The search for bound kaonic states in nuclei, experimental status and theoretical predictions

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Outline of Talk

- Introduction and theoretical overview
- Overview of experimental methods and "evidences"
- Recent experimental results
  - Study of strange systems with two nucleons
  - Study of strange systems with three nucleons
  - Critical revision of experimental results vs theoretical expectations
- Summary and Conclusions

Introduction – theoretical approach

- General understanding of $\bar{K}N$ ($\bar{K}A$) interaction
  - Small binding energies: 10-30 MeV
  - Large decay widths: 80-100 MeV
    - … practically impossible to observe

- Recent theoretical developments:

  – **YES!** DBKS exist as narrow states, they can be experimentally observed

  – **NO!** nuclear-antikaon interaction provides a shallow and wide potential, the $\bar{K}A$ states cannot be observed

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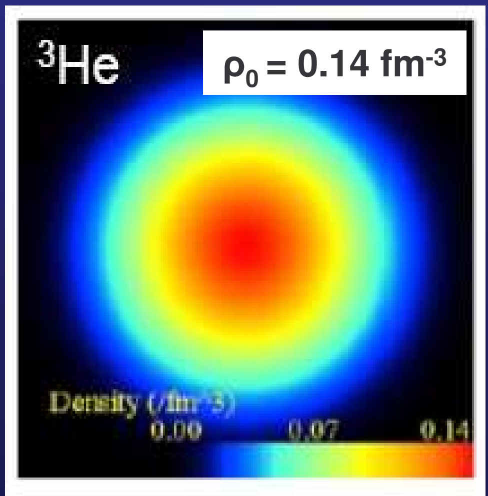
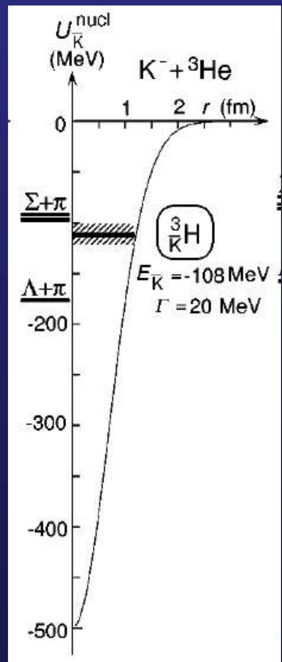
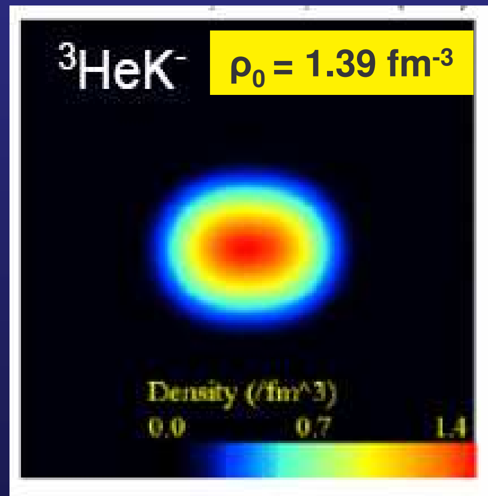
Akaishi & Yamazaki: What a Deeply Bound Kaon Nuclear State is

- Nuclear bound states formed by a single (double) K^- and few nucleons, S = -1
- Deeply bound due to the strength of the $\bar{K}N$ strongly attractive interaction, I = 0
  - Simplest case: ($\bar{K}N$) bound state: Λ(1405)
- The presence of Λ(1405) prevents a reliable perturbative treatment
- More composite states: can be interpreted as molecules formed by Λ(1405)+xN
  - covalent bonding K^--nucleons, much stronger than the nuclear force
  - The Λ(1405) should persist as such in a nuclear system





High nuclear density in a low temperature system !!!



Akaishi & Yamazaki (PLB535(2002), 70; PRC65(2002)…)

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Oset, Weise, Mares …the skeptical side I

- Akaishi-Yamazaki use a G-matrix treatment simplifying some absorption effects, and neglecting some couplings ($\pi\Sigma$, $\pi\Lambda$)

- Common view (Gal, Weise, Schaffner-Bielich, Wychech)
  - K^- -nuclear aggregates existence is not denied, but the potential is shallow the expected widths are large. $\Rightarrow$ possible signals only from heavy systems

- Microscopic chiral approach (Ramos, Oset NPA671 (2000) 481):
  - Shallow nuclear potential, weak attractive $\bar{K}N$ interaction
  - Small binding energy (30-40 MeV) and large width (80-100 MeV)

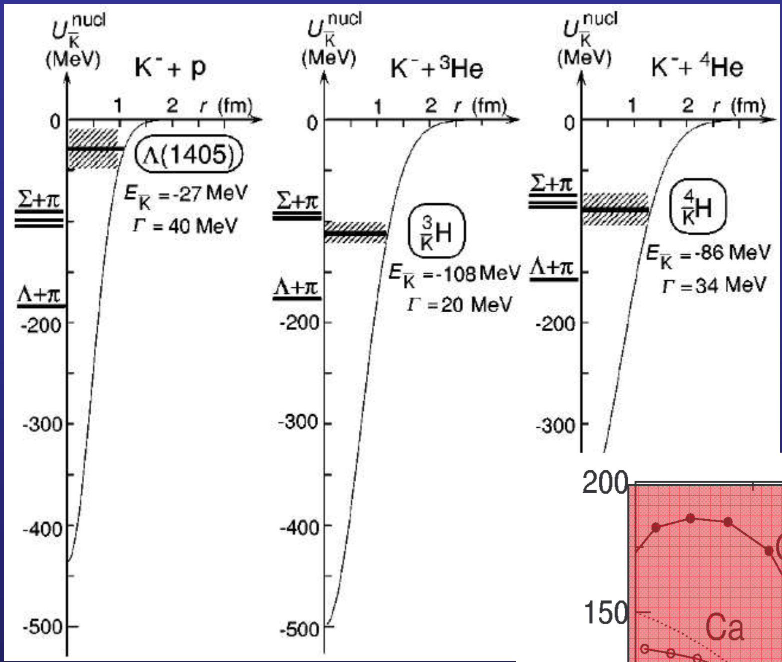
- Density dependent potential (Mares et al. NPA770 (2006) 84)
  - Sizeable binding energy (100-200 MeV), widths > 50 MeV but only for heavy nuclei

Oset, Weise, Mares …the skeptical side II

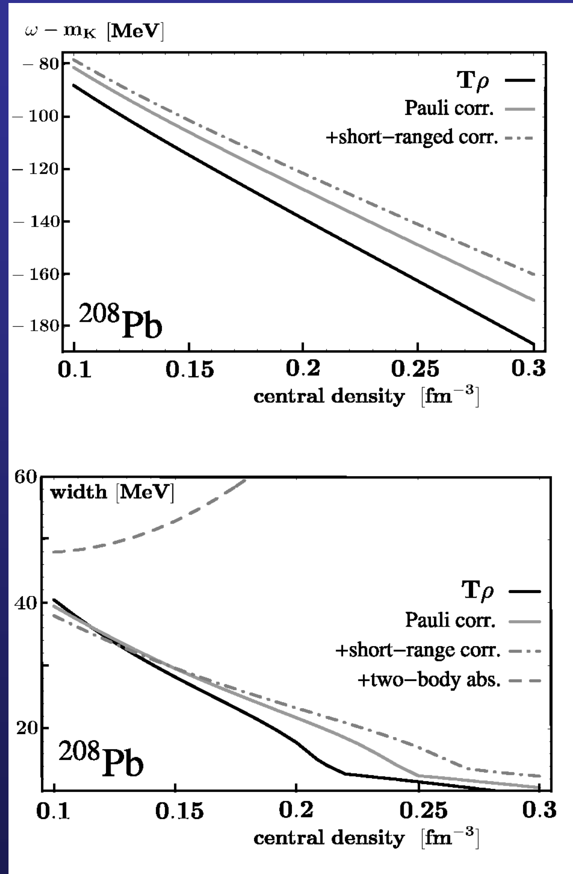
- 3-body Faddeev calculations (Shevchenko et al. PRL98 (2007), 082301)
  - Small binding energy (~50 MeV) and large width (~100 MeV)
- Green function method (Yamagata, Nagahiro, Hirenzaki PRC74 (2006), 014604)
  - Phenomenological optical potential: small structures
  - Chiral unitary optical potential: not observable structures
  - The signals of the kaonic nuclear states formation are very small
- Interpretations of observed signals via FSI
  - Magas et al. PRC74 (2006), 025206
  - Oset, Toki PRC74(2006), 015207

Where to observe DBKS ?

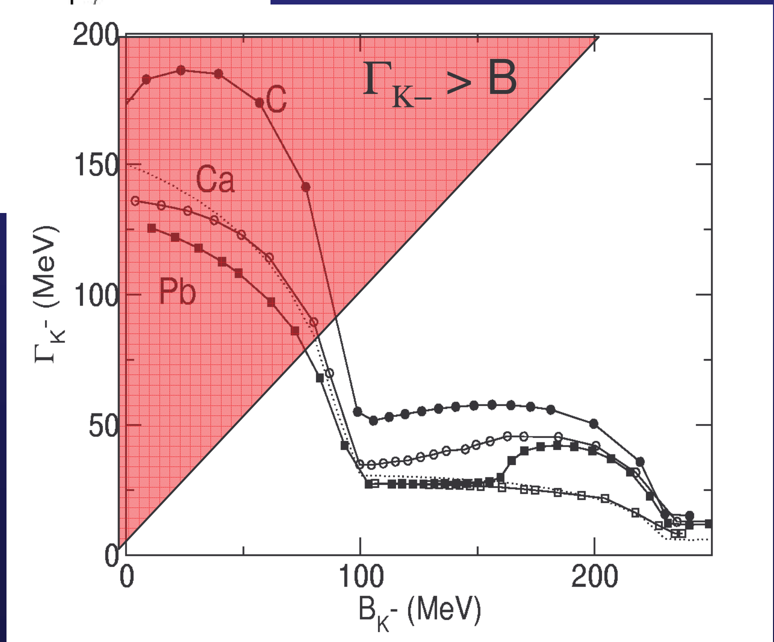
Akaishi-Yamazaki



Weise



Mares et al.

