Results on light Λ-hypernuclei by the FINUDA experiment

Elena Botta
INFN-Torino and Torino University

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THE UNIVERSITY of ADELAIDE

ANPhA
Asian Nuclear Physics Association

Overview

- DAΦNE and FINUDA
- FINUDA Scientific Program
- Light Λ-hypernuclei: results
  - ✓ Hypernuclear Spectroscopy
  - ✓ MWD & NMWD
  - ✓ $^{6}_{\Lambda}$H observation

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Study of Strongly Interacting Matter
HadronPhysics

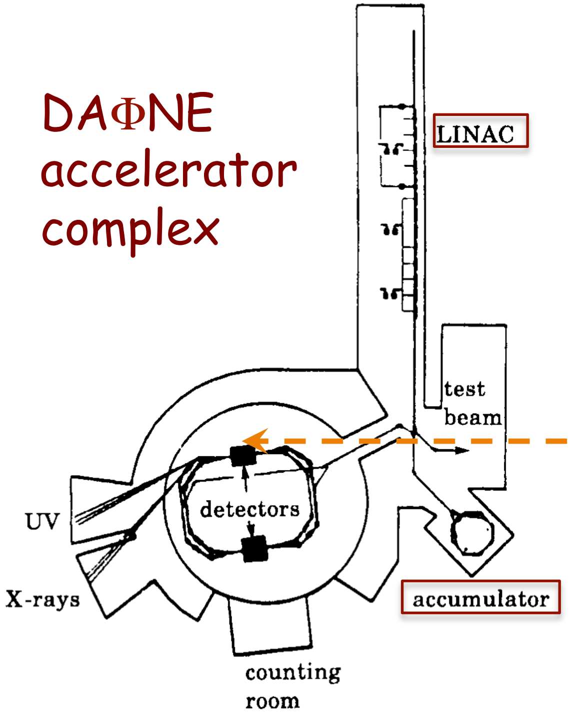
FINUDA: FIsica NUcleare a DAΦNE

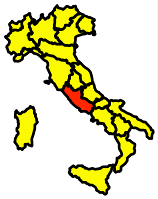
DAΦNE

Double Annular Φ-factory for Nice Experiments

low energy Kaon factory

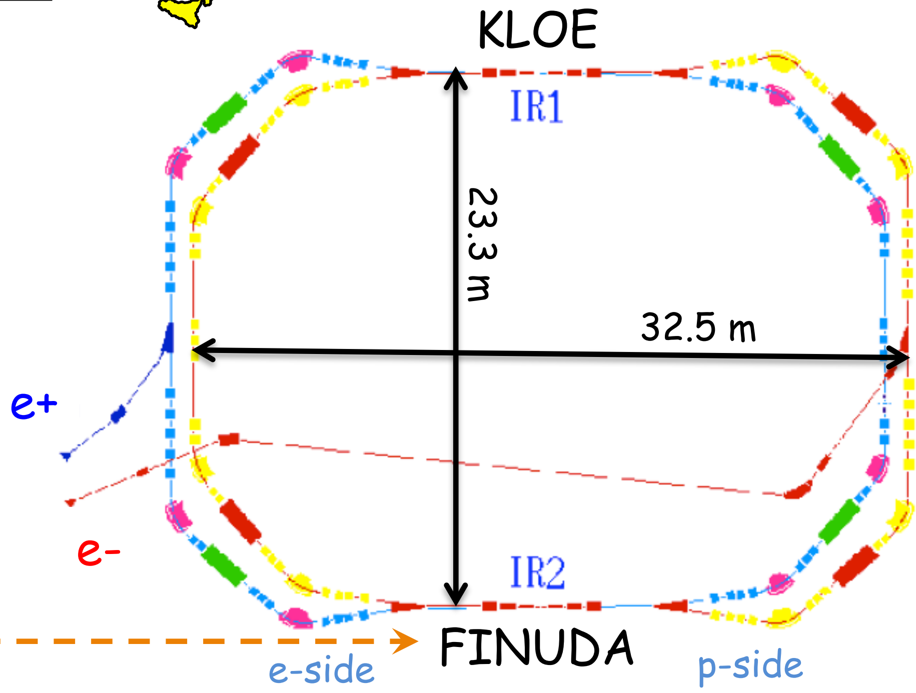
DAΦNE accelerator complex



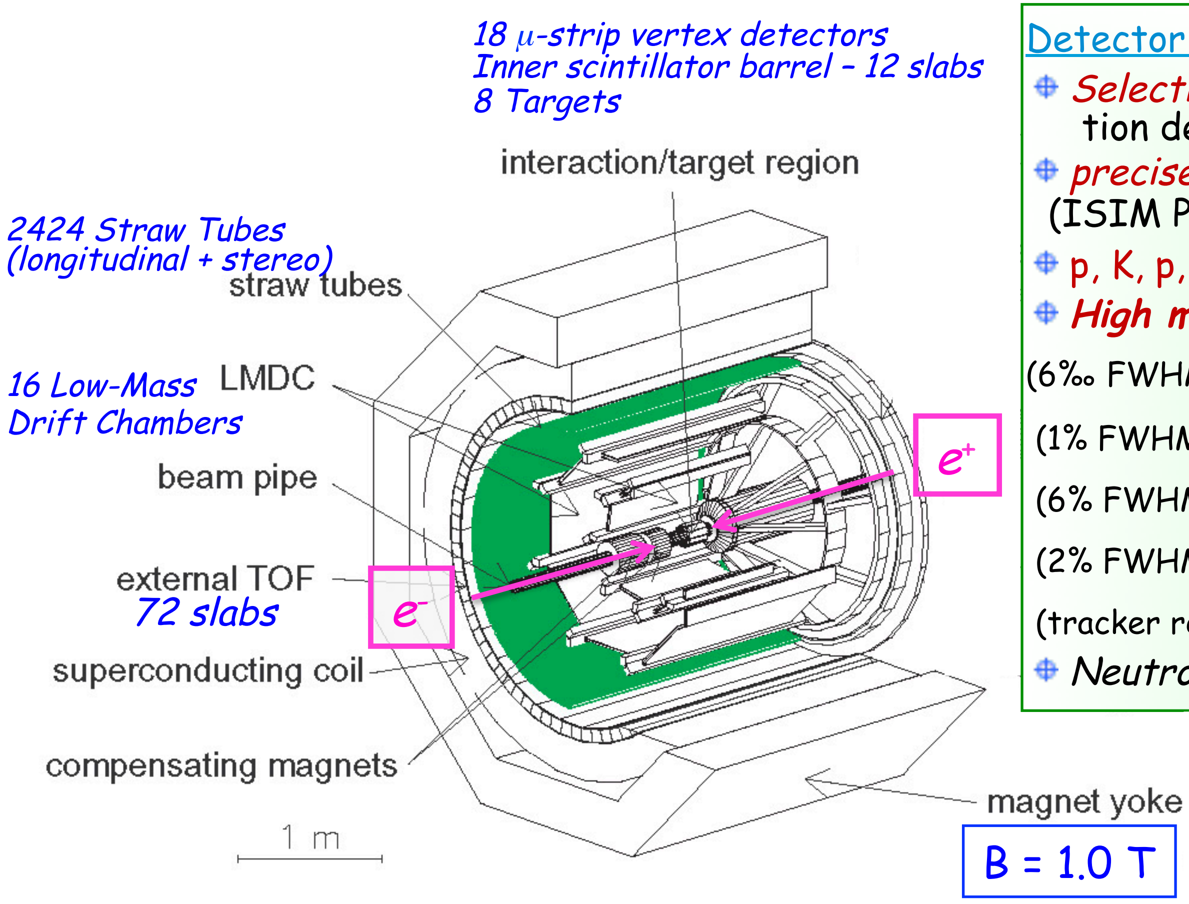


Energy (GeV)	0.51
Luminosity (cm-2 s-1)	10^{32}
Beam Hor. Dim. at IP (mm)	2.11
Beam Vert. Dim. at IP (mm)	0.021
R.M.S. Bunch length (mm)	30
Crossing angle (mrad)	25
Collision frequency (MHz)	380.44
Bunches/ring	120
Max number of particles/bunch	$9.0\ 10^{10}$
Max total mean current (A)	5.5

ϕ(1020) ~ at rest



The FINUDA detector



B = 1.0 T

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)

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*

The very first example of a *(hyper)nuclear physics* fixed-target experiment at a *collider*

Hypernuclear Physics @FINUDA

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

$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \boxed{\pi^-}$

spectroscopy

${}^{A}_{\Lambda}Z \rightarrow {}^{A}(Z+1) + \boxed{\pi^-}$ $\Gamma_{\pi-}$ MWD

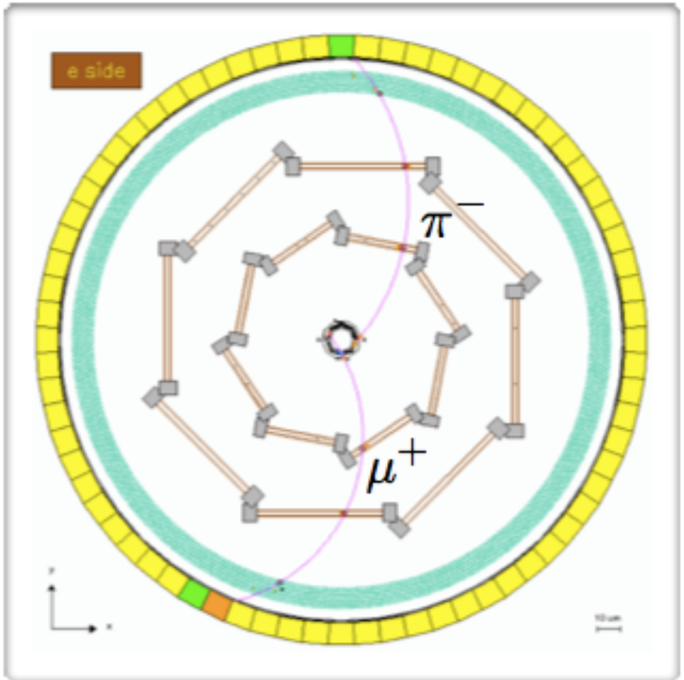
${}^{A}_{\Lambda}Z \rightarrow {}^{A-2}(Z-1) + \boxed{p + n}$ 1N induced Γ_p

${}^{A}_{\Lambda}Z \rightarrow {}^{A-3}(Z-1) + \boxed{p + n + n}$ 2N induced Γ_{np}

NMWD

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

FINUDA key features



- very thin targets ($0.1 \div 0.3\ g/cm^2$)
  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
  $K^+ \rightarrow \mu^+\nu_\mu$ ➥ energy and rate calibration

FINUDA Scientific Program

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 $^{5}_{\Lambda}He$, $^{7}_{\Lambda}Li$, $^{9}_{\Lambda}Be$, $^{11}_{\Lambda}B$, $^{12}_{\Lambda}C$, $^{13}_{\Lambda}C$, $^{15}_{\Lambda}N$, $^{16}_{\Lambda}O$
PLB 701 (2011) 556: NMWD & 2N $^{5}_{\Lambda}He$, $^{7}_{\Lambda}Li$, $^{9}_{\Lambda}Be$, $^{11}_{\Lambda}B$, $^{12}_{\Lambda}C$, $^{13}_{\Lambda}C$, $^{15}_{\Lambda}N$, $^{16}_{\Lambda}O$
NPA 881 (2012) 322 : (n, n, p) events from 2N
Rare Decays: NPA 835 (2010) 439; $^{4}_{\Lambda}He$, $^{5}_{\Lambda}He$ 2-body decays

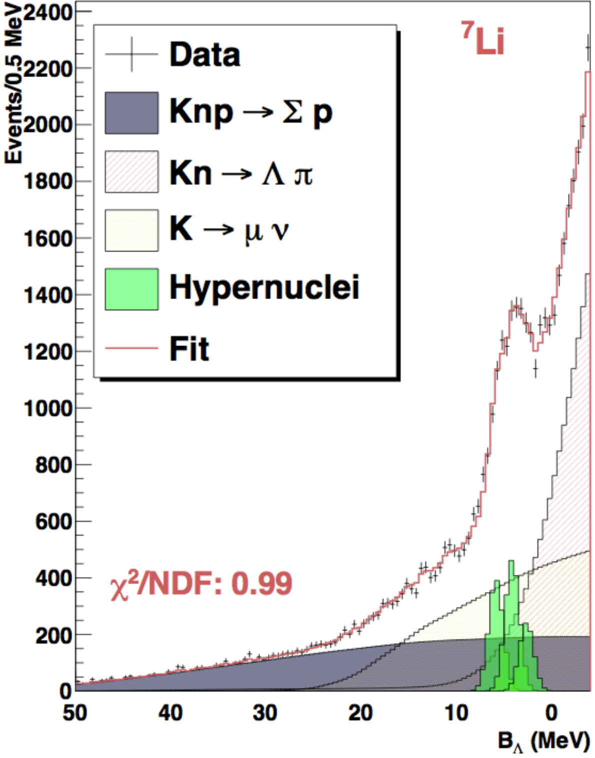
Neutron-rich Hypernuclei: PLB 640 (2006) 145: upper limits $^{6}_{\Lambda}H$, $^{7}_{\Lambda}H$ and $^{12}_{\Lambda}Be$
PRL 108 (2012) 042501: $^{6}_{\Lambda}H$ observation
NPA 881 (2012) 269: $^{6}_{\Lambda}H$ observation
PRC 86 (2012) 057301: $^{9}_{\Lambda}He$ upper limit

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 Spectroscopy: p-shell

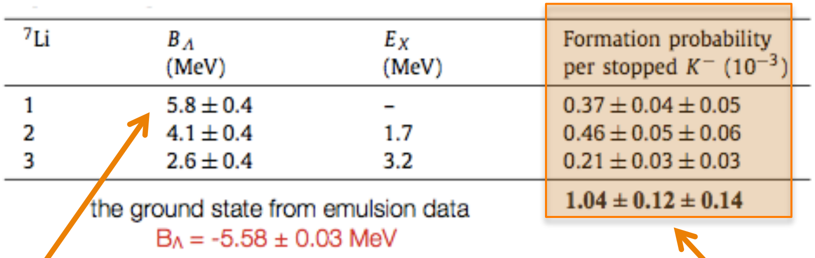
$B_{\Lambda} = M(^{A}Z) + M(\Lambda) - M_{hyp}$



M.Agnello et al., PLB 622 (2005) 35: $^{12}{}_{\Lambda}C$

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

First world measurement of formation probability for $^{7}{}_{\Lambda}$Li, $^{9}{}_{\Lambda}$Be, $^{13}{}_{\Lambda}$C, $^{16}{}_{\Lambda}$O



^{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

Formation probability
connected to the number of events in the peaks, calculated taking into account acceptances and efficiencies
($K^{+} \to \mu\nu$ – rate calibrated apparatus)

Absolute energy scale known at the level of 0.3 MeV
(we know from the $K^{+} \to \mu\nu$ – self calibrated apparatus)
momentum resolution: 0.5-0.9% FWHM

Comparison with theory:
A.Cieply et al., PLB 698 (2011) 226

Constraints on the threshold K- nuclear potential from FINUDA $^{A}Z(K^{-}_{stop}, \pi^{-})^{A}{}_{\Lambda}Z$ spectra: partial formation rates slightly favors a deep K- nuclear potential,
Re $V_{K-}(\rho_0)$ = 150-200 MeV

Comparison with:
$B_{\Lambda g.s.}$: emulsion exp. M. Juric et al., NPB 52 (1973), 1 ($^{7}{}_{\Lambda}$Li, $^{9}{}_{\Lambda}$Be, $^{13}{}_{\Lambda}$C)
Excitation energies: (π+,K+) KEK experiments: O. Hashimoto, H. Tamura, PPNP 57 (2006) 564 (KEK E336 data) ($^{7}{}_{\Lambda}$Li, $^{9}{}_{\Lambda}$Be, $^{16}{}_{\Lambda}$O)
γ spectroscopy: $^{7}{}_{\Lambda}$Li, $^{9}{}_{\Lambda}$Be: KEK E419, H. Tamura et al. NPA 754 (2005) 58c
$^{13}{}_{\Lambda}$C: (K-,π- γ) CERN, PRC 65, 034607
$^{16}{}_{\Lambda}$O: BNL E930('01) PRC 77 (2008) 054315.

