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Neutron rich Lambda hypernuclei study with the FINUDA experiment

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Outline

- Physics motivations
- The FINUDA experiment
- Neutron rich detection and analysis
  - ${}^{6}_{\Lambda}H$
  - ${}^{9}_{\Lambda}He$

Physics motivations

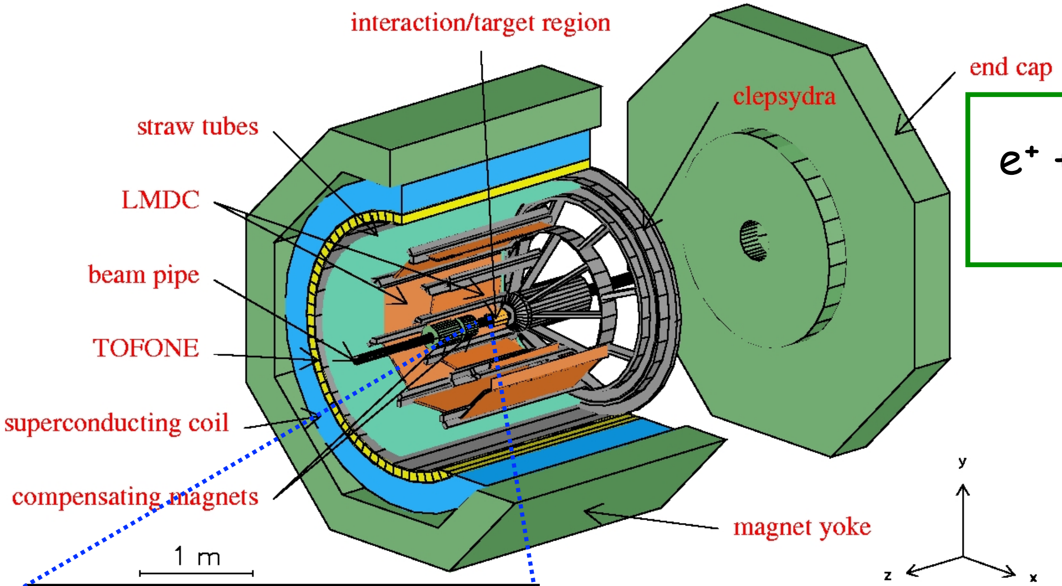
- Hypernuclei with a large neutron excess: R.H. Dalitz, R. Levi Setti., N. Cim. **30** (1963) 489, L. Majling, NP **A 585** (1995) 211c, Y. Akaishi et al., Frascati Physics Series **XVI** (1999) 59.

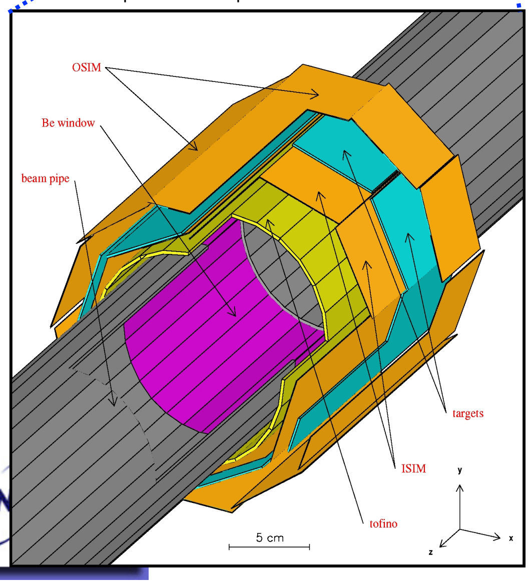
- The Pauli principle does not apply to the Λ inside the nucleus + *extra binding energy (Λ "glue-like" role) ⇒ a larger number of neutrons can be bound with respect to ordinary nuclei.*

- **Neutron (proton) 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@DAΦNE (LNF)





$$e^+ + e^- \to \phi\,(1020) \to K^+ + K^-\ (127\ \mathrm{MeV/c})$$
$$K^-_{\ stop} + {}^{A}Z \to {}^{A}_{\Lambda}Z + \pi^-$$

Solenoid: B=1T

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)

(9% FWHM for n @ 80 MeV for decay study)

2003 data taking: (2x^{6}Li, ^{7}Li, 3x^{12}C, ^{27}Al, ^{51}V)
2006 data taking: (2x^{6}Li, 2x^{7}Li, 2x^{9}Be, ^{13}C, D_2O)

Hypernuclear physics with FINUDA

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

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

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

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

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

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 ($\Delta\Omega \sim 2\pi$ srad)
  complete event ➥ decay mode study

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

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n-rich hypernuclei in FINUDA

Production reaction (K^-_{stop}, π^+)

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

References

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 $10^{-5}/K^-_{stop}$

PLB 640 (2006) 145: upper limits ${}^{6}_{\Lambda}$H, ${}^{7}_{\Lambda}$H and ${}^{12}_{\Lambda}$Be
Oct 2003 - Jan 04: ~220 pb^{-1}
${}^{6}_{\Lambda}$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) $10^{-5}/K^-_{stop}$ (inclusive π^+ spectra analysis)

- PRL 108 (2012) 042501, NPA 881 (2012) 269: ${}^{6}_{\Lambda}$H observation
- PRC 86 (2012) 057301: upper limits ${}^{9}_{\Lambda}$He

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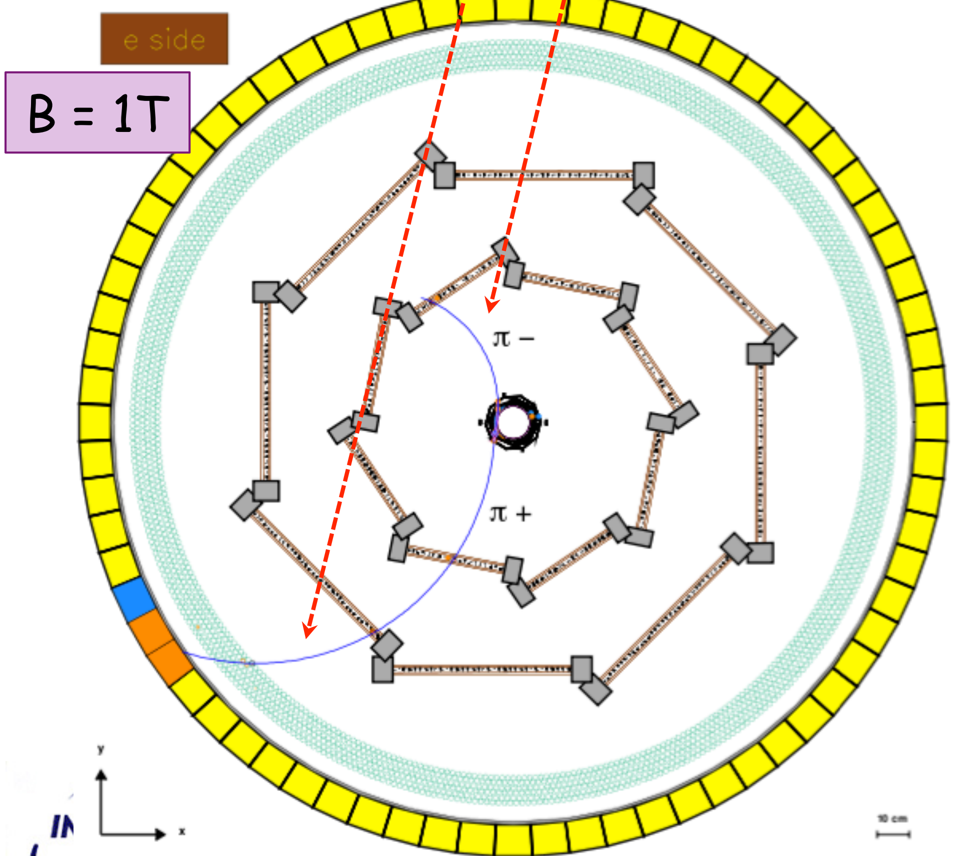
Coincidence measurement

