STRONG 2020

THEIA-STRONG2020 - Workshop 2019

The (π^-,K^0) reaction: a new tool for hypernuclear physics

Alessandro Feliciello

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Outline

- physics cases

  ❶ the $^3H_\Lambda$ 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

The hottest topic in hypernuclear physics

Recent experimental attempts to determine the $\tau({}^{3}\mathrm{H}_{\Lambda})$

❶ STAR @ BNL $\mathrm{Au}+\mathrm{Au}\ @\ \sqrt{S_{NN}}=200\ \mathrm{GeV}$ (2010, 17, 18, …)

❷ HypHI @ GSI ${}^{6}\mathrm{Li}\ +\ {}^{12}\mathrm{C}\ @\ 2\ \mathrm{A\ GeV}$ (2013)

❸ ALICE @ CERN $\mathrm{Pb}+\mathrm{Pb}\ @\ \sqrt{S_{NN}}=2.76,\ 5.02\ \mathrm{TeV}$ (2016, 18, 19, …)

❹ NKS2 @ ELPH $\gamma+{}^{3}\mathrm{He}\rightarrow K^{+}+{}^{3}_{\Lambda}\mathrm{H}$ (proposal / in preparation)

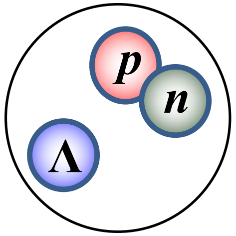
see S. Nakamura's talk on Monday

❺ P73 @ J-PARC $K^{-}+{}^{3}\mathrm{He}\rightarrow\pi^{0}+{}^{3}_{\Lambda}\mathrm{H}$ (proposal / in preparation)

❻ P74 @ J-PARC $\pi^{-}+{}^{3}\mathrm{He}\rightarrow K^{0}+{}^{3}_{\Lambda}\mathrm{H}$ (proposal)

direct measurements

The naïve expectation



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

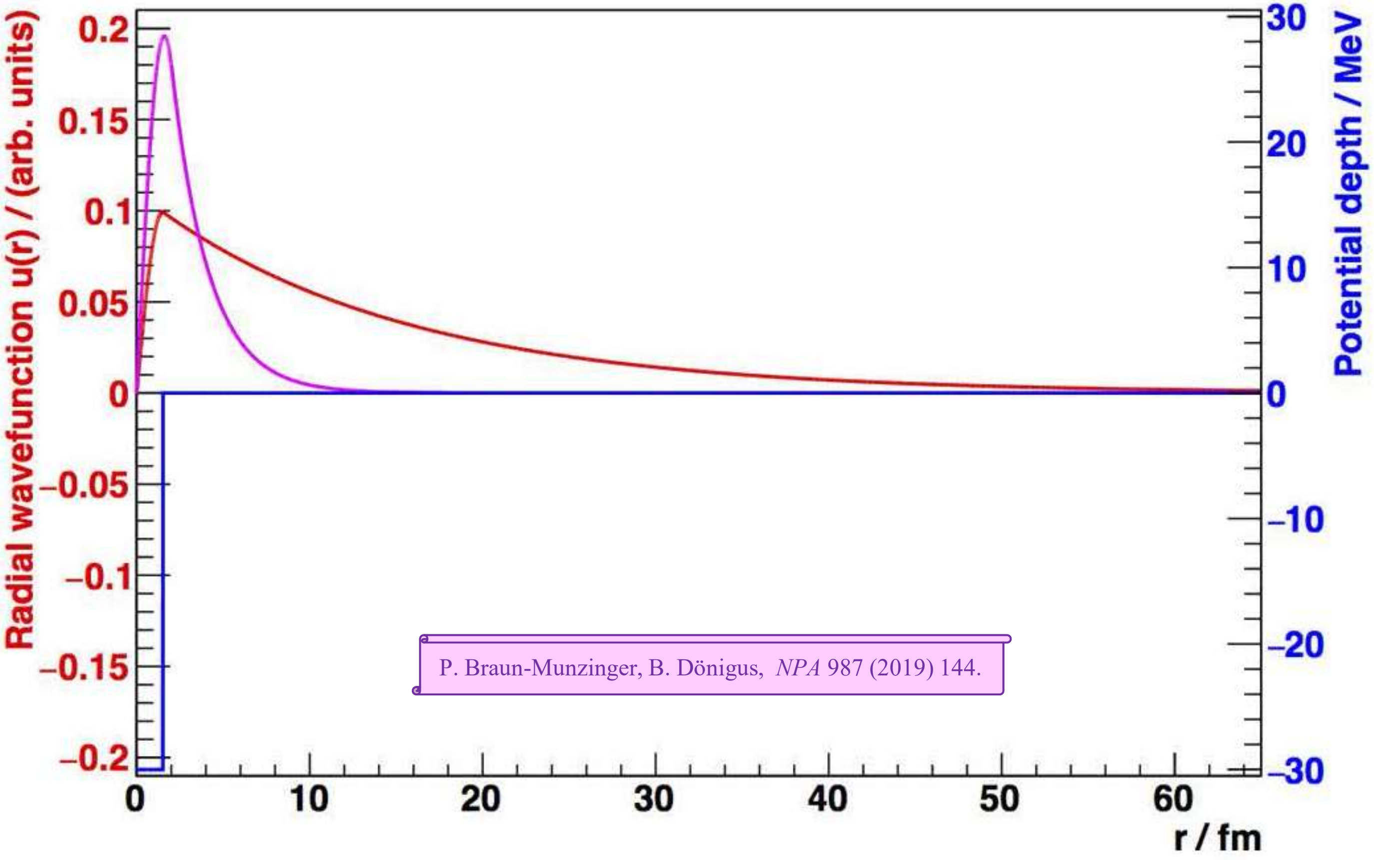
M. Juric *et al.*, *NPB* 52 (1973) 1.

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

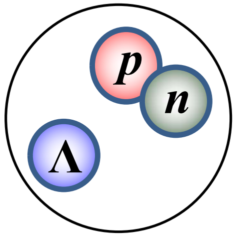
supported by several theoretical predictions, e.g.: M. Rayet, R.H. Dalitz, NCA 46 (1966) 786
H. Kamada *et al.*, PRC 57 (1998) 1595

what does it means «approximately»?