Hypernuclear weak decay studies: p-shell

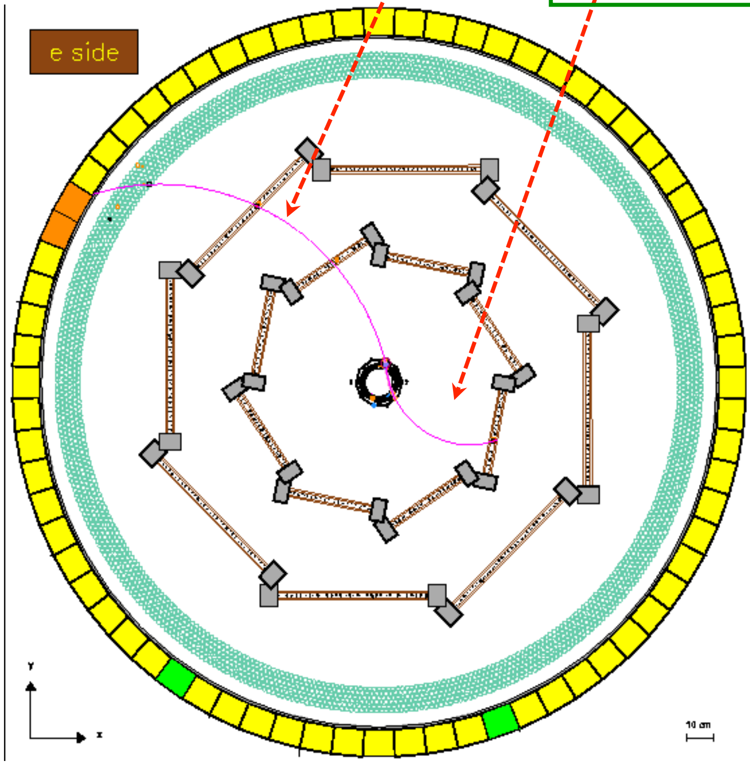
Coincidence measurement: decay from g.s./low lying states

charged Mesonic channel

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

S-EX
260-280 MeV/c

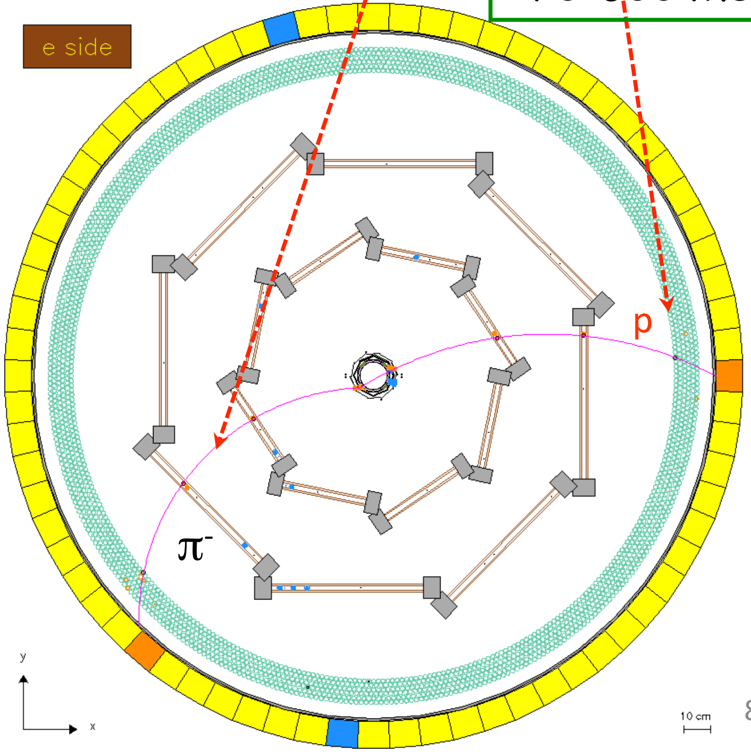
MWD
80-110 MeV/c



charged Non-Mesonic channel

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

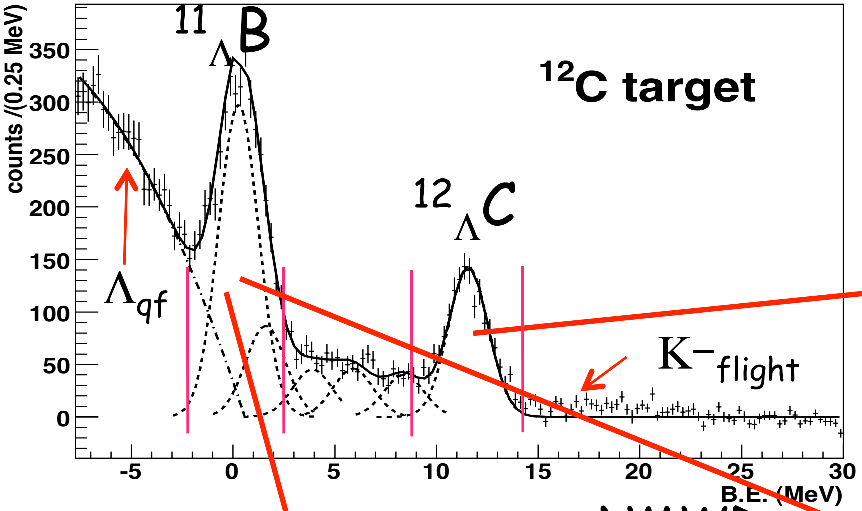
NMWD
170-600 MeV/c



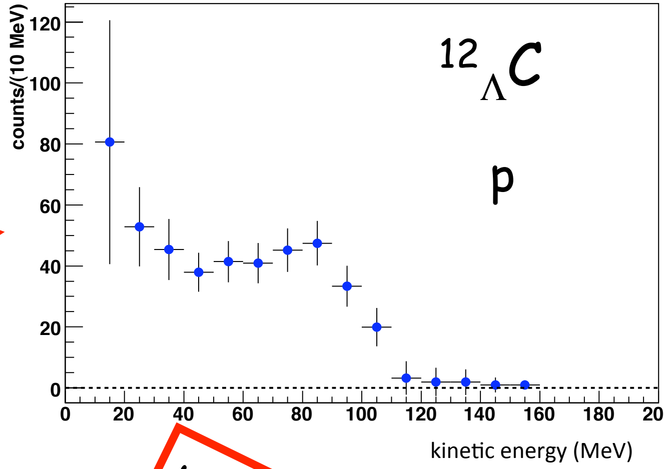
MWD & NMWD in FINUDA: strategy

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

$K^- np \rightarrow \Sigma^- p$
$\Sigma^- \rightarrow n \pi^-$



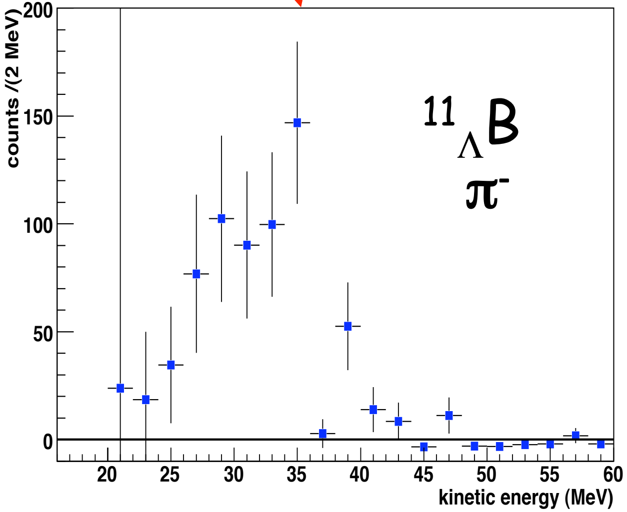
NMWD

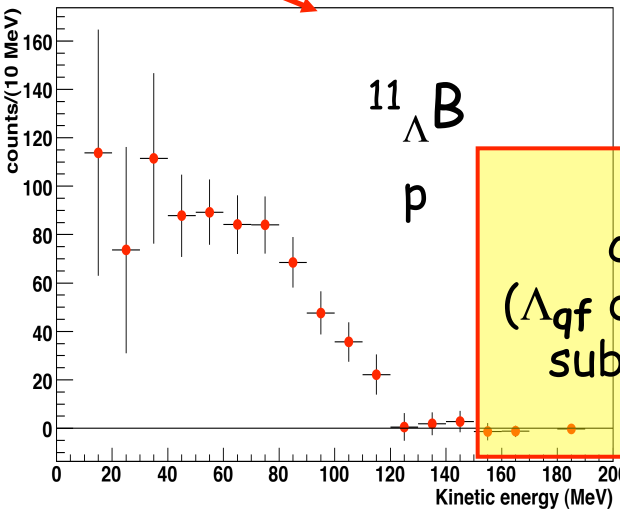


MWD

NMWD

magnetic analysis !!



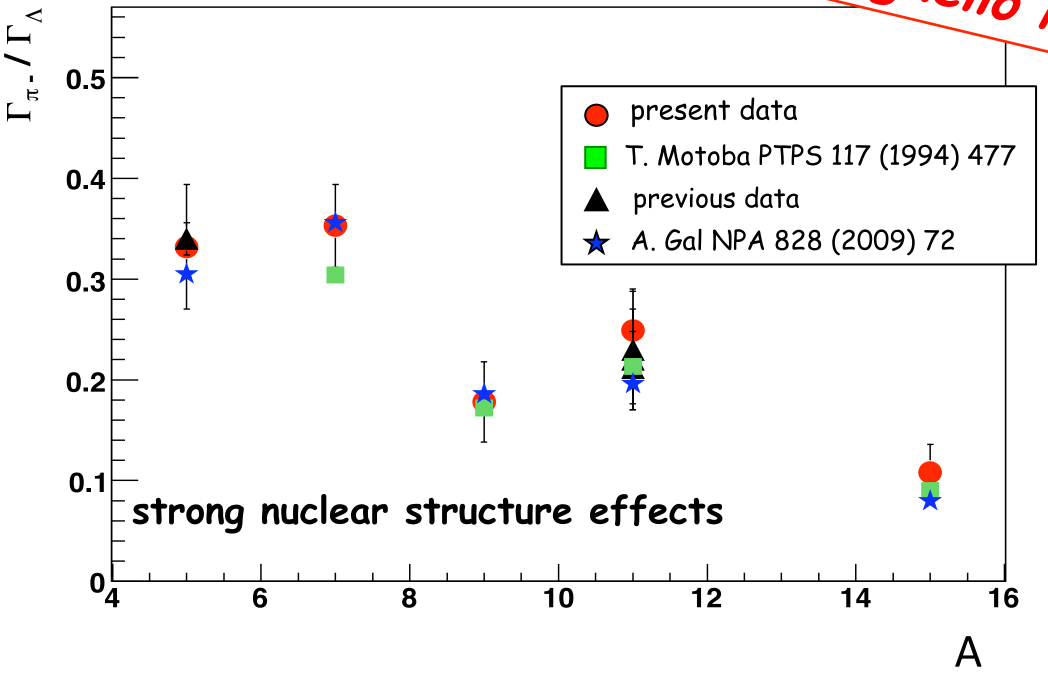


decay π^- and p
coincidence spectra
(Λ_{qf} decay)/K^-np background
subtracted & acceptance
corrected

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

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

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



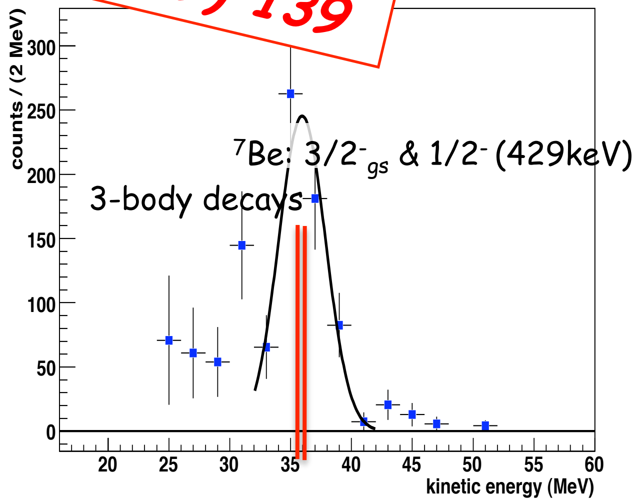
strong nuclear structure effects

M. Agnello PLB 681 (2009) 139

J^π assignment:

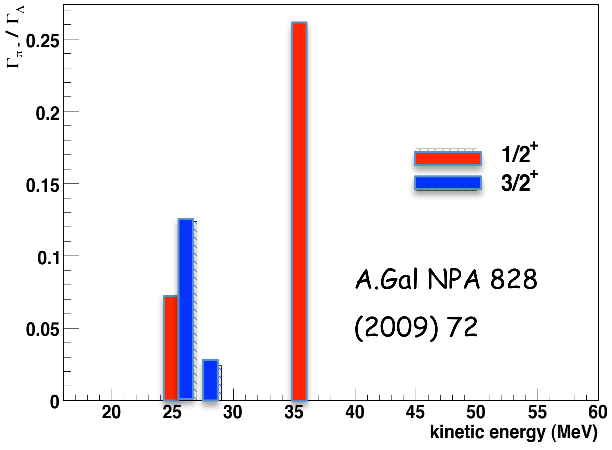
${}^{7}_{\Lambda}$Li (1/2+), ${}^{9}_{\Lambda}$Be (1/2$^+$), ${}^{11}_{\Lambda}$B (5/2$^+$), **${}^{15}_{\Lambda}$N (3/2$^+$)**

first determination



^{7}Be: 3/2$^-_{gs}$ & 1/2$^-$ (429keV)

3-body decays



A.Gal NPA 828 (2009) 72

Extensive calculations:

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

π distortion, MWD enhancement proved !

MWD indirect spectroscopic tool !

