Kaon-nuclei interaction studies at DAΦNE

exploring single and multi-nucleon K^- absorptions on light nuclei.

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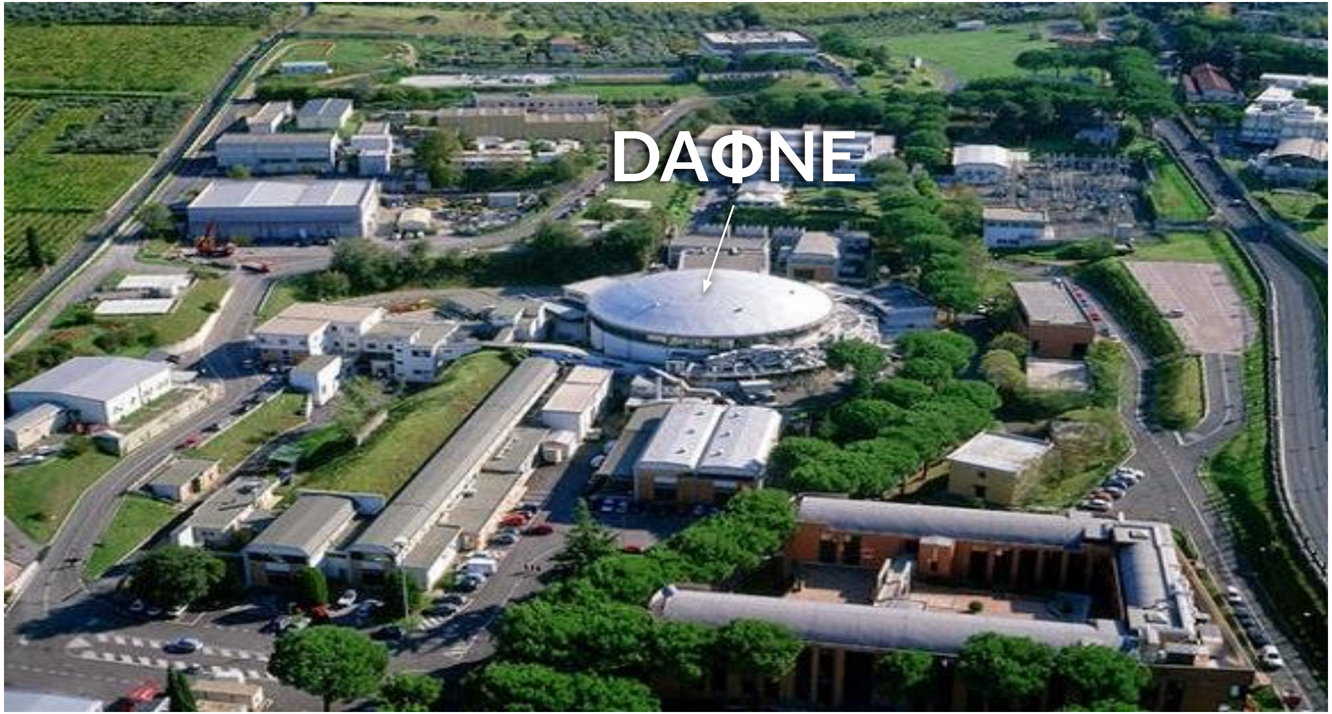
[2] INFN Laboratori Nazionali di Frascati, 00044 Frascati, Italy

On the behalf of the AMADEUS collaboration

***kristian.piscicchia@cref.it**

AMADEUS at LNF

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI



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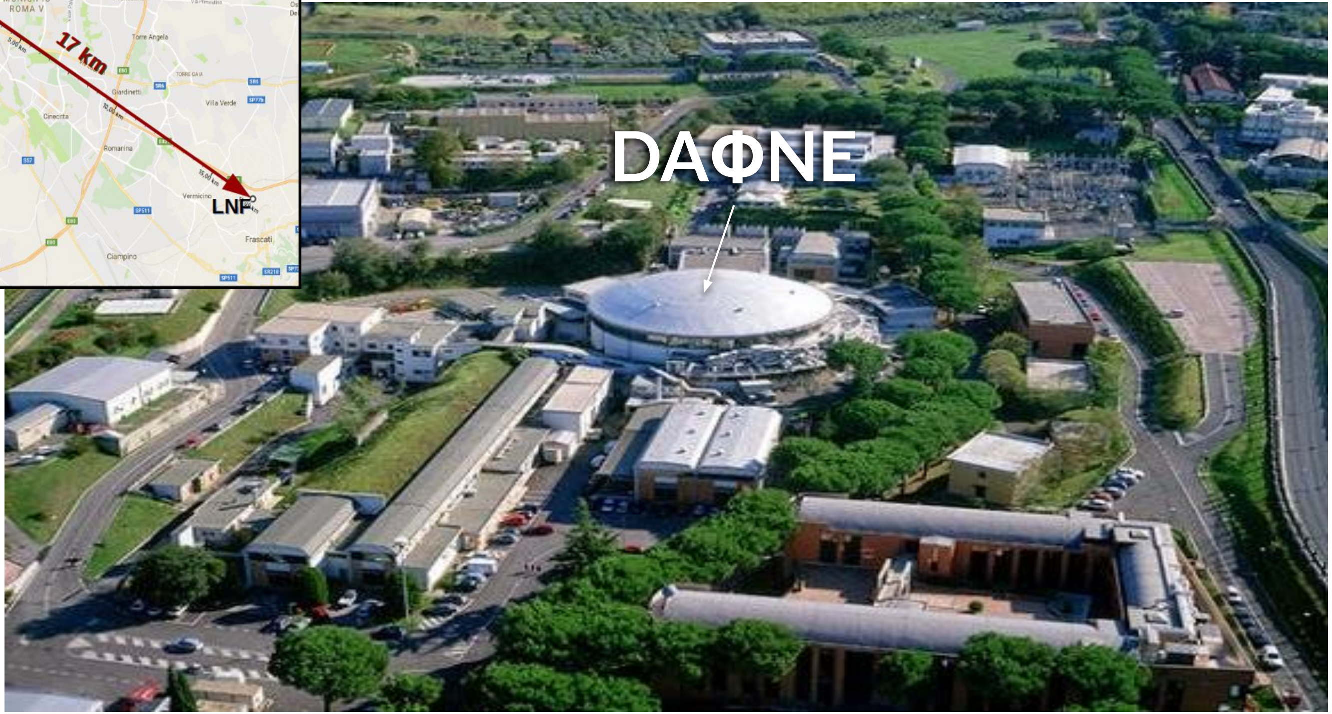


The AMADEUS collaboration

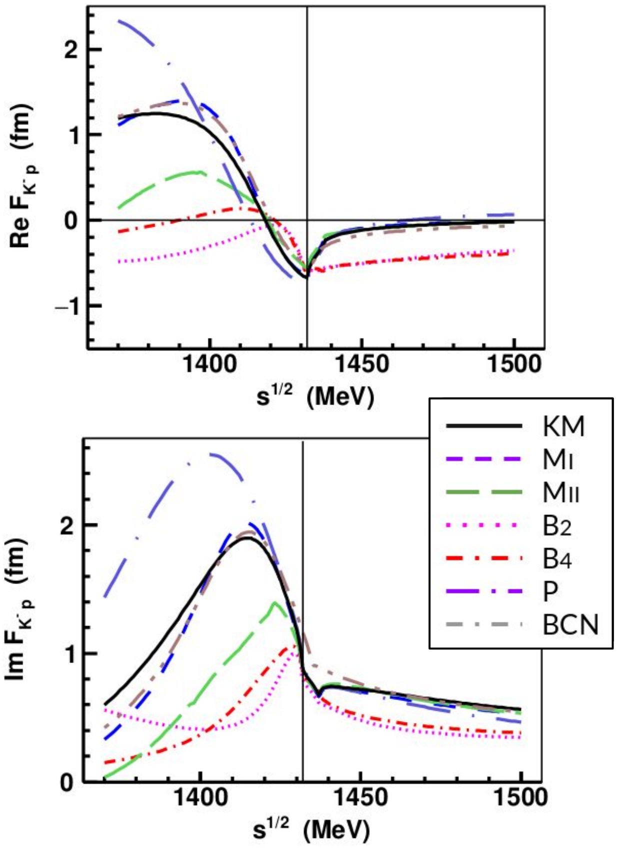
Anti-kaonic **M**atter **A**t **D**AΦNE: an **E**xperiment with **U**nravelling **S**pectroscopy

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
  - 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



[from A. Cieply talk at MENU2019 conference]

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)

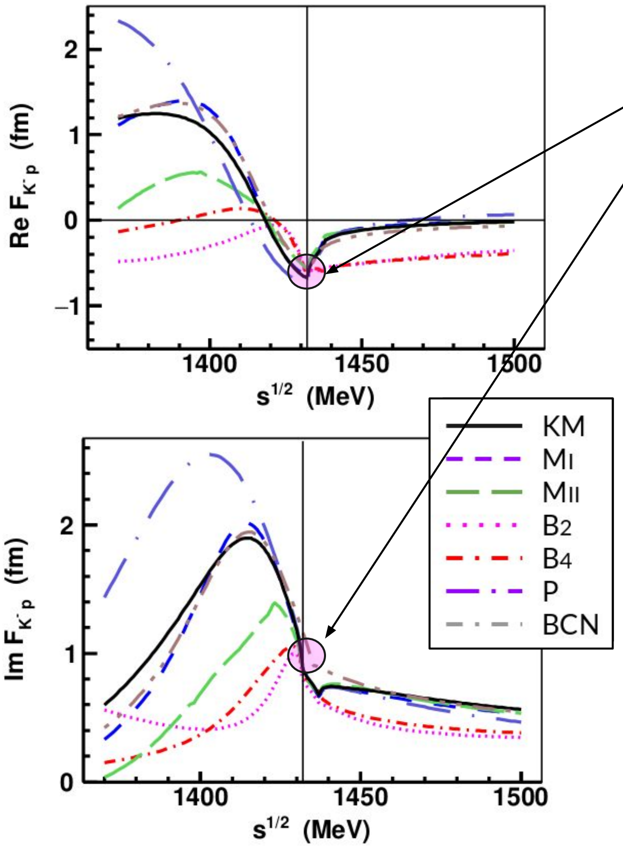
  Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202
- Bonn (B2 , B4)

  M. Mai, U.-G. Meißner - Eur. Phys. J. A 51 (2015) 30
- Prague (P)

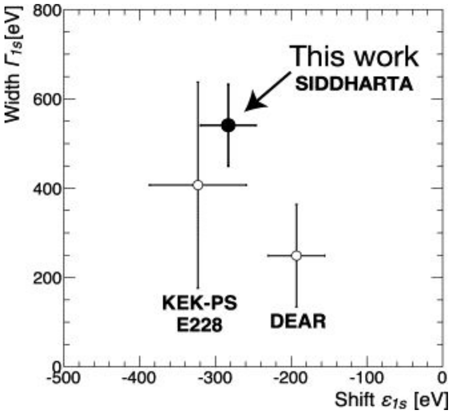
  A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115
- Barcelona (BCN)

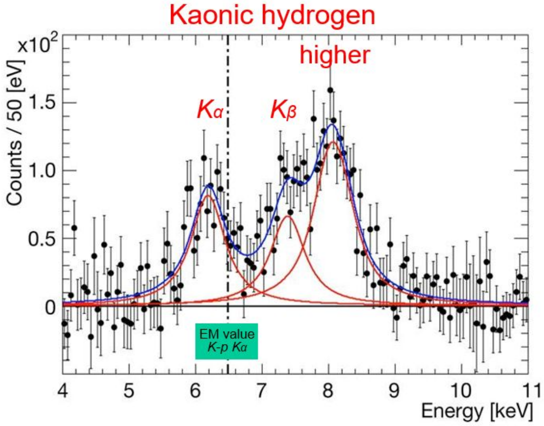
  A. Feijoo, V. Magas, À. Ramos, Phys. Rev. C 99 (2019) 035211

Experimental constraints at K̄N threshold



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





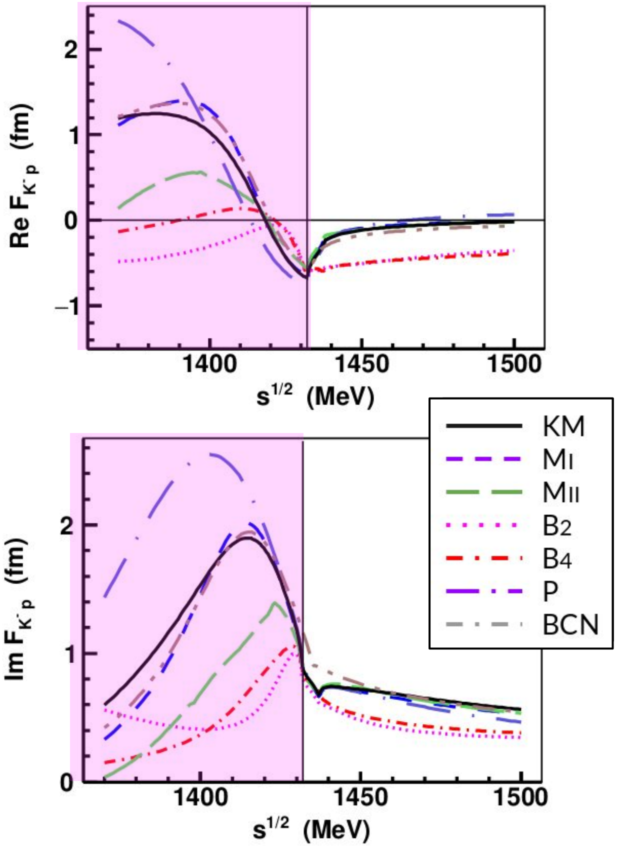
M. Bazzi et al.. 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113

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

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

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

K^-p scattering amplitude



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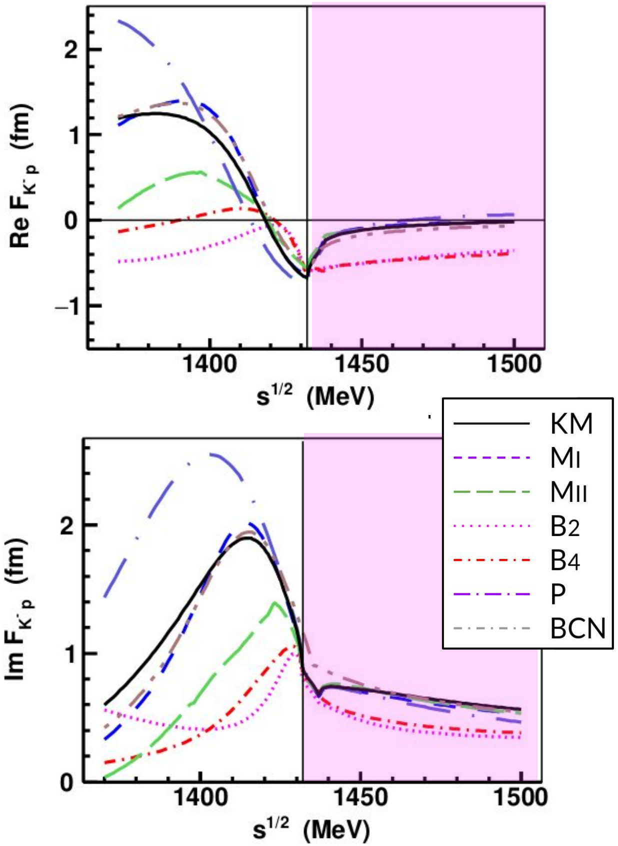
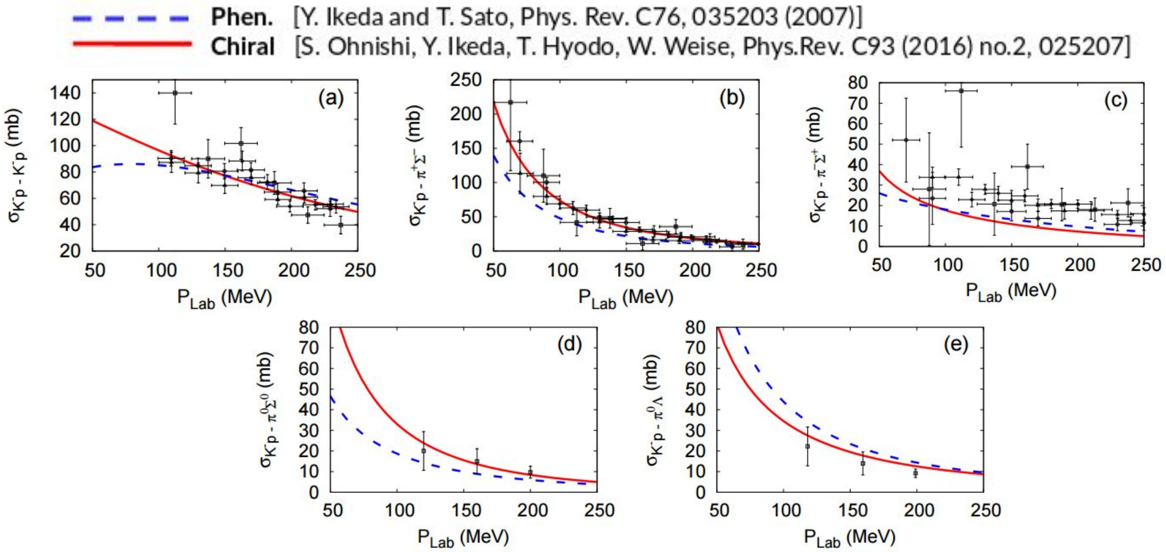
Large discrepancies in the region below threshold!