A quantitative explanation

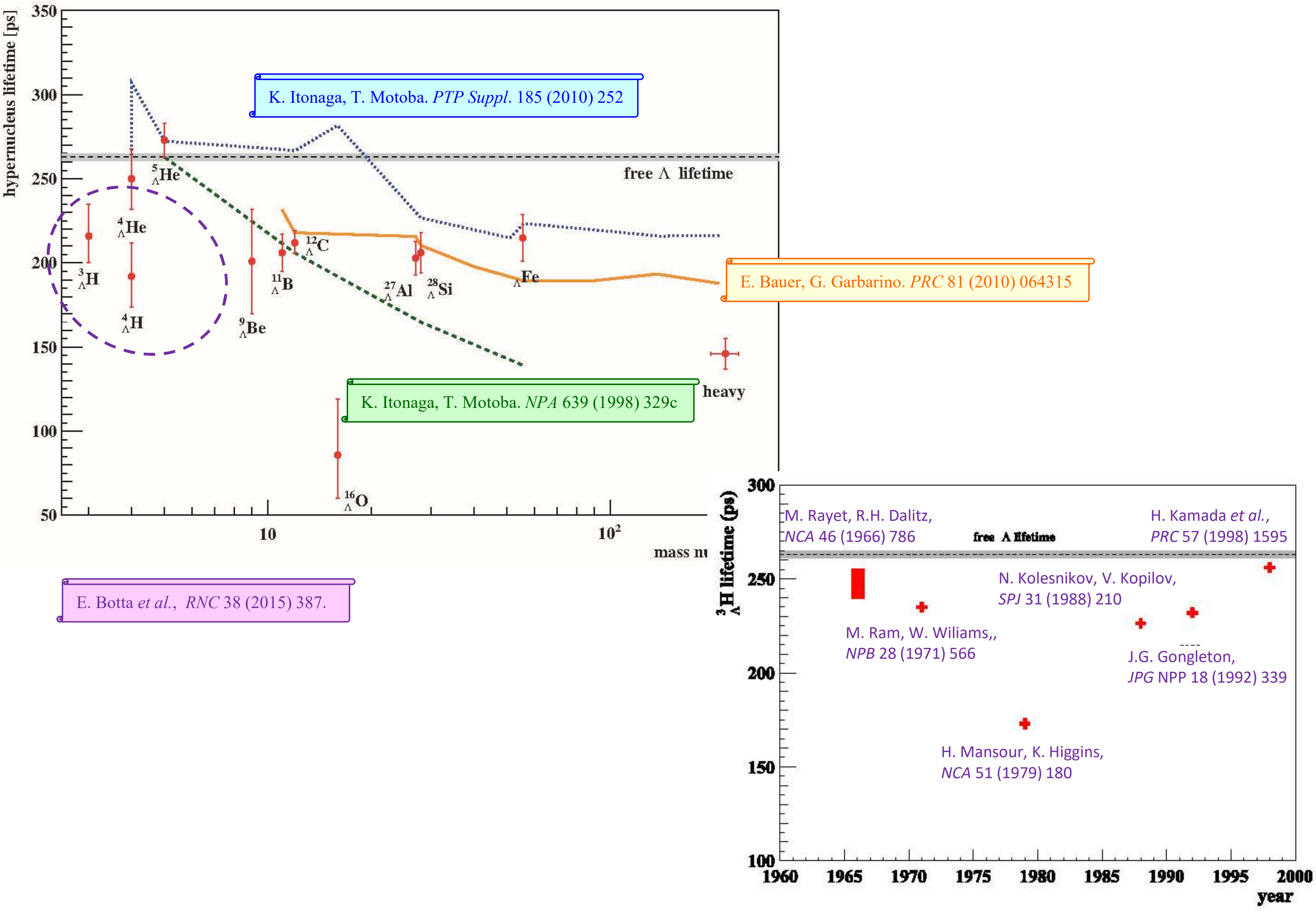


P. Braun-Munzinger, B. Dönigus, *NPA* 987 (2019) 144.

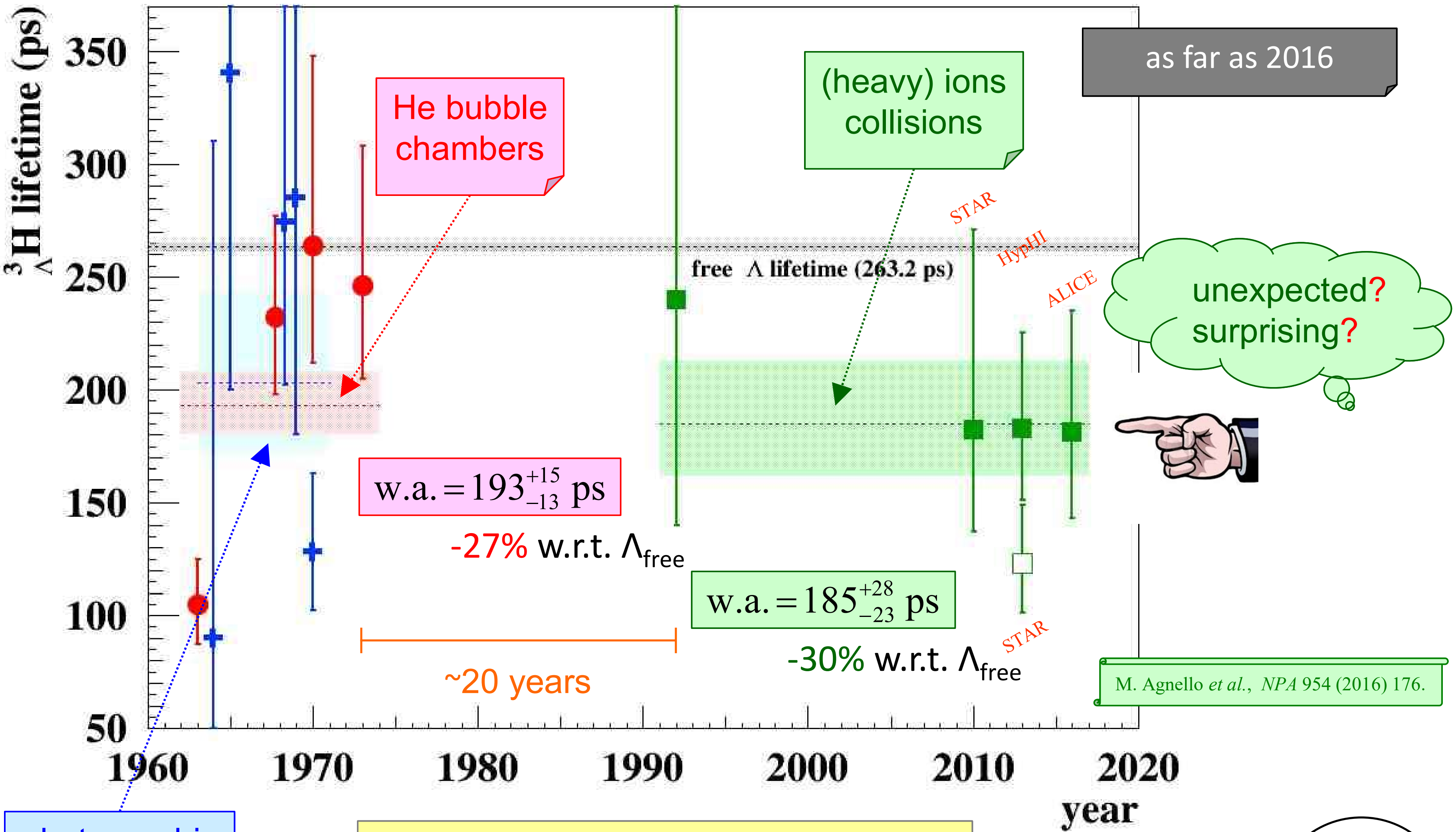


$$\sqrt{\left\langle r_{\Lambda d}^{2} \right\rangle} = 10.6\ \text{fm}$$

The theoretical predictions



$^3H_\Lambda$ lifetime world data compilation

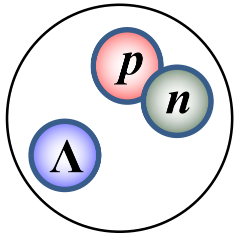


photographic emulsions

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

-23% w.r.t. Λ_{free}

large error bars ↔ small data samples



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

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

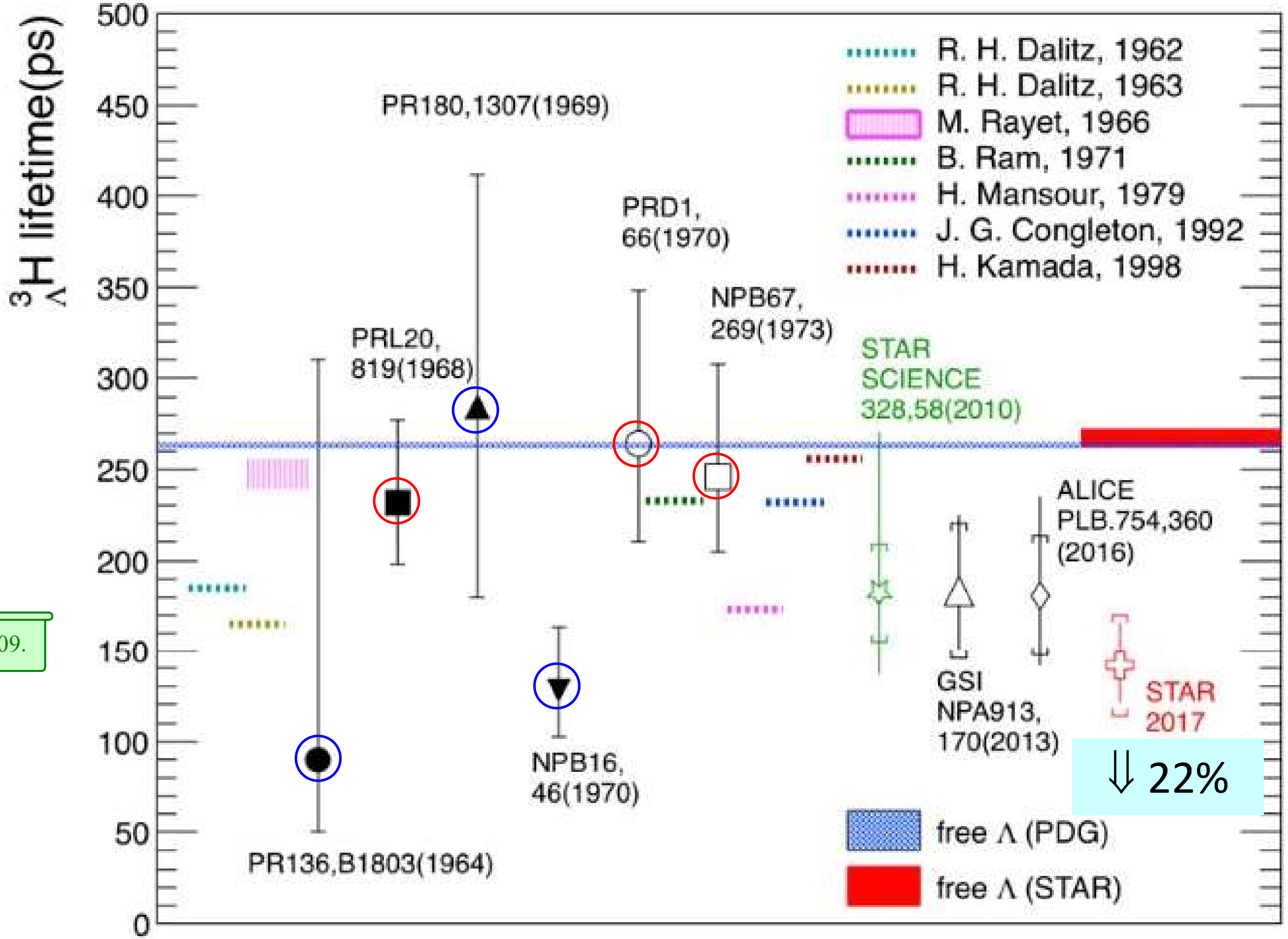
$$^3_\Lambda H \rightarrow d + p + \pi^-$$

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

-46% w.r.t. Λ_{free} !!!

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

Au + Au@200 GeV



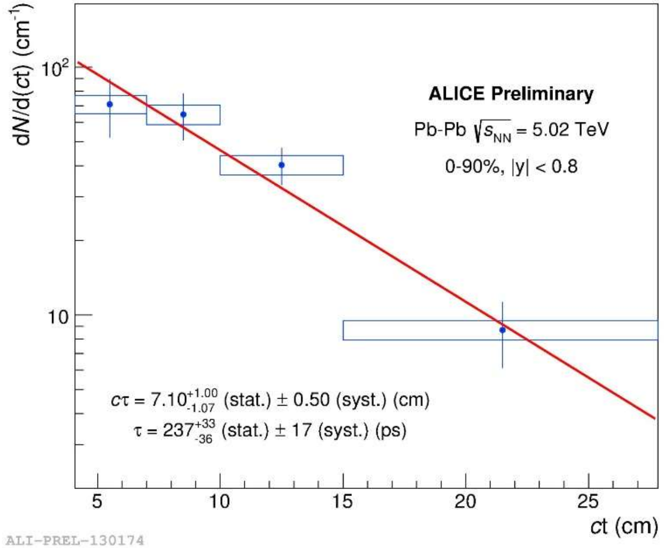
caveat: several existing measurements were arbitrarily excluded by the w.a.!

ALICE suprise?

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

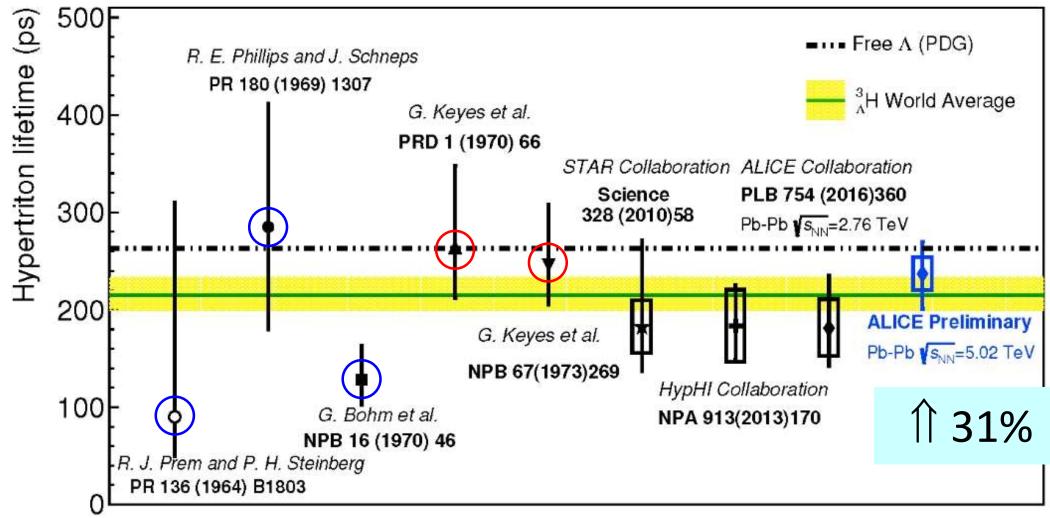
$$ {}^{3}_{\Lambda}\overline{\mathrm{H}} \rightarrow {}^{3}\overline{\mathrm{He}} + \pi^{+} $$

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



ALICE Collaboration, *NPA* 982 (2019) 815.

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



⇑ 31%

ALI-PREL-130195

$\tau = 237^{+33}_{-36} \pm 17$ 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 excluded by the w.a.!

Alessandro Feliciello / THEIA – STRONG2020 Workshop 2019, Speyer, Germany, November 25-29, 2019.

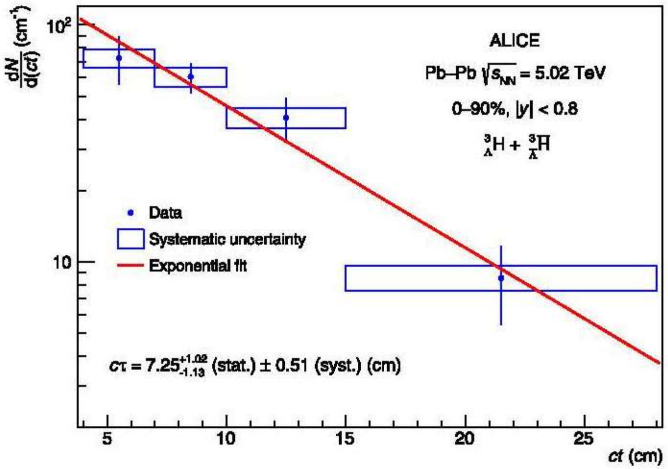
The latest ALICE result

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

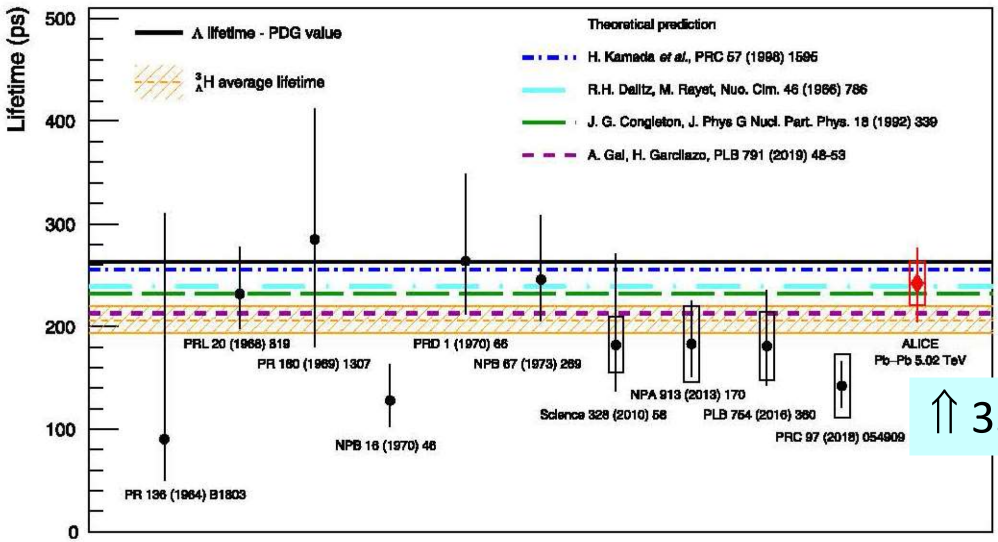
$${}^{3}_{\Lambda}\overline{\mathrm{H}} \rightarrow {}^{3}\overline{\mathrm{He}} + \pi^{+}$$

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

World Average: $\tau = 206^{+15}_{-13}$ ps



ALICE Collaboration, *PLB* 797 (2019) 134905.



⇑ 33%

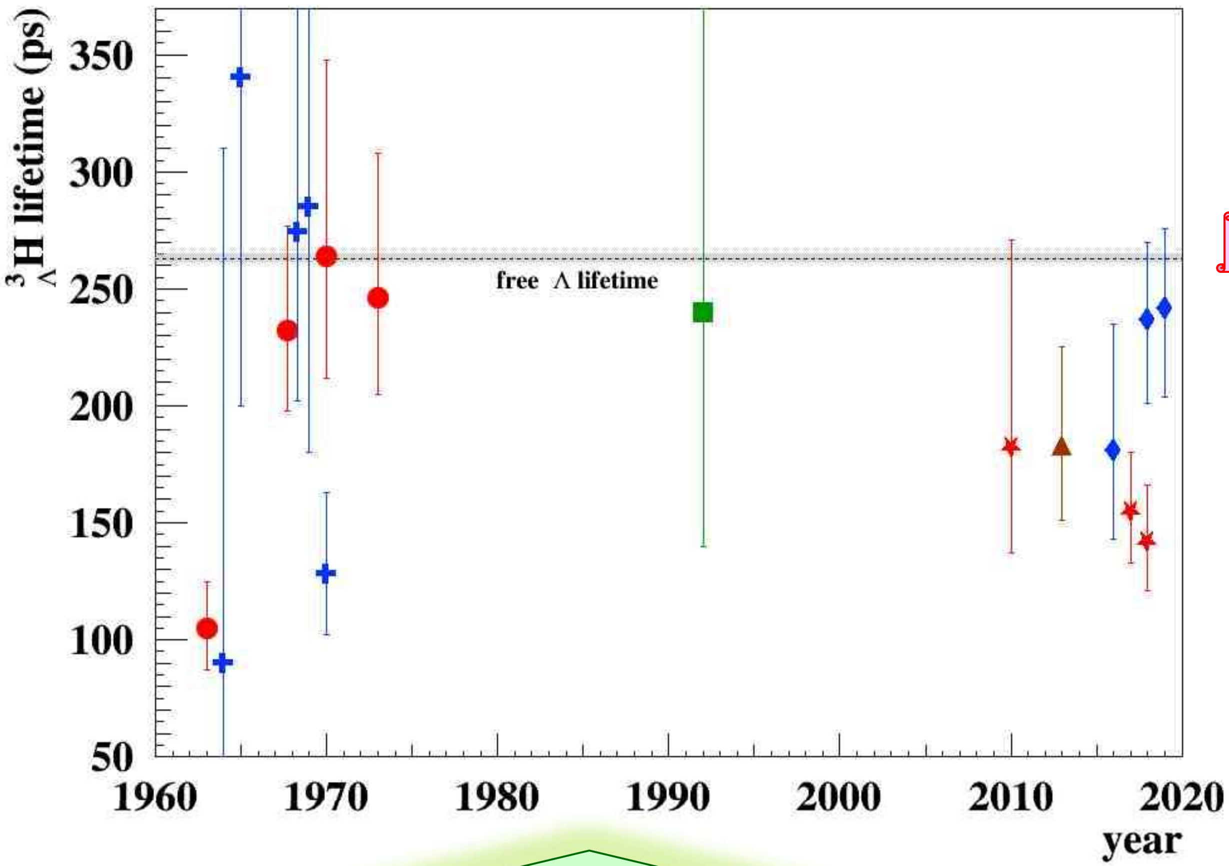
$\tau = 242^{+34}_{-38} \pm 17$ ps

-8% w.r.t. Λ_{free} only!!!