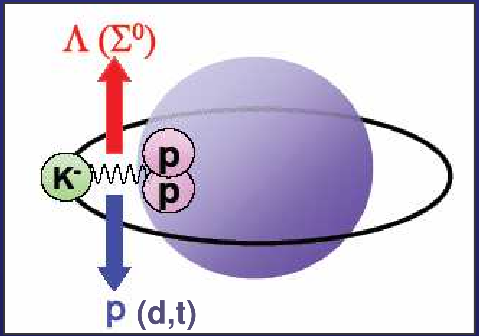


What is:

1. Decay signature
2. Role of FSI

Experimental approaches

- Missing mass spectroscopy
  - Measurement of the momentum of monochromatic recoiling particles in the A(K^-,N)X reaction
    - KEK-PS E471 (K^-_{stop})
    - AGS E930 ($K^-_{in\text{-}flight}$)
    - FINUDA (K^-_{stop})
    - KEK-PS E549 (K^-_{stop})
- Invariant mass spectroscopy
  - Based on the kaonic nuclear state decaying into YN pairs
    - (K^-pp) $\rightarrow \Lambda + p$
    - (K^-ppn) $\rightarrow \Lambda + d$
    - Typically:
      - $p_{p(\Lambda)} \sim 500$ MeV/c
      - $p_{\pi(\Lambda)} < 200$ MeV/c
      - $p_{\,p} \sim 500$ MeV/c



  - Full event reconstruction desirable (necessary)
  - Angular correlation between the emitted pairs necessary (desirable)
    - FOPI (heavy ion collisions)
    - FINUDA (K^-_{stop})
    - OBELIX ($\bar{p}$ He)
    - KEK-PS E549 (K^-_{stop})

Initial experimental results…

- Hunting K^- bound systems [K^-NNN] with (semi) inclusive reactions $^4He(K^-_{stop}, N)$ by KEK-PS E-471
  - Peak in the recoiling nucleon momentum at ~ 500 MeV/c, observed in coincidence with a fast π^-
    - Results compatible with the predictions by Akaishi-Yamazaki (but I = 1 !)
  - $^4He(K^-_{stop}, p)$: withdrawn (arXiv:0708.2968v1)
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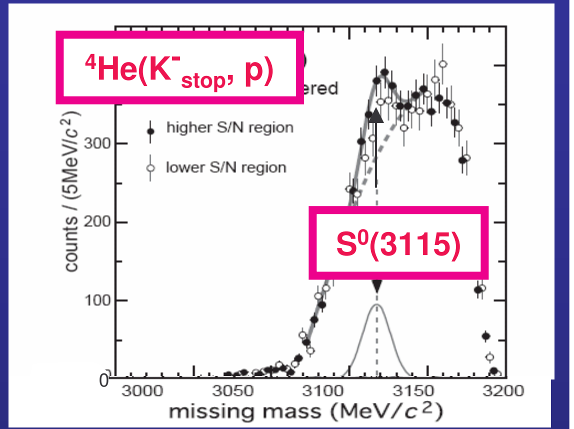
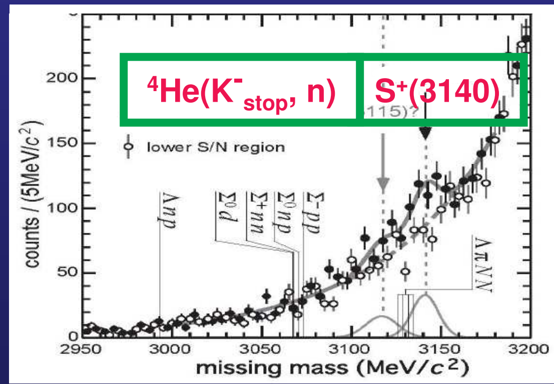
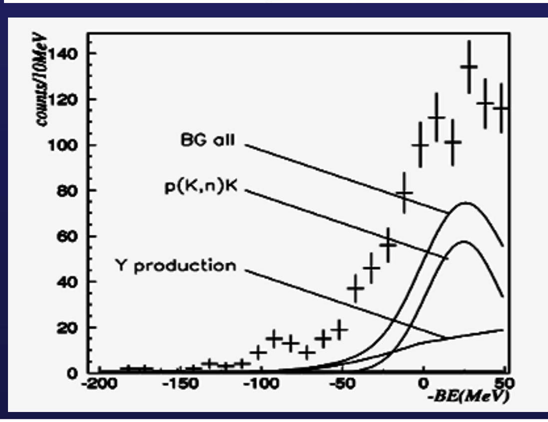
- A further observation: E930@AGS
  - $^{16}O(K^-, n)^{15}{}_{K}$-O

    $^{15}{}_{K^-}$O: bound state at ~90 MeV

⇒ Careful about relying on (missing mass) inclusive measurements only !







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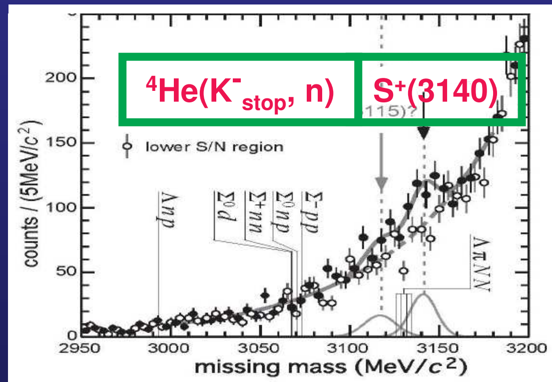

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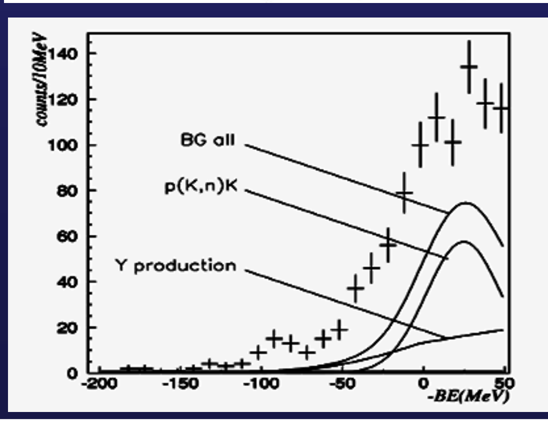

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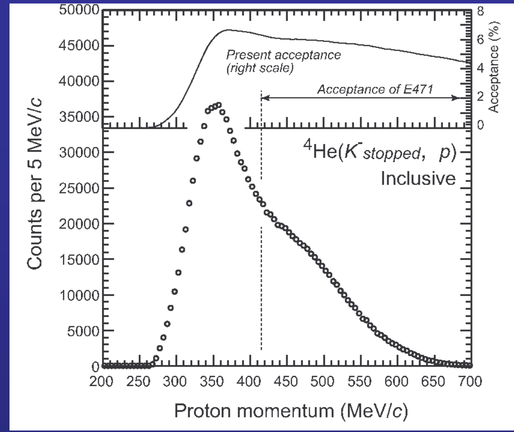

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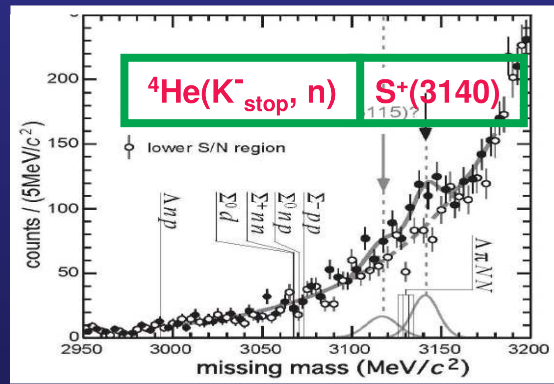

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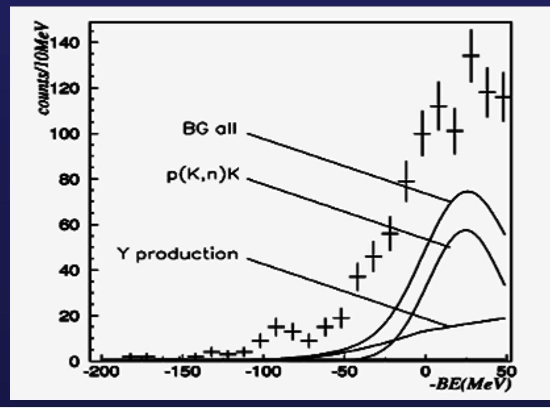

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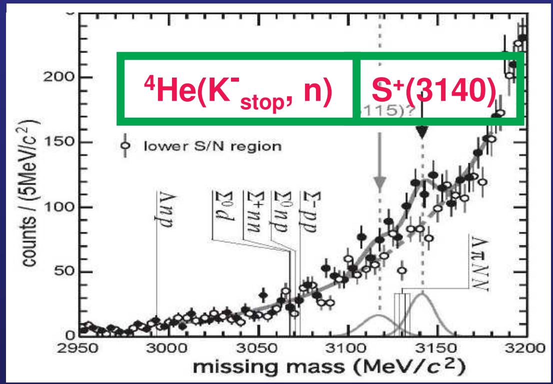

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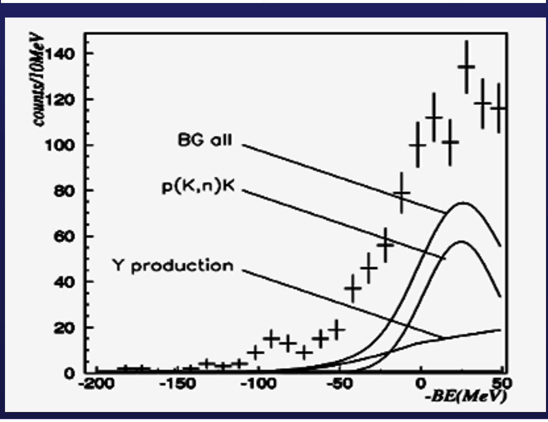

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$^4He(K^-_{stop}, n)$

See talk of Sato,M.

