Workshop on
Study of Neutron Stars and Core-Collapse Supernovae
December 16th-20th, 2014, RIKEN, Japan

Observation of neutron-rich Λ-hypernuclei by the FINUDA experiment

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Outline

- physics motivations
- the FINUDA experiment @ DAΦNE
- experimental results:
  - FINUDA @ INFN/LNF
  - E10 @ J-PARC

Search for neutron-rich hypernuclei

central issue in hypernuclear physics

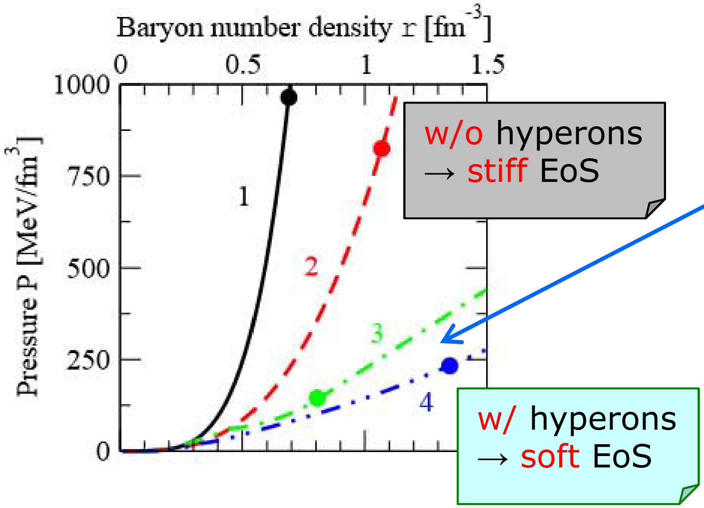
- historical paper: R.H. Dalitz and R. Levi Setti, Nuovo Cimento 30 (1963) 489

1. Pauli effect not effective for Λ
2. Λ extra binding energy

⇨ existence of hypernuclei with core nucleus near (or even beyond) the neutron drip line

- unique opportunity to study: - effect of 3-body forces (Λ𝒩𝒩)
  - Λ𝒩- Σ𝒩 coupling contribution to binding en.
  - hyperon behaviour in n-rich environment

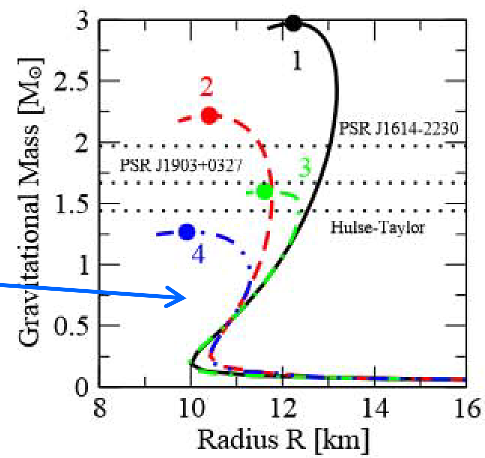
⇩



direct influence on neutron star EoS

prediction of neutron star main parameters

I. Vidaña *et al.*, *EPL* 94 (2011) 11002



The status of the art (as of 2011)

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

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

experimental results

KEK

- ${}^9_\Lambda He({}^9Be) : u.l. = 2.3 \cdot 10^{-4} / K^-_{stop}$
- ${}^{12}_\Lambda Be({}^{12}C) : u.l. = 6.1 \cdot 10^{-5} / K^-_{stop}$
- ${}^{16}_\Lambda C({}^{16}O) : u.l. = 6.2 \cdot 10^{-5} / K^-_{stop}$

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

INFN-LNF

- ${}^6_\Lambda H({}^6Li) : u.l. = (2.5 \pm 1.4) \cdot 10^{-5} / K^-_{stop}$
- ${}^7_\Lambda H({}^7Li) : u.l. = (4.5 \pm 1.4) \cdot 10^{-5} / K^-_{stop}$
- ${}^{12}_\Lambda Be({}^{12}C) : u.l. = (2.0 \pm 0.4) \cdot 10^{-5} / K^-_{stop}$

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

theoretical predictions

$10^{-6} \div 10^{-7} / K^-_{stop}$

T.Y. Tretyakova *et al.*, *NPA* 691 (2001) 51c

$$\pi^- + {}^A Z \rightarrow {}^A_\Lambda (Z-2) + K^+$$

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

experimental results

KEK

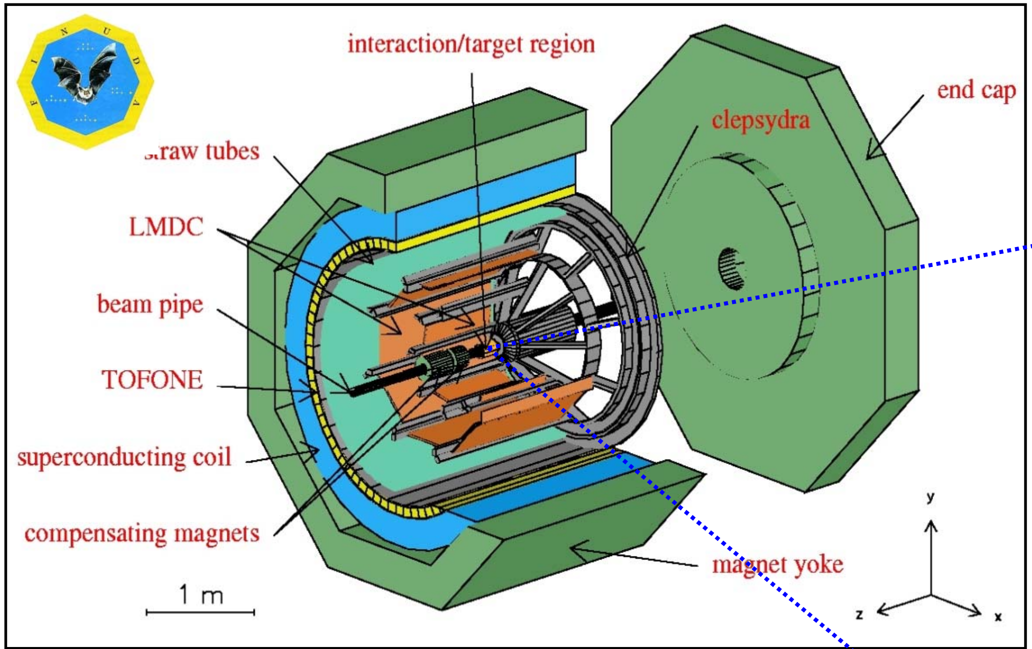
${}^{10}_\Lambda Li({}^{10}B) : d\sigma / d\Omega = 11.3 \pm 1.9 \;\; nb/sr$

