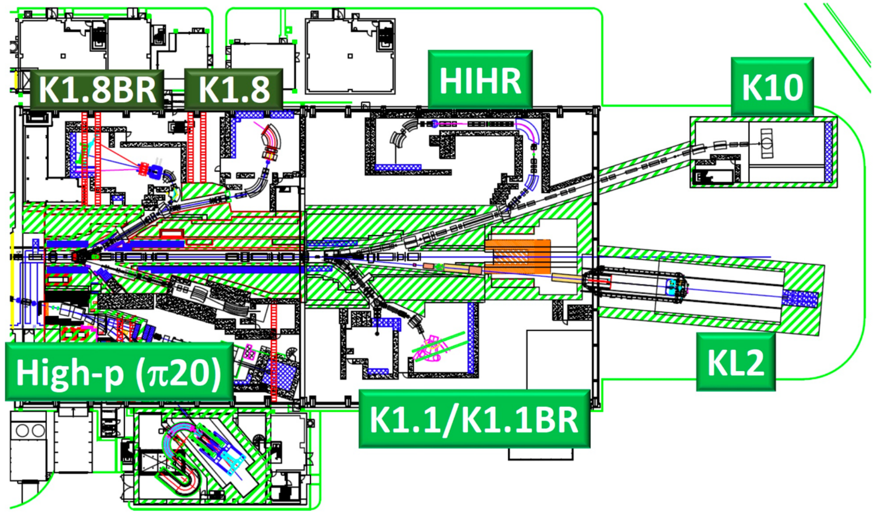
Study of Λ-hypernuclei weak decays at the K1.1 beam line



2nd International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility, February 16-18, 2022

Alessandro Feliciello

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Outline

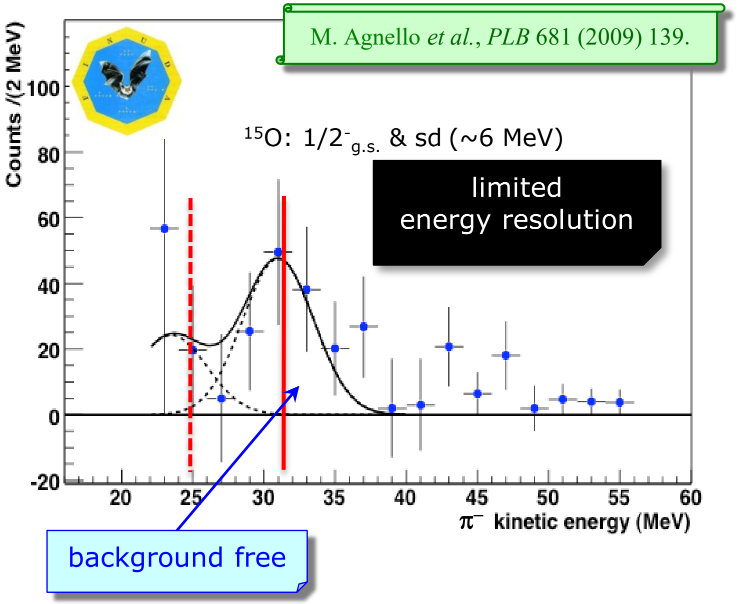
- physics motivations
  - ❶ "a posteriori" (discovery tool)
    - ✓ MWD decay exploited as indirect spectroscopic analysis tool
  - ❷ intrinsic

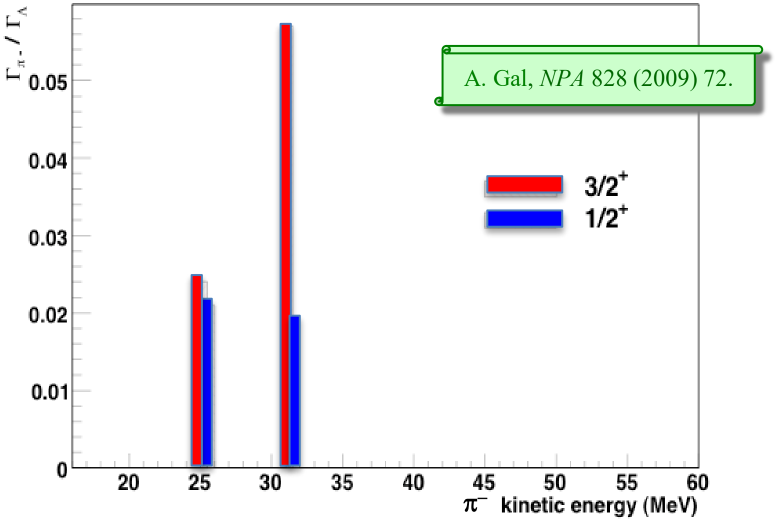
- a look to a further opportunity:
  - Extension Project for the J-PARC Hadron Experimental Facility

    high-statistics (i.e. precise) and systematic (i.e. vs. A) study
    to determine the full pattern of the partial weak decay widths
    (in particular for *p*-shell neutron-rich Λ-hypernuclei)

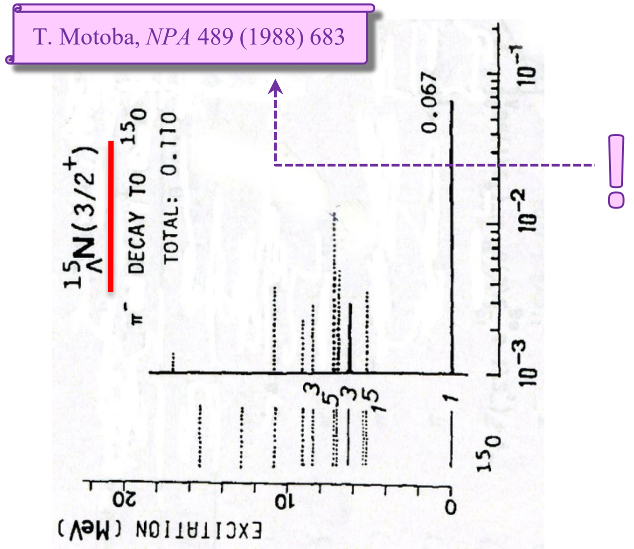
$^{15}N_{\Lambda}$ J^{π} assignment

1st experimental determination



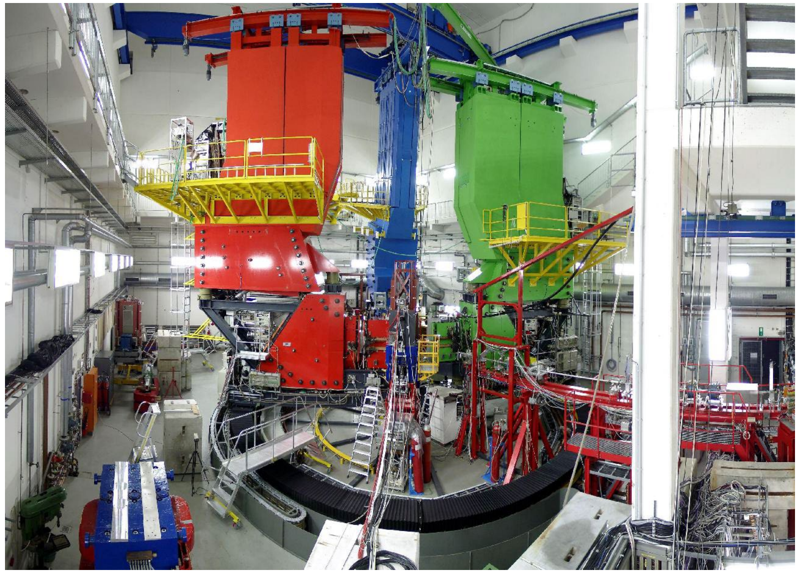


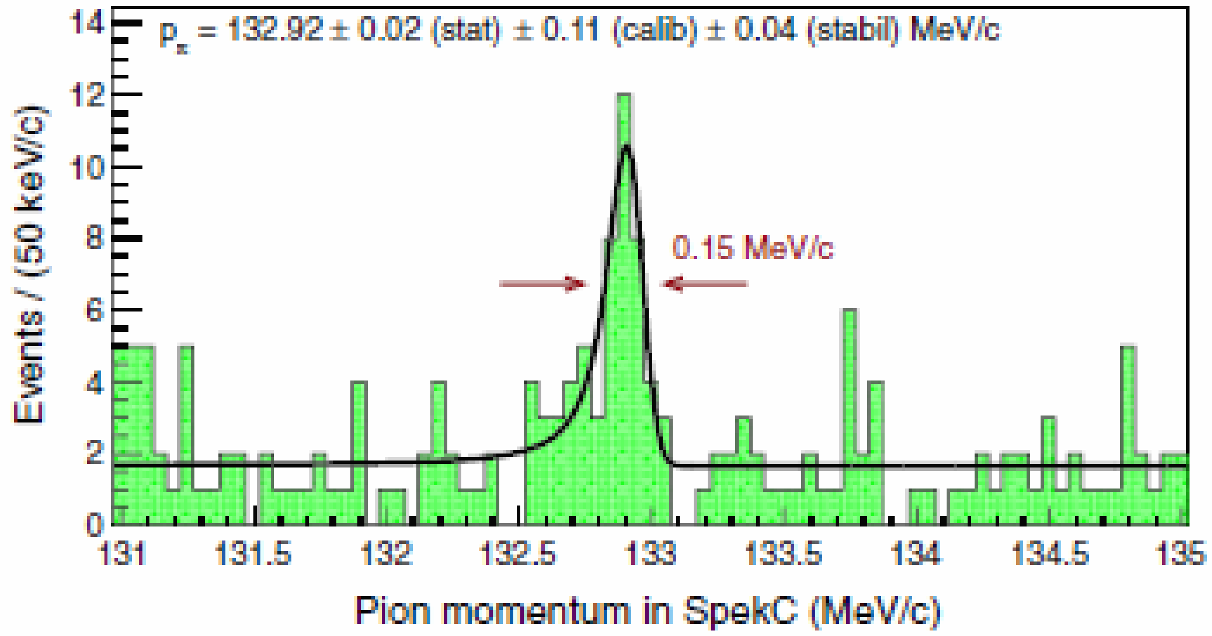
- Clear correspondence with the calculated strength functions:
  - T. Motoba *et al.*, Nucl. Phys. A 489 (1988) 683.
  - A. Gal, Nucl. Phys. A 828 (2009) 72.
- $^{15}N_{\Lambda\ g.s}$ spin not known J^{π} ($^{15}N_{\Lambda\ g.s.}$) = $3/2^{+}$
  D.J. Millener, A. Gal, C.B. Dover, Phys. Rev. C 31 (1985) 499.
  Spin ordering not obtained from γ-rays of $^{16}O_{\Lambda}$
  M. Ukai *et al.*, Phys. Rev. C 77 (2008) 054315.
- First experimental determination of
  J^{π} (**$^{15}N_{\Lambda\ g.s.}$**) = $3/2^{+}$ from decay rate value (and spectrum shape)



pion decay spectroscopy

$${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$$





B_{Λ} = (2.12 ± 0.01 ± 0.09) MeV

unprecedented precision!

