3rd International Workshop on
"State of the Art in Nuclear Cluster Physics"

KGU Kannai Media Center,
Kanto Gakuin University, Yokohama, Japan.

May 26-30, 2014

First experimental evidence for $^{6}H_{\Lambda}$ by the FINUDA experiment

Alessandro Feliciello

I.N.F.N. - Sezione di Torino

Acknowledgement

A **warm thanks** to the organizers
for the **invitation**

and to

Grant-In-Aid for Scientific Research on Innovative Areas "Nuclear Matter in Neutron Stars Investigated by Experiments and Astronomical Observations"

for the **financial support**

Outline

- physics motivations
- experimental results:
  - FINUDA @ INFN/LNF
  - E10 @ J-PARC
- a look to the (next) future:
  - what next?

see
H. Sugimura's talk
(Thursday)

Search for neutron-rich hypernuclei

central issue in hypernuclear physics

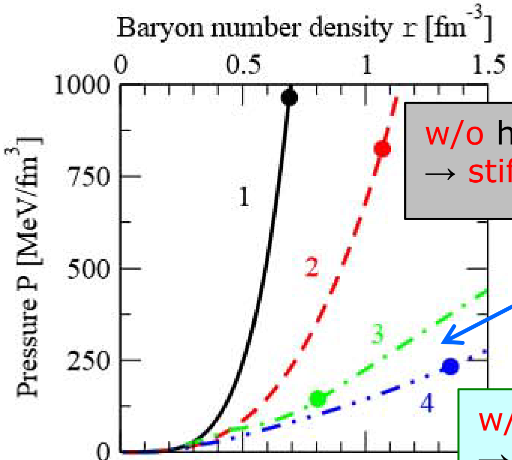
❖ historical paper: R.H. Dalitz and R. Levi Setti, Nuovo Cimento 30 (1963) 489

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

⇩

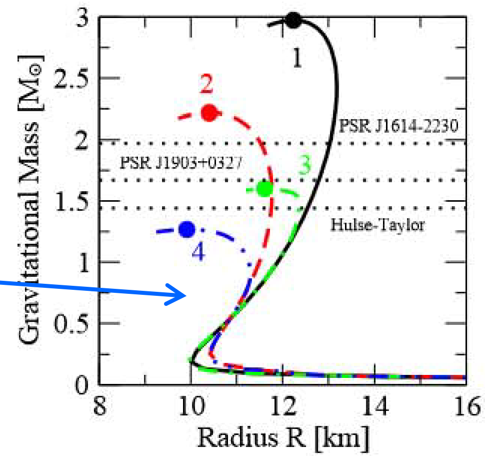


w/o hyperons → stiff EoS

w/ hyperons → soft EoS

direct influence on neutron star EoS

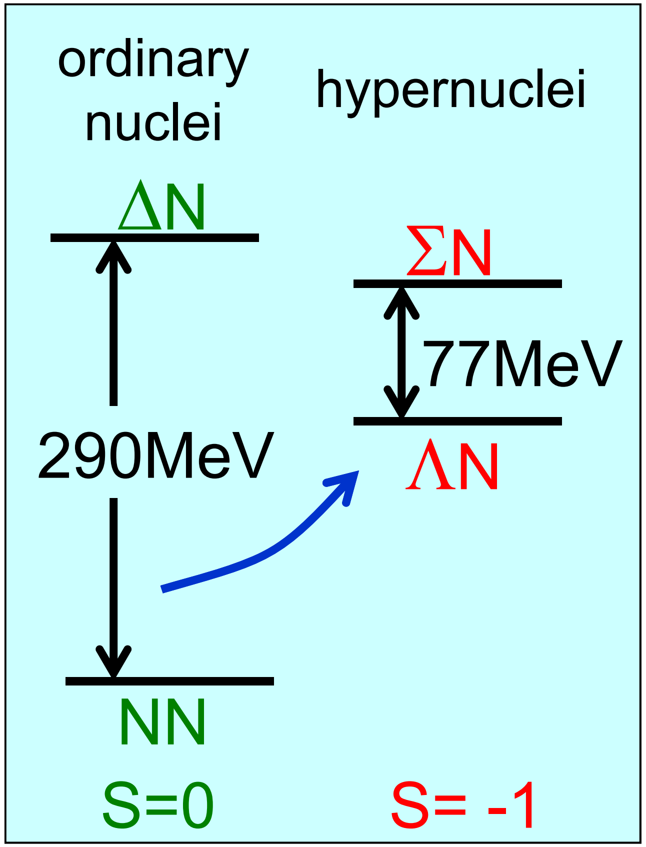
prediction of neutron star main parameters



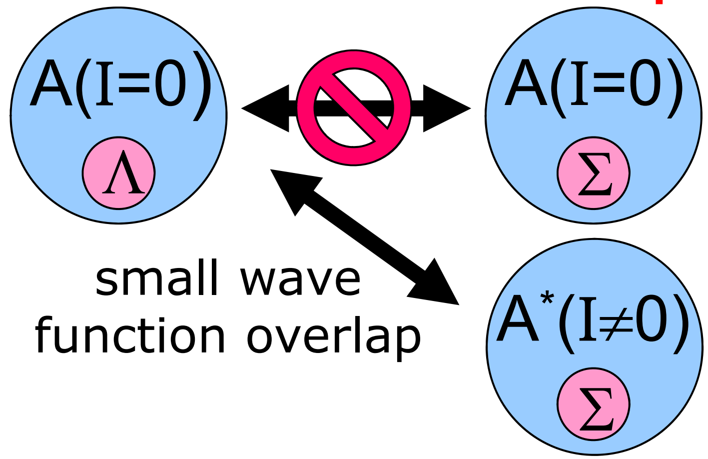
I. Vidaña *et al.*, *EPL* 94 (2011) 11002

ΛN-ΣN mixing effect

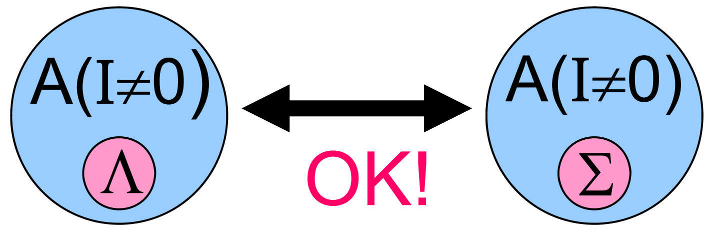
B.F. Gibson *et al.*, *PRC* 6 (1972) 741



for nuclear core isospin = 0



for nuclear core isospin ≠ 0



important effect in *n*-rich hypernuclei!

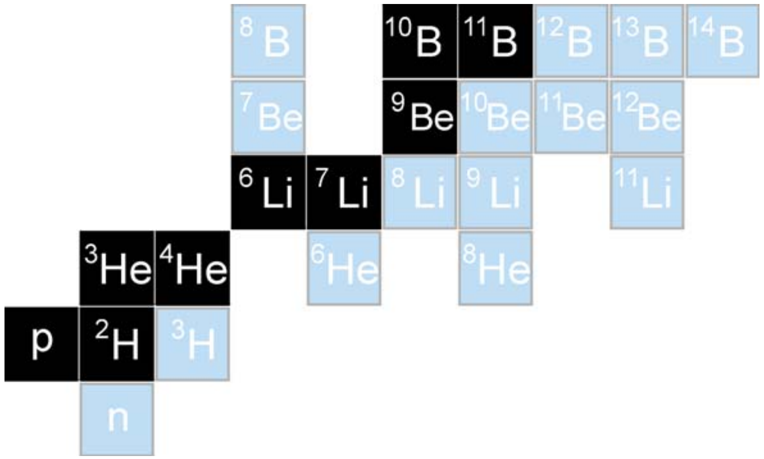
is it responsible for extra Λ binding energy?

