Results on K^- absorption on few-nucleon systems with FINUDA at LNF

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FINUDA Collaboration

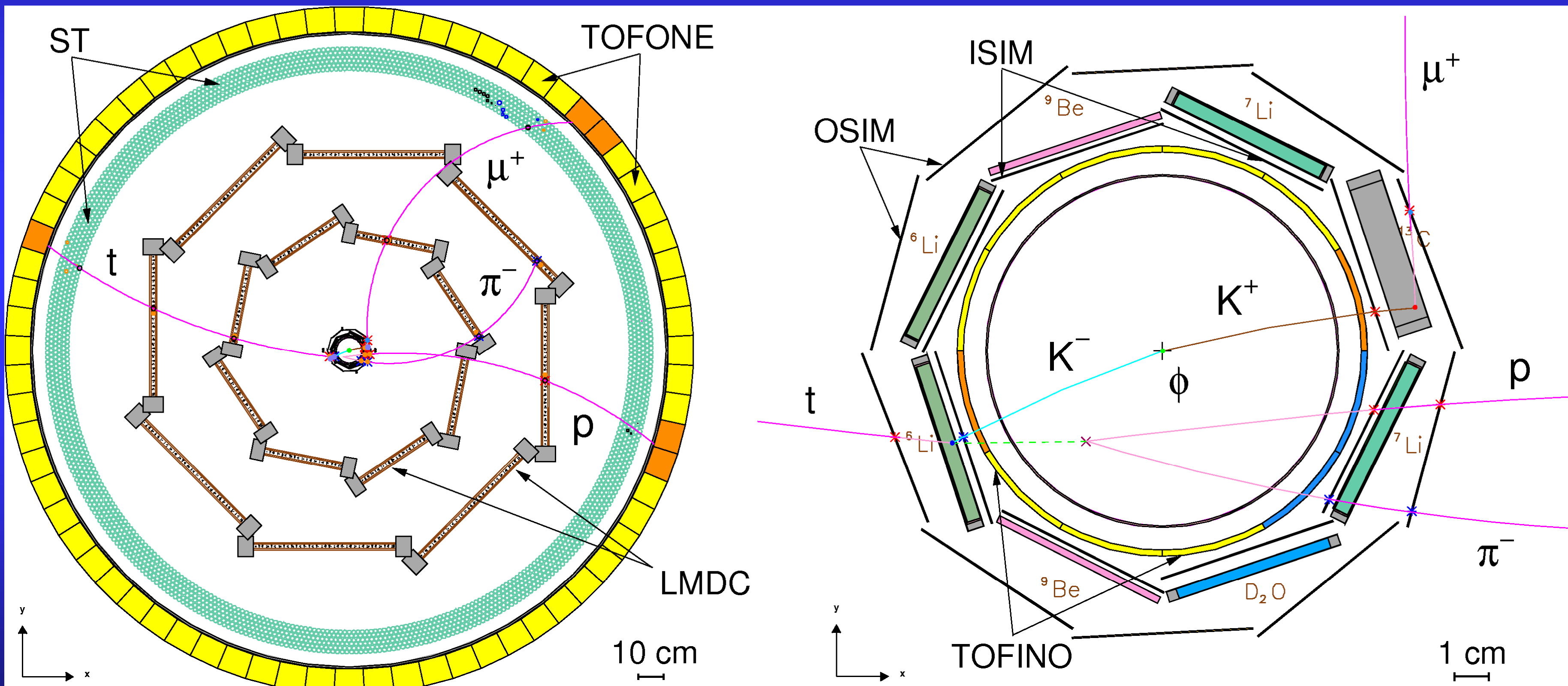
K^- absorption by few nucleons (on nuclei)

- Study of hypernuclei and their decays:
  - One nucleon absorption (pion-emission)
  - $K^- N \rightarrow \pi Y \Rightarrow K^- A \rightarrow \Lambda(\Sigma)\ \pi X$
- Search for possible deeply bound kaon states:
  - Two nucleon absorption (no-pion emission)
  - $K^- (2N) \rightarrow N Y \Rightarrow K^- A \rightarrow \Lambda(\Sigma)\ pX$, $K^- A \rightarrow \Lambda(\Sigma)\ nX$
  - Three nucleon absorption (no-pion emission)
  - $K^- (3N) \rightarrow NN Y \Rightarrow K^- A \rightarrow \Lambda(\Sigma)\ dX$
  - Four nucleon absorption (no-pion emission)
  - $K^- (4N) \rightarrow NNN Y \Rightarrow K^- A \rightarrow \Lambda(\Sigma)\ tX$

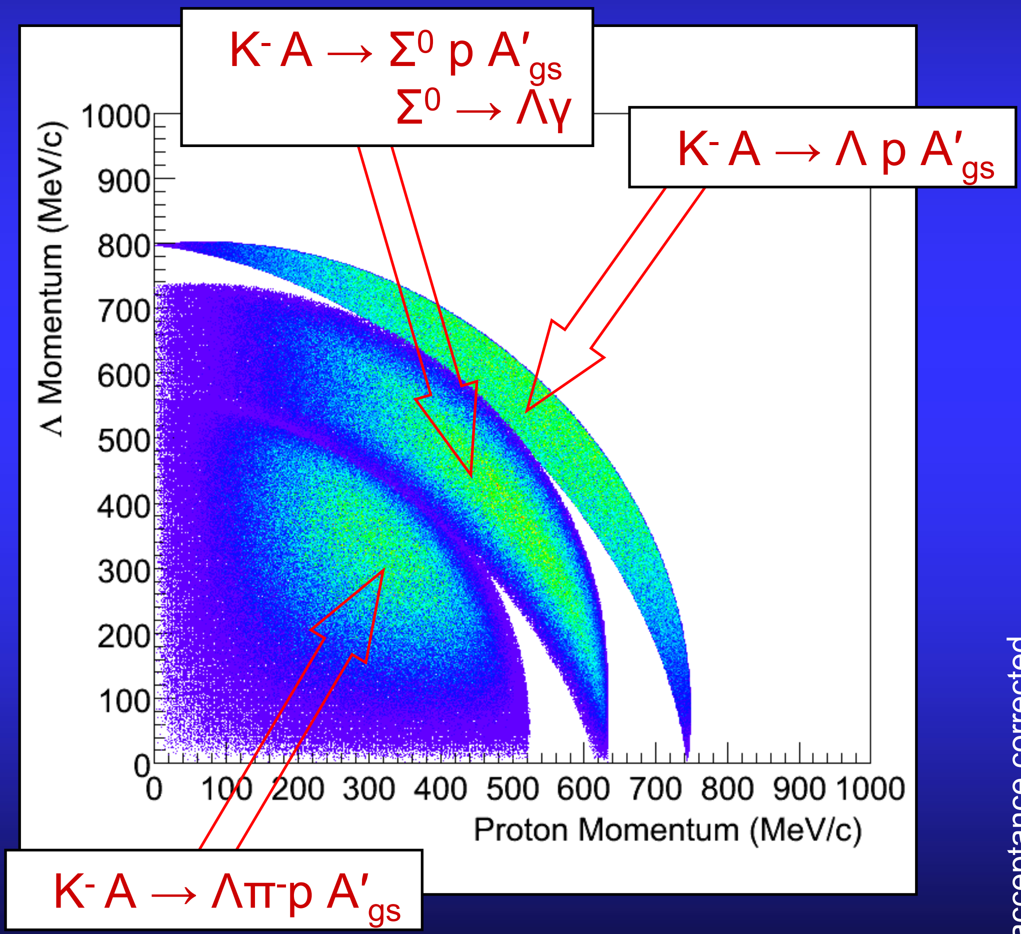
Λ identification with FINUDA

FINUDA FRONTAL VIEW

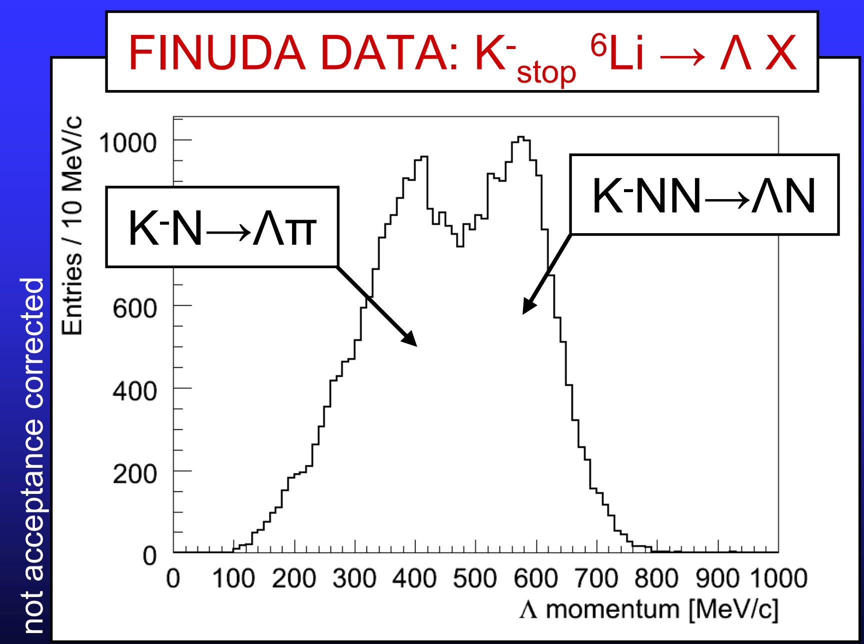
VERTEX REGION



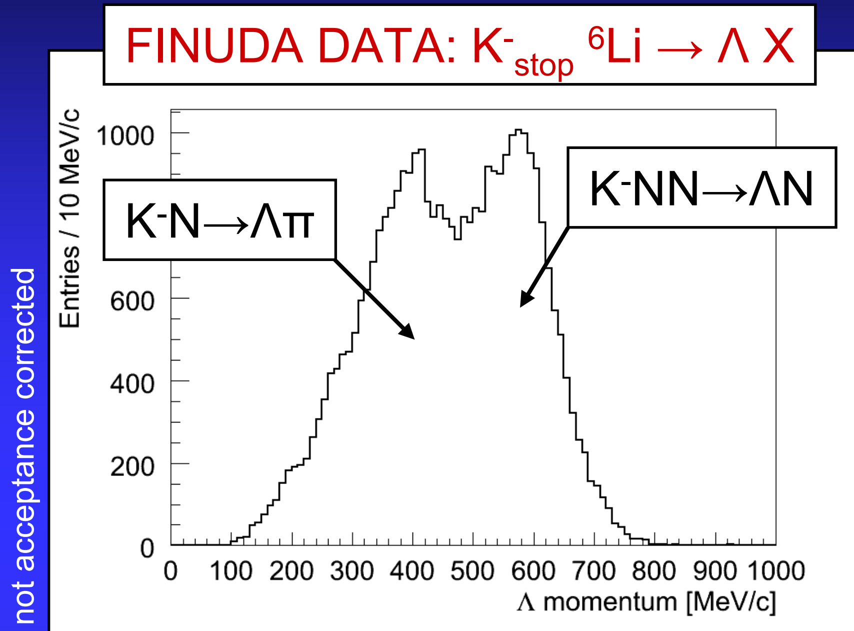
$^{6}Li(K^{-}_{stop},\Lambda)X$ Phase Space Simulations

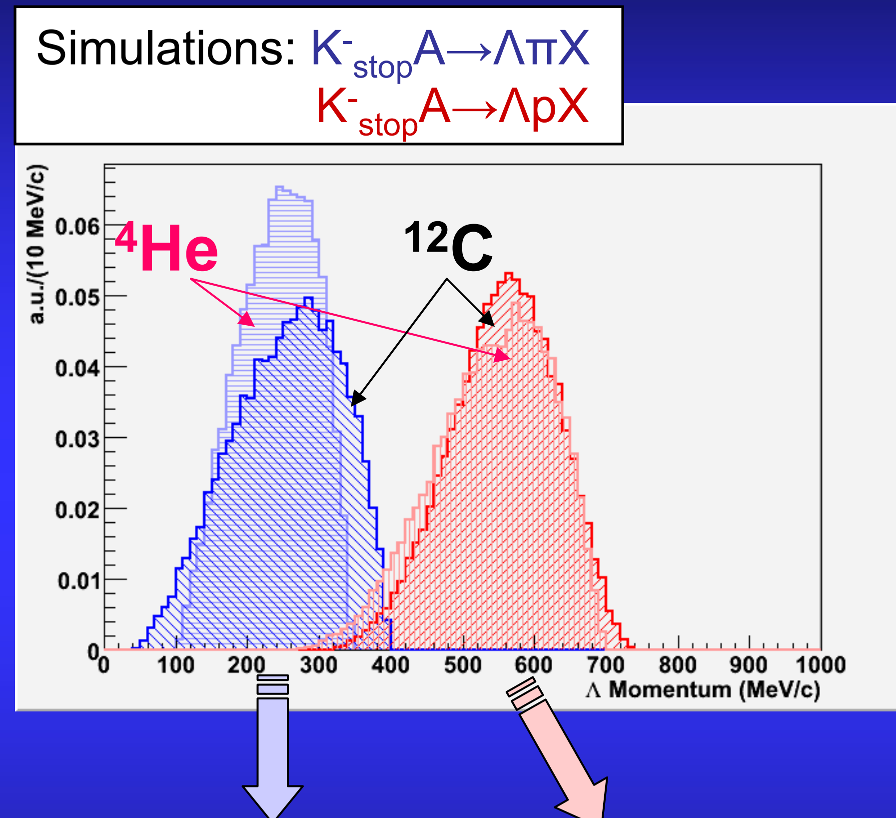


To measure the non-mesonic channels it is necessary to detect p (n,d,t) and Λ with high resolution in the high momentum region (mesonless Λ-production region)



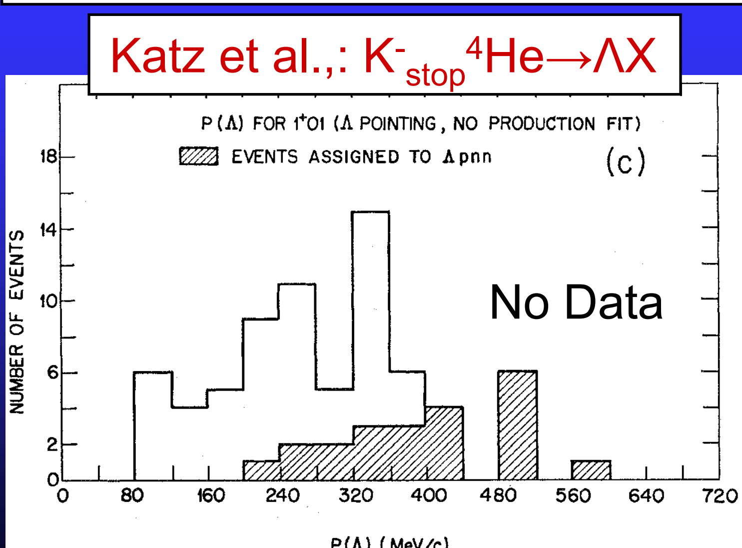
Λ momentum from K^-_{stop}





$K^-N \rightarrow \Lambda\pi$ absorption

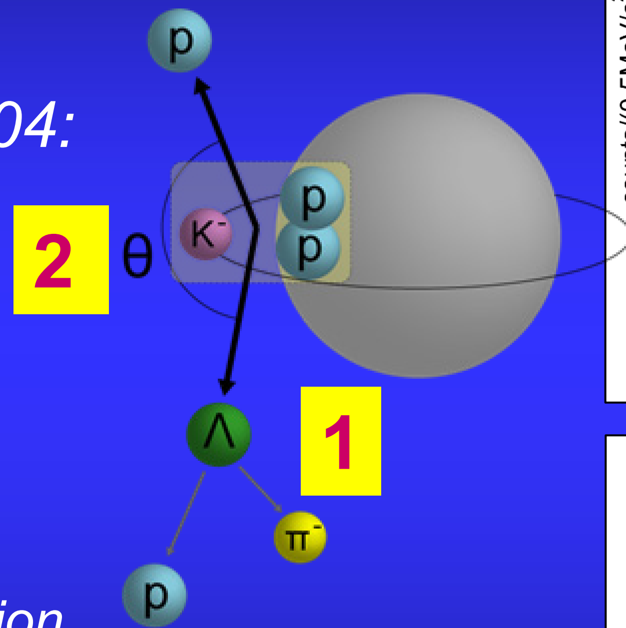
$K^-NN \rightarrow \Lambda p$ absorption

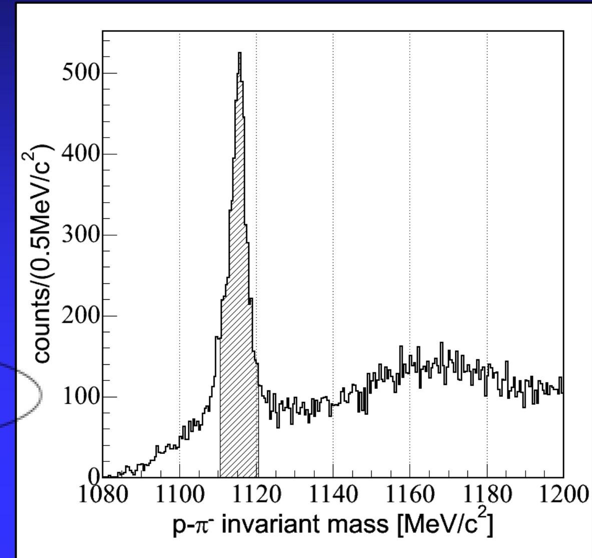


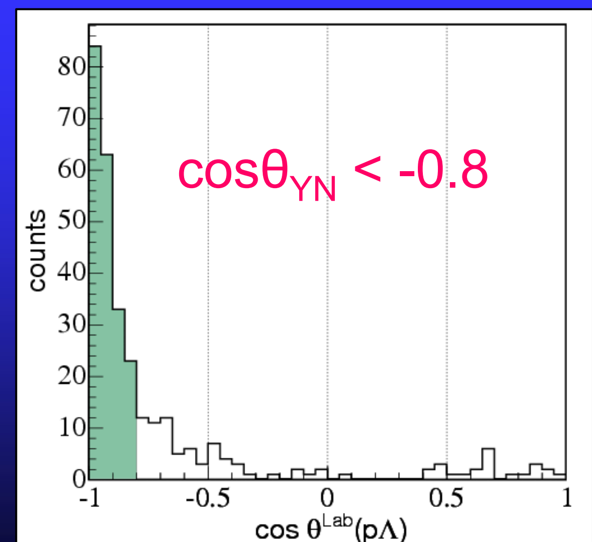
2NA: K^- pp identification with FINUDA

Λp Invariant Mass to measure K^-pp:

1. *Data taking 2003-2004:*
   - *200 pb^{-1}*
2. *reconstruction of Λ's*
   - p_Λ > 300 MeV/c
   - 6 MeV FWHM
3. *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 emitted in opposite directions, apart from FSI







Λp invariant mass in FINUDA

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

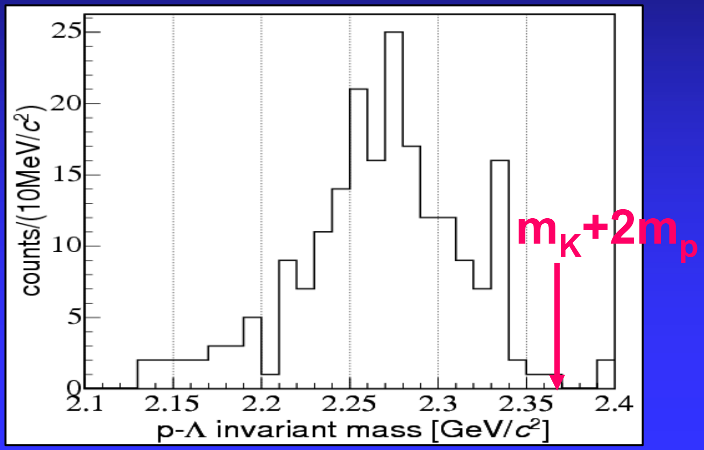
      peak expected at 2.34 GeV
    - $K^- + (pp) \rightarrow \Sigma^0 p \rightarrow \Lambda\gamma\, p$

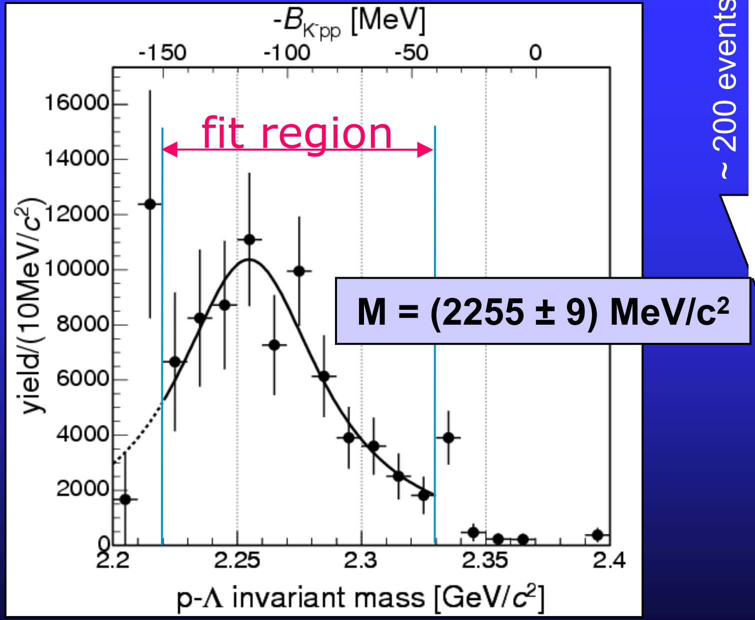
      74 MeV lower distribution, and broadened
  - **Kaon nuclear bound state formation**
    - $\mathbf{K^-(pp) \rightarrow X \rightarrow \Lambda p}$

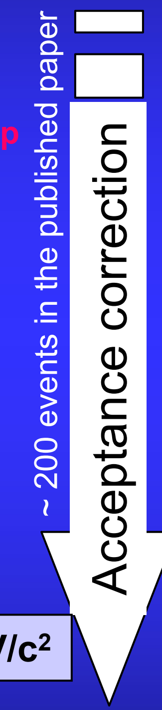
      $\mathbf{\rightarrow \Sigma^0 p \rightarrow \Lambda\gamma\, p}$

B = 115^{+6}_{-5}(stat)$^{+3}_{-4}$(sys) MeV
Γ = 67^{+14}_{-11}(stat)$^{+2}_{-3}$(sys) MeV

SEMI-EXCLUSIVE ANALYSIS







FINUDA Coll., PRL 94(2005)212303

Alternative interpretations of the Λp bump

- $K^- pp \rightarrow [K^- pp] \rightarrow \Lambda p$: [K-pp] bound state (FINUDA)
- QF-2NA $K^- pp \rightarrow \Lambda p$ followed by FSI (Magas et al.)
- Dominance of Σ^0 production over Λ:

  QF-2NA $K^- pp \rightarrow \Sigma^0 p$ followed by $\Sigma^0 \rightarrow \Lambda\gamma$ decay
- QF-2NA $K^- NN \rightarrow \Sigma N$ followed by $\Sigma N \rightarrow \Lambda N$ conversion reaction:

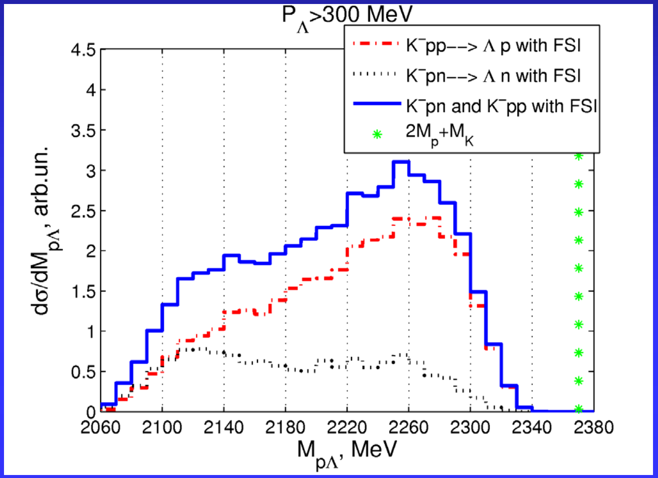
$K^- A \rightarrow \Sigma^{0,+} \pi^{0,-} X$	$K^- A \rightarrow \Sigma^{0,+} n X$	$K^- A \rightarrow \Sigma^{0,-} p X$
$\Sigma^0 p \rightarrow \Lambda p$	$\Sigma^0 p \rightarrow \Lambda p$	$\Sigma^0 n \rightarrow \Lambda n$
$\Sigma^+ n \rightarrow \Lambda p$	$\Sigma^+ n \rightarrow \Lambda p$	$\Sigma^- p \rightarrow \Lambda n$

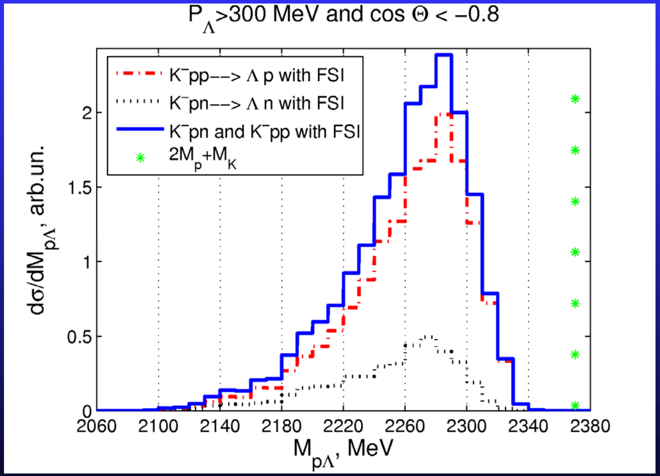
- Decay of heavier kaonic nuclei (Mares et al.)

QF-2NA = Quasi Free Two Nucleon Absorption

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

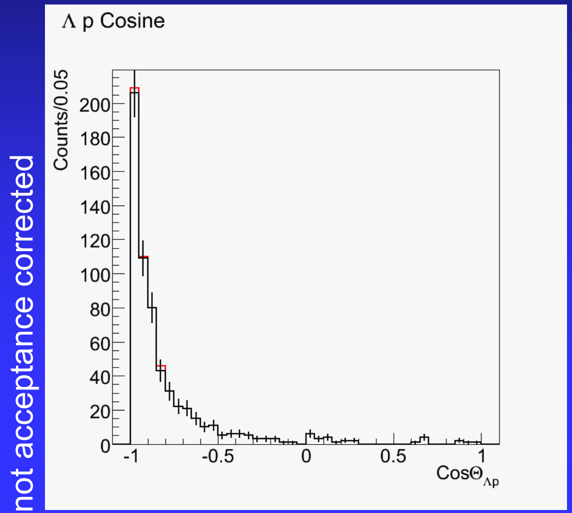
- Magas, Oset et al, PRC74 (2006), 0252006
  - The peak is due to ~90% FSI of p and Λ, no DBKS
  - The bump is a result of the angular cuts applied in the analysis (i.e., a deformation of a flat distribution)
  - 115 MeV as a binding energy is quite too much!
- …but:
  - Analysis of the higher statistics data shows that the deformation of the spectrum is not due to angular cuts
  - No strong dependence on angular distribution from A=6 to A=16
  - FSI alone cannot explain the full spectrum
  - Back-to-back correlation belongs to the data themselves

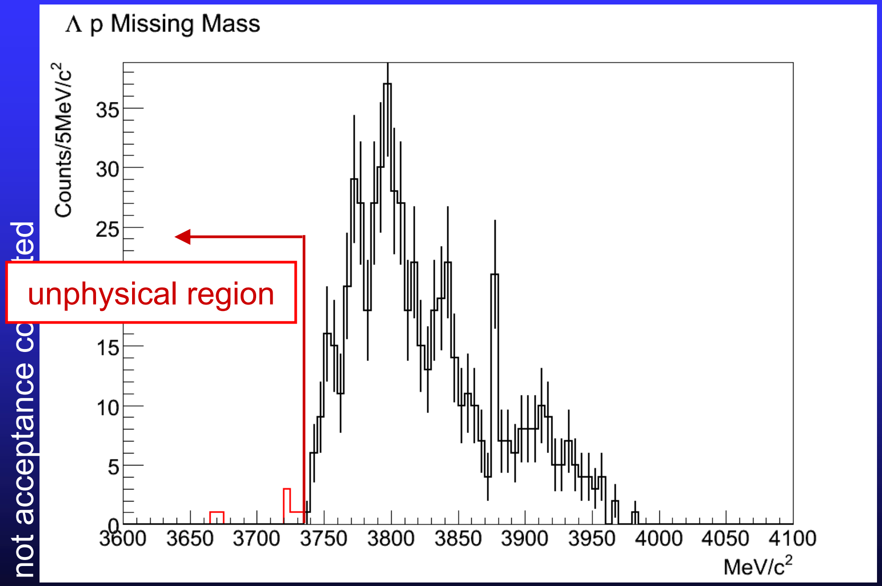


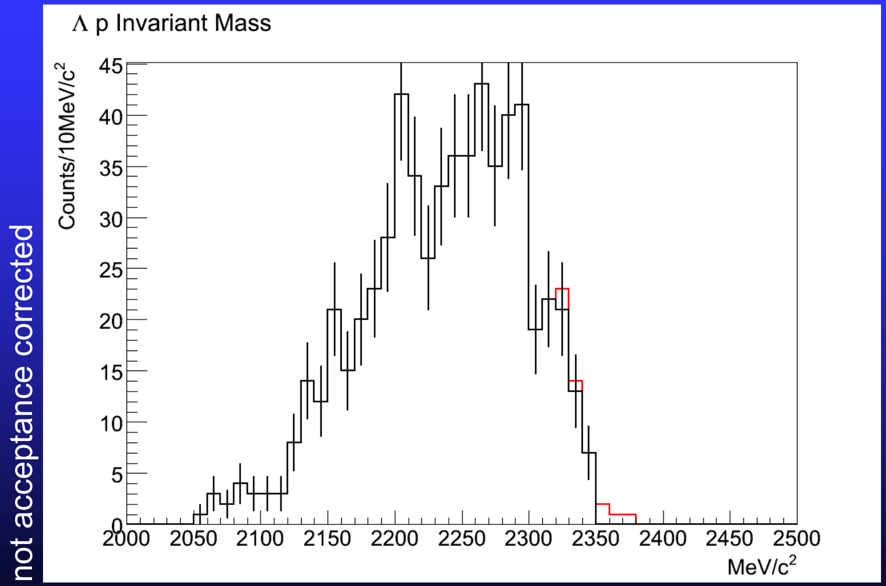


FINUDA: $^{6}Li(K^{-}_{stop},\Lambda p)X$
2006-2007 Data Taking

- 8x statistics on: ^{6}Li (^{7}Li, ^{9}Be)
  - Improved tracking efficiency
  - Extended range of the reconstructed momentum
  - Improved selections (missing mass)
  - Statistics large enough to study single tgt spectra

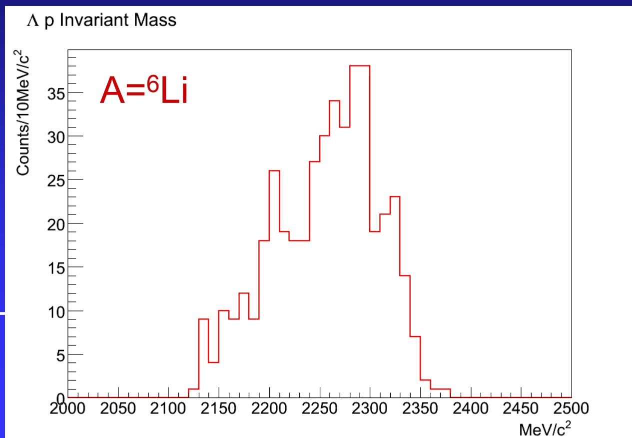






FINUDA: ^{6}Li(K^-_{stop},Λp)X

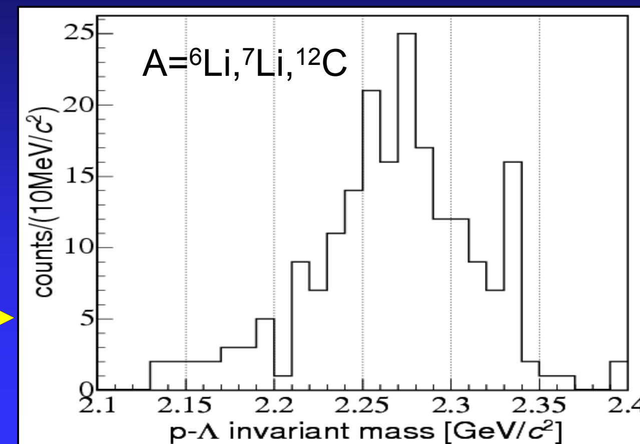
not acceptance corrected



New
inv mass spectra
compatible with
published one

New data ⟷ Old data

Same cuts applied



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FINUDA Coll., PRL 94(2005)212303

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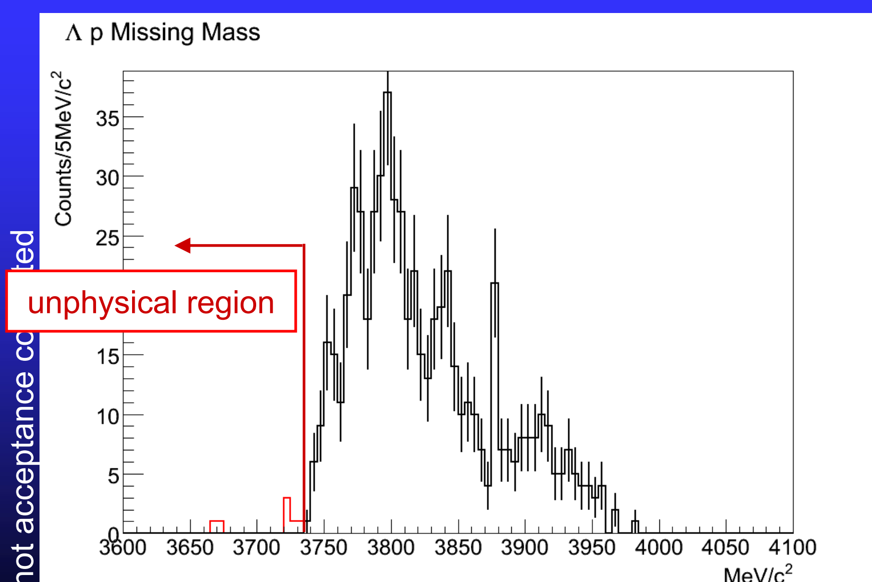

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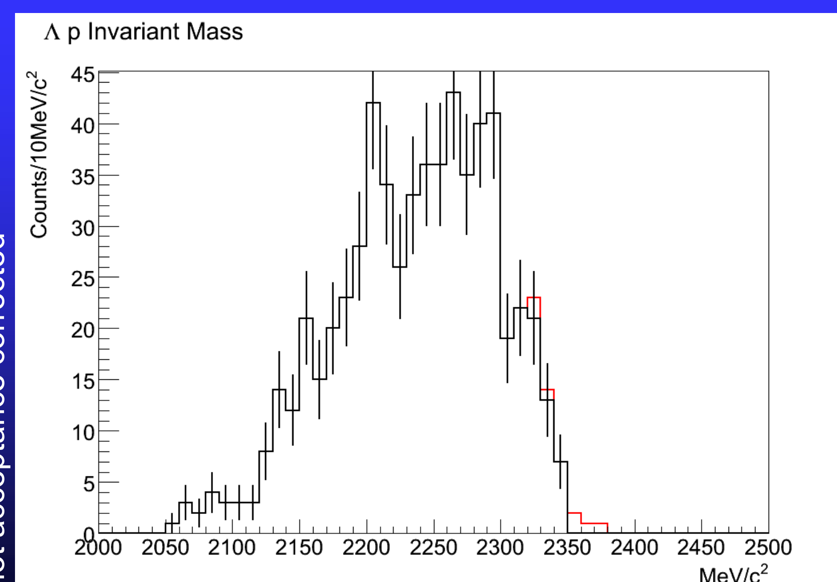
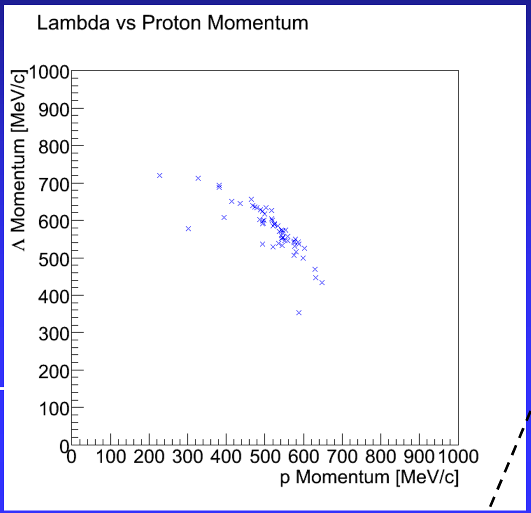


