

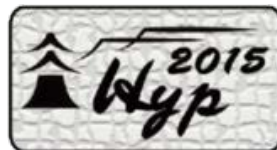
The 12th International Conference on
Hypernuclear and Strange Particle Physics

HYP2015

September 7 – 12, 2015
Tohoku University, Sendai, Japan



Museum of Fine Arts Boston

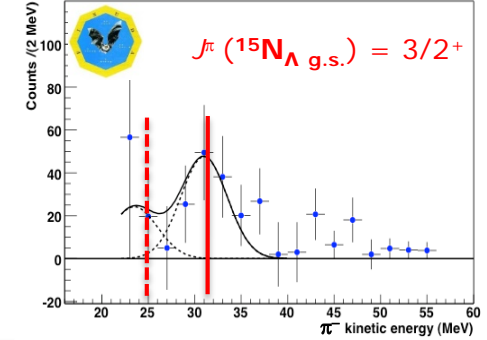
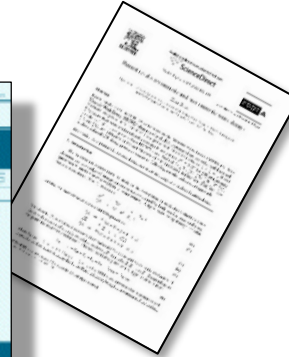
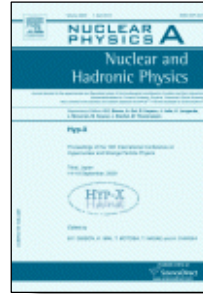
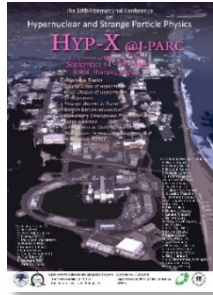


Experimental studies on the weak decay of Λ -hypernuclei

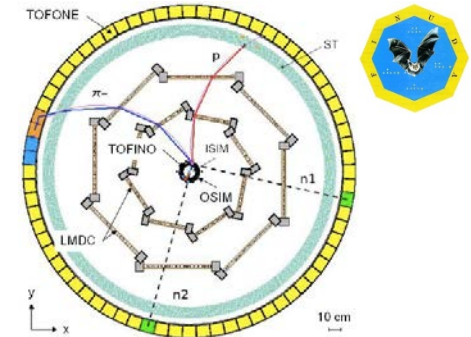
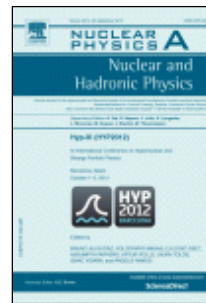
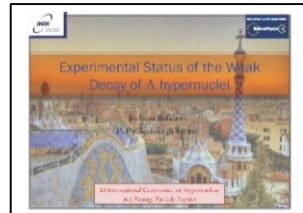


Alessandro Feliciello
I.N.F.N. - Sezione di Torino

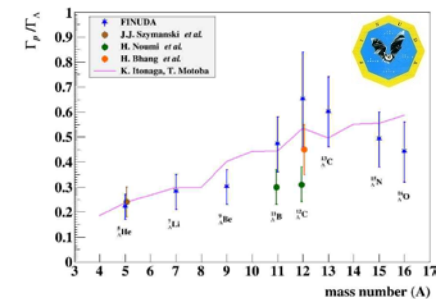
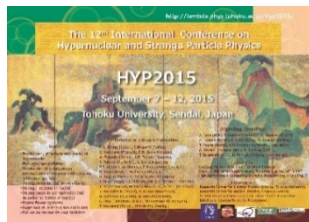
Mission accomplished



- 1st, experimental assignment of $J^{\pi}(^{15}\text{N}_{\Lambda}) = 3/2^{+}$
- determination of the $\Gamma_{2e\nu}$









1st, direct experimental evidence for $2e\nu$ -induced NMWD

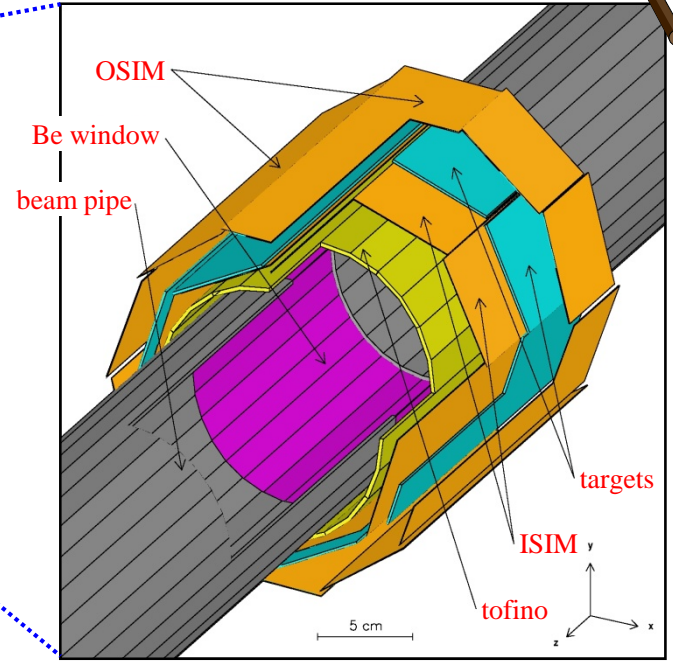
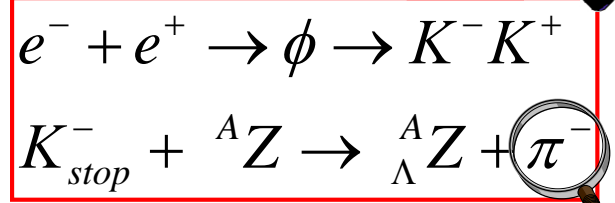
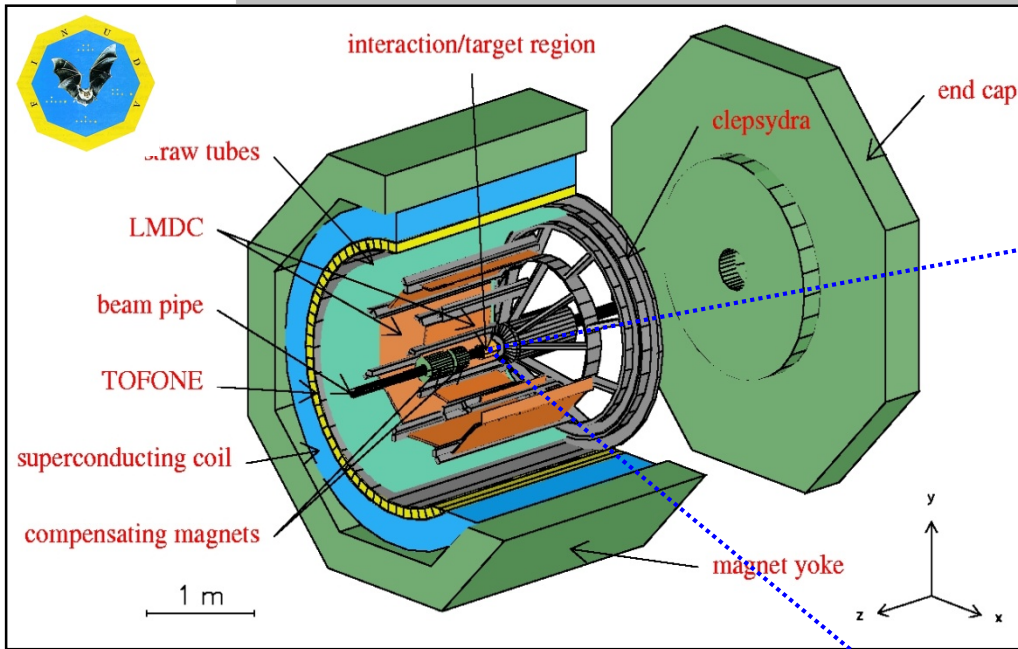


