Investigation of the low-energy K^- interactions in nuclear matter with AMADEUS

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On behalf of the AMADEUS collaboration

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AMADEUS: the scientific goal

Low-energy K^- interaction studies with **light nuclei** (H, ^{4}He, ^{9}Be, ^{12}C) in order to extract conclusive constrains on:

- **$\overline{K}N$ Potential** → how deep can an antikaon be bound in a nucleus?

  - $U_{\overline{K}N}$ strongly affects the position of the $\Lambda(1405)$ state

    → we investigate it through $(\Sigma-\pi)^0$ decay --- Y π CORRELATION

  - if $U_{\overline{K}N}$ is strongly attractive then possible K^- multi-N bound states

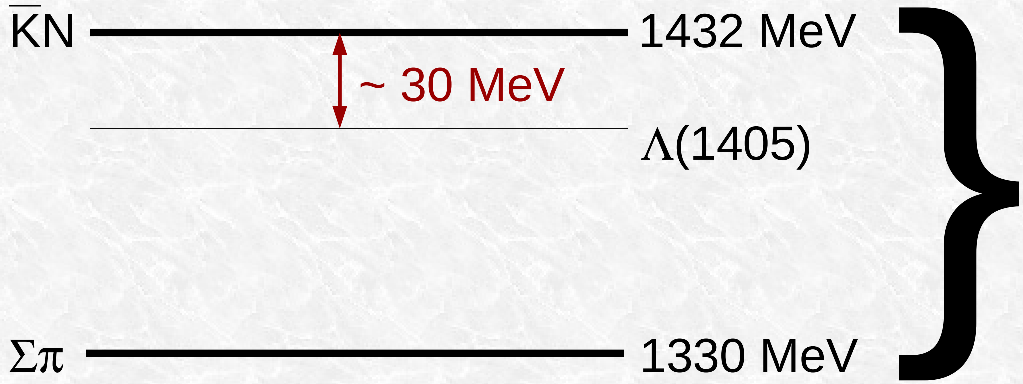
    → we investigate through (Λ/Σ–N) decay ---Y N CORRELATION

- **Y-N potential** → extremely poor experimental information from scattering data

  - U_{YN} determines the strength of the final state YN (elastic & inelastic) scattering in nuclear environment

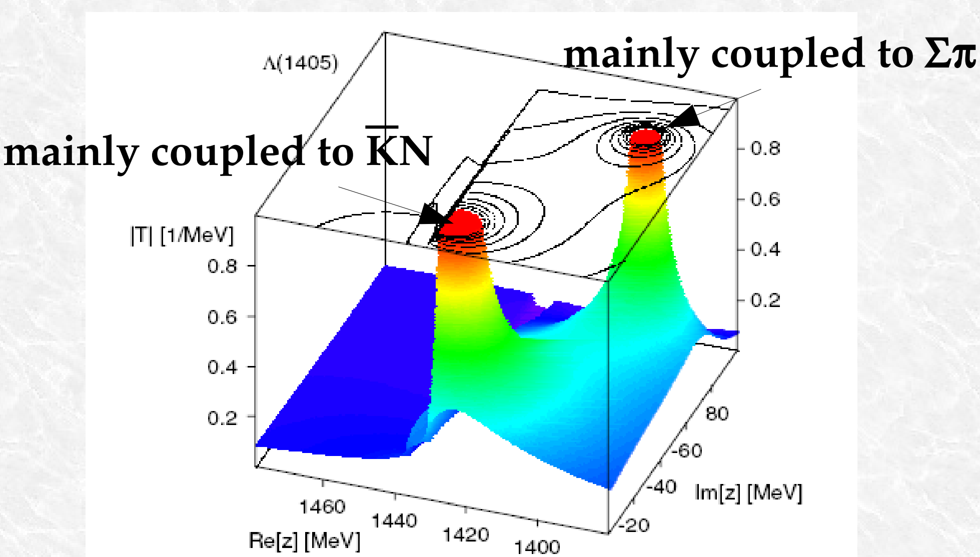
    → could be tested with Y N CORRELATION

Λ(1405) ... resonance or/and bound state?



- 3 quark?
- **molecular?**
- **$\bar{K}N$ bound state?**
- pentaquark?

- Chiral unitary models. Two poles in the neighborhood of the Λ(1405):



[Nucl. Phys. A881, 98 (2012)]

- Akaishi-Esmaili-Yamazaki phenomenological potentials

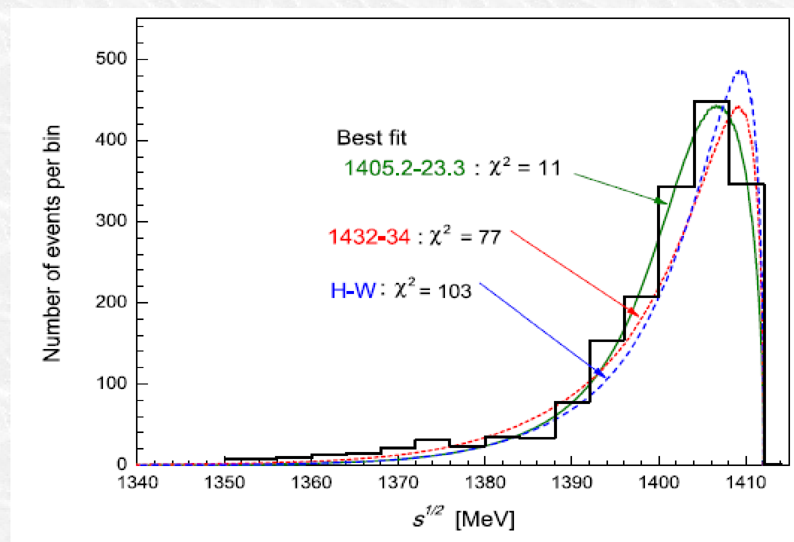


Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

[Phys. Lett. B 686 (2010) 23-28]

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Fit from $K^- + {}^4He \rightarrow \Sigma\,\pi\;{}^3He$ Bubble Chamber experiments

→ **Single pole ansatz?**

$$E_{\Sigma\pi} = m_K + m_N - BE - p^2/(2\mu) \xrightarrow{p \to 0} E_{max} \sim 1412\ \text{MeV}$$

CUT AT THE ENERGY LIMIT AT-REST ?

