Some recent results on the weak decay of Λ-hypernuclei

Japan Atomic Energy Agency

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Outline

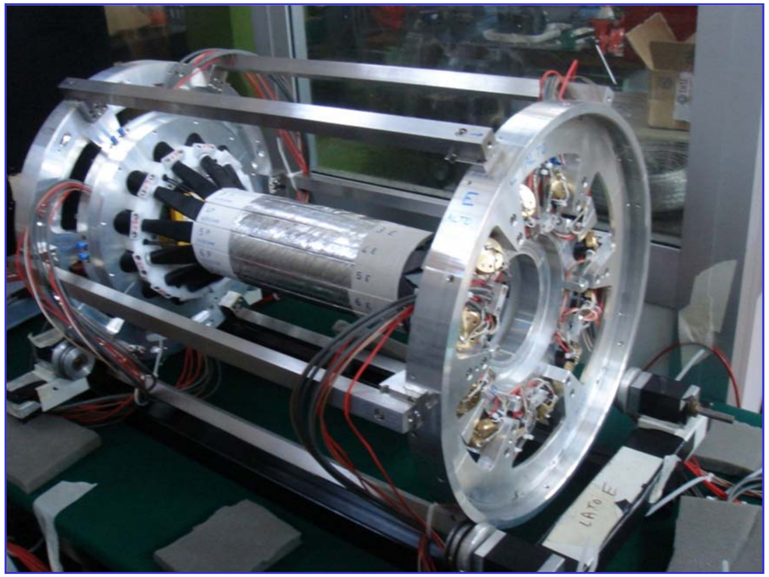
- The FINUDA apparatus @ INFN/LNF DAΦNE:
  - a spectrometer designed for decay of hypernuclei study
- A revisited analysis of the proton spectra from NMWD of Λ−hypernuclei
- First determination of Γ_p/Γ_Λ for 8 Λ−hypernuclei (A = 5-16)
- Determination of the full set of NMWD widths for ${}^{5}He_\Lambda$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

The FINUDA Collaboration

- I.N.F.N. Bari and Bari University
- Brescia University
- KEK
- I.N.F.N. / L.N.F. Frascati
- I.N.F.N. Pavia and Pavia University
- RIKEN
- Seoul National University
- Teheran Shahid Beheshty University
- I.N.F.N. Torino and Torino University
- Torino Polytechnic
- Trieste University and I.N.F.N. Trieste
- TRIUMF

A paradigmatic example of collaboration

FINUDA

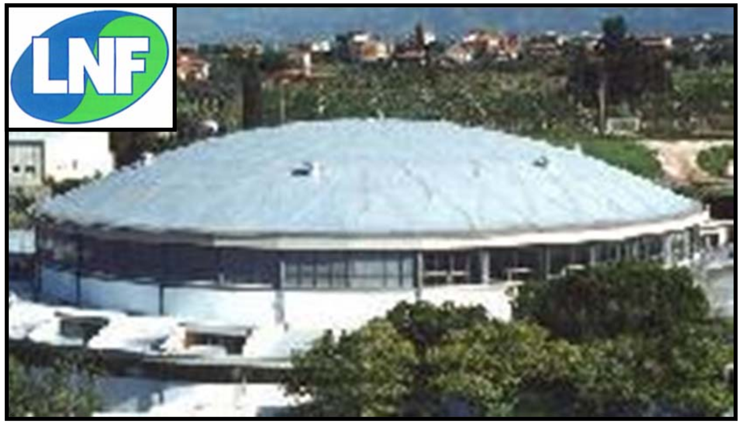


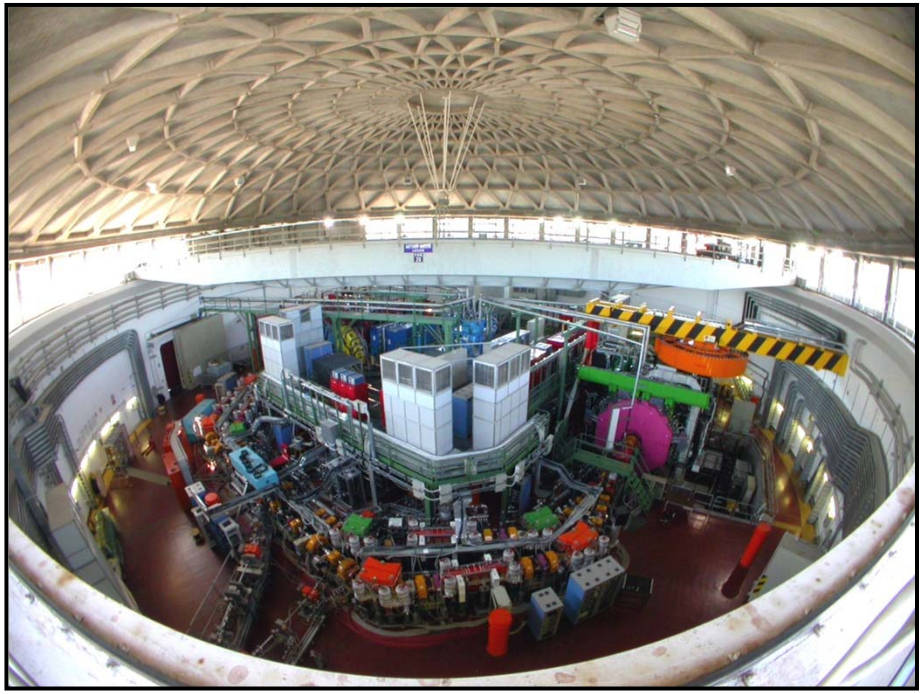
FINUDA

JAPAN

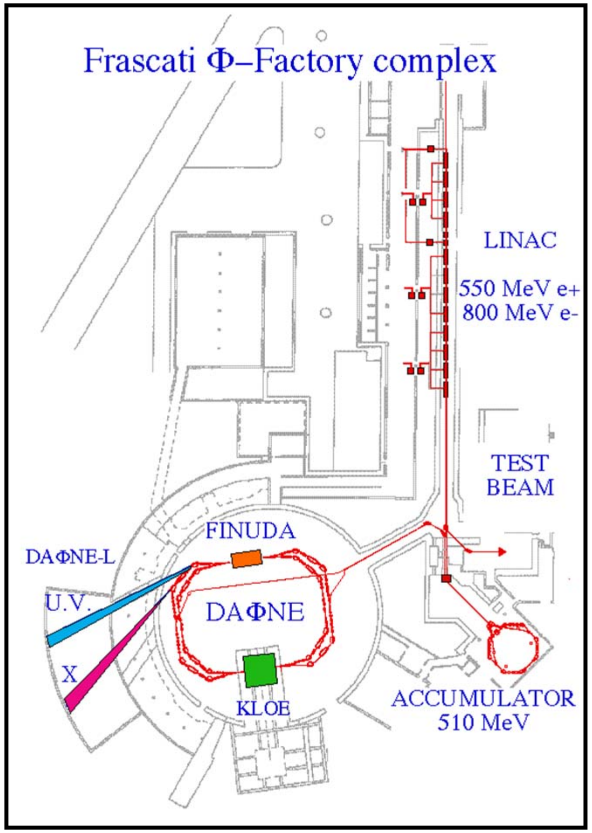
The DAΦNE machine

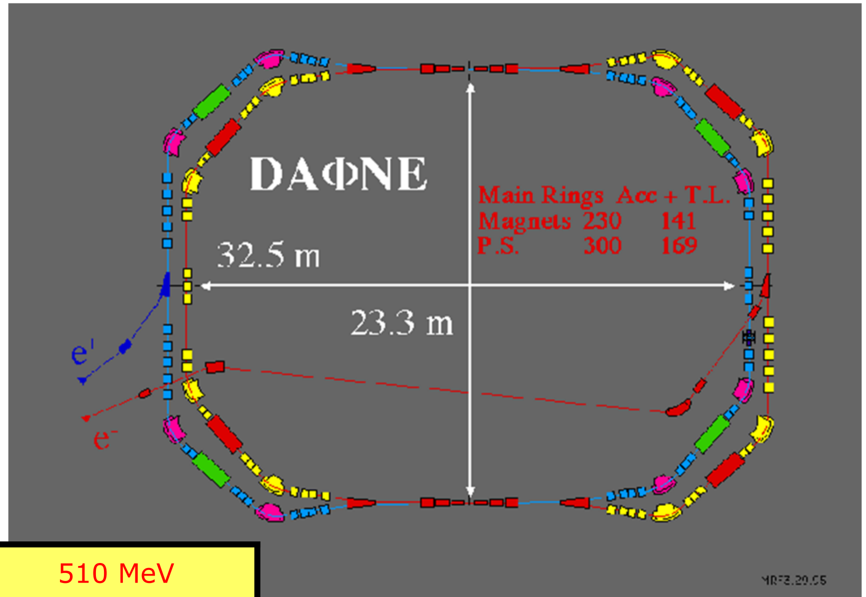
The DAΦNE Φ-factory



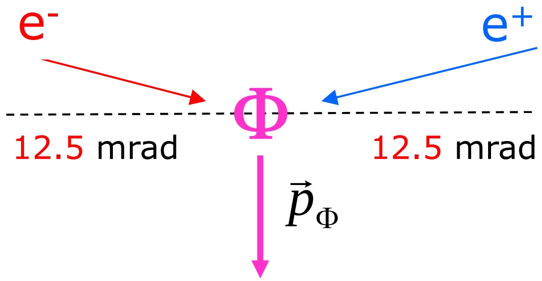


The DAΦNE e^+e^- collider





energy	510 MeV
luminosity	≤ 5 x 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)



What one can do with a Φ-factory?

