

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

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Outline

- 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

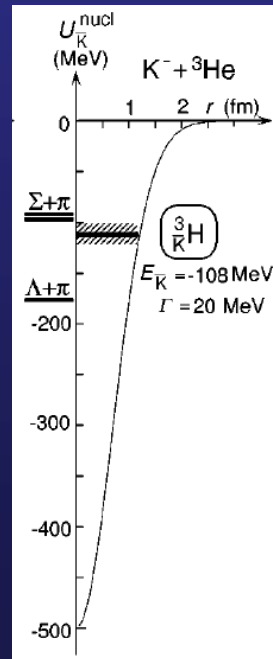
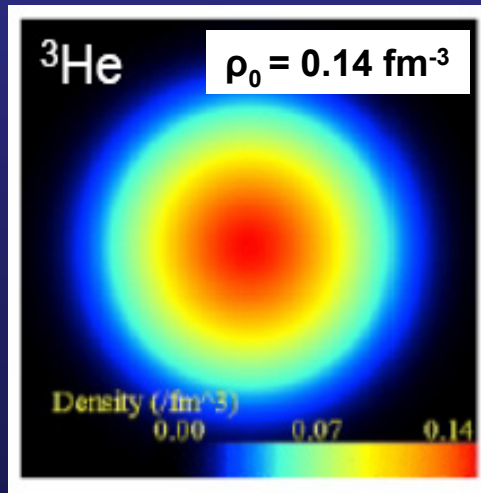
- General understanding of $\bar{K}N$ ($\bar{K}A$) interaction
 - Small binding energies: 30-50 MeV
 - Large decay widths: 80-100 MeV
 - ... practically impossible to observe
- Recent theoretical developments:
 - **YES!** DBKS exist as narrow states, they can be experimentally observed
 - **NO!** nuclear-antikaon interaction provides a shallow and wide potential, the $\bar{K}A$ states cannot be observed

Introduction – theoretical approach

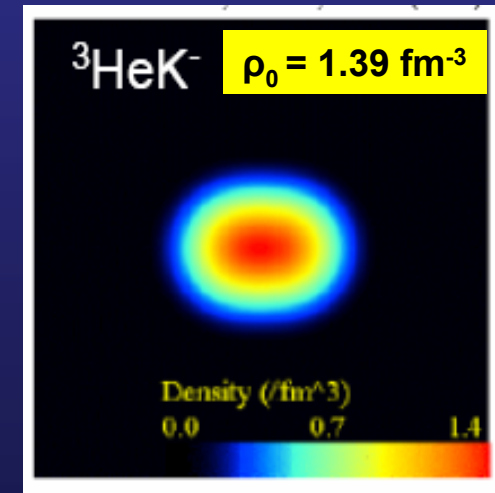
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Akaishi & Yamazaki: What a Deeply Bound Kaon Nuclear State is

- 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: $\Lambda(1405)$
- The presence of $\Lambda(1405)$ prevents a reliable perturbative treatment
- More composite states: can be interpreted as molecules formed by $\Lambda(1405)+xN$
 - covalent bonding K^- -nucleons, much stronger than the nuclear force
 - The $\Lambda(1405)$ 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

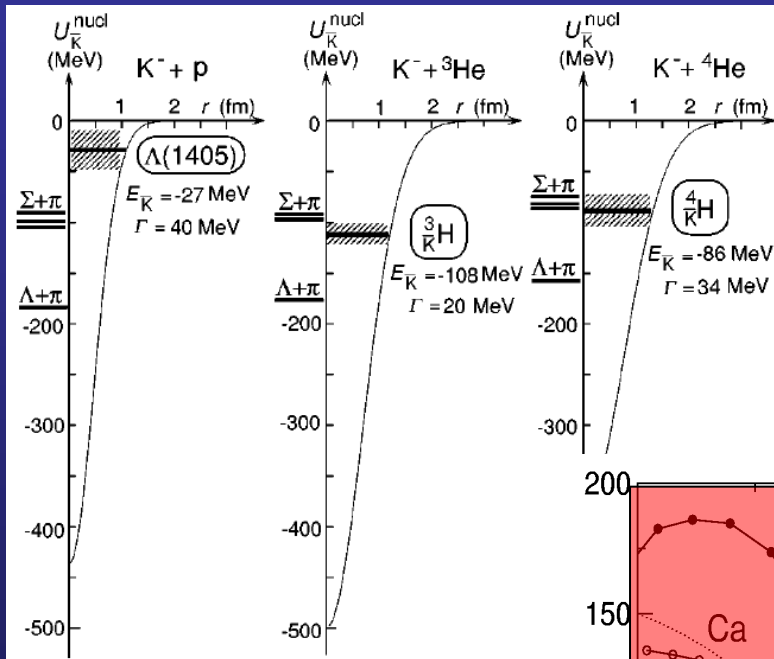
- Akaishi-Yamazaki use a G-matrix treatment simplifying some absorption effects, and neglecting some couplings ($\pi\Sigma$, $\pi\Lambda$)
- Common view (Gal, Weise, Schaffner-Bielich, Wychech)
 - K^- -nuclear aggregates existence is not denied, but the potential is shallow and the expected widths are 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

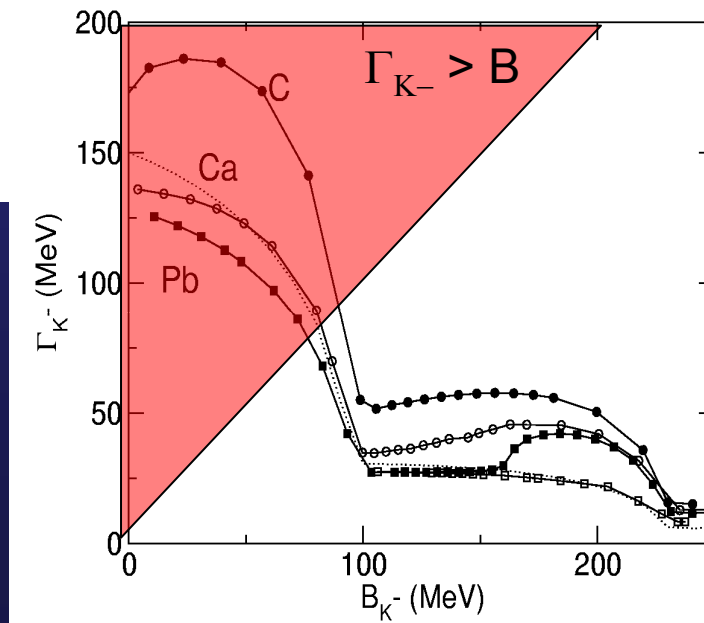
- 3-body Faddeev calculations (Shevchenko et al. PRL98 (2007), 082301)
 - Small binding energy (~ 50 MeV) and large width (~ 100 MeV)
- Green function method (Yamagata, Nagahiro, Hirenzaki PRC74 (2006), 014604)
 - Phenomenological optical potential: small structures
 - Chiral unitary optical potential: 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 ?

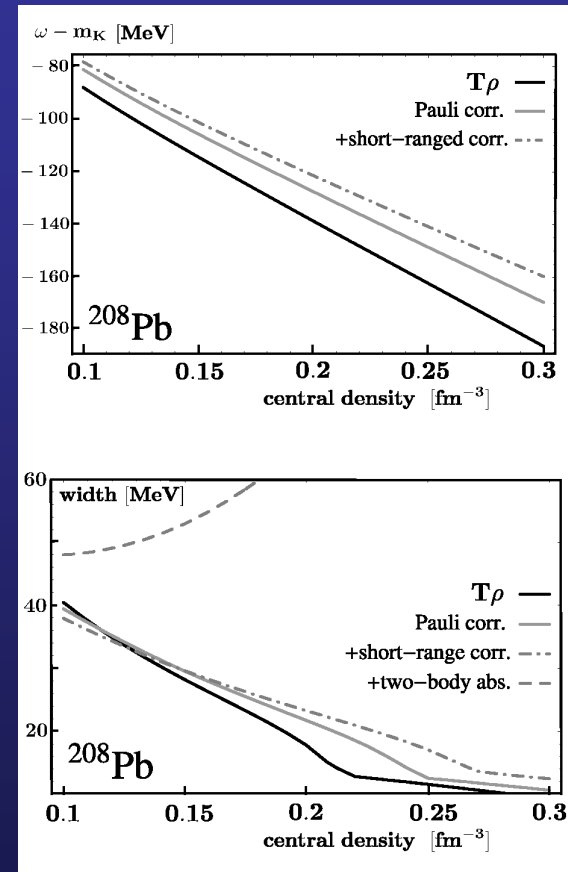
Akaishi-Yamazaki



Mares et al.