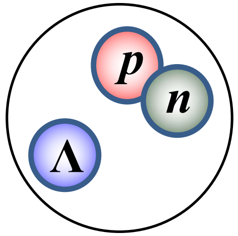
error bars are, of course, significant
but
mean values are still important?

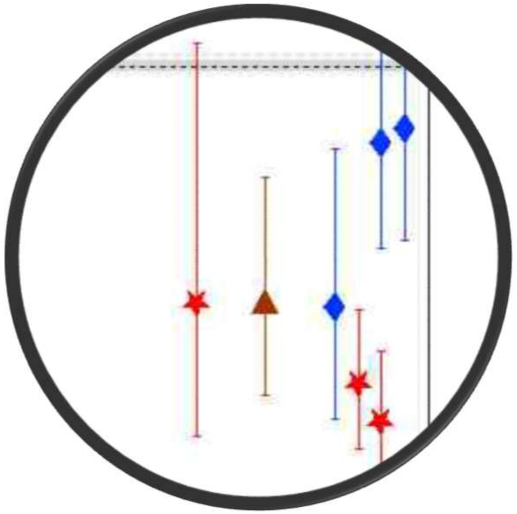
caveat: several existing measurements were arbitrarily excluded by the w.a.!

The current situation



$^3H_\Lambda$: the lightest and "simplest" Λ-hypernucleus





STAR Coll., *Science* 328 (2010) 58.

HypHI Coll., *Nucl. Phys.* A 913 (2013) 170.

ALICE Coll., *Phys. Lett.* B 754 (2016) 360.

ALICE Coll., *Nucl. Phys.* A 982 (2019) 815.

ALICE Coll., *Phys. Lett.* B 797 (2019) 134905.

STAR Coll., *Phys. Rev.* C 97 (2018) 054909.

Who is right?

see A. Gal's talk today

definitive need: first direct measurement of $\tau(^3H_\Lambda)$

INFN

What's the matter?

see P. Braun-Munzinger @ HYP2015

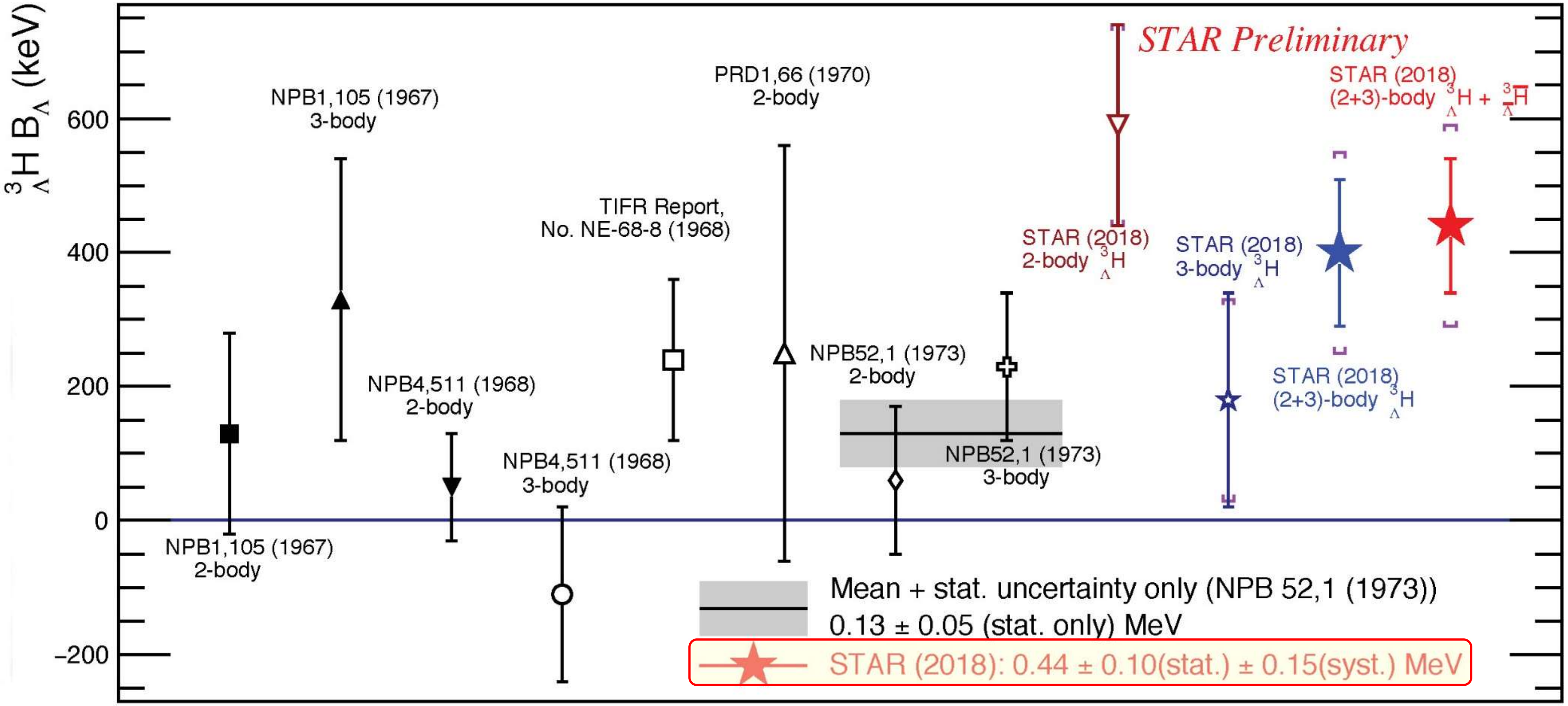
- is something wrong in the new measurements?

(are we using
the most suitable experimental technique?)

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

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

A new exciting result?



see
H. Le and 's and P. Herrmann's talks
today

3 times the currently accepted value!!!

STAR @

How?

a different experimental approach

The P74 approach

dσ/dΩ

mb/sr

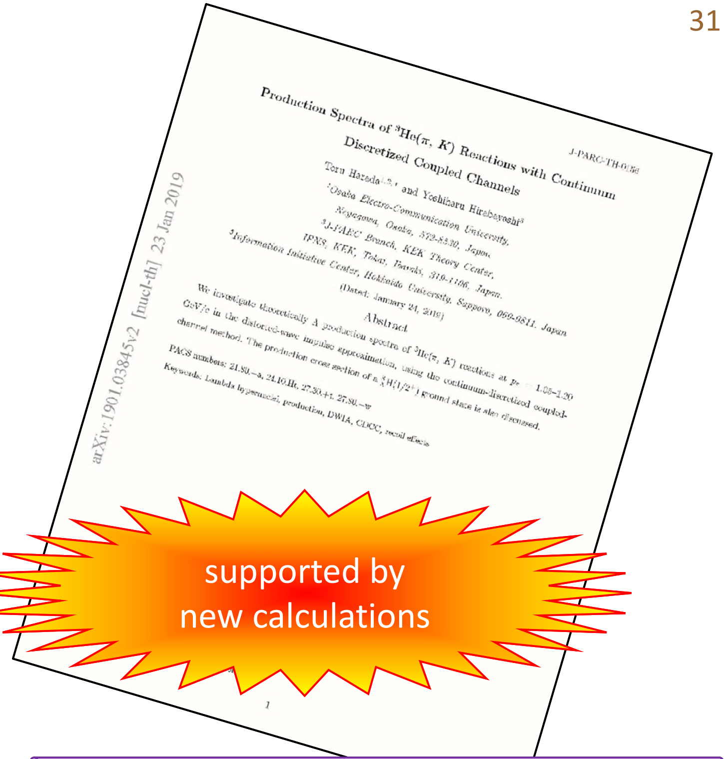
μb/sr

nb/sr

never exploited before!!!

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

NEW! @ J-PARC



supported by new calculations

T. Harada and Y. Hirabayashi, *JPS Conf. Proc.* 26 (2019) 023004.

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

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

advantages: charged particle only in the final state! → no need of large acceptance e.m. calorimeter

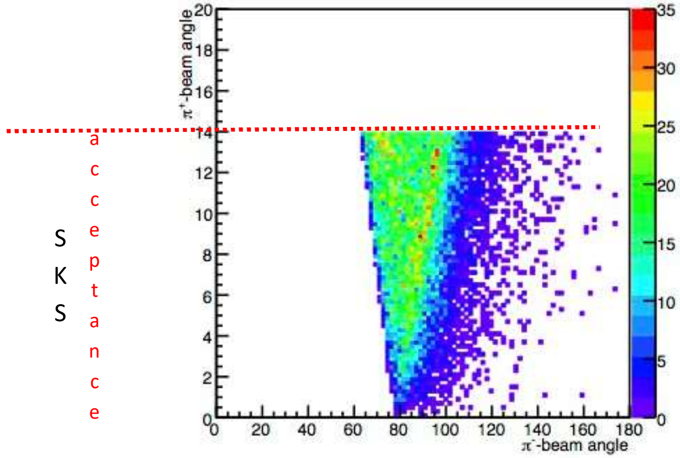
- relative simple apparatus
- cheap detectors

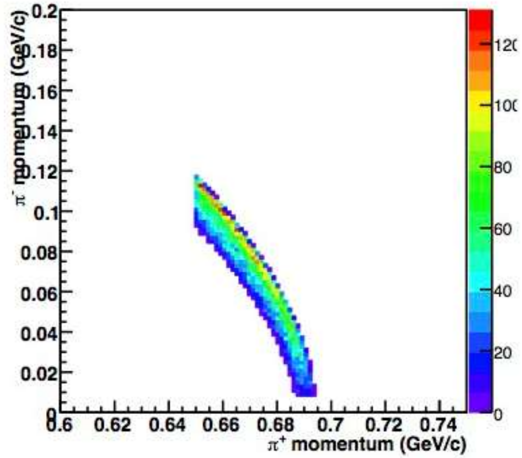
Advantages of the (π^-,K^0) reaction

- well established reaction:
  - ! cross section experimentally known from the isospin symmetric (π^+,K^+) ➔ good $^3H_\Lambda$ production rate
- experimental feasibility to be demonstrated
- important investigation tool for hydrogen Λ hyper-isotopes lifetime measurement
- doorway to neutron-rich Λ-hypernuclei study
  - further investigation of the hypernuclear weak decay process
  - $^4H_\Lambda$ non-mesonic Γ_p to check the validity of the $\Delta I = ½$ rule
  - systematic and precise (≤ 5%) determination of the full pattern of the partial weak decay widths
  - systematic and precise determination of the level schemes of many mirror hypernuclei aiming to the CSB effect investigation

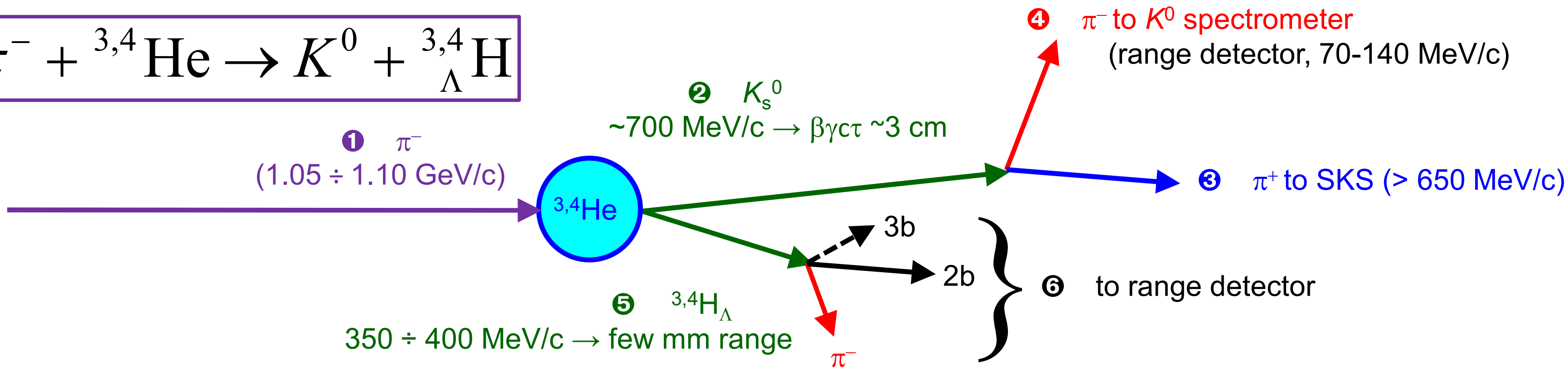
see T.O. Yamamoto's talk @ HYP2018

Reaction kinematics





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



kinematical features:

❸ π^+: p > 650 MeV/c, 0° < ϑ < 14°

❹ π^-: 10 < p < 120 MeV/c, 60° < ϑ < 100° ← from K_S^0

❻ π^-: 0 < p < 114 (133) MeV/c, 0° < ϑ < 180° ← from ${}^{3,4}H_\Lambda$

INFN

Physical background

elementary process in P74:

charge exchange + strangeness associated production

NEVER measured before!