Y. Akaishi and T. Yamazaki, *Frascati Phys. Ser.* XVI 6 (1999) 59

H. Sugimura for the E10 Collaboration @ INPC 2013; @ APPC12.

Λ-hypernuclei production

ordinary nuclei

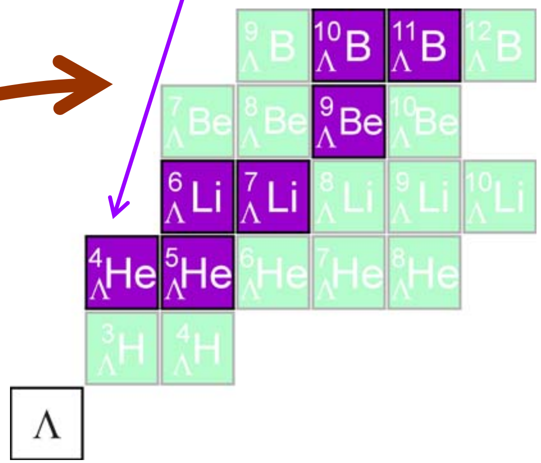


Λ-hypernuclei

(K^-,π^-), (π^+,K^+)

Non Charge-Exchange (NCX)

N~Z (I=0 or ½)



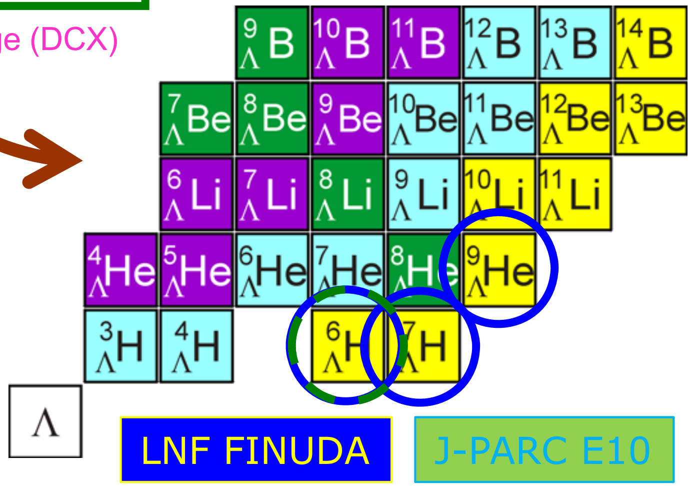
hyperfragments
by emulsions exp.

(K^-,π^+), (π^-,K^+)

Double Charge-Exchange (DCX)

2-3 order of magnitude
lower cross section
(two-step reaction)

N»Z (I=3/2 or 2)



H. Sugimura for the E10 Collaboration @ INPC 2013; @ APPC12.

The status of the art (as of 2011)

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

- $K^- + p \rightarrow \pi^0 + \Lambda$, $\pi^0 + p \rightarrow \pi^+ + n$: 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

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

- $\pi^- + p \rightarrow \pi^0 + n$, $\pi^0 + p \rightarrow K^+ + \Lambda$: 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

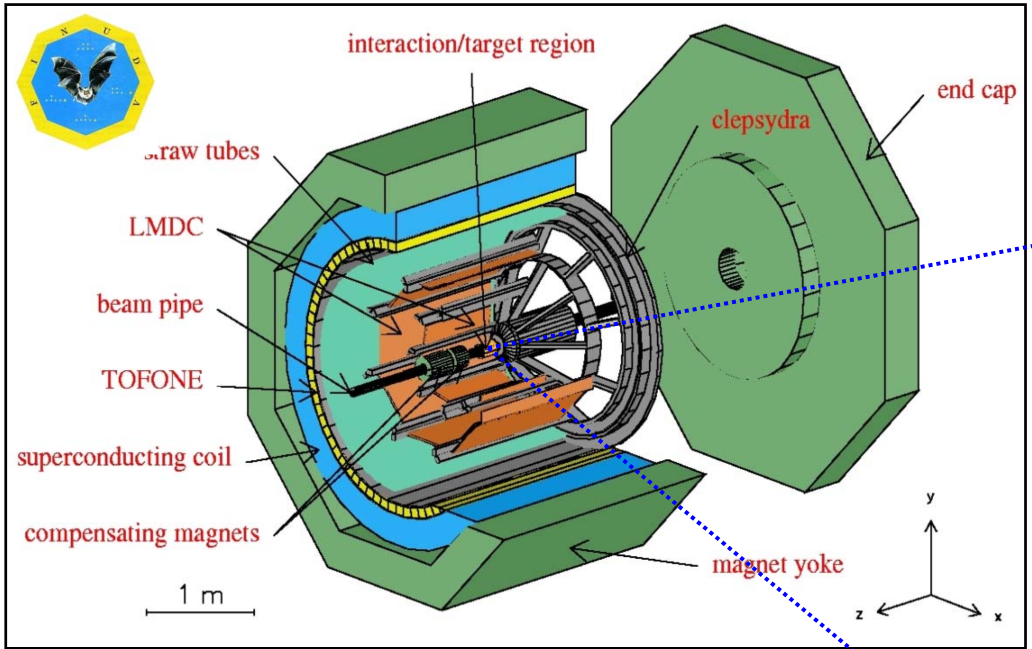
theoretical predictions

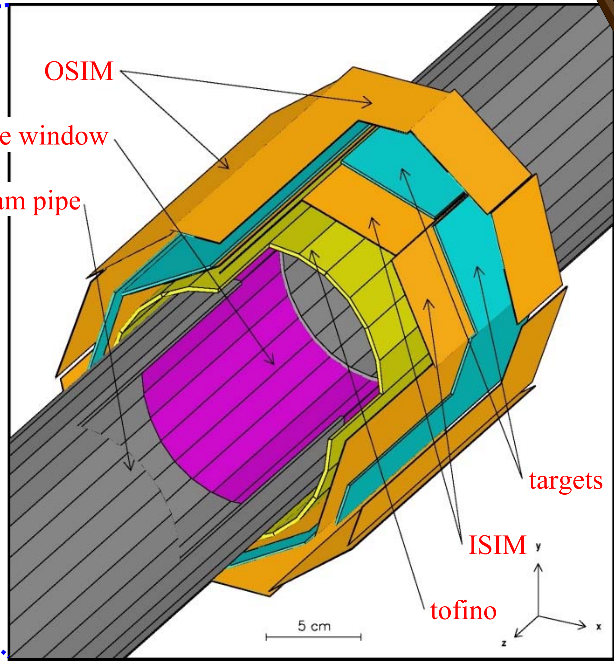
T.Y. Tretyakova *et al.*, *PAT* 66 (2003) 1681

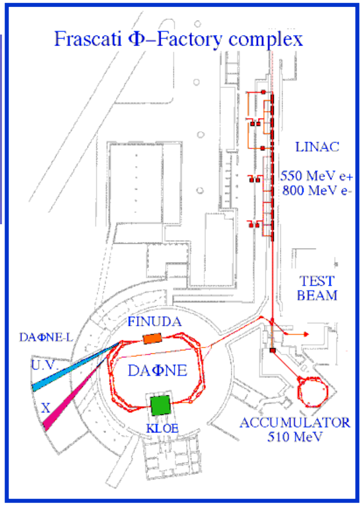
FINUDA @ DAΦNE

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

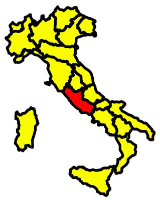
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$