Weise



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 ($K^-_{\text{in-flight}}$)
- FINUDA (K^-_{stop})
- KEK-PS E549 (K^-_{stop})

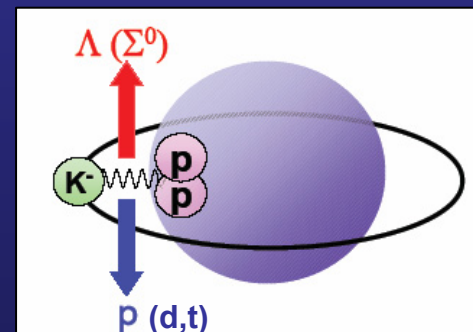
- **Invariant mass spectroscopy**

- Based on the kaonic nuclear state decaying into YN pairs

- $(K^-pp) \rightarrow \Lambda + p$
- $(K^-ppn) \rightarrow \Lambda + d$
- Typically:
 - $p_{p(\Lambda)} \sim 500 \text{ MeV}/c$
 - $p_{\pi(\Lambda)} < 200 \text{ MeV}/c$
 - $p_p \sim 500 \text{ MeV}/c$

- Full event reconstruction desirable (necessary)
- Angular correlation between the emitted pairs necessary (desirable)

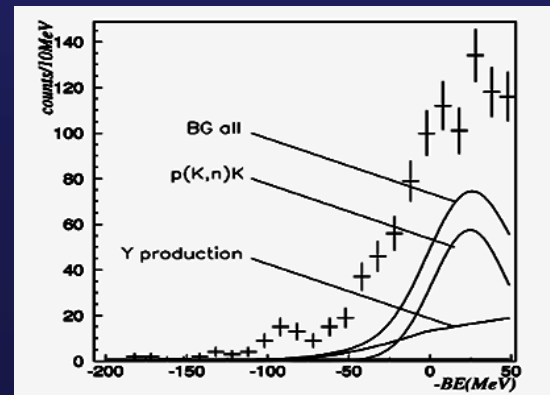
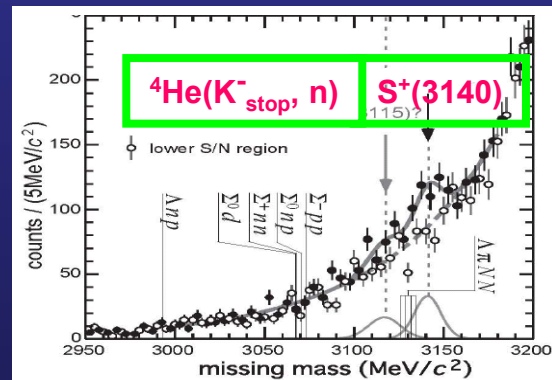
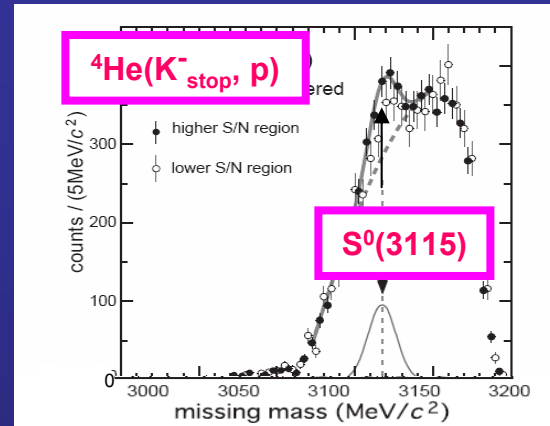
- FOPI (heavy ion collisions)
- FINUDA (K^-_{stop})
- OBELIX ($\bar{p} \text{ He}$)
- KEK-PS E549 (K^-_{stop})



Initial experimental results...

- Hunting K^- bound systems [K^- NNN] with (semi) inclusive reactions ${}^4\text{He}(K^-_{\text{stop}}, N)$ by KEK-PS E-471
 - Peak in the recoiling nucleon momentum at $\sim 500 \text{ MeV}/c$, observed in coincidence with a fast π^-
 - Results compatible with the predictions by Akaishi-Yamazaki
 - ${}^4\text{He}(K^-_{\text{stop}}, p)$: withdrawn (arXiv:0708.2968v1)
 - ${}^4\text{He}(K^-_{\text{stop}}, n)$: currently under revision
- A further observation: E930@AGS
 - ${}^{16}\text{O}(K^-_{\text{in-flight}}, n){}^{15}_{K^-}\text{O}$
 ${}^{15}_{K^-}\text{O}$: bound state at $\sim 90 \text{ MeV}$

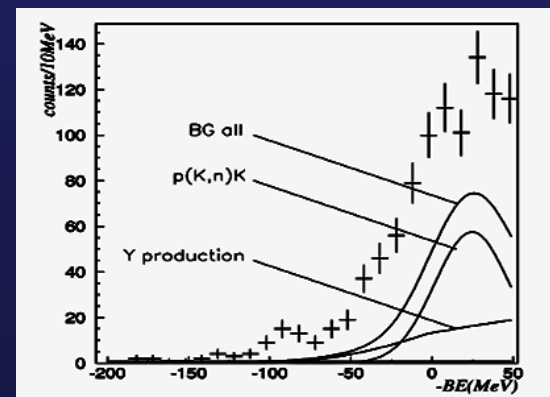
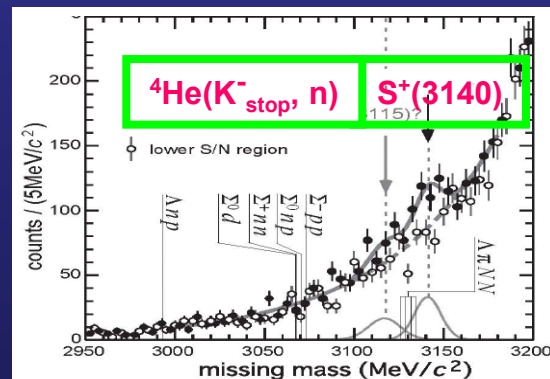
⇒ Careful about relying on (missing mass) inclusive measurements only !



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${}^4\text{He}(K^-_{\text{stop}}, p)$

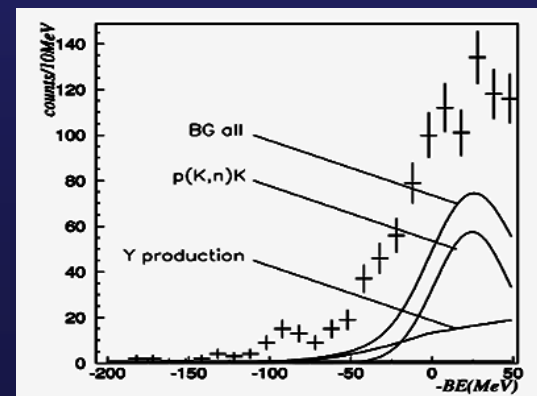
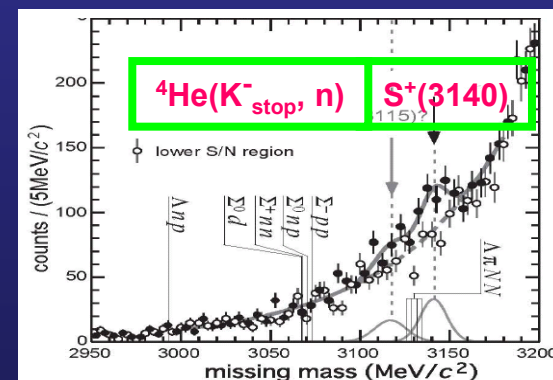
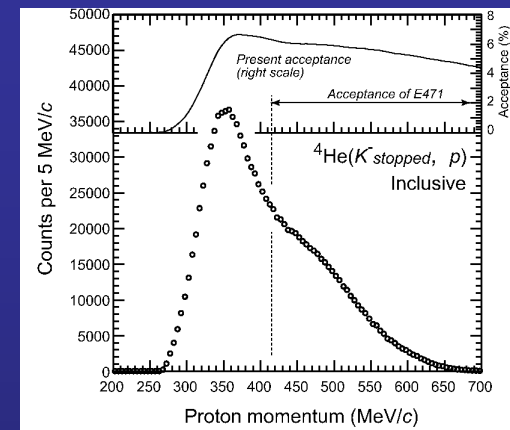


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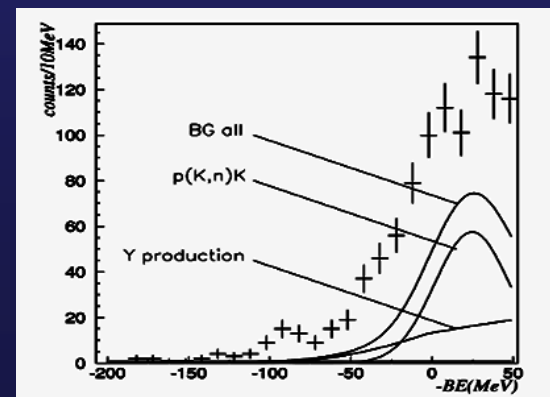
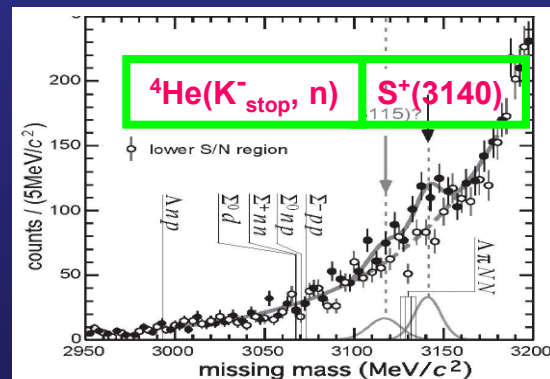