What above the threshold?

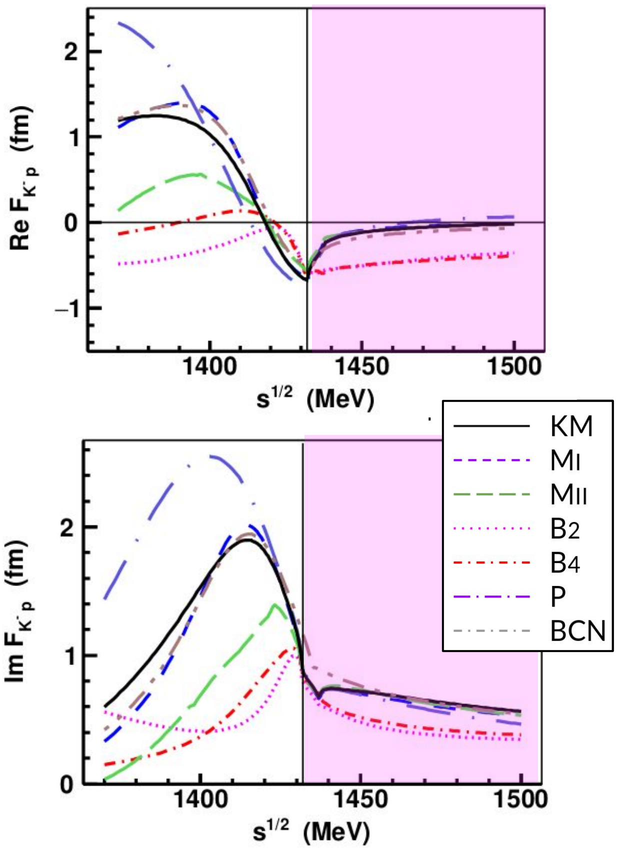


[from A. Cieply talk at MENU2019 conference]

K-p elastic and inelastic low-energy cross sections



What above the threshold?



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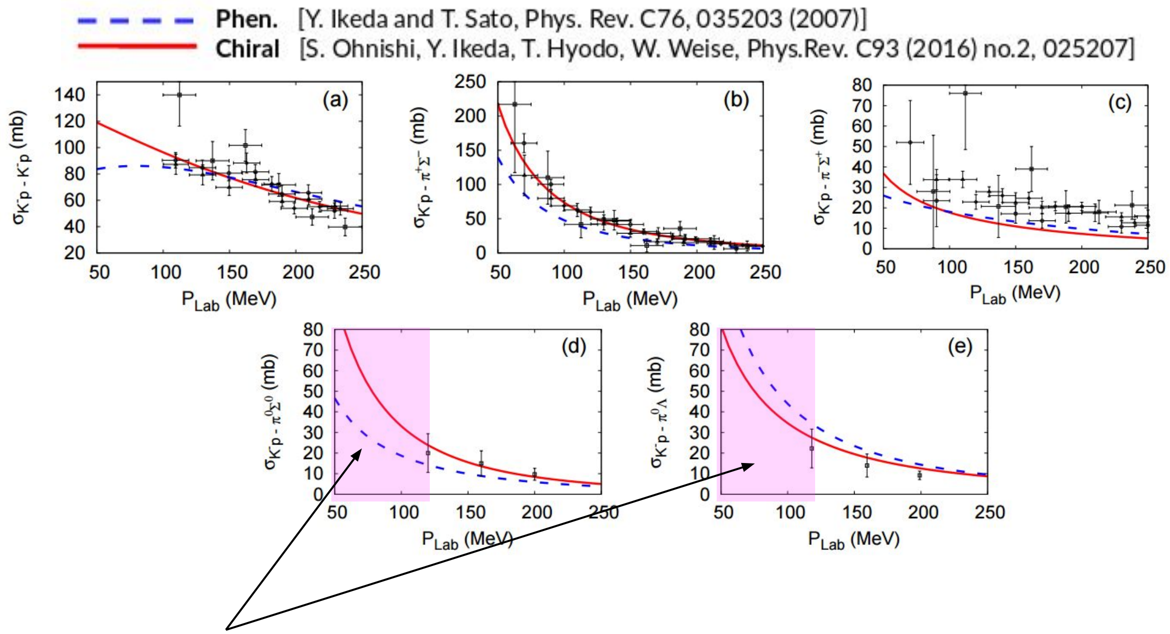
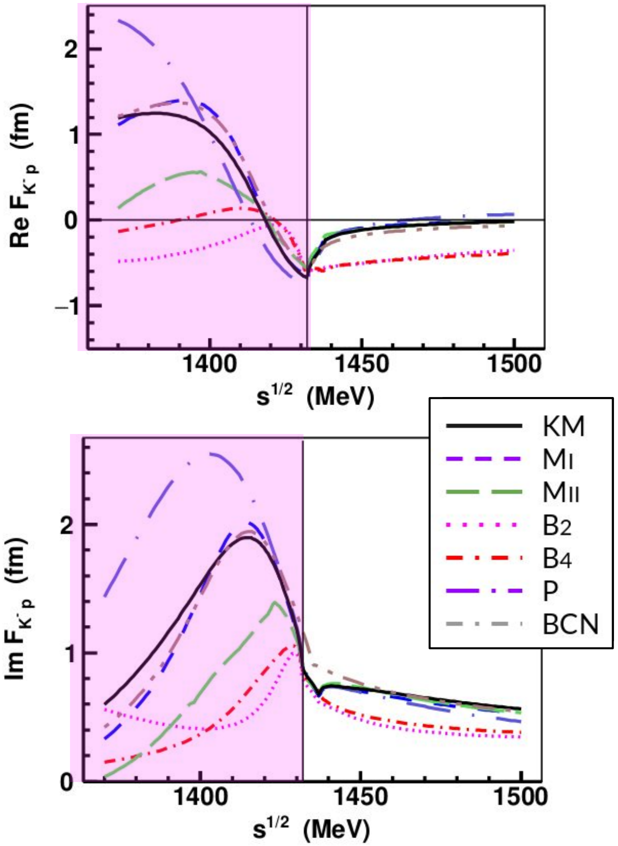


lack of data for $p_K < 120$ MeV/c

AMADEUS can give this info

And below the threshold?

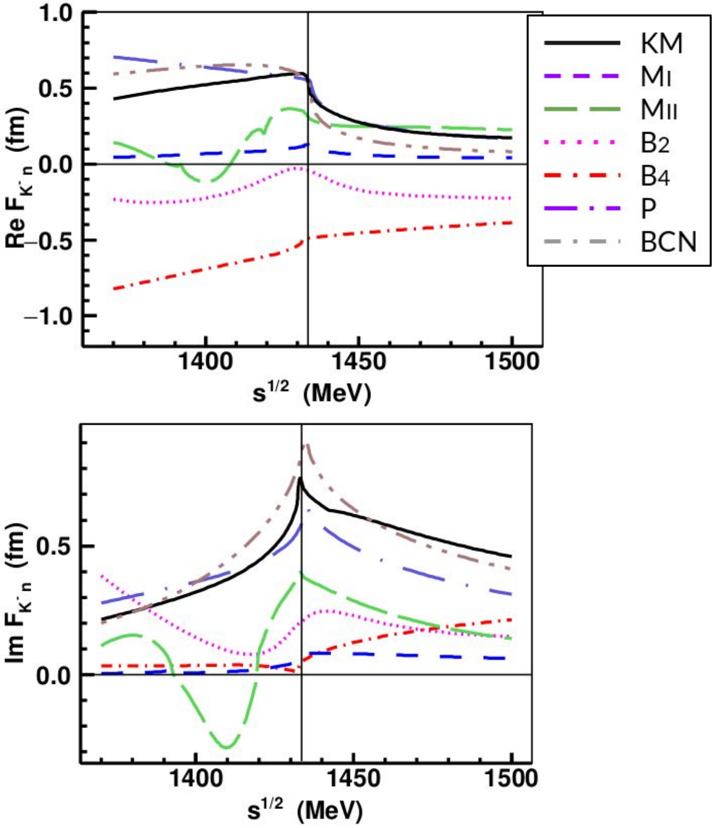


No direct amplitude measurements below threshold

…

AMADEUS CAN GIVE THIS INFO

K^-n scattering amplitude



[from A. Cieply talk at MENU2019 conference]

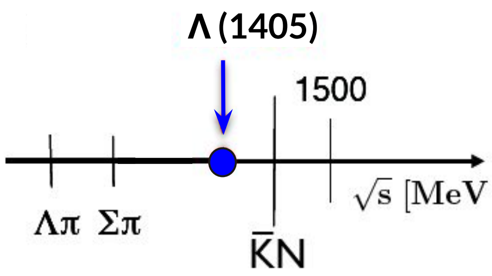
K^-n scattering amplitude (s-wave .. non resonant) in chiral calculations

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

Experimental information is missing:

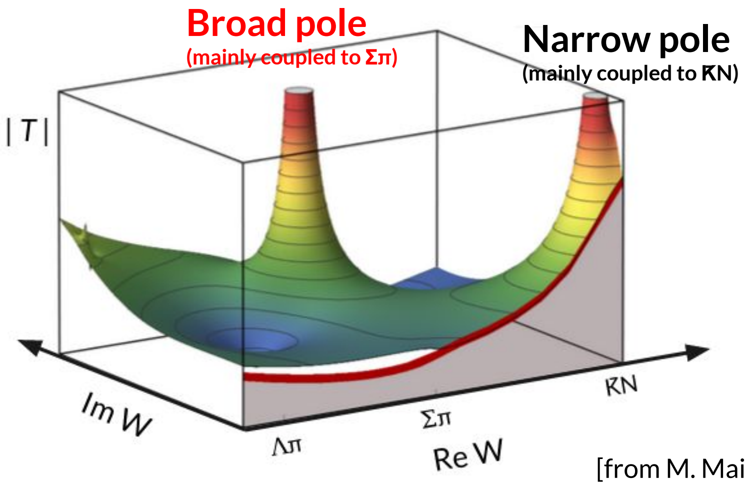
- **SIDDHARTA-2** → **first experimental constraint at threshold (*see Catalina Curceanu's talk 9 Dec*)**
- **AMADEUS** → **first experimental constraint below threshold**

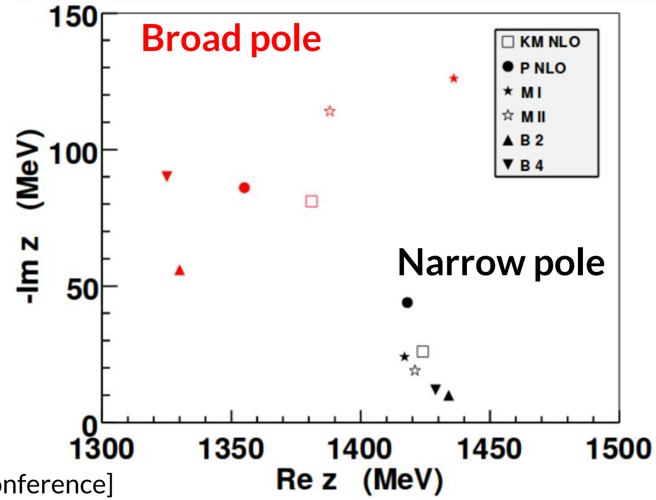
Impact on Λ(1405) nature



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

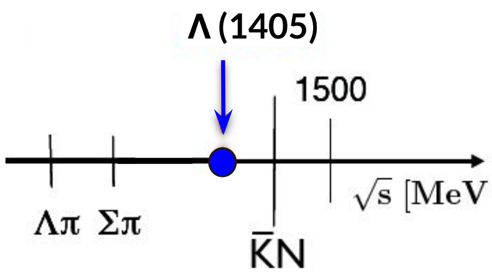
Chiral models: dynamical origin. Two poles of the scattering amplitude → pole positions is model dependent (relative contributions not measured experimentally)





[from M. Mai talk at NSTAR19 conference]

Impact on Λ(1405) nature



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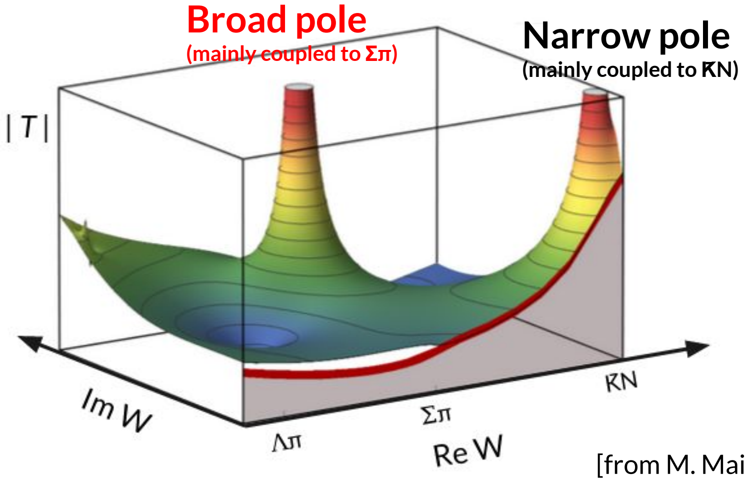

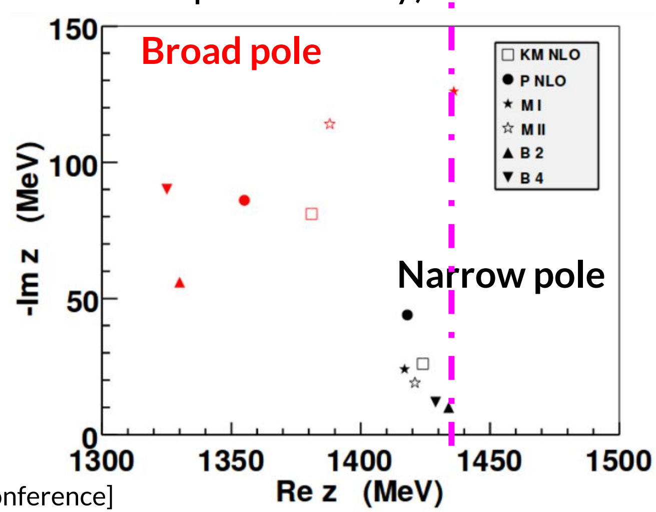

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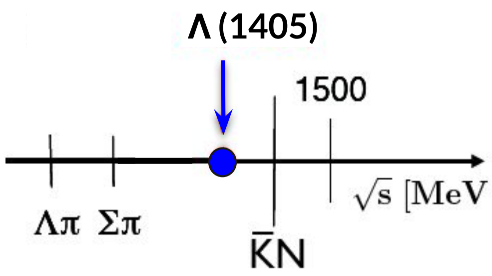
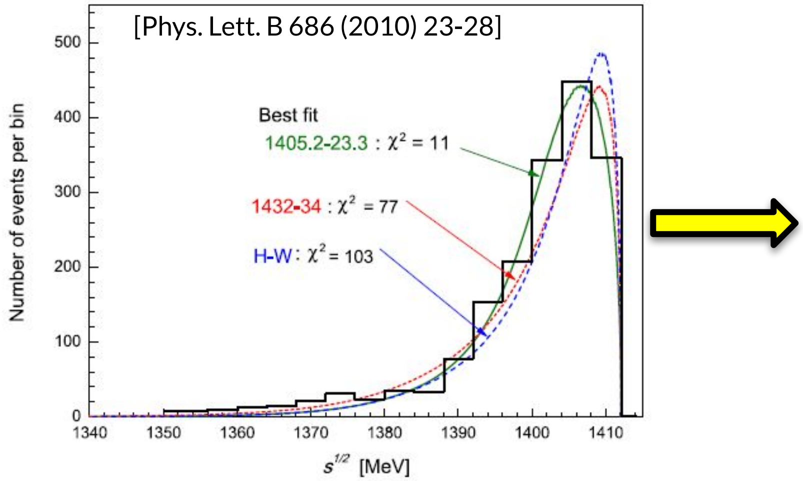
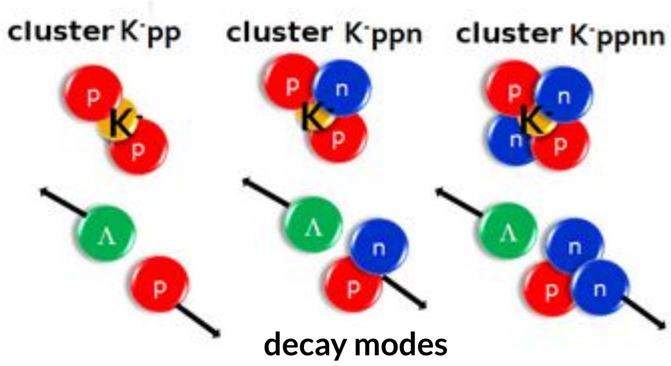