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

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

D-CEX
~252 MeV/c

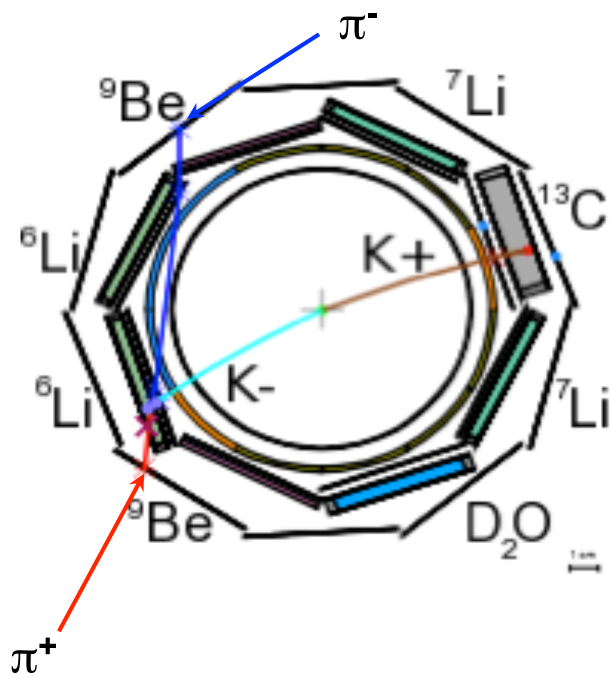
MWD
~134 MeV/c



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 dE/dx)
- **High momentum resolution** (tracker resolution + He bag + thin targets)

Nov 2006 - Jun 2007: 960 pb^{-1}



n-rich search: the idea

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

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

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

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

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

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

$$\boxed{\begin{array}{l}\sqrt{M^2({}^6_\Lambda H) + p^2(\pi^+)} - M({}^6_\Lambda H) \\ M({}^6_\Lambda H) = M({}^5H) + M(\Lambda) - B(\Lambda)\end{array}}$$

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

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

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

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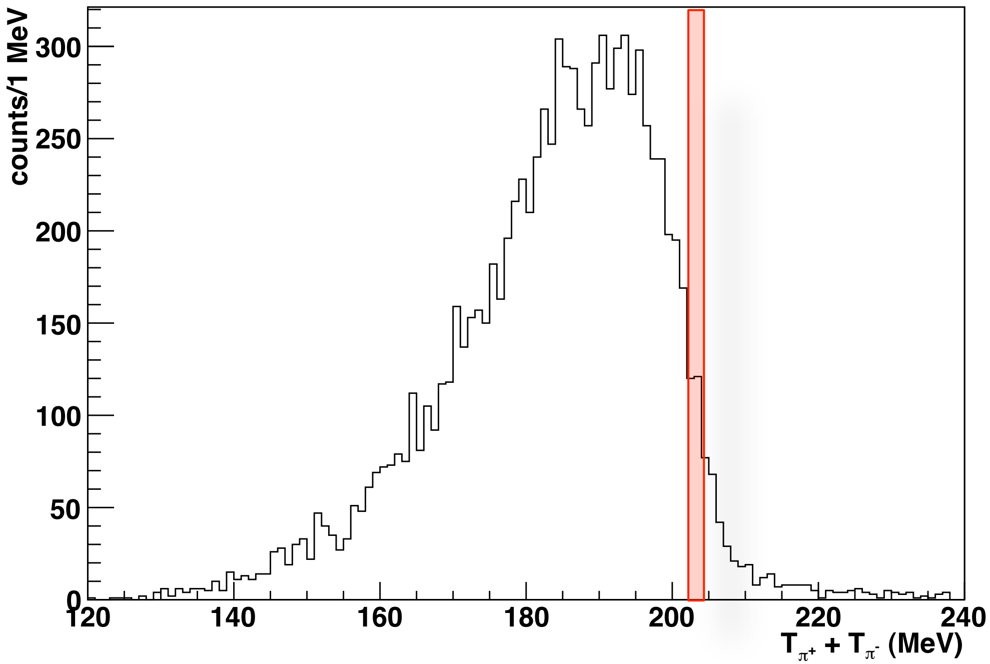


selection:
$T(\pi^+)+T(\pi^-)$ = 202÷204 MeV

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

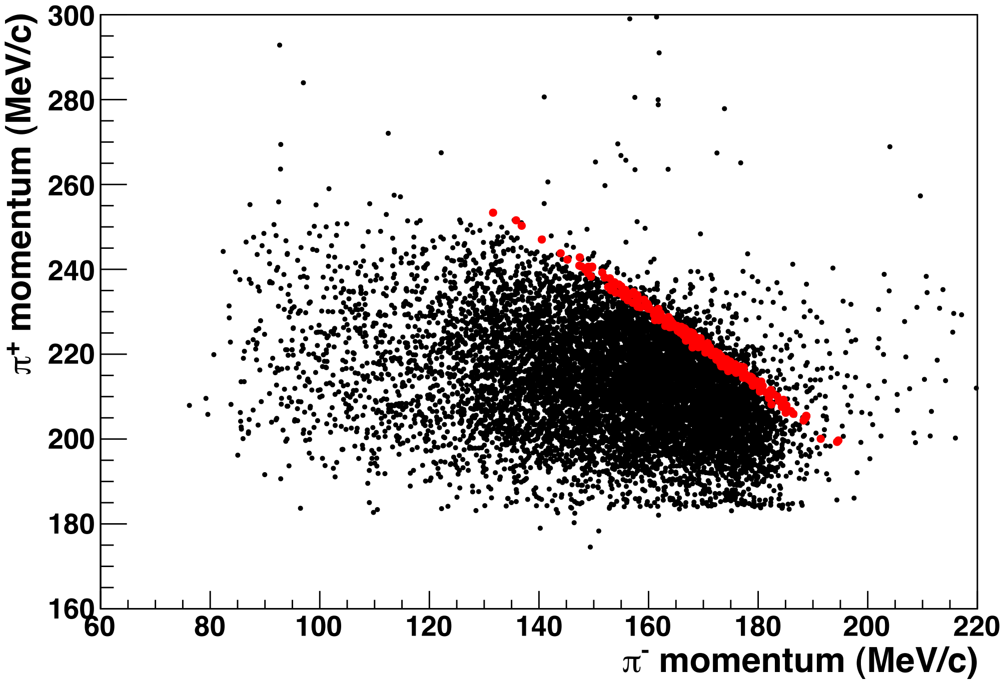
absolute energy scale:
μ+(235.6 MeV/c) from $K_{\mu 2}$
Δ_p< 0.12 MeV/c

