# *Λ-hypernucleus decay: a discovery tool*

from the point of view of an experimentalist

# NUFRA2013

29 September - 6 October, 2013, Kemer (Antalya), Turkey

Study of Strongly Interacting Matter
HadronPhysics


*Alessandro Feliciello*

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

# Outline

- physics motivations
  1. "a posteriori" (discovery tool)
  2. intrinsic

- experimental results:
  - mesonic decay
  - (exclusive) non-mesonic decay
  - 2$\mathcal{N}$ induced decay

- a look to the (next) future:
  - waiting for J-PARC
  - waiting for J-Lab
  - waiting for MAMI

see Y. Fujii's talk (today)

see F. Schulz's talk (today)

# The original NRH search strategy

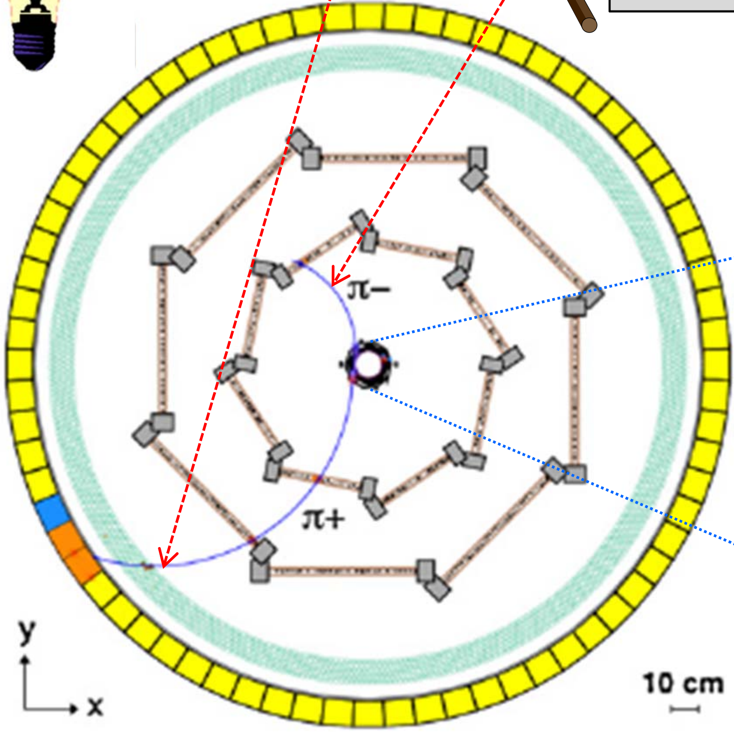
$\mathcal{L}_{int} \approx$ 1156 pb$^{-1}$ → coincidence measurements

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

double C-EX
p ~ 252 MeV/c

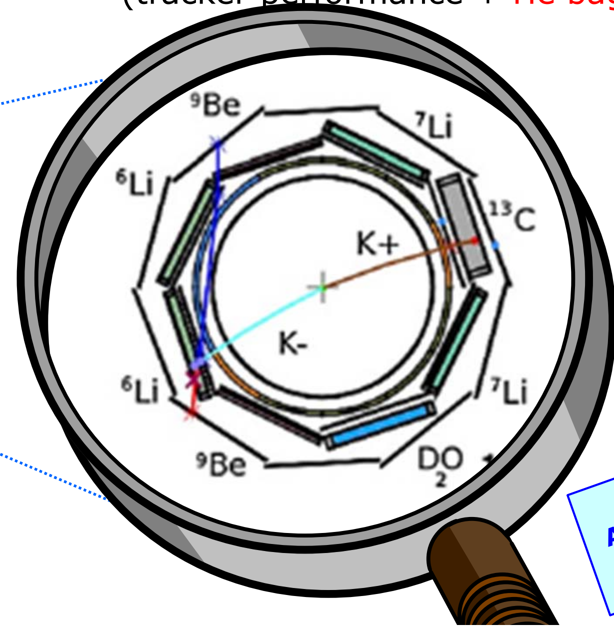
$$^6_\Lambda H \rightarrow {}^6He + \pi^-$$

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)
- $\pi$, $K$, $p$, $d$, … separation (OSIM & LMDC dE/dx)
- high momentum resolution
  6‰ FWHM $\pi^-$ @ 270 MeV/c
  6% FWHM $\pi^-$ @ 110 MeV/c
  (tracker performance + He bag + thin target)




see **A. Sakaguchi's talk** (Friday)

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



## background sources

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

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

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

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

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

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

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

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

# Kinematics and binding energy



| $T_{tot}$ (MeV) | $p_{\pi^+}$ (MeV/c) | $p_{\pi^-}$ (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) |
|---|---|---|---|---|---|---|
| $202.6 \pm 1.3$ | $251.3 \pm 1.1$ | $135.1 \pm 1.2$ | $5802.33 \pm 0.96$ | $5801.41 \pm 0.84$ | $5801.87 \pm 0.96$ | $0.92 \pm 1.28$ |
| $202.7 \pm 1.3$ | $250.1 \pm 1.1$ | $136.9 \pm 1.2$ | $5803.45 \pm 0.96$ | $5802.73 \pm 0.84$ | $5803.09 \pm 0.96$ | $0.72 \pm 1.28$ |
| $202.1 \pm 1.3$ | $253.8 \pm 1.1$ | $131.2 \pm 1.2$ | $5799.97 \pm 0.96$ | $5798.66 \pm 0.84$ | $5799.32 \pm 0.96$ | $1.31 \pm 1.28$ |

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

formation mass values systematically higher than the ones from decay

(0.98 ± 0.74) MeV

excited states production

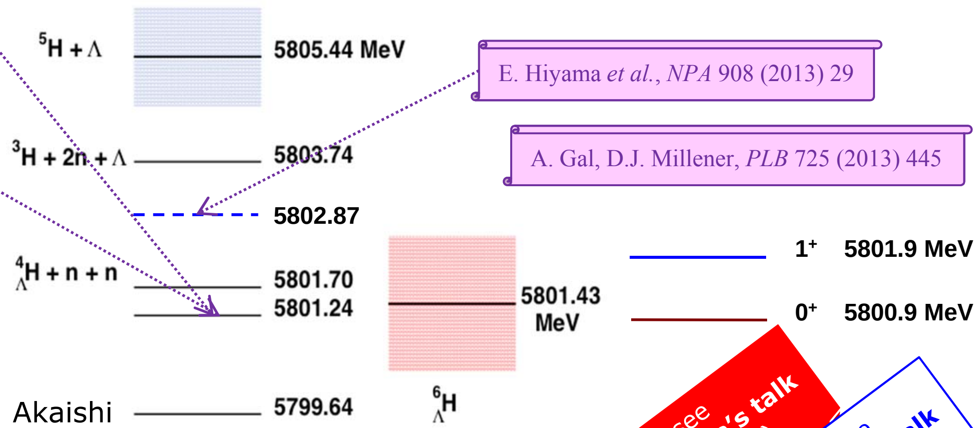
theoretical predictions

- $B_\Lambda$ = 4.2 MeV — R.H. Dalitz and R. Levi Setti, *NC* 30 (1963) 489
- $B_\Lambda$ = 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 ($K^-_{stop}$, $\pi^-$)

$\bar{M}$ = (5801.4 ± 1.1) MeV




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

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

$B_\Lambda$ = (4.0 ± 1.1) MeV (${}^5$H + Λ)

see E. Hiyama's talk (Tuesday)

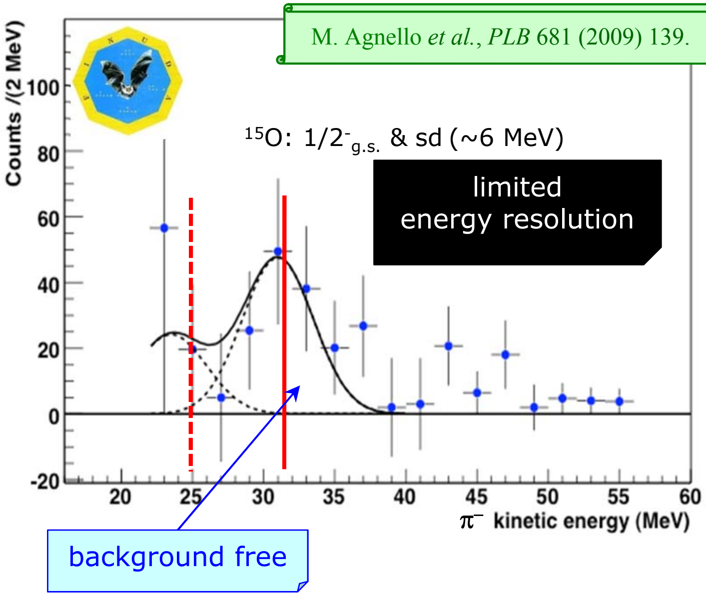
see A. Gal's talk (Friday)

~~$B_\Lambda$ = 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

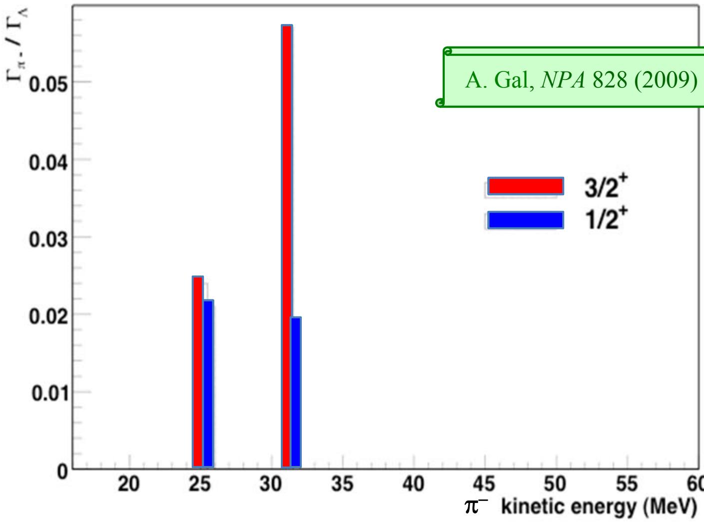
# $^{15}N_\Lambda$ $J^\pi$ assignment

1st experimental determination

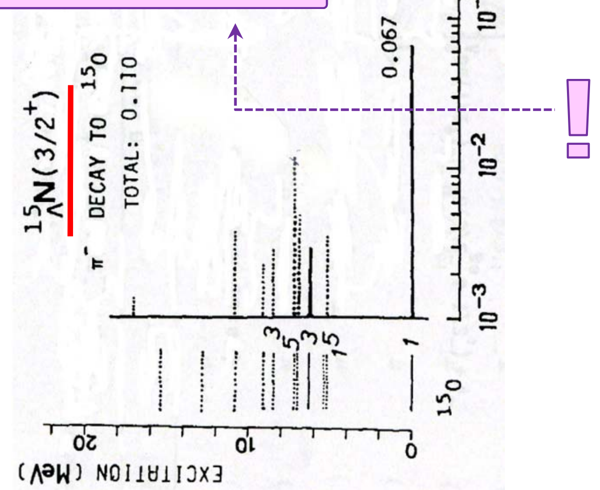



M. Agnello *et al.*, *PLB* 681 (2009) 139.

- Clear correspondence with the calculated strength functions:
  - T. Motoba *et al.*, Nucl. Phys. A 489 (1988) 683.
  - A. Gal, Nucl. Phys. A 828 (2009) 72.
- $^{15}N_{\Lambda\ g.s}$ spin not known $J^\pi(^{15}N_{\Lambda\ g.s.}) = 3/2^+$
  D.J. Millener, A. Gal, C.B. Dover, Phys. Rev. C 31 (1985) 499.
  Spin ordering not obtained from $\gamma$-rays of $^{16}O_\Lambda$
  M. Ukai *et al.*, Phys. Rev. C 77 (2008) 054315.
- First experimental determination of
  $J^\pi(^{15}N_{\Lambda\ g.s.}) = 3/2^+$ from decay rate value (and spectrum shape)