1st determination of $\Gamma_p / \Gamma_{\Lambda}$ or 8 Hypernuclei

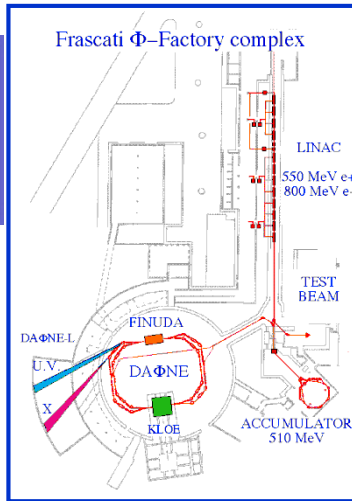
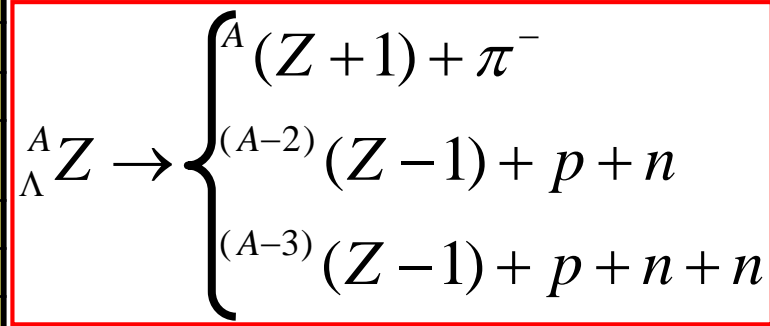
Outline

- 
 The **FINUDA** apparatus @ INFN/LNF **DAΦNE**:
 - 
 a detector **designed** for **decay** of hypernuclei **study**
- 
 A **revisited** analysis of the **proton spectra** from **NMWD** of Λ -hypernuclei
- 
First determination of Γ_p/Γ_Λ for 8 Λ -hypernuclei ($A = 5-16$)
- 
 Determination of the **full set** of **NMWD widths** for ${}^5\text{He}_\Lambda$ and ${}^{11}\text{B}_\Lambda$
- 
 A look to the **future**

FINUDA in a nutshell



energy	510 MeV
luminosity	$5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
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	$8.9 \cdot 10^{10}$
current/ring	5.2 A (max)

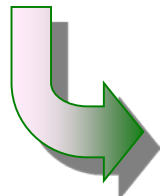




FINUDA key features

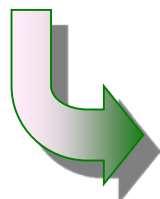


- ☛ very thin nuclear targets ($0.1 \div 0.3 \text{ g/cm}^2$)



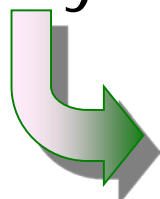
high resolution spectroscopy

- ☛ coincidence measurements with large acceptance ($2\pi \text{ sr}$)



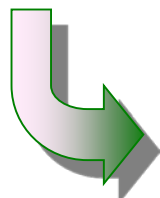
decay mode study

- ☛ 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 motivations

see Tuesday's
topical session

- ☞ **lifetime** of (**light**) Λ -hypernuclei
- ☞ **check** of the **validity** of the $\Delta I = 1/2$ rule
- ✓ MWD decay exploited as **indirect spectroscopic** analysis tool
- ☞ the NMWD study provides the **only practical means** of exploring the four-fermion, strangeness changing $e\Lambda \rightarrow e\mathcal{N}$ weak interaction
- ✓ Γ_n/Γ_p puzzle
- ✓ **experimental evidence** of $2e\mathcal{N}$ -induced process
- ☞ **in medium modifications** of hyperons weak decay
- ☞ ...

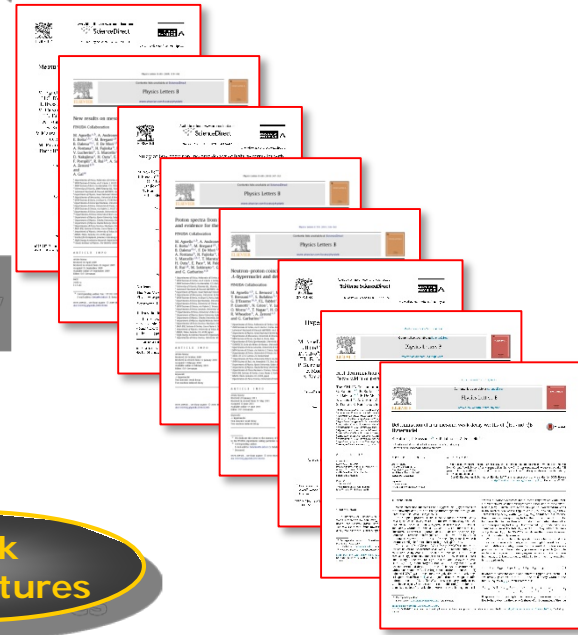
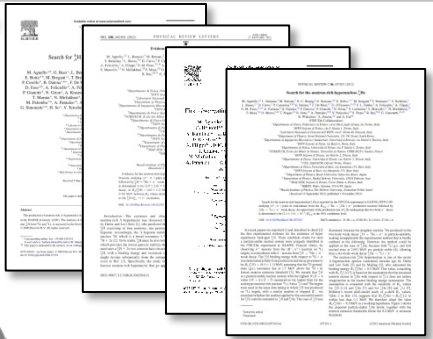


Physics output ($S = -1$)



