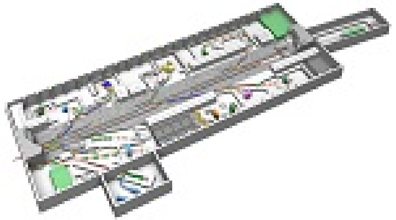
Measurement of the $^3H_\Lambda$ lifetime and of weak decay partial widths of mirror p-shell Λ-hypernuclei



International Workshop on the project for the extended Hadron Experimental Facility of J-PARC

March 26-28, 2018, J-PARC, Tokai, Japan

Alessandro Feliciello

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Outline

❶ physics goals

❷ physics motivations

❸ a possible experimental program

- needed detectors
- necessary beam time

What?

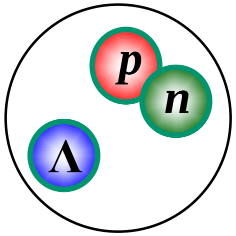
Physics aims

- precise, direct measurement of the $^{3}H_{\Lambda}$ ($^{4}H_{\Lambda}$) lifetime (delayed time spectrum technique)

- further studies of *p*-shell Λ-hypernuclei
  (in particular of the neutron-rich ones, e.g. $^{12}B_{\Lambda}$)

  – determination of:
    - $\Gamma_{tot} \equiv \hbar/\tau$
    - $\Gamma\pi^{-}$
    - $\Gamma\pi^{0}$ (possibly)
    - Γ_{p}

The naïve expectation



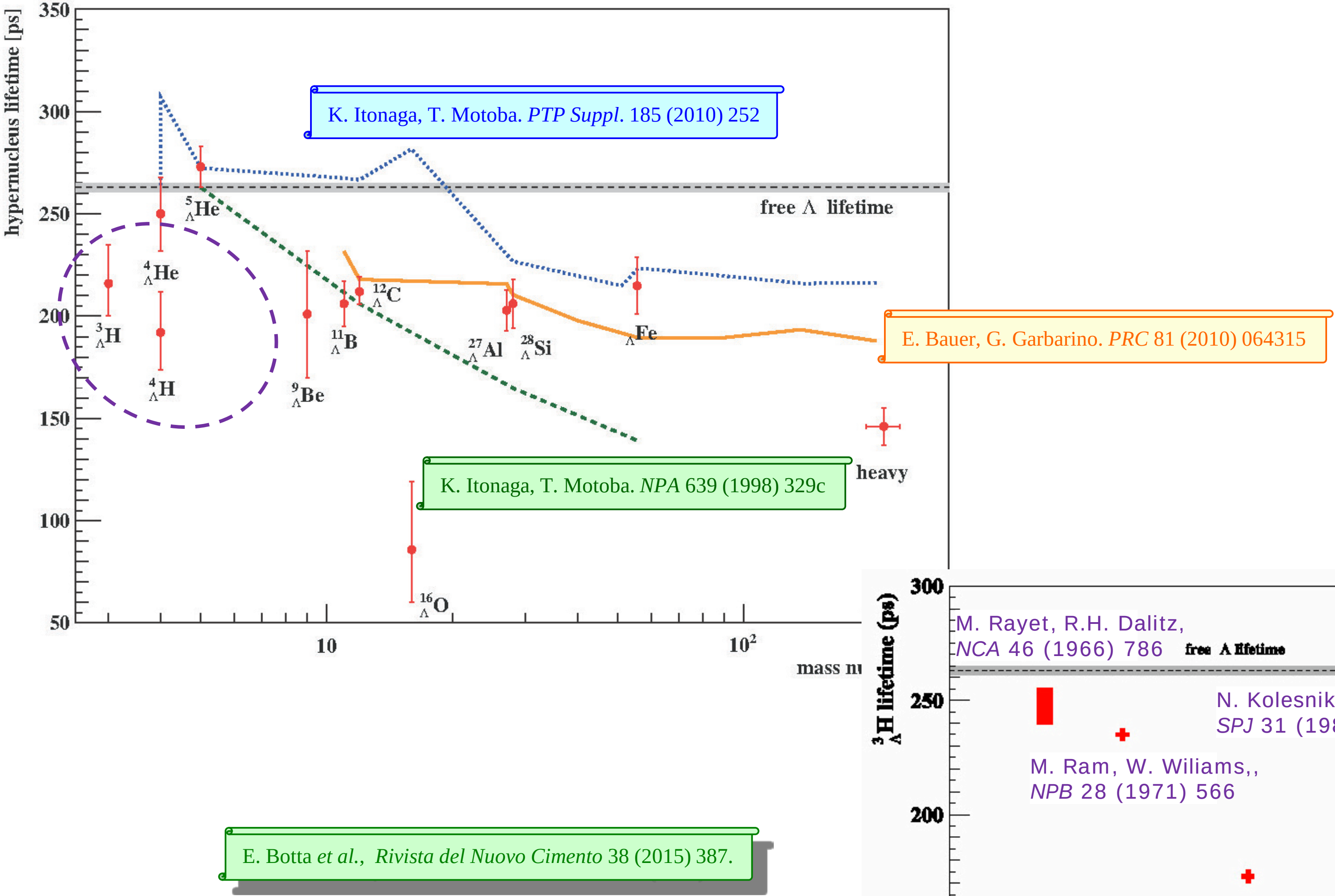
$$B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H}) = 0.13 \pm 0.05\,\mathrm{MeV}$$

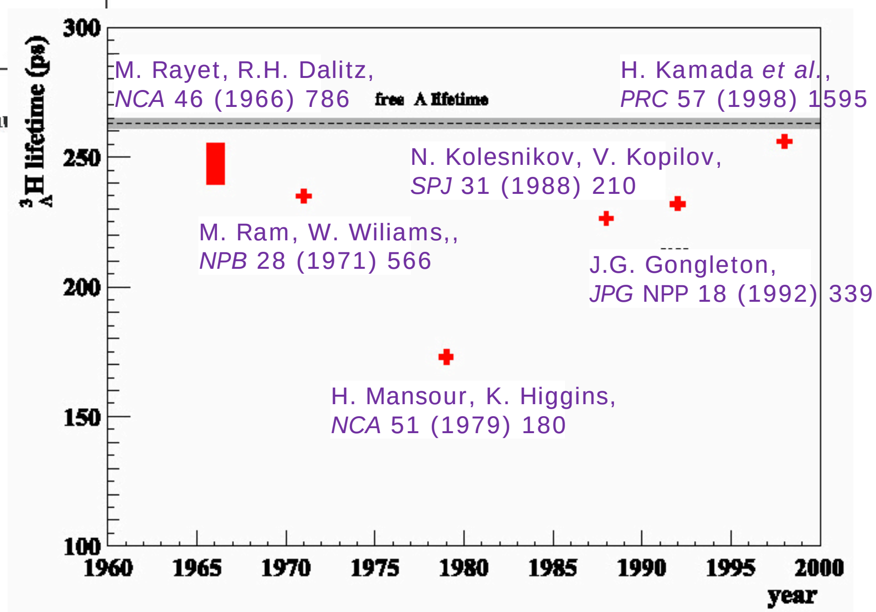
$$\tau({}^{3}_{\Lambda}\mathrm{H}) \approx \tau(\Lambda_{free})$$

supported by several theoretical predictions, e.g.: M. Rayet, R.H. Dalitz, NCA 46 (1966) 786
H. Kamada *et al.*, PRC 57 (1998) 1595

what does it means «approximately»?