NON RESONANT SHAPE ?

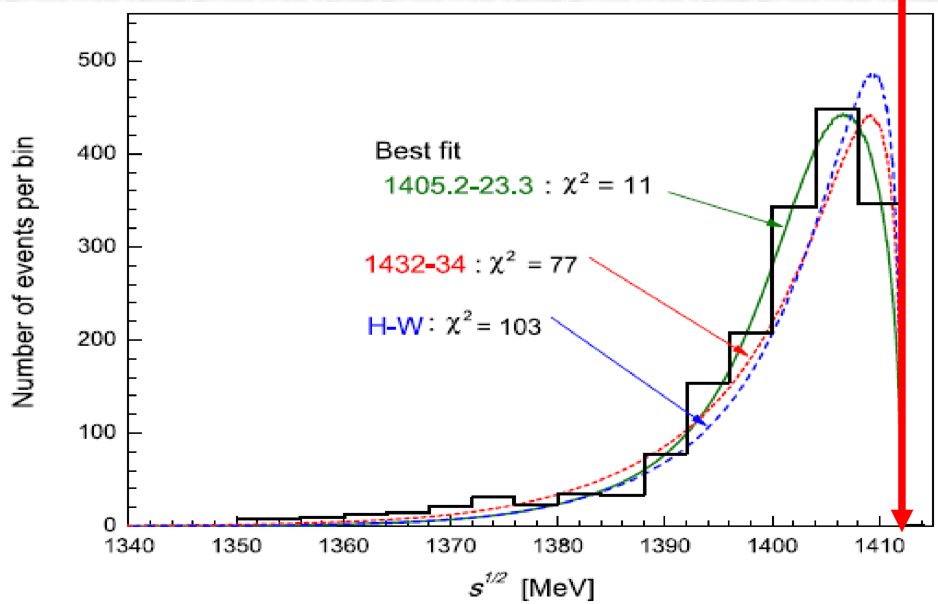

Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

[Phys. Lett. B 686 (2010) 23-28]

Resonant VS Non-Resonant

$K^- N \rightarrow (Y^*\ ?) \rightarrow Y\pi$

$K^- N \rightarrow Y\pi$

in medium, how much comes from resonance ?

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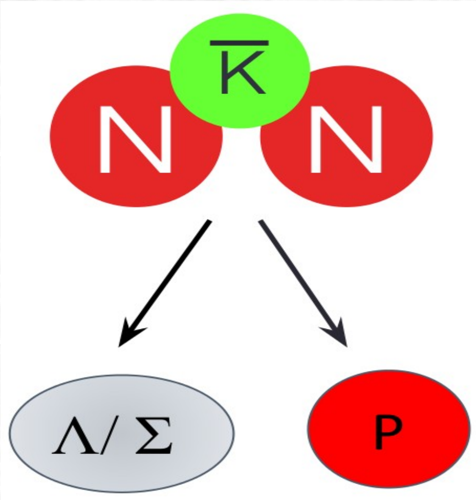
How deep can an antikaon be bound in a nucleus?



Possible Bound States:

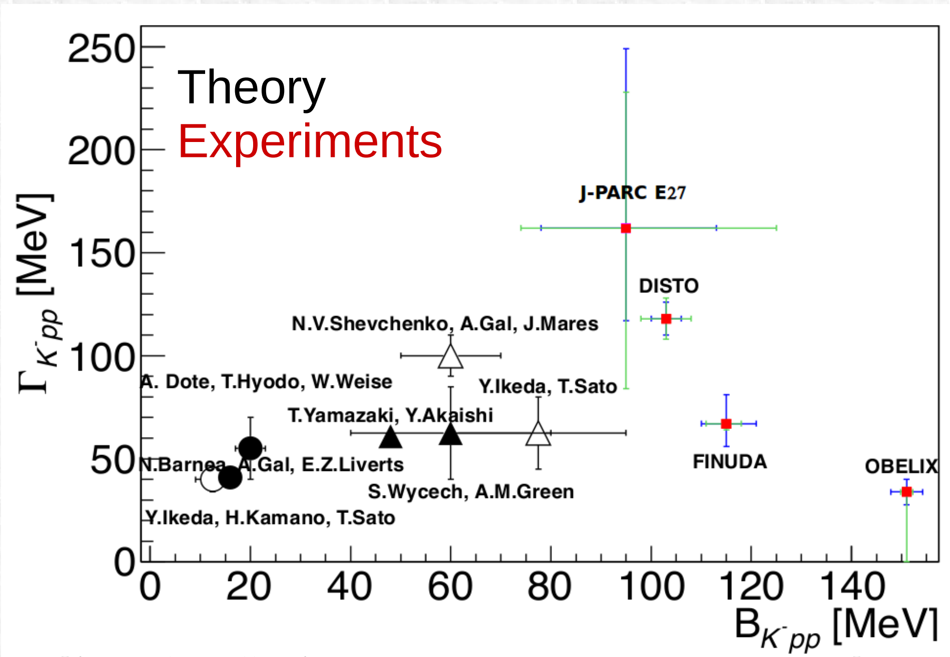
$(K^- pp) \rightarrow \Lambda\, p$ or $\Sigma^0 p$ $(K^- ppn) \rightarrow \Lambda\, d$ or $\Sigma^0 d$

predicted due to the strong $\overline{K}$N interaction in the I=0 channel.
[Wycech (1986) - Akaishi & Yamazaki (2002)]

Multinucleon absorption processes:

2NA: $K^- + \text{“pp”} \rightarrow \Lambda\, p$ or $\Sigma^0 p$

3NA: $K^- + \text{“ppn”} \rightarrow \Lambda\, d$ or $\Sigma^0 d$



[from the talk of T. Nagae at HYP2015, Sep. 10, 2015]

K^-pp bound state

Experiments reporting DBKNS		
KEK-PS E549	T. Suzuki at al. MPLA23, 2520-2523 (2008)	
FINUDA	M. Agnello et al. PRL94, 212303 (2005)	Extraction of a **signal**
DISTO	T. Yamazaki et al. PRL104 (2010)	Extraction of a **signal**
OBELIX	G. Bendiscioli et al. NPA789, 222 (2007)	Extraction of a **signal**
HADES	G. Agakishiev et al. PLB742, 242-248 (2015)	**Upper limit**
LEPS/SPring-8	A.O. Tokiyasu et al. PLB728, 616-621 (2014)	**Upper limit**
J-PARC E15	T. Hashimoto et al. PTEP, 061D01 (2015)	**Upper limit**
J-PARC E27	Y. Ichikawa et al. PTEP, 021D01 (2015)	Extraction of a **signal**