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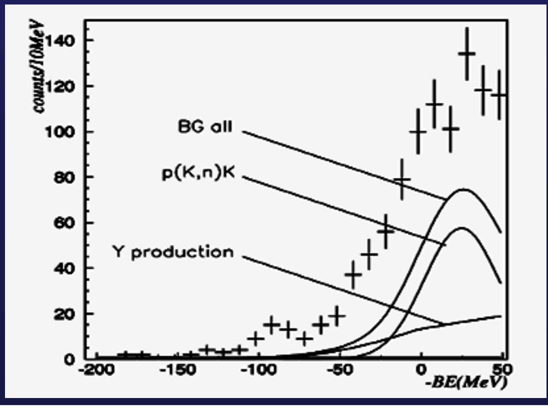
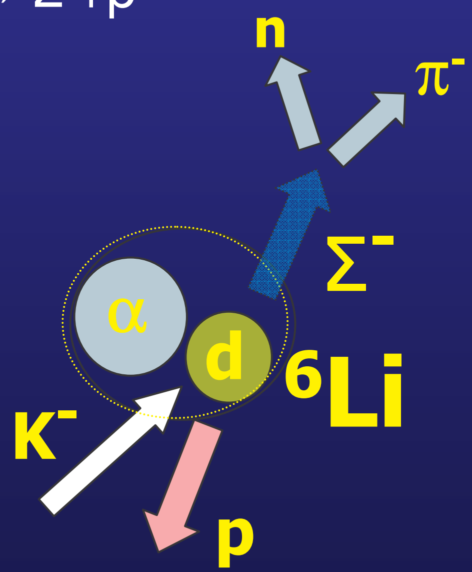


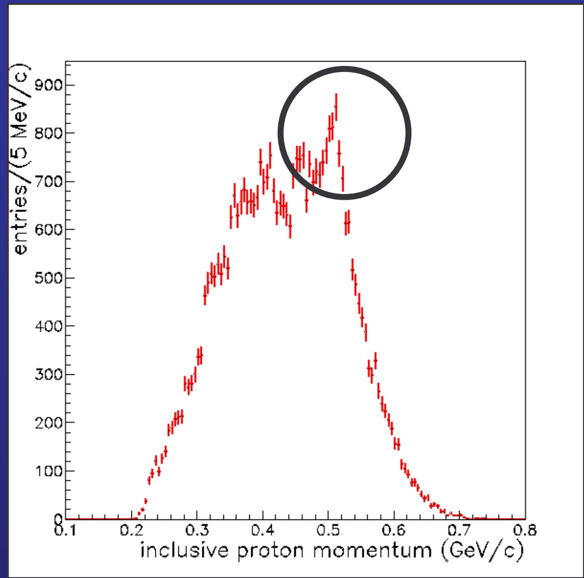
FINUDA: Study of the ^{6}Li(K^-,p)X reaction

- Study of the proton missing mass:
  - Found peak at about 500 MeV/c
  - Interpretation: the proton peak is simply due to two nucleon absorption reaction:

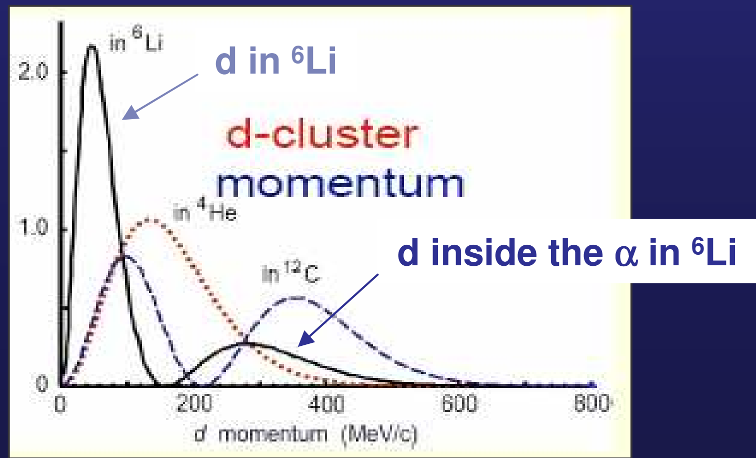
    K^-"d"$\rightarrow$ Σ^-+p



  - Nothing exotic: simple reaction mechanism

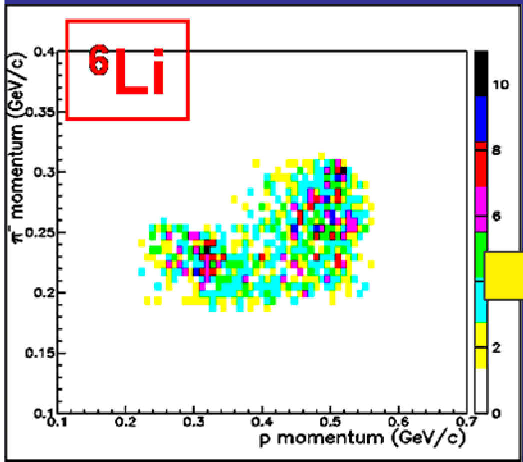


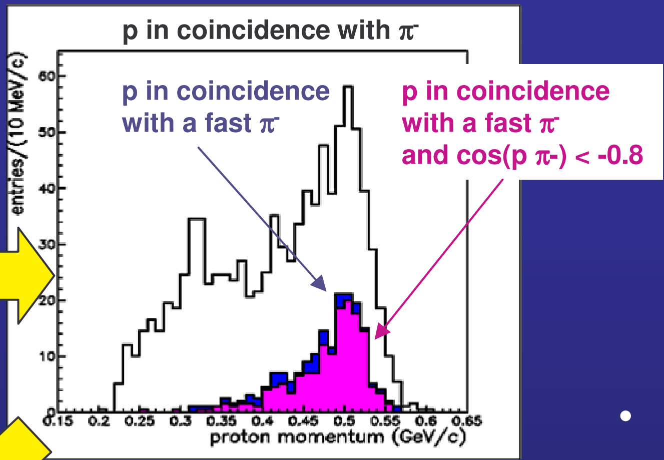
FINUDA Coll., NPA 775 (2006), 35

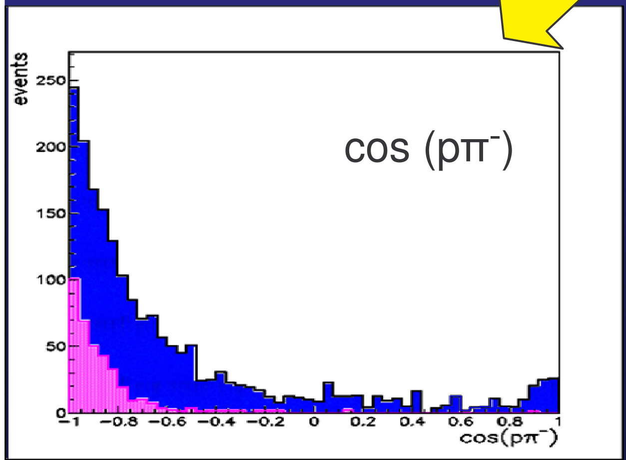


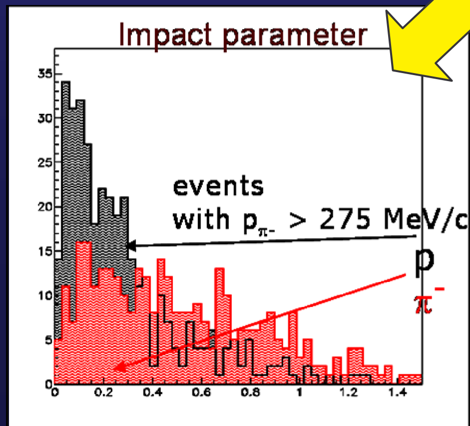
Yamazaki, Akaishi, NPA 792 (2007), 229

Semi-inclusive p spectra (in coincidence with a fast π^-)









- The Σ^- hyperon does not come from the decay of a [K^-NNN] cluster

Back-to-back angular correlation proper of a two-body reaction (isotropy expected from DBKS decay)

- capture rate K^- (np) $\rightarrow \Sigma^-$p:
  - 1.6%/stopped K^-
  - OK!