KLOE
CP, CPT violation
chiral dynamics
and more...

FINUDA
hypernuclear physics

$K_S K_L$
(34%)

$\rho\pi$
(13%)

K^+K^-
(49%)

DEAR/SIDDHARTA
exotic atoms

Double
Annular
Φ-factory for
Nice
Experiments

source of (nearly) monochromatic, collinear, background free, tagged neutral and charged kaons

The FINUDA way

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

σ = 3.26 μb

$\mathscr{L} \approx 1 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$

≈ 300 Hz

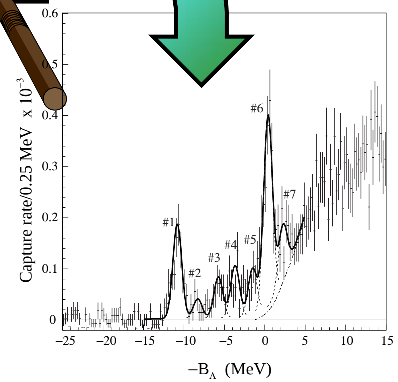
$K^- + K^+$

$T_{K^-} \approx 16.1\ \mathrm{MeV}$

≈ 150 Hz

a real unconventional experimental approach

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



$$\frac{\Delta T_\pi}{T_\pi} = \frac{\sqrt{p_\pi^2+m_\pi^2}+m_\pi}{\sqrt{p_\pi^2+m_\pi^2}} \cdot \frac{\Delta p_\pi}{p_\pi} \equiv f(p_\pi)\frac{\Delta p_\pi}{p_\pi}$$