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

continuous monitoring: stability



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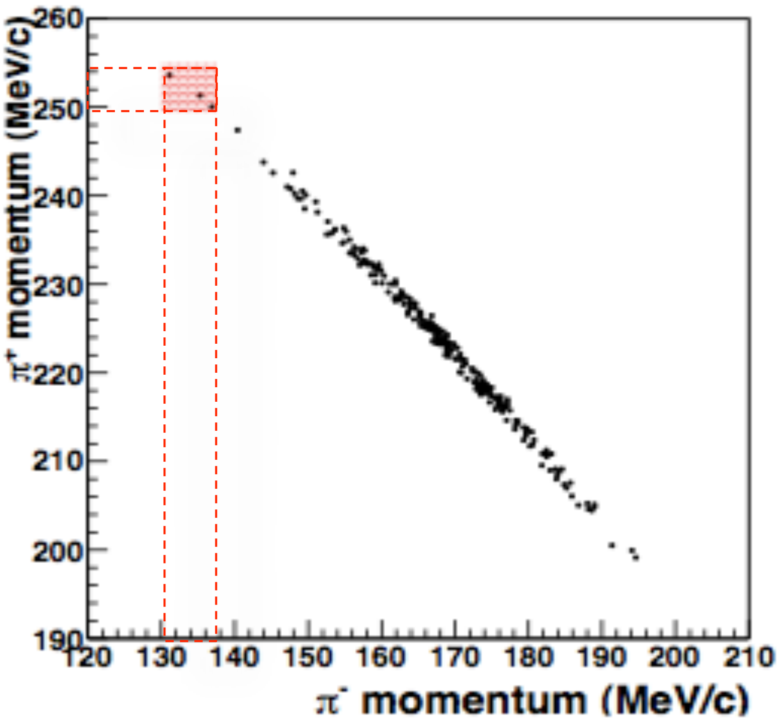


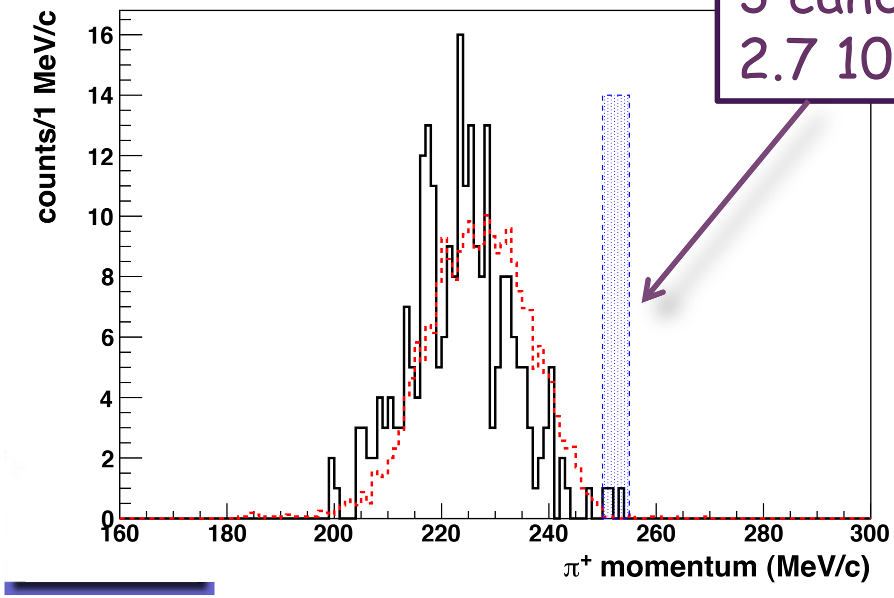
250÷255 MeV/c (σ_p= 1.1 MeV/c)

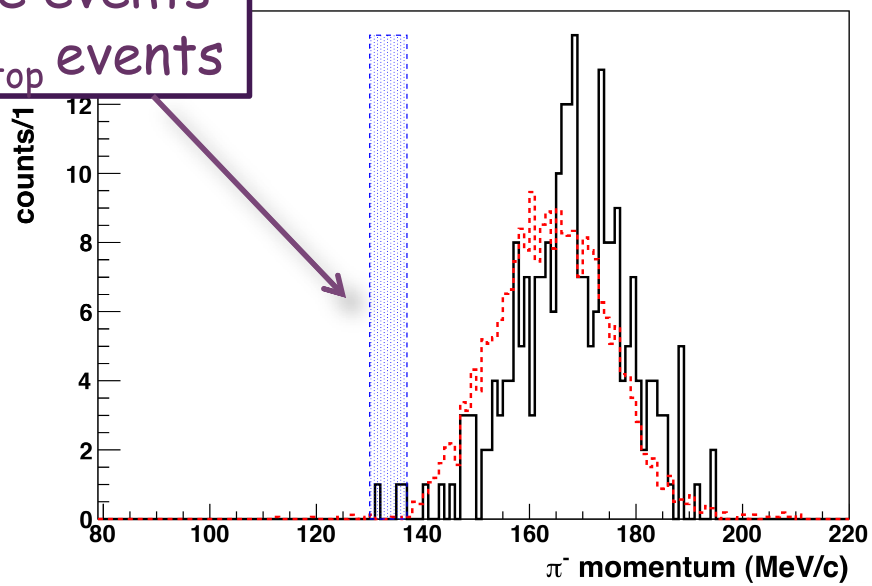
130÷137 MeV/c (σ_p= 1.2 MeV/c)

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

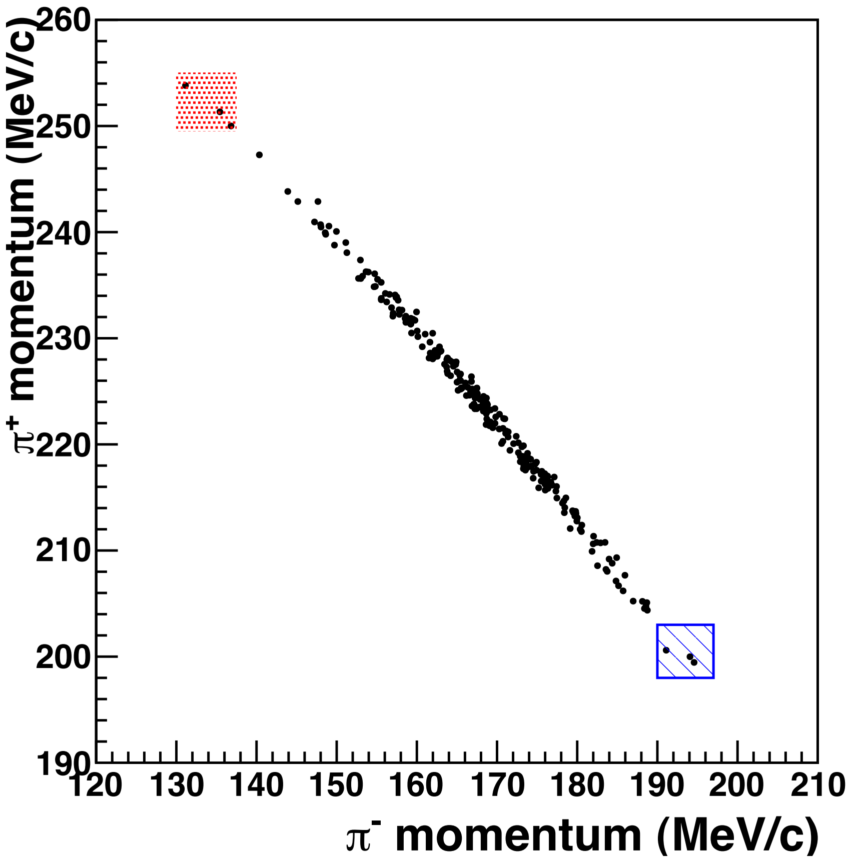
3 candidate events
2.7 10^7 K^-_{stop} events