$^{3}H_{\Lambda}$ (signal)

bound

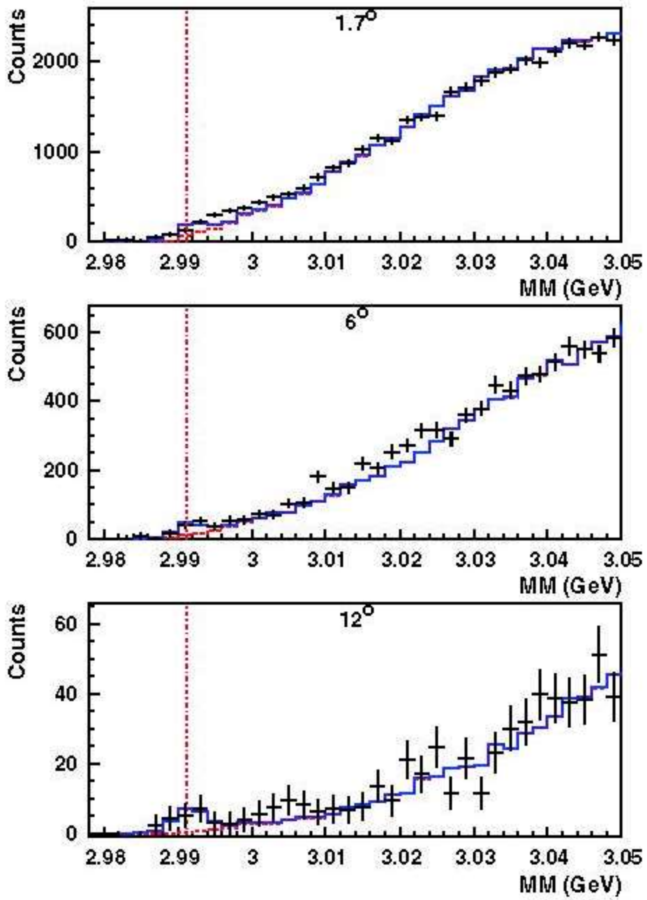
$$\pi^{-} + p \rightarrow K^{0} + \Lambda$$

NOT bound

q.f. Λ (background)

nobody knows about it!!!

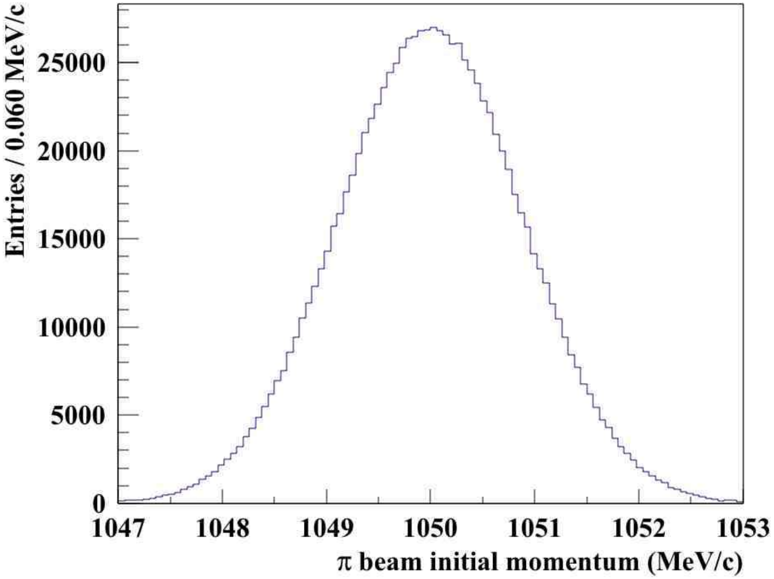
The only existing MM experimental data about $^{3}H_{\Lambda}$ production



$^{3}He(e,e'K^{+})^{3}H_{\Lambda}$

F. Dohrmann *et al.*, *PRC* 90 (2014) 034320.

Expected $^3H_\Lambda$ missing mass spectrum



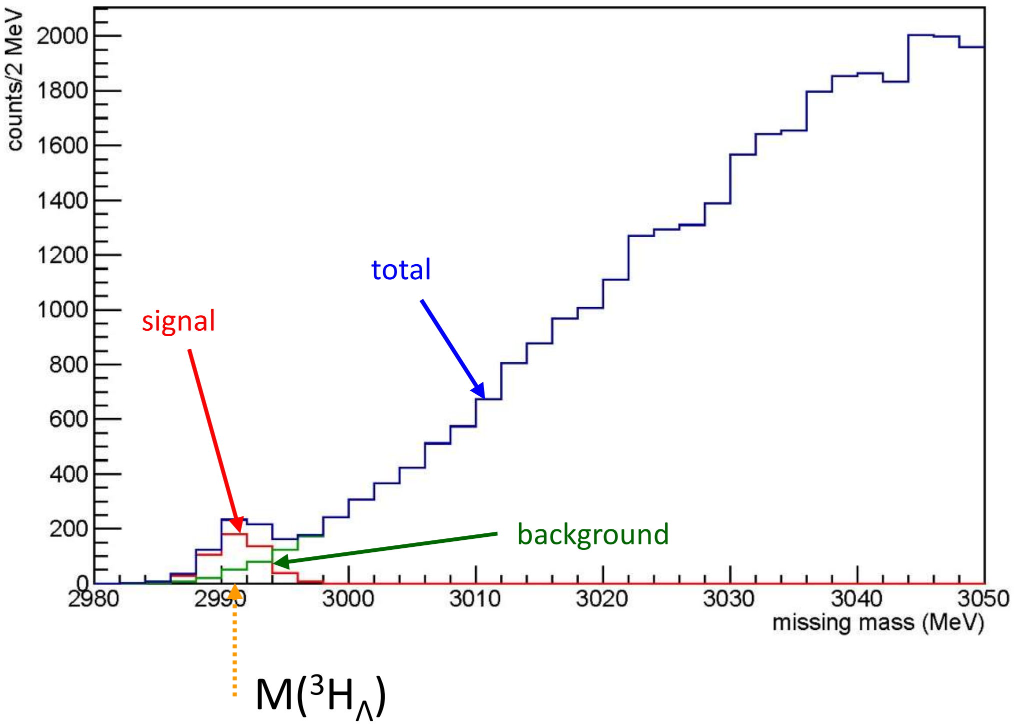
$$\pi^- + {}^3\mathrm{He} \rightarrow K^0 + {}^3_\Lambda\mathrm{H}$$

K1.1 beam line:

$\Delta p/p = 2 \times 10^{-3}$ FWHM

☛ $\Delta_{MM} \approx 4.5$ MeV (FWHM)

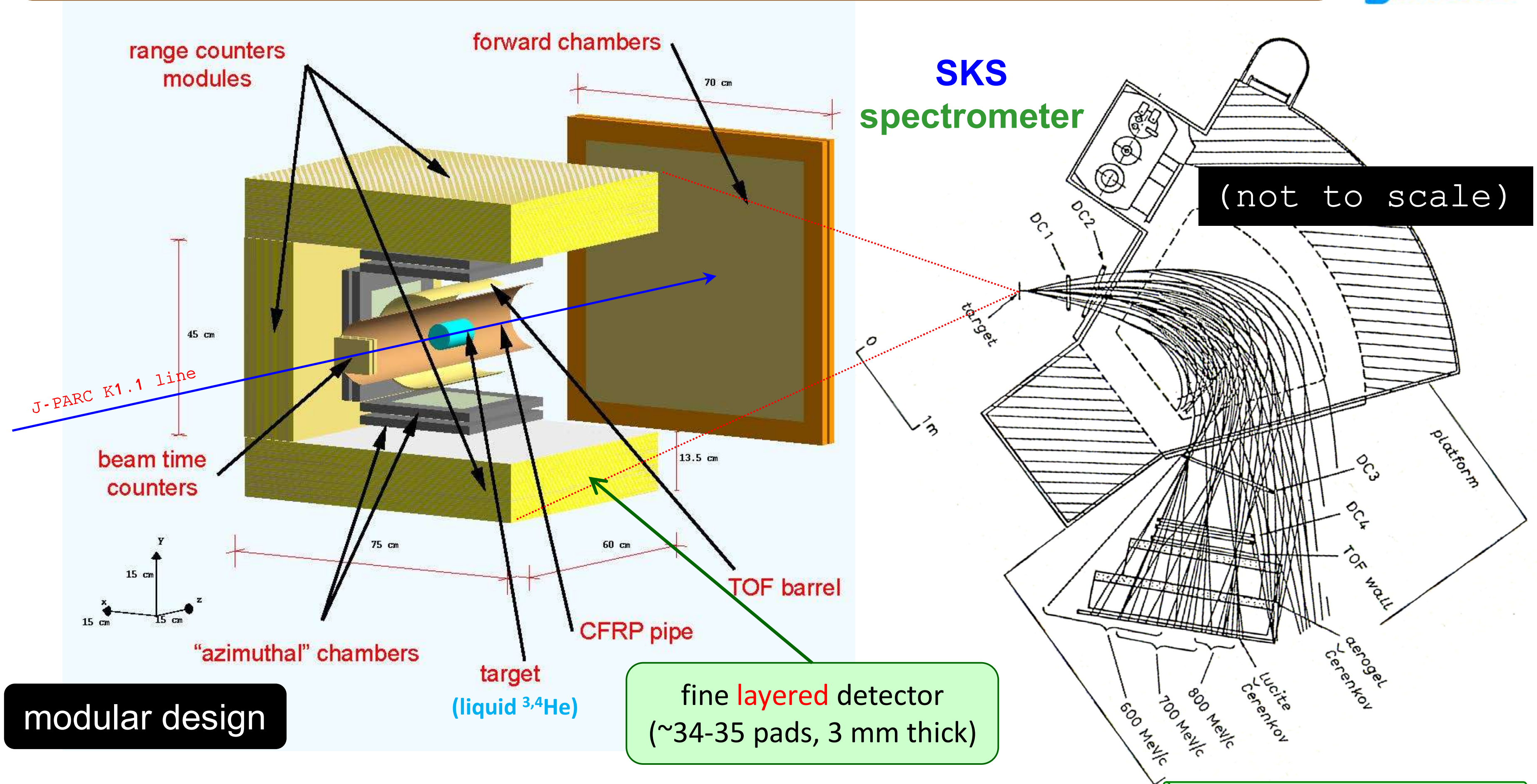
S/N ≈ 2



How?