P.K. Saha *et al.*, *PRL* 94 (2005) 052502

theoretical predictions

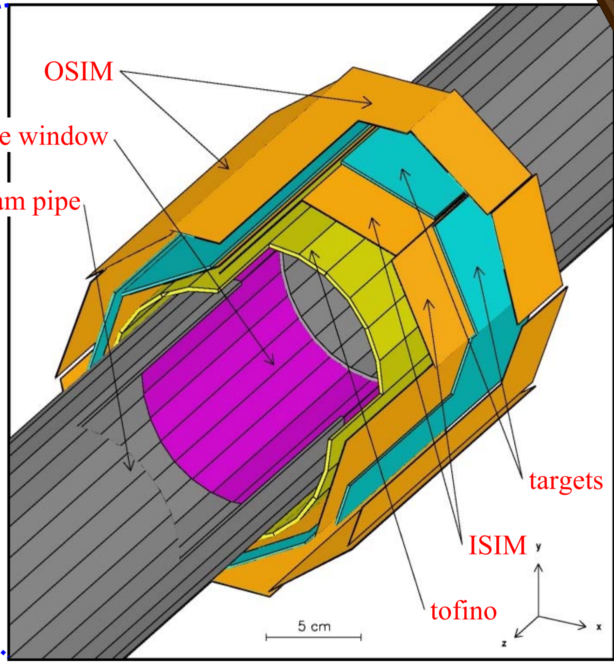
T.Y. Tretyakova *et al.*, *PAT* 66 (2003) 1681

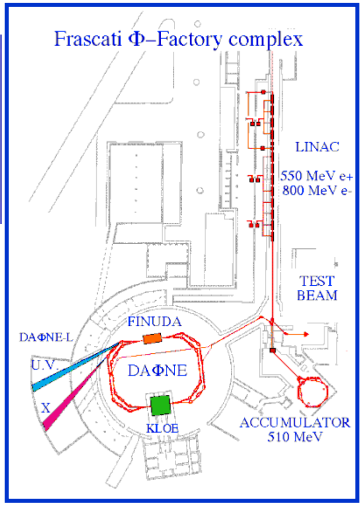
FINUDA @ DAΦNE

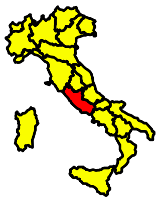


$$e^- + e^+ \rightarrow \phi \rightarrow K^- K^+$$

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







energy	510 MeV
luminosity	5 10^{32} cm^{-2} s^{-1}
σ_x (rms)	2.11 mm
σ_y (rms)	0.021 mm
σ_z (rms)	35 mm
bunch length	30 mm
crossing angle	12.5 mrad
frequency (max)	368.25 MHz
bunch/ring	up to 120
part./bunch	8.9 10^{10}
current/ring	5.2 A (max)

$${}^{A}_{\Lambda}Z \rightarrow \begin{cases} {}^{A}(Z+1) + \pi^- \\ {}^{(A-2)}(Z-1) + p + n \\ {}^{(A-3)}(Z-1) + p + n + n \end{cases}$$

FINUDA key features

- very thin nuclear targets (0.1 ÷ 0.3 g/cm^2)
  - → high resolution spectroscopy
- coincidence measurement with large acceptance
  - → decay mode study ← indirect discovery tool
- event by event K^+ tagging
  - → continuous energy and rate calibration
- irradiation of different targets in the same run
  - → systematic error reduction

Physics output (S = -1)

M. Agnello *et al.*, *PLB* 640 (2006) 145
M. Agnello *et al.*, *PRL* 108 (2012) 042501
M. Agnello *et al.*, *NPA* 881 (2012) 269
M. Agnello *et al.*, *PRC* 86 (2012) 057301

possible thanks to apparatus performance and stability

nuclear models

neutron-rich Λ-hypernuclei

4B weak interaction

spectroscopy

(weak) decay

medium effect

quark substructures

low-energy $\mathcal{N}$-Y interaction

deeply bound $\bar{K}$ states

M. Agnello *et al.*, *PLB* 622 (2005) 35
M. Agnello *et al.*, *PLB* 681 (2009) 139
M. Agnello *et al.*, *NPA 835* (2010) 414
M. Agnello *et al.*, *PLB* 698 (2011) 219

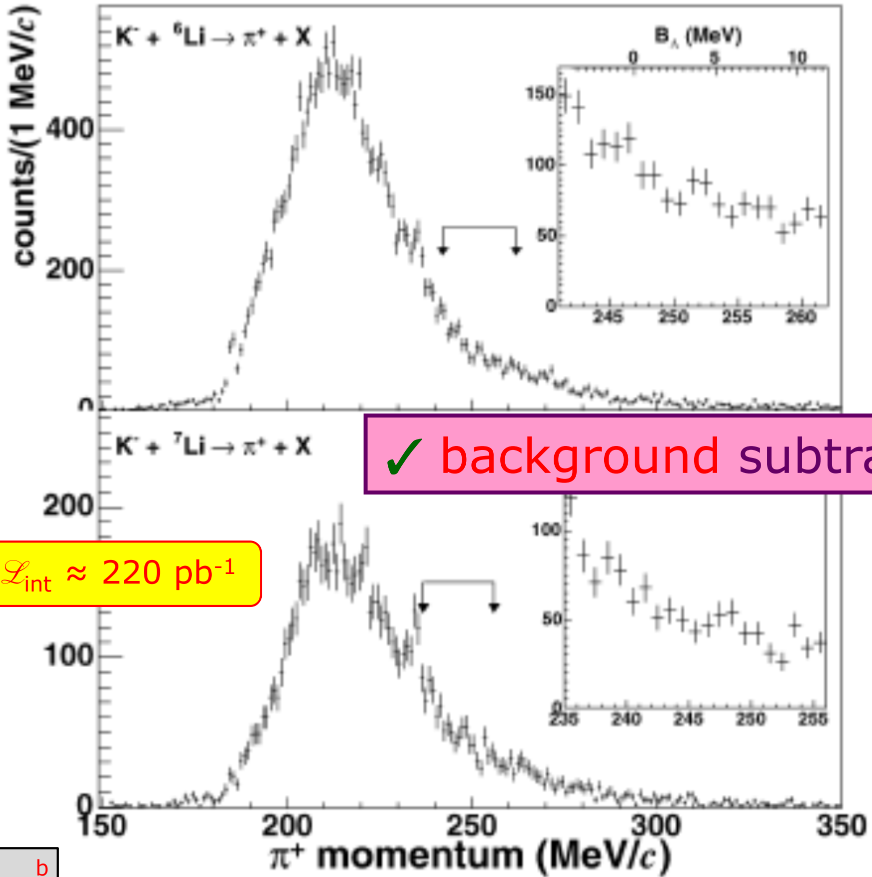
M. Agnello *et al.*, *PRL* 94 (2005) 212303

M. Agnello *et al.*, *NPA* 804 (2008) 151
M. Agnello *et al.*, *PLB* 681 (2009) 139
M. Agnello *et al.*, *NPA* 835 (2010) 439
M. Agnello *et al.*, *PLB* 685 (2010) 247
M. Agnello *et al.*, *PLB* 701 (2011) 556
M. Agnello *et al.*, *NPA* 881 (2012) 322
M. Agnello *et al.*, *PLB* 739 (2014) 499

