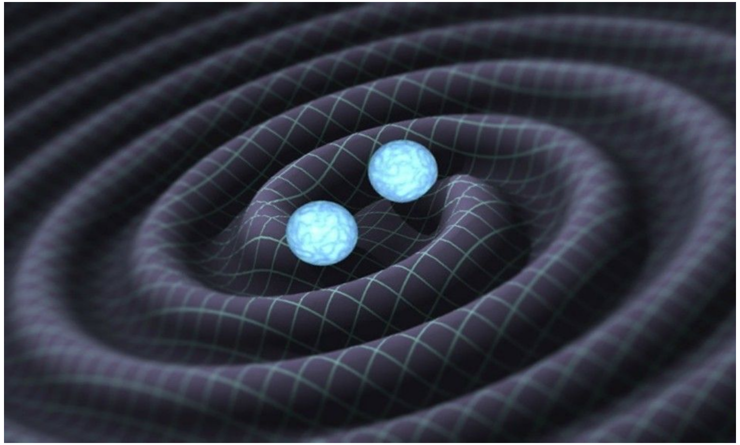
Essential impact on the EoS of Neutron Stars

Role of strangeness in dense baryonic matter, kaon condensation? Strange quark matter? Hyperons in Neutron Stars?



The central densities are expected to be large enough to activate the strangeness production:

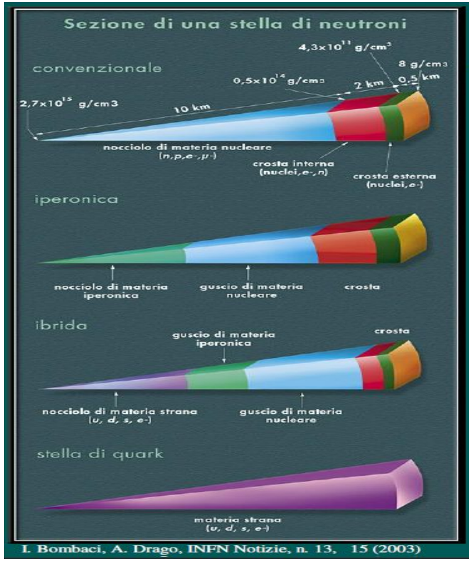
$$p + e^- \rightarrow n + \nu_e$$
$$n \rightarrow p + K^-$$



HOT TOPIC after the measurement of the gravitational waves signal emitted by binary system of Neutron Stars (GW170817)

YN/NN scatterings

Y-N/NN interaction essential impact on the case of NEUTRON STARS



"Neutron

Nucleon Stars

Hyperon Stars

Hybrid Stars

Strange Stars

Microscopic approach to hyperonic matter EOS

input

2BF: nucleon-nucleon (NN), nucleon-hyperon (NY), hyperon-hyperon (YY)
e.g. Nijmegen, Julich models

3BF: NNN, NNY, NYY, YYY

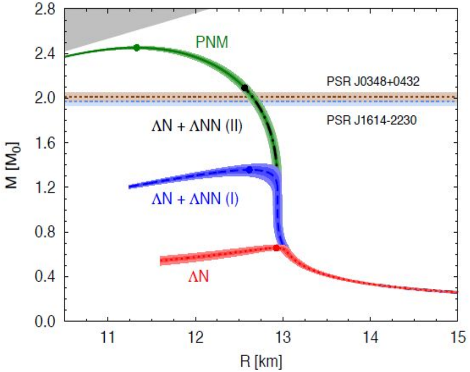
Hyperonic sector: experimental data

1. YN scattering (very few data)
2. Hypernuclei

YN/NN scatterings

No experimental information on Σ^0-N/NN interaction

Λ-neutron matter



Lonardoni, Lovato, Gandolfi, Pederiva, PRL (2015)

Drastic role played by ΛNN. Calculations can be compatible with neutron star observations.

Note: no $v_{\Lambda\Lambda}$, no protons, and no other hyperons included yet...

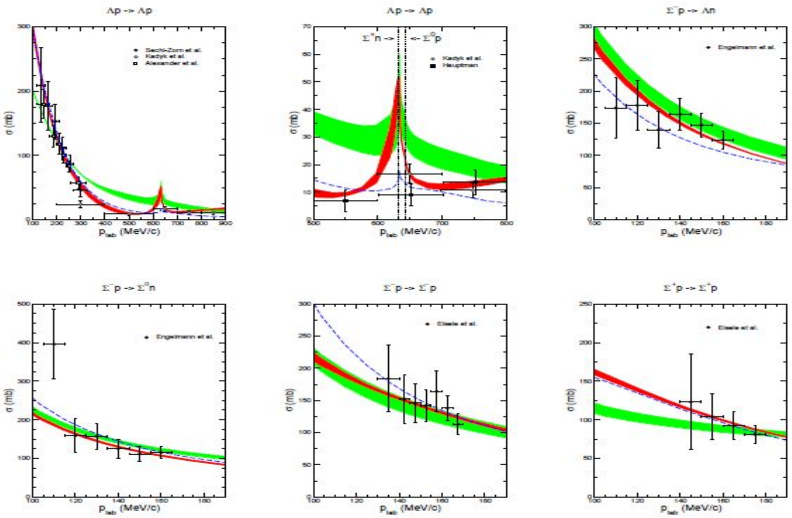


Figure 2: "Total" cross section σ (as defined in Eq. (24)) as a function of p_{lab}. The experimental cross sections are taken from Refs. [52] (filled circles), [53] (open squares), [65] (open circles), and [66] (filled squares) ($\Lambda p \to \Lambda p$), from [54] ($\Sigma^- p \to \Lambda n$, $\Sigma^- p \to \Sigma^0 n$) and from [55] ($\Sigma^- p \to \Sigma^- p$, $\Sigma^+ p \to \Sigma^+ p$). The red/dark band shows the chiral EFT results to NLO for variations of the cutoff in the range $\Lambda = 500, \ldots, 650$ MeV, while the green/light band are results to LO for $\Lambda = 550, \ldots, 700$ MeV. The dashed curve is the result of the Jülich '04 meson-exchange potential [36].

Nucl. Phys. A 915 (2013) 24-58