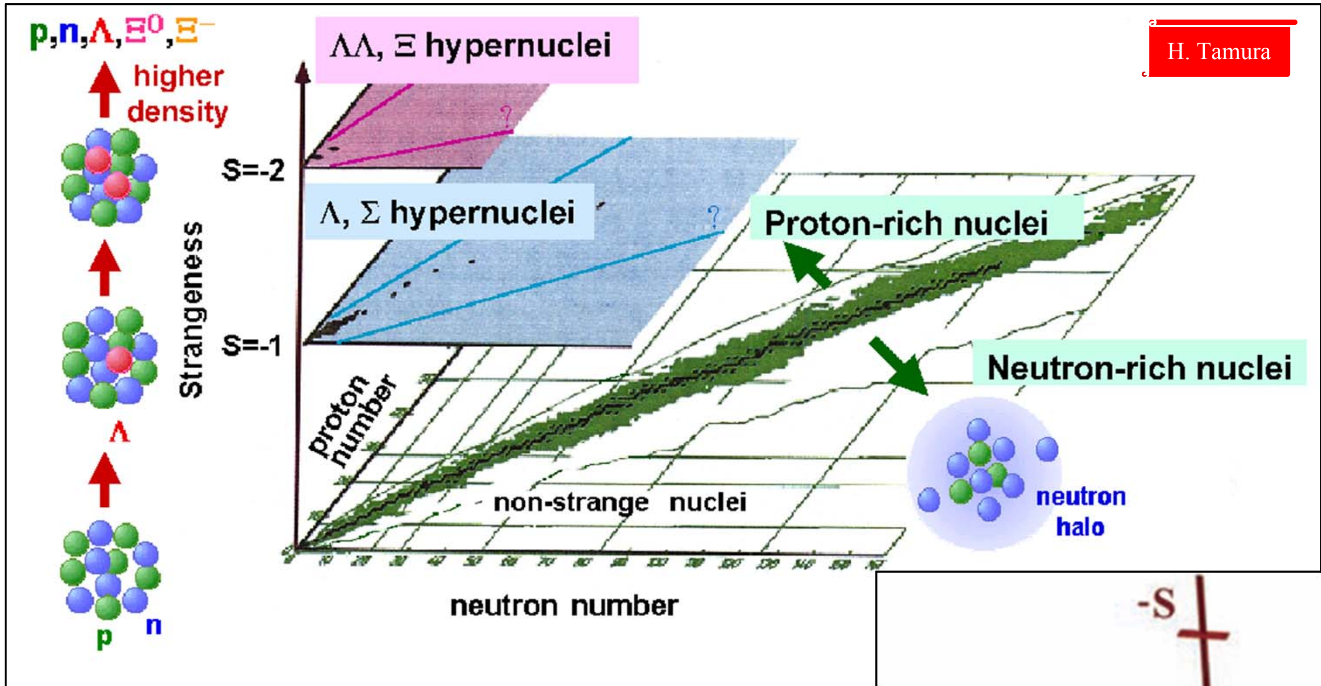

A. Gal, *NPA* 828 (2009) 72.

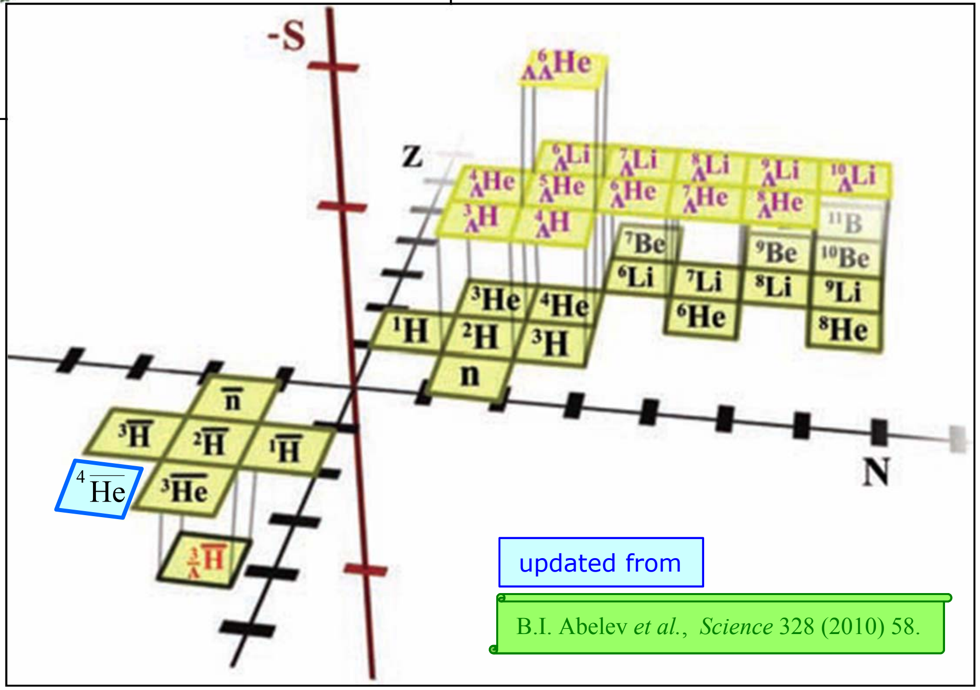



T. Motoba, *NPA* 489 (1988) 683

# Expanding the horizon...

H. Tamura

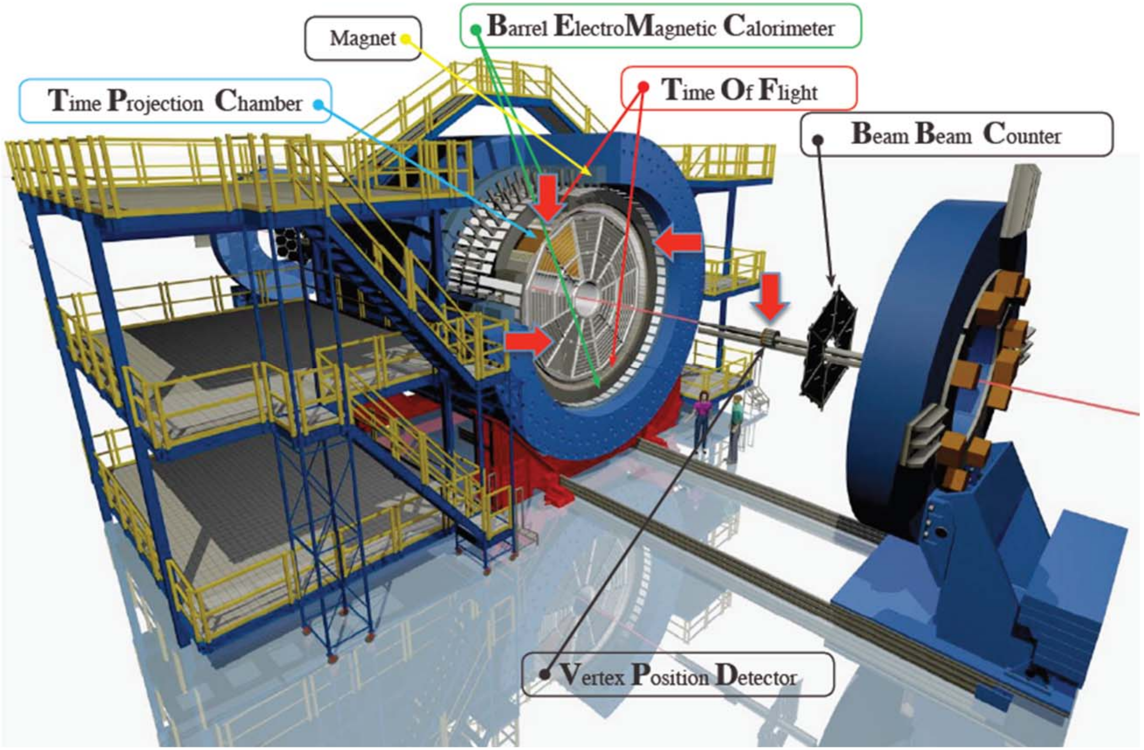



updated from

B.I. Abelev *et al.*, *Science* 328 (2010) 58.

# STAR $^3\overline{H}_{\overline{\Lambda}}$ signal

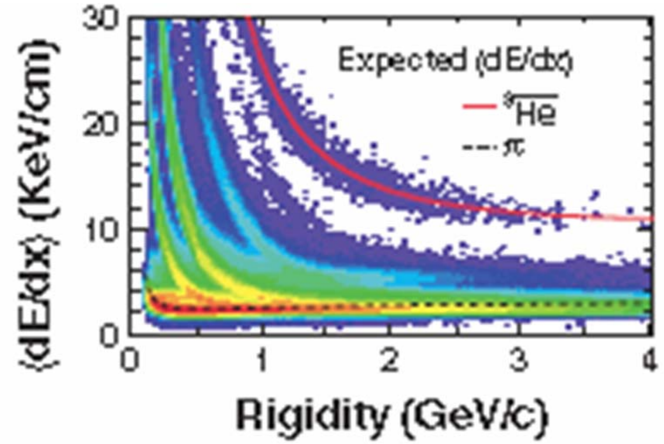


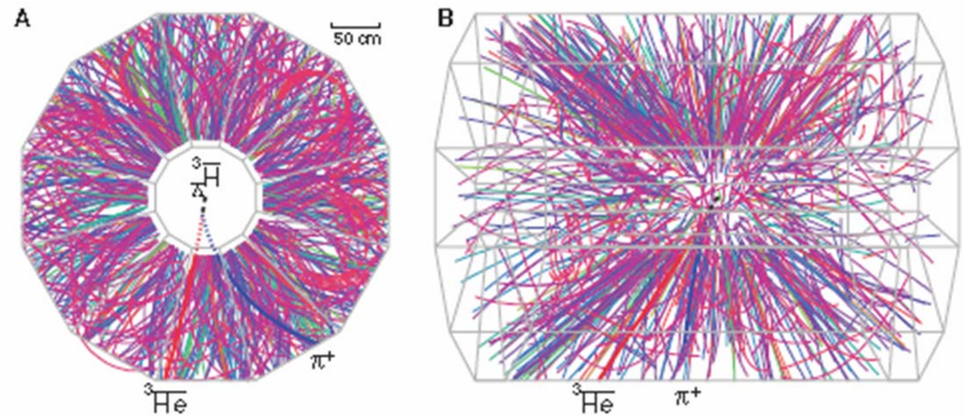

$$Au + Au @ 200\ \text{GeV}$$

$$^3_\Lambda H \rightarrow {}^3He + \pi^-$$

$$^3_{\overline{\Lambda}}\overline{H} \rightarrow {}^3\overline{He} + \pi^+$$

see Y.-G. MA's talk (Wednesday)

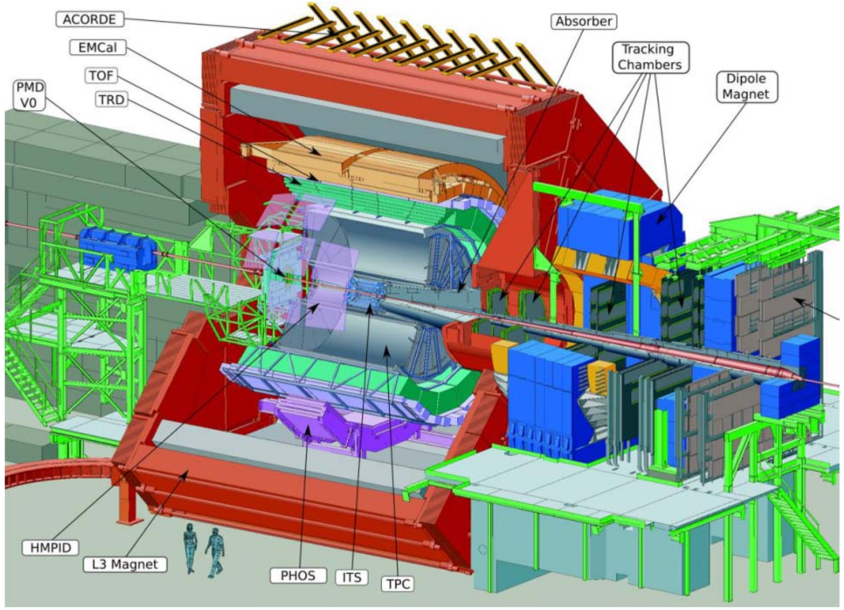



B.I. Abelev *et al.*, *Science* 328 (2010) 58.

# Hypernuclei in HI collisions

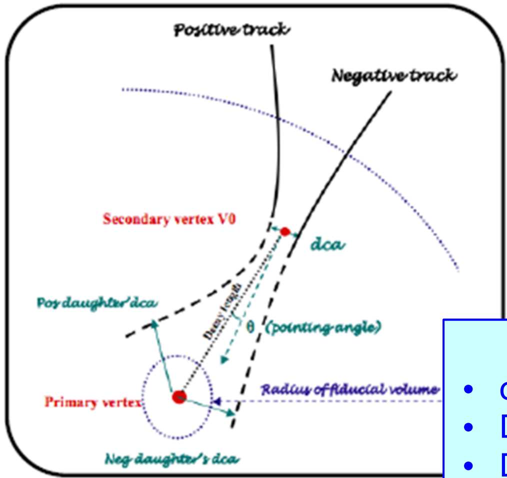





$$Pb + Pb @ \sqrt{S_{NN}} = 2.76\ \text{TeV}$$

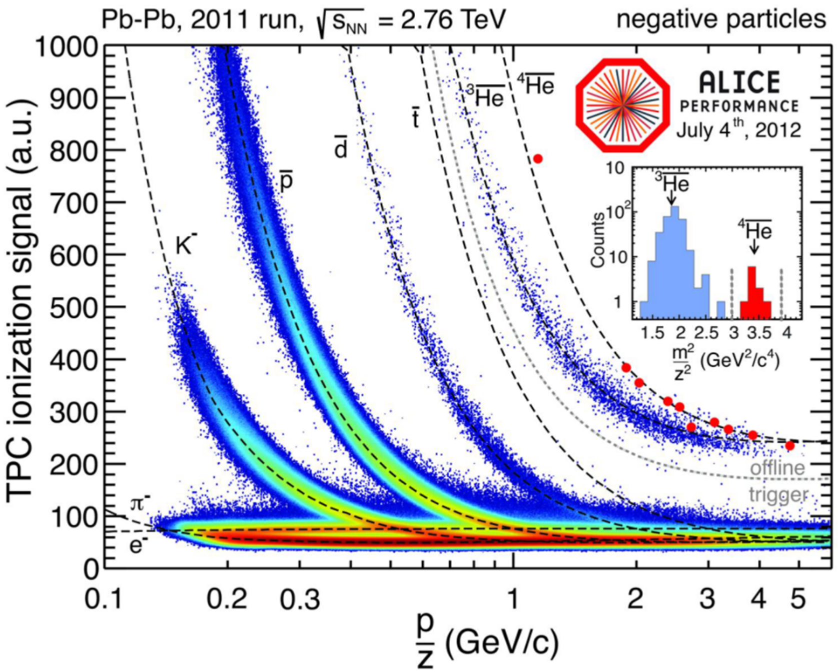
$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

$$^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$$




see **P. Camerini's talk** (Wednesday)