NMWD: single p spectra

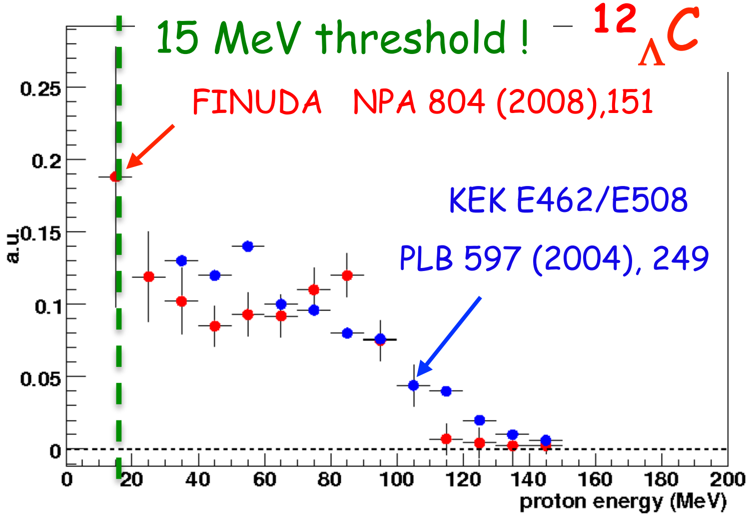
$$^{A}_{\Lambda}Z \rightarrow {}^{A-2}(Z-1) + p + n$$

$$^{A}_{\Lambda}Z \rightarrow {}^{A-3}(Z-1) + p + n + n$$

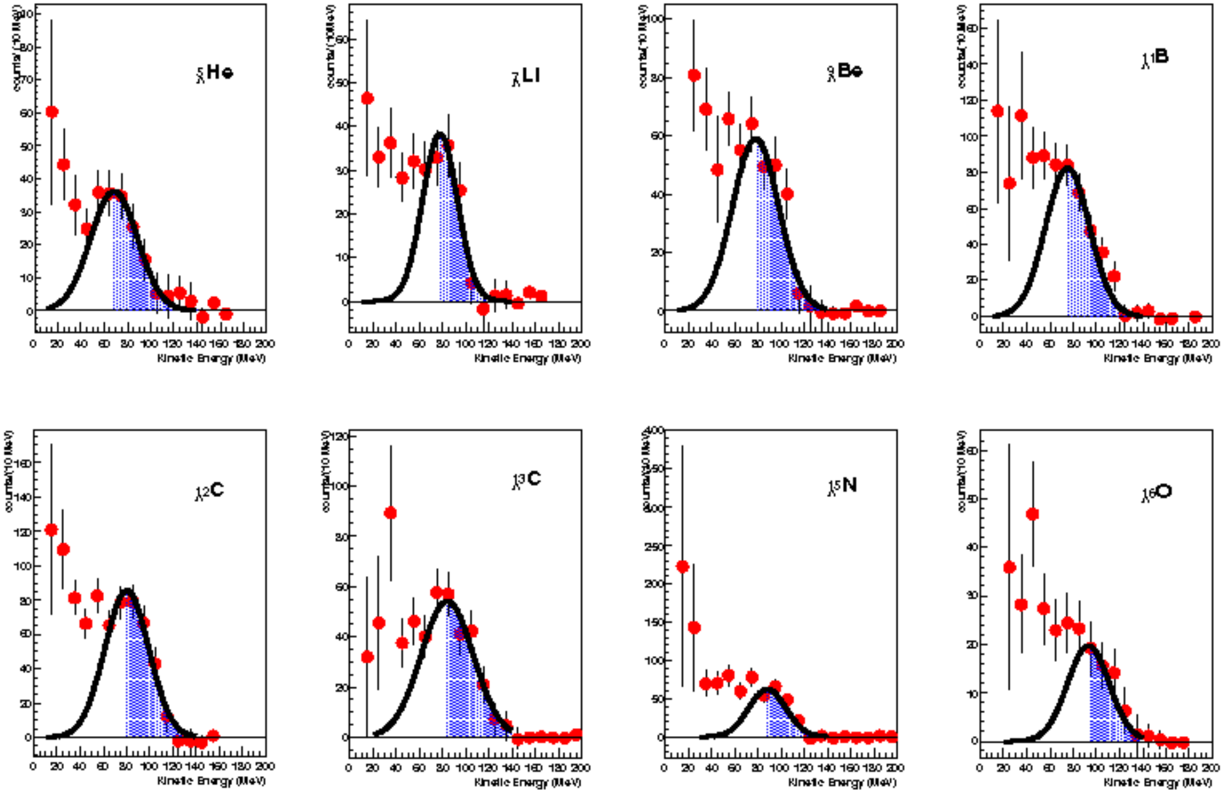
M. Agnello et al., NPA 804 (2008), 151

$^{5}_{\Lambda}$He, $^{7}_{\Lambda}$Li and $^{12}_{\Lambda}$C

2N induced NMWD: W.M. Alberico, A. De Pace, M. Ericson, A. Molinari, PLB 256, 134 (1991).



Garbarino PRC 69 (2004), 054603



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

$^{5}_{\Lambda}$He, $^{7}_{\Lambda}$Li $^{9}_{\Lambda}$Be, $^{11}_{\Lambda}$B, $^{12}_{\Lambda}$C, $^{13}_{\Lambda}$C, $^{15}_{\Lambda}$N, $^{16}_{\Lambda}$O

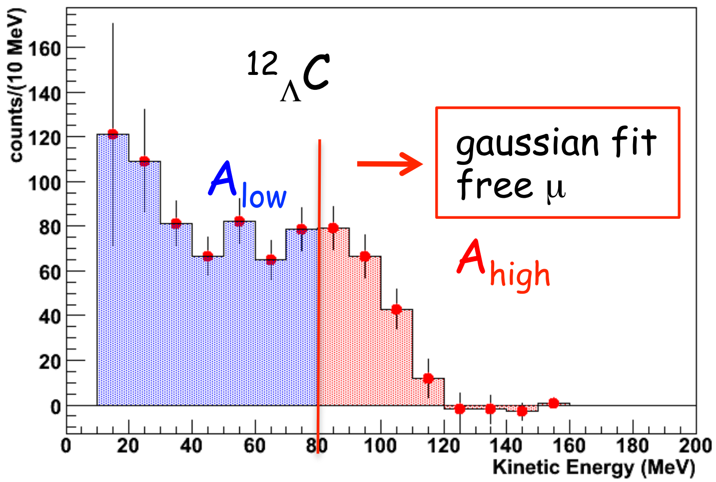
systematics: all *p*-shell

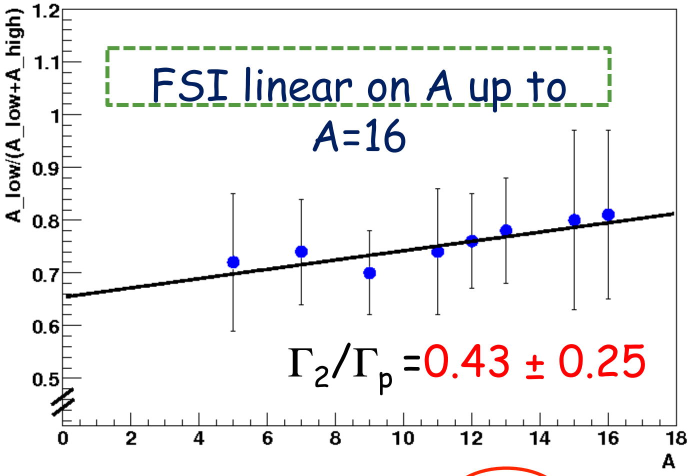
15 MeV threshold !

NMWD: Γ_{2N} from systematics

M.Agnello et al. PLB 685 (2010) 247 from (π^-, p) events

NMWD p





$$R = \frac{A_{low}}{A_{low} + A_{high}}$$

$$= \frac{0.5 + \Gamma_2/\Gamma_p}{1 + \Gamma_2/\Gamma_p} + b\,A$$

1N induced
2N induced
FSI

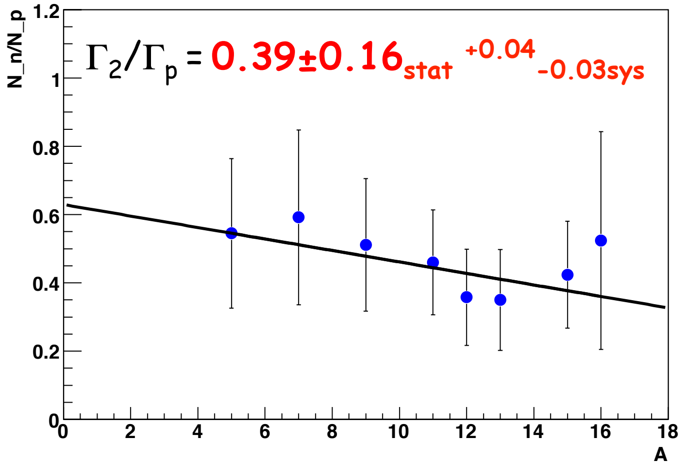
Γ not distinguishable in single spectra

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

Bhang et al., EPJ A33 (2007) 259

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) $^{4}_{\Lambda}He$

M.Agnello et al., PLB 701 (2011) 556 from (π^-, p, n) events



$$R(A) = \frac{N_n\ (\cos\theta \geq -0.8,\ E_p < \mu\text{-}20\ \text{MeV})}{N_p\ (E_p > \mu\ \text{p single spectra fit})} = \frac{\Gamma_2}{0.5\ \Gamma_p} + b\,A$$

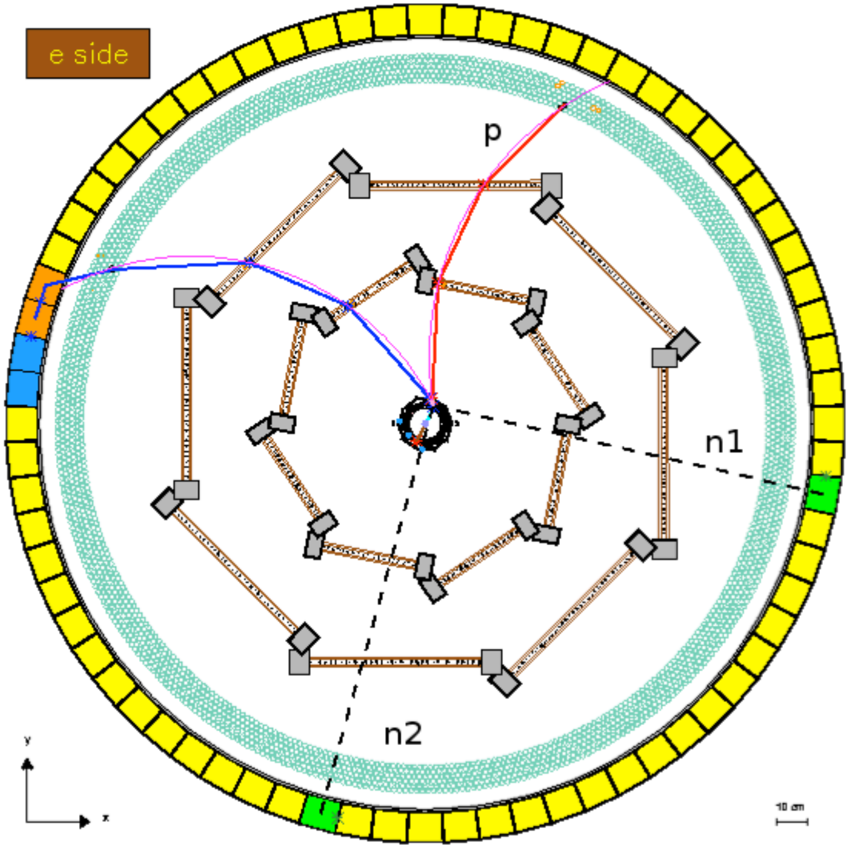
$$\Gamma_2/\Gamma_{NM} = 0.21\pm0.07_{stat}+0.03_{sys}\ -0.02_{sys}$$

NMWD: evidence for (π^-, p, n, n) events

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

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

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



p_{π^-} = 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 !!

Search for light n-rich hypernuclei physics motivations

Hypernuclei with a large neutron excess: R.H. Dalitz, R. Levi Setti., N. Cim. **30** (1963) 489, L. Majling, NP **A 585** (1995) 211c, Y. Akaishi et al., Frascati Physics Series **XVI** (1999) 59.

The Pauli principle does not apply to the Λ inside the nucleus + *extra binding energy (Λ "glue-like" role) ⇒ a larger number of neutrons can be bound with respect to ordinary nuclei.*

Neutron drip-line:
response of neutron halo on embedding of Λ hyperon, hypernuclear species with unstable nuclear core, extending the neutron drip line beyond the standard limits of n-rich nuclei

Hypernuclear physics:
ΛN interactions at low densities, the rôle of 3-body forces
nuclear core compression ($^{7}_{\Lambda}$Li vs ^{6}Li: H.Tamura et al., Phys.Rev. Lett. 84 (2000) 5963)

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

Search for light n-rich hypernuclei

- (K^-_{stop}, π^+)

$K^- + p \rightarrow \Lambda + \pi^0$ $\pi^0 + p \rightarrow n + \pi^+$ (2-step) S-EX + C-EX
$K^- + p \rightarrow \overline{K^0} + n$ $\overline{K^0} + p \rightarrow \Lambda + \pi^+$ (2-step) C-EX + S-EX
$K^- + p \rightarrow \Sigma^- + \pi^+$ $\Sigma^- + p \leftrightarrow n + \Lambda$ (1-step) S-EX

Inclusive π+ spectrum

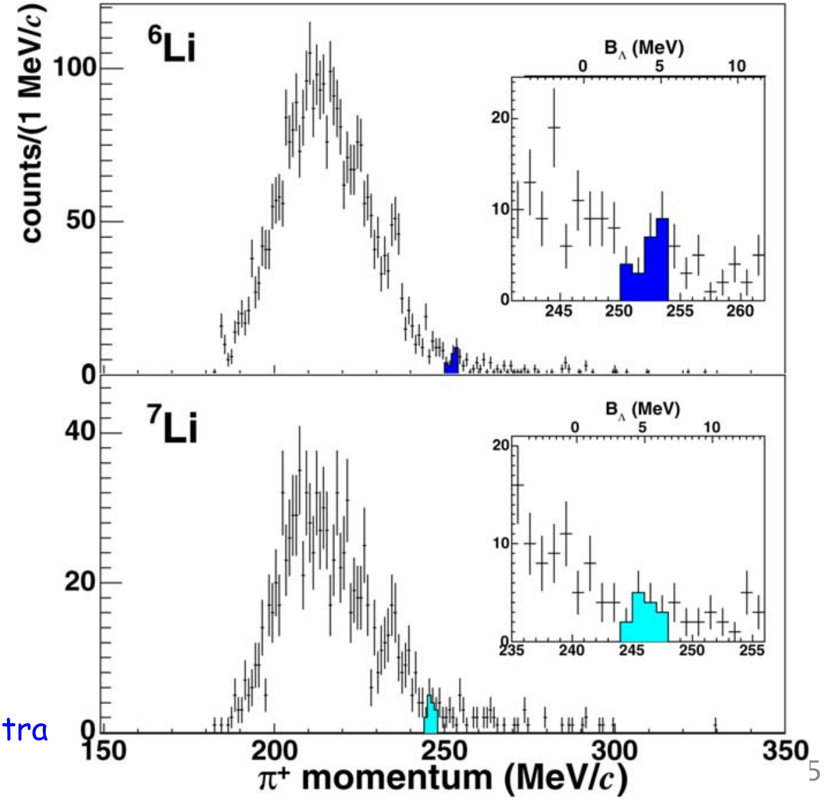
K.Kubota et al, NPA 602 (1996) 327.
${}^{9}_{\Lambda}He$ (${}^{9}Be$) U.L.=2.3 $10^{-4}/K^-_{stop}$; ${}^{12}_{\Lambda}Be$(${}^{12}C$) U.L.=6.1 $10^{-5}/K^-_{stop}$;
${}^{16}_{\Lambda}C$(${}^{16}O$) U.L.=6.2 $10^{-5}/K^-_{stop}$ bound core nuclei

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) $10^{-5}/K^-_{s}$;
${}^{12}_{\Lambda}Be$(${}^{12}C$) U.L.= (2.0 ± 0.4) $10^{-5}/K^-_{stop}$
U.L.@90% C.L.

background:

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

$\Sigma^+ \longrightarrow n\, \pi^+$ (~100-320 MeV/c)



background subtracted spectra
not acceptance corrected

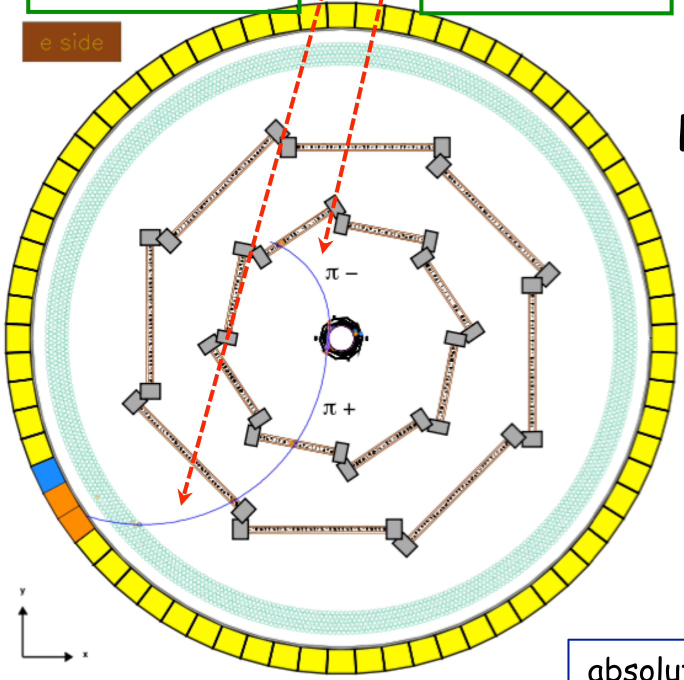
Coincidence measurement

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

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

D-CEX
~252 MeV/c

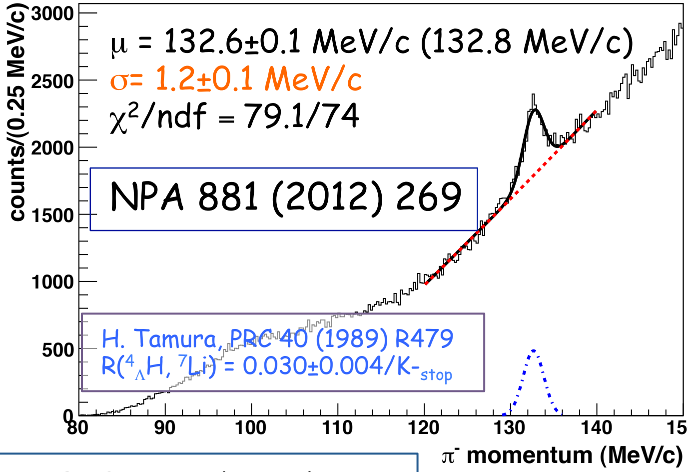
MWD
~134 MeV/c



B = 1T

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

π^-: ${}^4_\Lambda H$ hyperfragment decay at rest

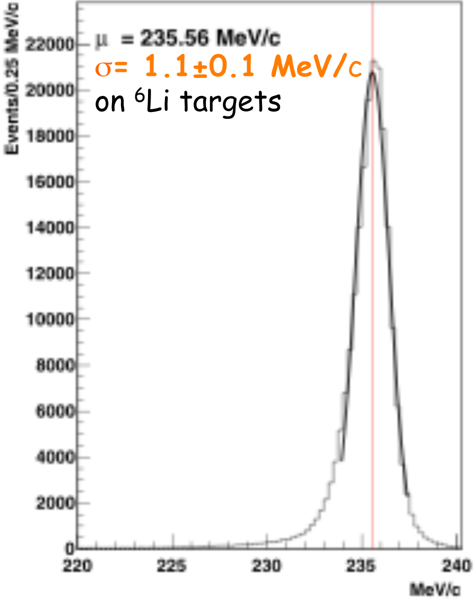


μ = 132.6±0.1 MeV/c (132.8 MeV/c)
σ= 1.2±0.1 MeV/c
χ^2/ndf = 79.1/74

NPA 881 (2012) 269

H. Tamura, PRC 40 (1989) R479
R(${}^4_\Lambda H$, ${}^7Li$) = 0.030±0.004/K^-_{stop}

$K_{\mu 2}$ decay: PLB 698 (2011) 219



μ = 235.56 MeV/c
σ= 1.1±0.1 MeV/c
on ${}^6Li$ targets

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
σT_{sys} = 0.17 MeV

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

Coincidence measurement

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

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

$(\tau({}^6He)\sim 801\ ms)$

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

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

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

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

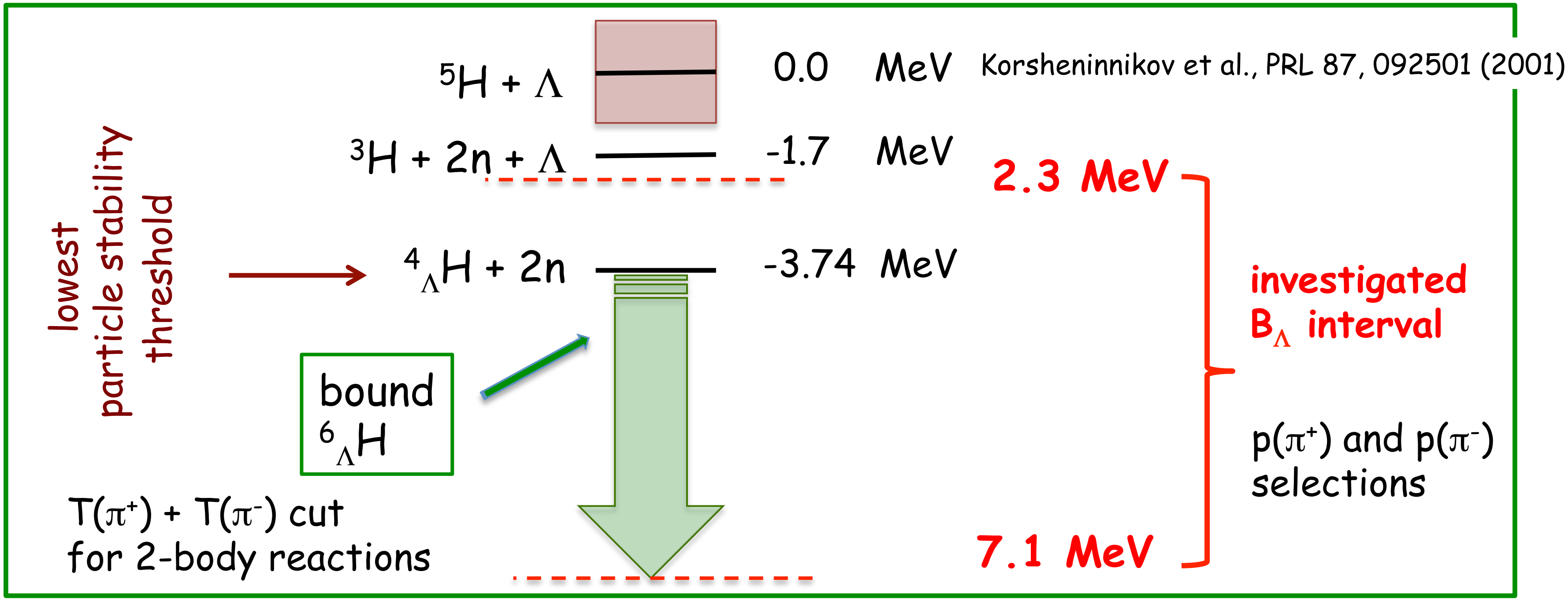
$T(\pi^+) + T(\pi^-) =$

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

$=$ **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

cut on $p(\pi^+)$ and $p(\pi^-)$



$^5H + \Lambda$ 0.0 MeV Korsheninnikov et al., PRL 87, 092501 (2001)

$^3H + 2n + \Lambda$ -1.7 MeV

$^4_\Lambda H + 2n$ -3.74 MeV

lowest particle stability threshold

bound ${}^6_\Lambda H$

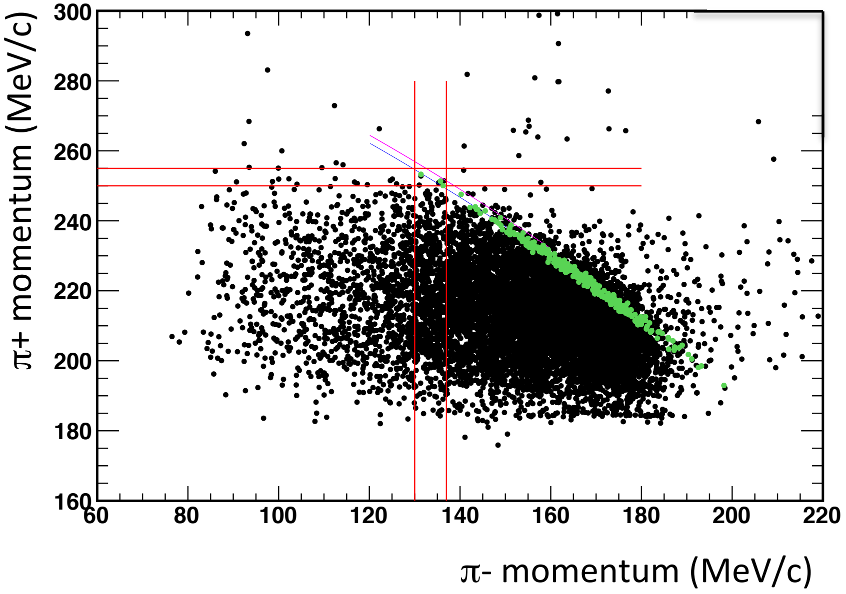
$T(\pi^+) + T(\pi^-)$ cut for 2-body reactions

2.3 MeV

7.1 MeV

investigated B_Λ interval

$p(\pi^+)$ and $p(\pi^-)$ selections

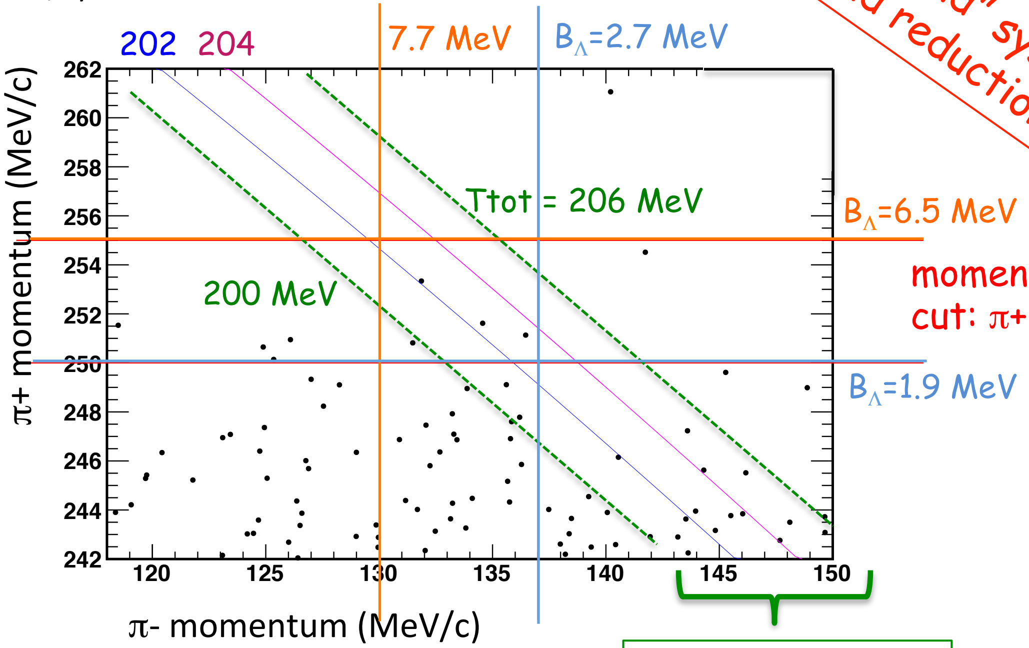


Finuda Coll. and A. Gal, NPA 881 (2012) 269.

"completely bound" system
Σ+ background reduction

momentum cut: π-

momentum cut: π+



$T(\pi^+)+T(\pi^-)$ = 202÷204 MeV

250÷255 MeV/c (σ_p= 1.1 MeV/c)

130÷137 MeV/c (σ_p= 1.2 MeV/c)

B$_\Lambda$=7.1 MeV

B$_\Lambda$=2.3 MeV

Mprod = Mdecay
cut: Ttot

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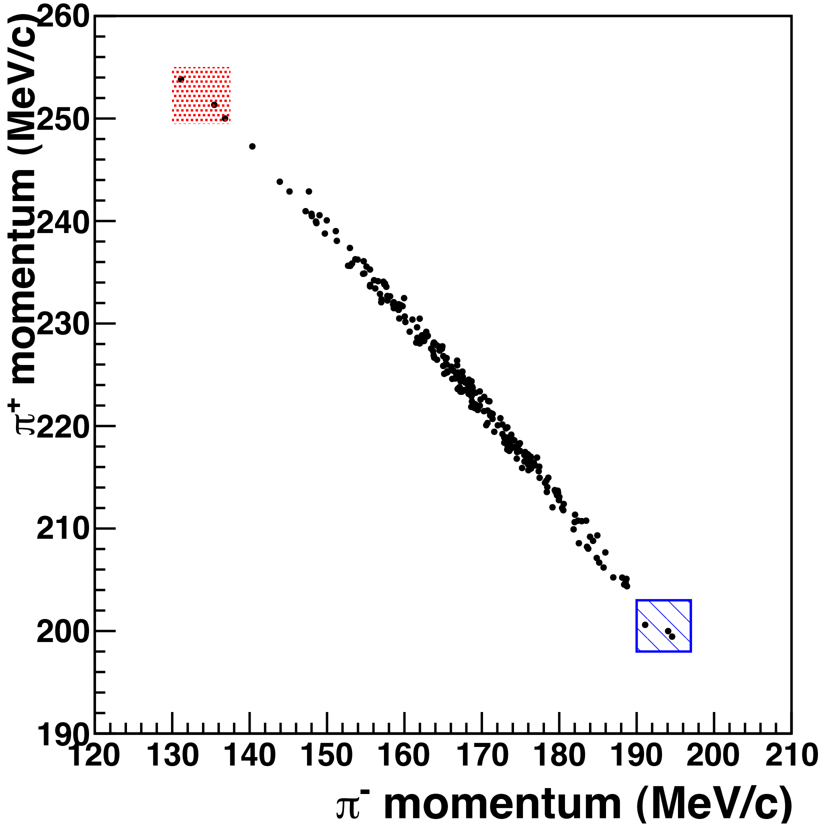
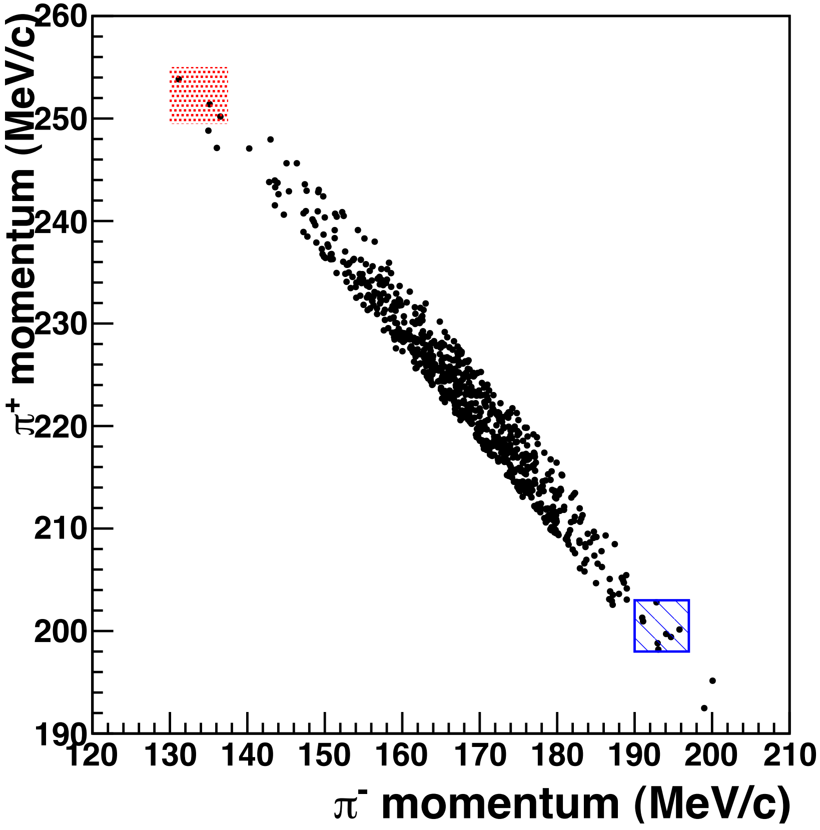
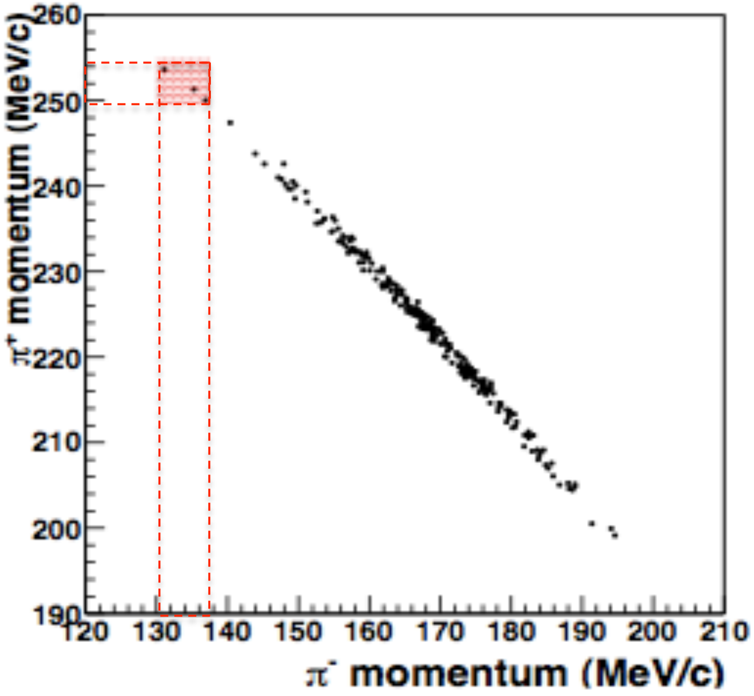
$T(\pi^+)+T(\pi^-)$ cut : systematics