coincidence measurement

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

The FINUDA apparatus

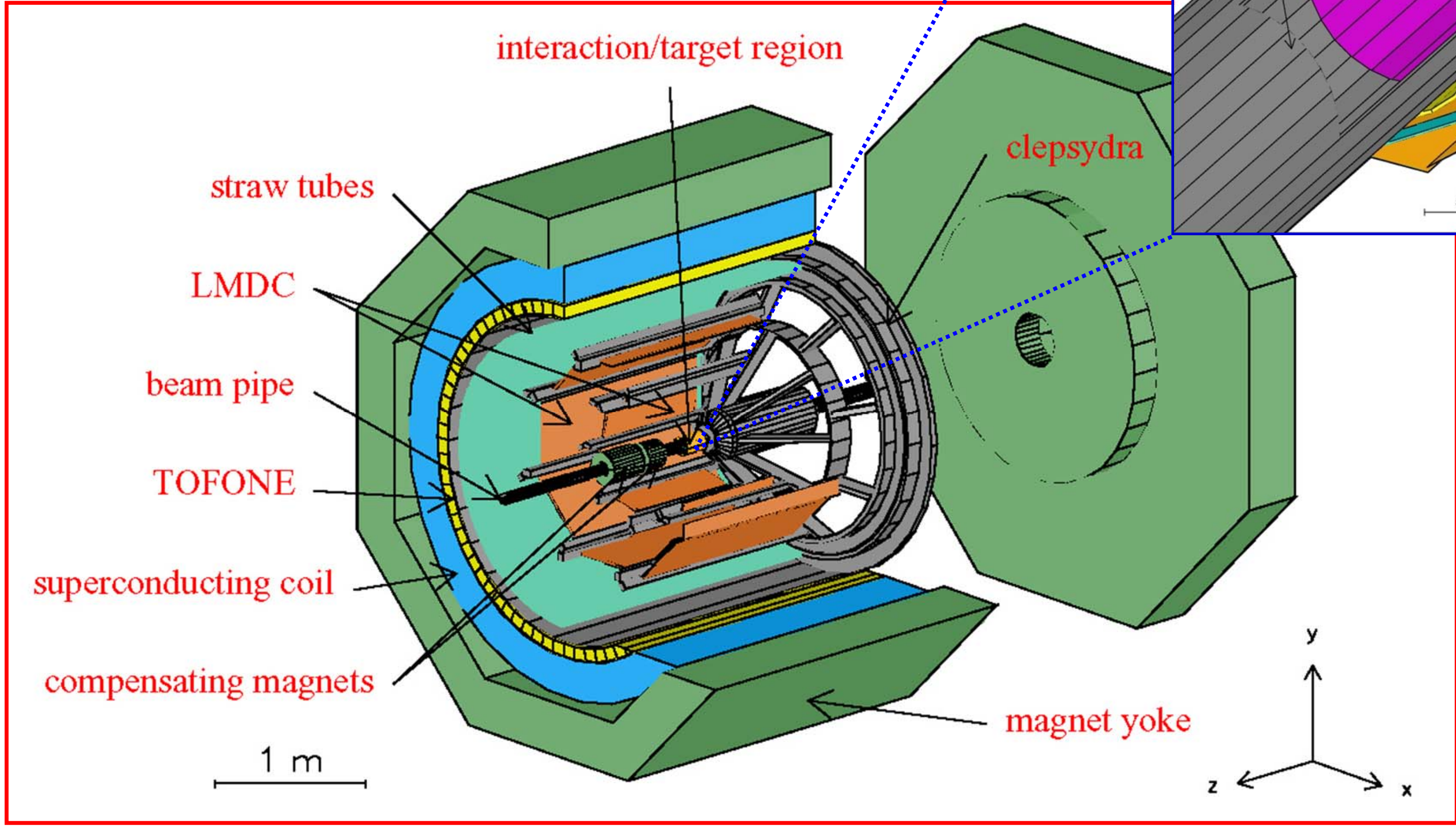
… nothing by chance

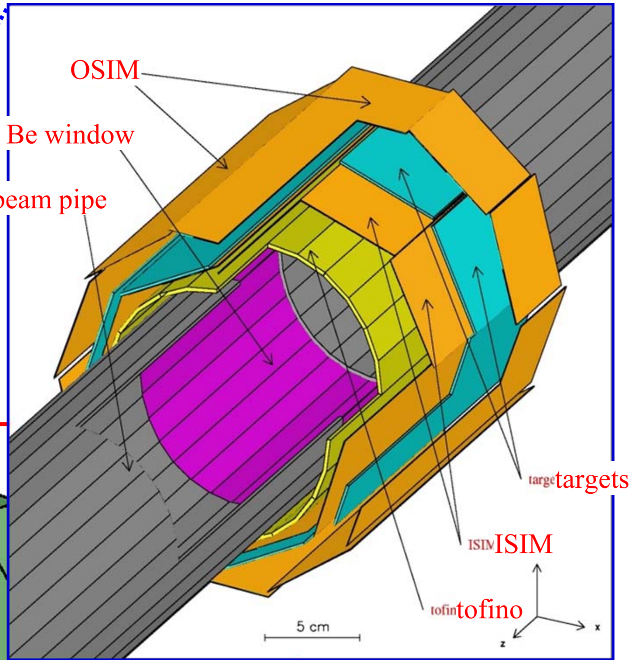
The FINUDA apparatus

- high resolution
- high acceptance

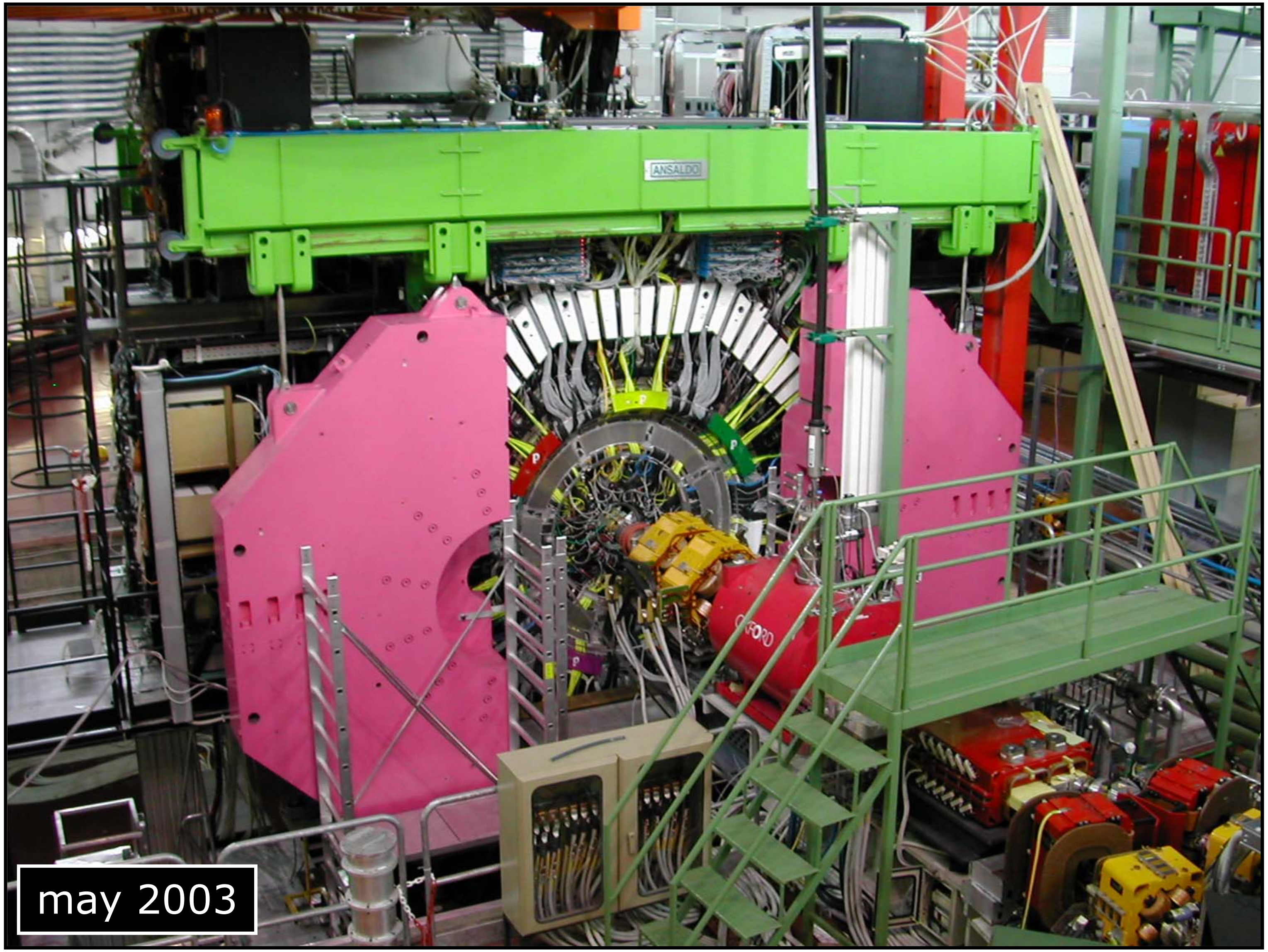
} magnetic spectrometer

- realistic (feasible)
- reasonable cost





Concept becomes reality



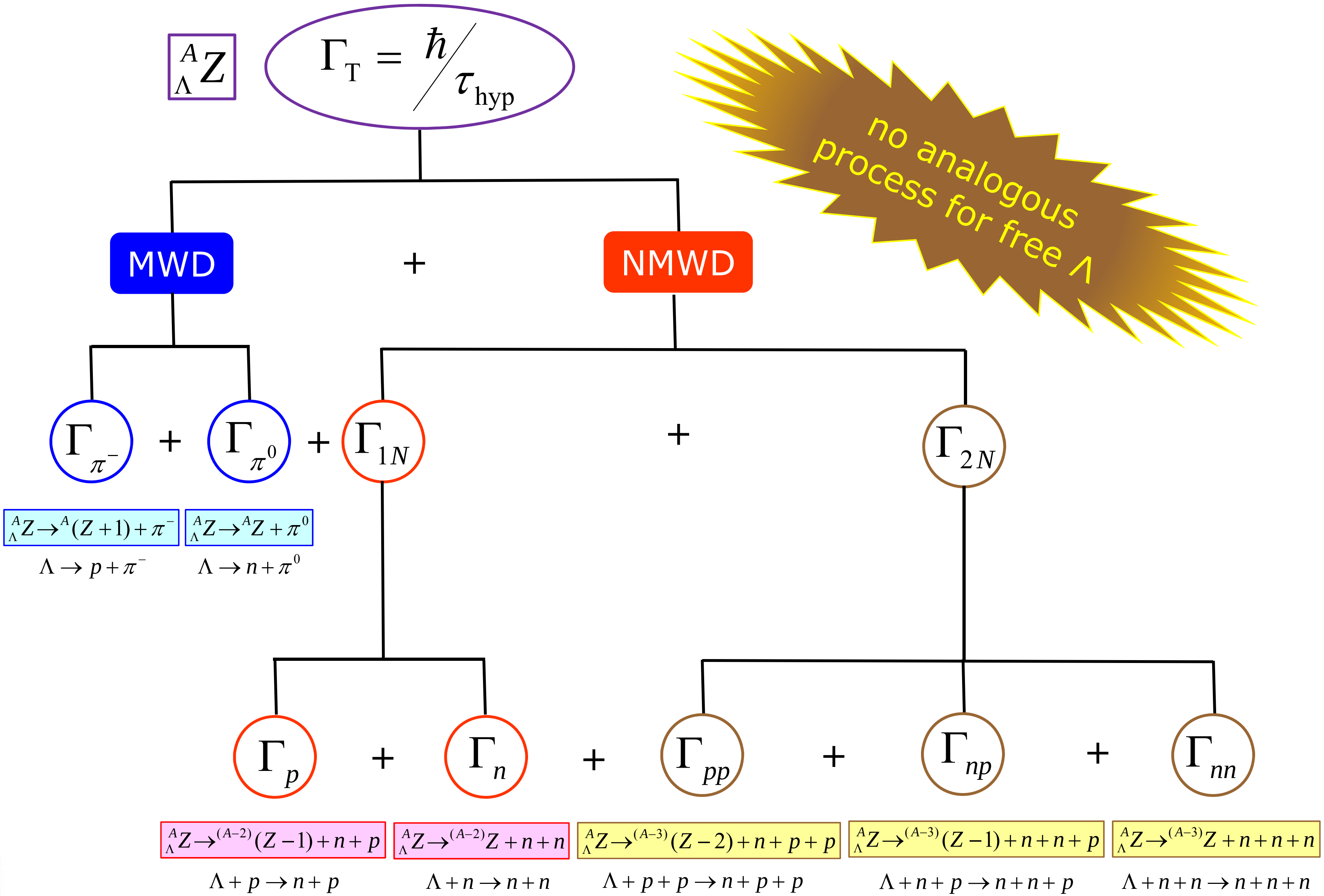
FINUDA key features

- very thin nuclear targets (0.1 ÷ 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*

Λ-hypernucleus non-mesonic weak decay

Observables in Weak Decay of Λ–Hypernuclei



Physics motivations

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

Physics output (S = -1)

