Hypernuclear physics studies with FINUDA: setup, method, results, inheritance

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Overview

- the FINUDA experiment
- physics program
- methods & results
- inheritance

FINUDA: FIsica NUcleare a DAΦNE

DAΦNE

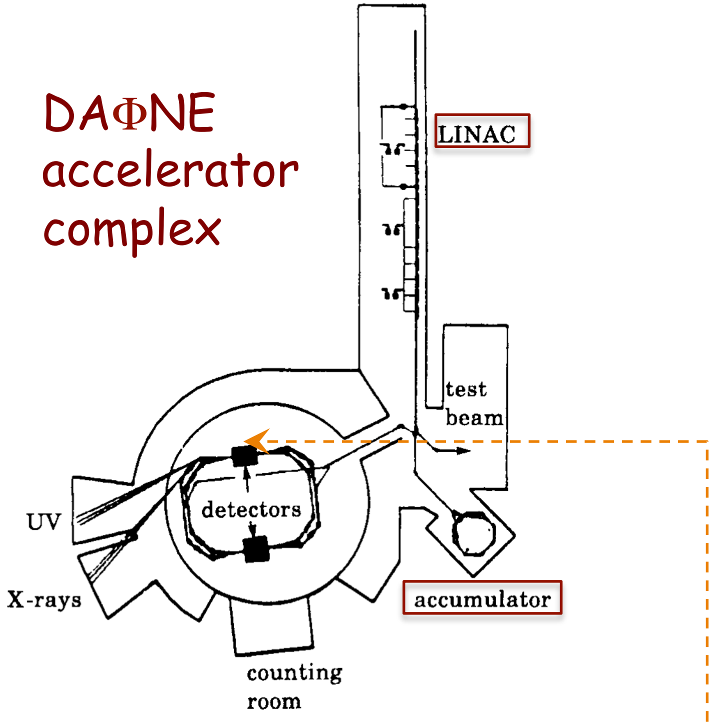
Double **A**nnular **Φ**-factory for **N**ice **E**xperiments

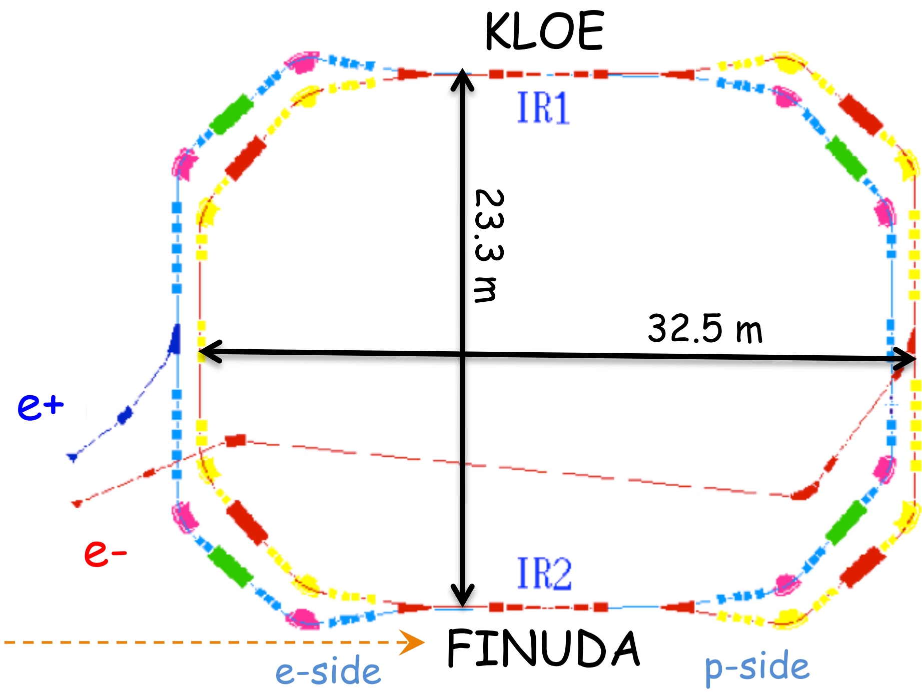
facility for low momentum not collimated K^- beam

Energy (GeV)	0.51
Luminosity (cm-2 s-1)	10^{32}
Beam Hor. Dim. at IP (mm)	2.11
Beam Vert. Dim. at IP (mm)	0.021
R.M.S. Bunch length (mm)	30
Crossing angle (mrad)	25
Collision frequency (MHz)	380.44
Bunches/ring	120
Max number of particles/bunch	$9.0\ 10^{10}$
Max total mean current (A)	5.5

ϕ(1020) ~ at rest

DAΦNE accelerator complex

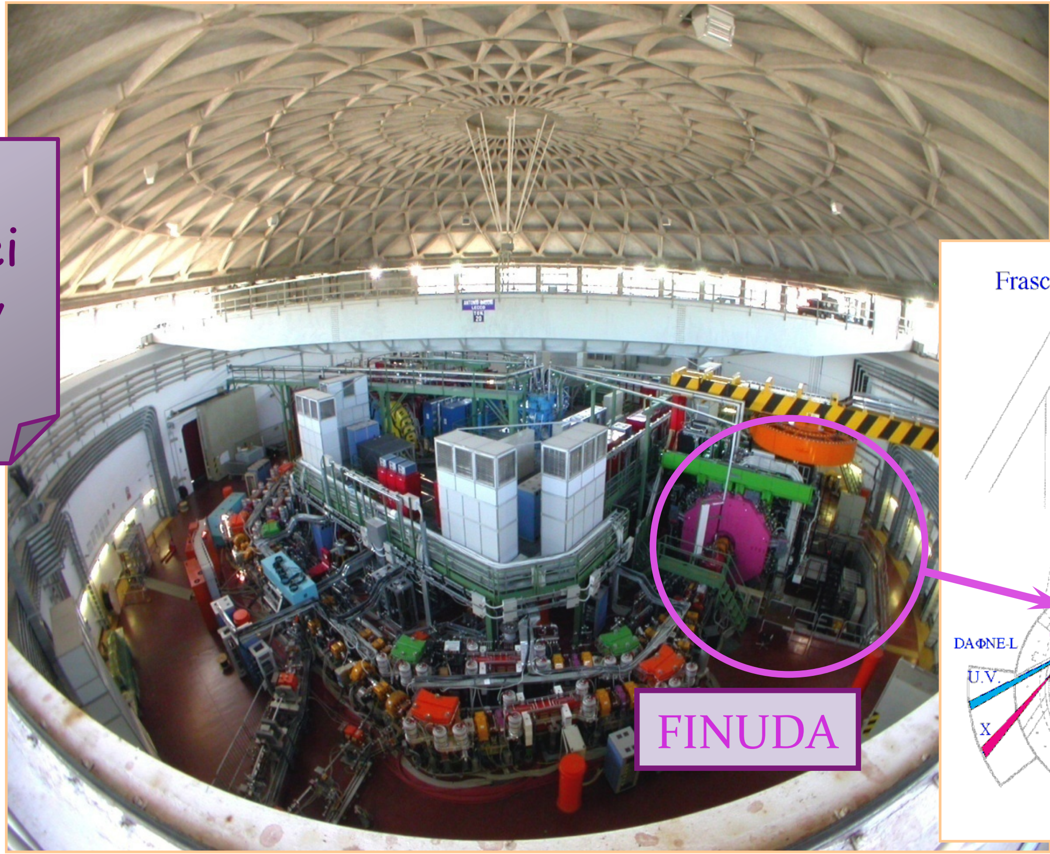


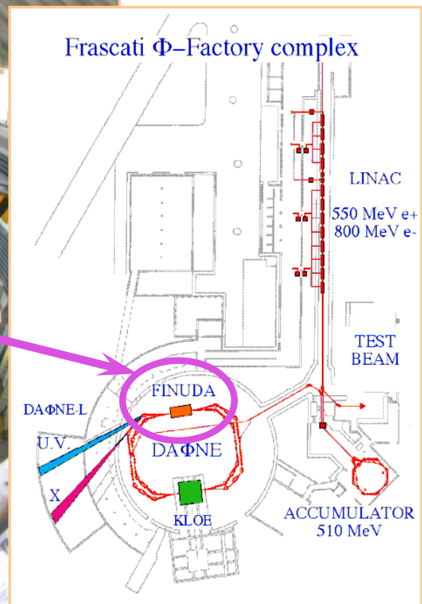


FINUDA: FIsica NUcleare a DAΦNE

The very first example of a *(hyper)nuclear physics* fixed-target experiment carried on at a *collider* (DAΦNE @ LNF)

Optimized to produce hypernuclei $^{A}_{\Lambda}Z$ in a completely new way





FINUDA: the Collaboration

Collaborating institutes

University of Victoria

Seoul National University

JINR Dubna

Bari University & INFN Bari
Brescia University & INFN Pavia
Pavia University & INFN Pavia
Torino Polytechnic & INFN Torino
Torino University & INFN Torino
Trieste University & INFN Trieste
L.N.F. / INFN Frascati

Kyoto, KEK, RIKEN

Teheran Shahid Beheshty University

Data takings

data taking	oct 2003 - jan 04	nov 2006 - jun 07
int. luminosity	220 pb^{-1}	960 pb^{-1}
daily luminosity	6 pb^{-1}	10 pb^{-1}
Total events (M)	30	200
Targets	^{6}Li (2), ^{7}Li (1), ^{12}C (3), ^{27}Al (1), ^{51}V (1)	^{6}Li (2), ^{7}Li (2), ^{9}Be (2), ^{13}C (1), D_2O (1)

Hypernuclear Physics @FINUDA

$e^+ + e^- \to \phi\,(1020) \to K^+ + K^-$ (127 MeV/c,~49%)

"secondary" K- beam $\quad K^-_{stop} + {}^AZ \to {}^A_\Lambda Z + \pi^-$

Spectroscopy

${}^A_\Lambda Z \to {}^A(Z+1) + \pi^-$ $\quad \Gamma_{\pi-}$ $\quad$ MWD

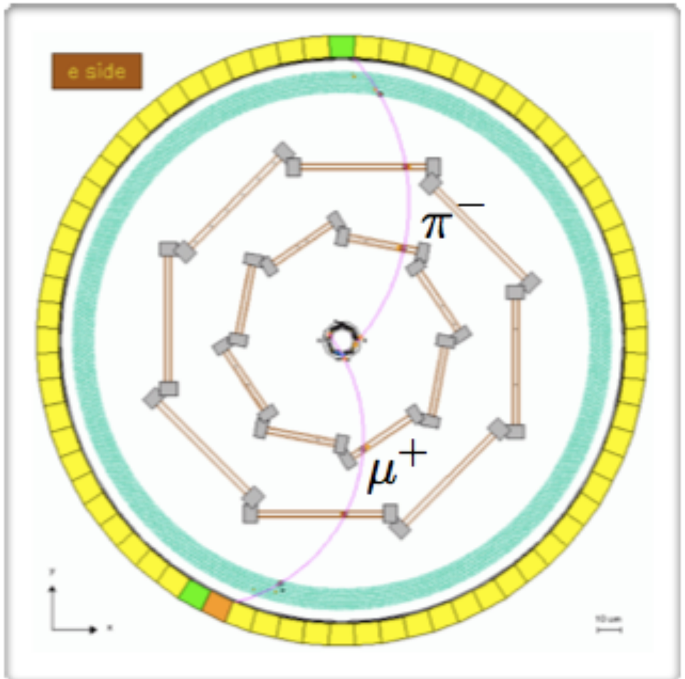
${}^A_\Lambda Z \to {}^{A-2}(Z-1) + p + n$ $\quad$ 1N induced Γ_p

${}^A_\Lambda Z \to {}^{A-3}(Z-1) + p + n + n$ $\quad$ 2N induced Γ_{np}

} NMWD

$\mathcal{L} = 10^{32}\ cm^{-2}\ s^{-1}$
ϕ: ~$4.4\times10^2\ s^{-1}$
(K^+, K^-) pairs:~$2.2\times10^2\ s^{-1}$
collinear, background free,
very low energy

FINUDA key features



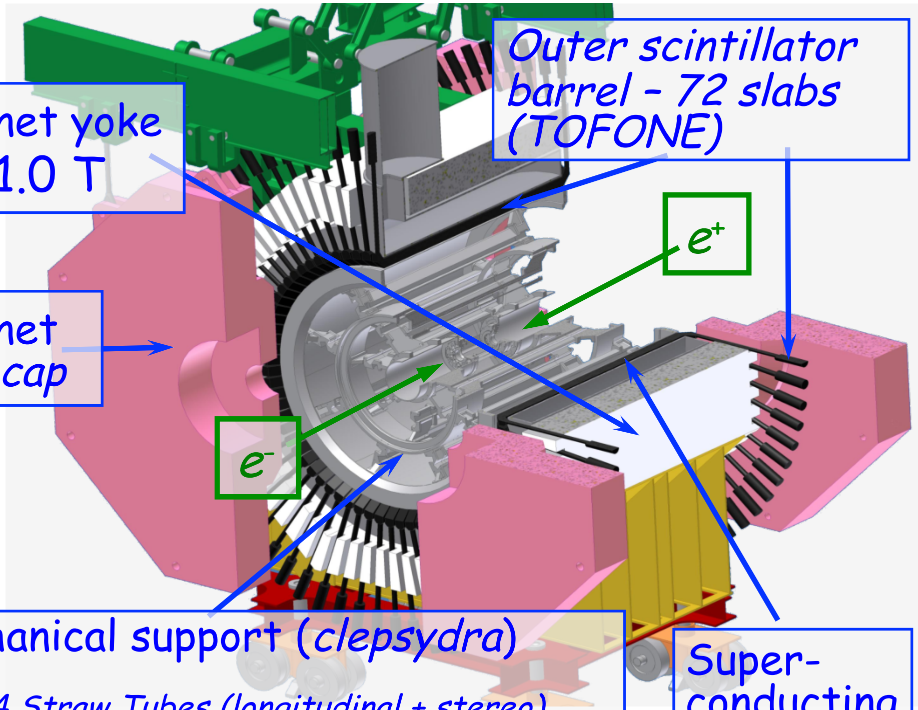
- very thin targets (0.1 ÷ 0.3 g/cm^2)
  transparency ➥ "high" resolution spectroscopy

- different targets in the same run
  ➥ high degree of flexibility

- coincidence measurement with large acceptance
  complete event ➥ decay mode study

- simultaneous tracking of μ^+ from the K^+ decay
  $K^+ \to \mu^+ \nu_\mu$ ➥ energy and rate calibration

The FINUDA detector



Mechanical support (*clepsydra*)

For:

- *2424 Straw Tubes (longitudinal + stereo)*
- *16 Low-Mass Drift Chambers (LMDC)*
- *18 μ-strip vertex detectors (ISIM/OSIM)*
- *Inner scintillator barrel - 12 slabs (TOFINO)*
- *8 Targets*

Detector capabilities:

- *Selective trigger* based on fast scintillation detectors (TOFINO, TOFONE)
- *precise K^- vertex identification* (< 1 mm^3) (ISIM P.ID.+ *x,y,z* resolution + K^+ tagging)
- p, K, p, d, … P.ID. (OSIM and LMDC d*E*/d*x*)
- ***High momentum resolution***

(6‰ FWHM for π- @270 MeV/c for spectroscopy)

(1% FWHM for π- @270 MeV/c for decay study)

(6% FWHM for π- @110 MeV/c for decay study)

(2% FWHM for p @400 MeV/c for decay study)

(tracker resolution + He bag + thin targets)

- *Neutron detection* TOF (TOFONE-TOFINO)

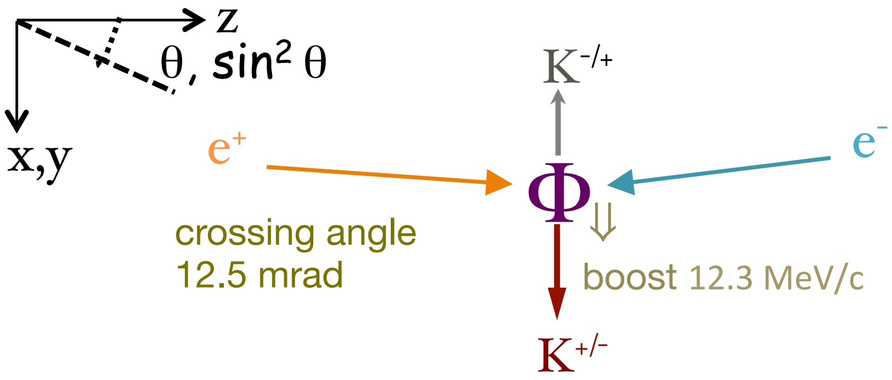
(13% FWHM for n @10 MeV, 20% @100 MeV)

Apparatus designed for a typical collider experiment:

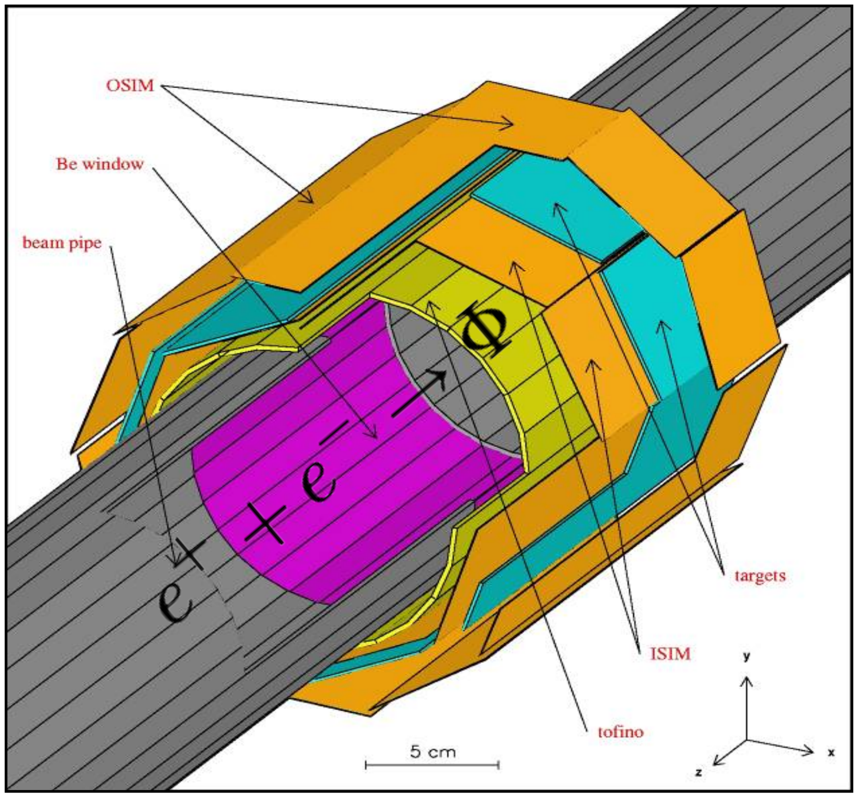
- Cylindrical geometry
- large solid angle (~ 2π sr)
- multi-tracks analysis

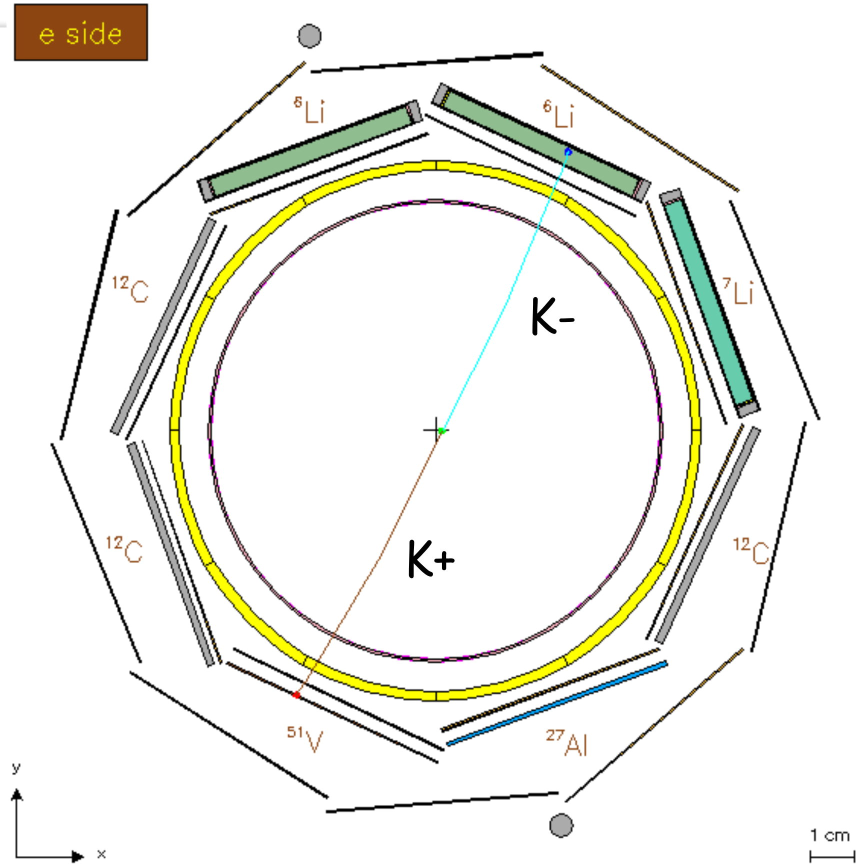
Simultaneous study of formation and decay of strange hadronic systems by *full event reconstruction*

FINUDA: the interaction region

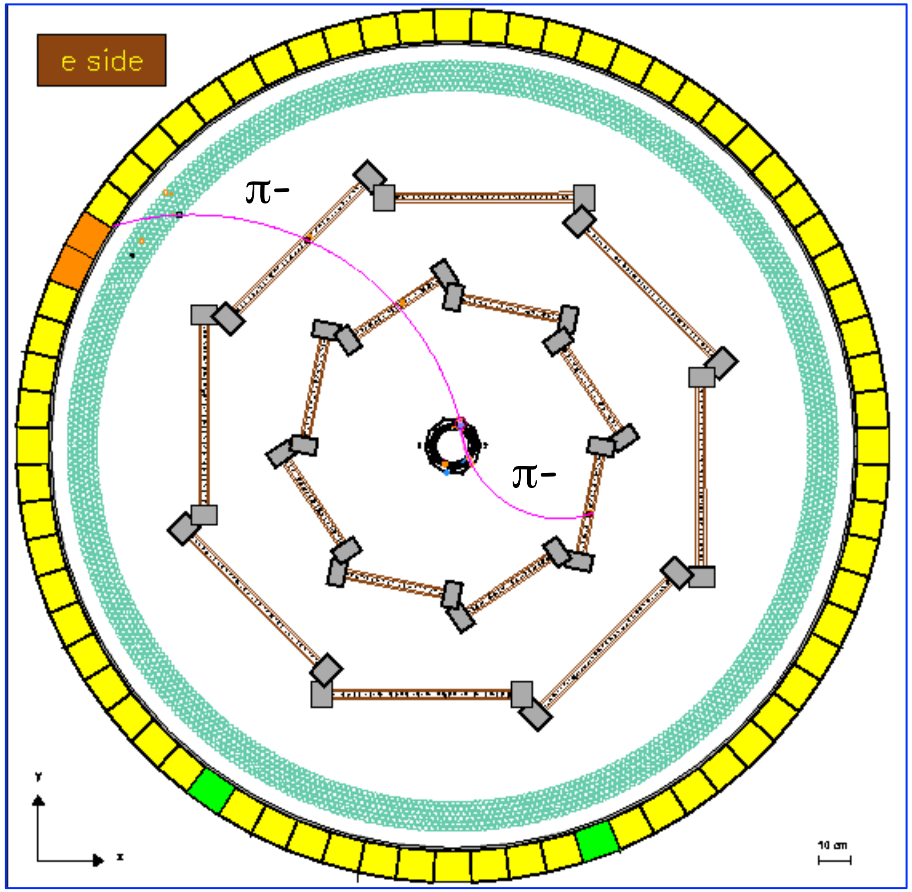


target region
- 12 scintillators (TOFINO)
- 8 silicon microstrips layer (ISIM)
- 8 targets
- 10 silicon microstrip layer (OSIM)

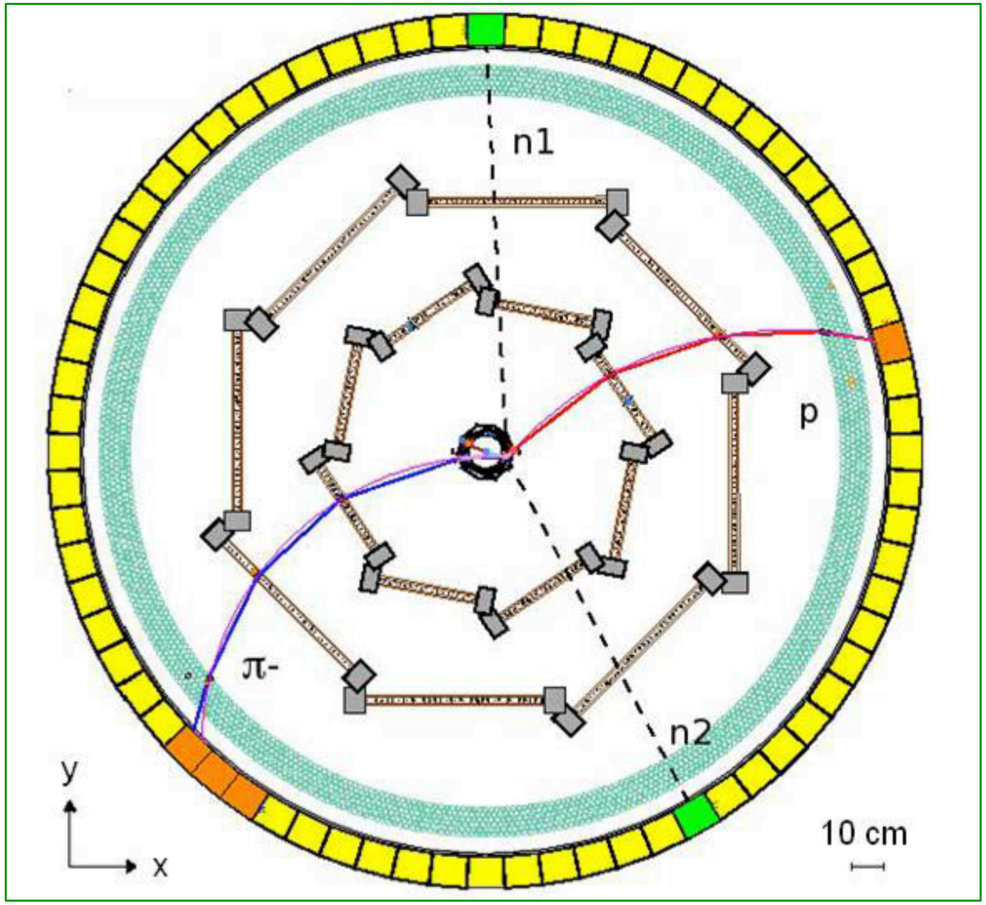




FINUDA: the tracking/outer regions



tracker
- 10 silicon microstrip layer (OSIM)
- 2x8 Low Mass Drift Chamber layers
- 6x404 stereo straw tube layer system
- B=1 T
- He bag



outer region
- 72 scintillator slab system
- trigger
- n detection

FINUDA Scientific Program - Results

Main topics (.. not complete!):