The Λ(1405) state does not fit with the simple three quarks model (*uds*) and it is commonly accepted to be **partially, a K̄N bound state.**

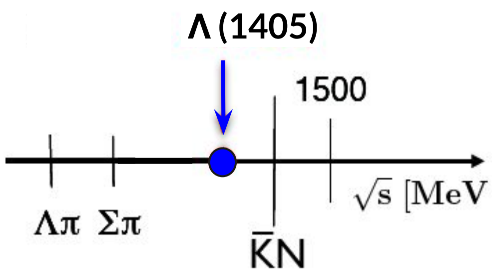
Single pole ansatz (Esmaili-Akaishi-Yamazaki phenomenological potential model): Very strongly attractive K̄N interaction in the I = 0 channel → existence of deeply bound kaonic states



Kaonic Bound States

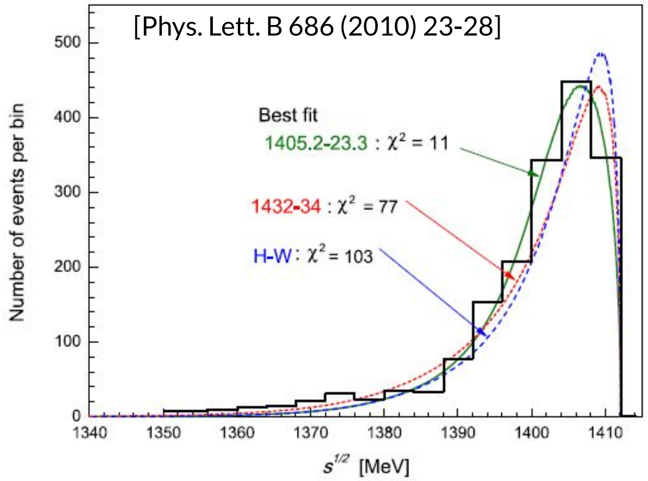


Impact on Λ(1405) nature

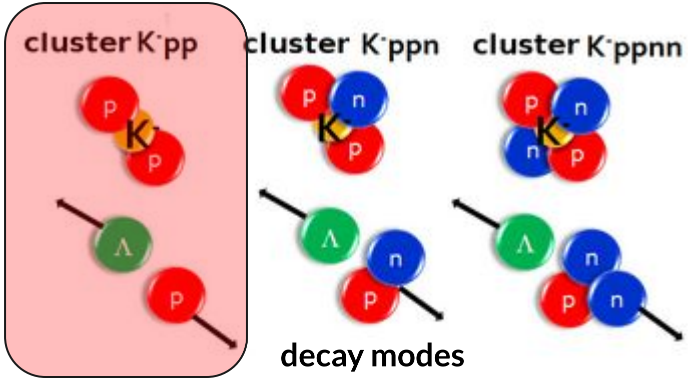


The Λ(1405) state does not fit with the simple three quarks model (*uds*) and it is commonly accepted to be **partially, a $\bar{K}$N bound state.**

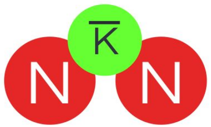
Single pole ansatz (Esmaili-Akaishi-Yamazaki phenomenological potential model): Very strongly attractive $\bar{K}$N interaction in the I = 0 channel → existence of deeply bound kaonic states



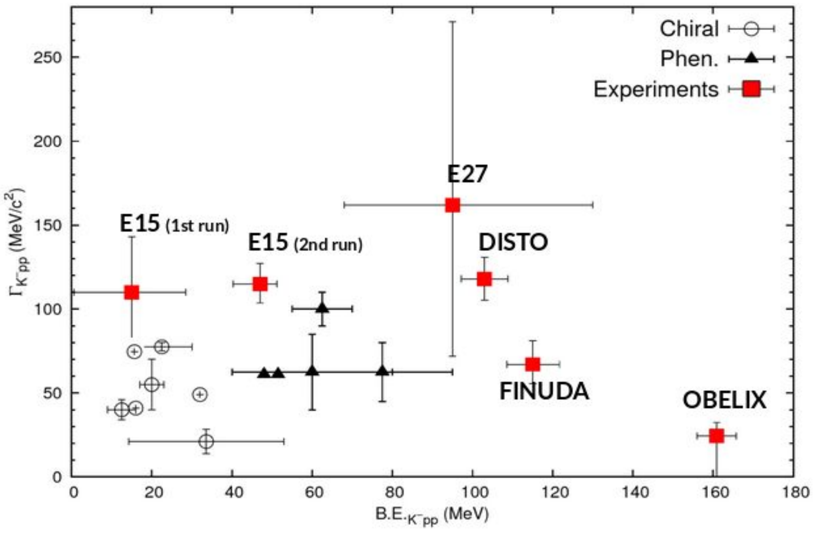
Kaonic Bound States



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) see Takumi Yamaga's talk.



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

Goals of AMADEUS

Unprecedented studies of the **low-energy charged kaons interactions in nuclear matter**: solid and gaseous targets (H, ^{4}He, ^{9}Be, ^{12}C ...) in order to obtain unique quality information about:

1. Controversial **nature of the $\Lambda(1405)$** 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**; **YN CORRELATION STUDIES**

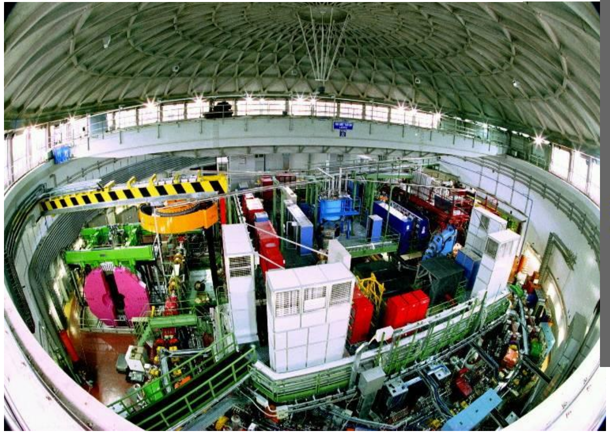
3. a) Interaction of K^- with more nucleons (**multi-nucleon K^- absorptions**) → **YN CORRELATION STUDIES** (i.e. Λ p, Σ^0 p, and Λ t final states)

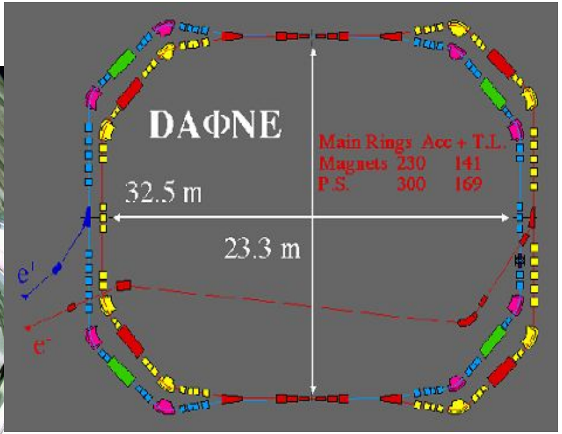
   b) possible existence of **kaonic bound states** → **YN CORRELATION STUDIES**

4. ***future*: YN scattering** → extremely **poor experimental information** from scattering data (important for the EoS of Neutron Stars)

DAΦNE the Φ factory

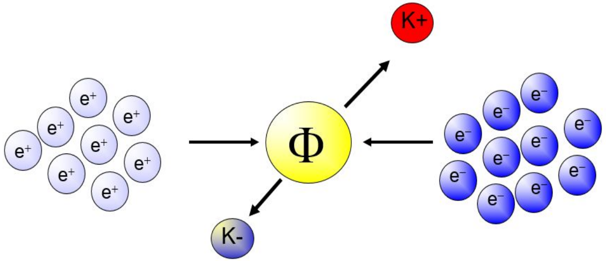
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI





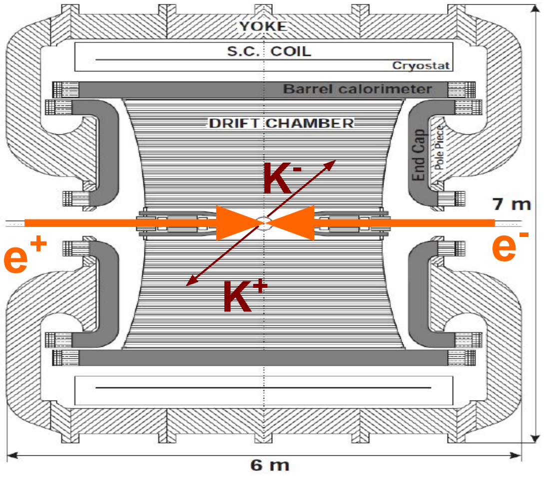
- $e^+ e^-$ at 510 MeV
- φ resonance decays at 49.2 % in $K^+ K^-$ back to back pair
- Very low momentum (≈ 127 MeV) K^- beam
- Flux of produced kaons: about 1000/second

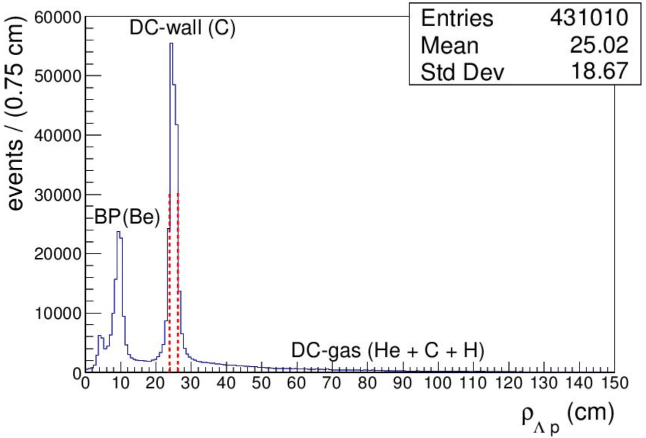
Best low momentum K^- factory in the world



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

AMADEUS step 0





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)]

Presently we use KLOE as an active target

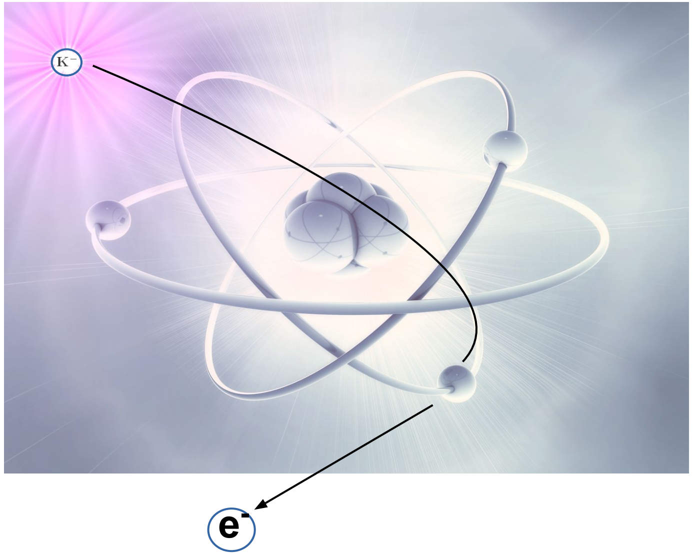
- DC wall (750 μm C foil , 150 μm Al foil);
- DC gas (90% He, 10% C_4H_{10}).

K^- absorptions at-rest and in-flight

AT-REST

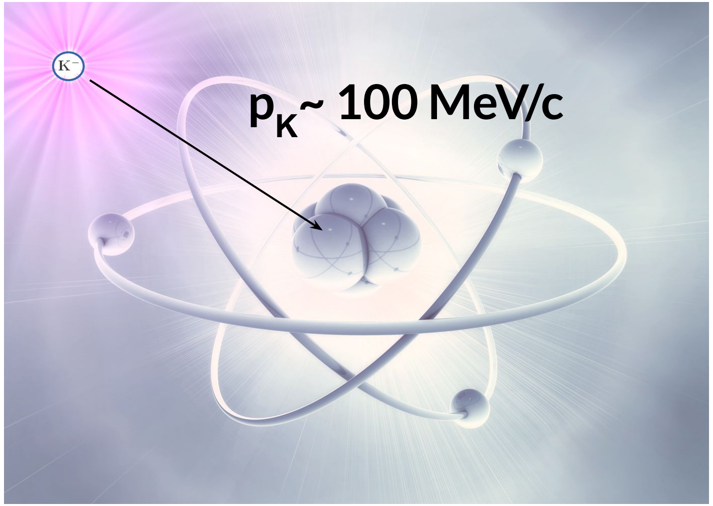
K^- absorbed from atomic orbitals

(p_K ~ 0 MeV/c)

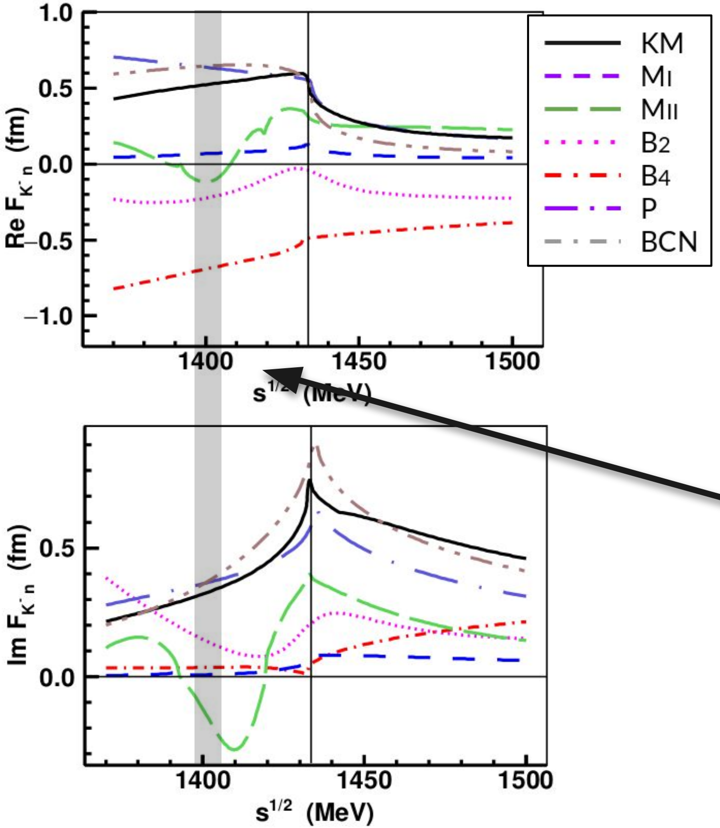


IN-FLIGHT

(p_K~ 100 MeV/c)



Experimental constraints below threshold



K^-n scattering amplitude with Chiral models

Large spread in I=1 channel

Experimental information is totally missing:

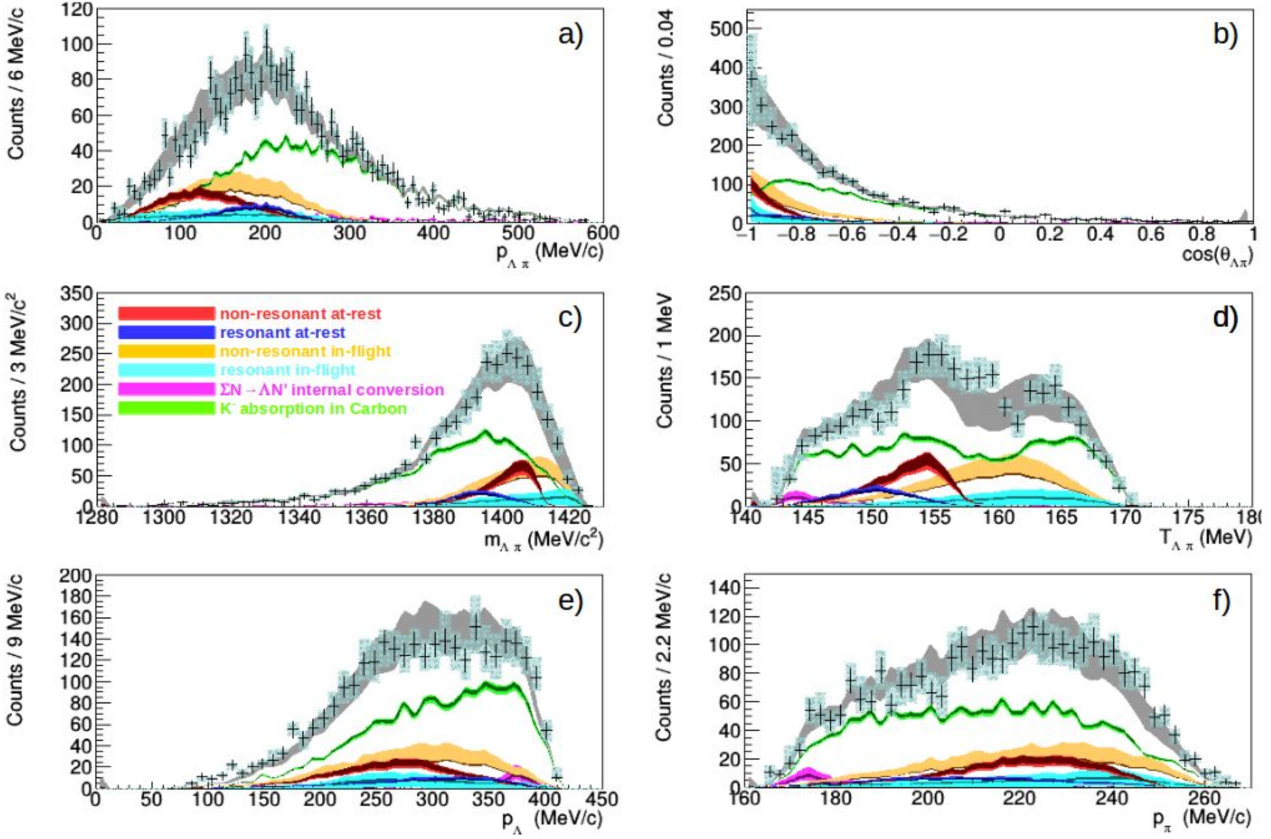
- **SIDDHARTA-2** → **first experimental constraint at threshold**

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

  Investigated using:

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

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



Investigated using:

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

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

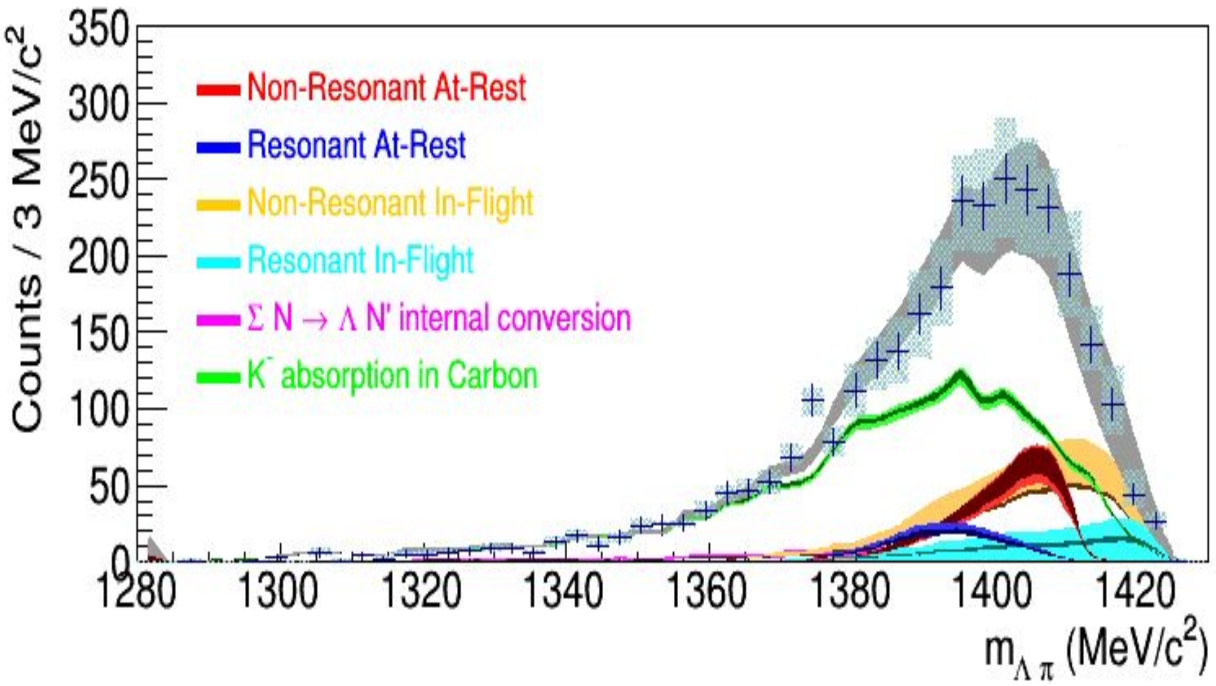
[K. Piscicchia, S. Wycech, L. Fabbietti et al. Phys.Lett. B782 (2018) 339-345]
[K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A 954 (2016) 75-93]

Outcome of the measurement

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

Energy of the K$^-$n system:

$$E_{\mathrm{Kn}} \sim -B_n - \left\langle \frac{p^2_{\Lambda\pi}}{2\mu_{\pi,\Lambda,3\mathrm{He}}} \right\rangle$$

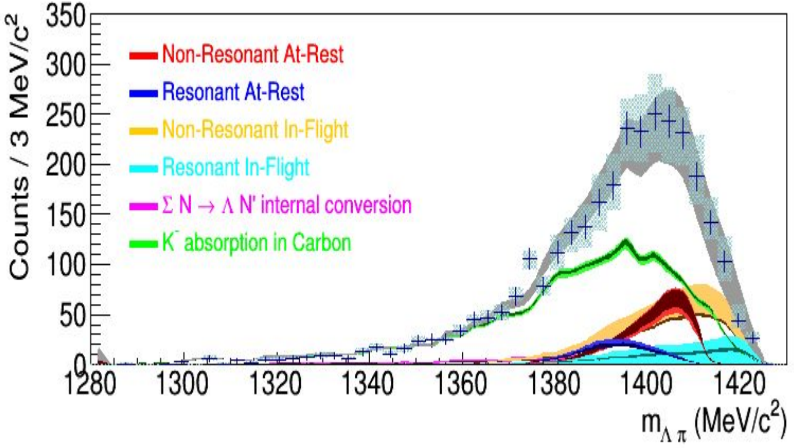


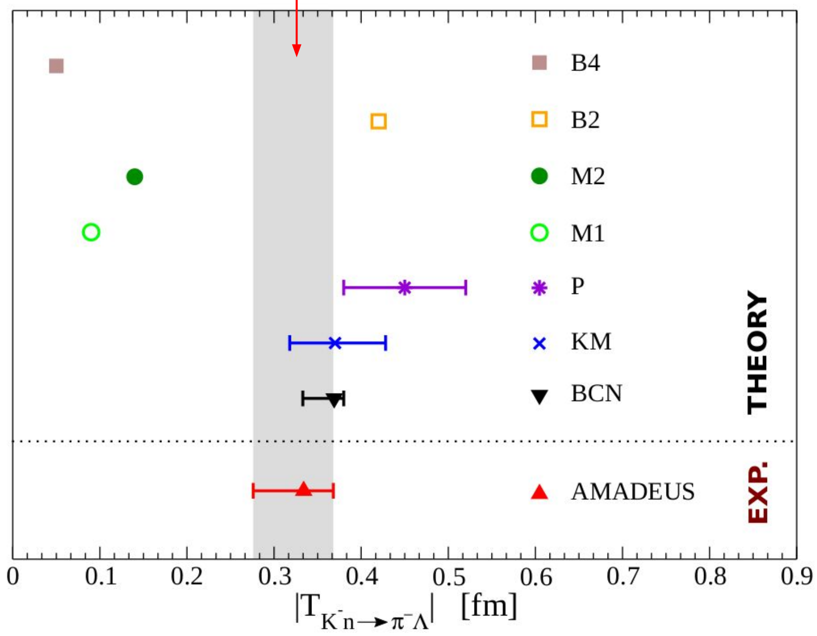
[K. Piscicchia, S. Wycech, L. Fabbietti et al. Phys.Lett. B782 (2018) 339-345]
[K. Piscicchia, S. Wycech, C. Curceanu, Nucl. Phys. A 954 (2016) 75-93]

Outcome of the measurement

Investigated using: **K⁻ "n"** ^{3}He $\rightarrow$ **Λπ⁻** ^{3}He

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





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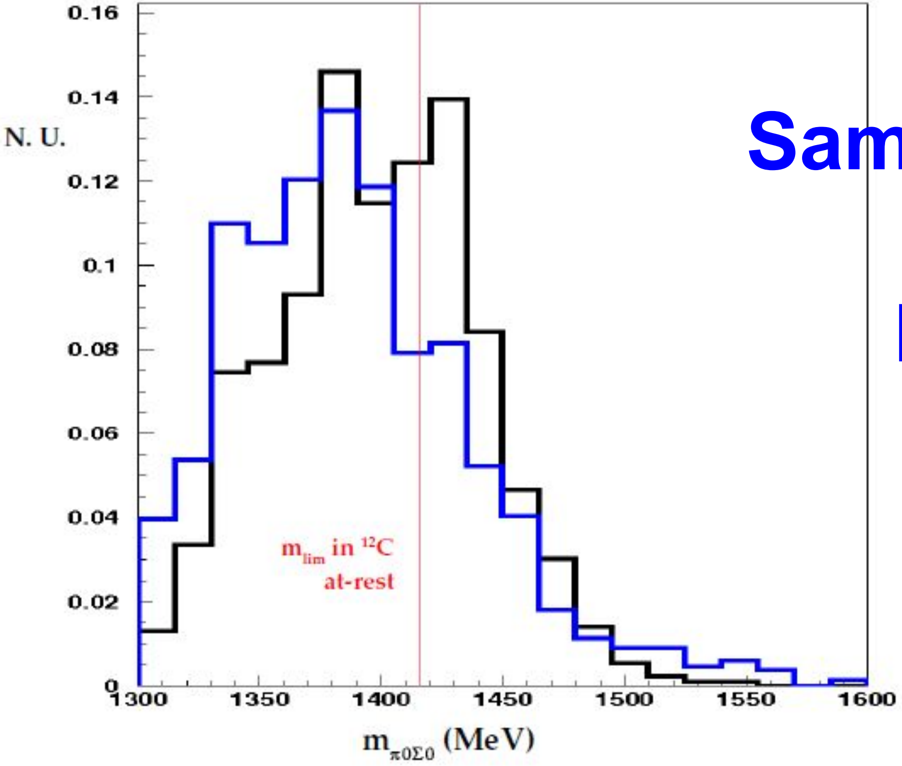
Next step...



Same analysis for the I = 0 counterpart by using the chiral amplitudes

Λ(1405) case

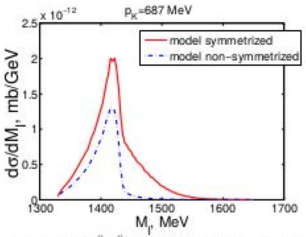


FIG. 4: Theoretical ($\pi^0\Sigma^0$) invariant mass distribution for an initial kaon lab momenta of 687 MeV. The non-symmetrized distribution also contains the factor 1/2 in the cross section.

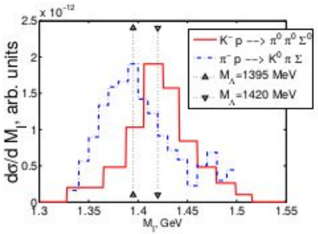
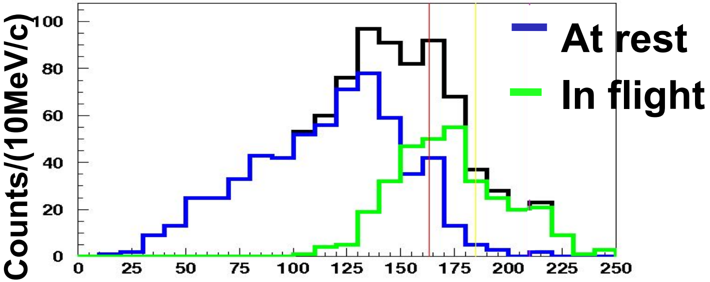
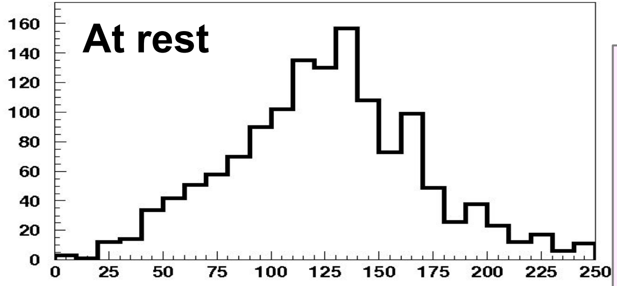


FIG. 5: Two experimental shapes of Λ(1405) resonance. See text for more details.

Phys.Rev.Lett.95:052301,2005
Phys. Rev. C 70 (2004) 034605.