FINUDA: $^{6}Li(K^{-}_{stop},\Lambda p)X$

not acceptance corrected



Final States are separated by reconstructing the Missing Mass:

1) QF-TNA $K^{-}A \rightarrow \Lambda p X$
2) QF-TNA $K^{-}A \rightarrow \Sigma^{0} p X$
3) QF-TNA $K^{-}A \rightarrow \Lambda \pi p X$

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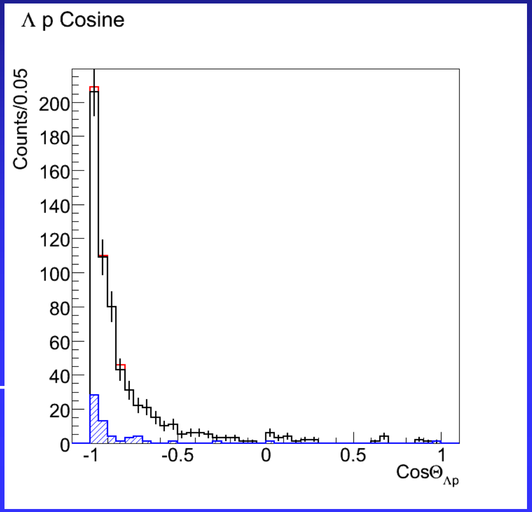

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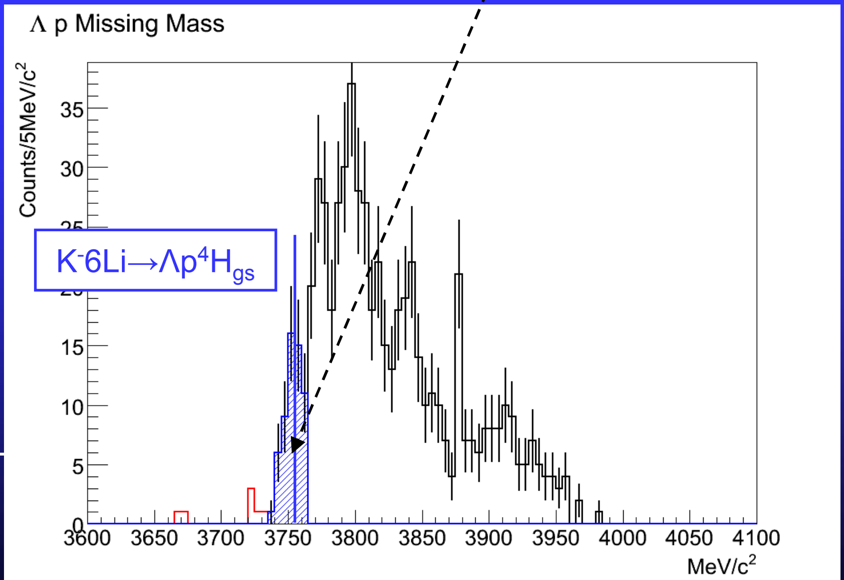

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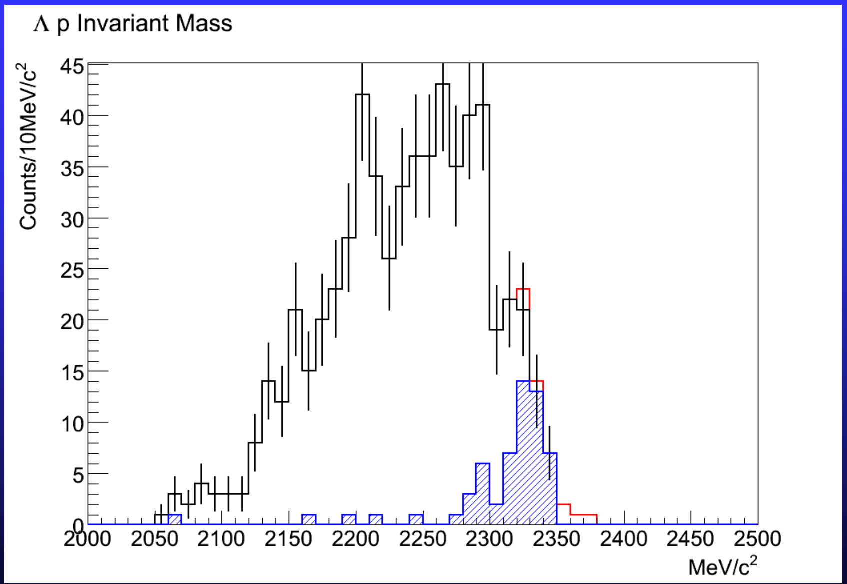

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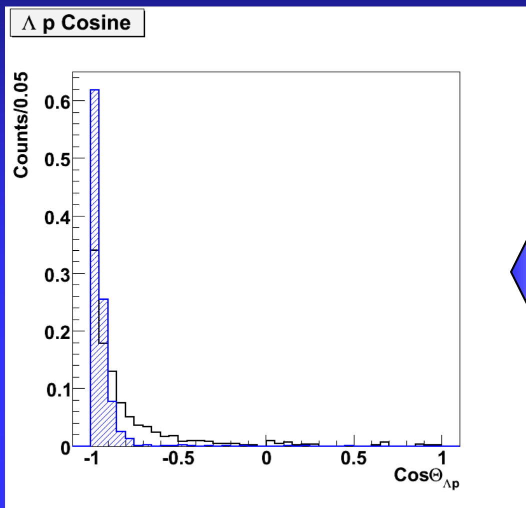
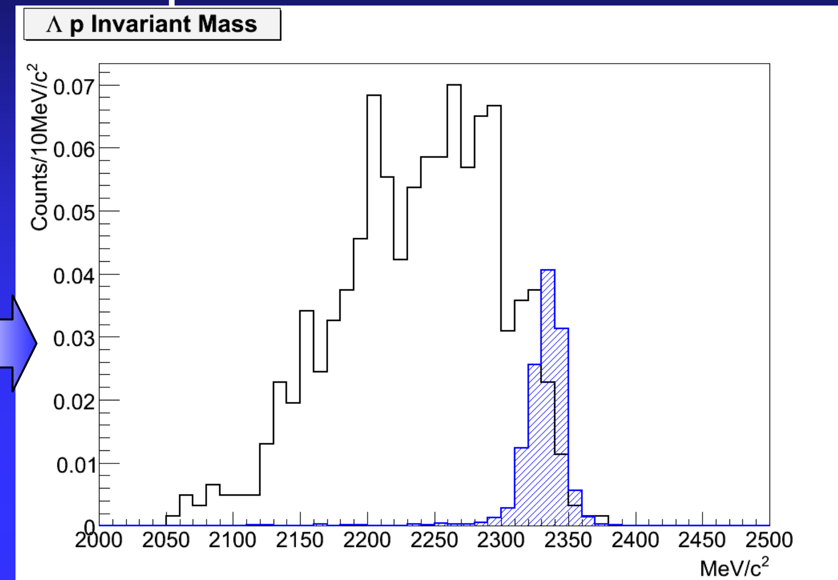


Simulation:
$K^{-6}Li \rightarrow \Lambda p\, ^{4}H_{gs}$



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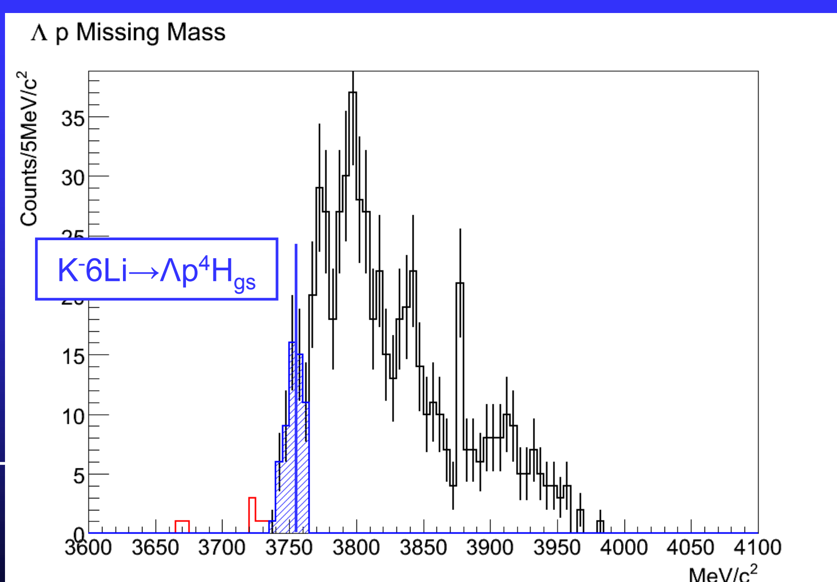

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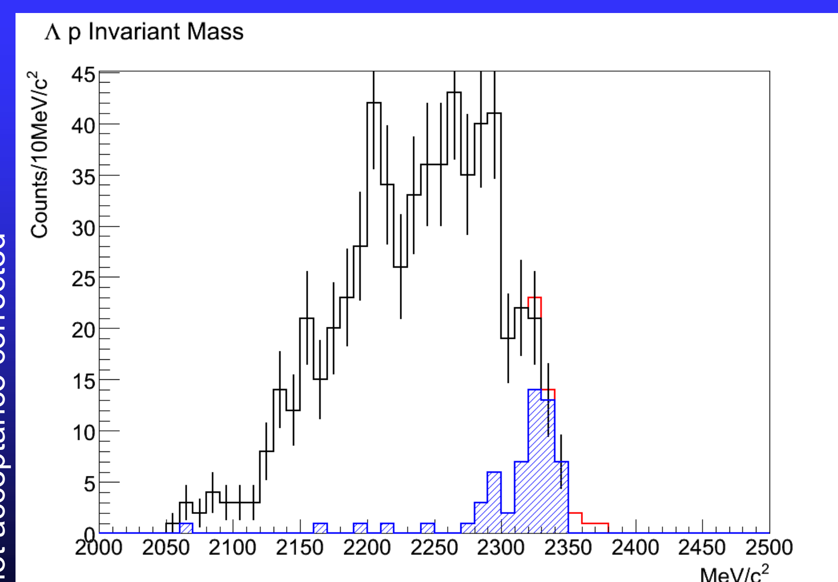

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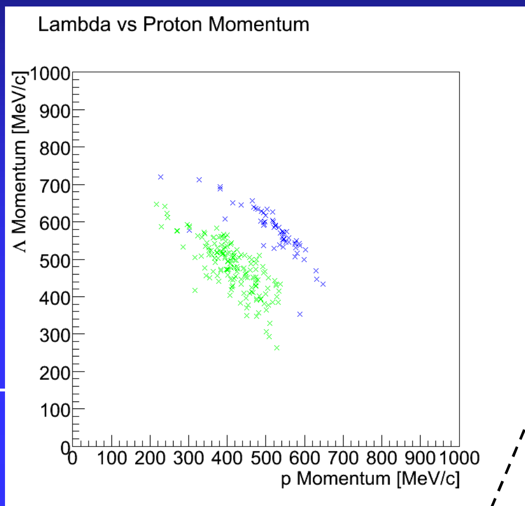

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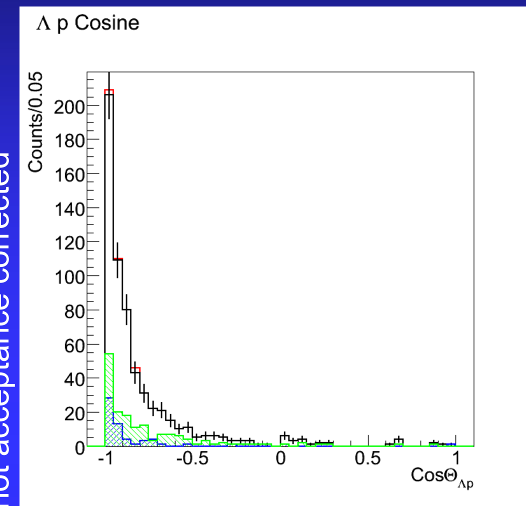

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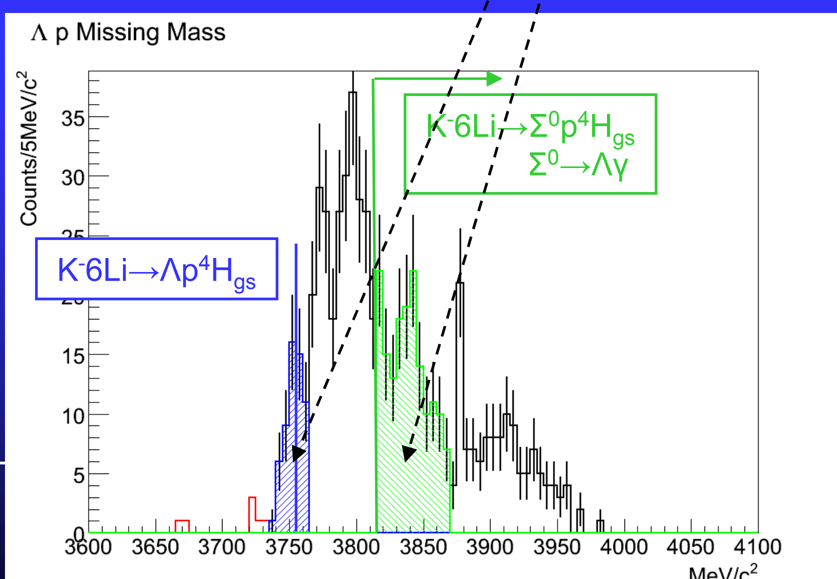

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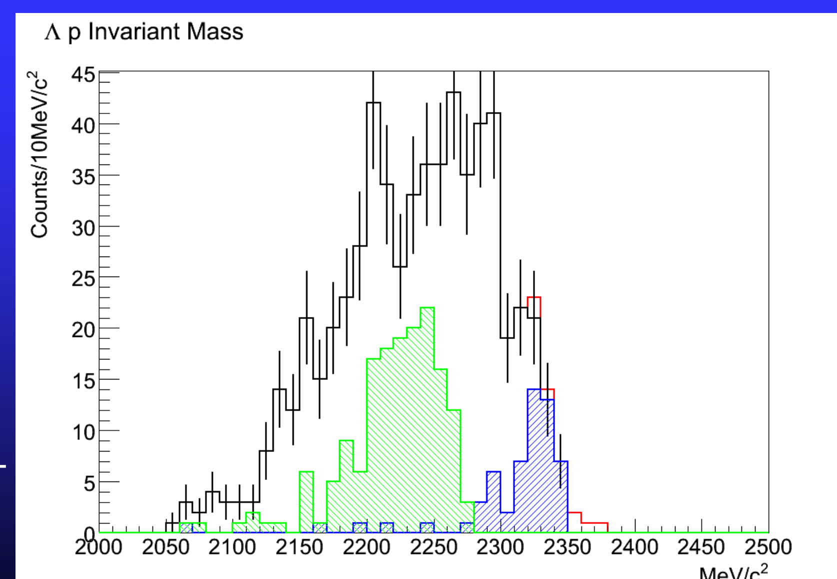

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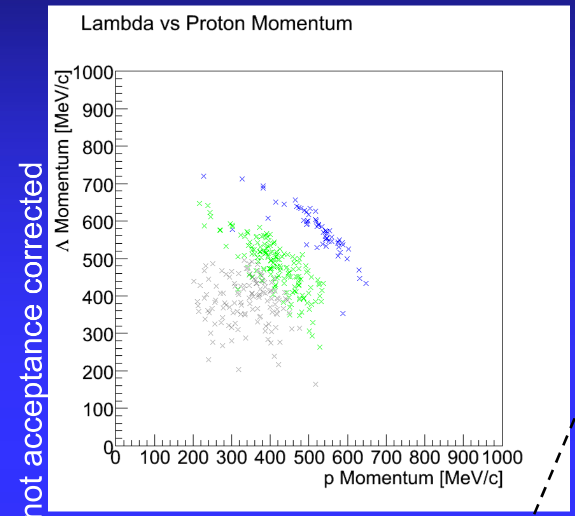