A. Esser *et al.*, PRL 114 (2015) 12501

Mesonic weak decay (MWD)

Experimental observables

- τ
- $\Gamma_{\pi^-}/\Gamma_\Lambda$, $\Gamma_{\pi^0}/\Gamma_\Lambda$
- (single) particle decay spectra

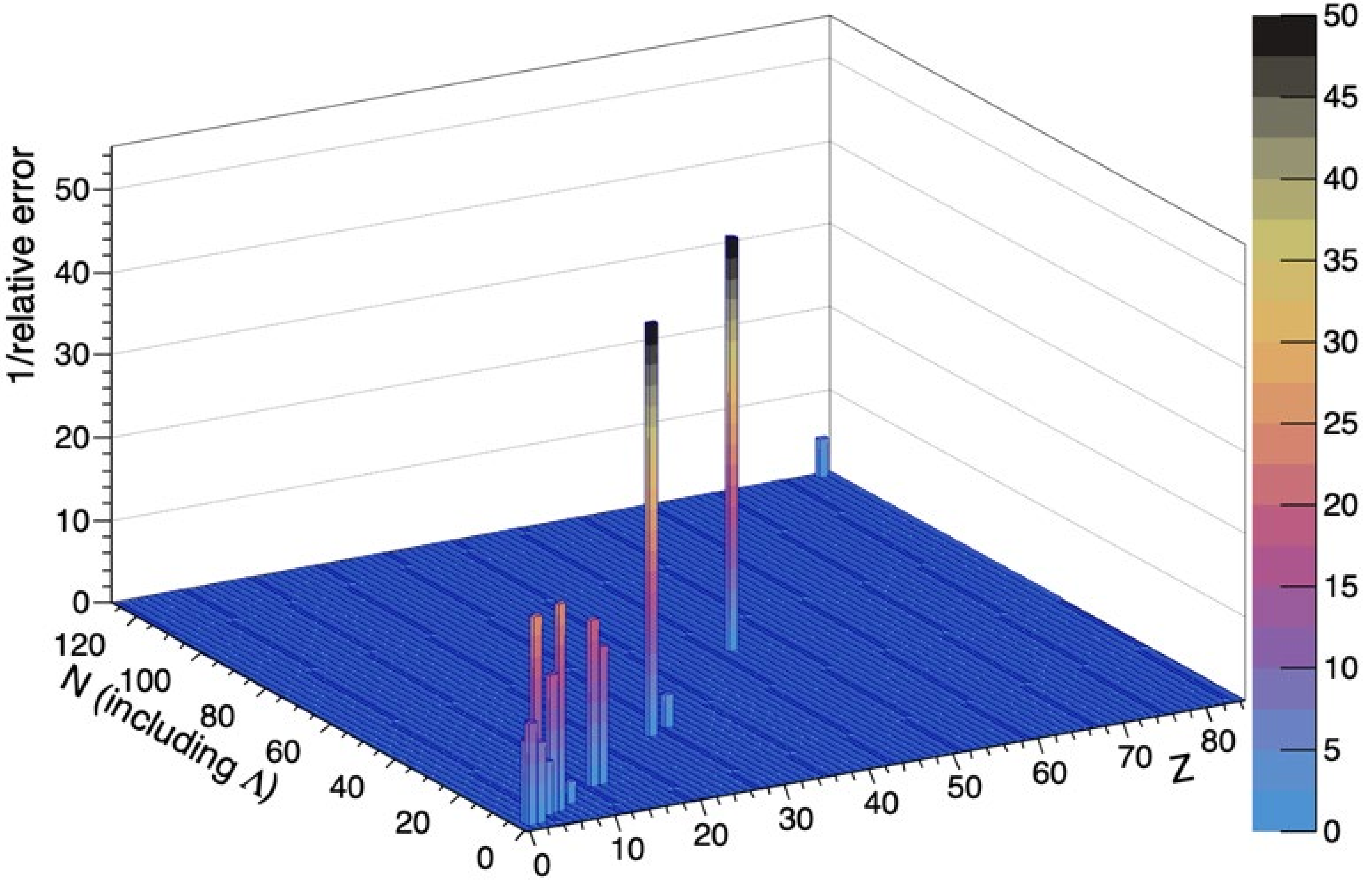
Addressed/addressable issues

- *s*-shell hypernuclei
  - ✓ Λ-$\mathcal{N}$ potential
- *p*-shell hypernuclei
  - ✓ π distortion effect and MWD enhancement
  - ✓ π^--nucleus optical potential
  - ✓ J^π assignment ☛ indirect spectroscopic tool

