Study of the (π^-, K^0) reaction on nuclei at J-PARC

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Outline

- physics cases
  - ❶ the $^{3}H_{\Lambda}$ lifetime puzzle
  - ❷ further investigation of the hypernuclear weak decay process
- a possible experimental program at J-PARC
  - the experimental setup
  - ultimate assessment of the lifetime of Λ-hypernuclei with a direct measurement (in particular for light systems)
  - systematic and precise (≤ 5%) determination of the full pattern of the partial weak decay widths (in particular for *p*-shell neutron-rich Λ-hypernuclei)

Why?

the physics case

Part I

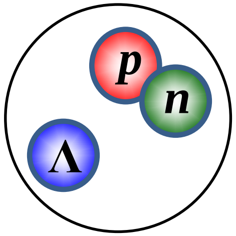
In order to solve a puzzle...

to look for missing tiles

OR

to reorganise the pieces already at our disposal

The naïve expectation



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

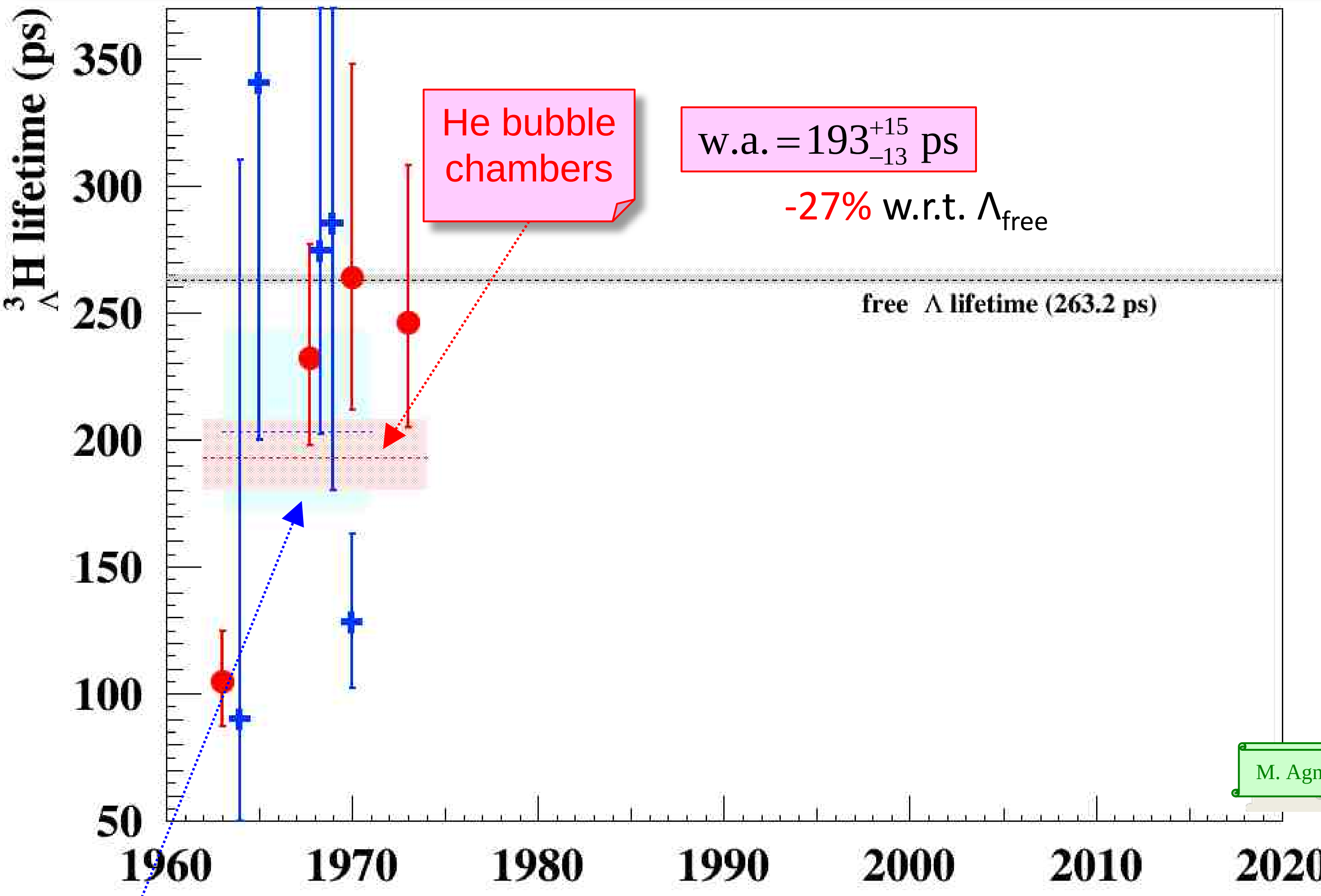
M. Juric *et al.*, *NPB* 52 (1973) 1.

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

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»?