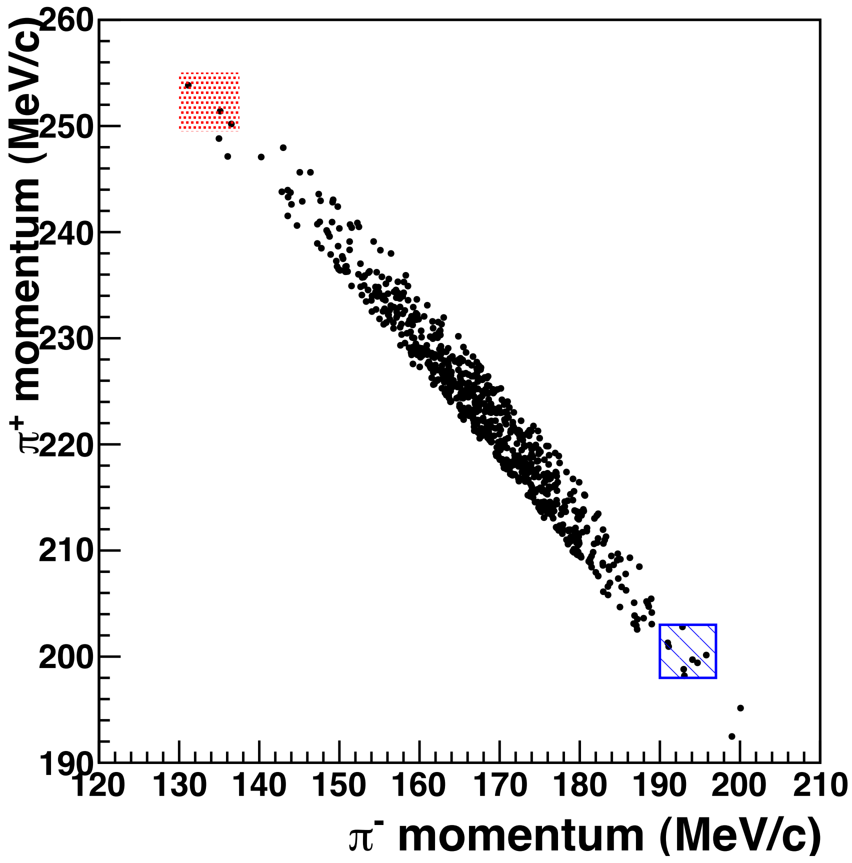


$T(\pi^+)+T(\pi^-)$ cut

$T(\pi^+)+T(\pi^-)$ = 202÷204 MeV



$T(\pi^+)+T(\pi^-)$ = 200÷206 MeV



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

Background sources:

- fake coincidences: π^+(249÷255 MeV/c) & π^-(130÷138 MeV/c) 0.27±0.27 ev.

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

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

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

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

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

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

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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 and NPA 881 (2012) 269

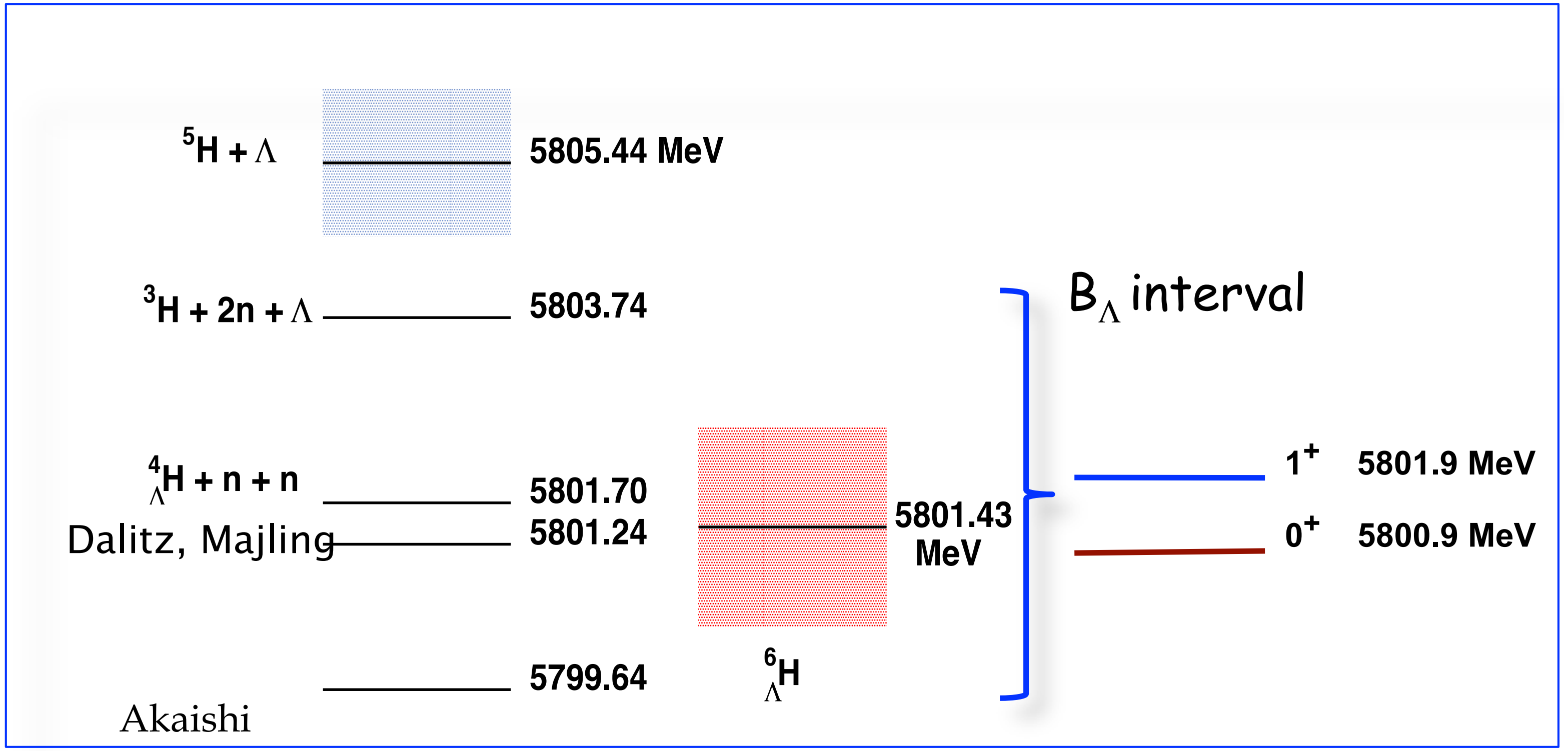
✓ **B_Λ determination**
✓ **formation – decay mass difference**

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



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

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

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

→ $B_{\Lambda}({}^{6}_{\Lambda}H) = (4.5 \pm 1.2)$ 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.