The status of the art about τ

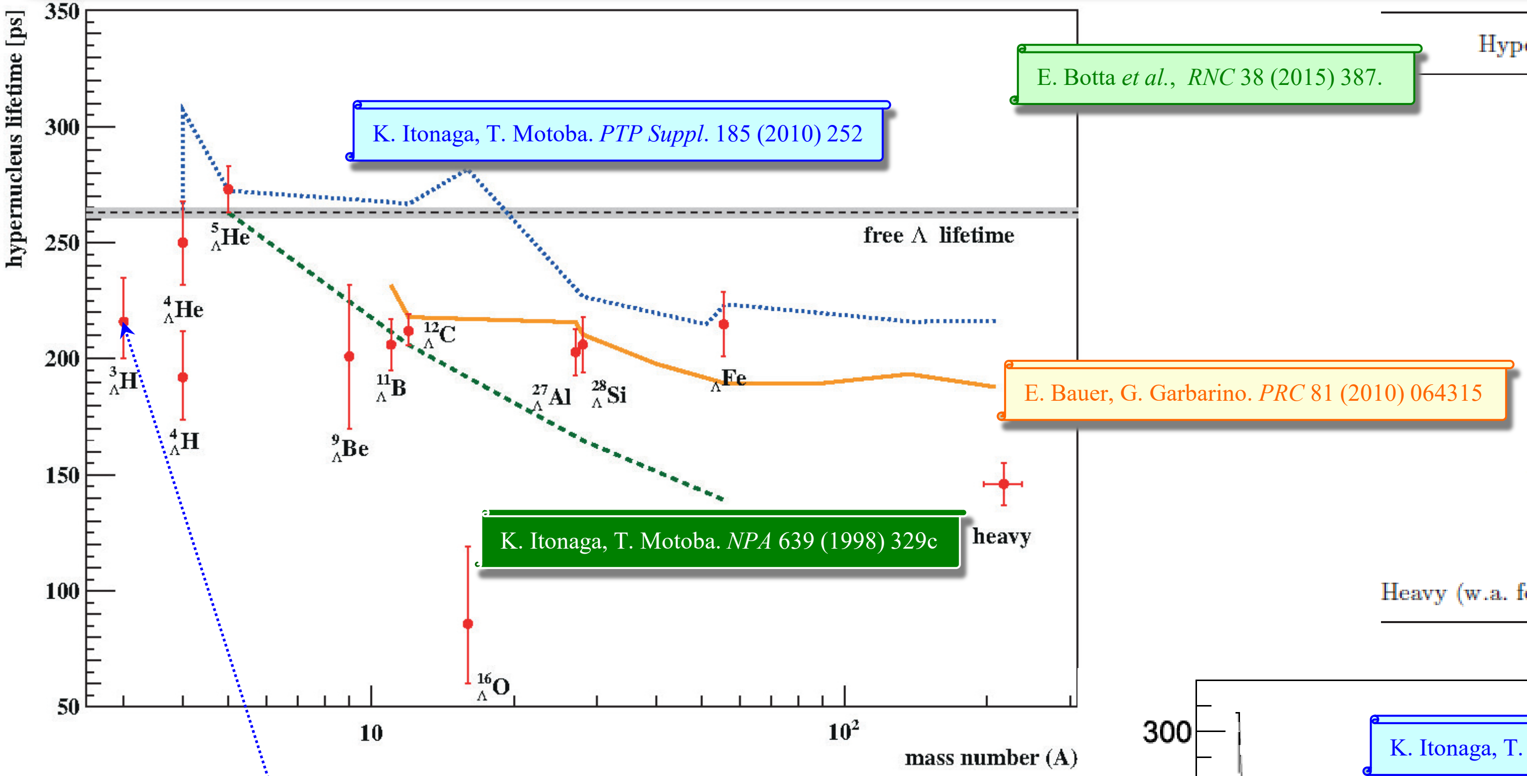
quality of
the measurement

Lifetime measurements



14 data
points

The status of the art about τ

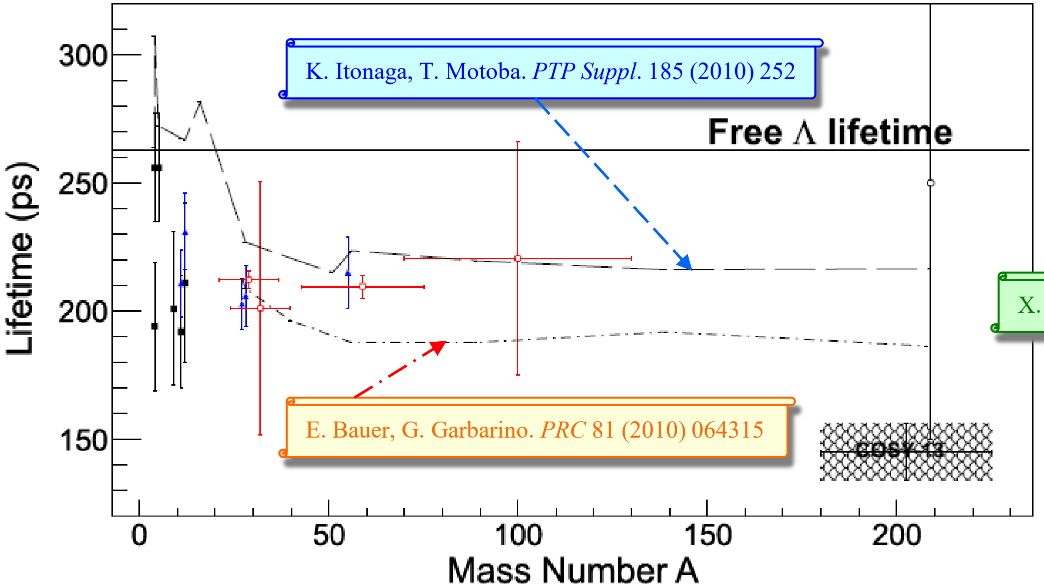


Hypernucleus	$\tau(^{A}_{\Lambda}Z)$ (ps)	Γ_T/Γ_Λ
$^{3}_{\Lambda}$H	216^{+19}_{-16}	$1.219^{+0.090}_{-0.107}$
$^{4}_{\Lambda}$H	192^{+20}_{-18}	$1.37^{+0.13}_{-0.14}$
$^{4}_{\Lambda}$He	250 ± 18	1.053 ± 0.076
$^{5}_{\Lambda}$He	273 ± 10	0.963 ± 0.034
$^{9}_{\Lambda}$Be	201 ± 31	1.31 ± 0.20
$^{11}_{\Lambda}$B	206 ± 11	1.276 ± 0.070
$^{12}_{\Lambda}$C	212^{+7}_{-6}	1.242 ± 0.040
$^{16}_{\Lambda}$O	86^{+33}_{-26}	not reliable
$^{27}_{\Lambda}$Al	203 ± 10	1.297 ± 0.064
$^{28}_{\Lambda}$Si	206 ± 12	1.278 ± 0.074
$_{\Lambda}$Fe	215 ± 14	1.224 ± 0.080
Heavy (w.a. for $180 < A < 238$)	146 ± 9	1.81 ± 0.12

w.a. recently updated:

206^{+15}_{-13} ps

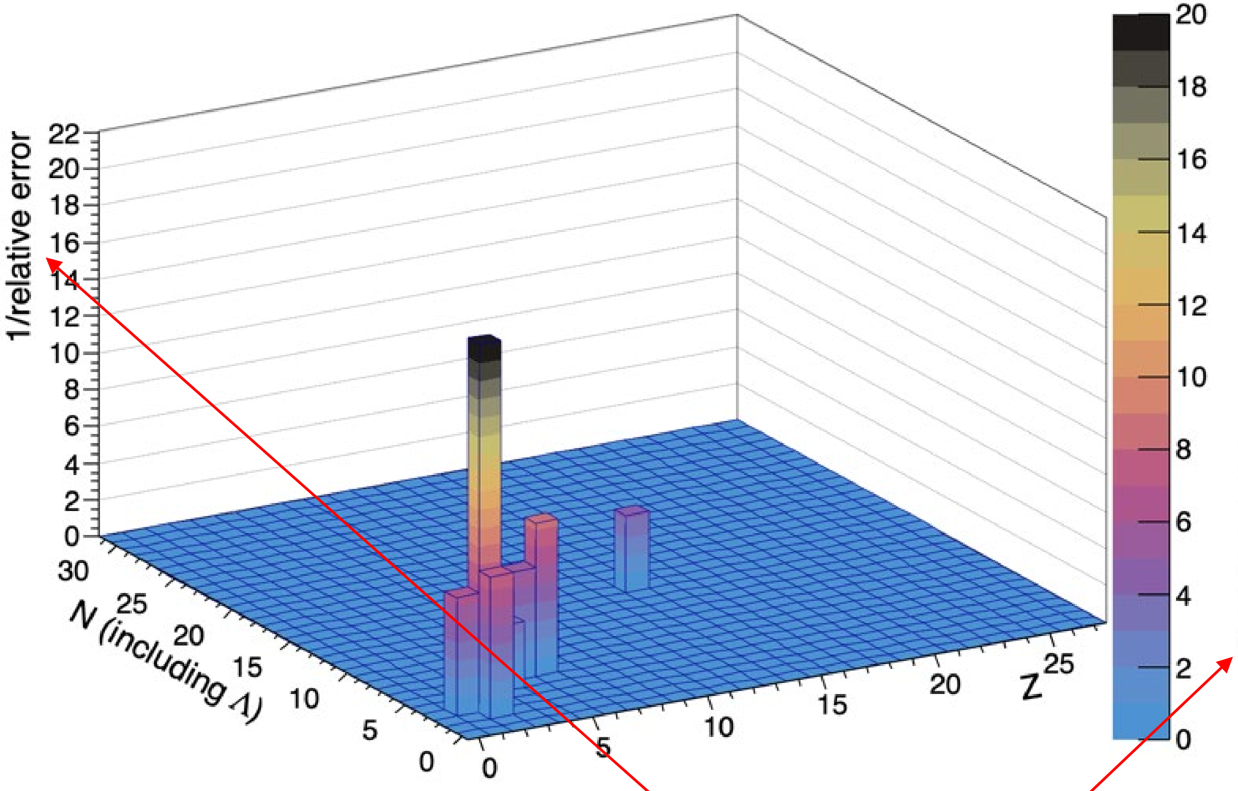
ALICE Coll., PLB (2019) 134905.



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

Γ_{π^-} and Γ_{π^0}: current experimental situation

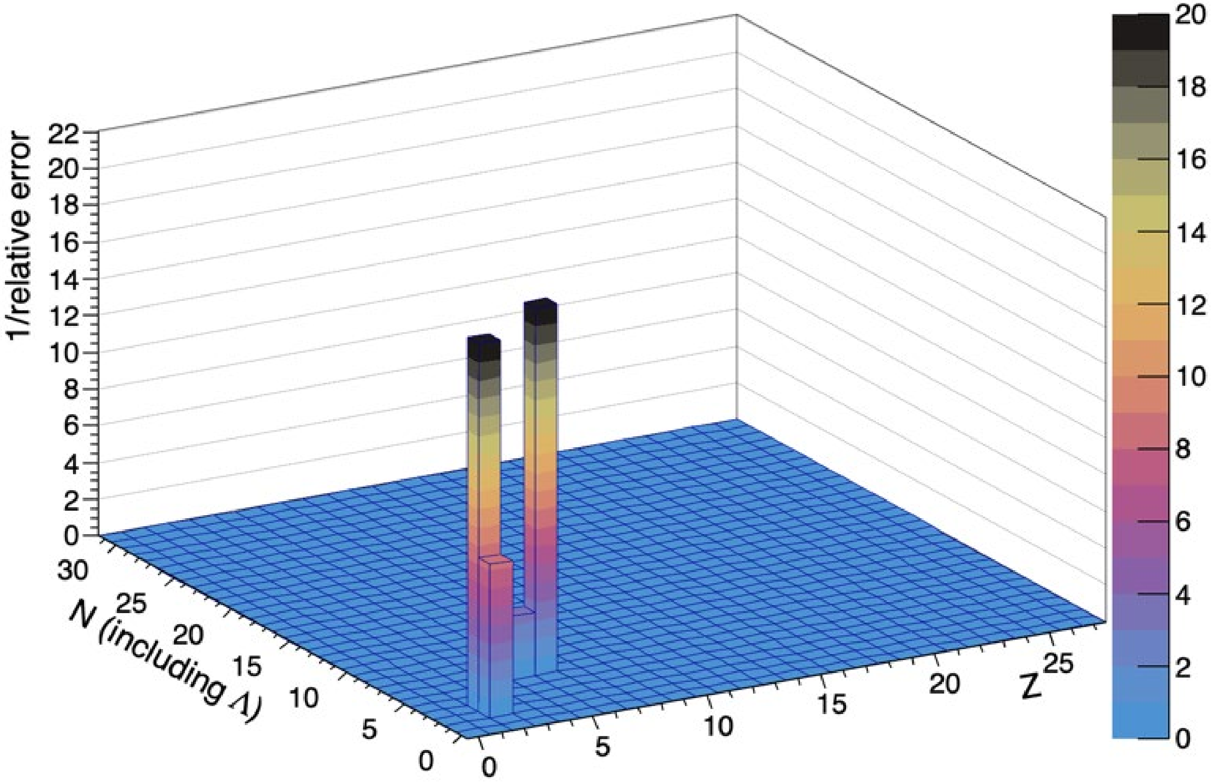
MWD, Γ_{π^-} measurements



9 data points

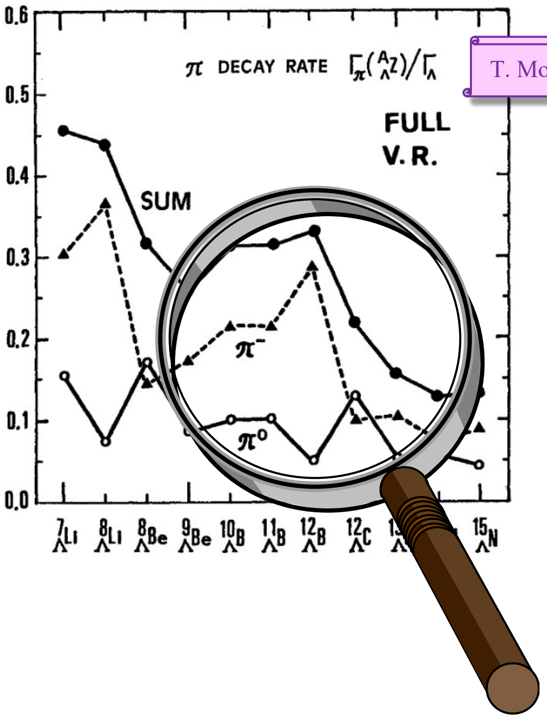
4 data points **only**!