Hypernuclear spectroscopy: PLB 622 (2005) 35: $^{12}{}_{\Lambda}C$
PLB 698 (2011) 219: $^{7}{}_{\Lambda}Li$, $^{9}{}_{\Lambda}Be$, $^{13}{}_{\Lambda}C$, $^{16}{}_{\Lambda}O$

Weak Decay: NPA 804 (2008) 151: NMWD $^{5}{}_{\Lambda}He$, $^{7}{}_{\Lambda}Li$, $^{12}{}_{\Lambda}C$
PLB 681 (2009) 139: MWD ($^{5}{}_{\Lambda}He$,) $^{7}{}_{\Lambda}Li$, $^{9}{}_{\Lambda}Be$, $^{11}{}_{\Lambda}B$, $^{15}{}_{\Lambda}N$

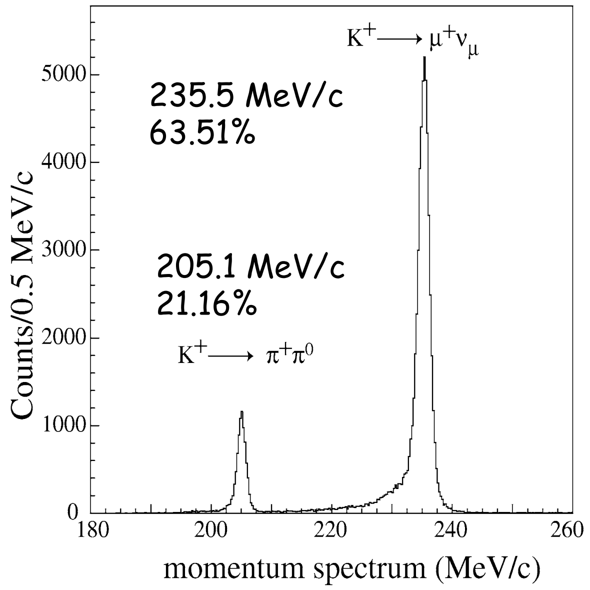
PLB 685 (2010) 247 } NMWD & 2N $^{5}{}_{\Lambda}He$, $^{7}{}_{\Lambda}Li$, $^{9}{}_{\Lambda}Be$, $^{11}{}_{\Lambda}B$, $^{12}{}_{\Lambda}C$,
PLB 701 (2011) 556 } $^{13}{}_{\Lambda}C$, $^{15}{}_{\Lambda}N$, $^{16}{}_{\Lambda}O$

NPA 881 (2012) 322 : (n, n, p) events from 2N
PLB 738 (2014) 499: NMWD Γ_{2N}/Γ_{NM} & $\Gamma_{p}/\Gamma_{\Lambda}$ $^{5}{}_{\Lambda}He$, $^{7}{}_{\Lambda}Li$, $^{9}{}_{\Lambda}Be$, $^{11}{}_{\Lambda}B$, $^{12}{}_{\Lambda}C$, $^{13}{}_{\Lambda}C$, $^{15}{}_{\Lambda}N$, $^{16}{}_{\Lambda}O$
(PLB 748 (2015) 86: $\Gamma_{p,}$ $\Gamma_{n,}$ Γ_{2N} $^{5}{}_{\Lambda}He$, $^{11}{}_{\Lambda}B$)

Rare Decays: NPA 835 (2010) 439; $^{4}{}_{\Lambda}He$, $^{5}{}_{\Lambda}He$ 2-body decays

Neutron-rich Hypernuclei: PLB 640 (2006) 145: upper limits $^{6}{}_{\Lambda}H$, $^{7}{}_{\Lambda}H$ and $^{12}{}_{\Lambda}Be$
PRL 108 (2012) 042501: $^{6}{}_{\Lambda}H$ observation
NPA 881 (2012) 269: $^{6}{}_{\Lambda}H$ observation
PRC 86 (2012) 057301: $^{9}{}_{\Lambda}He$ upper limit

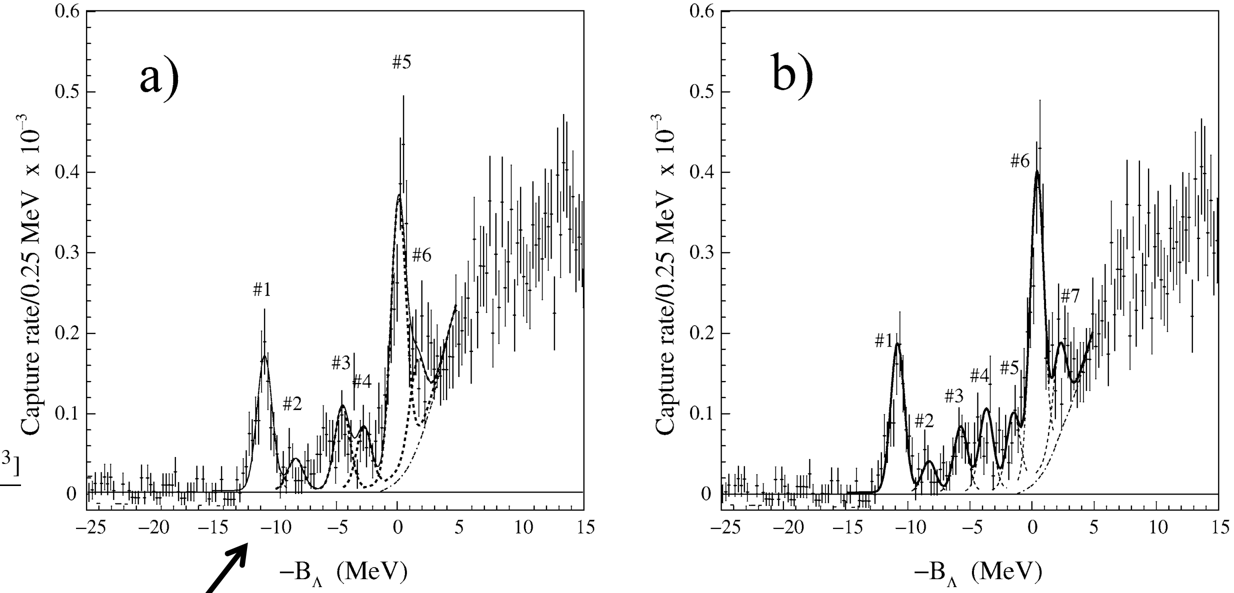
Hypernuclear Spectroscopy: $^{12}{}_{\Lambda}C$



M.Agnello et al., PLB 622 (2005) 35

$\Delta p/p$ = 0.6% FWHM
absolute momentum scale: 200 kev/c
ΔE = 1.29 MeV FWHM

Peak number	$-B_\Lambda$ (MeV)	Capture rate/(stopped K^-)[$\times 10^{-3}$]
1	-10.94 ± 0.06	$1.01 \pm 0.11_{stat} \pm 0.10_{syst}$
2	-8.4 ± 0.2	0.21 ± 0.05
3	-5.9 ± 0.1	0.44 ± 0.07
4	-3.8 ± 0.1	0.56 ± 0.08
5	-1.6 ± 0.2	0.50 ± 0.08
6	0.27 ± 0.06	2.01 ± 0.17
7	2.1 ± 0.2	0.58 ± 0.18



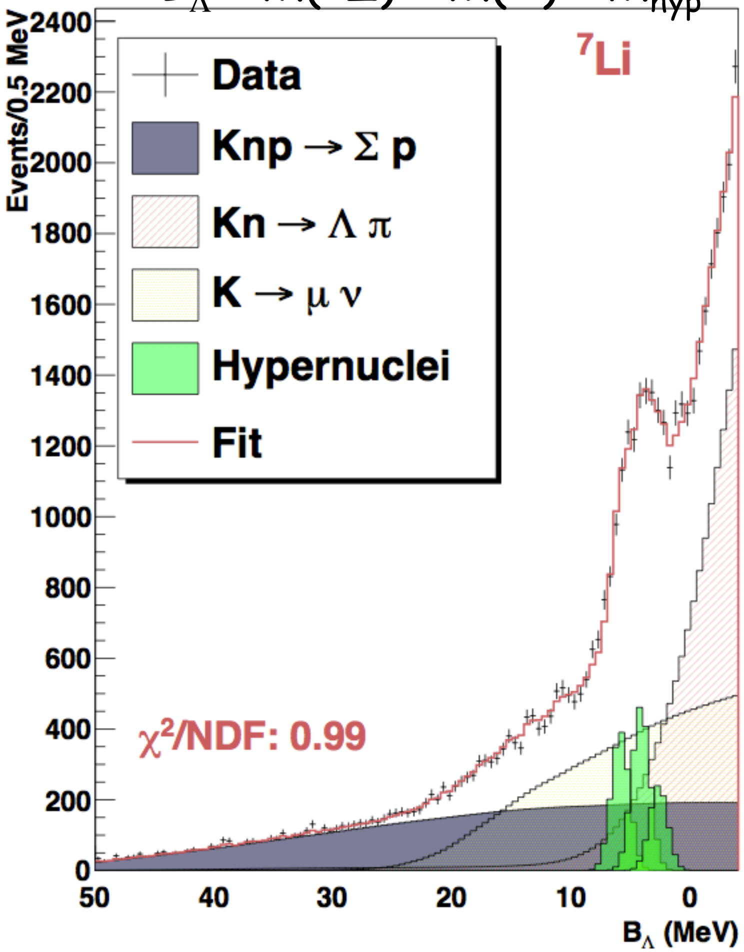
KEK E369: 6 peaks
1.45 MeV FWHM

Hypernuclear Spectroscopy: p-shell

M.Agnello et al., PLB 698 (2011) 219

First world measurement of formation probability

$B_\Lambda = M(^AZ) + M(\Lambda) - M_{hyp}$

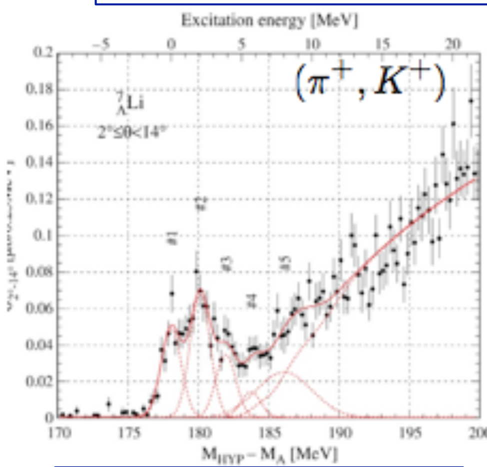


^{7}Li	B_Λ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	5.8 ± 0.4	-	$0.37 \pm 0.04 \pm 0.05$
2	4.1 ± 0.4	1.7	$0.46 \pm 0.05 \pm 0.06$
3	2.6 ± 0.4	3.2	$0.21 \pm 0.03 \pm 0.03$
			$1.04 \pm 0.12 \pm 0.14$

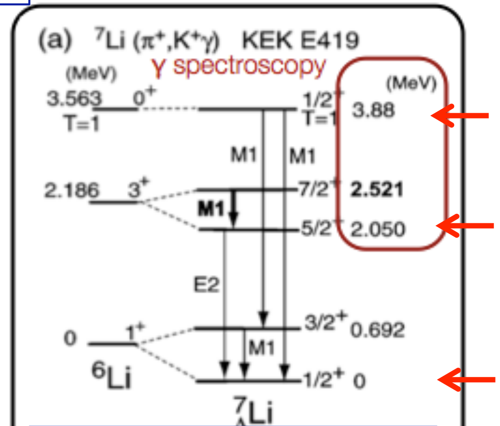
the ground state from emulsion data
$B_\Lambda = -5.58 \pm 0.03$ MeV

M. Juric et al., NPB 52 (1973), 1

~4000 events



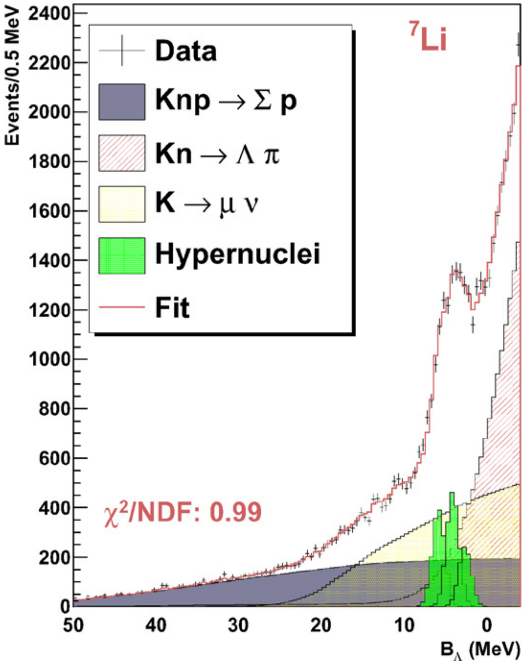
O. Hashimoto, H. Tamura
PPNP 57 (2006) 564
(E336 data)

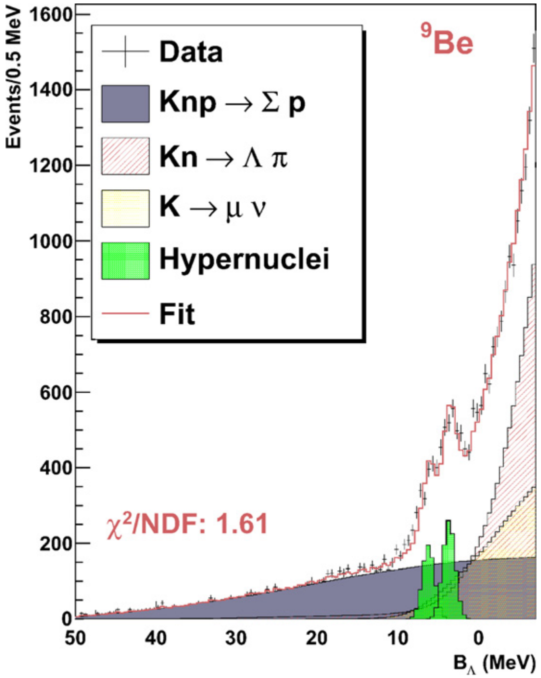


H. Tamura et al.
NPA 754 (2005) 58c

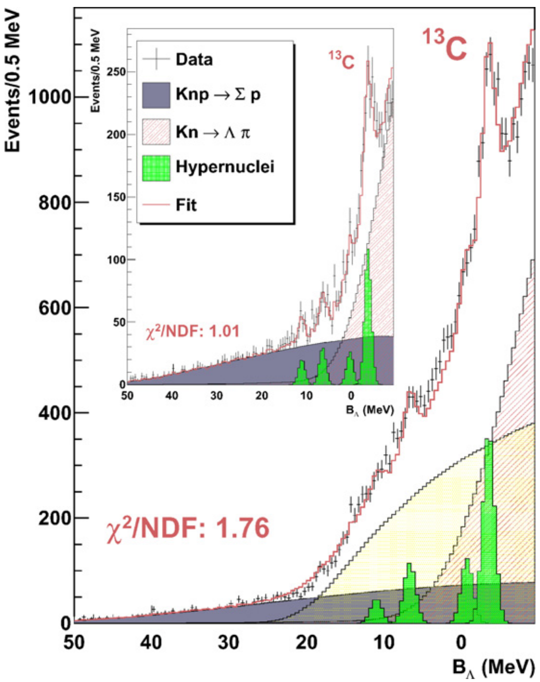
absolute energy scale known at the level of 0.3 MeV
(we know from the $K^+ \to \mu\nu$ – <u>self calibrated apparatus</u>)
momentum resolution: 0.5-0.9% FWHM ($\sigma(B_\Lambda)$ = 0.4 MeV)

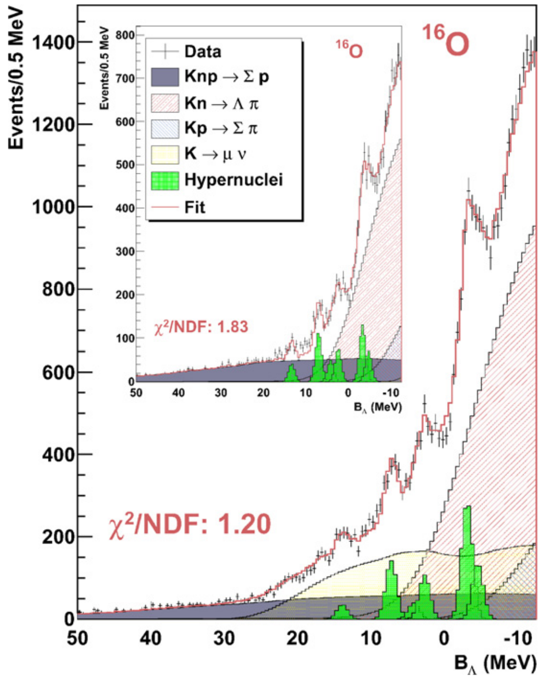
Formation probability
it is connected to the number of events in the peaks, calculated taking into account acceptances and efficiencies
($K^+ \to \mu\nu$ – <u>rate calibrated apparatus</u>)





"backward" tracks to reduce background from K→ $\mu\nu$



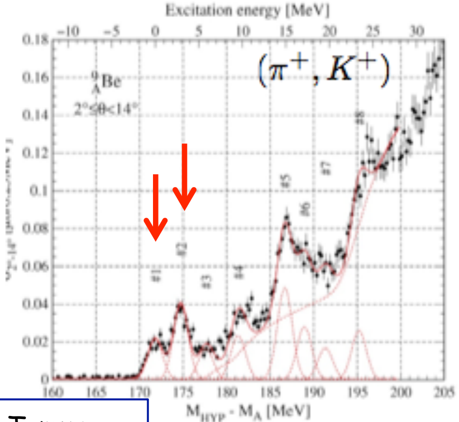


^{9}Be	B_Λ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	6.2 ± 0.4	–	$0.16 \pm 0.02 \pm 0.02$
2	3.7 ± 0.4	2.5	$0.21 \pm 0.02 \pm 0.03$
			$0.37 \pm 0.04 \pm 0.05$

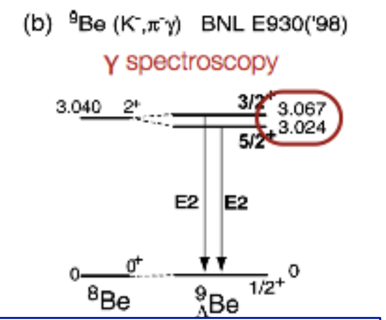
the ground state from emulsion data
B_Λ = -6.71 ± 0.04 MeV

M. Juric et al., NPB 52 (1973), 1

~1800 events



O. Hashimoto, H. Tamura
PPNP 57 (2006) 564
(E336 data)



H. Tamura et al.
NPA 754 (2005) 58c

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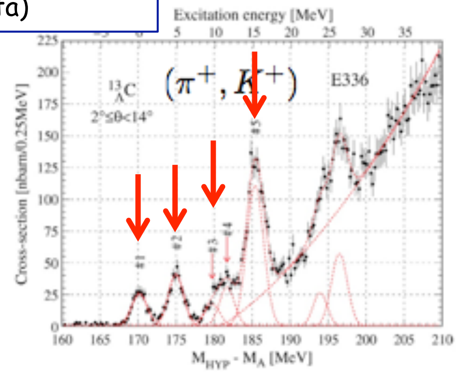
^{13}C	B_Λ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	11.0 ± 0.4	–	$0.10 \pm 0.02 \pm 0.01$
2	6.4 ± 0.4	4.6	$0.19 \pm 0.02 \pm 0.03$
3	0.3 ± 0.4	10.7	$0.16 \pm 0.02 \pm 0.02$
4	-3.7 ± 0.4	14.7	$0.47 \pm 0.04 \pm 0.07$ ← $^{12}_{\Lambda}$C + n

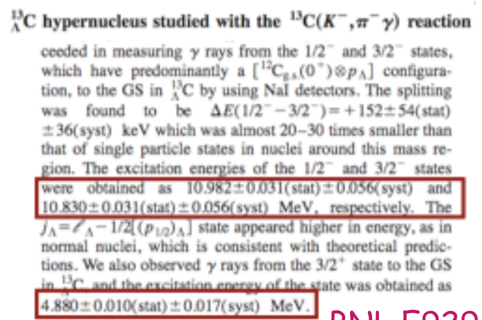
the ground state from emulsion data
B_Λ = -11.22 ± 0.08 MeV

M. Juric et al., NPB 52 (1973), 1

~1100 events 3p



H. Kohri, et al., Phys. Rev. C 65 (2002) 034607.


PHYSICAL REVIEW C, VOLUME 65, 034607

$^{13}_{\Lambda}$C hypernucleus studied with the ^{13}C(K^-,$\pi^-\gamma$) reaction

ceeded in measuring γ rays from the 1/2$^-$ and 3/2$^-$ states, which have predominantly a [^{12}C$_{g.s.}$(0$^+$)⊗p_Λ] configuration, to the GS in $^{13}_{\Lambda}$C by using NaI detectors. The splitting was found to be $\Delta E(1/2^- - 3/2^-) = +152 \pm 54$(stat) ±36(syst) keV which was almost 20–30 times smaller than that of single particle states in nuclei around this mass region. The excitation energies of the 1/2$^-$ and 3/2$^-$ states were obtained as 10.982±0.031(stat)±0.056(syst) and 10.830±0.031(stat)±0.056(syst) MeV, respectively. The $j_\Lambda = \ell_\Lambda - 1/2[(p_{1/2})_\Lambda]$ state appeared higher in energy, as in normal nuclei, which is consistent with theoretical predictions. We also observed γ rays from the 3/2$^+$ state to the GS in $^{13}_{\Lambda}$C and the excitation energy of the state was obtained as 4.880±0.010(stat)±0.017(syst) MeV.

BNL E929
γ spectroscopy

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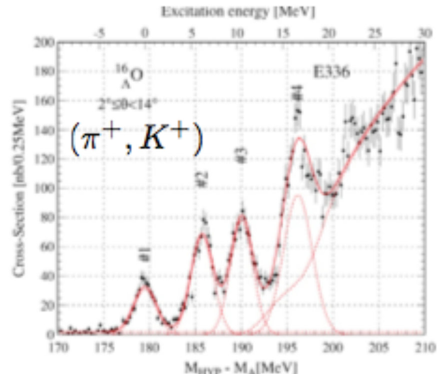
^{16}O	B_Λ (MeV)		E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	13.4 ± 0.4	$^{16}_{\Lambda}$O	–	$0.10 \pm 0.02 \pm 0.01$
2	7.1 ± 0.4		6.3	$0.26 \pm 0.04 \pm 0.04$
3	4.3 ± 0.4	$^{15}_{\Lambda}$N	9.1	$0.13 \pm 0.03 \pm 0.02$
4	2.4 ± 0.4		11.0	$0.15 \pm 0.03 \pm 0.02$
5	-3.3 ± 0.4		16.7	$0.55 \pm 0.07 \pm 0.08$
6	-4.7 ± 0.4		18.1	$0.28 \pm 0.06 \pm 0.04$

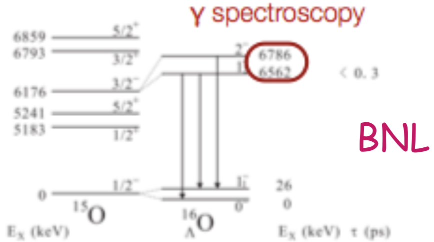
~750 events 2p

M.Agnello et al., PLB 698 (2011) 219



O. Hashimoto, H. Tamura
PPNP 57 (2006) 564
(E336 data)

PHYSICAL REVIEW C 77, 054315 (2008)



BNL

E930('01) Collaboration

M.Agnello et al., PLB 698 (2011) 219 **A.Cieply et al., PLB 698 (2011) 226**

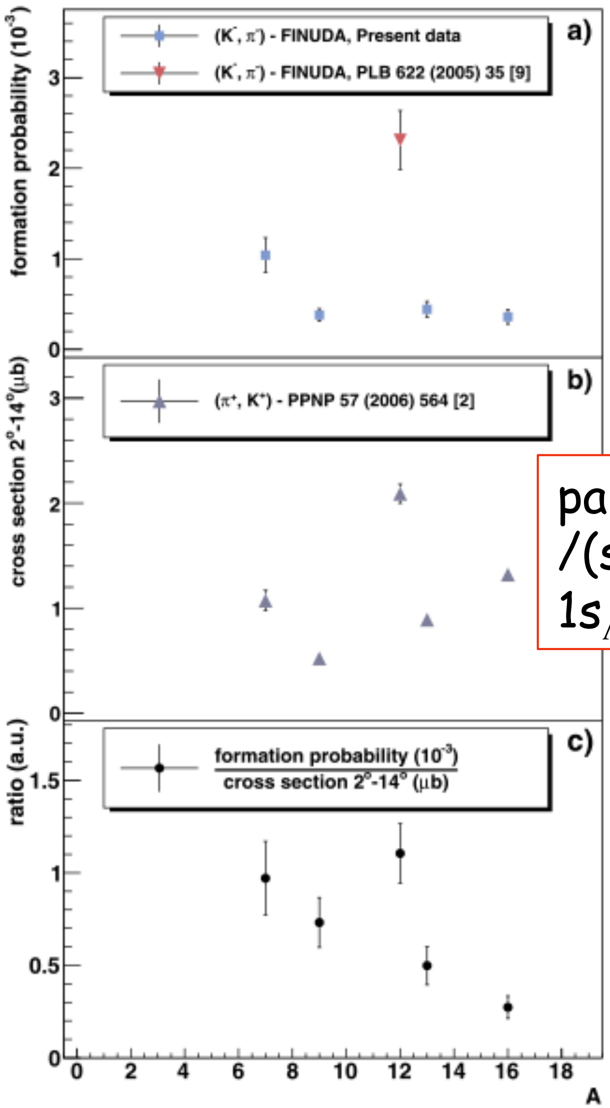
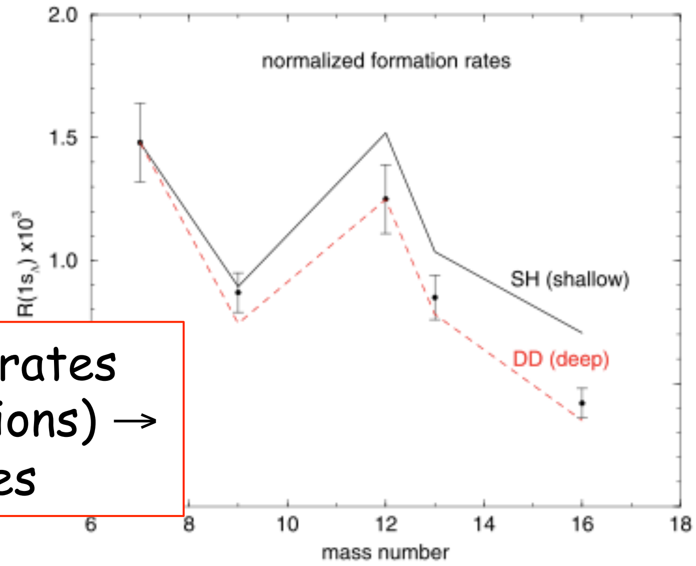


Fig. 7. Formation probabilities from FINUDA (a) and cross section from E336 [2] (b) for bound states, see text for details. In (c) the ratio between the two is shown.