$p_{\pi 0}$ resolution: $\sigma_p \approx 12$ MeV/c





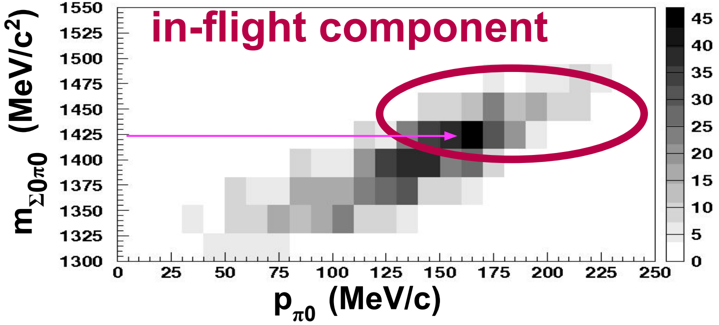
IN-FLIGHT

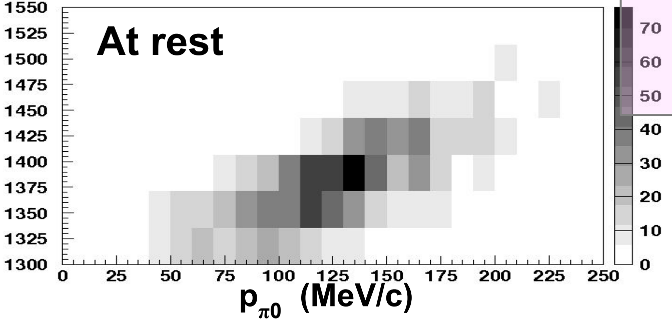
K- 12C

opens a window

between 1416 MeV

and K-Nth



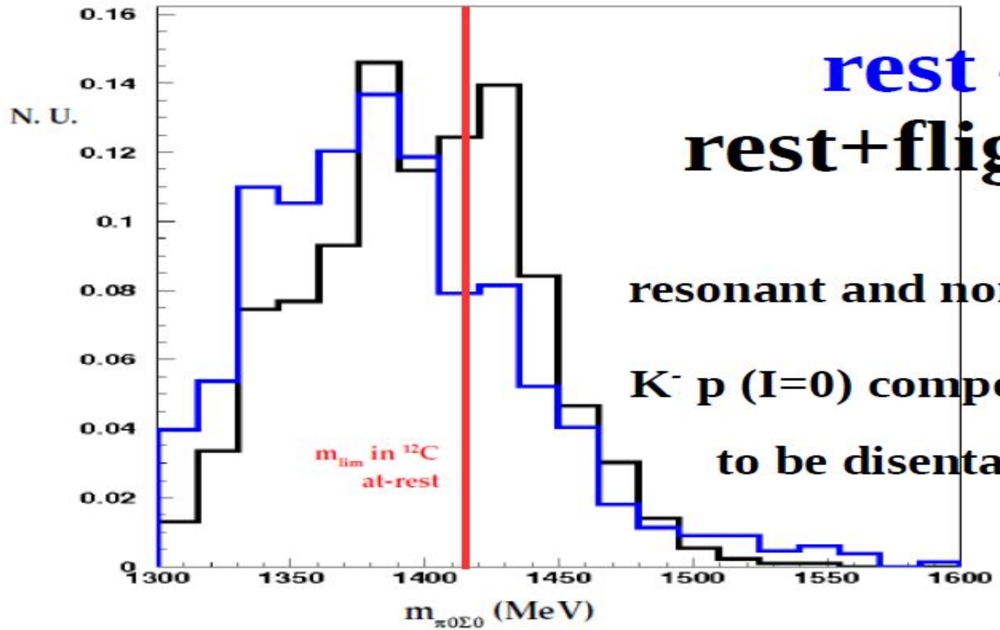


Λ(1405) : extracting the resonant I = 0 contribution

PID optimised, data fit is ongoing

necessary the input of the $\Lambda\pi^-$ measurement

- K. Piscicchia et al., APP B48 (2017) 10, 1875
- C. Curceanu, K. Piscicchia et al., APP B46 (2015) 1, 203



resonant and non-resonant

K^- p (I=0) components are

to be disentangled

IN-FLIGHT

K- 12C

opens a window

between 1416 MeV

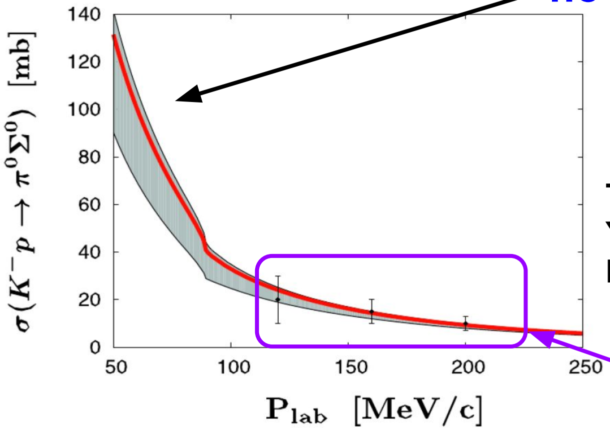
and K-Nth

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

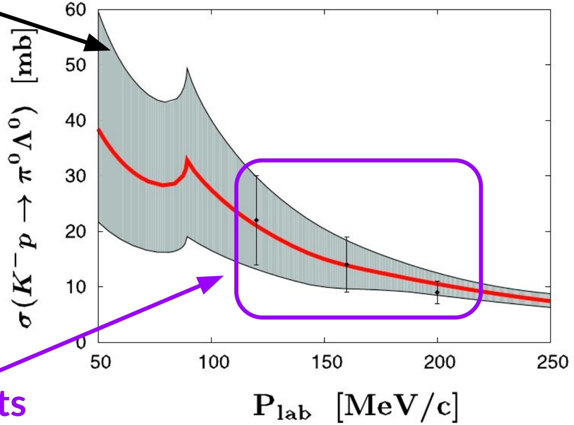
- three points in the p_K=120-200 MeV/c range (bubble chamber experiments),
- uncertainties larger than 30%,
- the $K^- p \rightarrow \Sigma^0 \pi^0$ cross sections measurements are **not direct.** Obtained from $K^- p \rightarrow \Lambda\pi^0$ based on isospin symmetry arguments

[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

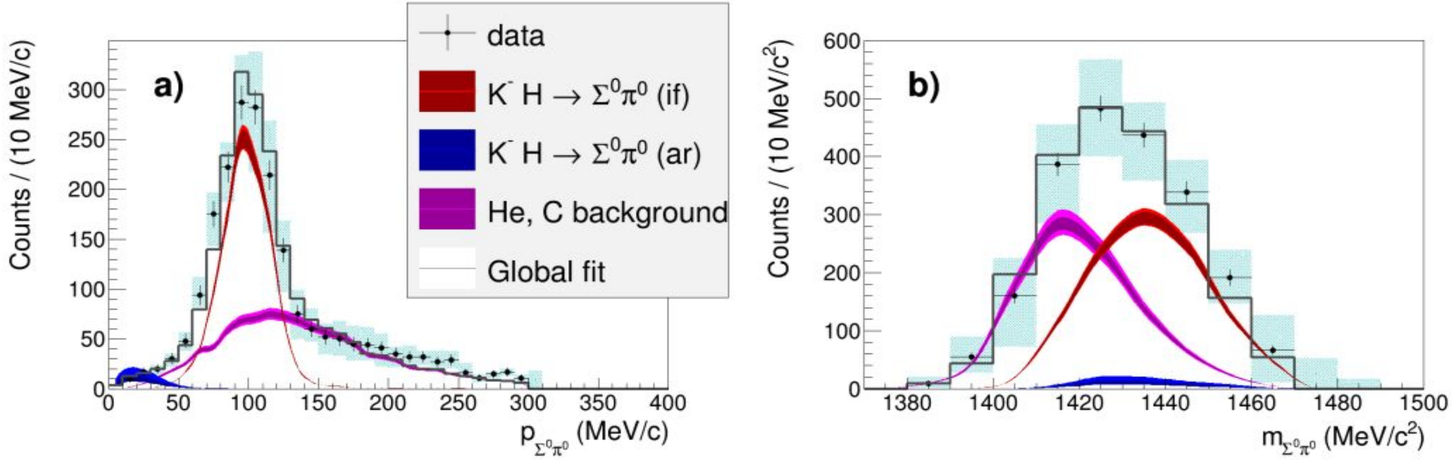


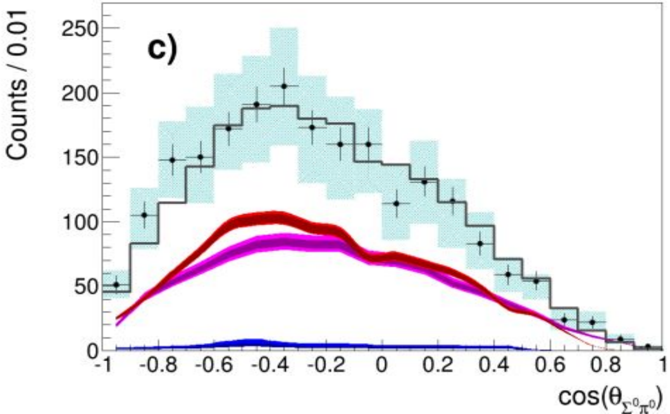
Theoretical calculation:
Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98.



bubble chamber experiments

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

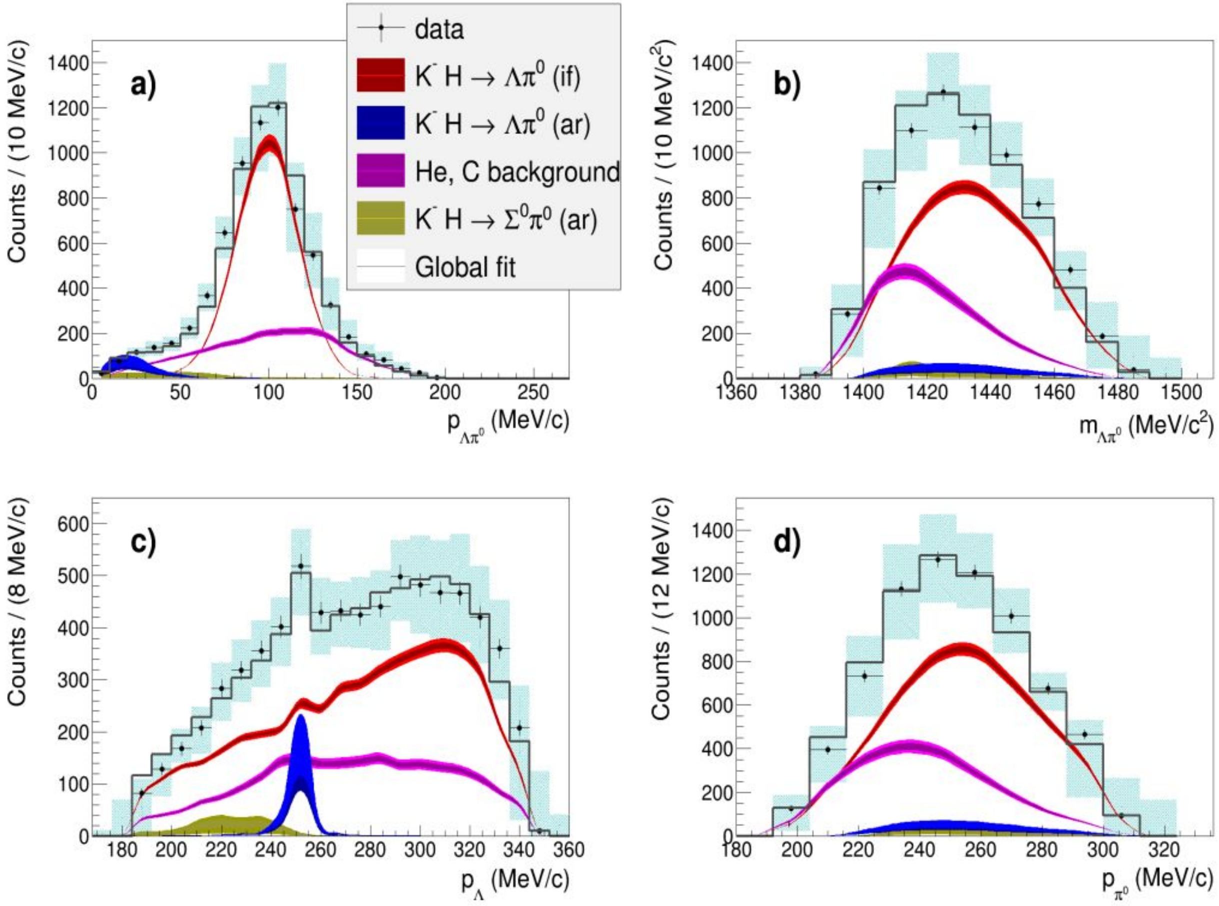




DC gas: a mixture of
90% in volume of ^{4}He and
10% in volume of Isobutane C_4H_{10}

$K^- p \rightarrow \Sigma^0\pi^0 \rightarrow (\Lambda(1116)\,\gamma_3)\,(\gamma_1\gamma_2) \rightarrow (p\pi^-)\,3\gamma$

$K^- p \rightarrow \Lambda \pi^0$ cross section



DC gas: a mixture of
90% in volume of ^{4}He and
10% in volume of Isobutane C_4H_{10}

$K^- p \rightarrow \Lambda \pi^0 \rightarrow \Lambda(1116)\,(\gamma_1\gamma_2)$
$\rightarrow (p\pi^-)\, 2\gamma$

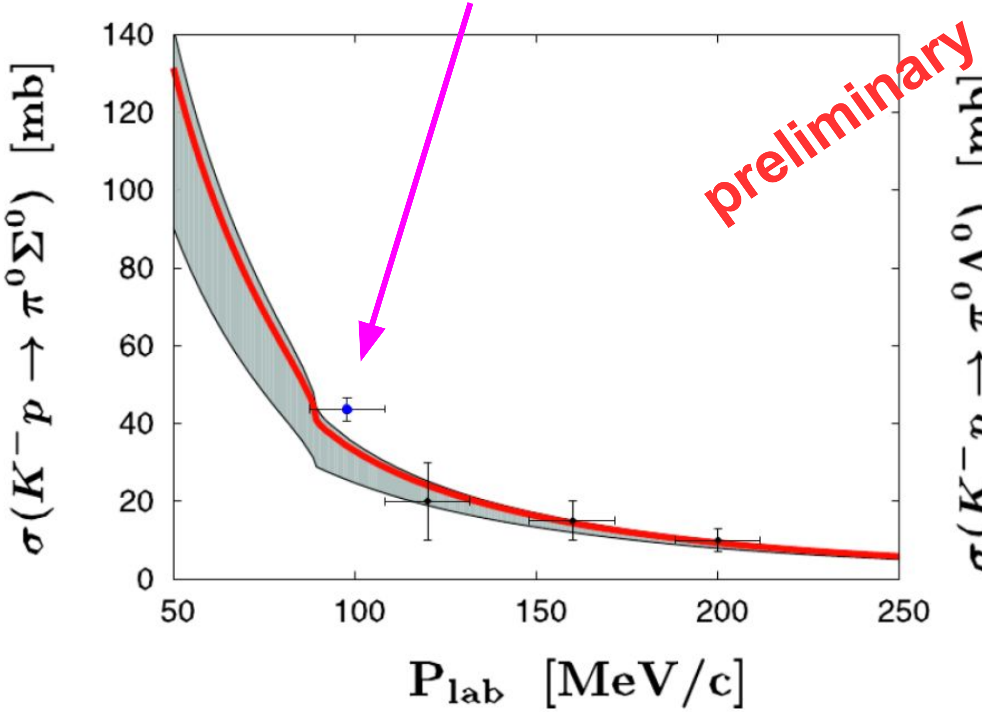
$K^- p \rightarrow \Sigma^0\pi^0$ ($\Lambda\, \pi^0$) cross sections

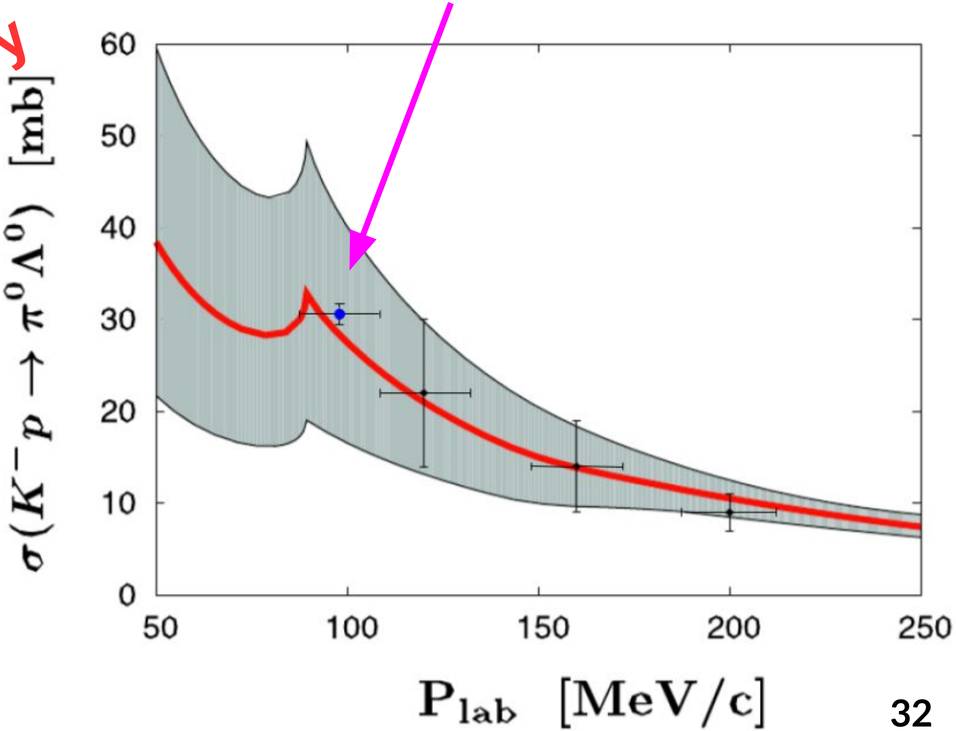
$$\sigma(K^- p \rightarrow \Sigma^0\pi^0)(p_K = (98 \pm 10) MeV/c) =$$

$$= 42.8 \pm 1.5(stat.)^{+2.4}_{-2.0}(syst.)\ \text{mb}$$

$$\sigma(K^- p \rightarrow \Lambda\pi^0)(p_K = (98 \pm 10) MeV/c) =$$

$$= 31.0 \pm 0.5(stat.)^{+1.2}_{-1.2}(syst.)\ \text{mb}$$





K^- multi-nucleon absorptions

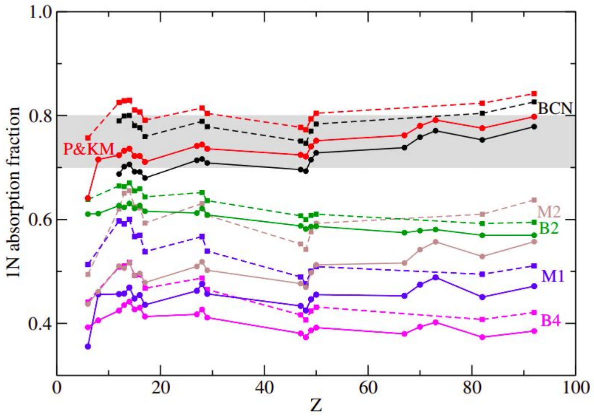
In order to fit the kaonic atoms data a K^- multi-nucleon absorption term is necessary in the K^--nuclei optical potential:

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

→ **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

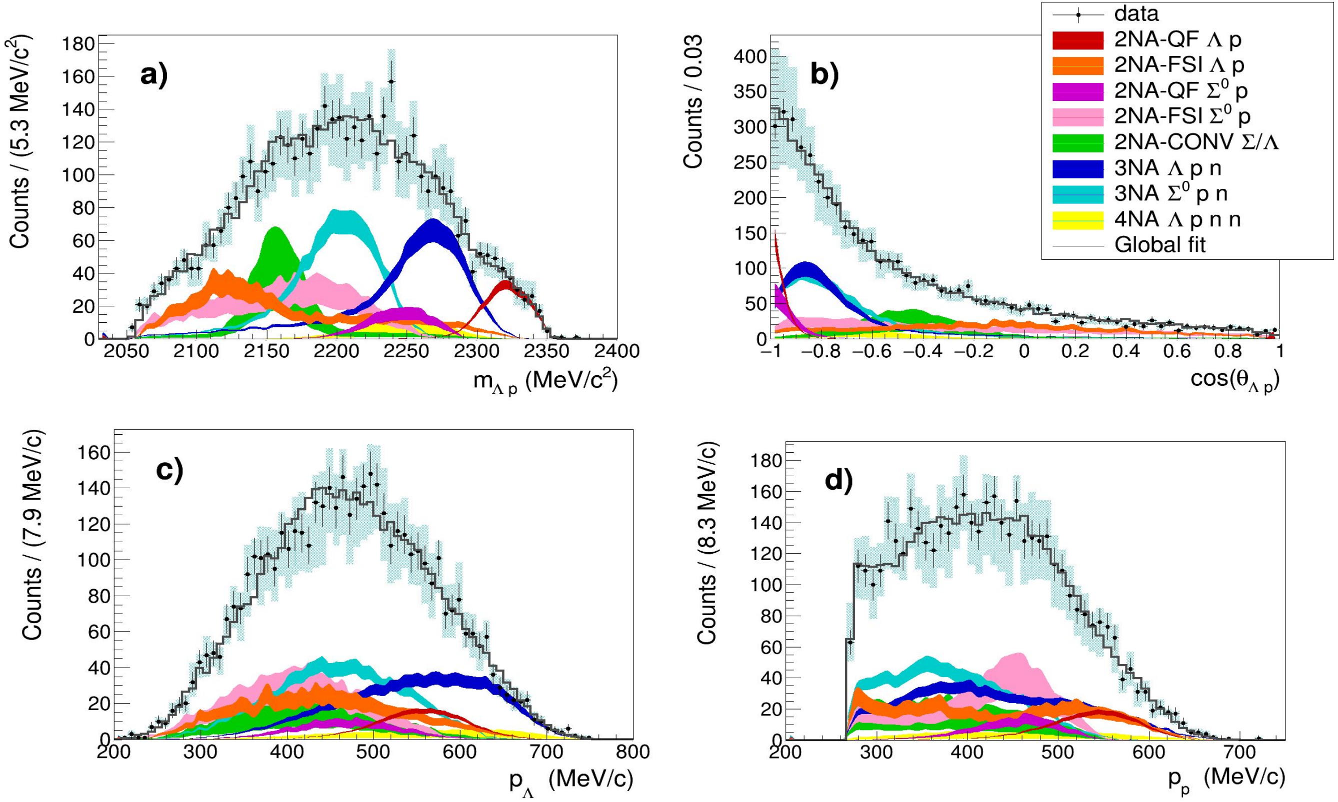
bound nucleons = "N", "NN", "NNN", "NNNN"
bound or unbound nucleons = (NN), (NNN)
Y = Λ, Σ

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]

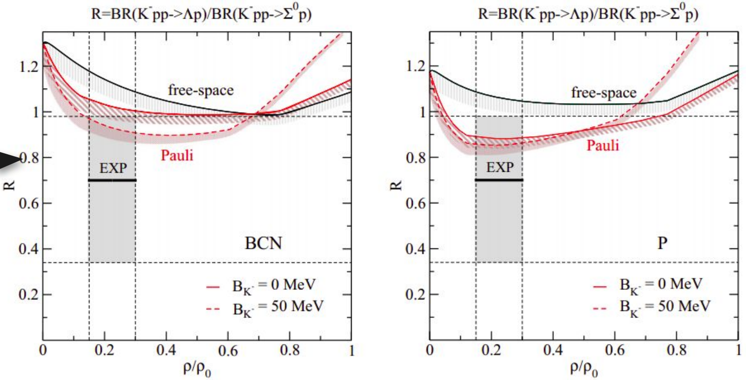
Process	Branching Ratio (%)	σ (mb)	@	p_K (MeV/c)
2NA-QF Λp	0.25 ± 0.02 (stat.) $^{+0.01}_{-0.02}$(syst.)	2.8 ± 0.3 (stat.) $^{+0.1}_{-0.2}$ (syst.)	@	128 ± 29
2NA-FSI Λp	6.2 ± 1.4(stat.) $^{+0.5}_{-0.6}$(syst.)	69 ± 15 (stat.) ± 6 (syst.)	@	128 ± 29
2NA-QF Σ^0p	0.35 ± 0.09(stat.) $^{+0.13}_{-0.06}$(syst.)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

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

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

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 ± 0.02 (stat.) $^{+0.01}_{-0.02}$(syst.)
2NA-FSI Λp	6.2 ± 1.4(stat.) $^{+0.5}_{-0.6}$(syst.)
2NA-QF $\Sigma^0 p$	0.35 ± 0.09(stat.) $^{+0.13}_{-0.06}$(syst.)
2NA-FSI $\Sigma^0 p$	7.2 ± 2.2(stat.) $^{+4.2}_{-5.4}$(syst.)
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.)
3NA $\Sigma^0 pn$	3.7 ± 0.4(stat.) $^{+0.2}_{-0.4}$(syst.)
4NA Λpnn	0.13 ± 0.09(stat.) $^{+0.08}_{-0.07}$(syst.)
Global $\Lambda(\Sigma^0)p$	21 ± 3(stat.) $^{+5}_{-6}$(syst.)

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

(16.1 ± 2.9(stat.) $^{+4.3}_{-5.5}$ (syst.))%,

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

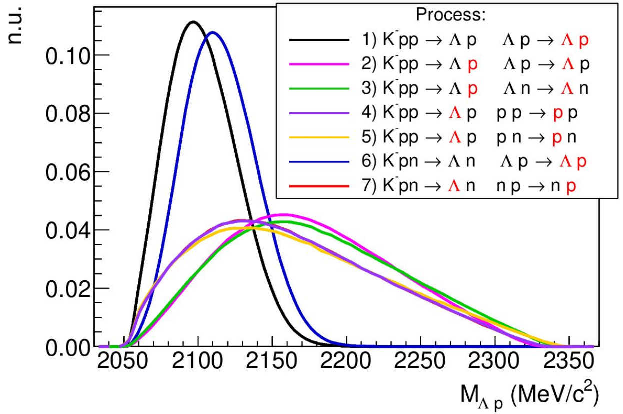
....information on the remaining YN pairs provided by FSI e Conversion reactions

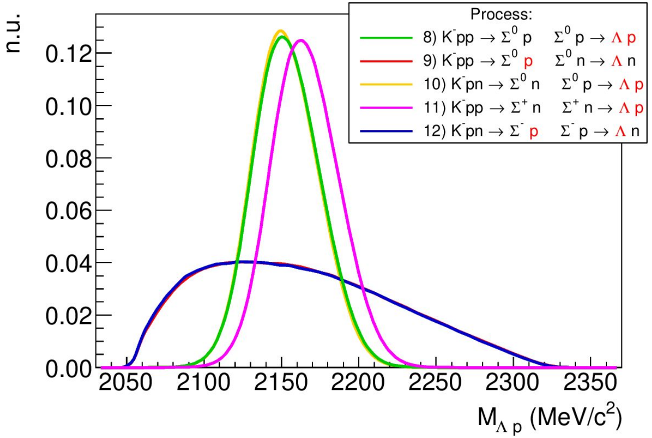
[R. Del Grande, K. Piscicchia et al., 2020 Phys. Scr.95 084012]

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	$K^- pn \rightarrow \Lambda n$	$\Lambda p \rightarrow \Lambda p$
	$K^- pn \rightarrow \Lambda n$	$n p \rightarrow n p$
	$K^- pp \rightarrow \Lambda p$	$\Lambda N \rightarrow \Lambda N$
	$K^- pp \rightarrow \Lambda p$	$p N \rightarrow p N$
2NA-FSI $\Sigma^0 p$	$K^- pn \rightarrow \Sigma^0 n$	$\Sigma^0 p \rightarrow \Sigma^0 p$
	$K^- pn \rightarrow \Sigma^0 n$	$n p \rightarrow n p$
	$K^- pp \rightarrow \Sigma^0 p$	$\Sigma^0 N \rightarrow \Sigma^0 N$
	$K^- pp \rightarrow \Sigma^0 p$	$p N \rightarrow p N$
2NA-Conv.	$K^- pn \rightarrow \Sigma^0 n$	$\Sigma^0 p \rightarrow \Lambda p$
	$K^- pp \rightarrow \Sigma^0 p$	$\Sigma^0 p \rightarrow \Lambda p$
	$K^- pp \rightarrow \Sigma^0 p$	$\Sigma^0 n \rightarrow \Lambda n$
	$K^- pn \rightarrow \Sigma^- p$	$\Sigma^- p \rightarrow \Lambda n$
	$K^- pp \rightarrow \Sigma^+ n$	$\Sigma^+ n \rightarrow \Lambda p$





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., 2020 Few Body Systems *accepted*]

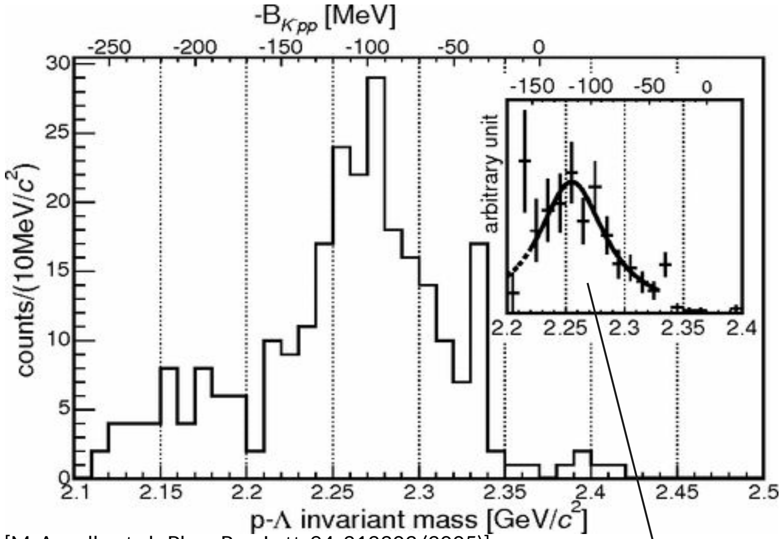
Including the missing components the total BR of the K^-2NA is:

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

Experimental search in K^- induced reactions

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

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:

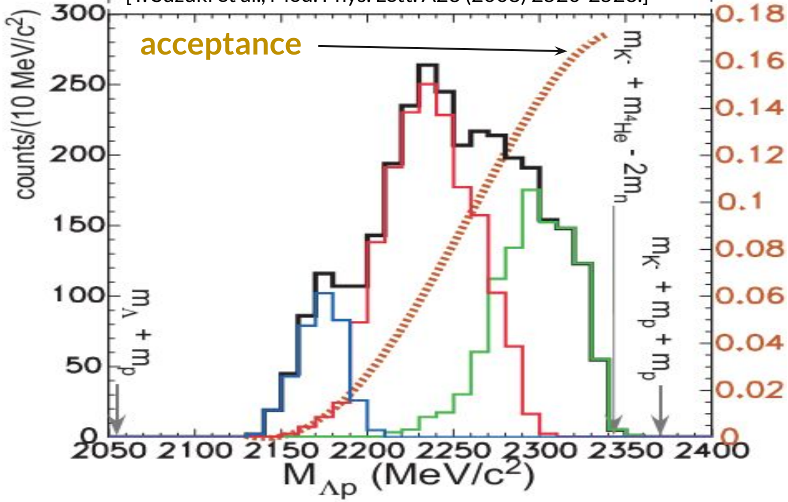
BE = $(115^{+6}_{-5}\,(\text{stat.})^{+3}_{-4}\,(\text{syst.}))$ MeV

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

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

detected particles

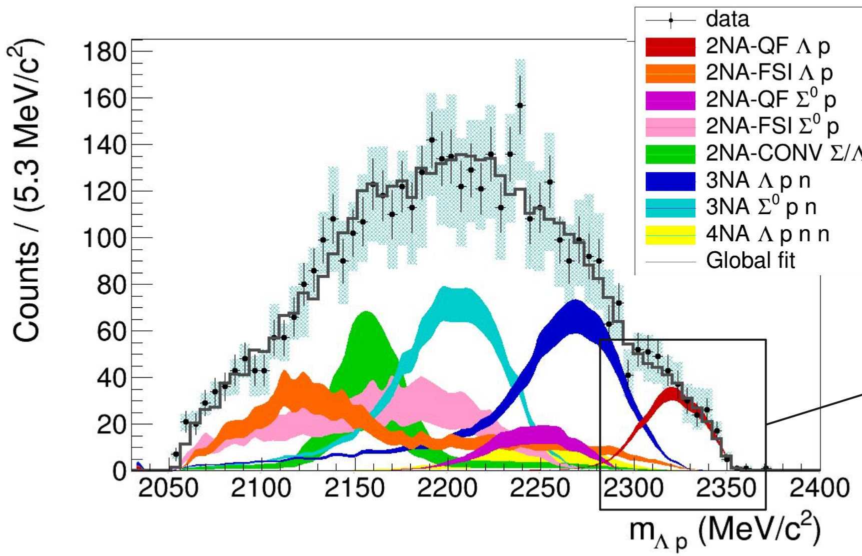
[T. Suzuki et al., Mod. Phys. Lett. A23 (2008) 2520-2523.]