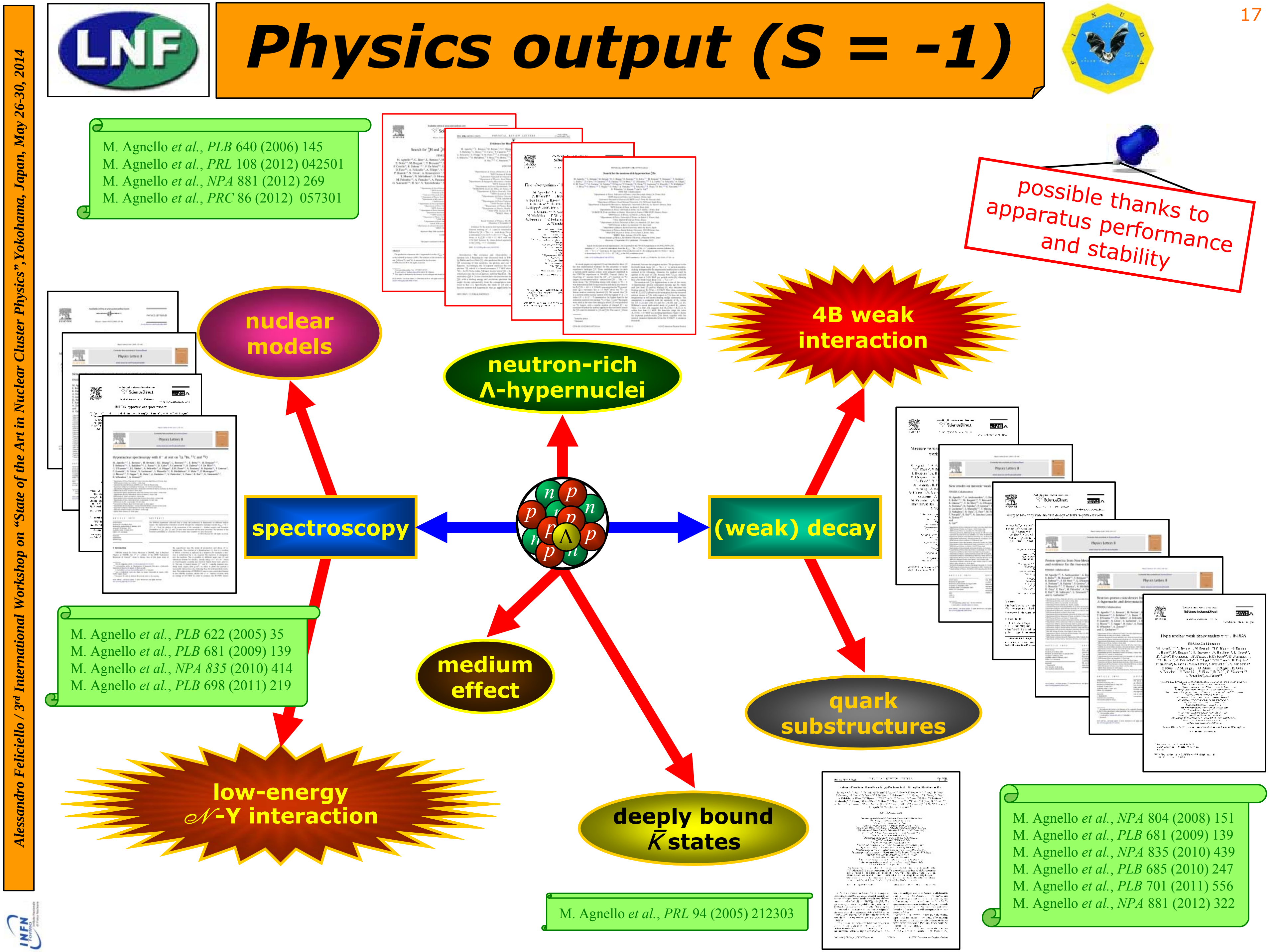
energy	510 MeV
luminosity	5 10^{32} $cm^{-2} s^{-1}$
σ_x (rms)	2.11 mm
σ_y (rms)	0.021 mm
σ_z (rms)	35 mm
bunch length	30 mm
crossing angle	12.5 mrad
frequency (max)	368.25 MHz
bunch/ring	up to 120
part./bunch	8.9 10^{10}
current/ring	5.2 A (max)



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

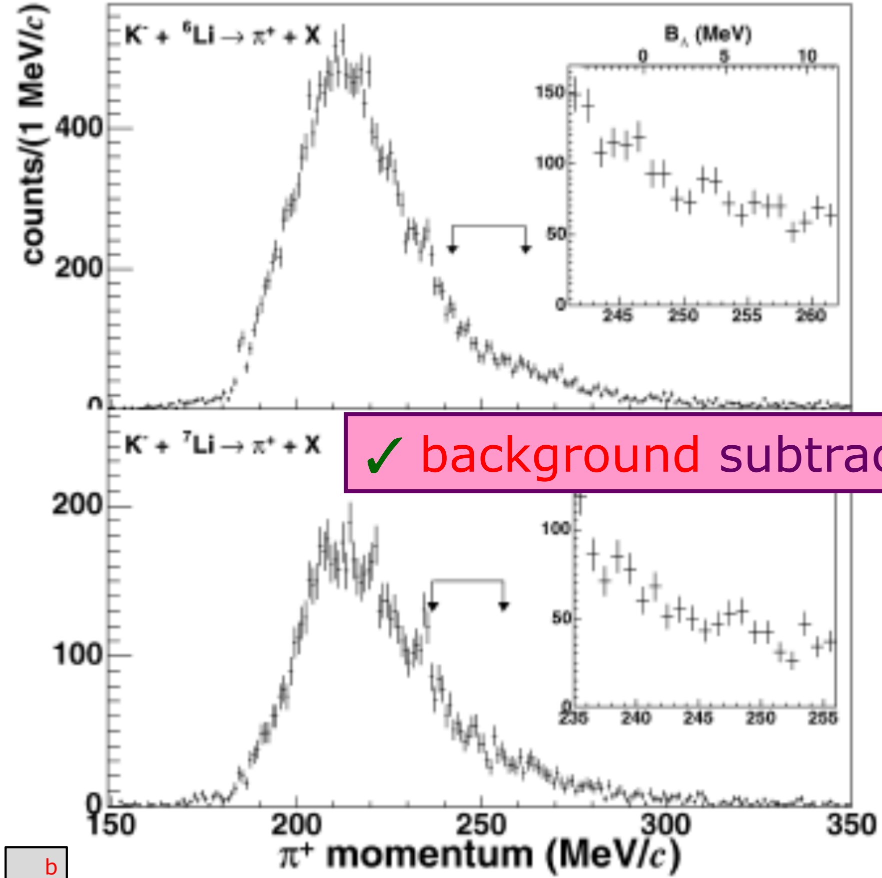
FINUDA key features

- 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


Alessandro Feliciello / 3rd International Workshop on "State of the Art in Nuclear Cluster Physics", Yokohama, Japan, May 26-30, 2014
LNF
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
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
low-energy 𝒩-Y interaction
deeply bound $\bar{K}$ states
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

The background issue

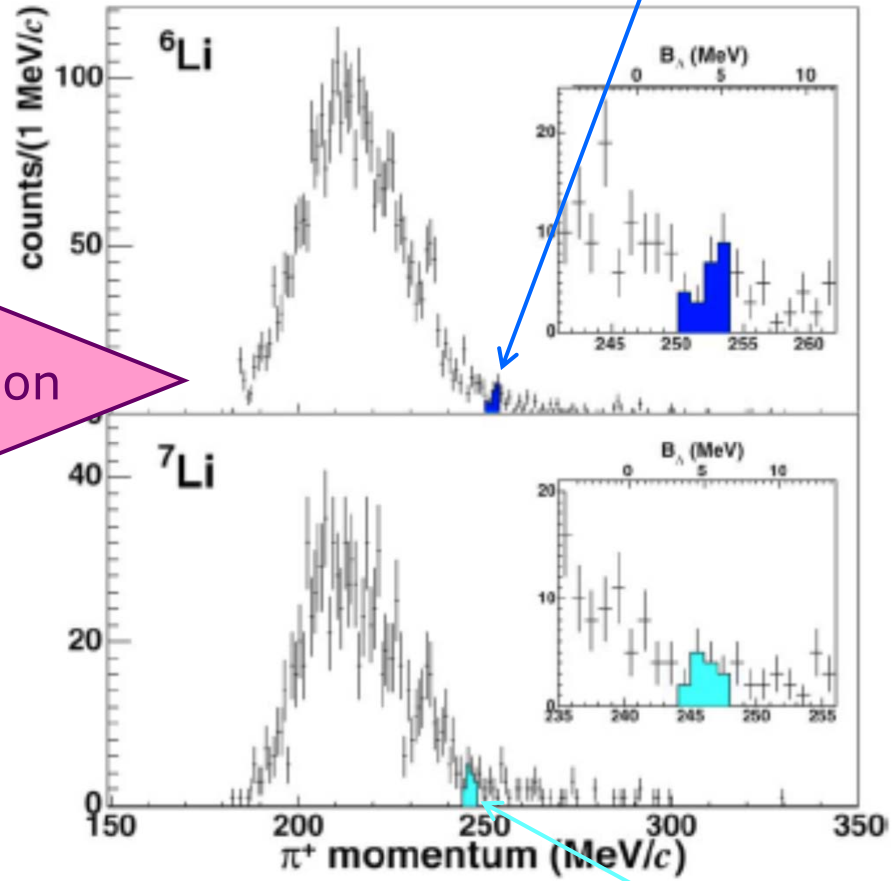
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}(Z-2) + \pi^+$$



✓ background subtraction

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

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



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

main background

$$K^- + p \rightarrow \Sigma^+ + \pi^-$$
$$\hookrightarrow n + \pi^+ \quad (\sim 130 < p_{\pi^+} < \sim 250 \text{ MeV}/c)$$
$$K^- + pp \rightarrow \Sigma^+ + n$$
$$\hookrightarrow n + \pi^+ \quad (\sim 100 < p_{\pi^+} < \sim 320 \text{ MeV}/c)$$