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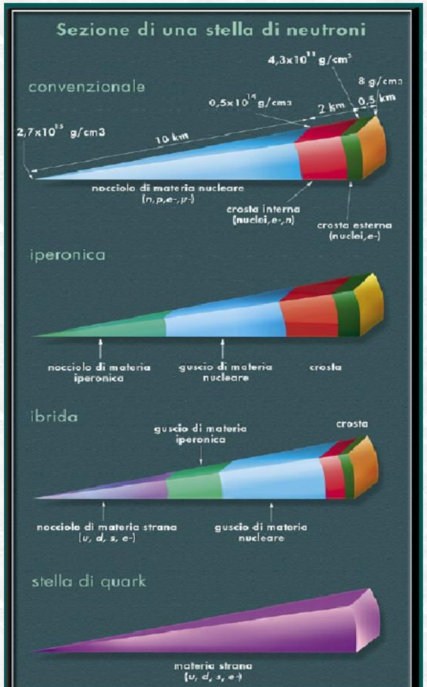
Essential impact on the case of NEUTRON STARS



I. Bombaci, A. Drago, INFN Notizie, n. 13, 15 (2003)

Nucleon Star

Hyperon Star

Hybrid Star

Quark Star

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

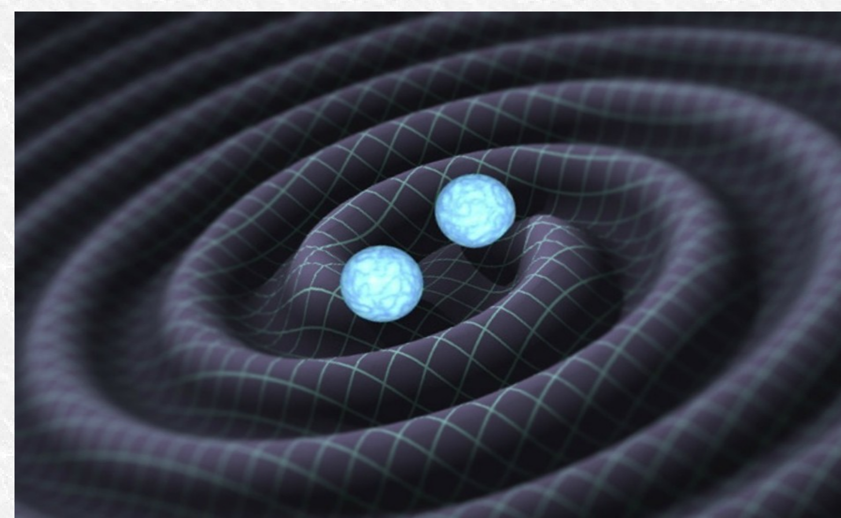
1. **YN scattering** **(very few data)**
2. **Hypernuclei**

A M A D E U S proposal:

Y N CORRELATION STUDIES

Isolate hyperon scattering processes with:

- single nucleon $Y N \rightarrow Y' N'$
- two nucleons $Y N_1 N_2 \rightarrow Y' N_1' N_2'$



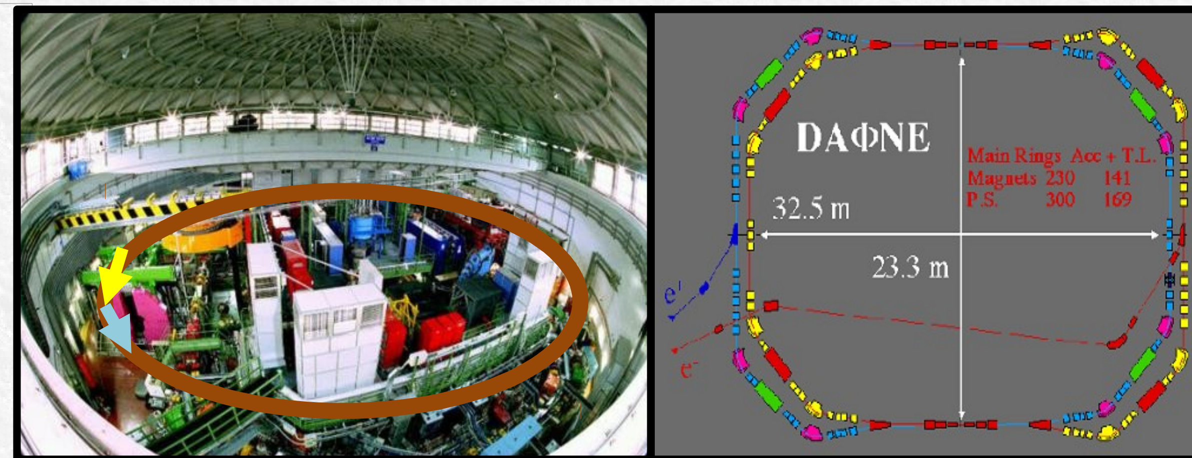
AMADEUS & DAΦNE

DAΦNE

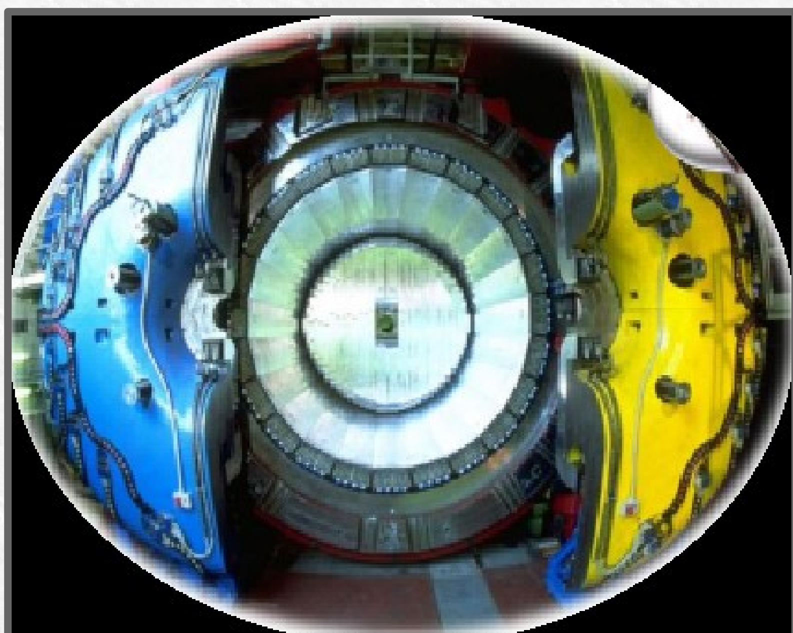
- double ring e^+e^- collider working at C.M. energy of ϕ, producing **≈ 1000 ϕ /s**