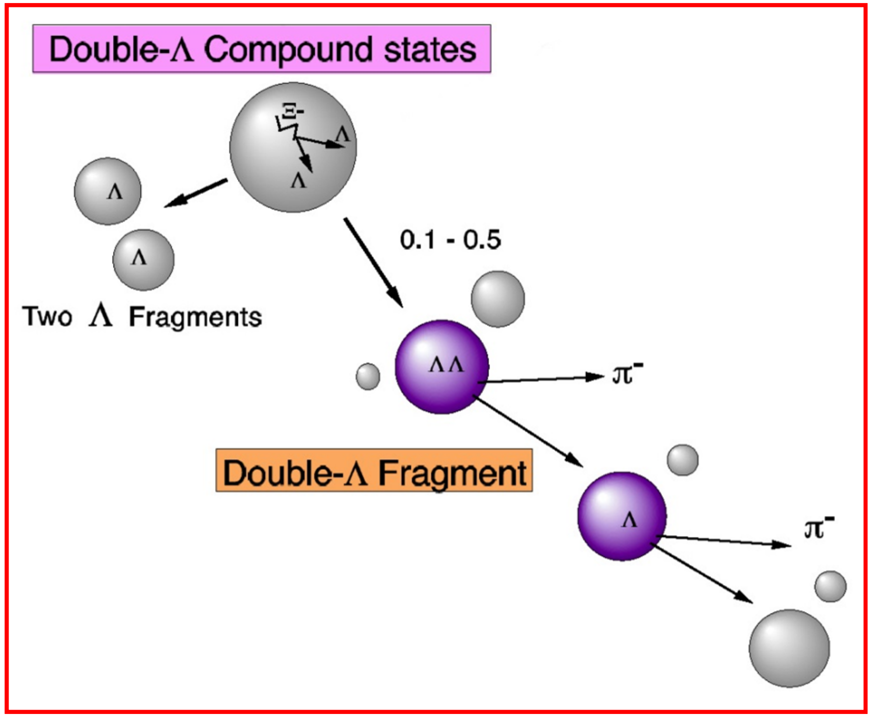
topological cuts
- cos(pointing angle) > 0.9
- DCA $\pi$ track to PV > 0.4 cm
- DCA between tracks < 0.7 cm
- $p_T(^3He,\pi)$ > 1 GeV/c
- $c\tau$ > 1 cm




R. Lea, *NPA* 914 (2013) 415.

# How to identify a ΛΛ-hypernucleus



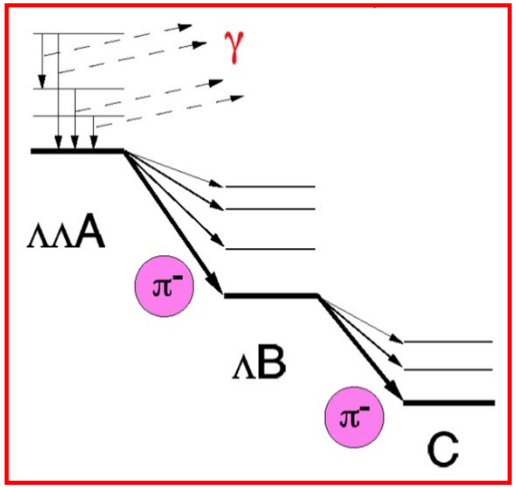



limited target choice
(at least for the pilot runs)

$^{6}Li$, $^{7}Li$, $^{8}Be$, $^{9}Be$, $^{12}C$

sequential pionic decay

$${}^{A}_{\Lambda\Lambda}Z \rightarrow {}^{A'}_{\Lambda}Z' \rightarrow {}^{A''}_{\Lambda}Z''$$




main background

$\Xi^{-} \rightarrow \Lambda + \pi^{-}$

$\Lambda \rightarrow p + \pi^{-}$

critical!

see A. Sanchez's talk (Friday)

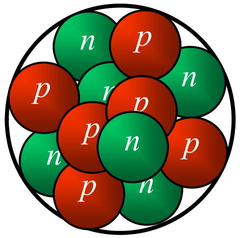
# Two different stories


| | | |
|---|---|---|
| *n*(udd) | *I*(*J*$^P$) = | ½(½$^+$) |
| | mass: | 939.57 MeV |
| | τ: | 880.00 s |

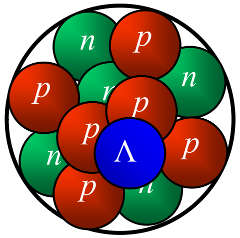
$$n \rightarrow p + e^- + \bar{\nu}_e$$


| | | |
|---|---|---|
| Λ(uds) | *I*(*J*$^P$) = | 0(½$^+$) |
| | mass: | 1115.68 MeV |
| | τ: | 263.20 ps |

$$\Lambda \rightarrow n + \pi^0 + \quad 41\text{ MeV } (36\%)$$
$$\Lambda \rightarrow p + \pi^- + \quad 38\text{ MeV } (64\%)$$



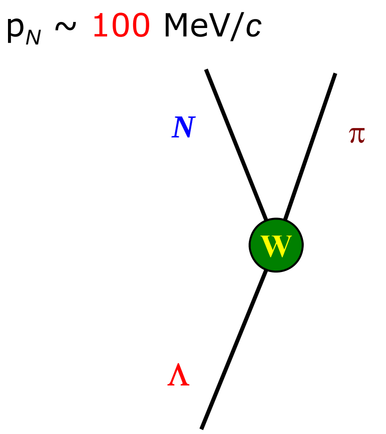

*n* stable (!)

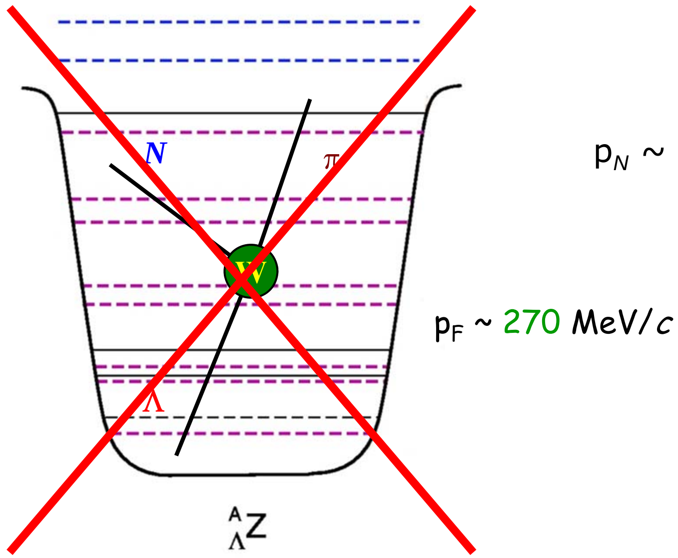


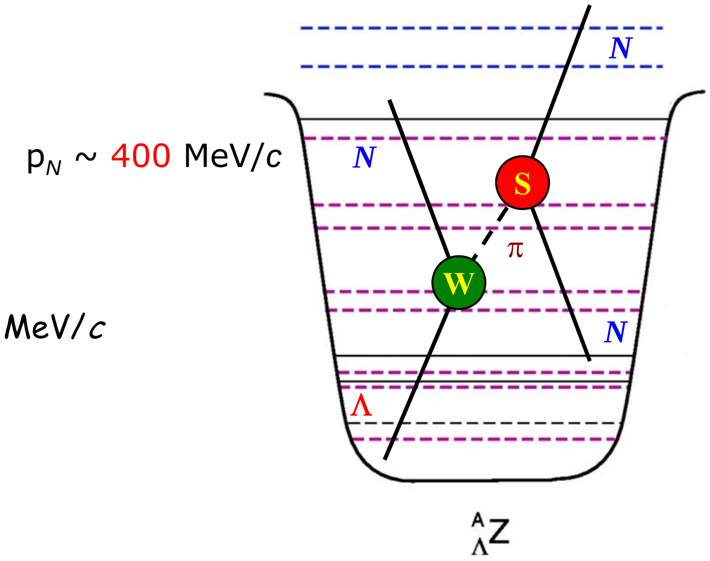

...

# Λ-hypernucleus weak decay

| free Λ decay | hypernucleus mesonic decay | hypernucleus non-mesonic decay |
|---|---|---|




$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)
$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)
$\tau_\Lambda \approx 263$ ps

**suppressed by Pauli blocking**

$\Lambda + n \rightarrow n + n + 176$ MeV
$\Lambda + p \rightarrow n + p + 176$ MeV
$\tau_\Lambda \approx$ ???

**ΔI = ½ rule**
(not theoretically understood)

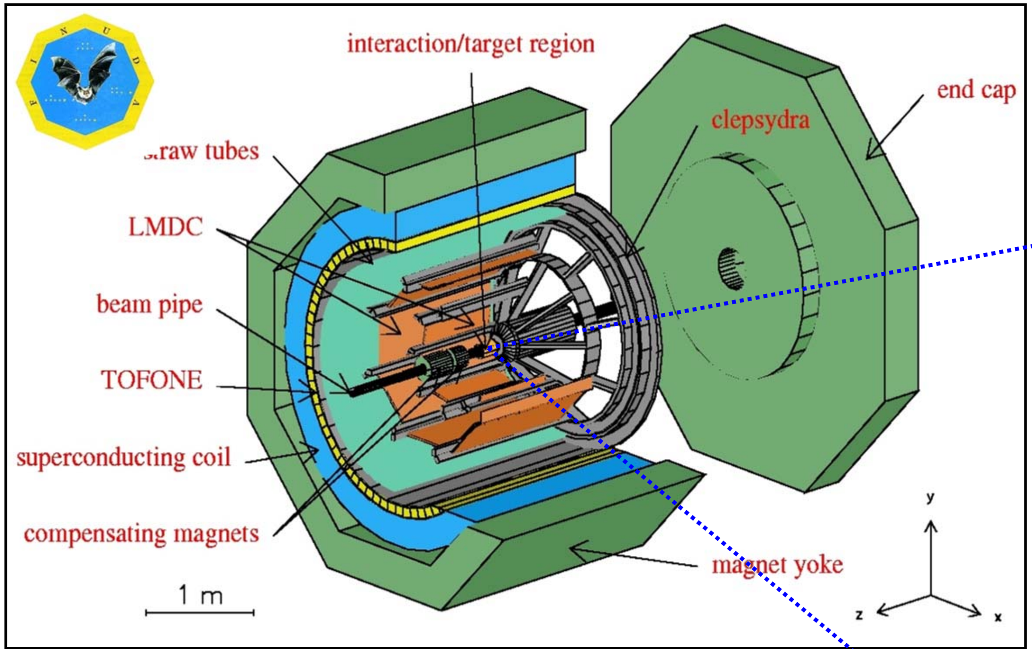
$$\Gamma_T = \Gamma_M + \Gamma_{NM}$$
$$\Gamma_M = \Gamma_{\pi 0} + \Gamma_{\pi -}$$
$$\Gamma_{NM} = \Gamma_n + \Gamma_p + \Gamma_2$$

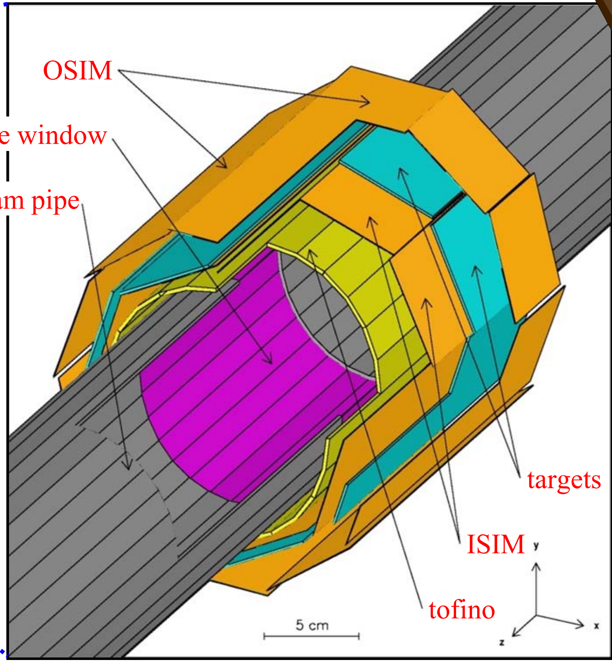
**dominant in all but the lightest hypernuclei**

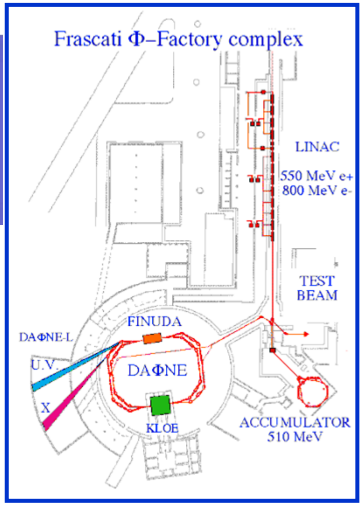
# FINUDA @ DAΦNE

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

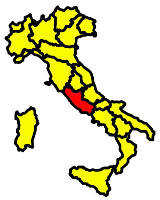
$$K^-_{stop} + {}^A Z \to {}^A_\Lambda Z + \pi^-$$




| | |
|---|---|
| energy | 510 MeV |
| luminosity | 5 $10^{32}$ $cm^{-2}$ $s^{-1}$ |
| $\sigma_x$ (rms) | 2.11 mm |
| $\sigma_y$ (rms) | 0.021 mm |
| $\sigma_z$ (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) |



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

# FINUDA key features

- very thin nuclear targets ($0.1 \div 0.3$ g/cm$^2$)
  - → high resolution spectroscopy
- coincidence measurement with large acceptance
  - → decay mode study
- 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 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

# Mesonic weak decay (MWD)

Experimental observables

- $\tau$
- $\Gamma_{\pi^-}/\Gamma_\Lambda$, $\Gamma_{\pi^0}/\Gamma_\Lambda$
- (single) particle decay spectra

