First experimental determination of the one-proton induced non-mesonic weak decay width for p-shell Λ-hypernuclei

Alessandro Feliciello

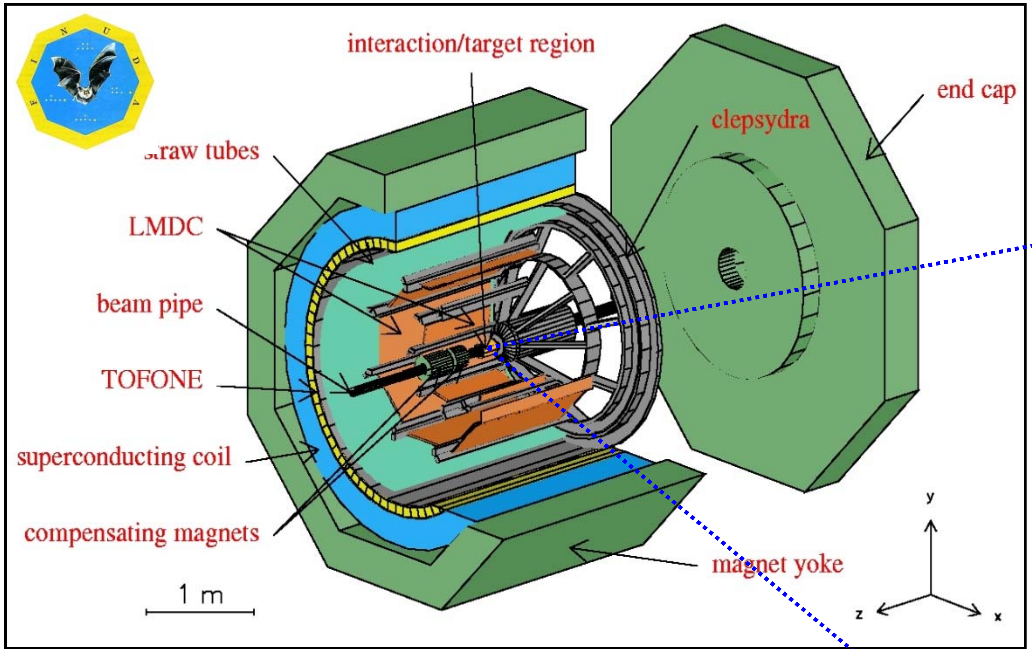
I.N.F.N. - Sezione di Torino

on behalf of the FINUDA Collaboration

Outline

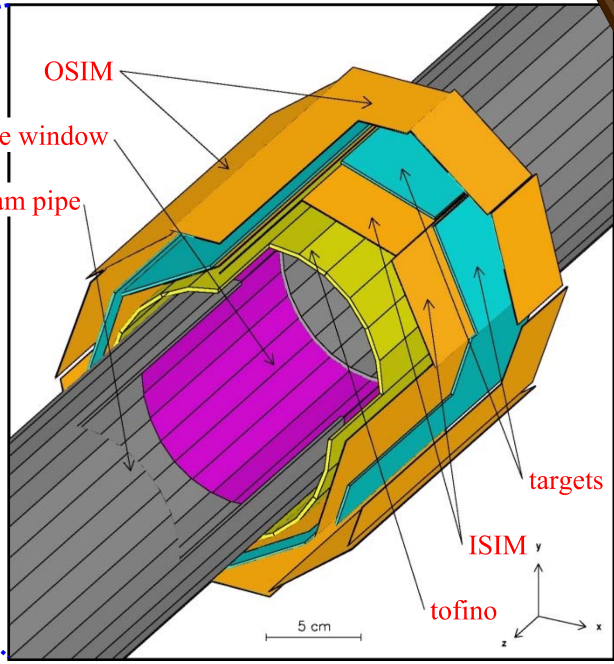
- The FINUDA experiment @ INFN/LNF DAΦNE
- A revisited analysis of the proton spectra from NMWD of Λ−hypernuclei
- First determination of Γ_p/Γ_Λ for 8 Λ−hypernuclei (A = 5 - 16)
- A look to the future

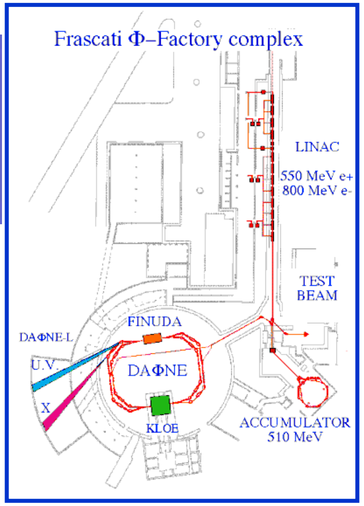
FINUDA in a nutshell



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

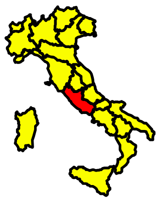
$$K^-_{stop} + {}^{A}Z \to {}^{A}_{\Lambda}Z + \pi^-$$





energy	510 MeV
luminosity	$5\ 10^{32}\ cm^{-2}\ s^{-1}$
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)

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



FINUDA key features

- very thin nuclear targets ($0.1 \div 0.3$ g/cm^2)
  - → high resolution spectroscopy
- coincidence measurements with large acceptance (2π sr)
  - → decay mode study
- event by event K^+ tagging
  - → continuous energy and rate calibration
- irradiation of different targets in the same run
  - → systematic error reduction
  - ← systematics on A