The theoretical predictions



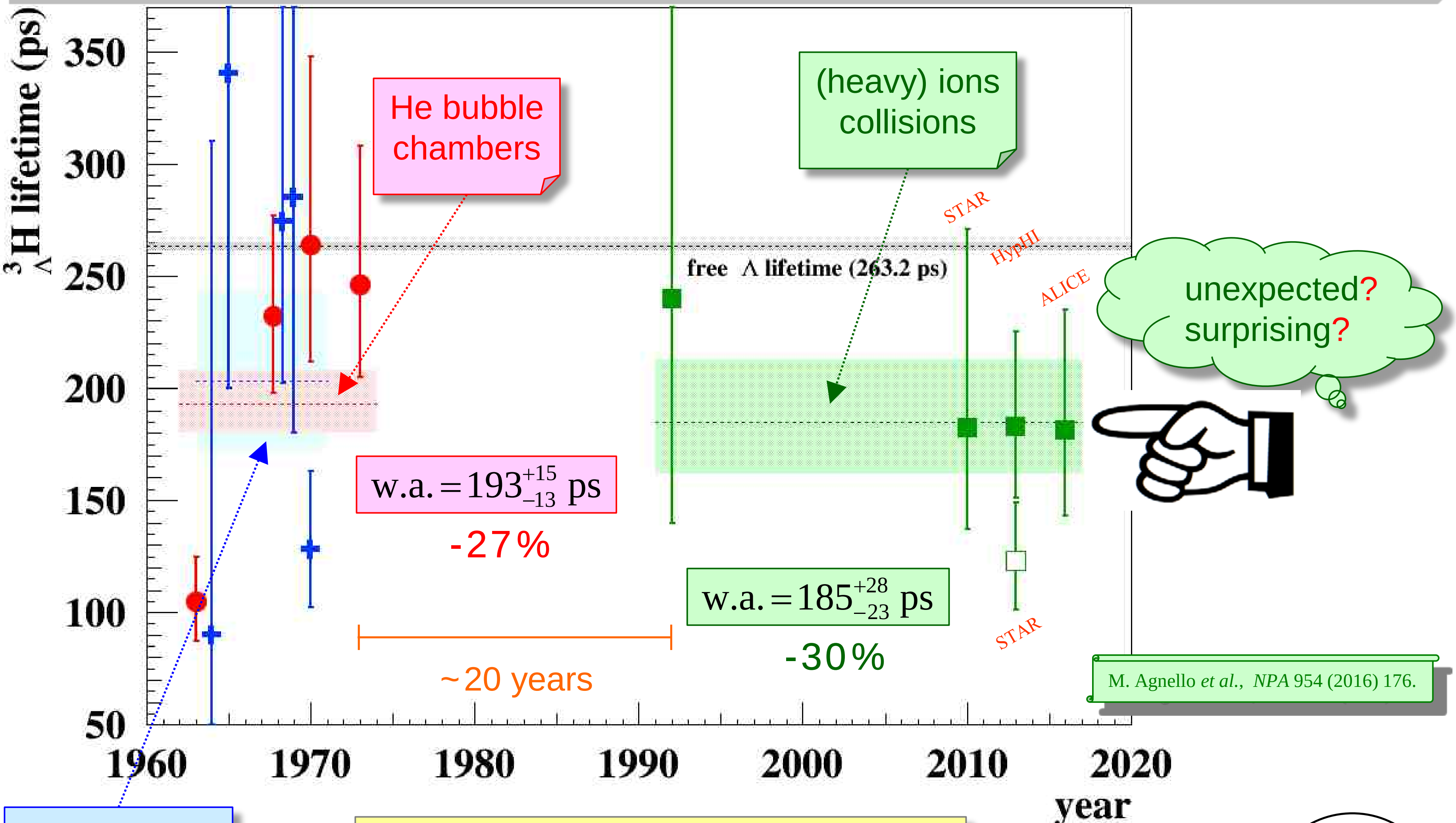


Why?

the physics case

Part I

$^3H_\Lambda$ lifetime world data compilation

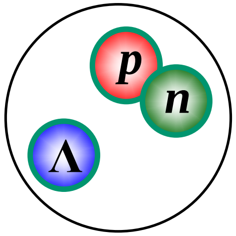


photographic emulsions

large error bars ↔ small data samples

w.a. = 203^{+40}_{-31} ps

-23%



BROOKHAVEN NATIONAL LABORATORY

3rd $\tau(^3H_\Lambda)$ measurement

STAR

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

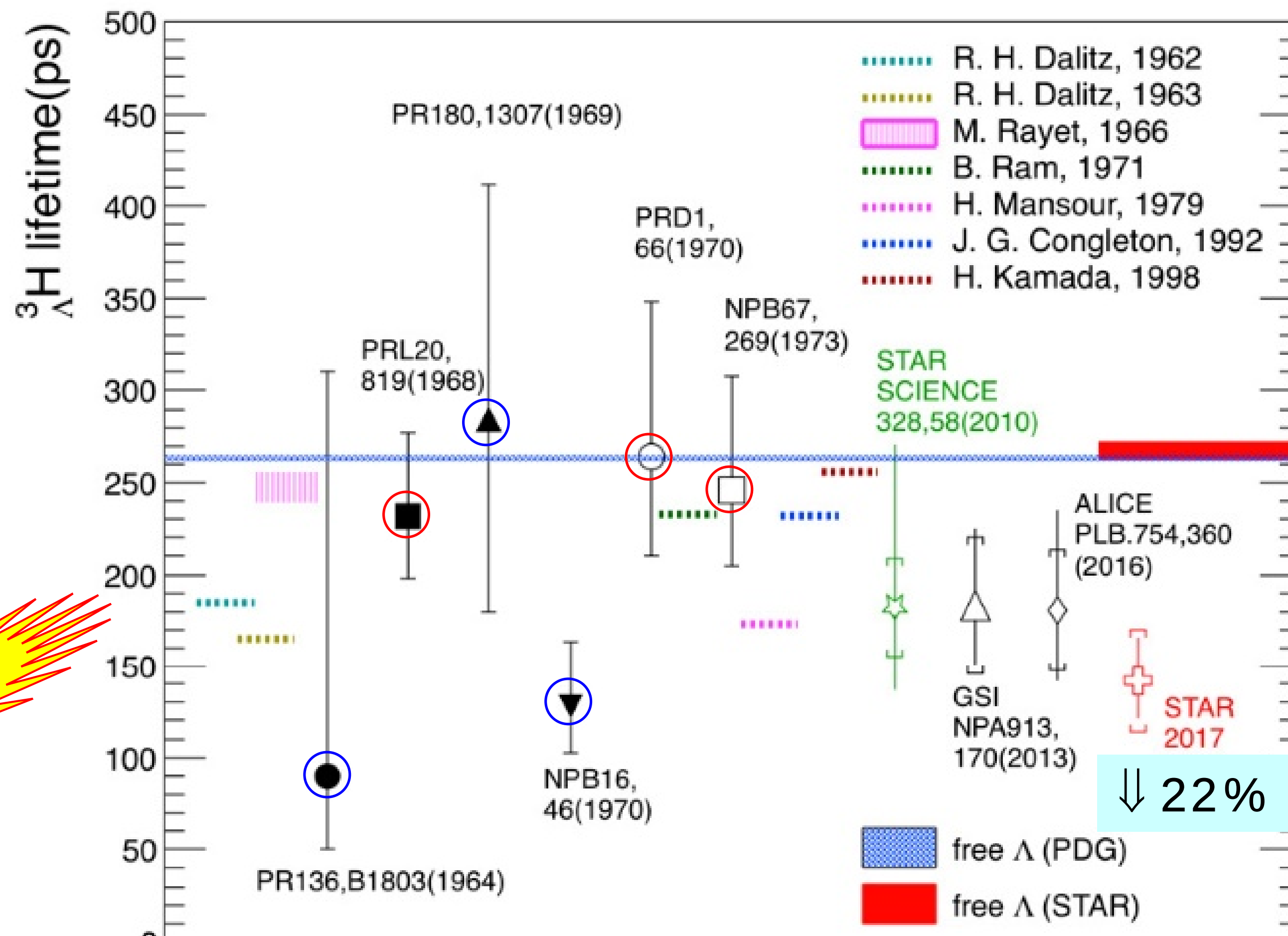
$$^3_\Lambda\mathrm{H} \rightarrow d + p + \pi^-$$

Au + Au @ 200 GeV

$$\tau = 142^{+24}_{-21} \pm 31 \text{ ps}$$

-46% !!!

recent paper on arXiv:1710.00436v1 [nucl-ex]



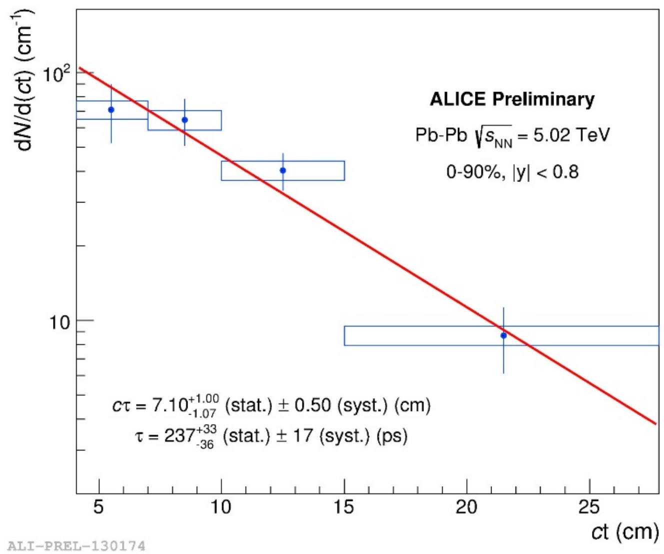
⇓ 22%

caveat: several existing measurements were arbitrarily ignored!

INFN

ALICE suprise?

$$\text{Pb} + \text{Pb} @ \sqrt{S_{NN}} = 5.02 \ \text{TeV}$$

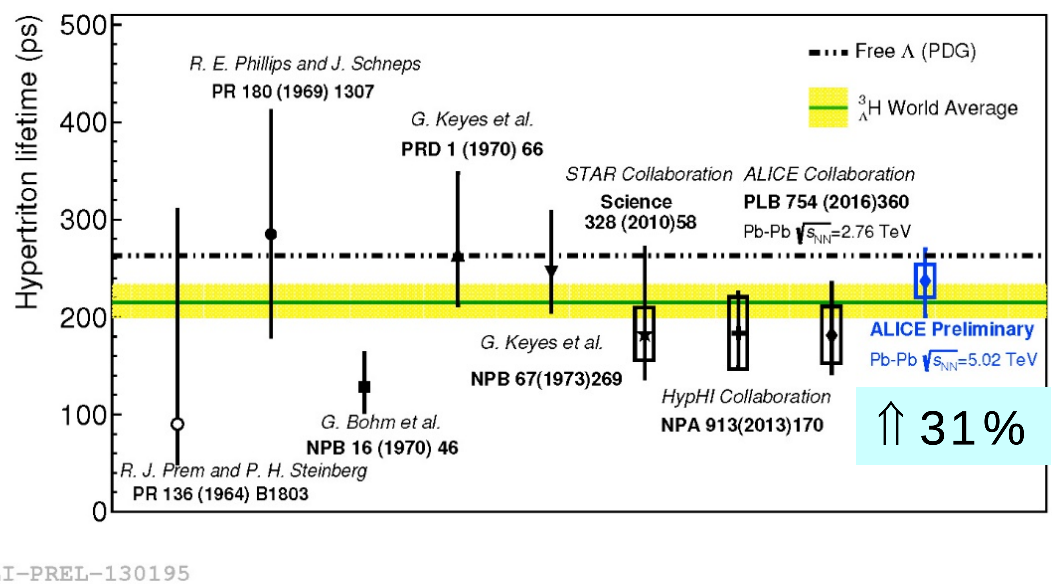


S. Bufalino @ HADRON 2017

$$\tau = 237^{+33}_{-36} \pm 17 \text{ ps}$$

-10% only

World Average: $\tau = 215^{+18}_{-16}$ ps



⇑ 31%

caveat: several existing measurements were arbitrarily ignored!