$\phi \rightarrow K^+K^-$ (BR = (49.2 ± 0.6)%)

- **low momentum** Kaons ≈ 127 Mev/c
- **back to back** K^+K^- topology



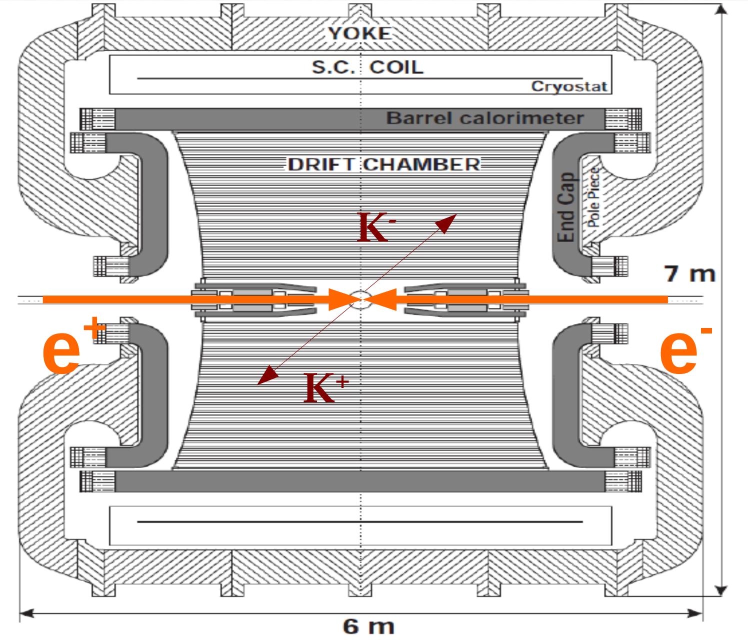
AMADEUS step 0 → KLOE 2004-2005 dataset analysis ($\mathscr{L}$ = 1.74 pb^{-1})



KLOE

- Cilindrical 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)]

K^- absorption on light nuclei

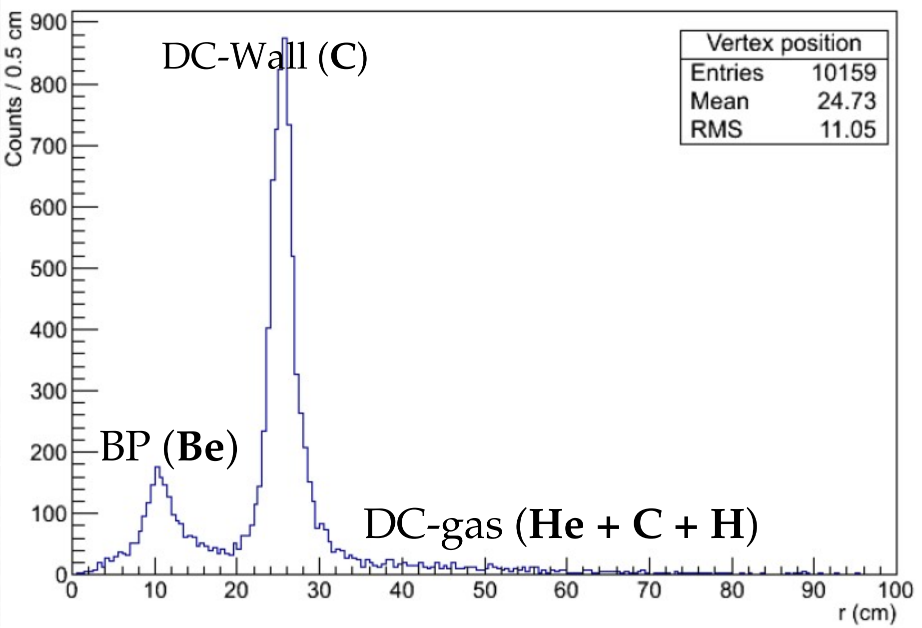


Possibility to use KLOE materials as an active target

- DC wall (750 μm C foil , 150 μm Al foil);
- DC gas (90% He, 10% C_4H_{10}).

Events:

AT-REST (K^- absorbed from atomic orbit)
IN-FLIGHT (p_K~100MeV)



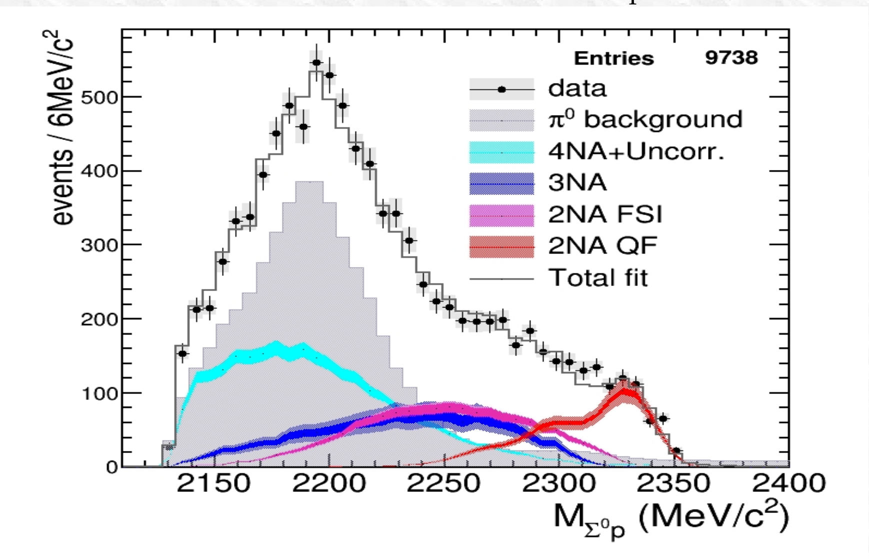
Advantages:
Excellent resolutions..
$\sigma_{p\Lambda}$ = 0.49±0.01 MeV/c in DC gas
$\sigma_{m\gamma\gamma}$ = 18.3±0.6 MeV/c^2

Disadvantages:
Not dedicated target → different nuclei contamination → complex interpretation.