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

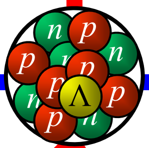
possible thanks to apparatus performance and stability

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

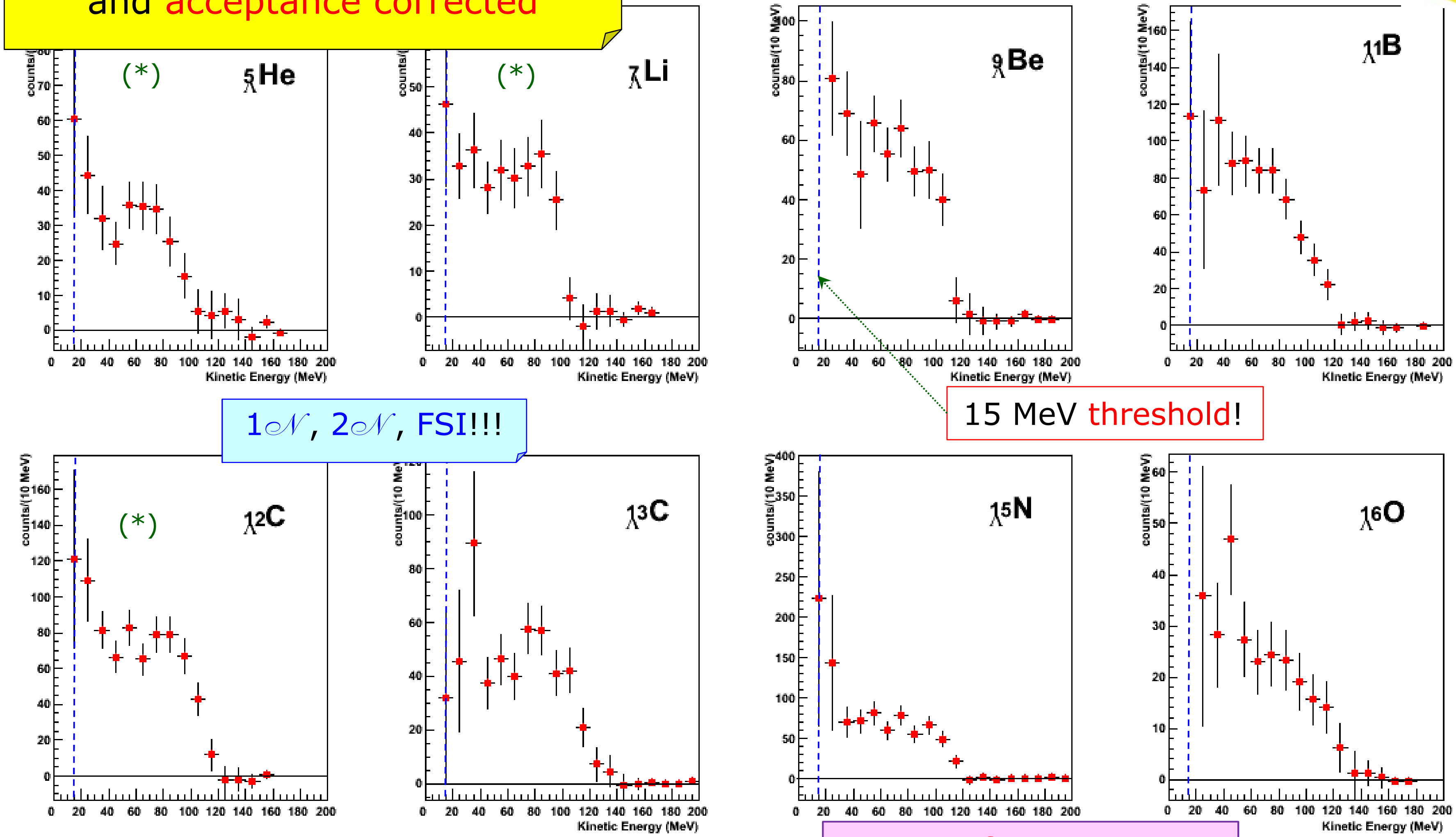
M. Agnello *et al.*, *PRL* 94 (2005) 212303

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

Anatomy of NMWD p spectra

p spectra background subtracted and acceptance corrected

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



1$\mathcal{N}$, 2$\mathcal{N}$, FSI!!!