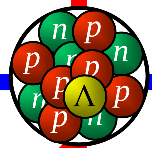
1. M. Agnello *et al.*, *PLB* 640 (2006) 145
2. M. Agnello *et al.*, *PRL* 108 (2012) 042501
3. M. Agnello *et al.*, *NPA* 881 (2012) 269
4. M. Agnello *et al.*, *PRC* 86 (2012) 057301

possible thanks to apparatus performance and stability

4B weak interaction

nuclear models

neutron-rich Λ-hypernuclei



spectroscopy

(weak) decay

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

medium effect

quark substructures

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

deeply bound $\bar{K}$ states

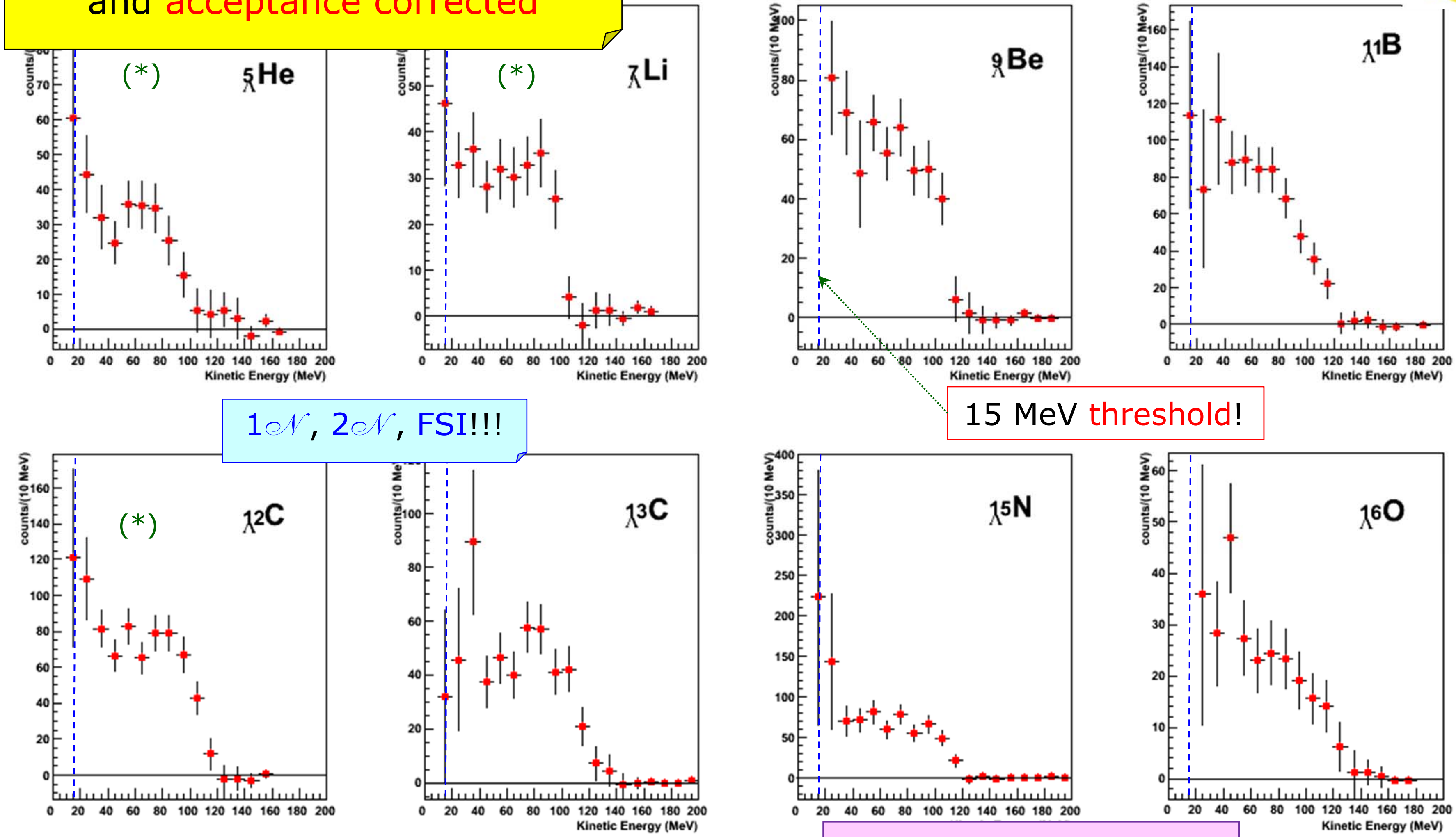
1. M. Agnello *et al.*, *PRL* 94 (2005) 212303
2. M. Agnello *et al.*, PLB 654 (2007) 80

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

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!

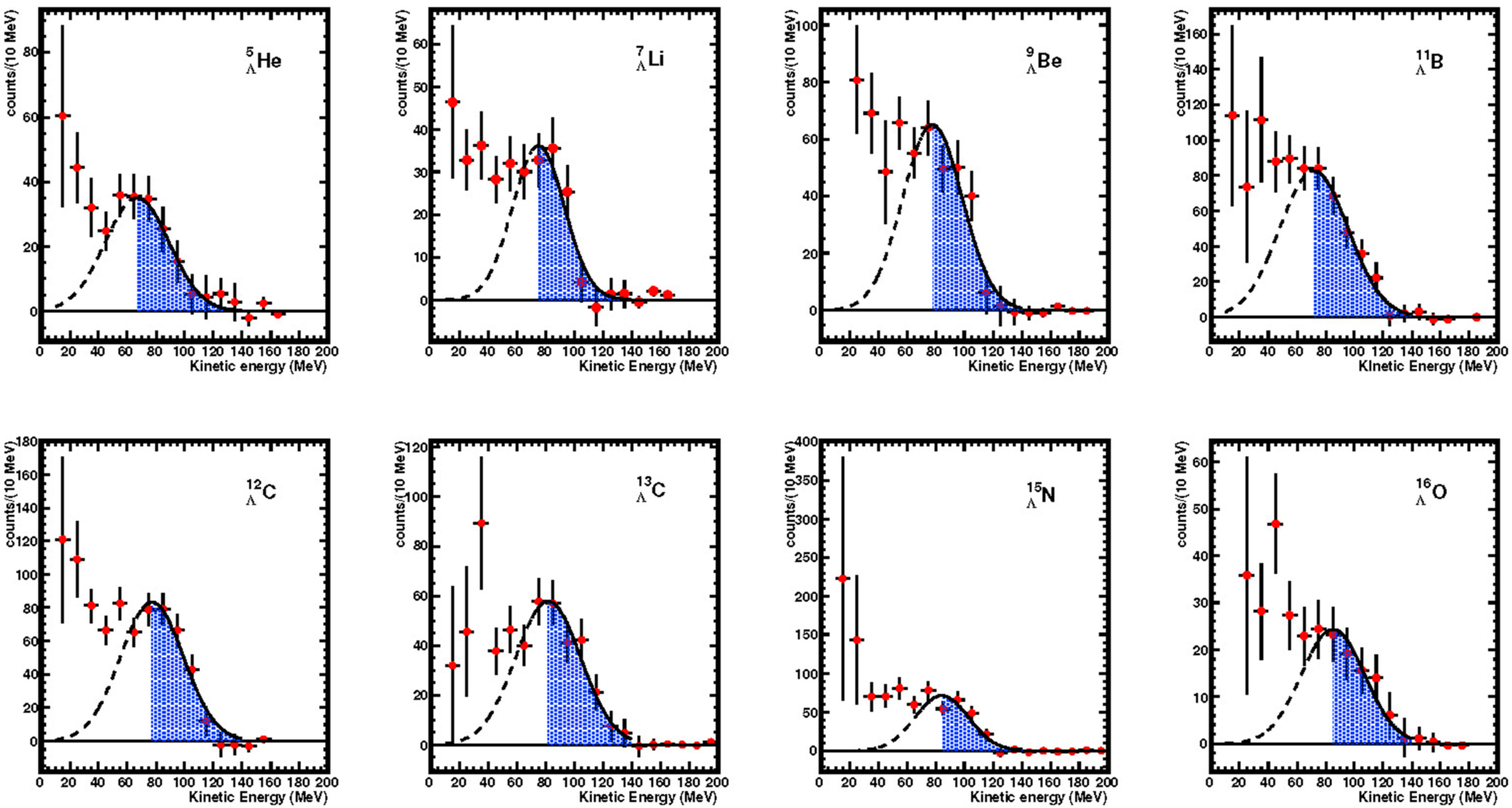
(*) M. Agnello *et al.*, *NPA* 804 (2008) 151.

common features:
- 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 χ^2/n = 1.33 when choosing the starting point at 70 MeV

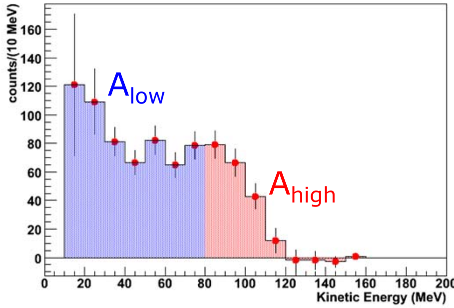


Refined determination of $\Gamma_{2\mathcal{N}} / \Gamma_{NMWD}$

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

It was found (single particle spectra):

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

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:

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

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

With the new μ values, we got:

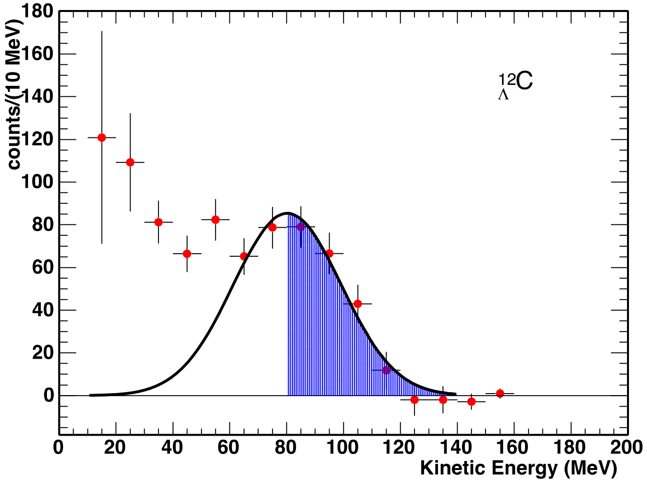
$$\frac{\Gamma_{2N}}{\Gamma_p} = 0.36 \pm 0.14_{stat}{}^{+0.05}_{-0.04}{}_{sys} \qquad \left(\frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.20 \pm 0.08_{stat}{}^{+0.03}_{-0.02}{}_{sys} \right)$$

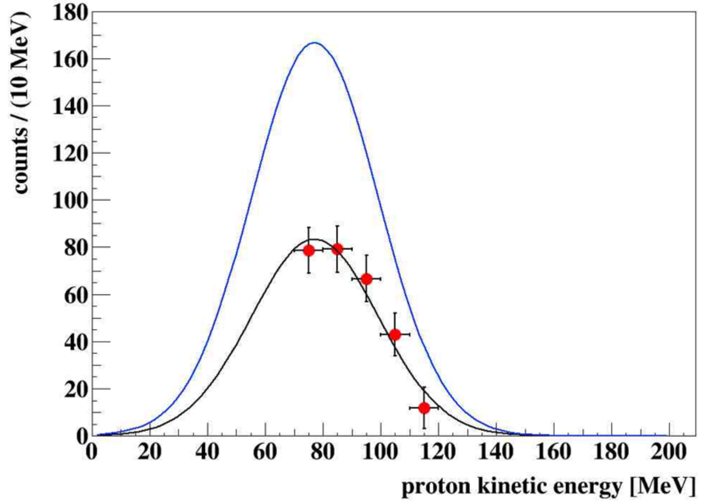
- fully compatible with the previous one, within the errors.

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

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

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

where α accounts for FSI:

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

input: experimental results only

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

no INC calculation

$\Gamma_p/\Gamma_\Lambda({}^{5}He_\Lambda)$ = 0.22 ± 0.03

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

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

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

$\alpha_5({}^{5}He_\Lambda)$ = 1.15 ± 0.26

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

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

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

assumption

α scales linearly with A

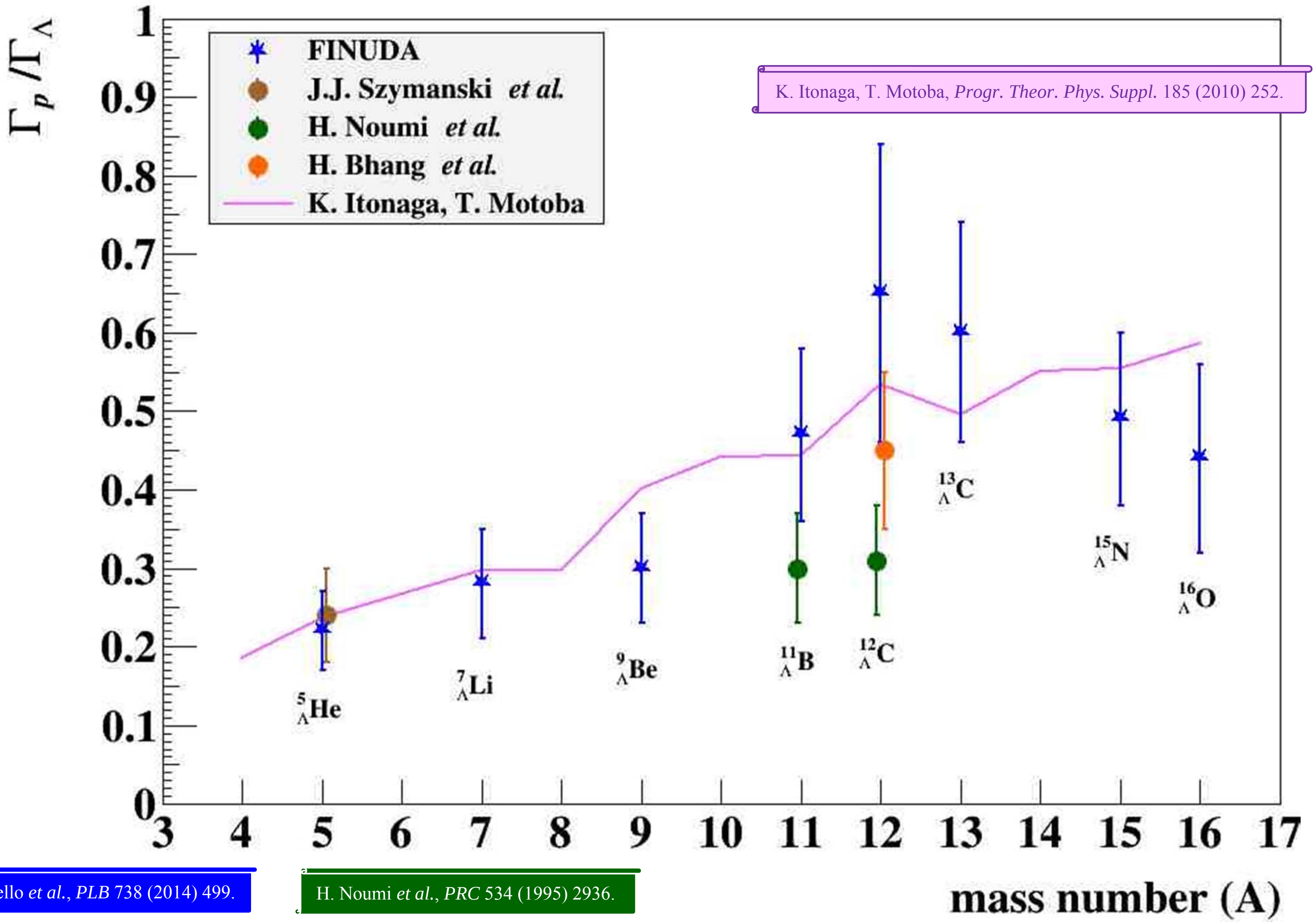
weighted average

$\overline{\alpha_5}$ = 1.08 ± 0.16

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

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

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



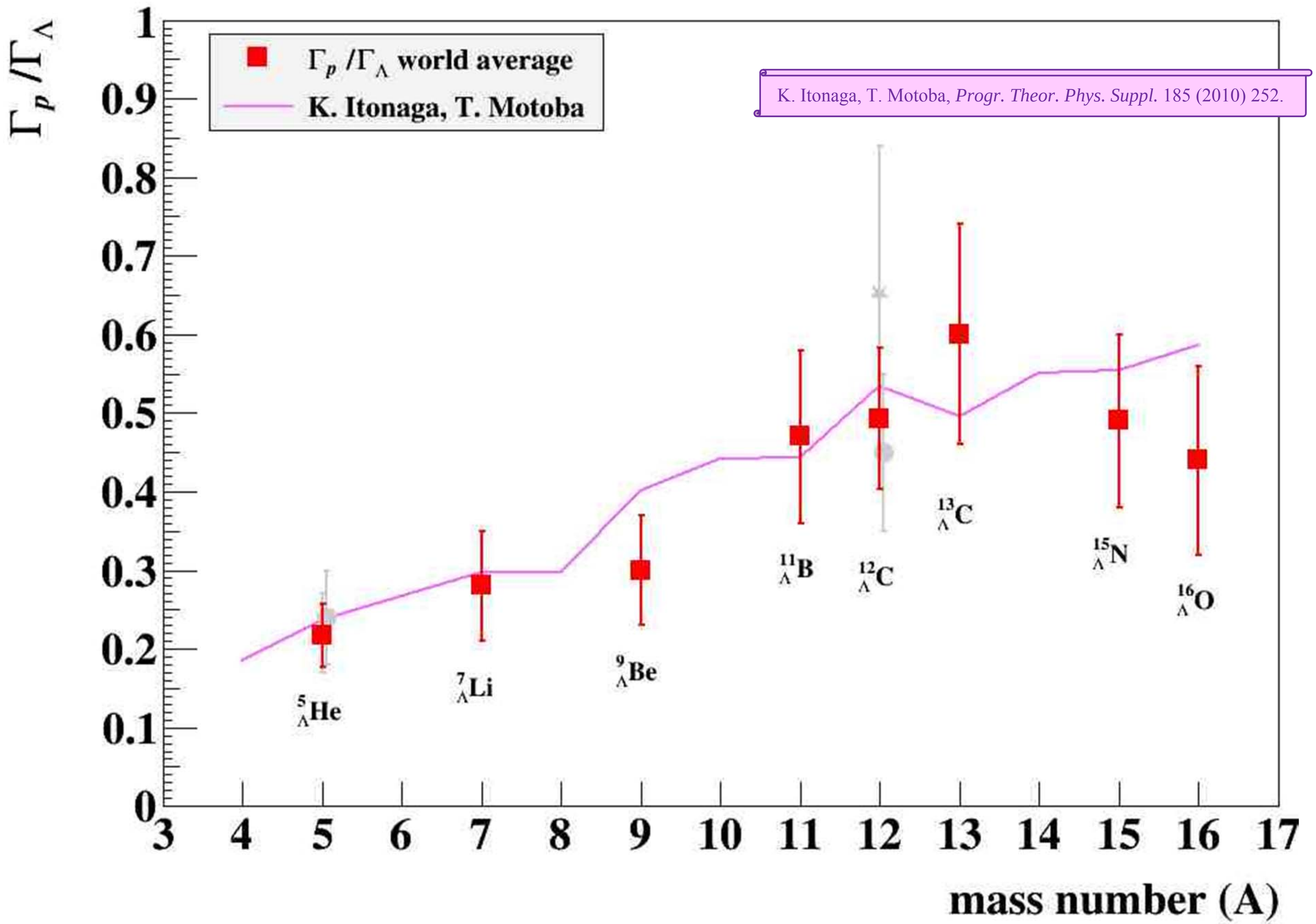
M. Agnello *et al.*, *PLB* 738 (2014) 499.

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

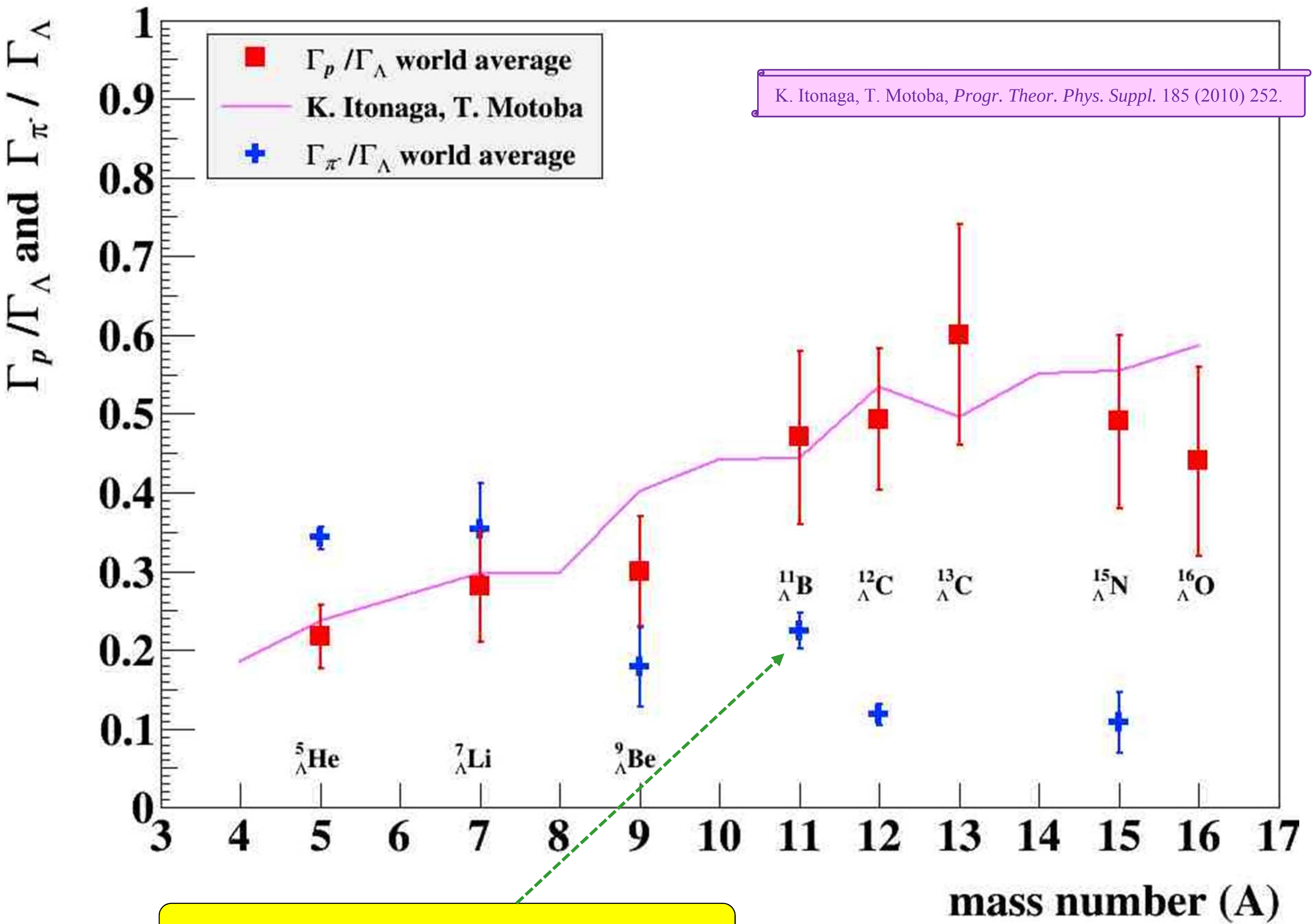
J.J. Szymanski *et al.*, *PRC* 43 (1991) 849.

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

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



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



strong nuclear structure effects

Completion of decay pattern for $^{5}He_{\Lambda}$ and $^{11}B_{\Lambda}$

	$^{5}_{\Lambda}He$	$^{11}_{\Lambda}B$	$^{12}_{\Lambda}C$	$^{12}_{\Lambda}C$
Γ_T/Γ_Λ	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
Γ_p/Γ_Λ	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
Γ_n/Γ_Λ	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