What's the matter?

is something wrong in the new measurements?

(are we using
the most suitable experimental technique?)

OR

is our understanding of the $^{3}H_{\Lambda}$ structure correct?

($B_{\Lambda}(^{3}H_{\Lambda})$ is not as small as it is believed?)

How?

A new $\tau(^{3,4}H)$ measurement @ J-PARC

challenging idea: K^0 spectroscopy

M. Agnello *et al.*, *NPA* 954 (2016) 176.

$$\pi^- + {}^{3,4}\mathrm{He} \rightarrow K^0 + {}^{3,4}_{\Lambda}\mathrm{H} \quad @\ p_\pi \approx 1.0 \div 1.1\,\mathrm{GeV}/c$$

$$\hookrightarrow \pi^+ + \pi^-$$

asymmetric decay

Letter of Intent
for precise measurement of the lifetime of
Hydrogen Hyperisotopes $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H

Michelangelo Agnello[1,2], Elena Botta[2,3], Tullio Bressani[2], Stefania Bufalino[1,2], Alessandro Feliciello[2], Tomofumi Nagae[4], Toshiyuki Takahashi[5], Hirokazu Tamura[6]

[1] *Politecnico di Torino, Dipartimento di Scienze Applicate e Tecnologia, Corso Duca degli Abruzzi 24, Torino Italy*
[2] *INFN - Sezione di Torino, Via P. Giuria 1, Torino Italy*
[3] *Università di Torino, Dipartimento di Fisica , Via P. Giuria 1, Torino Italy*
[4] *Department of Physics, Kyoto University, Kitashirakawa, Sakyo-ku, Kyoto, Japan*
[5] *Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[6] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*

We are planning to propose an experiment to precisely measure the lifetimes of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H using the ^{3,4}He$(\pi^-, K^0)^{3,4}_{\Lambda}$H reaction at the K1.1 beamline by employing the SKS spectrometer and scintillation counters around the target.

never exploited before!!!

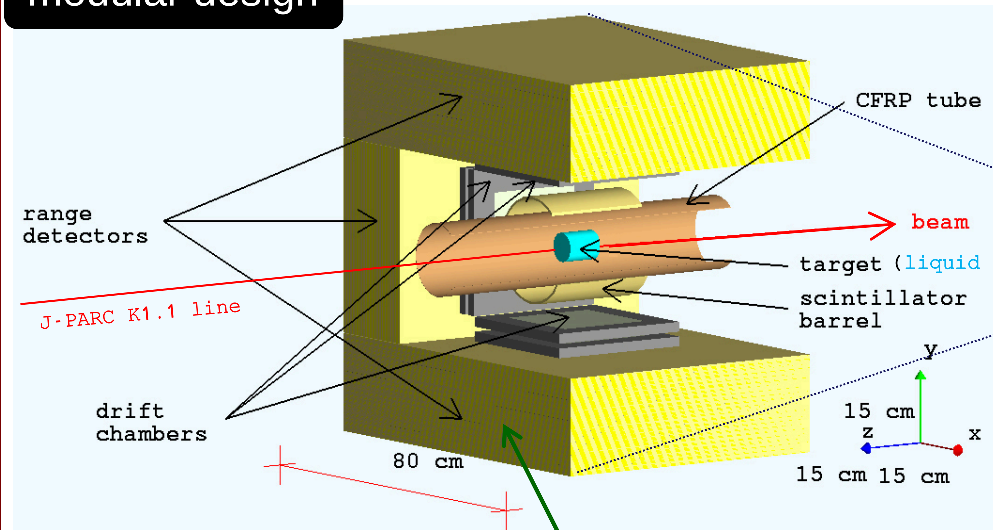
direct measurement!!!

delayed time spectrum technique $\Rightarrow \tau(^{A}Z_{\Lambda})$ $(t_{decay} - t_{production})$

Experimental concept layout

M. Agnello *et al.*, NPA 954 (2016) 176.

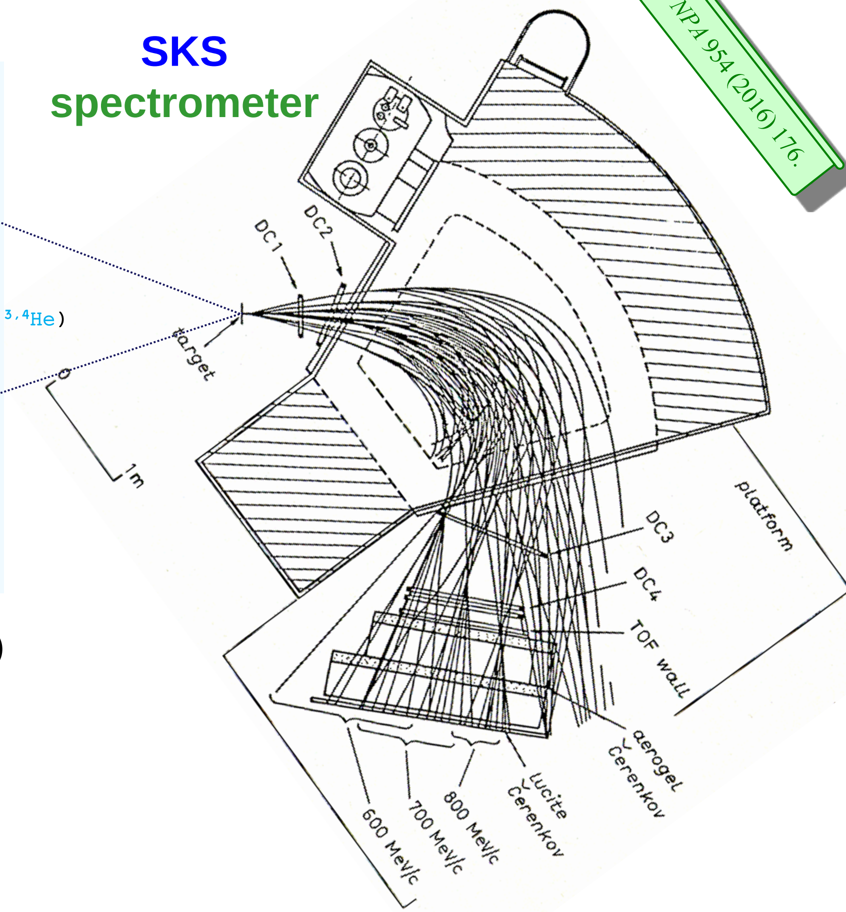
modular design



(not to scale)

fine layered detector (~100 pads)

SKS spectrometer



design performances:

- σ_{MM} ≤ 3 MeV (FWHM)
- σ_{time} ≤ 100 ps (FWHM)
- $\Delta\Omega$ ≈ 2 π sr
- $\sigma_{T(prongs)}$ ≤ 3 MeV
- σ_{ϑ} ≤ 100 mrad

Expected rate for $^4H_\Lambda$ production

$$\mathrm{yield}({}^4_\Lambda\mathrm{H}) = \mathrm{N_{beam}} \times \frac{\mathrm{N_{target}}}{4} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{sp} \times \varepsilon_{sp} \times \varepsilon_{an}$$

$$\mathrm{N_{beam}} = 5 \cdot 10^{13}\ \pi^-$$

$$\mathrm{N_{target}} = 1\ \mathrm{g/cm^2}$$

$$\frac{d\sigma}{d\Omega} \approx 10\ \mu\mathrm{b/sr}$$

$$\Omega_{sp} = 0.05\ \mathrm{sr}$$

$$\varepsilon_{sp} = \mathrm{BR}(K^0 \to K^0_s \to \pi^+\pi^-) \times \varepsilon_{rc}(\pi^+\pi^-) \approx 0.01$$

$$\varepsilon_{an} = 0.5$$

$$\mathrm{yield}({}^4_\Lambda\mathrm{H}) \approx 1.5 \times 10^4$$

detected

$$\mathrm{yield}({}^4_\Lambda\mathrm{H} \to \pi^- + {}^4\mathrm{He}) = \mathrm{yield}({}^4_\Lambda\mathrm{H}) \times \mathrm{BR} \times \Omega_\pi \times \varepsilon_\pi \times \varepsilon_{an}$$

0.49

H. Tamura *et al.*, *PRC 40* (1989) 479

$$\Omega_\pi \approx 0.5$$

$$\varepsilon_\pi \approx 1$$

$$\varepsilon_{an} \approx 0.8$$

$$\mathrm{observed}({}^4_\Lambda\mathrm{H} \to \pi^- + {}^4\mathrm{He}) \approx 3 \times 10^3$$