possible thanks to apparatus performance and stability

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

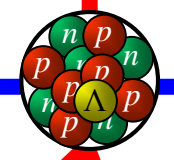


nuclear models

neutron-rich Λ -hypernuclei

4B weak interaction

spectroscopy



(weak) decay

medium effect

quark substructures

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

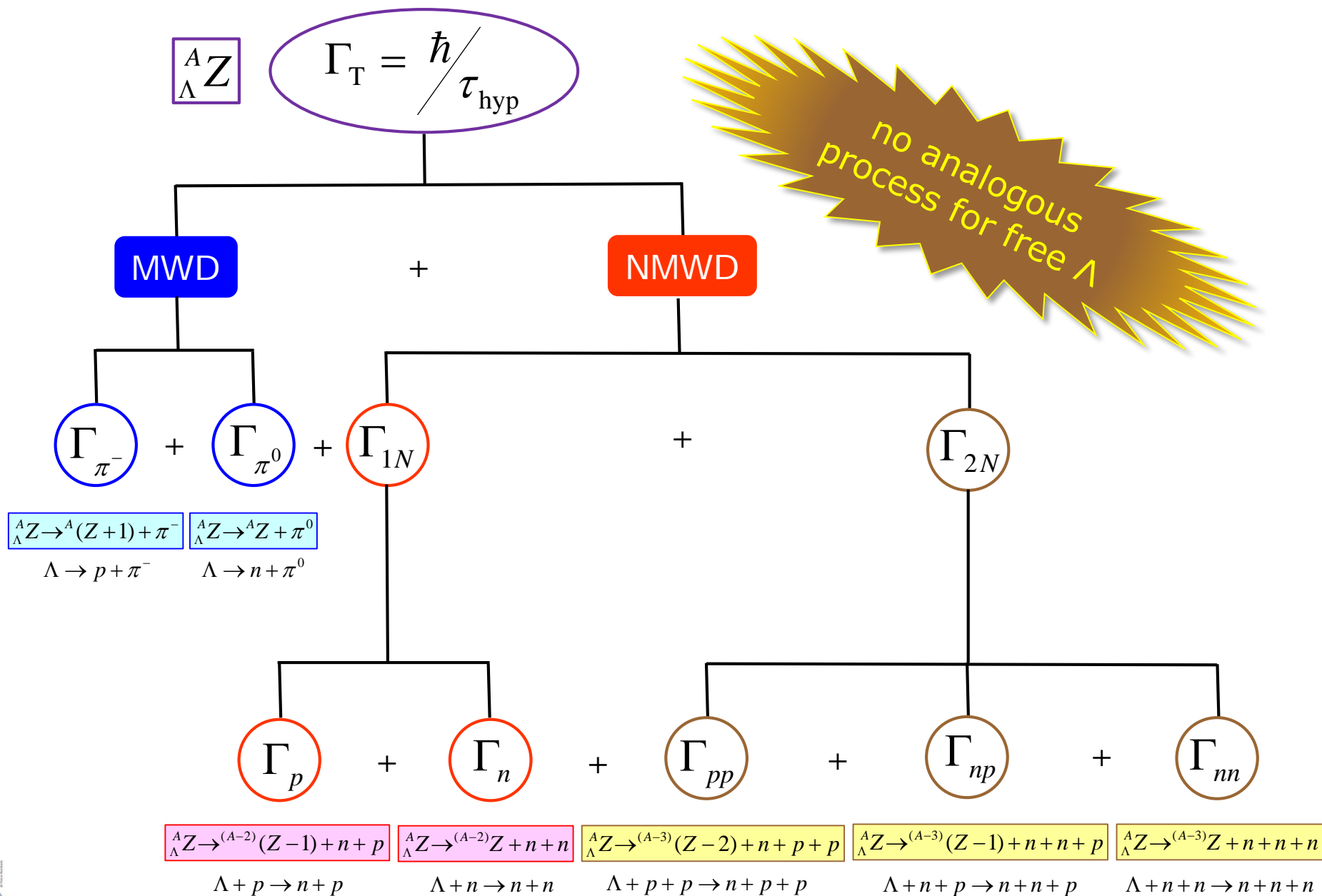
low-energy N - Y interaction

deeply bound \bar{K} states

1. M. Agnello *et al.*, *PRL* 94 (2005) 212303
2. M. Agnello *et al.*, *PLB* 654 (2007) 80

1. M. Agnello *et al.*, *NPA* 804 (2008) 151
2. M. Agnello *et al.*, *PLB* 681 (2009) 139
3. M. Agnello *et al.*, *NPA* 835 (2010) 439
4. M. Agnello *et al.*, *PLB* 685 (2010) 247
5. M. Agnello *et al.*, *PLB* 701 (2011) 556
6. M. Agnello *et al.*, *NPA* 881 (2012) 322
7. M. Agnello *et al.*, *PLB* 738 (2014) 499
8. E. Botta *et al.*, *PLB* 748 (2015) 86

Observables in Weak Decay of Λ -Hypernuclei

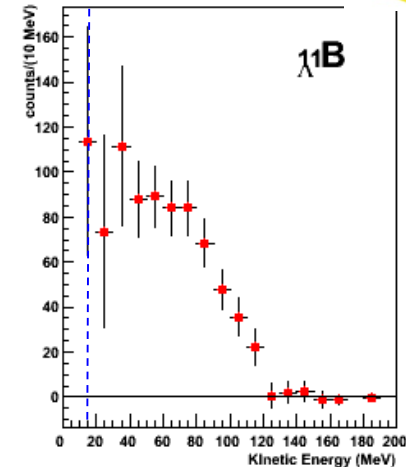
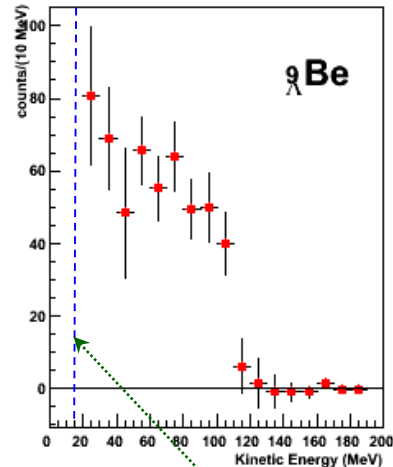
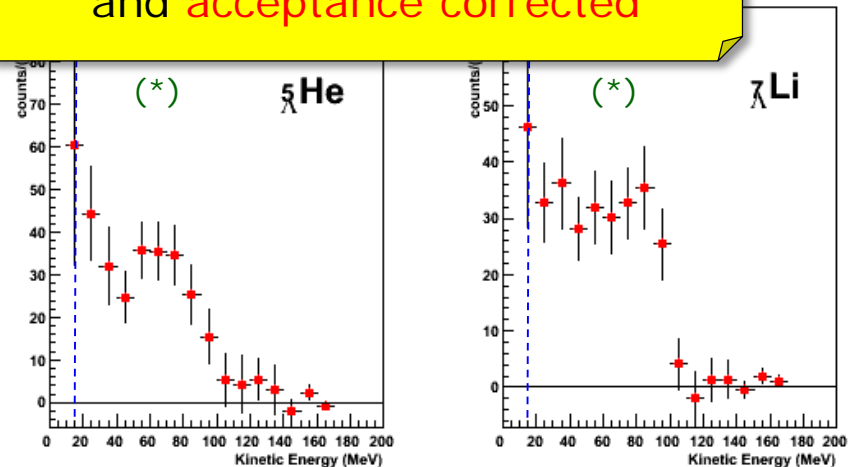


Anatomy of NMWD p spectra



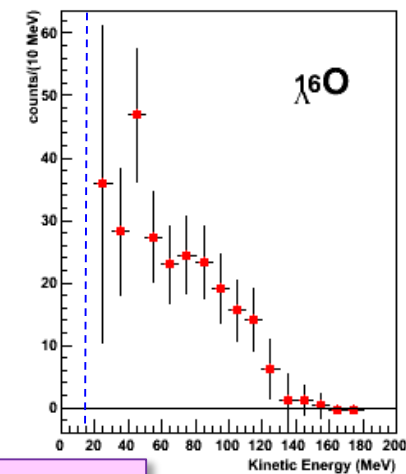
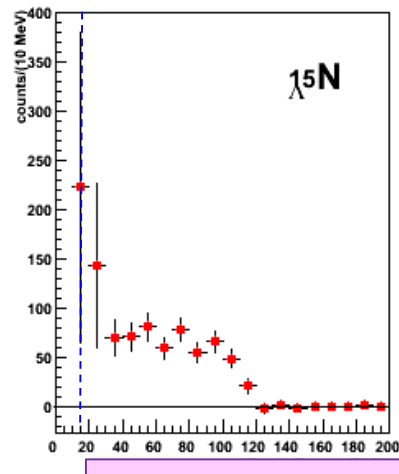
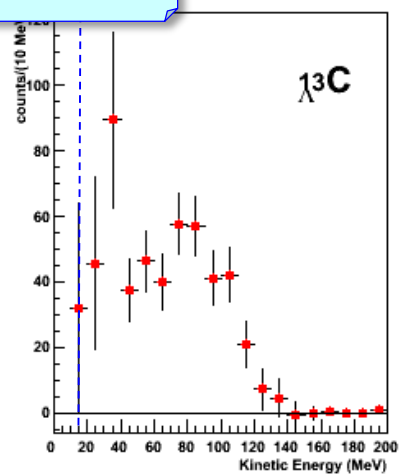
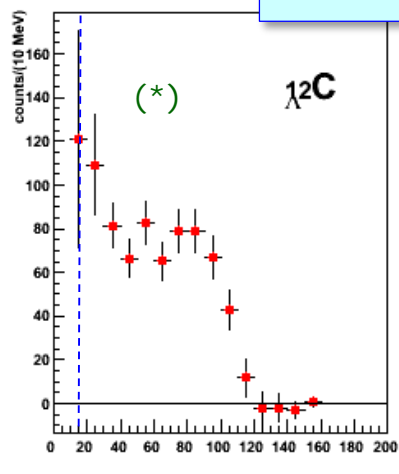
M. Agnello *et al.*, *PLB* 685 (2010) 247.

p spectra background subtracted and acceptance corrected



15 MeV threshold!

1 σ , 2 σ , FS!!!!