The background issue

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

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

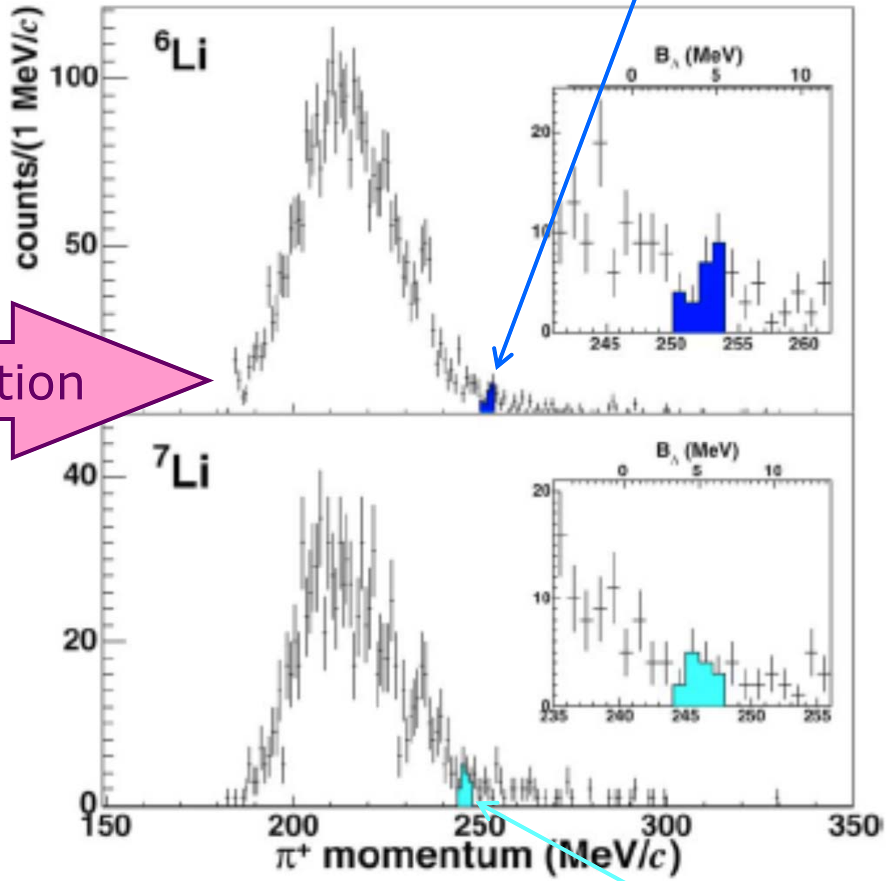


$\mathscr{L}_{int} \approx 220\ pb^{-1}$

✓ background subtraction

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

$${}^{6}_{\Lambda}H({}^{6}Li): u.l. = (2.5 \pm 1.4)\cdot 10^{-5} / K^-_{stop}\ @\ 90\%\ c.l.$$



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

$${}^{7}_{\Lambda}H({}^{7}Li): u.l. = (4.5 \pm 1.4)\cdot 10^{-5} / K^-_{stop}\ @\ 90\%\ c.l.$$

main background

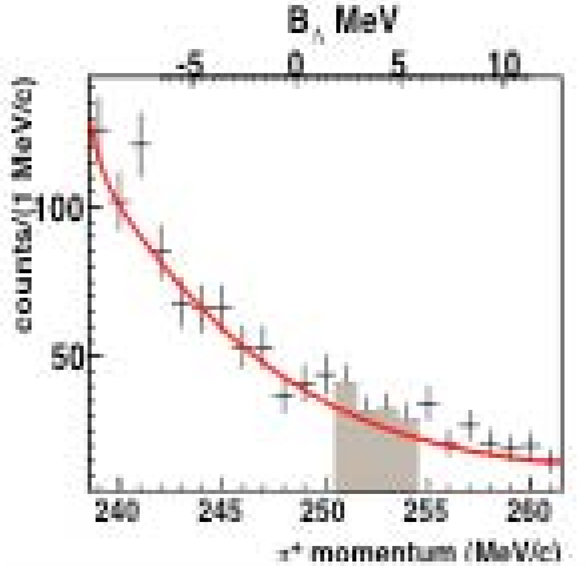
$$K^- + p \rightarrow \Sigma^+ + \pi^-$$
$$\hookrightarrow n + \pi^+ \quad (\sim 130 < p_{\pi^+} < \sim 250\ MeV/c)$$

$$K^- + pp \rightarrow \Sigma^+ + n$$
$$\hookrightarrow n + \pi^+ \quad (\sim 100 < p_{\pi^+} < \sim 320\ MeV/c)$$

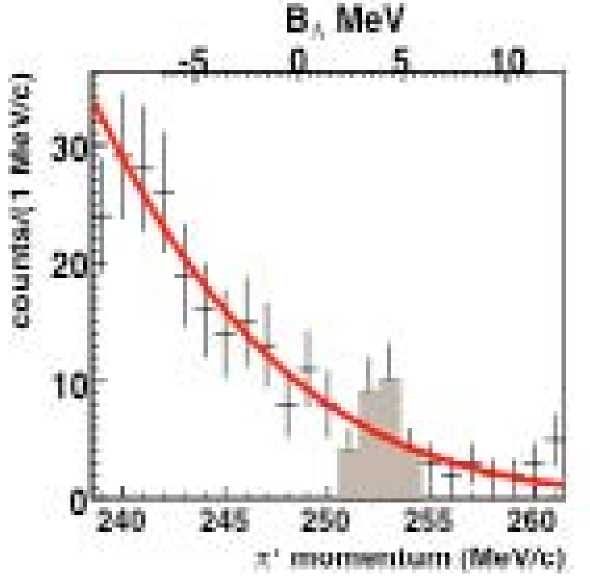
Higher statistics was not enough...