Constraints on the threshold K- nuclear potential from FINUDA $^{A}Z(K^{-}_{stop}, \pi^{-})^{A}{}_{\Lambda}Z$ spectra



partial formation rates /(structure fractions) → $1s_\Lambda$ formation rates

Fig. 2. Comparison between $1s_\Lambda$ formation rates derived from the FINUDA K^- capture at rest data [8,14] and DWIA calculations normalized to the $1s_\Lambda$ formation rate of $^7_\Lambda$Li listed in Table 1 for shallow (SH, solid) and deep (DD, dashed) K^- nuclear potentials. The calculated $1s_\Lambda$ formation rates use $K^- n \to \pi^- \Lambda$ in-medium BRs without self energies, see Section 3, and pion optical potential π_e from Ref. [6]. The error bars consist of statistical uncertainties only.

two different potentials have been tested (shallow SH and deep DD)

$$Re\ V_{K^-}(\rho_0) \sim -(40-60)MeV$$

$$Re\ V_{K^-}(\rho_0) \sim -(150-200)MeV$$

the comparison with the FINUDA data slightly favors a deep K- nuclear potential

Hypernuclear weak decay studies: p-shell

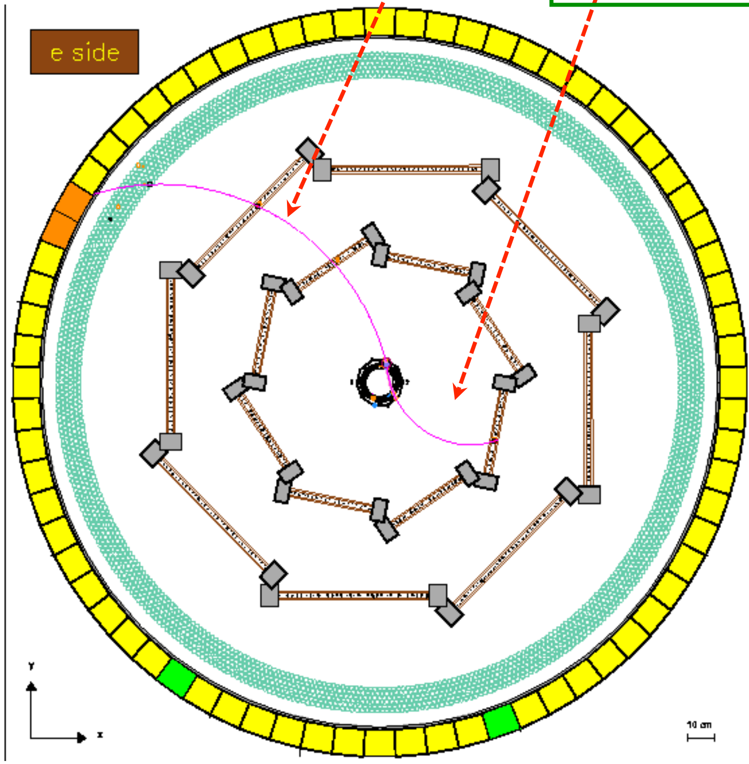
Coincidence measurement

<u>charged Mesonic channel</u>

$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$
$$^{A}_{\Lambda}Z \rightarrow {}^{A}(Z+1) + \pi^-$$

S-EX
260-280 MeV/c

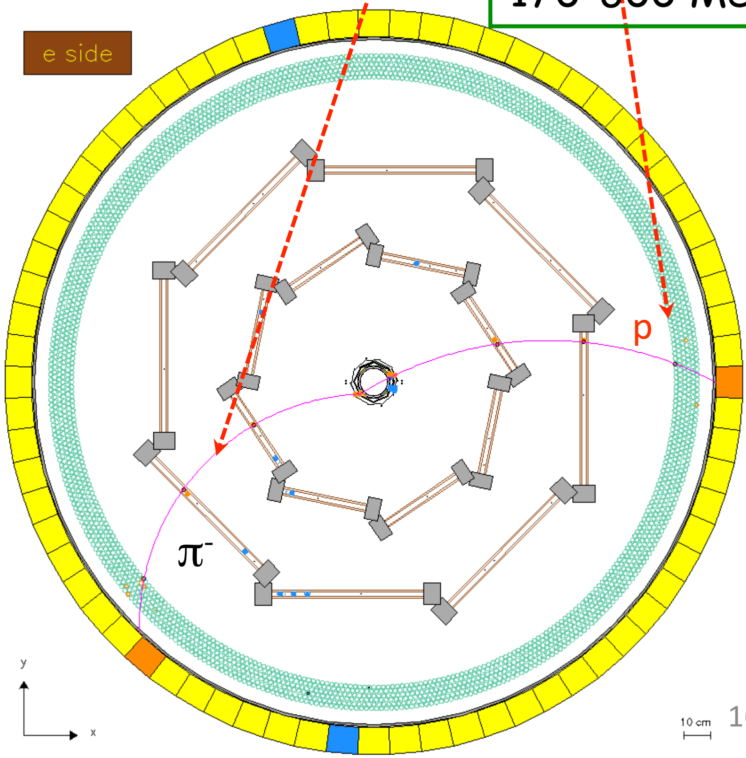
MWD
80-110 MeV/c



<u>charged Non-Mesonic channel</u>

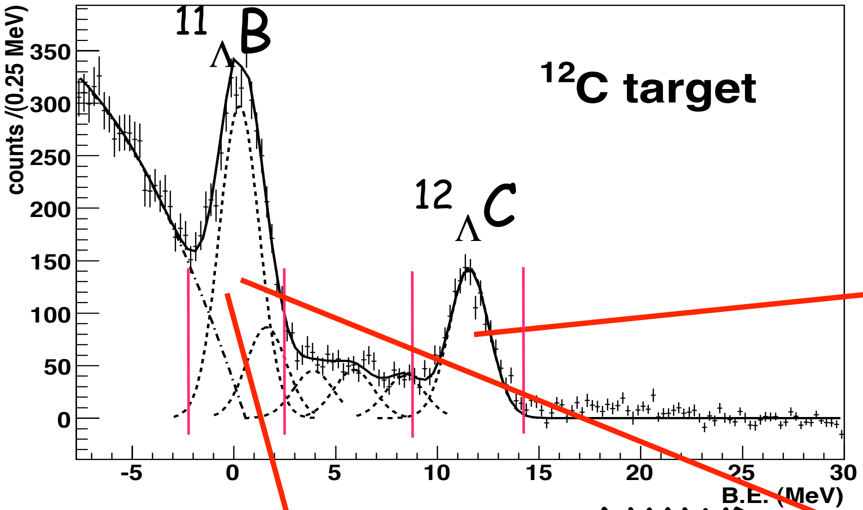
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$
$$^{A}_{\Lambda}Z \rightarrow {}^{A-2}(Z-1) + p + n$$

NMWD
170-600 MeV/c

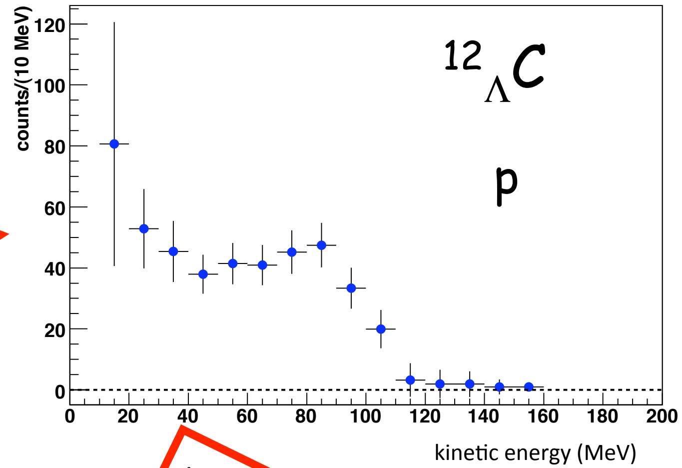


MWD & NMWD in FINUDA: strategy

Inclusive production π^- spectra
K^-np background corrected



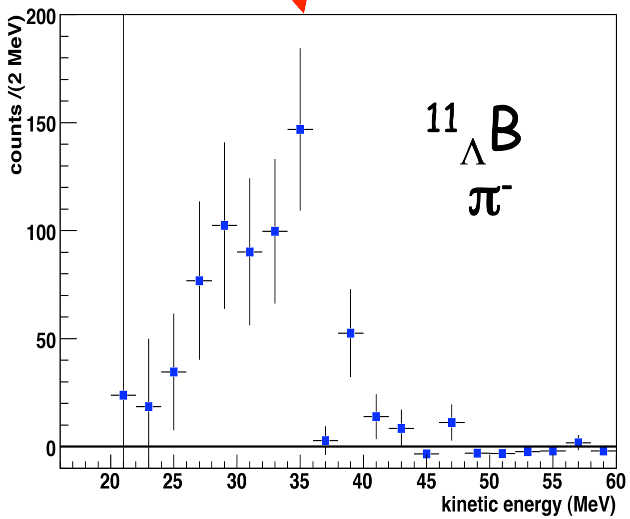
NMWD

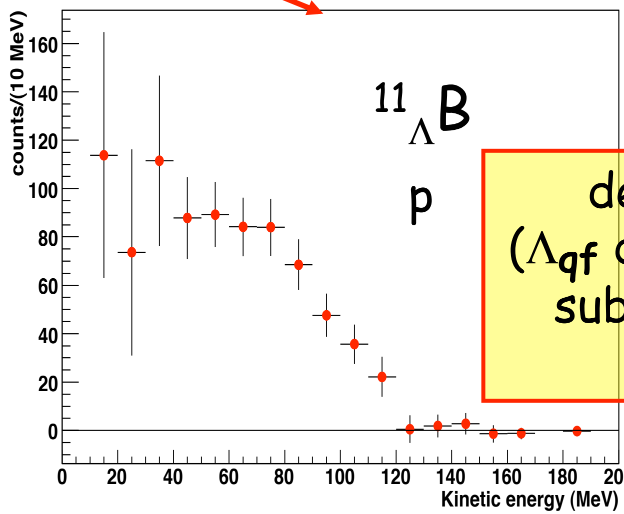


MWD

NMWD

magnetic analysis !!

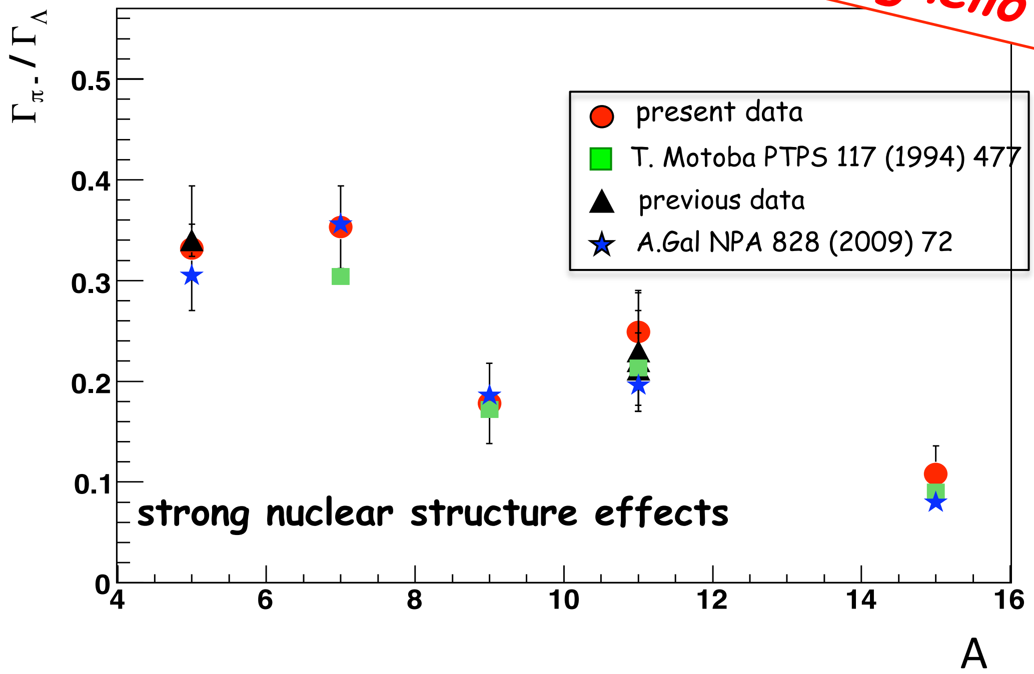




decay π^- and p spectra
(Λ_{qf} decay)/K^-np background
subtracted & acceptance
corrected

Mesonic decay ratio: $\Gamma_{\pi-} / \Gamma_\Lambda$

$$\Gamma_{\pi-} / \Gamma_\Lambda = \Gamma_{tot} / \Gamma_\Lambda \bullet BR_{\pi-}$$



Extensive calculations:

- Motoba et al., Progr. Theor. Phys. Suppl. 117 (1994) 477
- Gal Nucl. Phys. A 828 (2009) 72.

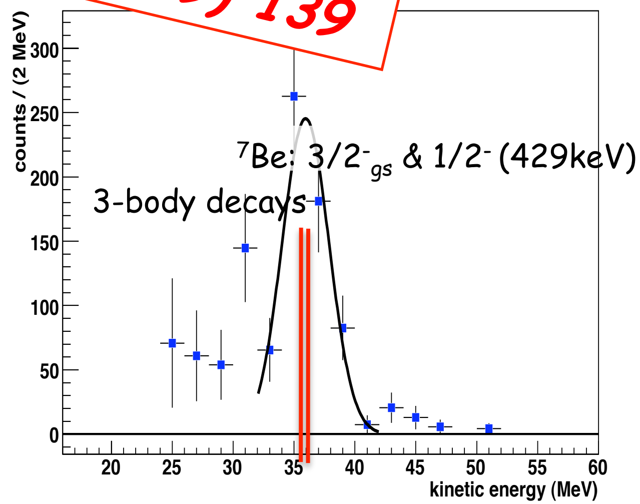
π distortion, MWD enhancement proved !

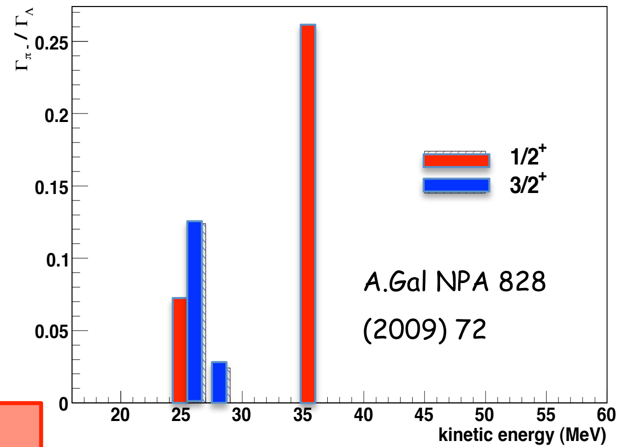
J^π assignment:

$^{7}_{\Lambda}$Li (1/2+), $^{9}_{\Lambda}$Be (1/2+), $^{11}_{\Lambda}$B (5/2+), $^{15}_{\Lambda}$N (3/2+)

first determination

M.Agnello PLB 681 (2009) 139

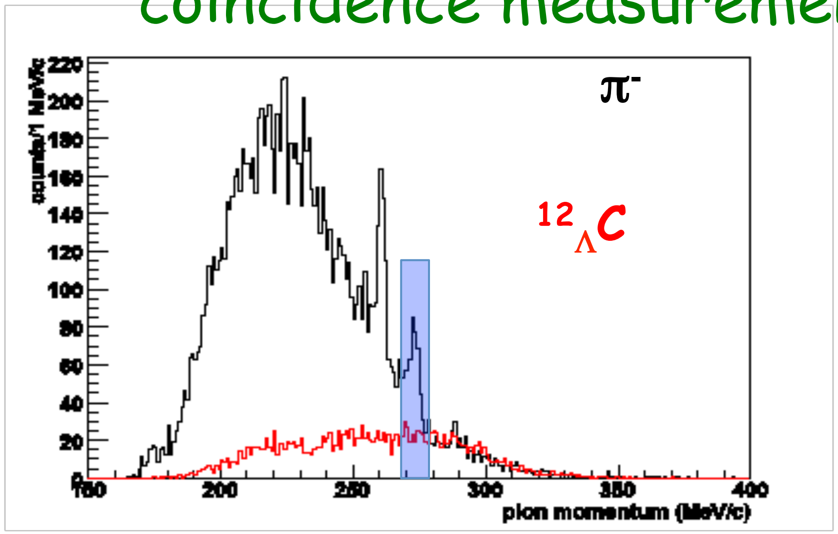




MWD indirect spectroscopic tool !

NMWD: p spectra

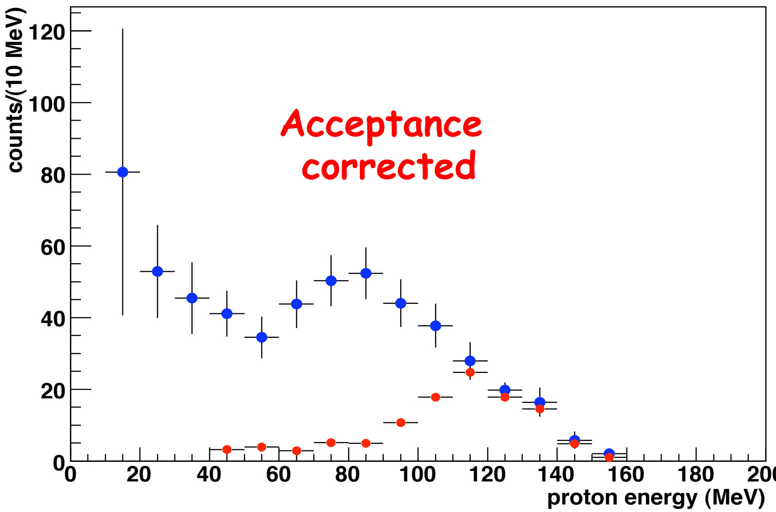
coincidence measurement: method

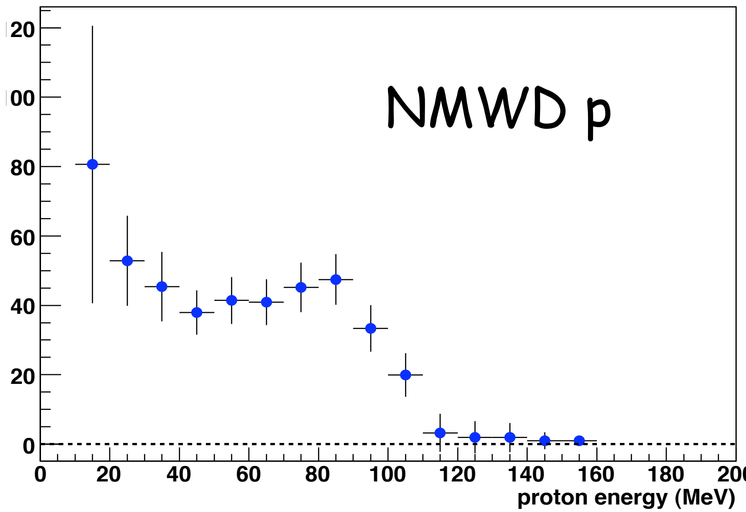


- Spectrum of negative pions for events in which a proton is detected in coincidence with a π^-
- Asking for the proton coincidence a clear peak emerges at 272 MeV/c (ground state)
- Background: $K^- np \rightarrow \Sigma^- p$

  $\Sigma^- \rightarrow n \pi^-$

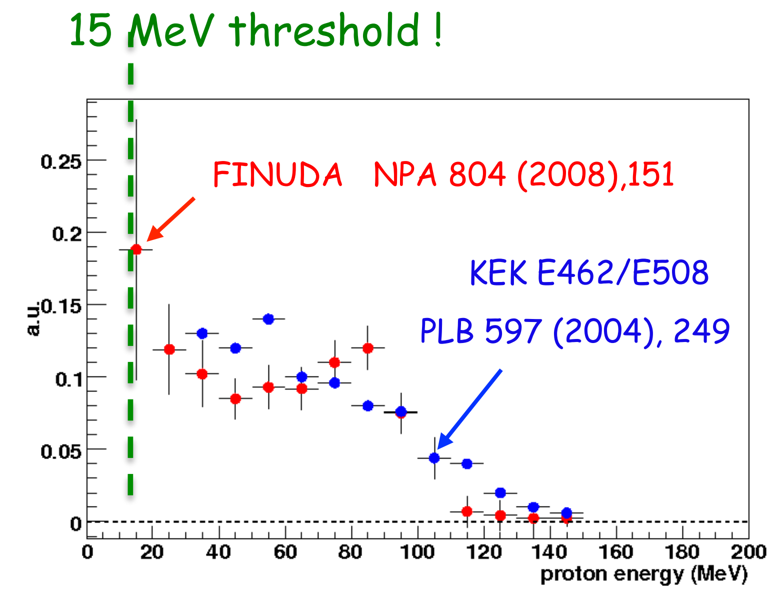
M. Agnello et al., NPA 804 (2008), 151: $^{5}_{\Lambda}He$, $^{7}_{\Lambda}Li$ and $^{12}_{\Lambda}C$