- The p and the high momentum π- produced in two different vertices
  - The π^- comes from the decay of a Σ^- hyperon

No need to DBKS to explain the signal: agreement with the Oset-Toki expectations

Missing mass combined with π^- vs p momenta, cos(pπ^-), topological constraint …

Experimental approaches

- Missing mass spectroscopy
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    - KEK-PS E471 (K^-_{stop})
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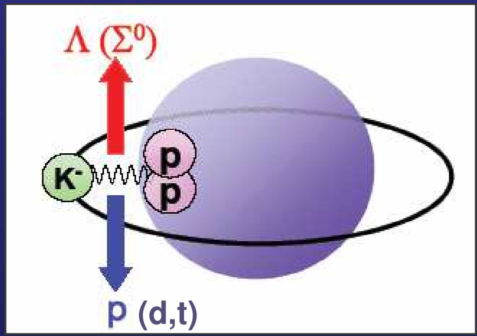
- Invariant mass spectroscopy
  - Based on the kaonic nuclear state decaying into YN pairs
    - (K^-pp) $\rightarrow \Lambda + p$
    - (K^-ppn) $\rightarrow \Lambda + d$
    - Typically:
      - $p_{\Lambda,p}$ ~ 500 MeV/c
      - $p_{\Lambda,\pi} < 200$ MeV/c
      - $p_{\text{decay p}}$ ~ 500 MeV/c



  - Full event reconstruction desirable (necessary)
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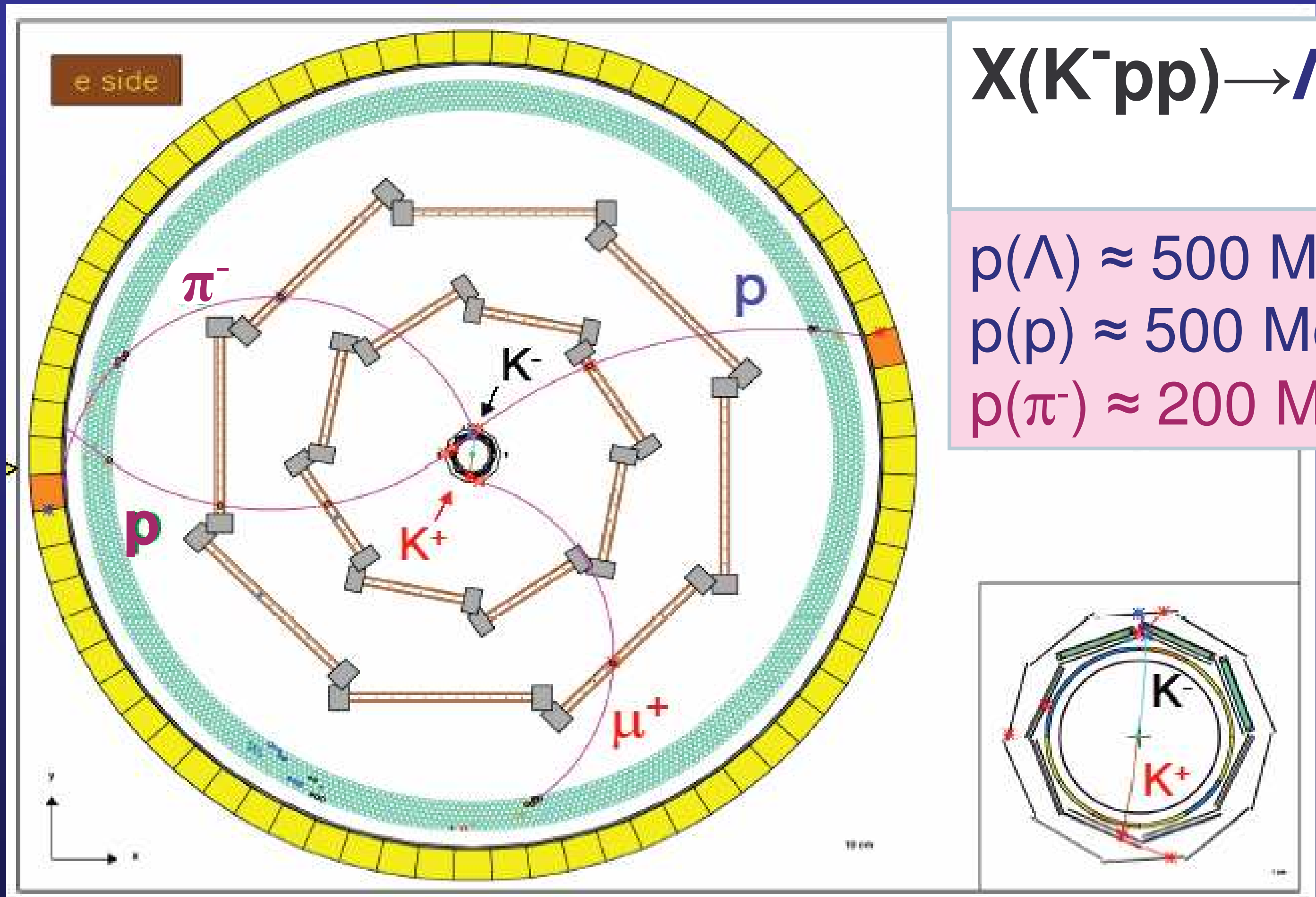
$K^{-}pp$ invariant mass studies with FINUDA



$X(K^{-}pp) \rightarrow \Lambda p$

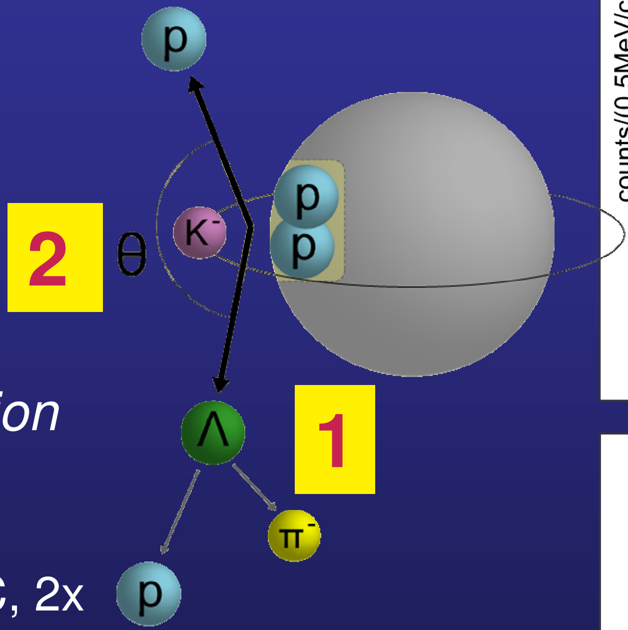
$\Lambda \rightarrow \pi^{-} p$

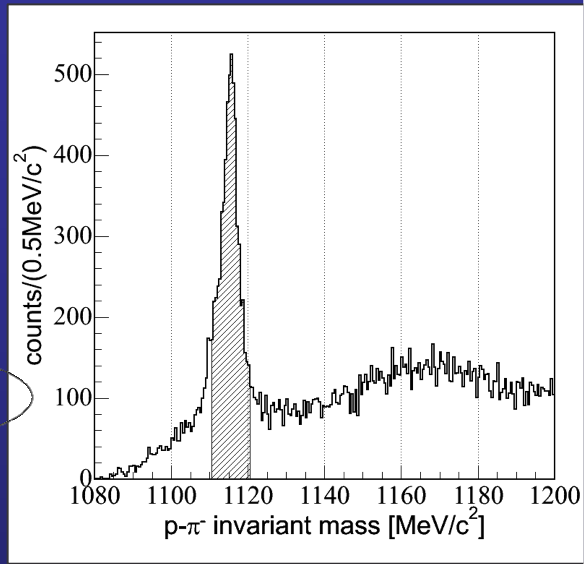
$p(\Lambda) \approx 500$ MeV/c
$p(p) \approx 500$ MeV/c
$p(\pi^{-}) \approx 200$ MeV/c

FINUDA is equipped with a variety of nuclear targets:
A = ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C, ^{13}C, ^{16}O, ^{27}Al, ^{51}V

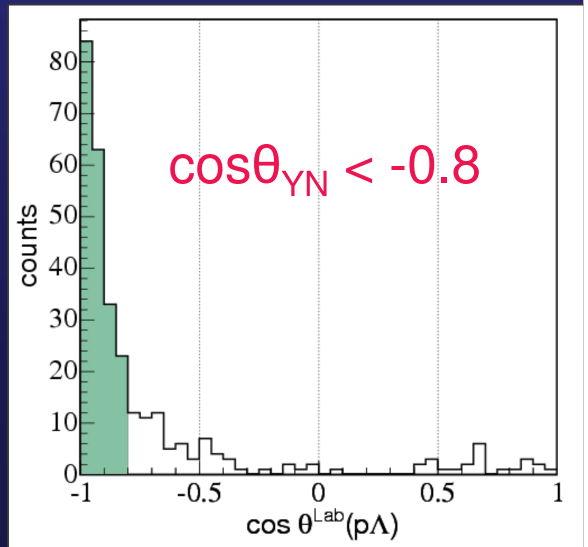
(K^-pp) system identification in FINUDA

1. *reconstruction of Λ's*
   - $p_\Lambda > 300$ MeV/c
   - 6 MeV FWHM





2. *Λ and p angular correlation*
   - Events with a Λ-p coincidence: ~ 5%
   - Light targets only (3x ^{12}C, 2x ^{6}Li, 1x ^{7}Li)
   - Λ p should be oppositely emitted, apart from FSI



(Λp) invariant mass: observation of a possible bound state I

- High resolution tracks *only*
- A bump is observed
  - **Two nucleon absorption**
    - $K^- + (pp) \rightarrow Y^* N \rightarrow \Lambda p$