$^{3}H_{\Lambda}$ lifetime historical compilation



$\text{w.a.} = 193^{+15}_{-13}$ ps

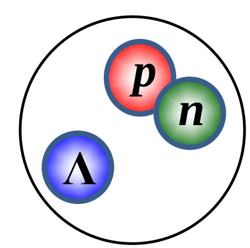
-27% w.r.t. Λ_{free}

photographic emulsions

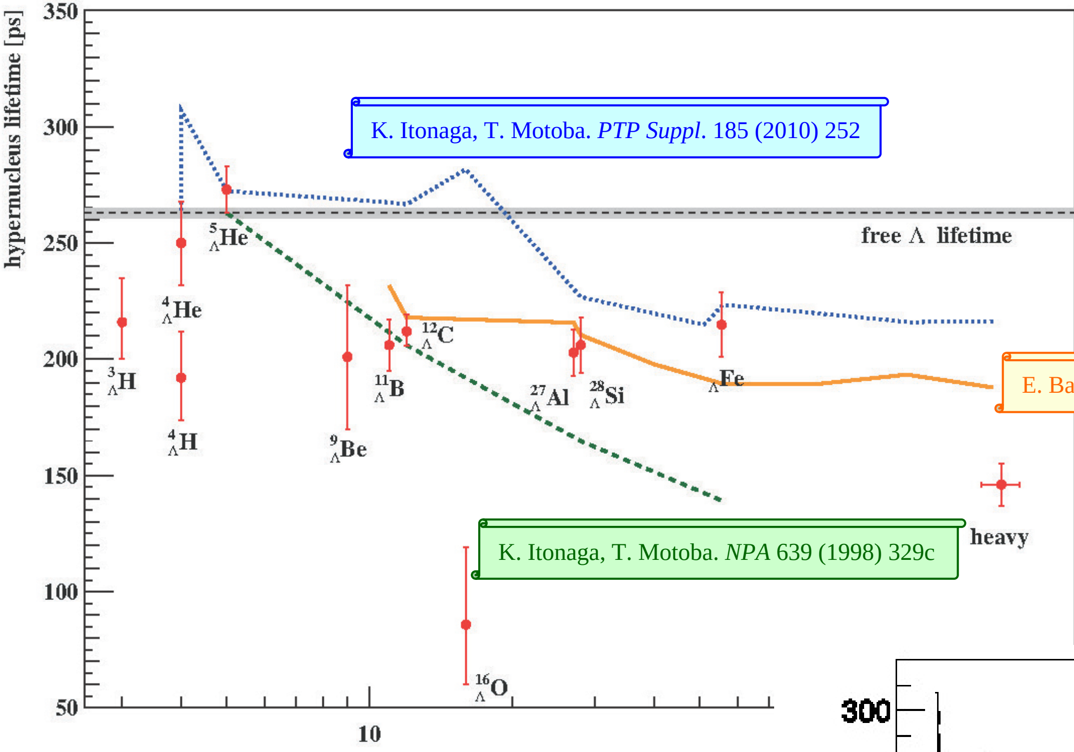
large error bars ↔ small data samples

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

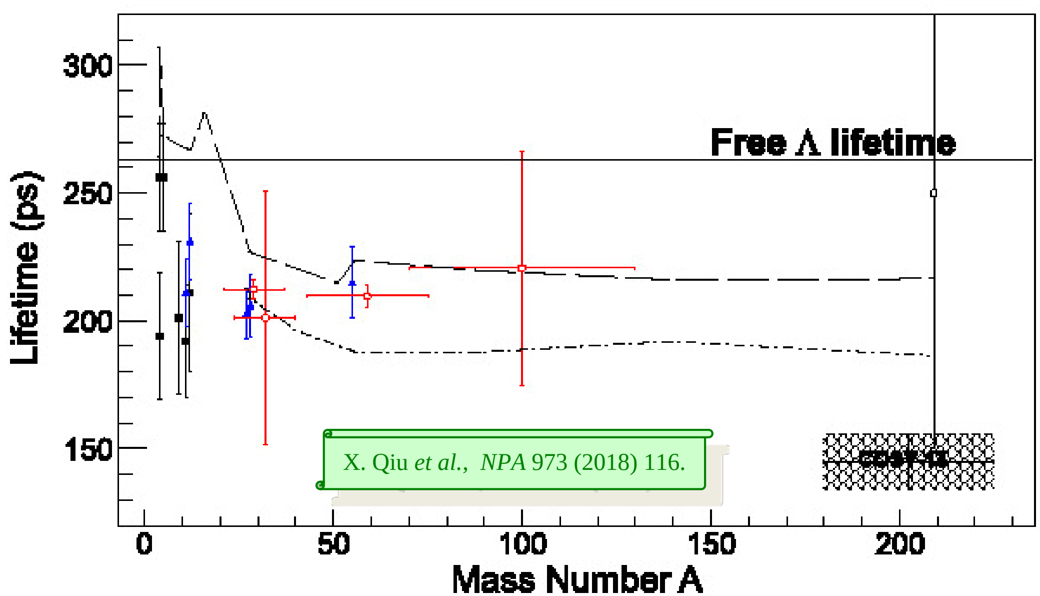
-23% w.r.t. Λ_{free}



The theoretical predictions

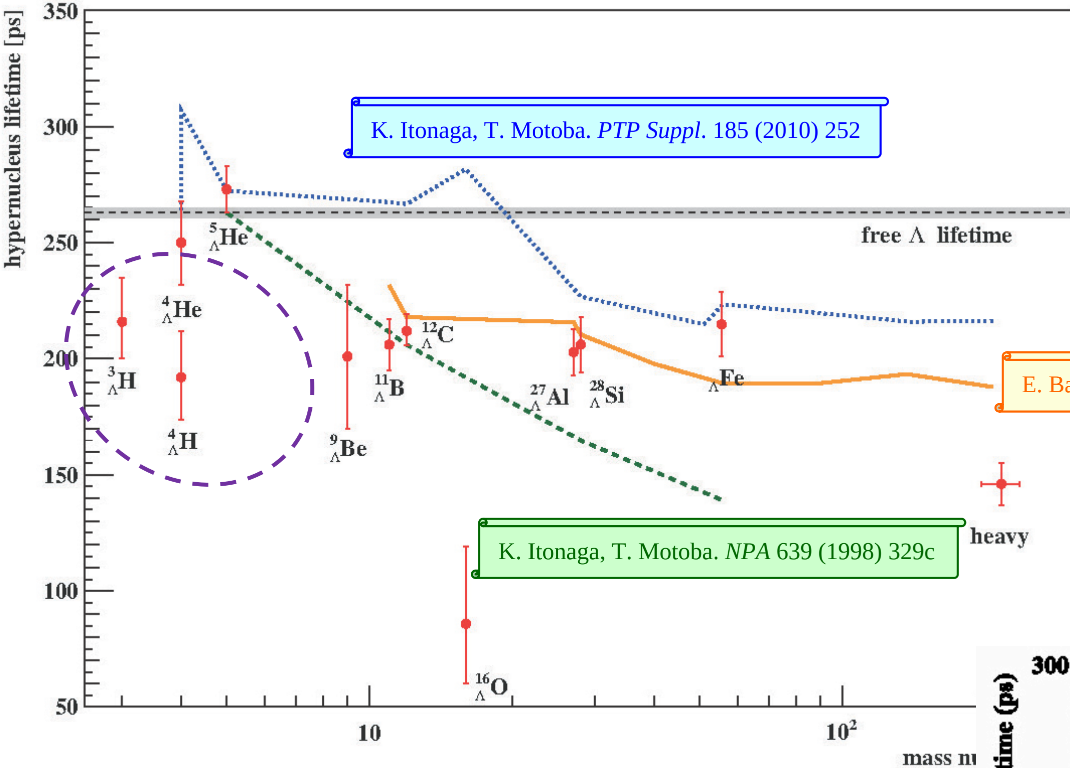


E. Botta *et al.*, *RNC* 38 (2015) 387.

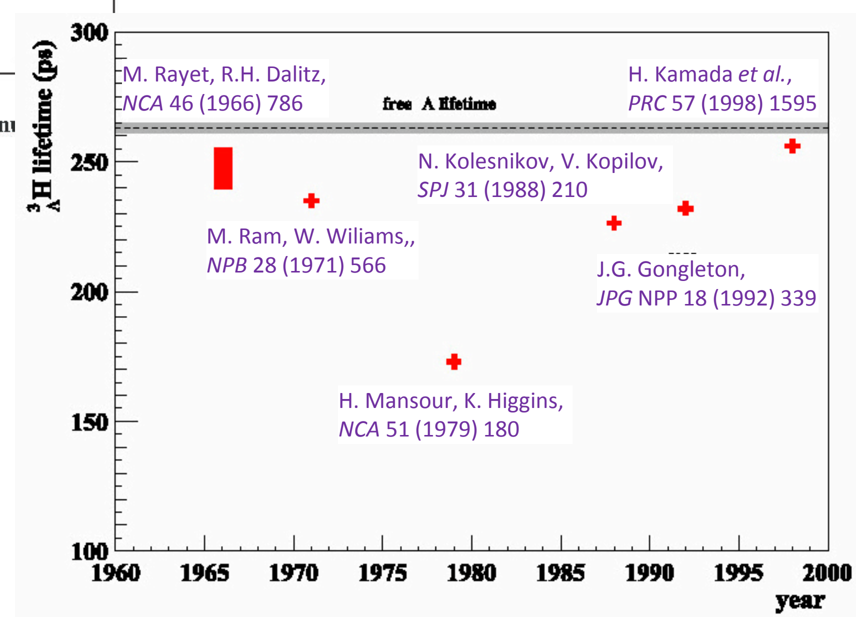


X. Qiu *et al.*, *NPA* 973 (2018) 116.

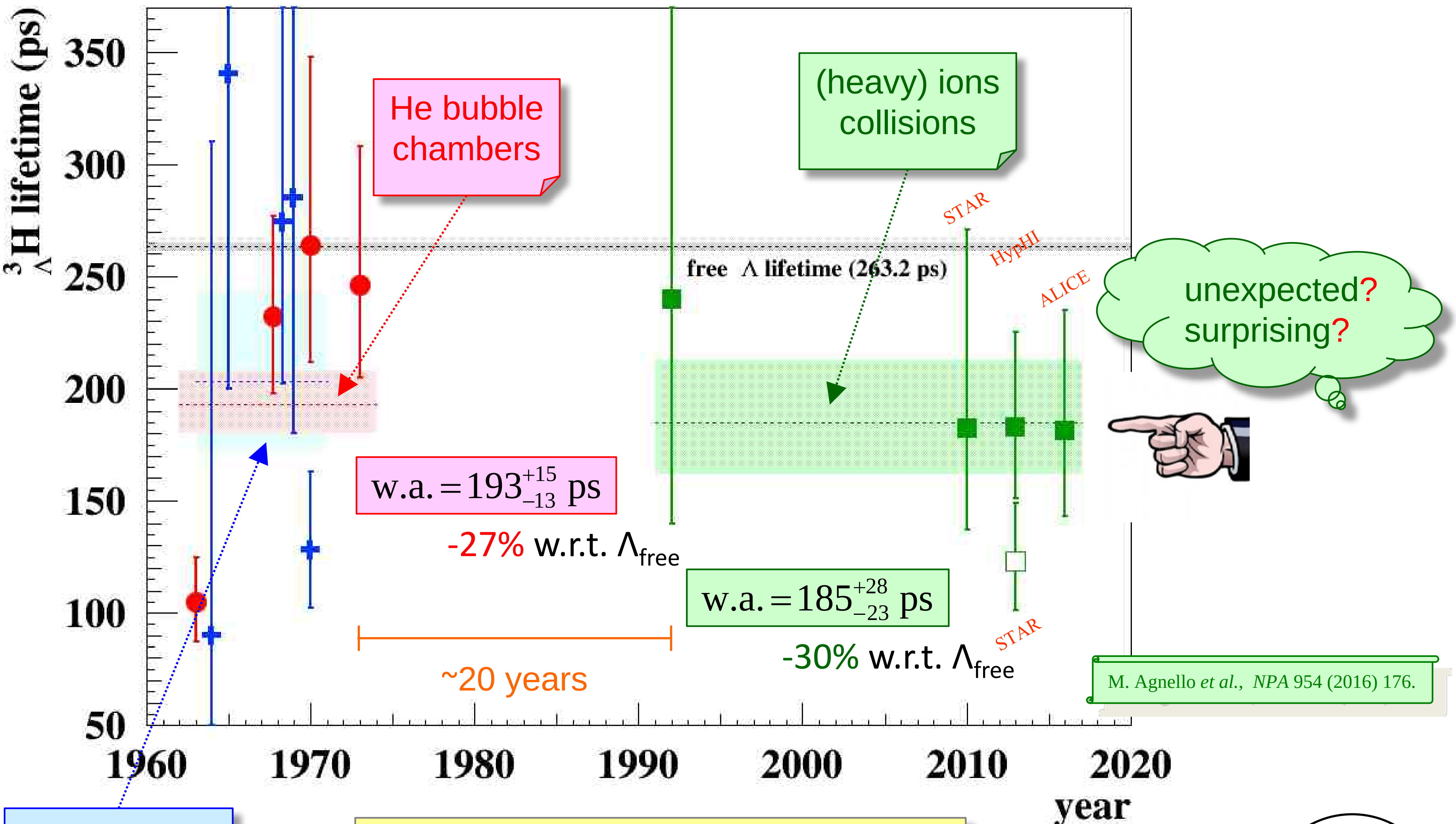
The theoretical predictions



E. Botta *et al.*, *RNC* 38 (2015) 387.



$^{3}H_{\Lambda}$ lifetime world data compilation

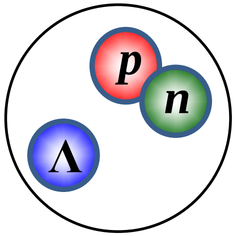


photographic emulsions

large error bars ↔ small data samples

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

-23% w.r.t. Λ_{free}