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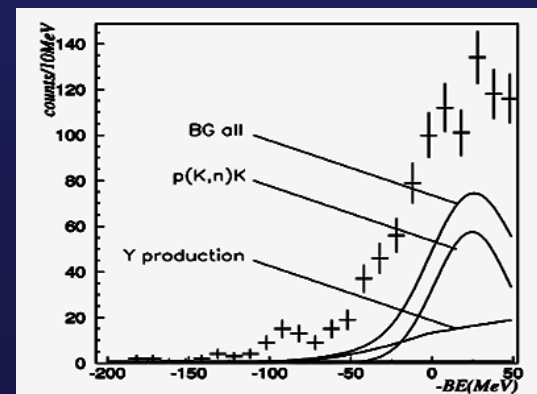
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${}^4\text{He}(K^-_{\text{stop}}, p)$

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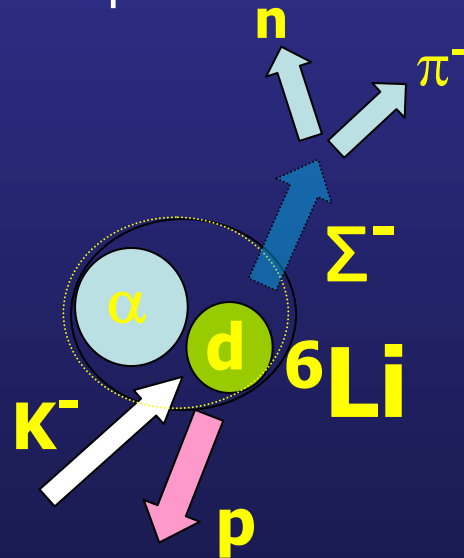
See talk of Sato, M.

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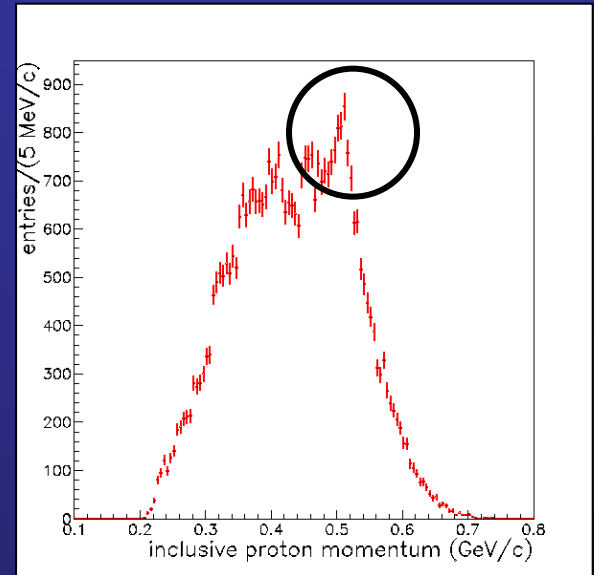


FINUDA: Study of the ${}^6\text{Li}(\text{K}^-, \text{p})\text{X}$ reaction

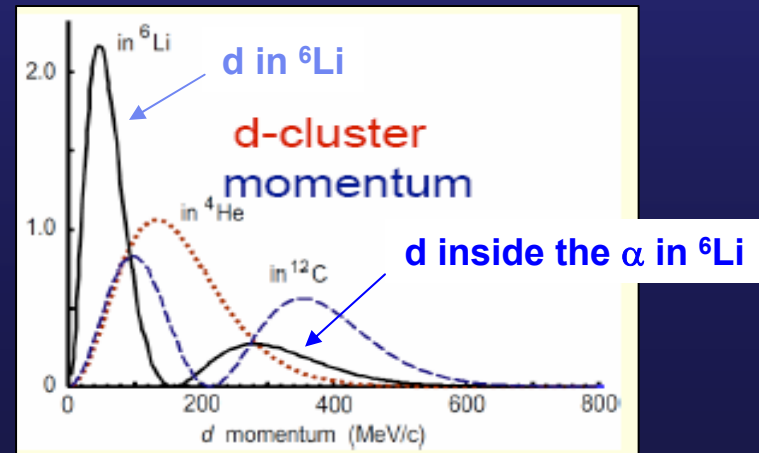
- Study of the proton missing mass:
 - Peak found at about 500 MeV/c
 - Interpretation: the proton peak is simply due to two nucleon absorption reaction:



- Nothing exotic: simple reaction mechanism

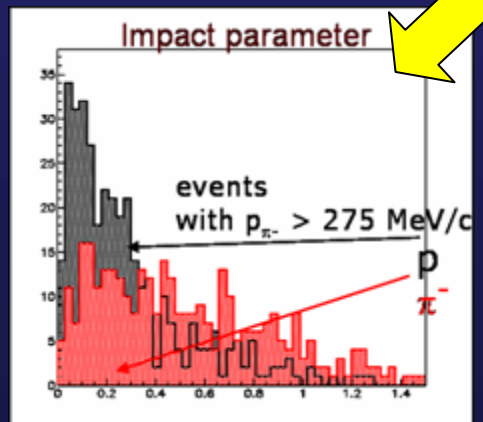
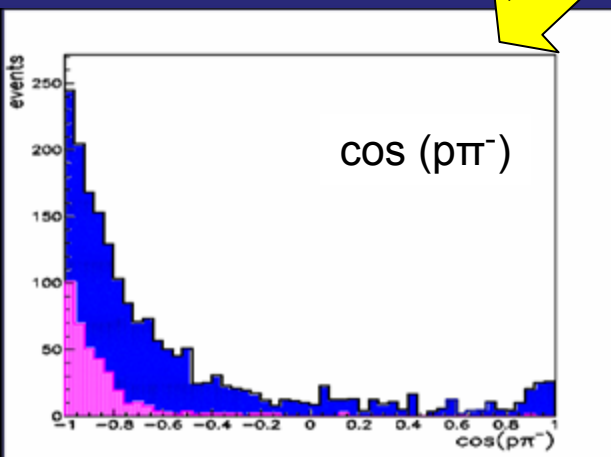
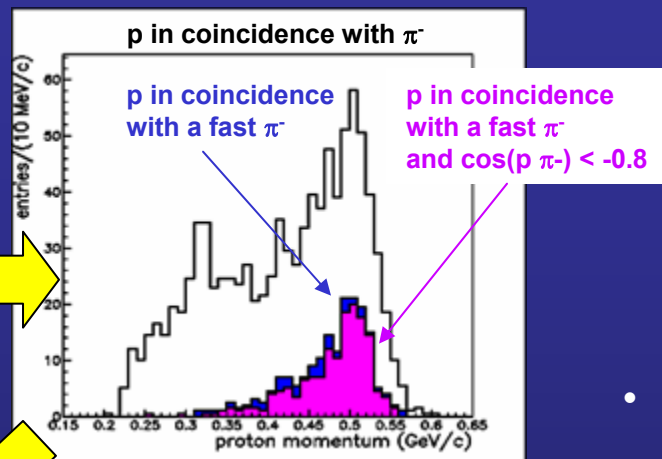
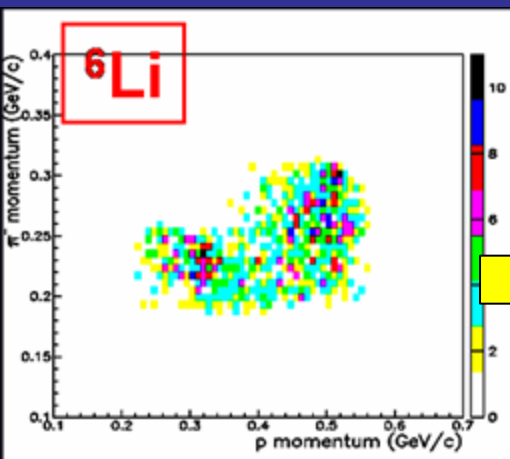


FINUDA Coll., NPA 775 (2006), 35



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 $[K^0NNN]$ cluster

Back-to-back angular correlation proper of a two-body reaction (isotropy expected from DBKS $p \pi^-$)

- 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, $\cos(p\pi^-)$, topological constraint ...