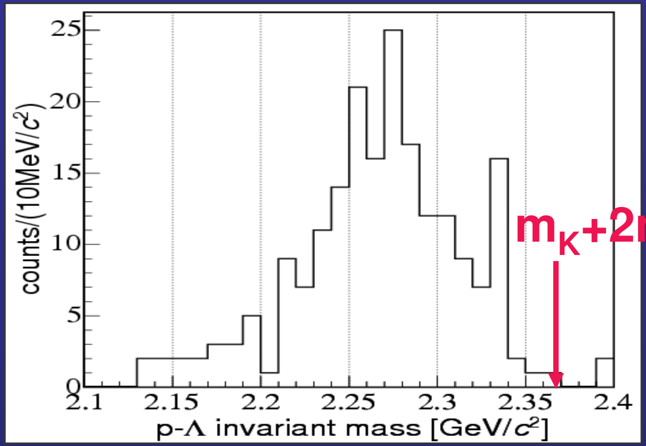
      peak expected at 2.34 GeV
    - $K^- + (pp) \rightarrow \Sigma^0 p \rightarrow \Lambda\gamma\, p$

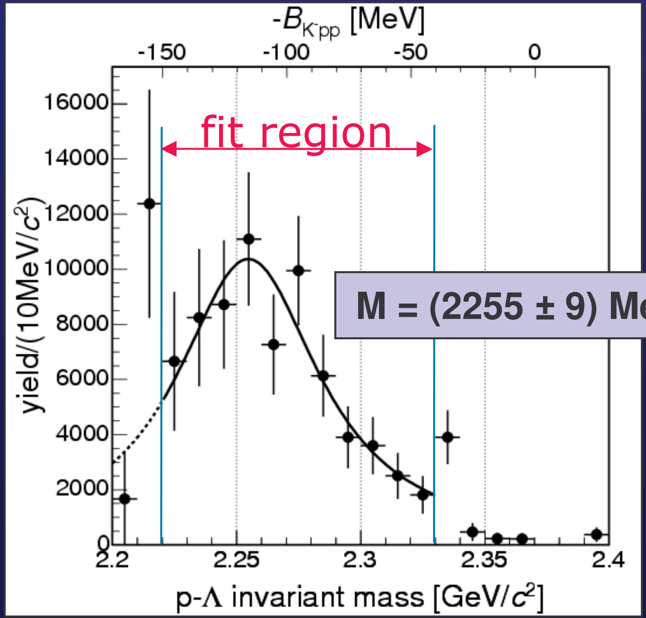
      74 MeV lower distribution, and broadened
  - **Kaon nuclear bound state formation**
    - $\mathbf{K^- (pp) \rightarrow X \rightarrow \Lambda p}$

      $\mathbf{\rightarrow \Sigma^0 p \rightarrow \Lambda\gamma\, p}$

B = 115$^{+6}_{-5}$ (stat)$^{+3}_{-4}$ (sys) MeV
Γ= 67$^{+14}_{-11}$(stat)$^{+2}_{-3}$ (sys) MeV
Yield ≈ 0.1%/stopped K^-

EXCLUSIVE ANALYSIS





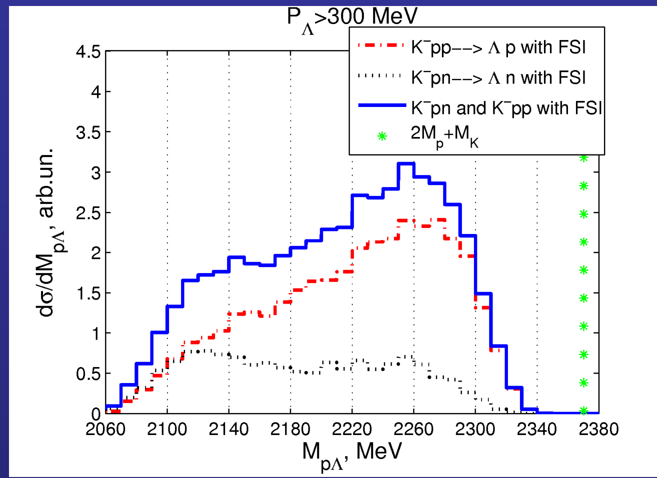
~ 200 events in the published paper

Acceptance correction

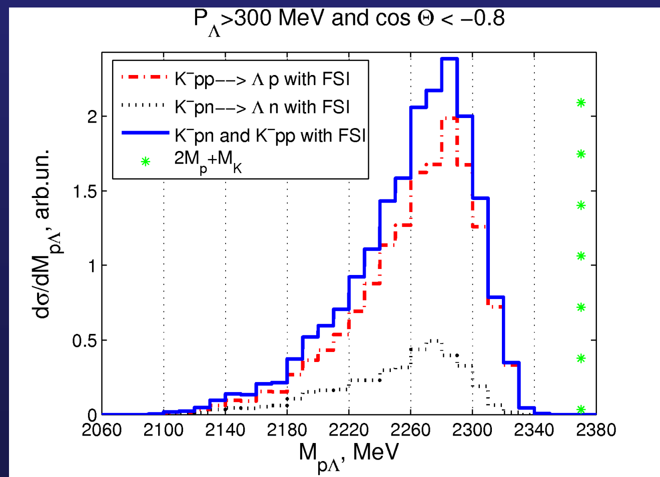
FINUDA Coll., PRL 94(2005)212303

A different interpretation of the $M_{p\Lambda}$ bump

- Magas, Oset et al, PRC74 (2006), 0252006
  - The peak is due to a rescattering effect of p and/or Λ, no need for DBKS
  - The bump is a result of the angular cuts applied in the analysis (i.e., a deformation of a flat distribution)
  - 115 MeV as a binding energy is quite too much!



- …but:
  - The newest analysis shows that the deformation of the spectrum is not due to angular cuts
    - Rescattering alone cannot explain the full spectrum
    - Back-to-back correlation belongs to the data themselves



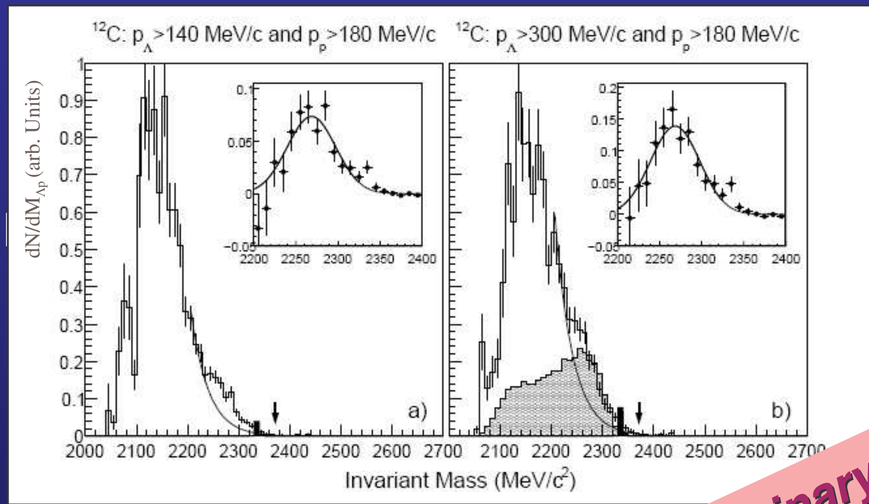
- …moreover:
  - A similar bump was observed in a different reaction, p̄ ^{4}He, where the rescattering effects should be less sizeable

($pp\pi^-$) invariant mass: observation of a possible bound state II

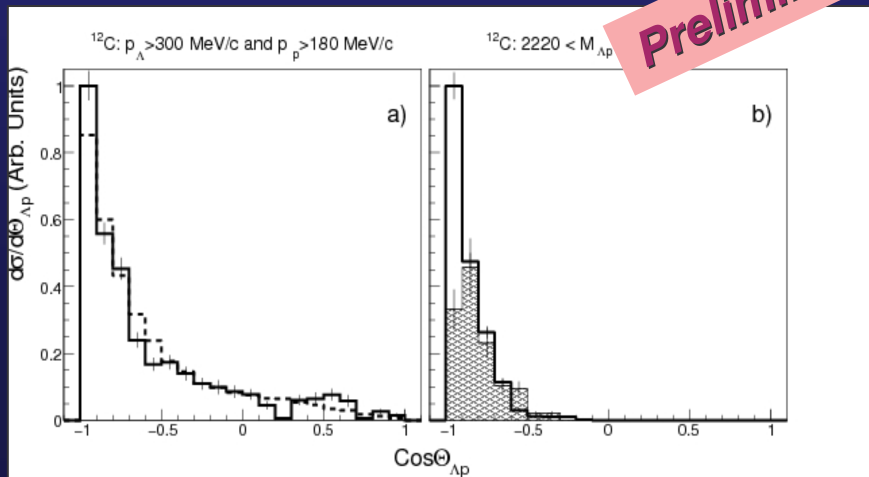
Shorter tracks with less resolution included

INCLUSIVE ANALYSIS

- Larger acceptance
- Larger background
- Bump confirmed below the mass threshold of the unbound K^-pp system: m=2274 MeV, Γ= 56 MeV (slightly narrower)
  - Good agreement with the first result
  - 750 events in the bump (statistics 8x)
  - No angular cuts
- Angular correlations:
  - Back-to-back trend
  - Bump events: strong back-to-back correlation (1 or 2 bins populated)
  - unlikely to be obtained by FSI's