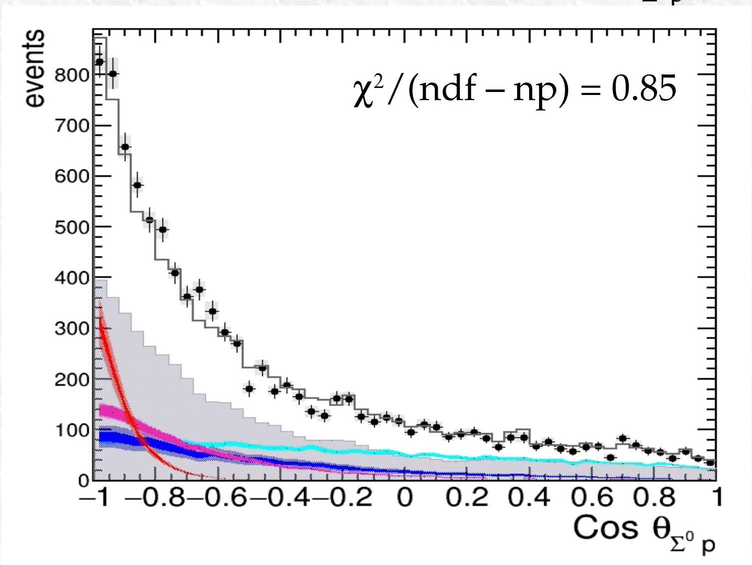
$\Sigma^0 p$ correlation studies in ^{12}C

$$K^- + {}^{12}C \rightarrow \Sigma^0 + p + R$$

- Invariant mass $M_{\Sigma^0 p}$;



- Angular correlation $\cos\theta_{\Sigma^0 p}$;

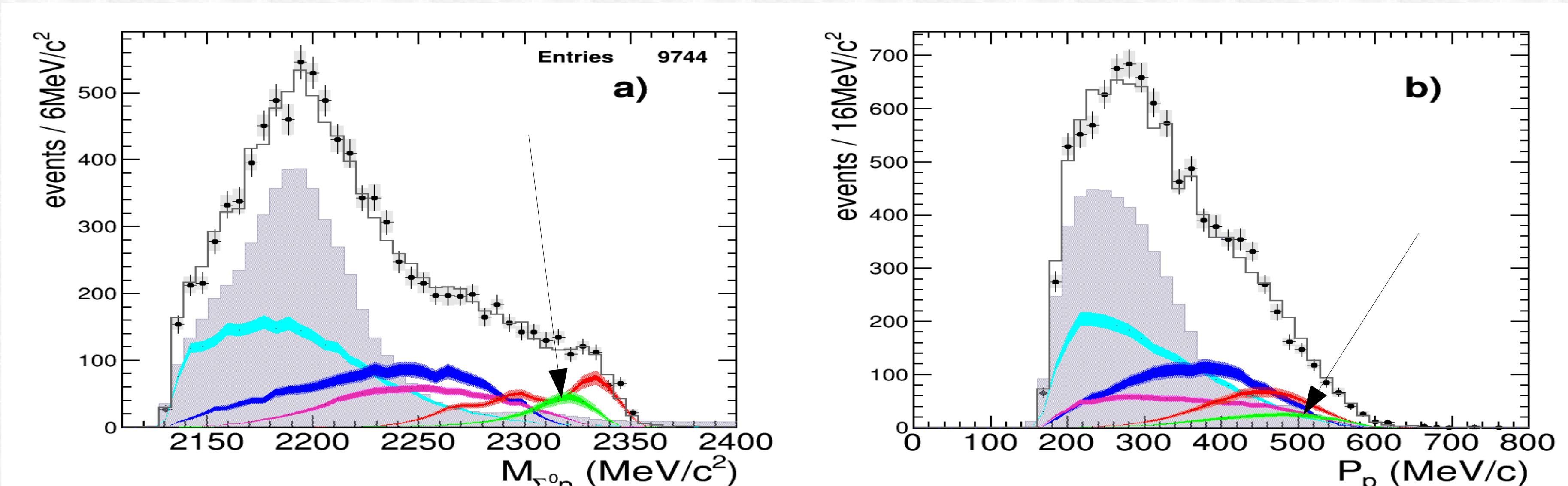


First measure of the **2NA-QF** yield

	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 3 body	0.546	± 0.074	$^{+0.048}_{-0.033}$
4NA + bkg.	0.773	± 0.053	$^{+0.025}_{-0.076}$

Published in PLB: O. Vazquez Doce et al., Phys.Lett. B 758, 134-139 (2016)

$\Sigma^0 p$ correlation studies in ^{12}C

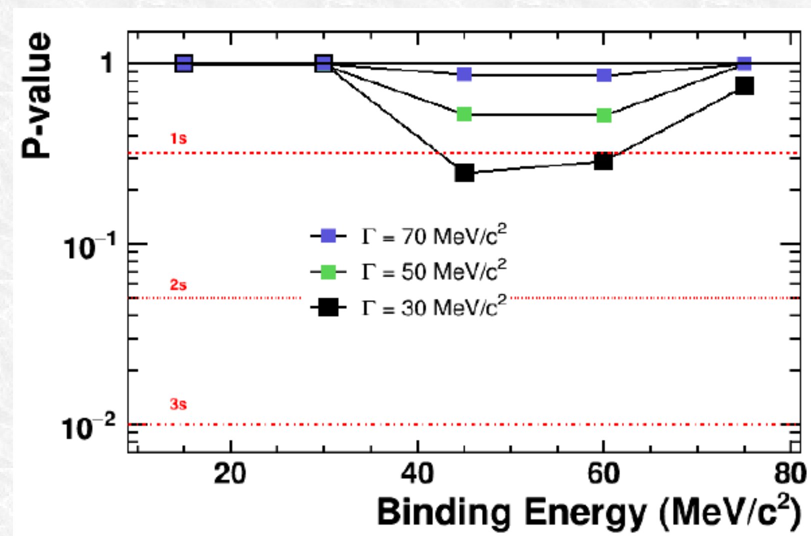


$\chi^2/(\text{ndf}-\text{np})=0.807$

Published in PLB: O. Vazquez Doce et al., Phys.Lett. B 758, 134-139 (2016)