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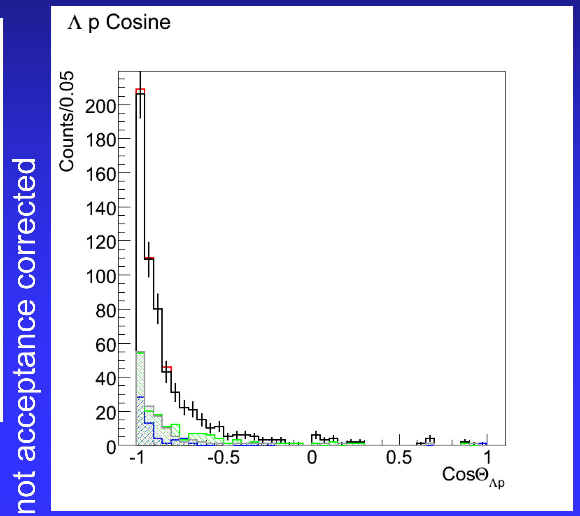
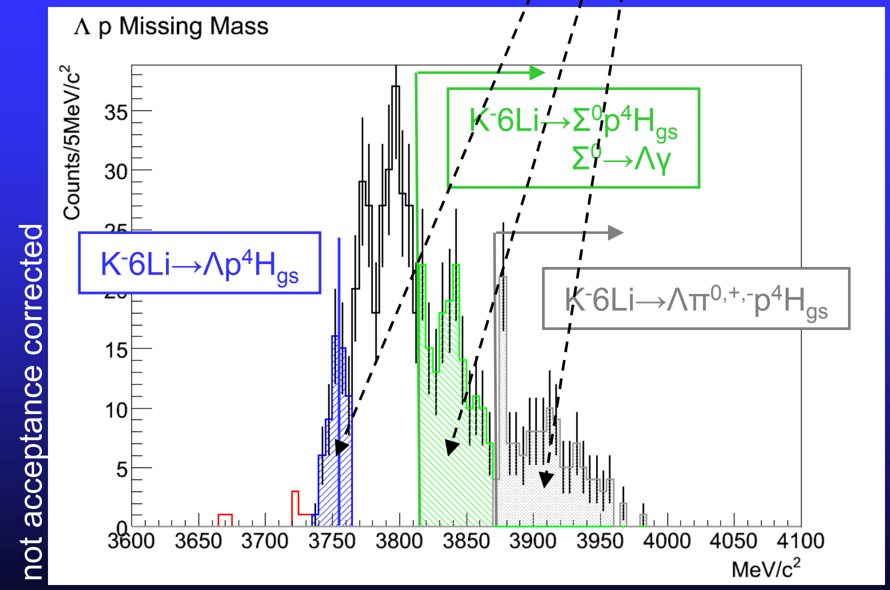
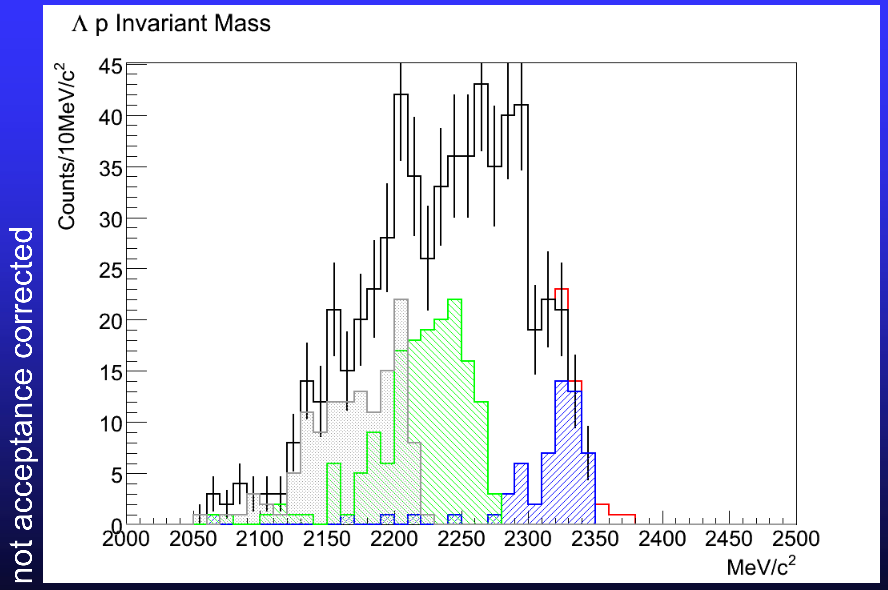
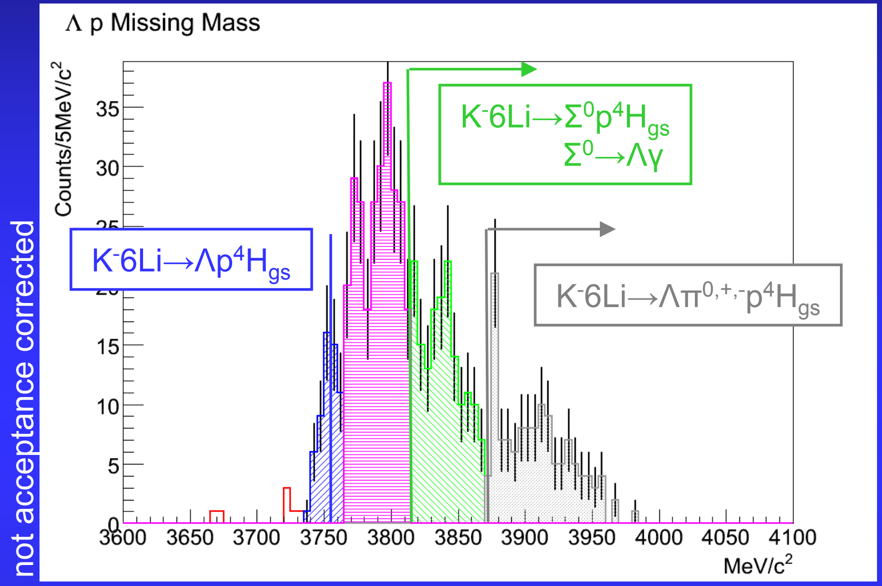


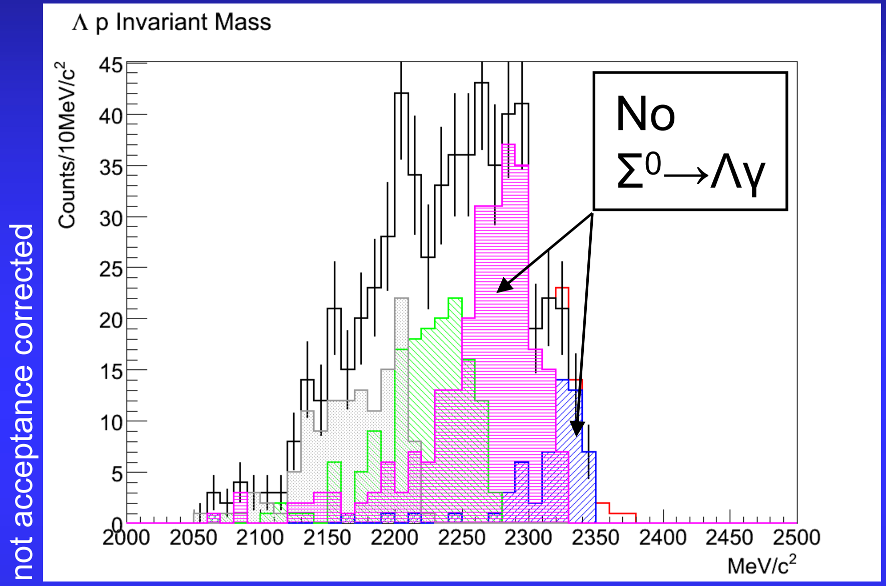




FINUDA: $^{6}Li(K^{-}_{stop},\Lambda p)X$

Only a minor fraction of the bump can be associated to $K^{-}pp \rightarrow \Sigma^{0}p \rightarrow \Lambda\gamma$





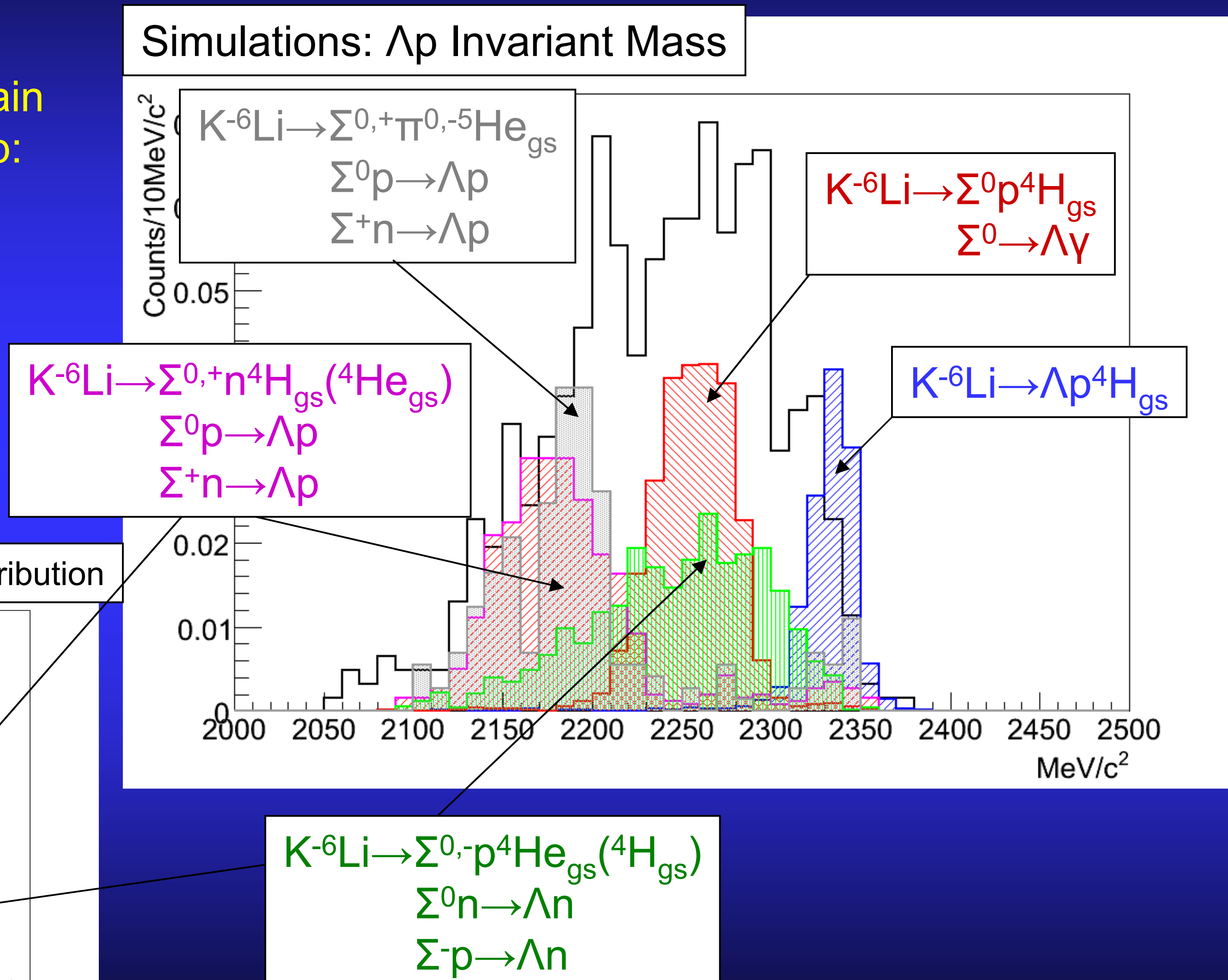
But …the Missing Mass selection cannot exclude $\Sigma N \rightarrow \Lambda N$ conversion reactions:

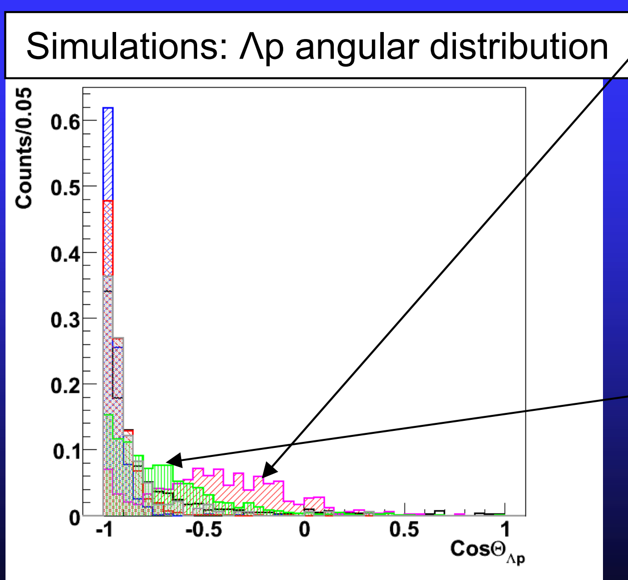
$K^{-}A \rightarrow \Sigma^{0,+}\pi^{0,-}X$	$K^{-}A \rightarrow \Sigma^{0,+}nX$	$K^{-}A \rightarrow \Sigma^{0,-}pX$
$\Sigma^{0}p \rightarrow \Lambda p$	$\Sigma^{0}p \rightarrow \Lambda p$	$\Sigma^{0}n \rightarrow \Lambda n$
$\Sigma^{+}n \rightarrow \Lambda p$	$\Sigma^{+}n \rightarrow \Lambda p$	$\Sigma^{-}p \rightarrow \Lambda n$

FINUDA: ΣN→ΛN conversion reactions

ΣN→ΛN cannot explain the FINUDA Λp bump:

Inv Mass Spectra is out of range
and/or
Angular Distribution has a different shape





Alternative interpretations of Λp bump

- $K^-pp \rightarrow [K^-pp] \rightarrow \Lambda p$: [K-pp] bound state (FINUDA)
- ~~QF-TNA $K^-pp \rightarrow \Lambda p$ followed by FSI (Magas et al.)~~
- ~~Dominance of Σ^0 production over Λ:~~
  ~~QF-TNA $K^-pp \rightarrow \Sigma^0 p$ followed by $\Sigma^0 \rightarrow \Lambda\gamma$ decay~~
- ~~QF-TNA $K^-NN \rightarrow \Sigma N$ followed by $\Sigma N \rightarrow \Lambda N$ conversion reaction:~~

$K^-A \rightarrow \Sigma^{0,+}\pi^{0,-}X$	$K^-A \rightarrow \Sigma^{0,+}nX$	$K^-A \rightarrow \Sigma^{0,-}pX$
$\Sigma^0 p \rightarrow \Lambda p$	$\Sigma^0 p \rightarrow \Lambda p$	$\Sigma^0 n \rightarrow \Lambda n$
$\Sigma^+ n \rightarrow \Lambda p$	$\Sigma^+ n \rightarrow \Lambda p$	$\Sigma^- p \rightarrow \Lambda n$

- Decay of heavier kaonic nuclei (Mares et al.)

QF-TNA = Quasi Free Two Nucleon Absorption

Alternative interpretations of Λp bump

- K-pp→[K-pp]→Λp: [K-pp] bound state (FINUDA)
- ~~QF-2NA K-pp→Λp followed by FSI (Magas et al.)~~
- ~~Dominance of Σ^0 production over Λ:~~
  ~~QF-2NA K-pp→Σ^0p followed by Σ... decay~~
- ~~QF-2NA K-NN→ΣN follo... →ΛN conversion reaction:~~

~~$K^-A\to\Sigma^{0,+}$...~~ ~~...p~~ ~~...n→Λp~~	~~$K^-A\to\Sigma^{0,+}nX$~~ ~~$\Sigma^0p\to\Lambda p$~~ ~~$\Sigma^+n\to\Lambda p$~~	~~$K^-A\to\Sigma^{0,-}pX$~~ ~~$\Sigma^0n\to\Lambda n$~~ ~~$\Sigma^-p\to\Lambda n$~~

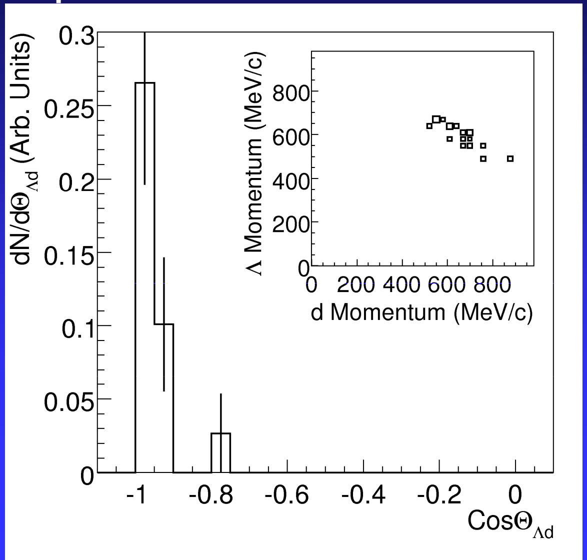
To explain all the observables we need a realistic model:
K^- dynamics (bound state) and proton pair momenta

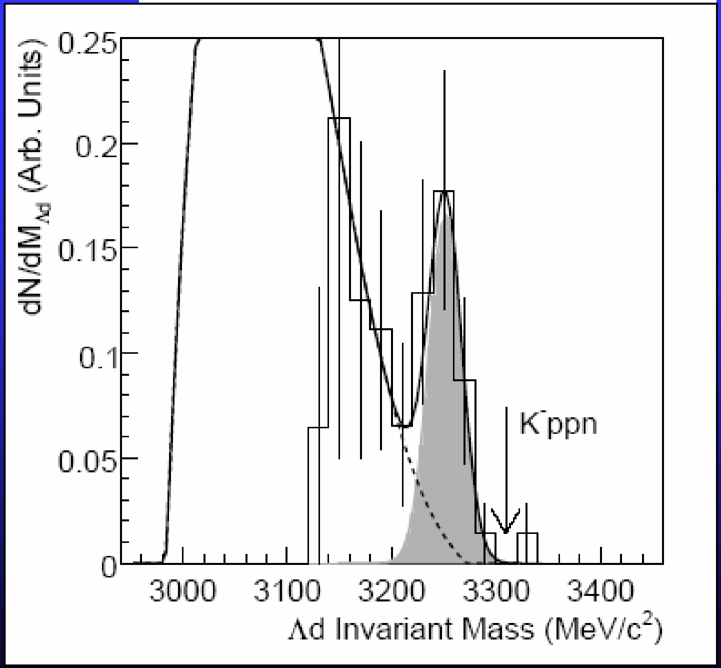
- Decay of heavier kaonic nuclei (Mares et al.)