the apparatus

Experimental concept layout

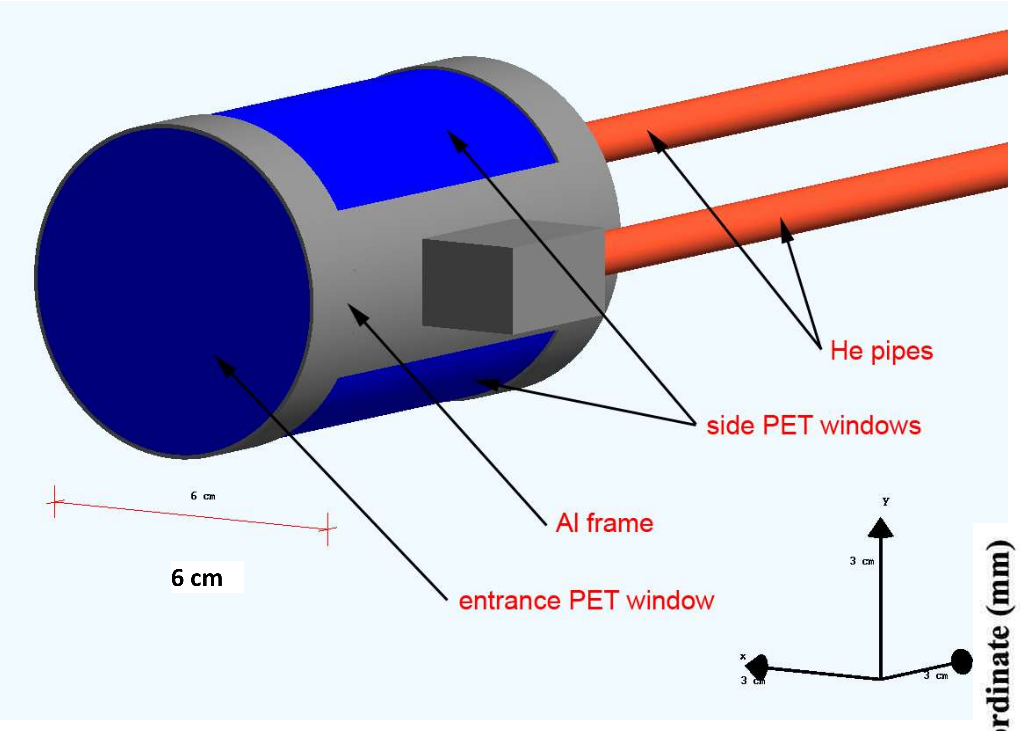


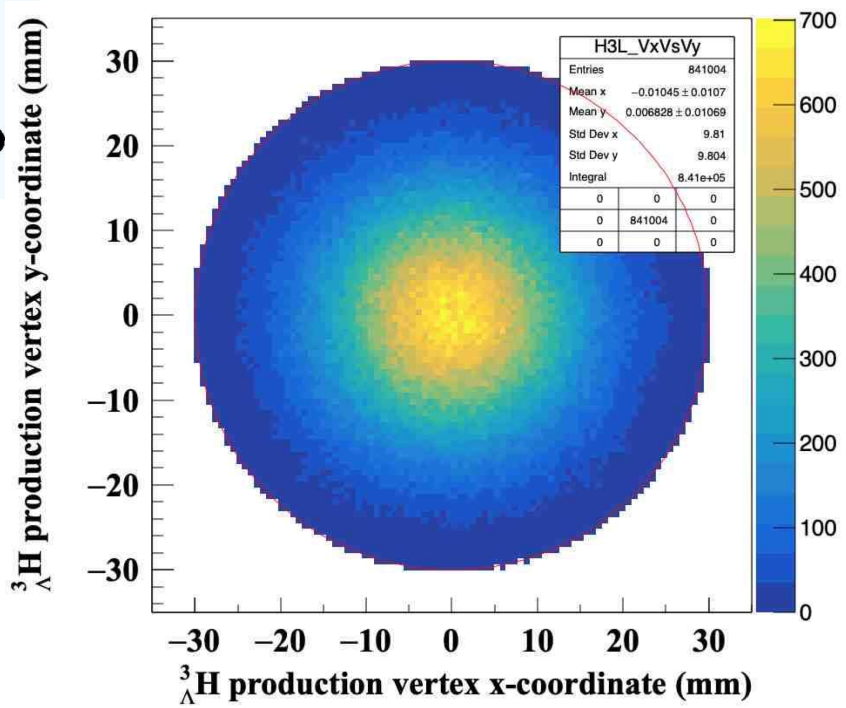
M. Agnello *et al.*, *NPA* 954 (2016) 176.

design performances:

- Δ_{MM} ≤ 4 MeV (FWHM)
- Δ_{time} ≤ 100 ps (rms)
- Ω ≈ 2 π sr
- $\Delta_{T(prongs)}$ ≤ 3 MeV (FWHM)
- σ_{ϑ} ≤ 100 mrad (FWHM)

Liquid ^{3,4}He targets



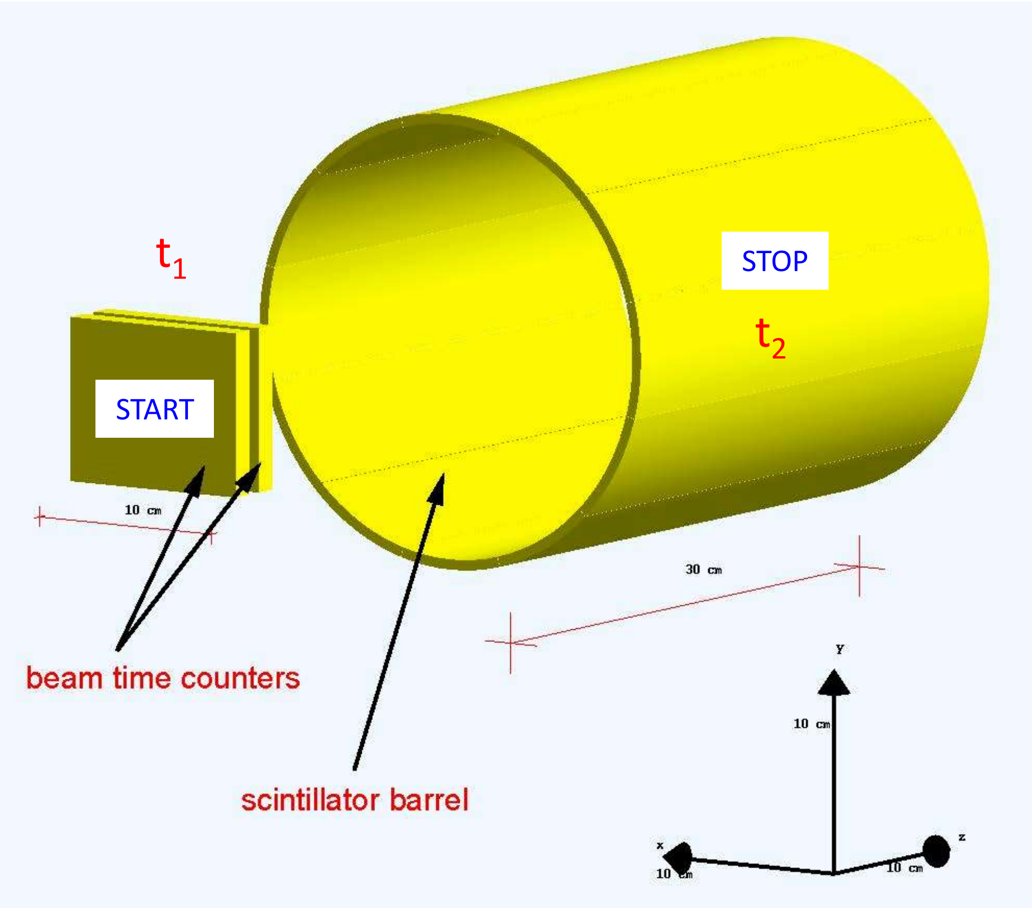


Ø = 6 cm

L = 10 cm

ρ(^{3}He) = 0.081 g/cm^3 ~ 1 g/cm^2

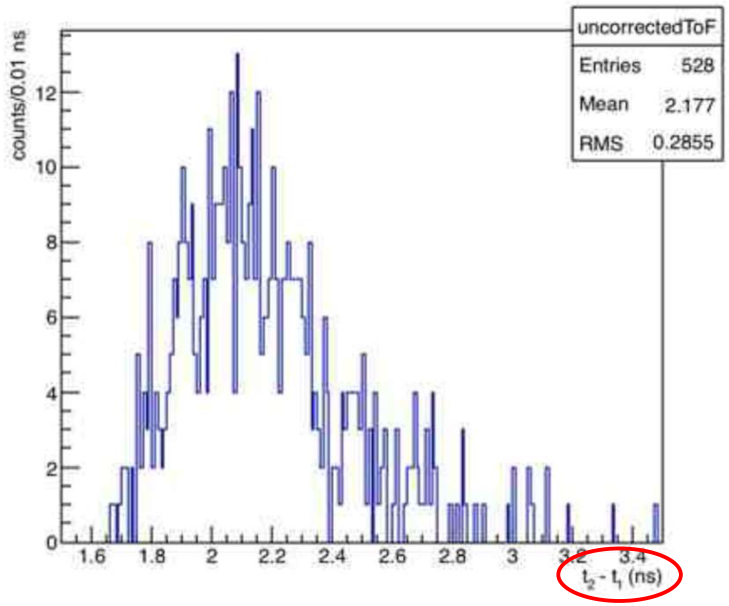
The time measurement system



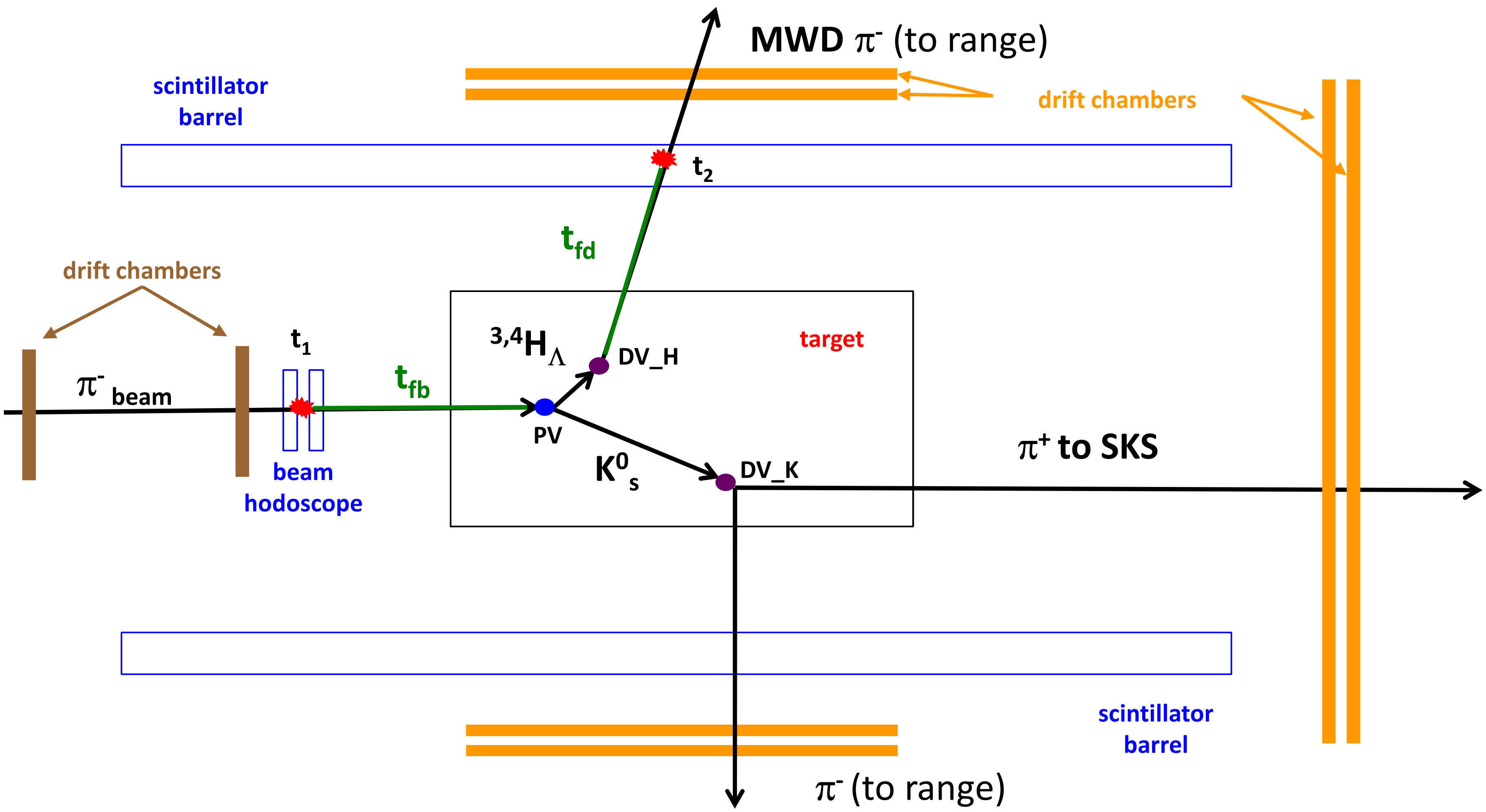
Ø ≈ 10.5 cm
L = 30 cm
T = 0.5 cm

12 ÷ 30 slabs

$\sigma_{time} \approx$ 80 ps (rms)

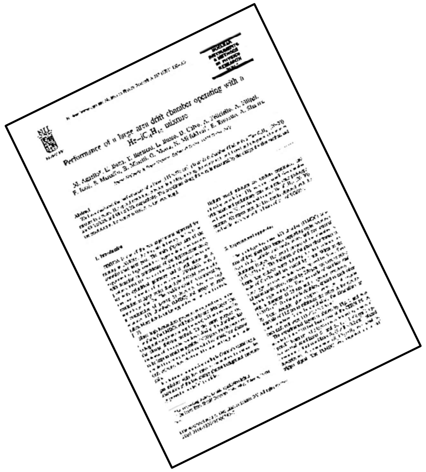


Why time resolution it is not enough?