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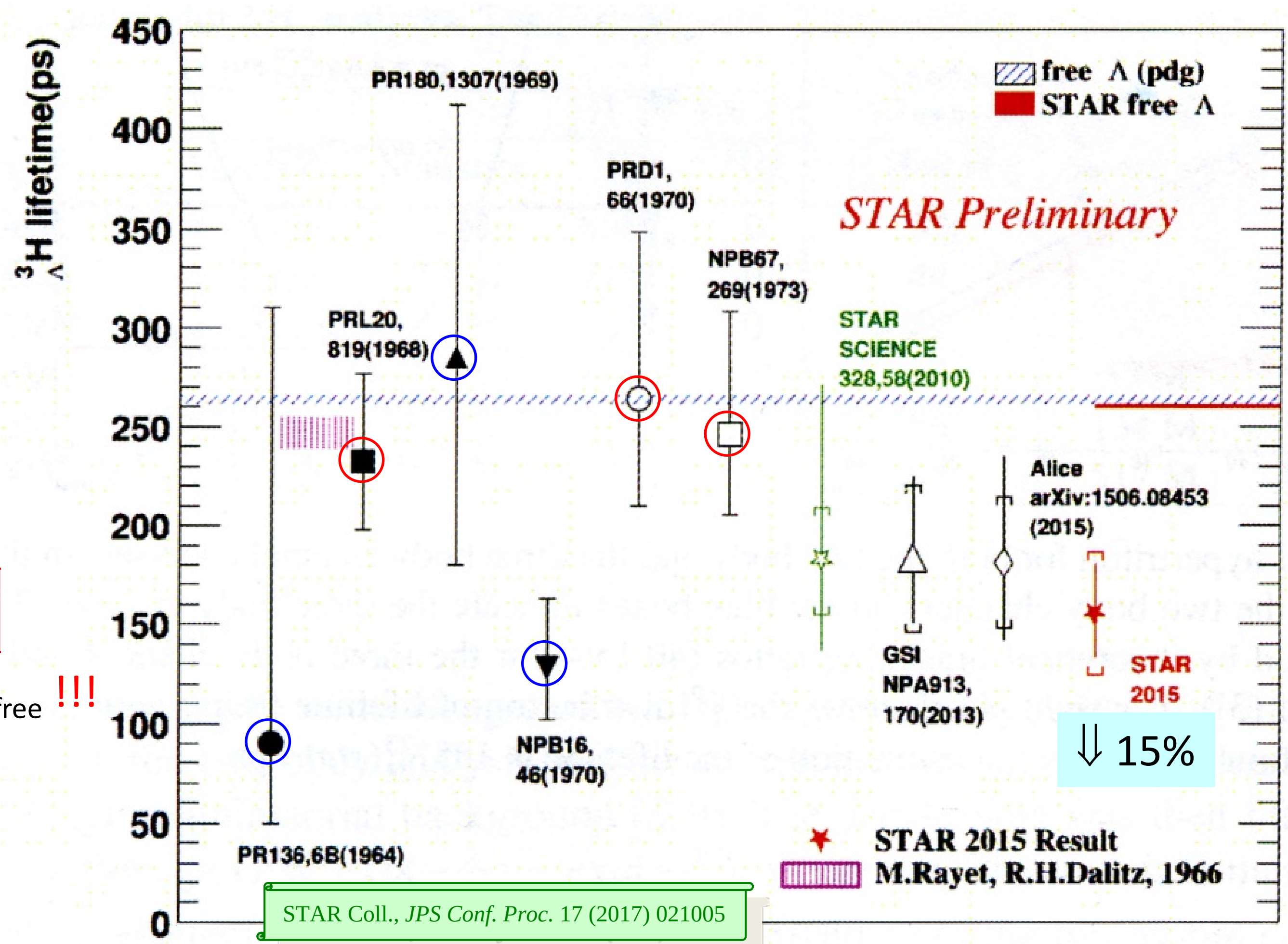
2nd $\tau({}^3H_\Lambda)$ measurement

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

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

Au + Au @ 200 GeV



STAR Coll., *JPS Conf. Proc.* 17 (2017) 021005

$$\tau = 155^{+25}_{-22} \pm 31$$

-41% w.r.t. Λ_{free} !!!

caveat: several existing measurements were arbitrarily ignored!

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

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

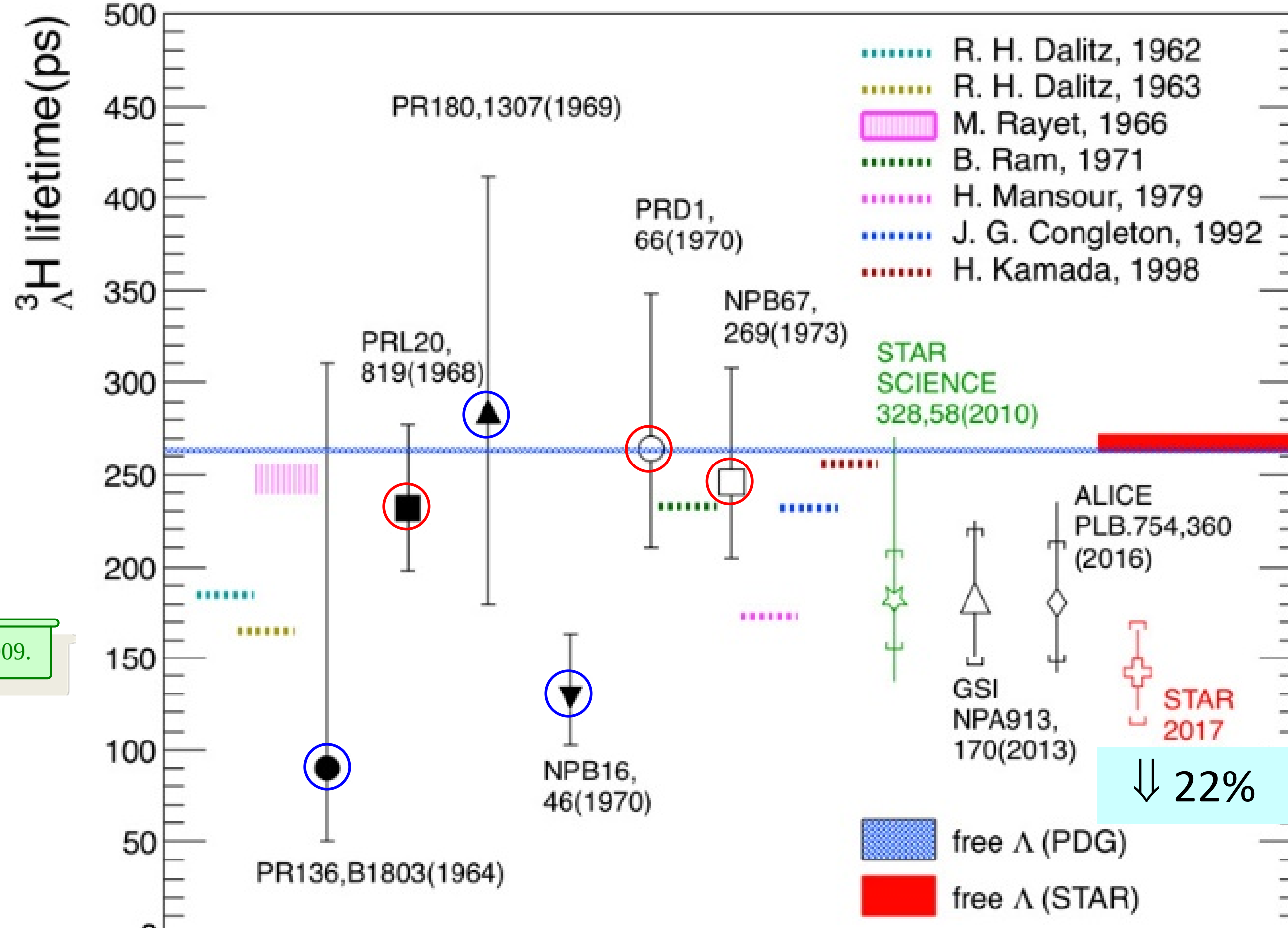
$$ {}^3_\Lambda\mathrm{H} \rightarrow d + p + \pi^- $$

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

-46% w.r.t. Λ_{free} !!!

STAR Coll., *PRC* 97 (2018) 054909.

Au + Au @ 200 GeV

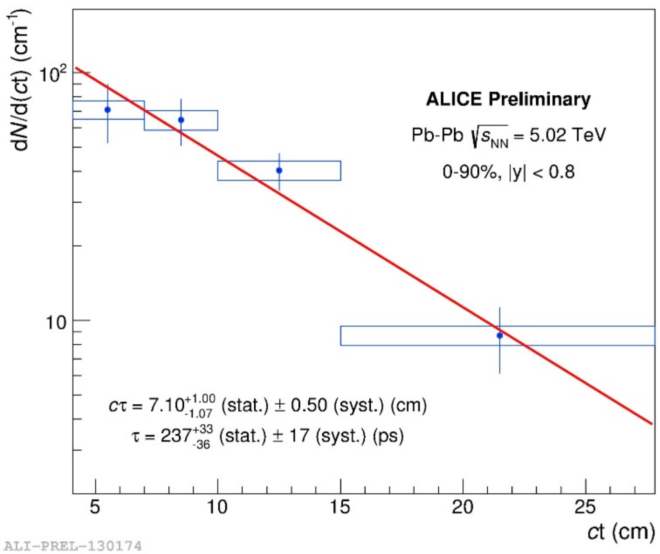


⇓ 22%

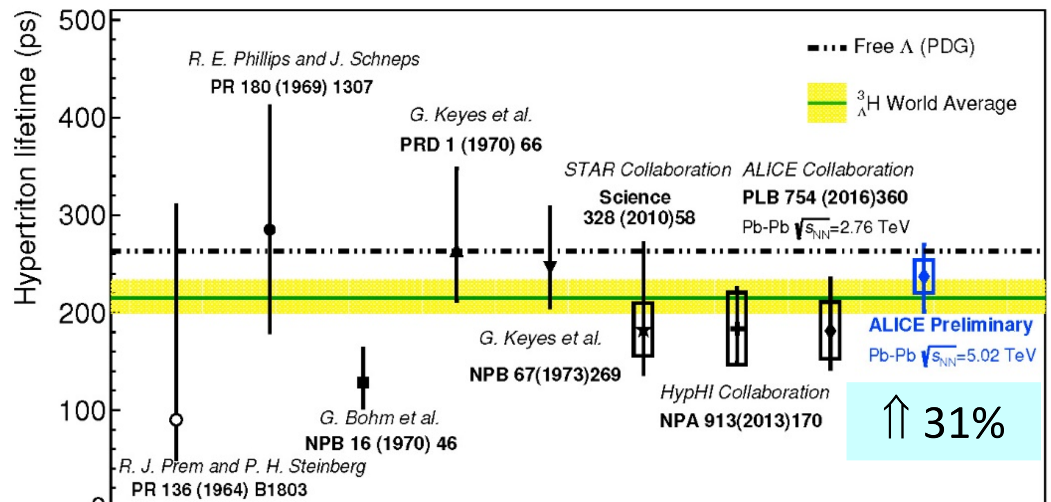
caveat: several existing measurements were arbitrarily ignored!