$\mathscr{L}_{int} \approx 1156\ pb^{-1}$

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



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



The new NRH search strategy

$\mathcal{L}_{int} \approx 1156\ pb^{-1}$ → coincidence measurements

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

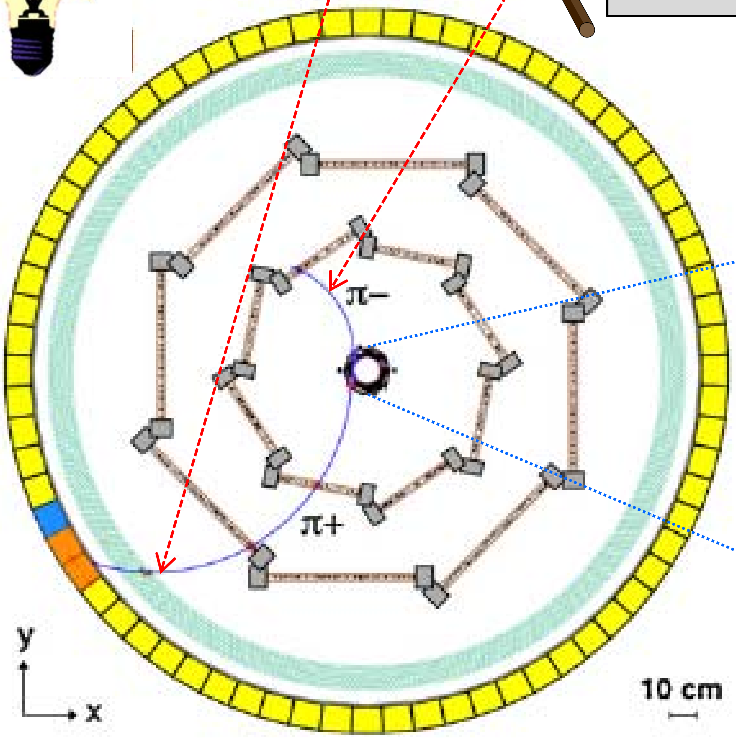
double C-EX
p ~ 252 MeV/c

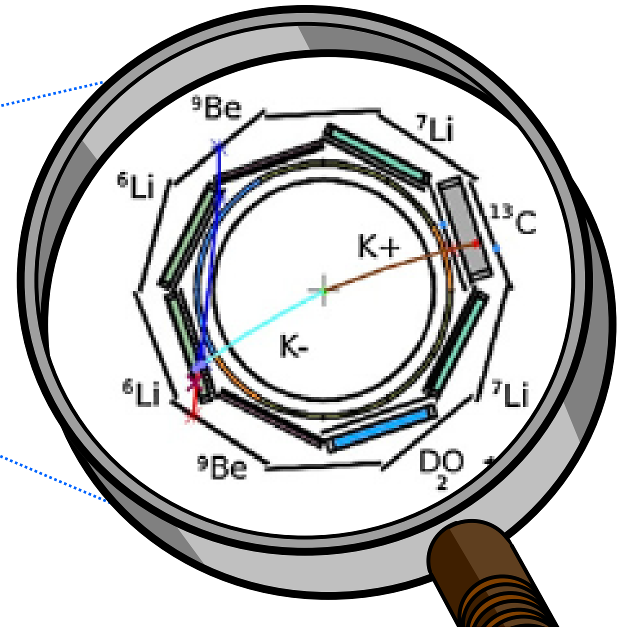
$${}^6_\Lambda H \rightarrow {}^6He + \pi^-$$

n.m. decay
p ~ 134 MeV/c

apparatus capabilities:

- selective trigger
  (based on fast scintillator detectors)
- precise K^- vertex identification < 1 mm^3
  (PID + spatial resolution + K^- tagging)
- π, K, p, d, … separation (OSIM & LMDC dE/dx)
- high momentum resolution
  6‰ FWHM π^- @ 270 MeV/c
  6% FWHM π^- @ 110 MeV/c
  (tracker performance + He bag + thin target)





Analysis technique

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

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

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

if $^6H_\Lambda$ is a stable system ⇒ 2 independent two-body reactions:

decay at rest

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

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

atomic mass tables

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

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

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

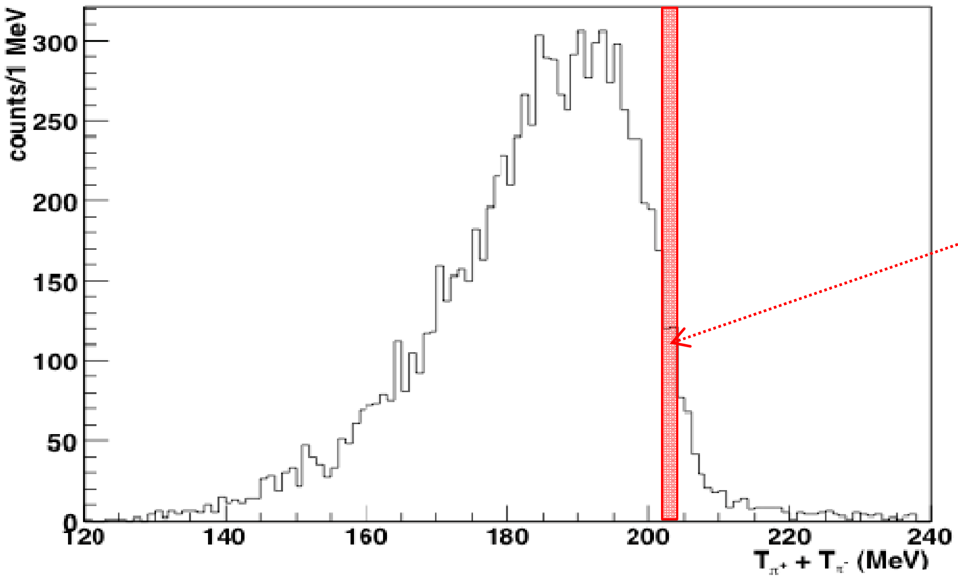
$$T(\pi^+) + T(\pi^-) = M(K^-) + M(p) - M(n) - 2M(\pi) - B({}^6\text{Li}) + B({}^6\text{He}) - T({}^6\text{He}) - T({}^6_\Lambda\text{H})$$

$$= 203.0 \pm 1.3 \text{ MeV}$$

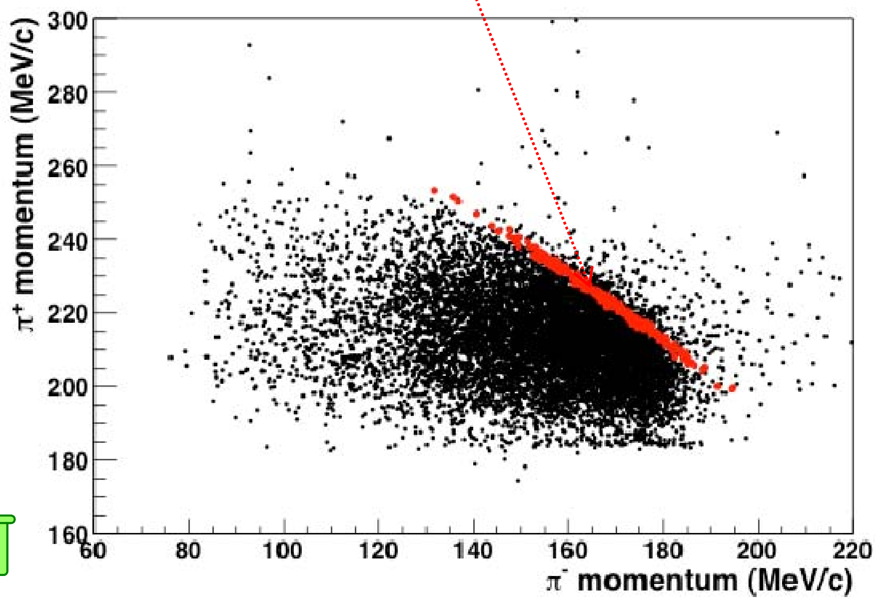
$(203.5 \div 203.3 \text{ MeV with } B_\Lambda = 0 \div 6 \text{ MeV})$

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

Data selection



$T(\pi^+) + T(\pi^-)$: 202 ÷ 204 MeV



absolute energy scale:

- μ^+ (235.6 MeV/c) from $K_{\mu 2}$
  $\Delta_p < 0.12$ MeV/c
- π^-(132.8 MeV/c) from $^4H_\Lambda$
  $\Delta_p < 0.2$ MeV/c