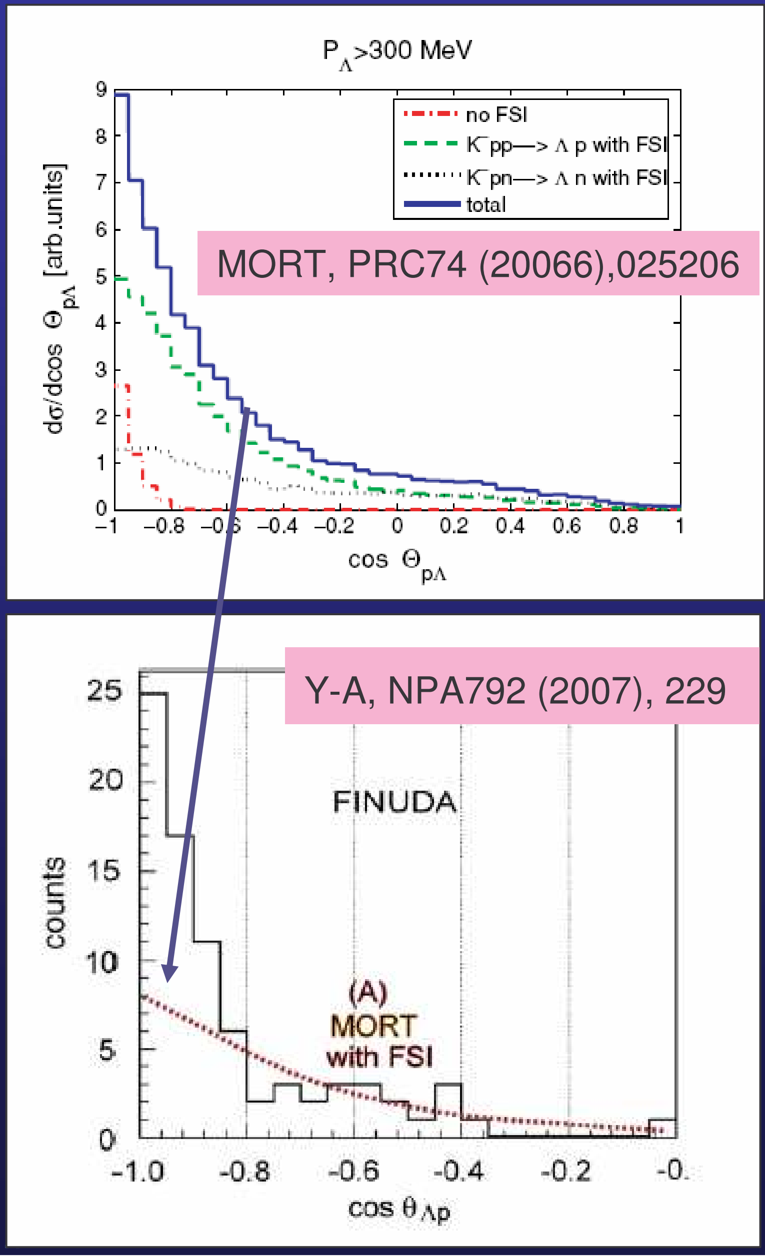


Preliminary



Angular distributions: a closer look

- All the experimental spectra are corrected for acceptance
- Inclusive analysis: FSI simulation normalized to the data
  - They account for 30% on the whole reaction strength
- Exclusive analysis: at the variance of the theoretical predictions, the experimental distribution is sharply peaked at $\cos(\Theta_{\Lambda p}) = -1$



(Λp) Invariant mass from p̄ annihilation at rest in ^4He

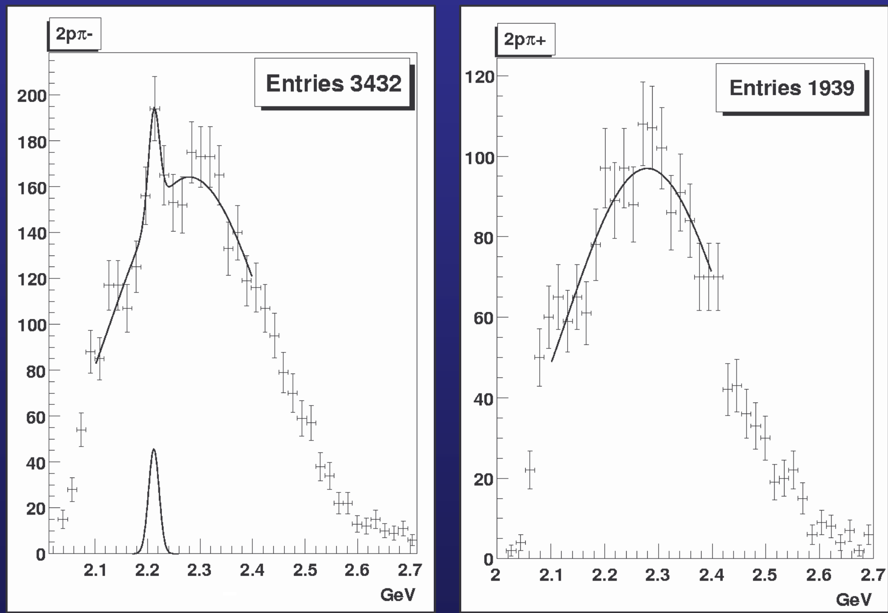
- Antiproton annihilation at rest: a good environment for the production of strangeness
- OBELIX data: $\bar{p}^4He \rightarrow$ 5 prongs:
  - $\bar{p}^4He \rightarrow (p\pi^-)p\,K^0X$

- Study of the (pΛ) system
  - Experiment not suitable for detection of particles out of a secondary vertex
  - Limited statistics
  - Background due to phase-space and N and Δ resonances (large)

- Signal found in the $(pp\pi^-)$ channel while is absent in the $(pp\pi^+)$ channel:
  - Statistical significance 3.7σ
  - $Y < 1.5 \times 10^{-4}$/stopped p
  - FSI effect?
    - Lower number of residual nucleons
    - No angular cuts

G. Bendiscioli et al., NPA789(2007)222

$(pp\pi^-)$ $(pp\pi^+)$



invariant mass spectrum

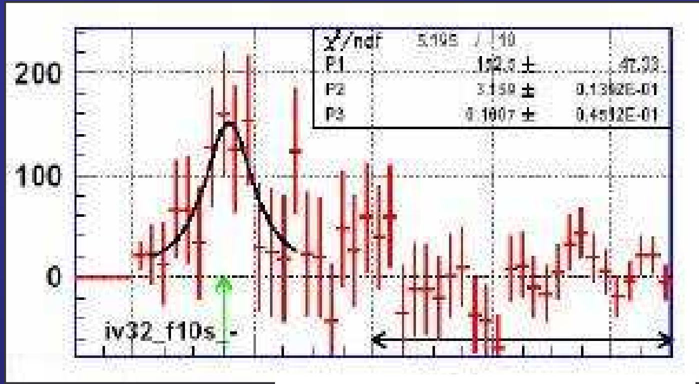
M = 2212.1 ± 4.9 MeV
B = 169 ± 4.9 MeV
Γ= < 24.4 ± 8.0 MeV

Search for a 3-baryon [K^-NNN] kaon-nuclear state: invariant mass of the Λd system

- FOPI - GSI
  - Ni+Ni @ 1.93 AGeV
  - Use of invariant mass spectroscopy to search for short-lived ΛX resonances
  - [K^-ppn] → Λd

M = 3159 ± 20 MeV
B = 151 ± 20 MeV
Γ = 100 ± 50 MeV

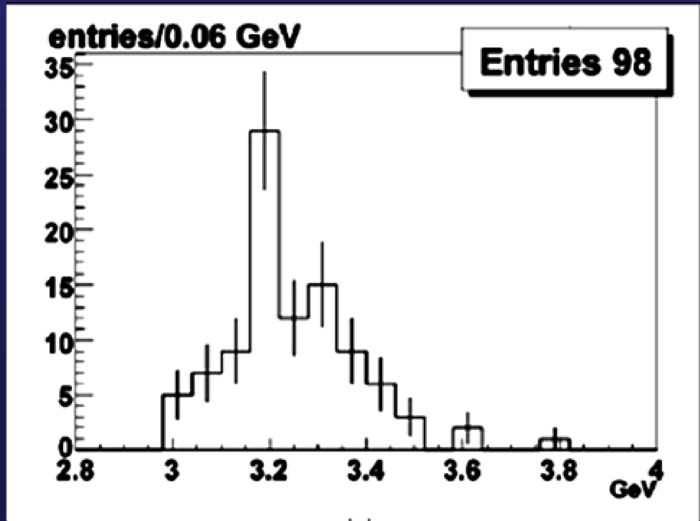
PRELIMINARY (AND ONLY) RESULTS EXA05



Λd invariant mass

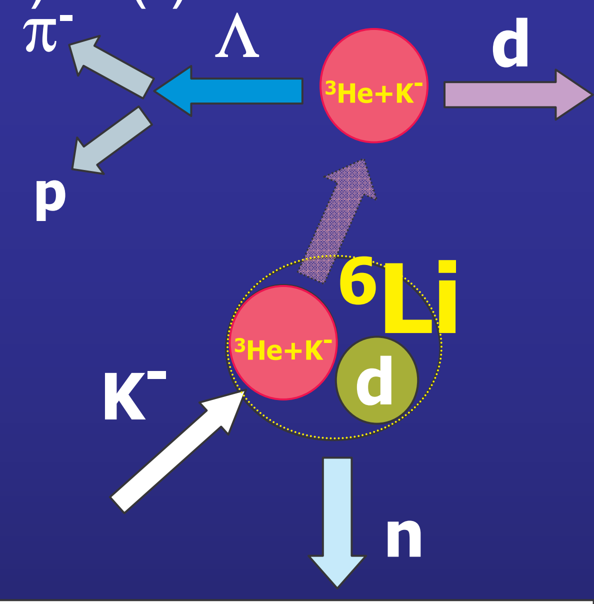
- OBELIX $\bar{p}\,^4He$
  - Hints of a Λd signal at 2.6σ
    - Fewer statistics
    - Lower background