ALICE suprise?

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



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



⇑ 31%

S. Trogolo @

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

-10% w.r.t. Λ_{free} only!!!

error bars are, of course, significant
but
mean values are still important?

caveat: several existing measurements were arbitrarily ignored!

What's the matter?

see P. Braun-Munzinger @ HYP2015

is something wrong in the new measurements?

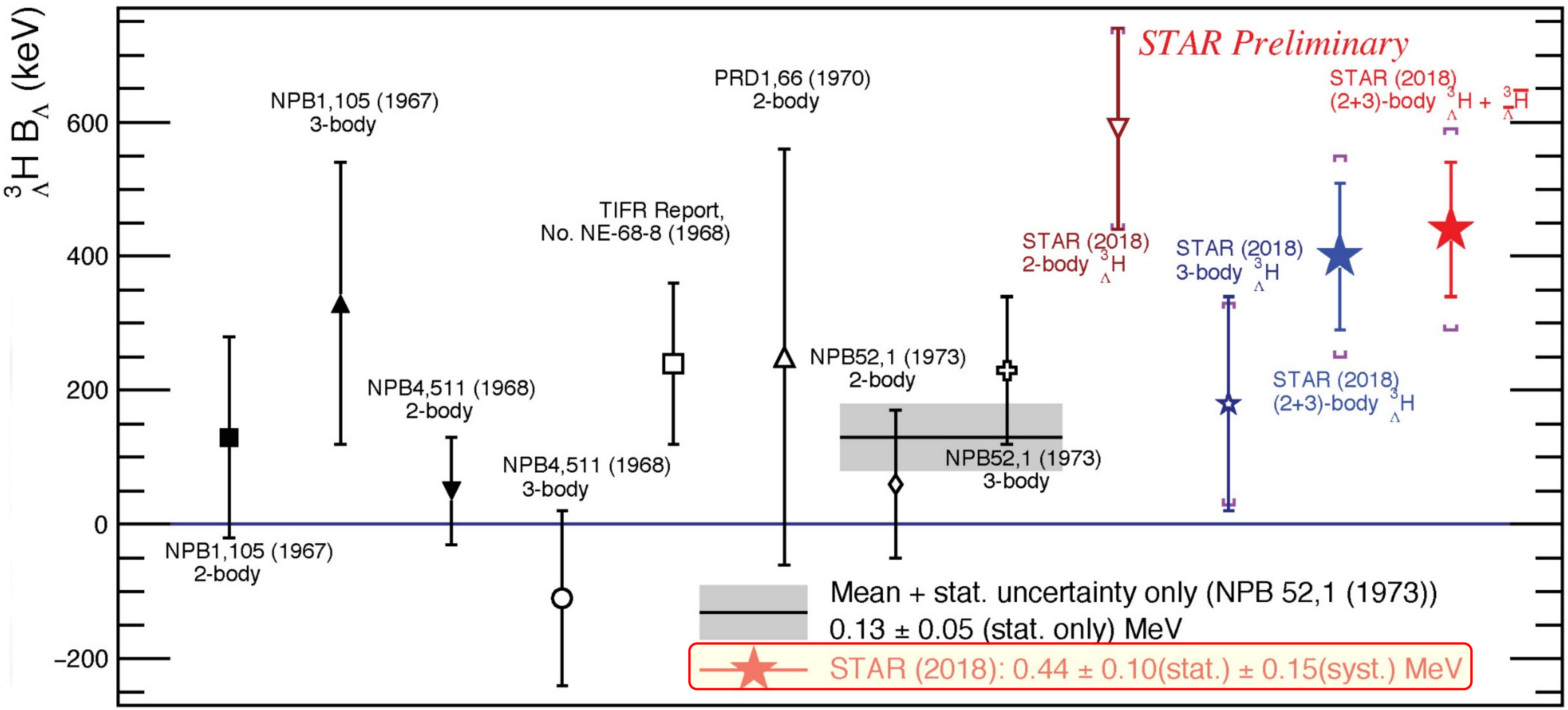
(are we using
the most suitable experimental technique?)

OR

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

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

A new exciting result?



3 times the currently accepted value!!!

see
J. Chen's talk
(this afternoon)

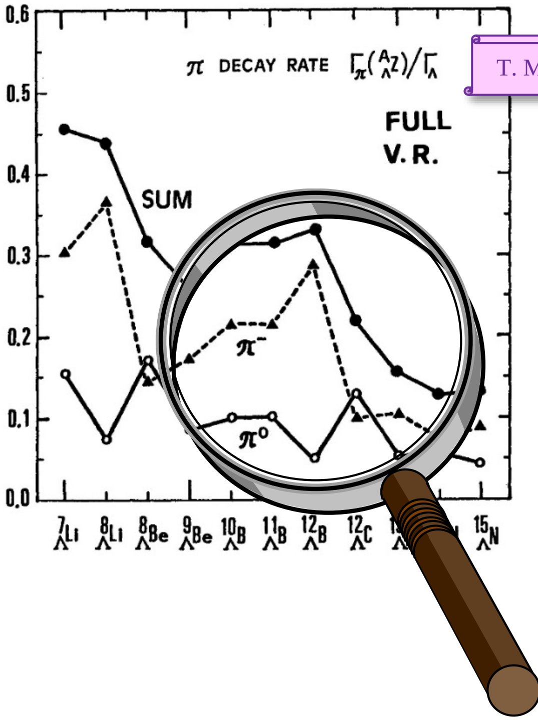
STAR @

Why?

