An insight of the sub-threshold KbarN interaction
(a story which instructed and inspired me :)

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STRANU: Hot Topics in STRANgeness NUclear and Atomic Physics

ECT* 24-28 May 2021

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AMADEUS at LNF

INFN Istituto Nazionale di Fisica Nucleare
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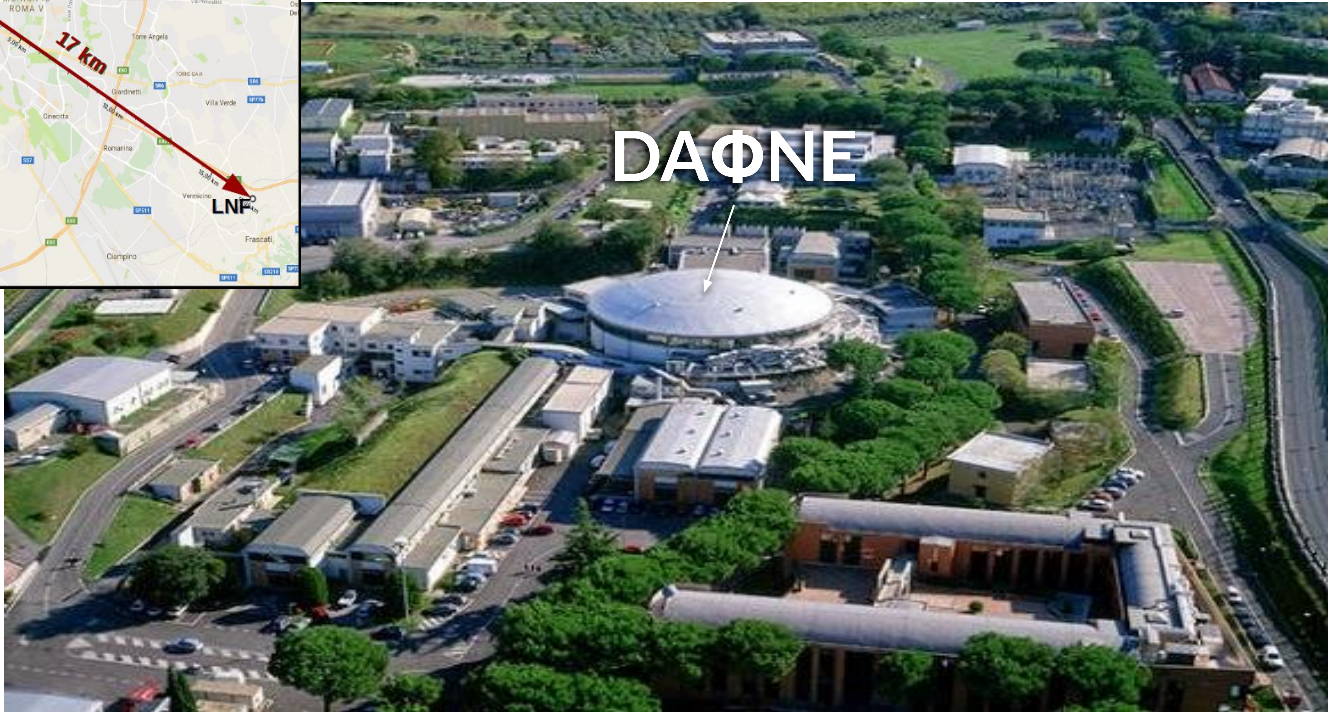

TWO SAMPLES OF DATA:

- **2004-2005 KLOE data (Analyzed luminosity of ~2 fb^{-1})**

K^- absorbed in KLOE materials (H, ^4He, ^9Be, ^{12}C)

At-rest + In-flight

. Dedicated 2012 run with pure graphite Carbon target inside KLOE

(~90 pb^{-1}; analyzed 37 pb^{-1}, x1.5 statistics)

K^- ^{12}C absorptions At-rest

DAΦNE the Φ factory

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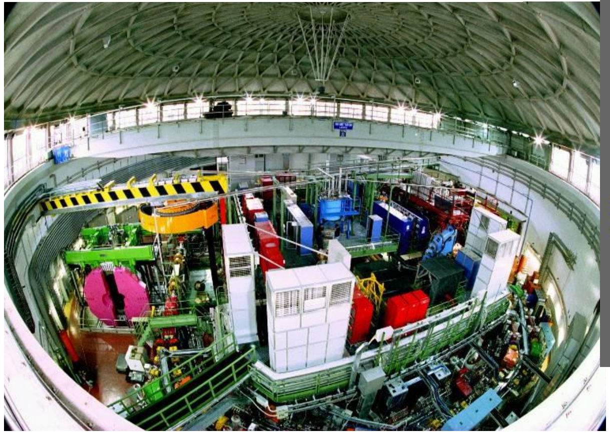
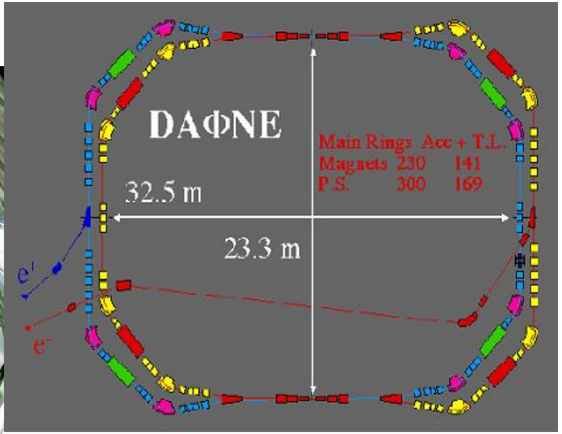
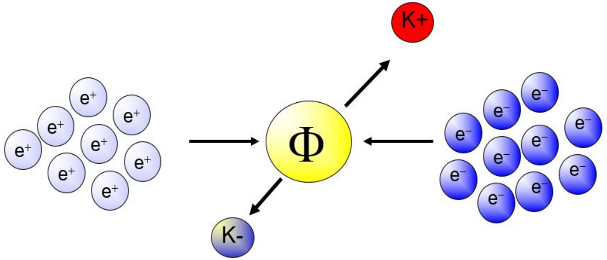




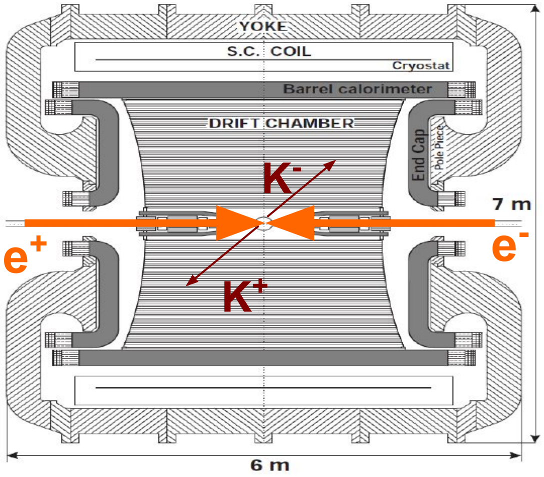
- $e^+ e^-$ at 510 MeV
- φ resonance decays at 49.2 % in $K^+ K^-$ back to back pair
- Very low momentum (≈ 127 MeV) K^- beam
- Flux of produced kaons: about 1000/second

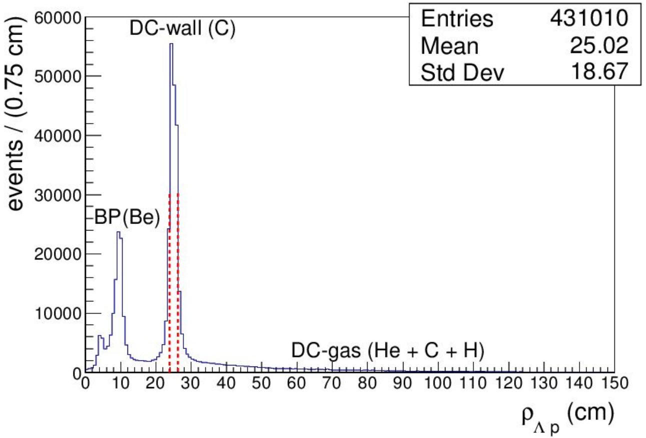
Best low momentum K^- factory in the world



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

AMADEUS





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)]

KLOE as active target

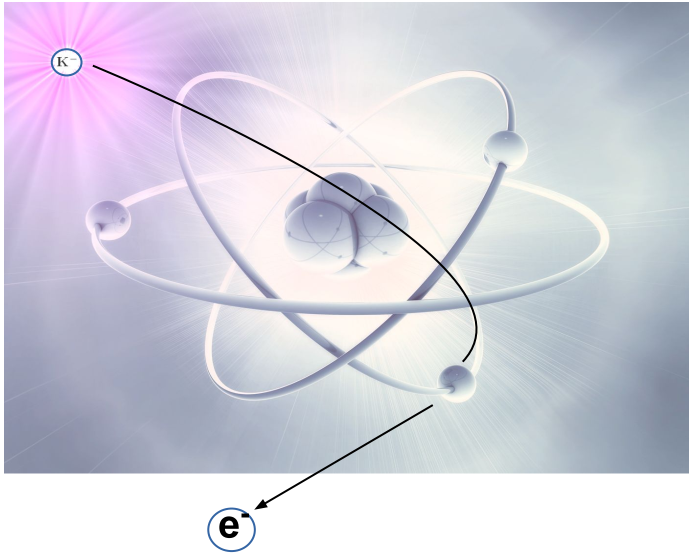
- DC wall (750 μm C fibre , 150 μm Al foil);
- DC gas (90% He, 10% C_4H_{10}).