Q2-TNA = Quasi Free Two Nucleon Absorption

3NA: FINUDA study of ^{6}Li(K^-_{stop},Λd)X

- Λd invariant mass to measure K^- ppn absorption
- Use of ^{6}Li target: low background
- ^{6}Li is a well known [α+d] cluster
  - Bump observed at $M_{\Lambda d}$= 3251 MeV, $\Gamma_{\Lambda d}$=37 MeV
  - 25 events in the peak, statistical significance 3.9σ
  - Yield: (4.4±1.4)x10^{-3}/K^-_{stop}





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FINUDA: $^6Li(K^-_{stop},\Lambda d)X$
2006-2007 Data Taking

- 8x statistics
  - Improved tracking efficiency
  - Extended range of the rec. momentum
  - Improved selections (missing mass)

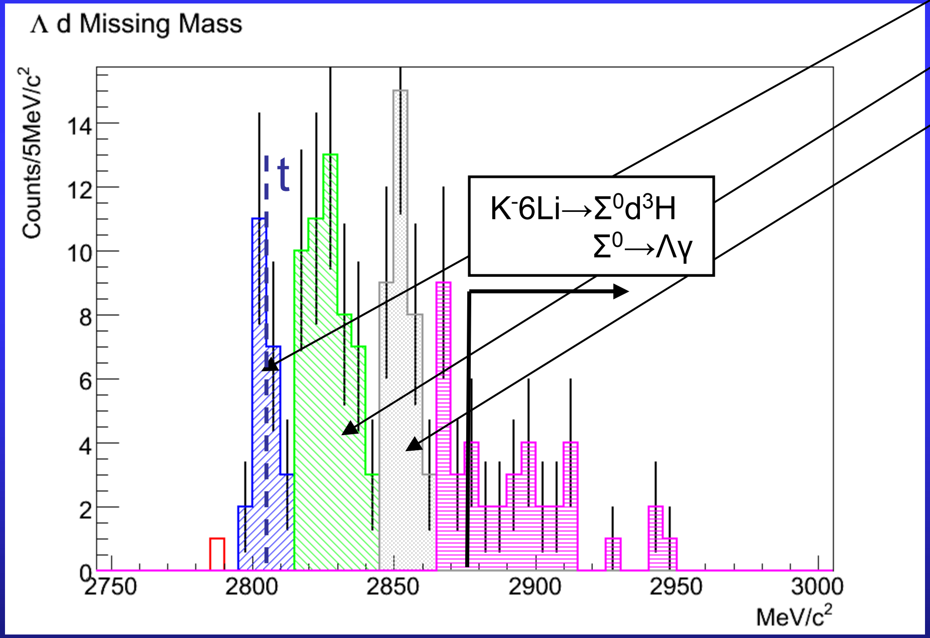
3 well defined states in missing mass with Λ d emitted back-to-back:

<u>2805 ± 4 MeV/c^2 ⇒ QF-3NA: $K^{-6}Li \rightarrow \Lambda dt$</u>

2824 ± 11 MeV/c^2

2852 ± 6 MeV/c^2

not acceptance corrected



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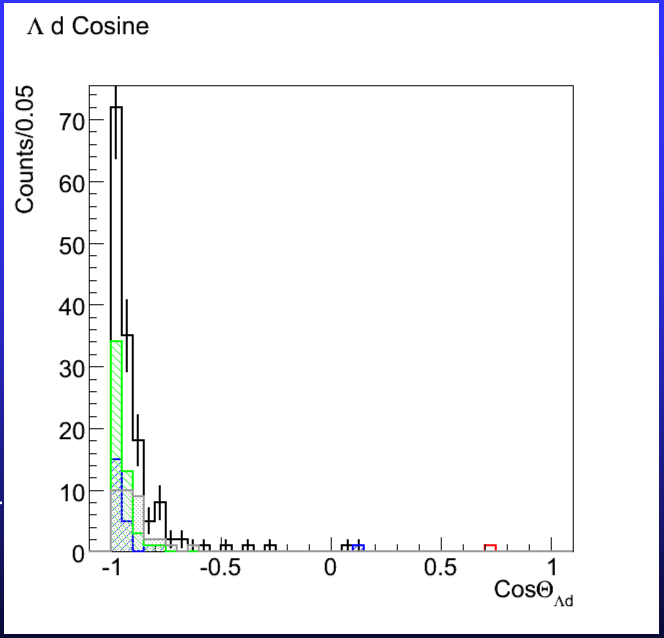

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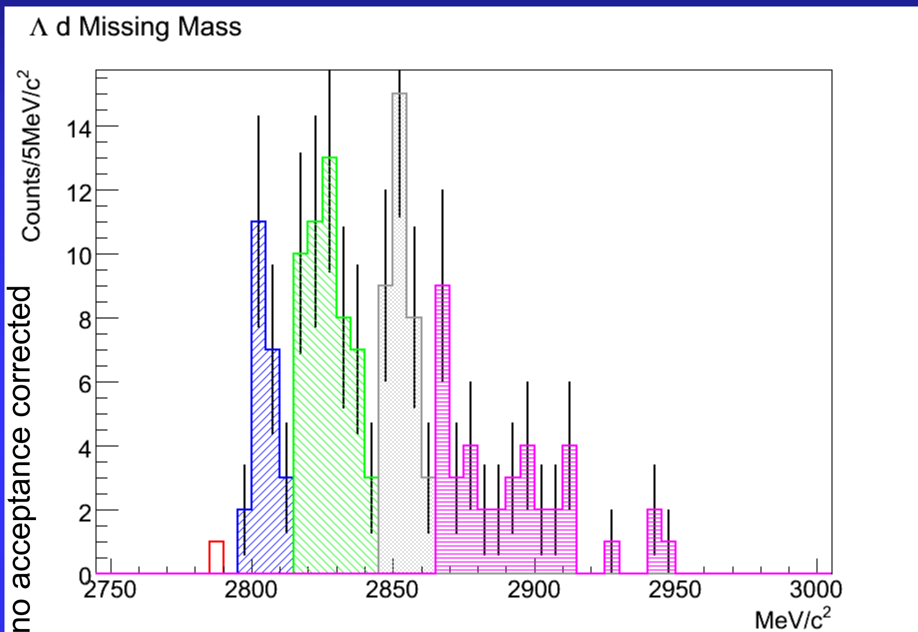
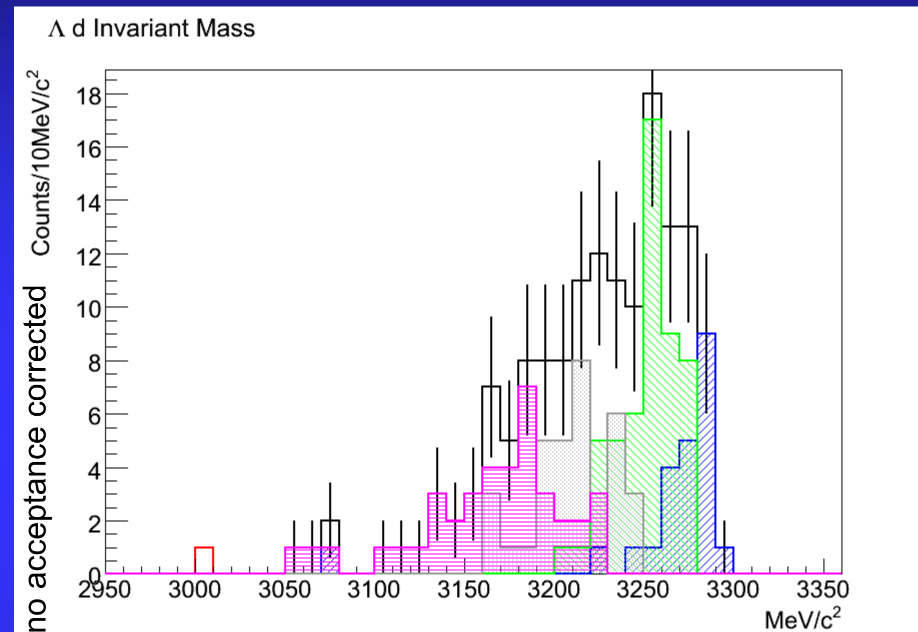
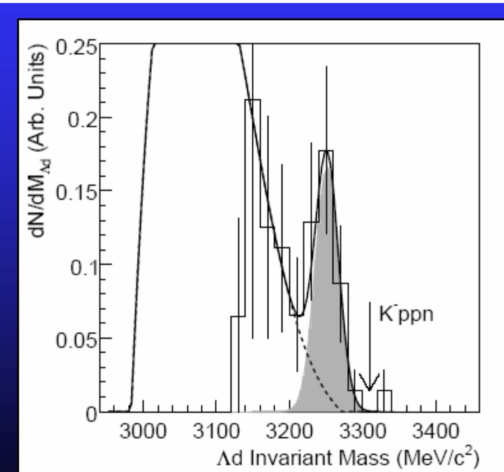
2006-2007 Data Taking





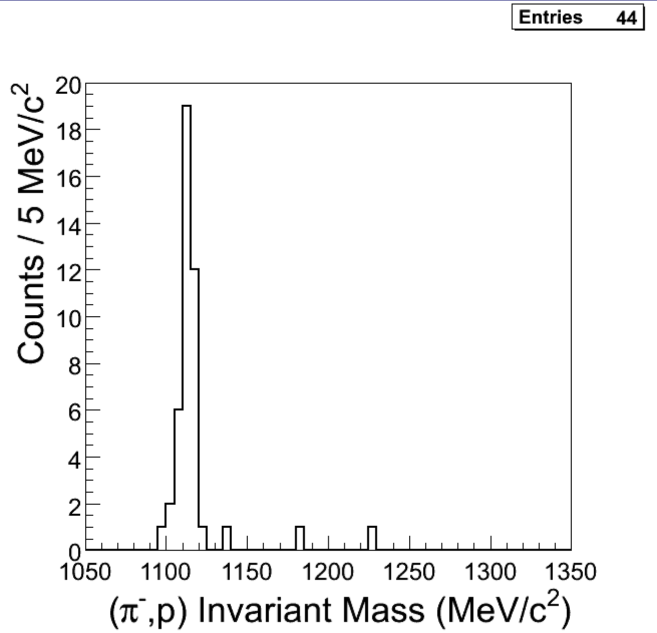
The Λd bump published is a superimposition of three different final states.
The QF-3NA is identified ($K^{-}6Li \rightarrow \Lambda dt$).
The nature of the other two states will soon be clarified (analysis in progress).
The Σ^0 doesn't play a relevant role.

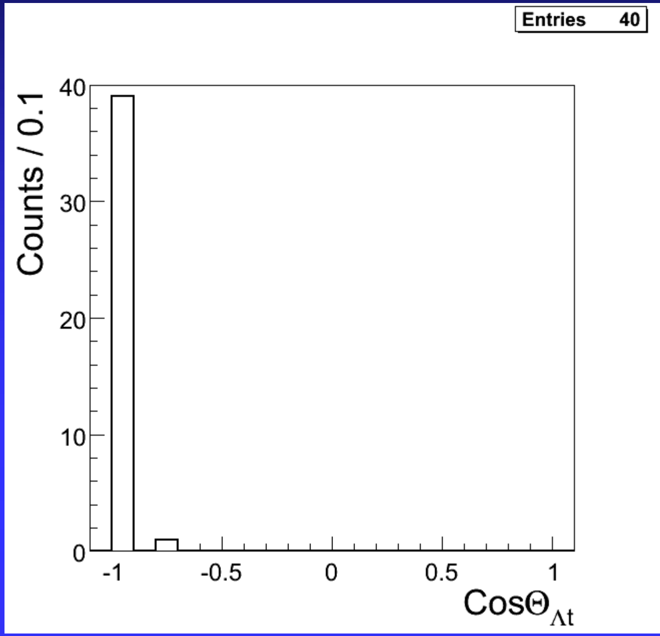


FINUDA Coll., PLB 654 (2007) 80

FINUDA: study of A(K^-,Λt)X (A=^{6}Li,^{7}Li,^{9}Be) (I)

FINUDA Coll., PLB 669 (2008) 229





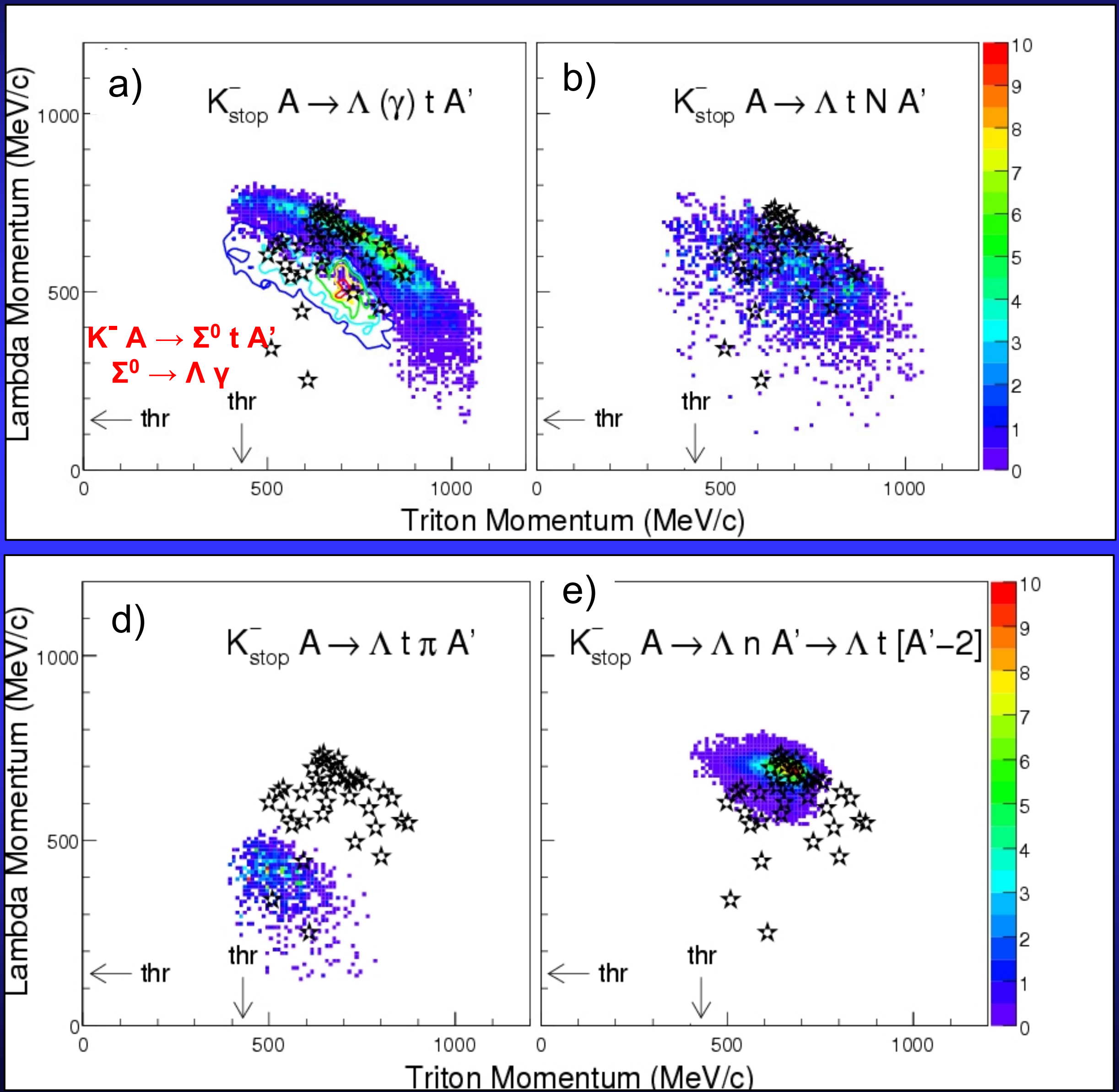
- K^- A → Λ t X
- A = ^{6}Li,^{7}Li,^{9}Be
- FINUDA thresholds:
  - Λ 140 MeV/c
  - t 430 MeV/c

Direct measurement of
K^- absorption on ^{4}He

- Λ signal background free
- Λ, t pairs emitted back-to-back
- High momenta for Λ, t

Only one measurement exists so far,
from bubble chamber: 3 events by kin fit
40 events observed in FINUDA
Capture rate: ~1x10^{-3}/K^-

FINUDA: study of $A(K^-,\Lambda t)X$ ($A={}^6Li, {}^7Li, {}^9Be$) (II)



Many body K^- absorption role

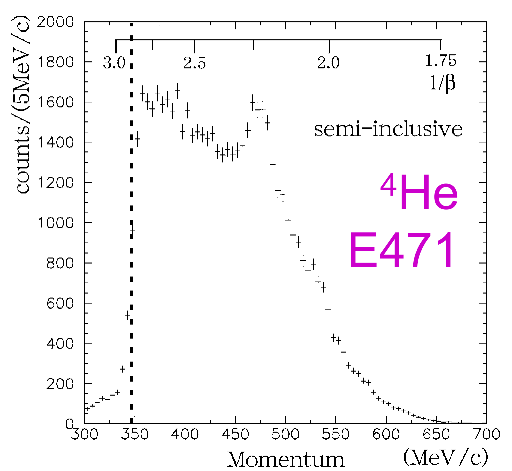
- Simulations of different phase space reactions with $\cos(\Theta_{\Lambda t})<-0.9$ (filtered through apparatus acceptance)
- Λ and t momentum distribution compatible with:
  - a) Four nucleon absorption with (Λt) or (Σt) emission
  - b) Four nucleon absorption with (Λt)N emission
  - c) NOT with (Λt)π: too small Λ momentum
  - d) 2-step pickup reaction (suppressed?)

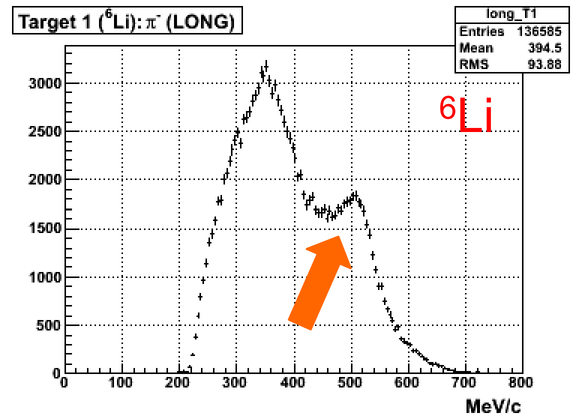
Outlook and Conclusions

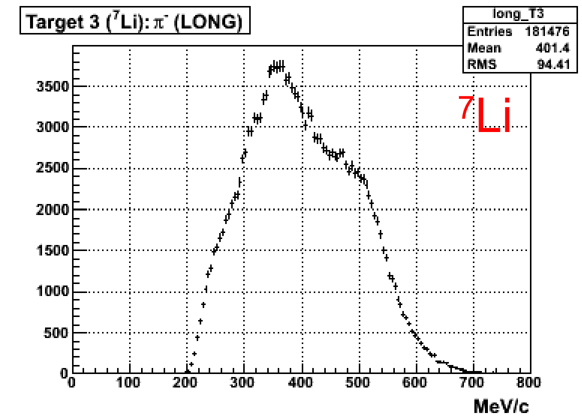
- $[K^-pp] \rightarrow \Lambda p$:
  - $M_{\Lambda p}$ signal on different targets
  - $Cos\Theta_{\Lambda p} \sim -1$
  - FSI alone cannot explain at the same time $M_{\Lambda p}$ and $Cos\Theta_{\Lambda p}$
  - Needed a realistic model: K^- dynamics (bound state) + proton pairs momenta
  - What is the role of short-range correlated proton pairs ?