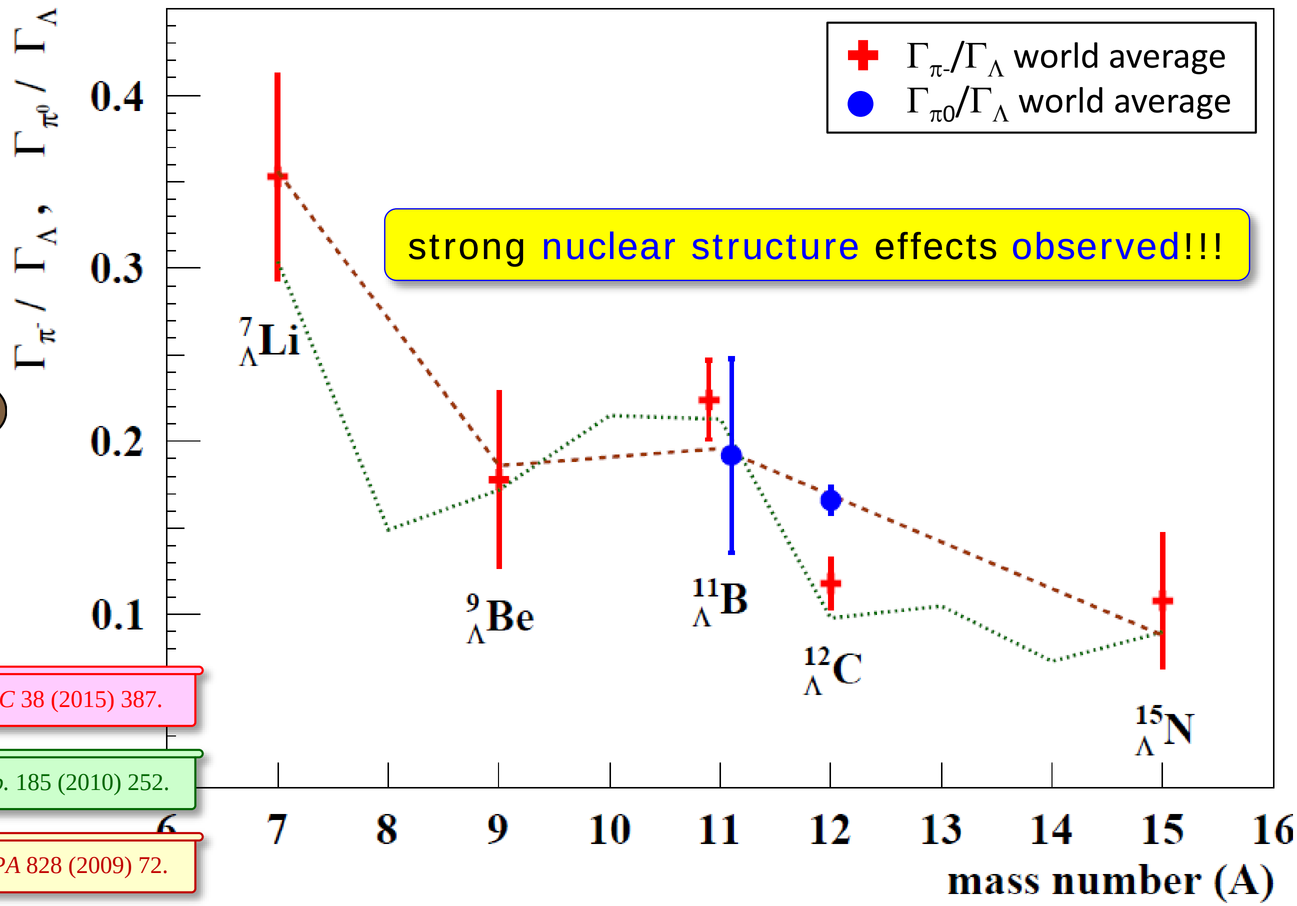
the physics case

Part II

Γ_{π^-} and Γ_{π^0}: current exp. situation



T. Motoba, K. Itonaga , *PTP Suppl.* 117 (1994) 477.

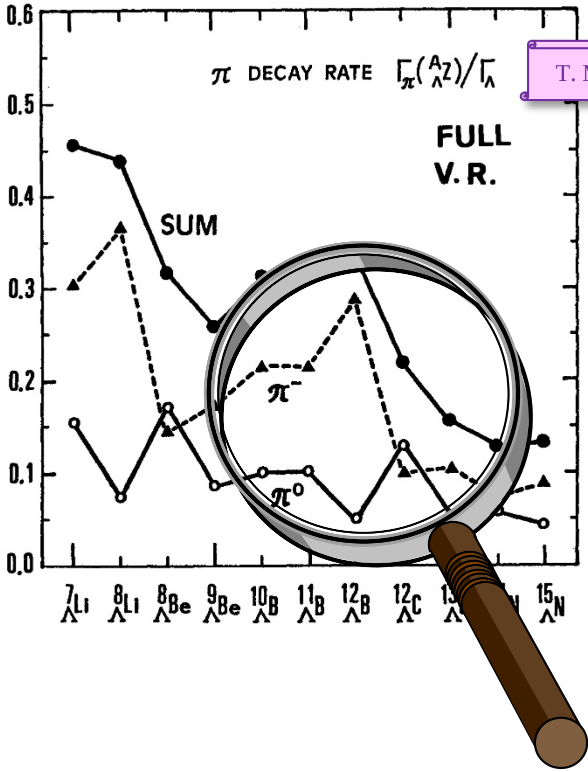


E. Botta, T. Bressani, S. Bufalino, A.F., *RNC* 38 (2015) 387.

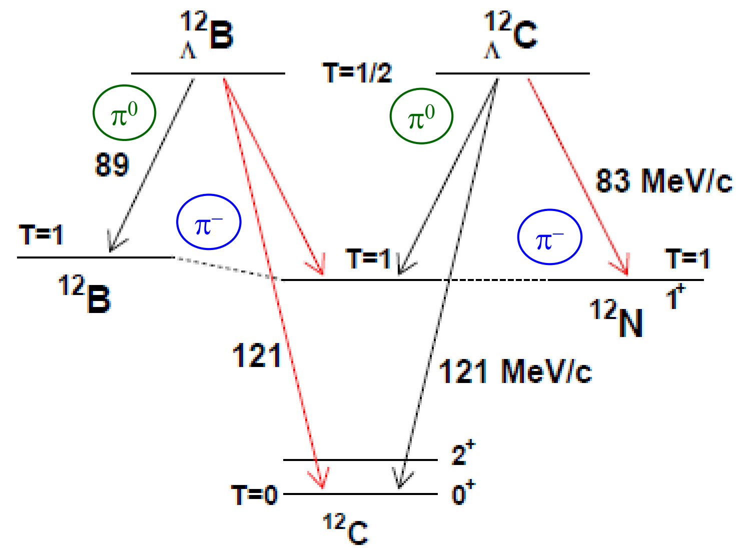
K. Itonaga, T. Motoba, *PTP Supp.* 185 (2010) 252.

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

Looking for nuclear structure effects



T. Motoba, K. Itonaga , *PTP Suppl.* 117 (1994) 477.



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

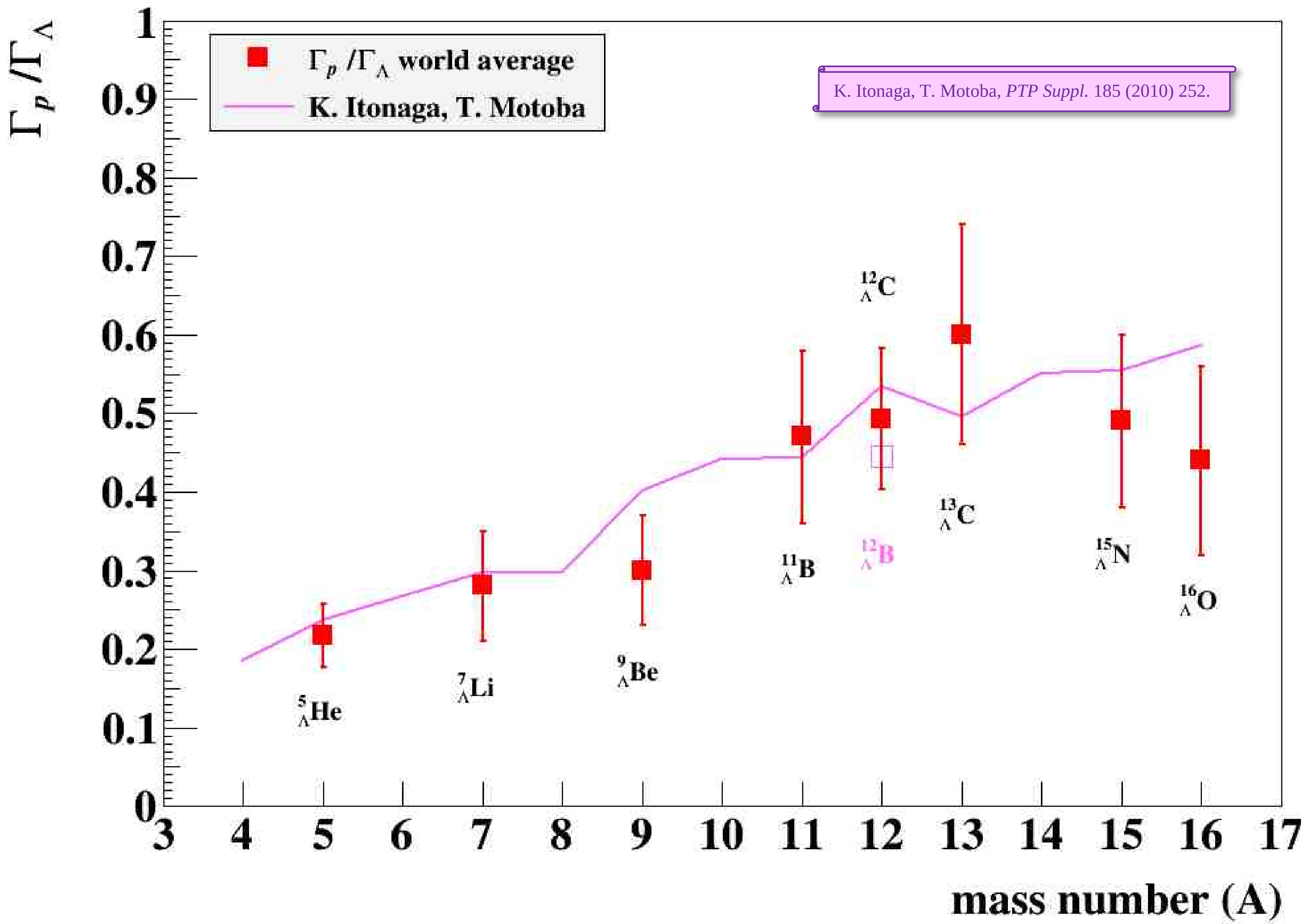
T. Motoba, *NPA* 547 (1992) 115c. ≈ 3

K. Itonaga, T. Motoba, *PTP Suppl.* 185 (2010) 252. = 2.9

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

T. Motoba, *NPA* 547 (1992) 115c. ≈ 8

Γ_p: current experimental situation



How?

the apparatus

Part I

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

challenging idea: K^0 spectroscopy

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

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

asymmetric decay

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

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

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 ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ using the ${}^{3,4}\mathrm{He}(\pi^-, K^0){}^{3,4}_{\Lambda}\mathrm{H}$ reaction at the K1.1 beamline by employing the SKS spectrometer and scintillation counters around the target.

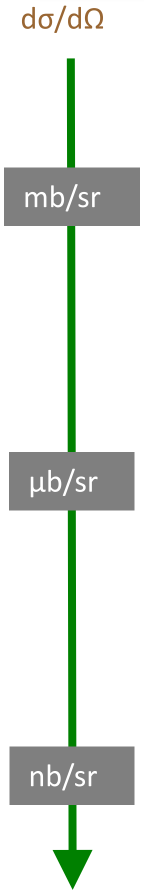
never exploited before!!!

direct measurement!!!

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

Pros & Cons

low cross section → long data taking



1) strangeness and charge exchange (at rest):

$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}(Z-1) + \pi^0$$

2) associated strangeness and charge exchange production:

$$\pi^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}(Z-1) + K^0$$

NEW! @ J-PARC

3) "electro-production":

$$e^- + {}^{A}Z \rightarrow e^{-\prime} + {}^{A}_{\Lambda}(Z-1) + K^+$$

@ JLab

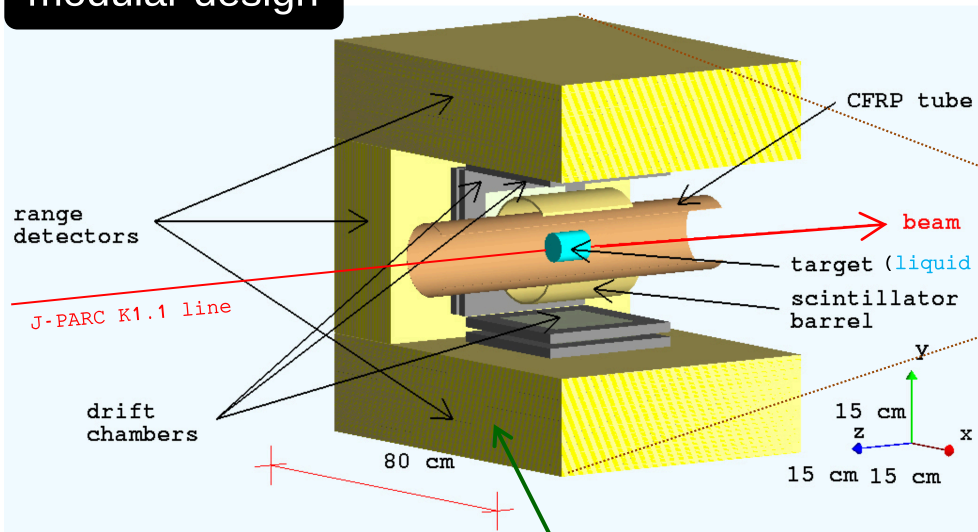
L. Tang *et al.*, *PRC* 90 (2014) 034320.

however: charged particle only in final state of reaction 2)! → no need of large acceptance e.m. calorimeter