The **ppK⁻ bound state** signal was included:

- The best fit gives **BE=45 MeV** and **Γ = 30 MeV**
- p-value=0.25 → Statistical significance of **1σ**

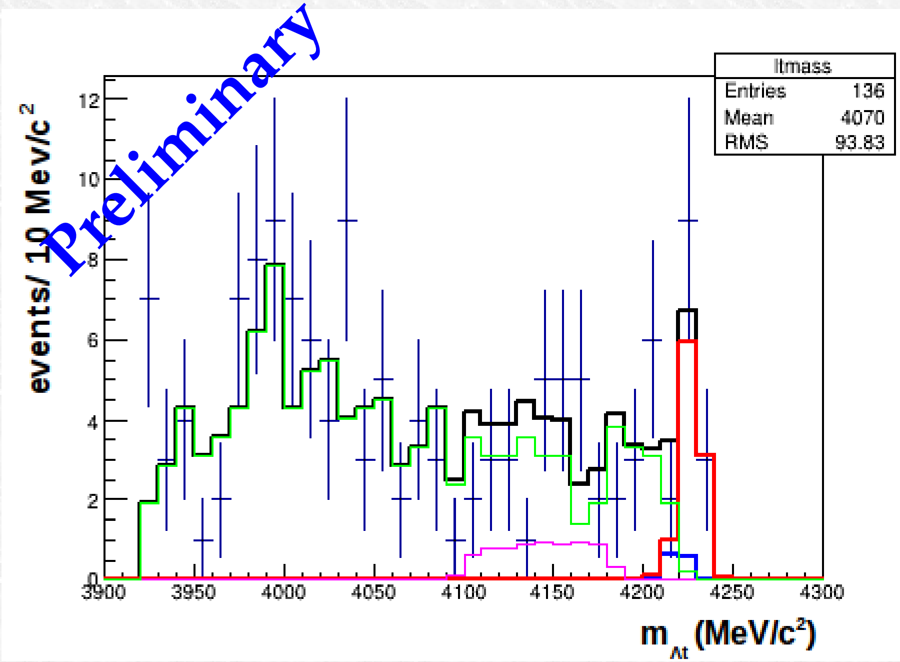


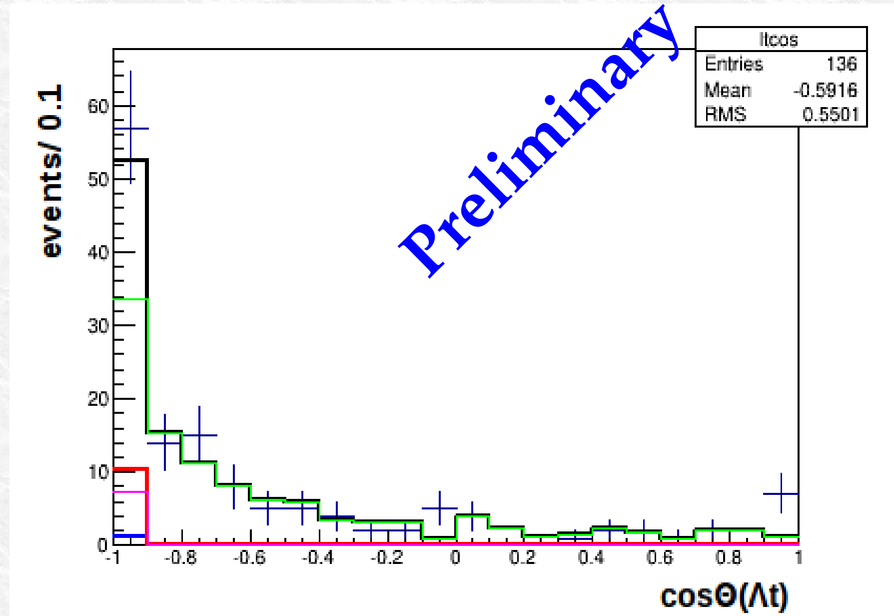
Upper limit:

$$ppK^-/K^-_{stop} = (0.044 \pm 0.009 stat^{+0.004}_{-0.005} syst) \cdot 10^{-2}$$

K^- 4NA cross section and yield measurement

$K^- + {}^4He \rightarrow \Lambda + t$





data

--- carbon data from DC wall

--- 4NA $K^- \, {}^4He \rightarrow \Lambda t$ in flight MC

--- 4NA $K^- \, {}^4He \rightarrow \Lambda t$ at rest MC

--- 4NA $K^- \, {}^4He \rightarrow \Sigma^0 t$, $\Sigma^0 \rightarrow \Lambda\gamma$ MC

--- 4NA $K^- \, {}^4He \rightarrow \Sigma^0 t$, $\Sigma^0 \rightarrow \Lambda\gamma$ MC

Total number of events = 136

4NA $K^- \, {}^4He \rightarrow \Lambda t$ at rest → 1 ± 1 events

4NA $K^- \, {}^4He \rightarrow \Lambda t$ in flight → 12 ± 3 events

BR($K^- \, {}^4He$(4NA) → Λt) **< 1.3 × 10⁻⁴ /K$_{stop}$**

σ(100 ± 19 MeV/c) ($K^- \, {}^4He$(4NA) → Λt) =

= (0.42 ± 0.13(stat) $^{+0.01}_{-0.02}$ (syst)) mb

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Fit from $K^- + {}^4He \rightarrow \Sigma\,\pi\,{}^3He$ Bubble Chamber experiments