15 MeV threshold!

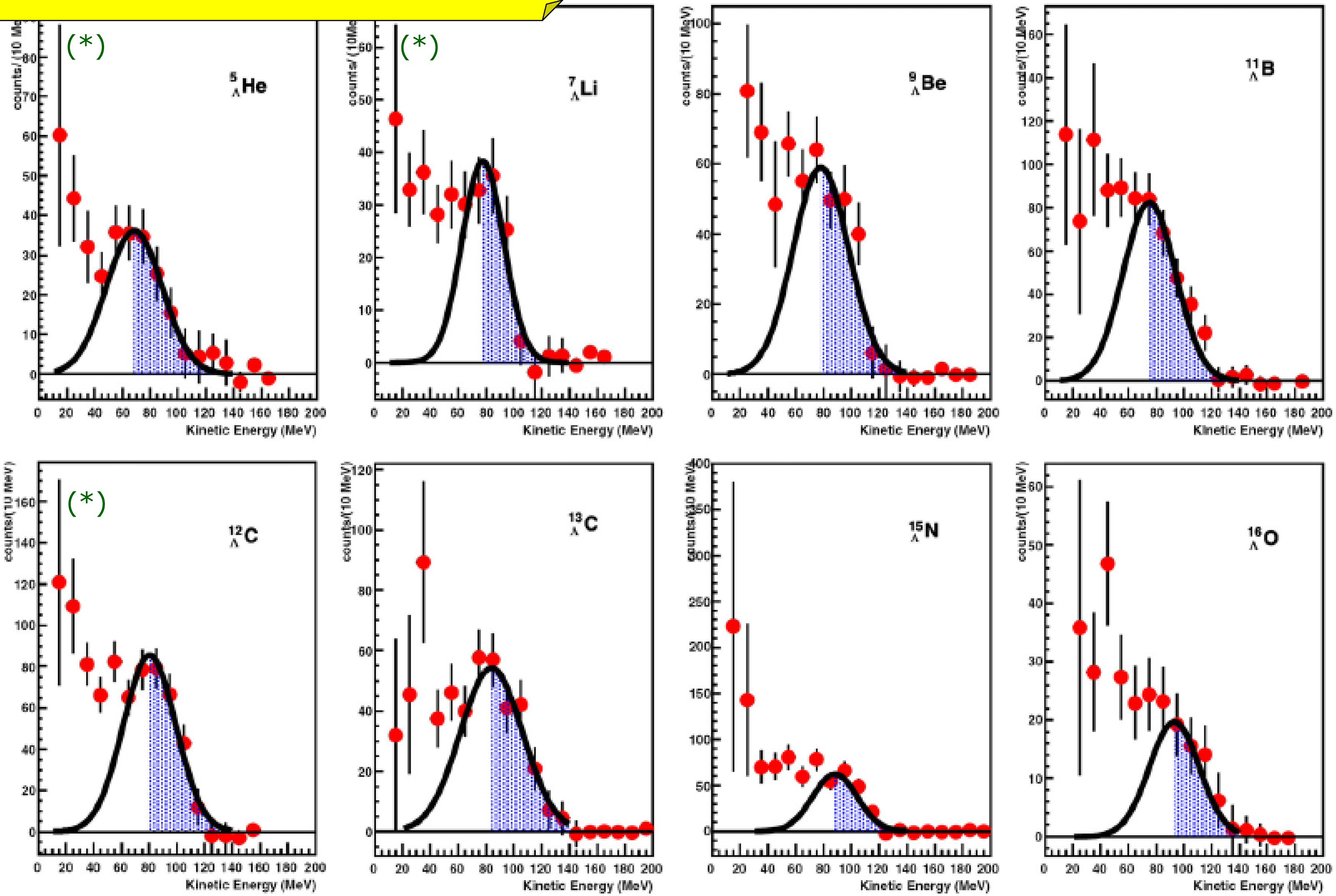
(*) M. Agnello *et al.*, *NPA* 804 (2008) 151.