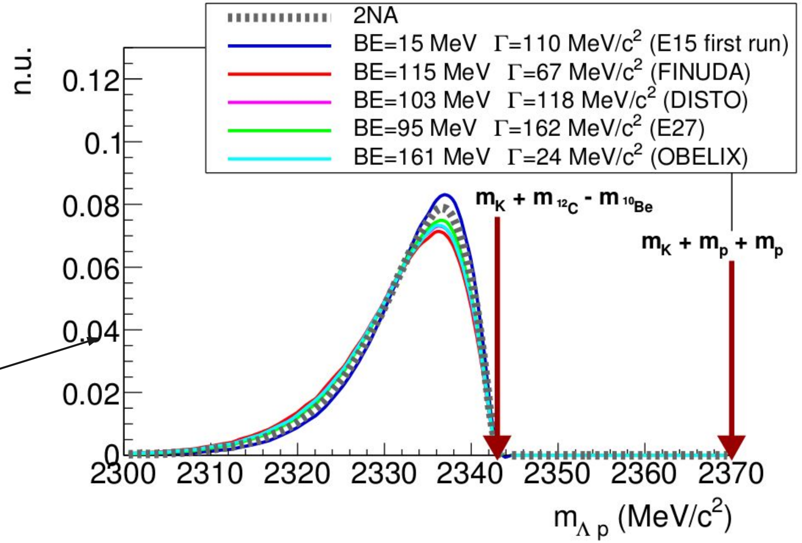


Using the missing mass information, three components to the invariant mass spectrum are found:

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

Λp analysis: K$^-$ pp bound state

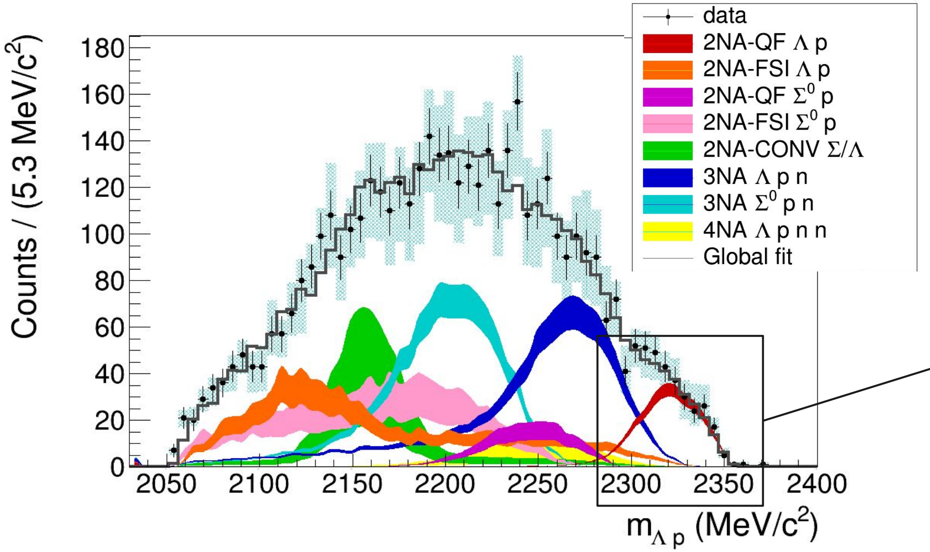


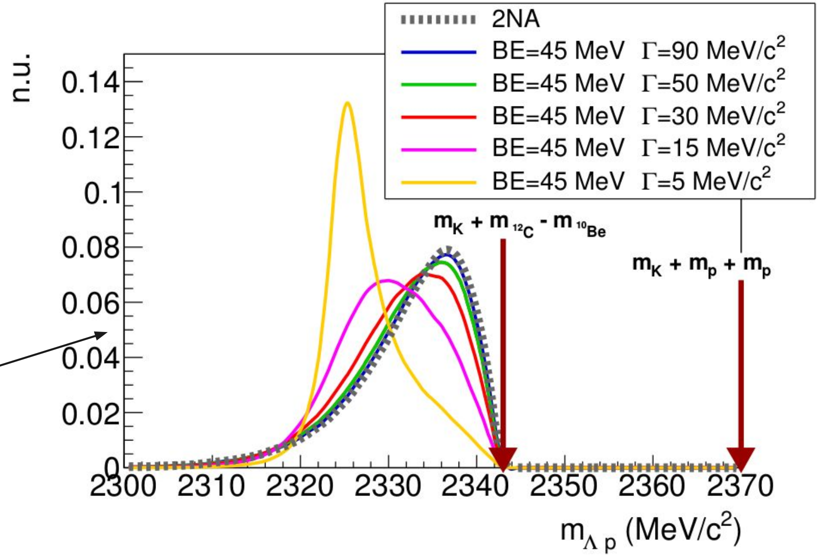


K$^-$pp bound state contribution **completely overlaps** with the K$^-$2NA

[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



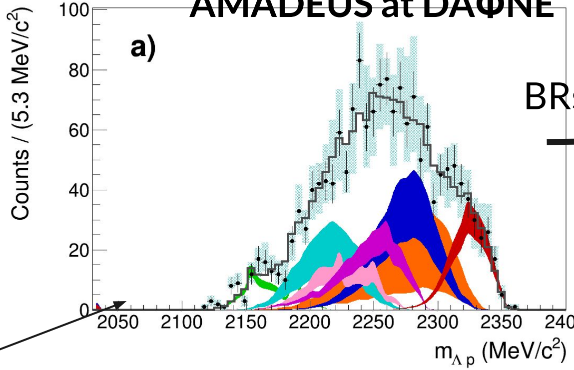


K^-pp bound state contribution **completely overlaps** with the K^-2NA

[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

AMADEUS at DAΦNE

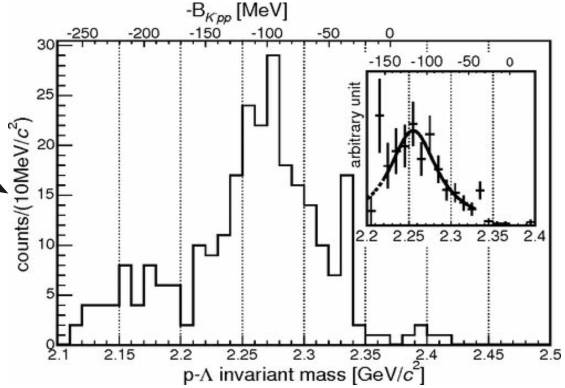


BRs evaluation

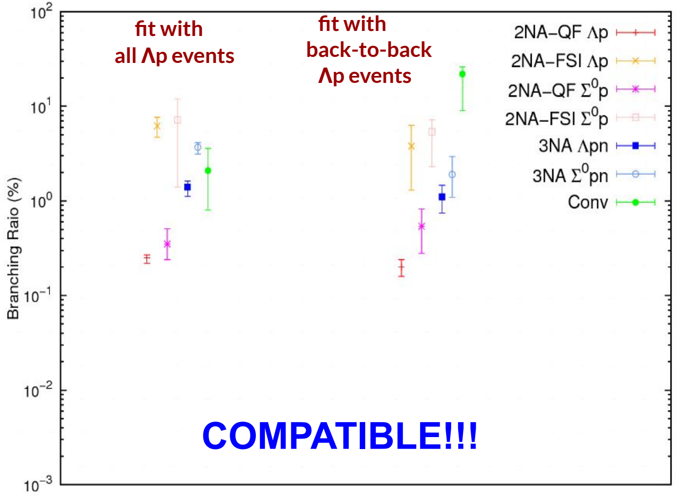
Process	Branching Ratio (%)
2NA-QF Λp	$0.20 \pm 0.04(\text{stat.}) \pm 0.02(\text{syst.})$
2NA-FSI Λp	$3.8 \pm 2.3(\text{stat.}) \pm 1.1(\text{syst.})$
2NA-QF Σ^0p	$0.54 \pm 0.20(\text{stat.})\ ^{+0.20}_{-0.16}(\text{syst.})$
2NA-FSI Σ^0p	$5.4 \pm 1.5(\text{stat.})\ ^{+1.0}_{-2.7}(\text{syst.})$
2NA-CONV 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 ($\cos\theta_{\Lambda p} < -0.8$)

FINUDA at DAΦNE



[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 ± 2) × 10^{-4} / K^-_{stop} → global, no 4NA

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

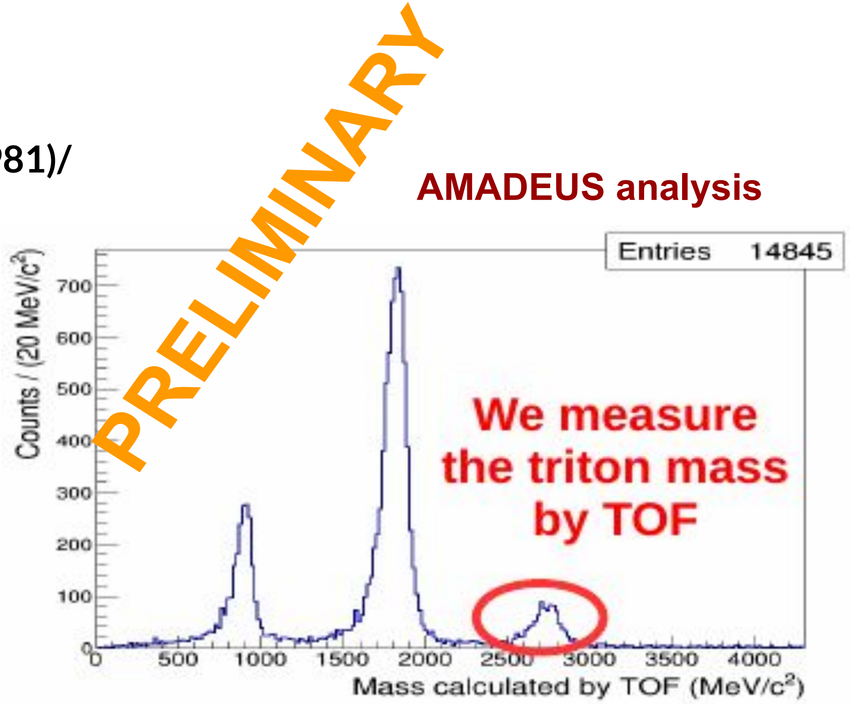
/Phys. Lett. B, 229 (2008)/

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 $\mathbf{K^{-}\,{}^{4}He \rightarrow \Lambda t}$ process

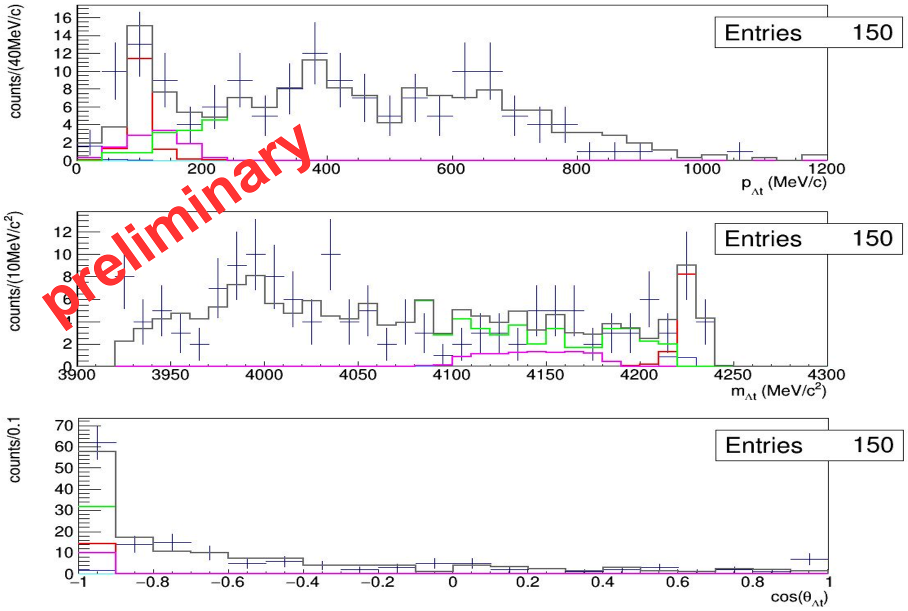
BR($K^{-4}He(4NA) \rightarrow \Lambda t$) **< 2.0 × 10^{-4} /K$_{stop}$ (95% c. l.)**

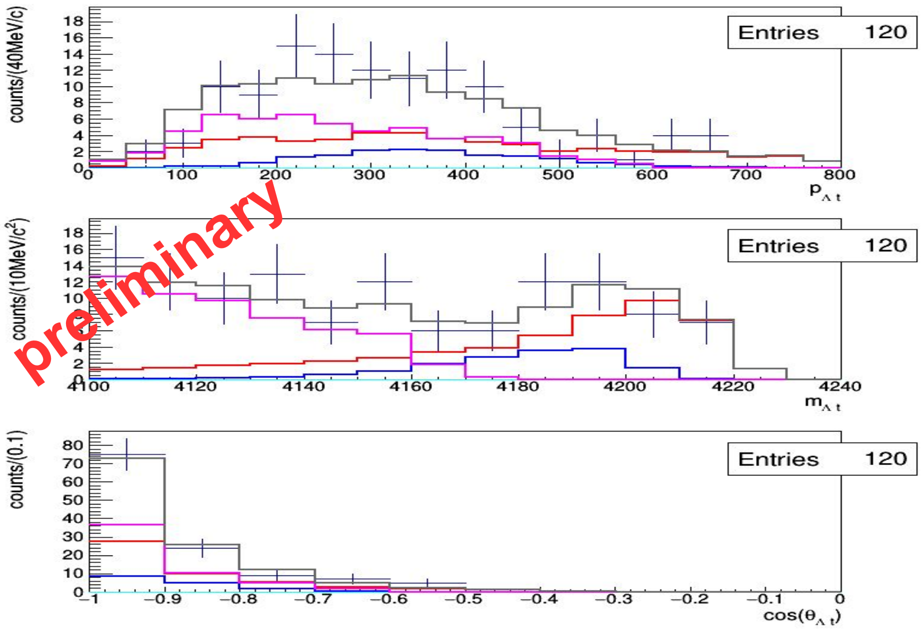
σ(100 ± **19** MeV/c) (K^{-4}He(4NA) →Λt) **=**
= (0.81 ± 0.21 (stat) $^{+0.03}_{-0.04}$ (syst)) mb

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

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

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

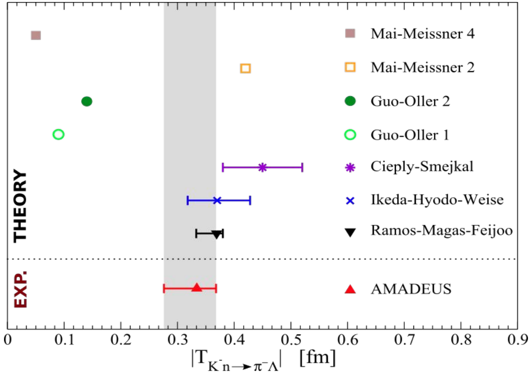




Summary

K^-n amplitude below threshold

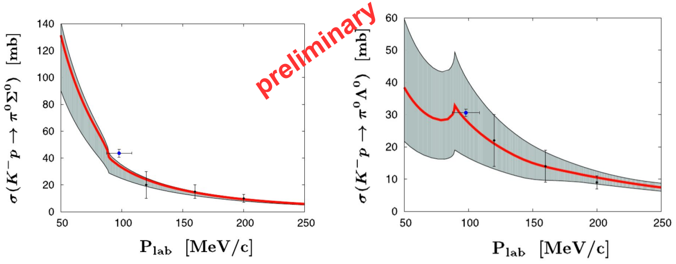
$$|f^s_{ar}| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst})\ \mathrm{fm}\,.$$



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 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.) $\pm$ 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.)	-		

$K^-p \to \Sigma^0\pi^0$ ($\Lambda\pi^0$) at 100 MeV/c



Λ t channel: 4NA BRs and σ

BR(K^- ^{4}He(4NA) → Λt) < 2.0×10^{-4} /K_{stop} (95% c. l.)

