The (K^{-},p) reaction on nuclei with in-flight kaons

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The claimed experimental evidences of deeply bound K^- nuclear states (B_K ~ 100 MeV) are difficult to reconcile with state-of-the-art theoretical calculations that use *realistic* Kbar N interactions

- ✓ reproduce Kbar N free scattering data
- ✓ (possibly) implement chiral dynamics

(W. Weise's talk)

The observed peaks in nuclear reactions using slow kaons:

1. (K^-_{stop}, p)
2. (K^-_{stop}, Λp) M. Agnello et al. Phys. Rev. Lett. 94, 212303 (2005)
   T. Suzuki et al., Mod. Phys. Lett. A23, 2520 (2008)
3. (K^-_{stop}, Λd) M. Agnello et al. Phys. Lett. B654, 80 (2007)
   T. Suzuki al. Phys. Rev .C76, 068202 (2007)

can be explained in terms of conventional input that combines:

a) an absorption mechanism

$K^-NN \rightarrow \Lambda N$ (in 1. and 2.) E. Oset, H. Toki, Phys. Rev. C74, 015207 (2006)

$K^-NNN \rightarrow \Lambda d$ (in 3.) V.K. Magas, E. Oset and A. Ramos, Phys. Rev C77, 065210 (2008)

b) nuclear medium effects:

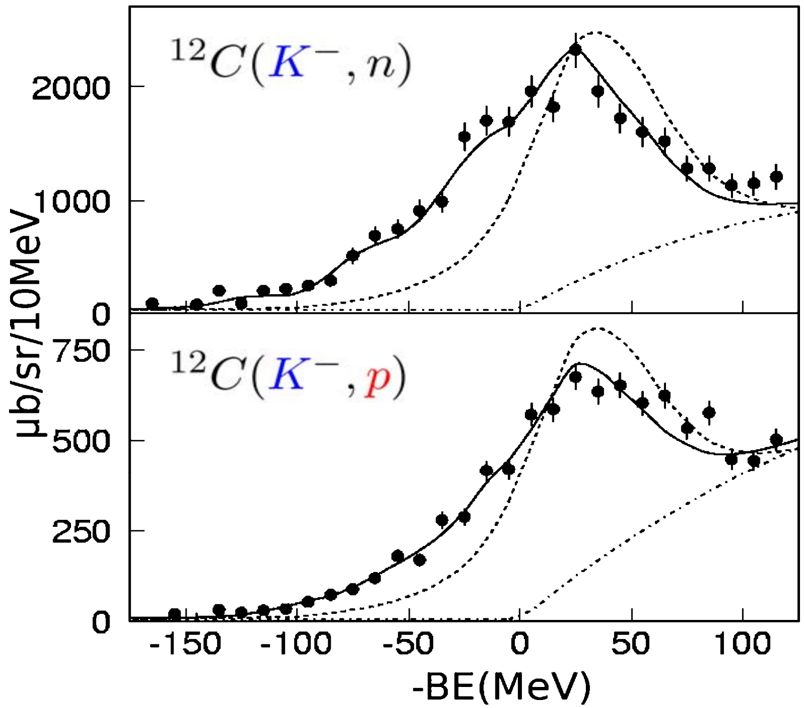
Fermi motion/recoil V.K. Magas, E. Oset, A. Ramos and H. Toki, Nucl.Phys. A804, 219 (2008)
(→direct reaction peaks broaden)

FSI of the emitted particles (if daughter nucleus is big enough)
(→ secondary peaks/structures may appear)
V.K. Magas, E. Oset, A. Ramos and H. Toki, Phys. Rev. 74 (2006) 025206

Another "evidence" for a very deeply attractive K- nucleus potential:

The (K^-,p) reaction on ^{12}C at KEK

T. Kishimoto et al., Prog. Theor. Phys. 118 (2007) 181



$$K^- + ^{12}C \rightarrow p + X$$

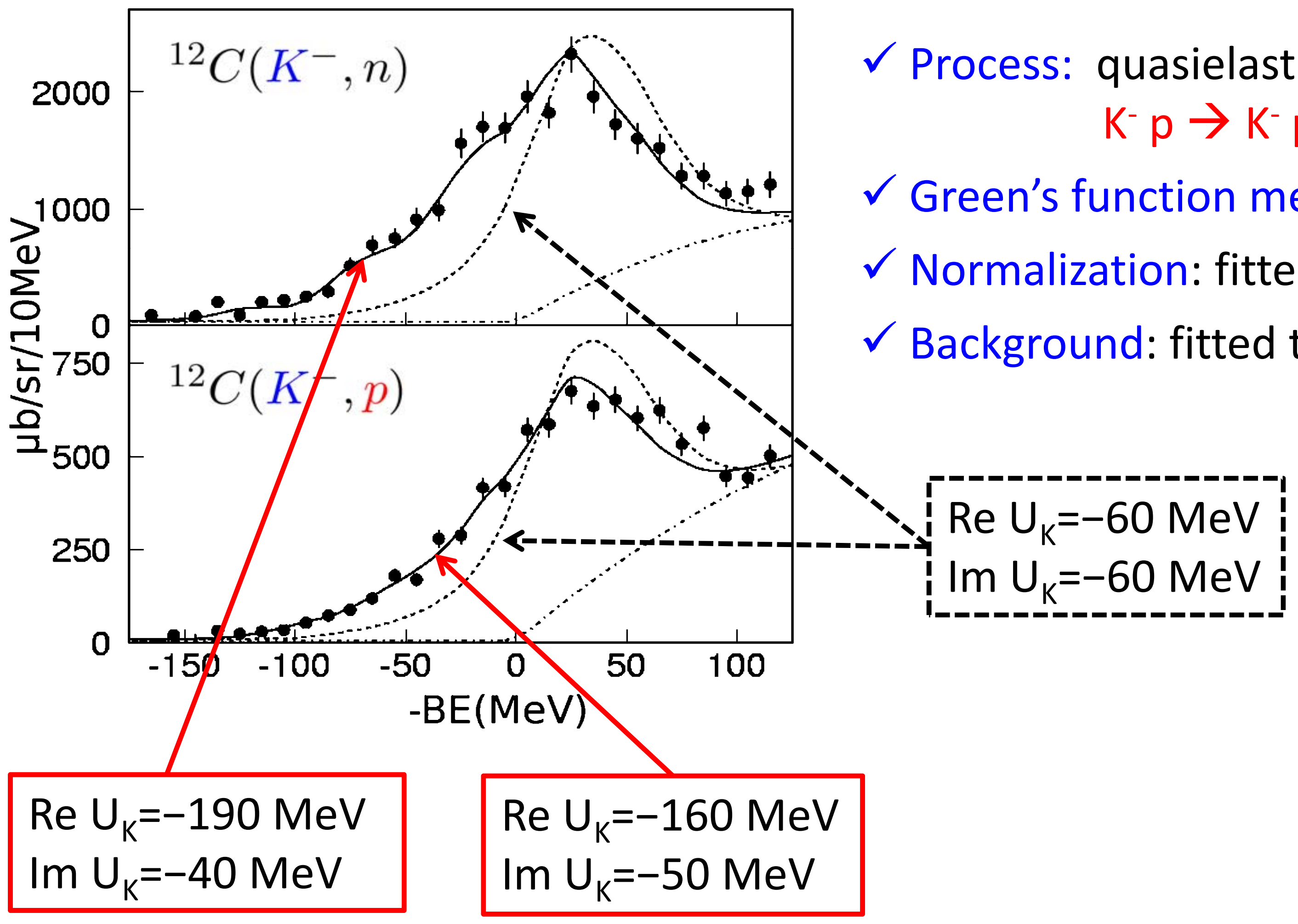
p_K = 1 GeV/c → in-flight kaons

$\theta_p < 4.1^o$ → forward nucleons (the most energetic)

plus "coincidence requirement": (at least one charged particle in decay counters surrounding the target) claimed not to affect the spectrum shape