(*)

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

common features:

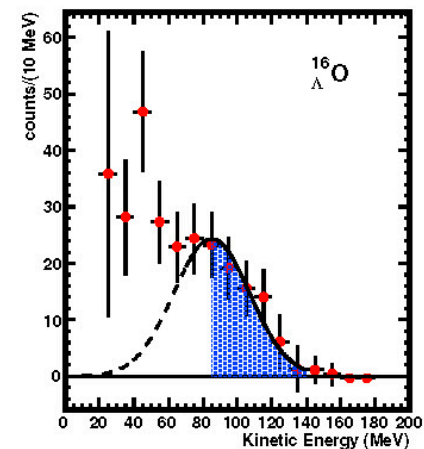
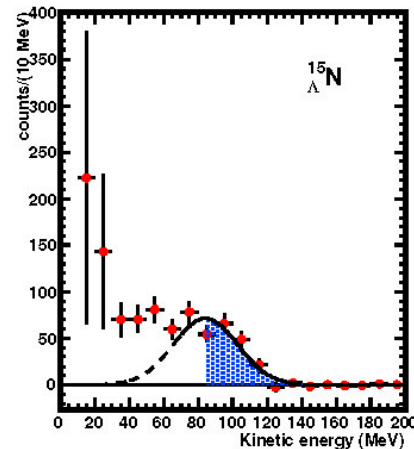
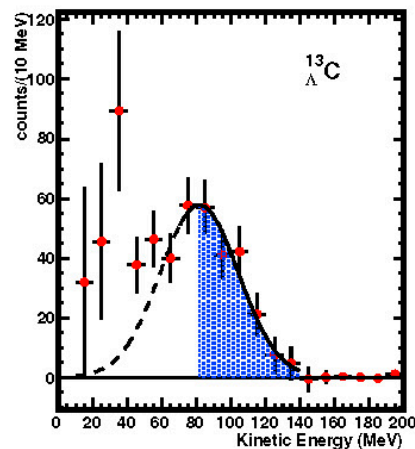
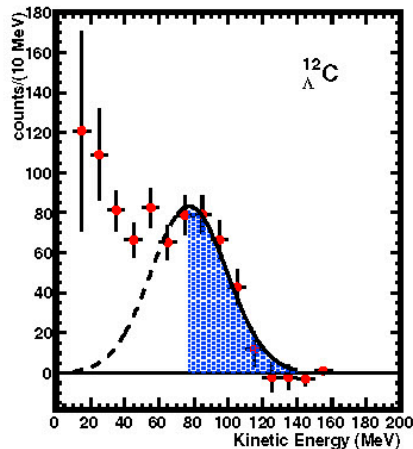
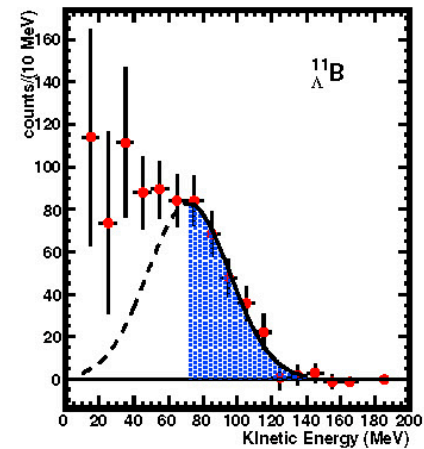
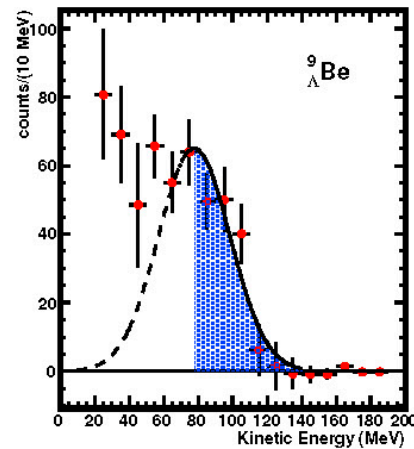
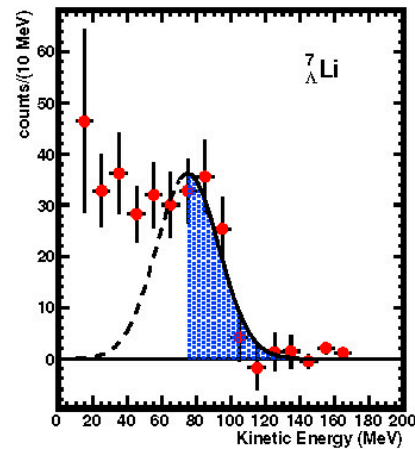
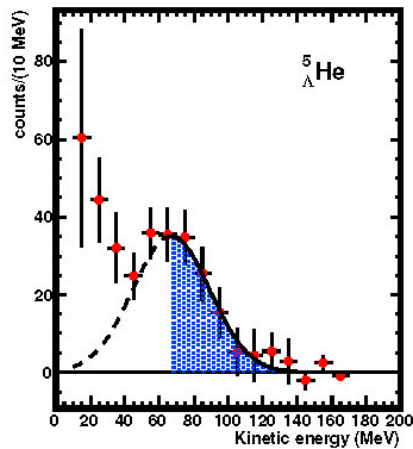
- structure at ~80 MeV
- low energy rise

Revisited 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**



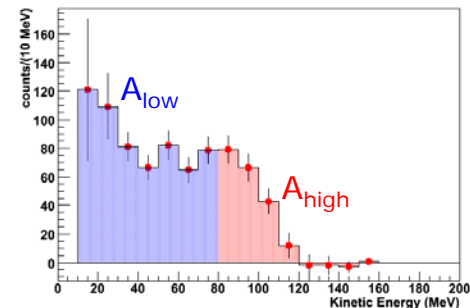
Refined determination of $\Gamma_{2e\nu}/\Gamma_{NMWD}$

The central values of the fitting Gaussians (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 $\Gamma_{2e\nu}/\Gamma_p$ can be obtained (under the assumption that it is **constant** in the range $A = 5 \div 16$).

It was found (**single particle spectra**):

$$\Gamma_{2e\nu}/\Gamma_p = 0.43 \pm 0.25$$

$$(\Gamma_{2e\nu}/\Gamma_{NMWD} = 0.24 \pm 0.10)$$

With the **new values** we find:

$$\Gamma_{2e\nu}/\Gamma_p = 0.50 \pm 0.24$$

$$(\Gamma_{2e\nu}/\Gamma_{NMWD} = 0.25 \pm 0.12)$$

👍 **compatible** with the previous one, within the errors.