Expected rate for $^3H_\Lambda$ production

$$\text{yield}({}^3_\Lambda\text{H}) = \text{yield}({}^4_\Lambda\text{H}) \times \frac{4}{3} \times \frac{[d\sigma / d\Omega]_{{}^3_\Lambda\text{H}}}{[d\sigma / d\Omega]_{{}^4_\Lambda\text{H}}}$$

$$\frac{[d\sigma / d\Omega]_{{}^3_\Lambda\text{H}}}{[d\sigma / d\Omega]_{{}^4_\Lambda\text{H}}} = \textbf{?} \qquad \approx (0.1 \div 1)$$

rough guess

$$\text{yield}({}^3_\Lambda\text{H} \to \pi^- + p + d) = \text{yield}({}^3_\Lambda\text{H}) \times \text{BR} \times \Omega_\pi \times \varepsilon_\pi \times \varepsilon_{an}$$

$\Omega_\pi \approx 0.5$

$\varepsilon_\pi \approx 1$

$\varepsilon_{an} \approx 0.4$

0.40

H. Kamada *et al.*, *PRC* 57 (1998) 1595

$$\text{observed}({}^3_\Lambda\text{H} \to \pi^- + p + d) \approx 0.1 \times \text{yield}({}^3_\Lambda\text{H})$$

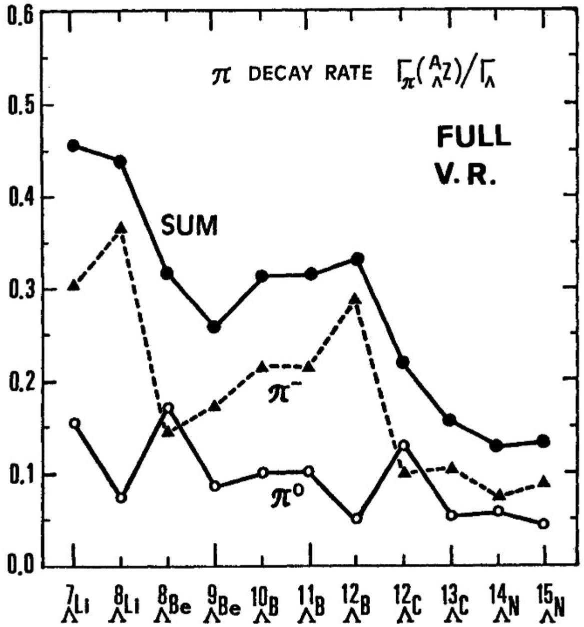
detected

Why?