Experimental approaches

- **Missing mass spectroscopy**

- Measurement of the momentum of monochromatic recoiling particles in the $A(K^-,N)X$ reaction

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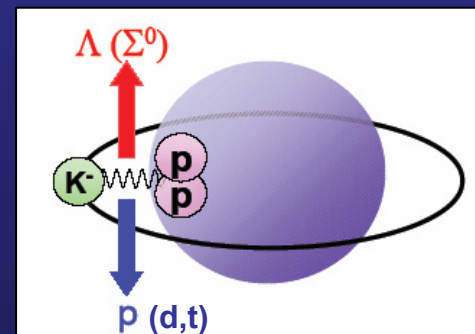
- **Invariant mass spectroscopy**

- Based on the kaonic nuclear state decaying into YN pairs

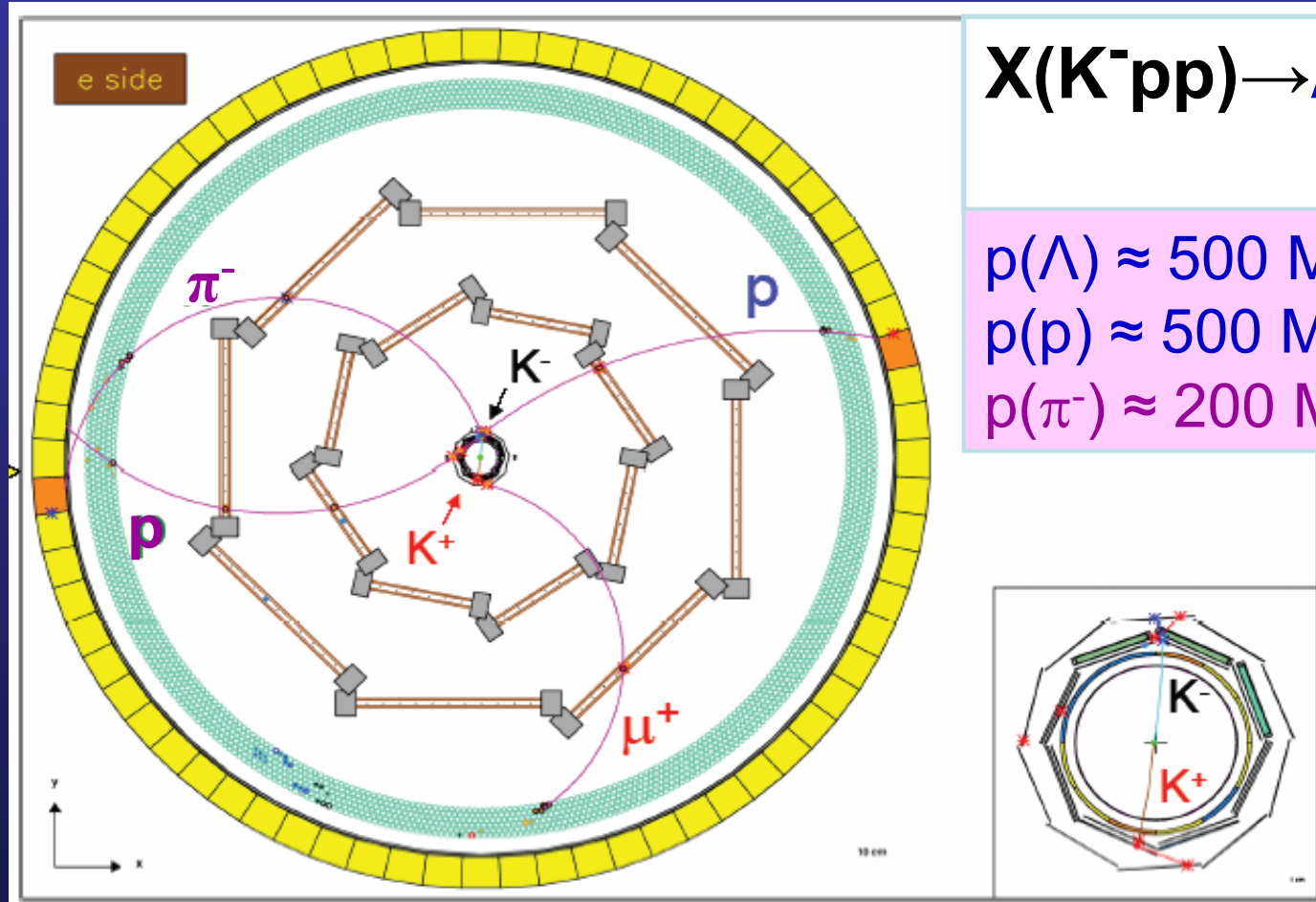
- $(K^-pp) \rightarrow \Lambda + p$
- $(K^-ppn) \rightarrow \Lambda + d$
- Typically:
 - $p_{\Lambda,p} \sim 500 \text{ MeV}/c$
 - $p_{\Lambda,\pi} < 200 \text{ MeV}/c$
 - $p_{\text{decay } p} \sim 500 \text{ MeV}/c$

- Full event reconstruction desirable (necessary)
- Angular correlation between the emitted pairs necessary (desirable)

- FOPI (heavy ion collisions)
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K-pp invariant mass studies with FINUDA



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

$\searrow \pi^- p$

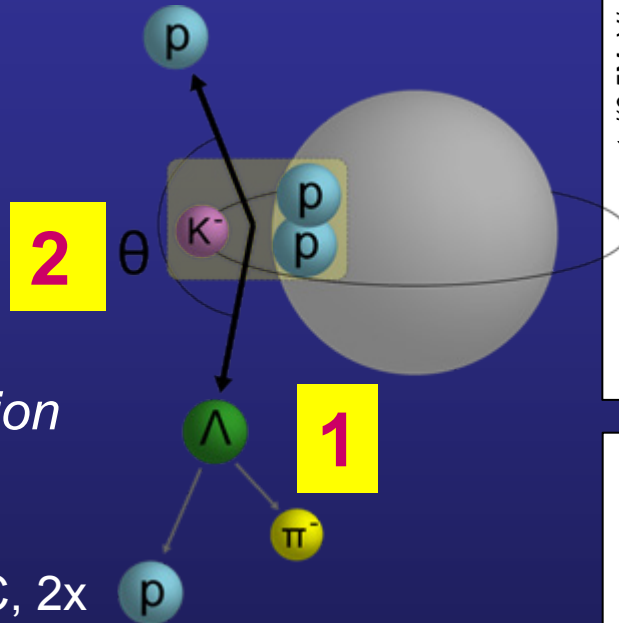
$p(\Lambda) \approx 500 \text{ MeV}/c$
 $p(p) \approx 500 \text{ MeV}/c$
 $p(\pi^-) \approx 200 \text{ MeV}/c$

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

[K-pp] system identification in FINUDA

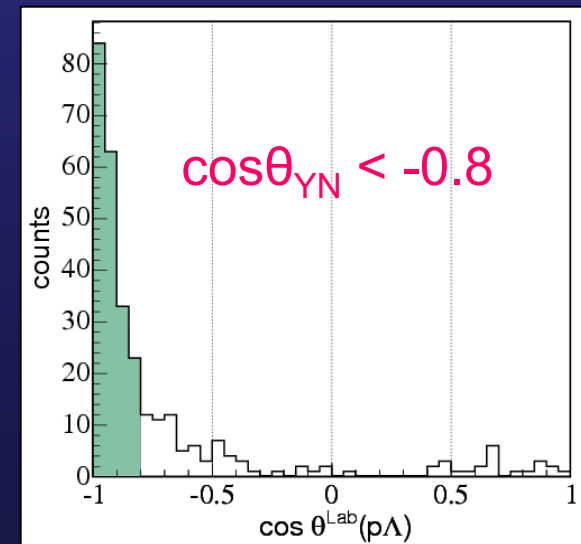
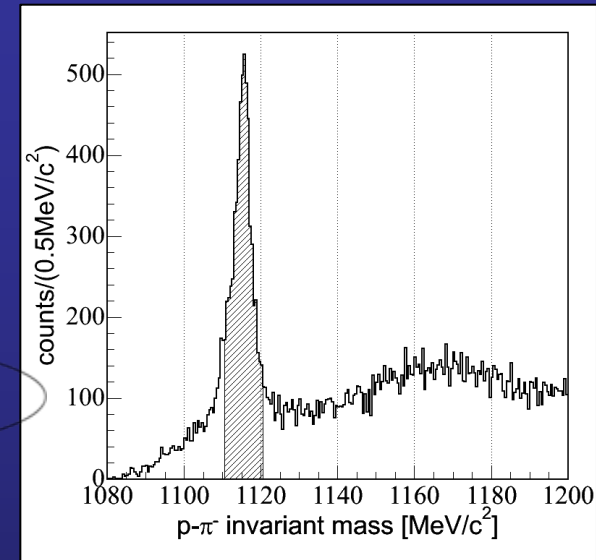
1. reconstruction of Λ 's

- $p_{\Lambda} > 300 \text{ MeV}/c$
- 6 MeV FWHM



2. Λ and p angular correlation

- Events with a Λ - p coincidence: $\sim 5\%$
- Light targets only ($3 \times {}^{12}\text{C}$, $2 \times {}^6\text{Li}$, $1 \times {}^7\text{Li}$)
- Λ p should be oppositely emitted, apart from FSI