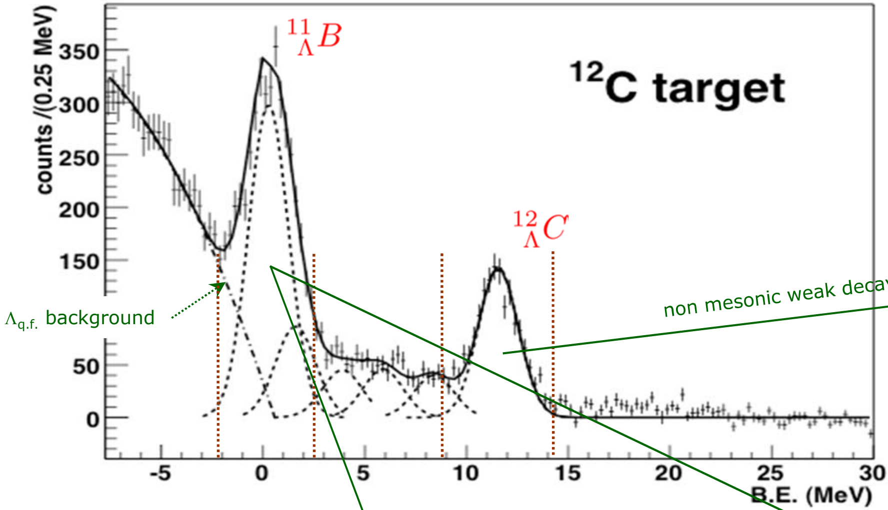
Addressed/addressable issues

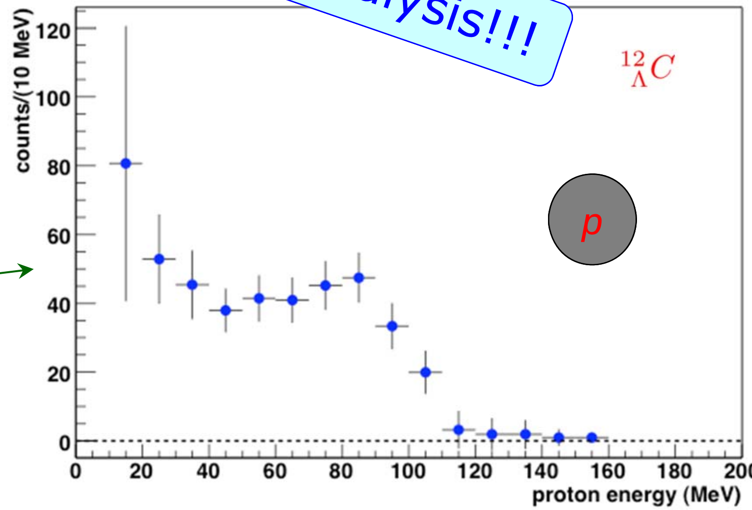
- *s*-shell hypernuclei
  - ✓ $\Lambda$-$\mathcal{N}$ potential
- *p*-shell hypernuclei
  - ✓ $\pi$ distortion effect and MWD enhancement
  - ✓ $\pi^-$-nucleus optical potential
  - ✓ $J^\pi$ assignment ☛ indirect spectroscopic tool

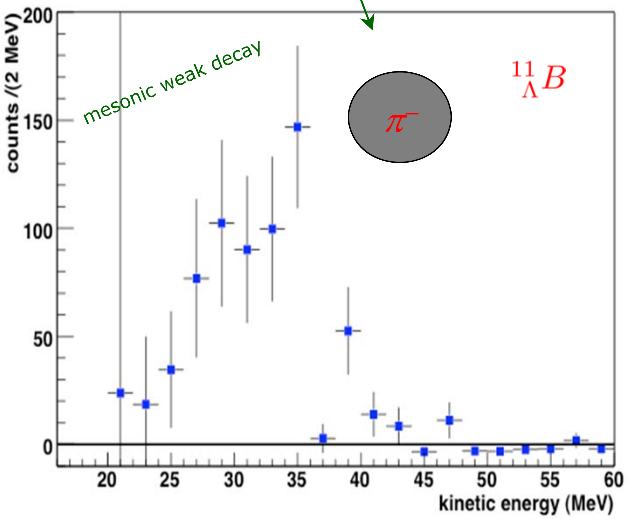
# Hypernucleus decay: the FINUDA strategy

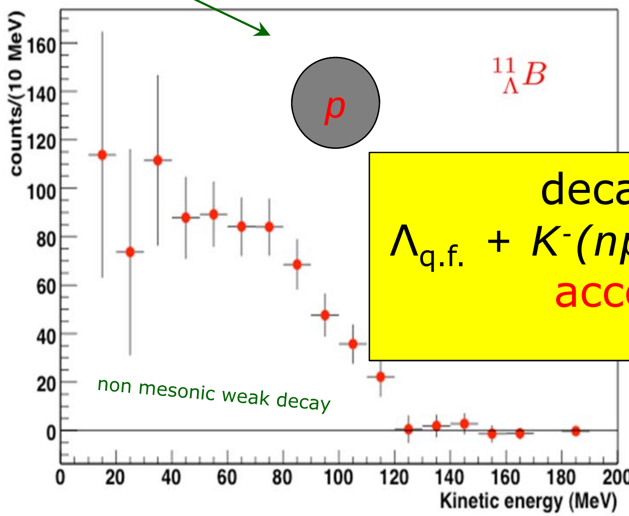
inclusive production $\pi^-$ spectrum
$K^-(np)$ background subtracted

magnetic analysis!!!



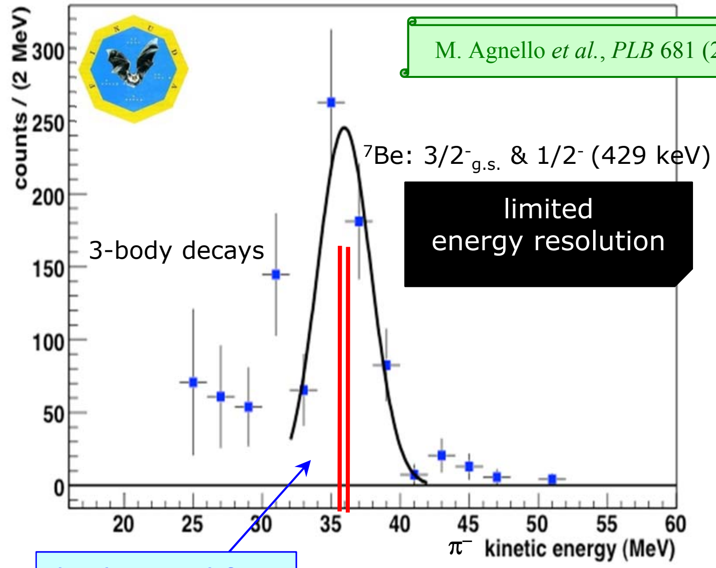




decay $\pi^-$ and $p$ spectra
$\Lambda_{q.f.}$ + $K^-(np)$ background subtracted
acceptance corrected

# $^{7}Li_{\Lambda}$ $J^{\pi}$ assignment

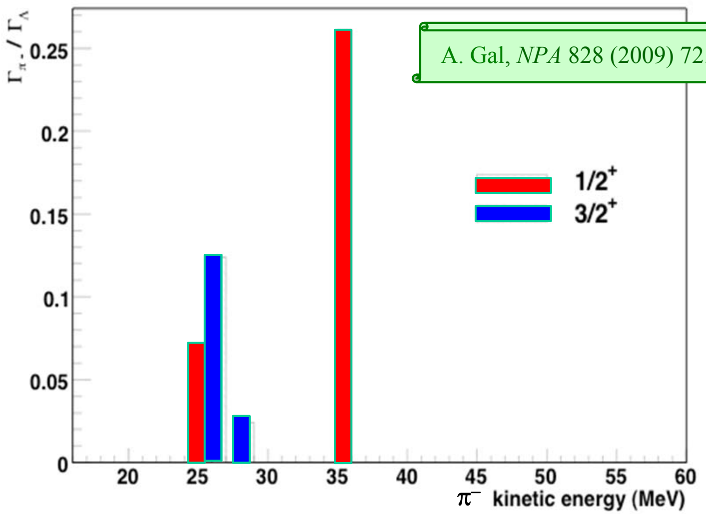
indirect spectroscopy tool




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

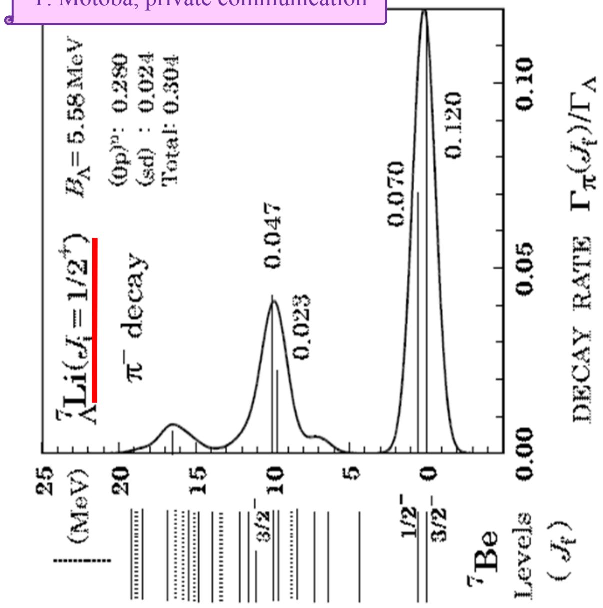
background free

- Clear correspondence with the calculated strength functions:
  - T. Motoba et al, Progr. Theor. Phys. Suppl. 117 (1994) 477.
  - A. Gal, Nucl. Phys. A 828 (2009) 72.
- Formation of different excited states of the daughter nucleus
- Initial hypernucleus spin
  $J^{\pi}$ ($^{7}Li_{\Lambda g.s.}$) = $1/2^{+}$ (J. Sasao, Phys. Lett. B 579 (2004) 258.)




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

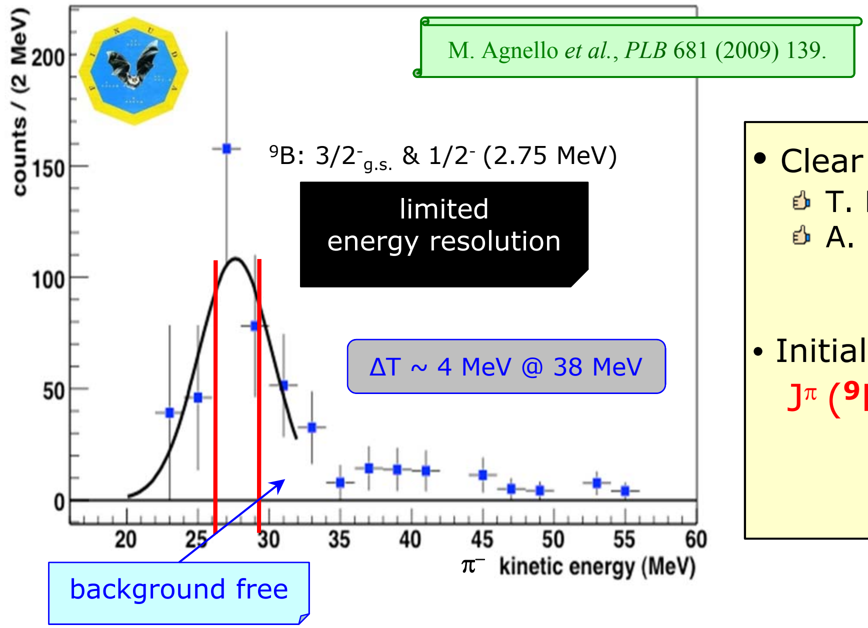
T. Motoba, private communication



# $^{9}Be_{\Lambda}$ $J^{\pi}$ assignment

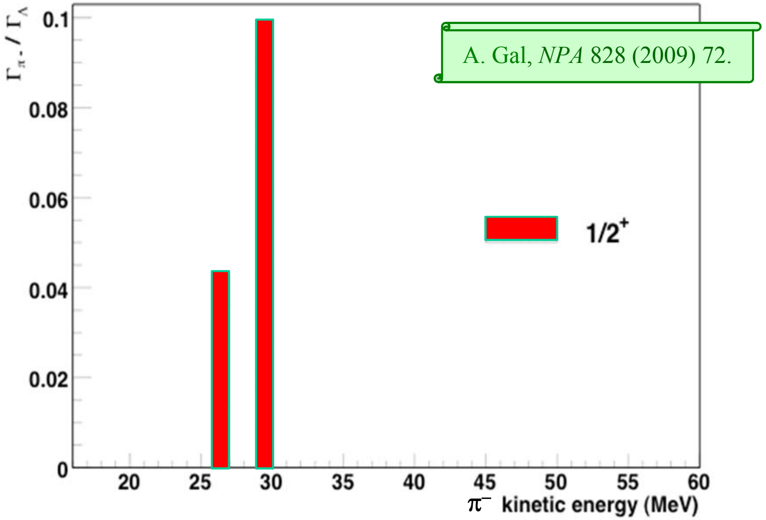


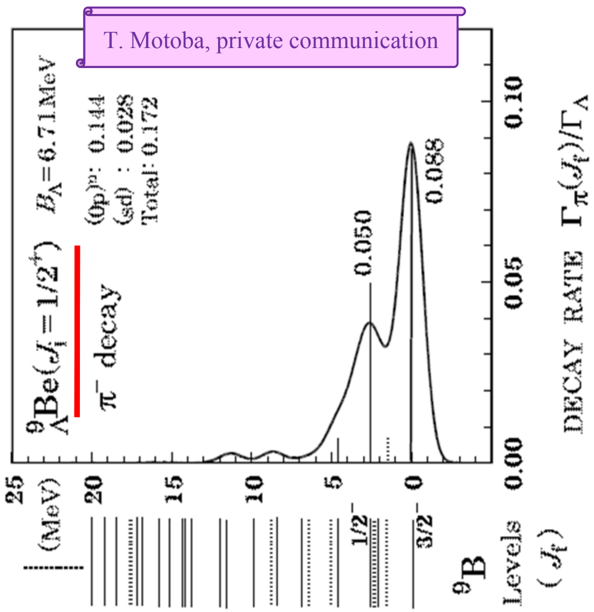
indirect spectroscopy tool




- Clear correspondence with the calculated strength functions:
  - T. Motoba *et al.*, Progr. Theor. Phys. Suppl. 117 (1994) 477.
  - A. Gal, Nucl. Phys. A 828 (2009) 72.