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

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

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

8.5 $^{5}_{\Lambda}He + 4n$

$^{8}He+\Lambda$

8.3 $^{6}_{\Lambda}He + 3n$

4.9 $^{7}_{\Lambda}He + 2n$

3.9 $^{8}_{\Lambda}He + n$

5 MeV

3.1 $3/2^{+}, 5/2^{+}$

0.0 $1/2^{+}$

(MeV) $^{9}_{\Lambda}He$

explored
B_{Λ} interval

10 MeV

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

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

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

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

independent 2-body reactions:
decay at rest

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

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

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

$$\boxed{\begin{array}{l}\sqrt{M^2({}^9_{\Lambda}He) + p^2(\pi^+)} - M({}^9_{\Lambda}He) \\ M({}^9_{\Lambda}He) = M({}^8He) + M(\Lambda) - B(\Lambda)\end{array}}$$

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

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

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

cut on $\boxed{T(\pi^+) + T(\pi^-)\text{: } 194.5 \div 197.5 \text{ MeV}}$

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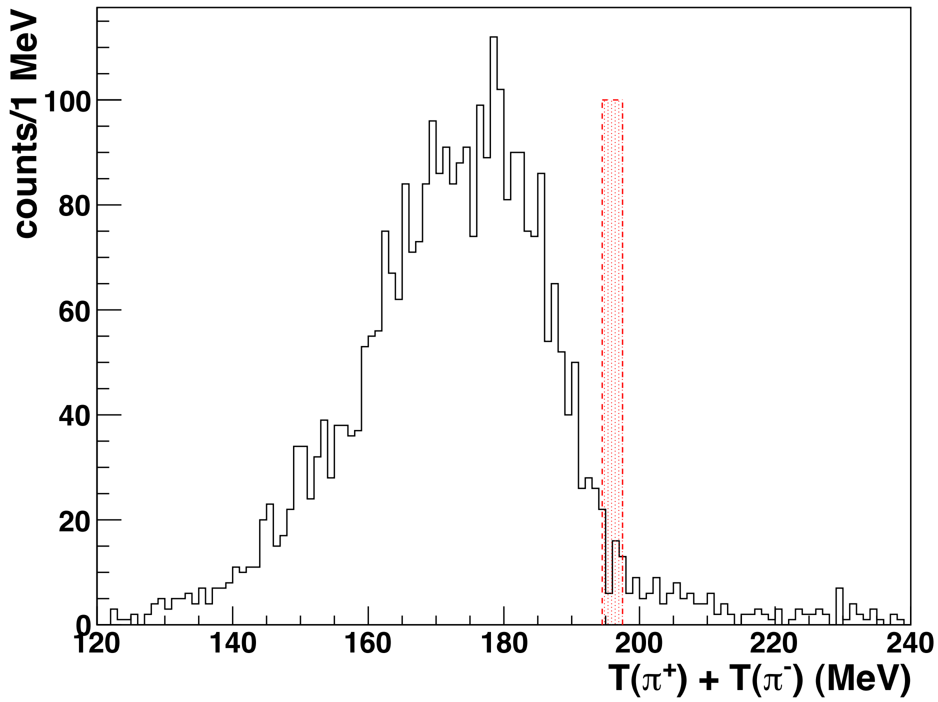
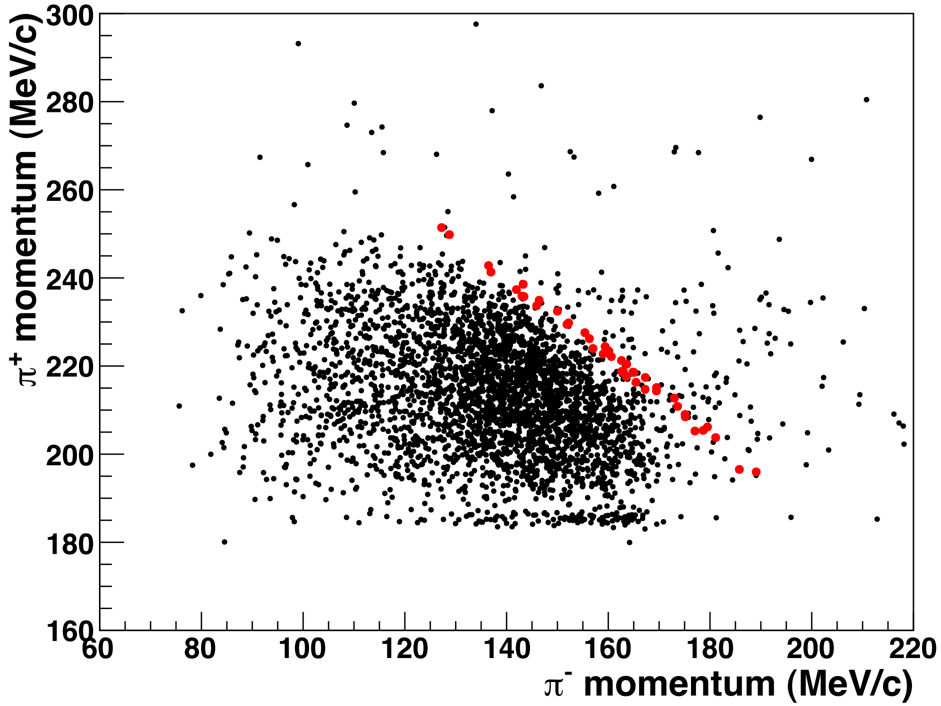
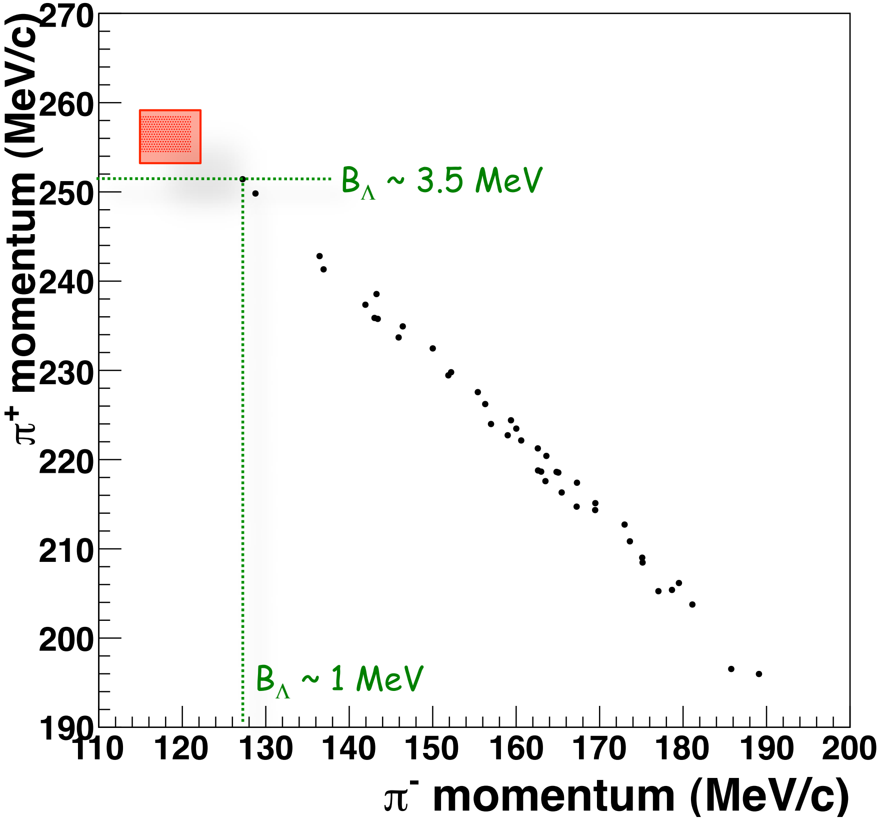