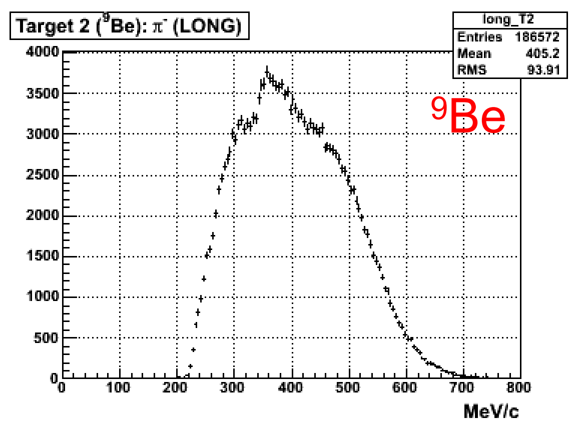
    (R. Subedi et al., Science 320(2008)1476)
  - The models should explain most the observables !
- $[K^-ppn] \rightarrow \Lambda d$:
  - $Cos\Theta_{\Lambda d} \sim -1$
  - Identified the QF-3NA
  - Other two bumps in missing mass (analysis in progress)
  - K^- is absorbed on quasi "α" ($^6Li = \alpha + d$)
  - The role of Σ^0 seems negligible
- $[K^-ppnn] \rightarrow \Lambda t$:
  - $Cos\Theta_{\Lambda t} \sim -1$
  - Direct measurement of K^- absorption on ^4He
  - Capture rate: $\sim 1 \times 10^{-3}/K^-$
- Near Future:
  - acceptance correction and final analysis of Λp (and Λd)
    - bump position and width as function of A from 6 to 16
  - neutron on coincidence with Λ, Λp and Λd
    - participant (energy carrier) and spectator
    - role of K^- α absorption on Λp and Λd spectra

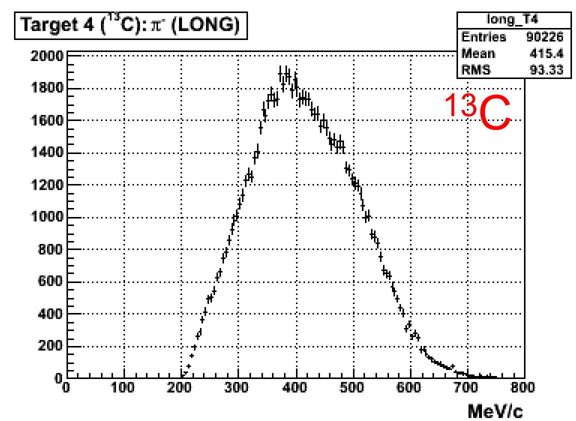
Inclusive proton spectra (FINUDA)

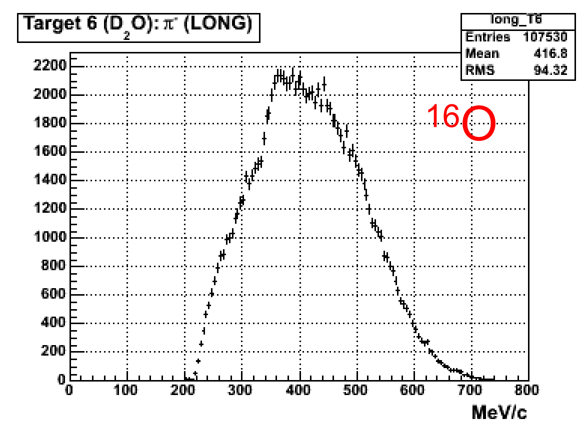










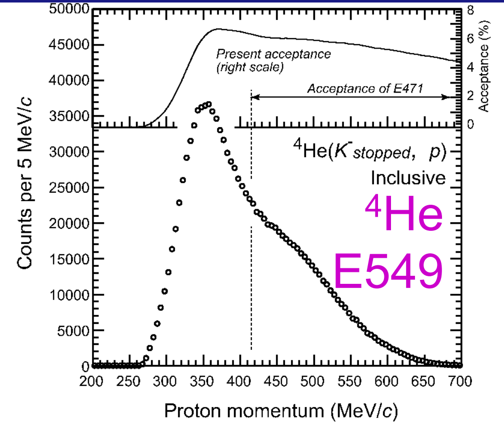


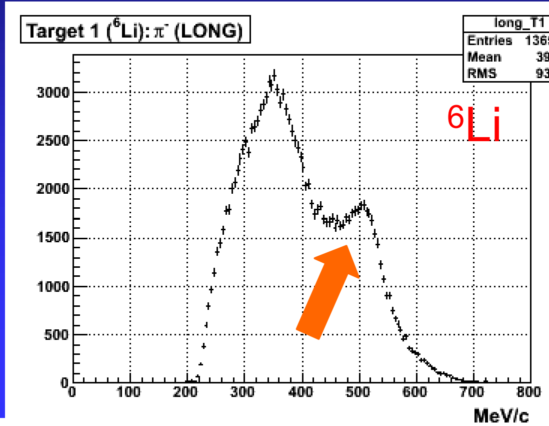
No mono-energetic emission of N and Y

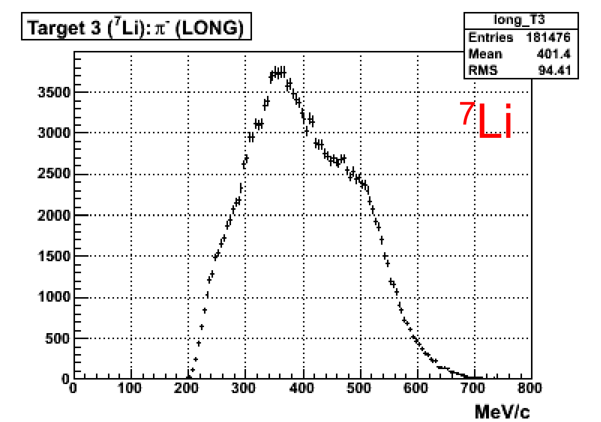
Only on ^{6}Li FINUDA observes a bump (FINUDA Coll., NPA 775 (2006), 35) :

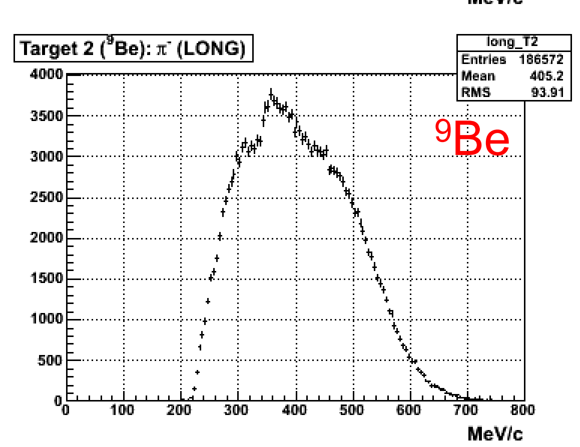
two nucleon absorption reaction on quasi-deuteron: K^{-}"d"$\rightarrow \Sigma^{-}+p$ [^{6}Li = α + d]

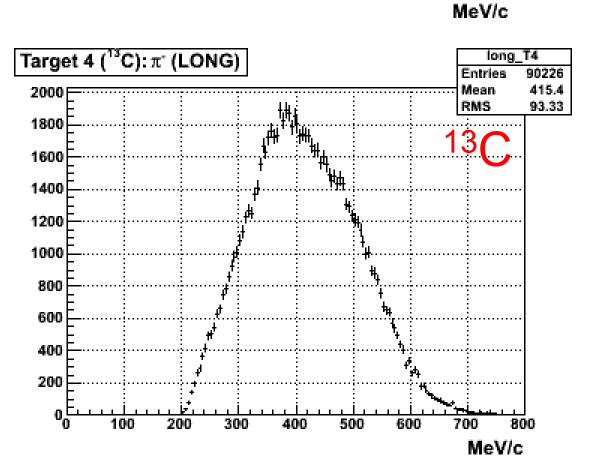
Inclusive proton spectra (FINUDA)

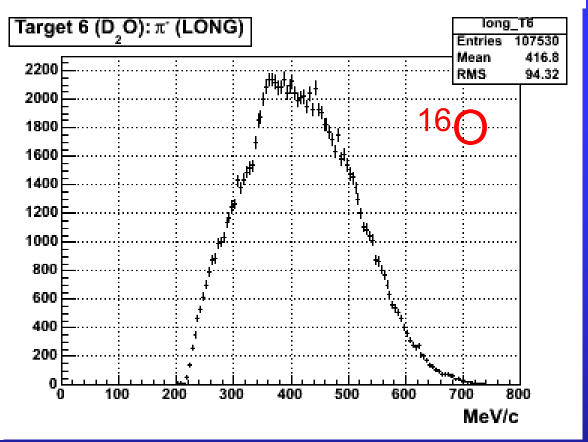












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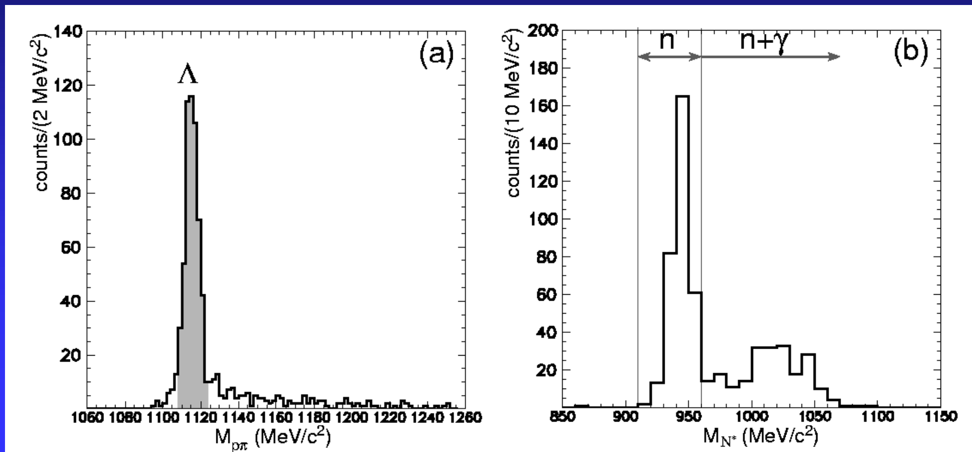
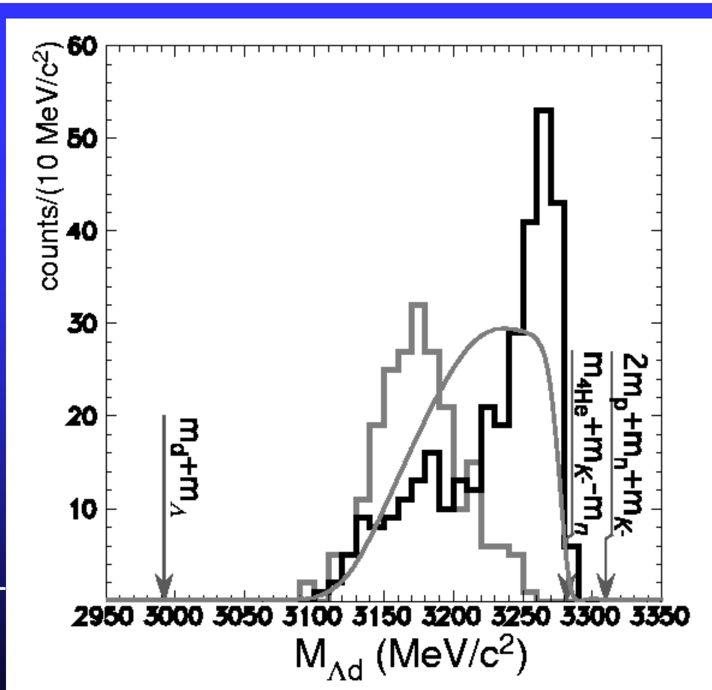
E549: Λd correlation from $^{4}He(K^{-}_{stop}, d)$



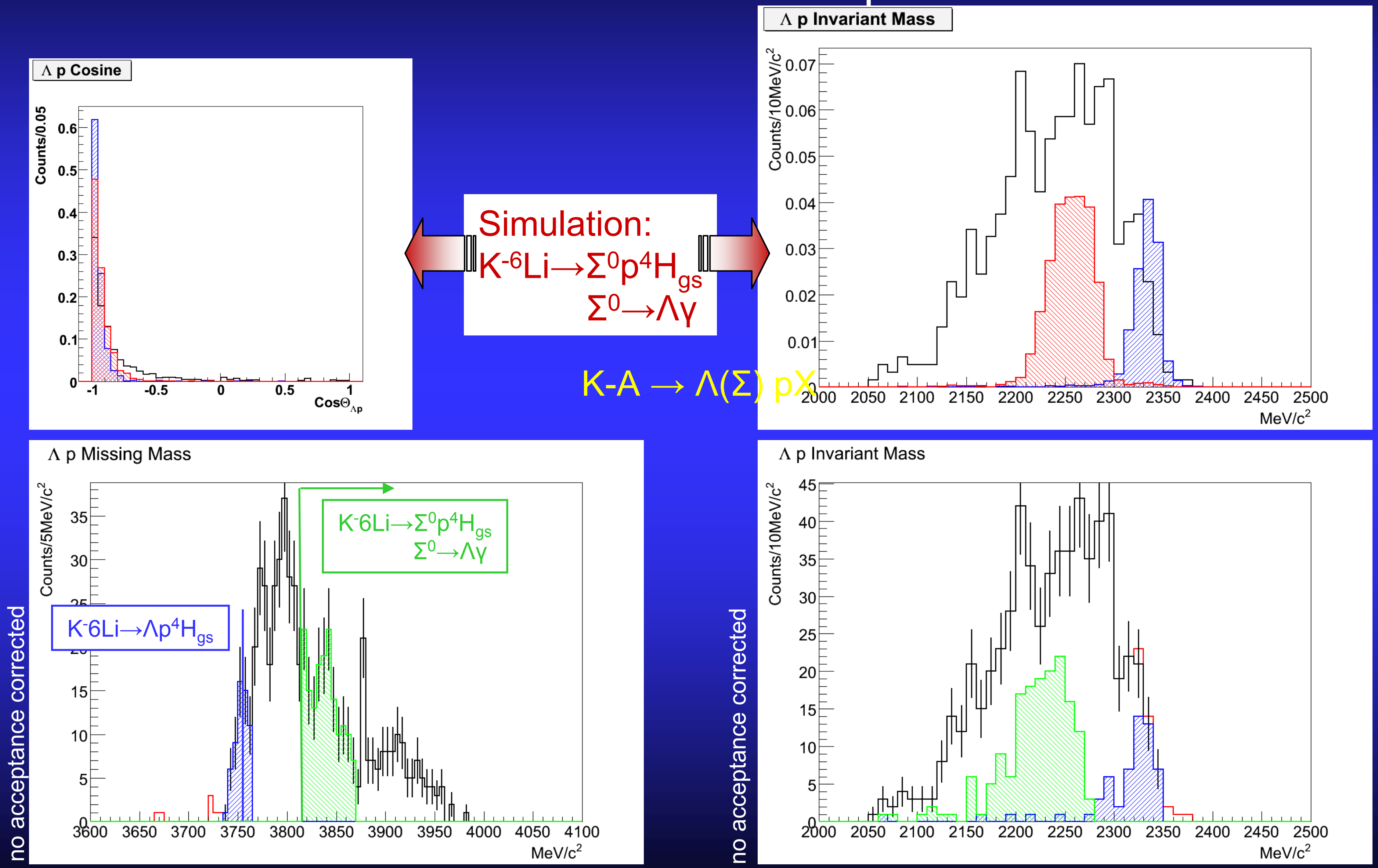
PRC 76(2007)068202

no acceptance corrected



- $K^{-}\,{}^{4}He \rightarrow \Lambda\, d\, (n)$
- detected back-to-back d p pairs with π^{-} in coincidence
- Λ discriminated from Σ^0 (Λγ) event by missing mass
- Λ d peak at 3282 MeV/c^2 just below mass threshold
- interpreted as 3N absorption $K^{-}ppn\ (n) \rightarrow \Lambda\, d\, (n)$
- accepted d p back-to-back only, spectra are shaped by the limited phase-space
- spectra are not corrected for the apparatus acceptance

FINUDA: $^{6}Li(K^{-}_{stop},\Lambda p)X$



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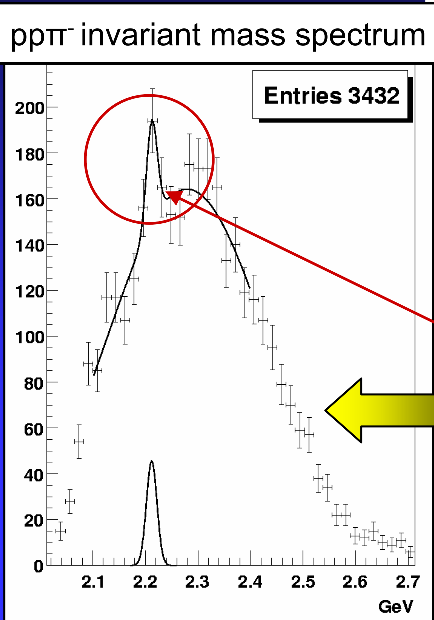
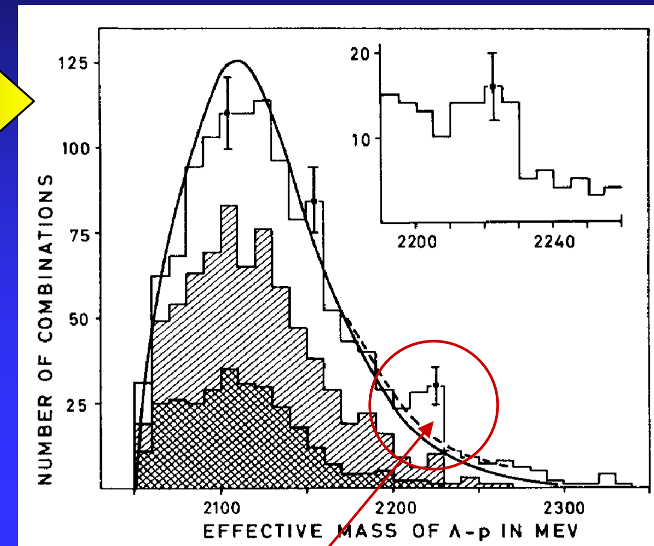
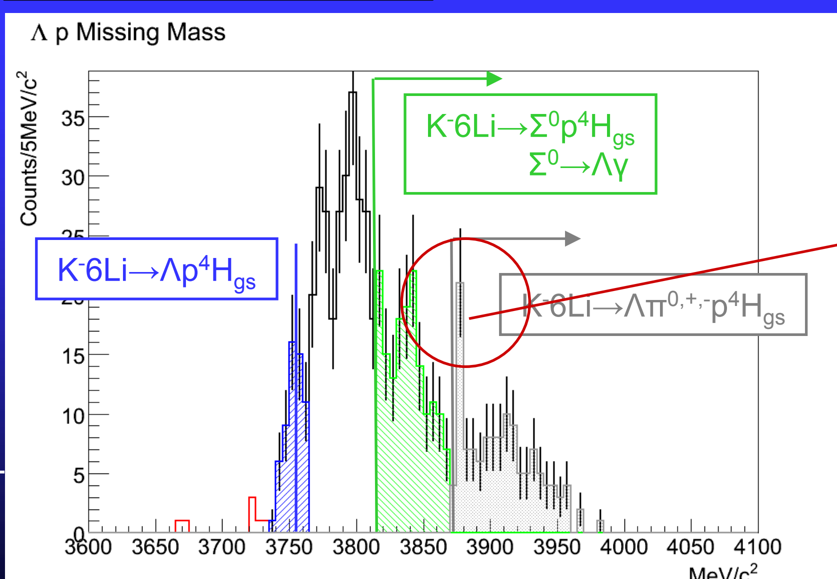