K^- absorptions at-rest and in-flight

AT-REST

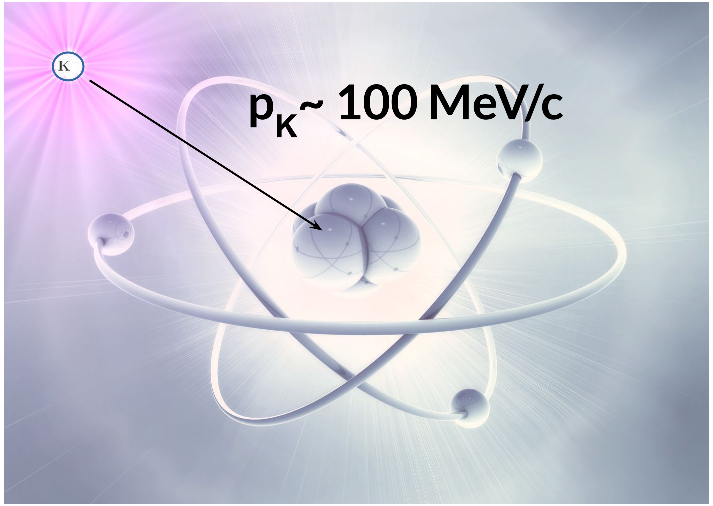
K^- absorbed from atomic orbitals

($p_K \sim 0$ MeV/c)

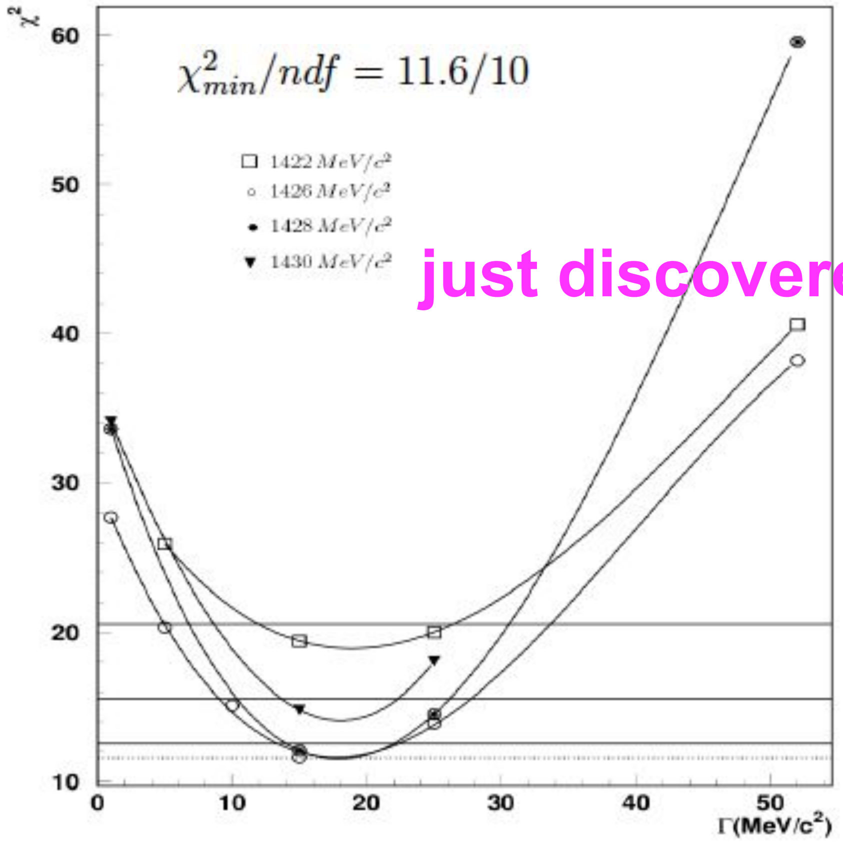


IN-FLIGHT

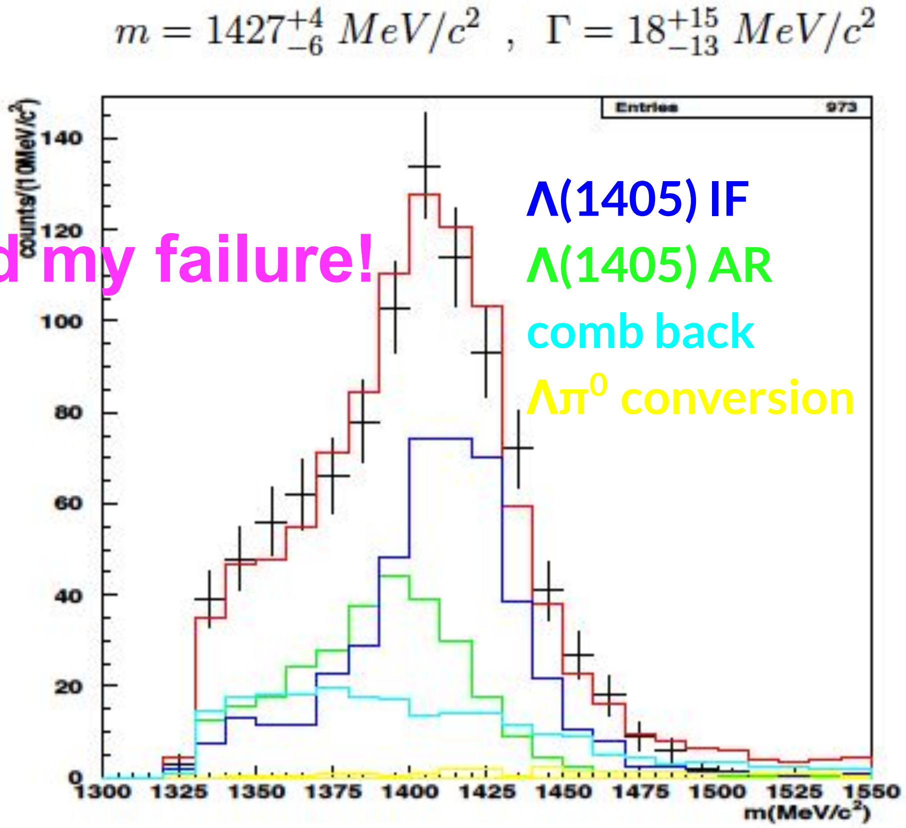
($p_K \sim 100$ MeV/c)



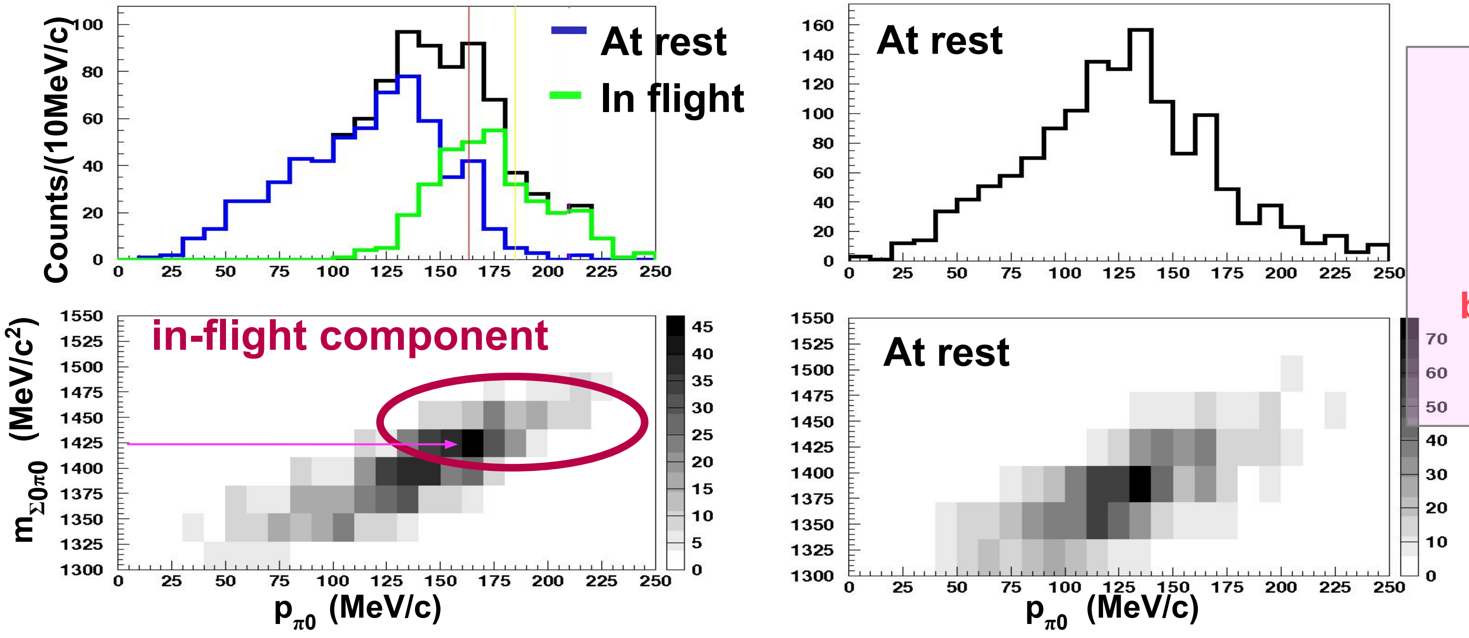
$K^- p \rightarrow \Sigma^0 \pi^0$ (bound proton in ^{12}C and ^{4}He)



just discovered my failure!



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



IN-FLIGHT

K- 12C

opens a window

between 1416 MeV

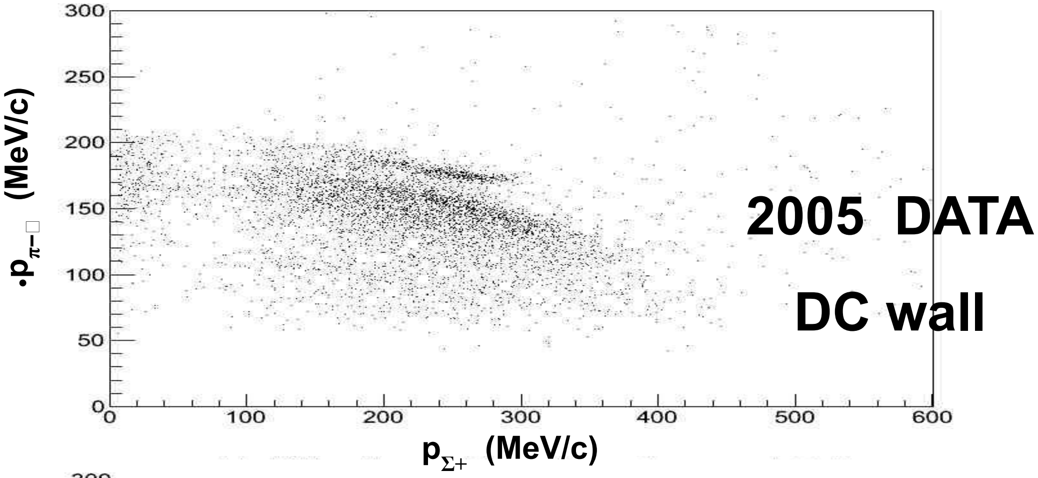
and K-Nth

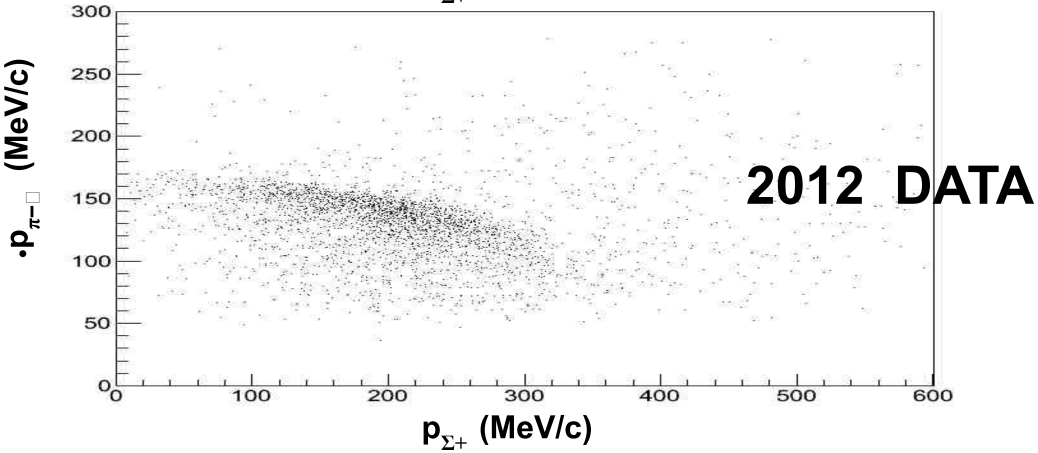
difficulty: epoxy resin, contained in the carbon fibre target, contains H