MWD, Γ_{π^0} measurements

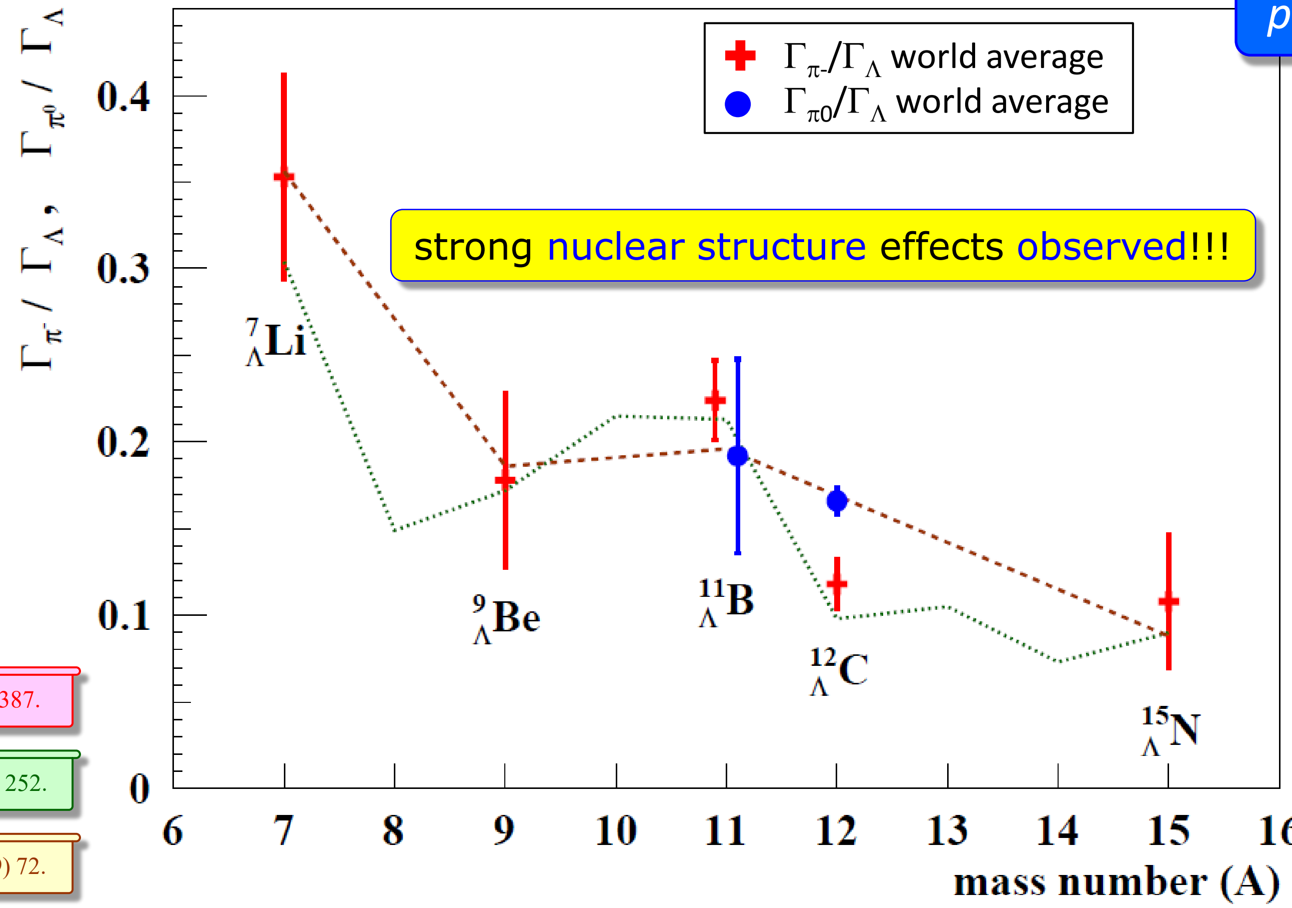


quality of the **measurement**

Γ_{π^-} and Γ_{π^0}: current experimental situation



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



p-shell

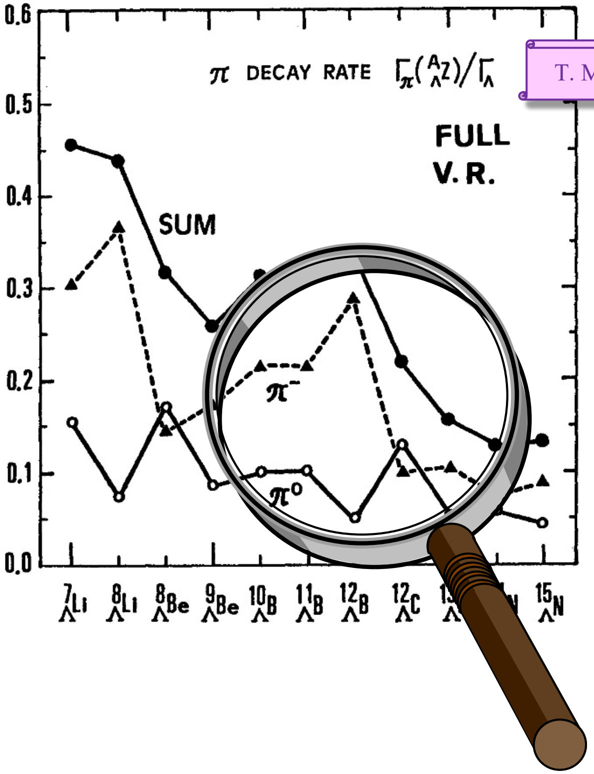
strong nuclear structure effects observed!!!

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

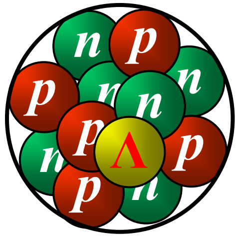
K. Itonaga, T. Motoba, *PTP Supp.* 185 (2010) 252.

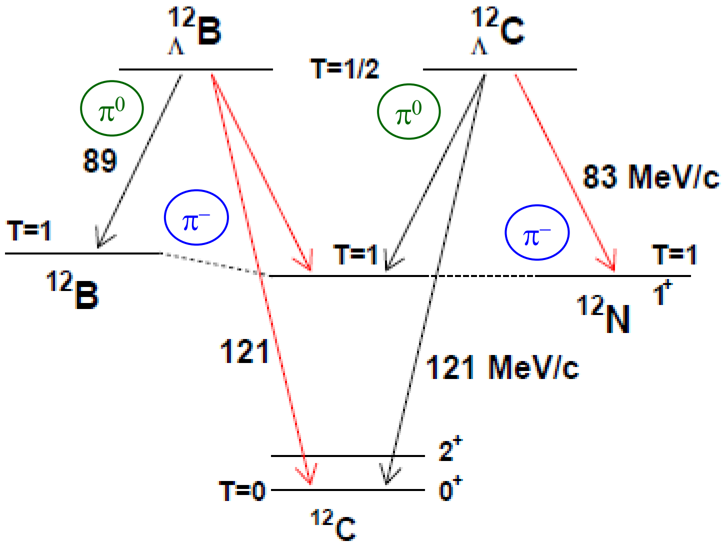
A. Gal, *NPA* 828 (2009) 72.

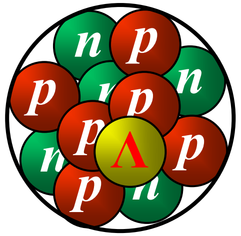
Looking for nuclear structure effects



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







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

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

theoretical predictions ☛

T. Motoba, *NPA* 547 (1992) 115c. ≈ 3

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

T. Motoba, *NPA* 547 (1992) 115c. ≈ 8

Non-mesonic weak decay (NMWD)

Experimental observables

- Γ_p, Γ_n
- $\Gamma_{2\mathcal{N}}$ and FSI contributions
- $\Gamma_{NM} = \Gamma_n + \Gamma_p + \Gamma_{2\mathcal{N}}$
- (single & coincidence) particle decay spectra