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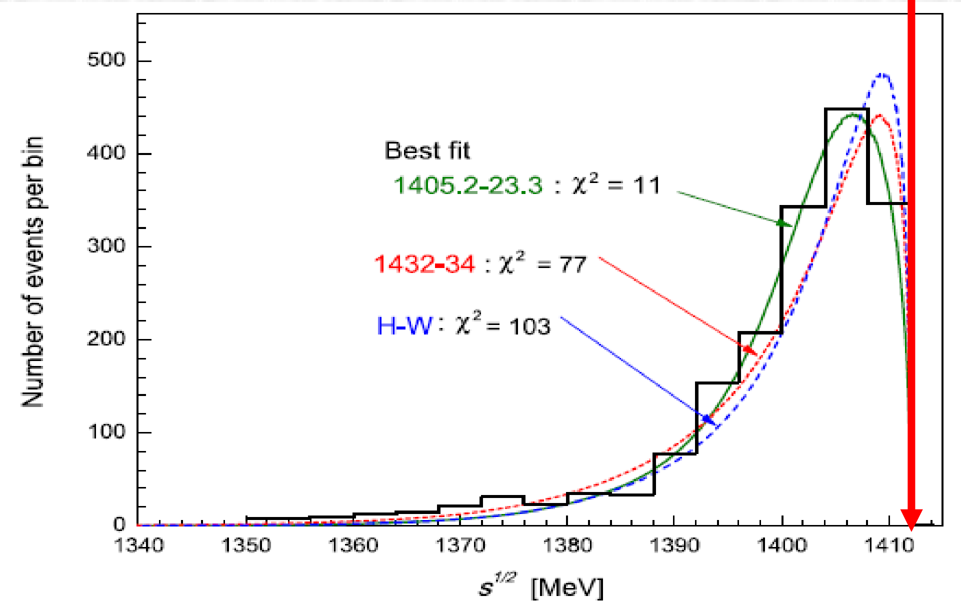


Fig. 6. Detailed differences in $M_{\Sigma\pi}$ spectra among the Hyodo–Weise prediction and the present model predictions.

[Phys. Lett. B 686 (2010) 23-28]

Resonant VS Non-Resonant

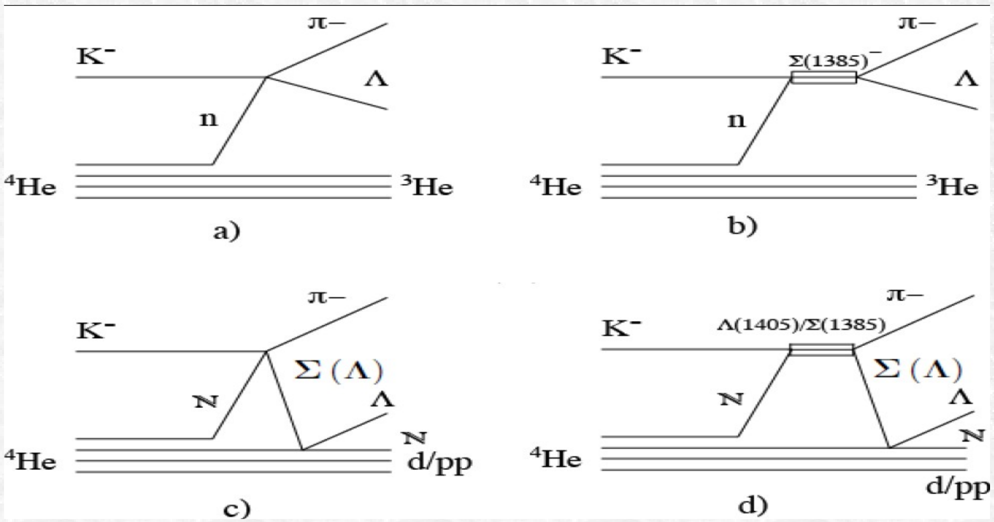
$$K^- N \rightarrow (Y^*\ ?) \rightarrow Y\,\pi$$

$$K^- N \rightarrow Y\,\pi$$

in medium, how much comes from resonance ?

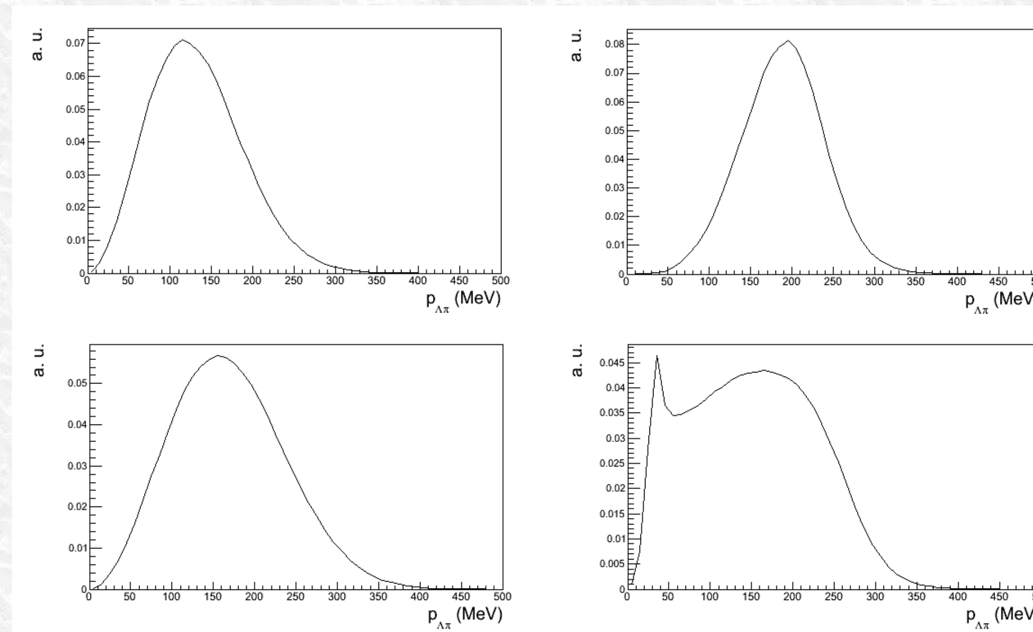
On the $K^{-}\,{}^{4}He \rightarrow \Lambda\pi^{-}\,{}^{3}He$ resonant and non-resonant processes

(K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A954 (2016) 75-93)



The determination of the $K^{-}N \rightarrow Y\pi$ non-resonant transition amplitude below threshold (about 33 MeV in ^{4}He) is essential to pin-down the Λ(1405) resonant shape in absorption experiments.