- relative simple apparatus
- cheap detectors

Experimental concept layout

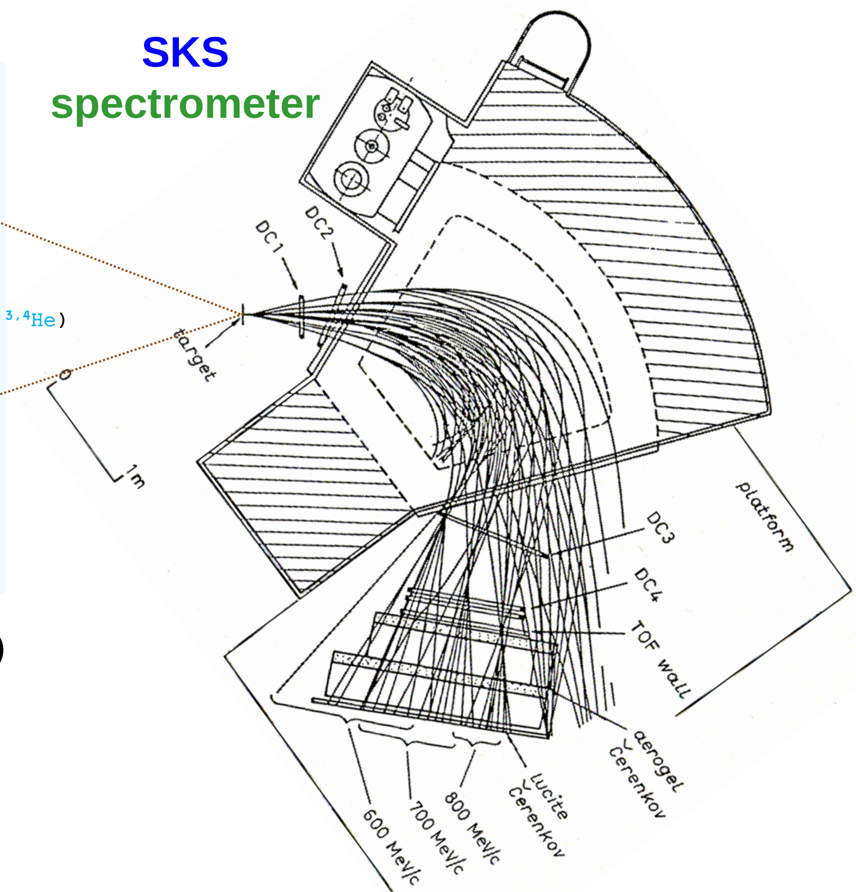
modular design



(not to scale)

fine layered detector
(~100 pads)

SKS
spectrometer



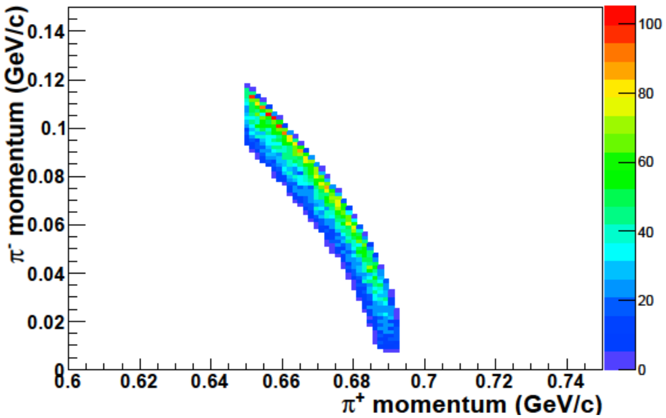
M. Agnello *et al.*, *NPA* 954 (2016) 176.

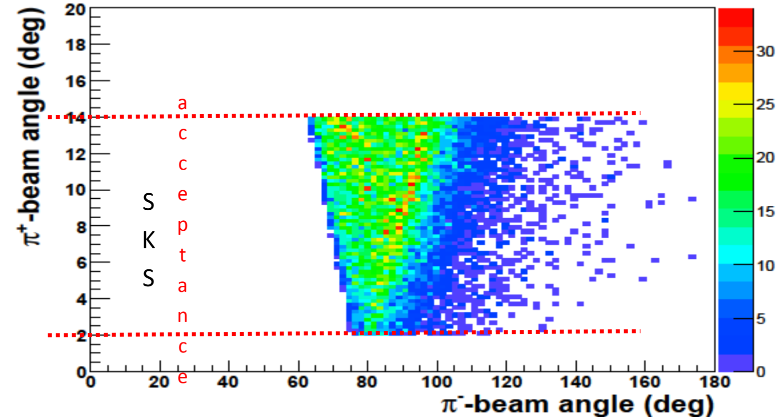
design performances:

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

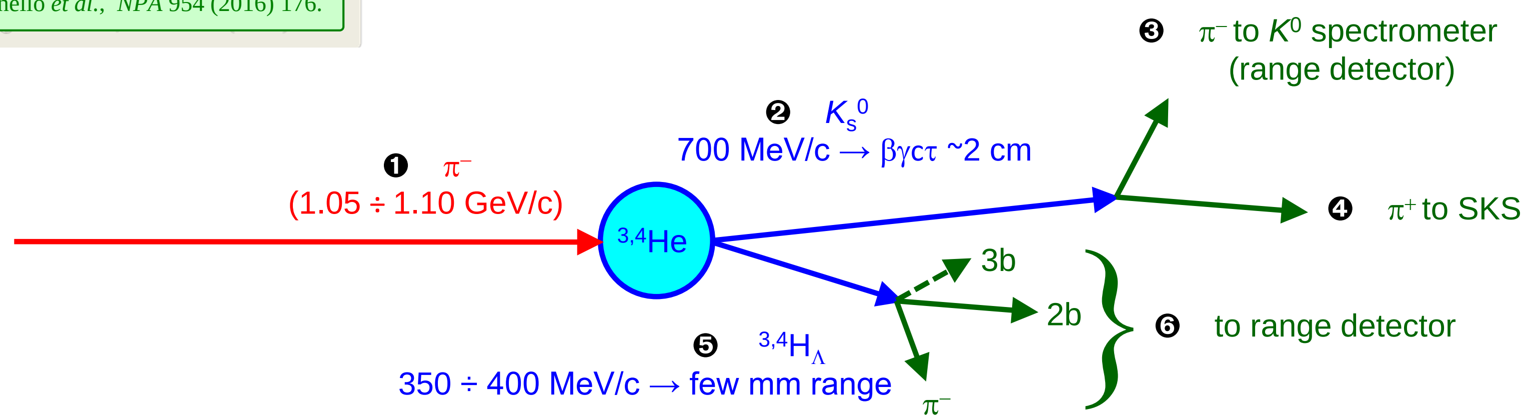
Reaction kinematics

$$\pi^- + {}^{3,4}\mathrm{He} \to K^0 + {}^{3,4}_{\Lambda}\mathrm{H}$$





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 < 133 MeV/c, 0° < ϑ < 180°

Expected rate for $^4H_\Lambda$ production

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

$$\text{N}_{\text{beam}} = 5\cdot 10^{13}\ \pi^-$$

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

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

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

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

$$\varepsilon_{an} = 0.5$$

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

detected

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

$$\Omega_\pi \approx 0.5$$

$$\varepsilon_\pi \approx 1$$

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

0.49

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

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

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Expected rate for $^3H_\Lambda$ production

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

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

rough guess

detected

$$\text{yield}({}^3_\Lambda\text{H}) = (0.1 \div 1) \times \text{yield}({}^4_\Lambda\text{H}) = 1.5 \times 10^3 \div 1.5 \times 10^4$$

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

$\Omega_\pi \approx 0.5$

$\varepsilon_\pi \approx 1$

$\varepsilon_{an} \approx 0.4$

0.40

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

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

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How?