BUT - **K^-H interaction probability**, **based on K^- interaction AT-REST in hydrocarbons mixture data (Lett. Nuovo Cimento, C 1099 (1972)) gives max contribution order of 1% !!!**

HYDROGEN contamination $\rightarrow$ from $\Sigma^+ \pi^-$

$K^- p \rightarrow \Sigma^+ \pi^-$ detected via: $(p\pi^0)\, \pi^-$





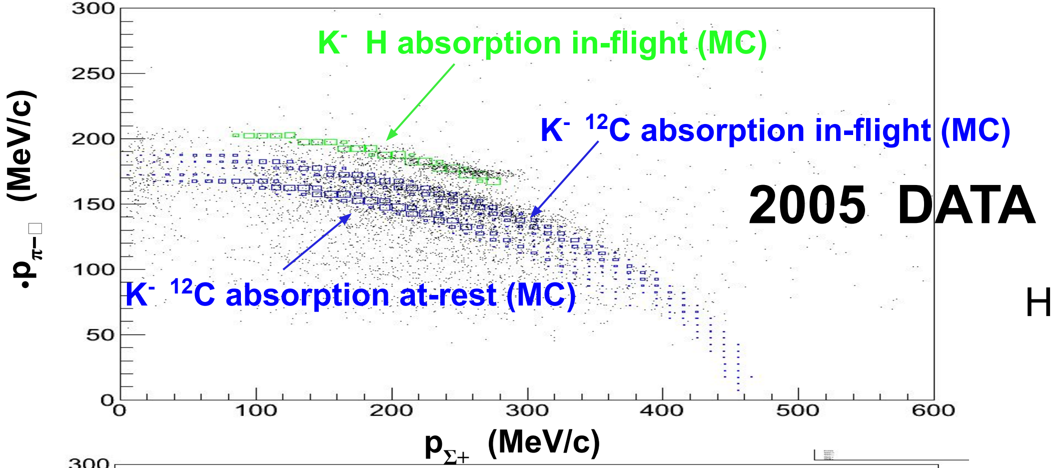
NOW

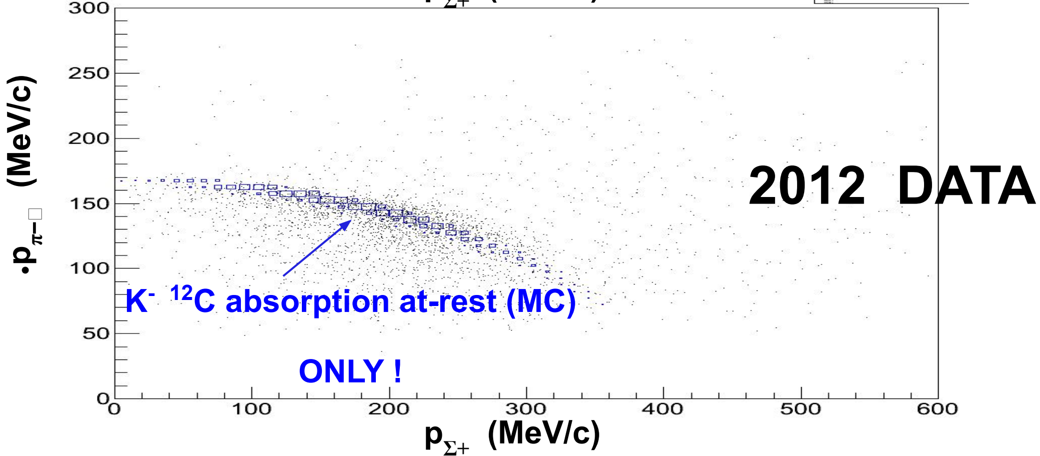
Thanks to the good $p_{\pi-}$ resolution

= 1 MeV

HYDROGEN contamination $\rightarrow$ from $\Sigma^+ \pi^-$

$K^- p \rightarrow \Sigma^+ \pi^-$ detected via: $(p\pi^0)\, \pi^-$



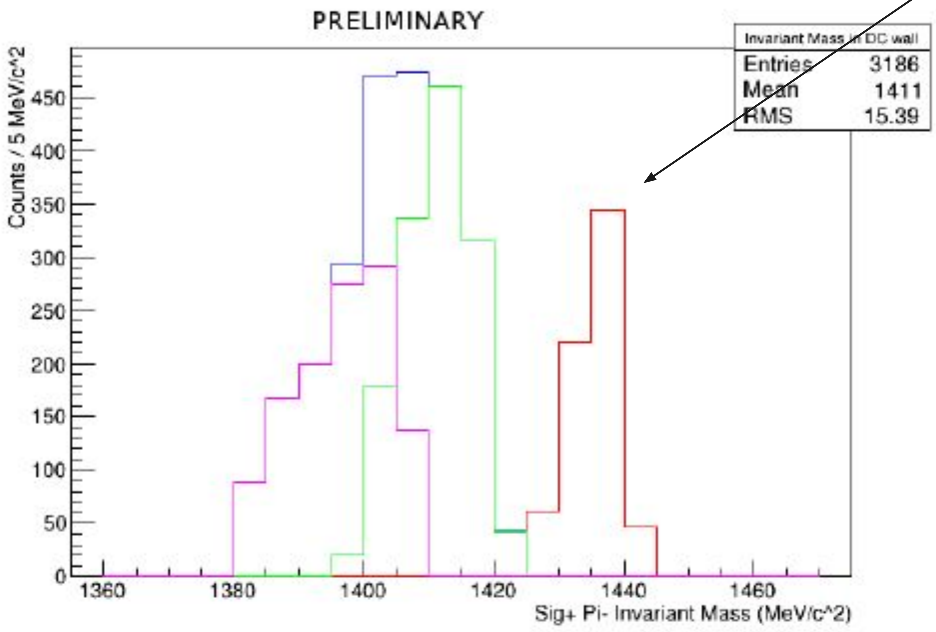


K^- H contribution ~ 20%

H atoms in the molecules mainly contribute to **K- H absorption in-flight**, resulting in a **non-resonant background in the $\Sigma^0 \pi^0$ spectra**

measured channel: $K^- p \rightarrow \Sigma^+ \pi^-$ (bound proton in ^{12}C)

p_π resolution about 1MeV → K- capture at-rest/in-flight/on H can be distinguished



but, neglecting the small I = 2 component

$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}\,(T^{(0)}T^{(1)*}),$$

$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}\,(T^{(0)}T^{(1)*}),$$

$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2,$$

extraction of the non-resonant I=1 amplitude below threshold in the $\Lambda\pi^-$ channel serves to determine the corresponding background in $\Sigma^+ \pi^-$

Figure 3: *(Colour online.) $m_{\Sigma\pi}$ invariant mass distributions in-flight (green) and at-rest (violet) in ^{12}C. Blue histogram represents the sum of green and violet histograms. The red distribution refers to K^- absorptions on Hydrogen*

The non-resonant production is interesting by itself

In **$\Lambda\pi^-$** direct production in 4He the isospin I = 1, P-wave amplitude, dominated by the Σ(1385) is well known -> the non-resonant I = 1, S -wave amplitude **$|f^{N\text{-}R}_{\Lambda\pi}(I=1)|$** can be extracted for the first time below threshold.

IDEA - in bubble chamber experiments the reaction $K^- \, {}^4\mathrm{He} \rightarrow \Lambda\pi^- \, {}^3\mathrm{He}$

interpreted as direct capture on a neutron with 3He being a spectator. The recoil energy of 3He indicated a low energy component due to S wave KN capture from atomic S state. Atomic experiments confirmed that due to molecular collisions the bulk of capture occurs from the high n, S states of the atom.

K. Bunnell et al., Phys. Rev. D 2, 98 (1970), D. Riley et al., Phys. Rev. D 11, 3065 (1975), J. Uretsky et al. Phys. Rev. D 2, 119 (1970), B. R. Wienke, Phys. Rev. D 1, 2514 (1970), . Suzuki et al., Mod. Phys. Lett. A 23, 2520-2523 (2008),
C. Curceanu et al., Eur. Phys. J. A 31 , 537-539 (2007)

The non-resonant production is interesting by itself

IDEA - Bubble chamber experiments discovered also a higher energy component in the recoil energy spectrum, whose origin has not been understood.

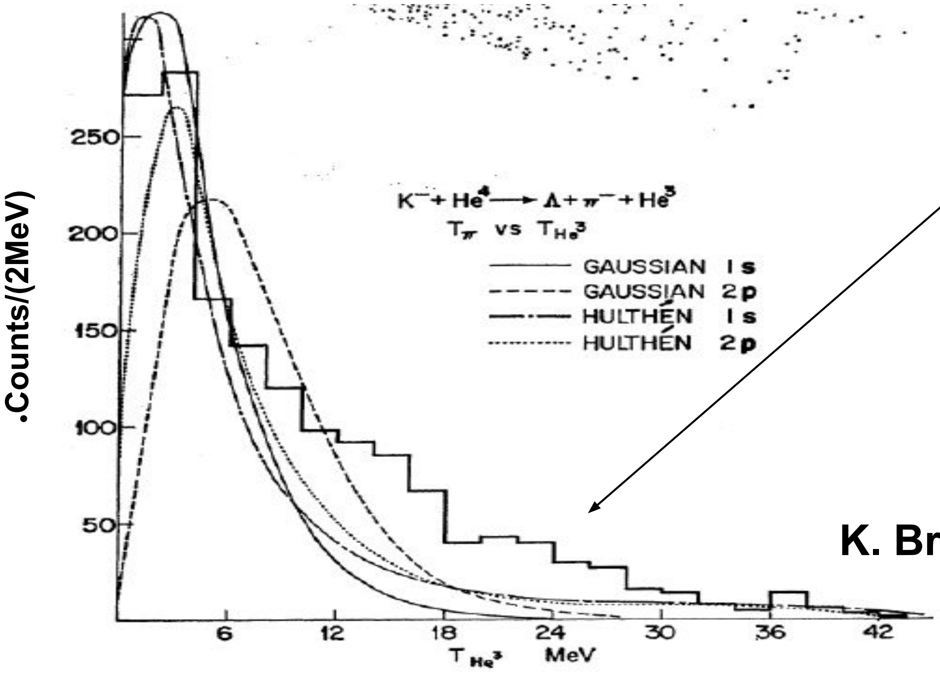
$$K^- (n + R) \rightarrow \Lambda \pi^- \ {}^3\mathrm{He}$$

(n + R) denotes the initial nucleus with the first struck neutron n singled out. The final nucleus is not assumed to be a spectator. The **Λ** may be formed directly or indirectly in an inelastic collision of an initially produced **Σ**.