$T(\pi^+)+T(\pi^-)$ = 202÷204 MeV



$T(\pi^+)+T(\pi^-)$ = 200÷206 MeV



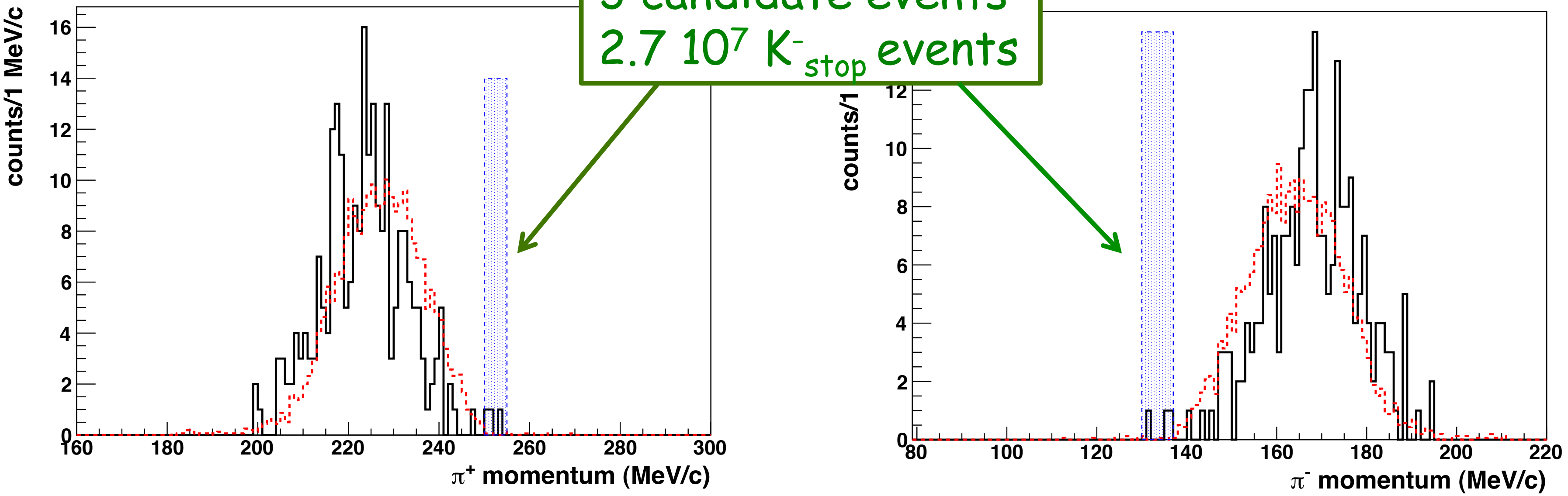


$250 \div 255$ MeV/c (σ_p= 1.1 MeV/c)

$130 \div 137$ 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=$2.3 \div 7.1$ MeV



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

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

Background sources:

- fake coincidences: $T(\pi+)+T(\pi-)$(202÷204 MeV) & $\pi+$(249÷255 MeV/c) & π^-(130÷138 MeV/c) 0.27±0.27 ev.

- $K^-_{stop} + {}^6Li \rightarrow \Sigma^+ + \pi^- + {}^4He + n$ (end point ~190 MeV/c)
  $\hookrightarrow n + \pi^+$ (end point ~282 MeV/c) 0.16±0.07 ev.

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

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

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

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

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

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

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

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 (S=3.9)

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

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

mass mean value = 5801.4±1.1

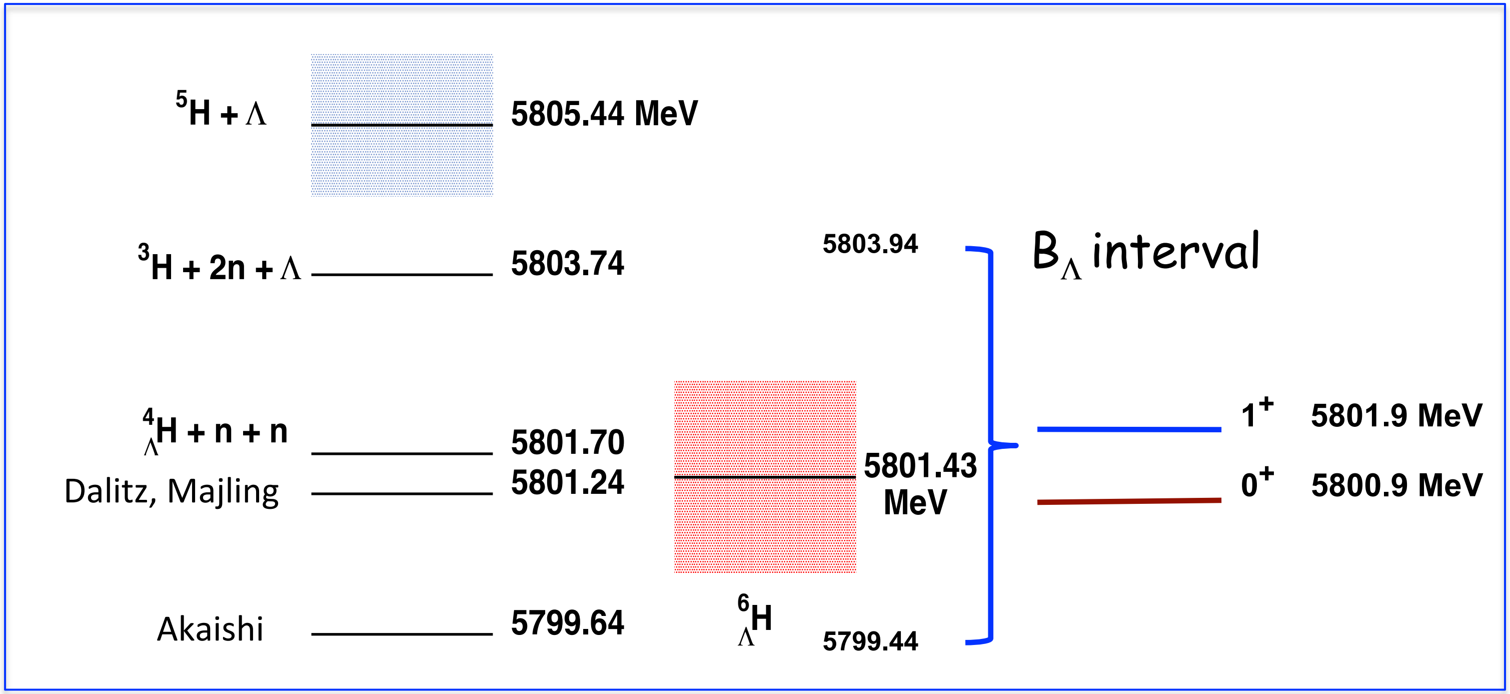
B_Λ = 4.0±1.1 MeV (^{5}He + Λ)

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

Dalitz et al., N. Cim. 30 (1963) 489 (B_Λ ~ 4.2 MeV)

L. Majling, NPA 585 (1995) 211c

Y. Akaishi et al., AIP Conf. Proc. 1011 (2008) 277
"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



formation – decay = 0.98±0.74 MeV
→ excitation spectrum of $^6_\Lambda$H

formation – decay ΔM

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

spin flip is forbidden in production at rest:

E. Hiyama et al.,
NPA 908 (2013) 29.

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

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

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

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

A.Gal, D.J.Millener
PLB 725 (2013) 445.
upper bound: 3.83 MeV

→ $B_{\Lambda}({}^{6}_{\Lambda}H) = (4.5 \pm 1.2)$ 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 (PLB 729 (2014) 39) no signal of ${}^{6}_{\Lambda}H$ formation in (π-, K+)

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

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

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

Majling, NPA 585 (1995) 211c: B_{Λ} = 8.5 MeV

Selections:

- $T(\pi^{+}) + T(\pi^{-})$: 194.5÷197.5 MeV (195.8÷195.7 MeV with B_{Λ}= 0÷10 MeV)
- 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

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

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

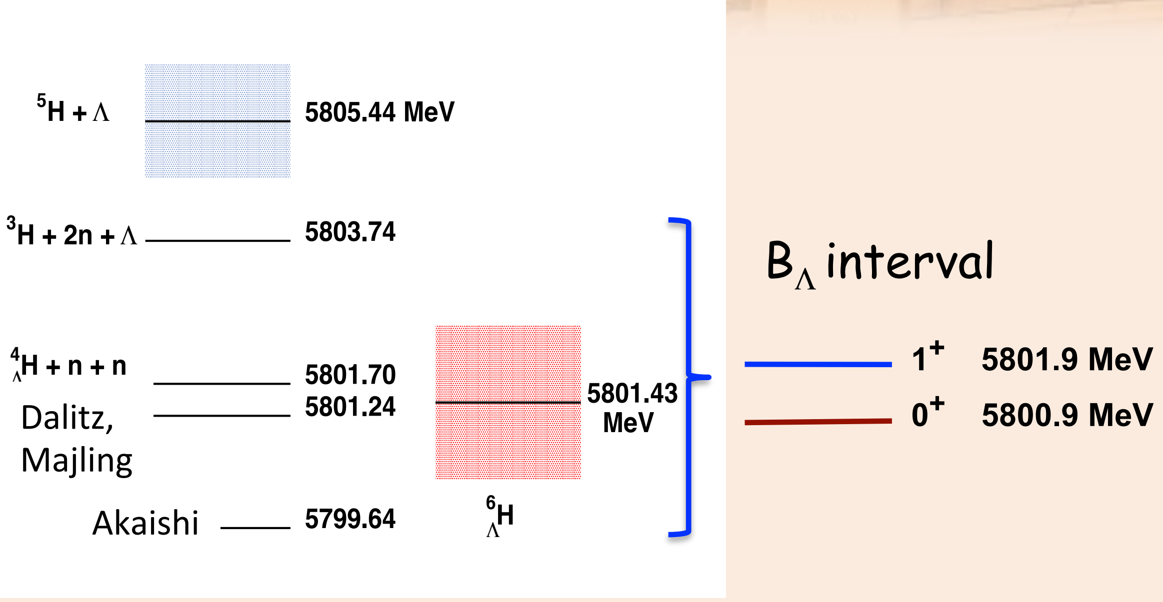
$$\Gamma(^{9}_{\Lambda}He_{gs} \rightarrow {}^{9}Li_{gs} + \pi^{-}) = 0.261\ \Gamma_{\Lambda}$$

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}



$^{5}H + \Lambda$ 5805.44 MeV

$^{3}H + 2n + \Lambda$ 5803.74

$^{4}_{\Lambda}H + n + n$ 5801.70

Dalitz, Majling 5801.24

Akaishi 5799.64

5801.43 MeV

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

B_{Λ} interval

1^{+} 5801.9 MeV

0^{+} 5800.9 MeV

Thank you for your attention!

6th Asia-Pacific Conference on
Few Body Problems in Physics (APFB 2014)

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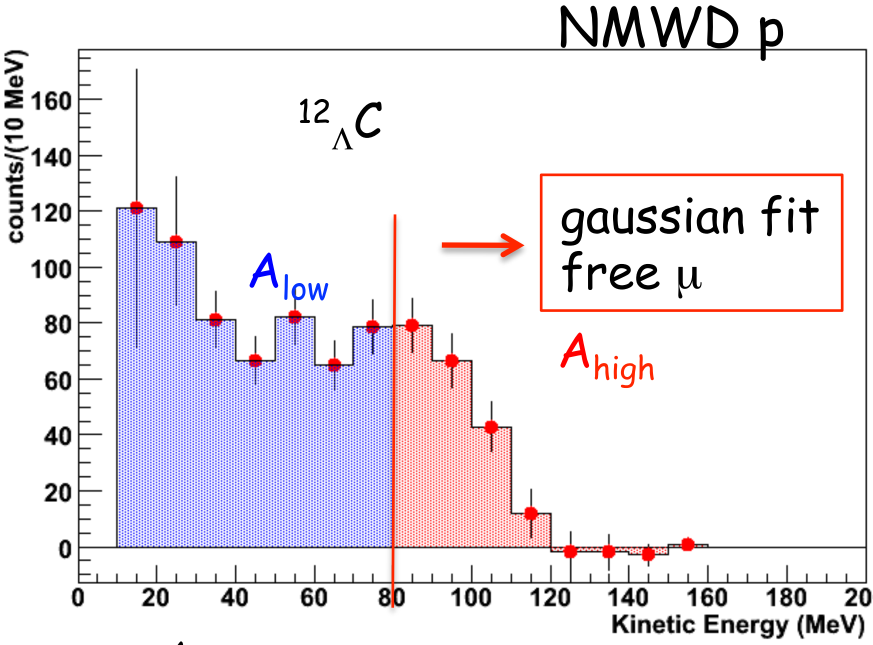
ANPhA Asian Nuclear Physics Association

NMWD: Γ_{2N} from (π^-, p) events

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



gaussian fit free μ

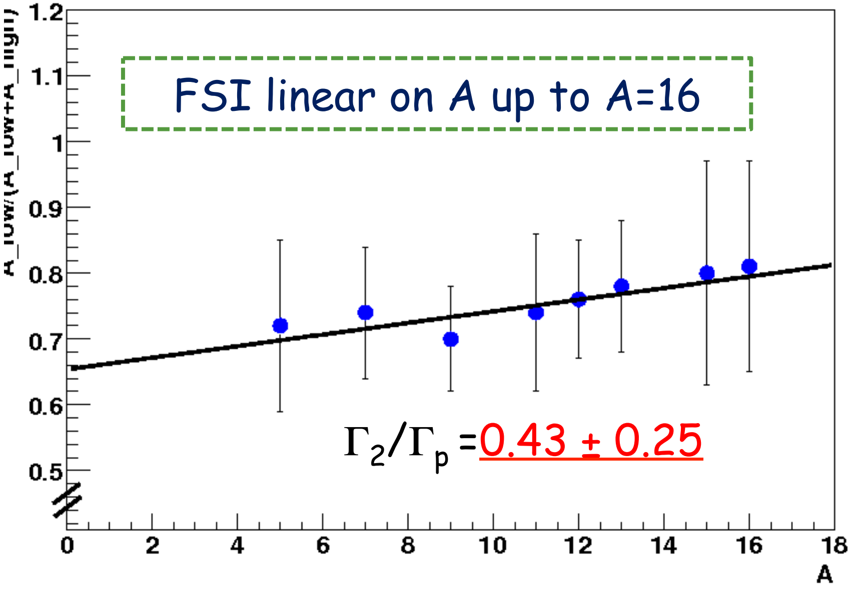
$$R = \frac{A_{low}}{A_{low} + A_{high}} = \frac{0.5\,N(\Lambda p \rightarrow np) + N(\Lambda np \rightarrow nnp) + N_p^{FSI}}{N(\Lambda p \rightarrow np) + N(\Lambda np \rightarrow nnp) + N_p^{FSI\,'}}$$