- Initial hypernucleus spin
  $J^{\pi}$ ($^{9}Be_{\Lambda g.s.}$) = $1/2^{+}$ (O.Hashimoto *et al.*, Nucl. Phys. A 639 (1998) 93c.)

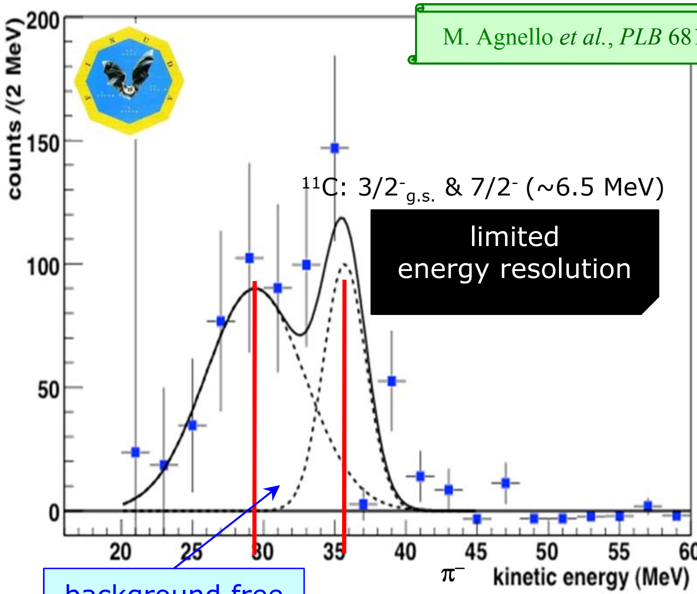


# $^{11}B_{\Lambda}$ $J^{\pi}$ assignment

indirect spectroscopy tool

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

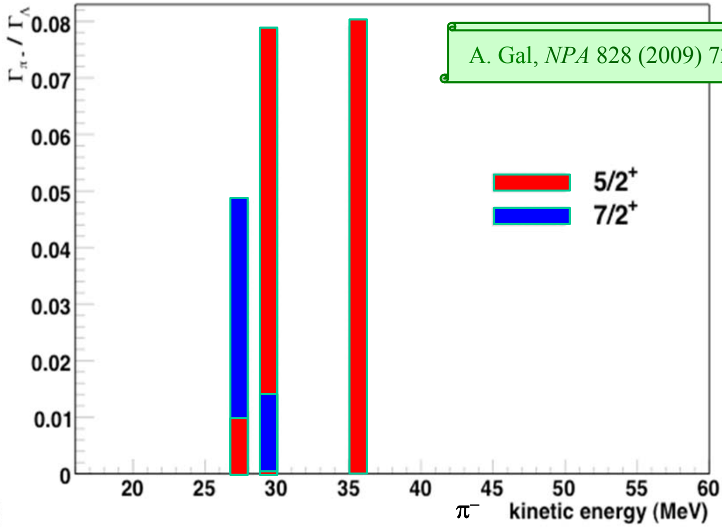



background free

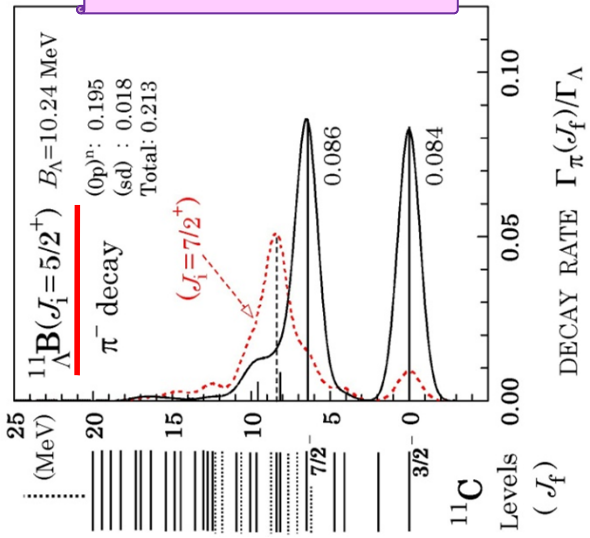
- Clear correspondence with the calculated strength functions:
  - H. Bandō et al, Pers. Meson Science (1992) p.571
  - A. Gal, Nucl. Phys. A 828 (2009) 72.
- Two contributions of the $^{11}$C ground state $5/2^-$ and its $7/2^-$ excited state
- Initial hypernucleus spin

  $J^{\pi}$ ($^{11}B_{\Lambda\ g.s.}$) = $5/2^+$ experimental confirmation by different observable (Y. Sato et al., Phys. Rev. C 71 (2005) 025203)

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




T. Motoba, private communication

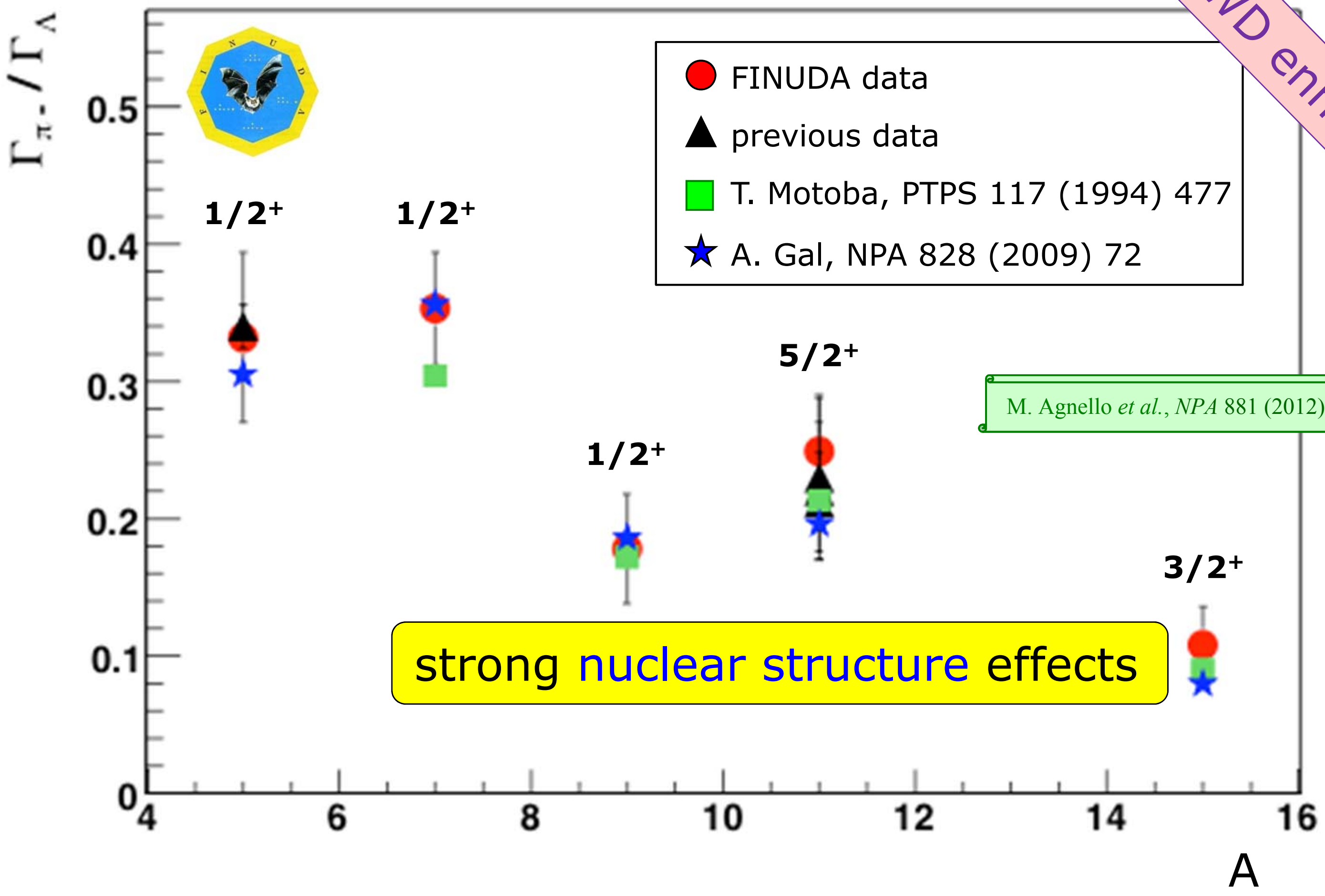


# $\Gamma_{\pi^-}/\Gamma_\Lambda$ ratio dependence on A

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

$$\Gamma_{tot}/\Gamma_\Lambda = (0.990 \pm 0.094) + (0.018 \pm 0.010)\, A$$

fit to measured values for A = 4-12 hypernuclei




strong nuclear structure effects

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

π distortion, MWD enhancement proved

# Non-mesonic weak decay (NMWD)

Experimental observables

- $\Gamma_n$, $\Gamma_p$
- $\Gamma_{2\mathcal{N}}$ and FSI contributions
- $\Gamma_{NM} = \Gamma_n + \Gamma_p + \Gamma_{2\mathcal{N}}$
- (single & coincidence) particle decay spectra

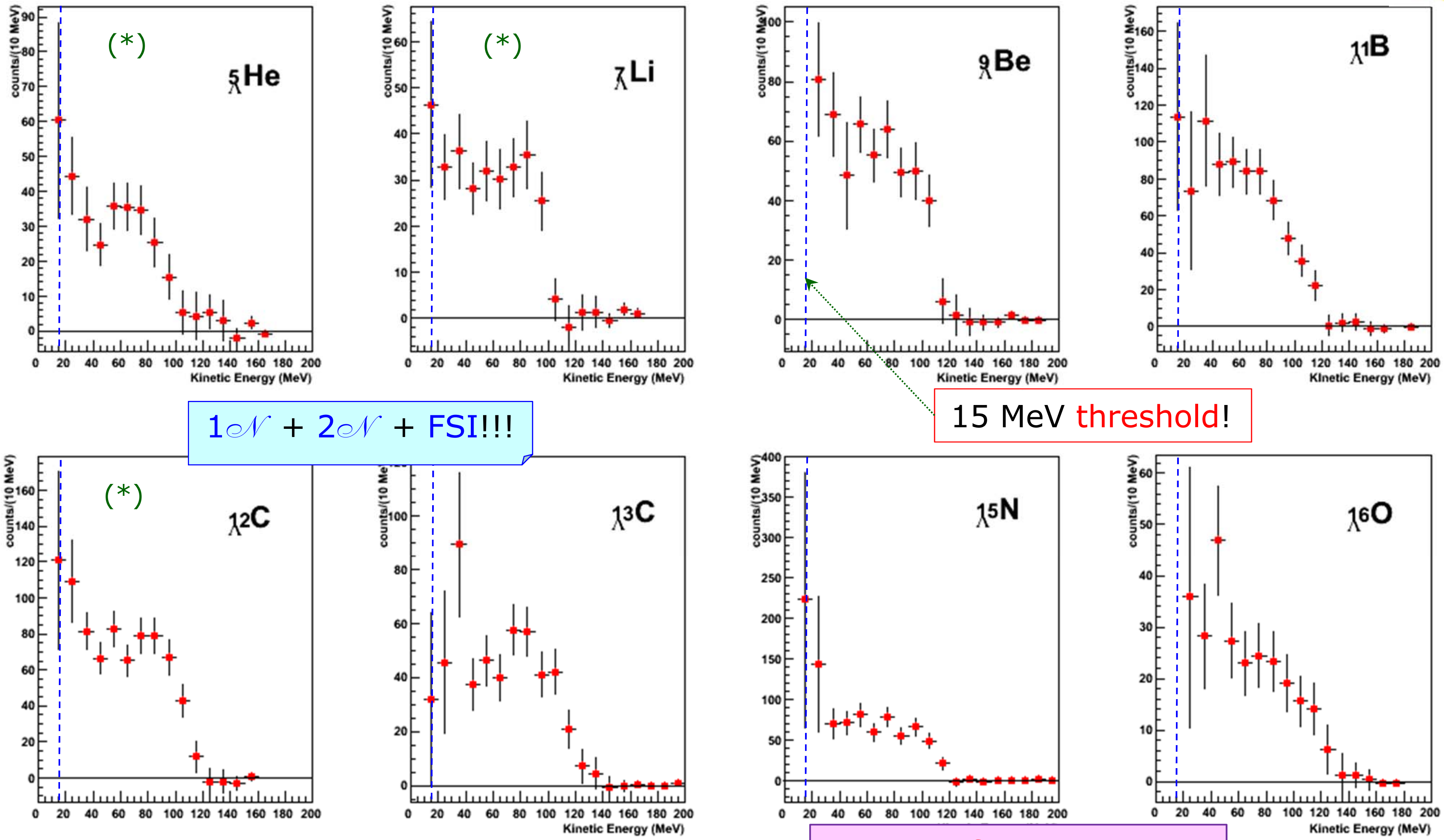
Addressed/addressable issues

- 4-baryon strangeness-changing weak interaction
- $\Delta I = 1/2$ rule validity from *s*-shell ($^4H_\Lambda$) and heavier hypernuclei
- ✓ $\Gamma_n/\Gamma_p$
- ✓ $\Gamma_{2\mathcal{N}}$ determination
- ✓ search for $\Gamma_{2\mathcal{N}}$ experimental evidence