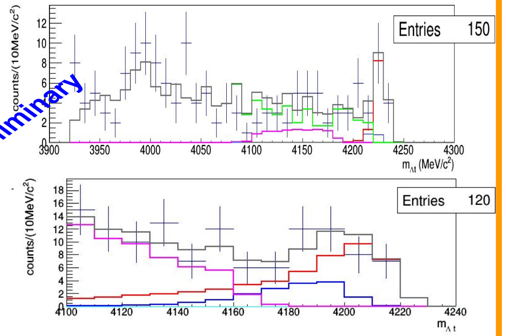
σ(100 ± 19 MeV/c) (K^- ^{4}He(4NA) → Λt) =

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

BR(K^- ^{12}C(4NA) → Λt ^{8}Be) = 1.5 ± 0.5 × 10^{-4} (stat) /K_{stop}

σ(K^- ^{12}C (4NA) → Λt ^{8}Be) = 0.58 ± 0.11 (stat) mb

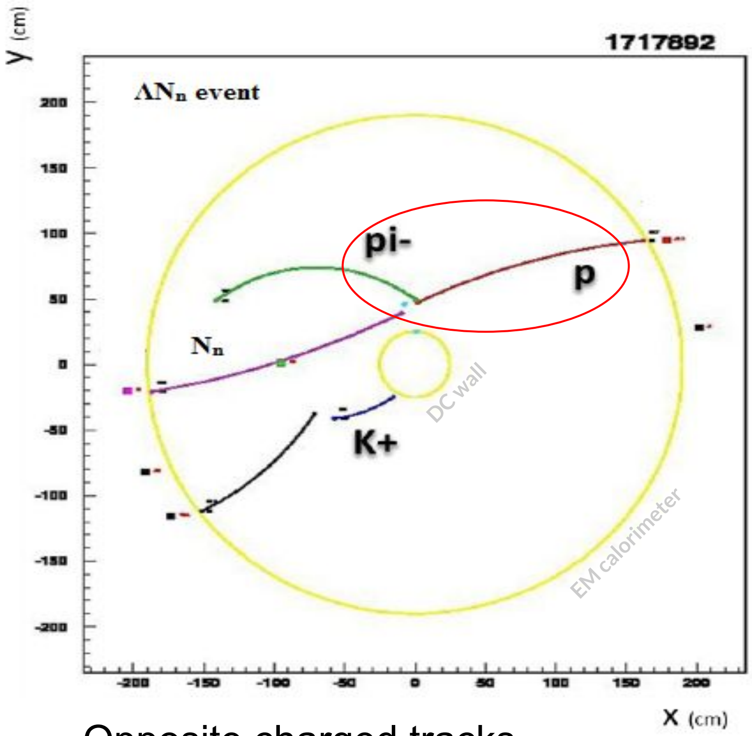
σ(K^- ^{12}C (4NA) → Σ^0t ^{8}Be) = 1.88 ± 0.35 (stat) mb



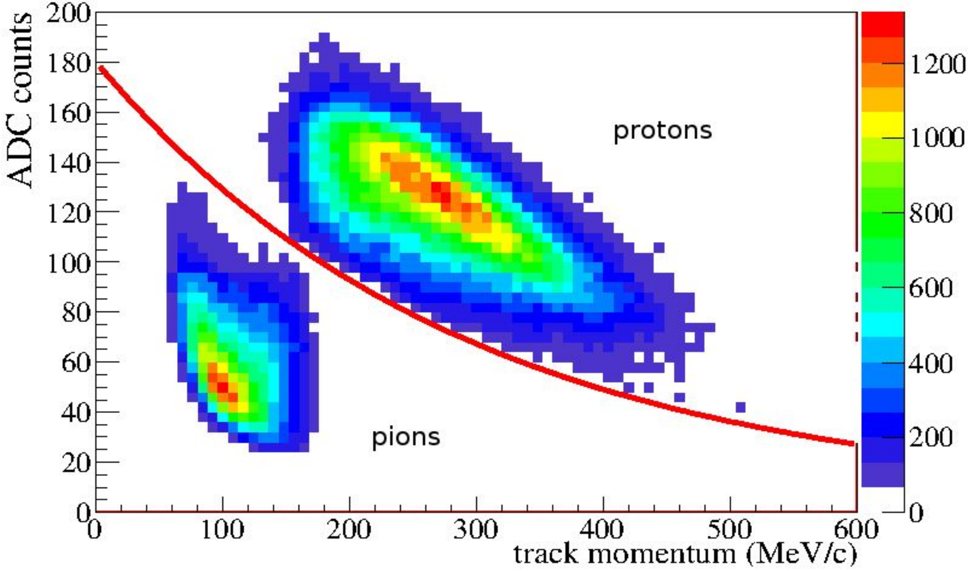
Thank You

Λ(1116) identification

1[st] Step: **Λ → p + π⁻** reconstruction (BR = 63.9 ± 0.5 %)



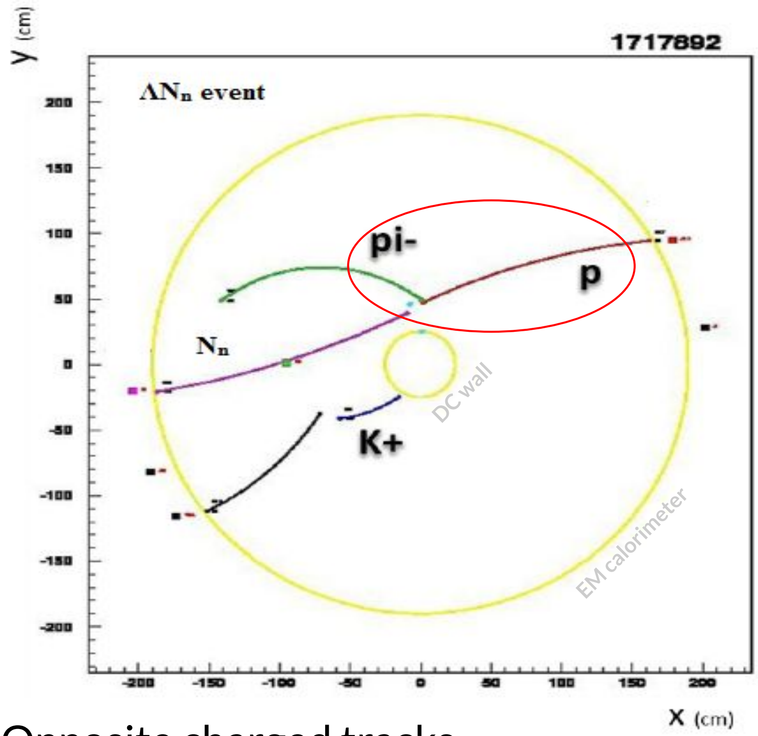
Opposite charged tracks
with common vertex



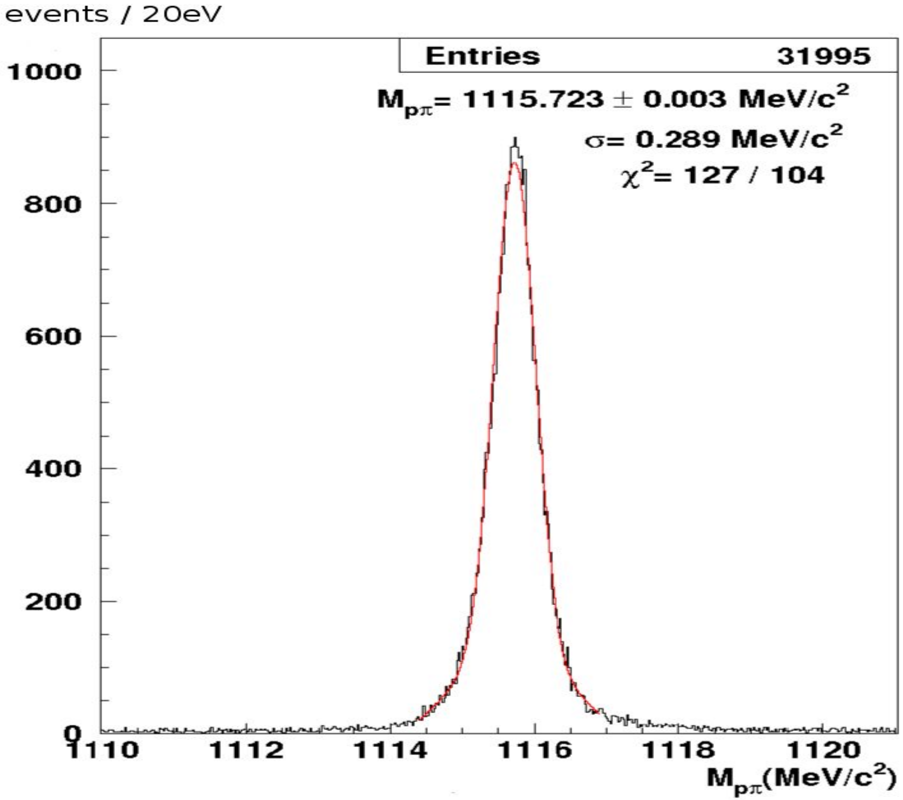
dE/dx information in the DC wires

Λ(1116) identification

<u>1st Step</u>: **Λ → p + π⁻** reconstruction (BR = 63.9 ± 0.5 %)

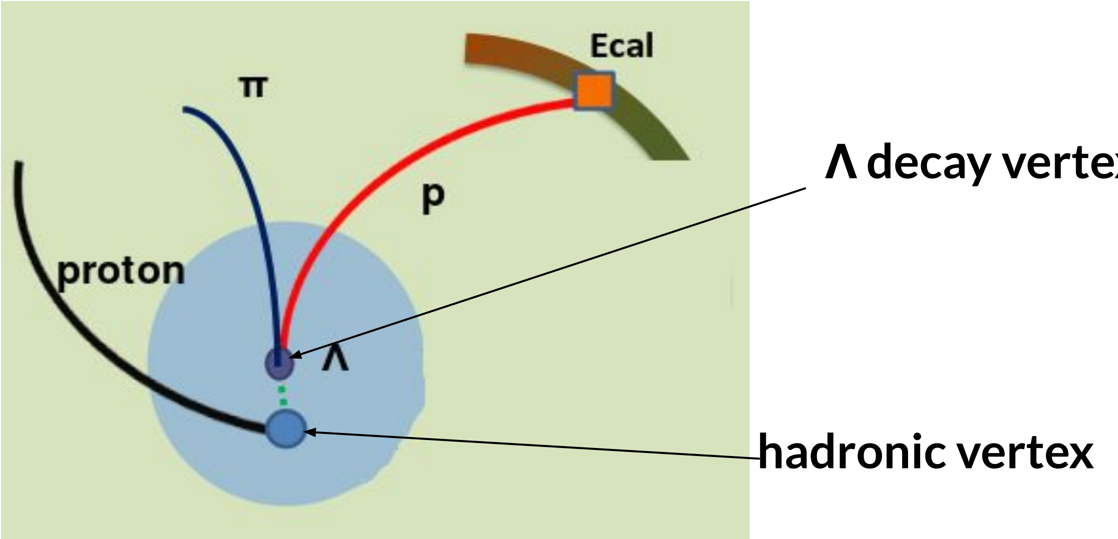


Opposite charged tracks
with common vertex



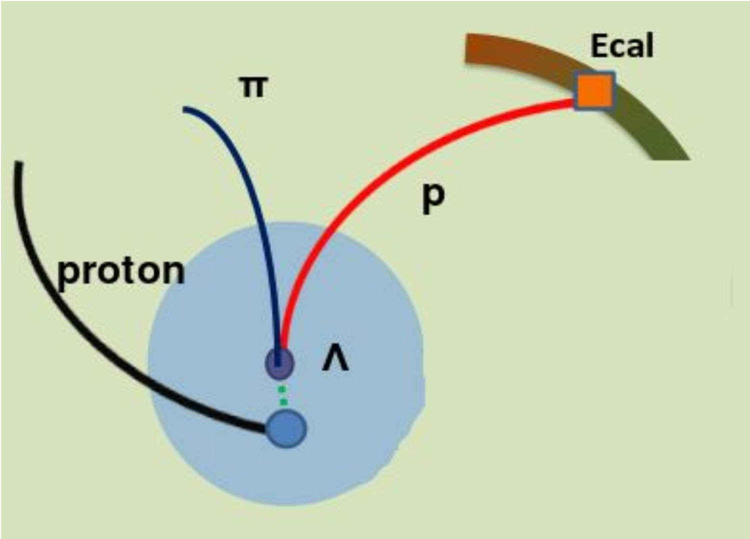
Hadronic vertex reconstruction

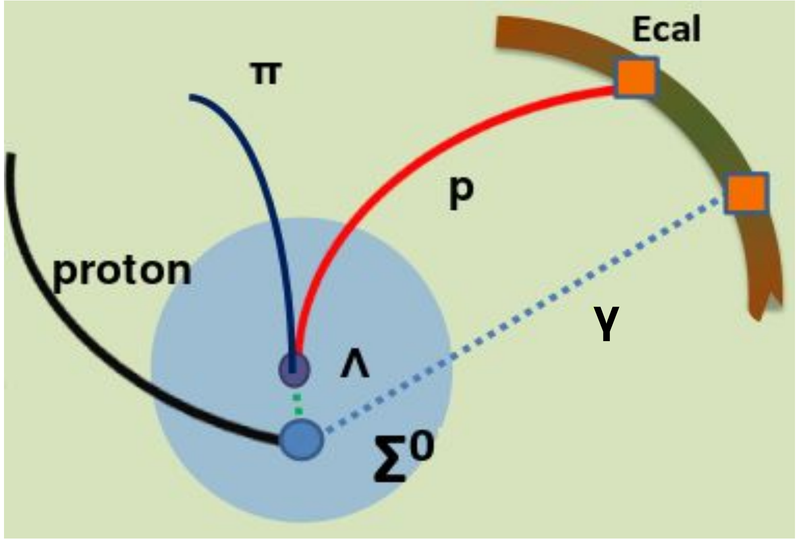
2nd Step: **hadronic interaction vertex** searched extrapolating backwards the Λ path and an extra positive track



Hadronic vertex reconstruction

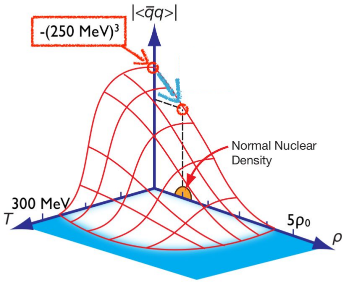
2nd Step: **hadronic interaction vertex** searched extrapolating backwards the Λ path and an extra positive track





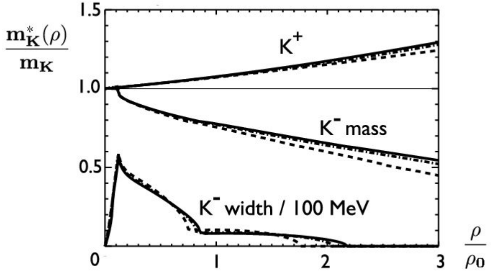
Impact on in-medium $\bar{K}N$ interaction

- Partial restoration of chiral symmetry in medium

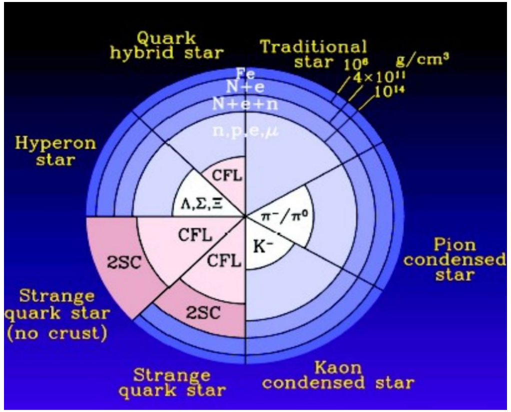


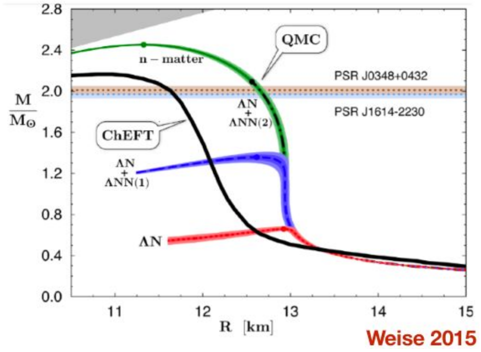
kaon mass modification:

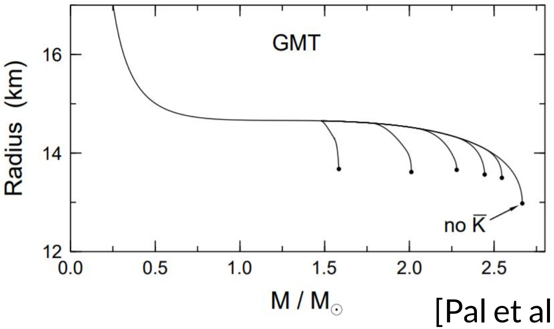
$$m_K^{*2} = m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\rho + \mathcal{O}\left(k_F^4\right)$$



- Impact on Equation of State (EoS) of Neutron Stars:







K⁻ condensate can change EoS-stiffness

but: hyperons become more relevant at higher densities [Gal et al. Rev. Mod. Phys. 88, 035004 (2016)]

[Pal et al. Nucl.Phys. A674 (2000) 553-577]