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

$\Gamma_{2N}/\Gamma_{NMWD,}$ Γ_2/Γ_1 & Γ_n/Γ_p independent on A

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

A_{high}: spectrum area above μ
1N + FSI
2N(>70 MeV) ~ 5% $2N_{tot}$



FSI linear on A up to A=16

Γ_2/Γ_p =0.43 ± 0.25

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

Bhang et al., EPJ A33 (2007) 259

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) $^4{}_{\Lambda}He$

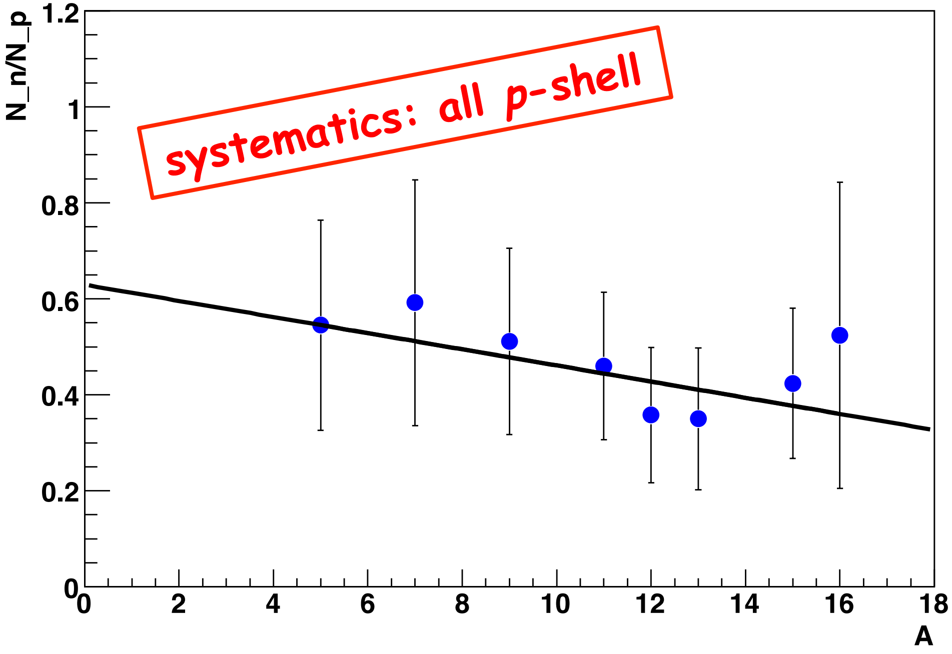
NMWD: Γ_{2N} from (π^-, p, n) events

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

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

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

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
- reduced error

${}^{9}_{\Lambda}He/K^{-}_{stop}$ 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 $10^{-4}/K^{-}_{stop}$

Renewed theoretical interest

- **E. Hiyama** et al., NPA 908 (2013) 29.

tnnΛ four-body cluster model of ${}^{6}_{\Lambda}$H: particle unstable, $\Lambda-\Sigma$ mixing not explicitly included, complex pole position of ^{5}H

- **A.Gal, D.J.Millener**, PLB 725 (2013) 445.
- Shell model calculations for p-shell hypernuclei, D.J. Millener, NPA 881 (2012) 298.
- ΛN effective interactions from γ-ray p-shell data & theoretically motivated $\Lambda-\Sigma$ terms: n-rich hypernuclei in p-shell and beyond (${}^{9}_{\Lambda}$He, ${}^{10}_{\Lambda}$Li, ${}^{12}_{\Lambda}$Be, ${}^{14}_{\Lambda}$B, ${}^{49}_{\Lambda}$Ca, ${}^{209}_{\Lambda}$Pb)
- beyond mean-field $\Delta B^{g.s.}_{\Lambda}$ SM contributions to normal parity g.s. of n-rich hypernuclei
- modest effect from $\Lambda-\Sigma$ coupling
- beyond mean-field $\Delta B^{g.s.}_{\Lambda}$ generated by ΛN spin dependence terms

${}^{6}_{\Lambda}$H: spin-flip production forbidden; is ($1^{+}_{exc.}$) particle stable? is ($0^{+}_{g.s.}$) particle stable?

- upper bound: $B_{\Lambda}({}^{6}_{\Lambda}H) \sim B_{\Lambda}({}^{4}_{\Lambda}H)+0.8[B_{\Lambda}({}^{7}_{\Lambda}He)-B_{\Lambda}({}^{5}_{\Lambda}He)] =$ 3.83 MeV (${}^{4}_{\Lambda}$H + 2n: -3.74 MeV);
- very weakly bound ${}^{6}_{\Lambda}$H (0^{+}g.s.) and particle-unstable ${}^{6}_{\Lambda}$H (1^{+} exc.) that decays by emitting a low-energy neutron pair: ${}^{6}_{\Lambda}$H(1^{+} exc.) → ${}^{4}_{\Lambda}$H(0^{+} g.s.) + 2n.
- strong decay suppressed kinematically and dynamically:
  - kinematically: since s-wave emission requires a ${}^{3}S_{1}$ dineutron configuration which is Pauli-forbidden,
  - the Pauli allowed p-wave emission, kinematically suppressed at low energy, requires that both ${}^{6}_{\Lambda}$H constituents, ${}^{4}_{\Lambda}$H and 2n, flip their Pauli spin which is disfavored dynamically.

This leaves open the possibility that M1 γ emission to ${}^{6}_{\Lambda}$H (0^{+} g.s.) provides a competitive decay mode of the 1^{+} exc. level.

$$\left.\begin{aligned} &K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda H + \pi^+ \\ &{}^6_\Lambda H \rightarrow {}^6He + \pi^- \end{aligned}\right\} \text{reactions at rest}$$

stable ${}^6_\Lambda H$

$T(\pi^+) + T(\pi^-) =$

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

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

$K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda H(1^+) + \pi^+$

${}^6_\Lambda H(1^+) \rightarrow {}^4_\Lambda H_{g.s.} + n + n$

${}^4_\Lambda H_{g.s.} \rightarrow {}^4He_{g.s.} + \pi^-$

reactions at rest

$S({}^6Li) = 1$

resonant ${}^6_\Lambda H$
above ${}^4_\Lambda H_{g.s}$+n+n
threshold

$T(\pi^+) + T(\pi^-) = [T(\pi^+) + T(\pi^-)]({}^6_\Lambda H)$ - 203 MeV

$[M({}^6_\Lambda H(1^+)) - M({}^4_\Lambda H_{g.s.}) - 2M(n)]$ - ${}^6_\Lambda H(1^+)$ available decay energy: (1±1) MeV

$[B({}^6He) - B({}^4He)]$ + (29.3 – 28.3) MeV

$[T({}^6He) - T({}^4He)]$ << 1 MeV, neglected

= **201 MeV** (stronger Σ+ background)

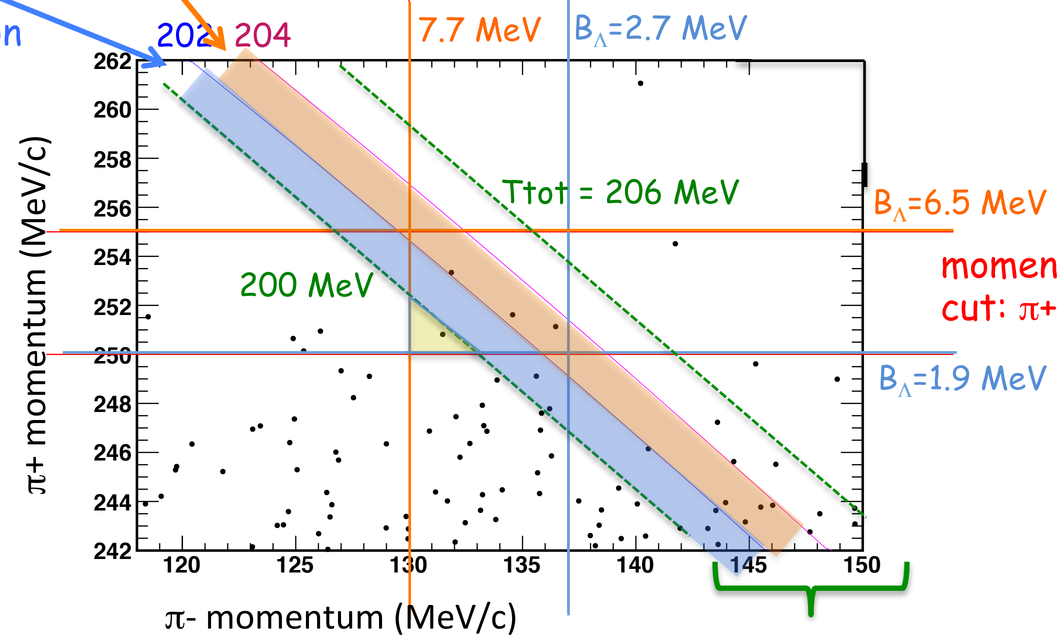
FINUDA's strong **points in favor** of a particle stable $^{6}_{\Lambda}H$ 0^{+} g.s. and of a M1 γ emission $^{6}_{\Lambda}H(1^{+}\,exc.) \to {}^{6}_{\Lambda}H(0^{+}\,g.s.)$:

- observation of a weak-decay π^{-} with momentum distinctly different from 132.8 MeV/c ($^{4}_{\Lambda}H \to {}^{4}He_{g.s.} + \pi^{-}$)
- kinematic cut on Ttot (Mprod=Mdecay)

stable $^{6}_{\Lambda}H$
(or "metastable")

momentum
cut: π-

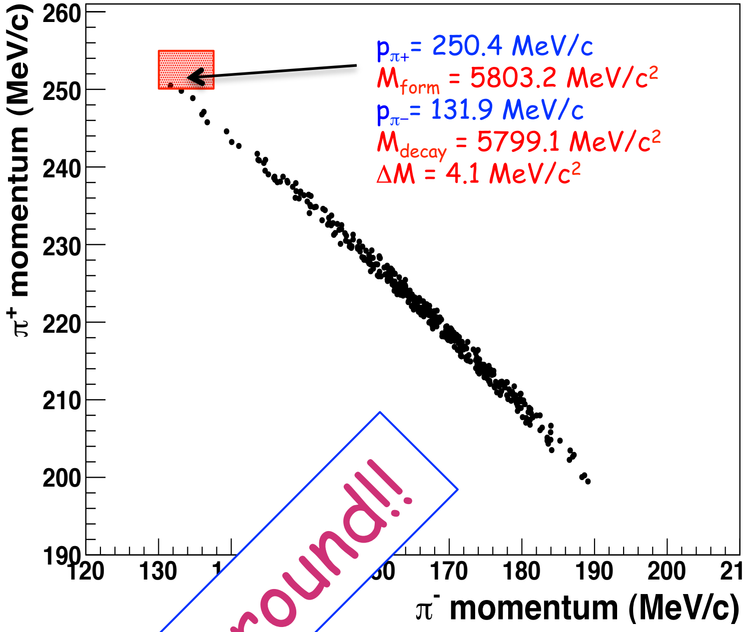
resonant $^{6}_{\Lambda}H \to {}^{4}_{\Lambda}H + 2n$
2 MeV $T(\pi^{+}) + T(\pi^{-})$ selection



momentum
cut: π+

Mprod = Mdecay
cut: Ttot

stable or resonant
$^{6}_{\Lambda}H$?



$p_{\pi+}$= 250.4 MeV/c
M_{form} = 5803.2 MeV/c²
$p_{\pi-}$= 131.9 MeV/c
M_{decay} = 5799.1 MeV/c²
ΔM = 4.1 MeV/c²

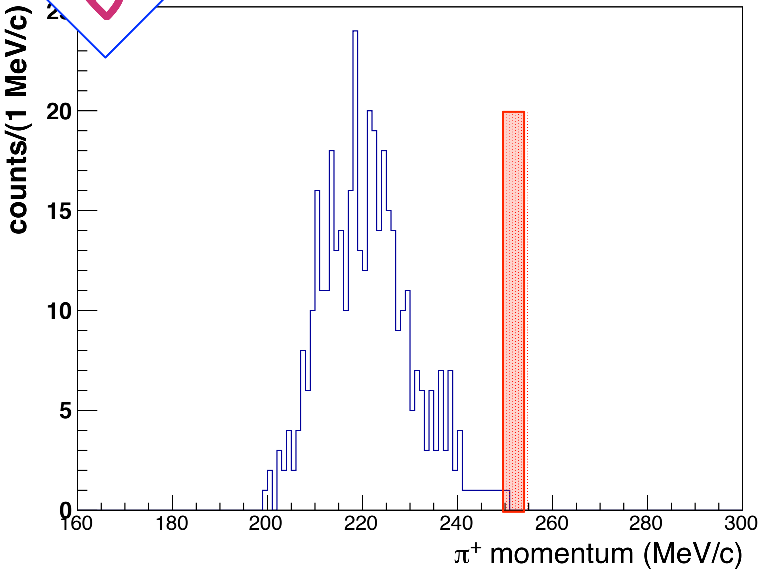
selection:
$T(\pi^+)+T(\pi^-)$ = 199÷201 MeV

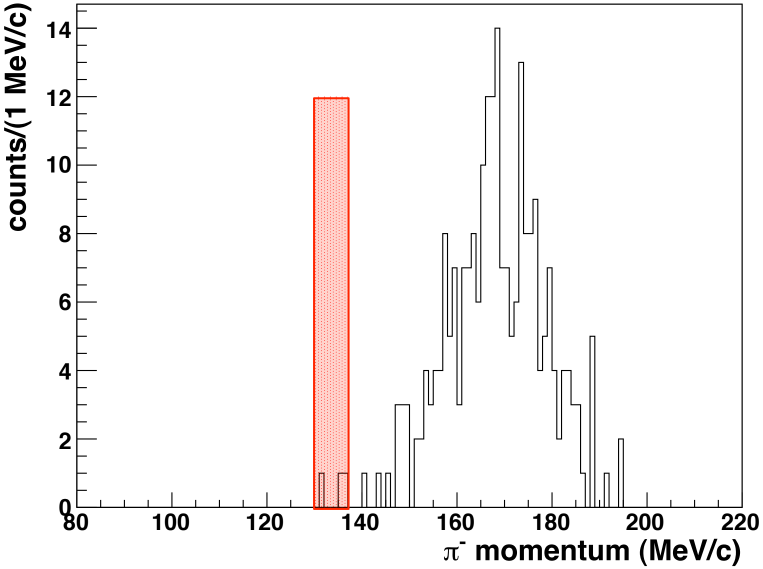
250÷255 MeV/c (σ_p= 1.1 MeV/c)

130÷137 MeV/c (σ_p= 1.2 MeV/c)