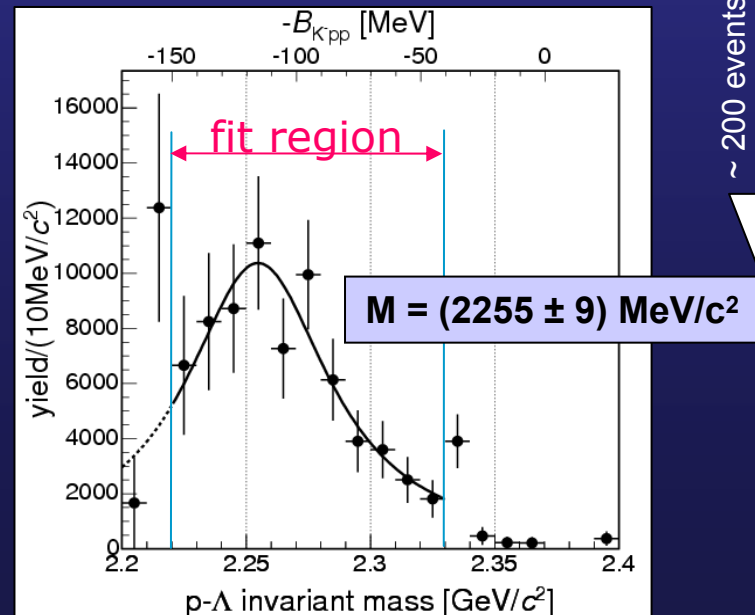
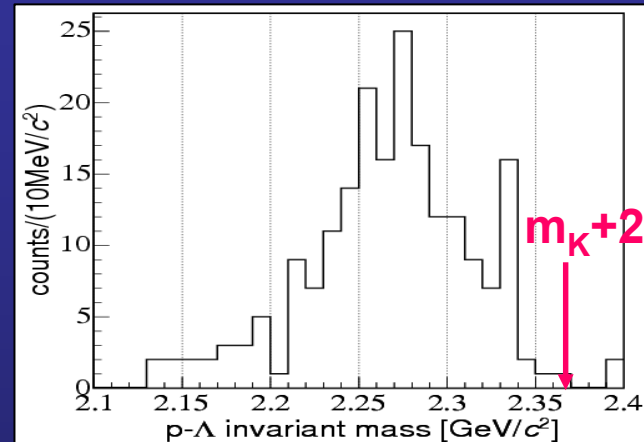


(Λ p) invariant mass in FINUDA: observation of a possible bound state I

- High resolution tracks *only*
- A bump is observed
 - **Two nucleon absorption**
 - $K^- + (pp) \rightarrow \Lambda p$
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**
 - $K^- (pp) \rightarrow X \rightarrow \Lambda p$
 $\rightarrow \Sigma^0 p \rightarrow \Lambda \gamma p$

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

SEMI-EXCLUSIVE ANALYSIS



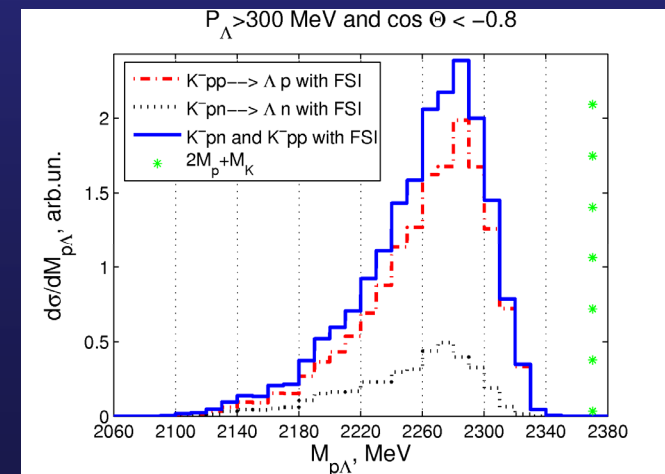
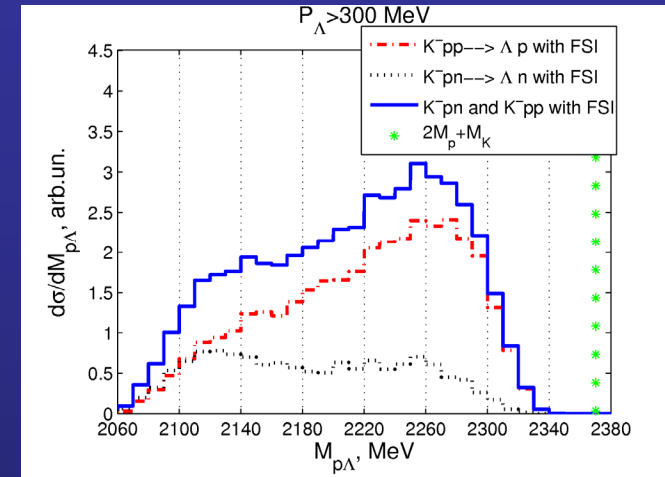
~ 200 events in the published paper

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, $\bar{p}^4\text{He}$, where the rescattering effects should be less sizeable

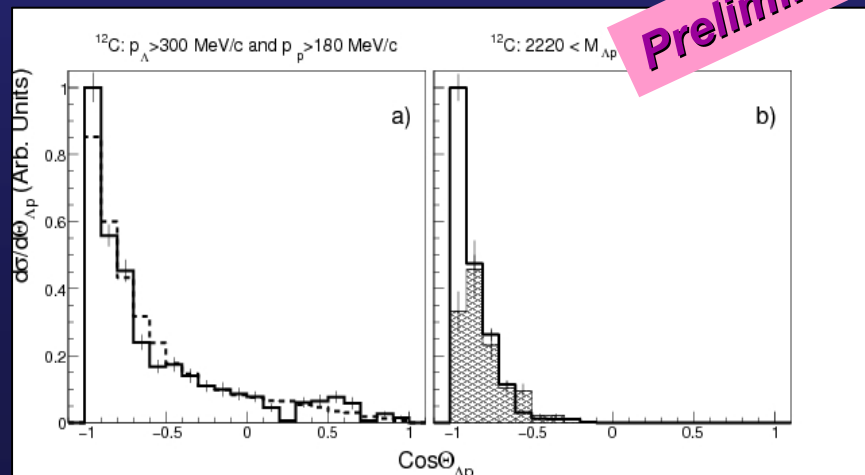
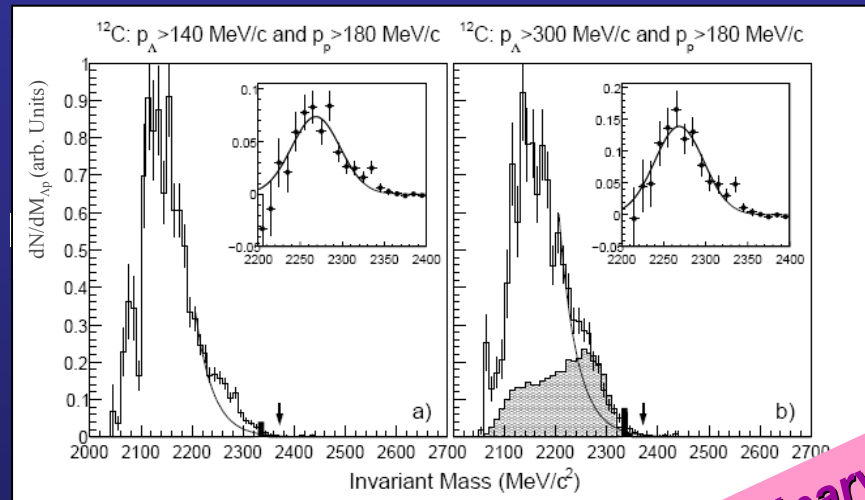