Total $\Lambda\pi^{-}$ momentum spectra for the resonant (Σ^{*-}) and non-resonant (I = 1) processes were calculated, for both S-state and P-state K^{-} capture at-rest and in-flight. Corrections to the amplitudes due to Λ/π final state interactions were estimated.



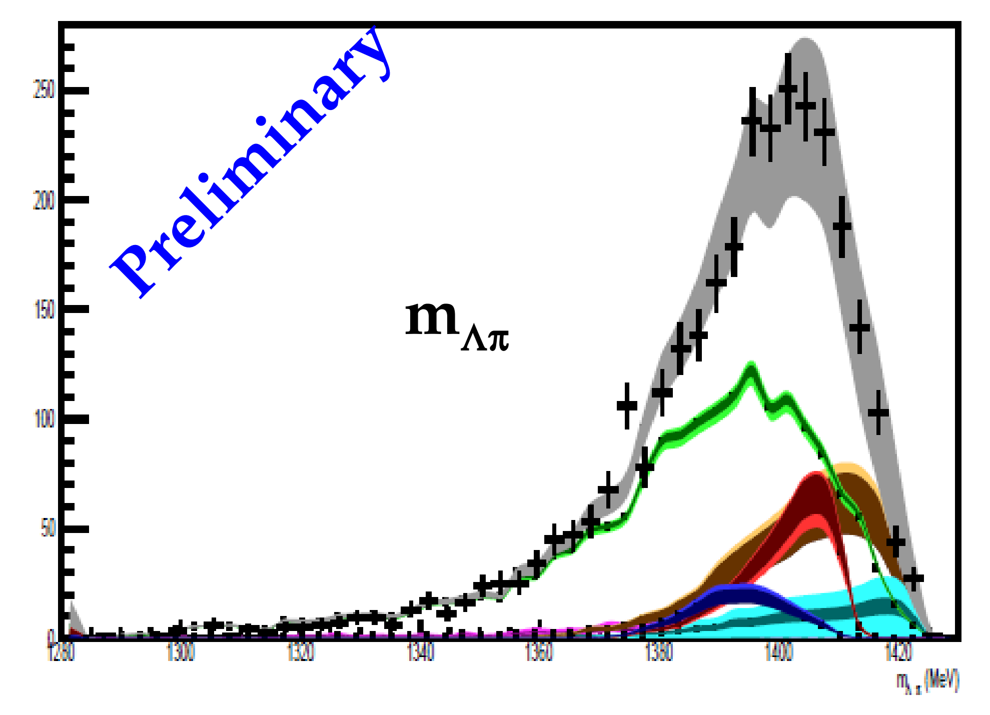
These will be used by the AMADEUS collaboration to fit the Yπ measured spectra and extract, for the first time, the non-resonant transition amplitude

($|f^{N-R}{}_{\Lambda\pi}(I=1)|$ and $|f^{N-R}{}_{\Sigma\pi}(I=0)|$) fundamental to determine the Λ(1405) properties.

Non resonant transition amplitude: $K^- + n \rightarrow \Lambda + \pi^-$

The resonant transition amplitude for the **Σ*(1385)** in I = 1 channel is **well known**

Resonant: $K^- + n \rightarrow \Sigma^{*-} \rightarrow \Lambda + \pi^-$ Non-Resonant: $K^- + n \rightarrow \Lambda + \pi^-$



+ Data
Global fit
Resonant Σ^* (at-rest)
Resonant Σ^* (in-flight)
Non-Resonant (at-rest)
Non-Resonant (in-flight)
Σ/Λ nuclear conversion
Absorptions in ^{12}C (from Carbon wall data)

	percentage $\cdot 10^{-2}$	$\sigma_{stat} \cdot 10^{-2}$	$\sigma_{syst} \cdot 10^{-2}$
NR-ar	12.00	± 1.66	+1.96 -2.77
RES-ar/NR-ar	0.39	± 0.04	+0.18 -0.07
NR-if	19.24	± 4,38	+5.90 -3.33
RES-if//NR-if	0.23	± 0.03	+0.23 -0.22
$\Sigma \rightarrow \Lambda$ conv.	2.16	± 0.30	+1.62 -0.83
K^{-12}C capture	57.00	± 1.23	+2.21 -3.19

the **non resonant transition amplitude** 33 MeV under K^-N threshold is

$$|f^s_{ar}| = (0.334 \pm 0.018\, stat^{+0.34}_{-0.58}\, syst)\, fm.$$

Conclusions

AMADEUS step 0 → KLOE 2004-2005 dataset analysis

- K^- single and multi-nucleon absorption processes
- Possible formation of Deeply Bound Kaonic Nuclear States (DBKNS)
- Nature of the controversial $\Lambda(1405)$ state
- Scattering processes between hyperons and nucleons ($YN \rightarrow Y'N'$)

ONGOING ANALYSIS : Λp , Λd , $\Sigma^0 d$, $\Sigma^0 \pi^0$, $\Sigma^+ \pi^-$, $\Sigma^- \pi^+$

COMPLETED ANALYSIS :

- **$\Sigma^0 p$**
  - Yields **2NA:** $2NA/K^-_{stop} = (0.127 \pm 0.019 \text{ stat } ^{+0.004}_{-0.008} \text{ syst}) \times 10^{-2}$
  - Upper limit **ppK$^-$:** $ppK^-/K^-_{stop} = (0.044 \pm 0.009\, stat^{+0.004}_{-0.005}\, syst) \cdot 10^{-2}$
  - **Published in PLB:** O. Vazquez Doce et al., Phys.Lett. B 758, 134-139 (2016)
- **Λt**
  - **4NA** at-rest: **BR**$(K^{-4}He(4NA) \rightarrow \Lambda t) < 1.3 \times 10^{-4} / K_{stop}$
  - **4NA** in-flight: $\sigma(100 \pm 19 \text{ MeV/c})(K^{-4}He(4NA) \rightarrow \Lambda t) = (0.42 \pm 0.13 \text{ stat } ^{+0.01}_{-0.02} \text{ syst})$ mb
- **$\Lambda \pi^-$**
  - K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A954 (2016) 75-93
  - $|f^s_{ar}| = (0.334 \pm 0.018\, stat^{+0.34}_{-0.58}\, syst)\, fm.$

Future → AMADEUS DEDICATED SETUP

THANK^-S

" There's two possible outcomes: if the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery. "

Enrico Fermi (1901 – 1954)