$$t({}^{3,4}_{\Lambda}H) = (t_2 - t_1) - t_{fb} - t_{fd}$$

The low-mass drift chambers



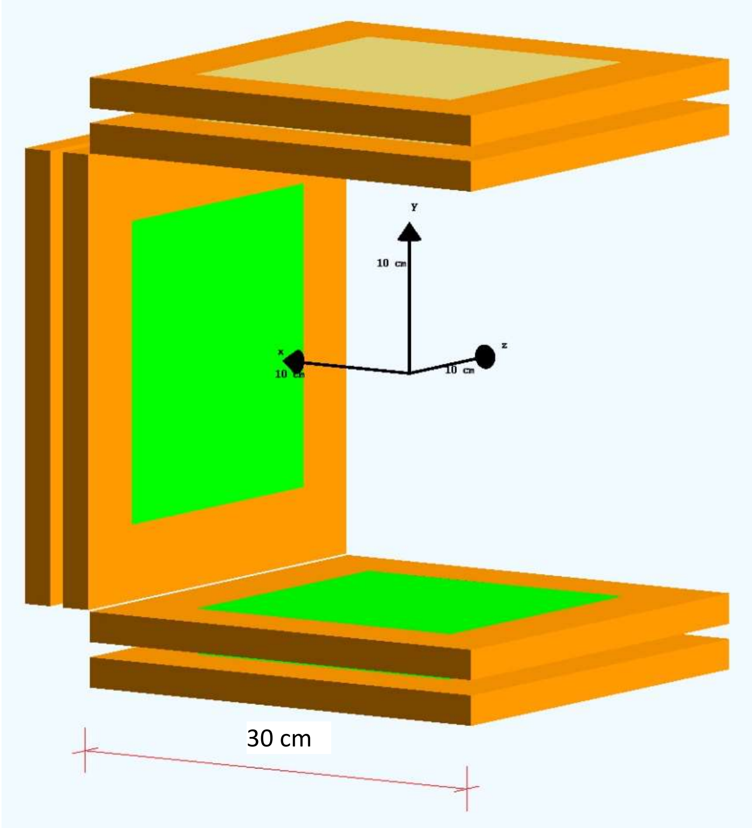
Dimensions:
30 x 30 x 5 cm^3

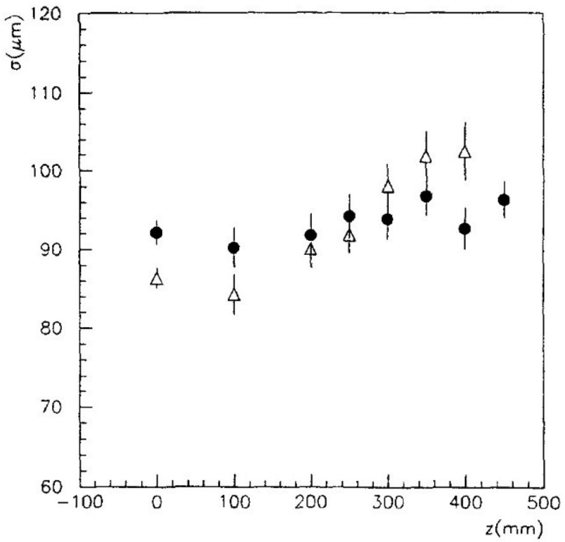
gas mixture:
70% He + 30% iC_4H_{10}

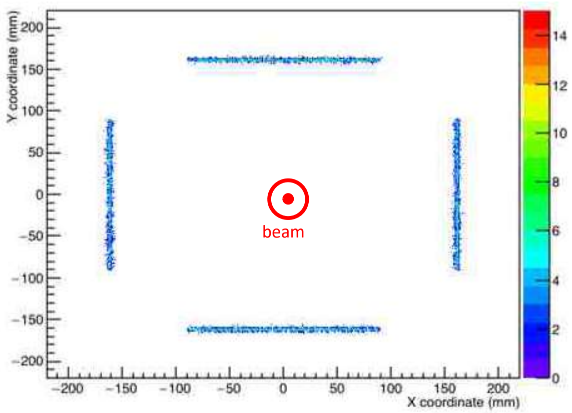
spatial resolution:
≈ 250 μm (FWHM)

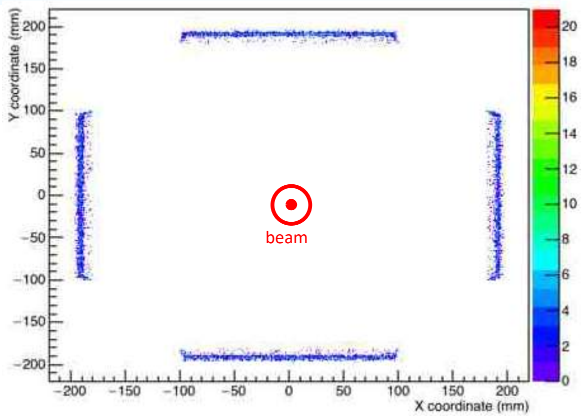
angular resolution:
< 100 mrad (FWHM)

M. Agnello *et al.*, *NIM* A 367 (1995) 100.

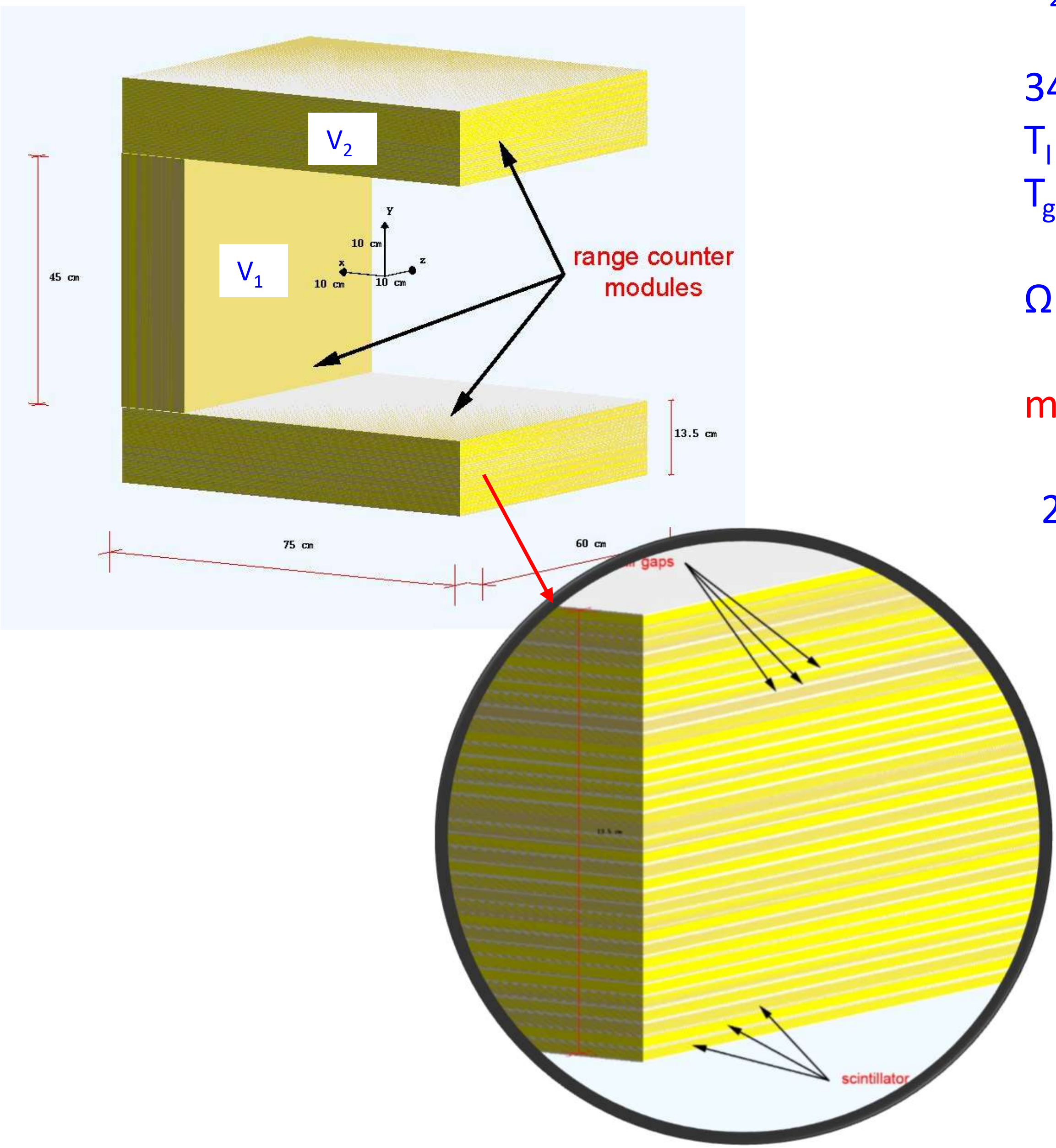








The range detector

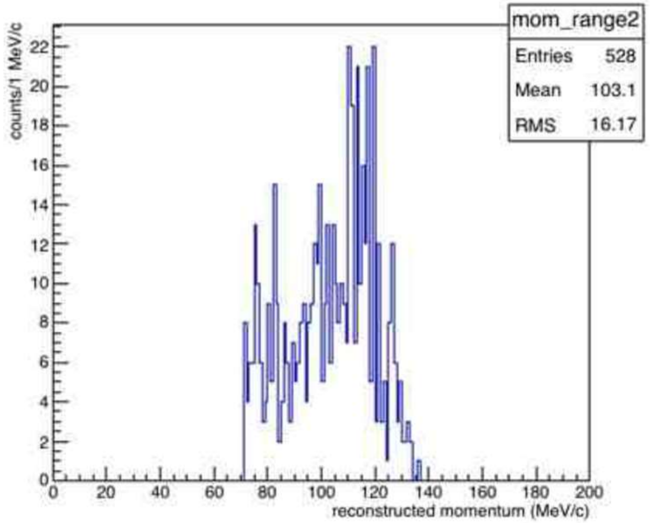


$V_1 = 45 \times 60 \times 13.5\ cm^3$
$V_2 = 75 \times 60 \times 13.5\ cm^3$

34-35 layers
$T_l \approx 3$ mm
$T_g \approx 1$ mm (air)

$\Omega \approx 2\pi$ sr

momentum acceptance:
70 MeV/c $< p_\pi <$ 140 MeV/c
250 MeV/c $< p_p <$ 450 MeV/c



Expected rate for $^3H_\Lambda$ production

$$\text{yield}({}^3_\Lambda\text{H}) = \text{N}_{\text{beam}} \times \frac{\text{T}_{\text{target}}}{\text{A}} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{sp} \times \varepsilon_{sp} \times \varepsilon_{an}$$

$$\text{N}_{\text{beam}} \approx 5 \times 10^{12}\ \pi^-$$

$$\text{T}_{\text{target}} = 0.81\ \text{g/cm}^2$$

$$\frac{d\sigma}{d\Omega} \approx 5\ \mu\text{b/sr}$$

$$\Omega_{sp} = 0.1\ \text{sr}$$

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

$$\varepsilon_{an} = 0.7$$

$$\text{yield}({}^3_\Lambda\text{H}) \approx 2.6 \times 10^3$$

produced in the detector acceptance

$$\text{yield}({}^3_\Lambda\text{H} \to \text{2-/3-body}) = \text{yield}({}^3_\Lambda\text{H}) \times \text{BR} \times \Delta\Omega_\pi \times \varepsilon_\pi \times \varepsilon_{an}$$

$$\Delta\Omega_\pi \approx 0.5$$

$$\varepsilon_\pi \approx 1$$

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

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

BR: **0.25** (2-body), **0.40** (3-body)