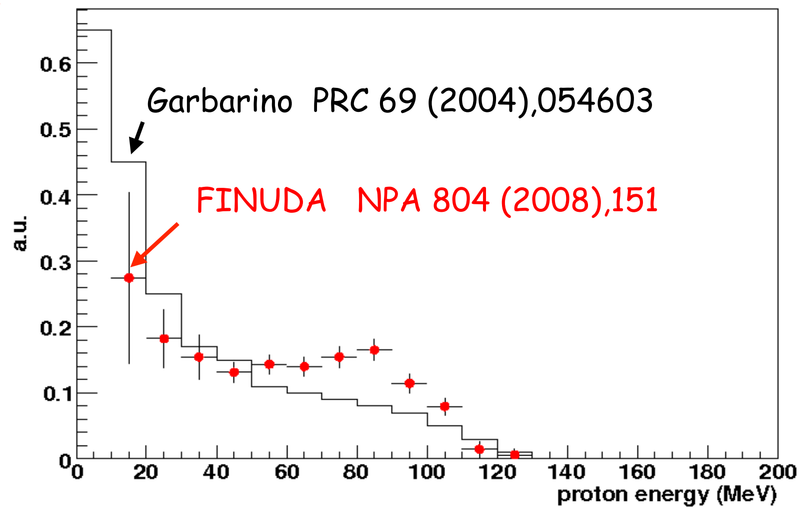




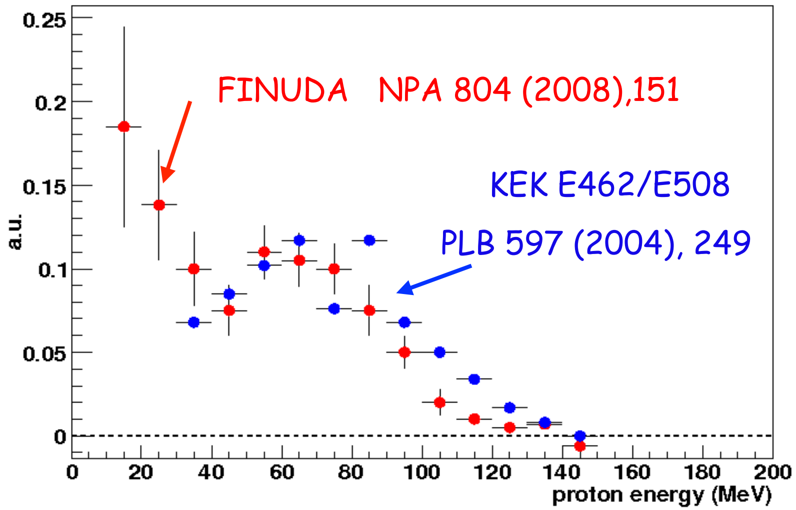
Comparisons with theory and KEK results

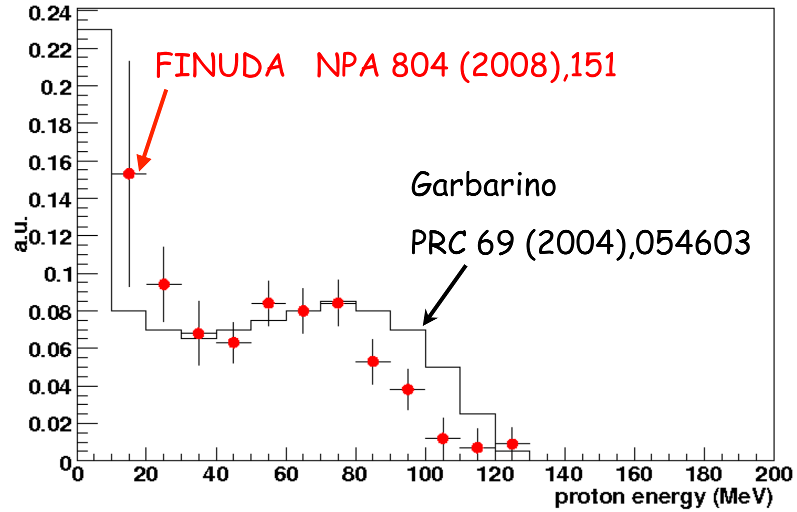
$^{12}{}_{\Lambda}C$





$^{5}{}_{\Lambda}He$



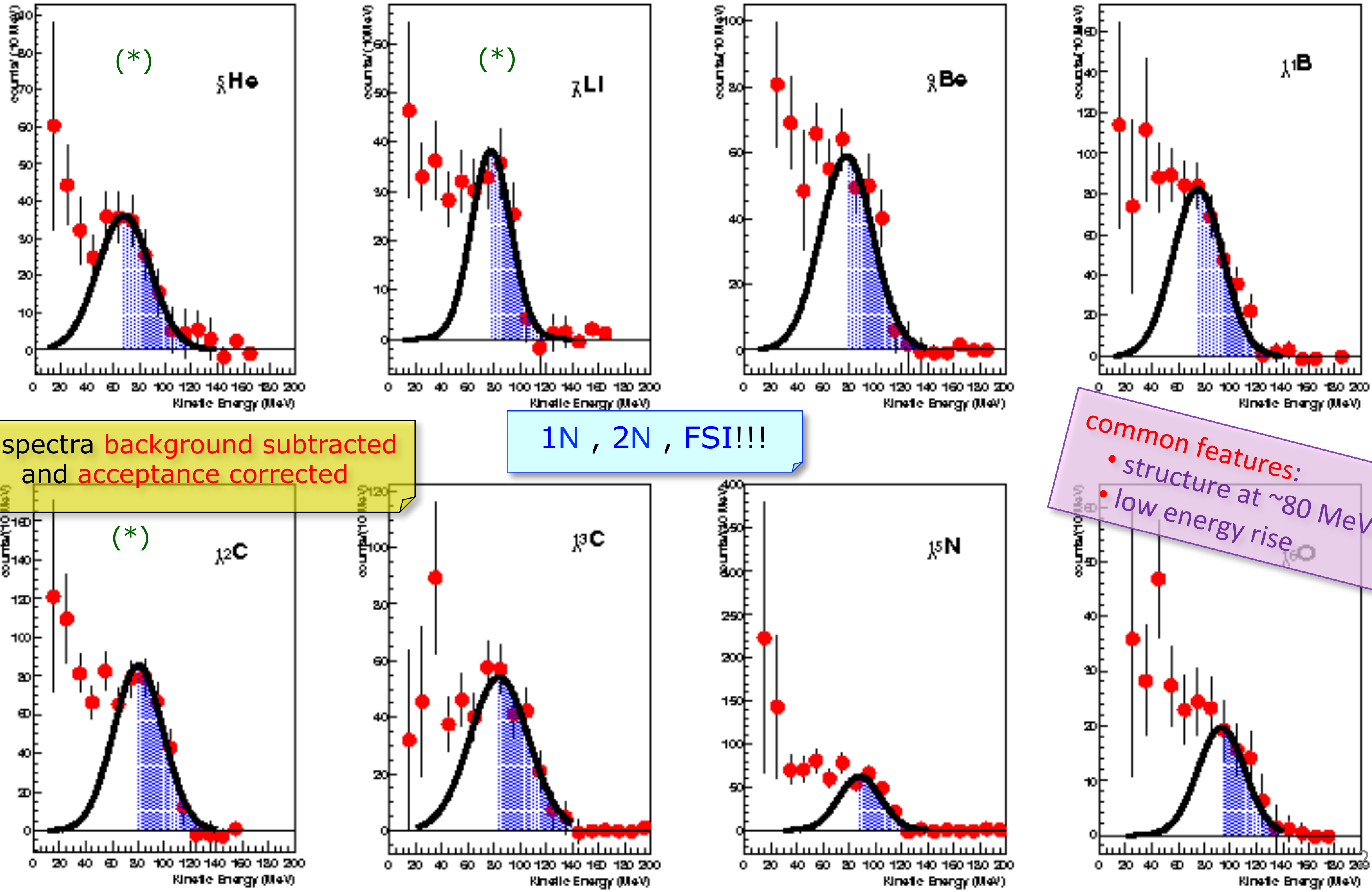


NMWD: Γ_{2N}

(*) M. Agnello *et al.*, *NPA* 804 (2008) 151.

M. Agnello *et al.*, *PLB* 685 (2010) 247.

FSI & ΛNN contribution evaluation: systematics



p spectra background subtracted and acceptance corrected

1N , 2N , FSI!!!

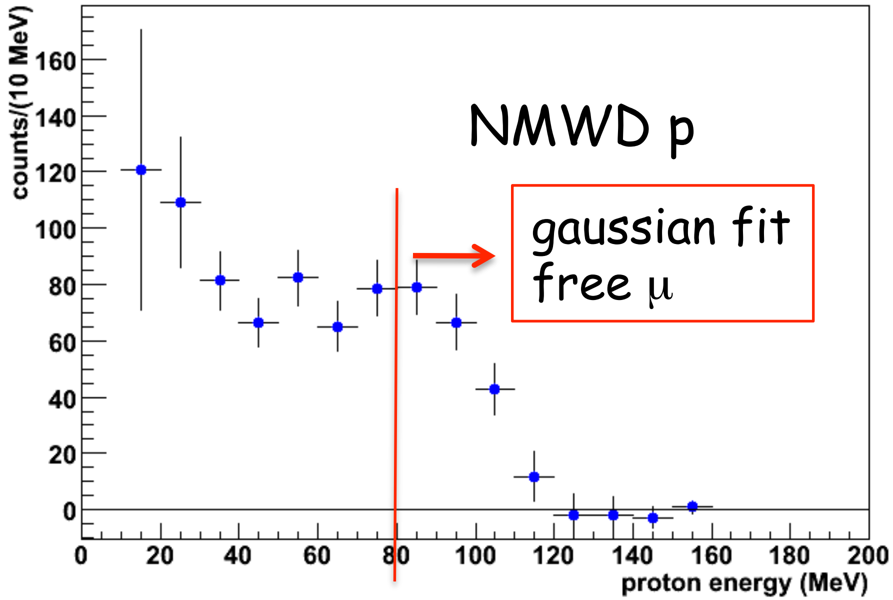
common features:
- structure at ~80 MeV
- low energy rise

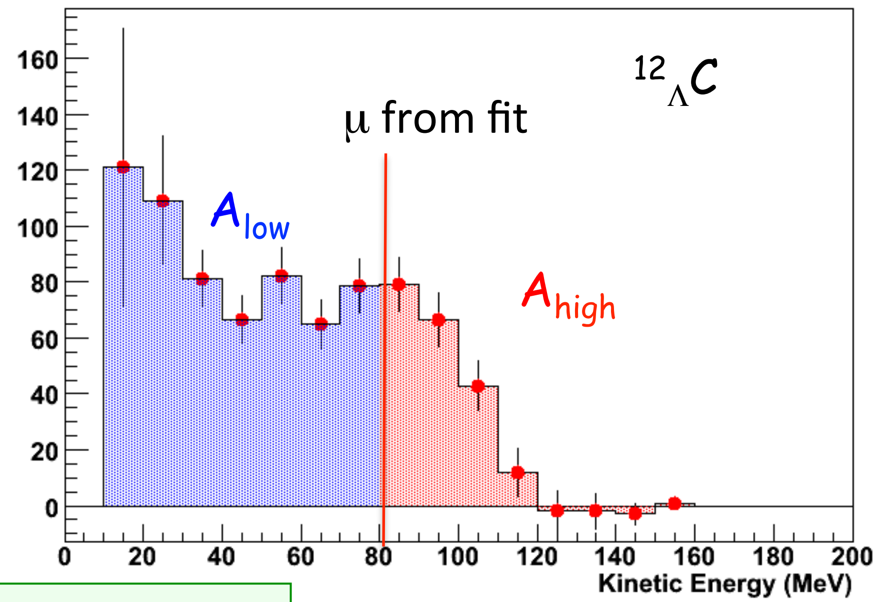
NMWD: Γ_{2N} from (π^-, p) events

M.Agnello et al., PLB 685 (2010) 247

$\Gamma_{2N}/\Gamma_{NMWD}$ & Γ_n/Γ_p independent on *A* ⇐ assumption

W.Alberico and G.Garbarino, Phys. Rev. 369 (2002) 1.





A_{low}: spectrum area below μ
1N + 2N + FSI

A_{high}: spectrum area above μ
1N + FSI ⇐ assumption
p(2N, >70 MeV) ~ 5% p(2N, tot)

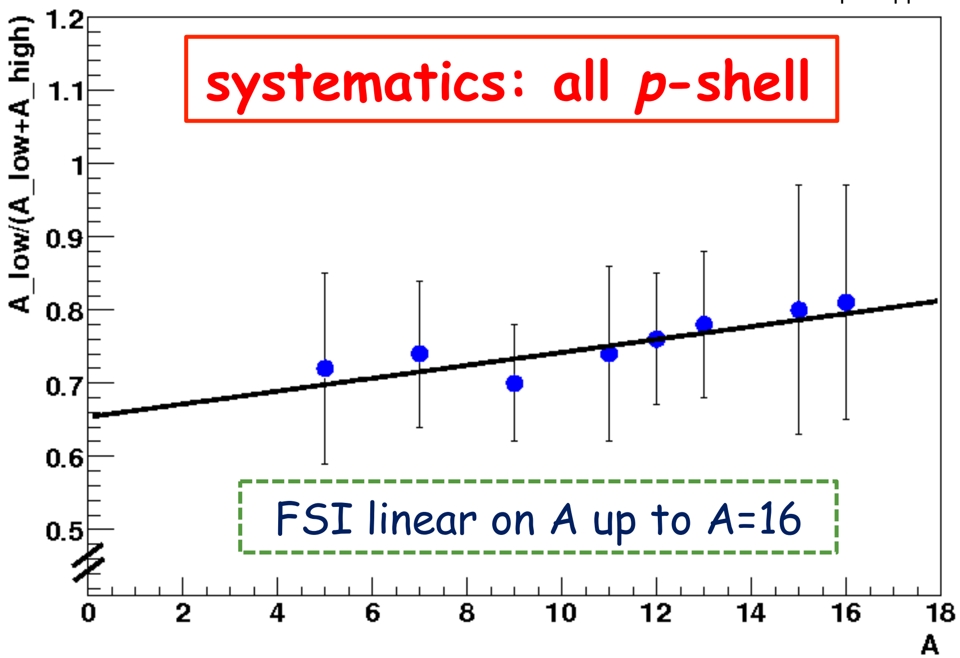
G.Garbarino, A.Parreno and A.Ramos, Phys.Rev.Lett. 91 (2003) 112501.
Phys.Rev. C 69 (2004) 054603.

$$R = \frac{A_{low}}{A_{low} + A_{high}} = \frac{0.5\ N(\Lambda p \to np) + N(\Lambda np \to nnp) + N_p^{FSI\text{-}low}}{N(\Lambda p \to np) + N(\Lambda np \to nnp) + N_p^{FSI\text{-}low} + N_p^{FSI\text{-}high}}$$

$$R(A) = a + b\,A = \frac{0.5 + \Gamma_2/\Gamma_p}{1 + \Gamma_2/\Gamma_p} + b\,A$$

Assumption: Γ_2/Γ_1 and Γ_n/Γ_p not dependent on A → supported by exp and theory

$\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$ Bauer et al., NPA 828 (2009) 29



Bauer et al., NPA 828 (2009) 29

Bhang et al., EPJ A33 (2007) 259: ~ 0.4 $^{12}_{\Lambda}C$
M. Kim et al., PRL 103 (2009) 182502: 0.29 ± 0.13 $^{12}_{\Lambda}C$
J.D.Parker et al., PRC 76 (2007), 035501: ≤ 0.24 (95% CL) $^{4}_{\Lambda}He$

Bhang et al., EPJ A33 (2007) 259.

$$\frac{\Gamma_2}{\Gamma_p} = \frac{[R(A) - bA] - 0.5}{1 - [R(A) - bA]} = 0.43 \pm 0.25$$

$$\frac{\Gamma_2}{\Gamma_{NM}} = \frac{\Gamma_2/\Gamma_p}{\Gamma_n/\Gamma_p + 1 + \Gamma_2/\Gamma_p} = 0.24 \pm 0.10$$

NMWD: Γ_{2N} from (π^-, p, n) events

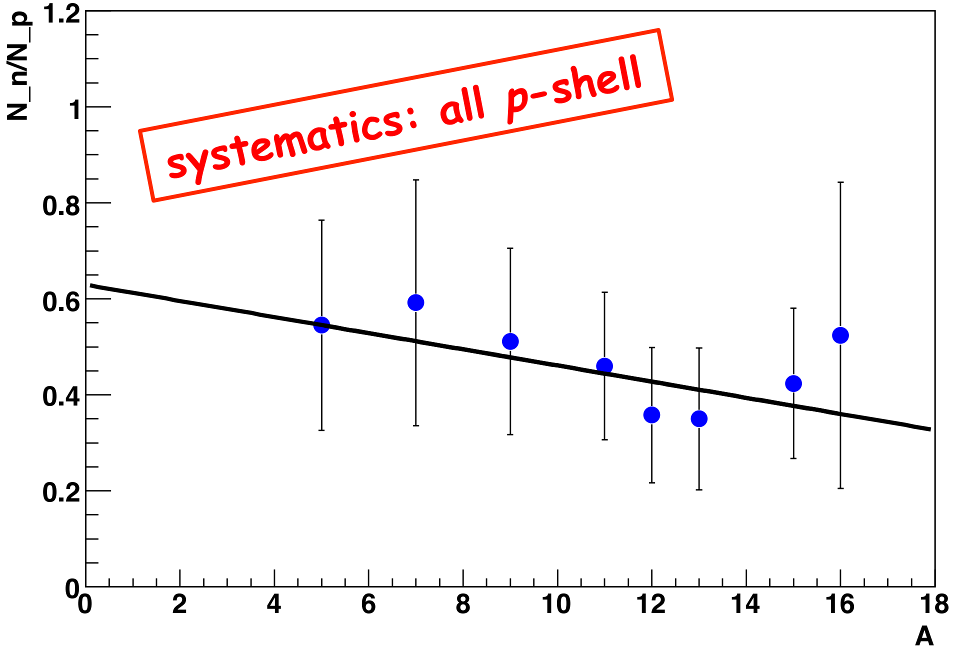
M.Agnello et al., PLB 701 (2011) 556

$$R(A) = \frac{N_n\ (\cos\theta \geq -0.8,\ E_p < \mu - 20\ \text{MeV})}{N_p\ (E_p > \mu\ \text{p single spectra fit})} = \frac{N(\Lambda np \rightarrow nnp) + N^{FSI}}{0.5\ N(\Lambda p \rightarrow np) + N^{FSI}}$$

$\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$ Bauer et al., NPA 828 (2009) 29

$$R(A) = a + b\,A = \frac{\Gamma_2}{0.5\,\Gamma_p} + b\,A$$

Γ_2/Γ_p not dependent on A



Γ_2/Γ_p
$0.39 \pm 0.16_{stat} + 0.04_{sys} - 0.03_{sys}$

Γ_2/Γ_{NM}
$0.21 \pm 0.07_{stat} + 0.03_{sys} - 0.02_{sys}$

M. Kim et al., PRL 103 (2009) 182502:
0.29 ± 0.13 $^{12}_{\Lambda}C$
FINUDA Coll. et al., PLB 685 (2010) 247:
0.24 ± 0.10

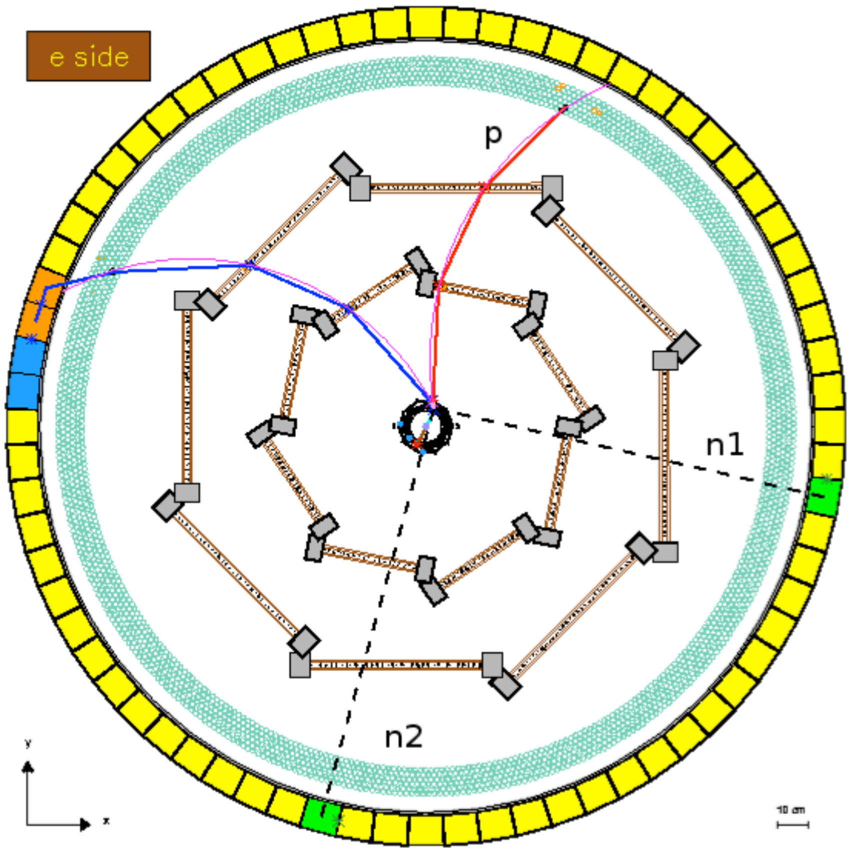
- low statistics
- direct measurement (n, p)
- reduced error

NMWD: evidence for (π−, p, n, n) events

3 fourfold coincidence (π-,n,n,p) events:

1 exclusive $^{9}_{\Lambda}Be \rightarrow ^{6}Li+p+n+n$ event

2 exclusive $\Lambda np \rightarrow nnp$ $^{7}_{\Lambda}Li \rightarrow ^{4}He+p+n+n$ decay events



$p_{\pi-}$ = 276.93 MeV/c
E_{tot} = 178.3 MeV
Q-value = 167 MeV
p miss = 216.6 MeV/c

E(n1) = 110.2 MeV
E(n2) = 16.9 MeV
E(p) = 51.0 MeV

θ (n1 n2) = 95°
θ (n1 p) = 102°
θ (n2 p) = 154°
no n-n or p/n scattering

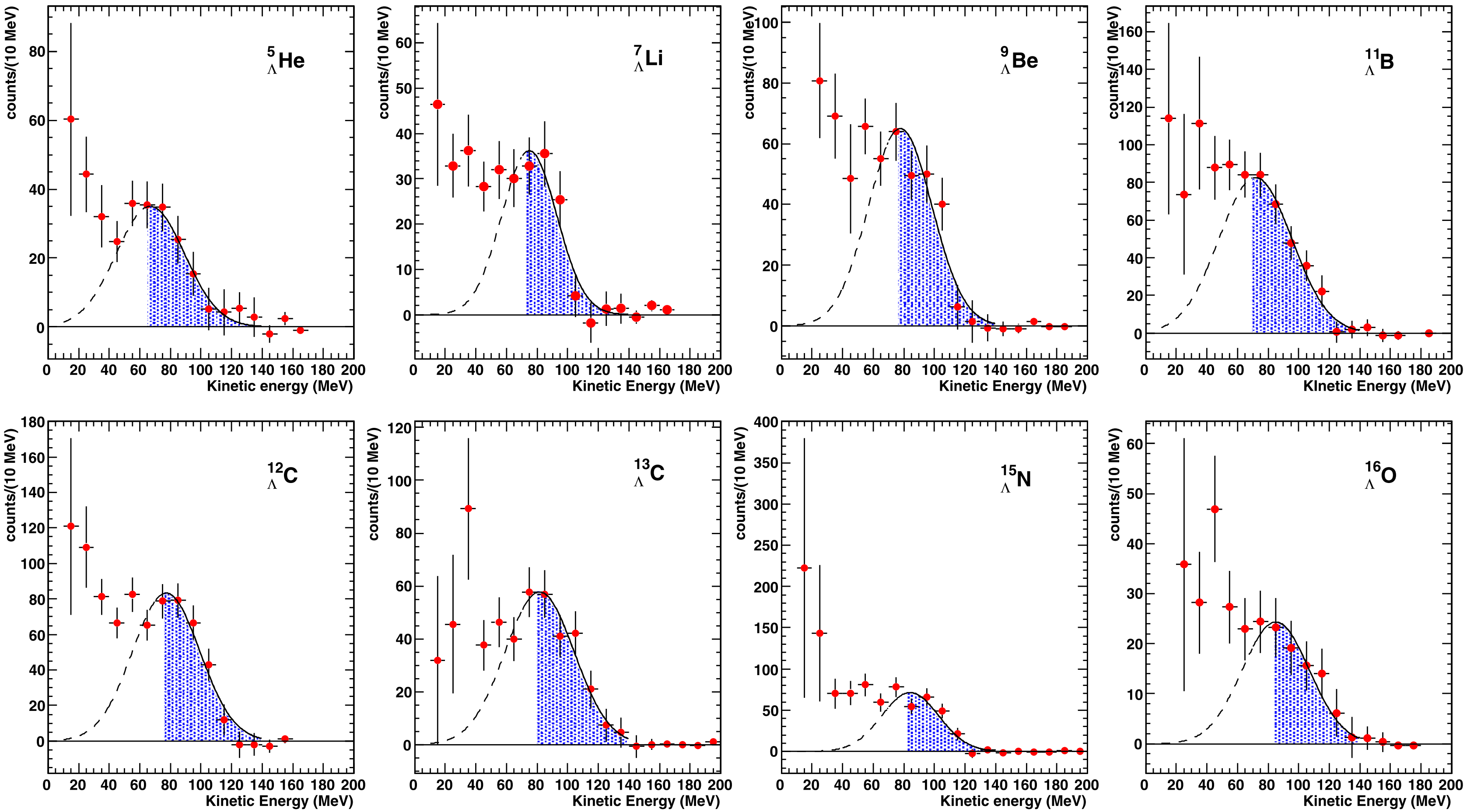
M.Agnello et al., NPA 881 (2012) 322

First direct experimental evidence of 2N-induced NMWD !!