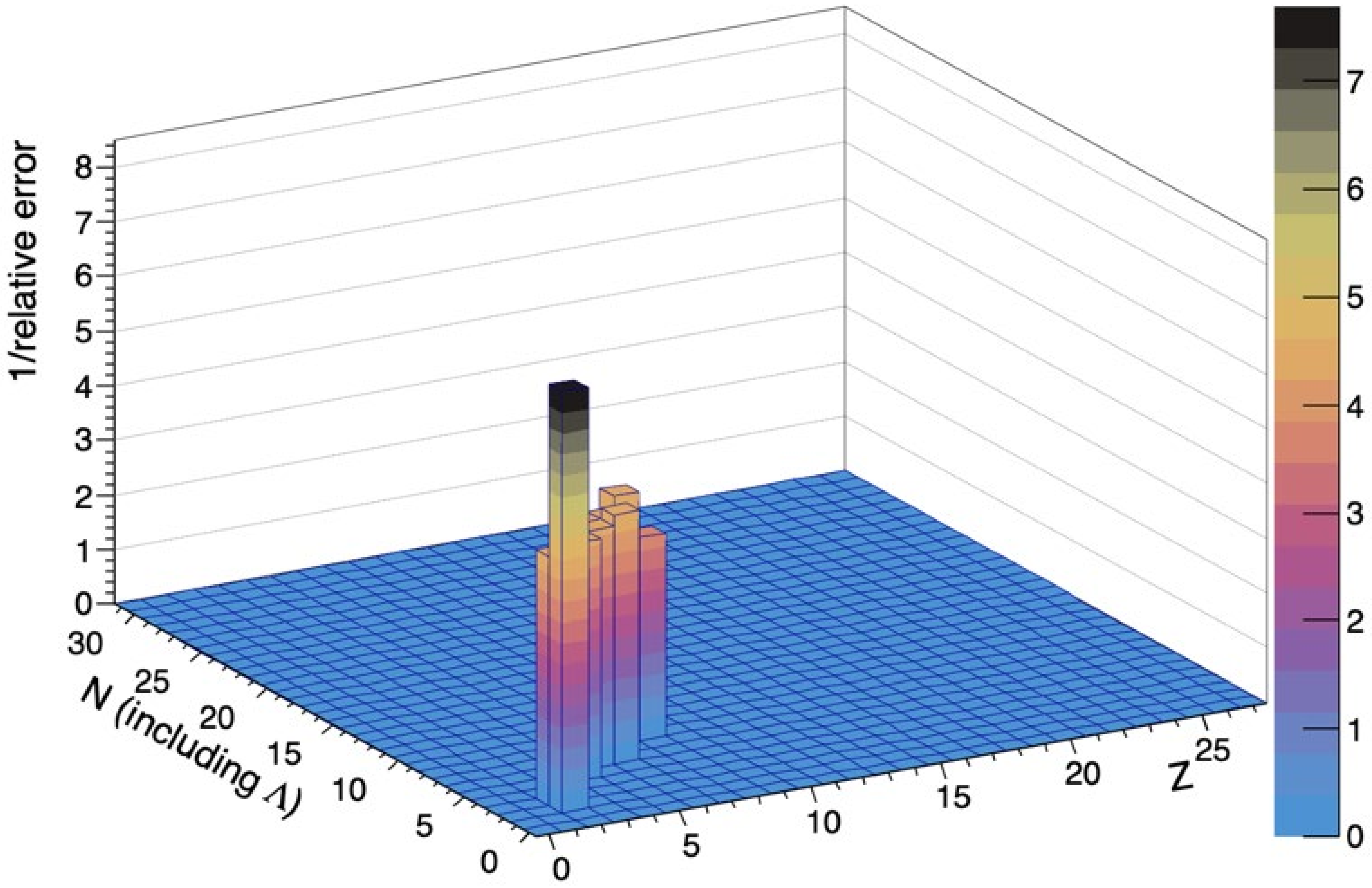
Addressed/addressable issues

- 4-baryon strangeness-changing weak interaction
- $\Delta I = 1/2$ rule validity from *s*-shell ($^4H_\Lambda$) and heavier hypernuclei
- ✓ Γ_n/Γ_p
- ✓ $\Gamma_{2\mathcal{N}}$ determination
- ✓ search for $\Gamma_{2\mathcal{N}}$ experimental evidence

Γ_p: current experimental situation

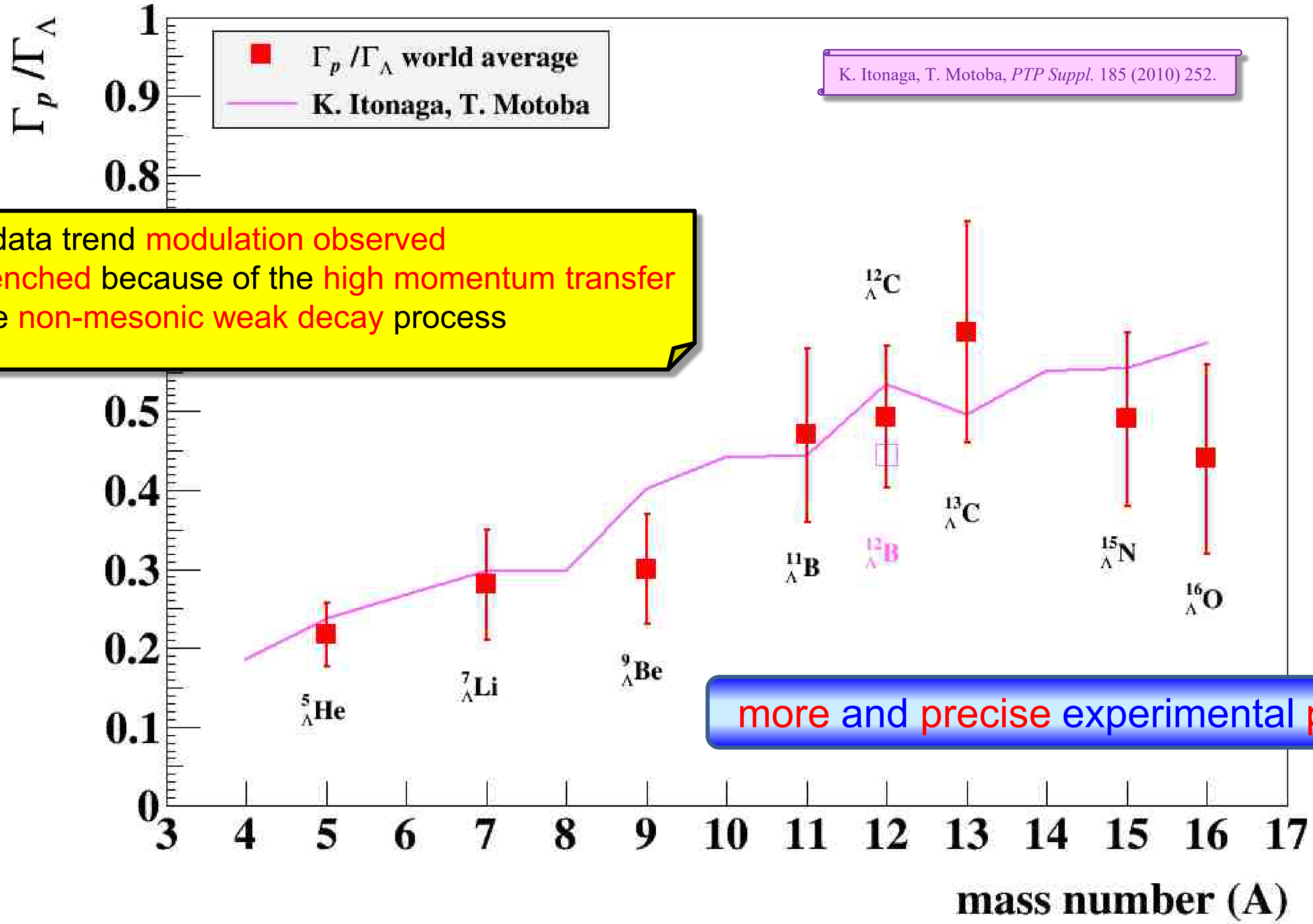
quality of
the measurement

NMWD, Γ_p measurements



9 data points

Γ_p: current experimental situation



data trend modulation observed
even though quenched because of the high momentum transfer
in the non-mesonic weak decay process

more and precise experimental points required!

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

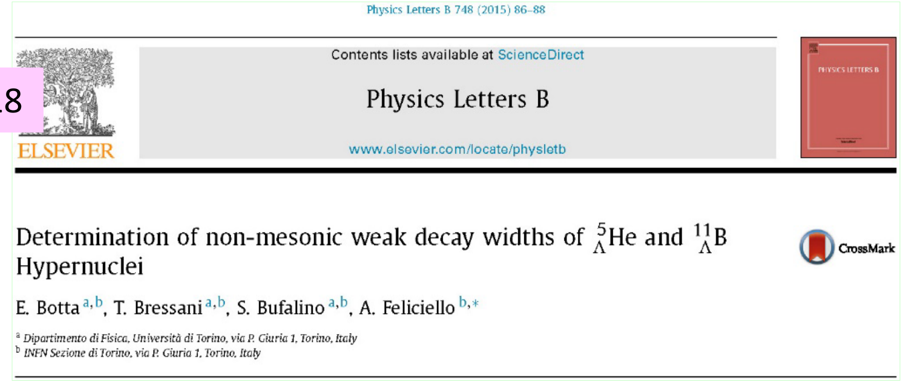
	${}^{5}_{\Lambda}\mathrm{He}$	${}^{11}_{\Lambda}\mathrm{B}$	${}^{12}_{\Lambda}\mathrm{C}$	${}^{12}_{\Lambda}\mathrm{C}$
Γ_T/Γ_Λ	0.962±0.034	1.274±0.072	1.241±0.041	1.241±0.041
$\Gamma_{\pi^-}/\Gamma_\Lambda$	0.342±0.015	0.228±0.027	0.120±0.014	0.123±0.015
$\Gamma_{\pi^0}/\Gamma_\Lambda$	0.201±0.011	0.192±0.056	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

Contents lists available at ScienceDirect

Physics Letters B

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

A new experimental approach @ J-PARC

original idea: K^0 spectroscopy

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

never exploited before!!!

dσ/dΩ

mb/sr

μb/sr

nb/sr

$$\pi^- + {}^A Z \rightarrow {}^A_\Lambda(Z-1) + K^0 \quad @\, p_\pi \approx 1.0 \div 1.1\, \mathrm{GeV}/c$$

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

NEW! @ J-PARC

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

- relative simple apparatus
- cheap detectors

Alessandro Feliciello / 2nd International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility, February 16-18, 2022