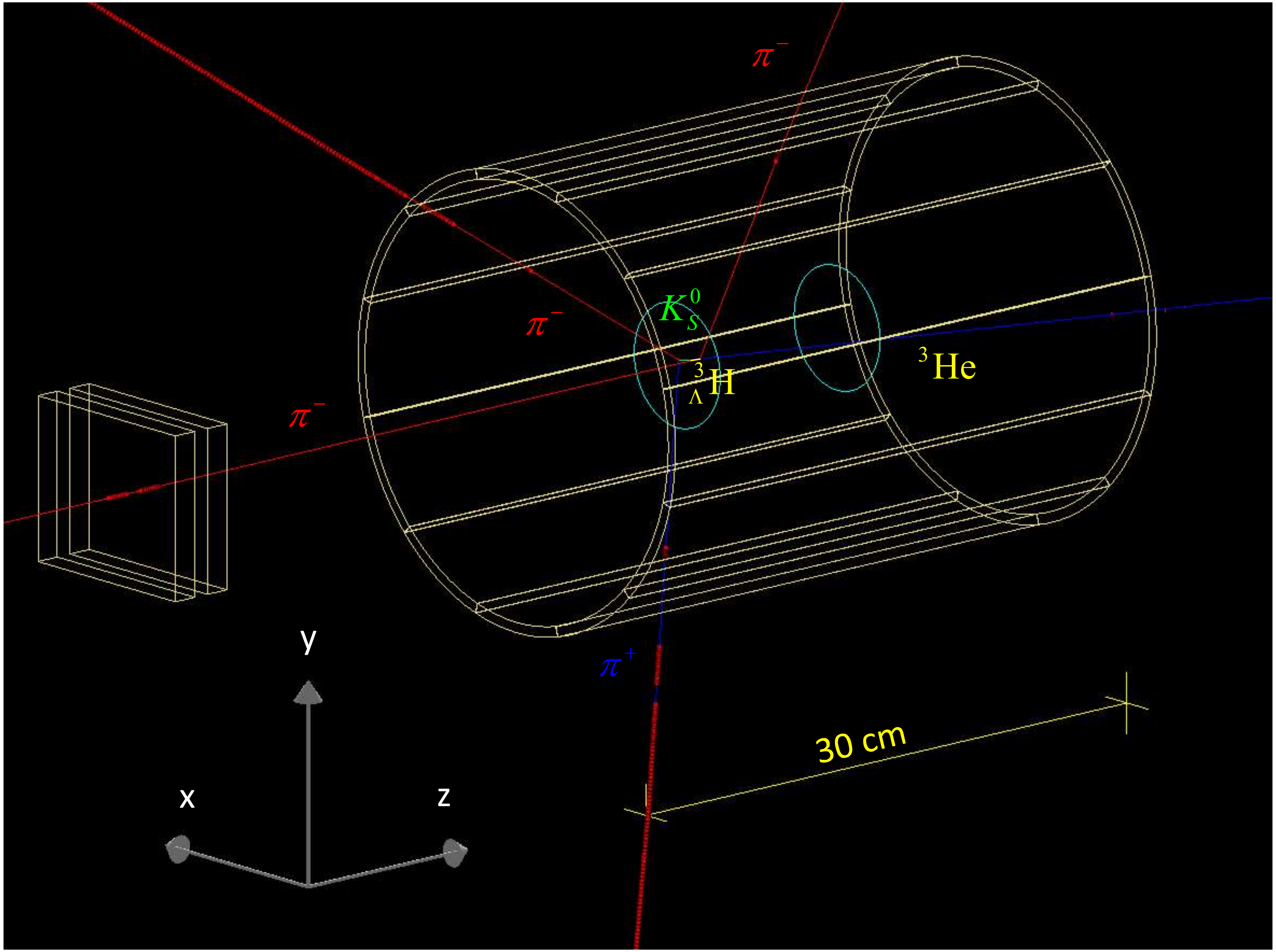
detected

$$^3_\Lambda\text{H} \to \pi^- + {}^3\text{He} \approx 2.5 \times 10^2$$

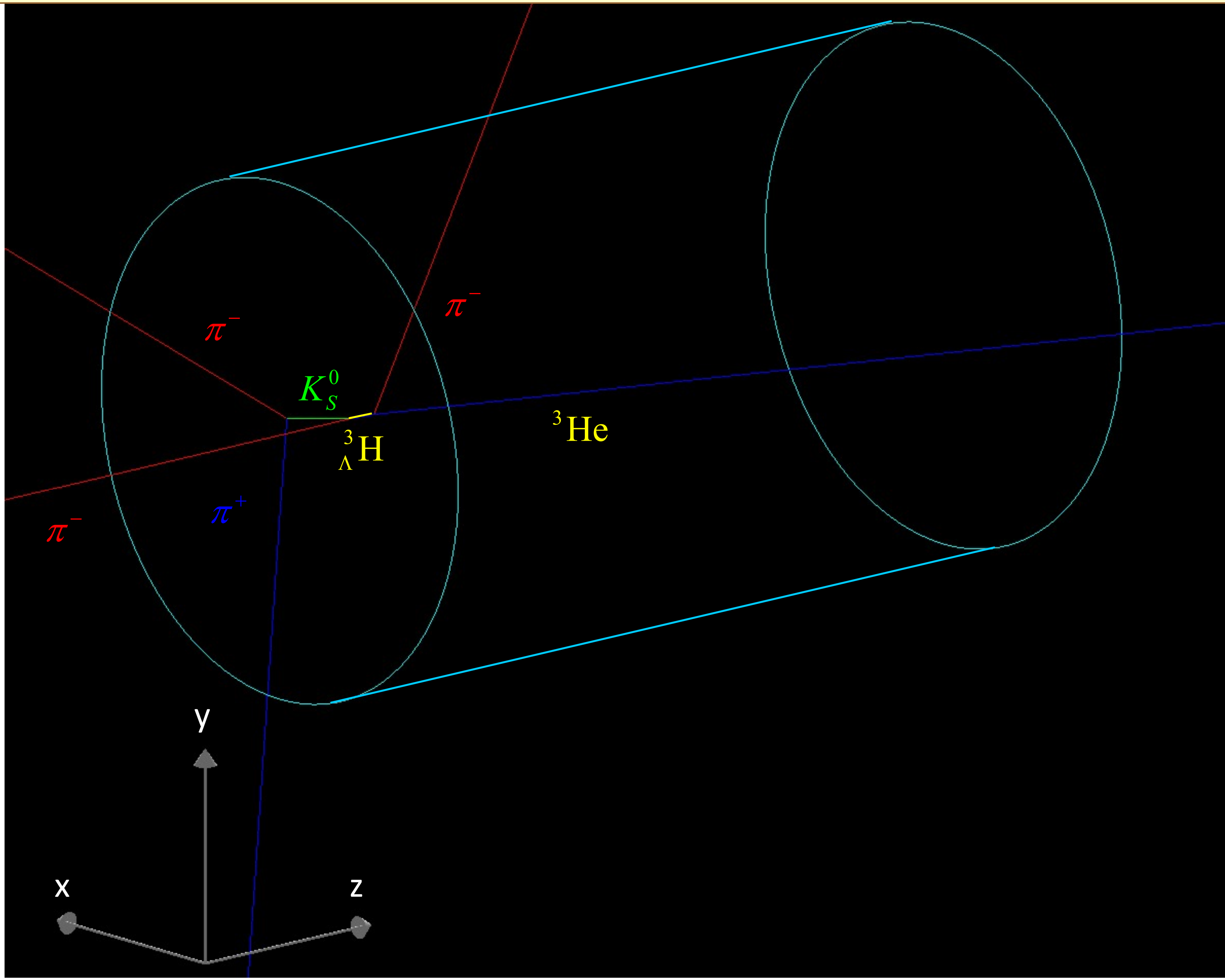
\+

$$^3_\Lambda\text{H} \to \pi^- + p + d \approx 3.5 \times 10^2$$

The $^3H_\Lambda$ "standard" event



The $^3H_\Lambda$ "standard" event (zoomed)

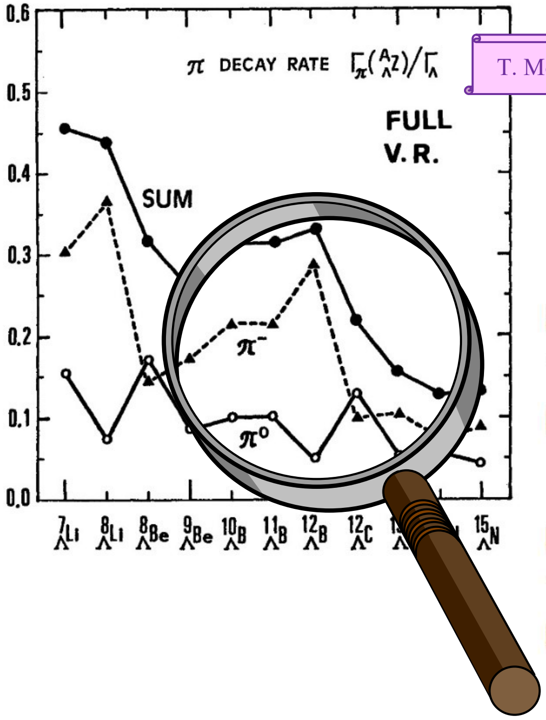


Why?

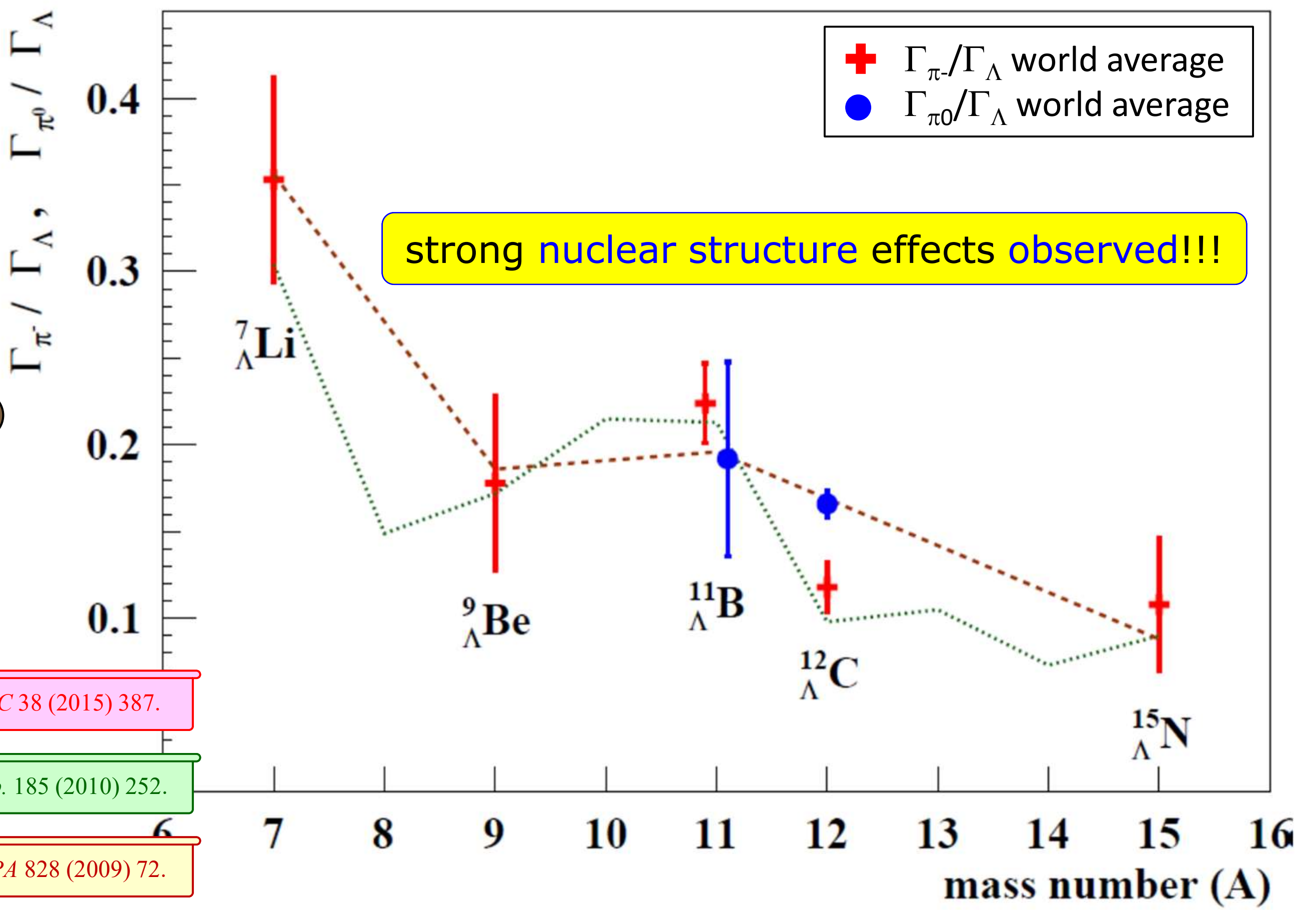
the physics case

Part II

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



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



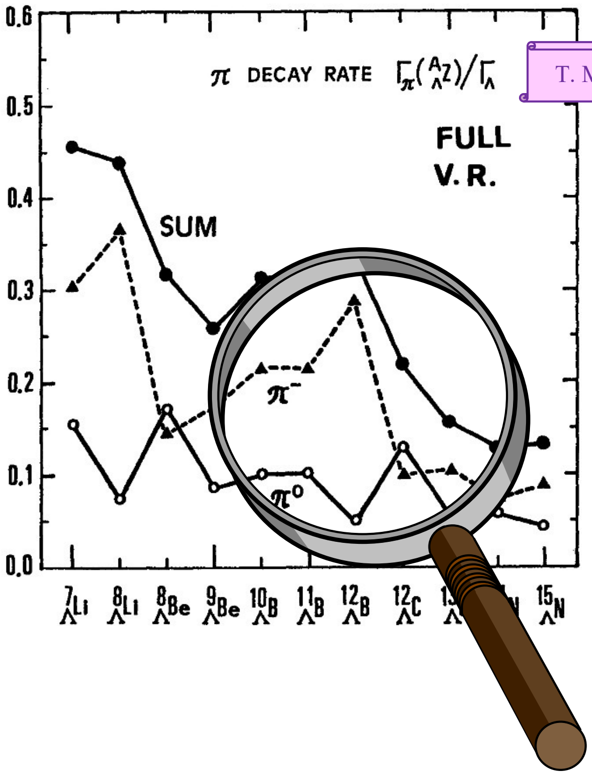
strong nuclear structure effects observed!!!

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

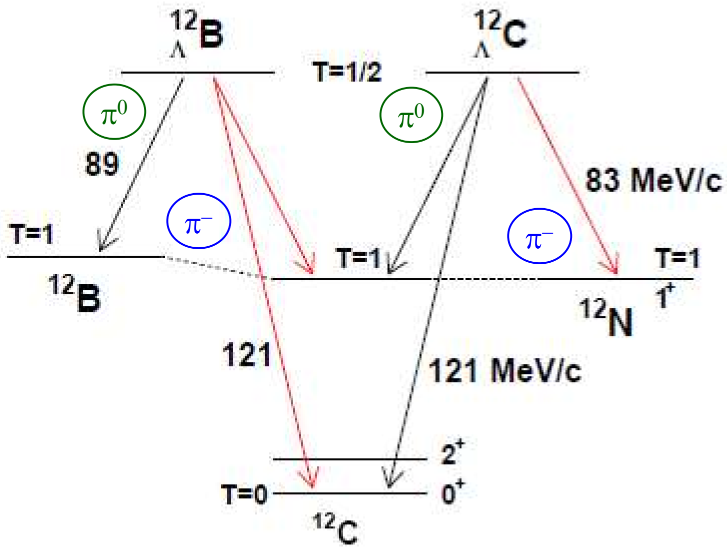
K. Itonaga, T. Motoba, *PTP Supp.* 185 (2010) 252.