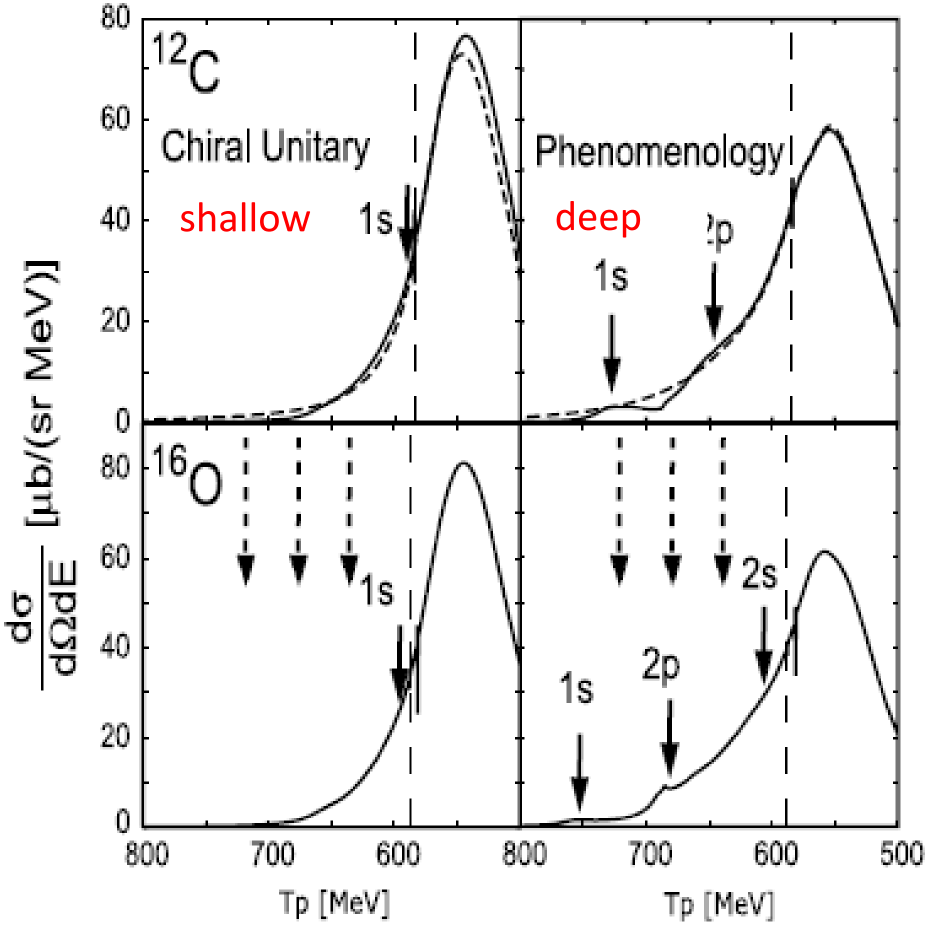
$$-E_B = \sqrt{(E_K + M_{^{12}C} - E_p)^2 - (\vec{p}_K - \vec{p}_p)^2} - M_{^{11}B} - M_K$$

Analysis of **T. Kishimoto et al., Prog. Theor. Phys. 118 (2007) 181**



- ✓ Process: quasielastic scattering $K^- p \rightarrow K^- p$ in nuclei
- ✓ Green's function method
- ✓ Normalization: fitted to experiment
- ✓ Background: fitted to experiment

J. Yamagata, H. Nagahiro and S. Hirenzaki, Phys.Rev. C74, 014604 (2006)



The (K- ,p) reaction on nuclei with in-flight kaons

The only mechanism for fast proton emission in the Green's function method is the quasielastic process $K^- p \rightarrow K^- p$ where the low-energy kaon in the final state feels a nuclear optical potential and can occupy stable orbits (no width), unstable orbits, or be in the continuum (quasifree process)

However, there are other mechanisms that can contribute:

- **Multistep processes:**

K^- and/or N undergo secondary collisions as they leave the nucleus

- **One-nucleon absorption**:

$K^- N \rightarrow \pi \Lambda$ and $K^- N \rightarrow \pi \Sigma$
followed by decay of Λ or Σ into π p

- **Two-body absorption:**

$K^- N N \rightarrow \Sigma N$ and $K^- N N \rightarrow \Lambda N$
followed by hyperon decays

	Process		T_p [MeV]
1	$K^- pp \to \Lambda ⓟ$		798.89
2	$K^- NN \to \Sigma ⓟ$		749.32
3	$K^- NN \to N\Sigma$	$\Sigma \to \pi ⓟ$	816.59
4	$K^- pN \to N\Lambda$	$\Lambda \to \pi^- ⓟ$	785.94
5	$K^- p \to \pi^- \Sigma^+$	$\Sigma^+ \to \pi^0 ⓟ$	644.71
6	$K^- p \to \pi^0 \Lambda$	$\Lambda \to \pi^- ⓟ$	610.35
7	$K^- p \to \pi^- \Sigma^+$	$\pi^- pp \to n ⓟ$	678.67
8	$K^- p \to \pi^0 \Sigma^0$	$\pi^0 pN \to N ⓟ$	676.16
9	$K^- p \to \pi^+ \Sigma^-$	$\pi^+ nN \to N ⓟ$	671.47
10	$K^- p \to \pi^0 \Lambda$	$\pi^0 pN \to N ⓟ$	756.78

Taken from J. Yamagata and S. Hirenzaki,
Eur. Phys. J. A 31, 255{262 (2007)

We implement these processes in a Monte Carlo simulation of K^- absorption in nuclei

Monte Carlo simulation

- The nucleus is described by a nuclear density profile $\rho(r)$

- The incoming K^- will experience a certain process (quasielastic, one-nucleon or two-nucleon absorption) at a point *r* with a probability given by $\sigma_{qe}\,\rho\,\delta l$, $\sigma_{1N}\,\rho\,\delta l$ or $\sigma_{2N}\,\rho\,\delta l$ where δl is a typical step size.

- Once a process has been decided, we determine the local momenta of the emitted particles according to phase space

- Further collisions of the emitted particles as they cross the nucleus are considered according to the probability that they collide with nucleons.
  We follow: the K- until it leaves the nucleus or gets absorbed
  all energetic nucleons (until they leave the nucleus)
  all energetic Λ and Σ (until they leave the nucleus and decay into

- Finally, we represent the spectra of the emerging protons

Cross sections: → taken from the PDG

Quasielastic scattering

$$K^- p \to K^- p \qquad K^- p \to \bar{K}^0 n \qquad K^- n \to K^- n$$

$$\sigma_{K^-p\to K^-p} = 21.22\ \mathrm{mb}\,, \quad \sigma_{K^-p\to K^0 n} = 7.15\ \mathrm{mb}\,, \quad \sigma_{K^-n\to K^-n} = 18.5\ \mathrm{mb}$$

One-nucleon absorption

$$K^- N \to \pi\Lambda \qquad K^- N \to \pi\Sigma$$

(and all possible charge combinations)

$$\sigma_{K^-p\to\pi^0\Lambda} = 4.32\ \mathrm{mb}\,, \quad \sigma_{K^-p\to\pi^+\Sigma^-} = 1.76\ \mathrm{mb}$$

$$\sigma_{K^-p\to\pi^-\Sigma^+} = 1.4\ \mathrm{mb}\,, \quad \sigma_{K^-p\to\pi^0\Sigma^0} = 1.58\ \mathrm{mb}$$

$$\sigma_{K^-n\to\pi^-\Lambda} = 6.35\ \mathrm{mb}\,, \quad \sigma_{K^-n\to\pi^-\Sigma^0} = 0.97\ \mathrm{mb}\,, \quad \sigma_{K^-n\to\pi^0\Sigma^-} = 1.15\ \mathrm{mb}$$

$$\sigma^{\mathrm{total}}_{K^-p} = 51.7\ \mathrm{mb}\,, \quad \sigma^{\mathrm{total}}_{K^-n} = 38\ \mathrm{mb}$$

Two-nucleon absorption

$K^- NN \rightarrow \Lambda N$ $K^- NN \rightarrow \Sigma N$ (and all possible charge combinations)

We assume:

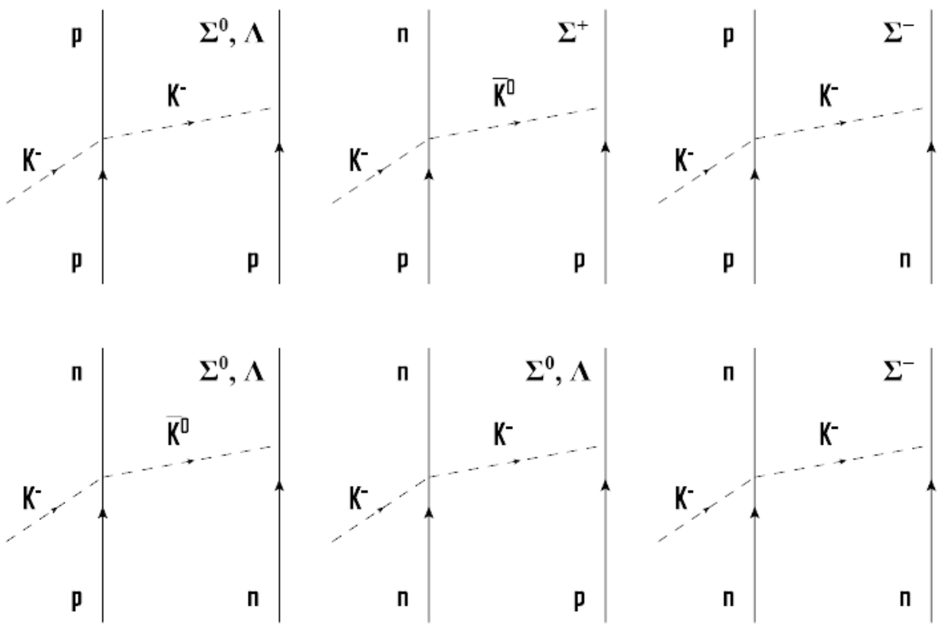
1. A probability per unit length for two-body absorption given by:

$P_{KNN} = C_{abs}\,\rho^2$ $C_{abs} \sim 6\ \mathrm{fm}^5$

(2N-absorption is 20% of 1N-absorption)

P.A. Katz et al, Phys.Rev.D 1, 1267 (1970)

2. Partial widths for the various channels according to a microscopic K-meson exchange picture



$K^- pp \to p\Sigma^0$	$A\,\sigma_{K^-p\to K^-p} \times \left(\frac{D-F}{2f}\right)^2$
$K^- pp \to p\Lambda$	$A\,\sigma_{K^-p\to K^-p} \times \frac{1}{3}\left(\frac{D+3F}{2f}\right)^2$
$K^- pp \to n\Sigma^+$	$A\,\sigma_{K^-p\to \bar{K}^0 n} \times 2\left(\frac{D-F}{2f}\right)^2$
$K^- pp \to p\Sigma^-$	$A\,\sigma_{K^-p\to K^-p} \times 2\left(\frac{D-F}{2f}\right)^2$
$K^- pn \to \Sigma^0 n$	$A\,\sigma_{K^-p\to \bar{K}^0 n} \times \left(\frac{D-F}{2f}\right)^2$
$K^- pn \to \Lambda n$	$A\,\sigma_{K^-p\to \bar{K}^0 n} \times \frac{1}{3}\left(\frac{D+3F}{2f}\right)^2$
$K^- np \to \Sigma^0 n$	$A\,\sigma_{K^-n\to K^-n} \times \left(\frac{D-F}{2f}\right)^2$
$K^- np \to \Lambda n$	$A\,\sigma_{K^-n\to K^-n} \times \frac{1}{3}\left(\frac{D+3F}{2f}\right)^2$
$K^- nn \to n\Sigma^-$	$A\,\sigma_{K^-n\to K^-n} \times 2\left(\frac{D-F}{2f}\right)^2$

Kaon optical potential:

The antikaon is assumed to have a mass distribution

$$S_K(\tilde{M}_K) = \frac{1}{\pi} \frac{-2M_K \mathrm{Im}\, U_K}{(\tilde{M}_K^2 - M_K^2 - 2M_K \mathrm{Re}\, U_K)^2 + (2M_K \mathrm{Im}\, U_K)^2}$$

which peaks at a mass shifted by Re U_K

$$\tilde{M}_K = M_K + \mathrm{Re}\, U_K$$

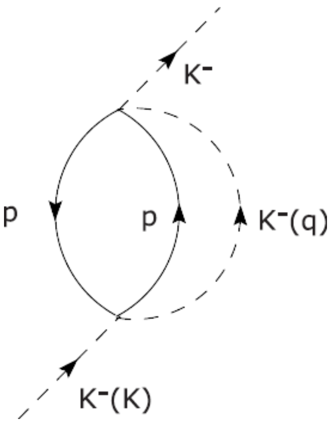
and has a width determined by Im U_K

$$\Gamma = -2\, \mathrm{Im}\, U_K$$

$$-600 \frac{\rho}{\rho_0} < \mathrm{Re}\, U_K < -60 \frac{\rho}{\rho_0}$$
$$\mathrm{Im}\, U_K = -60 \frac{\rho}{\rho_0}$$

Test: quasielastic process

Our simulation is tested by calculating the quasielastic contribution from the direct evaluation of the corresponding many-body Feynman diagram

$\Pi =$ 

$$\mathrm{Im}\,\Pi \rightarrow \sigma$$

Fermi motion

$$\frac{d\sigma}{d\Omega(\hat{p})E(\vec{p})} = -\frac{4p}{\bar{p}^2}\frac{d\sigma}{d\Omega(\hat{p})}\Big|_{\mathrm{lab}}\int d^3\vec{r}\, e^{-\int_{-\infty}^{\infty}\sigma\rho(b,z')dz'}\int\frac{d^3p_N}{(2\pi)^3}n(\vec{p}_N,\vec{r})\frac{M}{E(\vec{p}_N)}\theta(q^0)$$

$$\times[\bar{p}(k^0+M)-E(\bar{p})k]\frac{1}{\pi}\mathrm{Im}\frac{1}{q^{0\,2}-\vec{q}^{\,2}-m_K^2-\Pi(q^0,\vec{q})}\Bigg|^{q^0=k^0+E(\vec{p}_N)-\Delta-E(\vec{p})}_{\vec{q}=\vec{k}+\vec{p}_N-\vec{p}}$$

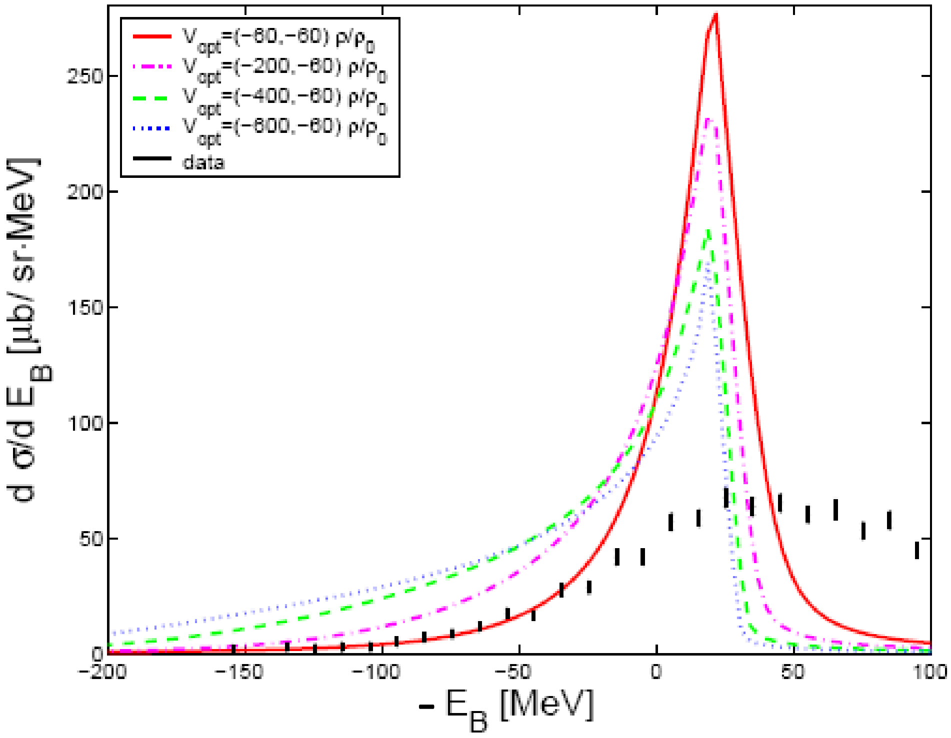
distortion factor
$\sigma_K \sim \sigma_N \sim 40$ mb$=\sigma$

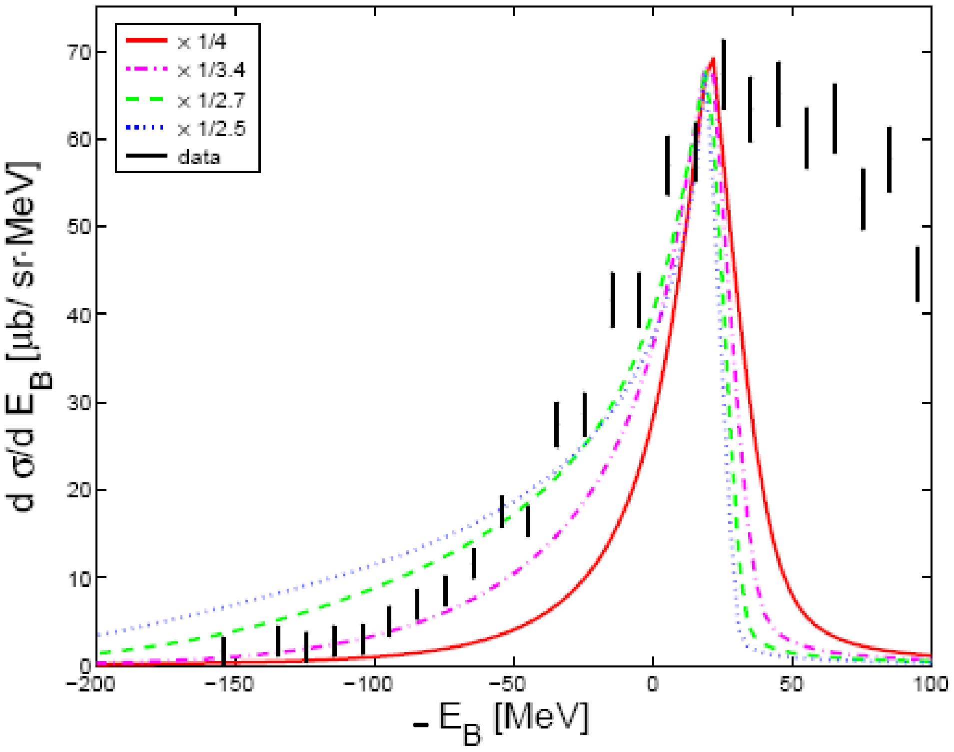
Normalization OK! (without distortions we recover 6 times the elementary differential cross-section)