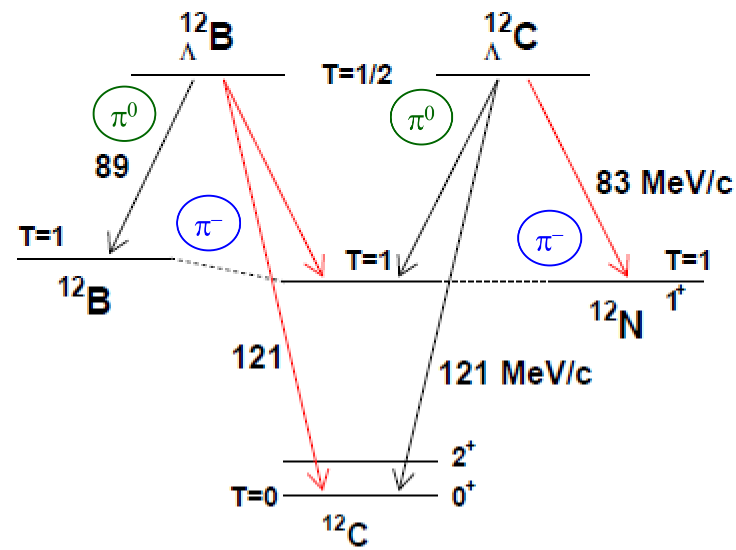
the physics case

Part II

Looking for nuclear structure effects



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



$$\Gamma_{\pi^-}(^{12}_\Lambda B)/\Gamma_{\pi^-}(^{12}_\Lambda C) = ?$$

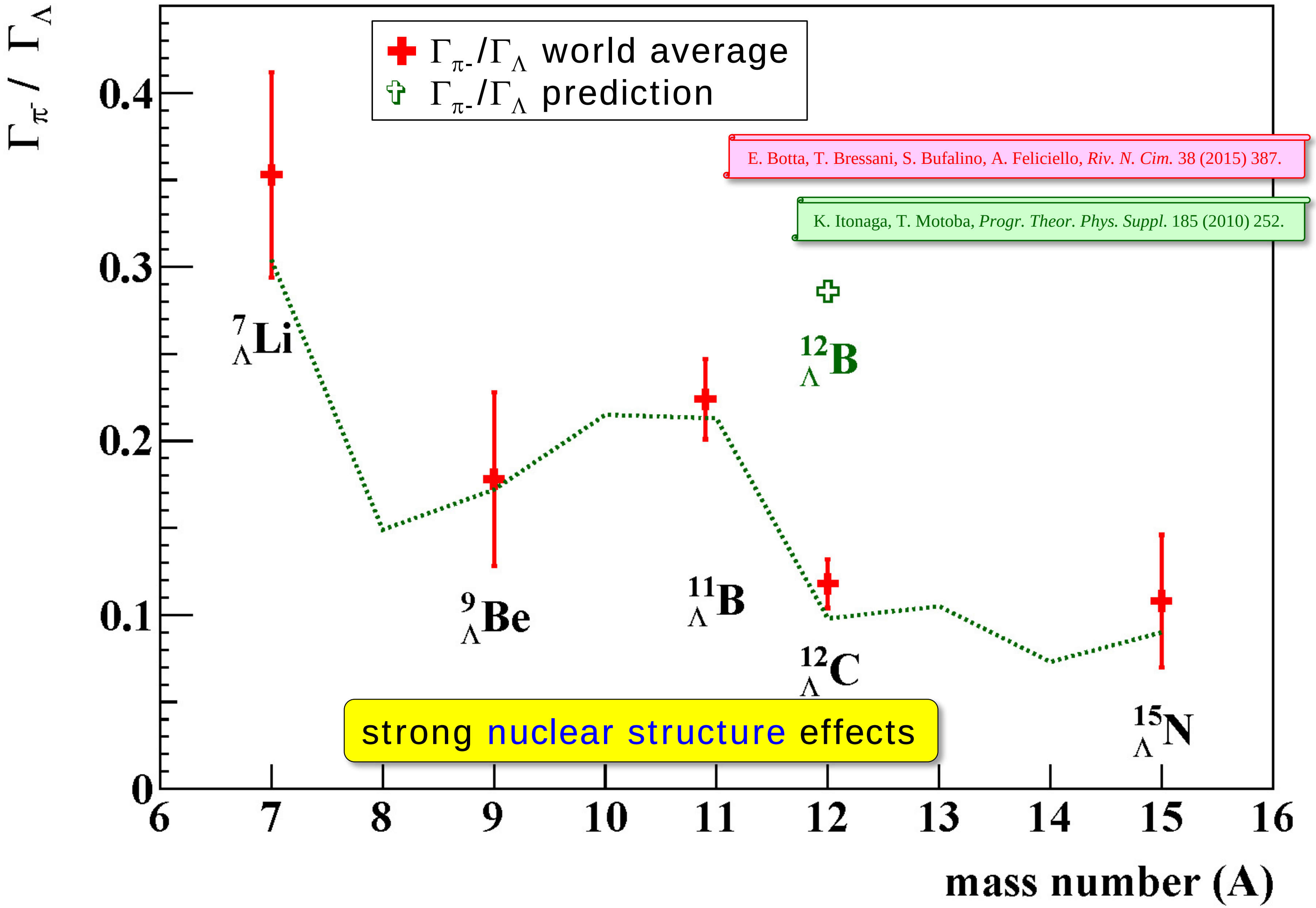
T. Motoba, *NPA* 547 (1992) 115c. ≈ 3

K. Itonaga, T. Motoba, *Prog. Theor. Phys. Suppl.* 185 (2010) 252. = 2.9

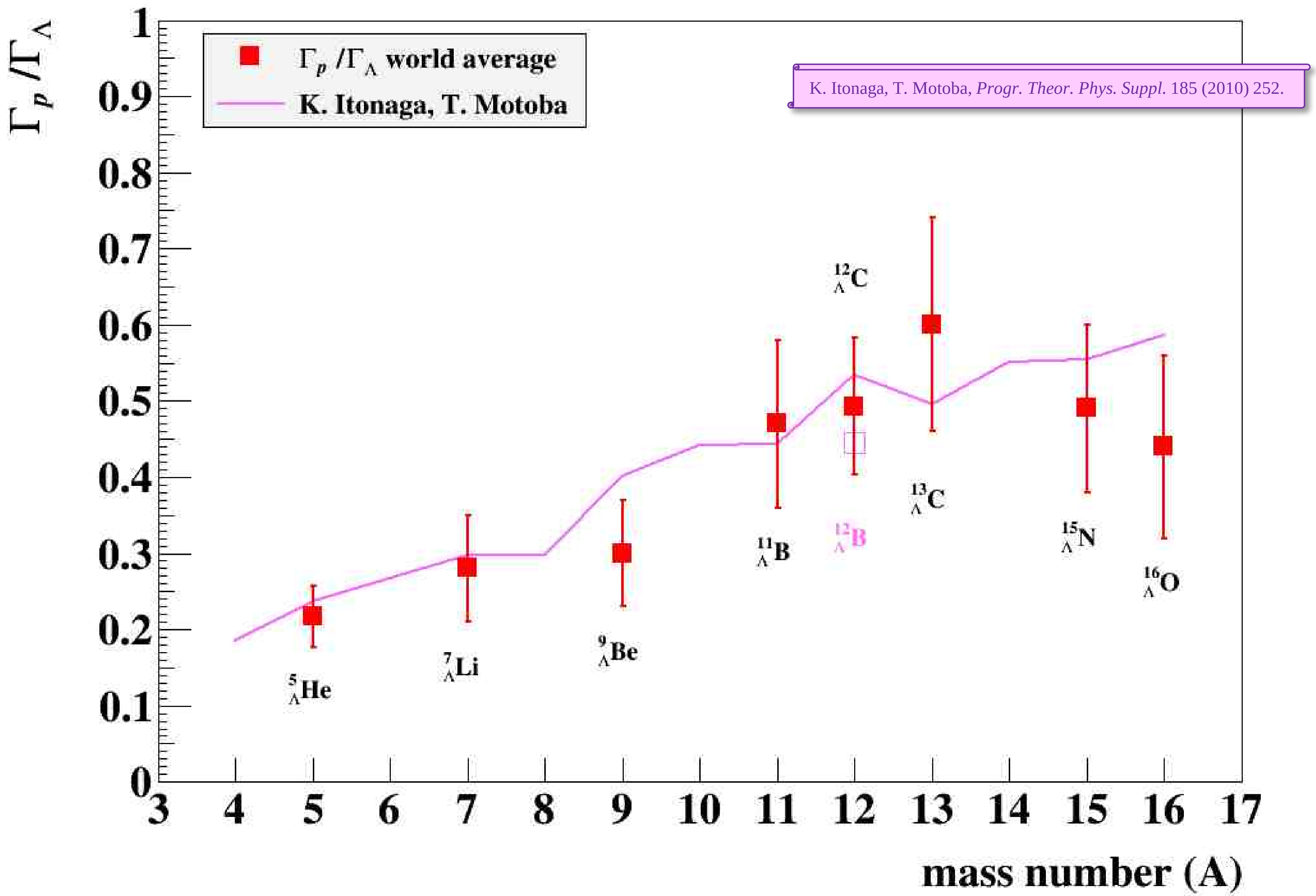
$$\frac{\Gamma_{\pi^0}(^{12}_\Lambda C)}{\Gamma_{\pi^-}(^{12}_\Lambda C)} \bigg/ \frac{\Gamma_{\pi^0}(^{12}_\Lambda B)}{\Gamma_{\pi^-}(^{12}_\Lambda B)} = ?$$

T. Motoba, *NPA* 547 (1992) 115c. ≈ 8

Γ_{π^-}: current experimental situation



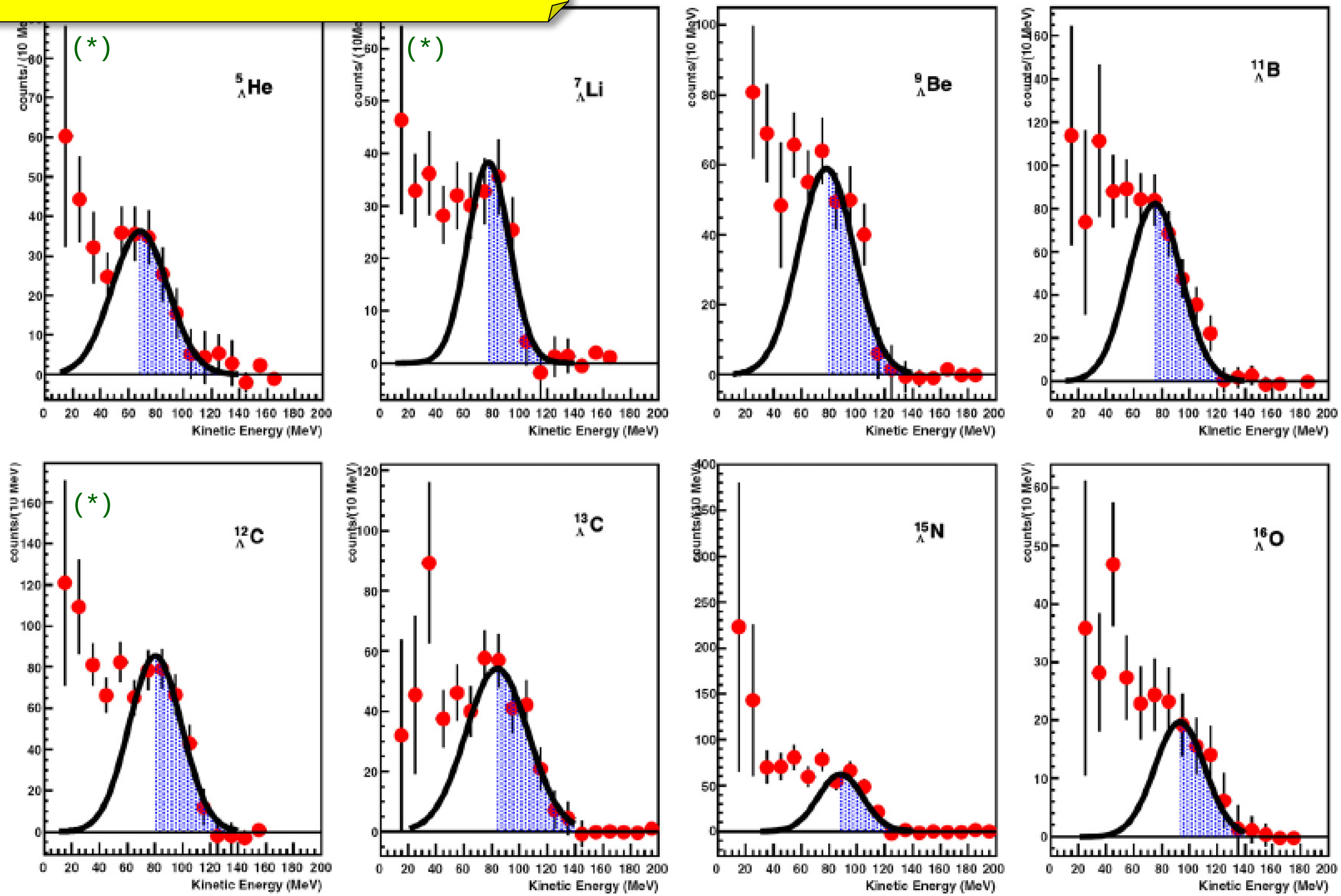
Γ_p: current experimental situation



A consolidated method to extract Γ_p

p spectra background subtracted and acceptance corrected

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



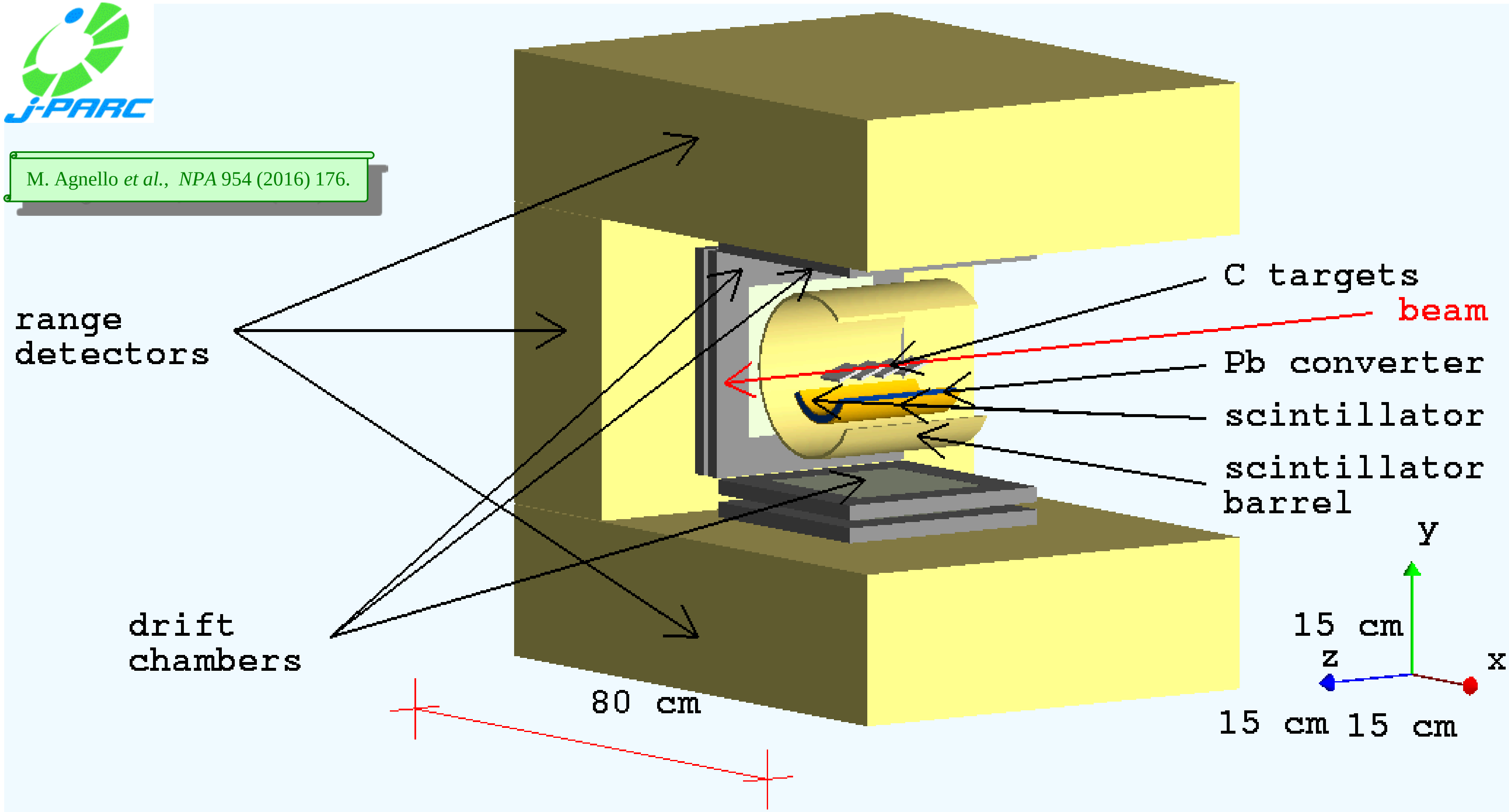
(*) M. Agnello *et al.*, *NPA* 804 (2008) 151.