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

FSI and 2𝒩 induced non-mesonic decay

p spectra background subtracted and acceptance corrected

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

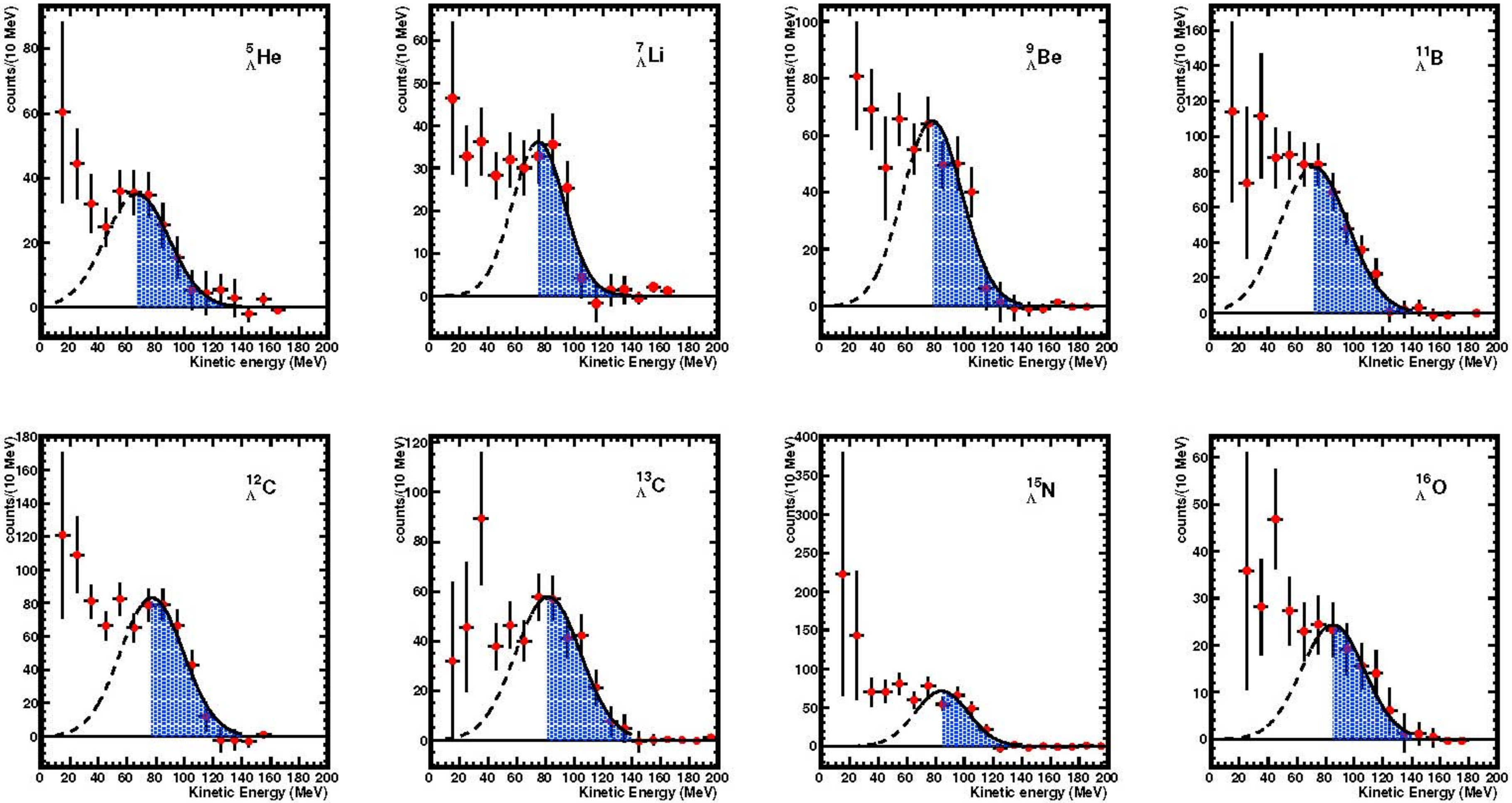


(*) M. Agnello *et al.*, *NPA* 804 (2008) 151.

Revised analysis of the proton spectra

Attempt of improving the fits by shifting down the lower edge for the fits to 50, 60 and 70 MeV:

better value of $\chi^2/n = 1.33$ when choosing the starting point at 70 MeV

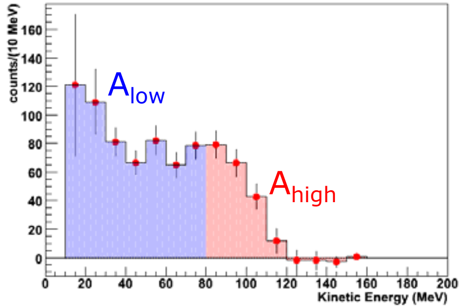


Refined determination of $\Gamma_{2\mathcal{N}} / \Gamma_{NMWD}$

The values of μ were used to divide the full area of the proton spectra into two regions, A_{low} and A_{high}.
It was shown that from the expression:

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

$$R_1(A) = \frac{A_{low}(A)}{A_{low}(A) + A_{high}(A)}$$



the ratio $\Gamma_{2\mathcal{N}}/\Gamma_p$ can be obtained
(under the assumption that it is constant in the range A = 5 ÷ 16).

It was found:

$\Gamma_{2\mathcal{N}}/\Gamma_p = 0.43 \pm 0.25$ ($\Gamma_{2\mathcal{N}}/\Gamma_{NMWD} = 0.24 \pm 0.10$)

With the new values we find:

$\Gamma_{2\mathcal{N}}/\Gamma_p = 0.50 \pm 0.24$ ($\Gamma_{2\mathcal{N}}/\Gamma_{NMWD} = 0.25 \pm 0.12$)

compatible with the previous one, within the errors.

Refined determination of $\Gamma_{2\mathcal{N}}/\Gamma_{NMWD}$

By selecting (*n*,*p*) coincidence events we found:

$$\frac{\Gamma_{2N}}{\Gamma_p} = 0.39 \pm 0.16_{stat}\,{}^{+0.04}_{-0.03}{}_{sys}$$

$$\left(\frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.21 \pm 0.07_{stat}\,{}^{+0.03}_{-0.02}{}_{sys}\right)$$

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

With the new μ values, we got:

$$\frac{\Gamma_{2N}}{\Gamma_p} = 0.36 \pm 0.14_{stat}\,{}^{+0.05}_{-0.04}{}_{sys}$$

$$\left(\frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.20 \pm 0.08_{stat}\,{}^{+0.03}_{-0.02}{}_{sys}\right)$$

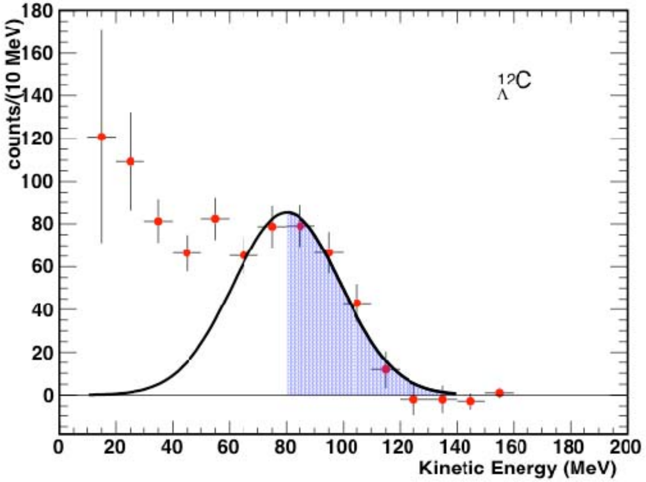
preliminary

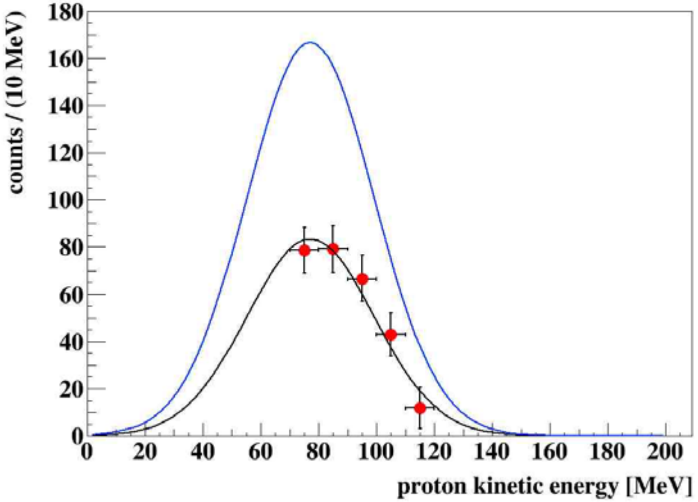
- fully compatible with the previous one, within the errors.