T. Buran et al., PL20(1966)318
$K^{-}(CF_{3}Br)\rightarrow\Lambda pX$



G. Bendiscioli et al., NPA789(2007)222
G. Bendiscioli et al., EPJA40(2009)11
$\bar{p}^{4}He\rightarrow(p\pi^{-})pK^{0}_{s}X$

no acceptance corrected



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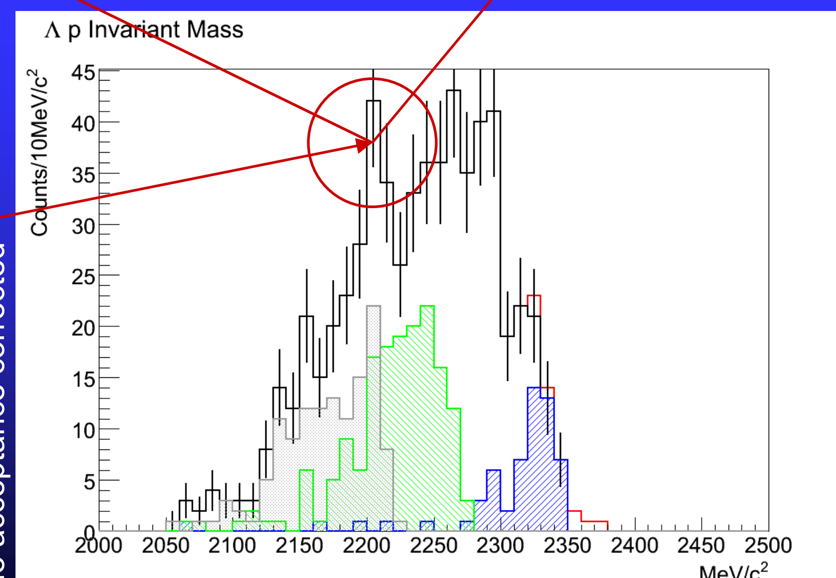


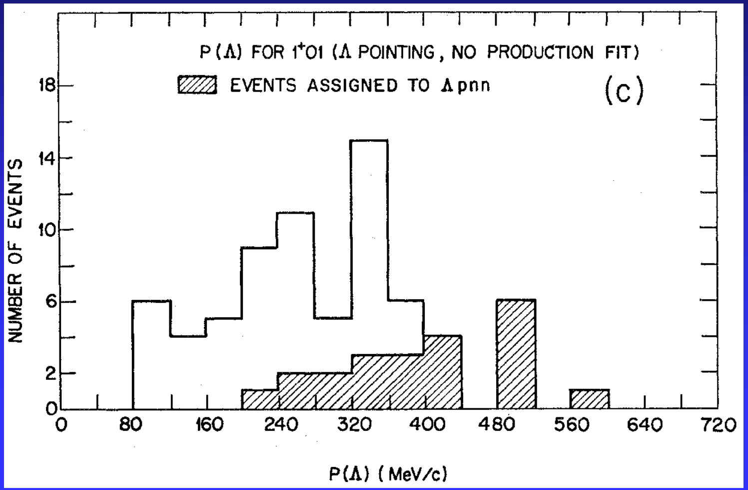
K$^-$(2N) is an old story…

Katz et al., Phys.Rev. D 1 (1970) 1267:
K$^-$ absorption at rest in Helium:

TABLE III. Branching ratios for K^- absorption at rest.

Reaction	Events/(stopping K^-) (%)
$K^-He^4 \rightarrow \Sigma^+\pi^-H^3$	9.3±2.3
$\rightarrow \Sigma^+\pi^- dn$	1.9±0.7
$\rightarrow \Sigma^+\pi^- pnn$	1.6±0.6
$\rightarrow \Sigma^+\pi^0 nnn$	3.2±1.0
$\rightarrow \Sigma^+ \; nnn$	1.0±0.4
Total $\Sigma^+ = (17.0\pm2.7)\%$	
$K^-He^4 \rightarrow \Sigma^-\pi^+H^3$	4.2±1.2
$\rightarrow \Sigma^-\pi^+ dn$	1.6±0.6
$\rightarrow \Sigma^-\pi^+ pnn$	1.4±0.5
$\rightarrow \Sigma^-\pi^0 He^3$	1.0±0.5
$\rightarrow \Sigma^-\pi^0 pd$	1.0±0.5
$\rightarrow \Sigma^-\pi^0 ppn$	1.0±0.4
$\rightarrow \Sigma^- \; pd$	1.6±0.6
$\rightarrow \Sigma^- \; ppn$	2.0±0.7
Total $\Sigma^- = (13.8\pm1.8)\%$	
$K^-He^4 \rightarrow \pi^-\Lambda \; He^3$	11.2±2.7
$\rightarrow \pi^-\Lambda \; pd$	10.9±2.6
$\rightarrow \pi^-\Lambda \; ppn$	9.5±2.4
$\rightarrow \pi^-\Sigma^0 He^3$	0.9±0.6
$\rightarrow \pi^-\Sigma^0 (pd, ppn)$	0.3±0.3
$\rightarrow \pi^0 \Lambda (\Sigma^0)(pnn)$	22.5±4.2
$\rightarrow \Lambda \; (\Sigma^0) \; (pnn)$	11.7±2.4
$\rightarrow \pi^+\Lambda (\Sigma^0) nnn$	2.1±0.7
Total $\Lambda (\Sigma^0) = (69.2\pm6.6)\%$	
Total $= \Lambda + \Sigma = (100_{-7}^{+0})\%$	

No-mesonic Λ (Σ^0) 11.7%
No-mesonic Σ^+ only 1.0%
No-mesonic Σ^- 3.6%



Λ fast: no pion emission

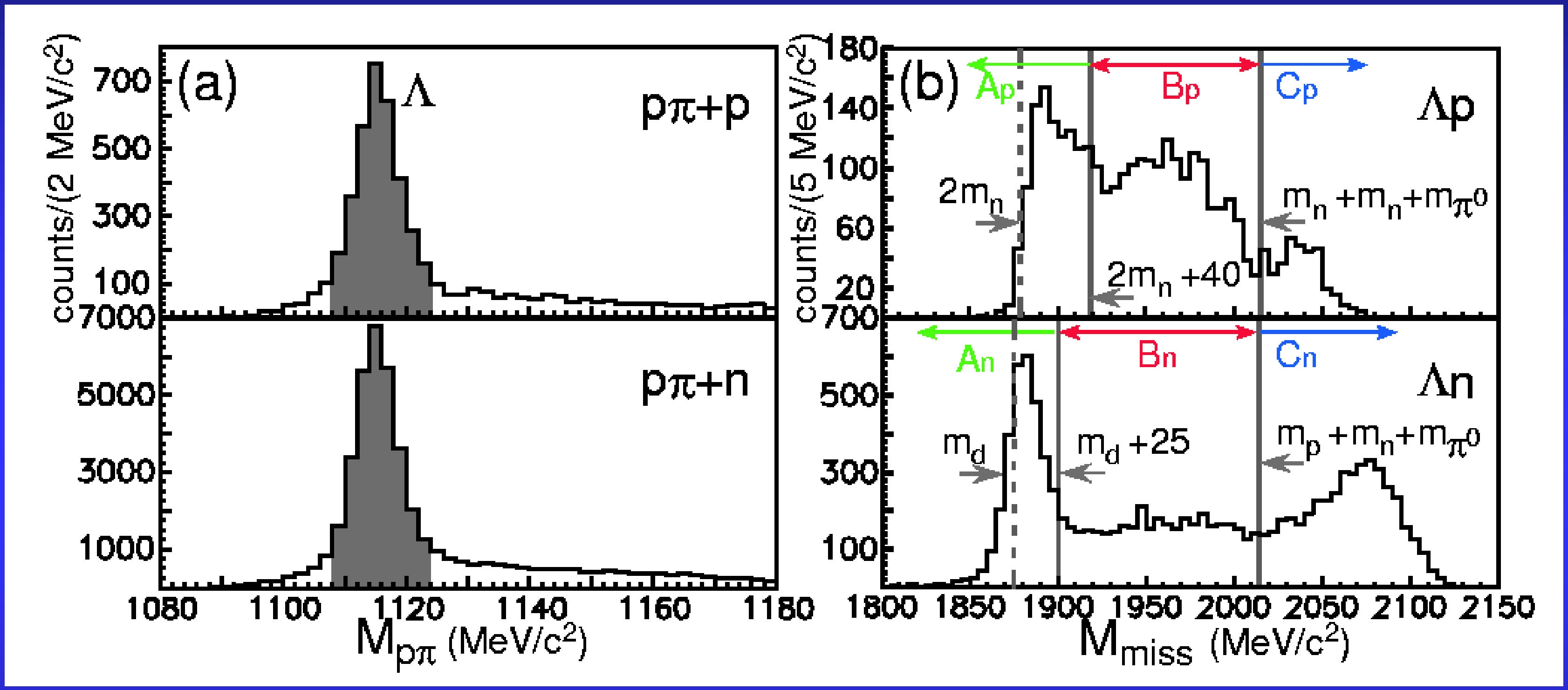
TABLE V. Comparative data on the frequency of emission of various particles.

	Capture nucleus					
	Hydrogen	Deuterium	Helium (this experiment)	Helium (Helium Bubble Chamber Collaboration)[a]	(76% CF_3Br) +(24% C_3H_8)	Nuclear emulsion
$[\pi^\pm]/[K^-]$	0.64	0.67	0.55±0.05	0.55	0.45	0.40
$[\pi^-]/[\pi^+]$	0.46	1.95	4.9 ±1.0	5.5	3.8	3.9
$[\Sigma^\pm]/[K^-]$	0.64	0.46	0.31±0.03	0.27	0.19	0.187
$[\Sigma^+]/[\Sigma^-]$	0.46	0.73	1.2 ±0.2	1.16	1.05	0.79
$[\Sigma^+ + \pi^-]/[\Sigma^- + \pi^+]$	0.46	0.85	1.8 ±0.5	1.82	1.52	1.43
Multinucleon (i.e., nonpionic) capture	…	0.01	0.16±0.03	0.17±0.04[b]	0.25	0.15–0.30

[a] Reference 2.
[b] Nonpionic ratio of (32±2)% for K^- in He^4 was quoted by M. M. Block, in *Proceedings of the International Conference on Hypernuclear Physics, Argonne National Laboratory, Argonne, 1969*, edited by A. R. Bodmer and L. G. Hyman (ANL, Argonne, 1969).

A-dependence:
no-mesonic production increasing with A

E549: $^4He(K^-_{stop},\Lambda N)X$ missing mass

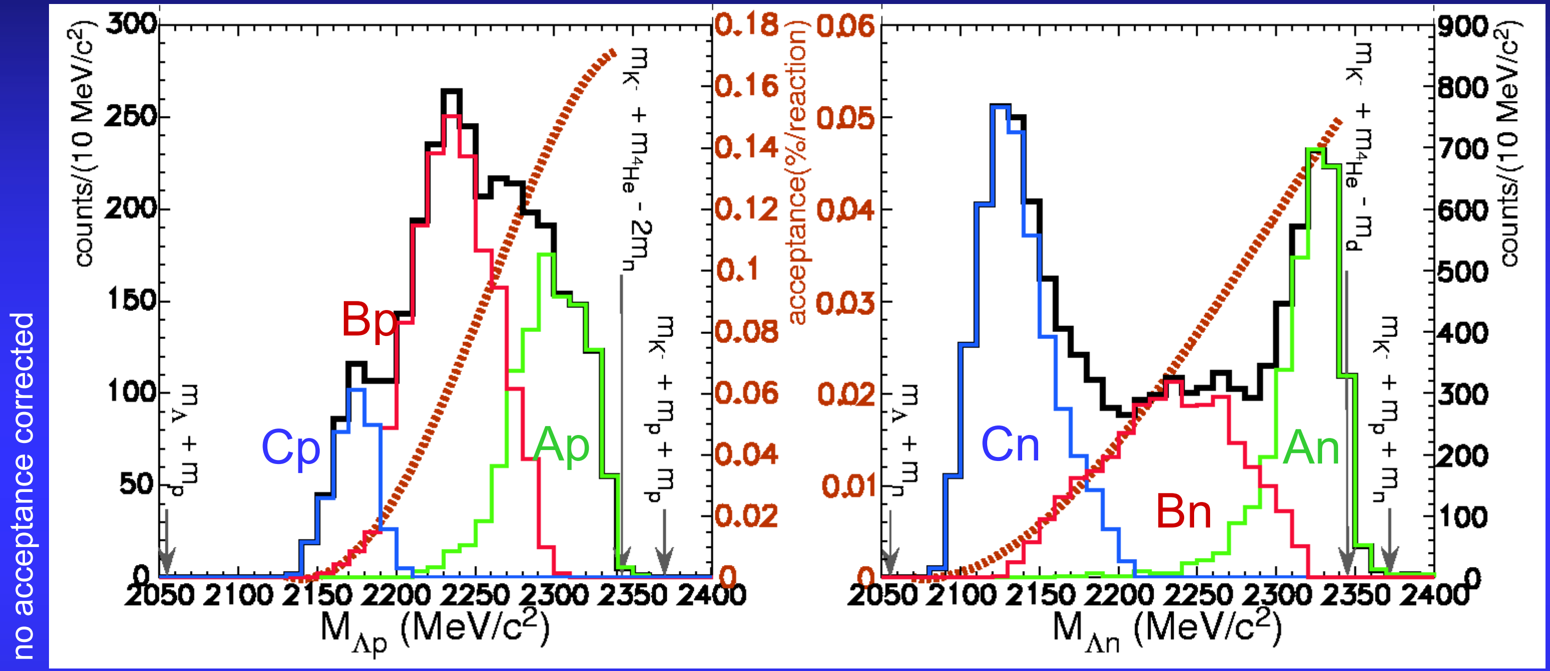


$\sigma_\Lambda \sim 4$ MeV/c^2
$\sigma_{\Lambda p} \sim 5$ MeV/c^2
$\sigma_{\Lambda n} \sim 7$ MeV/c^2

$K^-_{stop}\,^4He \rightarrow \Lambda p X$ Ap=nn
Cp=nnπ
$K^-_{stop}\,^4He \rightarrow \Lambda n X$ An=pn(d)
Cn=pn(d)π

Spectra are shaped by the limited phase-space: $-1 \leq \cos\theta_{\Lambda N} \leq -0.6$

E549: $^{4}He(K^{-}_{stop},\Lambda N)X$ invariant mass



E549 interpretation:

Cp,n : K^{-} $^{4}He \rightarrow \Sigma\pi(3N)$
$\Sigma N \rightarrow \Lambda N$

Ap,n : K^{-} $^{4}He \rightarrow \Lambda N(2N)$

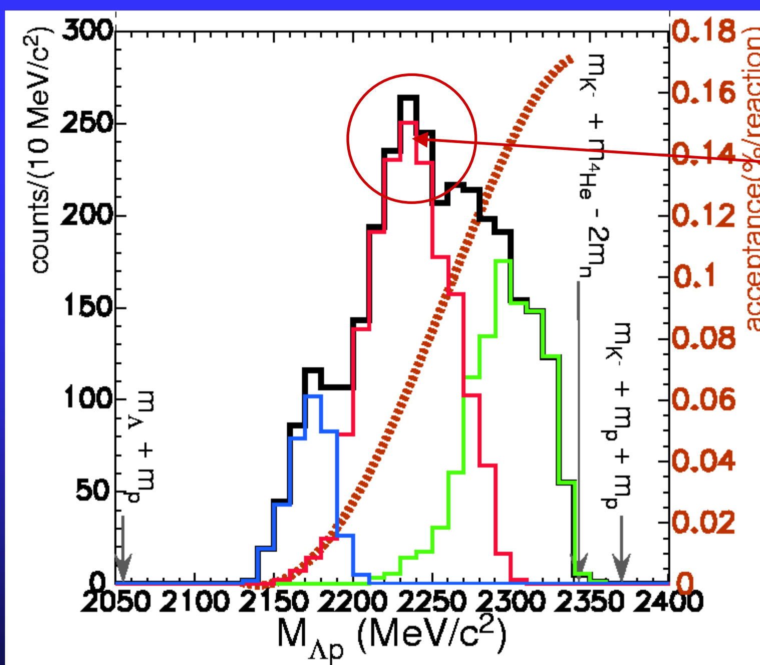
BR_{Ap}/BR_{An} ~ 0.1 $K^{-}pn >> K^{-}pp$
BR_{Ap} ~ 0.2% ; BR_{An} ~ 2% ;
$BR_{\Lambda N}$ ~ 11.7% (Katz) $\Rightarrow$ $BR_{Bp,n}$ ~ 80% ΛN
Bp/Ap >> Bn/An $\Rightarrow$ no FSI
Bp,n : ?
Bp,n : K^{-} $^{4}He \rightarrow \Sigma N(2N)$ ($\Sigma \rightarrow \Lambda\gamma$ 30% Bp,n)
$\Sigma N \rightarrow \Lambda N$
Bp,n : dibaryon; tribaryon

[K$^-$pp] search now is a "Λp puzzle"

What the experiments are measuring are Λp invariant mass signals: are they totally in disagreement ?