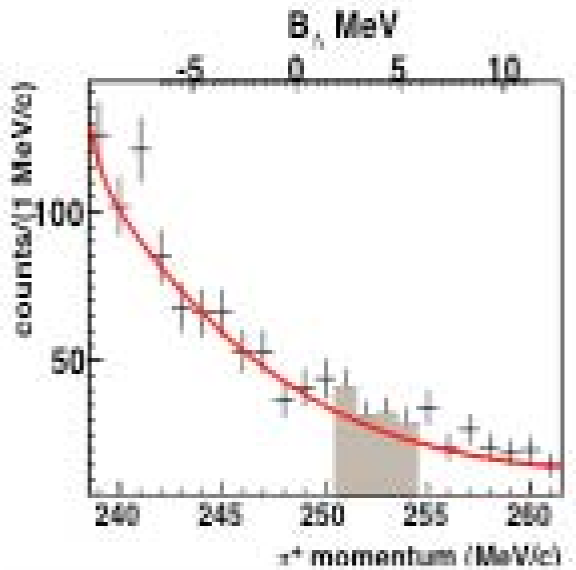
$\mathscr{L}_{int} \approx 220$ pb^{-1}

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

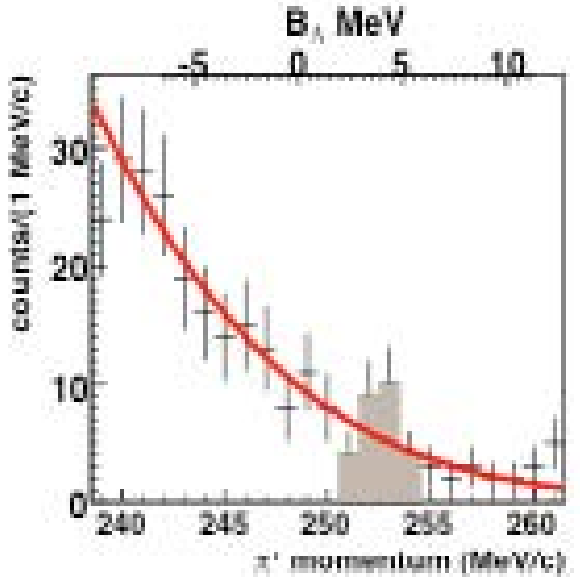
Higher statistics was not enough...

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

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



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



The new NRH search strategy

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

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

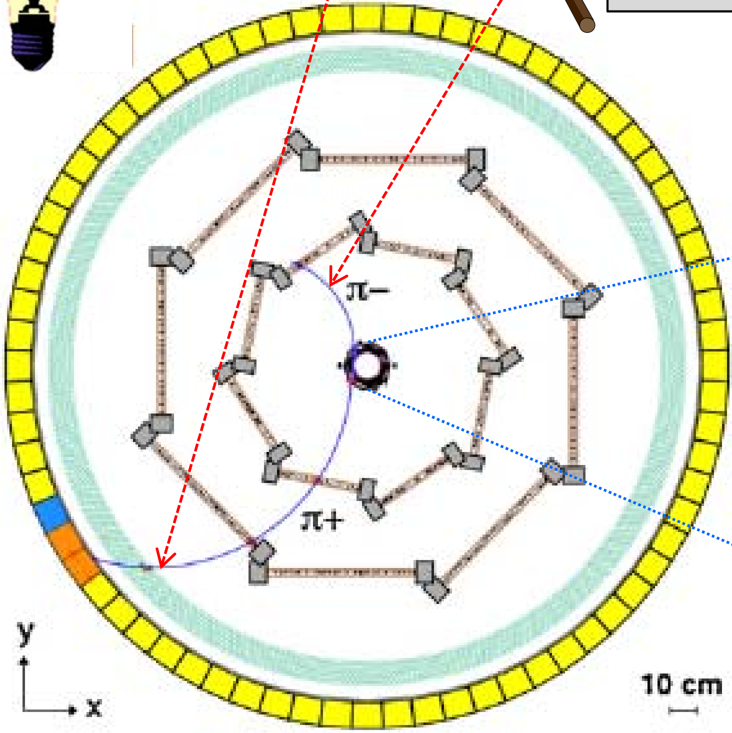
double C-EX
p ~ 252 MeV/c

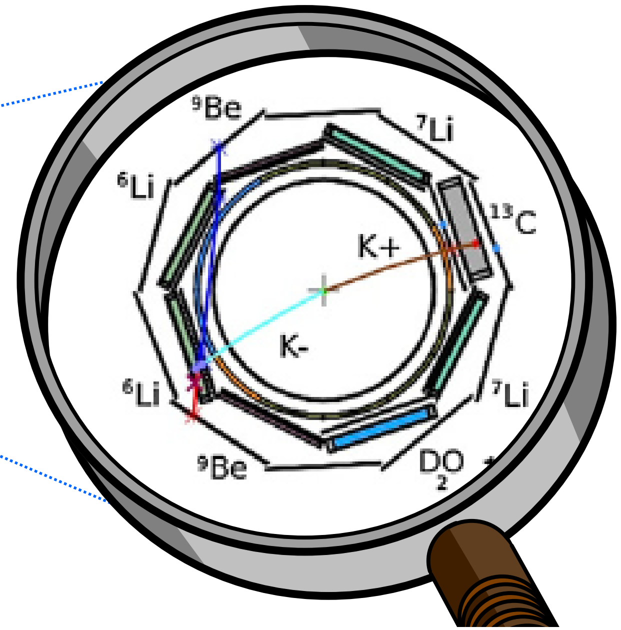
$${}^6_\Lambda H \rightarrow {}^6He + \pi^-$$

n.m. decay
p ~ 134 MeV/c

apparatus capabilities:

- selective trigger
  (based on fast scintillator detectors)
- precise K^- vertex identification < 1 mm³
  (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

Alessandro Feliciello / 3rd International Workshop on "State of the Art in Nuclear Cluster Physics", Yokohama, Japan, May 26-30, 2014

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

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

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

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

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

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

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

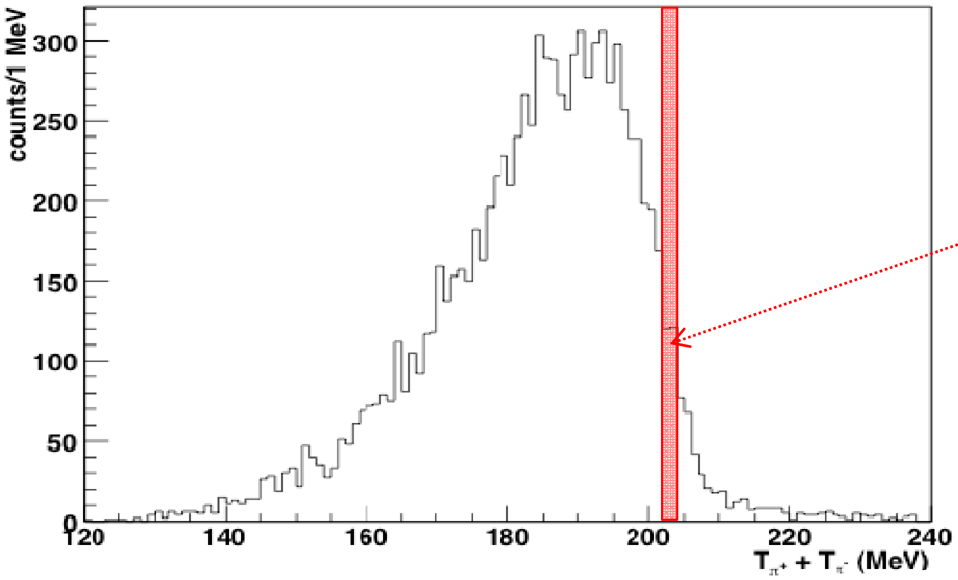
$$T(\pi^+) + T(\pi^-) = M(K^-) + M(p) - M(n) - 2M(\pi) - B(^6\text{Li}) + B(^6\text{He}) - T(^6\text{He}) - T(^6_\Lambda\text{H})$$