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

Physics Letters B 748 (2015) 86–88

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ELSEVIER

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

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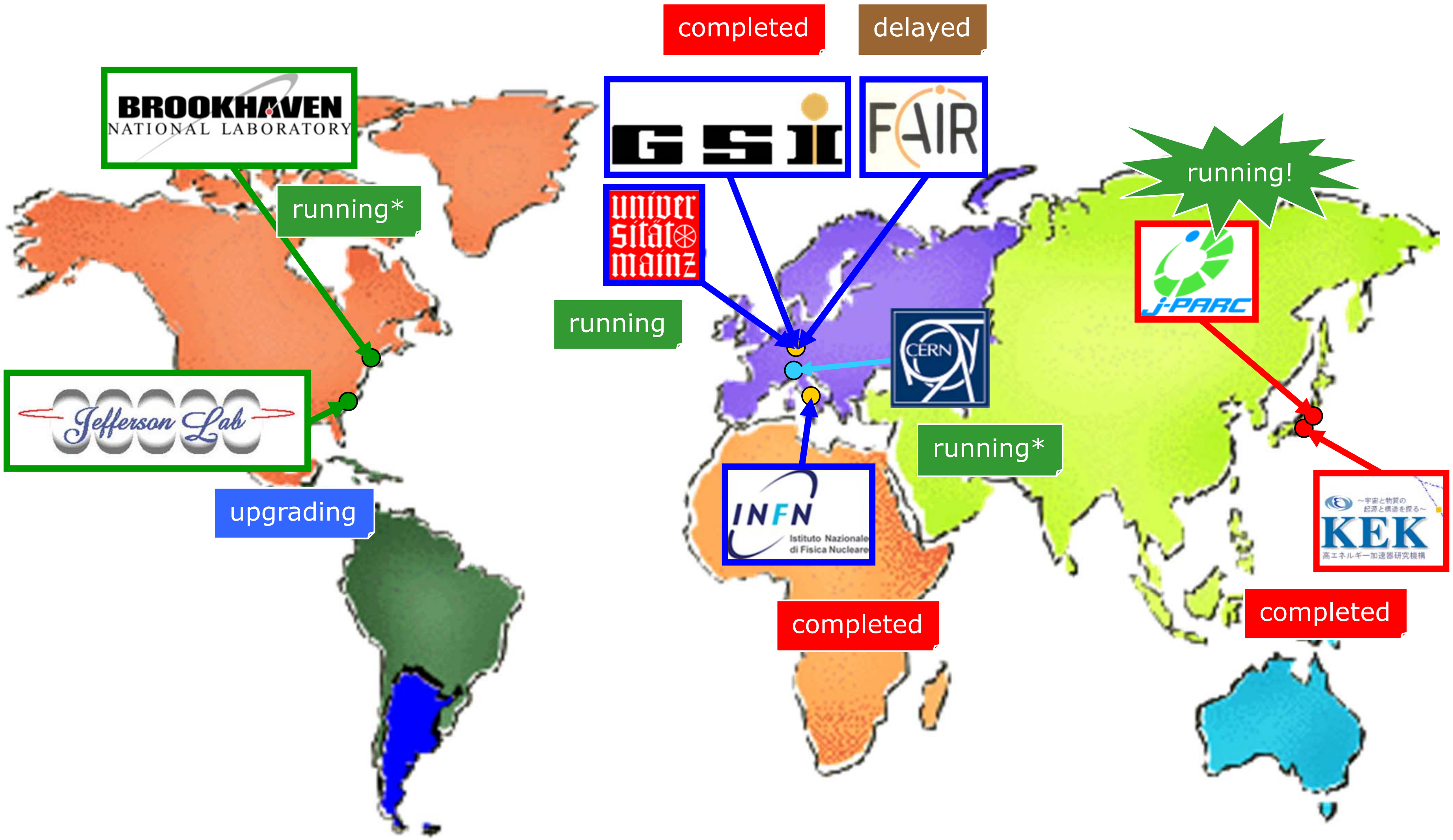
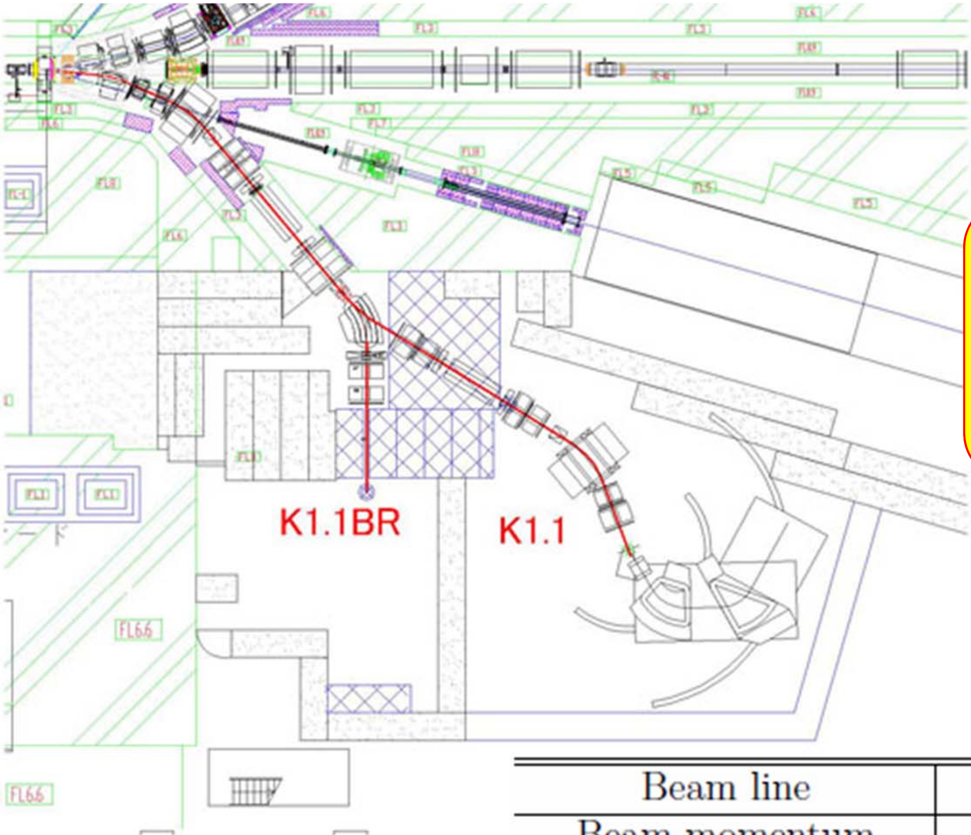
[b] INFN Sezione di Torino, via P. Giuria 1, Torino, Italy

A look to the future…

Hypernuclear Physics scenario



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
$\frac{d\sigma}{d\Omega}({}^7_\Lambda\mathrm{Li}(3/2^+), \theta = 10^0)$	7.1μb/sr	17μb/sr	
Relative γ-ray yield	1	5.7	4.8
K/π ratio		< 0.9	$\sim$3
γ-ray peak broadening	8.2%	6.1%	

old (2008) conservative (?) perspective

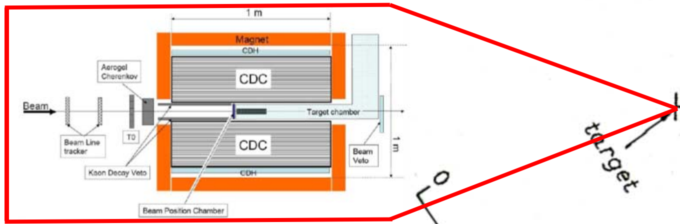
E10 published data: $> 1 \times 10^7\ \pi^+$/spill

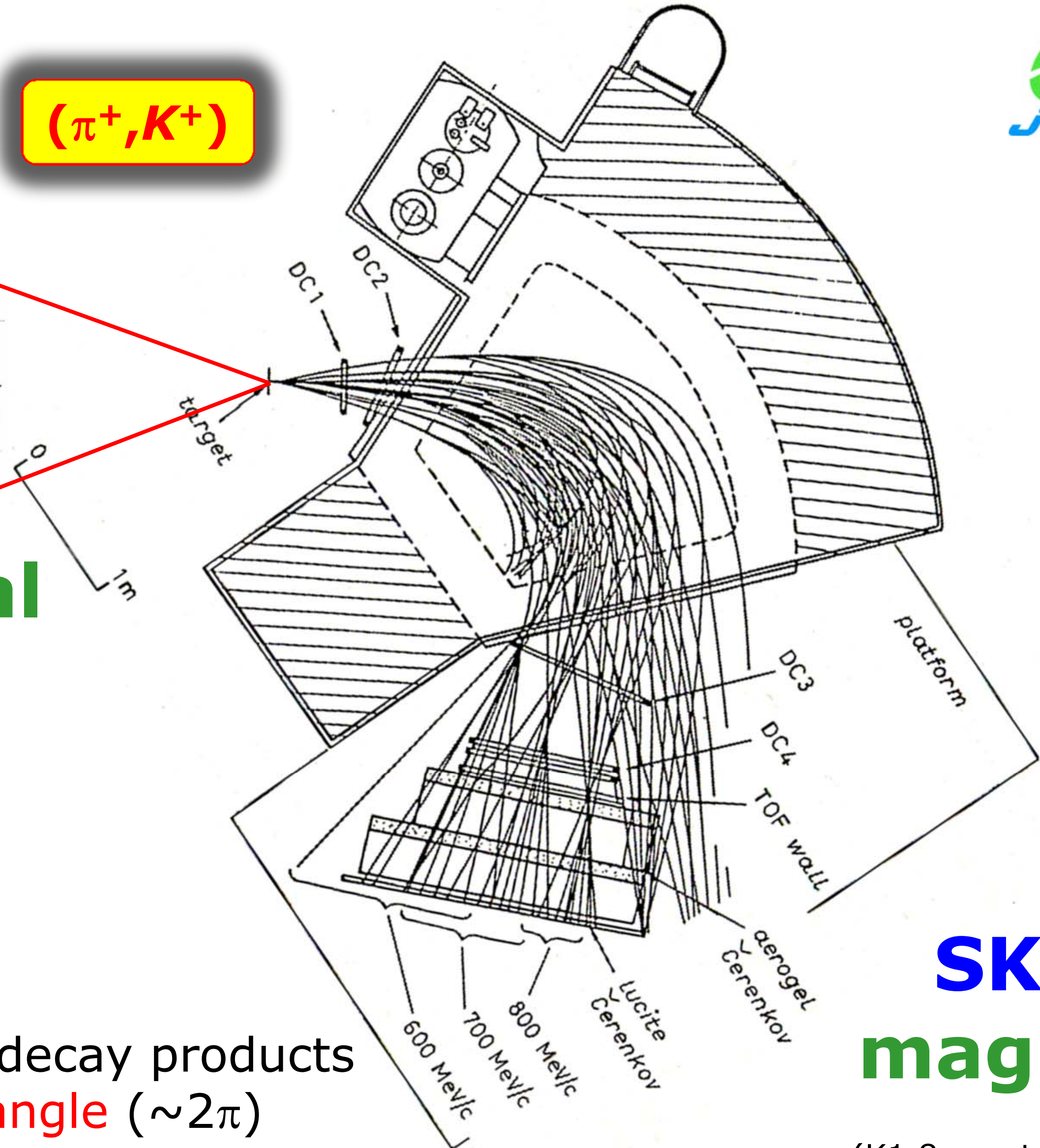
H. Sugimura *et al.*, *PLB* 729 (2014) 39.