($pp\pi^-$) invariant mass in FINUDA: observation of a possible bound state II

Shorter tracks with less resolution included

INCLUSIVE ANALYSIS

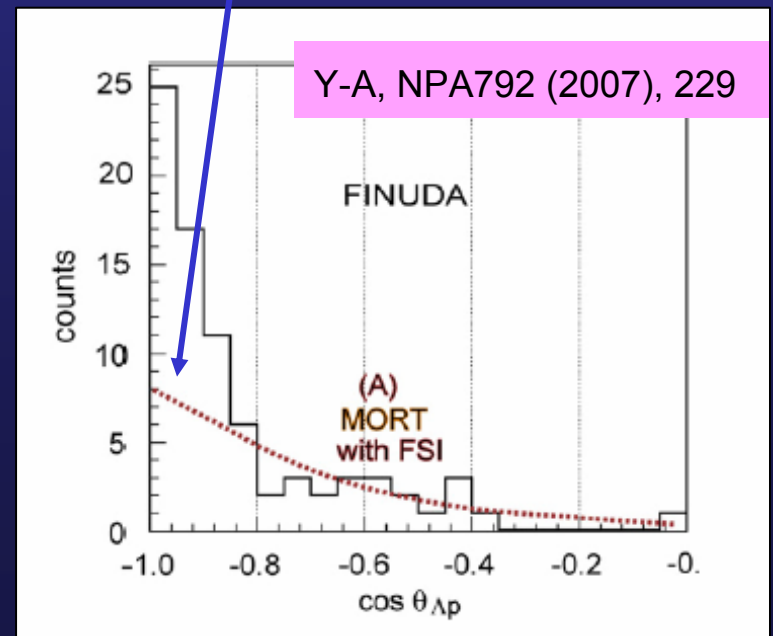
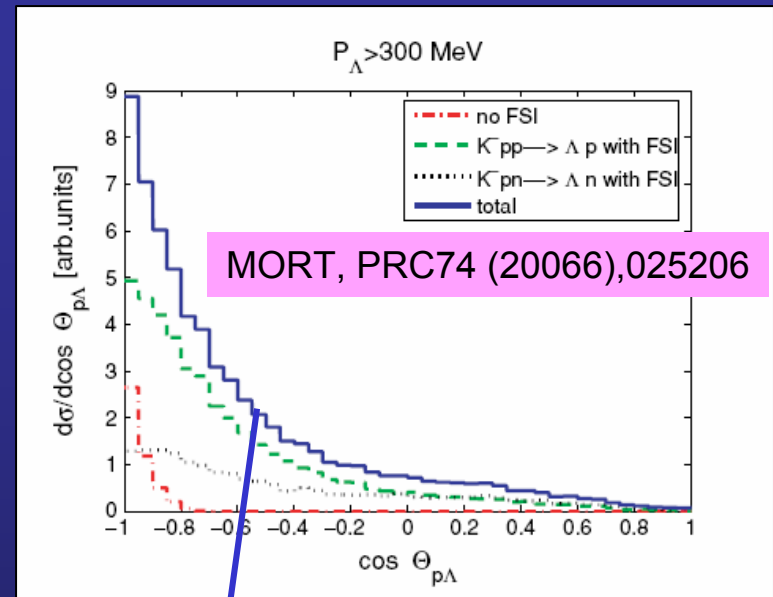
- Larger acceptance
- Larger background
- Bump confirmed below the mass threshold of the unbound K^-pp system:
 $m=2274$ MeV, $\Gamma= 56$ MeV (slightly narrower)
 - Good agreement with the first result
 - 750 events in the bump (statistics 8x)
 - No angular cuts
- Angular correlations:
 - Back-to-back 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

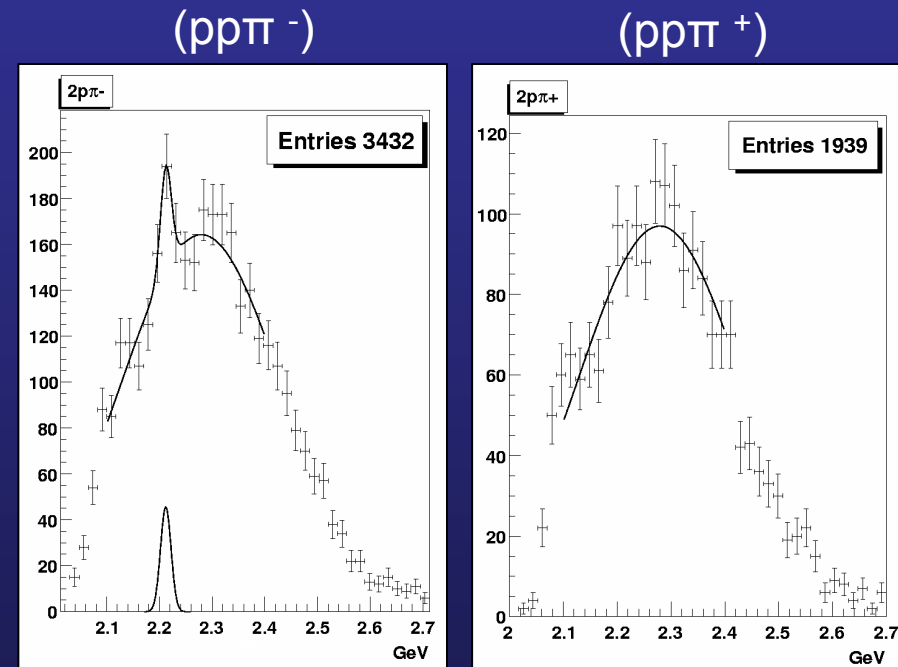
- All the experimental spectra are corrected for acceptance
- **Inclusive analysis:** FSI simulation normalized to the data
 - They account for 30% on the whole reaction strength
- **Exclusive analysis:** at the variance of the theoretical predictions, the experimental distribution is sharply peaked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



(Λp) Invariant mass from \bar{p} annihilation at rest in ${}^4\text{He}$ (OBELIX data)

- Antiproton annihilation at rest: a good environment for the production of strangeness
- OBELIX data: $\bar{p}{}^4\text{He} \rightarrow 5$ prongs:
 - $\bar{p}{}^4\text{He} \rightarrow (p\pi^-)p K^0 X$
- Study of the $(p\Lambda)$ 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 $(p\pi^-)$ channel while is absent in the $(p\pi^+)$ channel:
 - Statistical significance 3.7σ
 - $Y < 1.5 \times 10^{-4}/\text{stopped } p$
 - FSI effect?
 - Lower number of residual nucleons
 - No angular cuts

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



$$M = 2212.1 \pm 4.9 \text{ MeV}$$

$$B = 169 \pm 4.9 \text{ MeV}$$

$$\Gamma = < 24.4 \pm 8.0 \text{ MeV}$$

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

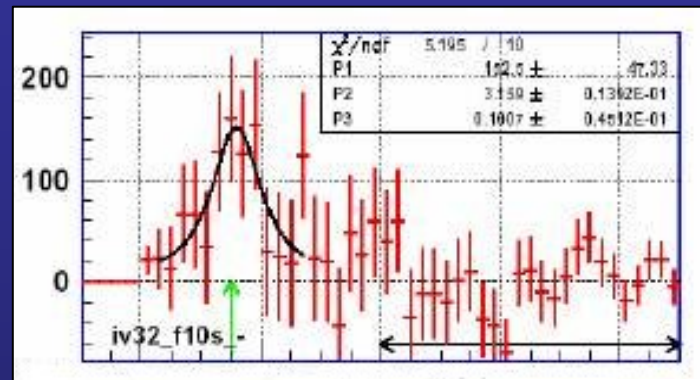
- FOPI - GSI
 - Ni+Ni @ 1.93 AGeV
 - Use of invariant mass spectroscopy to search for short-lived Λ X resonances
 - $[K^-ppn] \rightarrow \Lambda$ d

$$\begin{aligned} M &= 3159 \pm 20 \text{ MeV} \\ B &= 151 \pm 20 \text{ MeV} \\ \Gamma &= 100 \pm 50 \text{ MeV} \end{aligned}$$

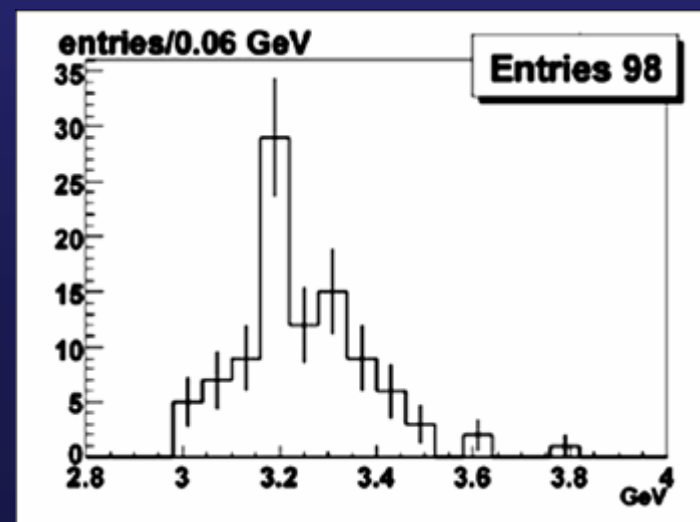
- OBELIX $\bar{p}^4\text{He}$
 - Hints of a Λ d signal at 2.6σ
 - Fewer statistics
 - Lower background

$$\begin{aligned} M &= 3190 \pm 15 \text{ MeV} \\ B &= 120 \pm 15 \text{ MeV} \\ \Gamma &= < 60 \text{ MeV} \end{aligned}$$