Revisited analysis of the proton spectra

Attempt of improving the fits by shifting down the lower edge for the fits to 50, 60 and 70 MeV:

better value of χ^2/n = 1.33 when choosing the starting point at 70 MeV



M.Agnello et al., PLB 738 (2014) 499

$$R_1(A) = \frac{A_{low}(A)}{A_{low}(A) + A_{high}(A)}$$

$\Gamma_{2N}/\Gamma_p = 0.50 \pm 0.24$	$(\Gamma_{2N}/\Gamma_{NMWD} = 0.25 \pm 0.12)$
$\Gamma_{2N}/\Gamma_p = 0.43 \pm 0.25$	$(\Gamma_{2N}/\Gamma_{NMWD} = 0.24 \pm 0.10)$ PLB 685 (2010) 247

$$R_2(A) = \frac{N_{np}[\cos\vartheta(np) \geq -0.8,\ E_p \leq (\mu - 20)\ \text{MeV}]}{N_p(E_p > \mu\ p\ \text{single spectra fit})}$$

$\frac{\Gamma_{2N}}{\Gamma_p} = 0.36 \pm 0.14_{stat}{}^{+0.05}_{-0.04}{}_{sys}$	$\left(\frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.20 \pm 0.08_{stat}{}^{+0.03}_{-0.02}{}_{sys}\right)$
$\frac{\Gamma_{2N}}{\Gamma_p} = 0.39 \pm 0.16_{stat}{}^{+0.04}_{-0.03}{}_{sys}$	$\left(\frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.21 \pm 0.07_{stat}{}^{+0.03}_{-0.02}{}_{sys}\right)$ PLB 701 (2011) 556

First determination of Γ_p/Γ_Λ for 8 Hypernuclei

$$\frac{\Gamma_p}{\Gamma_\Lambda} = \frac{\Gamma_T}{\Gamma_\Lambda} BR(p) = \frac{\Gamma_T}{\Gamma_\Lambda} \frac{2(N_p - N_{2N}) + \alpha(N_p - N_{2N})}{N_{hyp}}$$

$\left(\frac{\alpha}{2+\alpha}\right)$ "lost" protons FSI

on the basis of Γ's experimental values from FINUDA and KEK

$$\frac{\Gamma_T}{\Gamma_\Lambda} = \frac{\Gamma_{\pi^-}}{\Gamma_\Lambda} + \frac{\Gamma_{\pi^0}}{\Gamma_\Lambda} + \frac{\Gamma_p}{\Gamma_\Lambda} + \frac{\Gamma_n}{\Gamma_p} \cdot \frac{\Gamma_p}{\Gamma_\Lambda} + \frac{\Gamma_{2N}}{\Gamma_p} \cdot \frac{\Gamma_p}{\Gamma_\Lambda}$$

no INC calculation

$\Gamma_{2N}/\Gamma_p = 0.36 \pm 0.14$

$\Gamma_n/\Gamma_p = 0.45 \pm 0.10$ ($^5He_\Lambda$) $\Gamma_n/\Gamma_p = 0.51 \pm 0.15$ ($^{12}C_\Lambda$)

- $\Gamma_p/\Gamma_\Lambda = 0.22 \pm 0.03$ ($^5He_\Lambda$)
- $\Gamma_p/\Gamma_\Lambda = 0.49 \pm 0.06$ ($^{12}C_\Lambda$)

J.J. Szymanski *et al.*, PRC 43 (1991) 849: 0.21 ± 0.07

H. Noumi *et al.*, PRC 52 (1995) 2936: 031 ± 0.07
H. Bhang *et al.*, JKPS 59 (2011) 1461: 045± 0.10

- $\alpha_5(5) = 1.15 \pm 0.26$
- $\alpha_{12}(12) = 2.48 \pm 0.46$

linear scaling with *A*:

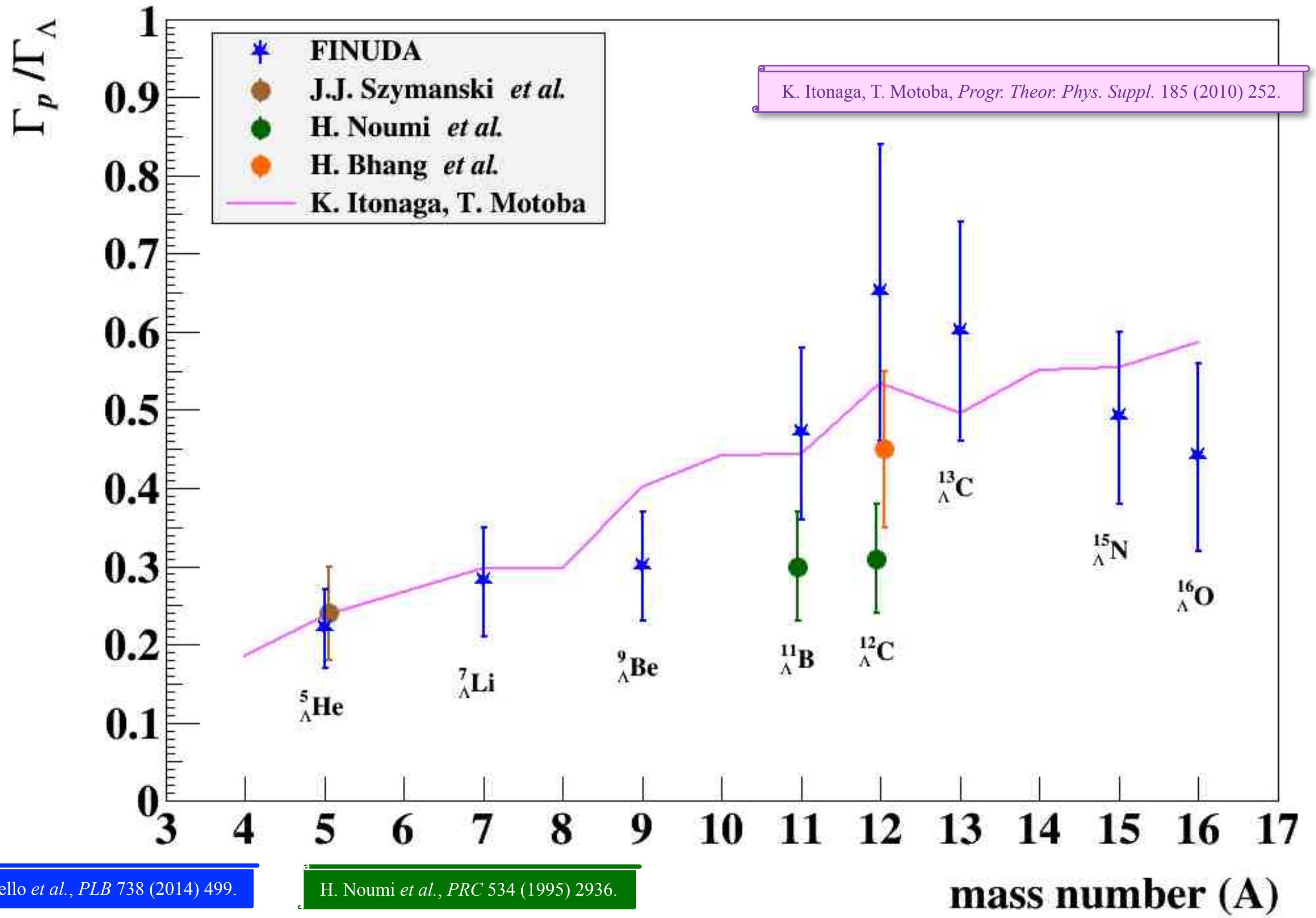
- $\alpha_5(12) = 1.04 \pm 0.19$
- $\alpha_{12}(5) = 2.77 \pm 0.63$

→ $\overline{\alpha_5} = 1.08 \pm 0.16$, $\overline{\alpha_{12}} = 2.58 \pm 0.37$ weighted average

general expression:

$$\alpha(A) = (0.215 \pm 0.031)A$$

First determination of $\Gamma_p / \Gamma_\Lambda$ for 8 Hypernuclei



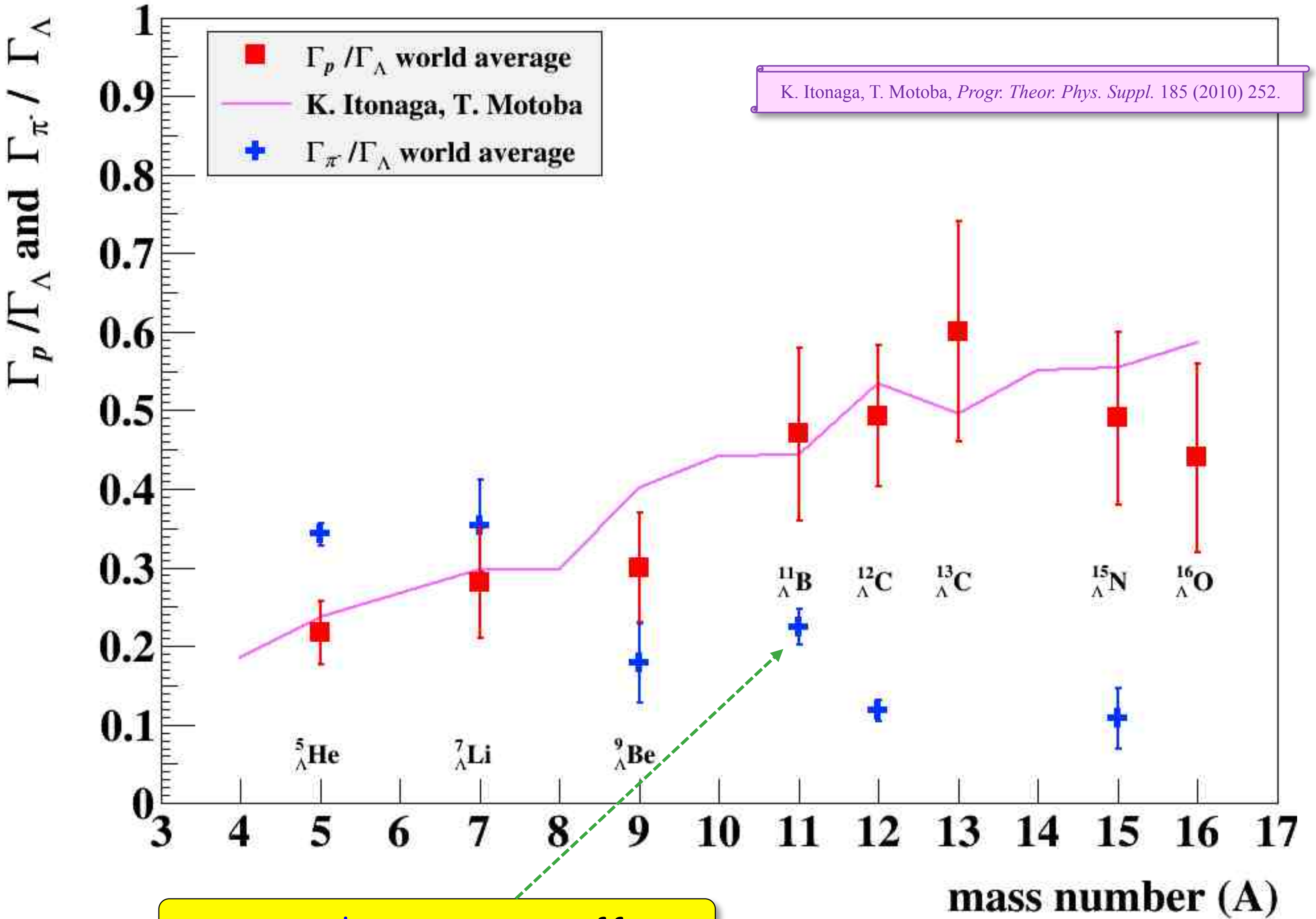
M. Agnello *et al.*, *PLB* 738 (2014) 499.

H. Noumi *et al.*, *PRC* 534 (1995) 2936.

J.J. Szymanski *et al.*, *PRC* 43 (1991) 849.

H. Bhang *et al.*, *JKPS* 59 (2011) 1461.

Complementarity of $\Gamma_p / \Gamma_\Lambda$ and $\Gamma_{\pi^-} / \Gamma_\Lambda$



strong nuclear structure effects

Completion of decay pattern for $^{5}He_{\Lambda}$ and $^{11}B_{\Lambda}$

	${}^{5}_{\Lambda}He$	${}^{11}_{\Lambda}B$	${}^{12}_{\Lambda}C$	${}^{12}_{\Lambda}C$
Γ_T/Γ_Λ	0.962±0.034	1.274±0.072	1.241±0.041	1.241±0.041
$\Gamma_{\pi^-}/\Gamma_\Lambda$	0.342±0.015	0.228±0.027	0.120±0.014	0.123±0.015
$\Gamma_{\pi^0}/\Gamma_\Lambda$	0.201±0.011	0.192±0.056	0.165±0.008	0.165±0.008
Γ_p/Γ_Λ	0.217±0.041	0.47±0.11	0.493±0.088	0.45±0.10
$\Gamma_{2N}/\Gamma_\Lambda$	0.078±0.034	0.169±0.077	0.178±0.076	0.27±0.13
Γ_n/Γ_Λ	0.125±0.066	0.21±0.16	0.28±0.12	0.23±0.08
Γ_n/Γ_p	0.58±0.32	0.46±0.37	0.58±0.27	0.51±0.14
Γ_n/Γ_p	0.508	0.502	0.418	

H. Bhang *et al.*, *JKPS* 59 (2011) 1461

B.H. Kang *et al.*, PRL 96 (2006) 062301: 0.45 ± 0.11

K. Itonaga, T. Motoba, PTP 185 (2010) 252

$$\Gamma_{2N}/\Gamma_p = 0.36 \pm 0.14_{stat}{}^{+0.05}_{-0.04}{}_{sys}$$

E. Botta et al., PLB 748 (2015) 86

${}^{6}_{\Lambda}H$ and ${}^{7}_{\Lambda}H$ (${}^{12}_{\Lambda}Be$) search with FINUDA

Inclusive measurement oct 2003 - jan 2004: 190 pb^{-1}

(K^-_{stop}, π^+)

M. Agnello et al. Phys. Lett. B 640 (2006) 145

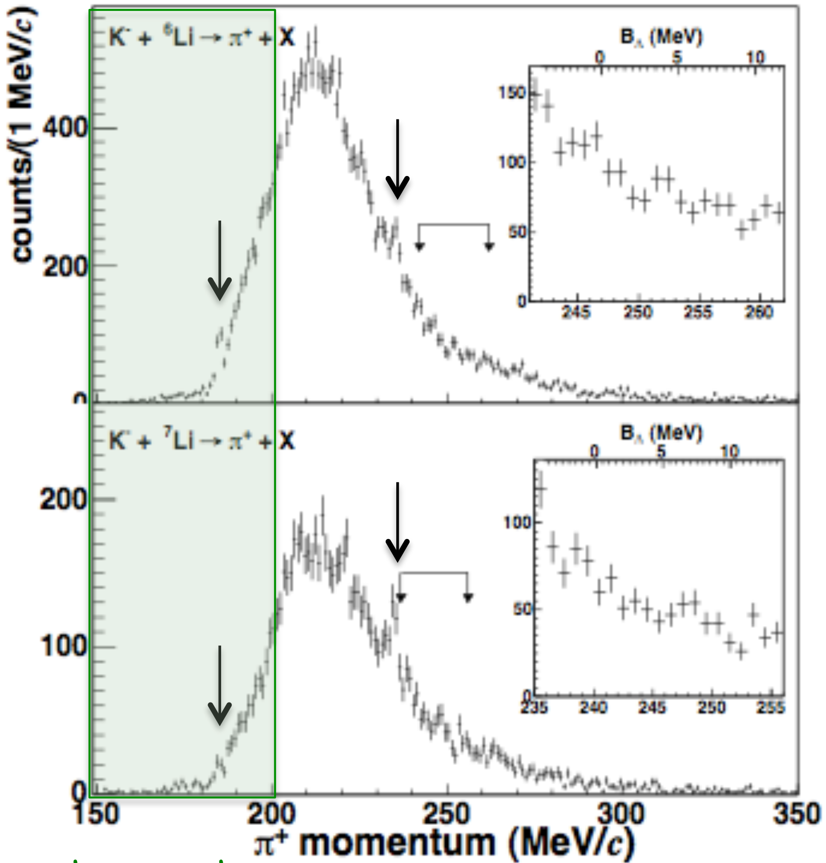
${}^{6}_{\Lambda}H$ (${}^{6}Li$) U.L.= (2.5 ± 1.4) $10^{-5}/K^-_{stop}$

${}^{7}_{\Lambda}H$(${}^{7}Li$) U.L.= (4.5± 1.4) $10^{-5}/K^-_{stop}$

${}^{12}_{\Lambda}Be$(${}^{12}C$) U.L.= (2.0 ± 0.4) $10^{-5}/K^-_{stop}$

$K^-_{stop} + {}^{6}Li \rightarrow {}^{6}_{\Lambda}H + \pi^+$

$K^-_{stop} + {}^{7}Li \rightarrow {}^{7}_{\Lambda}H + \pi^+$



raw inclusive spectra
not acceptance corrected

background:

$K^-_{stop} + p \rightarrow \Sigma^+ + \pi^-$

$\Sigma^+ \rightarrow n\,\pi^+$

(~130-250 MeV/c)

$K^-_{stop} + pp \rightarrow \Sigma^+ + n$

$\Sigma^+ \rightarrow n\,\pi^+$

(~100-320 MeV/c)

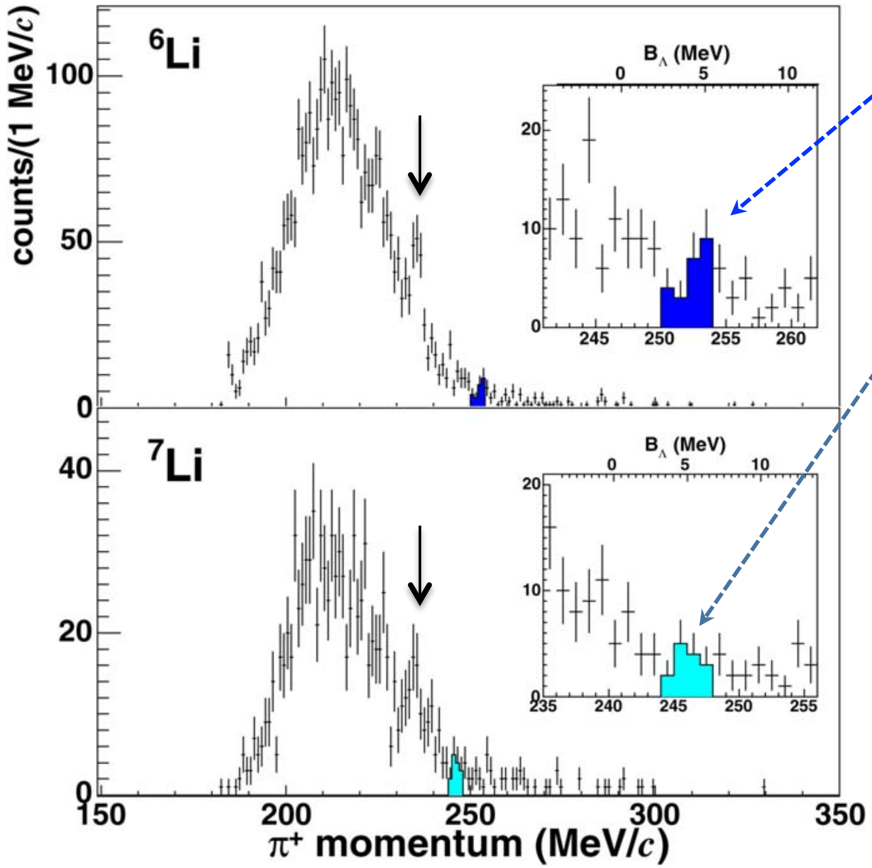
cut on K^-/π^+ distance: 2 mm

acceptance cut
for “long” tracks

M.Agnello et al., PLB 640 (2006) 145

$K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda H + \pi^+$ (~252 MeV/c, 4.1 MeV)

$K^-_{stop} + {}^7Li \rightarrow {}^7_\Lambda H + \pi^+$ (~246 MeV/c, 5.2 MeV)



statistics reduced (0.2)
shape only slightly modified

statistical significance
C.L. < 90%: U.L.

$$R_{\pi^+}({}^6_\Lambda H) < (2.5 \pm 0.4_{stat}{}^{+0.4}_{-0.1 syst}) \cdot 10^{-5}/K^-_{stop},$$

$$R_{\pi^+}({}^7_\Lambda H) < (4.5 \pm 0.9_{stat}{}^{+0.4}_{-0.1 syst}) \cdot 10^{-5}/K^-_{stop},$$

$$R_{\pi^+}({}^{12}_\Lambda Be) < (2.0 \pm 0.4_{stat}{}^{+0.3}_{-0.1 syst}) \cdot 10^{-5}/K^-_{stop},$$

background subtracted spectra
not acceptance corrected

Coincidence measurement

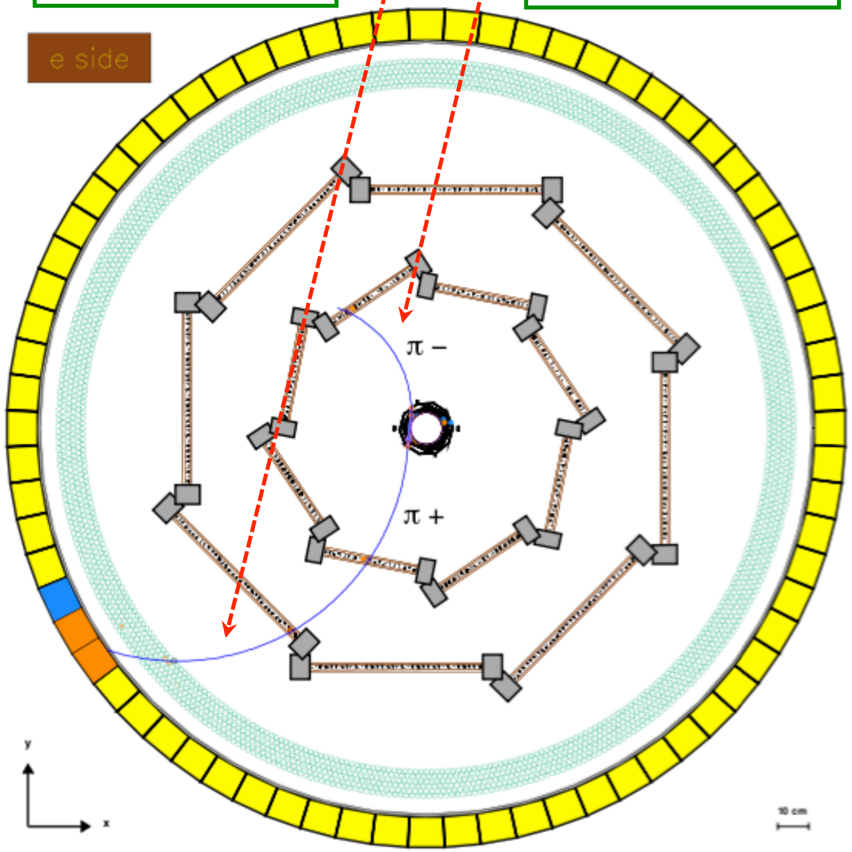
nov 2006 - jun 2007: 960 pb^{-1}

$K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda H + \pi^+$

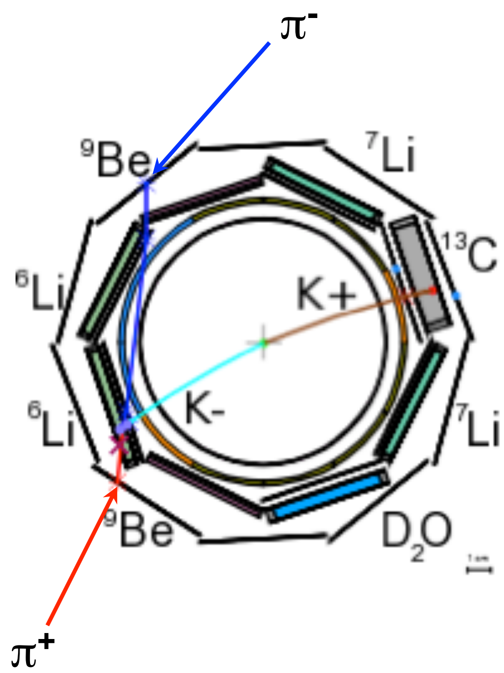
${}^6_\Lambda H \rightarrow {}^6He + \pi^-$

D-CEX
~252 MeV/c

MWD
~134 MeV/c



B = 1T



Detector capabilities:

- *Selective trigger* based on fast scint. detectors
- *precise* K^- *vertex identification* (~ 1 mm^3)
  (P.ID.+ *x,y,z* resolution + K^+ tagging)
- p, K, p, d, ... P.ID. (OSIM and LMDC d*E*/d*x*)
- ***High momentum resolution***

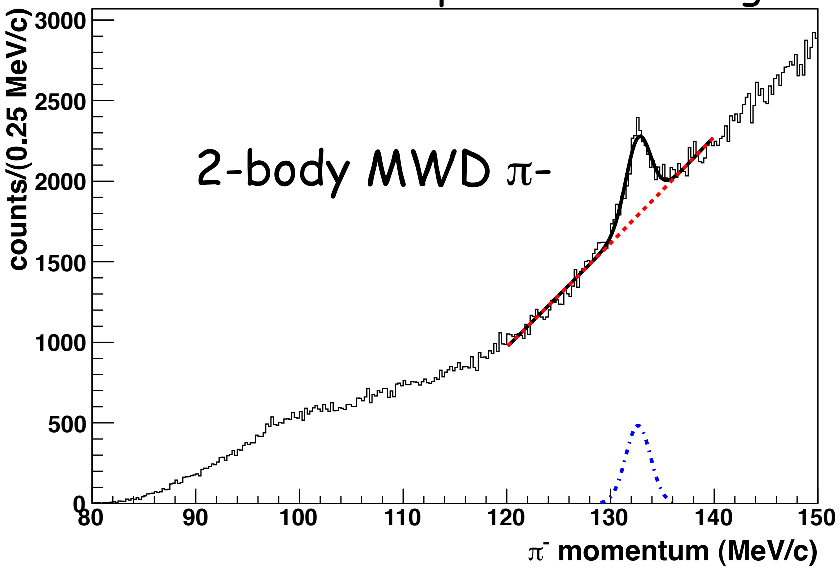
6‰ FWHM π- @270 MeV/c, 6% FWHM π- @110 MeV/c

(tracker resolution + He bag + thin targets)

FINUDA $\pi^{\pm}$ momentum calibration and resolution:
physical "monochromatic" signals