How?

Concept design

final goal:
SKS Λ-hypernucleus MM resolution
≤ 3 MeV (FWHM)

M. Agnello *et al.*, *NPA* 954 (2016) 176.



detector performance: solid angle coverage 50-60%

range detector

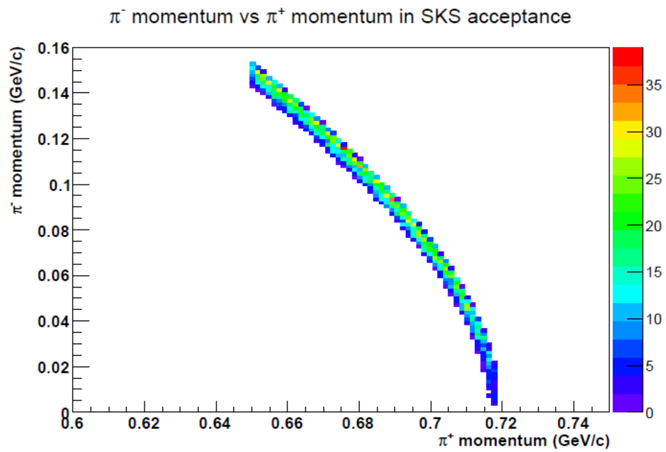
- energy resolution on π^- ≤ 2 MeV (FWHM)

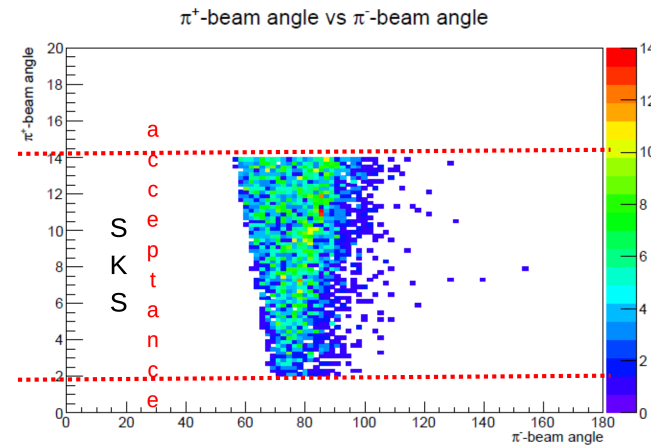
drift chambers

spatial resolution ≤ 300 μm
angular resolution ≤ 100 mrad

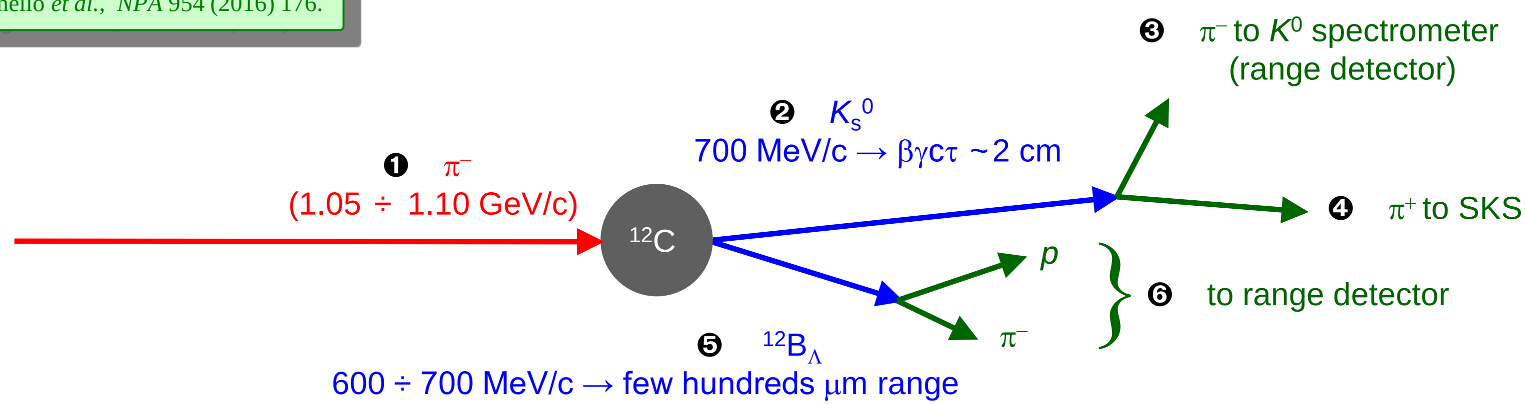
Reaction kinematics

$$\pi^- + {}^{12}\mathrm{C} \rightarrow K^0 + {}^{12}_{\Lambda}\mathrm{B}$$





M. Agnello *et al.*, *NPA* 954 (2016) 176.



kinematical features:

❹ π^+: p > 650 MeV/c, 2° < ϑ < 14°

❸ π^-: 10 < p < 120 MeV/c, 60° < ϑ < 100°

❻ π^-: 0 < p < 121 MeV/c, 0° < ϑ < 180° or p: 0 < p < 400 MeV/c, 0° < ϑ < 180°

Expected rates (preliminary estimate)

beam request: $2 \times 10^{13}\ \pi^-$ delivered

$$\frac{d\sigma}{d\Omega} \approx 15\ \frac{\mu b}{sr}$$

H. Hotchi *et al.*, *PRC* 64 (2001) 044302.

- target thickness
- angular acceptance
- $K^0 \to K^0_s$, $K^0_s \to \pi^+\pi^-$ BRs
- ε_{det}, ε_{rec}
- phase space factor

$1 \times 10^4\ {}^{12}B_\Lambda$ detected

Γ_{π^-} 0.286 → 1.5×10^3 events

Γ_{π^0} 0.049 → 1.5×10^2 events

Γ_p 0.446 → 3.0×10^3 events

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

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

2% on Γ_p

3% on Γ_π

2-3% on τ — $1.0\text{-}2.0 \times 10^3$ events — precise measurement → $\tau({}^{12}_{\Lambda}B)$

A challenging project

- ambitious physics program
- experimental approach never attempted before:

  (π^-, K^0) reaction

- long data taking campaign(s)
  - minimum 2-5 x 10^{13} π^- delivered on the target
- important human and economic efforts
  - costly liquid ^3He target

A staged approach

❶ test of the validity of the chosen strategy

- first attempt of missing-mass spectroscopy with the (π^{-},K^{0}) reaction

❷ reduced experimental setup

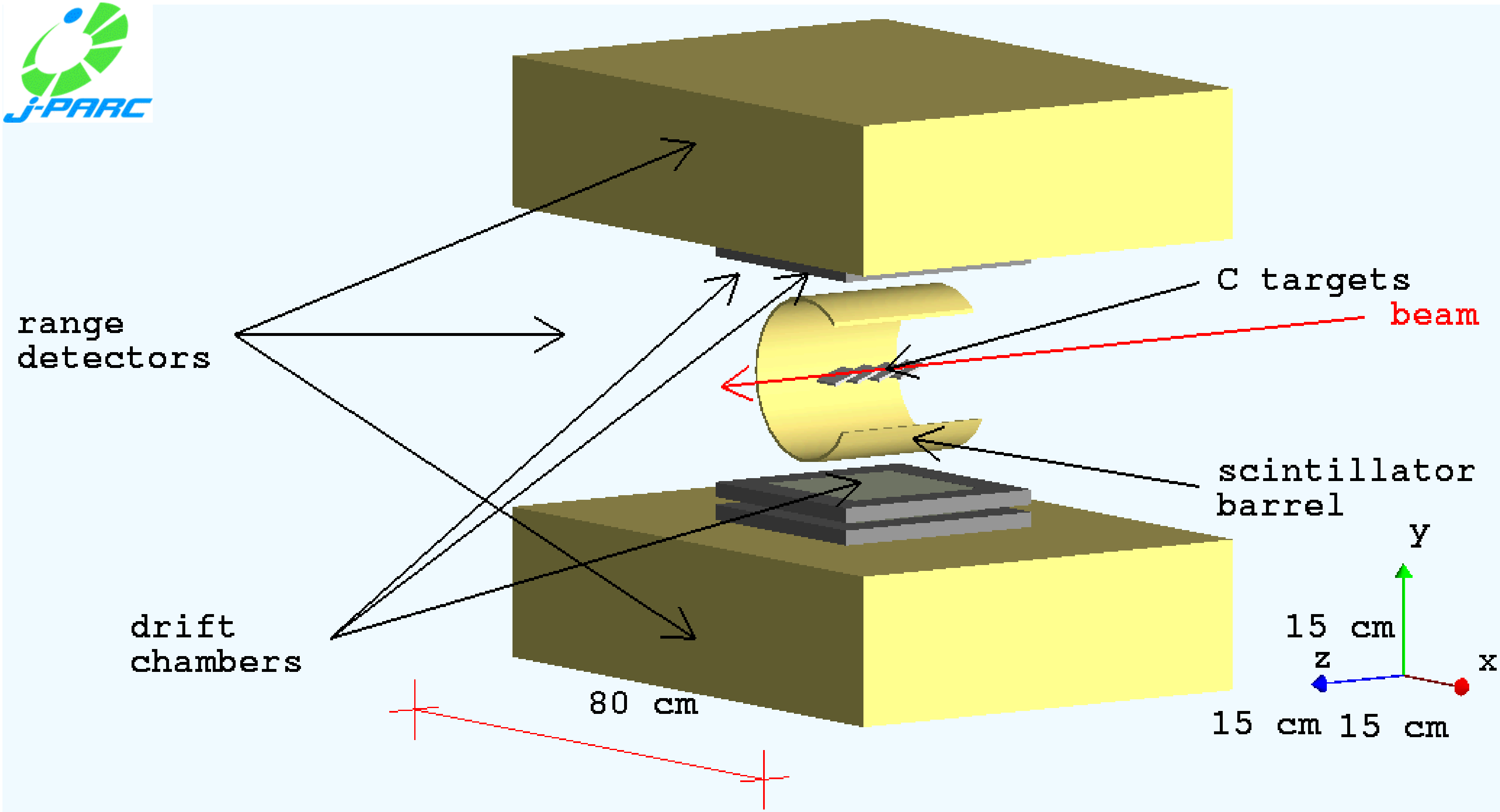
- test of the adopted technical solutions
- save money