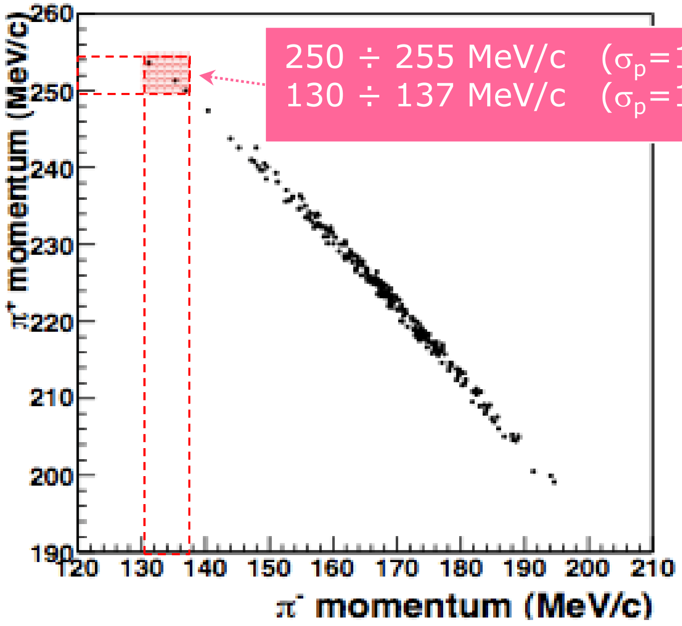
systematic errors

σT_{sys} = 0.17 MeV

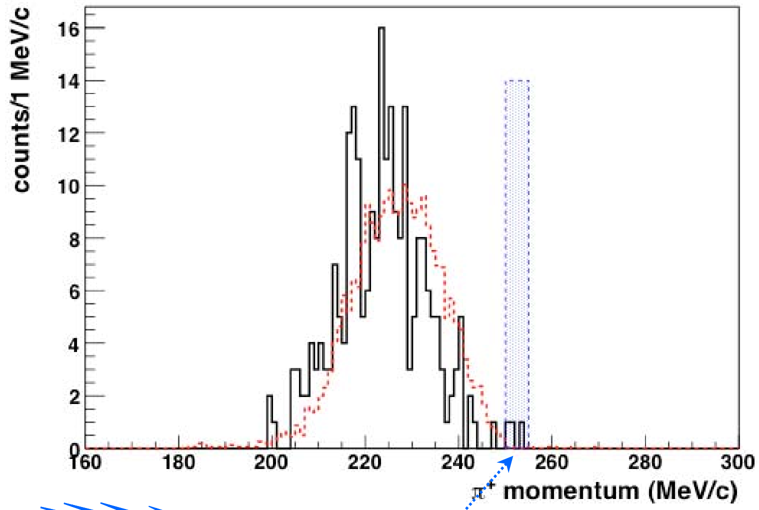
- $\sigma T(\pi^+)$ = 0.96 MeV, $\sigma T(\pi^-)$ = 0.84 MeV
- σT_{exp} = 1.3 MeV
- σT = 1.3 MeV

FINUDA Coll. And A. Gal, *NPA* 881 (2012) 269

Data selection

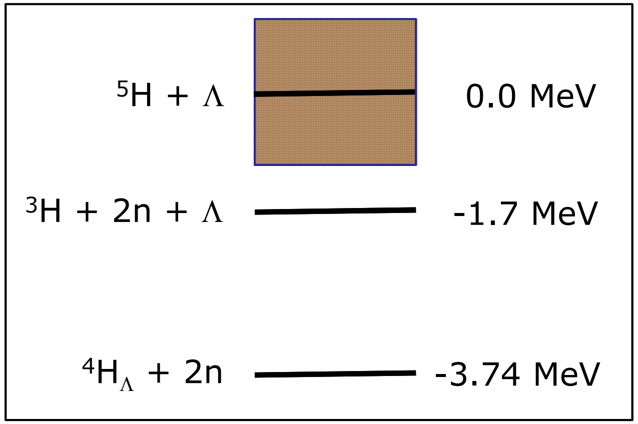


250 ÷ 255 MeV/c (σ_p=1.1 MeV/c)
130 ÷ 137 MeV/c (σ_p=1.2 MeV/c)



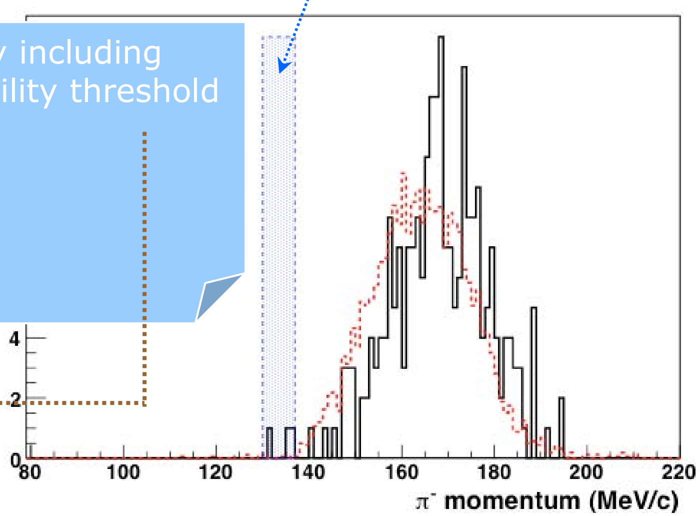
3 candidate events

(out of 27 10^6 stopped K^- events)



selection range fixed by including
^{6}H$_\Lambda$ lowest particle stability threshold
$p_{\pi+}$ = 251.9 MeV/c
$p_{\pi-}$ = 135.6 MeV/c

B_Λ = 1.5 ÷ 6 MeV



$^6H_\Lambda$ production rate

background sources

- accidentals: π^+ (250 ÷ 255 MeV/c) and π^- (130 ÷ 137 MeV/c) — 0.27 ± 0.27 ev. BGD2
- $K^-_{stop} + {}^6Li \rightarrow \Sigma^+ + \pi^- + {}^4He + n$ — end point ~190 MeV/c
  ↳ $n + \pi^+$ — end point ~282 MeV/c — 0.16 ± 0.07 ev. BGD1
- $K^-_{stop} + {}^6Li \rightarrow {}^4_\Lambda H + n + n + \pi^+$ — end point ~252 MeV/c
  ↳ ${}^4He + \pi^-$ — p(π^-) = 133 MeV/c — negligible

production rate

- total background on ^{6}Li: BGD1 + BGD2 = 0.43 ± 0.28 ev.
- Poisson statistics: 3 events DO NOT belong to pure background @ C.L. = 99%

assumption

$BR(\pi^-)\,{}^4_\Lambda H = 0.49$

H. Tamura *et al.*, *PRC* 40 (1989) R479

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

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

$$R = (5.9 \pm 4.0)\ 10^{-6} / K^-_{stop} \Leftrightarrow (2.5 \pm 0.5^{+0.4}_{-0.1}) \cdot 10^{-5} / K^-_{stop}$$