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

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

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

Data selection



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

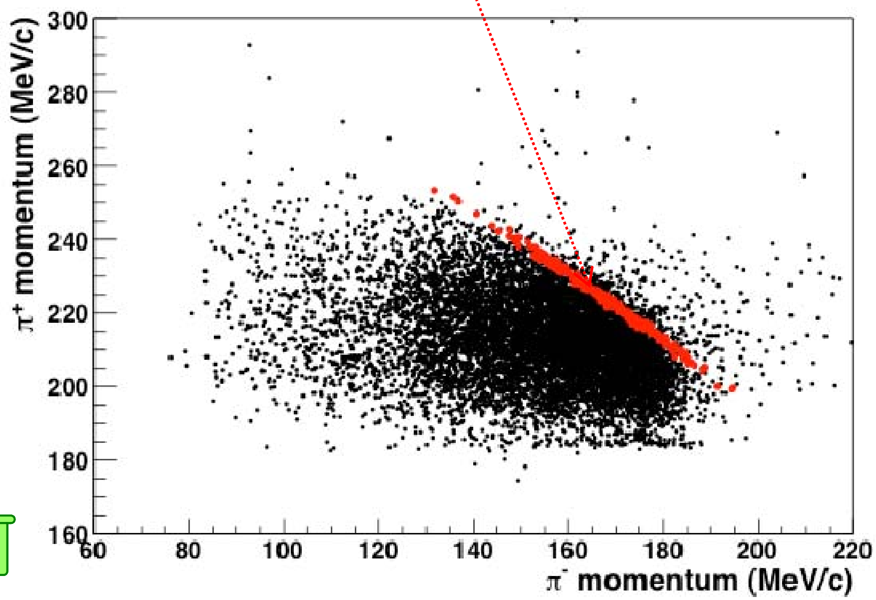
absolute energy scale:

- 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

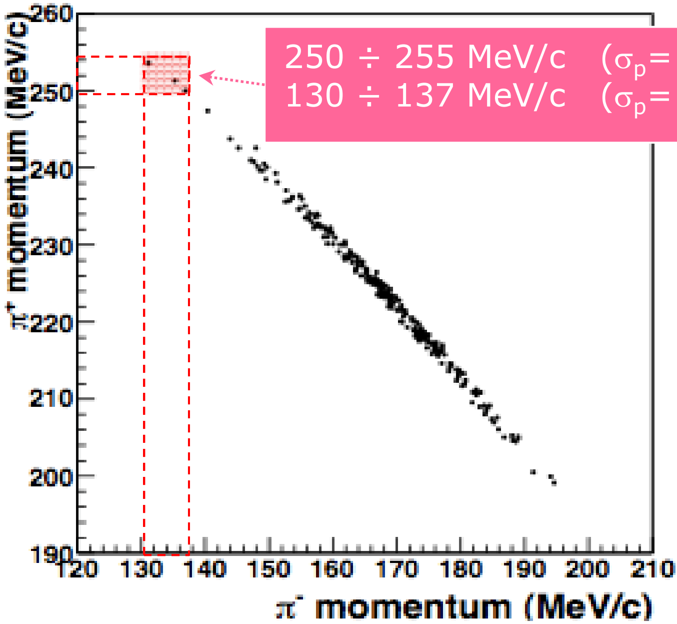
σT_{sys} = 0.17 MeV

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

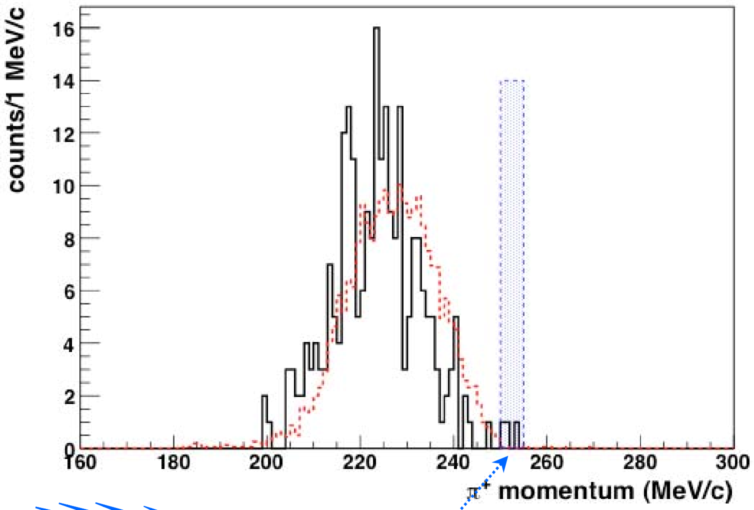


FINUDA Coll. And A. Gal, *NPA* 881 (2012) 269

Data selection

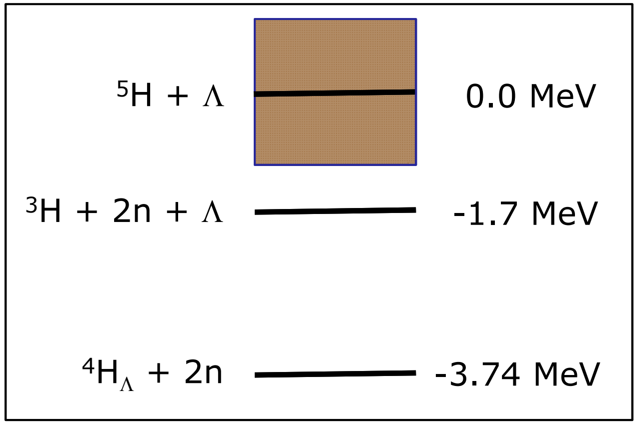


250 ÷ 255 MeV/c (σ_p=1.1 MeV/c)
130 ÷ 137 MeV/c (σ_p=1.2 MeV/c)



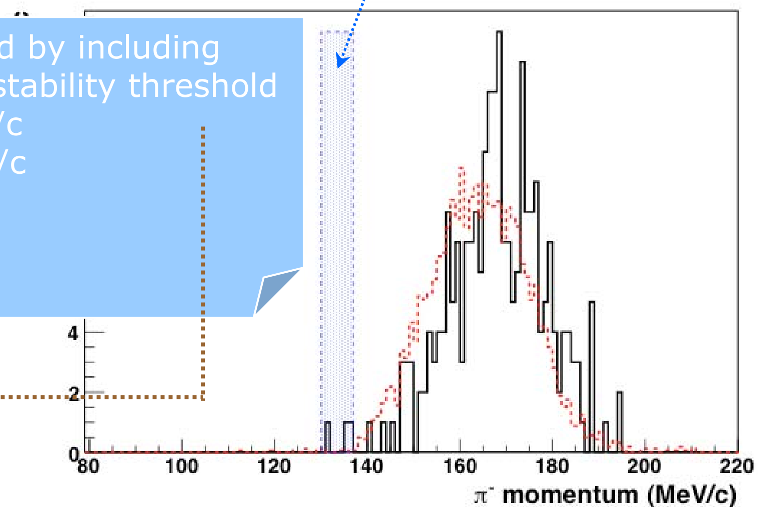
3 candidate events

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



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

B_Λ = 1.5 ÷ 6 MeV



$^{6}H_{\Lambda}$ production rate

background sources

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

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

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

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

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

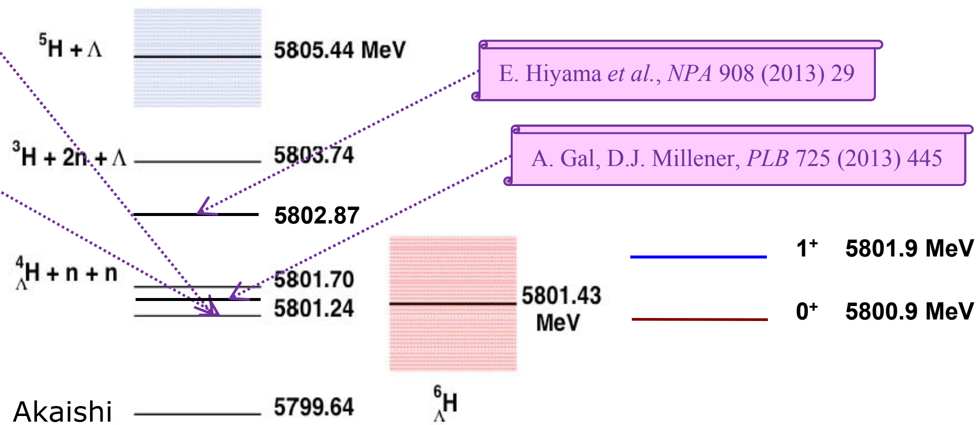
B $^4_\Lambda$He 2.39 Λ	$^5_\Lambda$He 3.12 Λ	◇ $^6_\Lambda$He 4.18 n 0.17 xxx	◇ $^7_\Lambda$He 5.23 α 2.92 halo	$^8_\Lambda$He 7.16 n 1.49 xxx	♠ $^9_\Lambda$He (8.5) n 3.9 halo
$^3_\Lambda$H 0.13 Λ	◇ $^4_\Lambda$H 2.04 Λ	$^5_\Lambda$H (3.1) n -1.8 xxx	♠ $^6_\Lambda$H (4.2) 2n -5 xxx	♠ $^7_\Lambda$H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