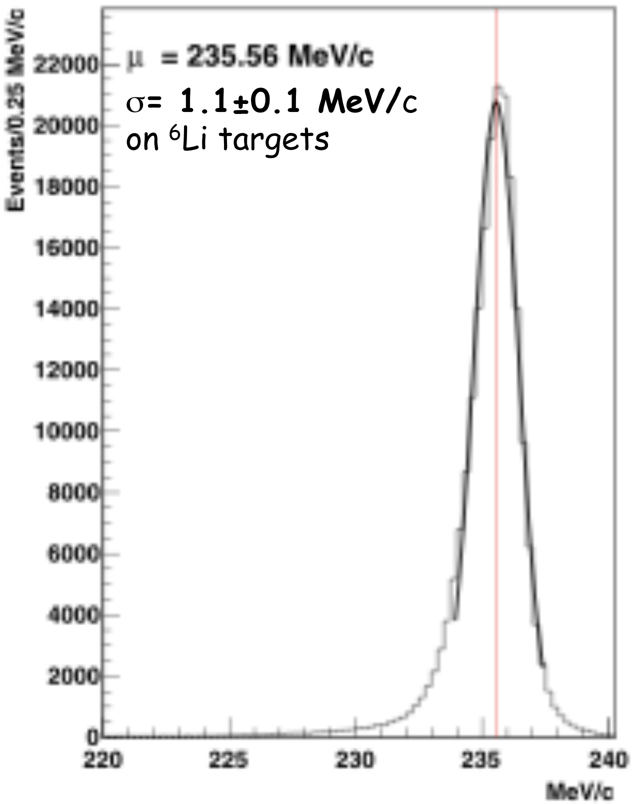
production of $^{4}_{\Lambda}H$ hyperfragment on ^{6}Li
and decay at rest

inclusive π- spectrum ^{6}Li target



μ = 132.6±0.1 MeV/c (132.8 MeV/c)
σ= 1.2±0.1 MeV/c
χ^2/ndf = 79.1/74

by-products: continuous monitoring stability



FINUDA π+ momentum resolution
(235 MeV/c): $K_{\mu 2}$ decay
(PLB 698 (2011) 219)

Coincidence measurement

$K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda H + \pi^+$

${}^6_\Lambda H \rightarrow {}^6He + \pi^-$
($\tau({}^6He)$~801 ms)

if ${}^6_\Lambda H$ is a **stable (bound) system**
independent 2-body reactions:
decay at rest

$$M(K^-) + \underbrace{3\,M(n) + 3M(p) - B({}^6Li)}_{{}^6Li} = M({}^6_\Lambda H) + T({}^6_\Lambda H) + M(\pi^+) + T(\pi^+)$$

$$M({}^6_\Lambda H) = \underbrace{4\,M(n) + 2M(p) - B({}^6He)}_{{}^6He} + T({}^6He) + M(\pi^-) + T(\pi^-)$$

$$T(\pi^+) + T(\pi^-) = M(K^-) + M(p) - M(n) - B({}^6Li) + B({}^6He) - T({}^6He) - T({}^6_\Lambda H) - M(\pi^+) - M(\pi^-)$$

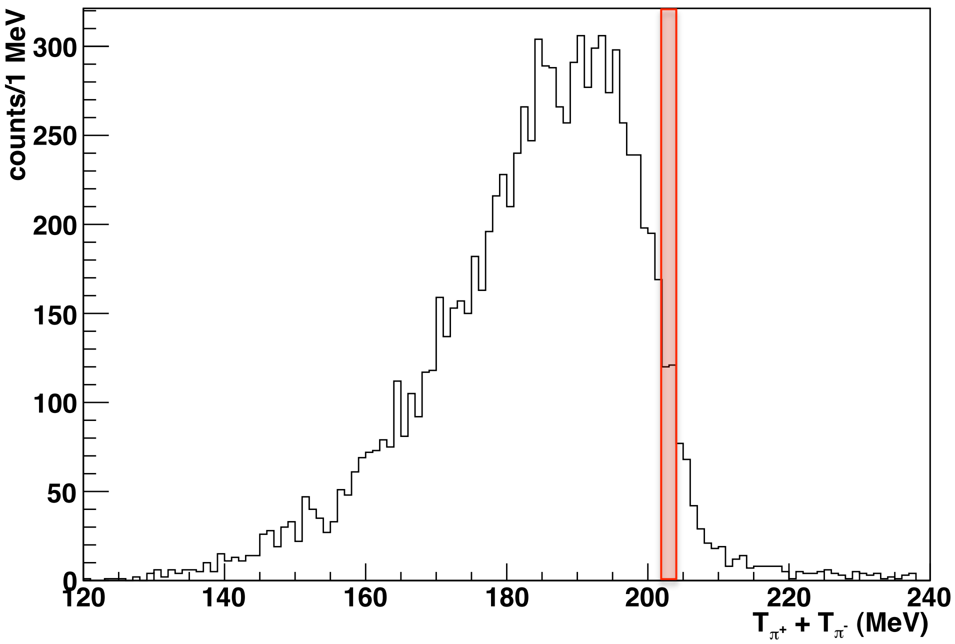
$$T({}^6He) = \sqrt{M^2({}^6He) + p^2(\pi^-)} - M({}^6He)$$

$$T({}^6_\Lambda H) = \sqrt{M^2({}^6_\Lambda H) + p^2(\pi^+)} - M({}^6_\Lambda H)$$

$$M({}^6_\Lambda H) = M({}^5H) + M(\Lambda) - B(\Lambda)$$

= **203.0 ± 1.3 MeV** (203.5÷203.3 MeV with B_Λ= 0÷6 MeV)

cut on $T(\pi^+) + T(\pi^-)$: 202÷204 MeV



selection:
$T(\pi^+)+T(\pi^-)$ = 202÷204 MeV

background contribution

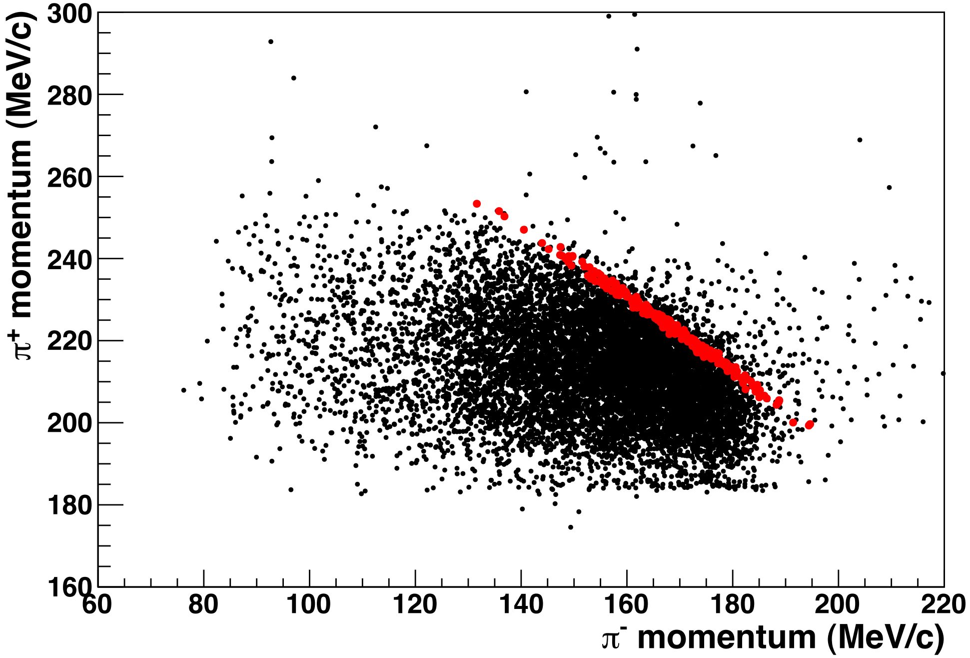
Finuda Coll. and A. Gal, NPA 881 (2012) 269.

absolute energy scale:
μ+(235.6 MeV/c) from $K_{\mu 2}$
Δ_p< 0.12 MeV/c

π-(132.8 MeV/c) from ${}^4{}_\Lambda$H
Δ_p< 0.2 MeV/c

systematic errors

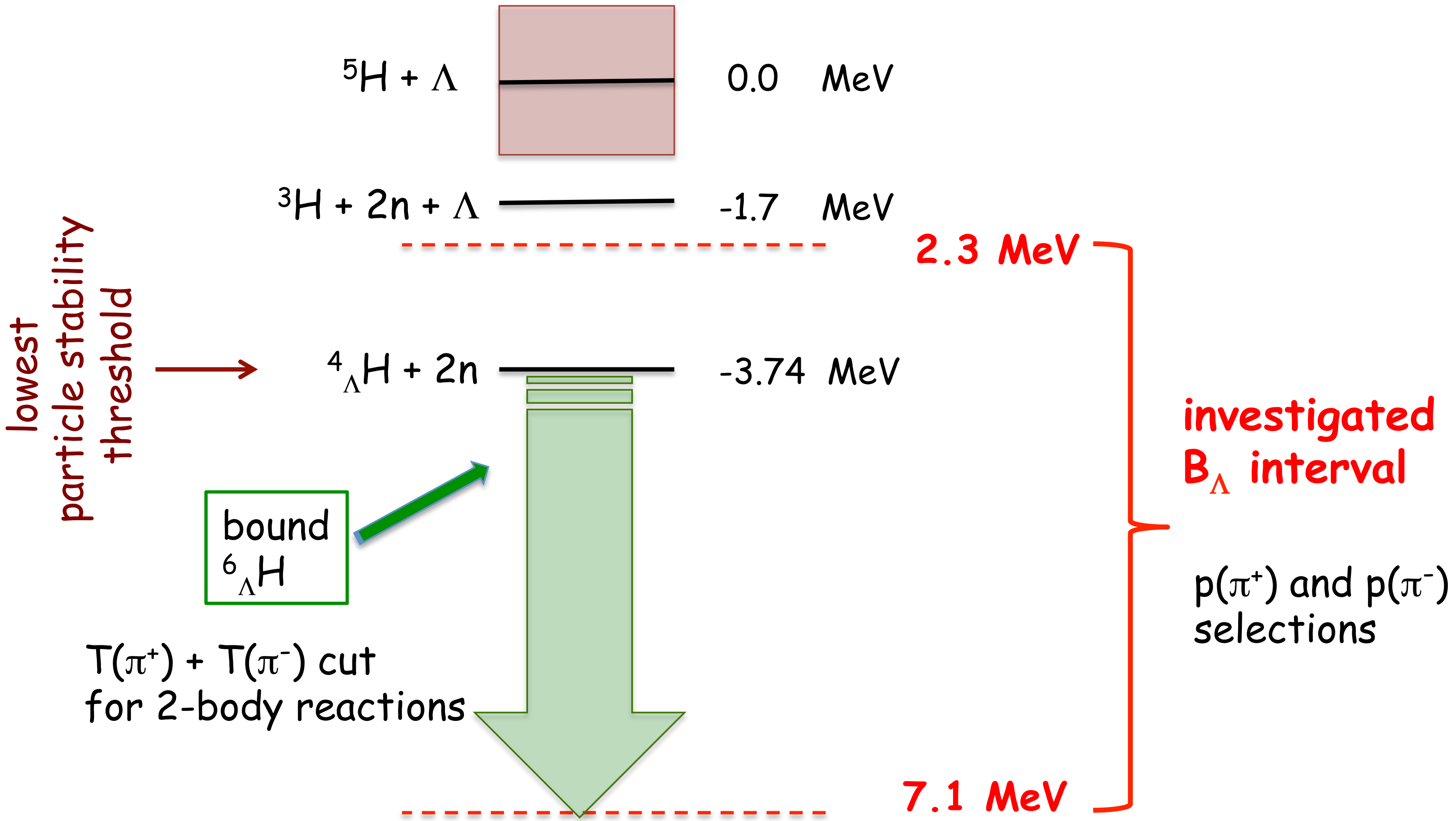
σT_{sys} = 0.17 MeV

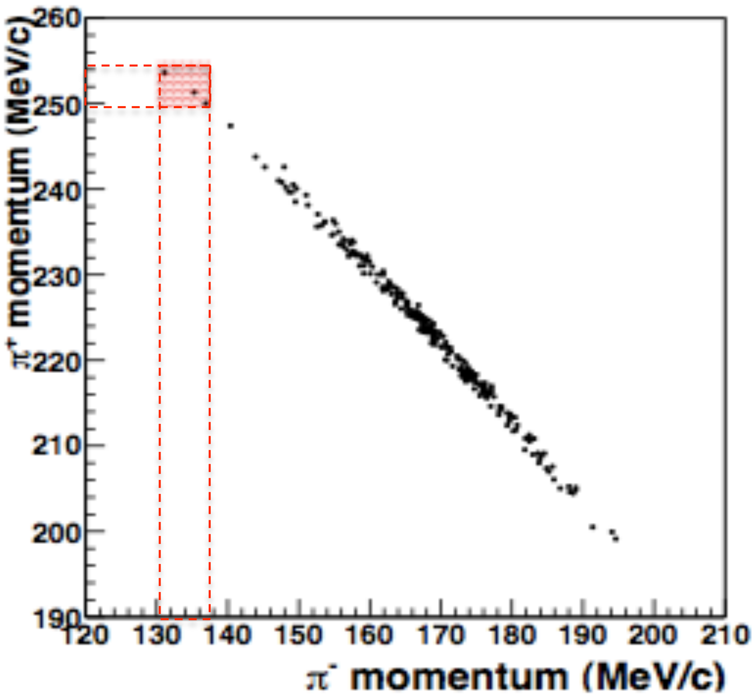


σT (π+) = 0.96 MeV, σT (π−) = 0.84 MeV
σT_{exp} = 1.3 MeV
σT = 1.3 MeV (~0.5 %)

uncertainty on $T(\pi+) + T(\pi-)$ = 0.2 MeV
sensitivity of 30 keV per MeV of $B_\Lambda({}^6{}_\Lambda H)$

Search for bound $^{6}_{\Lambda}H$





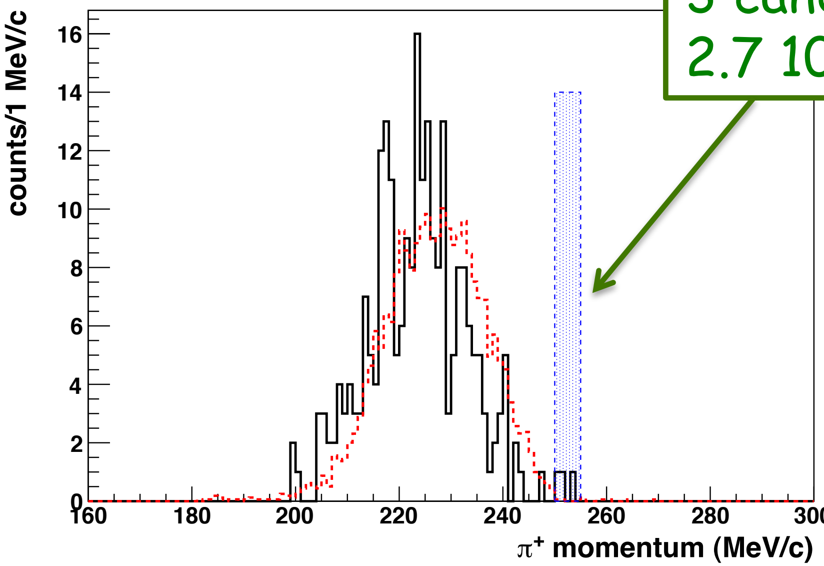
250÷255 MeV/c (σ_p= 1.1 MeV/c)

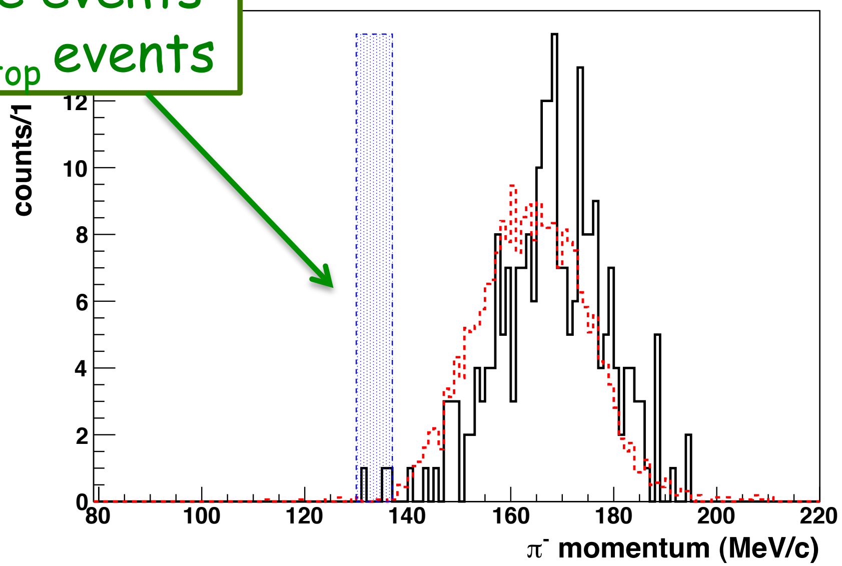
130÷137 MeV/c (σ_p= 1.2 MeV/c)

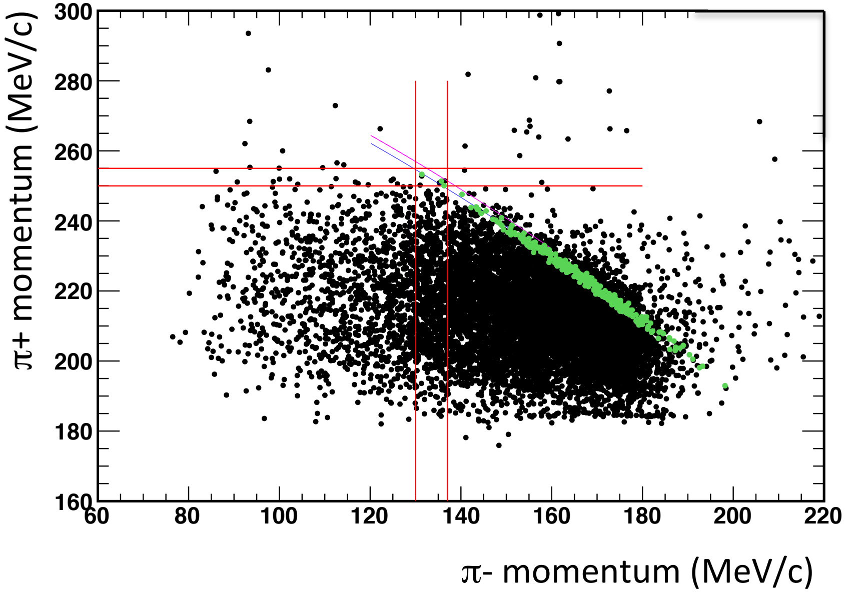
Finuda Coll. and A. Gal,
NPA 881 (2012) 269.

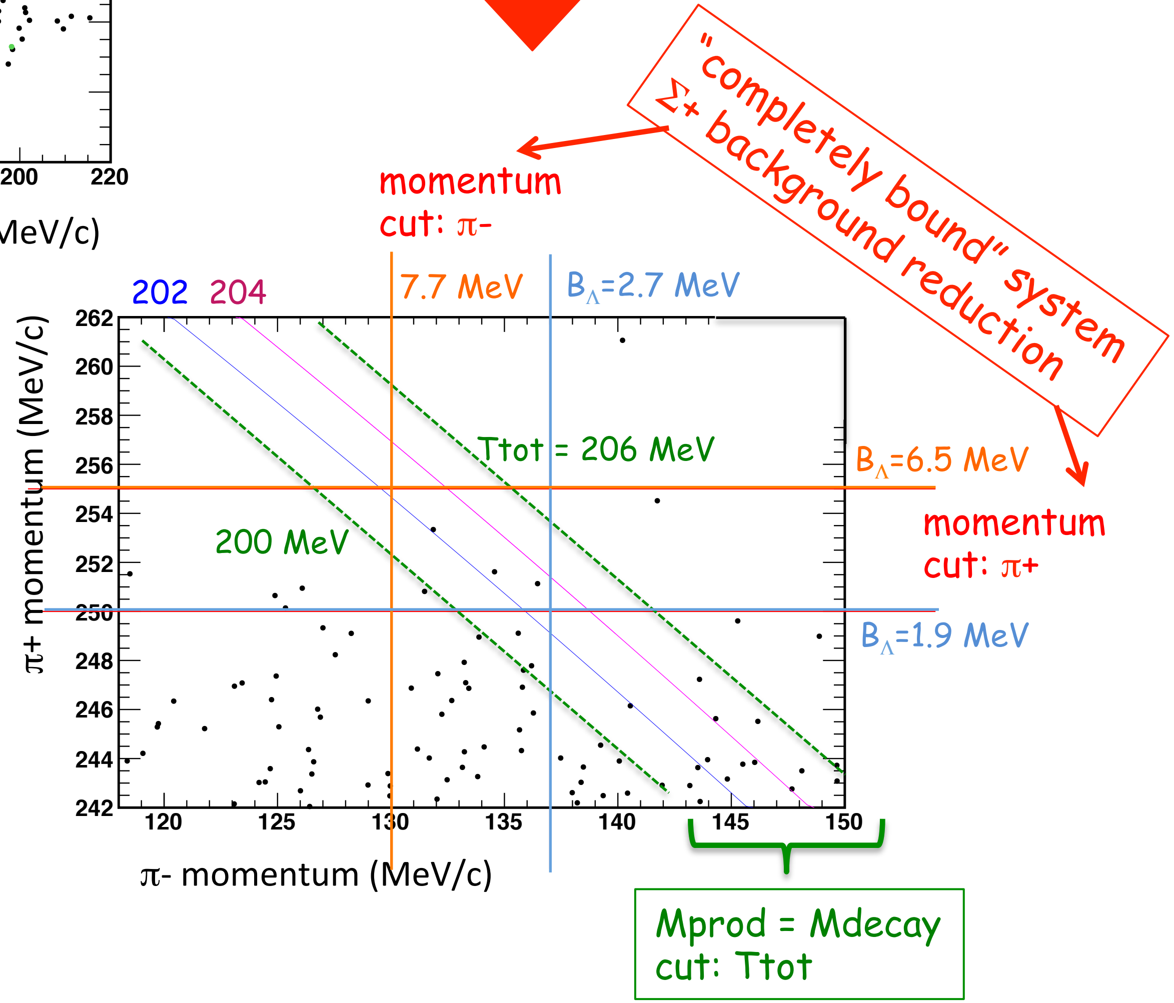
blue bars: $p_{\pi+/\pi-}$ selection regions including ${}^{6}_{\Lambda}H$ lowest particle stability threshold ${}^{4}_{\Lambda}H$+2n ($p_{\pi+}$=251.9 MeV/c, $p_{\pi-}$=135.6 MeV/c) B_{Λ}=2.3÷7.1 MeV

3 candidate events
2.7 10^7 K^-_{stop} events







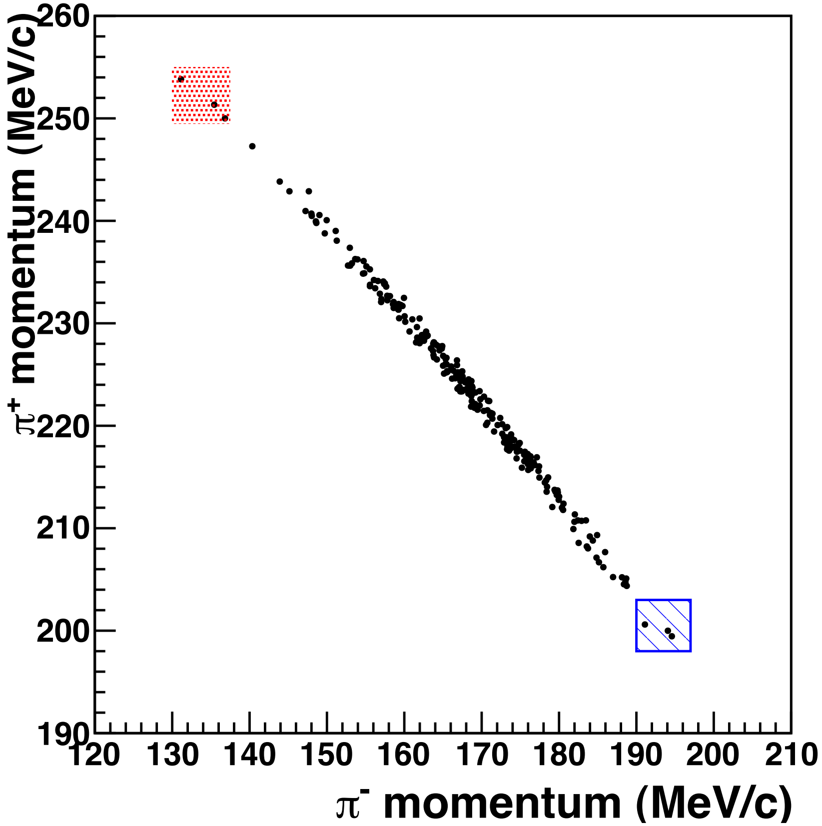


B_Λ=7.1 MeV

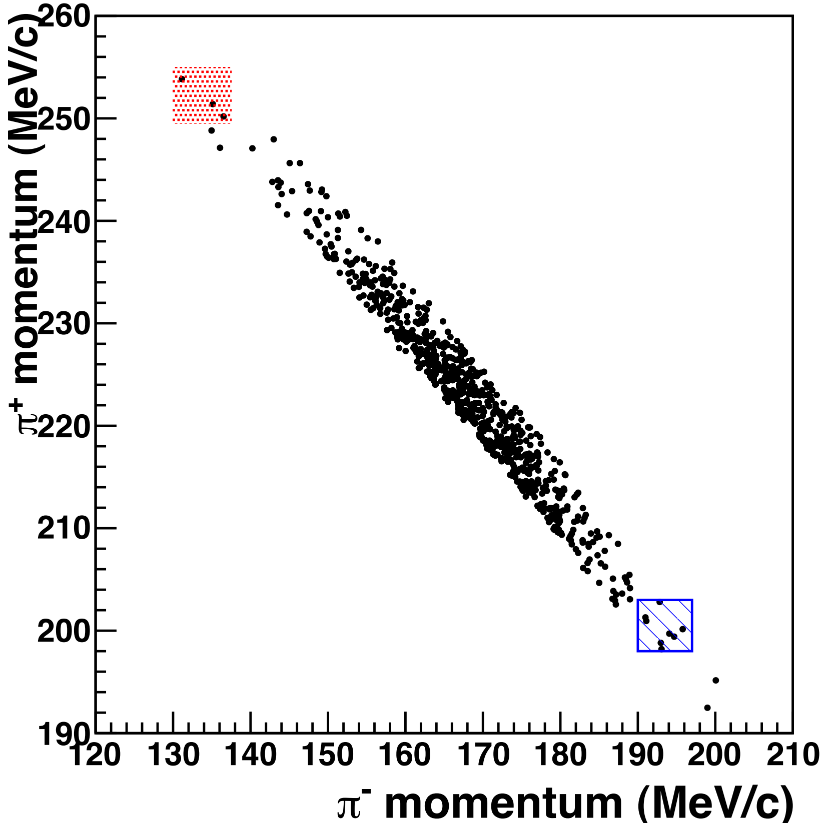
B_Λ=2.3 MeV

$T(\pi^+)+T(\pi^-)$ cut : systematics

$T(\pi^+)+T(\pi^-)$ = 202÷204 MeV



$T(\pi^+)+T(\pi^-)$ = 200÷206 MeV



${}^{6}_{\Lambda}H/K^{-}_{stop}$ production rate

•Background sources

$T(\pi+)+T(\pi-)(202\div204$ MeV) & $p(\pi+)(250\div255$ MeV/c) & $p(\pi^{-})(130\div137$ MeV/c):

• fake coincidences 0.27±0.27 ev.