FINUDA Coll. and A. Gal, *PRL* 108 (2012) 042501

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

Kinematics and binding energy

T_{tot} (MeV)	p_{π^+} (MeV/c)	p_{π^-} (MeV/c)	$M(^6_\Lambda H)$ prod. (MeV)	$M(^6_\Lambda H)$ decay (MeV)	$M(^6_\Lambda H)$ mean (MeV)	$\Delta M(^6_\Lambda H)$ (MeV)
202.6 ± 1.3	251.3 ± 1.1	135.1 ± 1.2	5802.33 ± 0.96	5801.41 ± 0.84	5801.87 ± 0.96	0.92 ± 1.28
202.7 ± 1.3	250.1 ± 1.1	136.9 ± 1.2	5803.45 ± 0.96	5802.73 ± 0.84	5803.09 ± 0.96	0.72 ± 1.28
202.1 ± 1.3	253.8 ± 1.1	131.2 ± 1.2	5799.97 ± 0.96	5798.66 ± 0.84	5799.32 ± 0.96	1.31 ± 1.28

$$(N+Y)/Z(^6_\Lambda H) = 5 >> N/Z(^8He) = 3$$

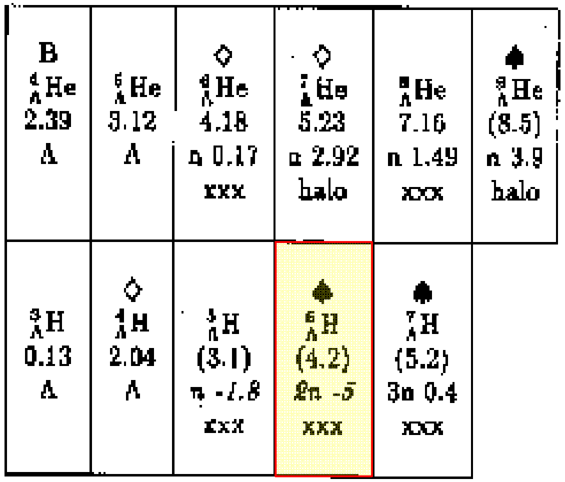
formation mass values systematically higher than the ones from decay

(0.98 ± 0.74) MeV

excited states production

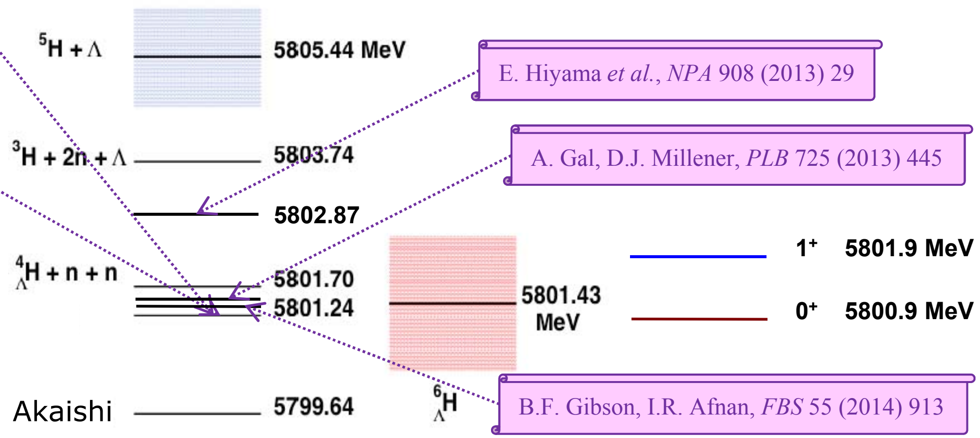
theoretical predictions

- B_Λ = 4.2 MeV — R.H. Dalitz and R. Levi Setti, *NC* 30 (1963) 489
- B_Λ = 4.2 MeV — L. Majling, *NPA* 585 (1995) 211c



nrh prod. rate: ~10^{-2} hyp. prod. rate in (K^-_{stop}, π^-)

$\bar{M}$ = (5801.4 ± 1.1) MeV

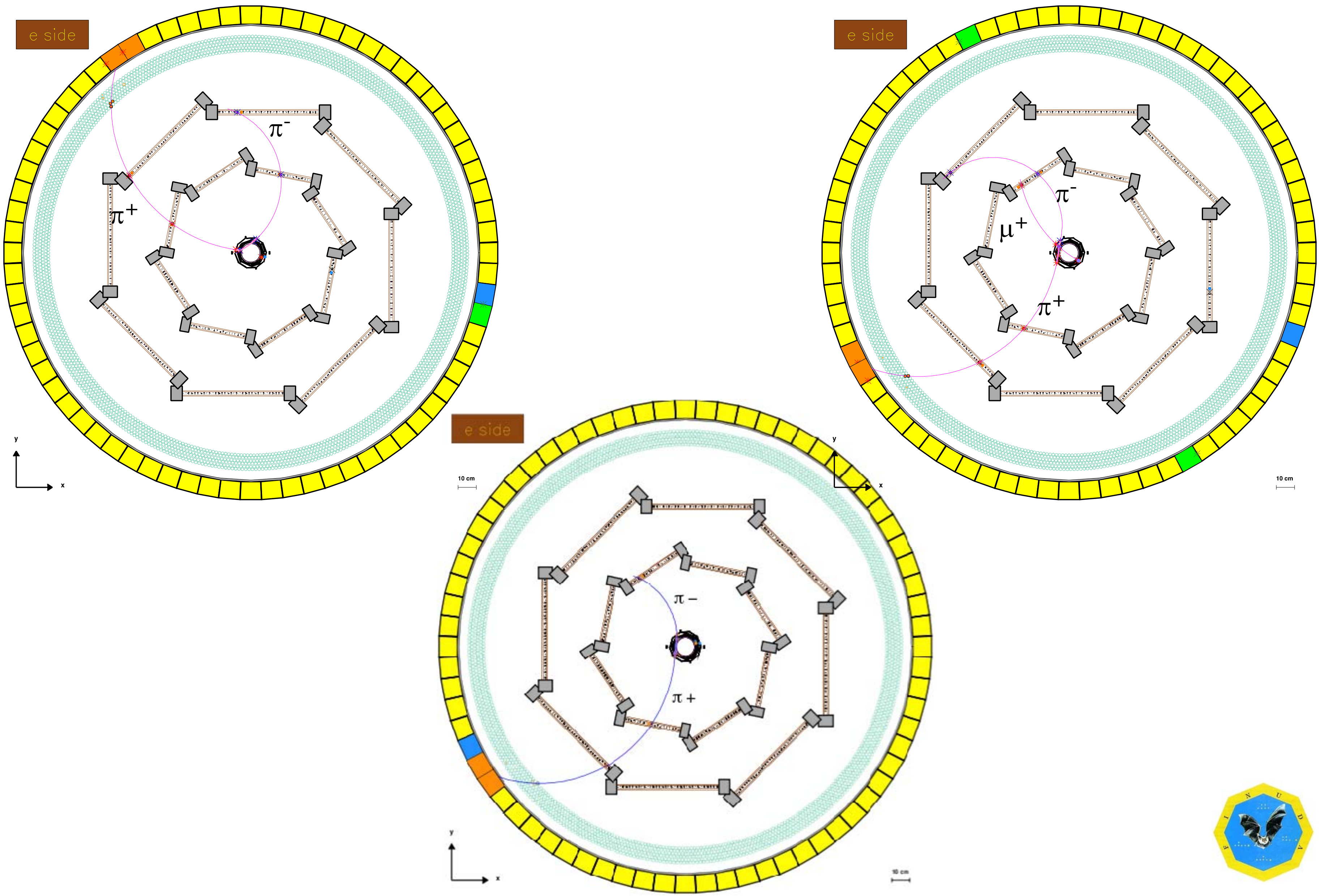


B_Λ = (4.0 ± 1.1) MeV (^{5}H + Λ)