M = 3190 ± 15 MeV
B = 120 ± 15 MeV
Γ= < 60 MeV



NPA789(2007), 222

FINUDA: study of ^{6}Li(K$^-$,Λd)X (I)

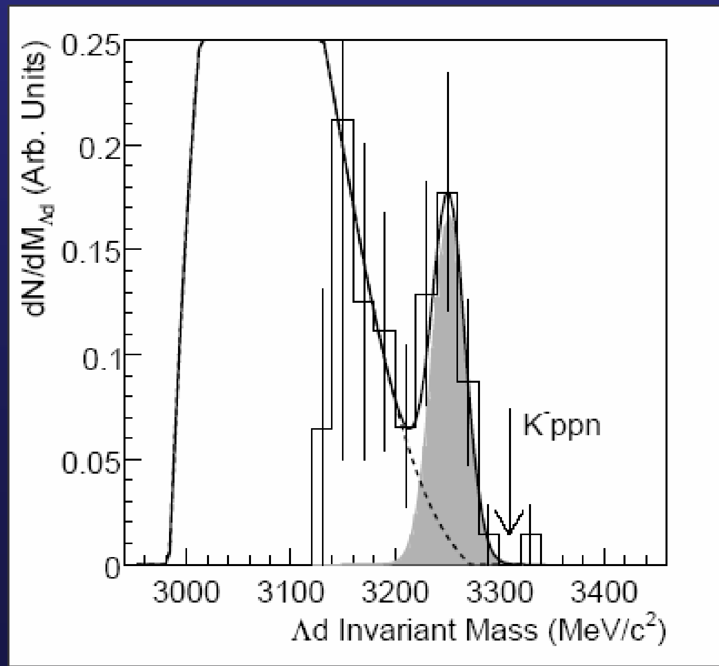


- Λd system invariant mass: EXCLUSIVE ANALYSIS

- Use of ^{6}Li target: low background

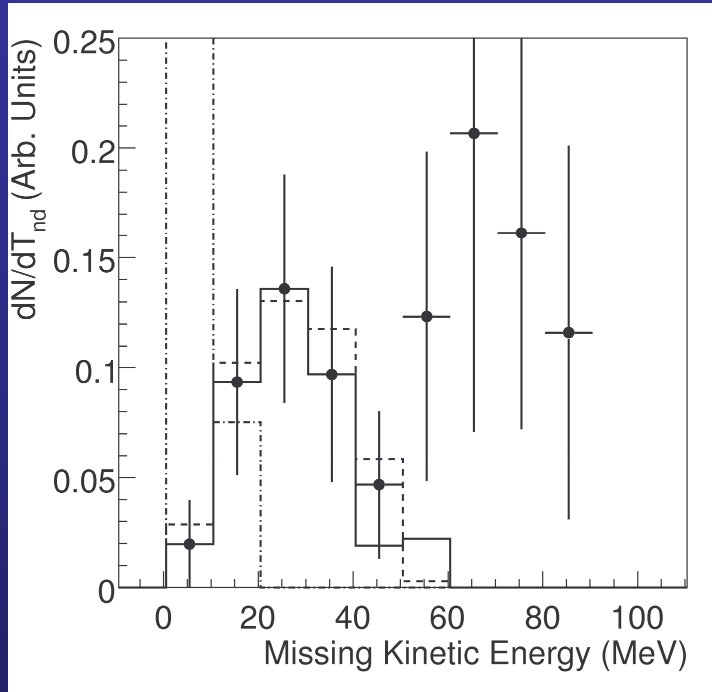
- ^{6}Li is a well known (α+d) cluster
  - Enhancement observed at 3251 MeV, with $\Gamma_{\Lambda d}$=37 MeV on ^{6}Li targets
  - 25 events in the peak, statistical significance 3.9σ

FINUDA Coll., PLB 654 (2007) 80



FINUDA: study of ^{6}Li(K$^-$,Λd)X (II)

- The kinetic energy spectrum can be reproduced only in the hypothesis of ^{6}Li(K$^-_{stop}$, Λd)nd with a spectator deuteron and the neutron carrying away the whole momentum



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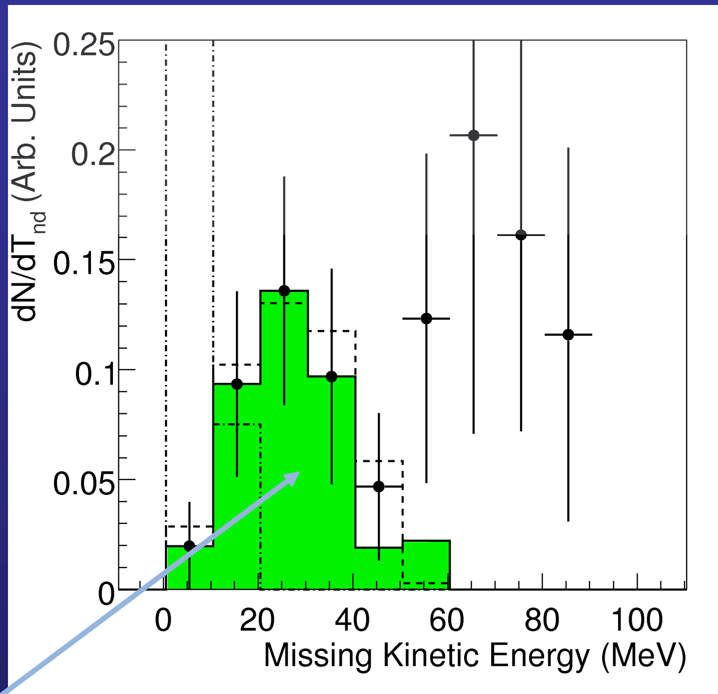

^{6}Li(K$^-_{stop}$, Λd)nd for events under the bump

FINUDA: study of ^{6}Li(K$^-$,Λd)X (II)

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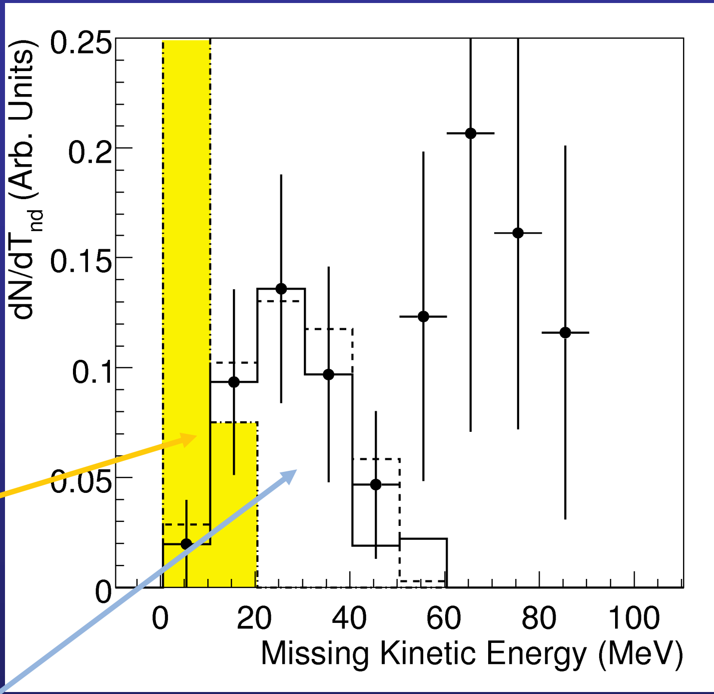


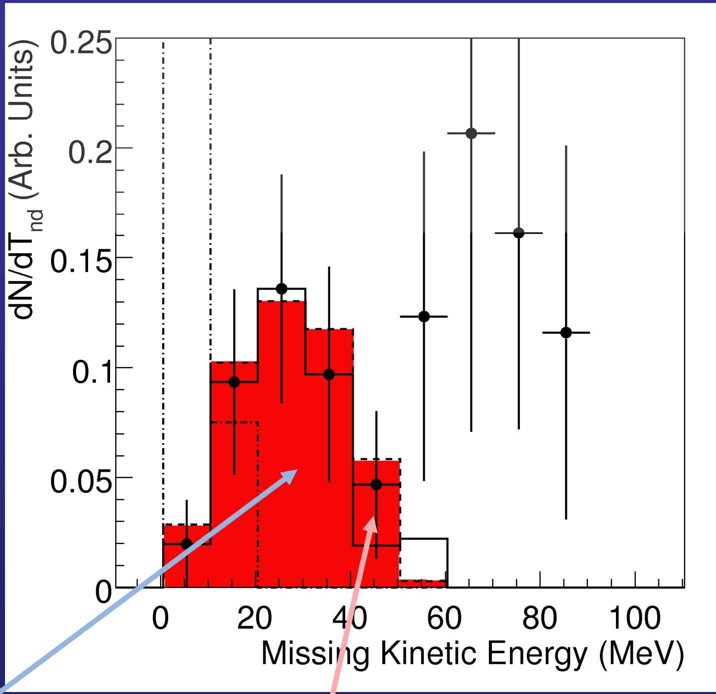
Simulation: ^{6}Li(K$^-_{stop}$, Λd) t

^{6}Li(K$^-_{stop}$, Λd)nd for events under the bump

FINUDA: study of ^{6}Li(K$^-$,Λd)X (II)