selection:
$T(\pi^+)+T(\pi^-)$ = 194.5÷197.5 MeV



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

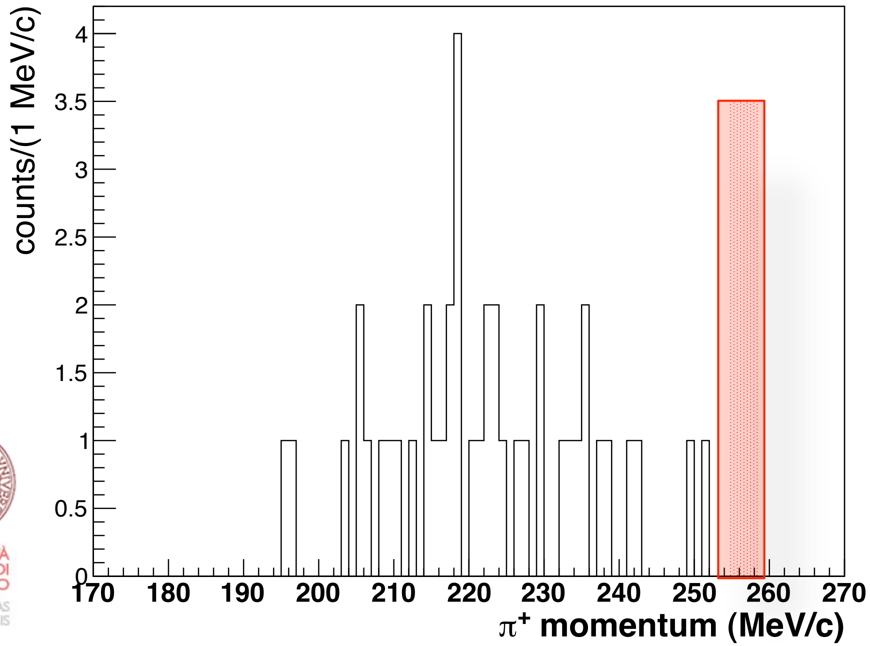


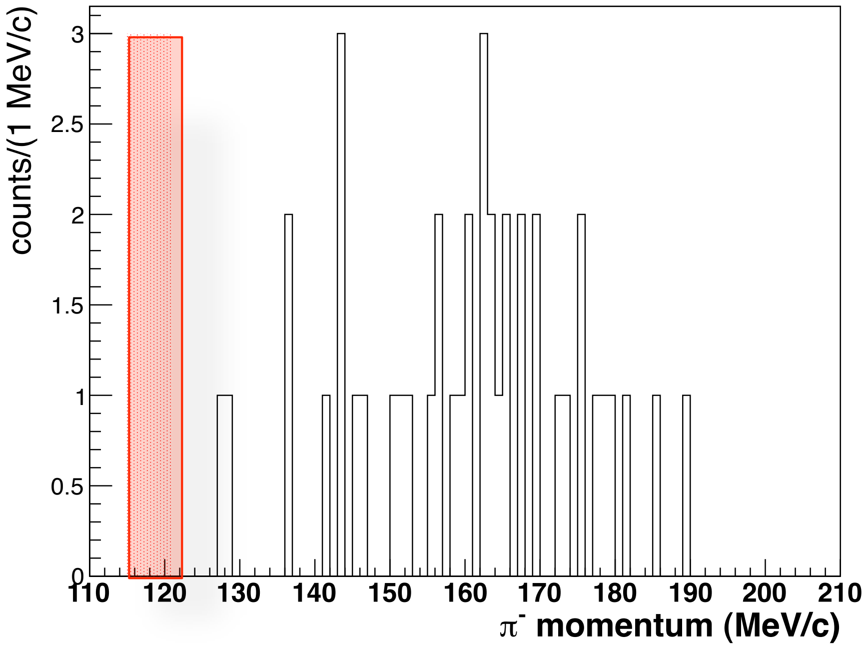
253.5÷259 MeV/c (σ_p= 1.1 MeV/c)

114.5÷122MeV/c (σ_p= 1.2 MeV/c)

B_Λ = 5÷10 MeV

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





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

$$R * BR(\pi-) < (2.3\pm1.9)\bullet 10^{-6} / (n.\ K^{-}_{stop}\ \text{on}\ ^{9}Be)\ (90\%\ C.L.)$$

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

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

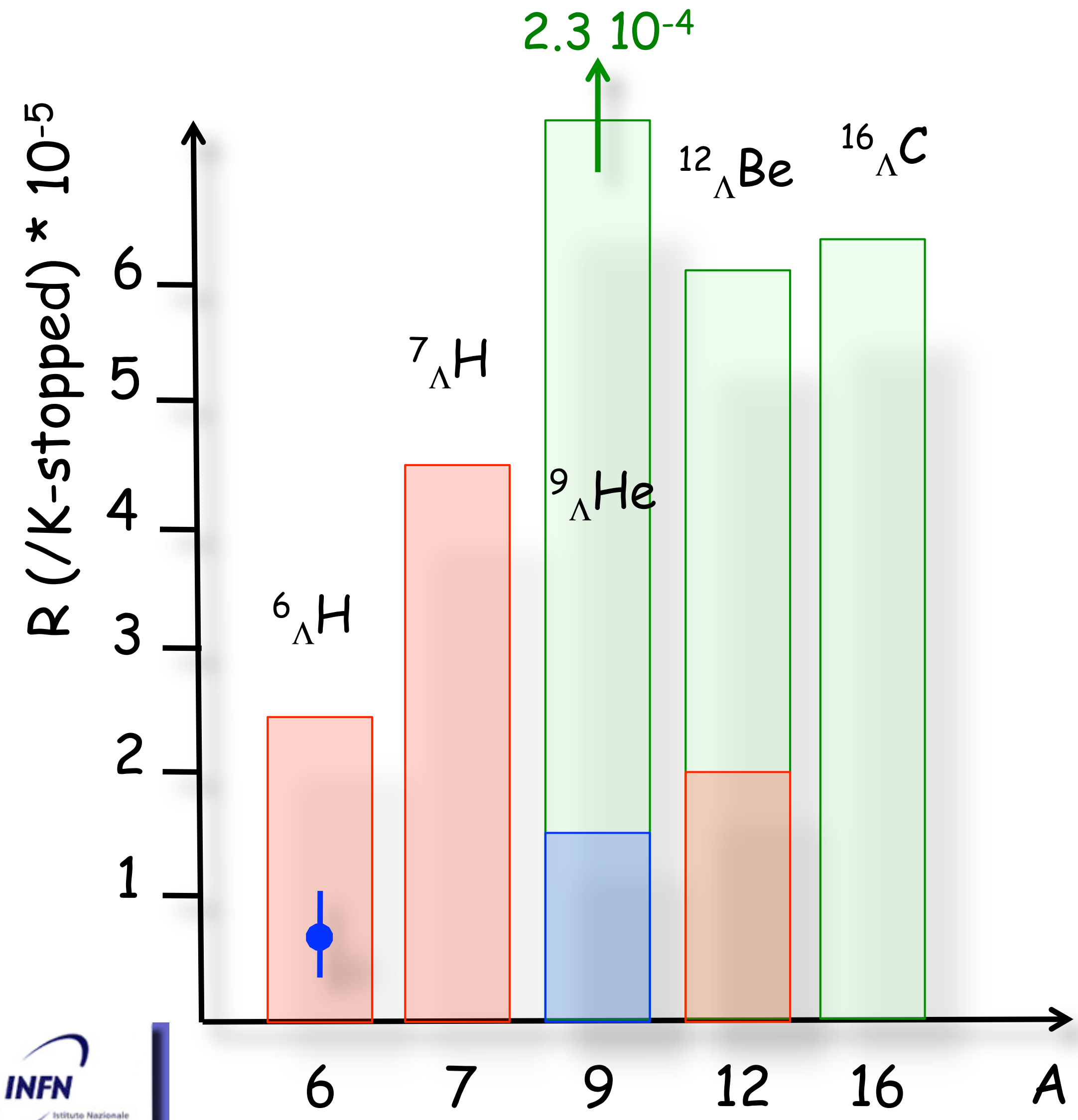
$$\mathbf{R < 1.6\ 10^{-5} / (n.\ K^{-}_{stop}\ on\ ^{9}Be)}\ (90\%\ C.L.)$$