Refined determination of $\Gamma_{2e\nu}/\Gamma_{NMWD}$



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

$$\frac{\Gamma_{2N}}{\Gamma_p} = 0.39 \pm 0.16_{\text{stat} - 0.03\text{sys}}^{+0.04} \quad \left(\frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.21 \pm 0.07_{\text{stat} - 0.02\text{sys}}^{+0.03} \right)$$

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

With the new μ values, we got:

$$\frac{\Gamma_{2N}}{\Gamma_p} = 0.36 \pm 0.14_{\text{stat} - 0.04\text{sys}}^{+0.05} \quad \left(\frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.20 \pm 0.08_{\text{stat} - 0.02\text{sys}}^{+0.03} \right)$$

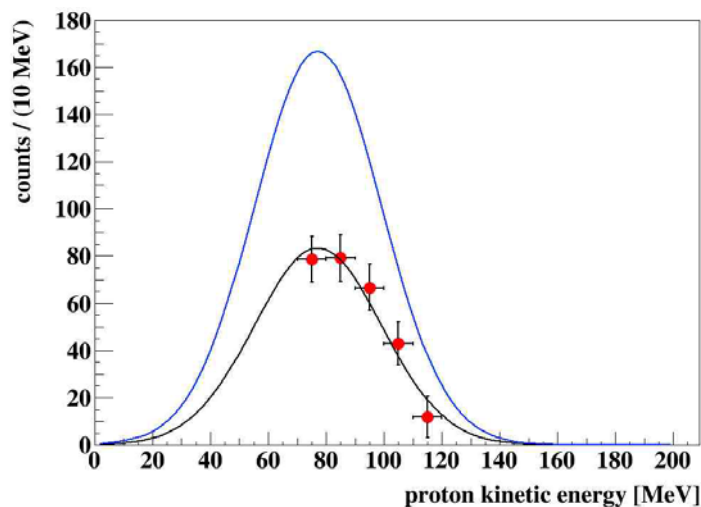
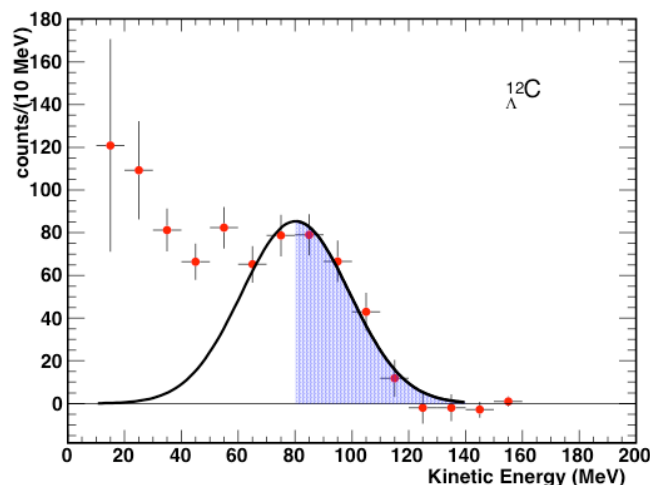
👍 fully compatible with the previous one, within the errors.

👍 M. Kim *et al.*, *PRL* 103 (2009) 182502: 0.29 ± 0.13 .

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

First determination of Γ_p/Γ_Λ 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:

- number of primary protons from NMWD decreased by FSI
- in a given region of the spectrum increase due to the FSI not only of higher energy protons, but of neutrons as well
- 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?



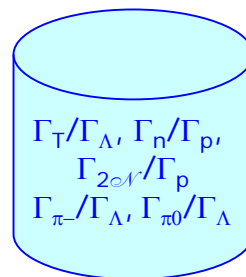
First determination of Γ_p/Γ_Λ for 8 Hypernuclei

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

where α accounts for FSI:

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

input: experimental results only



no INC calculation

$$\Gamma_p/\Gamma_\Lambda(^5\text{He}_\Lambda) = 0.22 \pm 0.03$$

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

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

H. Noumi *et al.*, PRC 52 (1995) 2936: 0.31 ± 0.07
 H. Bhang *et al.*, JKPS 59 (2011) 1461: 0.45 ± 0.10

$$\alpha_5(^5\text{He}_\Lambda) = 1.15 \pm 0.26$$

$$\alpha_5(^{12}\text{C}_\Lambda) = 1.04 \pm 0.19$$

$$\alpha_{12}(^{12}\text{C}_\Lambda) = 2.48 \pm 0.46$$

$$\alpha_{12}(^5\text{He}_\Lambda) = 2.77 \pm 0.63$$



α scales linearly with A

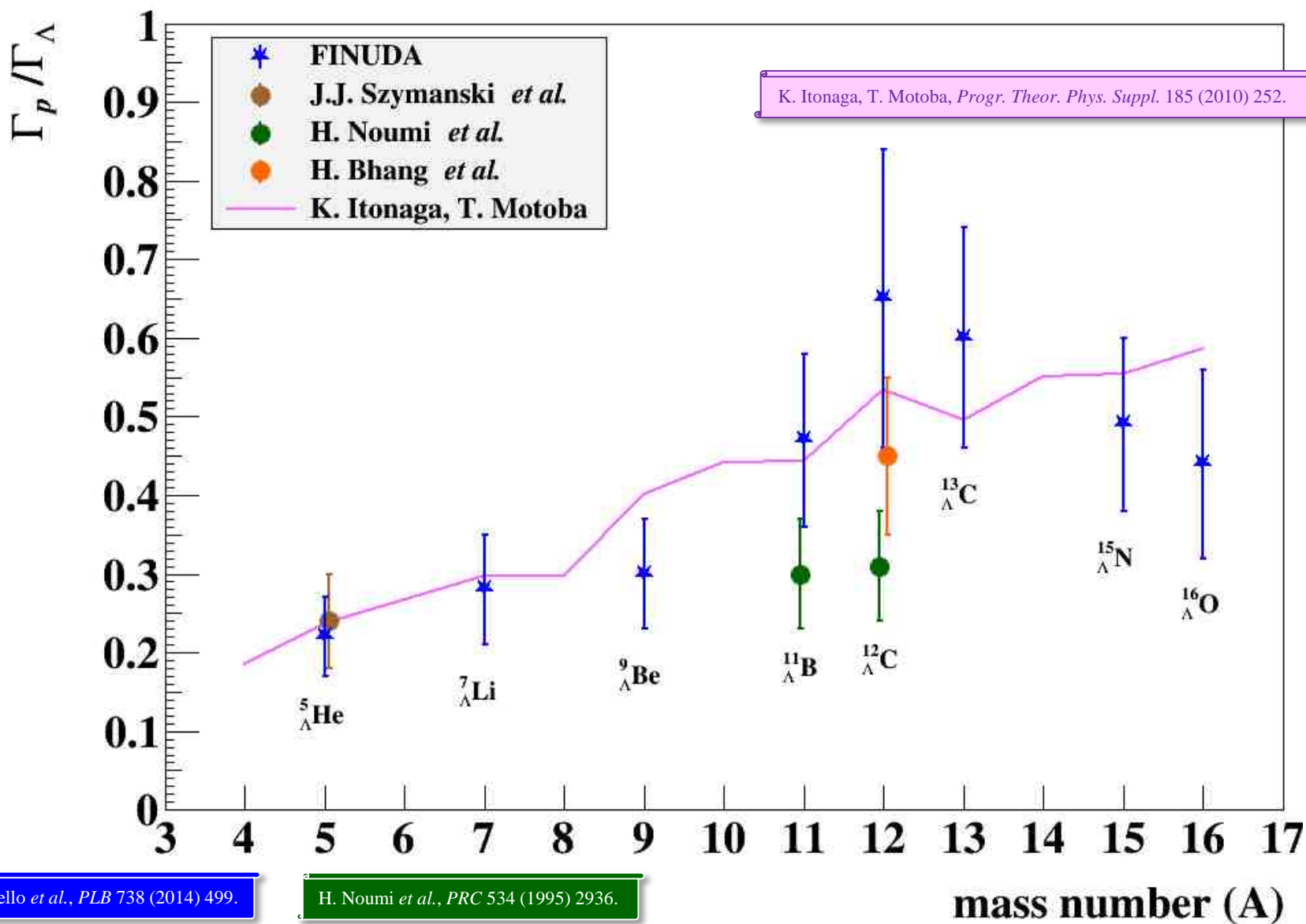
weighted average

$$\overline{\alpha}_5 = 1.08 \pm 0.16$$

$$\overline{\alpha}_{12} = 2.58 \pm 0.37$$

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

First determination of Γ_p/Γ_Λ for 8 Hypernuclei



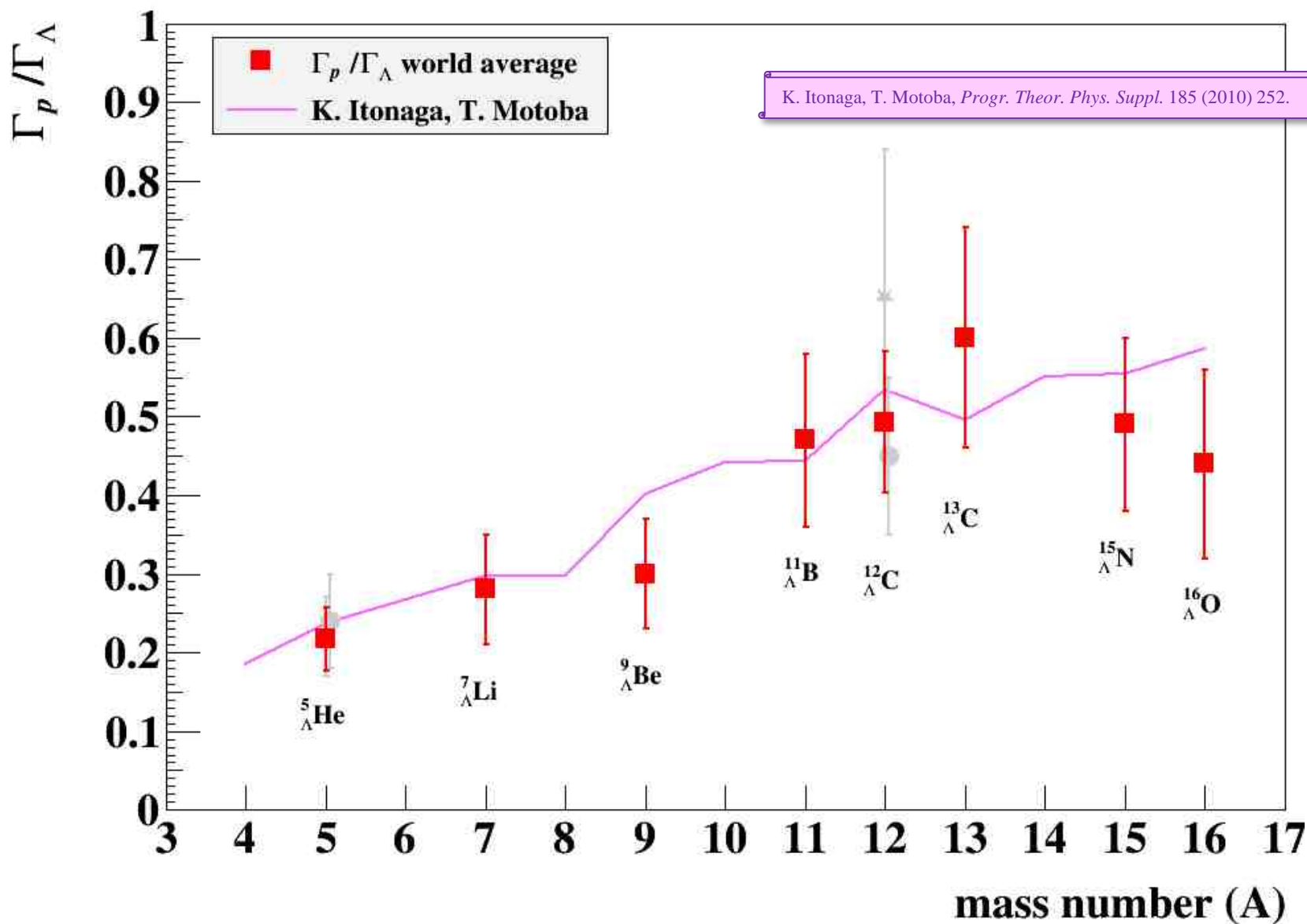
M. Agnello *et al.*, *PLB* 738 (2014) 499.

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

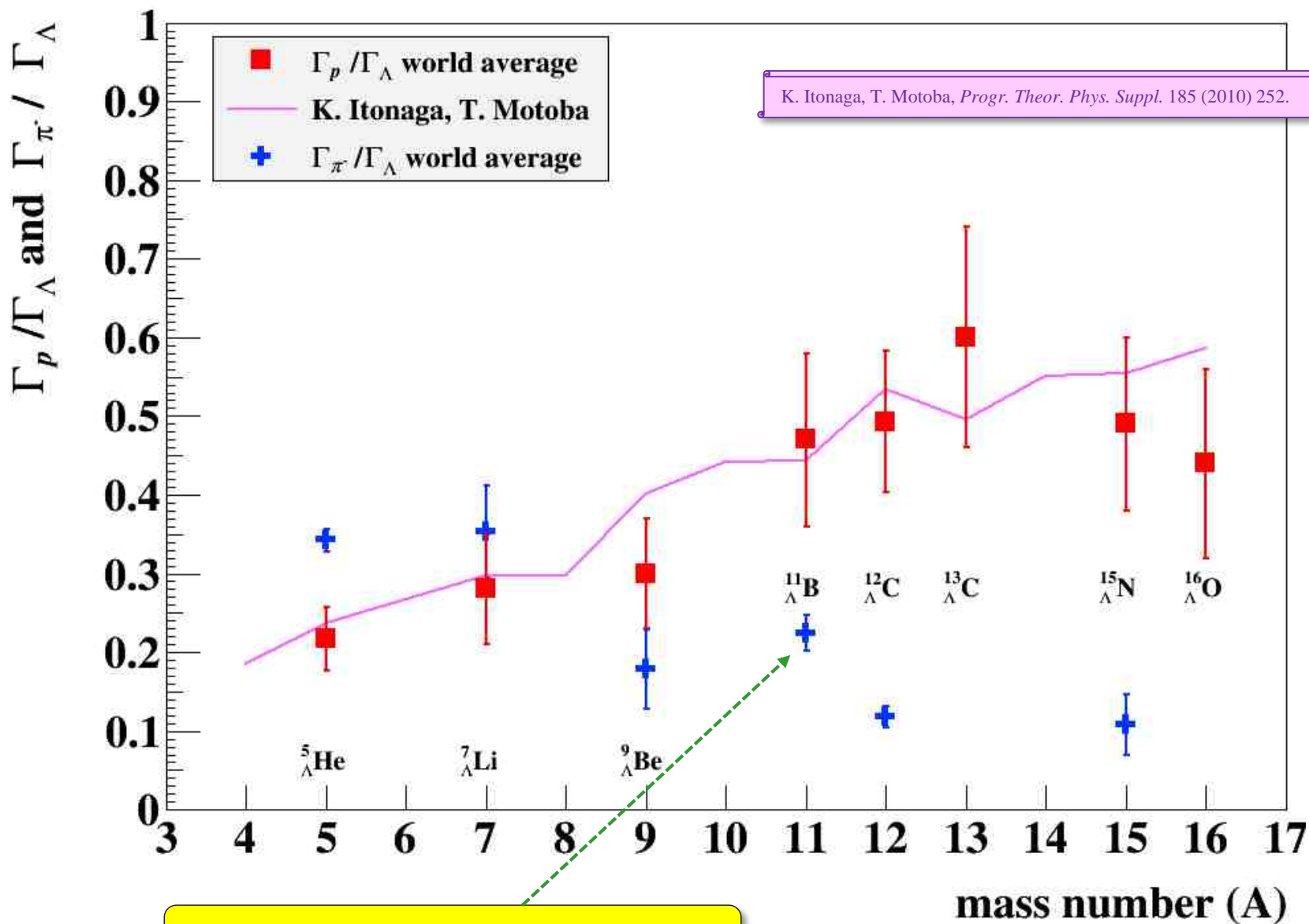
J.J. Szymanski *et al.*, *PRC* 43 (1991) 849.