Results: sensitivity to antikaon optical potential

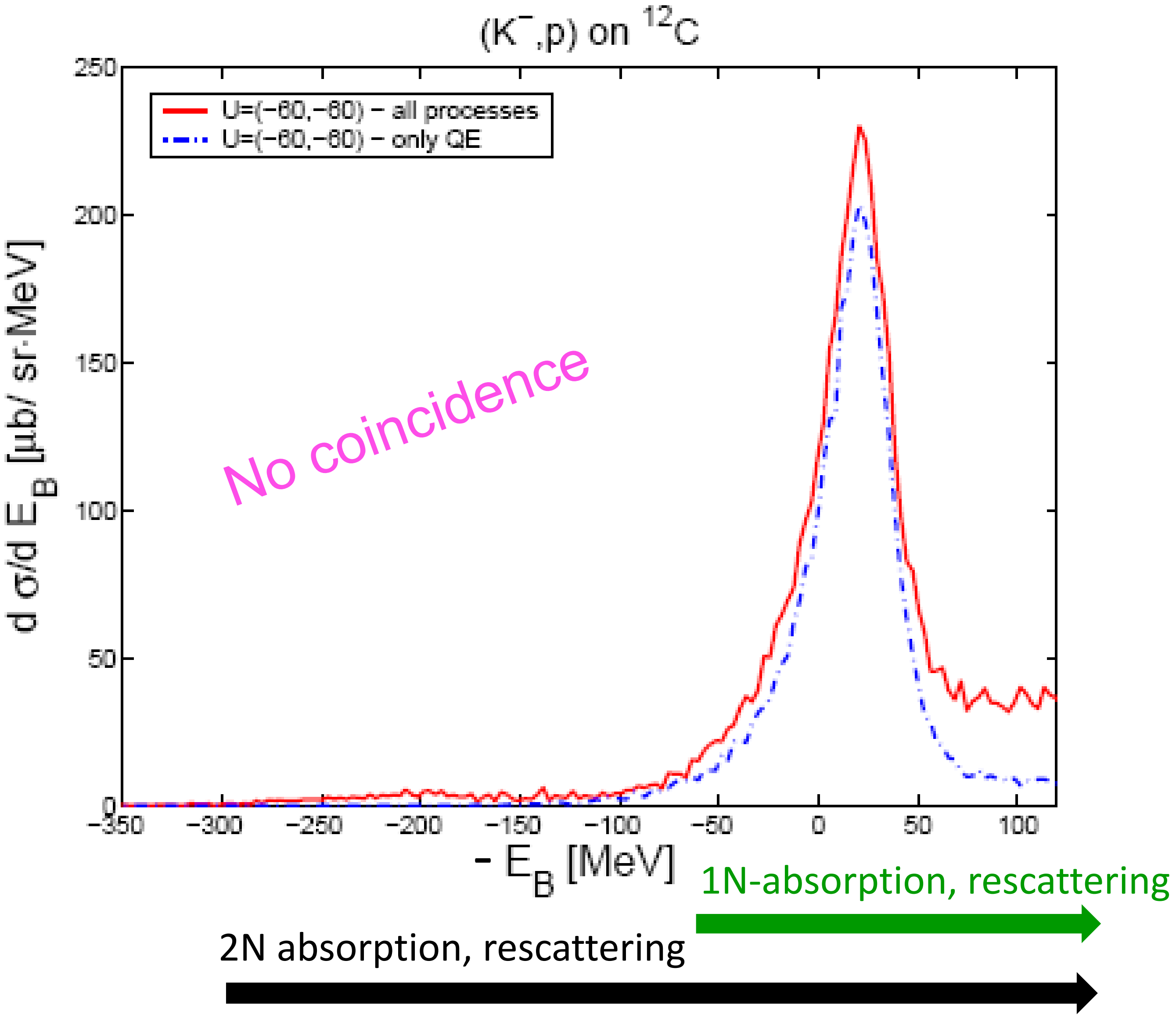
$$\text{Only } K^- p \rightarrow K^- p$$

$$^{12}C(K^-, p)$$





Results: full Monte Carlo calculation



Next: apply the coincidence requirement of the experiment

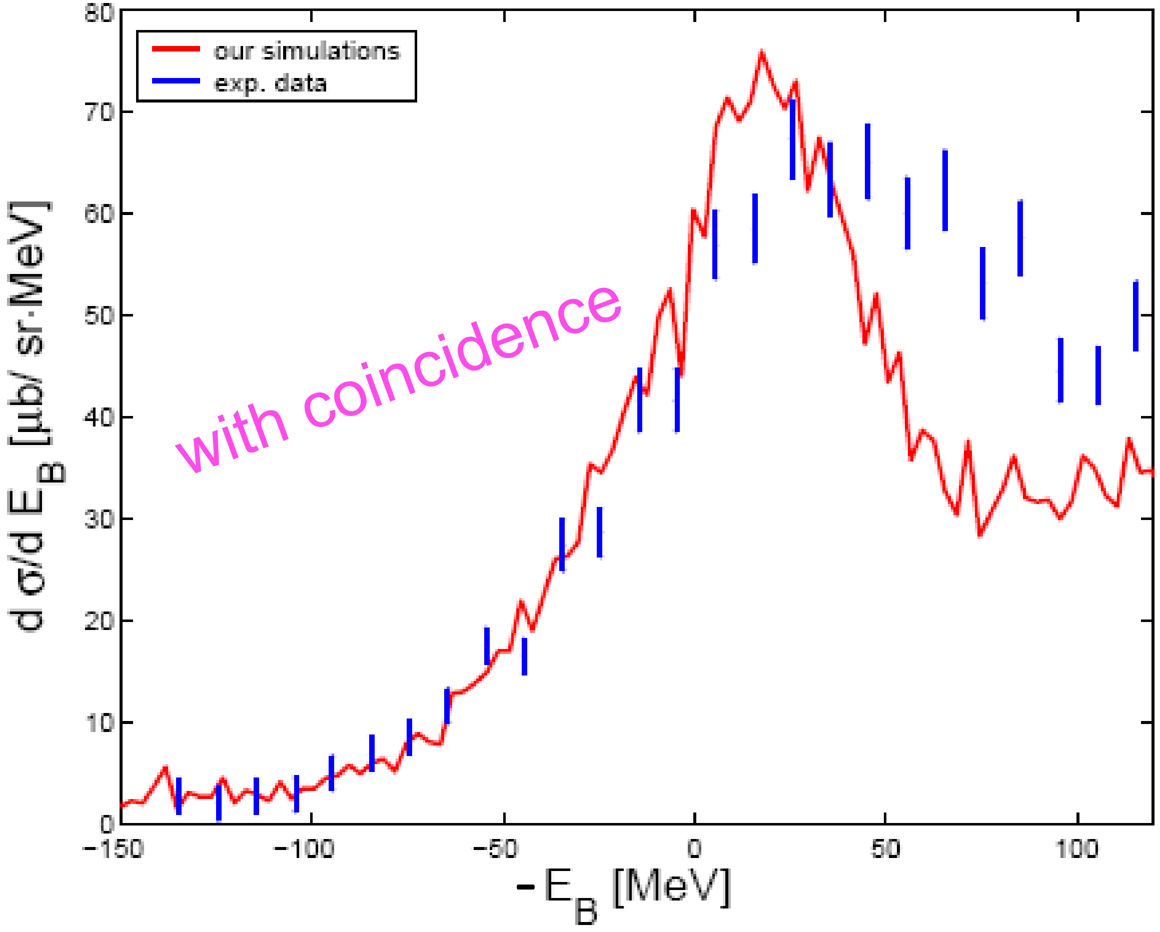
"have at least one charged particle in decay counters surrounding the target"

The simulation of such coincidence requirement is tremendously difficult, because it would imply keeping track of all charged particles coming out from all possible scatterings and decays.

The main source of energetic protons is the K^-N quasielastic scattering process

The best we can do is to eliminate processes that, for sure, cannot have a coincidence: these are the events where neither a proton, nor a K^- have had any other collision than a *primary* quasi-elastic event *with a "good"* (energetic and forward) *proton*. (The negatively charged kaon escapes undetected through the back and cannot produce a coincidence)

$^{12}C(K^-, p)$



The coincidence requirement removes a substantial fraction of events and changes the shape of the spectrum drastically

Conclusions

- The results of the in-flight $^{12}C(K^-,N)$ reaction at KEK (PS-E548) can probably be explained with a conventional kaon potential.

- Actually, the point of our analysis is not to state that the data supports an attraction of -60 MeV instead of ~ -200 MeV.

- We have seen that the coincidence requirement introduces a non-negligible distortion in the spectrum

- This distortion is comparable in size (even bigger) than that produced by different kaon optical potential.