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

$\bar{M}$ = (5801.4 ± 1.1) MeV

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

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



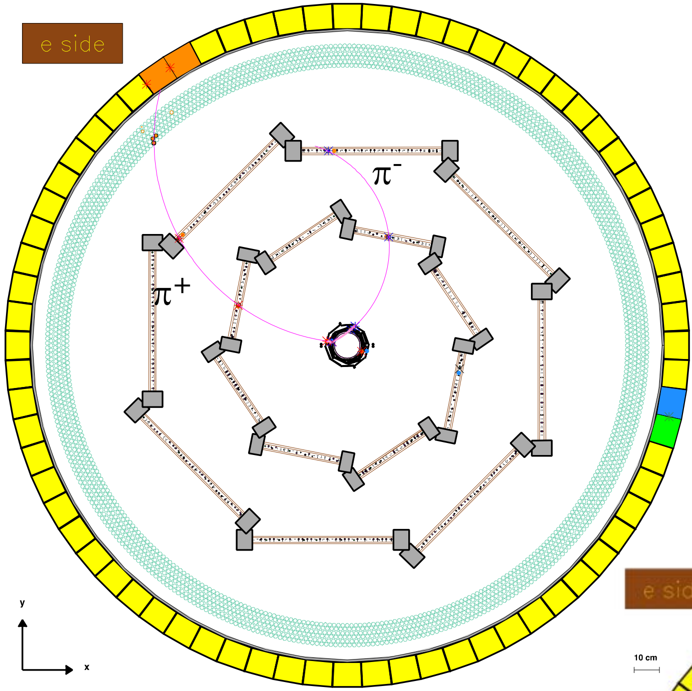
B_Λ = (4.0 ± 1.1) MeV (^{5}H + Λ)

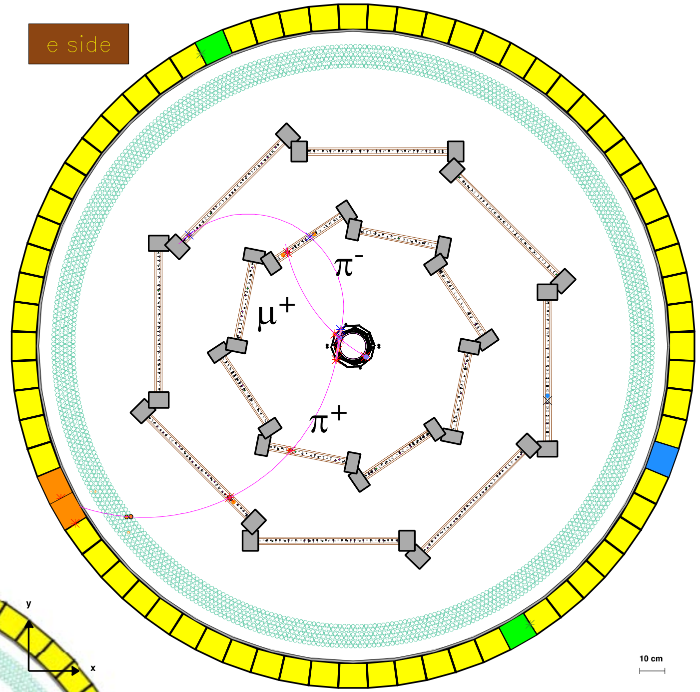
~~B_Λ = 5.8 MeV (^{5}H + Λ)~~
~~ΛNN force ≡ 1.4 MeV~~

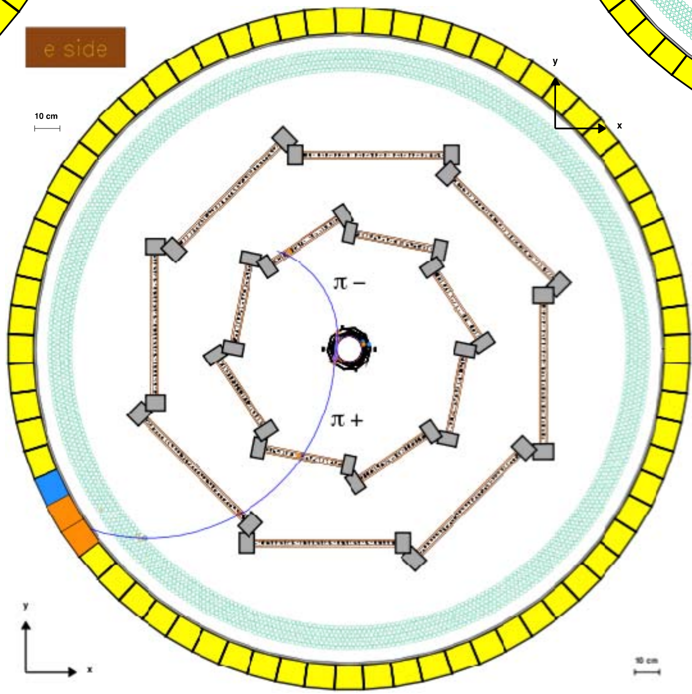
FINUDA Coll. and A. Gal, *PRL* 108 (2012) 042501
FINUDA Coll. and A. Gal, *NPA* 881 (2012) 269

Kinematics compatibility: visual scan

Alessandro Feliciello / 3rd International Workshop on “State of the Art in Nuclear Cluster Physics”, Yokohama, Japan, May 26-30, 2014







Analysis technique

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

$${}^9_\Lambda He \rightarrow {}^9Li + \pi^-$$

$(\tau({}^6Li) \approx 178\ \text{ms})$

if ${}^9He_\Lambda$ is a stable system ⇒ 2 independent two-body reactions:

decay at rest

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

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

atomic mass tables

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

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

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

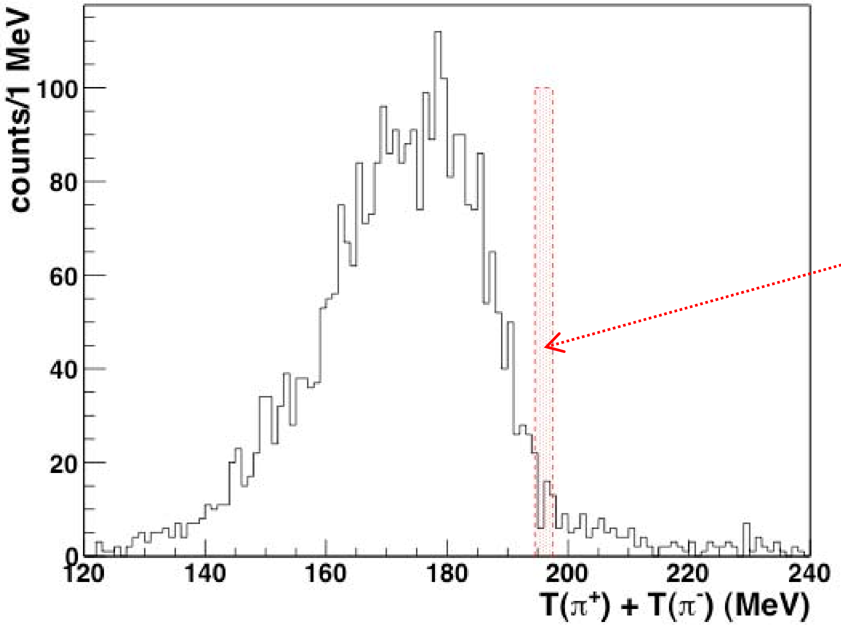
$$T(\pi^+) + T(\pi^-) = M(K^-) + M(p) - M(n) - 2M(\pi) - B({}^9\text{Be}) + B({}^9\text{Li}) - T({}^9\text{Li}) - T({}^9_\Lambda\text{He})$$

$$= 195.8 \pm 1.3\ \text{MeV}$$

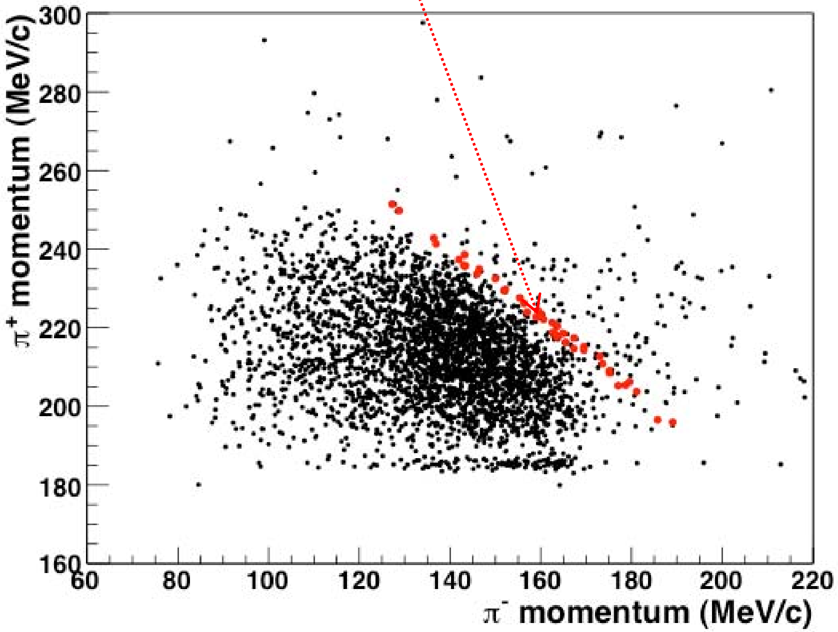
$(195.8 \div 195.7\ \text{MeV with } B_\Lambda = 0 \div 10\ \text{MeV})$