PRELIMINARY (AND ONLY)
RESULTS EXA05

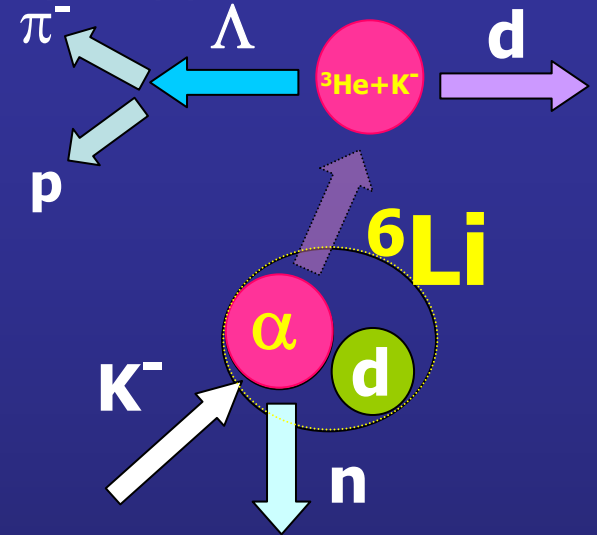


Λ d invariant mass

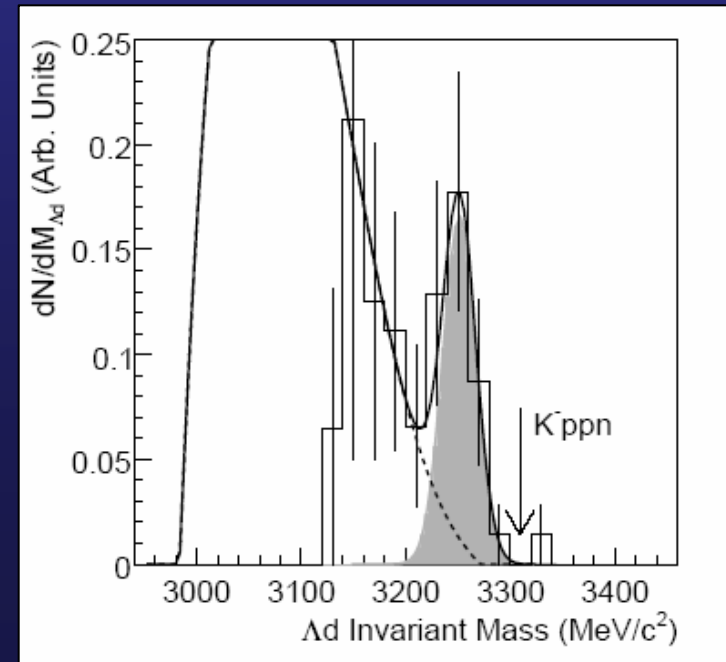


FINUDA: study of ${}^6\text{Li}(\text{K}^-, \Lambda\text{d})\text{X}$ (I)

- Λd invariant mass
- Use of ${}^6\text{Li}$ target: low background
- ${}^6\text{Li}$ is a well known $[\alpha+\text{d}]$ cluster
 - Bump observed at $M_{\Lambda\text{d}} = 3251 \text{ MeV}$, $\Gamma_{\Lambda\text{d}} = 37 \text{ MeV}$
 - 25 events in the peak, statistical significance 3.9σ

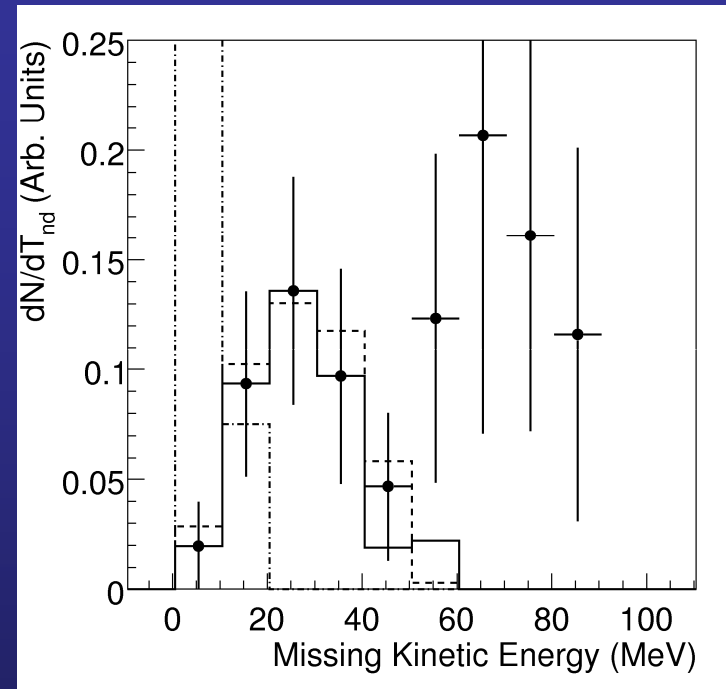


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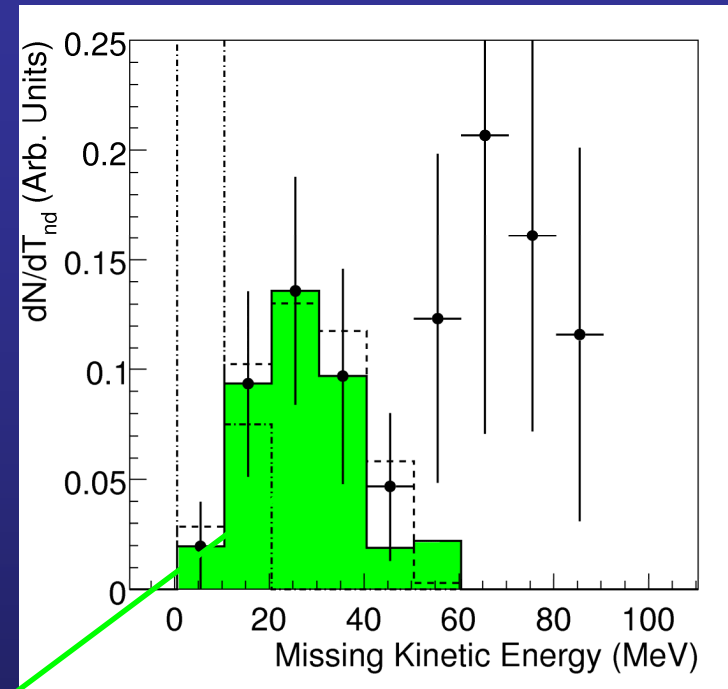
FINUDA: study of ${}^6\text{Li}(\text{K}^-, \Lambda\text{d})\text{X}$ (II)

- The shape of the missing kinetic energy distribution is reproduced only by the ${}^6\text{Li}(\text{K}^-_{\text{stop}}, \Lambda\text{d})\text{nd}$ reaction channel, with:
 1. a spectator deuteron and
 2. the neutron carrying away the whole momentum



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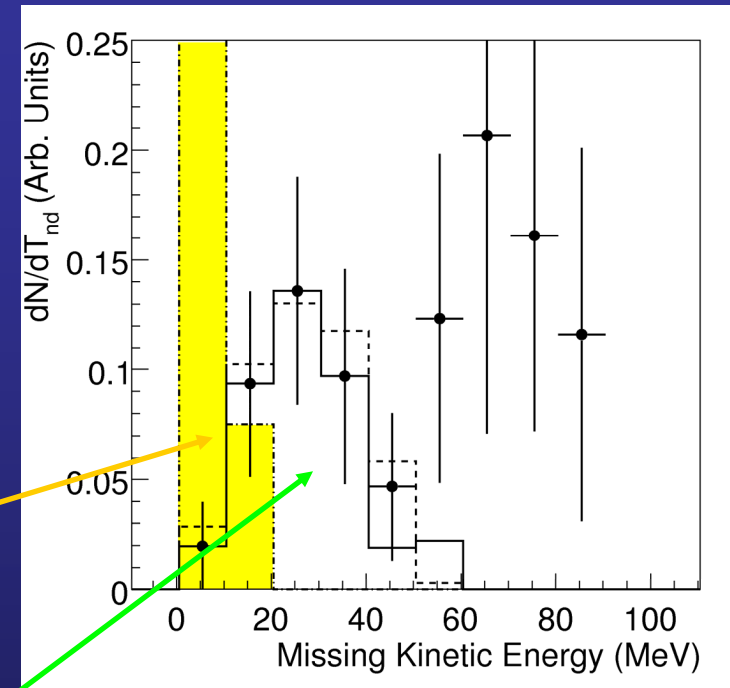
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${}^6\text{Li}(\text{K}^-_{\text{stop}}, \Lambda\text{d})\text{nd}$ for events under the bump, $3220 < M_{\Lambda\text{d}} < 3280 \text{ MeV}/c^2$