PRC 86 (2012) 057301

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

Conclusions

(K^-_{stop}, π^+) production rate vs A



- FINUDA: inclusive spectra

- FINUDA: coincidence

- KEK

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

experimental and theoretical efforts needed

Backup

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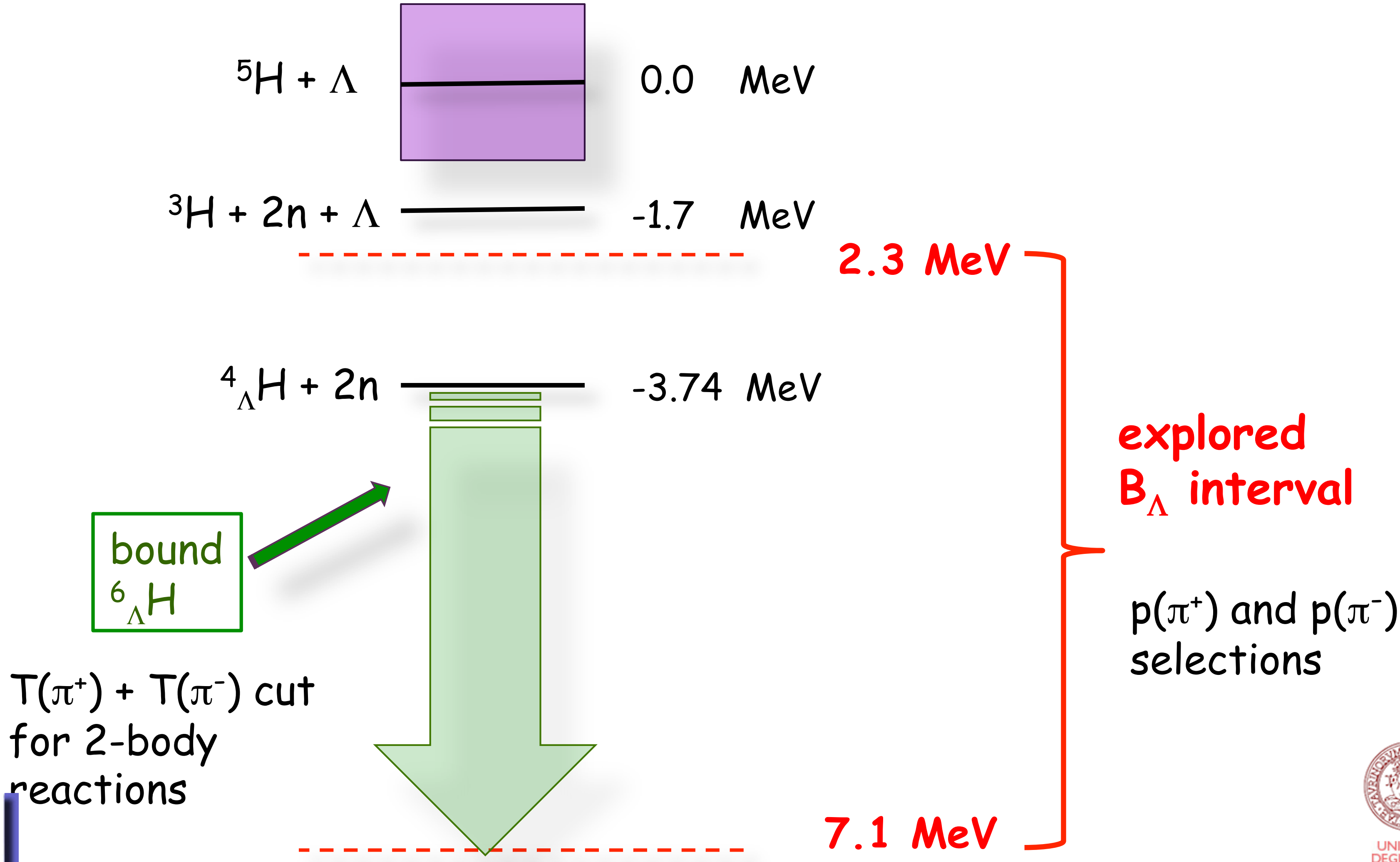
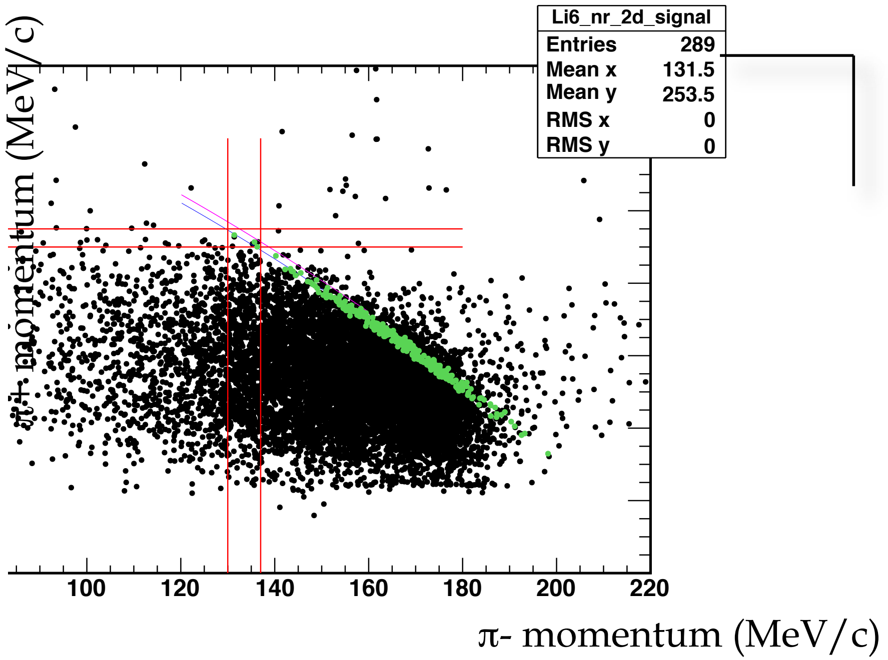
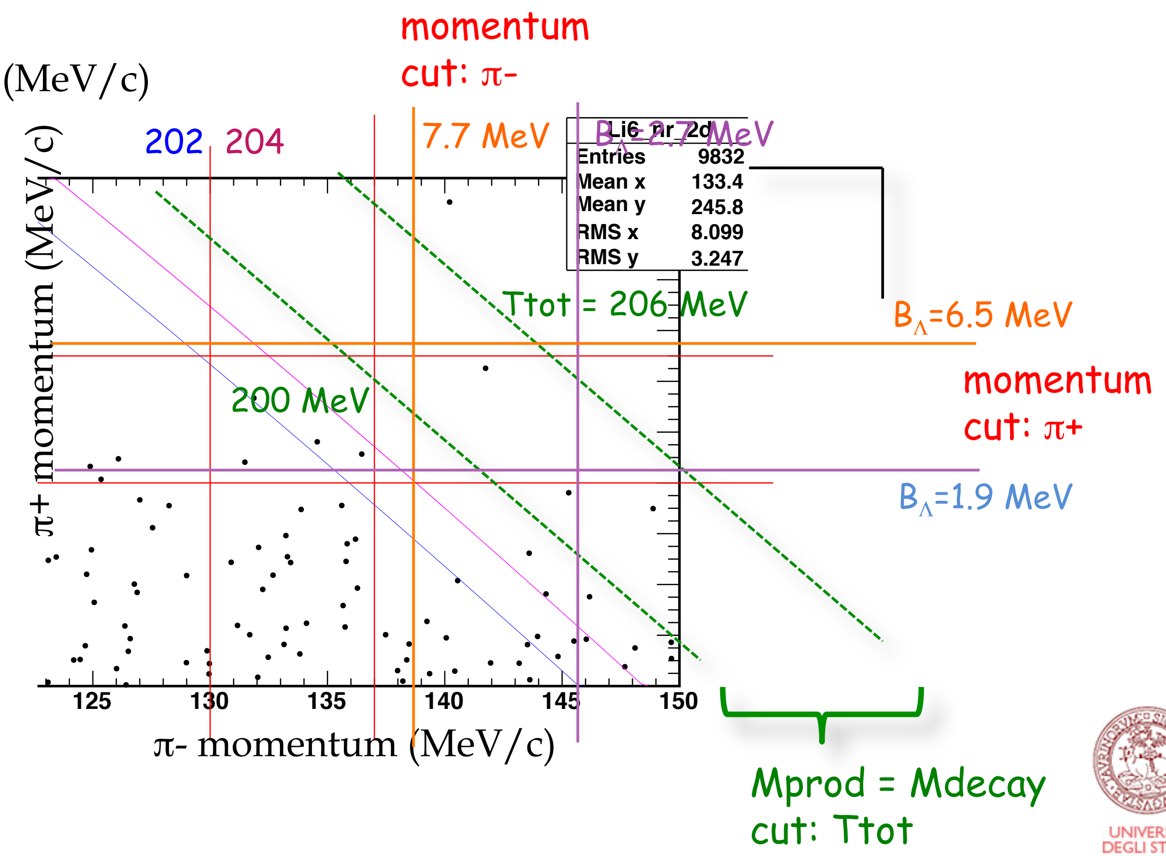
Search for bound $^{6}_{\Lambda}H$