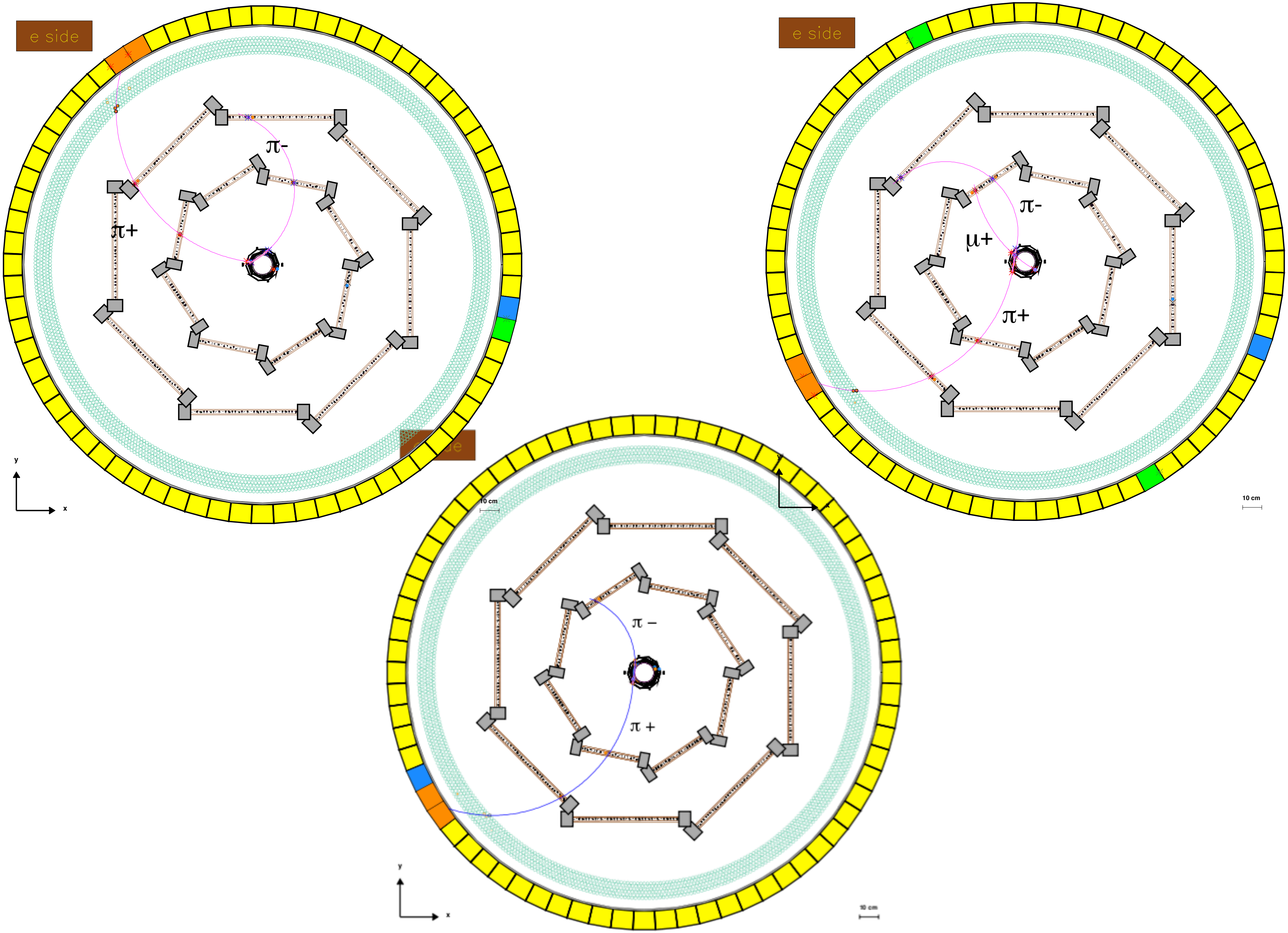
red bars: p $_{\pi+/\pi-}$ selection regions including ${}^6_\Lambda$H lowest particle stability threshold ${}^4_\Lambda$H+2n ($p_{\pi+}$=251.9 MeV/c, $p_{\pi-}$=135.6 MeV/c) B_Λ=2.3÷7.1 MeV

Background!!

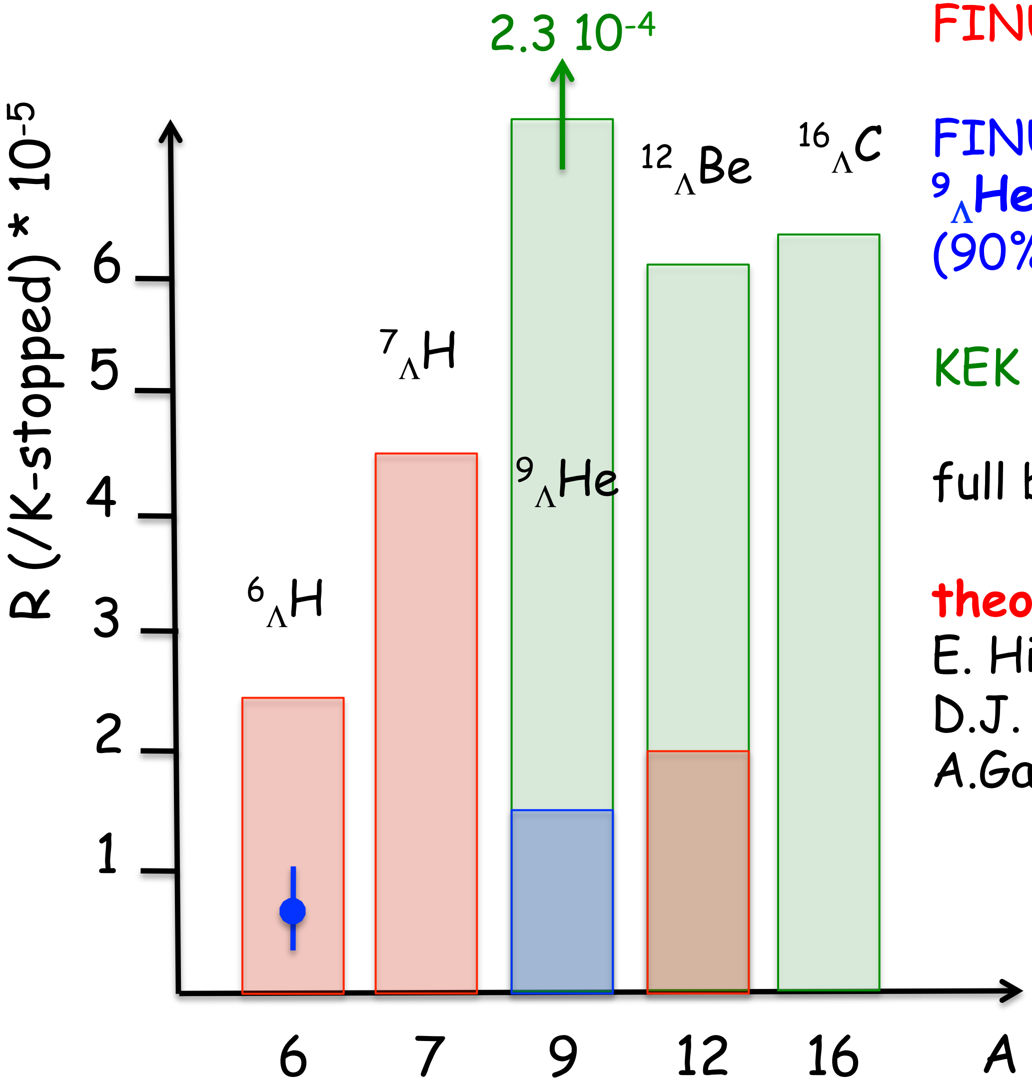




kinematics compatibility: events scan



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

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

- **Background sources**

$T(\pi+)+T(\pi-)$(202÷204 MeV) & $p(\pi+)$(250÷255 MeV/c) & $p(\pi^{-})$(130÷137 MeV/c):

- fake coincidences 0.27±0.27 ev.

Main physical sources

- $K^{-}_{stop} + {}^{6}Li \rightarrow \Sigma^{+} + \pi^{-} + {}^{4}He + n$ (end point ~190 MeV/c)
  $\hookrightarrow n + \pi^{+}$ (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)
  $\hookrightarrow {}^{4}He + \pi^{-}$ ($p(\pi^{-})$ = 133 MeV/c)
  negligible

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)

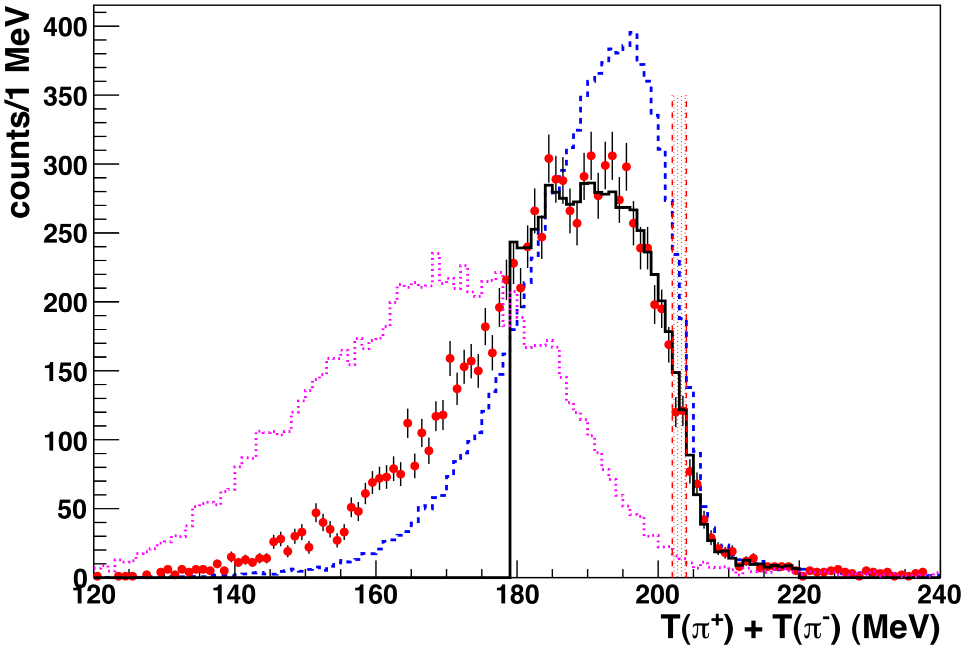
- $K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda He + \pi^0$ ($p(\pi^0) \sim 280$ MeV/c)
  $\hookrightarrow {}^6Li + \pi^-$ ($p(\pi^-) \sim 108$ MeV/c)
  $\pi^0 + {}^6Li \rightarrow {}^6He + \pi^+$ ($p(\pi^+) \sim 280$ MeV/c forw. dir.)

Background sources: Σ+ production and decay

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

$\hookrightarrow n + \pi^+$

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



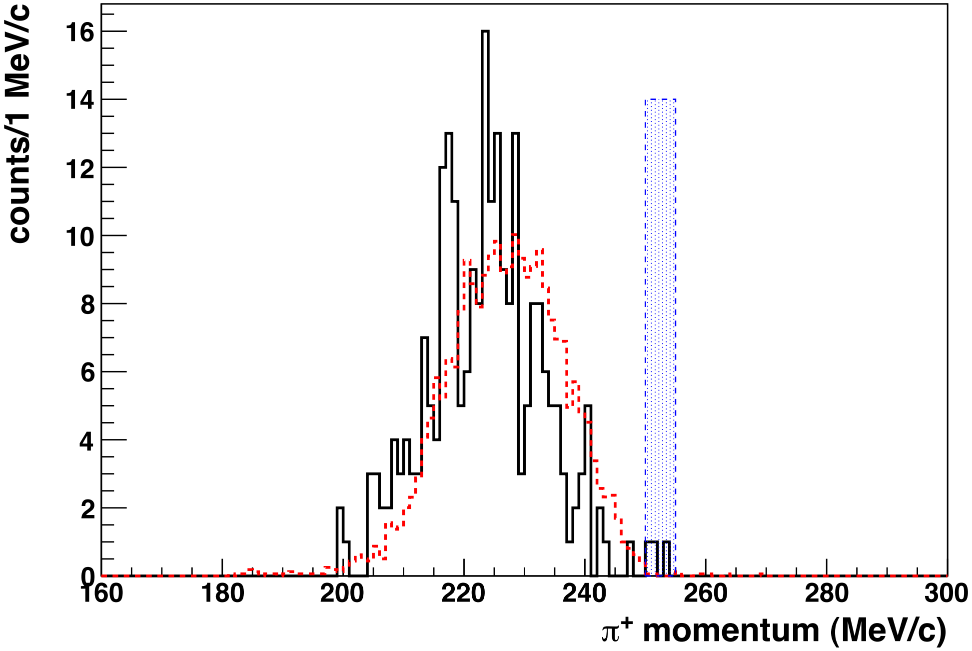
Finuda Coll. and A. Gal, NPA 881 (2012) 269.

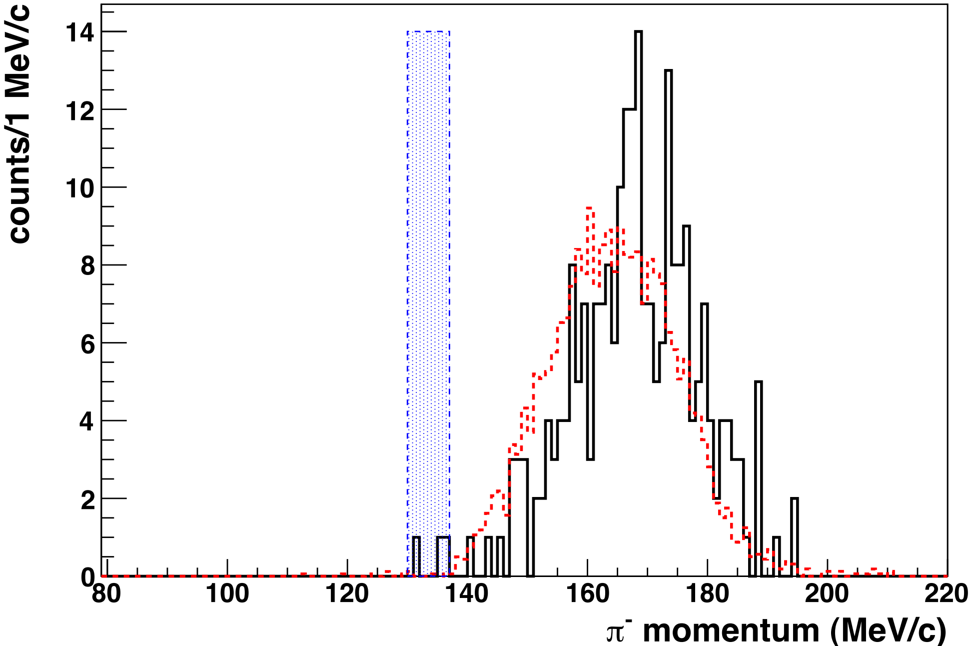
130–220 MeV

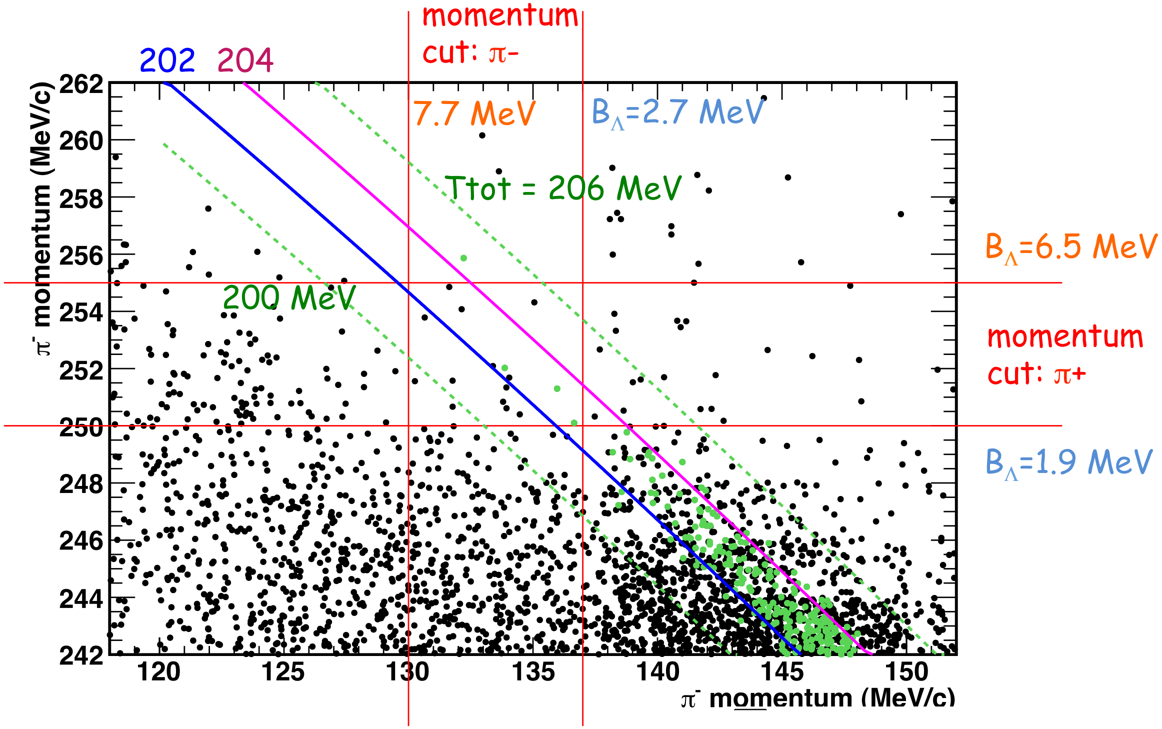
χ^2/ndf increases of ~ 3.8

fractions change <0.025 (1.3–1.5σ)