The direct process may go in two basic ways:

- non-resonant isospin I=1, S-wave reaction
- resonant I=1, P-wave reaction, may be formed in atomic S-wave states as a consequence of its three body structure (K- = 1, n = 2 and R = 3).

- **Bubble chamber experiments** exhibit two components:
- **Low momentum $\Lambda\pi^-$ pair $\rightarrow$ S-wave, I=1, non-resonant transition amplitude.**
- **High momentum $\Lambda\pi^-$ pair $\rightarrow$ P-wave resonant formation ?**



Also exsists in S-state K-mesic atom

as a result of the

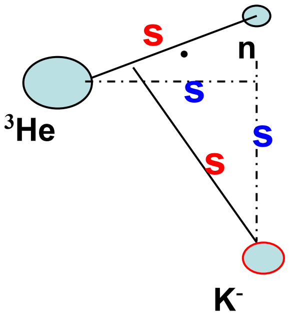
three body structure of the system

- **(K = 1, n=2, ^{3}He = 3)**

K. Brunnel et al., Phys.Rev. D2 (1970) 98

K^-(s=0) ^{4}He(s=0) n(s=1/2) Σ^{*-}(s=3/2) → resonance p-wave only

atomic s-state capture:

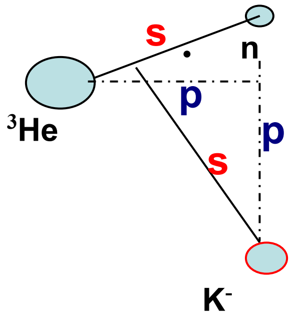


(K^- n) s-state interaction

Σ^{*-} not allowed

NON-RES only

+



consequence of 3-body effect

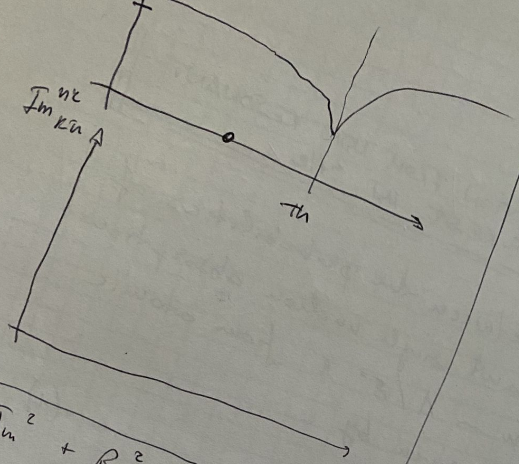
(K^- n) p-state interaction

Σ^{*-} allowed

- (K^- ^{4}He → $\Lambda\pi^-$ ^{3}He) absorptions from (n s) - atomic states are assumed →

^{4}He bubble chamber data (Fetkovich, Riley interpreted by Uretsky, Wienke)

- Coordinates recupling enables for P-wave resonance formation



F_n

P_T P_R

$P_R \equiv P_K$

$$\sqrt{Im^2 + Re^2} = |A|$$

$$(Im^2 + Re^2) = P^{nz}_{rob\; K^- n \to Y\pi} = \cancel{*}$$

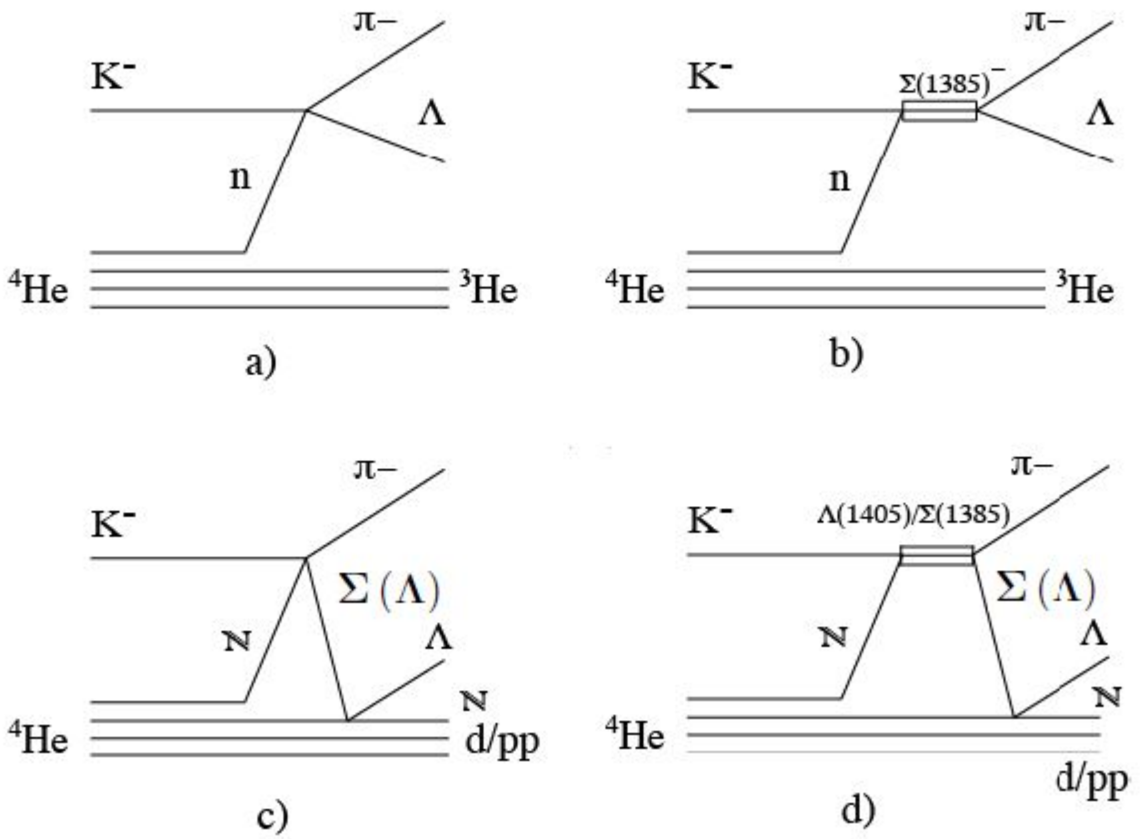
$$P^{nz}_{rob\; K^- n \to \Lambda\pi} = \frac{1}{2} *$$

$$\int |A^s| \underbrace{\int^{nuc} \varphi_K \varphi_n \, \delta \, d^3p_1 \, d^3p_2}_{f(p_{\Lambda\pi})}$$

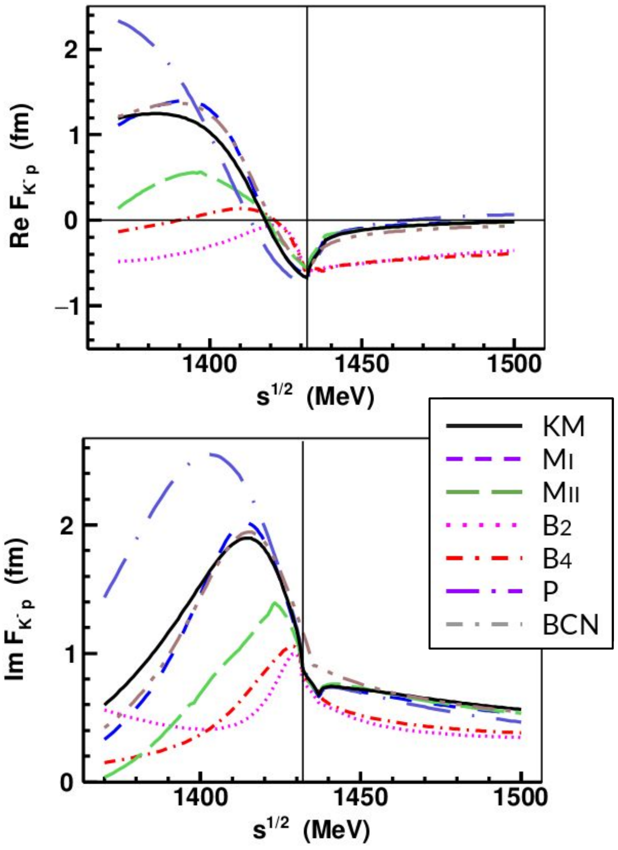
$$|A^s|^2 \cdot \cancel{F_n} \cdot P_h$$

$K^- n \to$

Direct and non-direct Λπ⁻ production



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)

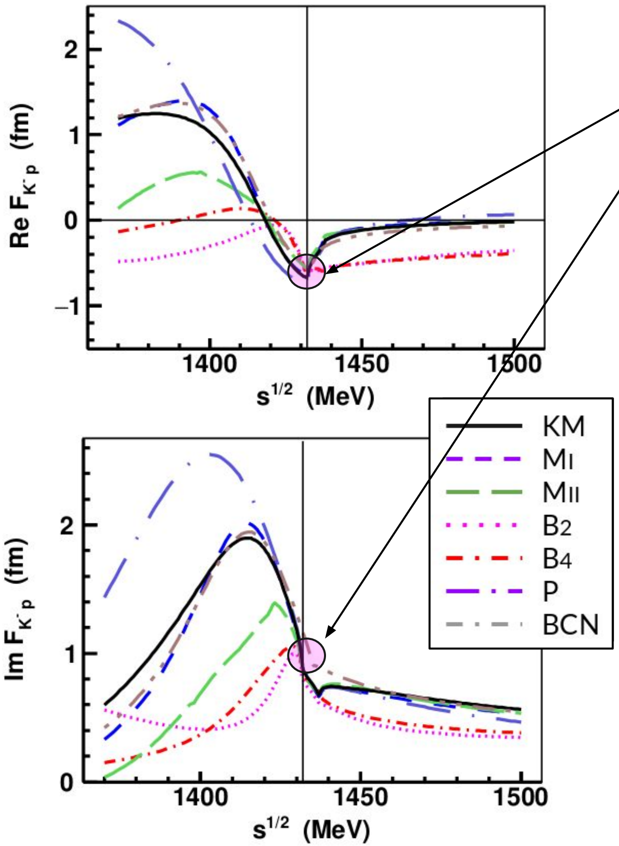
  Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202
- Bonn (B2 , B4)