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

Looking for nuclear structure effects



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



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

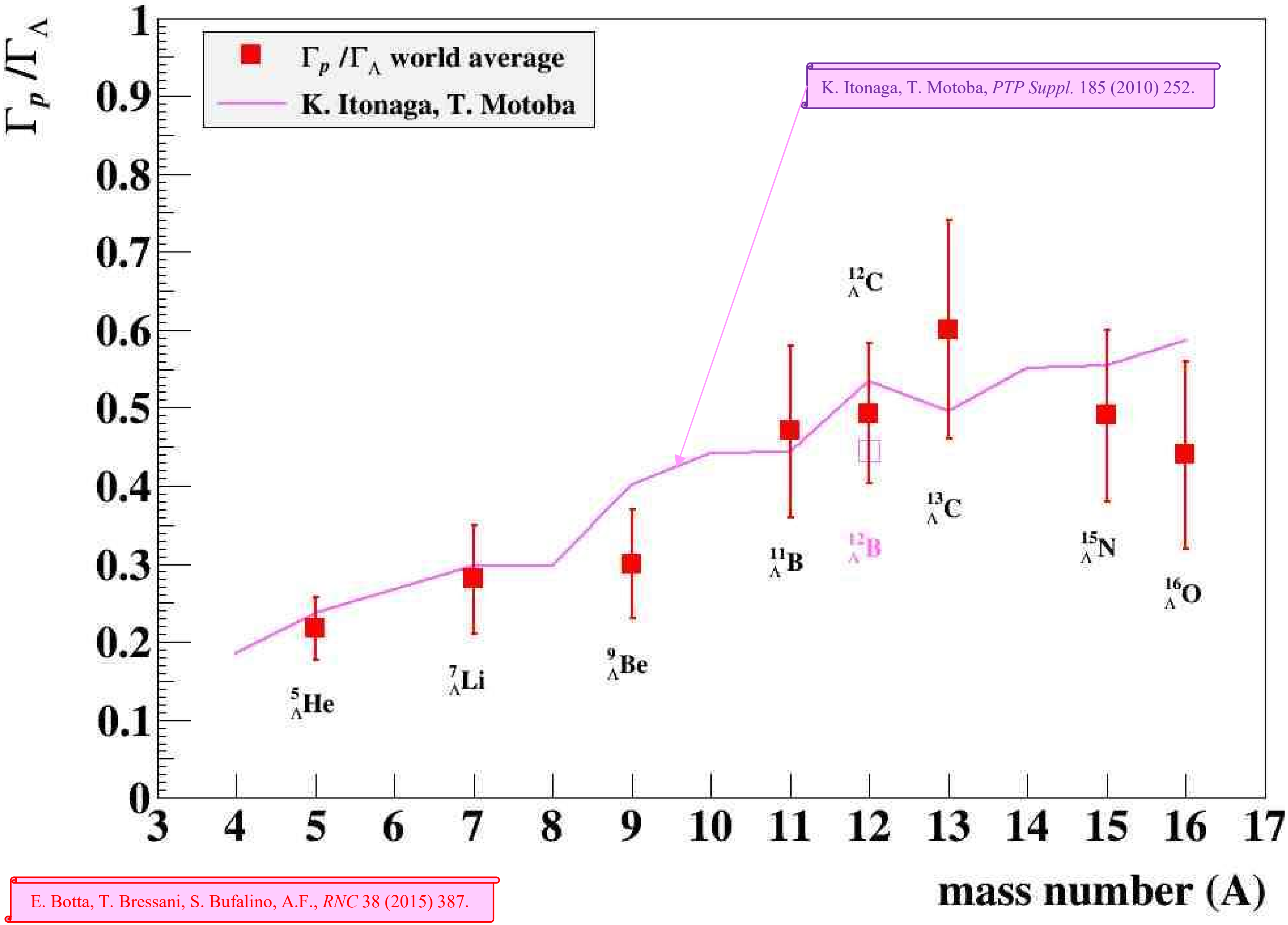
T. Motoba, *NPA* 547 (1992) 115c. ≈ 3

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

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

T. Motoba, *NPA* 547 (1992) 115c. ≈ 8

Γ_p: current experimental situation



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

Physics aims

further studies of *p*-shell Λ-hypernuclei

(in particular of the neutron-rich ones, e.g. $^{12}B_{\Lambda}$)

determination of:

- $\Gamma_{tot} \equiv \hbar/\tau$
- Γ_{π^-}
- Γ_{π^0} (possibly)
- Γ_p

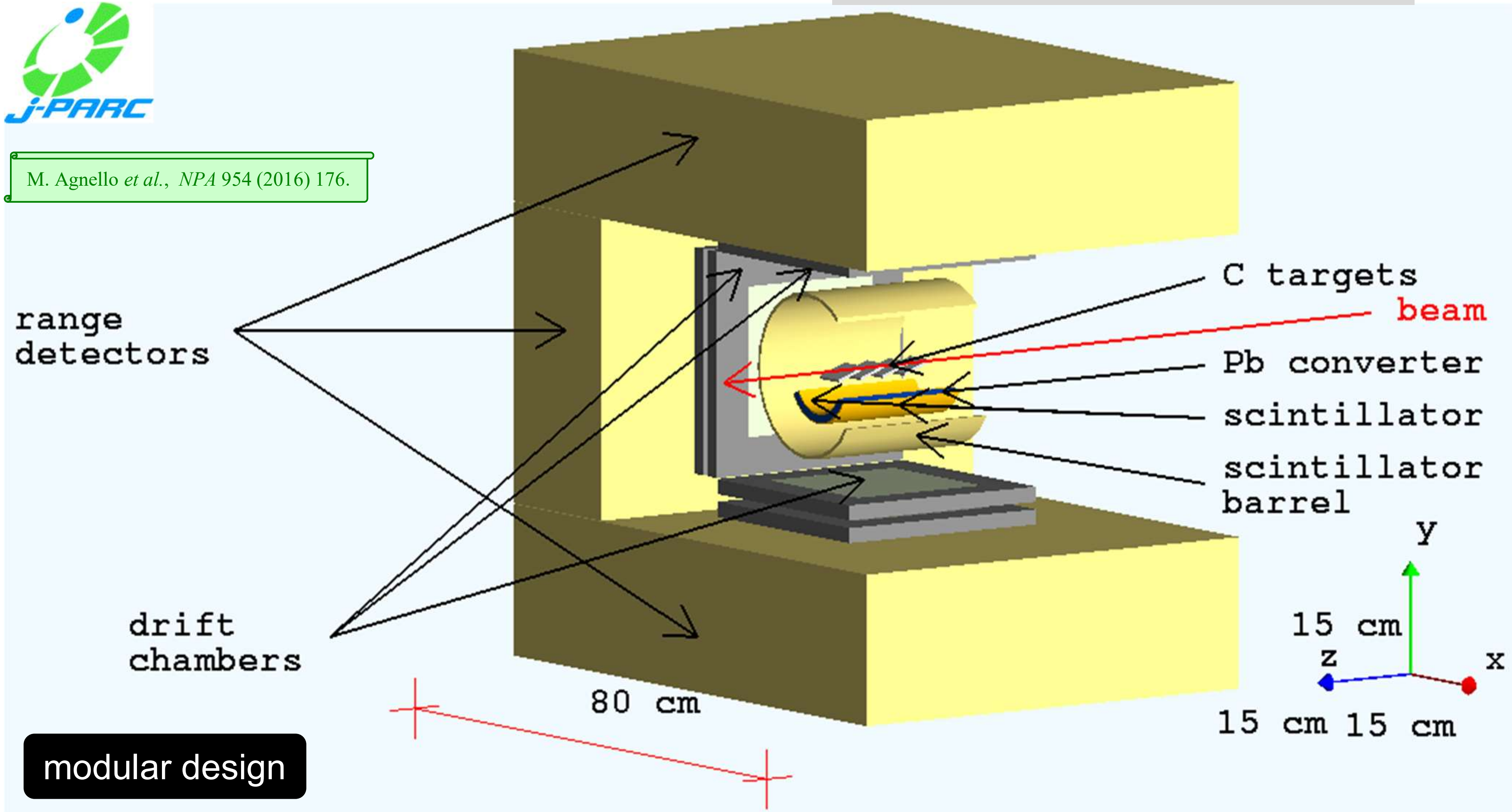
How?

the apparatus
Part II

Concept design

final goal:
SKS Λ-hypernucleus MM resolution
≤ 4 MeV (FWHM)

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



modular design

detector performance: solid angle coverage 50-60%

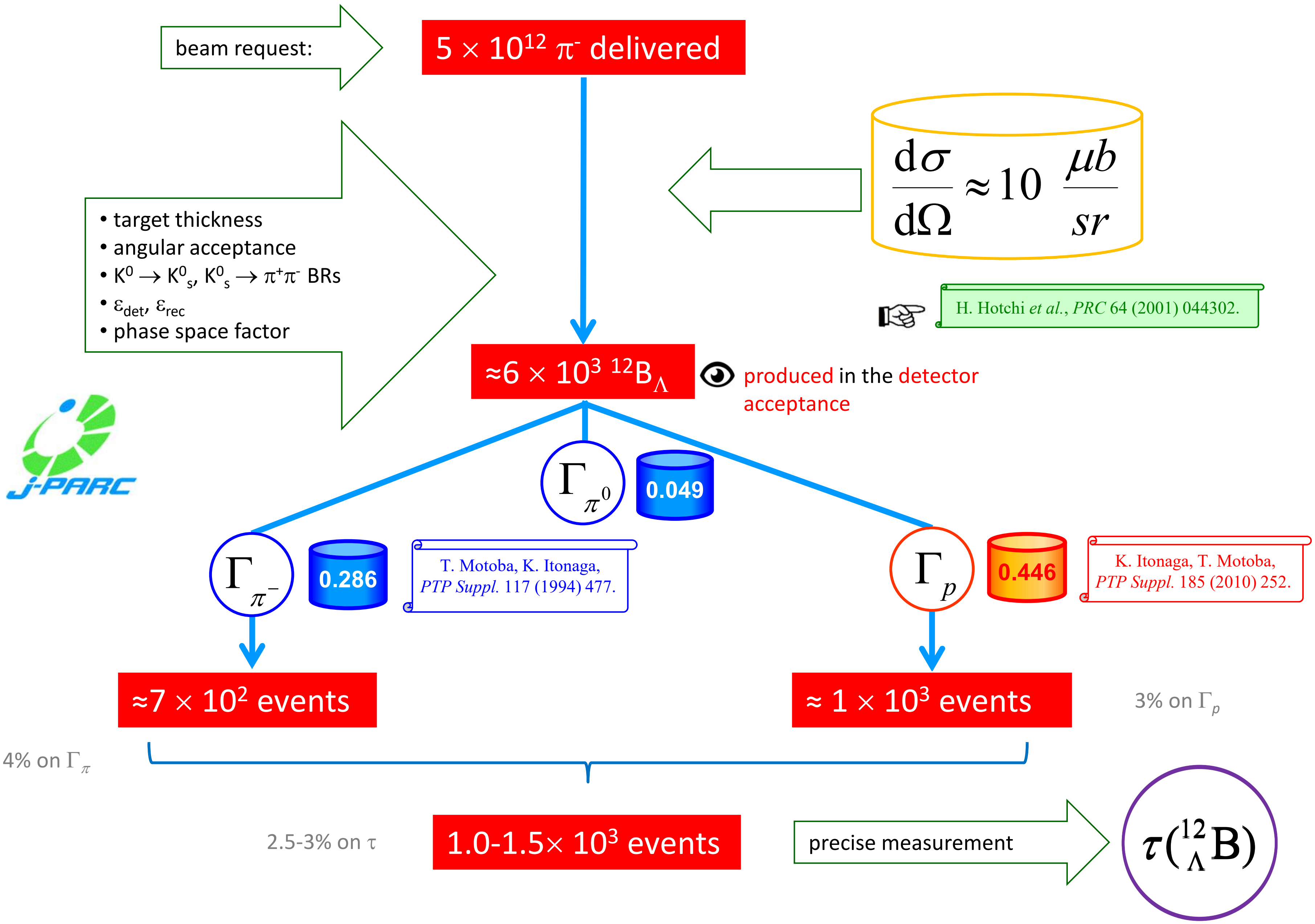
range detector

- energy resolution on π^- ≤ 3 MeV (FWHM)

drift chambers

spatial resolution ≤ 250 μm (FWHM)
angular resolution ≤ 100 mrad (FWHM)

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



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

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

$\text{N}_{\text{beam}} = 0.5 \times 10^{11}\ \pi^+$ $\quad$ $\text{T}_{\text{target}} = 4 \times 1\ \text{g/cm}^2$

limited request

$\frac{d\sigma}{d\Omega} \approx 15\ \mu\text{b/sr}$ $\quad$ $\Omega_{sp} = 0.1\ \text{sr}$

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

$\varepsilon_{sp} = 0.5$

$\varepsilon_{an} = 0.7$

$$\text{yield}({}^{12}_{\Lambda}\text{C}) \approx 5 \times 10^3$$

produced in the detector acceptance

Γ_p $\quad$ 0.535

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

$\Delta\Omega_{sp} \approx 0.5$

$\varepsilon_p \approx 1$

$\varepsilon_{an} \approx 0.8$

1-day data taking

~1 × 10³ ev.

3% on Γ_p

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

The P74 Collaboration

M. Agnello, S. Bufalino, G. Kaniadakis,
INFN Sezione di Torino and Politecnico di Torino

E. Botta,
INFN Sezione di Torino and Università di Torino

T. Bressani, D. Calvo, A. Feliciello,
INFN Sezione di Torino

H. Tamura, Y. Ishikawa, A. Rogers,
Tohoku University

T. Nagae,
Kyoto University

T. Takahashi, M. Ukai,
IPNS, KEK

T.O. Yamamoto,
ASRC, JAEA

S. Ajimura, A. Sakaguchi,
Osaka University

H. Outa
RIKEN