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

Data selection

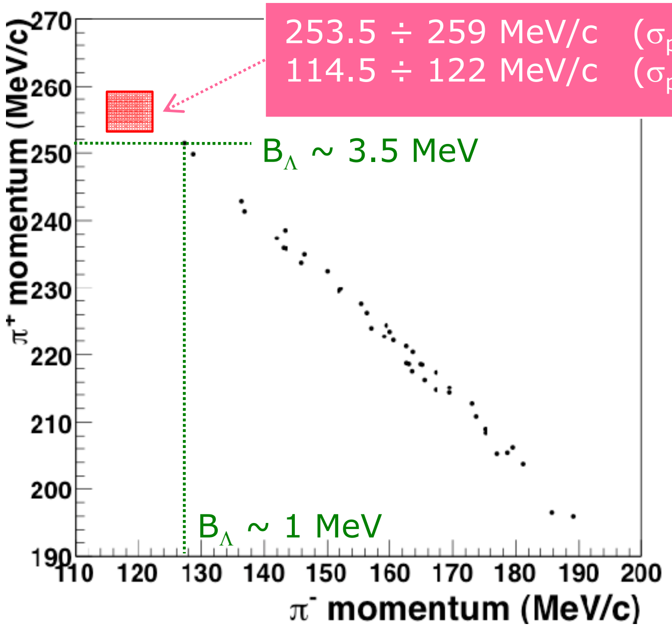


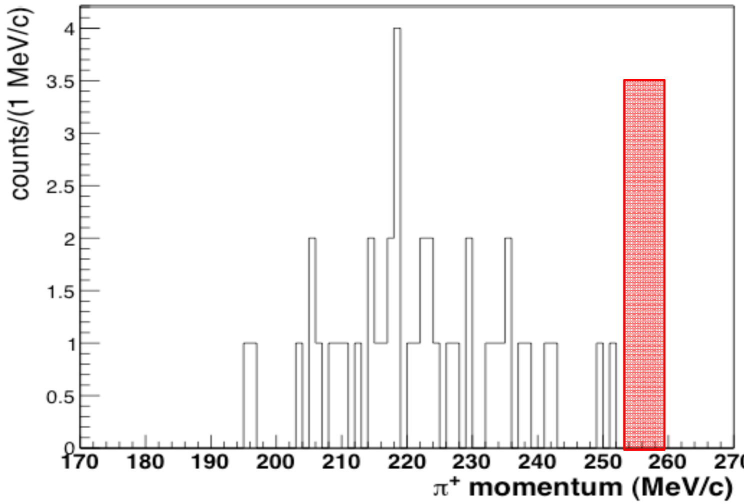
$T(\pi^+)+T(\pi^-):\ 194.5 \div 197.5\ \text{MeV}$



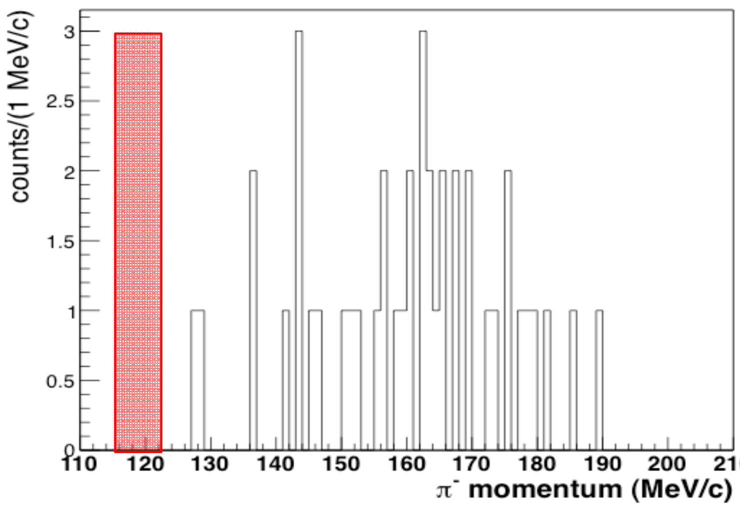
Data selection

253.5 ÷ 259 MeV/c (σ_p=1.1 MeV/c)
114.5 ÷ 122 MeV/c (σ_p=1.2 MeV/c)





B_Λ = 5 ÷ 10 MeV



Production rate

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

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

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

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

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

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

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

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

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

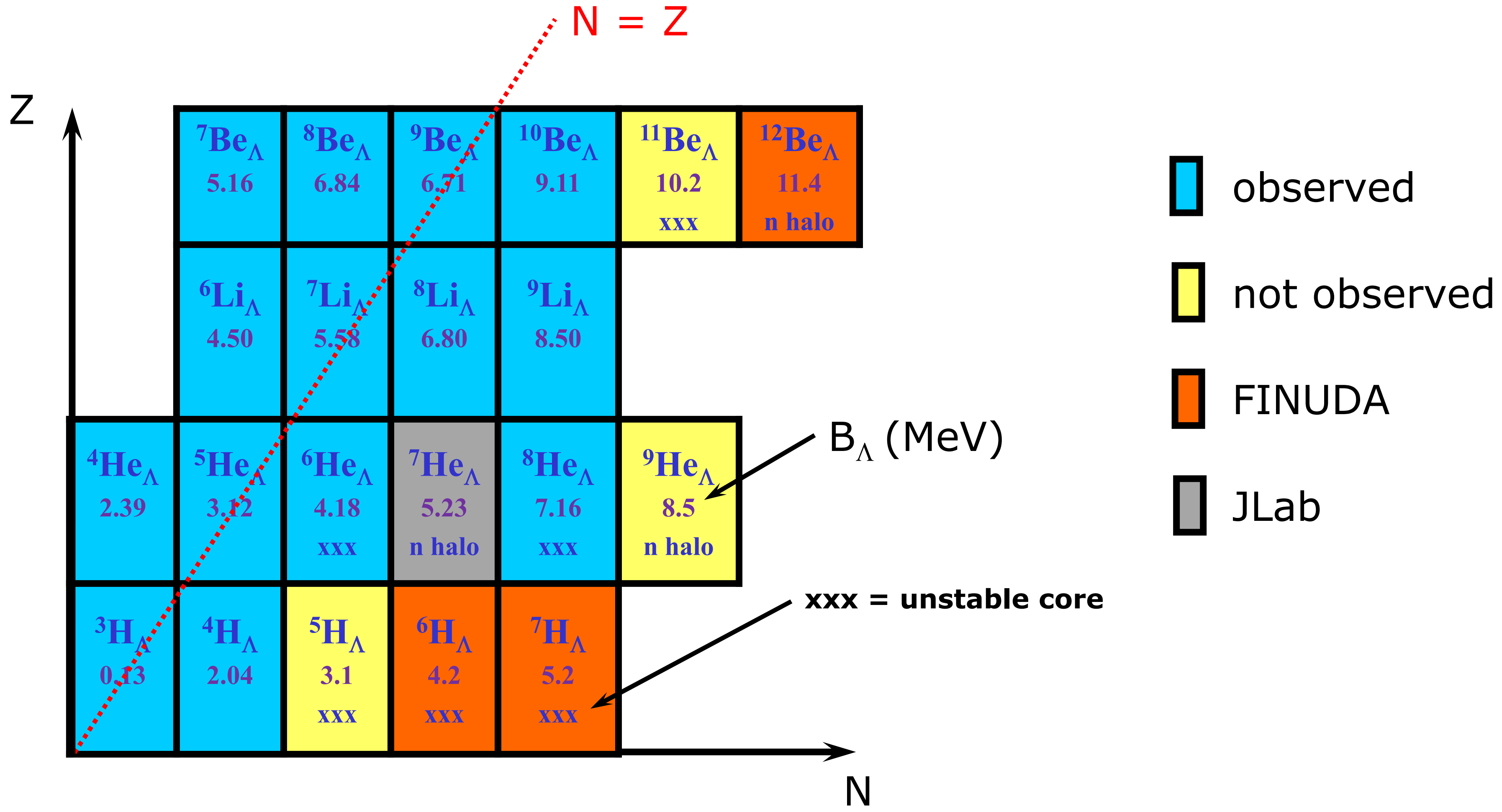
M. Agnello *et al.*, *PRC* 86 (2012) 057301