The (π^-, K^0) reaction

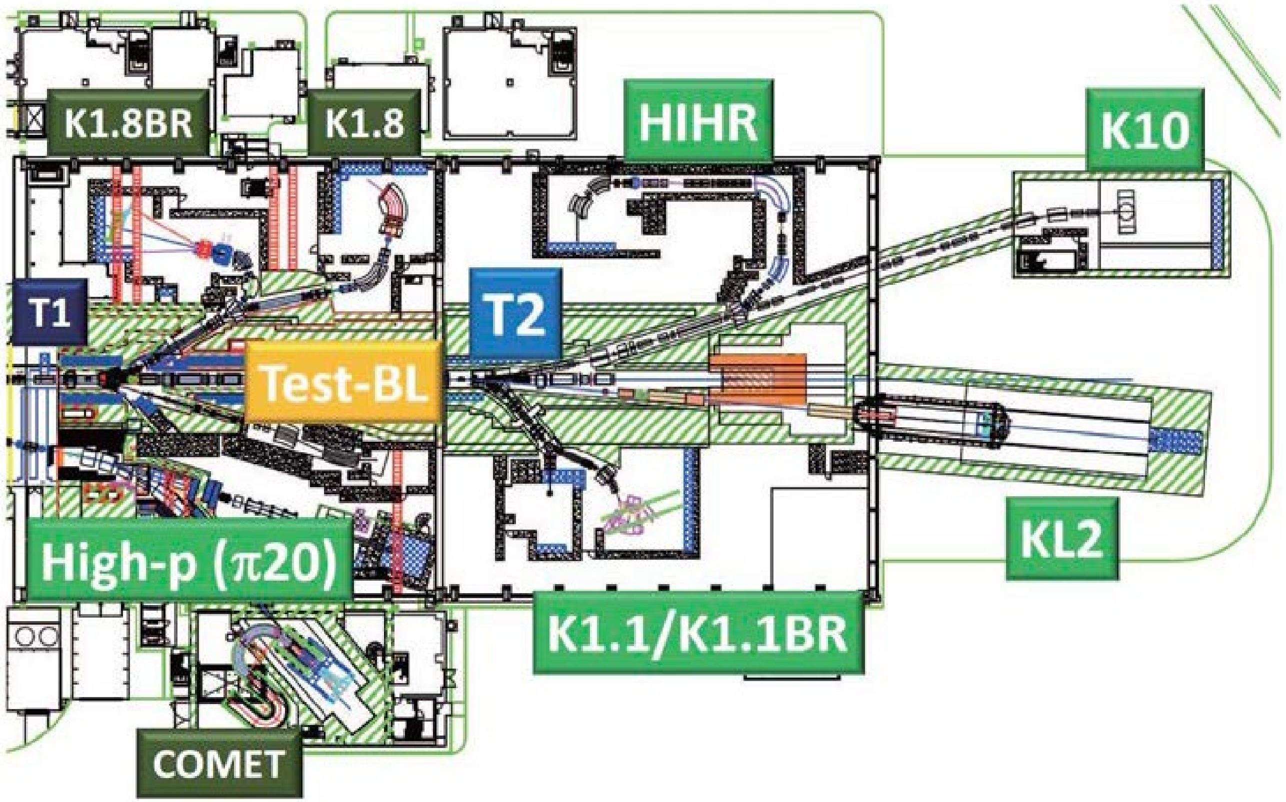
- well established reaction:
  - ! cross section experimentally known from the isospin symmetric (π^+, K^+)

- experimental feasibility to be demonstrated (experimental potentiality showed by K. Miwa in the E40 experiment)

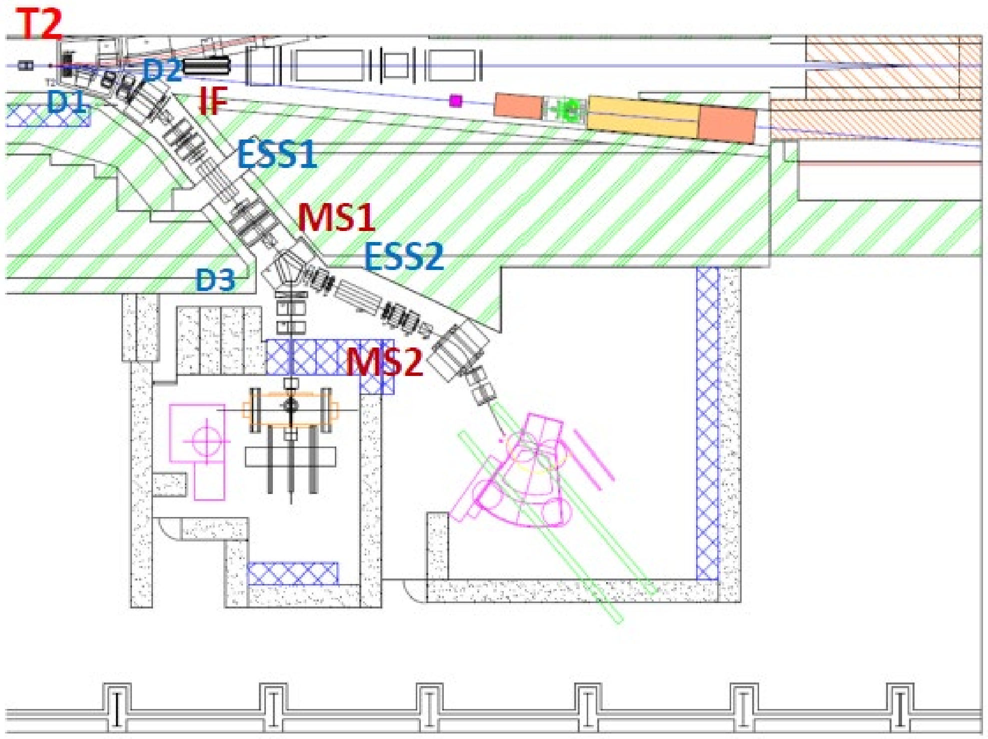
- doorway to neutron-rich Λ-hypernuclei study
  - further investigation of the hypernuclear weak decay process
  - $^4H_\Lambda$ non-mesonic Γ_p to check the validity of the $\Delta I = ½$ rule
  - systematic and precise (≤ 5%) determination of the full pattern of the partial weak decay widths

- important investigation tool
  - for hydrogen Λ hyper-isotopes lifetime measurement

The experimental layout



beam lines in the extended area				
K1.1	$K^{\pm}, \pi^{\pm}$	< 1.2 GeV/c	$\sim 4{\times}10^5$ K^- /spill (1.1)	mass separated
K1.1BR	$K^{\pm}, \pi^{\pm}$	0.7 – 0.8 GeVc	$\sim 1.5{\times}10^5$ K^- /spill	mass separated
HIHR	$\pi^{\pm}$	< 2.0 GeV/c	$\sim 2{\times}10^8$ π /spill (1.2)	mass separated $\times 10$ better $\Delta p/p$
K10	$K^{\pm}, \pi^{\pm}, \overline{p}$	< 10 GeV/c	$\sim 7{\times}10^6$ K^- /spill	mass separated
KL2	K_L	~ 5 GeV/c in ave.	$\sim 4{\times}10^7$ K_L /spill	5° extraction angle optimized n/K_L



Detector minimum performances requirements

✔ $\Delta_{T(prongs)}$ ≤ 3 MeV (FWHM) ☛ range detector

✔ σ_{ϑ} ≤ 100 mrad ☛ drift chambers, cylindrical drift chamber? LGADs pixels, MAPS?

✔ Δ_{MM} ≤ 4 MeV (FWHM)

✔ Δ_{time} ≤ 100 ps (rms) ☛ plastic scintillators, LGADs pixels?

✔ Ω ≥ 2π sr

? magnetic spectrometer?

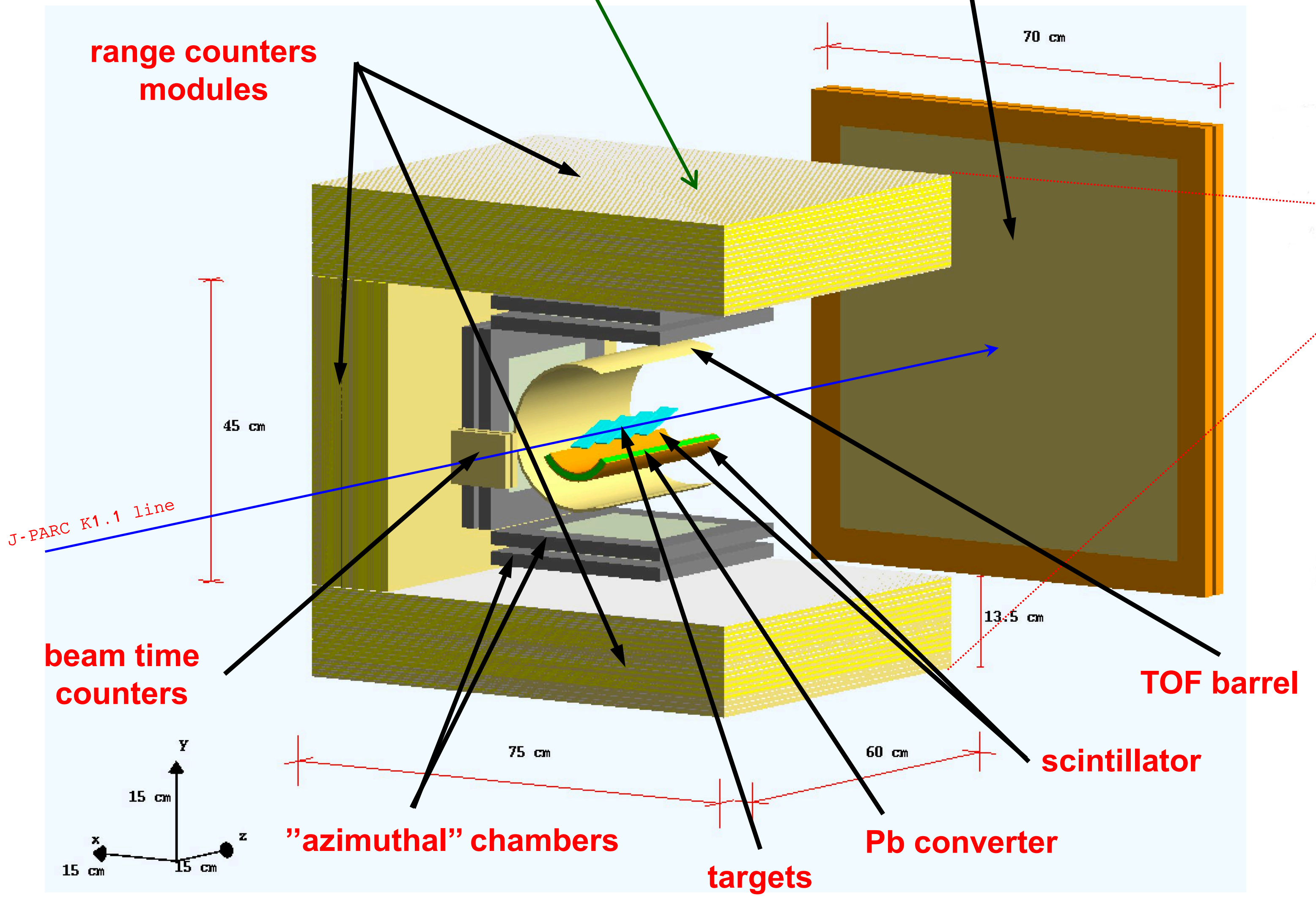
! desiderable but… impact on the target choice