❸ reduced beam request

- save time

pilot run but with a good physics output

Simplified concept design



detector performance: solid angle coverage 25-30% ☞ factor 1/2

range detector

- energy resolution on π^- ≤ 2 MeV (FWHM)
- angular resolution ≤ 100 mrad

drift chambers

spatial resolution ≤ 300 μm

Expected rate for $^{12}B_\Lambda$ production

$$\text{yield}({}^{12}_{\Lambda}\text{B}) = N_{\text{beam}} \times \frac{N_{\text{target}}}{12} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{sp} \times \varepsilon_{sp} \times \varepsilon_{an}$$

factor 1/2 ☞ $N_{\text{beam}} = 1 \cdot 10^{13}\ \pi^-$

$N_{\text{target}} = 4 \times 1\ \text{g/cm}^2$

$$\frac{d\sigma}{d\Omega} \approx 15\ \mu\text{b/sr}$$

H. Hotchi *et al.*, Phys. Rev. C 64 (2001) 044302.

$\Omega_{sp} = 0.02$ sr ☜ factor 1/2

$$\varepsilon_{sp} = \text{BR}(K^0 \to K^0_s \to \pi^+\pi^-) \times \varepsilon_{rc}(\pi^+\pi^-) \approx 0.01$$

$$\varepsilon_{an} = 0.5$$

$$\text{yield}({}^{12}_{\Lambda}\text{B}) \approx 3 \times 10^3$$

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

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

0.286 Γ_{π^-}

Γ_p **0.446**

$\Omega_{sp} \approx 0.25$ sr ☜ factor 1/2

$\varepsilon_{mx} \approx 0.8$

$\varepsilon_{\pi/p} \approx 1$

$\varepsilon_{an} \approx 0.8$

8% on Γ_π | **~1.5 × 10² ev.** | **~3 × 10² ev.** | 6% on Γ_p

5% on τ | **3.0-4.0 × 10² events** | measurement → $\tau({}^{12}_{\Lambda}\text{B})$

Expected rate for $^{12}C_\Lambda$ production

$$\text{yield}({}^{12}_{\Lambda}\text{C}) = \text{N}_{\text{beam}} \times \frac{\text{N}_{\text{target}}}{12} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{sp} \times \varepsilon_{sp} \times \varepsilon_{an}$$

limited request ☞ $\text{N}_{\text{beam}} = 2 \cdot 10^{11}\ \pi^+$

$\text{N}_{\text{target}} = 4 \times 1\ \text{g/cm}^2$

$\frac{d\sigma}{d\Omega} \approx 15\ \mu\text{b/sr}$

H. Hotchi *et al.*, Phys. Rev. C 64 (2001) 044302.

$\Omega_{sp} = 0.02\ \text{sr}$

$\varepsilon_{sp} = 0.5$

$\varepsilon_{an} = 0.5$

$$\text{yield}({}^{12}_{\Lambda}\text{C}) \approx 3.5 \times 10^3$$

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

Γ_p **0.535**

detected

$\Omega_{sp} \approx 0.25\ \text{sr}$

$\varepsilon_p \approx 1$

$\varepsilon_{an} \approx 0.8$

1-day data taking

~4 × 10² ev.

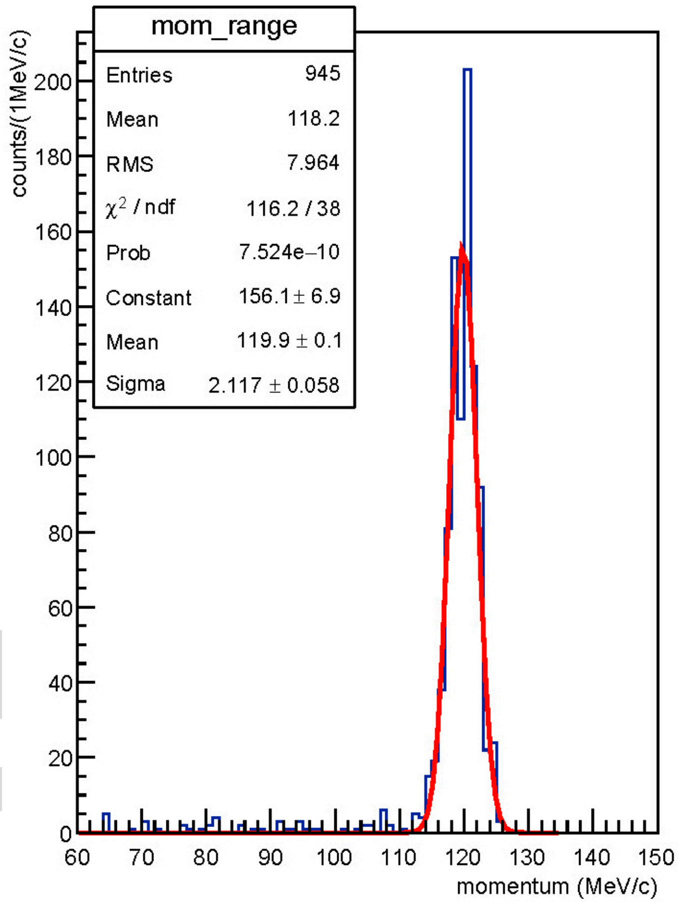
5% on Γ_p

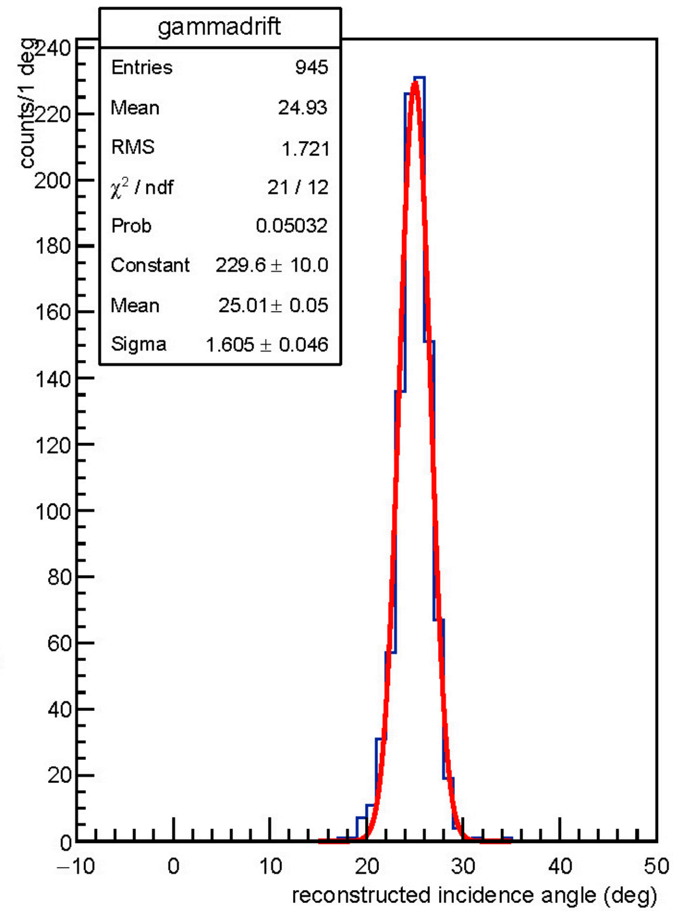
Preliminary performance study

input:

- p_π = 120 MeV/c
- θ = 25°

reconstruction:



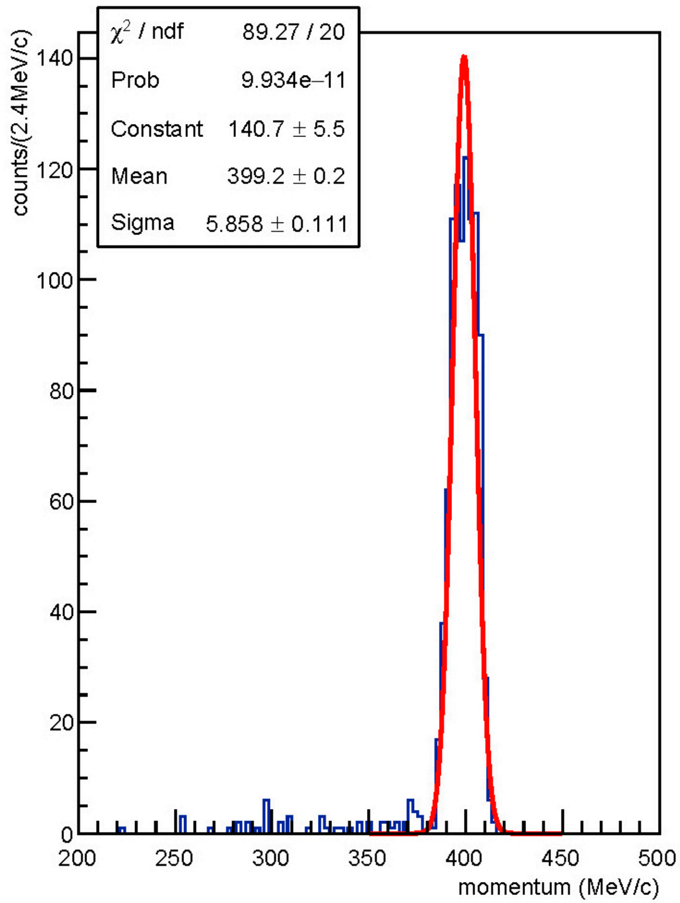


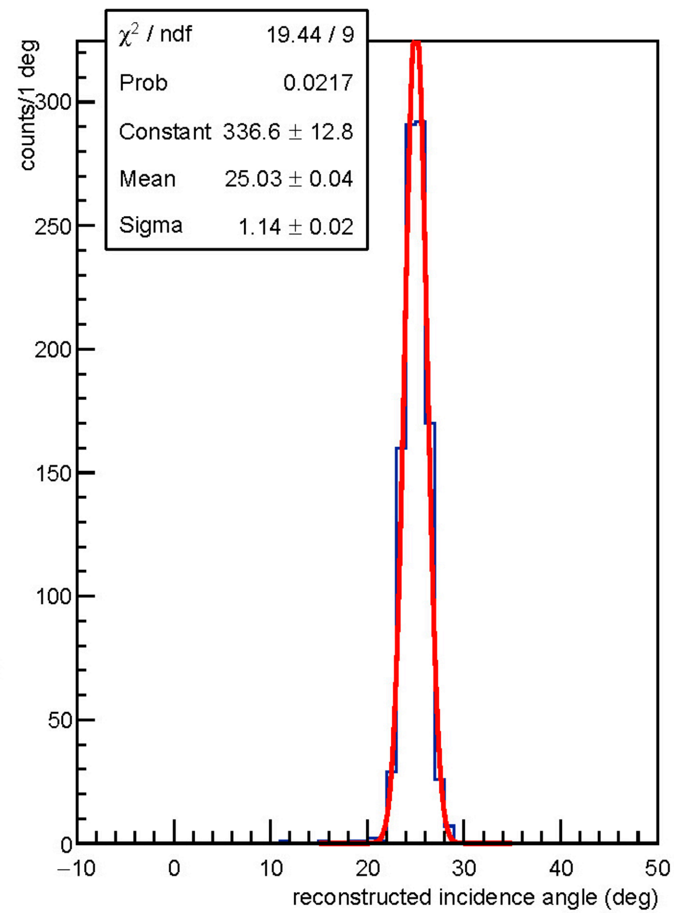
Preliminary performance study

input:

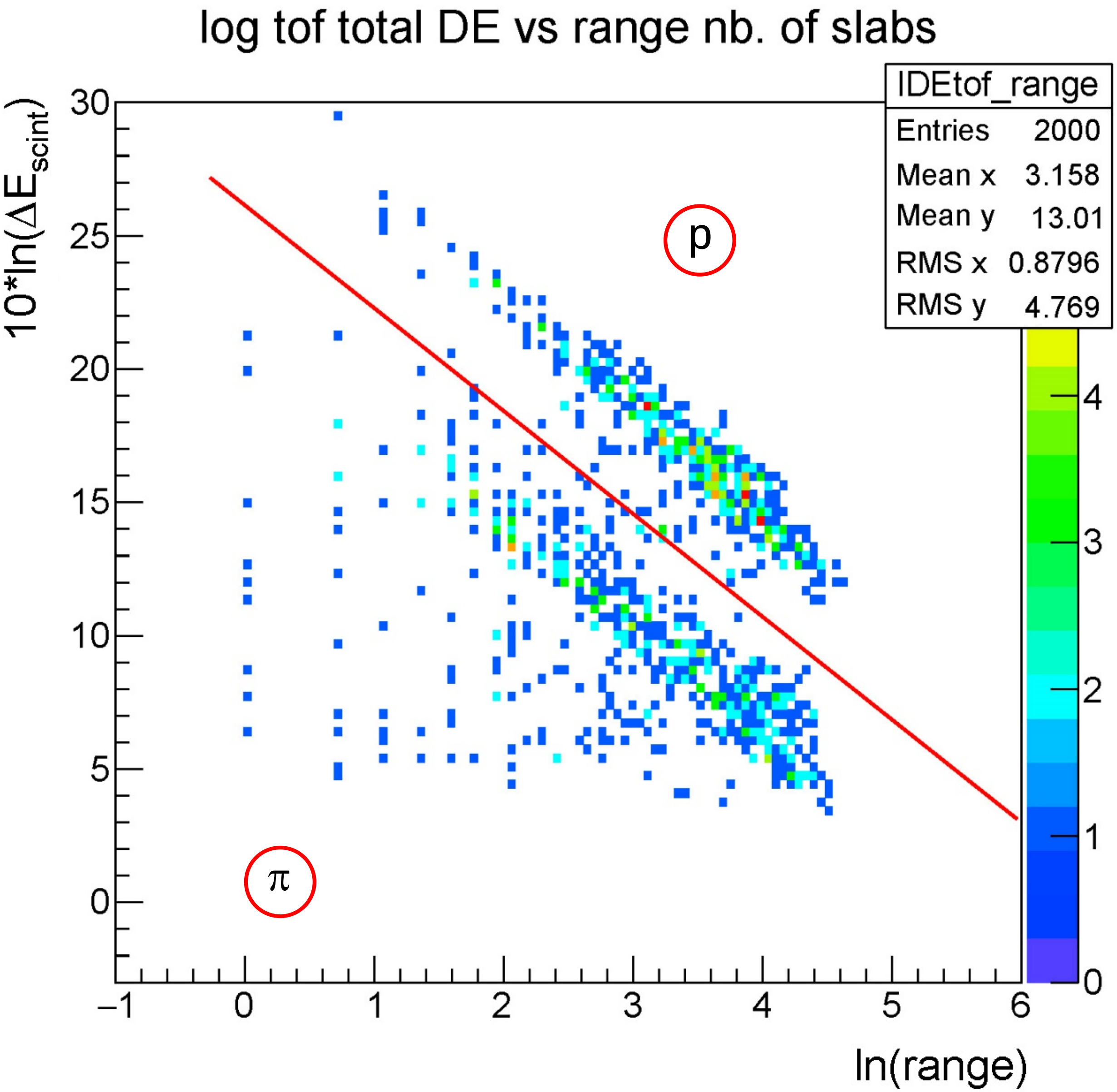
- p_p = 400 MeV/c
- θ = 25°

reconstruction:





Preliminary performance study: PID



p:

ε ≈ 96%

contamination ≈ 0.1%

π:

ε ≈ 99%

contamination ≈ 4%

Rates and beam time summary

beam request (x 10^{13} π^-)	target	thickness	exp. conf.	detected YN	observables		
					τ	$\Gamma_{\pi-}$	Γ_p
1	^{12}C	4 x 1 g/cm^2	1/4	1.5 x 10^3 $^{12}B_\Lambda$	possible	difficult	possible
1	^{12}C	4 x 1 g/cm^2	1/2	3.0 x 10^3 $^{12}B_\Lambda$	feasible	feasible	feasible
2	^{12}C	4 x 1 g/cm^2	full	1.0 x 10^4 $^{12}B_\Lambda$	OK	OK	OK
5	L ^{4}He	1 g/cm^2	full	1.5 x 10^4 $^4H_\Lambda$	OK	OK	-
5	L ^{3}He	1 g/cm^2	full	1.0 x 10^4 $^3H_\Lambda$	OK	OK	-
1 x 10^{11} π^+	^{12}C	4 x 1 g/cm^2	1/2	3.5 x 10^3 $^{12}C_\Lambda$	-	-	feasible

delivered π	10^7 π /spill (present)	1.5 x 10^7 π /spill	10^8 π /spill	10^9 π /spill (HIHR)
1 x 10^{13}	6.9 x 10^1 d	4.6 x 10^1 d	7 d	<1 d
2 x 10^{13}	1.4 x 10^2 d	9.3 x 10^1 d	1.4 x 10^1 d	1.4 d
5 x 10^{13}	3.5 x 10^2 d	2.3 x 10^2 d	3.5 x 10^1 d	3.5 d

Wrap-up

- exciting physics program possible at the J-PARC K1.1 line by exploting the (π^-, K^0) reaction
  - direct measurement of the $^3H_\Lambda$ and $^4H_\Lambda$ lifetime
  - detailed study of neutron-rich, *p*-shell Λ-hypernucleus ($^{12}B_\Lambda$) decay process

- ambitious and challenging experiment

☞ engineering run advisable

✓ test of both the strategy and the solution chosen

✓ added value !!! ☞ Good physics output

Thank you!

どうも　ありがとう