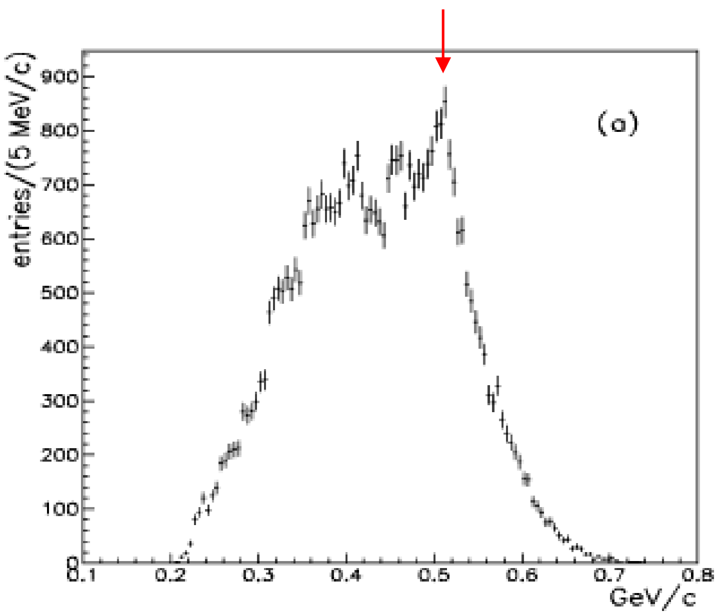
- This is not a good experiment to learn about the size of attraction of the K^- nucleus optical potential.

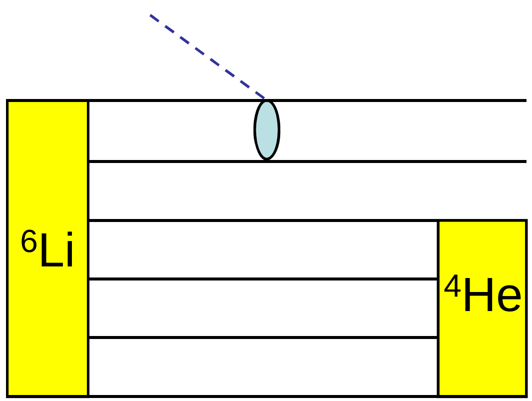
SLIDES NOT SHOWN

The FINUDA proton missing mass experiment:

$^{6}\mathrm{Li}(K^{-}_{\mathrm{stop}}, p)$

M. Agnello et al, Nucl. Phys. A775, 35 (2006)





The FINUDA collaboration observed a peak in the proton missing mass spectrum at ~ 500 MeV/c, (following stopped K^- absorption in ^{6}Li)

A study of the angular correlations (p and Σ^- are emitted back-to-back) allow them to conclude that the reaction:

$$K^- + d \rightarrow p + \Sigma^-$$

in ^{6}Li is the most favorable one to explain their signal

The new KEK proton missing mass spectrum:

M. Sato et al., Phys. Lett. B 659 (2008) 107

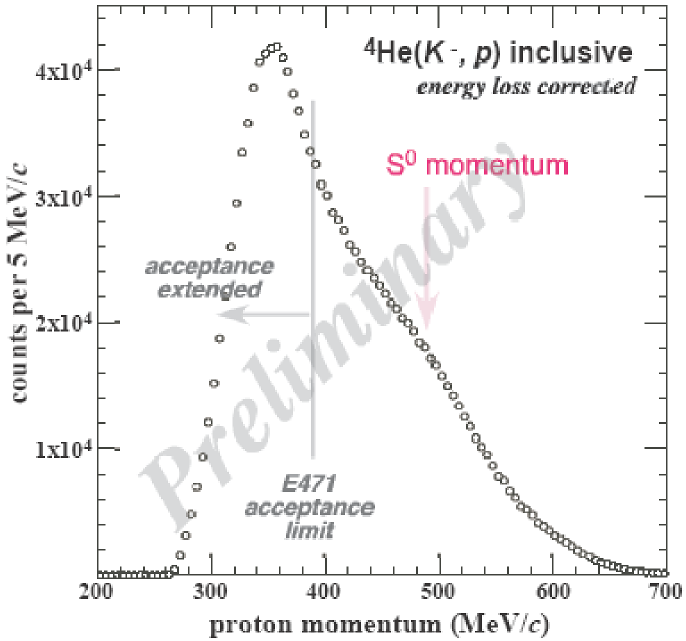
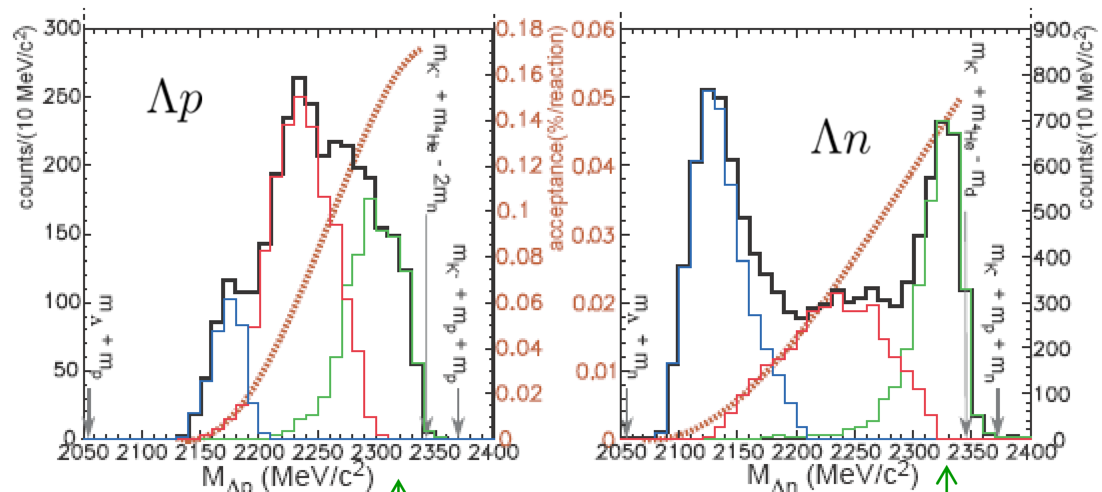


Fig. 3. Inclusive proton momentum spectrum. The proton TOF is measured by the time difference between P_{start} and P_{stop} counters.

$$K^- + {}^4\mathrm{He}$$

and the ΛN correlations:

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



$$K^-pp \rightarrow \Lambda p$$

also $K^-pp \rightarrow (\Sigma^+ n) \rightarrow \Lambda p$

$$K^-pp \rightarrow (\Sigma^0 p) \rightarrow \Lambda p$$

$$K^-pn \rightarrow \Lambda n$$

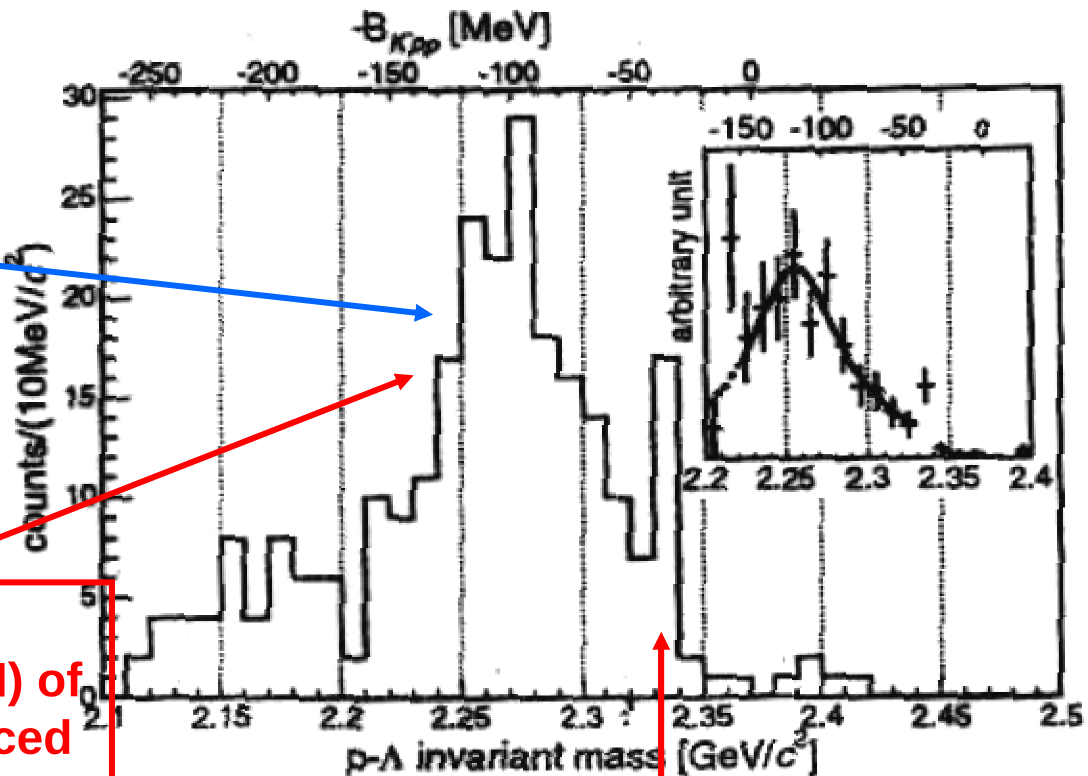
also $K^-pn \rightarrow (\Sigma^- p) \rightarrow \Lambda n$

$$K^-pn \rightarrow (\Sigma^0 n) \rightarrow \Lambda n$$

The FINUDA (Λp) invariant mass experiment

$$(K^-)_{\text{stopped}} \quad {}^AZ_{g.s.} \quad \rightarrow \quad (\Lambda\ p) \quad [A-2]$$