# *Anatomy of NMWD p spectra*

*p* spectra *K*[-]*(np)* background subtracted

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




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

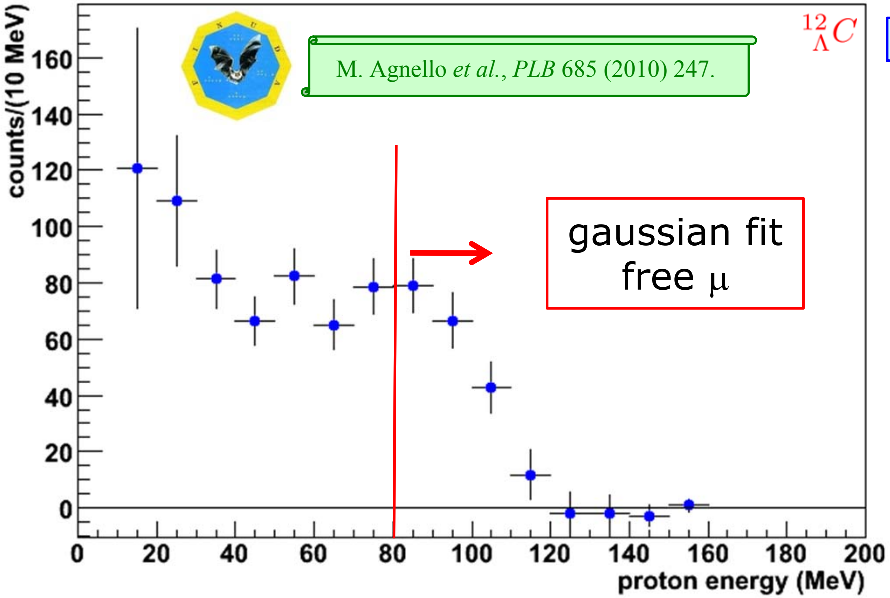
common features:
- low energy rise
- structure at ~80 MeV

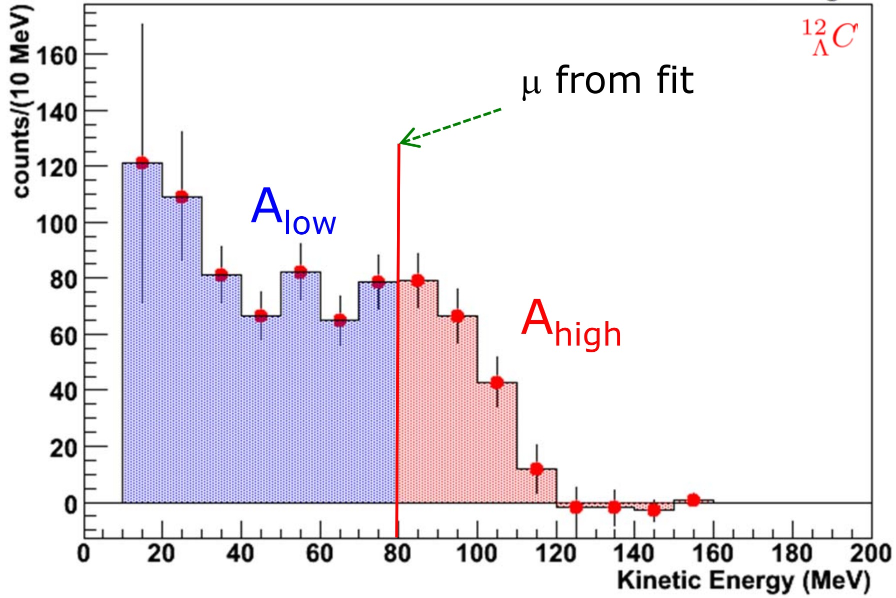
# $\Gamma_{2\mathcal{N}}$ and FSI determination

W. Alberico and G. Garbarino, *PR* 369 (2002) 1.

**assumption** → 1) $\Gamma_{2\mathcal{N}}/\Gamma_{NMWD}$ 2) $\Gamma_n/\Gamma_p$ } independent on A

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




G. Garbarino, A. Parreño and A. Ramos, *PRL* 91 (2003) 112501.
G. Garbarino, A. Parreño and A. Ramos, *PRC* 69 (2004) 054603.

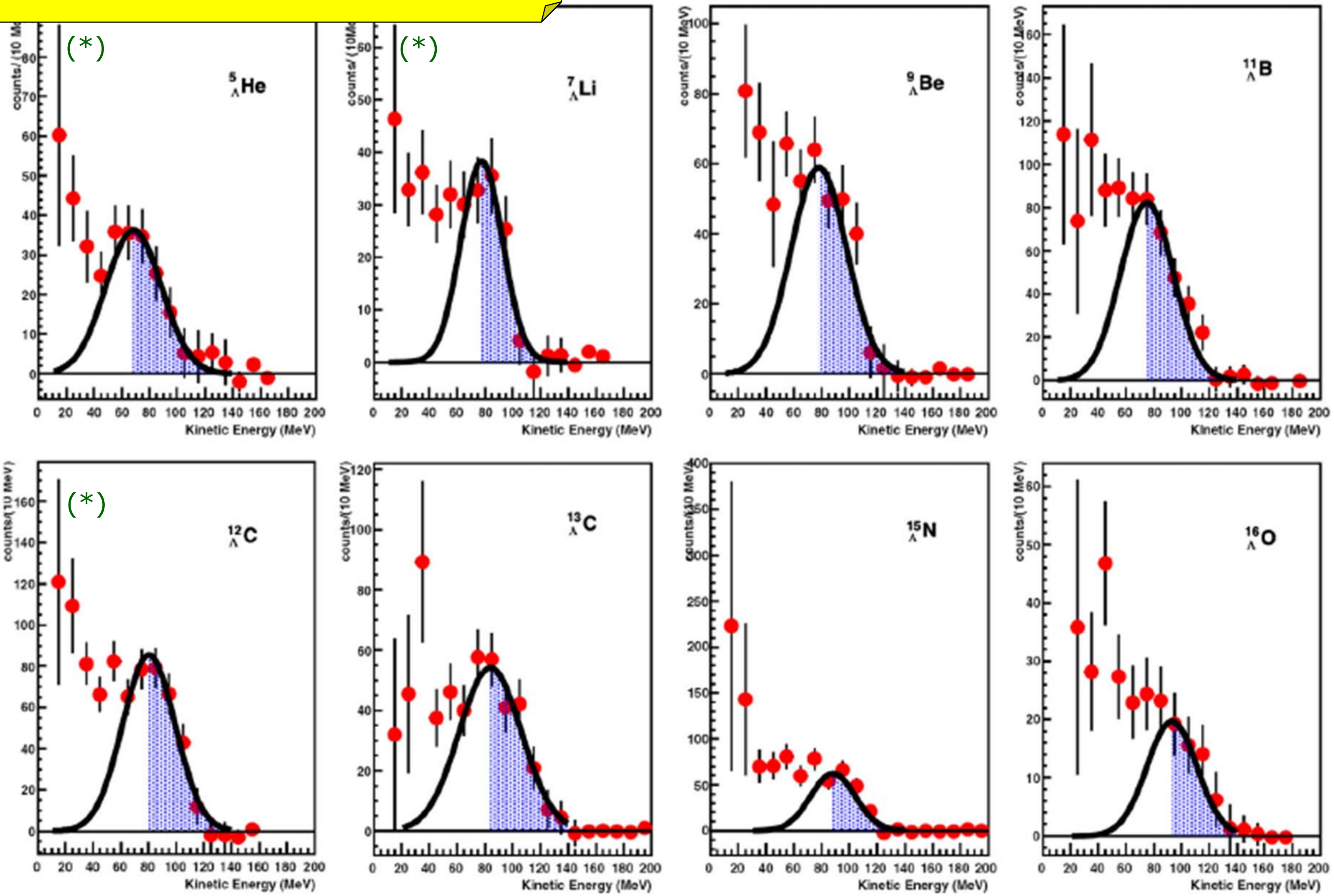
$A_{low}$ ☛ $1\mathcal{N}$ + $2\mathcal{N}$ + FSI

**assumption** → $A_{high}$ ☛ $1\mathcal{N}$ + FSI
$2\mathcal{N}$ ($T_p$ > 70 MeV) ~5% $\Gamma_{2\mathcal{N}}$

# FSI and 2N induced non-mesonic decay

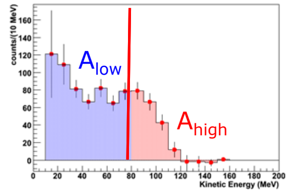
*p* spectra background subtracted
and acceptance corrected

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




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

# $\Gamma_{2\mathcal{N}}$ and FSI determination

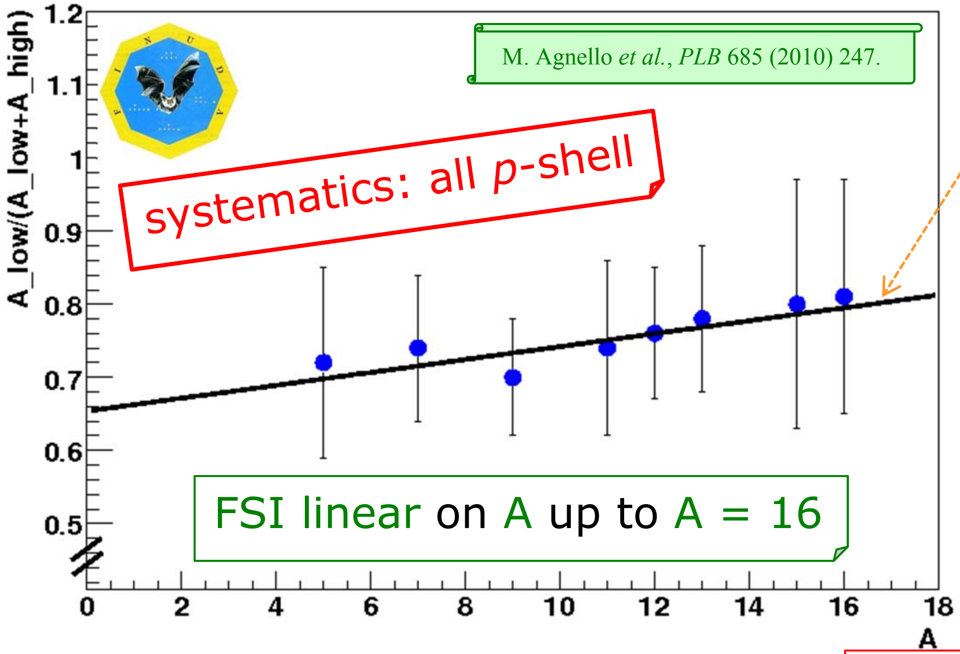



E. Bauer and G. Garbarino, *NPA 828* (2009) 29.

$\Gamma_{np} : \Gamma_{np} : \Gamma_{np} = 0.83 : 0.12 : 0.04$

**assumption** → $\Gamma_{2\mathcal{N}}/\Gamma_p \sim \Gamma_{np}/\Gamma_p$

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




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

**assumption** supported by both experiment and theory

$\Gamma_2/\Gamma_1$ and $\Gamma_n/\Gamma_p$ independent on $A$

$$\frac{\Gamma_2}{\Gamma_p} = 0.43 \pm 0.25$$

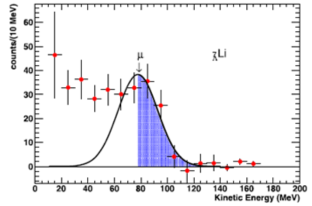
weighted average

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

H. Bhang *et al.*, *EPJA 33* (2007) 259.

- E. Bauer and G. Garbarino, *NPA 828* (2009) 29.
- H. Bhang *et al.*, *EPJA 33* (2007) 259: ~0.40 $^{12}C_\Lambda$
- J.D. Parker *et al.*, *PRC* 76 (2007) 035501: ≤ 0.24 $^{4}He_\Lambda$ (95% c.l.)
- M. Kim *et al.*, *PRL* 103 (2009) 182502: 0.29 ± 0.13 $^{12}C_\Lambda$

# $\Gamma_{2\mathcal{N}}$ improved determination




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

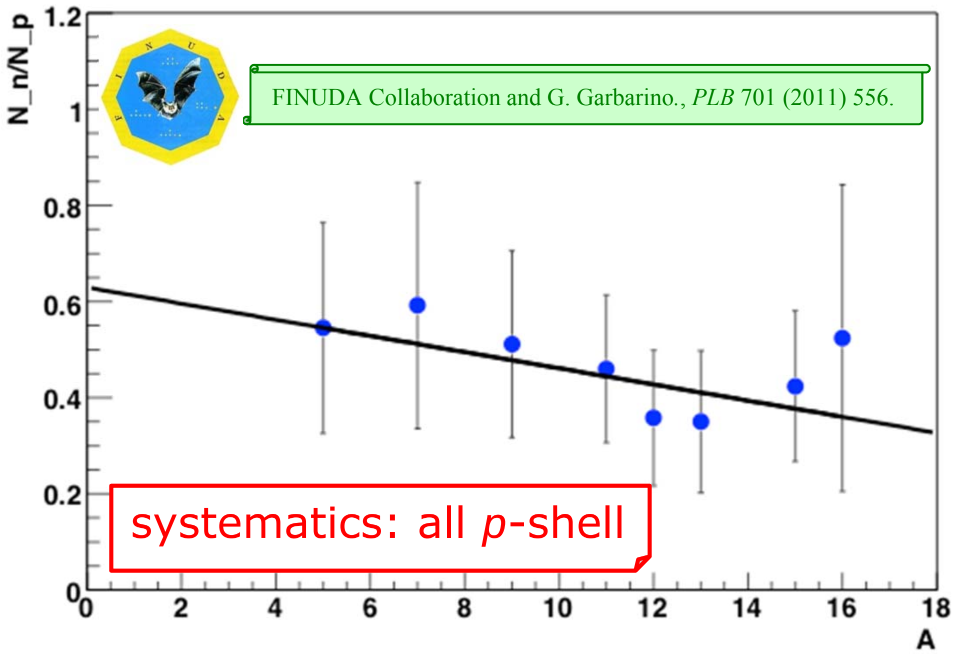
**assumption** — E. Bauer and G. Garbarino, *PRC 81* (2010) 064315.

$$R(A) = a + bA = \frac{\Gamma_2}{0.5 \cdot \Gamma_p} + bA$$

$\Gamma_2/\Gamma_p$ independent on A

$$\frac{\Gamma_2}{\Gamma_p} = 0.39 \pm 0.16_{stat}{}^{+0.04_{sys}}_{-0.03_{sys}}$$

$$\frac{\Gamma_2}{\Gamma_{NM}} = \frac{\Gamma_2/\Gamma_p}{\Gamma_n/\Gamma_p + 1 + \Gamma_2/\Gamma_p} = 0.21 \pm 0.07_{stat}{}^{+0.03_{sys}}_{-0.02_{sys}}$$




FINUDA Collaboration and G. Garbarino., *PLB* 701 (2011) 556.