- The kinetic energy spectrum can be reproduced only in the hypothesis of ^{6}Li(K$^-_{stop}$, Λd)nd with a spectator deuteron and the neutron carrying away the whole momentum

$K^-_{stop}\ ^6Li \rightarrow \Lambda\ d\ n\ d_{spect}$



^{6}Li(K$^-_{stop}$, Λd)nd for events under the bump

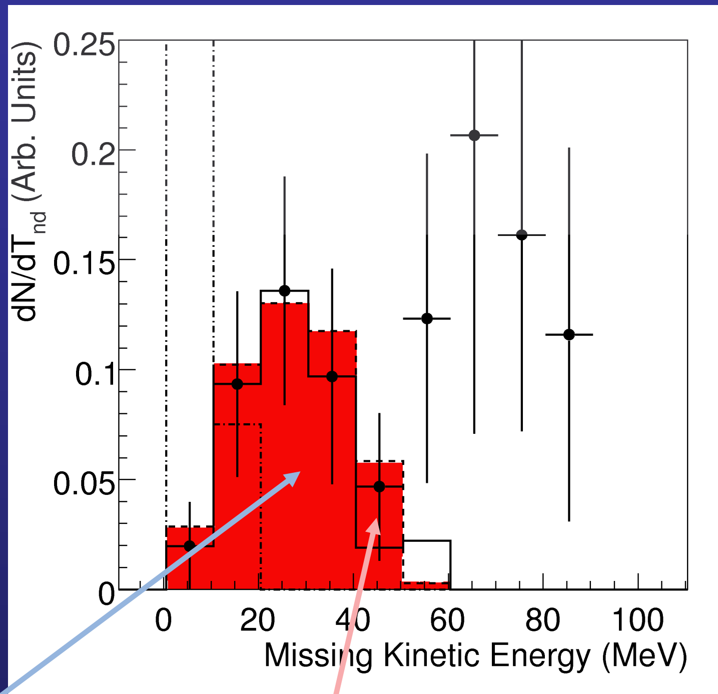
Simulation: ^{6}Li(K$^-_{stop}$, Λd)nd for events in the same mass region, with a spectator deuteron with T_d < 3 MeV

FINUDA: study of ^{6}Li(K^{-},Λd)X (II)

- The kinetic energy spectrum can be reproduced only in the hypothesis of ^{6}Li(K$^{-}_{stop}$, Λd)nd with a spectator deuteron and the neutron carrying away the whole momentum

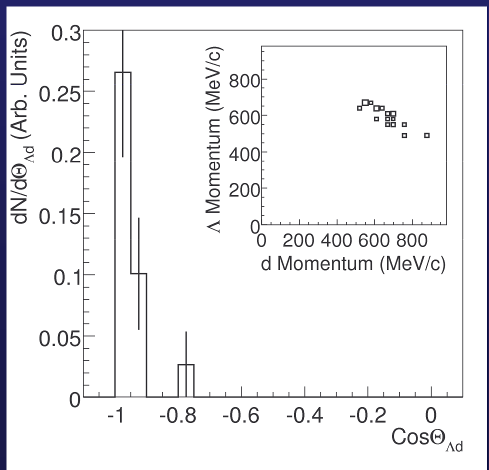
  $K^{-}_{stop}\ {}^{6}Li \rightarrow \Lambda\ d\ n\ d_{spect}$

- The events in the bump have a very marked back-to-back correlation

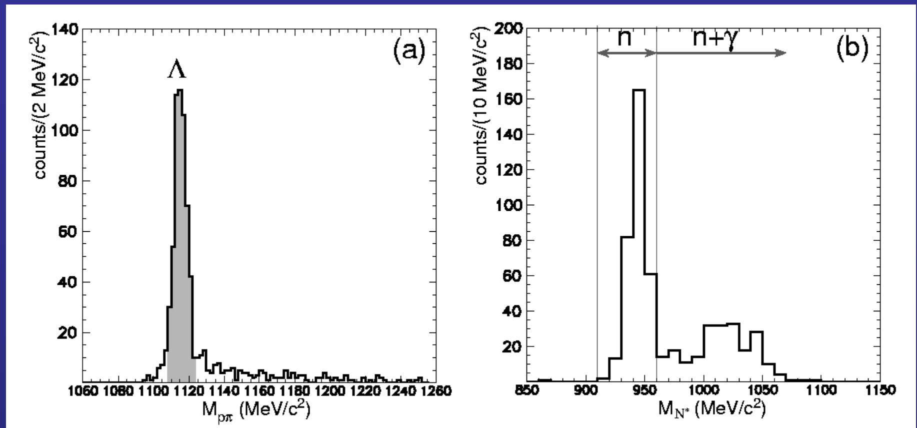


^{6}Li(K$^{-}_{stop}$, Λd)nd for events under the bump

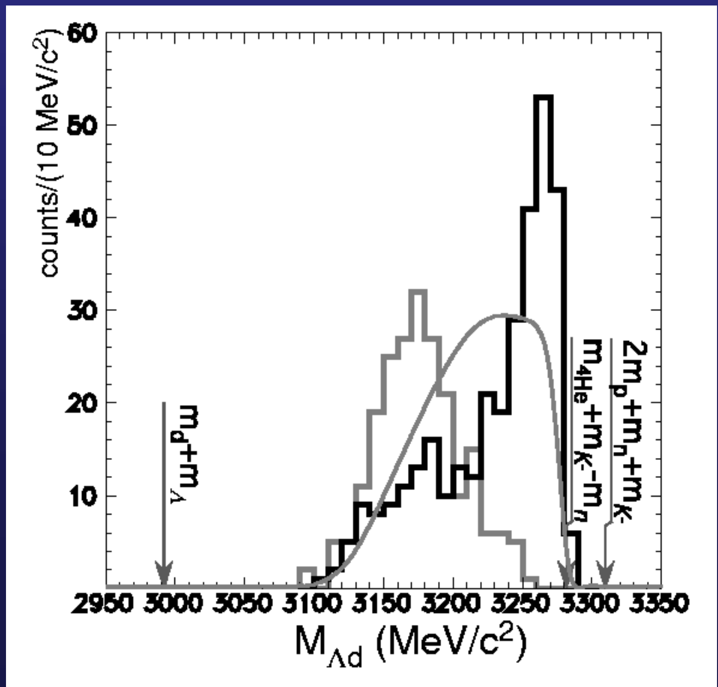
Simulation: ^{6}Li(K$^{-}_{stop}$, Λd)nd for events in the same mass region, with a spectator deuteron with T_d < 3 MeV



E549: Λd correlation from $^4He(K^-_{stop}, d)$



arXiv:0709.0996v1 [nucl-ex]



- $K^- \, ^4He \rightarrow \Lambda$ d (n)
- revealed d p pair back-to-back with π^- coincidence
- discrimination Λ from Σ^0 ($\Lambda\gamma$) event by missing mass
- Λd peak at 3282 MeV/c^2 just below mass threshold
- interpreted as 3NA process:

  K^-ppn (n) $\rightarrow \Lambda$ d (n)
- Acceptance: only d p back-to-back, spectra deformed.

Mass, Binding Energy and Width

ppK^-

M (MeV)	E_K(MeV)	Γ(MeV)	Reference
2255	115	67	FINUDA EXP
2212	161	<24	OBELIX EXP
--	55-70	95-100	Shevchenko
--	48	61	A-Y model
--	118	58	Ivanov et al.

New calculation with Skyrme model: see talk of Nishikawa,T.

$ppnK^-$

M (MeV)	E_K(MeV)	Γ(MeV)	Reference
3251	58	37	FINUDA EXP
3190	120	<60	OBELIX EXP
3159	151	100	FOPI EXP
--	108	20	A-Y model

Summary

- The search for DBKS is a recent field in hadronic physics raising considerable interest from both the theoretical and experimental point of view

- Several theoretical approaches, rather strong disagreement
  - Still under debate!

- Only few and very recent experimental observations of effects connected to the possible existence of strange-nuclear aggregates
  - AGS E930
    - K^- on ^{16}O
  - FINUDA @ LNF
    - K^--nuclei interaction at rest
  - FOPI @ GSI
    - ion collisions: high temperature regime
  - OBELIX @ CERN
    - Antiproton annihilation at rest on ^4He

Outlook and Conclusions

- FINUDA @ DAΦNE in the last year has collected ~1 fb^{-1} of K^-_{stop} on ^{6}Li, ^{7}Li, ^{9}Be, ^{13}C, ^{16}O, new results coming soon:
  - Λ p vs A
  - Λ d vs A
  - Λ t (?)

- Other experiments presently on floor
  - KEK: E549 – an extension of E471 (see talk of Sato,M.)
  - GSI, FOPI: study also in p+p collisions at 3.5 AGeV

- New analysis of old data:
  - OBELIX: S=-2 strangeness production in $\bar{p}^4$He (see talk of Panzarasa,A.)

- Future Projects dedicated to the search of K^--nuclear aggregates
  - E15 @ J-PARC: study of ^{3}He(K^-, n) in flight
  - AMADEUS @ LNF: K^- on cryogenic ^{4}He (see talk of Sirghi,F.C.)

- Increasing theoretical interest in obtaining a reliable physical framework for analysis of recent data is evidenced by the number of recent publications on this topic !