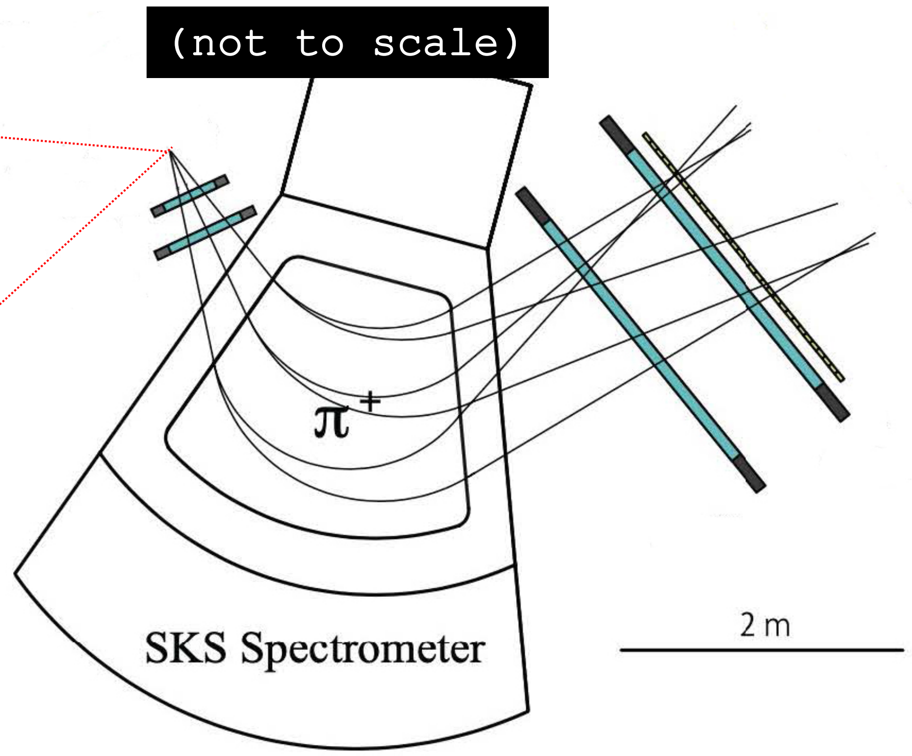
interest

→ know-how

Very basic concept design

modular design



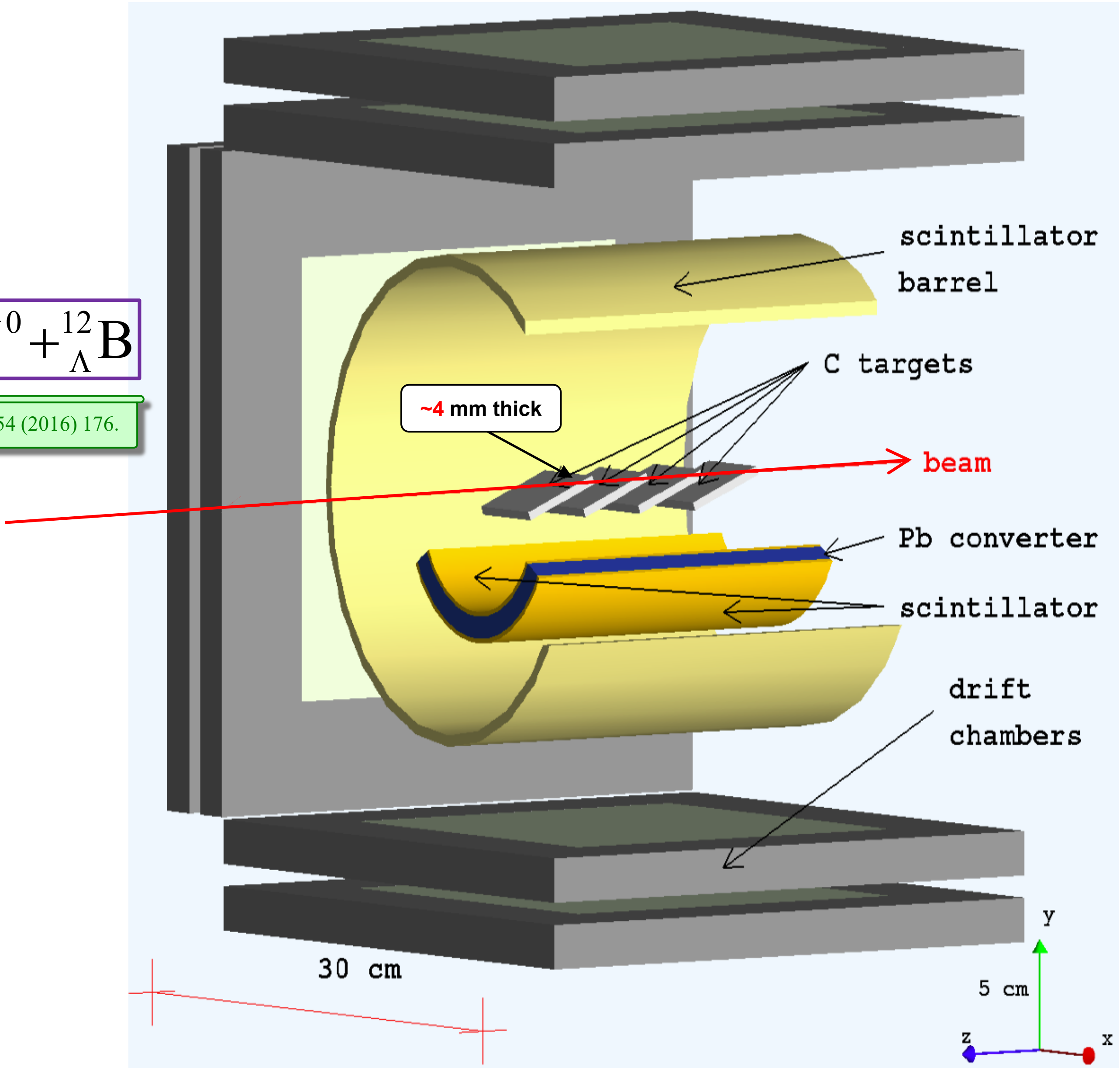


M. Agnello *et al.*, *NPA* 954 (2016) 176.

Very basic concept design

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

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



target tilt angle: ~15° ÷ 20°

C target thickness:
≈0.7 gr/cm^2

along the beam:
≈1.0 gr/cm^2

further alternatives:

In the same run

^{6}Li

^{7}Li

^{9}Be

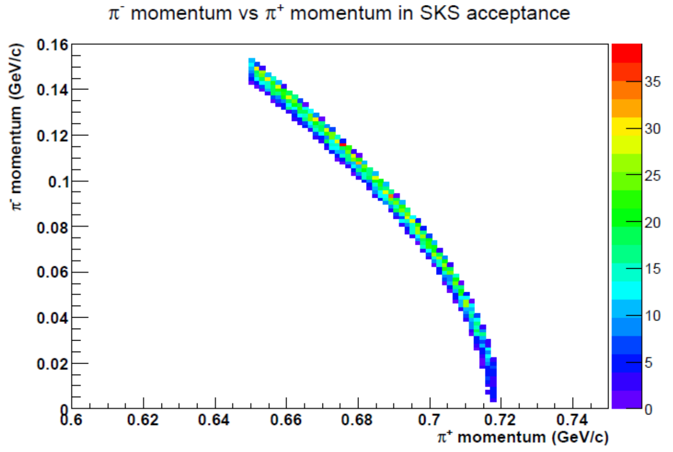
^{16}O

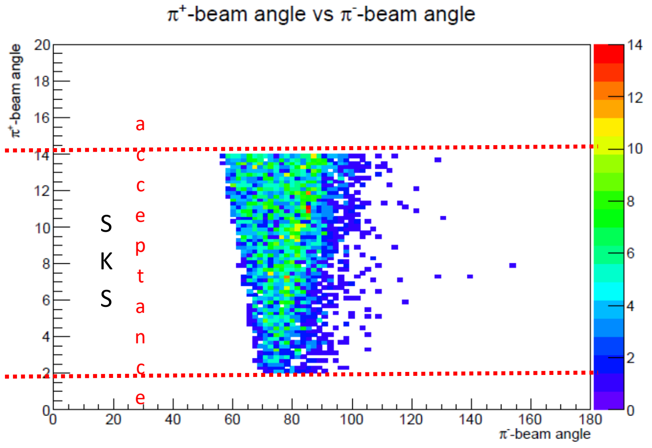
theoretical advice required!