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

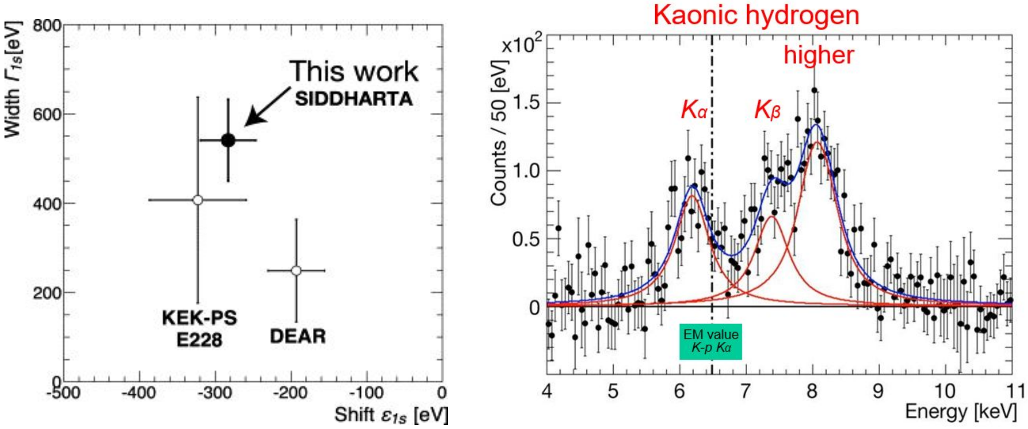
  A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115
- Barcelona (BCN)

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

Experimental constraints at $\bar{K}N$ threshold



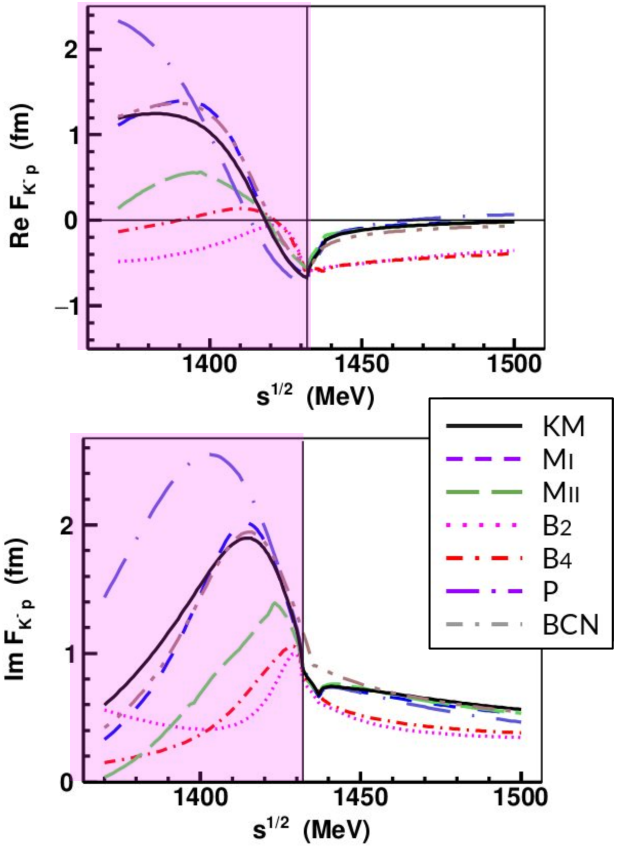
Precise SIDDHARTA measurement of kaonic hydrogen 1s level shift and width



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

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

K⁻p scattering amplitude



[from A. Cieply talk at MENU2019 conference]

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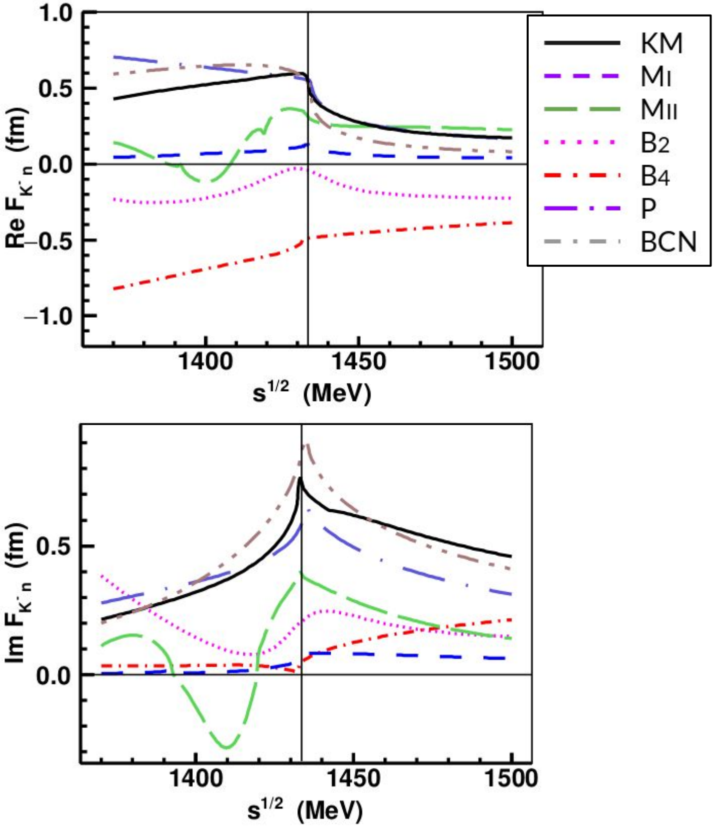
  A. Feijoo, V. Magas, À. Ramos, Phys. Rev. C 99 (2019) 035211

Large discrepancies in the region below threshold!

K⁻n scattering amplitude



[from A. Cieply talk at MENU2019 conference]

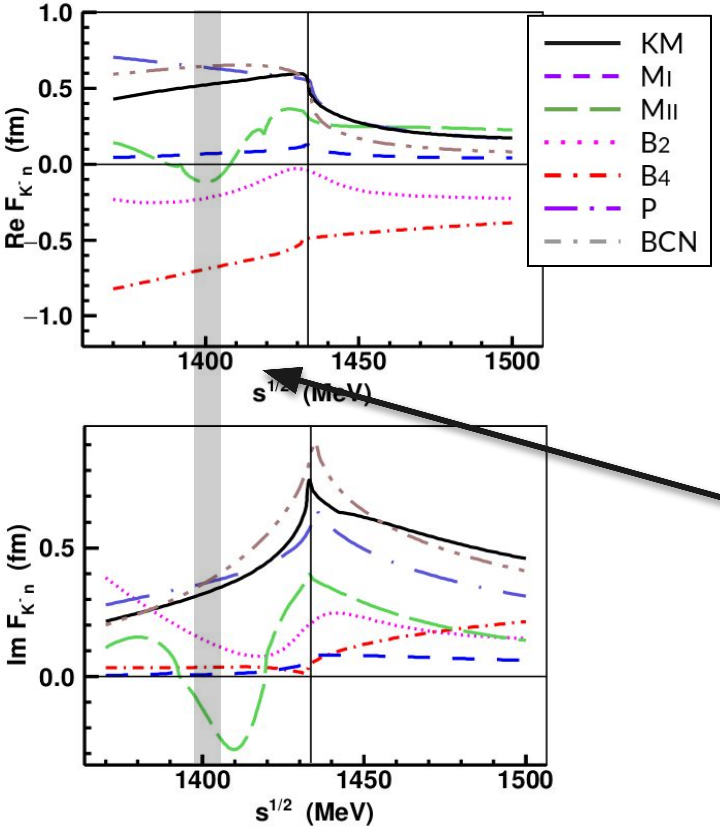
K$^-$n scattering amplitude (s-wave .. non resonant) in chiral calculations

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

Experimental information was missing:

- **SIDDHARTA-2** → **first experimental constraint at threshold**
- **AMADEUS** → **we could already give information below threshold**

Experimental constraints below threshold



K^-n scattering amplitude with Chiral models

Large spread in I=1 channel

Experimental information was 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 $|f^{N\text{-}R}_{\Lambda\pi}(I=1)|$

with bound neutron in ^{4}He

Strategy of the measurement

The kinetic energy in the K$^-$n CM system is:

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

recoil energy of the Λπ$^-$ pair with respect to the residual

$$B_n = 21 \text{ MeV}$$

$$< p_3^2/2\mu_{12,3} > \simeq 12 \text{ MeV}$$

see also

A. Cieply et al., Phys. Lett. B 702 (2011) 402,
T. Hoshino et al., Phys. Rev. C 96 (2017) 045204
N. Barnea, E. Friedman, A. Gal, Nucl. Phys. A968 (2017)

Strategy of the measurement

The kinetic energy in the K⁻n CM system is:

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recoil energy of the Λπ⁻ pair with respect to the residual

$B_n = 21$ MeV

$< p_3^2/2\mu_{12,3} > \simeq 12$ MeV

so we are testing the interaction about 33 MeV below the KbarN threshold.
The interaction is very short range (off shell dependence on relative momenta is neglected)

$$t_{Kn\to\Lambda\pi}(E_{Kn}) \equiv f^s$$

is a free parameter to be extracted by comparison of predicted and measured momentum probability distributions.

Strategy of the measurement

- The sub-threshold result can help to better determine the I=1 $\Sigma\pi$ background

- the modulus of the s-wave $K^-n \to \Lambda\pi^-$ amplitude below threshold can be used to constraint models of s-wave interaction,

- the subthreshold result is to be compared with the corresponding values extracted from experimental $K^-p \to \Lambda\pi^0$ cross section measurements above the threshold:

J. K. Kim, Phys. Rev. Lett. 19, 1074 (1967).
J. K. Kim, Columbia University report, Nevis, 149 (1966).

Table 1: The $K^-n \to \Lambda\pi^-$, S-Wave amplitude, $|f^s|$ fm extracted from $K^-p \to \Lambda\pi^0$ scattering [18, 19].