Main physical sources ($K^{-}_{stop}N$, $K^{-}_{stop}NN$)

• $K^{-}_{stop} + {}^{6}Li \rightarrow \Sigma^{+} + \pi^{-} + {}^{4}He + n$ (end point ~190 MeV/c)

$\quad\quad\quad\quad \hookrightarrow n + \pi^{+}$ (end point ~282 MeV/c)

0.16±0.07 ev.

• $K^{-}_{stop} + {}^{6}Li \rightarrow {}^{4}_{\Lambda}H + n + n + \pi^{+}$ (end point ~252MeV/c)

$\quad\quad\quad\quad \hookrightarrow {}^{4}He + \pi^{-}$ ($p(\pi^{-})$ = 133 MeV/c)

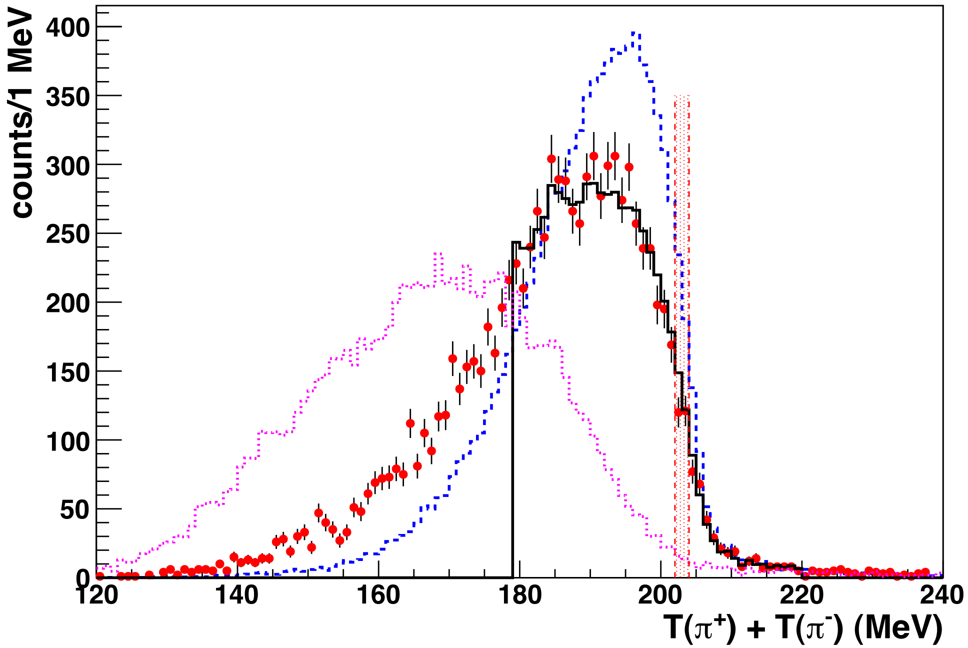
negligible

Background sources: Σ+ production and decay

$K^-_{stop} + {}^6Li \rightarrow \Sigma^+ + \pi^- + {}^4He + n$

$\quad\quad\quad\quad\quad\quad \hookrightarrow n + \pi^+$

- quasi free approach: 0.743 ± 0.019
- 4-body interaction: 0.257 ± 0.017 $\chi^2/ndf = 40.0/39$
- ^{4}He + n and "^{5}He" final state



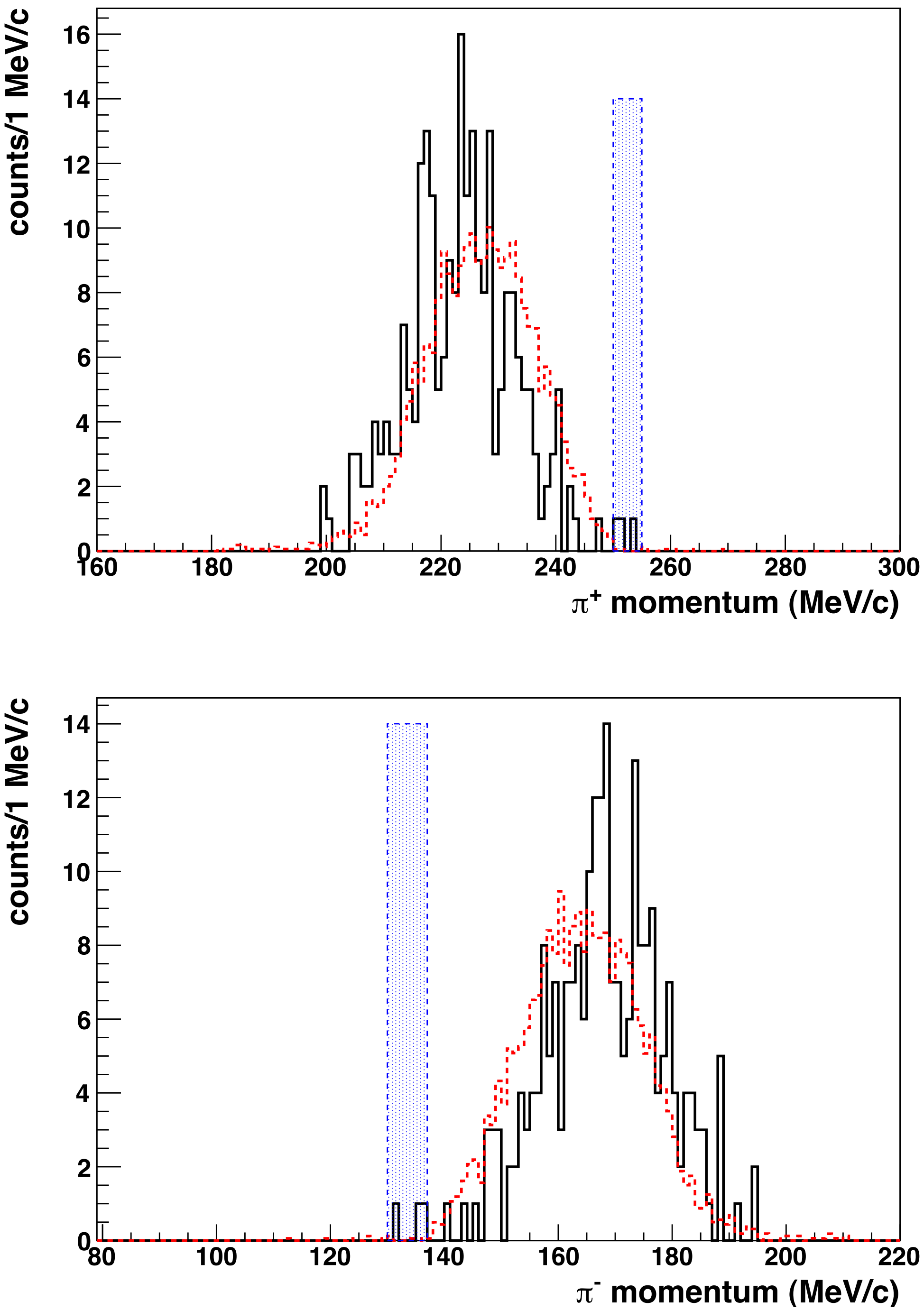
Finuda Coll. and A. Gal, NPA 881 (2012) 269.

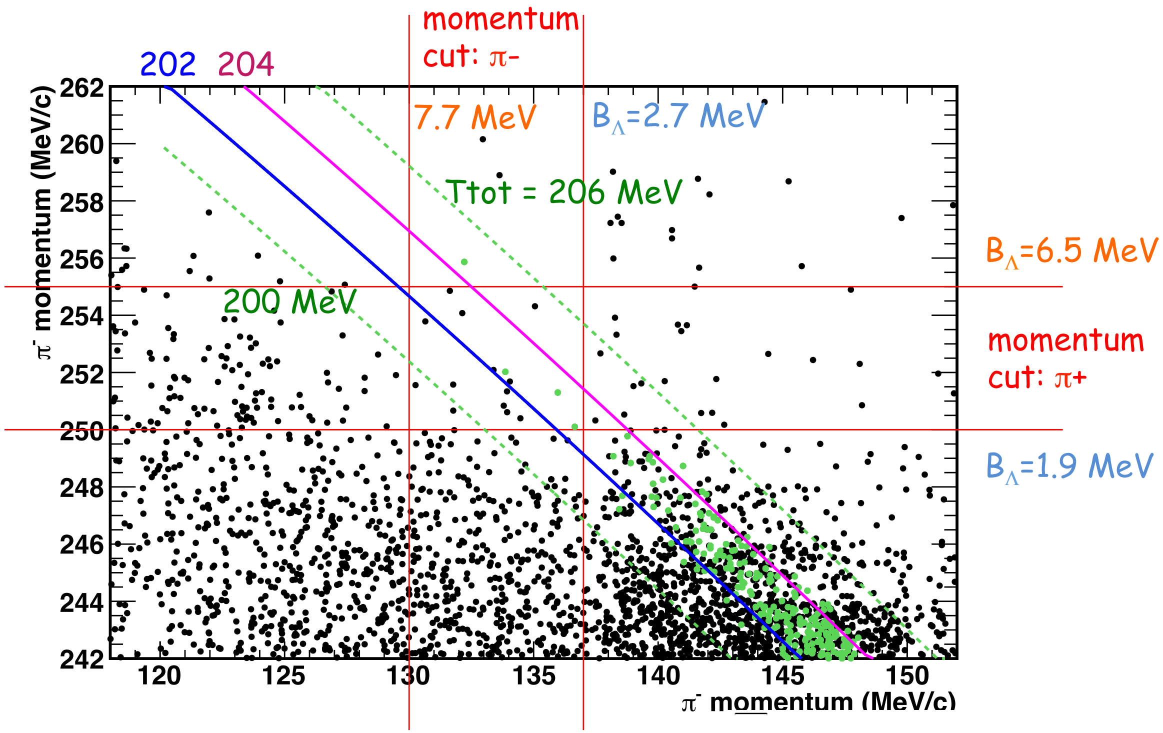
130–220 MeV

χ^2/ndf increases of ~ 3.8

fractions change <0.025 (1.3–1.5σ)

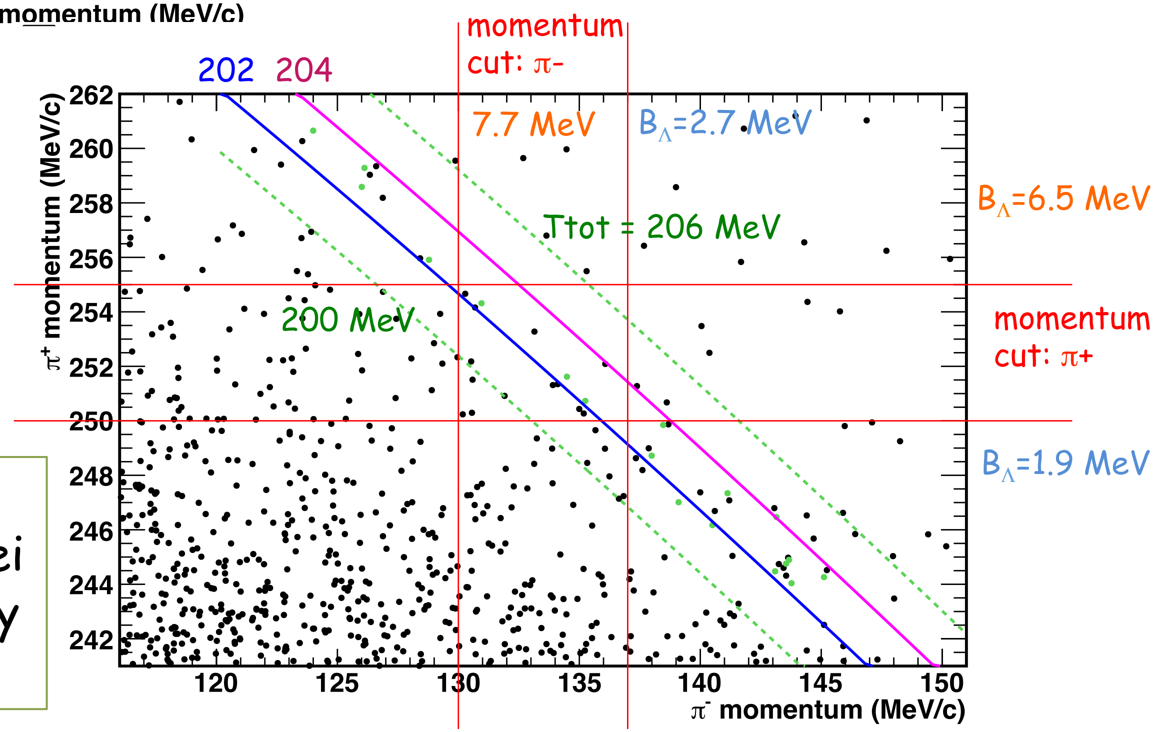
1d π+/π- spectra





- pure *quasi free approach*
- ~ 2.2 10^7 K^-_{stop} MC events
- 3 ev. → 0.15±0.09 ev.

- pure *4-body interaction*
- ~ 2.7 10^7 K^-_{stop} MC events
- 5 ev. → 0.20±0.11 ev.



- data: ~ 2.7 10^7 K^-_{stop} events
- BR(K^-_{stop} + p → Σ^+ + π-) on nuclei
- Σ^+ + n → Λ + p conv. probability
- BR(Σ^+ → n + π+)

Background sources:

- $K^-_{stop} + {}^6Li \rightarrow {}^4_\Lambda H + n + n + \pi^+$ (end point ~252MeV/c)
  $\hookrightarrow {}^4He + \pi^-$ ($p(\pi^-) = 133$ MeV/c) negligible

($p(\pi^+)$ cut: phase space strong reduction) $P \sim (2.8 \pm 0.5) \cdot 10^{-8}$

- $K^-_{stop} + {}^6Li \rightarrow \Sigma^+ + {}^3H + d + \pi^-$ ($p(\pi^-) < 165$ MeV/c)
  $\hookrightarrow n + \pi^+$ ($p(\pi^+) < 250$ MeV/c)

- $K^-_{stop} + {}^6Li \rightarrow {}^3_\Lambda H + 3n + \pi^+$ ($p(\pi^+) < 242$ MeV/c)
  $\hookrightarrow {}^3He + \pi^-$ ($p(\pi^-) \sim 115$ MeV/c)

- $K^-_{stop} + {}^6Li \rightarrow \Lambda + {}^3H + 2n + \pi^+$ ($p(\pi^+) < 247$ MeV/c)
  $\hookrightarrow p + \pi^-$ ($p(\pi^-) < 195$ MeV/c)

- $K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda He + \pi^0$ ($p(\pi^0) \sim 280$ MeV/c)
  $\hookrightarrow {}^6Li + \pi^-$ ($p(\pi^-) \sim 108$ MeV/c)

  $\pi^0 + {}^6Li \rightarrow {}^6He + \pi^+$ ($p(\pi^+) \sim 280$ MeV/c forw. dir.)

${}^{6}_{\Lambda}H/K^{-}_{stop}$ production rate

Total background: BGD1 + BGD2 = 0.43 ± 0.28 events on ^{6}Li

Poisson statistics: 3 events DO NOT belong to pure background: C.L.= 99% (S=3.9)

$$R * BR(\pi-) = (3 - BGD1 - BGD2)\,(\varepsilon(\pi-))^{-1}\,(\varepsilon(\pi+))^{-1} / (n.\ K^{-}_{stop} \text{ on } {}^{6}Li)$$

Corrections: ^{6}Li targets purity, ±0.77 σ T(π+)+T(π-) cut, decay in flight
90% 0.5588 10%

H. Tamura, et al., PRC 40 (1989) R479
${}^{4}_{\Lambda}H$ on ^{7}Li = 0.2

$$R * BR(\pi-) = (2.9 \pm 2.0)\ 10^{-6}/K^{-}_{stop}$$

H. Tamura, et al., PRC 40 (1989) R479
BR(π−) ${}^{4}_{\Lambda}H$ = 0.49

$$R = (5.9 \pm 4.0)\ 10^{-6}/K^{-}_{stop}$$

Agnello et al., *PLB 64(2006) 145*
U.L. 90%: $(2.5 \pm 0.4^{+0.4}_{-0.1})\ 10^{-5}/K^{-}_{stop}$

FINUDA Coll. and A. Gal, PRL 108 (2012) 042501, NPA 881 (2012) 269

first evidence of ${}^{6}_{\Lambda}H$ based on 3 events that cannot be attributed to pure instrumental and physical background

kinematics

T_{tot} (MeV)	$p(\pi^+)$ (MeV/c)	$p(\pi^-)$ (MeV/c)	$M({}^{6}_{\Lambda}H)$ formation (MeV/c^2)	$M({}^{6}_{\Lambda}H)$ decay (MeV/c^2)	ΔM (${}^{6}_{\Lambda}H$) (MeV)
202.5±1.3	251.3±1.1	135.1±1.2	5802.33±0.96	5801.41±0.84	0.92±1.28
202.7±1.3	250.0±1.1	136.9±1.2	5803.45±0.96	5802.73±0.84	0.71±1.28
202.1±1.3	253.8±1.1	131.2±1.2	5799.97±0.96	5798.66±0.84	1.31±1.28

FINUDA Coll. and A. Gal, PRL 108 (2012) 042501,
NPA 881 (2012) 269

- ✓ B_{Λ} determination
- ✓ formation – decay mass difference

${}^{6}_{\Lambda}H$ binding energy

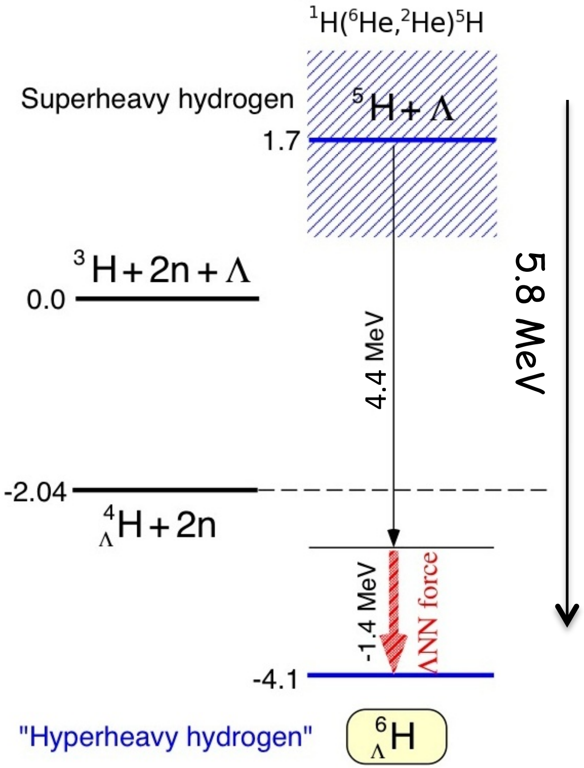
(N+Y)/Z=5

Dalitz et al., N. Cim. 30 (1963) 489 (binding energy 4.2 MeV)

B ${}^{4}_{\Lambda}He$ 2.39 Λ	${}^{5}_{\Lambda}He$ 3.12 Λ	◇ ${}^{6}_{\Lambda}He$ 4.18 n 0.17 xxx	◇ ${}^{7}_{\Lambda}He$ 5.23 n 2.92 halo	${}^{8}_{\Lambda}He$ 7.16 n 1.49 xxx	♠ ${}^{9}_{\Lambda}He$ (8.5) n 3.9 halo
${}^{3}_{\Lambda}H$ 0.13 Λ	◇ ${}^{4}_{\Lambda}H$ 2.04 Λ	${}^{5}_{\Lambda}H$ (3.1) *n -1.8* xxx	♠ ${}^{6}_{\Lambda}H$ (4.2) *2n -5* xxx	♠ ${}^{7}_{\Lambda}H$ (5.2) 3n 0.4 xxx	

4.2 MeV

L. Majling, NPA 585 (1995) 211c
- binding energy
- prod. rate ~ 10^{-2} * hyp. prod. rate in (K^{-}_{stop}, π^{-})



Y. Akaishi et al., AIP Conf. Proc. 1011 (2008) 277
K.S. Myint, et al., Few Body Sys. Suppl. 12 (2000) 383
Y. Akaishi et al., Frascati Phys. Series XVI (1999) 16

"coherent" Λ−Σ coupling in 0+ states
→ ΛNN three body force:
$B_{\Lambda NN}$ = 1.4 MeV, $\Delta E(0^{+}_{g.s.} - 1^{+})$ = 2.4 MeV
model originally developed for ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$

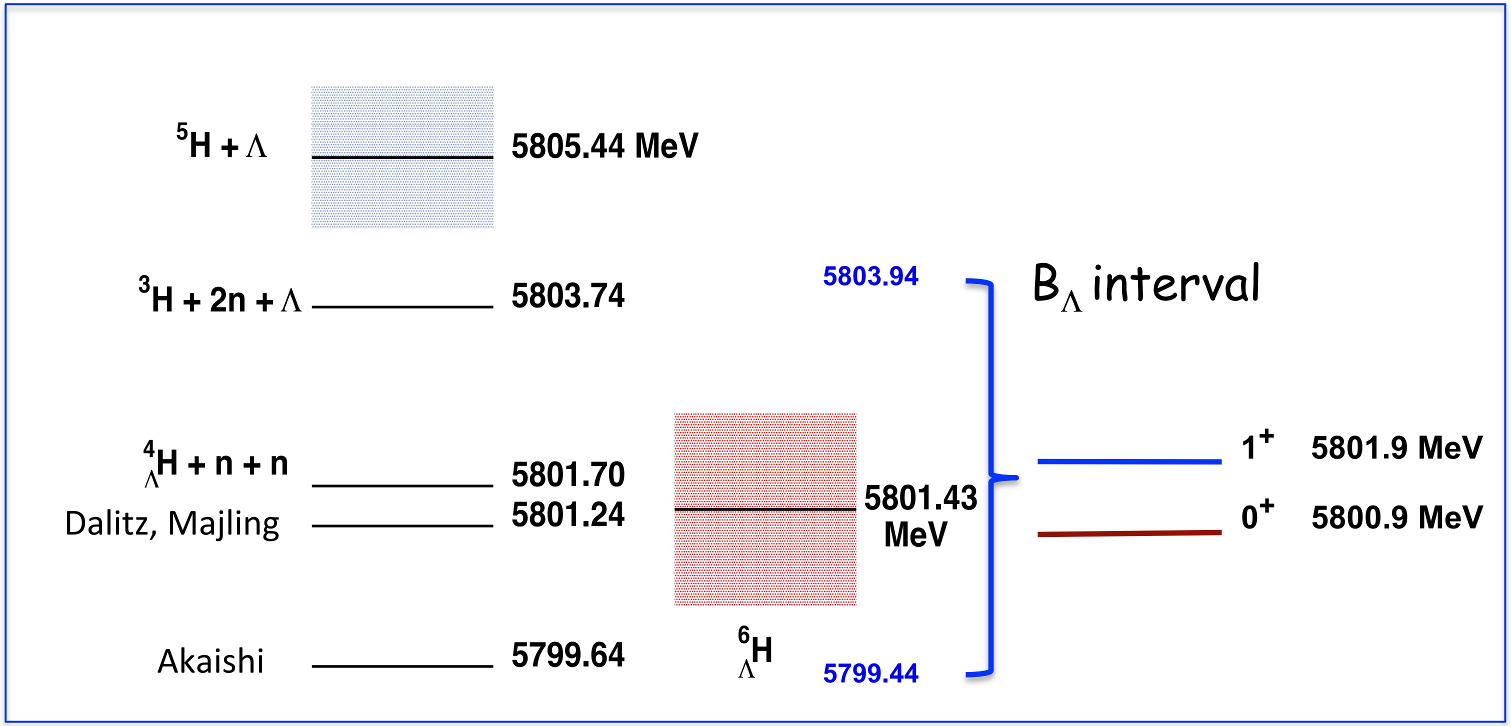
$B_\Lambda(^6_\Lambda H)$ determination

mass mean value = 5801.4±1.1

B_Λ = 4.0±1.1 MeV (^{5}He + Λ)

B = 0.3±1.1 MeV ($^4_\Lambda$H + 2n)

B_Λ= 5.8 MeV (^{5}He + Λ)
ΛNN force: 1.4 MeV



formation – decay = 0.98±0.74 MeV

formation – decay ΔM

Spin flip is forbidden in production at rest:

$K^{-}_{stop} + {}^{6}Li\ (L_i=0,\ S=1) \rightarrow {}^{6}_{\Lambda}H(L_f,\ S=1) + \pi^{+}$

$L_f = 0 \rightarrow {}^{6}_{\Lambda}H(1^{+}_{exc.})$ followed by :

(i) ${}^{6}_{\Lambda}H(1^{+}\ exc.) \rightarrow \gamma + {}^{6}_{\Lambda}H(0^{+}\ g.s.)$ (~ 10^{-13} s) M1

(ii) ${}^{6}_{\Lambda}H(0^{+}\ g.s.) \rightarrow \pi^{-} + {}^{6}He(0^{+}\ g.s.)$ (~ 10^{-10} s)

(${}^{6}_{\Lambda}H(1^{+}\ exc.) \rightarrow {}^{4}_{\Lambda}H(0^{+}\ g.s.) + n + n$: p-wave&spin-flip)

→ $B_{\Lambda}({}^{6}_{\Lambda}H) = (4.5 \pm 1.2)$ MeV vs ${}^{5}He+\Lambda$ from decay mass only
little neutron-excess effect compared to $B_{\Lambda}({}^{6}_{\Lambda}He) = (4.18 \pm 0.10)$ MeV

Excitation energy of the 1^{+} spin-flip state from a systematic difference $\Delta M = 0.98 \pm 0.74$ MeV between values of ${}^{6}_{\Lambda}H$ mass derived separately from production and from decay.