~~B_Λ = 5.8 MeV (^{5}H + Λ)~~
~~ΛNN force ≡ 1.4 MeV~~

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

Kinematics compatibility: visual scan



$^9He_\Lambda$ production rate

- 0 observed events → upper limit evaluation
- $\varepsilon(\pi^-)$, $\varepsilon(\pi^+)$
- n. stopped K^- on ^{9}Be = 2.5×10^7 ev.

$$R * BR(\pi^-) < (2.3 \pm 1.9) \times 10^{-6} / (n.\ K^-_{stop}\ \text{on}\ {}^9Be)\ (90\%\ \text{C.L.})$$

$$BR(\pi^-) = 0.323 \pm 0.062^{+0.025}_{-0.020}$$

$$\Gamma({}^9_\Lambda He_{g.s.} \to {}^9Li_{g.s.} + \pi^-) = 0.261\ \Gamma_\Lambda$$

$${}^5_\Lambda He + 4\ \text{spectator}\ neutrons$$

M. Agnello *et al.*, *PLB* 681 (2009) 139

A. Gal, *NPA* 828 (2009) 72

$$R = 1.3 \cdot 10^{-5} / K^-_{stop}\ \ (90\%\ C.L.)$$

$$R = 1.6 \cdot 10^{-5} / K^-_{stop}\ \ (90\%\ C.L.)$$

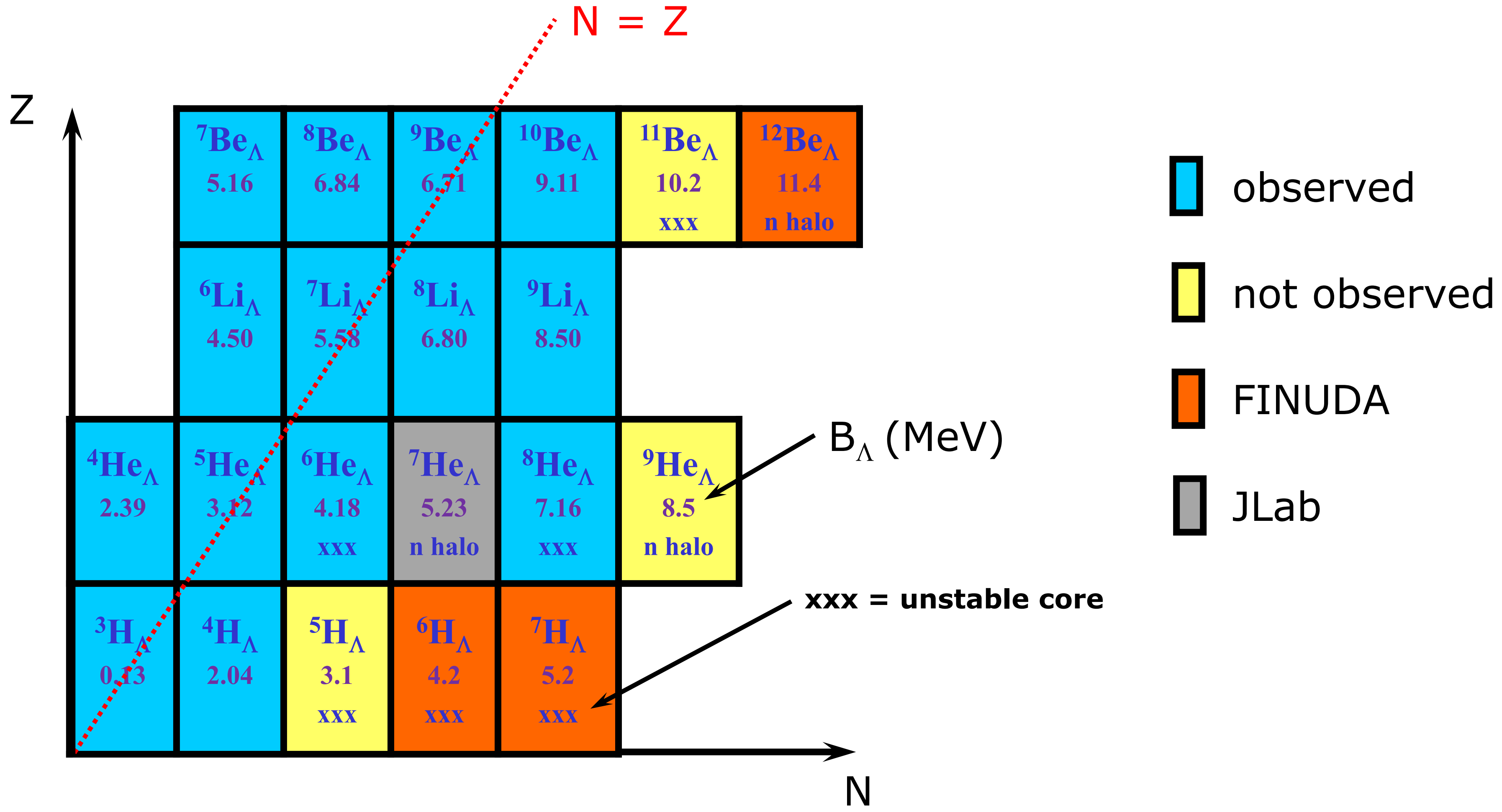
M. Agnello *et al.*, *PRC* 86 (2012) 057301