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

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

Neutron-rich hypernucley summary

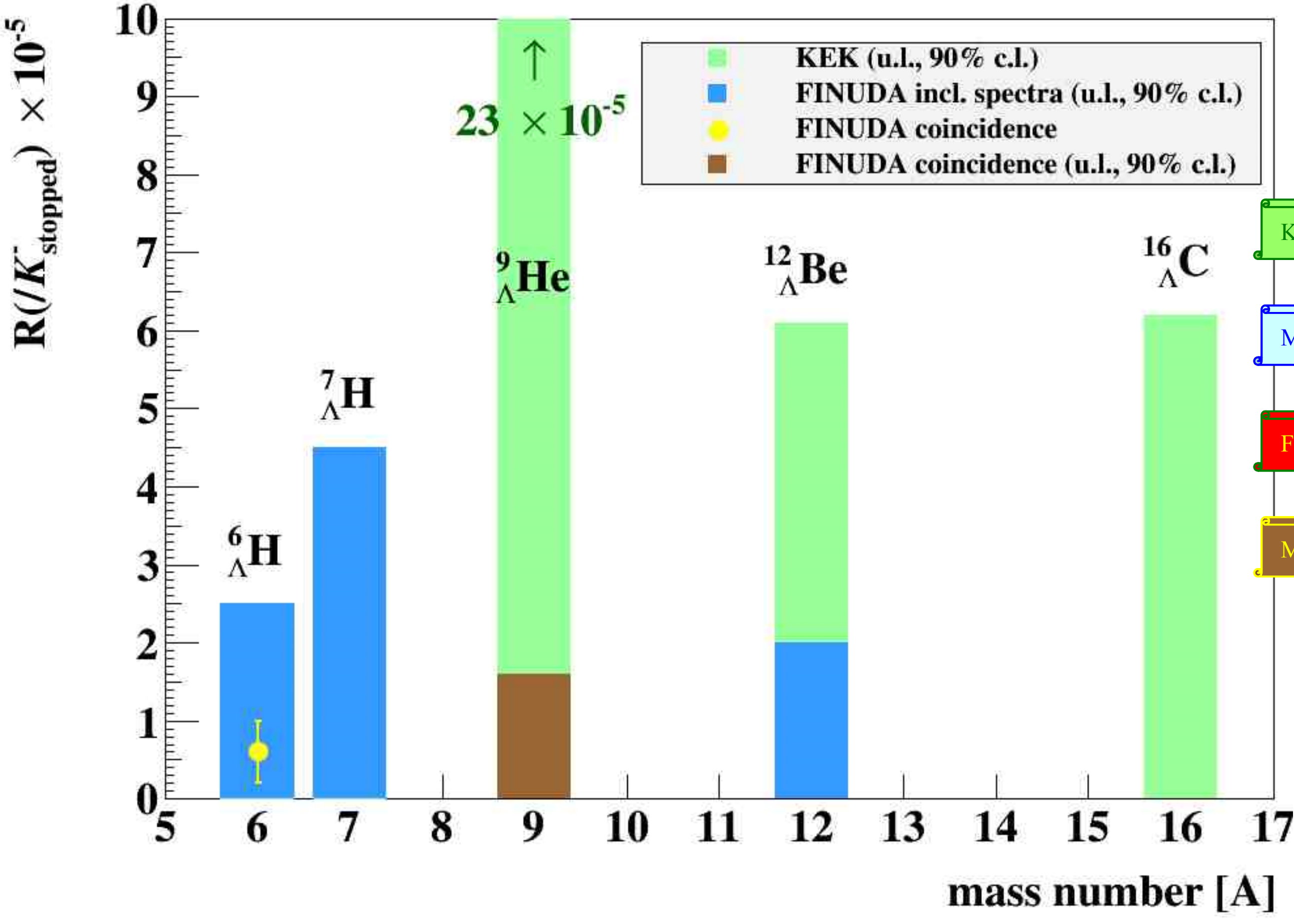
Glue-like role of Λ: observation of n-rich hyperfragments in emulsions
$^{6}He_{\Lambda}$, $^{8}He_{\Lambda}$, $^{9}Li_{\Lambda}$



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:

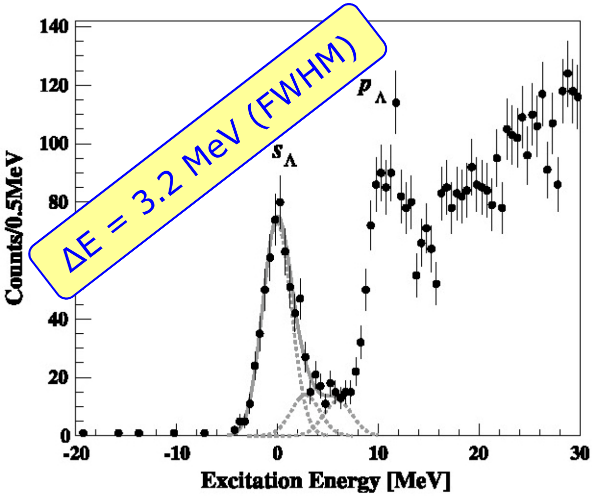
D.J. Millener, *NPA* 881 (2012) 298

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

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

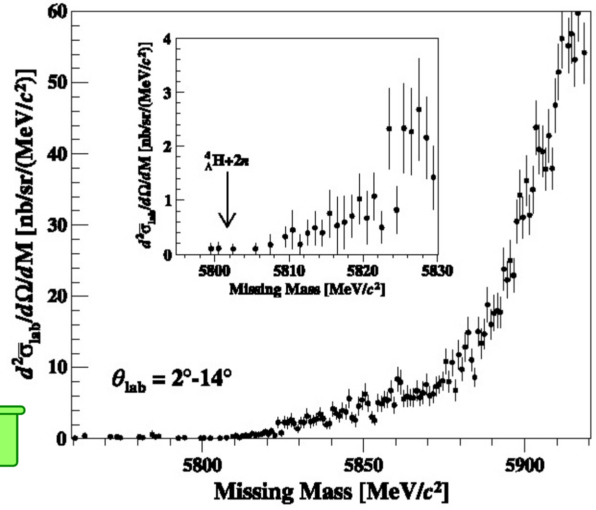
E10: no evidence!?!

J-PARC E10



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

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



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

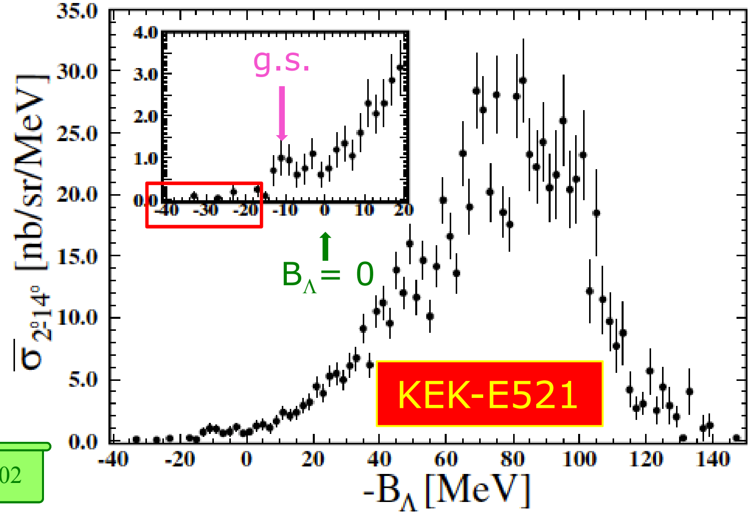
one order of magnitude lower than…

background free reactions

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

σ_B = 2.5 MeV (FWHM)

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



see **H. Sugimura's talk** (Thursday)

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)
  - negative results 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