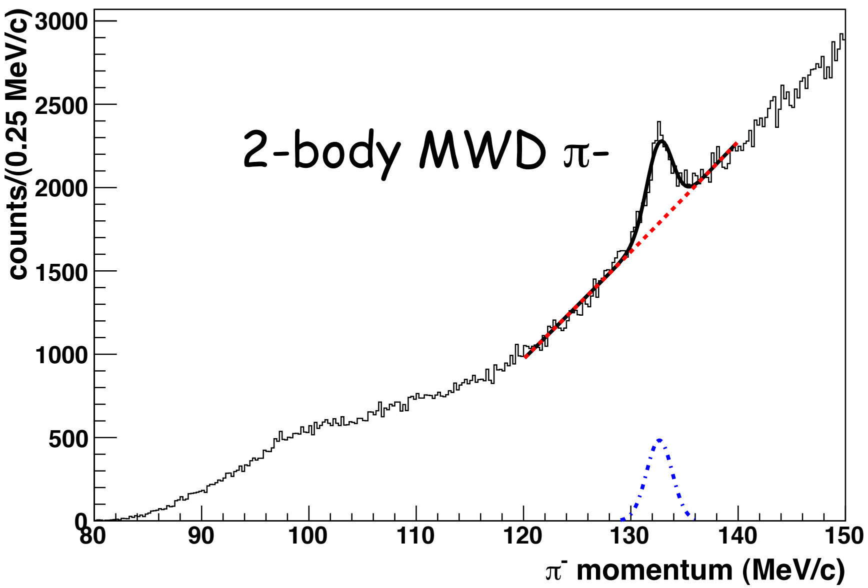


B_Λ=7.1 MeV

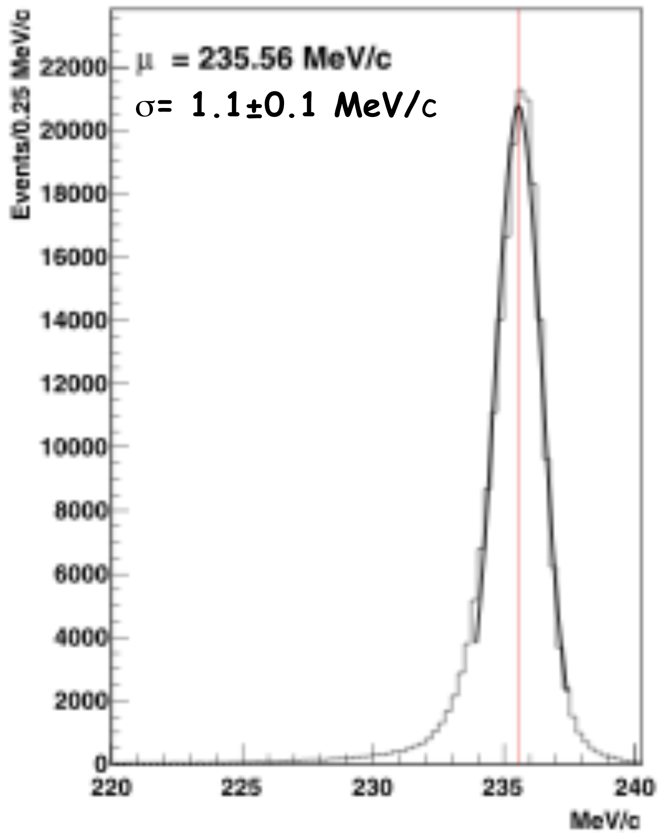
B_Λ=2.3 MeV

FINUDA momentum resolution

$\pi-$ production of ${}^{4}_{\Lambda}H$ hyperfragment on ${}^{6}Li$



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



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

- ✓ partial and cumulative spectra
- ✓ performance stability monitoring

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

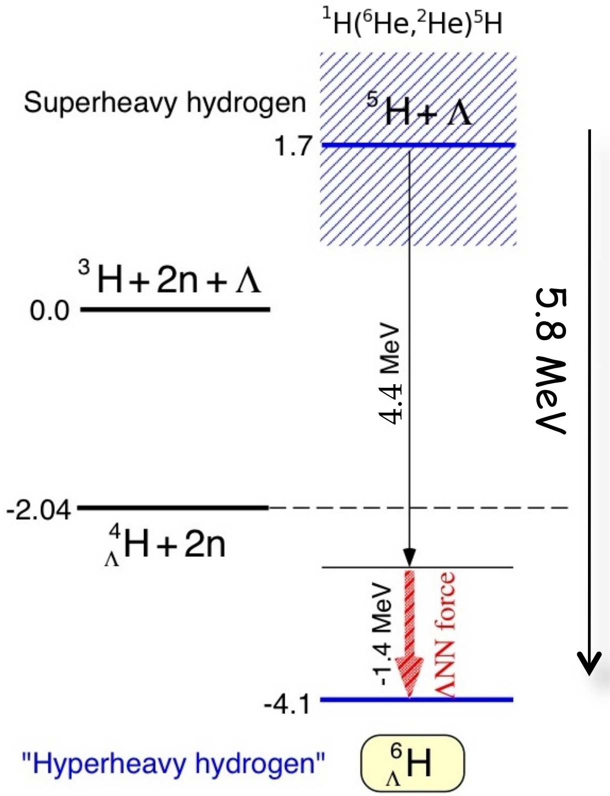
(N+Y)/Z=5

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
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"coherent" $\Lambda-\Sigma$ 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