$$2.3 \cdot 10^{-4} / K^-_{stop}$$

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

Neutron-rich hypernucley summary

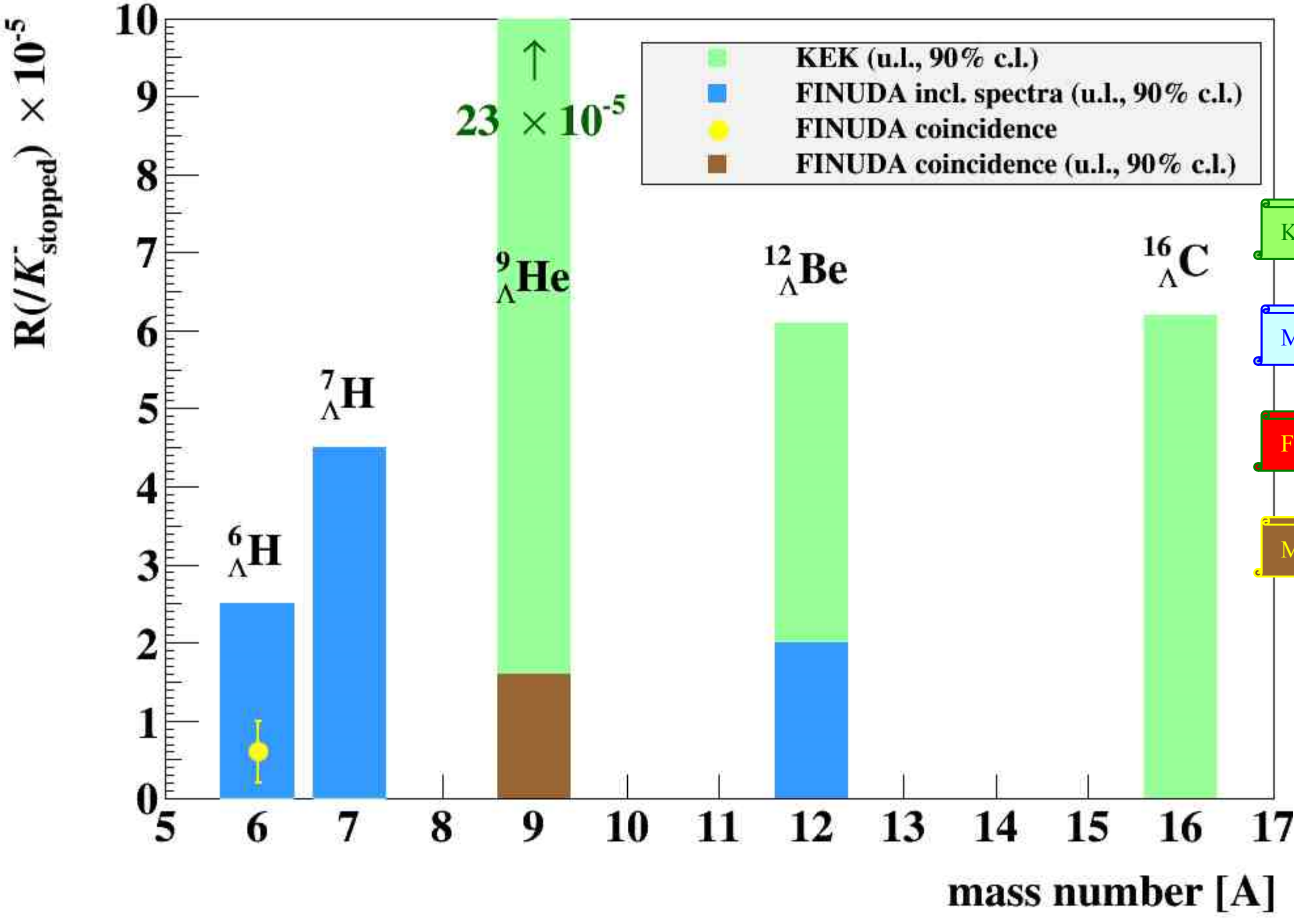
Glue-like role of Λ: observation of n-rich hyperfragments in emulsions
$^{6}He_{\Lambda}$, $^{8}He_{\Lambda}$, $^{9}Li_{\Lambda}$



from: Nuclear Wallet Cards 2001, NNDC, BNL

L. Majling, *NPA* 585 (1995) 211c

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



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

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

FINUDA Coll. and A. Gal, *PRL* 108 (2012) 042501

M. Agnello *et al.*, *PRC* 86 (2012) 057301

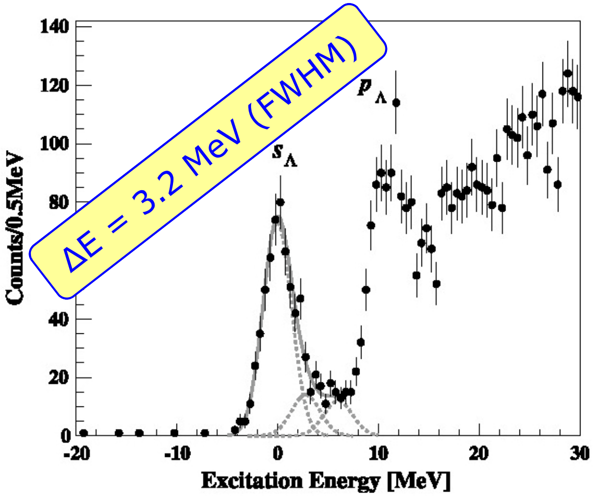
theoretical interest:

D.J. Millener, *NPA* 881 (2012) 298

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

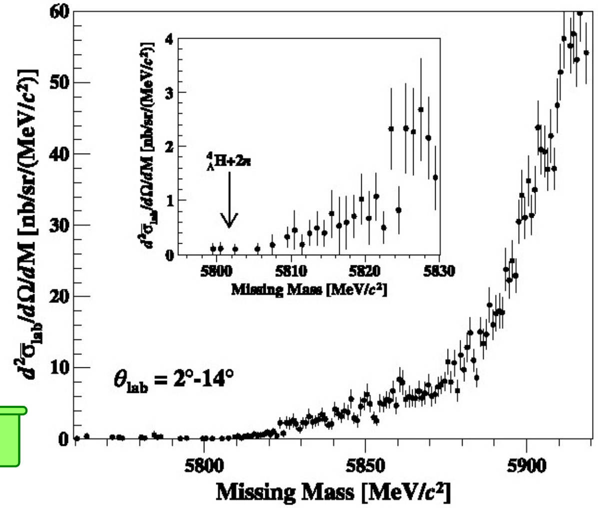
A. Gal, D.J. Millener, *PLB* 725 (2013) 445

E10: no evidence!?!



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

J-PARC E10



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

$$d\sigma / d\Omega \leq 1.2 \ \ nb/sr \ \ (90\% \ \ C.L.)$$

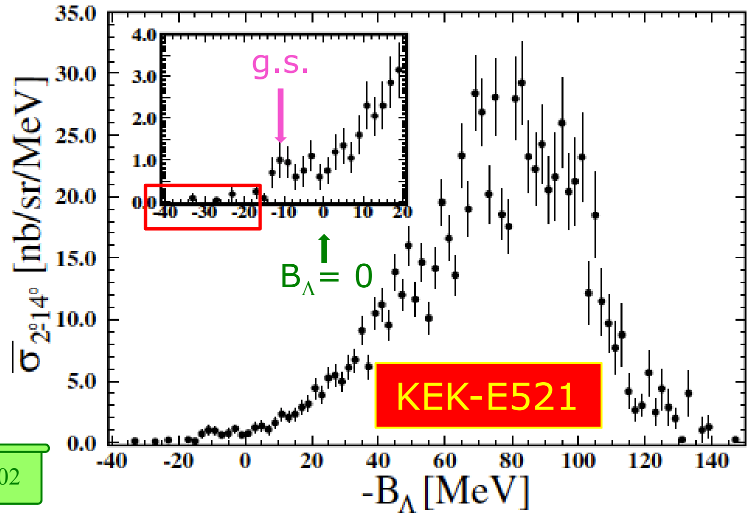
one order of magnitude lower than…

background free reactions

$$\pi^- + {}^{10}B \rightarrow {}^{10}_\Lambda Li + K^+$$

σ_B = 2.5 MeV (FWHM)

$$d\sigma / d\Omega = 11.3 \pm 1.9 \ \ nb/sr$$



P.K. Saha *et al.*, *PRL* 94 (2005) 052502

Summary and outlook

- Last but not least results from FINUDA:

    - first experimental evidence for the heavy hyperhydrogen $^{6}H_{\Lambda}$
    - limited number of candidates (3)
    - powerful but not universal method
    - puzzling result from J-PARC E10
    - theoretical predictions not in agreement

further investigations needed
both experimental and theoretical

Thank you!

どうも　ありがとう