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

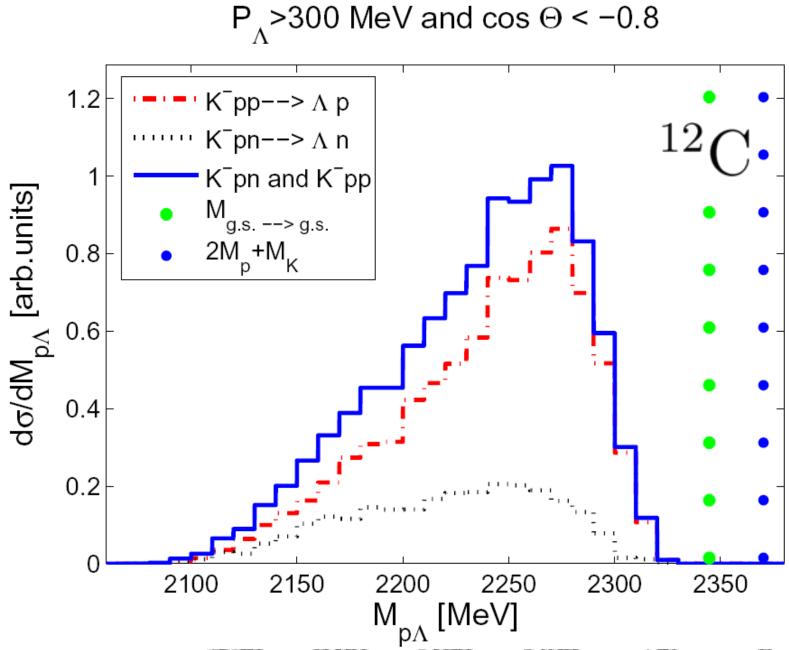


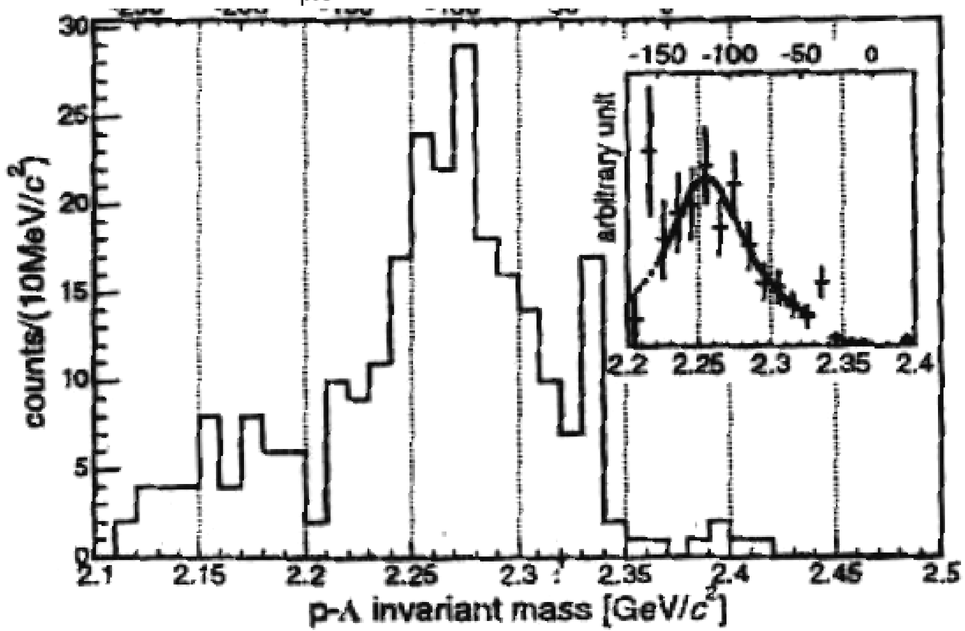
Interpreted by the FINUDA experiment as a (K^-pp) bound state

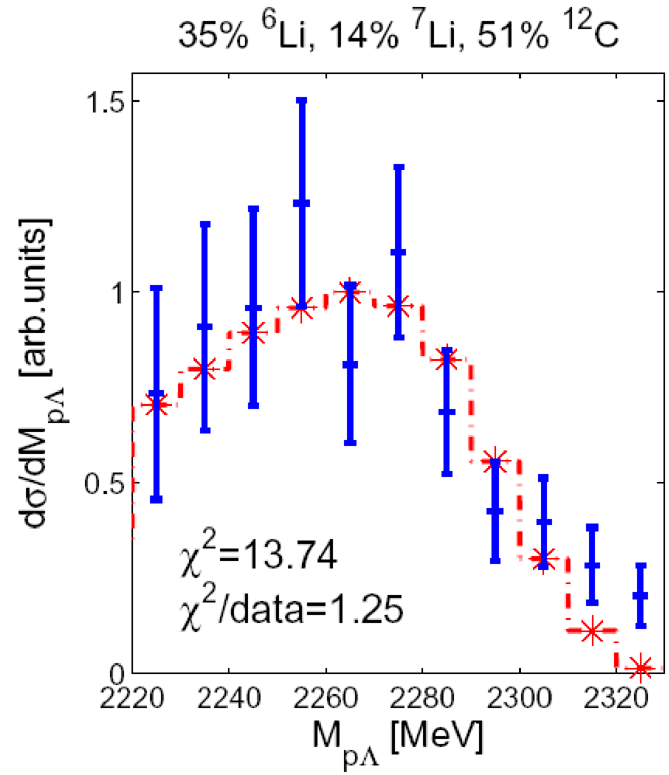
$$B_{K^-pp} = 115^{+6}_{-5}(\text{stat})^{+3}_{-4}(\text{syst})$$

Our view:
Final State Interactions (FSI) of the primary Λ and p (produced after K- absorption) in their way out of the daughter nucleus!

Transition to the g.s. of daughter nucleus







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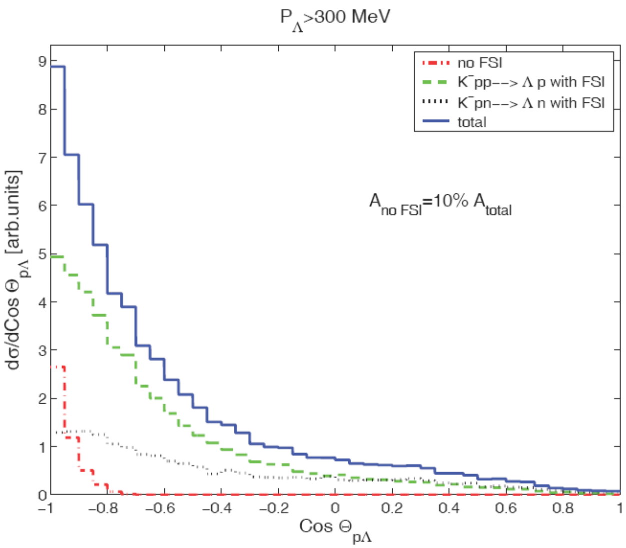
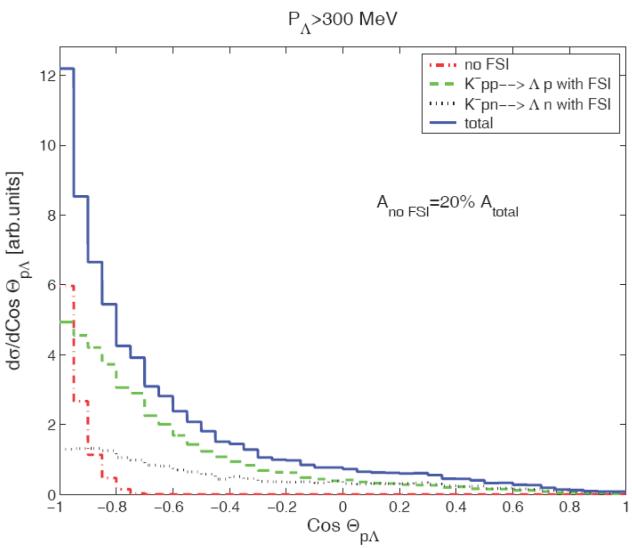
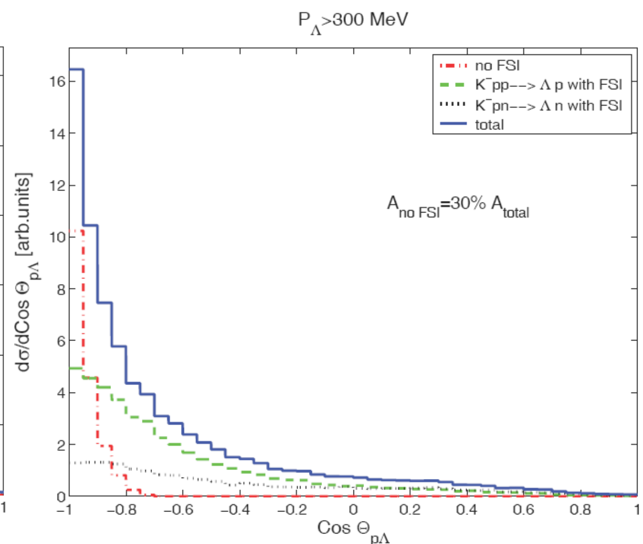
10% 20% 30%