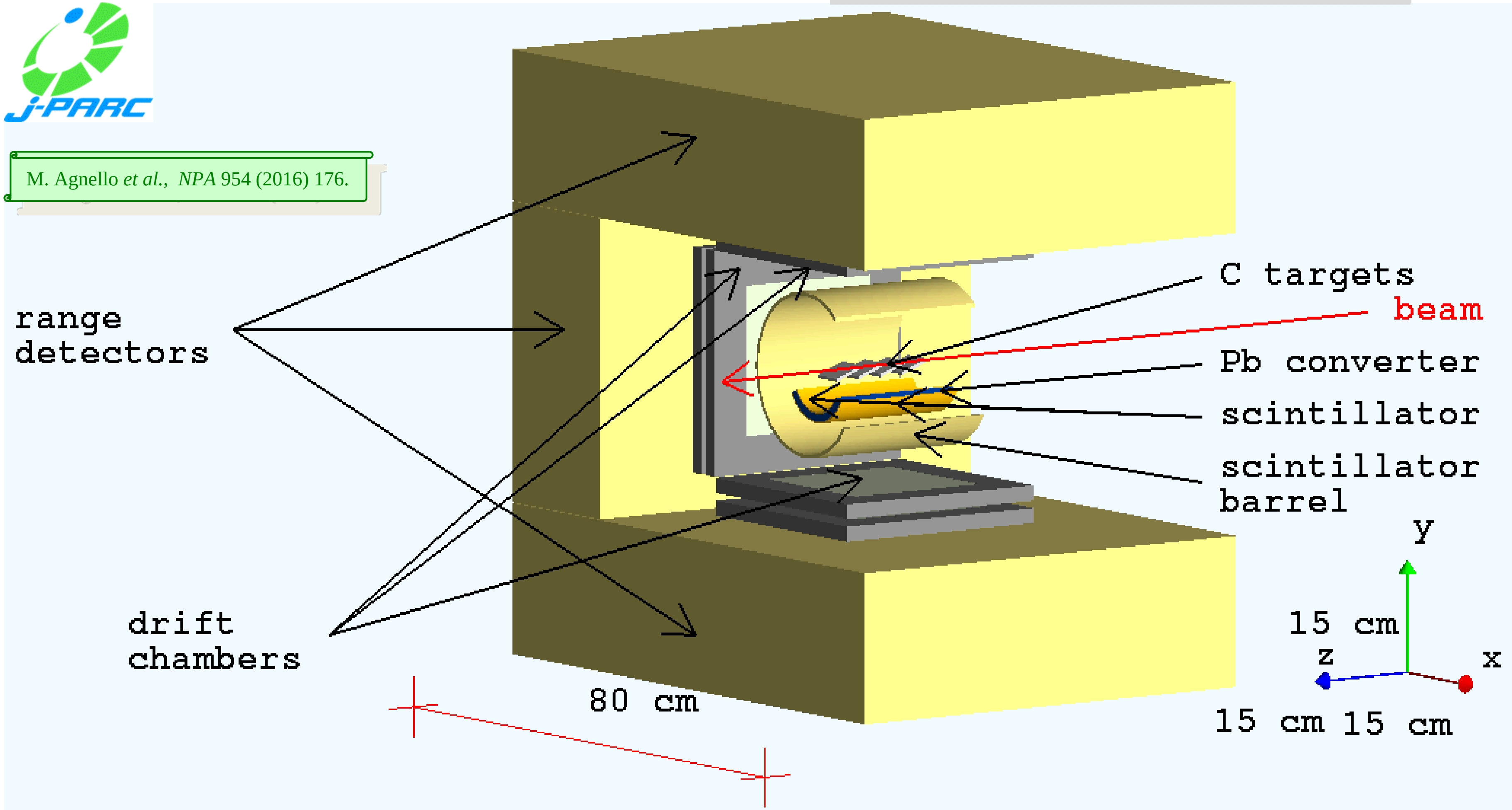
the apparatus

Part II

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

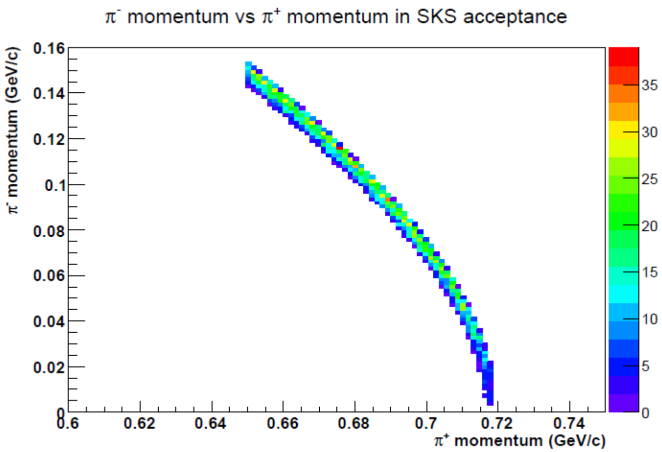
- energy resolution on π^- ≤ 2 MeV (FWHM)

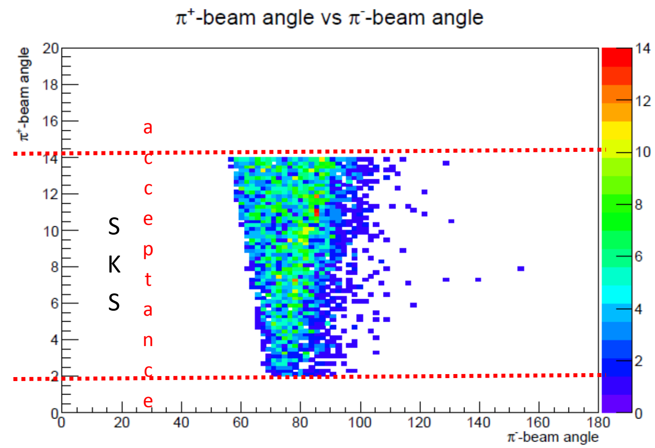
drift chambers

spatial resolution ≤ 300 μm
angular resolution ≤ 100 mrad

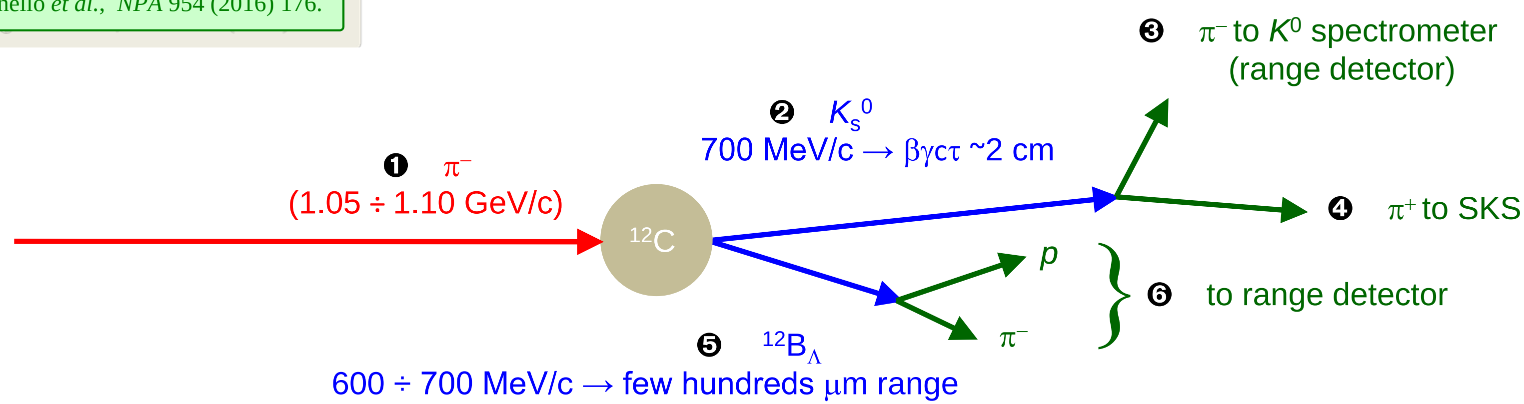
Reaction kinematics

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





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: → 2×10^{13} π^- 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

1×10^4 $^{12}B_\Lambda$ detected

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

Γ_{π^-}: 0.286 → 1.5×10^3 events

Γ_{π^0}: 0.049 → 1.5×10^2 events

T. Motoba, K. Itonaga, *PTP Suppl*. 117 (1994) 477.

Γ_p: 0.446 → 3.0×10^3 events

2% on Γ_p

3% on Γ_π

2-3% on τ

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

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

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

☞ $N_{beam} = 2 \cdot 10^{11}\ \pi^+$

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

limited request

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

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

$\Omega_{sp} = 0.02$ sr

$\varepsilon_{sp} = 0.5$

$\varepsilon_{an} = 0.5$

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

Γ_p

0.535

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

detected

$\Omega_{sp} \approx 0.5$ sr

$\varepsilon_p \approx 1$

$\varepsilon_{an} \approx 0.8$

1-day data taking

~8 × 10² ev.

5% on Γ_p

Rates and beam time summary

beam request (x 10^{13} π^-)	target	thickness	exp. conf.	detected YN	observables			
					τ	$\Gamma_{\pi-}$	$\Gamma_{\pi 0}$	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	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 $^4H_\Lambda$	OK	OK	-	-
2 x 10^{11} π^+	^{12}C	4 x 1 g/cm^2	full	8.0 x 10^3 $^{12}C_\Lambda$	-	-	-	feasible

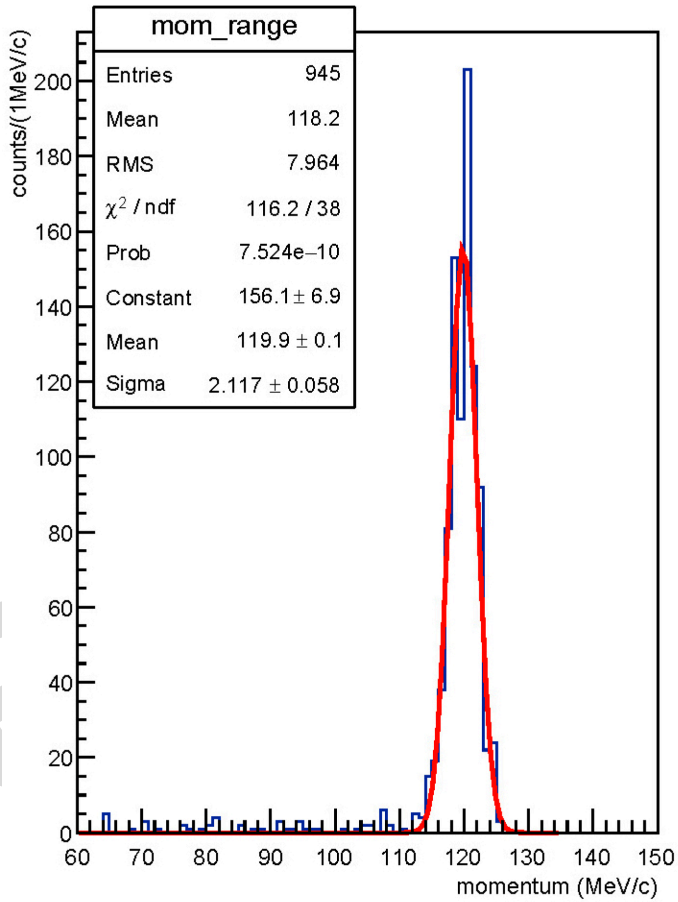
delivered π	10^7 π /spill (present)	1.5 x 10^7 π /spill	10^8 π /spill	10^9 π /spill (HIHR)
1 x 10^{13}	6.9 x 10^1 d	4.6 x 10^1 d	7 d	<1 d
2 x 10^{13}	1.4 x 10^2 d	9.3 x 10^1 d	1.4 x 10^1 d	1.4 d
5 x 10^{13}	3.5 x 10^2 d	2.3 x 10^2 d	3.5 x 10^1 d	3.5 d