$^5\mathrm{He}_\Lambda$ $^7\mathrm{Li}_\Lambda$ $^9\mathrm{Be}_\Lambda$ $^{15}\mathrm{N}_\Lambda$ $^{16}\mathrm{O}_\Lambda$ …

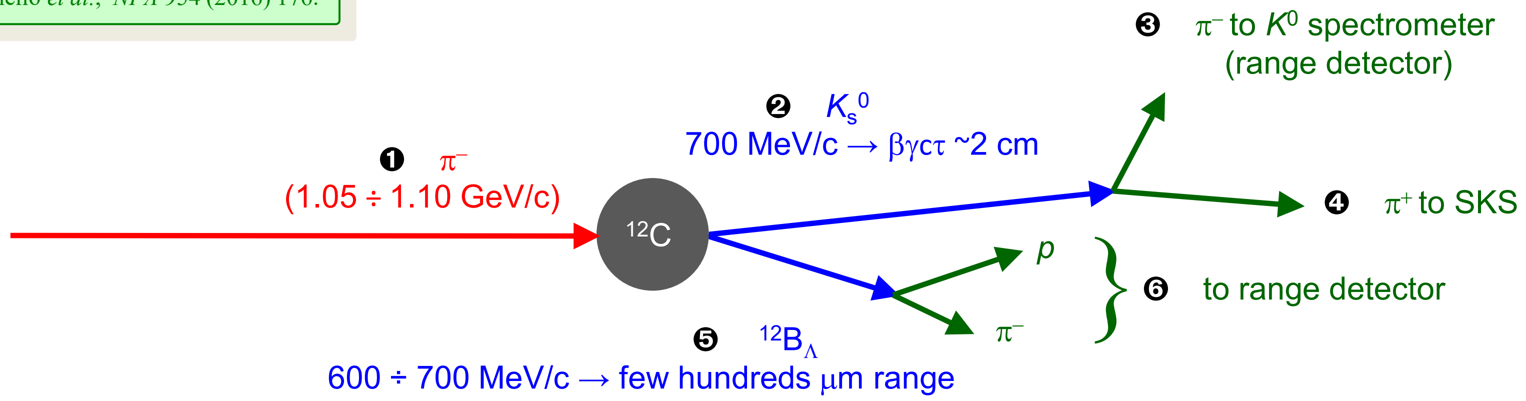
Event selection criteria

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





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°

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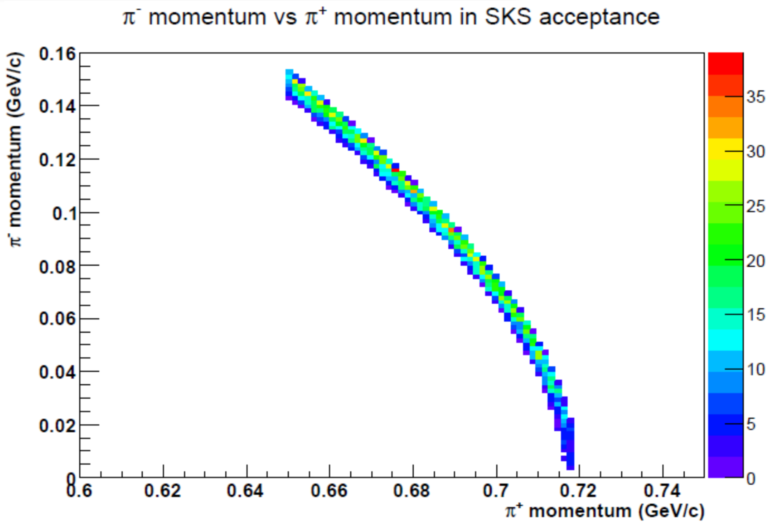
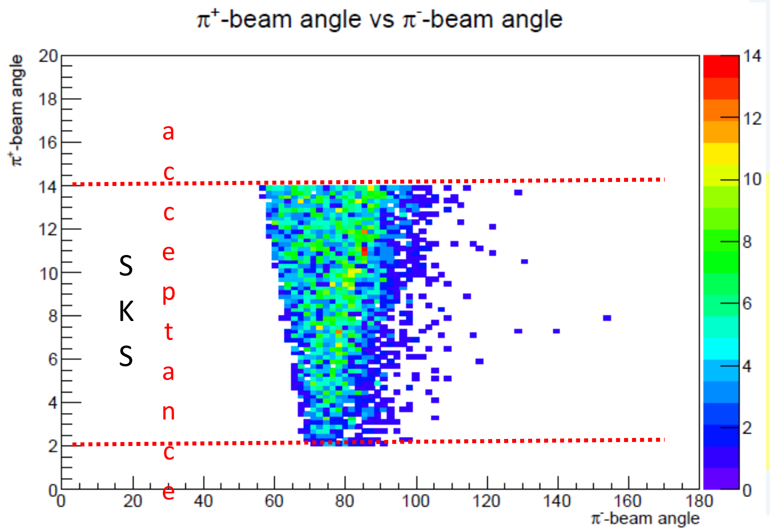
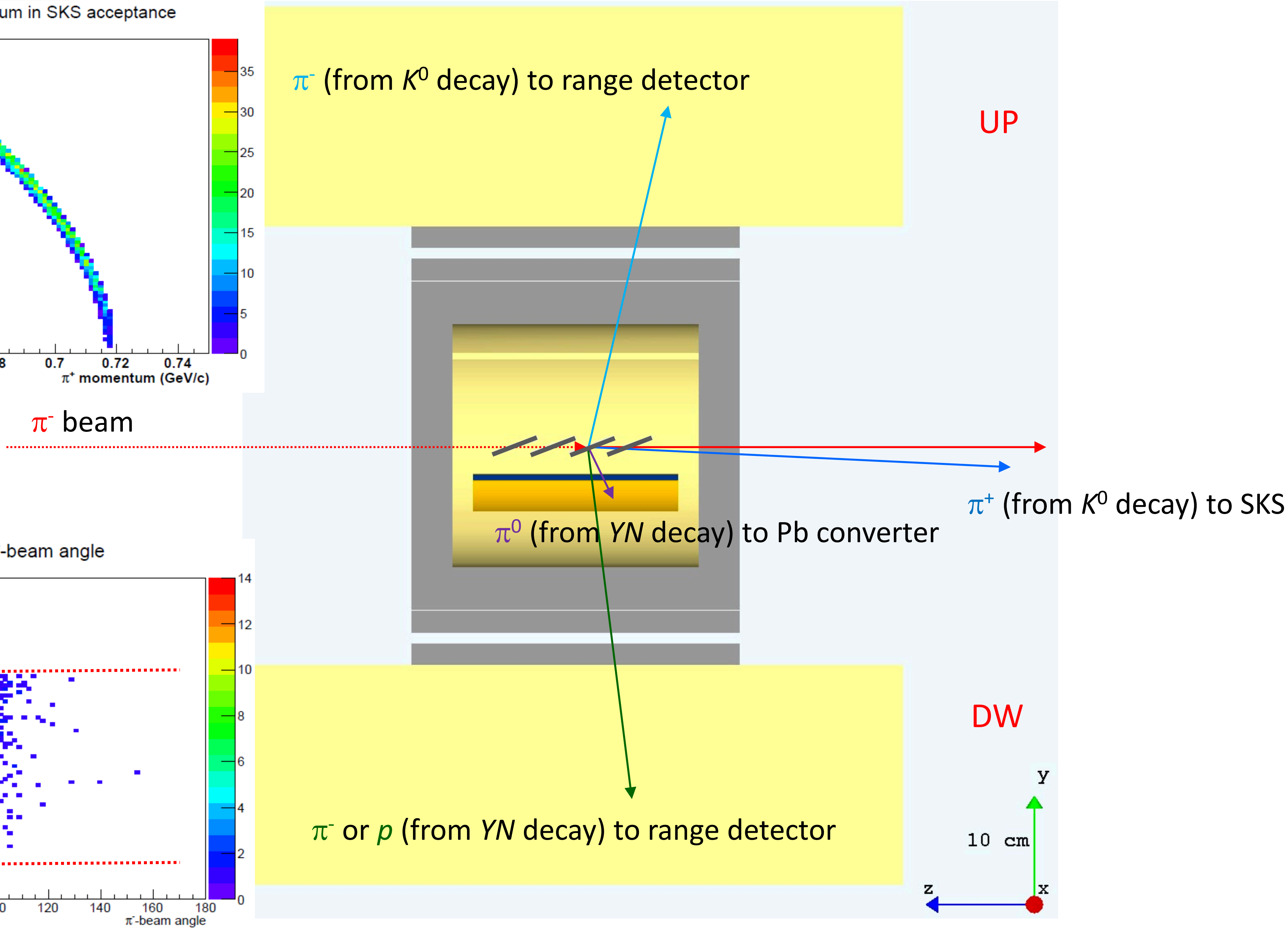
A typical event

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







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

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

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

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

Γ_{π^-} 0.286 — Γ_{π^0} 0.049 — Γ_p 0.446

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

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

$\approx 3\%$ on Γ_π — $\approx 1.5 \times 10^3$ events

$\approx 1.5 \times 10^2$ events

$\approx 3.0 \times 10^3$ events — $\approx 2\%$ on Γ_p

$\approx$ 2-3% on τ — $\approx 1.0\text{-}2.0 \times 10^3$ events

precise measurement → $\tau({}^{12}_{\Lambda}\mathrm{B})$

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

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

$\text{N}_{\text{beam}} = 0.5 \times 10^{11}\ \pi^+$ — limited request

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

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

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

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

$\varepsilon_{sp} = 0.5$

$\varepsilon_{an} = 0.7$

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

produced in the detector acceptance

Γ_p — **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 × 10^3 ev.

≈ 3% on Γ_p

1-day data taking

$$\pi^+ + {}^{12}\text{C} \rightarrow K^+ + {}^{12}_{\Lambda}\text{C}$$

Summary and outlook

- exciting physics program possible at the J-PARC K1.1 line by exploting the (π^-, K^0) reaction

- doorway to neutron rich Λ-hypernuclei investigation
  - detailed study of neutron-rich, *p*-shell Λ-hypernucleus ($^{12}B_\Lambda$) decay process
  - systematic and precise (≤ 5%) determination of
    - the full pattern of the partial weak decay widths
    - lifetimes


Thank you!
どうも ありがとう