A possible apparatus concept layout

unavoidably biased
by the FINUDA experience

(π^+, K^+)





Cylindrical Detector System

(K1.8BR spectrometer)

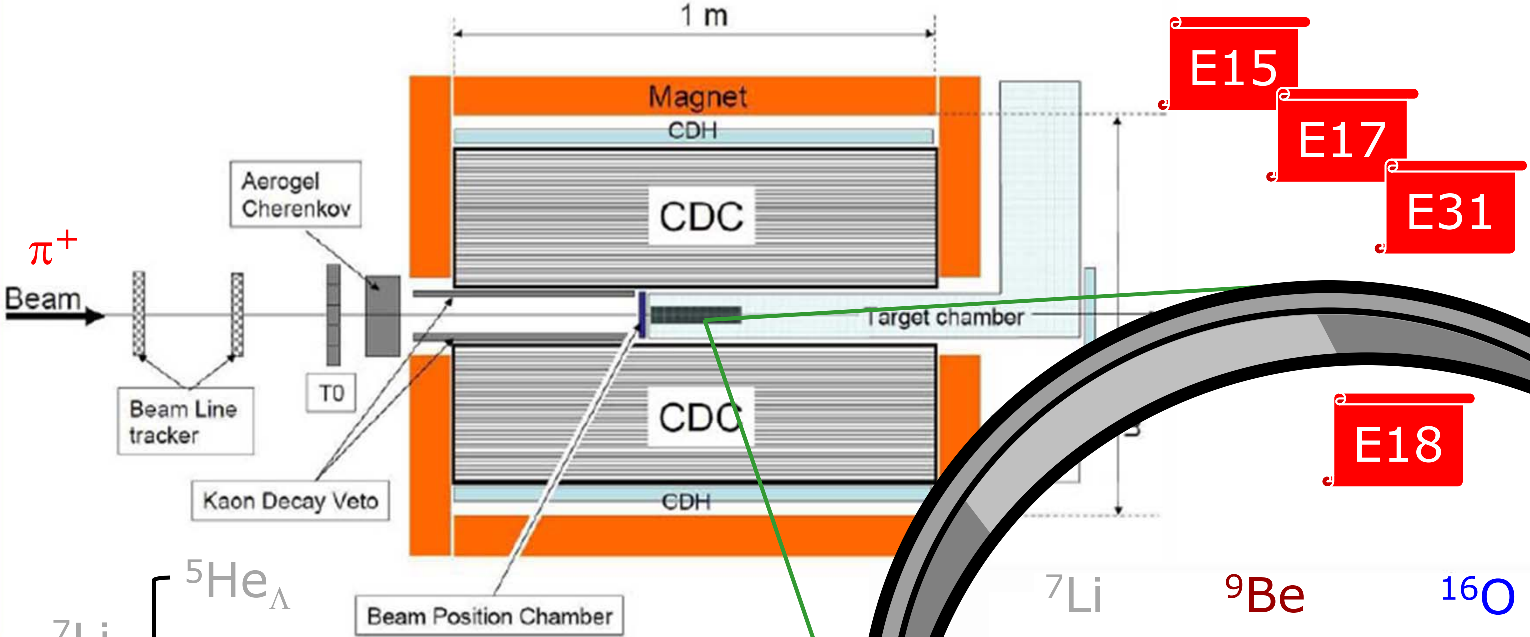
SKS magnet

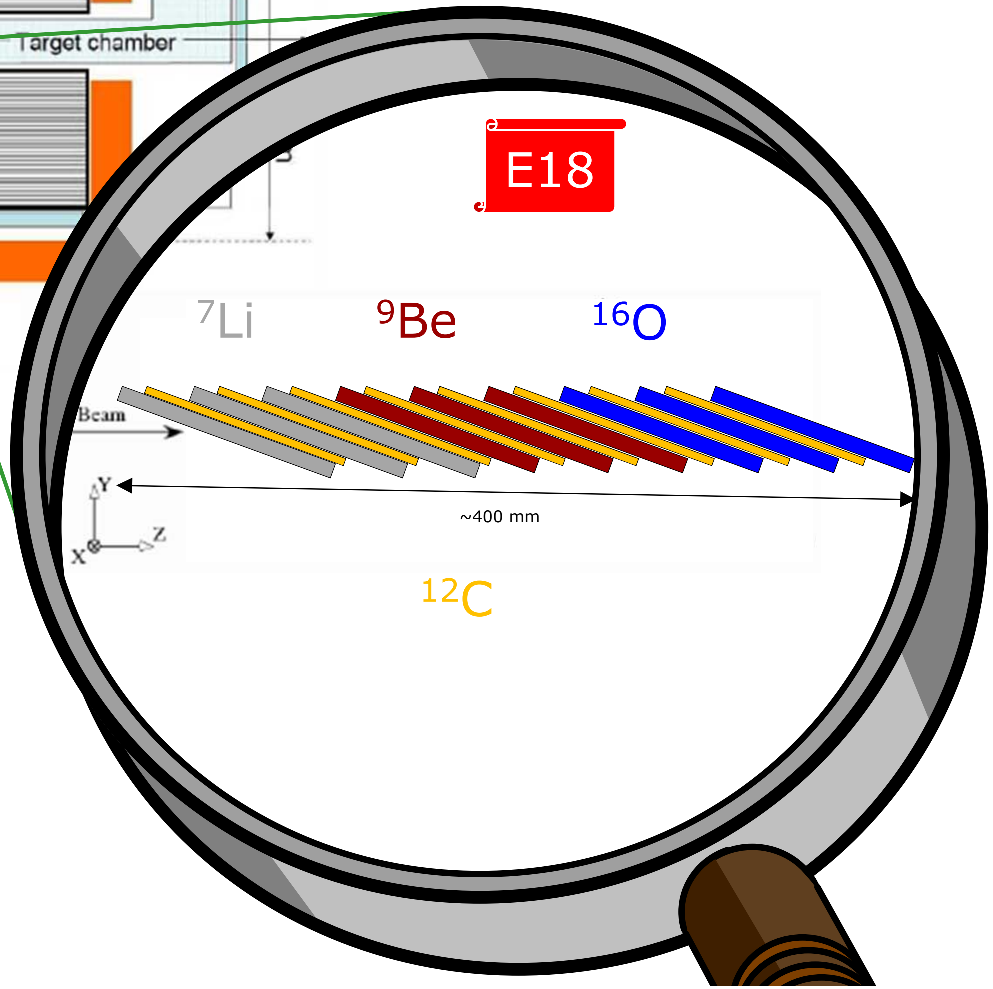
(K1.8 spectrometer)

essential requirements

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

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**

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

required beam time: 10 days

- $\sim 10^4$ *p* from $1\mathcal{N}$ → 1% on Γ_p/Γ_Λ, Γ_T/Γ_Λ
- $\sim 4 \times 10^3$ *p* from $2\mathcal{N}$ → 2% on $\Gamma_{2\mathcal{N}}/\Gamma_\Lambda$
- $\sim 10^3\ \pi^-$ → 3% on $\Gamma_{\pi^-}/\Gamma_\Lambda$
- $\sim 4 \times 10^2\ \pi^0$ → 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 $^{5}He_\Lambda$ and $^{11}B_\Lambda$ NMWD pattern
- Looking forward for new opportunities at J-PARC…

Thank you!

どうも　ありがとう