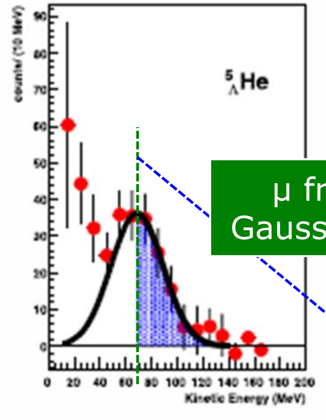
systematics: all *p*-shell

M. Kim *et al.*, PRL 103 (2009) 182502: 0.29 ± 0.13 $^{12}C_{\Lambda}$.
FINUDA Collaboration and A. Gal., *PLB* 685 (2010) 182502: 0.24 ± 0.10.

$\pi^-$, *p*, *n*, coincidence measurements

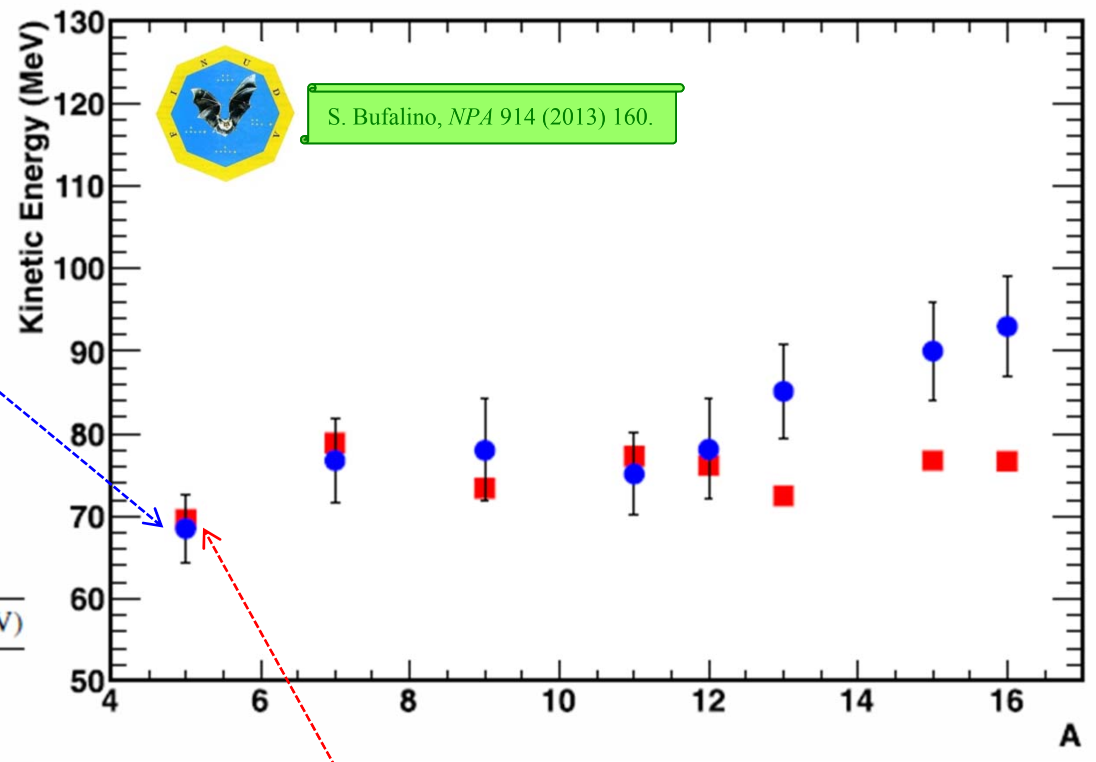
- low statistics
- direct measurement
- reduced error

# Exclusive NMWD?



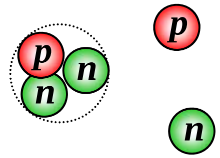

μ from Gaussian fit

theoretical advice urgently needed!




| Hypernucleus | $\mu$ from fit (MeV) |
|---|---|
| $^{5}_{\Lambda}$He | $68.5 \pm 4.1$ |
| $^{7}_{\Lambda}$Li | $76.7 \pm 5.1$ |
| $^{9}_{\Lambda}$B | $78.2 \pm 6.2$ |
| $^{11}_{\Lambda}$B | $75.1 \pm 5.0$ |
| $^{12}_{\Lambda}$C | $78.1 \pm 6.1$ |
| $^{13}_{\Lambda}$C | $85.1 \pm 5.6$ |
| $^{15}_{\Lambda}$N | $88.1 \pm 6.2$ |
| $^{16}_{\Lambda}$O | $93.1 \pm 6.2$ |

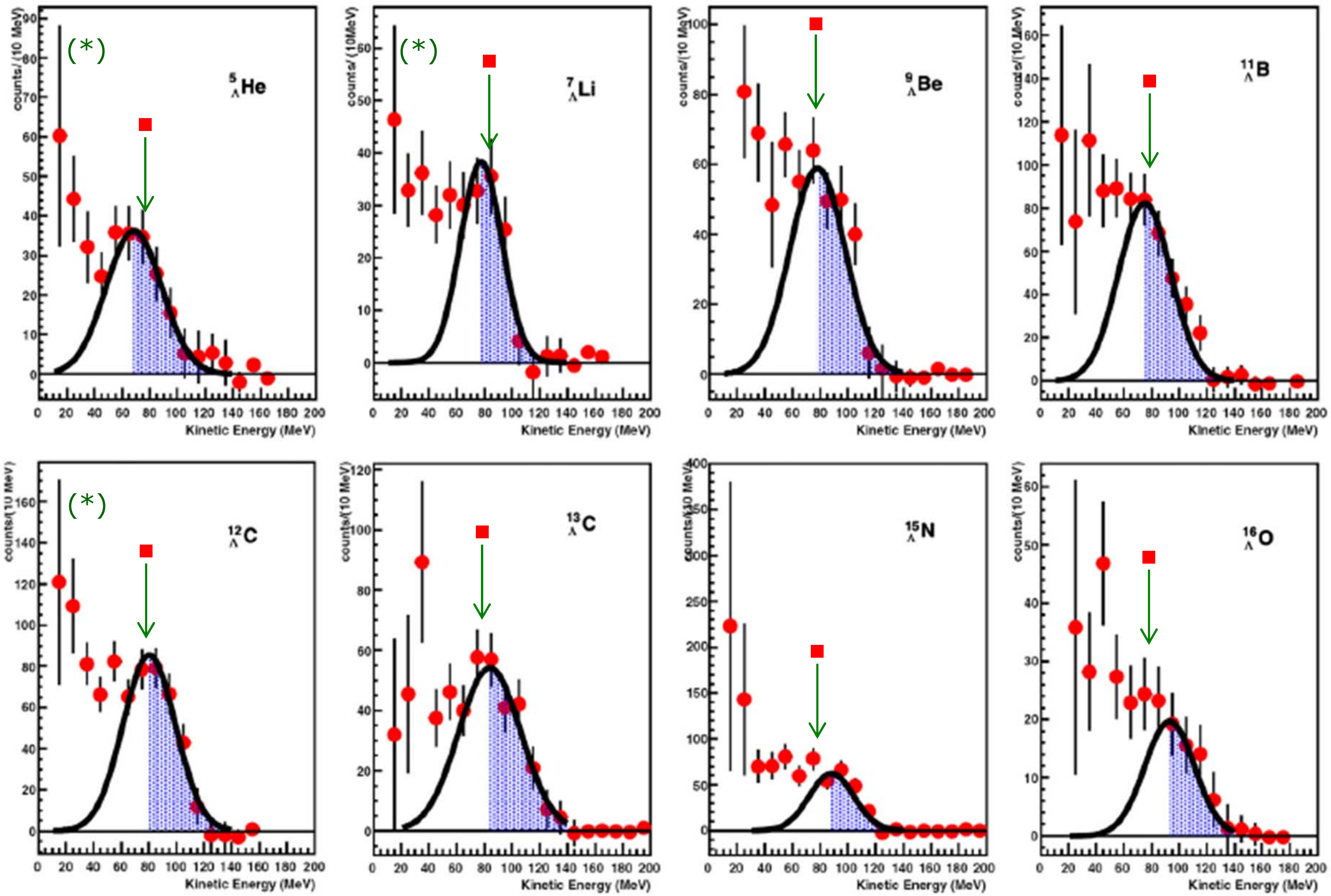
simplified hypothesis:




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

# FSI and 2N induced non-mesonic decay

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




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

■ "simple" kinematical calculation

# $2\mathcal{N}$ induced weak decay

- relevance first pointed out by: W.M. Alberico *et al.*, *PLB* 256 (1991) 134
- key role in data interpretation ⇒ many theoretical predictions

E. Bauer
G. Garbarino
A. Parreño
A. Ramos

- importance of the effect: ~20-25% of the total NMWD width
- several experimental evidences, but indirect

| Ref. | $\Gamma_2/\Gamma_\Lambda$ | $\Gamma_2/\Gamma_{NM}$ | Notes |
|---|---|---|---|
| BNL-E788 [47] | | $\leqslant 0.24$ | ${}^{4}_{\Lambda}$He, $n$ and $p$ spectra |
| KEK-E508 [48] | $0.27 \pm 0.13$ | $0.29 \pm 0.13$ | ${}^{12}_{\Lambda}$C, $nn$ and $np$ spectra |
| FINUDA [8] | | $0.24 \pm 0.10$ | $A = 5$–$16$, $p$ spectra |
| FINUDA [9] | | $0.21 \pm 0.07_{\text{stat}}\,{}^{+0.03\,\text{sys}}_{-0.02\,\text{sys}}$ | $A = 5$–$16$, $np$ spectra |

consistent within large errors

E. Botta, T. Bressani, G. Garbarino, *EPJA* 48 (2012) 21

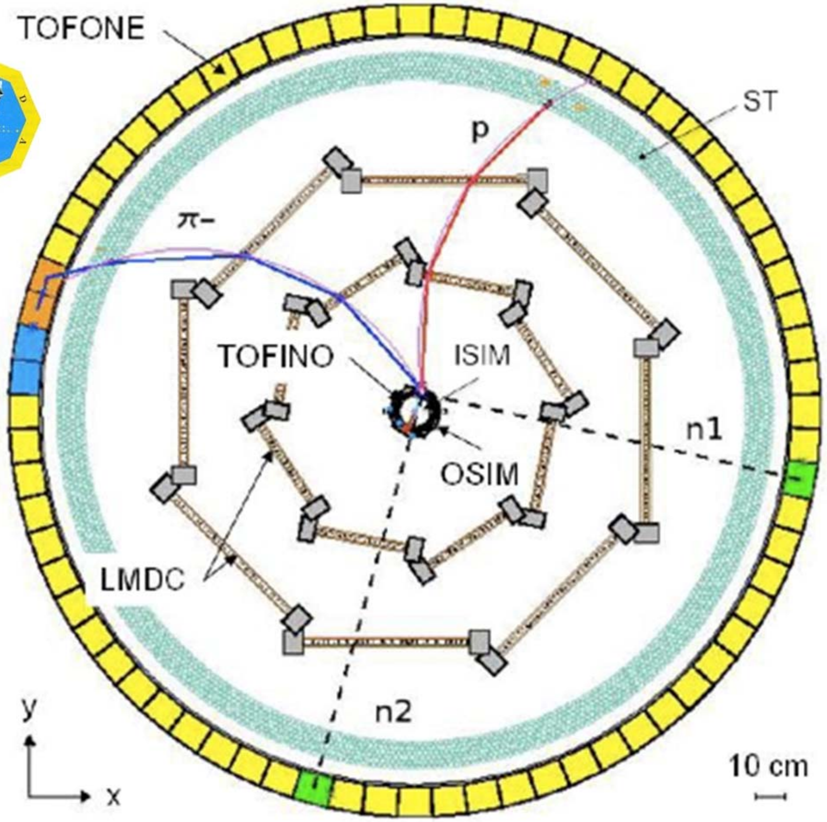
"smoking gun" evidence missing!