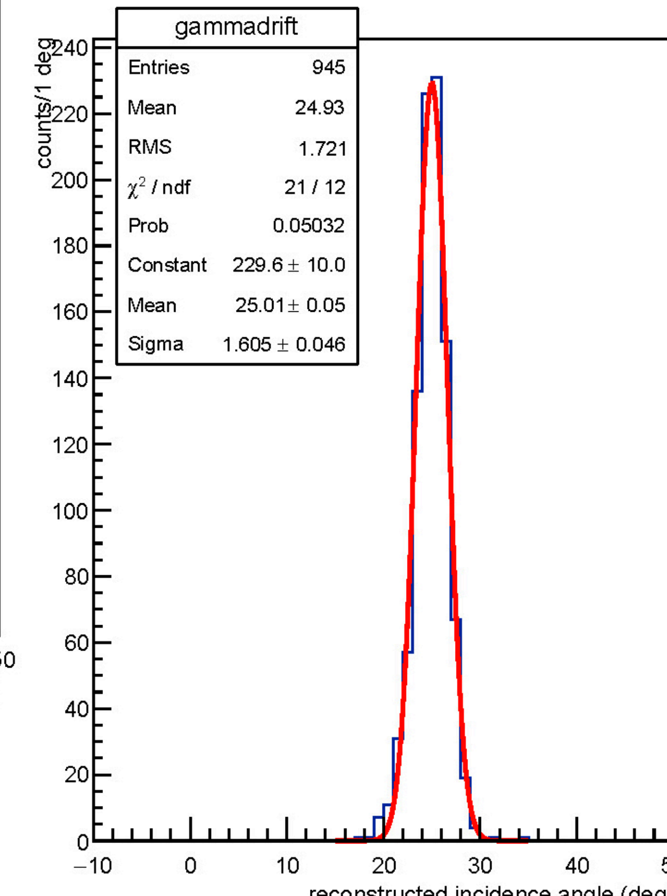
Preliminary performance study

input:

- p_π = 120 MeV/c
- θ = 25°

reconstruction:



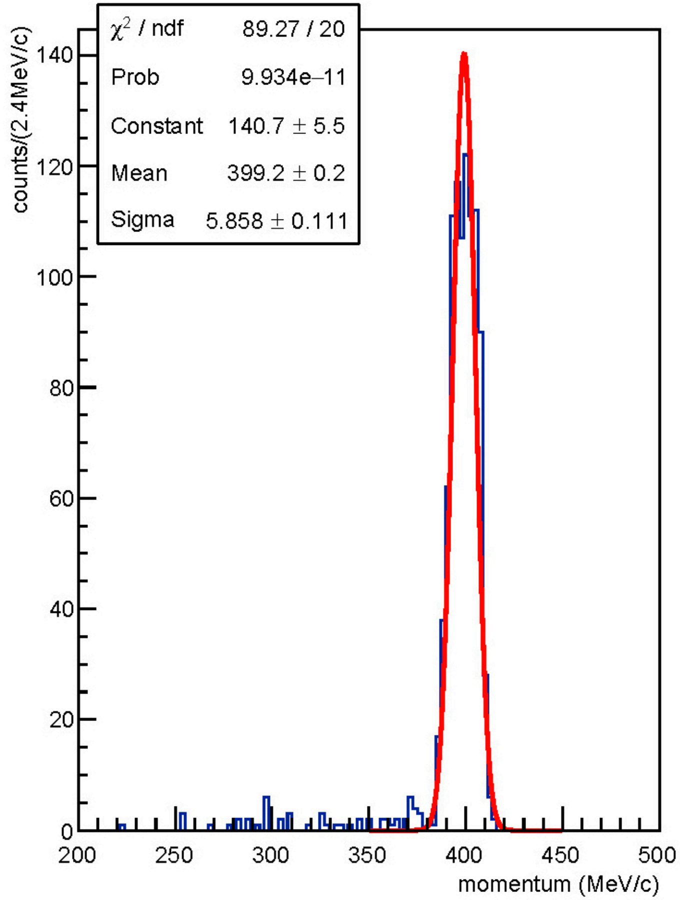


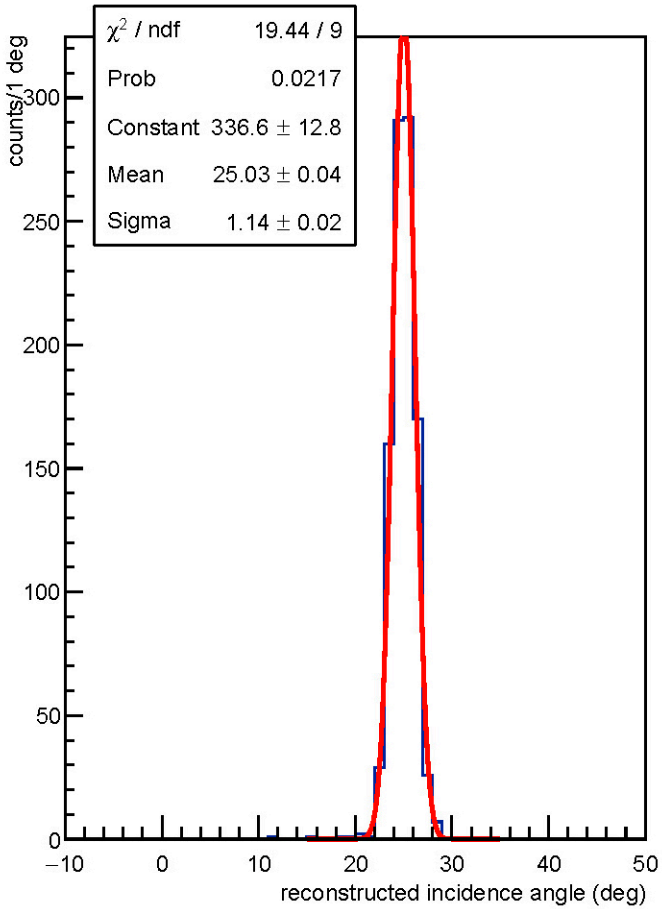
Preliminary performance study

input:

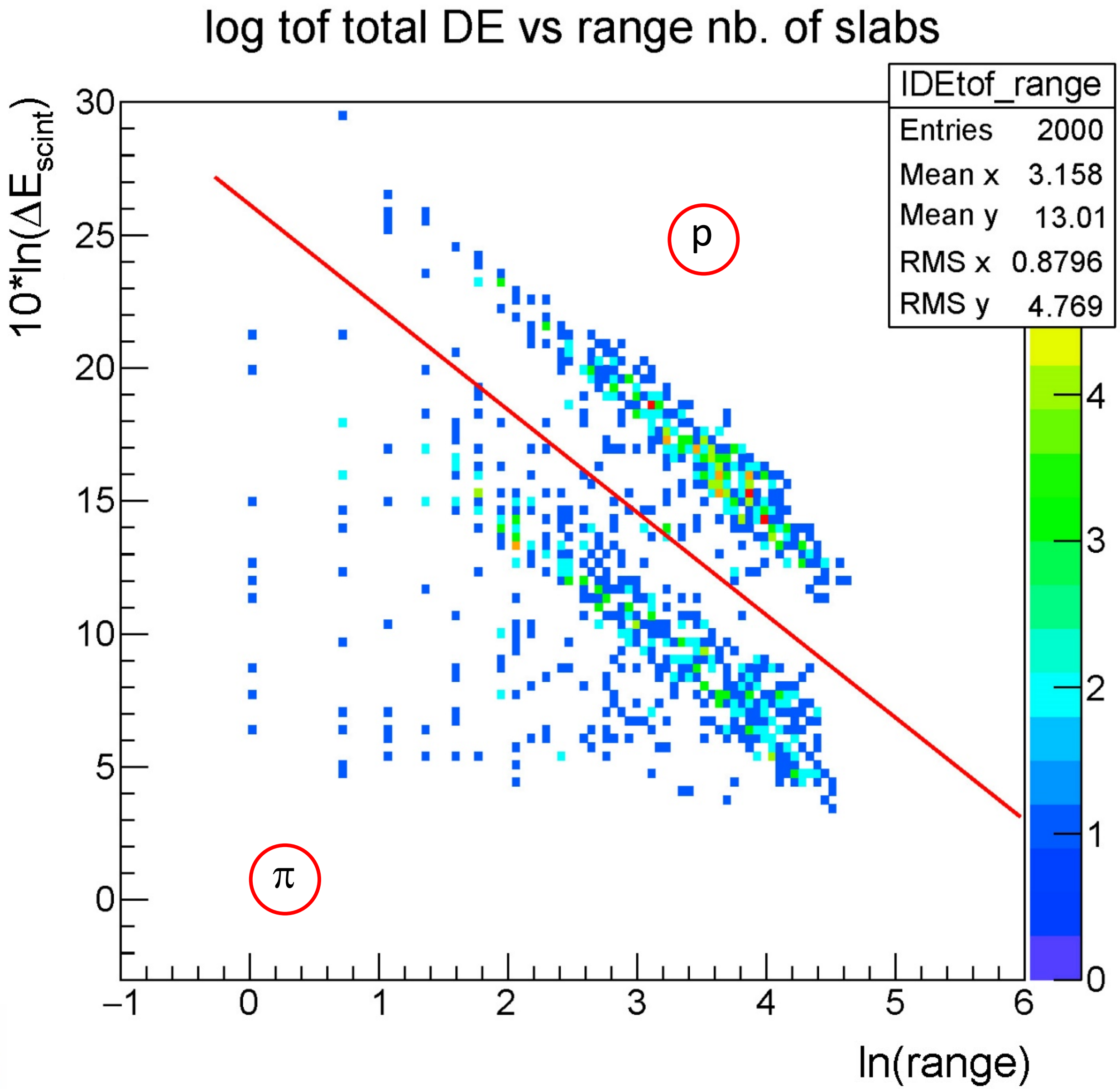
- p_p = 400 MeV/c
- θ = 25°

reconstruction:





Preliminary performance study: PID



p:

ε ≈ 96%

contamination ≈ 0.1%

π:

ε ≈ 99%

contamination ≈ 4%

Conclusions

from the point of view of an experimentalist

- Disagreement among experimental results
  - is there any problem related to the different experimental techniques?
- Disagreement among experimental results and theoretical predictions:
  - are we perhaps biased by a strong prejudice?
- Need for a new direct measurement of the lifetime of light Λ-hypernuclei
- Good opportunity to further investigate the Λ-hypernuclei weak decay process