- M. Kim *et al.*, *PRL* 103 (2009) 182502: 0.29 ± 0.13.
- E. Bauer and G. Garbarino, *PRC* 81 (2010) 064315.

First determination of $\Gamma_p / \Gamma_\Lambda$ for 8 Hypernuclei

Some information can be extracted by the proton spectra, but how it is possible to extract the “true” number of protons from NMWD.
Spectra are severely distorted by several FSI effects





At least 3 effects:

a) number of primary protons from NMWD decreased by FSI
b) in a given region of the spectrum increase due to the FSI not only of higher energy protons, but of neutrons as well
c) quantum mechanical interference effect

In the upper part of the experimental spectrum b) and c) are negligible

How to calculate a) without resorting to any INC models, but only from experimental data?

First determination of $\Gamma_p / \Gamma_\Lambda$ for 8 Hypernuclei

$$\frac{\Gamma_p}{\Gamma_\Lambda} = \frac{\Gamma_T}{\Gamma_\Lambda} \frac{2(N_p - N_{2N}) + \alpha(N_p - N_{2N})}{N_{Hyp}}$$

where α accounts for FSI:

$$\left(\frac{\alpha}{2+\alpha}\right)$$ protons lost

no INC calculation

input: experimental results only

Γ_T/Γ_Λ, Γ_n/Γ_p, $\Gamma_{2\mathcal{N}}/\Gamma_p$
$\Gamma_{\pi^-}/\Gamma_\Lambda$, $\Gamma_{\pi^0}/\Gamma_\Lambda$