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

First determination of Γ_p/Γ_Λ for 8 Hypernuclei



First determination of Γ_p/Γ_Λ for 8 Hypernuclei



Completion of decay pattern for ${}^5\text{He}_\Lambda$ and ${}^{11}\text{B}_\Lambda$

	${}^5\text{He}_\Lambda$	${}^{11}\text{B}_\Lambda$	${}^{12}\text{C}_\Lambda$	${}^{12}\text{C}_\Lambda$
$\Gamma_T / \Gamma_\Lambda$	0.962 ± 0.034	1.274 ± 0.072	1.241 ± 0.041	1.241 ± 0.041
$\Gamma_{\pi^-} / \Gamma_\Lambda$	0.342 ± 0.015	0.228 ± 0.027	0.120 ± 0.014	0.123 ± 0.015
$\Gamma_{\pi^0} / \Gamma_\Lambda$	0.201 ± 0.011	0.192 ± 0.056	0.165 ± 0.008	0.165 ± 0.008
$\Gamma_p / \Gamma_\Lambda$	0.217 ± 0.041	0.47 ± 0.11	0.493 ± 0.088	0.45 ± 0.10
$\Gamma_{2N} / \Gamma_\Lambda$	0.078 ± 0.034	0.169 ± 0.077	0.178 ± 0.076	0.27 ± 0.13
$\Gamma_n / \Gamma_\Lambda$	0.125 ± 0.066	0.21 ± 0.16	0.28 ± 0.12	0.23 ± 0.08
Γ_n / Γ_p	0.58 ± 0.32	0.46 ± 0.37	0.58 ± 0.27	0.51 ± 0.14
Γ_n / Γ_p	0.508	0.502	0.418	

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

B.H. Kang et al., PRL 96 (2006) 062301:
0.45 ± 0.11



K. Itonaga, T. Motoba, PTP 185 (2010) 252

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Determination of non-mesonic weak decay widths of ${}^5\text{He}_\Lambda$ and ${}^{11}\text{B}_\Lambda$ Hypernuclei

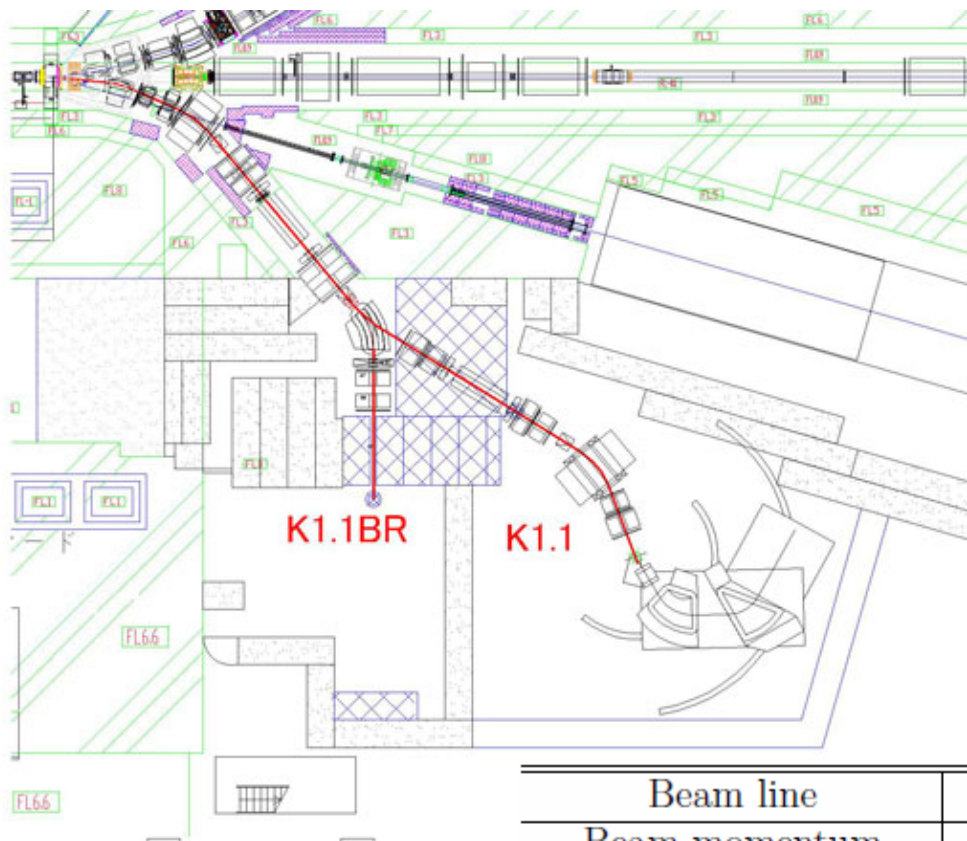
E. Botta^{a,b}, T. Bressani^{a,b}, S. Bufalino^{a,b}, A. Feliciello^{b,*}

^a Dipartimento di Fisica, Università di Torino, via P. Giuria 1, Torino, Italy
^b INFN Sezione di Torino, via P. Giuria 1, Torino, Italy



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

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
$\frac{d\sigma}{d\Omega}({}^7\text{Li}(3/2^+), \theta = 10^\circ)$	$7.1 \mu\text{b/sr}$		$17 \mu\text{b/sr}$
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

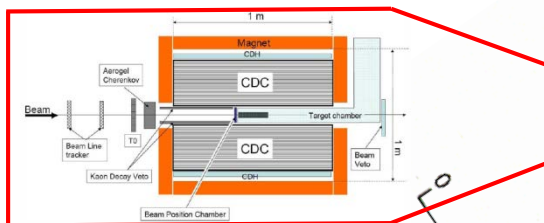
H. Sugimura *et al.*, *PLB* 729 (2014) 39.

A possible apparatus concept layout



unavoidably biased
by the FINUDA experience

(π^+, K^+)