$E = -33MeV$	$p_{lab} = 120\ MeV/c$	160	200	245
to be determined	0.33(11)	0.29(10)	0.24 (6)	0.28(2)

the amplitude is weakly energy dependent and downward extrapolation by 55 MeV is of interest.

Strategy of the measurement

Fit of the $p_{\Lambda\pi^-}$ observed distribution ($p_{\Lambda\pi^-}$ resolution about 2 Mev) using calculated distributions :

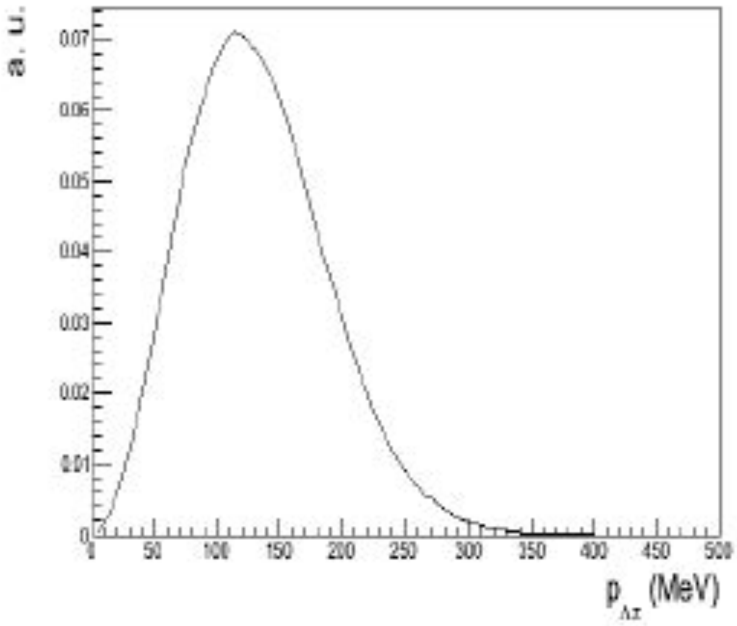
$$P_s^{\,s}\ (p_{\Lambda\pi}) = |\Psi_N\ (p_{\Lambda\pi})|^2\ |f^{\,s}\,(p_{\Lambda\pi})|^2\ \rho$$ **non-resonant**

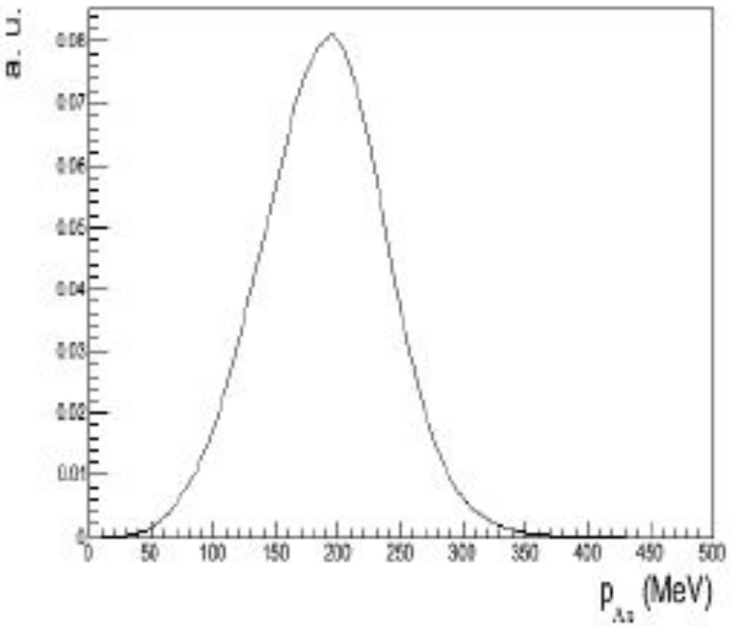
$$P_s^{\,p}\ (p_{\Lambda\pi}) = |\Psi_N\ (p_{\Lambda\pi})|^2\ c^2\ |2f^{\,\Sigma^*}\,(p_{\Lambda\pi})|^2\ \rho/3\ \ (k p_{\Lambda\pi})^2$$ **resonant**

Where $\rho = k\,p_{\Lambda\pi}^{\,2}$, $c = M_K/(M_K+M_n) = 0.345$ re-couples the S x S waves to P x P waves

To determine $|f^{\,N\text{-}R}{}_{\Lambda\pi}|$ given the fairly well known $|f^{\,\Sigma^*}{}_{\Lambda\pi}|$

Calculated $\mathbf{p}_{\Lambda\pi-}$ probability distributions



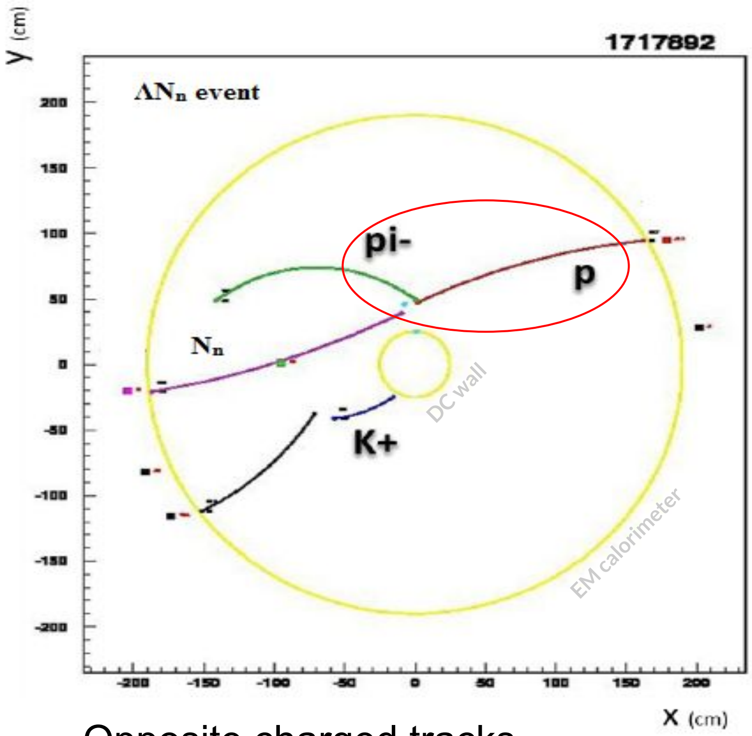


$\mathbf{P}_s^{\,s}\ (\mathbf{p}_{\Lambda\pi})$ **non-resonant**

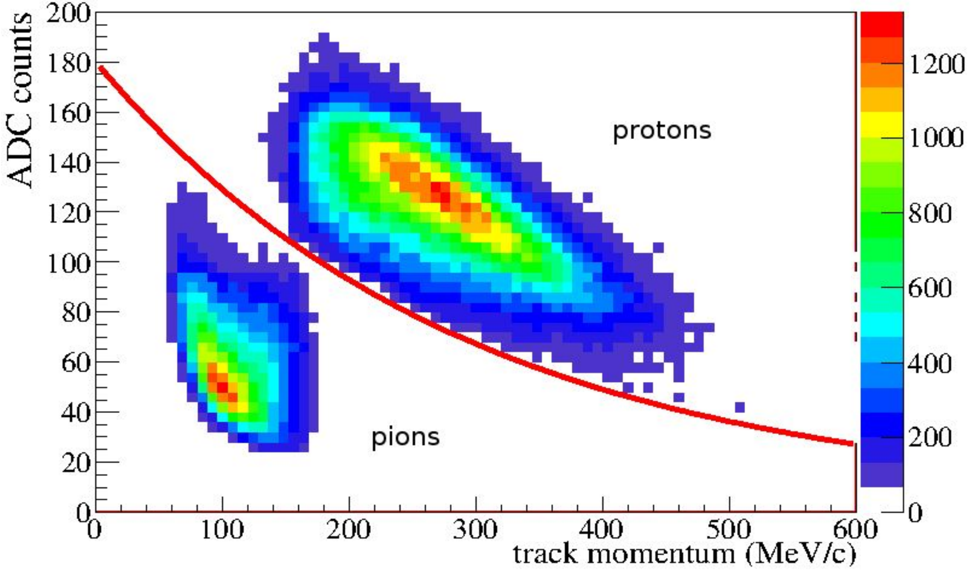
$\mathbf{P}_s^{\,p}\ (\mathbf{p}_{\Lambda\pi})$ **resonant**

Λ(1116) identification

1st Step: $\Lambda \rightarrow p + \pi^-$ reconstruction (BR = 63.9 ± 0.5 %)



Opposite charged tracks
with common vertex



dE/dx information in the DC wires

$K^- \ {}^4He \rightarrow \ \Lambda\pi^- \ {}^3He$ … calculated reactions

- Calculated primary hadronic interactions:

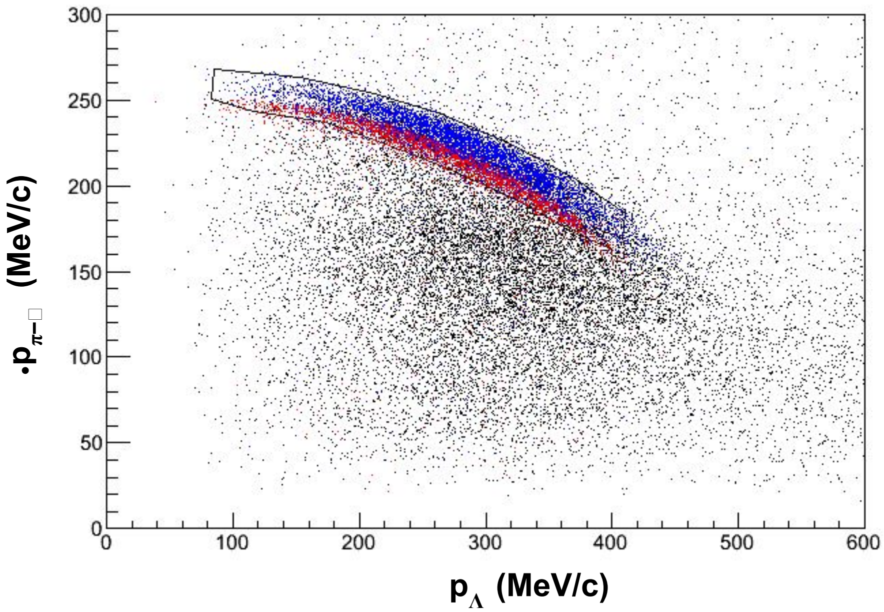
$K^- \ {}^4He \rightarrow \ \Lambda\pi^- \ {}^3He$