$\Gamma_p/\Gamma_\Lambda(^5He_\Lambda) = 0.22 \pm 0.03$

J.J. Szymansky *et al.*, PRC 43 (1991) 849: 0.21 ± 0.07

$\Gamma_p/\Gamma_\Lambda(^{12}C_\Lambda) = 0.49 \pm 0.06$

H. Noumi *et al.*, PRC 52 (1995) 2936: 031 ± 0.07
H. Bhang *et al.*, JKPS 59 (2011) 1461: 045± 0.10

$\alpha_5(^5He_\Lambda) = 1.15 \pm 0.26$

$\alpha_5(^{12}C_\Lambda) = 1.04 \pm 0.19$

assumption

α scaling linearly with A

$\alpha_{12}(^{12}C_\Lambda) = 2.48 \pm 0.46$

$\alpha_{12}(^5He_\Lambda) = 2.77 \pm 0.63$

weighted average

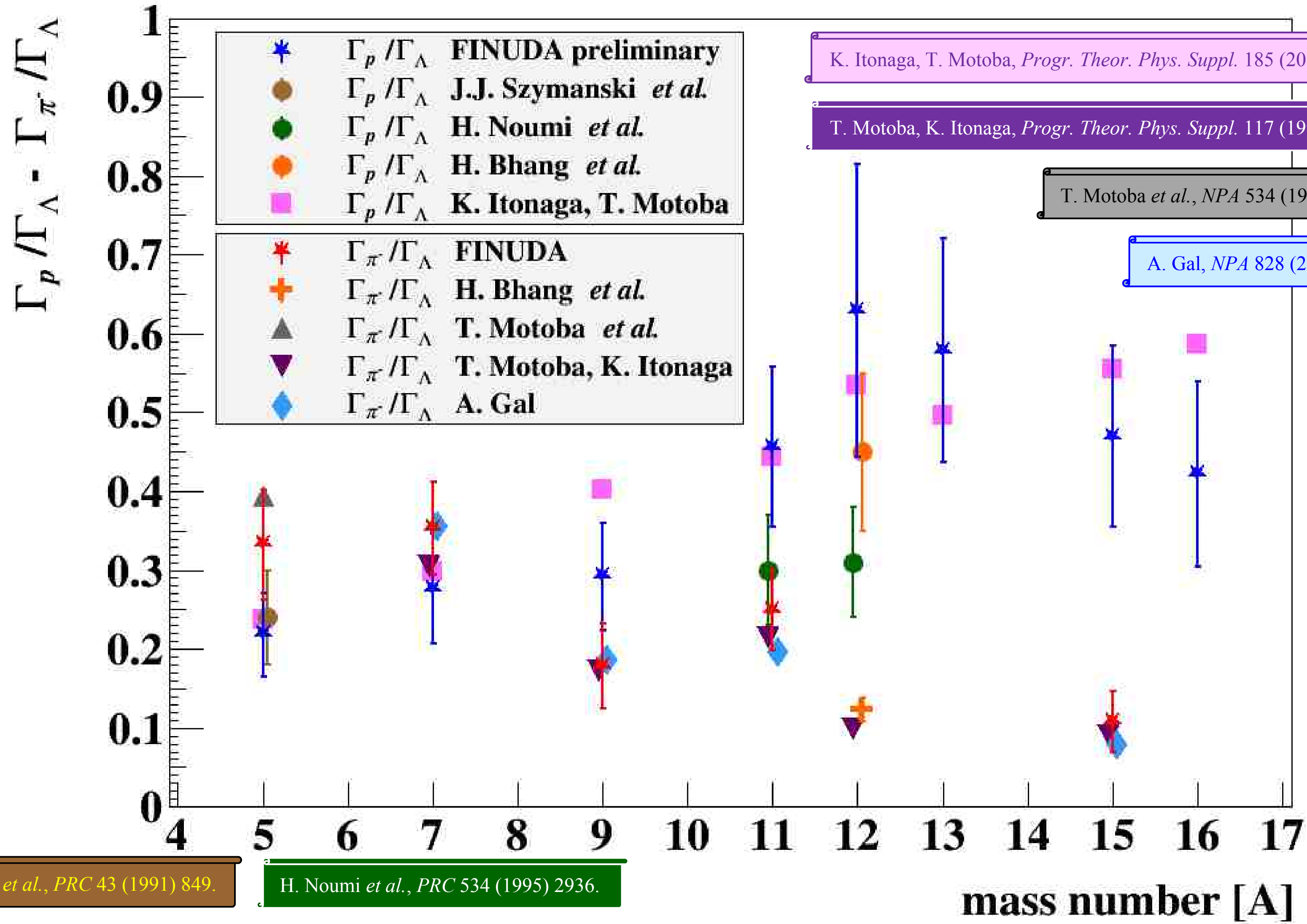
$\overline{\alpha_5} = 1.08 \pm 0.16$

$\overline{\alpha_{12}} = 2.58 \pm 0.37$

$\alpha(A) = (0.215 \pm 0.031) \cdot A$

Alessandro Feliciello / The 2nd International Symposium on Science at J-PARC, Tsukuba, Ibaraki, Japan, July 12 - 15, 2014

First determination of $\Gamma_p / \Gamma_\Lambda$ for 8 Hypernuclei



K. Itonaga, T. Motoba, *Progr. Theor. Phys. Suppl.* 185 (2010) 252.

T. Motoba, K. Itonaga, *Progr. Theor. Phys. Suppl.* 117 (1994) 477.

T. Motoba *et al.*, *NPA* 534 (1991) 597.

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

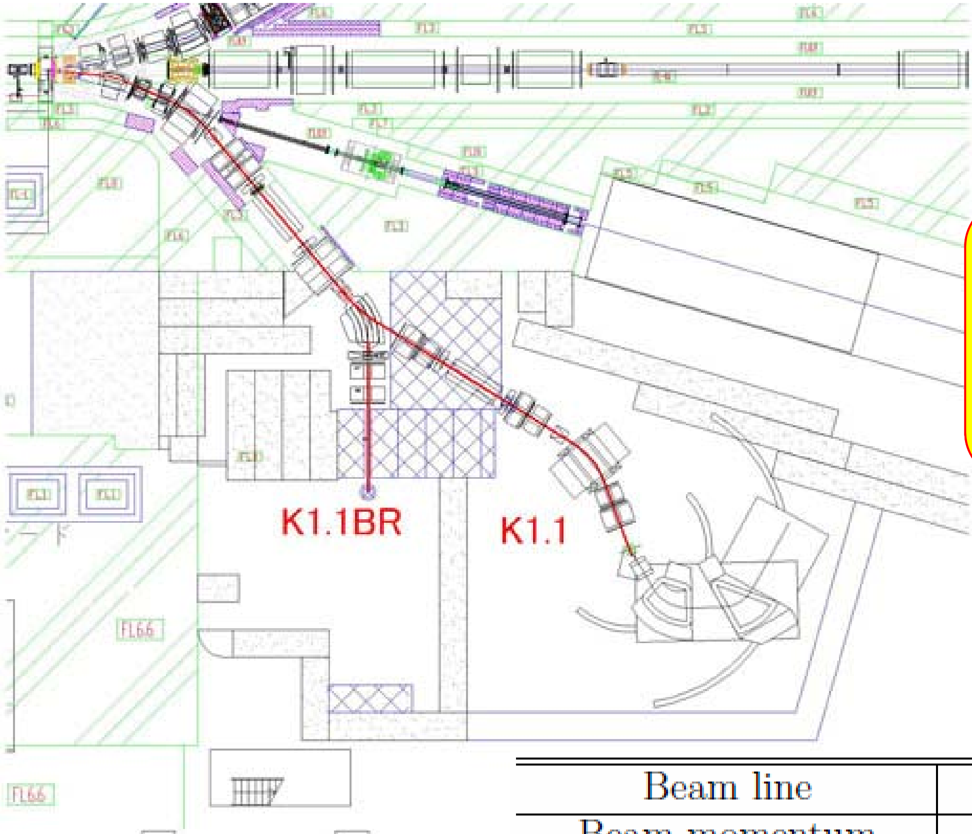
J.J. Szymansky *et al.*, *PRC* 43 (1991) 849.