1-Dim π+/π- spectra







- pure quasi free approach

~ 2.2 10^7 K^-_{stop} MC events

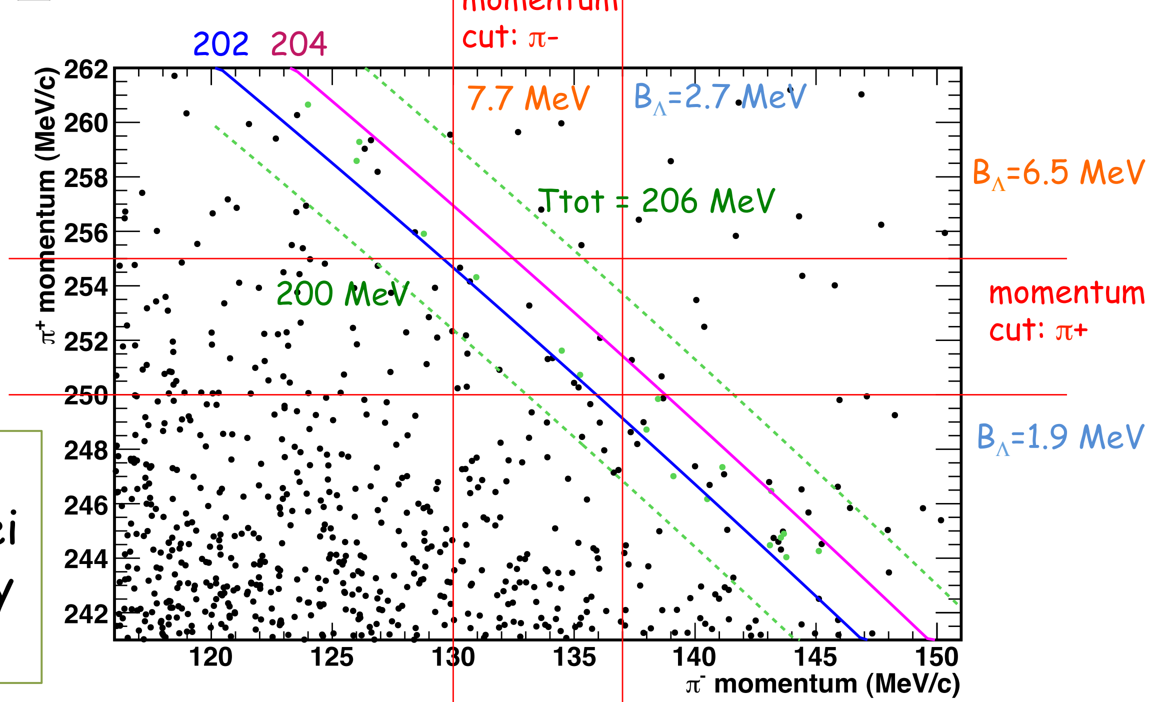
3 ev. → 0.15 ev.

- pure 4-body interaction

~ 2.7 10^7 K^-_{stop} MC events

5 ev. → 0.20 ev.

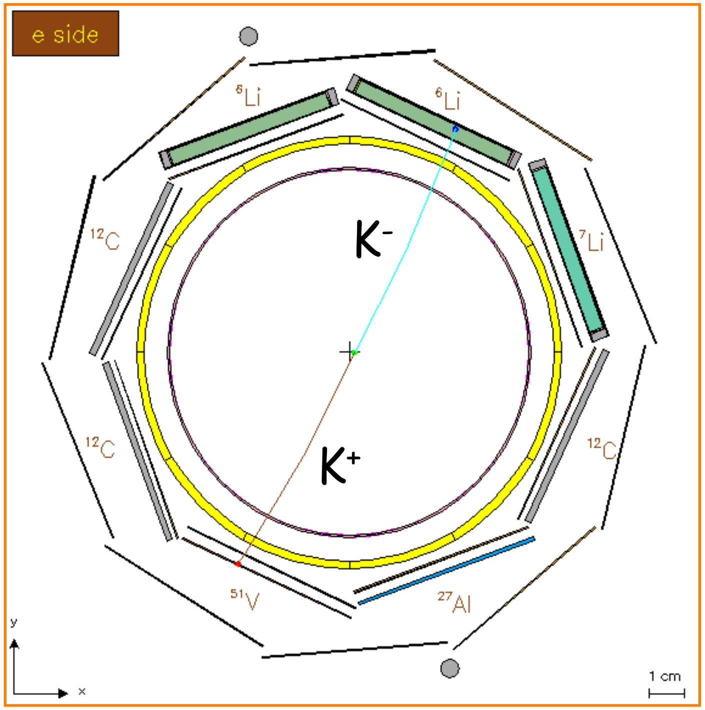
- data: ~ 2.7 10^7 K^-_{stop} events
- BR(K^-_{stop} + p → Σ^+ + π-) on nuclei
- Σ^+ + n → Λ + p conv. probability
- BR(Σ^+ → n + π+)



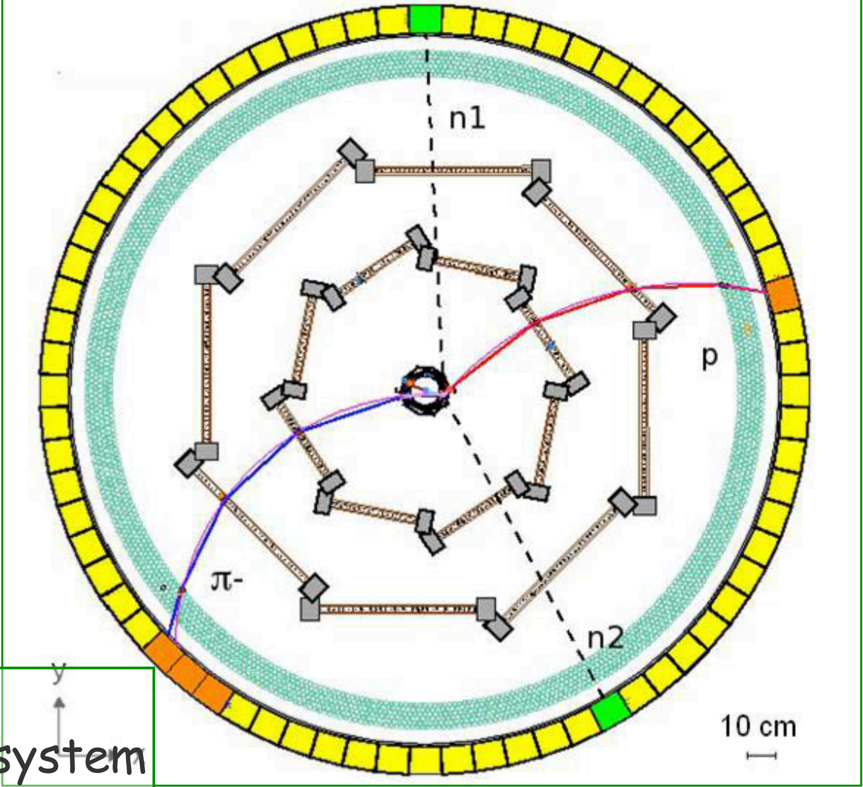
Interaction region

Tracking/outer regions

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



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

… coincidence method **limits**

target	hypernucleus	2-b MWD daughter nucleus	lifetime	MWD 'model'	MWD 'model' BR(π^-) **R*BR(π^-)**
${}^{6}Li$	${}^{6}_{\Lambda}H$	${}^{6}He$	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

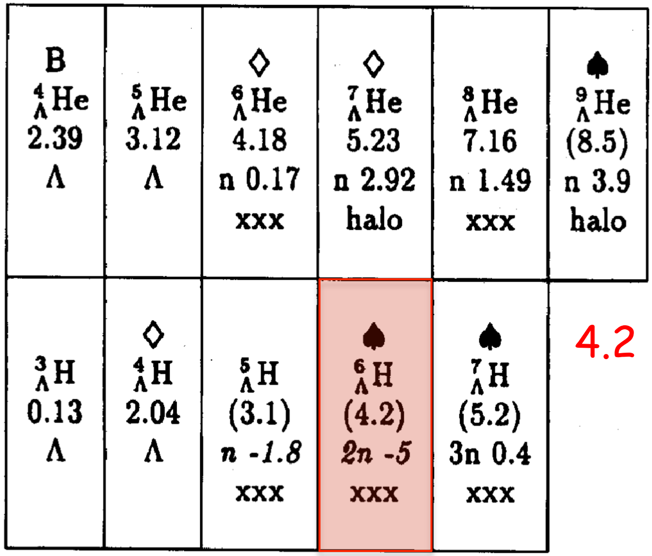
2-body processes production&decay

decreasing MWD BR

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

(N+Y)/Z=5

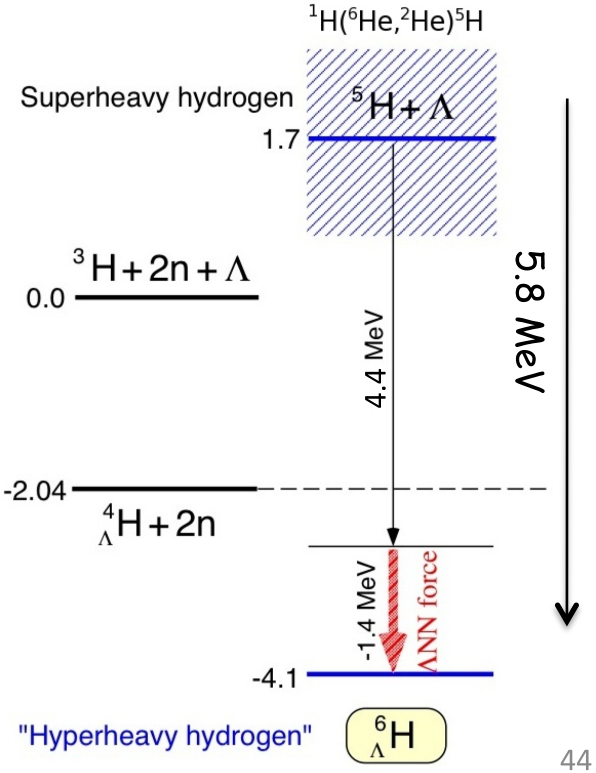
Dalitz et al., N. Cim. 30 (1963) 489 (binding energy 4.2 MeV)



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

FINUDA: the Collaboration

Collaborating institutes

University
of Victoria

Seoul
National University

JINR
Dubna

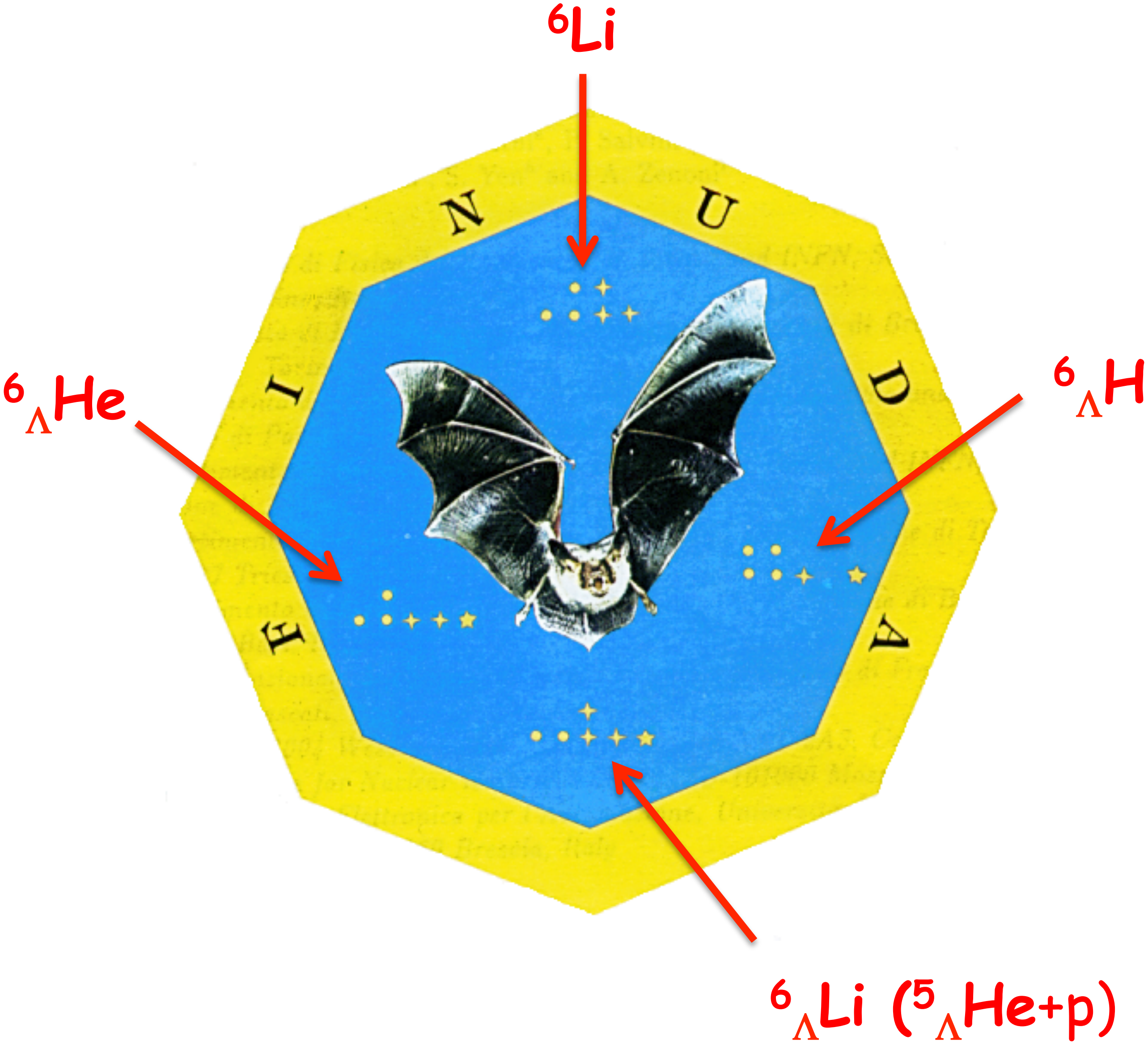
Bari University & INFN Bari
Brescia University & INFN Pavia
Pavia University & INFN Pavia
Torino Polytechnic & INFN Torino
Torino University & INFN Torino
Trieste University & INFN Trieste
L.N.F. / INFN Frascati

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)



${}^{6}\mathrm{Li}$

${}^{6}_{\Lambda}\mathrm{He}$

${}^{6}_{\Lambda}\mathrm{H}$

${}^{6}_{\Lambda}\mathrm{Li}$ (${}^{5}_{\Lambda}\mathrm{He}$+p)