- experimental hardness: 3 nucleons emitted from Λ-hypernucleus g.s.
  4-fold coincidence measurement ($\pi^-$, $p$, $n$, $n$)

# 2$\mathcal{N}$ induced decay exp. evidence

triple coincidence: ($n$ + $n$ + $p$) events

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




$p_{\pi-}$ = 276.9 ± 1.2 MeV/c
$p_{miss}$ = 217 ± 44 MeV/c
$E_{tot}$ = 178 ± 23 MeV
MM = 3710 ± 23 MeV/c$^2$

E(n1) = 110 ± 23 MeV
E(n2) = 16.9 ± 1.7 MeV
E(p) = 51.11 ± 0.85 MeV

$\vartheta$(n1 n2) = 94.8° ± 3.8°
$\vartheta$(n1 p) = 102.2° ± 3.4°
$\vartheta$(n2 p) = 154° ± 19°

no n-n or p/n scattering

| $^{7}_{\Lambda}$Li | MM (MeV/$c^2$) |
|---|---|
| $^4$He | 3727.4 |
| $^3$He + $n$ | 3748.0 |
| $^3$H + $p$ | 3747.2 |

first, direct experimental evidence

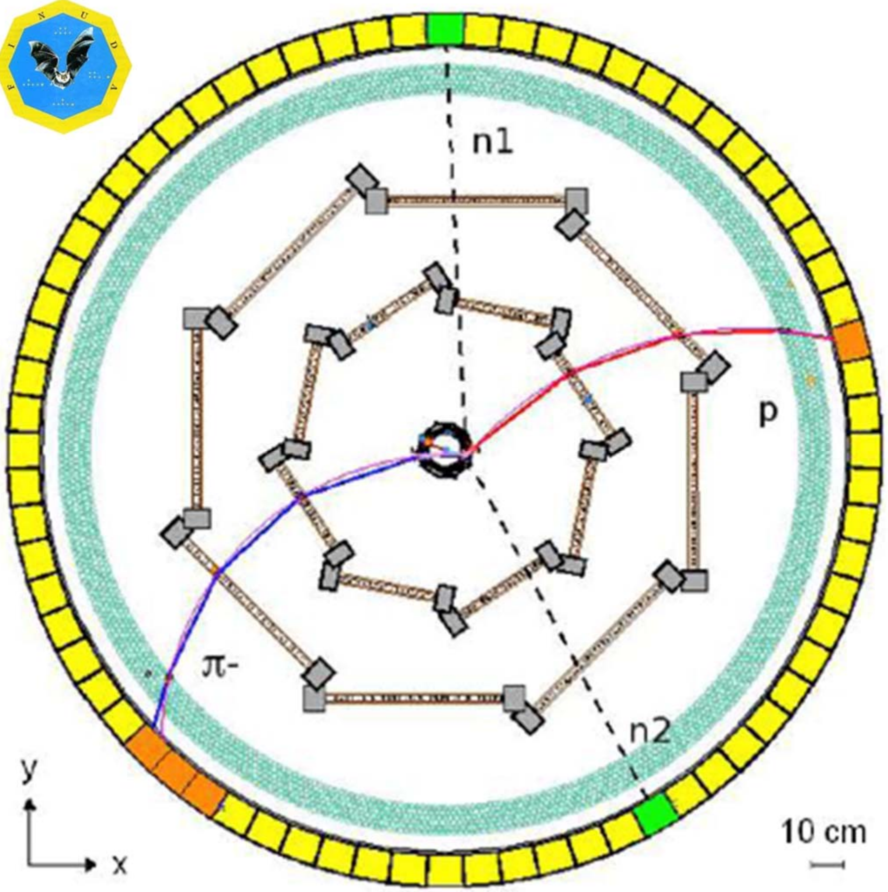
M. Agnello *et al.*, *NPA* 881 (2012) 322

# 2𝒩 induced decay exp. evidence

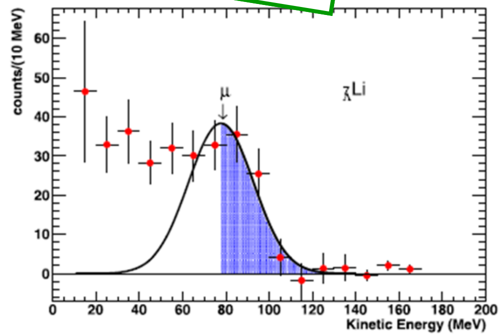


triple coincidence: $(n + n + p)$ events

exclusive $\Lambda np \to nnp$ decay event: $^{7}_{\Lambda}Li \to {}^{4}He + p + n + n$




cut on $E_p$ released




$p_{\pi-}$ = 276.5 ± 1.2 MeV/c
$P_{miss}$ = 447 ± 18 MeV/c
$E_{tot}$ = 147.1 ± 4.2 MeV
MM = 3720.3 ± 4.7 MeV/c$^2$

E(n1) = 21 ± 2.0 MeV
E(n2) = 35.3 ± 3.6 MeV
E(p) = 90.83 ± 0.50 MeV

ϑ(n1 n2) = 126.5° ± 5.4°
ϑ(n1 p) = 53.5° ± 4.3°
ϑ(n2 p) = 124.6° ± 3.9°

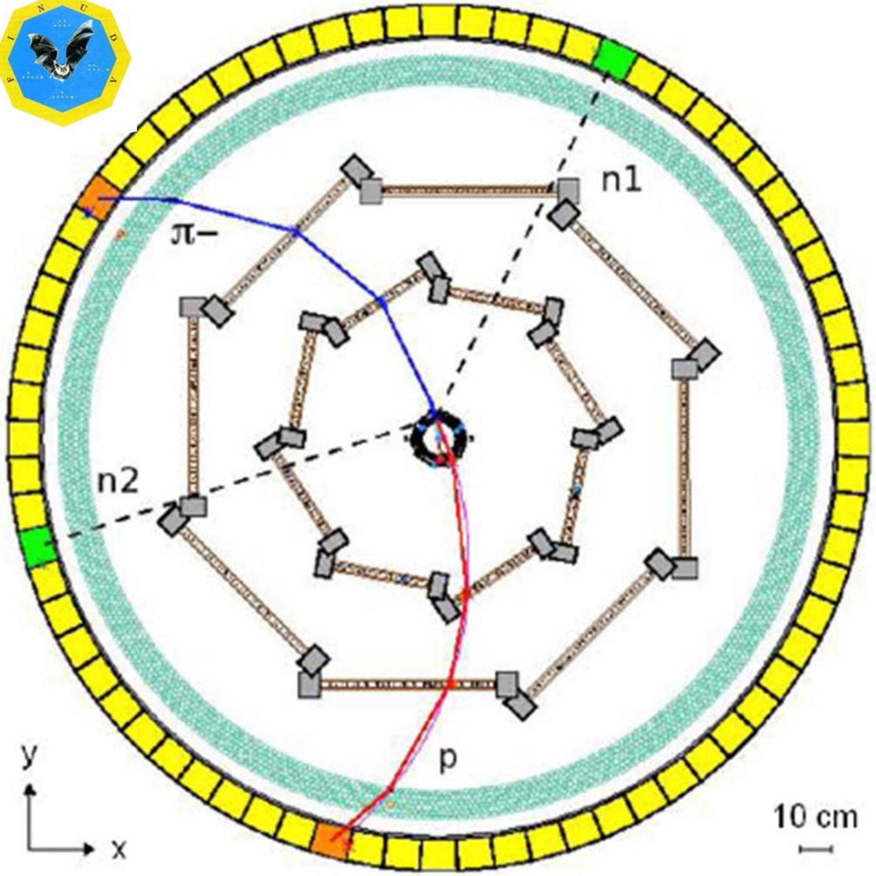
no n-n or p/n scattering

# 2$\mathcal{N}$ induced decay exp. evidence

triple coincidence: $(n + n + p)$ events

exclusive $\Lambda np \rightarrow nnp$ decay event: $^{9}_{\Lambda}Be \rightarrow {^3He} + {^3H} + p + n + n$

cut on $E_p$ released




$p_{\pi-}$ = 286.7 ± 1.2 MeV/c
$P_{miss}$ = 253 ± 18 MeV/c
$E_{tot}$ = 123.5 ± 4.9 MeV
MM = 5617.3 ± 5.0 MeV/$c^2$

E(n1) = 20.2 ± 2.5 MeV
E(n2) = 31.5 ± 4.2 MeV
E(p) = 71.77 ± 0.80 MeV

$\vartheta$(n1 n2) = 133.6 °± 7.5°
$\vartheta$(n1 p) = 128.5°± 5.5°
$\vartheta$(n2 p) = 95.4°± 3.6°

no n-n or p/n scattering

| $^{9}_{\Lambda}$Be | MM (MeV/$c^2$) |
|---|---|
| $^6$Li | 5601.5 |
| $^5$Li + $n$ | 5607.2 |
| $^4$He + $d$ | 5603.0 |
| $^3$He + $^3$H | 5617.3 |

# Summary and outlook



## MWD

- ✓ $\pi^-$ spectra for $^{7}Li_{\Lambda}$, $^{9}Be_{\Lambda}$, $^{11}B_{\Lambda}$ and $^{15}N_{\Lambda}$
- ✓ $^{7}Li_{\Lambda}$, $^{9}Be_{\Lambda}$ and $^{11}B_{\Lambda}$ g.s. $J^{\pi}$ assignment confirmed
- ✓ $^{15}N_{\Lambda}$ g.s. $J^{\pi}$ first determination
- ✓ MWD decay rate extracted
- ✓ strong nuclear structure effect put in evidence

## NMWD

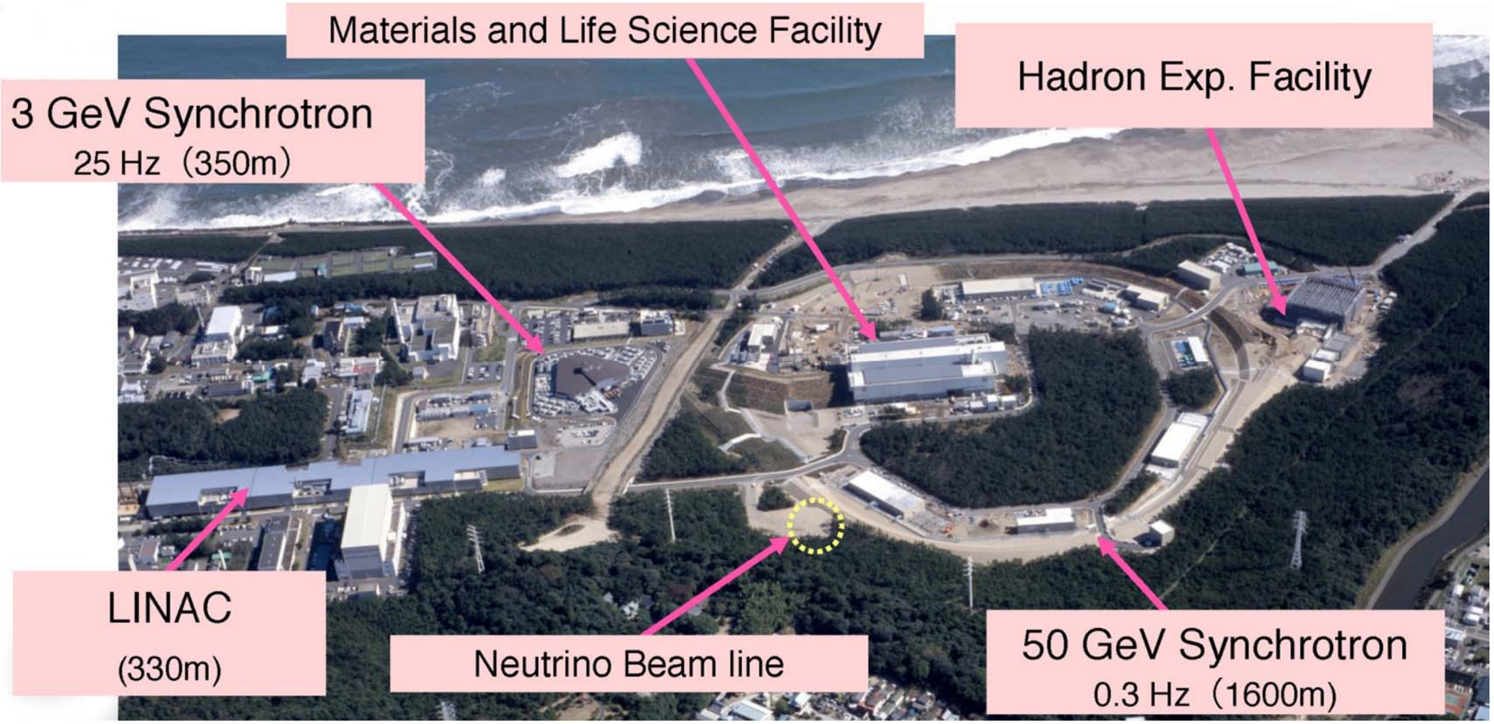
- ✓ *p*-induced NMWD proton spectra from $^{5}He_{\Lambda}$ to $^{16}O_{\Lambda}$
- ✓ $2\mathscr{N}$-induced NMWD contribution determination
- ✓ first experimental evidence of the $2\mathscr{N}$-induced NMWD
- ✓ exclusive process dominance in $1\mathscr{N}$ and $2\mathscr{N}$ decay?

Further investigations needed
both experimental and theoretical

# Future dedicated experiments

**E18** Coincidence measurement of the weak decay of $^{12}C_{\Lambda}$ and the three-body weak interaction process

**E22** Exclusive study of the $\Lambda\mathcal{N}$ weak interaction in A = 4 Λ-hypernuclei



# Aknowledgement

A special thanks to:

- Michelangelo Agnello
- Elena Botta
- Tullio Bressani
- Stefania Bufalino