At-rest : S-wave non-Res / P-wave $\Sigma(1385)$ Res

In-flight : S-wave non-Res / P-wave $\Sigma(1385)$ Res

Direct $\Lambda\pi^-$ production .. SIGNAL

$K^- \ {}^4He \rightarrow \ \Lambda\pi^- \ {}^3He$ <u>events selection</u>



direct production In-flight
RES + N-R

direct production At-rest
RES + N-R

- CUT based on MC simulations used to select $\Lambda\pi^-$ direct production events
- At-rest CAN NOT be separated from In-flight $\rightarrow$ global fit performed
- Background sources: - $\Lambda\pi^-$ events from Σ p/n $\rightarrow$ Λ p/n conversion
  - $\Lambda\pi^-$ events from K^- ${}^{12}C$ absorptions in Isobutane

- **Main Background due to Inelastic FSI :**

Λ comes from the Σ conversion on residual nucleons

$$K^- \, {}^4He \to \Sigma(1385)^- \, {}^3He \to \Sigma^0 \pi^- \, {}^3He \qquad \Sigma^0 N \to \Lambda N$$

$$K^- \, {}^4He \to \Sigma^0 \pi^- \, {}^3He \qquad \Sigma^0 N \to \Lambda N$$

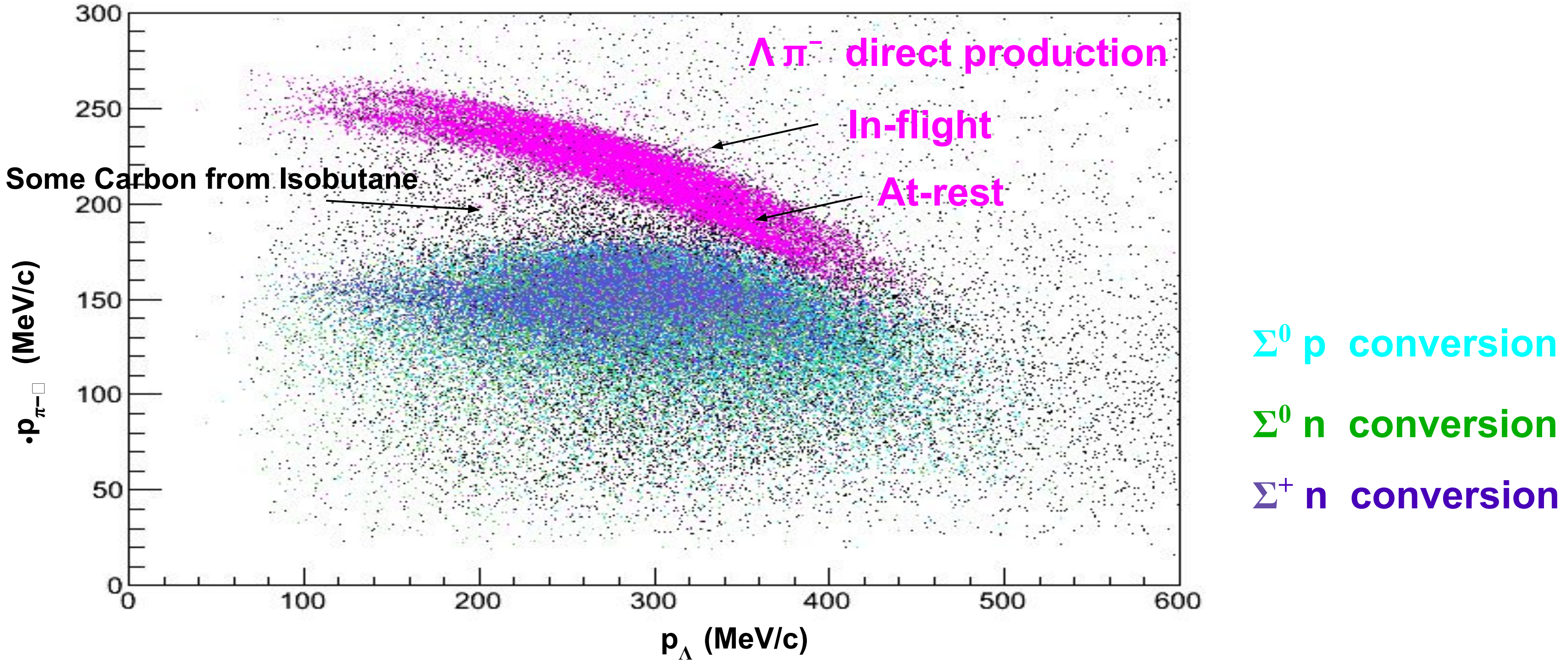
$$K^- \, {}^4He \to \Lambda(1405)(\Sigma(1385)^0) \, {}^3H \to \Sigma^+ \pi^- \, {}^3H \qquad \Sigma^+ n \to \Lambda p$$

$$K^- \, {}^4He \to \Sigma^+ \pi^- \, {}^3H \qquad \Sigma^+ n \to \Lambda p.$$

- **also Λ can follow a primary Σ^0 decay**

- **contribution of elastic FSI rescattering of Λ or π^- on the residual is found to introduce global 3% correction on the amplitude modulus**

All the involved non-direct production processes were calculated and introduced in KLOE MC simulation:



contamination of the $\Lambda\pi^-$ sample due to events from $K^-\,^{12}C$ absorptions in Isobutane (90% He, 10% C_4H_{10}):

- $K^-\,^{12}C$ DATA in the KLOE DC wall are used
- estimated contribution:

$$\frac{N_{K-^4He}}{N_{K-^{12}C}} = \frac{n_{^4He}\,\sigma_{K-^4He}\,BR_{K-^4He}(\Lambda\pi^-)}{n_{^{12}C}\,\sigma_{K-^{12}C}\,BR_{K-^{12}C}(\Lambda\pi^-)}$$

$$\%(K^-\,^{12}C) = 0.44 \pm 0.13$$

- Λ and π^- momentum resolutions checked for this sample to be comparable with the the gas sample
- uncertainty introduced by the geometric vertex cut considered in the systematic

Fit of the measured distributions

Strategy of the analysis: compare the measured rate of the resonant over non resonant $\Lambda\pi^-$ production to the theoretical prediction, from which to extract the modulus of the non resonant amplitude below threshold, exploiting K- absorption on a bound neutron

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

how much below the threshold?

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

33 ± 6 MeV below threshold

see also

A. Cieply et al., Phys. Lett. B 702 (2011) 402, T. Hoshino et al., Phys. Rev. C 96 (2017) 045204
N. Barnea, E. Friedman, A. Gal, Nucl. Phys. A968 (2017)

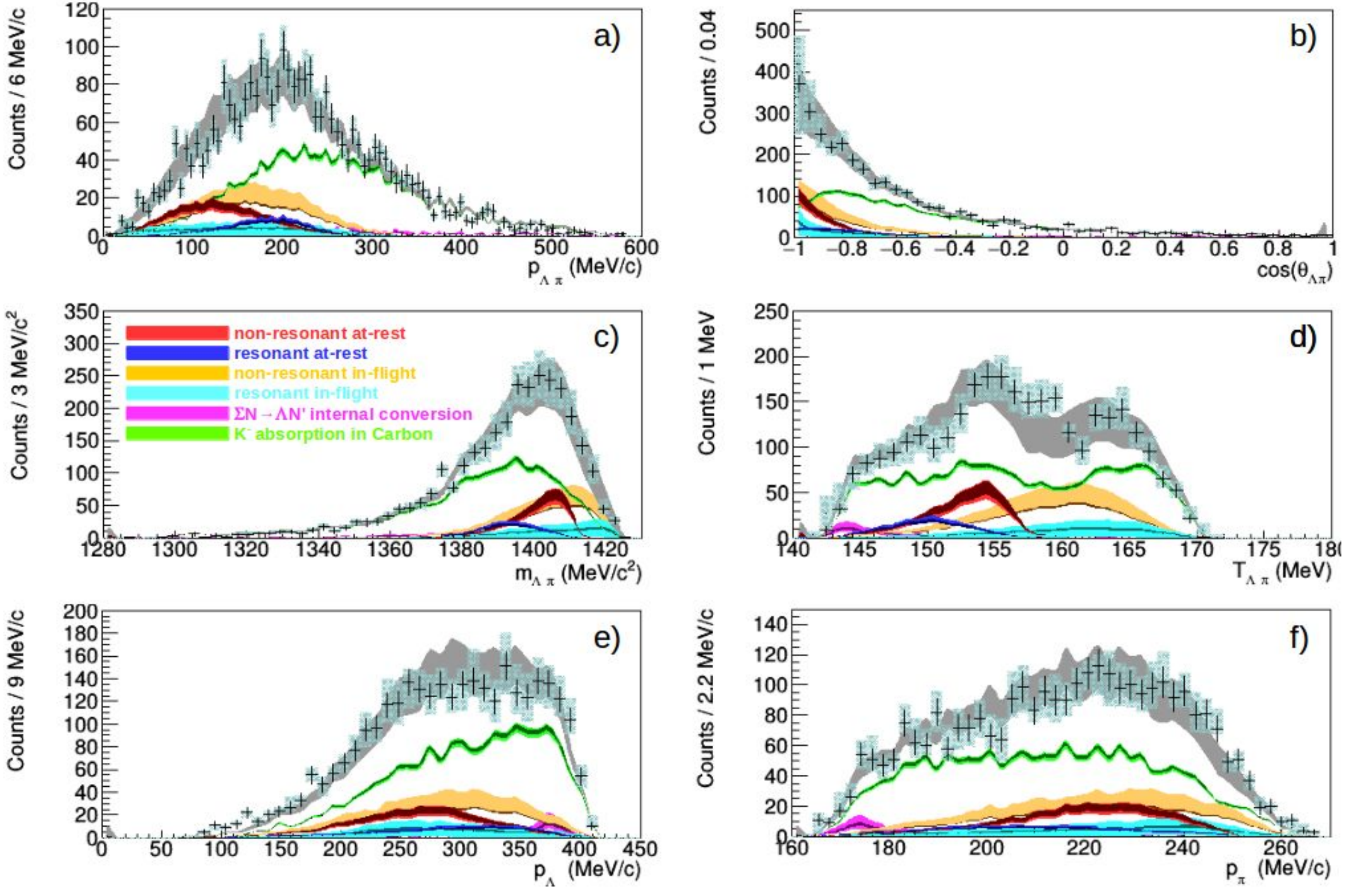
Fit of the measured distributions

The $p_{\Lambda\pi}$, $m_{\Lambda\pi}$ and $\cos(\theta_{\Lambda\pi})$ measured spectra are fitted simultaneously with the following contributions:

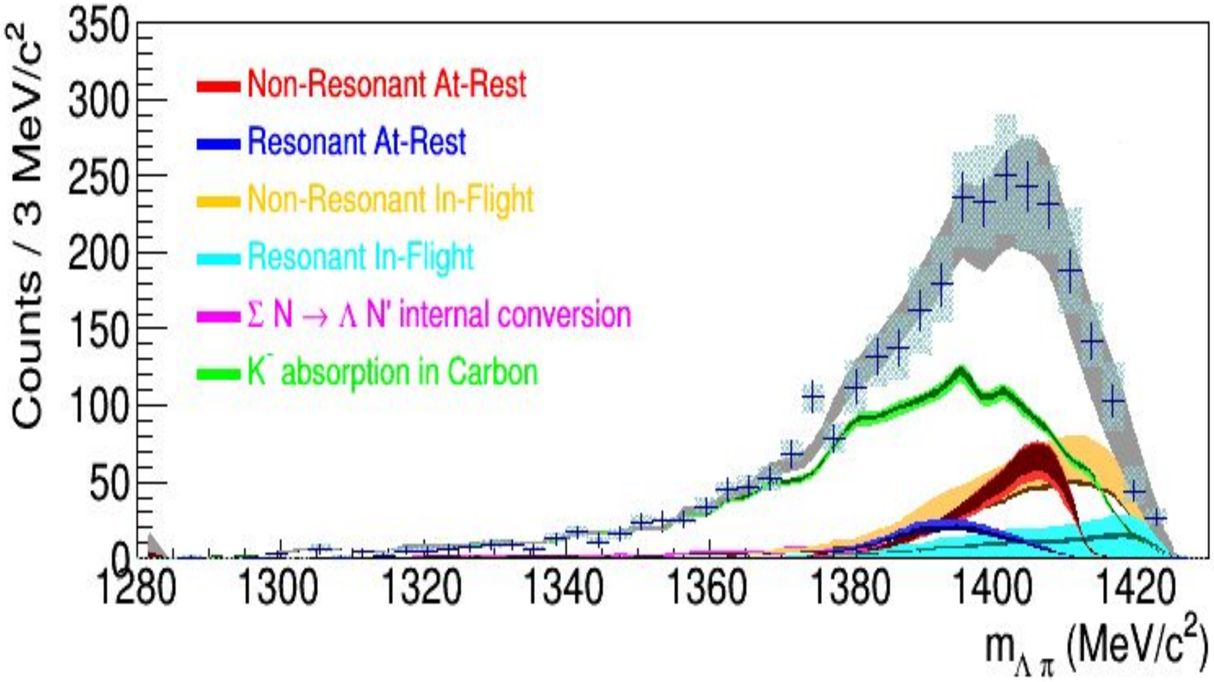
- non-resonant K^- capture at-rest from atomic S states in ^{4}He,
- resonant K^- capture at-rest from atomic S states in ^{4}He,
- non-resonant K^- capture in-flight in ^{4}He,
- resonant K^- capture in-flight in ^{4}He,
- primary $\Sigma\pi^-$ production followed by the Σ N $\rightarrow$ Λ N' conversion process,
- K^- capture processes in ^{12}C giving rise to $\Lambda\pi^-$ in the final state.

We also confirmed the contribution of the K- captures at-rest from atomic P states to be negligibly small.

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



Results of the analysis



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

Results of the analysis

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

$$= |f_{ar}^{nr}|^2 \cdot 8.94 \cdot 10^5 \mathrm{MeV}^2 \,,$$

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

$E = -33$ MeV	$0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\mathrm{syst}$
$p_{lab} = 120$ MeV	0.33 ± 0.11
$p_{lab} = 160$ MeV	0.29 ± 0.10
$p_{lab} = 200$ MeV	0.24 ± 0.06
$p_{lab} = 245$ MeV	0.28 ± 0.02

To be compared with the corresponding values extracted from cross section measurements

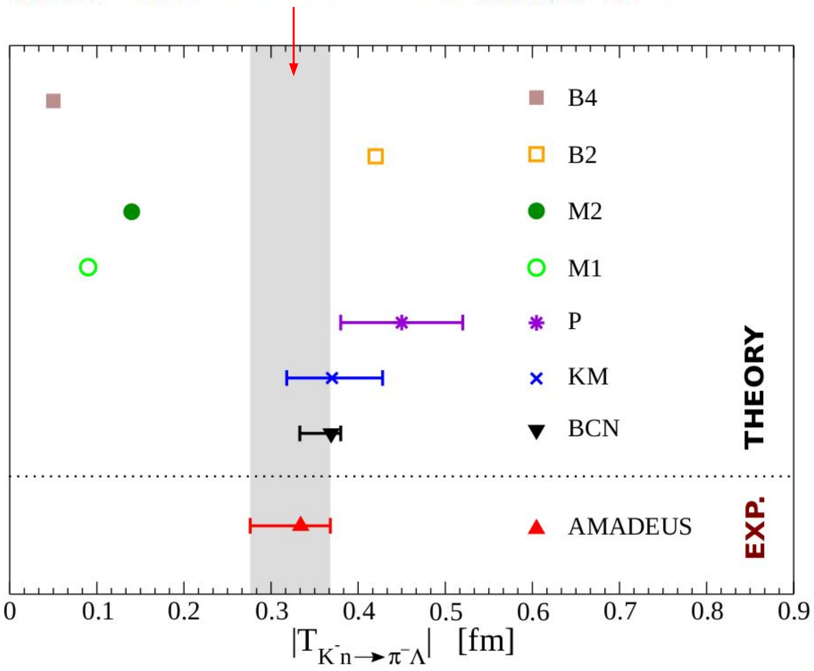
TABLE II. The S-wave non-resonant amplitude ($|f^{nr}|$ fm) extracted from $K^-p \to \Lambda\pi^0$ scattering [34, 35] and from this experiment ($E = -33$ MeV).

J. K. Kim, Columbia University Report, Nevis 149 (1966)
J. K. Kim, Phys. Rev. Lett. 19 (1977) 1074

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

Results of the analysis

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



Comparison with theoretically predicted real and imaginary parts of the non resonant, coupled channels, $K^-n \to \Lambda\pi/\Sigma\pi$ scattering amplitudes:

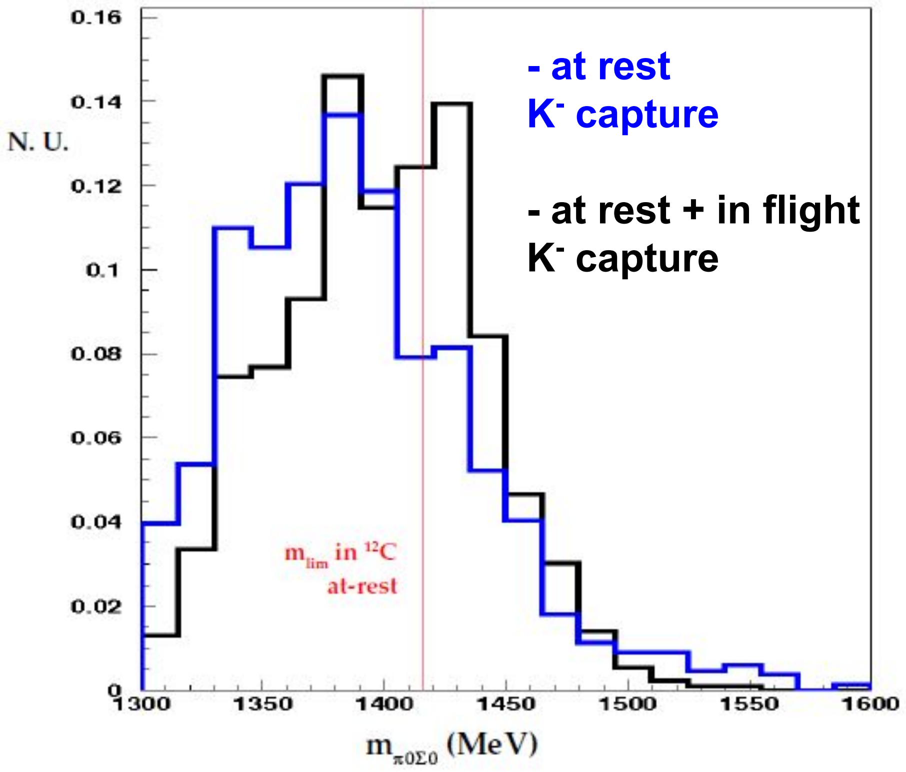
- for each model $|A_{K-n}|$ is calculated at 33 MeV below the KbarN threshold
- $|A_{K^-n\to\Lambda\pi^-}|$ is extracted from $|A_{K-n}|$ by calculating the probability ratios:

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

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

With gratitude,

and the wish this story will continue long

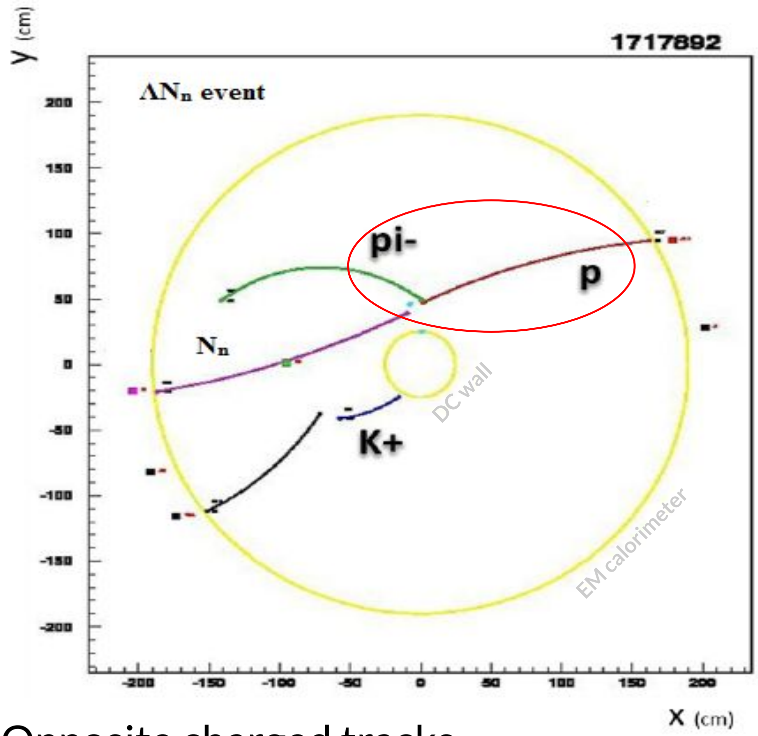


measured channel:
$K^- p \rightarrow \Sigma^0 \pi^0$
(bound proton in ^{12}C)

for the extraction of the
$\Lambda(1405)$ shape

Λ(1116) identification

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



Opposite charged tracks
with common vertex