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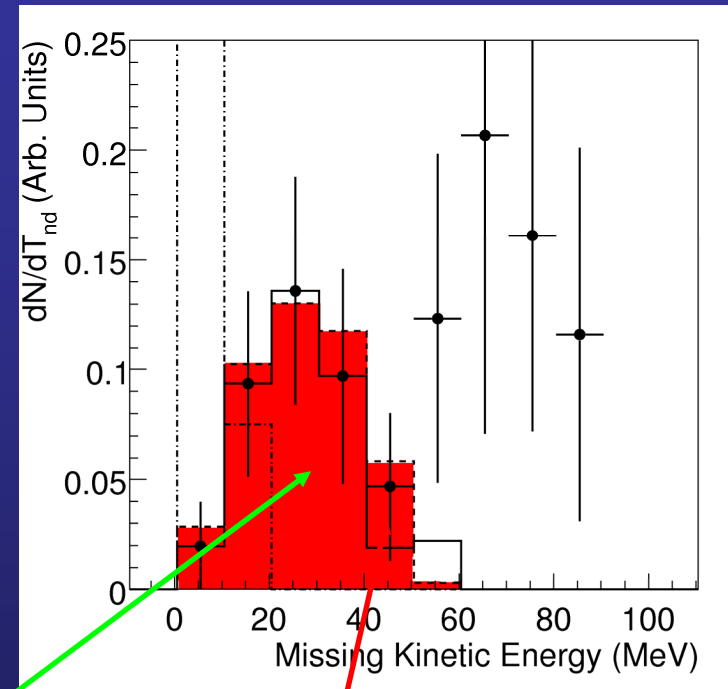


Simulation: ${}^6\text{Li}(\text{K}_{\text{stop}}^-, \Lambda\text{d})\text{t}$

${}^6\text{Li}(\text{K}_{\text{stop}}^-, \Lambda\text{d})\text{n}$ for events under the bump, $3220 < M_{\Lambda\text{d}} < 3280 \text{ MeV}/c^2$

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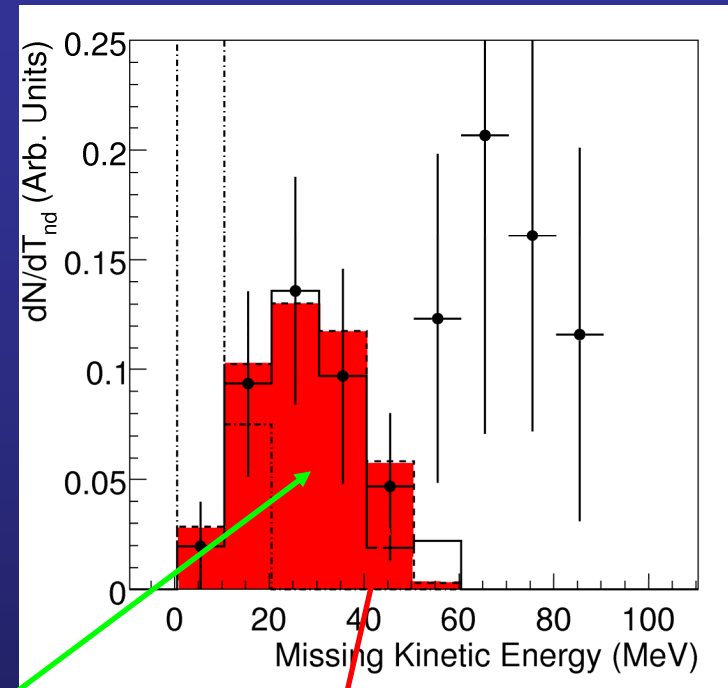
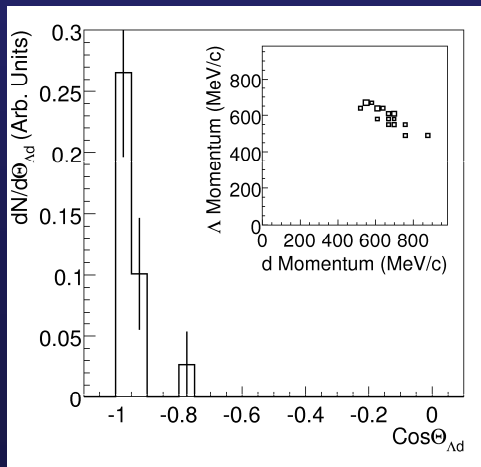
Simulation: ${}^6\text{Li}(\text{K}^-_{\text{stop}}, \Lambda\text{d})\text{nd}$ for events with $3220 < M_{\Lambda\text{d}} < 3280 \text{ MeV}/c^2$ and a spectator deuteron with $T_{\text{d}} < 3 \text{ MeV}$

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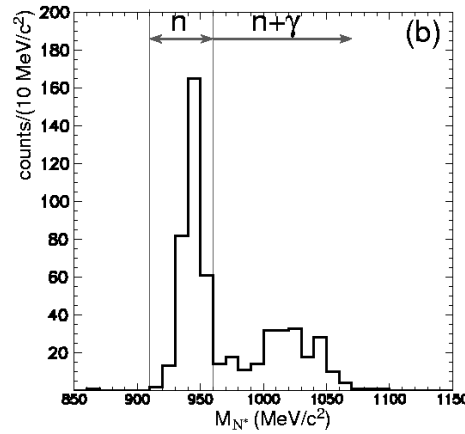
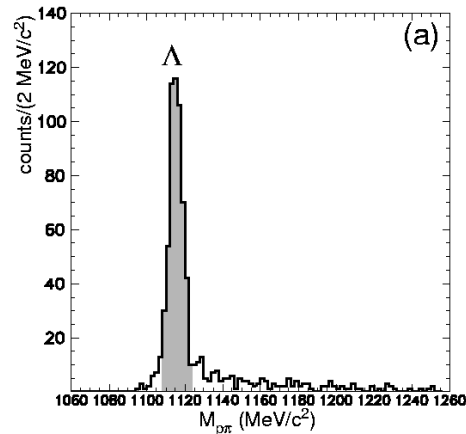
- The events in the bump are strongly back-to-back correlated



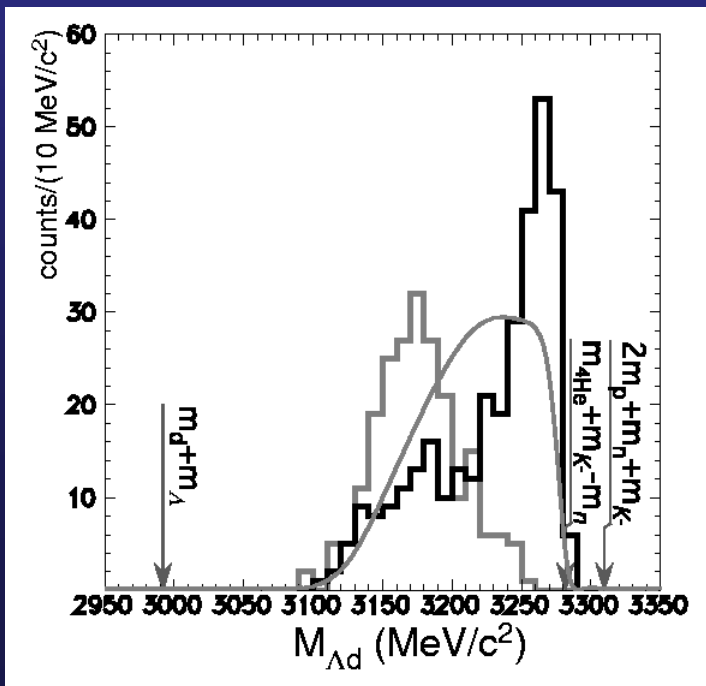
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E549: Λd correlation from $^4\text{He}(K^-_{\text{stop}}, d)$



- $K^- ^4\text{He} \rightarrow \Lambda d (n)$
- detected back-to-back $d p$ pairs with π^- in coincidence
- Λ discriminated from Σ^0 ($\Lambda\gamma$) event by missing mass
- Λd peak at $3282 \text{ MeV}/c^2$ just below mass threshold
- interpreted as 3N absorption $K\text{-ppn} (n) \rightarrow \Lambda d (n)$
- accepted $d p$ back-to-back only, spectra are shaped by the limited phase-space



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 bound kaonic states in nuclei is a recent field in hadron physics raising considerable theoretical and experimental interest
- Several theoretical approaches, rather strong disagreement
 - Hot debate!
- Only few and very recent experimental results claiming the observation of the bound kaonic states
 - 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
- ... but how do we know we are dealing with a “genuine” nuclear bound kaonic states ?
 - Y-A recipe for K^-pp (NPA792(2007)229):
 - the $M_{\Lambda p}$ spectrum is not enough
 - $\Theta_{\Lambda p}$, p_p , p_Λ distribution also needed

Outlook and Conclusions

- FINUDA @ DAΦNE in the last year has collected $\sim 1 \text{ fb}^{-1}$ of K^-_{stop} on ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{13}\text{C}$, ${}^{16}\text{O}$, new results coming soon:
 - Λp vs A
 - Λd vs A
 - Λn , Λpn , Λt (?)
- 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 $\bar{p}^4\text{He}$ ([see talk of Panzarasa, A.](#))
- Future Projects dedicated to the search for bound kaonic states:
 - E15 @ J-PARC: study of ${}^3\text{He}(K^-, n)$ in flight
 - AMADEUS @ LNF: K^- on cryogenic ${}^4\text{He}$ ([see talk of Sirghi, F.C.](#))
- Measurement of the strong interaction level shift of kaonic- ${}^3\text{He}$ atoms:
 - SIDDHARTA@DAΦNE
 - KEK-PS E570 and J-PARC E17
- 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 !