1^{+} particle stable? 0^{+} particle stable?

J-PARC E10

Recent searches: J-PARC – E10

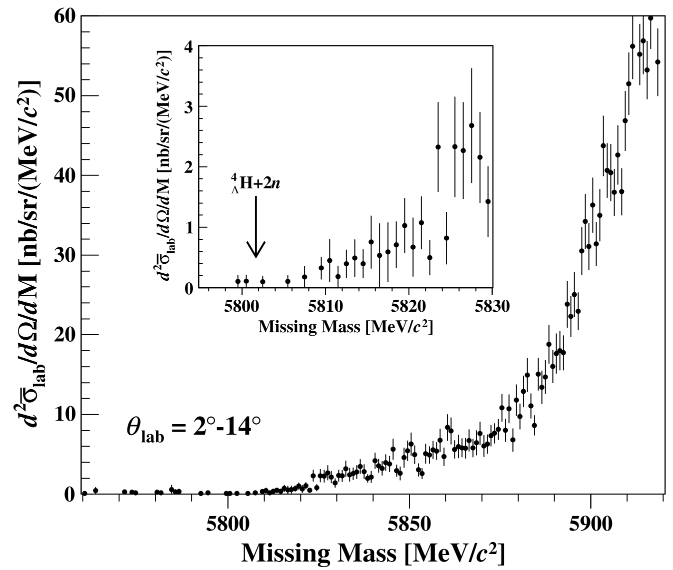
(π^-, K^+)

H.Sugimura et al., PLB 729 (2014) 39

J-PARC K1.8 beamline p_{π^-} = 1.2 GeV/c

no peak structure in the MM spectrum

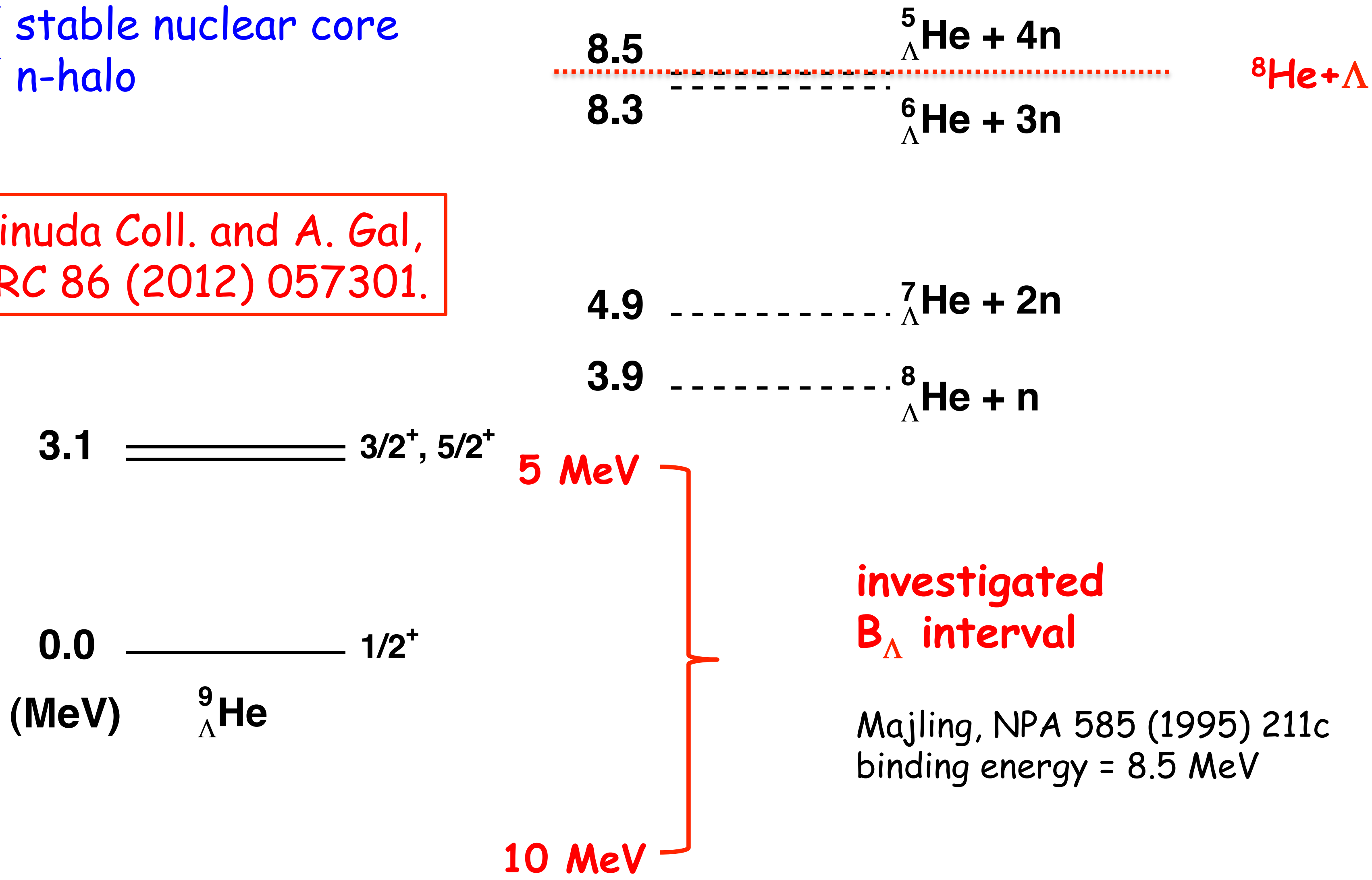
${}^{6}_{\Lambda}H$ (${}^{6}Li$) $d\sigma/d\Omega$: U.L. 1.2 nb/sr 90% C.L.



${}^{9}_{\Lambda}$He search with FINUDA

- ✓ (N+Y)/Z = 3.5
- ✓ stable nuclear core
- ✓ n-halo

Finuda Coll. and A. Gal, PRC 86 (2012) 057301.



Majling, NPA 585 (1995) 211c
binding energy = 8.5 MeV

${}^{9}_{\Lambda}He$ search with FINUDA

$K^-_{stop} + {}^9Be \rightarrow {}^9_{\Lambda}He + \pi^+$

${}^9_{\Lambda}He \rightarrow {}^9Li + \pi^-$
($\tau({}^9Li)$~178 ms)

independent 2-body reactions:
decay at rest

$$M(K^-) + 5\,M(n) + 4\,M(p) - B({}^9Be) = M({}^9_{\Lambda}He) + T({}^9_{\Lambda}He) + M(\pi^+) + T(\pi^+)$$

$$M({}^9_{\Lambda}He) = 6\,M(n) + 3M(p) - B({}^9Li) + T({}^9Li) + M(\pi^-) + T(\pi^-)$$

$$\sqrt{M^2({}^9Li) + p^2(\pi^-)} - M({}^9Li)$$

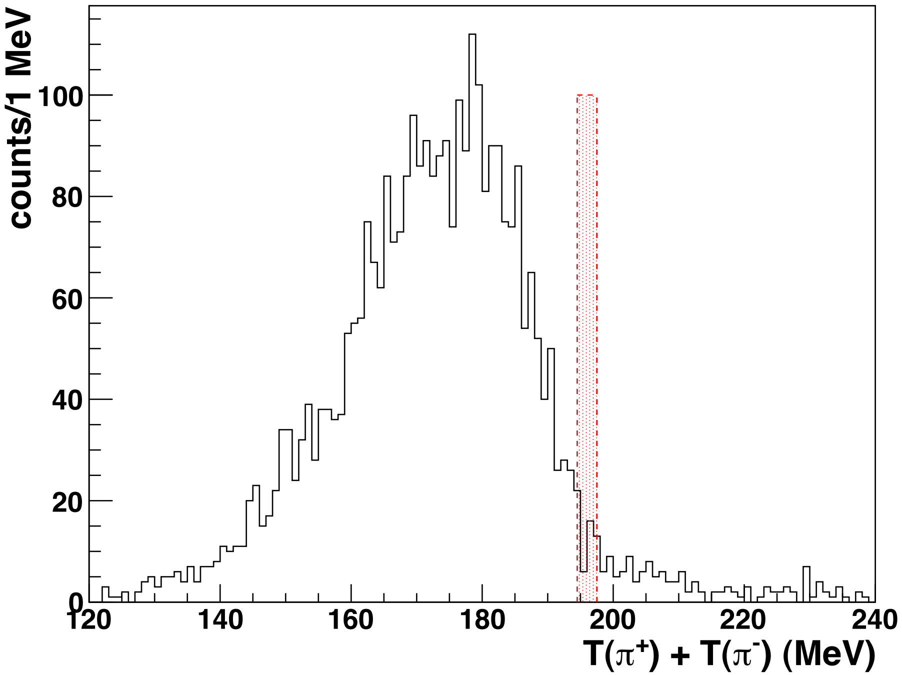
$$\sqrt{M^2({}^9_{\Lambda}He) + p^2(\pi^+)} - M({}^9_{\Lambda}He)$$

$$M({}^9_{\Lambda}He) = M({}^8He) + M(\Lambda) - B(\Lambda)$$

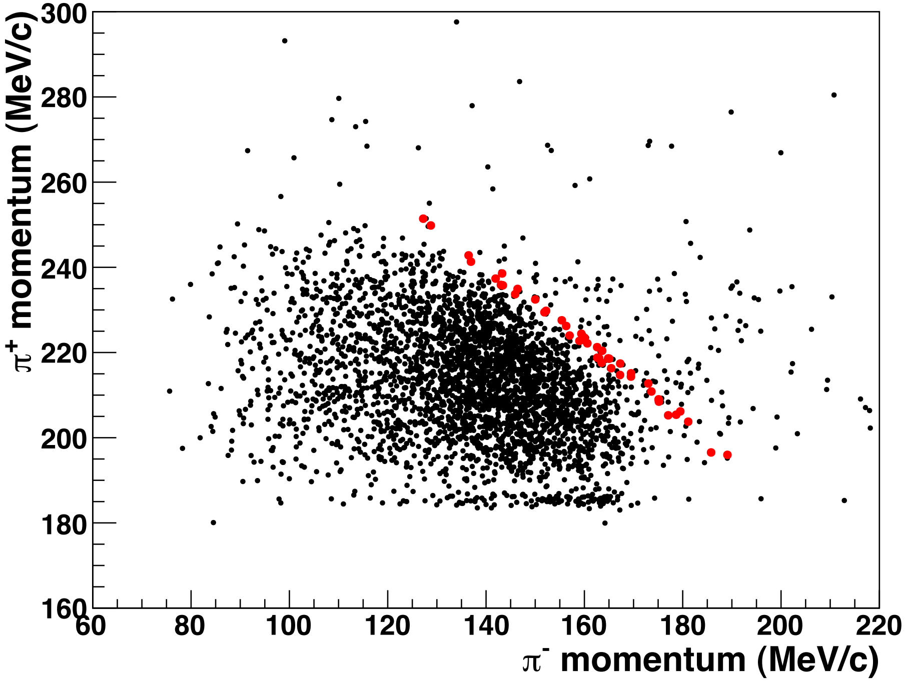
$$T(\pi^+) + T(\pi^-) = M(K^-) + M(p) - M(n) - B({}^9Be) + B({}^9Li) - T({}^9Li) - T({}^9_{\Lambda}He) - M(\pi^+) - M(\pi^-)$$

= **195.8 ± 1.3 MeV** (195.8÷195.7 MeV with B_{Λ}= 0÷10 MeV)

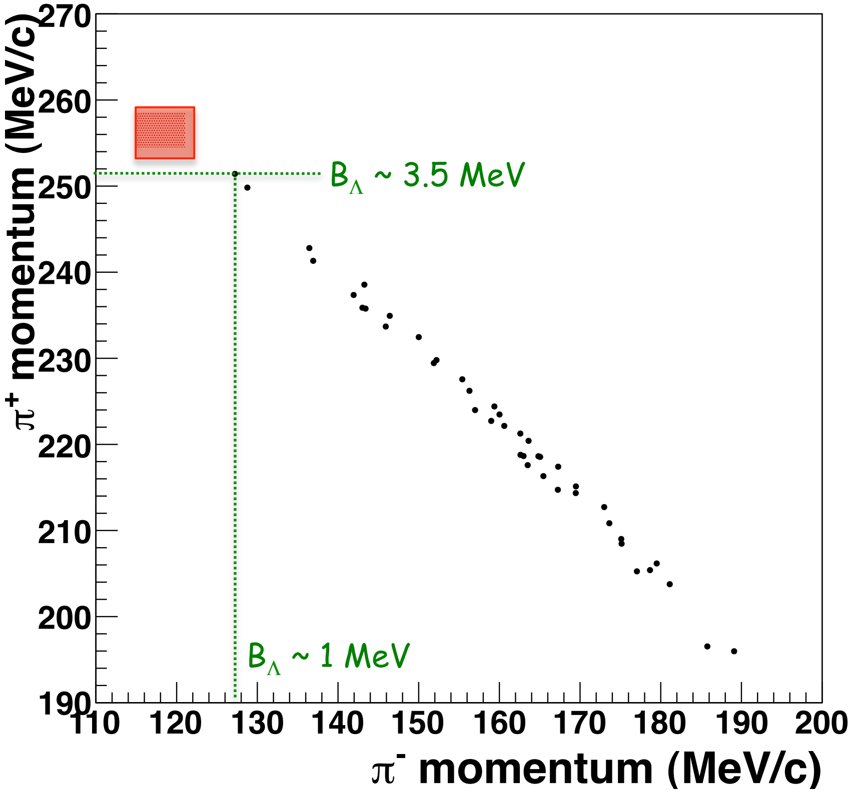
cut on $T(\pi^+) + T(\pi^-)$: 194.5÷197.5 MeV



selection:
$T(\pi^+)+T(\pi^-)$ = 194.5÷197.5 MeV



Finuda Coll. and A. Gal,
PRC 86 (2012) 057301.

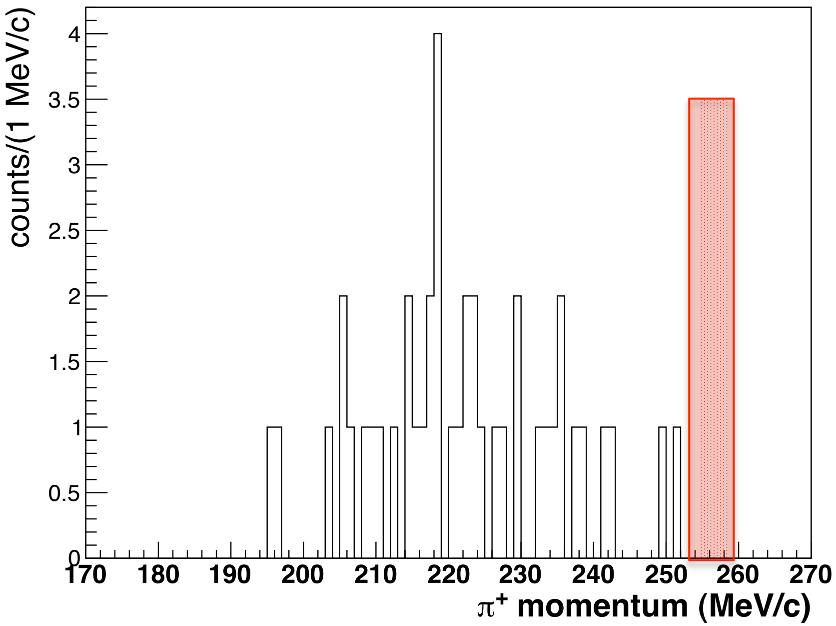


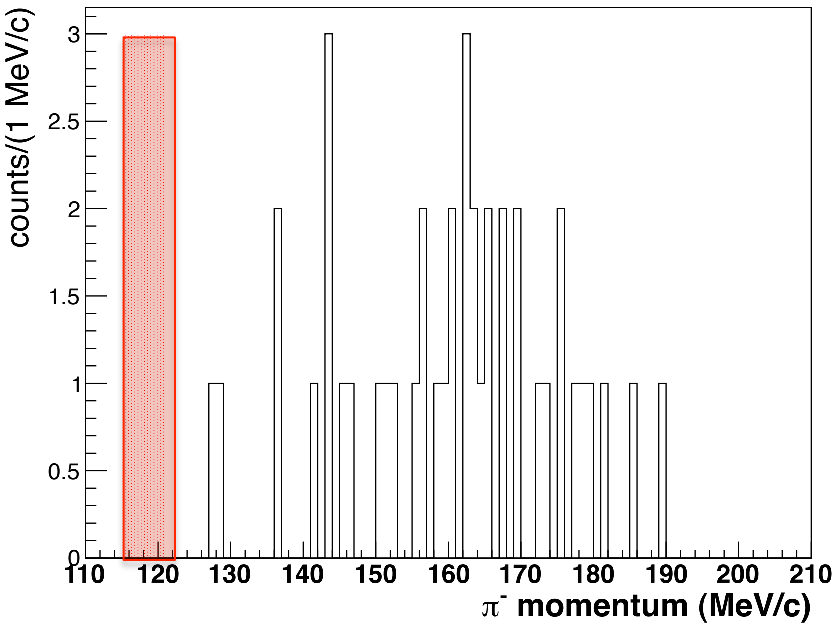
253.5÷259 MeV/c (σ_p= 1.1 MeV/c)

114.5÷122MeV/c (σ_p= 1.2 MeV/c)

B_Λ = 5÷10 MeV

Finuda Coll. and A. Gal, PRC 86 (2012) 057301.





${}^{9}_{\Lambda}He/K^-_{stop}$ production rate

upper limit evaluation

- ✓ 0 observed events
- ✓ $\varepsilon(\pi-)$, $\varepsilon(\pi+)$
- ✓ n. K^-_{stop} on ${}^{9}Be$ (2.5 10^7 K^-_{stop} events)

$$R * BR(\pi-) < (2.3\pm1.9)\bullet10^{-6} / (n.\ K^-_{stop}\ on\ {}^{9}Be)\ (90\%\ C.L.)$$

$$\Gamma({}^{9}_{\Lambda}He_{gs} \rightarrow {}^{9}Li_{gs} + \pi^-) = 0.261\ \Gamma_\Lambda$$

from A. Gal, Nucl. Phys. A 828, 72 (2009)

$$R < 1.6\ 10^{-5} / (n.\ K^-_{stop}\ on\ {}^{9}Be)\ (90\%\ C.L.)$$

PRC 86 (2012) 057301

K.Kubota et al, NPA 602 (1996) 327.
${}^{9}_{\Lambda}He$ (${}^{9}Be$) U.L.=2.3 $10^{-4}/K^-_{stop}$

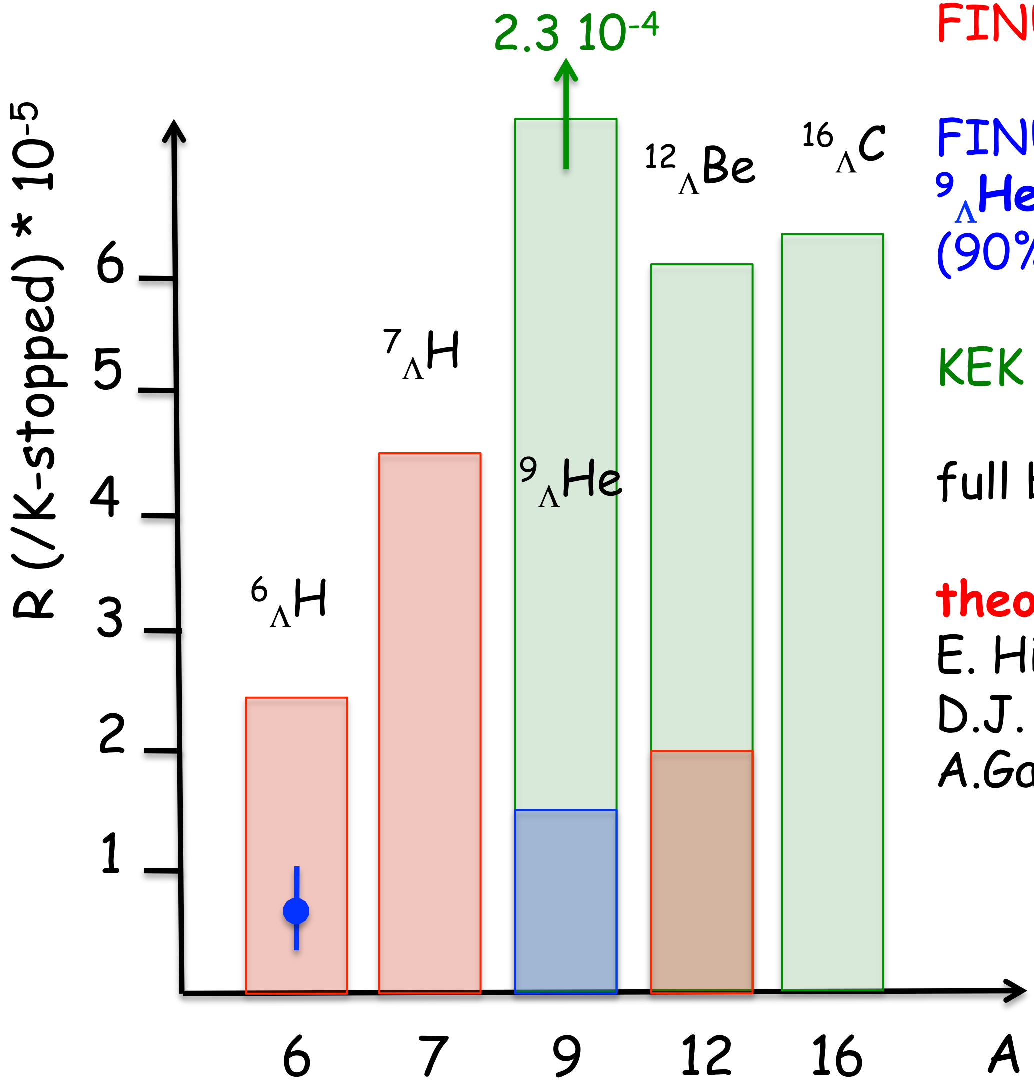
… coincidence method **limits**

target	hypernucleus	2-b MWD daughter nucleus	lifetime	MWD 'model'	MWD 'model' BR($\pi-$) **R*BR($\pi-$)**
^{6}Li	$^{6}{}_{\Lambda}H$	^{6}He	801 ms	$^{4}{}_{\Lambda}H$	0.49 H. Tamura, et al., PRC 40 (1989) R479
^{7}Li	$^{7}{}_{\Lambda}H$	^{7}He	unstable	$^{4}{}_{\Lambda}H$	0.49 H. Tamura, et al., PRC 40 (1989) R479
^{9}Be	$^{9}{}_{\Lambda}He$	^{9}Li	178 ms	$^{9}{}_{\Lambda}He$	0.261 A. Gal, Nucl. Phys. A 828, 72 (2009)
^{12}C	$^{12}{}_{\Lambda}Be$	^{12}B	20 ms	$^{9}{}_{\Lambda}Be$	0.154 FINUDA PLB 681 (2009) 139
^{13}C	$^{13}{}_{\Lambda}Be$	^{13}B	17.3 ms	$^{9}{}_{\Lambda}Be$	0.154 FINUDA PLB 681 (2009) 139
^{16}O	$^{16}{}_{\Lambda}C$	^{16}N	7.13 s	$^{12}{}_{\Lambda}C$	0.099 Y.Sato et al., PRC 71 (2005) 025203

production and decay from the same energy level ← **2-body processes production&decay** (↑ lifetime)

decreasing MWD BR (↑ MWD 'model' BR)

Overview of n-rich (K^-_{stop}, π^+) production rate vs *A*



FINUDA: inclusive spectra

FINUDA: coincidence
$^{9}_{\Lambda}$He: R < 1.6 10^{-5} / (n. K^-_{stop} on ^{9}Be)
(90% C.L.), PRC 86 (2012) 057301

KEK K.Kubota et al, NPA 602 (1996) 327

full bars: U.L., 90% C.L.

theoretical interest for $^{6}_{\Lambda}$H
E. Hiyama et al., NPA 908 (2013) 29
D.J. Millener, NPA 881 (2012) 298
A.Gal, D.J.Millener, PLB 725 (2013) 445

… inheritance

- very thin targets (0.1 ÷ 0.3 g/cm^2): transparency ➥ "high" resolution spectroscopy
- different targets in the same run ➥ high degree of flexibility
- coincidence measurement with large acceptance ➥ decay mode study
- simultaneous tracking of μ^+ from the K^+ decay ➥ energy and rate calibration
- systematic study of p-shell nuclei

Spectroscopy

Decay: MWD & NMWD

n-rich hypernuclei

- low statistics
- lifetime measurement
- (K^+, $\pi^+\pi^-$) method

indications for new, high statistics measurements with "complete" apparatuses