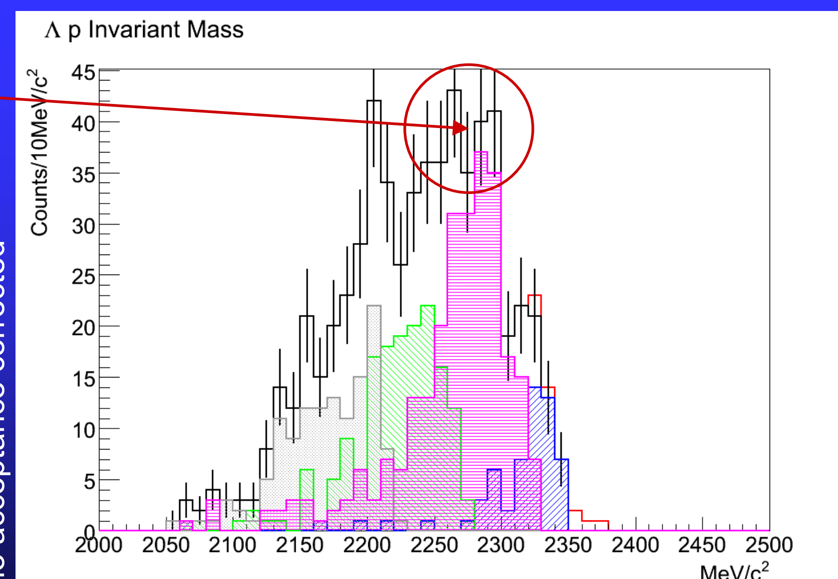
E549 Collaboration

no acceptance corrected

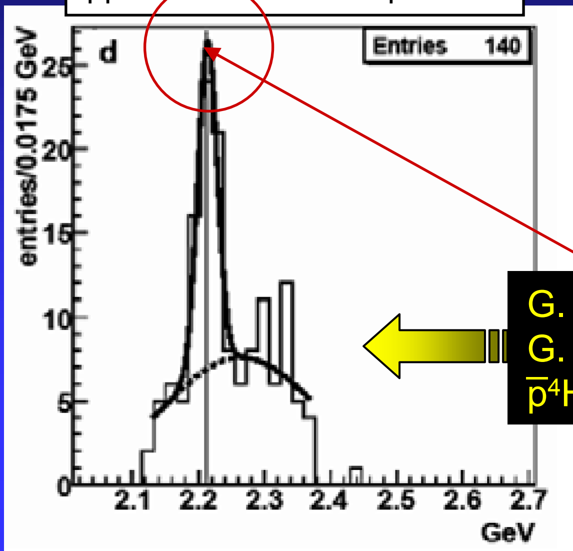


FINUDA Collaboration

no acceptance corrected



Λp inv mass: FINUDA vs OBELIX



T. Buran et al., PL20(1966)318
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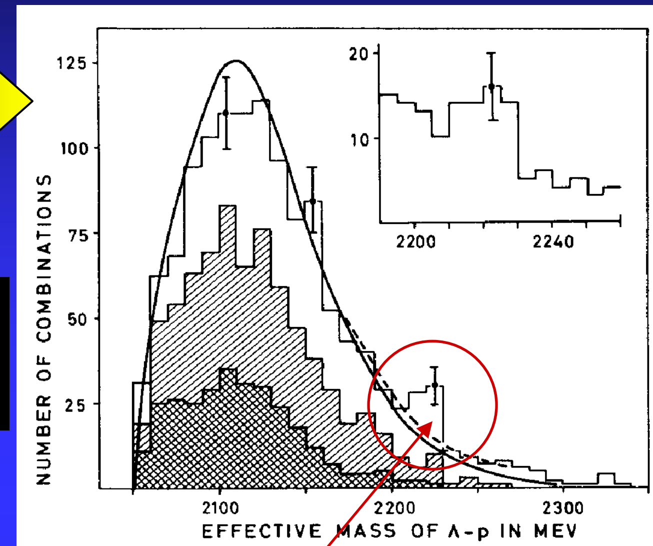

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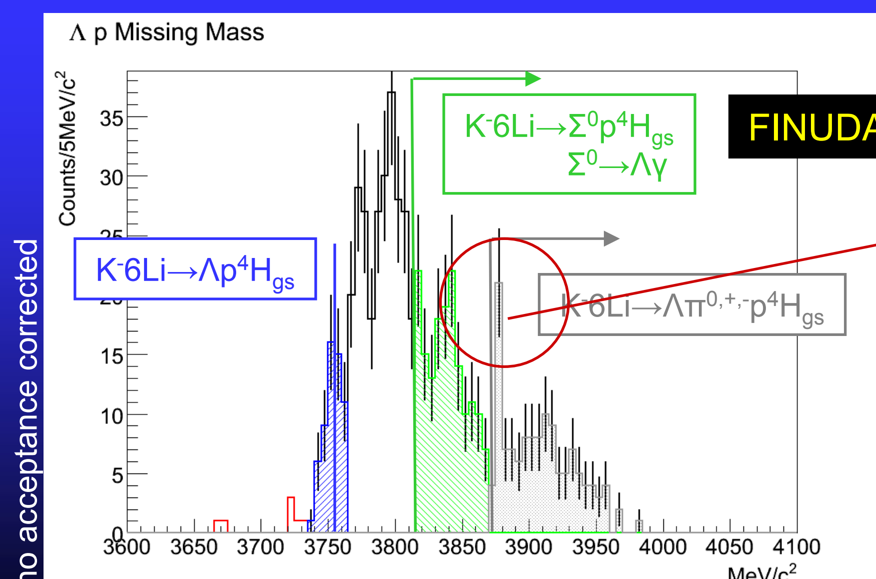
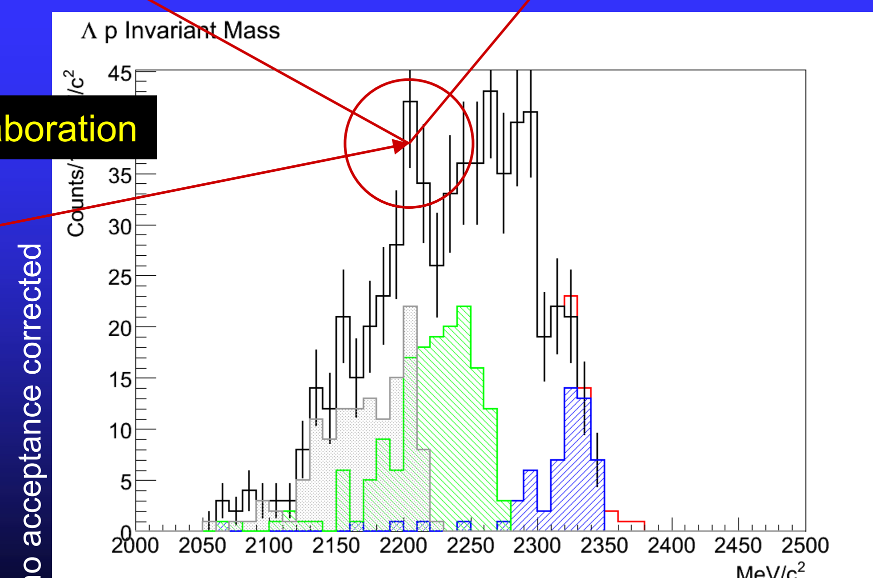
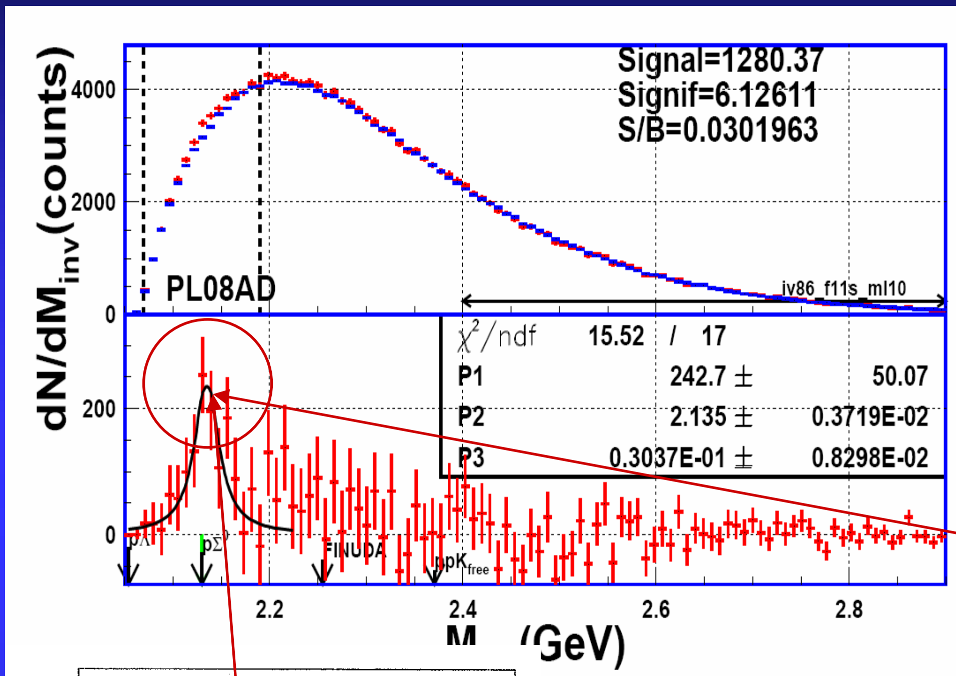
$\bar{p}\,^4He \to (p\pi^-) p K^0_s X$



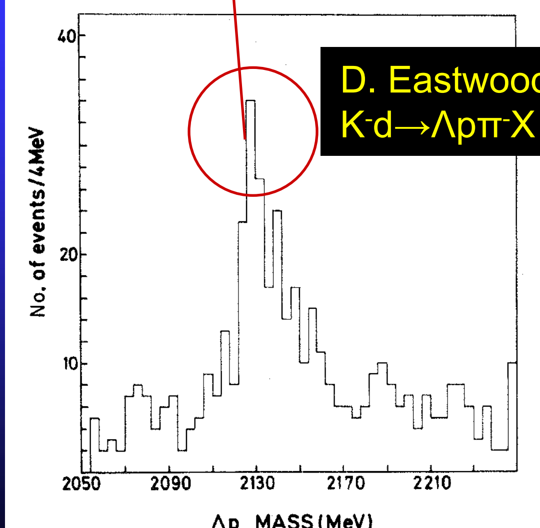
FINUDA Collaboration



Λp inv mass: FOPI vs K⁻d experiments

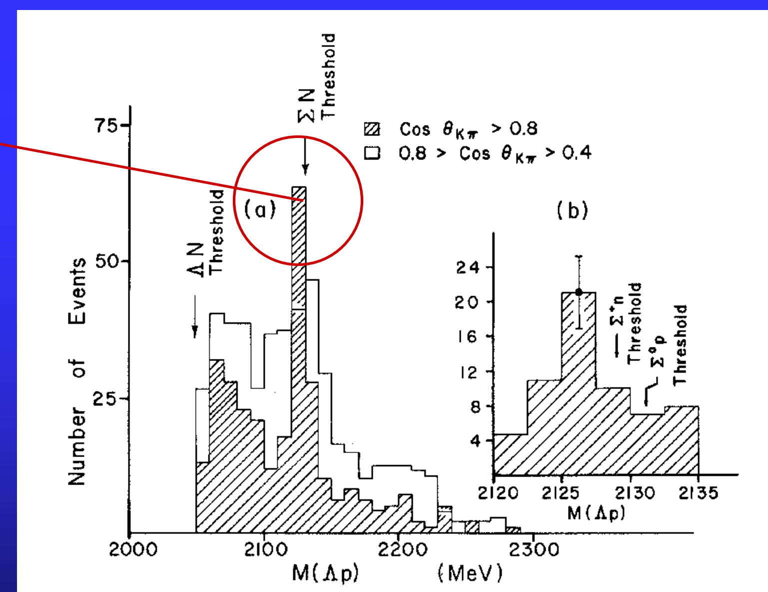


FOPI Collaboration



D. Eastwood et al., PRD3(1971)2603

$K^-d \rightarrow \Lambda p \pi^- X$ (1.45 GeV/c and 1.65 GeV/c)



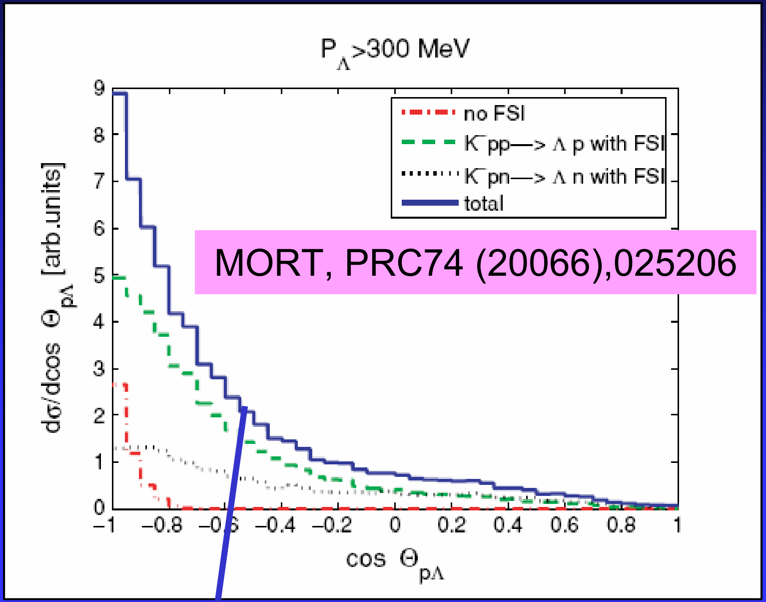
D. Cline et al., PRL20(1968)1452

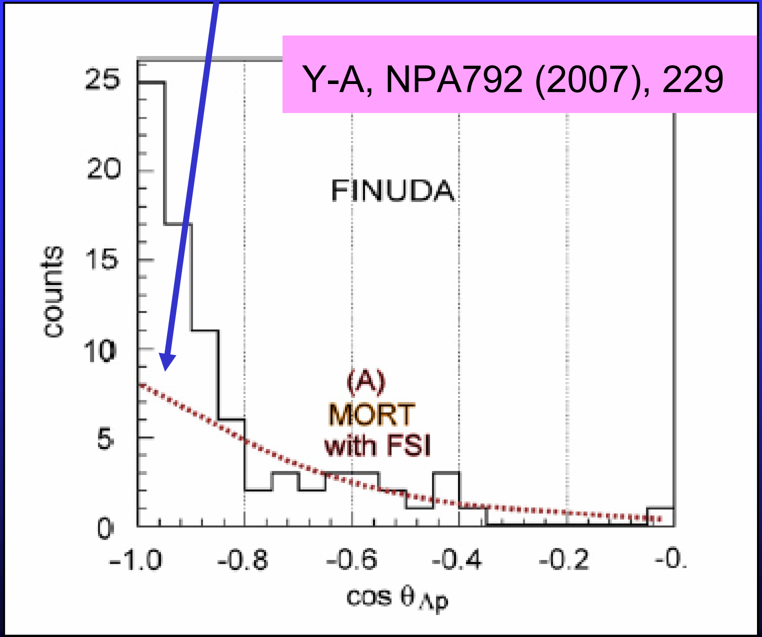
$K^-d \rightarrow \Lambda p \pi^- X$ (400 MeV/c)

Angular distributions: a closer look

- FSI alone cannot explain at the same time the inv. mass spectrum and angular distribution measured by FINUDA

- The angular correlation between Λp pairs comes naturally from the data without any constraint

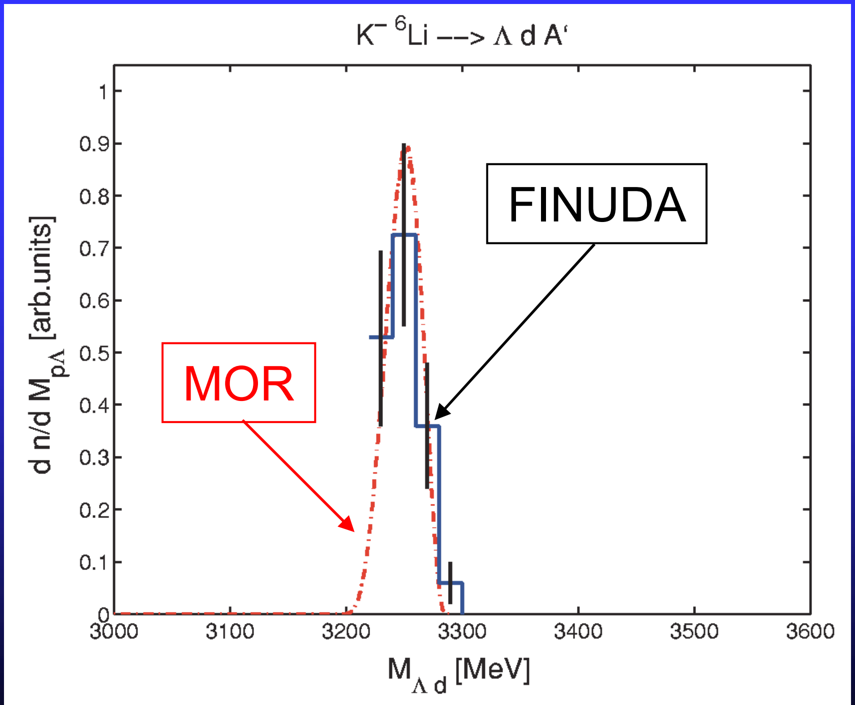


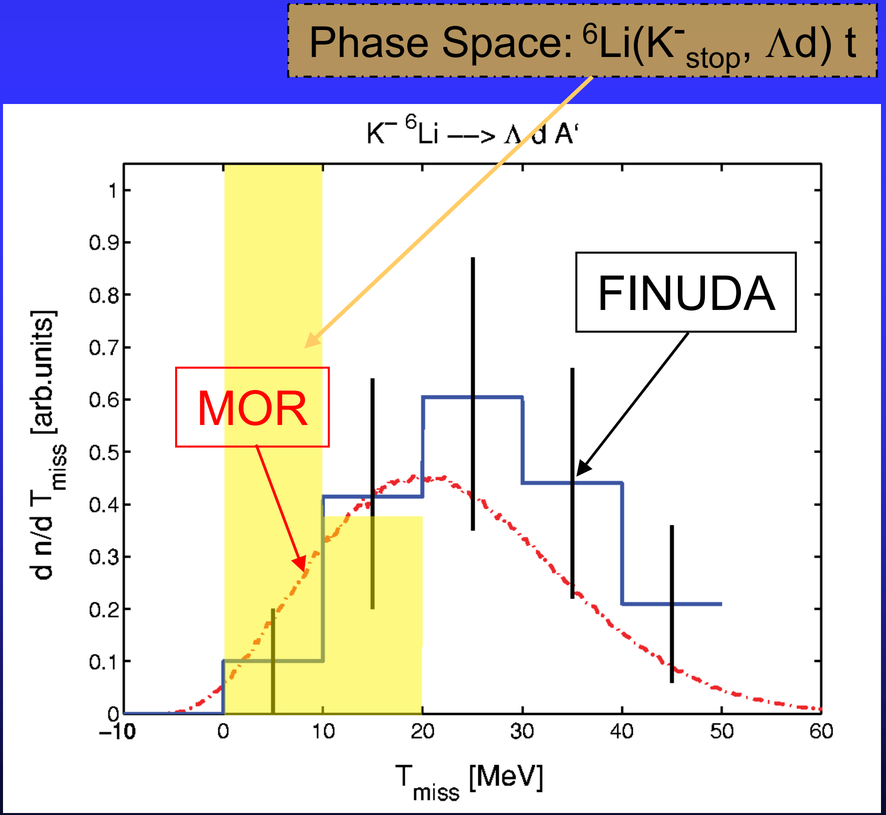


Critical review of the $M_{\Lambda d}$ bump

Magas, Oset and Ramos [PRC77(2008)065210] explain Λd FINUDA data with K^- absorption from three nucleons leaving the rest as spectator: $^6Li(K^-_{stop}, \Lambda d)A'$ with 0% FSI.

But ... FINUDA analysis showed that the missing kinetic energy of 3 body absorption can explain only a little fraction of the bump …





Λp acceptance