H. Noumi *et al.*, *PRC* 534 (1995) 2936.

H. Bhang *et al.*, *JKPS* 59 (2011) 1461.

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

J-PARC K1.1 beam line



one order of magnitude
more efficient data collection
expected
with respect to K1.8 beam line

Beam line	K1.8	K1.8BR	K1.1
Beam momentum	1.5 GeV/c	1.1 GeV/c	1.1 GeV/c
Beam intensity	0.5×10^6/spill	1.2×10^6/spill	1.0×10^6/spill
$\frac{d\sigma}{d\Omega}({}^{7}_{\Lambda}\text{Li}(3/2^+), \theta = 10^0)$	7.1μb/sr	17μb/sr	
Relative γ-ray yield	1	5.7	4.8
K/π ratio		< 0.9	~ 3
γ-ray peak broadening	8.2%	6.1%	

old (2008) conservative (?) perspective

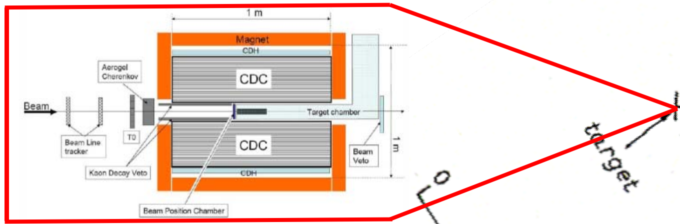
E10 published data: $> 1 \times 10^7\ \pi^+$/spill

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

A possible apparatus concept layout

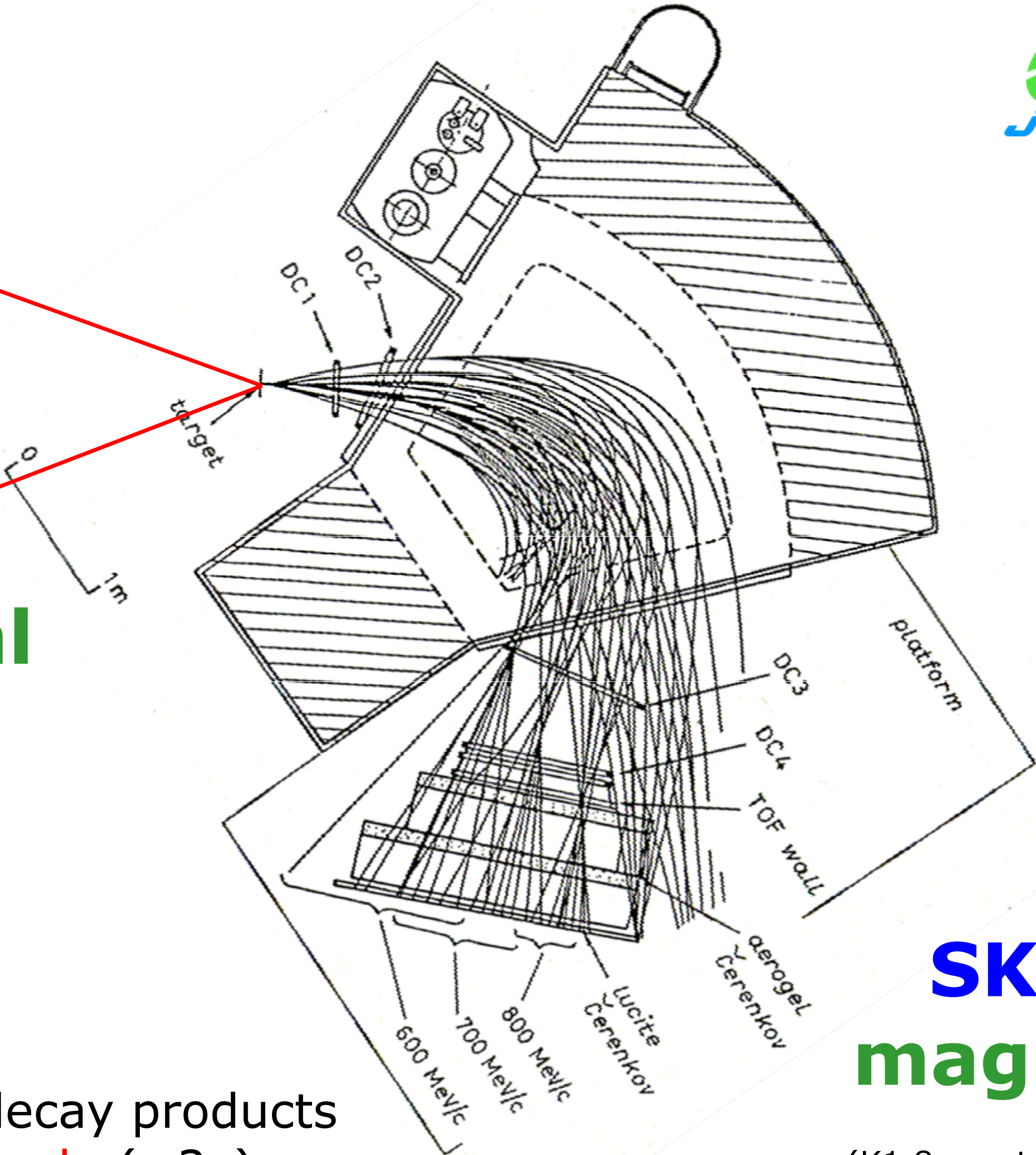
Alessandro Feliciello / The 2nd International Symposium on Science at J-PARC, Tsukuba, Ibaraki, Japan, July 12 - 15, 2014

unavoidably biased
by the FINUDA experience



Cylindrical Detector System

(K1.8BR spectrometer)