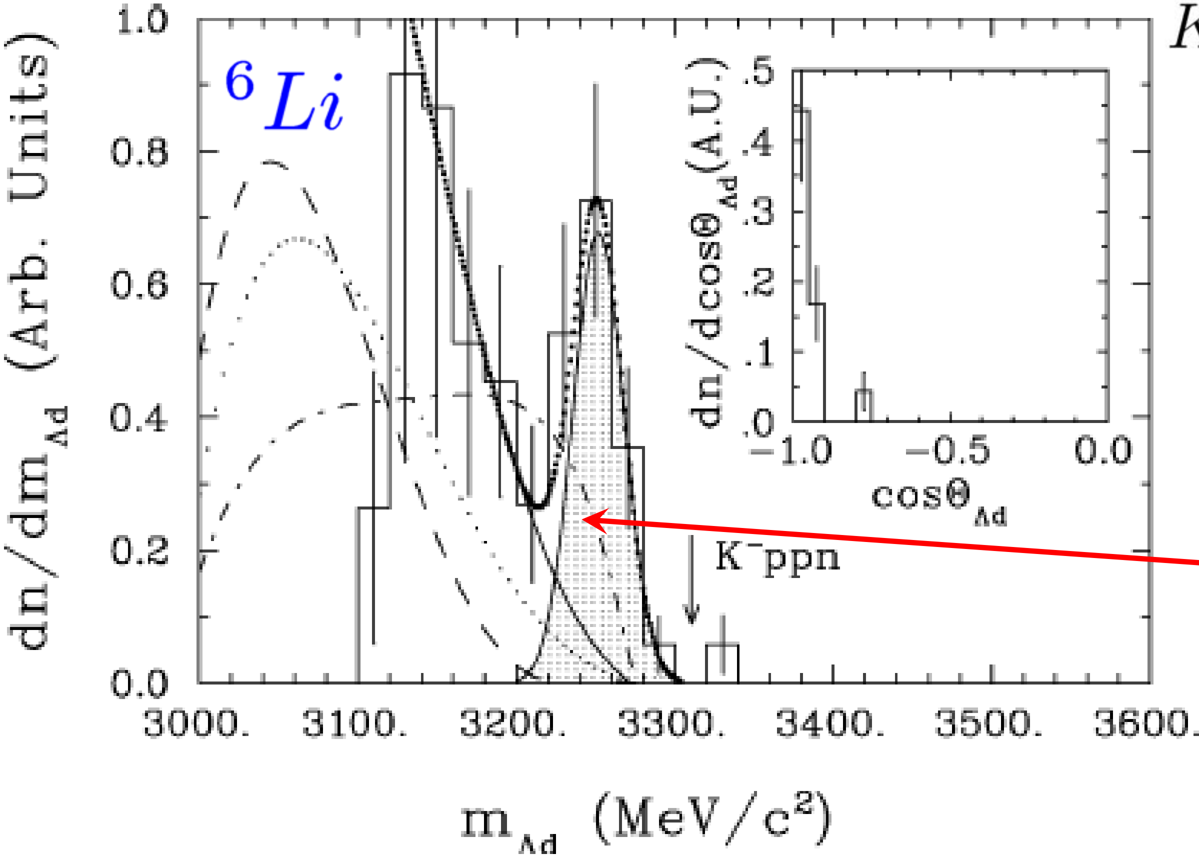


The angular distribution is compatible with the FINUDA Λp data within errors!

The FINUDA (Λd) invariant mass experiment

$$K^-_{\rm stop} A \longrightarrow (\Lambda d) A'$$
$$A = {}^6{\rm Li}, {}^{12}{\rm C}$$

M. Agnello et al. Phys. Lett. B654 (2007) 80-86



$$K^-_{\rm stop}\ {}^6{\rm Li} \longrightarrow (\Lambda\ d)\ [3N]$$
$$[3N] = nnp\ ,\ nd\ ,\ t$$

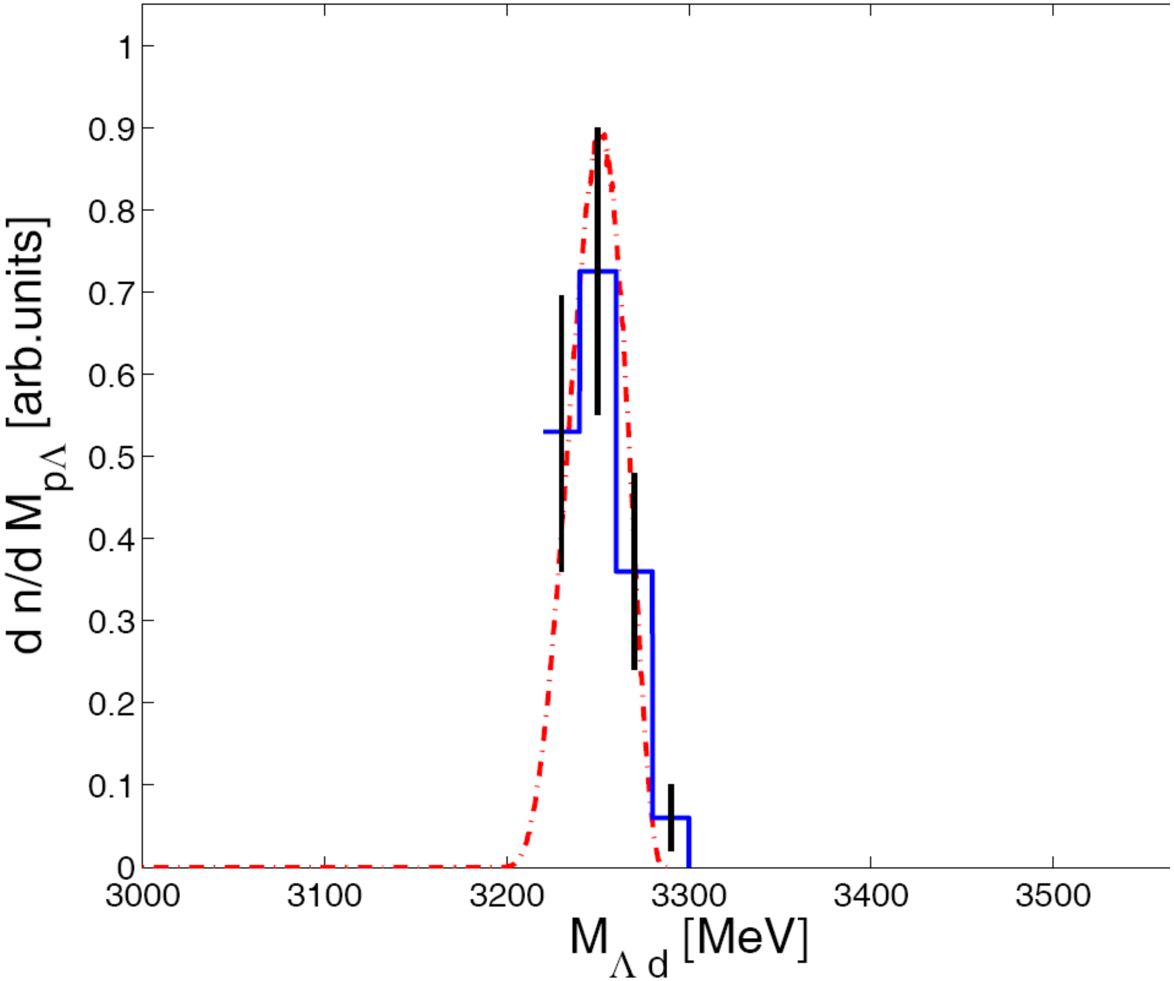
Interpreted as a [K-ppn] bound state with:

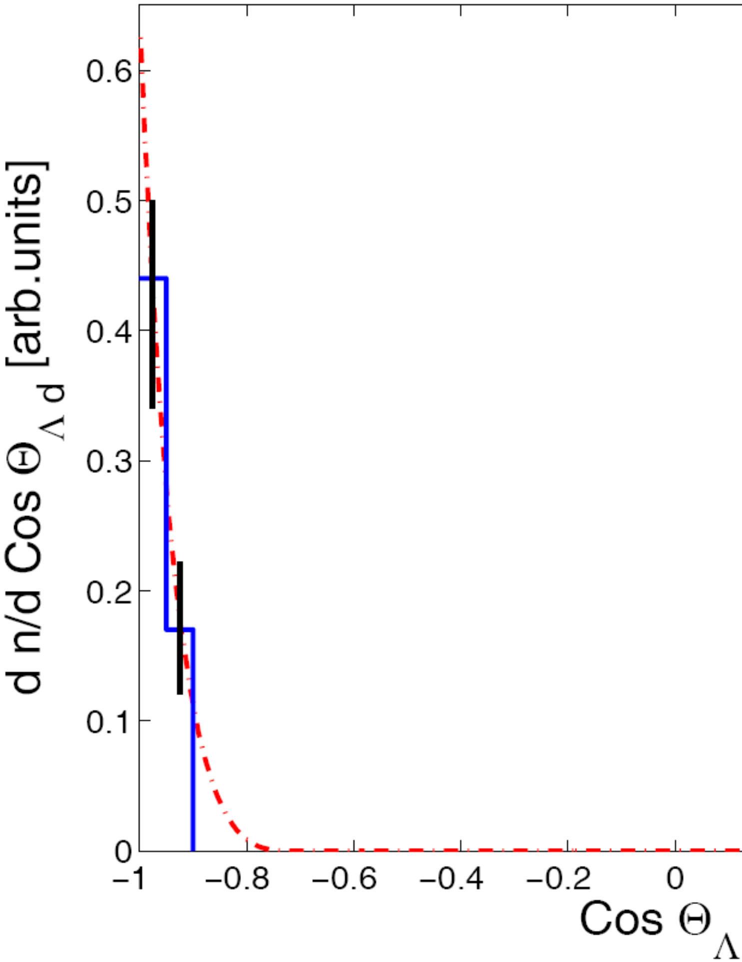
$$B_{K^-ppn} = 58 \pm 6\ {\rm MeV}$$
$$\Gamma_{\Lambda d} = 36.6 \pm 14.1\ {\rm MeV}$$

A simple analysis of Lp and Ld spectra...

Results:

^6Li





Our simple model based on a 3N absorption process can reproduce the FINUDA data

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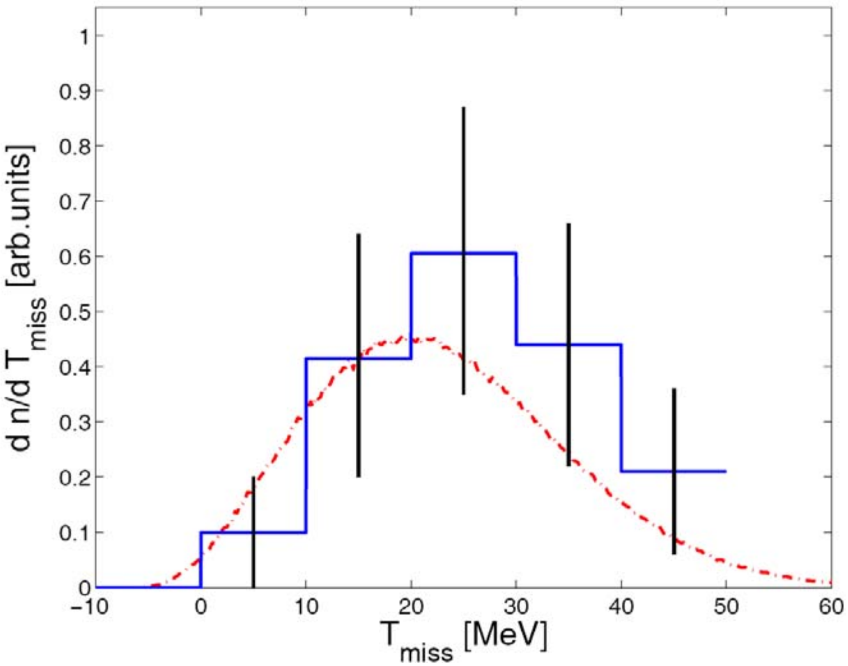
Results:

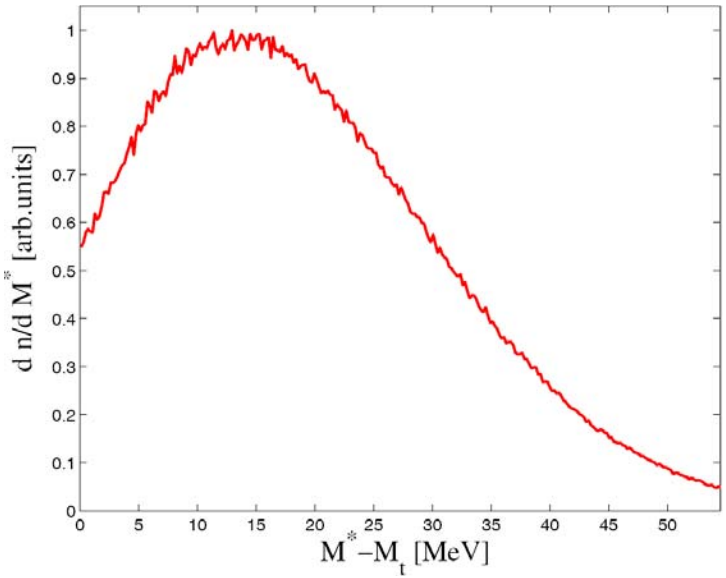
^{6}Li



$$K^-_{\rm stop}\ {}^6\mathrm{Li} \ \rightarrow\ (\Lambda\ d)\ [3N]$$

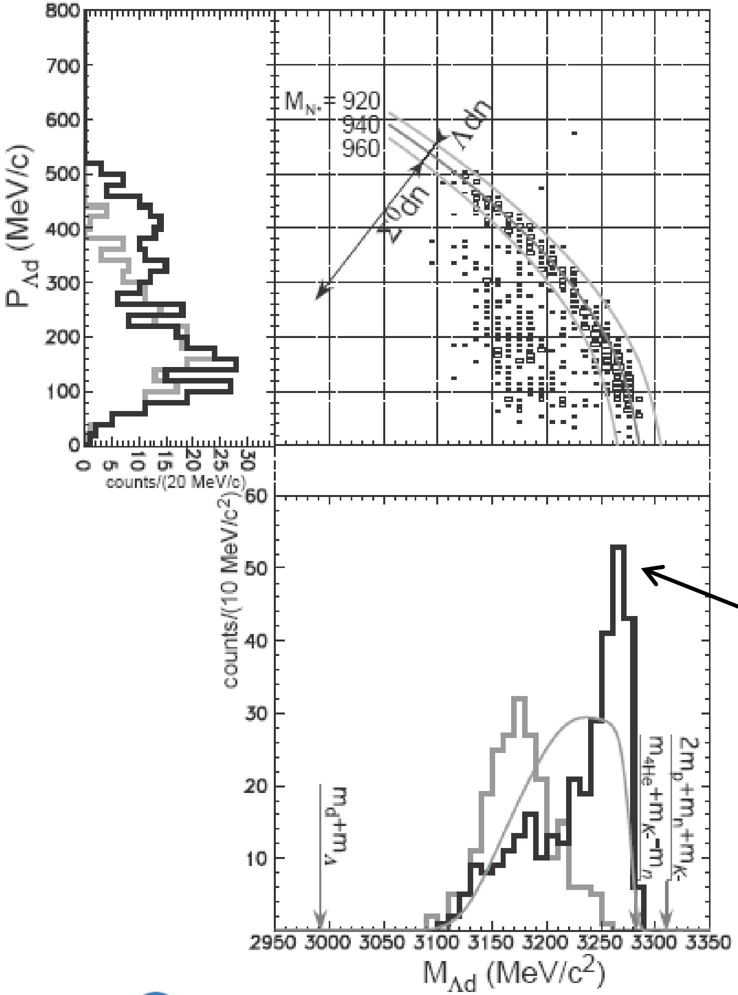
$$[3N] = nnp\ ,\ \ nd\ ,\ \ t$$

$$T_{miss} = m_{K^-} + M_{^6\mathrm{Li}} - m_\Lambda - m_n - $$
$$-2M_d - (T_\Lambda + T_d)$$



$$K^-_{\text{stop}} \quad {}^4\text{He} \quad \rightarrow \quad (\Lambda\ d)\ n$$

T. Suzuki al. Phys. Rev .C76 (2007) 068202



This is the same interpretation that has been given by the **KEK-PS E549** collaboration to explain the peak at $M_{\Lambda d}$ =3282 MeV invariant mass in ^{4}He reactions

Conclusions

Theoretical models seem to converge to a unified description of the ineteraction of antikaons with nucleons.
W.Weise dixit: “It seems unlikely that these models may produce kaonic-nuclear-light systems with binding energies of the order of 100 MeV”

At the moment, most of the signals of deeply bound states can be explained in terms of conventional (phase-space!) physics:
K^- absorption by two or three nucleons leaving the others as spectators

+ Final State Interactions for heavy nuclei !

There are a few cases that require a more extensive analysis of the data, a better correction of efficiencies, and a careful theoretical investigation of all possible “contaminating” channels, before any conclusion on the existence of deeply bound nuclear states can be drawn.

In any case, these K- nuclear reactions are providing us with valuable information for understanding the mechanisms of two- and three-nucleon kaon absorption in nuclei.