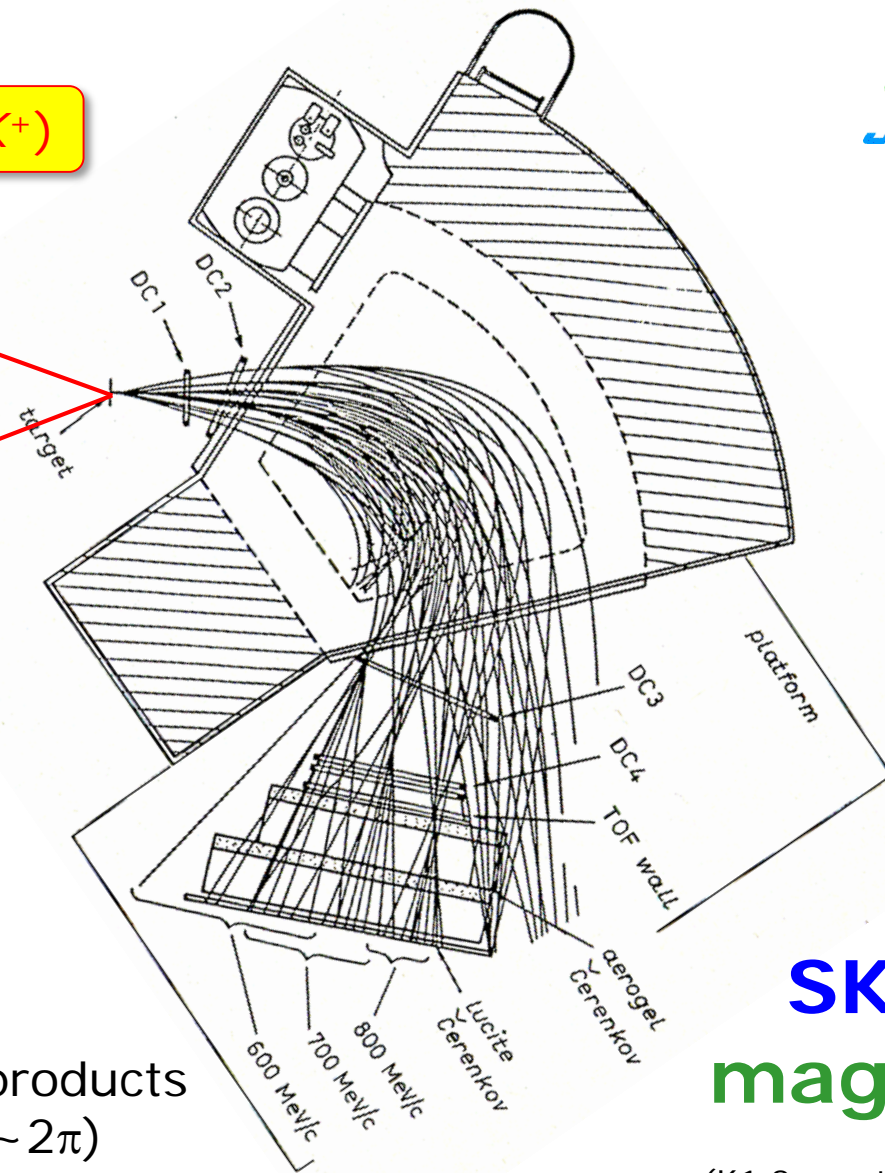


Cylindrical Detector System

(K1.8BR spectrometer)

essential requirements

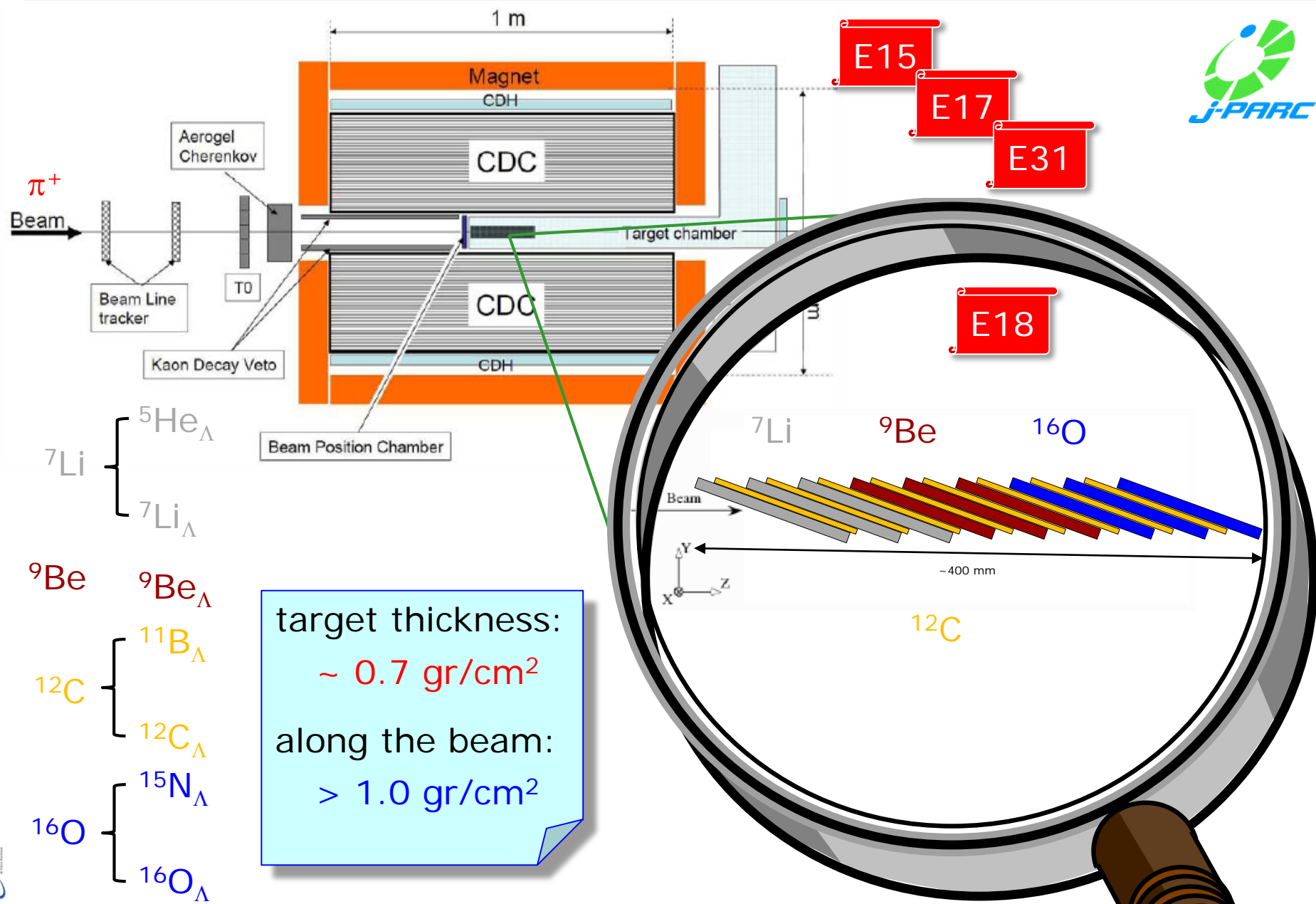
- 👉 magnetic analysis of decay products
- 👉 large detection solid angle ($\sim 2\pi$)
- 👉 low detection threshold



SKS
magnet

(K1.8 spectrometer)

A possible apparatus concept layout



target thickness:
 $\sim 0.7 \text{ gr/cm}^2$
 along the beam:
 $> 1.0 \text{ gr/cm}^2$

- $^5\text{He}_\Lambda$
- ^7Li
 - $^7\text{Li}_\Lambda$
- ^9Be
 - $^9\text{Be}_\Lambda$
- ^{12}C
 - $^{11}\text{B}_\Lambda$
 - $^{12}\text{C}_\Lambda$
- ^{16}O
 - $^{15}\text{N}_\Lambda$
 - $^{16}\text{O}_\Lambda$

Expected rates (rough estimate)

educated guess

$$\sim 10^8 \pi^+ / \text{spill}$$

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



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

interspill: 3.5 s

$$\sim 10^{12} \pi^+ / \text{day}$$

from previous experience

$$\sim 10^4 {}^{12}\text{C}_{\Lambda \text{ g.s.}} / \text{day}$$

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

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

formation rate on 1 g/cm² target

B.R. (0.5), $\Delta\Omega$ (0.5), $\epsilon_{\text{riv/rec}}$ (0.5)

$$\sim 10^3 {}^{12}\text{C}_{\Lambda \text{ g.s.}} / \text{day}$$

E18 request:
 $4 \times 10^{12} \pi^+$ on target(s)

required beam time: 10 days

- $\sim 10^4 p$ from $1\mathcal{N} \rightarrow 1\%$ on $\Gamma_p/\Gamma_{\Lambda}, \Gamma_T/\Gamma_{\Lambda}$
- $\sim 4 \times 10^3 p$ from $2\mathcal{N} \rightarrow 2\%$ on $\Gamma_{2\mathcal{N}}/\Gamma_{\Lambda}$
- $\sim 10^3 \pi^- \rightarrow 3\%$ on $\Gamma_{\pi^-}/\Gamma_{\Lambda}$
- $\sim 4 \times 10^2 \pi^0 \rightarrow 5\%$ on $\Gamma_{\pi^0}/\Gamma_{\Lambda}$

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
- 👉 Completion of ${}^5\text{He}_\Lambda$ and ${}^{11}\text{B}_\Lambda$ NMWD pattern
- 🌱 Looking forward for **new opportunities** at J-PARC...

Thank you!

どうも ありがとう