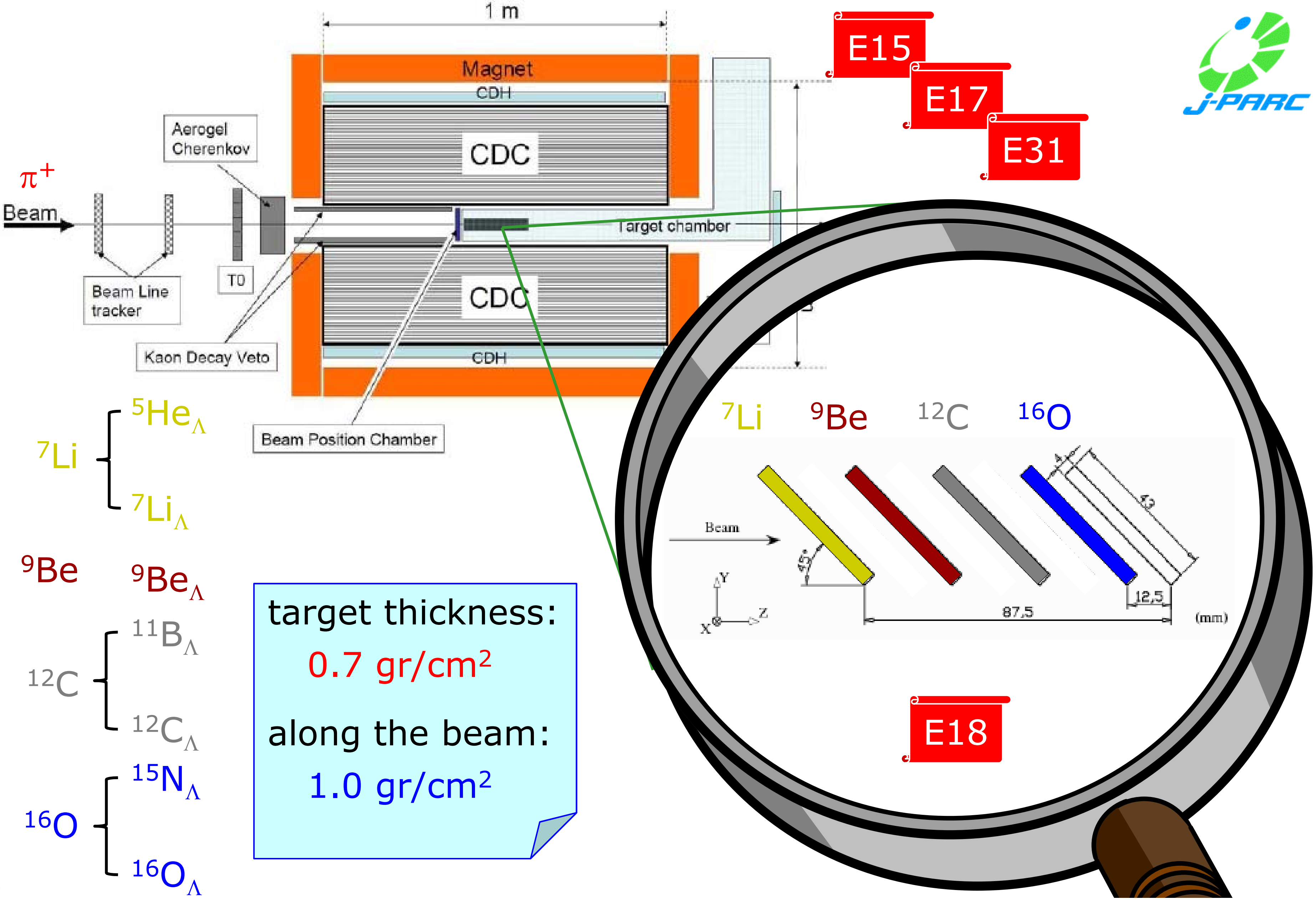
SKS magnet

(K1.8 spectrometer)

essential requirements

- magnetic analysis of decay products
- large detection solid angle (~2π)

A possible apparatus concept layout



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

^{9}Be — ^{9}Be$_\Lambda$

^{12}C { ^{11}B$_\Lambda$, ^{12}C$_\Lambda$

^{16}O { ^{15}N$_\Lambda$, ^{16}O$_\Lambda$

target thickness:
0.7 gr/cm^2

along the beam:
1.0 gr/cm^2

Expected rates (rough estimate)

educated guess → $\sim 10^8\ \pi^+$ / spill

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

$> 1 \times 10^7 \pi^+$/spill

interspill: 3.5 s → $\sim 10^{12}\ \pi^+$ / day

from previous experience → $\sim 10^4\ {}^{12}C_{\Lambda\ g.s.}$ / day

KEK-PS:
E336, E369, E419, E462, E508

$\sim 1\ {}^{12}C_{\Lambda\ g.s.}\ /\ 10^8\ \pi^+$

formation rate on 1 g/cm^2 target

B.R. (0.5), $\Delta\Omega$ (0.5), $\varepsilon_{riv/rec}$ (0.5) → $\sim 10^3\ {}^{12}C_{\Lambda\ g.s.}$ / day

Conclusions

- First systematic determination of $\Gamma_p / \Gamma_\Lambda$ for *p*-shell Hypernuclei

- experimental data agree with the latest calculations by Itonaga & Motoba,
  (even though the errors are quite large…)

K. Itonaga, T. Motoba, *Progr. Theor. Phys. Suppl.* 185 (2010) 252.

- First experimental verification of the complementary
  between MWD and NMWD, at least for charged channels

- Waiting for J-PARC scientific program restart…