Hypernuclear projects of the high-resolution mass spectroscopy at JLab

University of Tokyo
Sho Nagao

May 16, 2024

Outline

- Motivation
- Overview of hypernuclear exp. at JLab
- Prospects of JLab hypernuclear project

  (e,e'K^+) Missing Mass Spectroscopy

  Decay Pion Spectroscopy

Motivation

Light Λ hypernuclei

We have long-standing discussed about ΛN CSB, ΛN-ΣN coupling etc.

There are some update of B_Λ for ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$, ${}^{7}_{\Lambda}He$, ${}^{10}_{\Lambda}Be$

We have still used B_Λ data of 1960s emulsion

Data precision is enough ?

Only a few n-rich hypernuclei (${}^{8}_{\Lambda}He$, ${}^{6}_{\Lambda}H$) are available

Hypernuclides	ΔB_Λ(Exp) (keV) [4]
${}^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$	300 ± 60
${}^{7}_{\Lambda}\mathrm{Li}^{*} - {}^{7}_{\Lambda}\mathrm{He}$	-320 ± 140
${}^{8}_{\Lambda}\mathrm{Be} - {}^{8}_{\Lambda}\mathrm{Li}$	40 ± 80
${}^{9}_{\Lambda}\mathrm{B} - {}^{9}_{\Lambda}\mathrm{Li}$	-160 ± 210
${}^{10}_{\Lambda}\mathrm{B} - {}^{10}_{\Lambda}\mathrm{Be}$	100 ± 300
${}^{11}_{\Lambda}\mathrm{B}^{*} - {}^{11}_{\Lambda}\mathrm{Be}$	N/A

Medium-Heavy hypernuclei

(π^+,K^+) exp. have measured B_Λ wide mass range

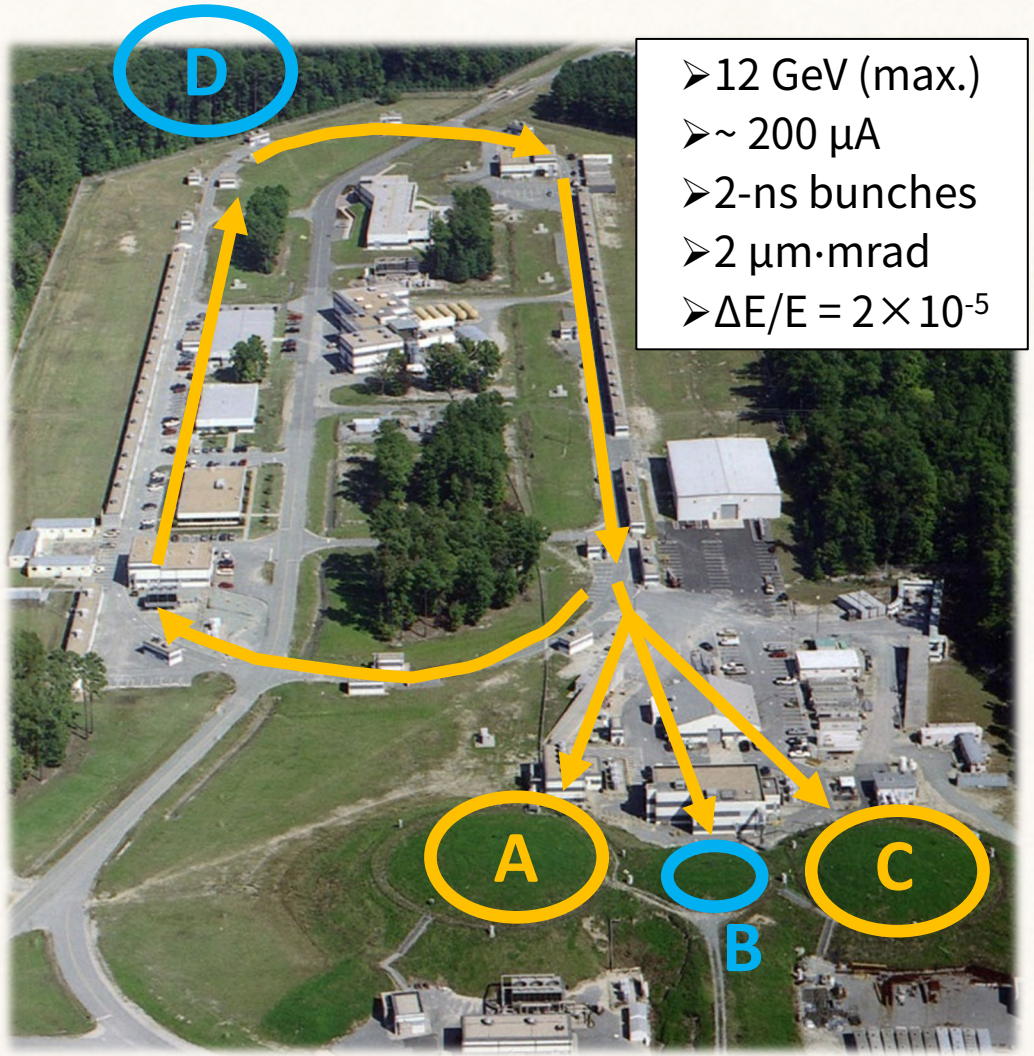
We have only B_Λ data on β-stability nuclei

Peak significance is not enough for several hypernuclei

B_Λ of ${}^{12}_{\Lambda}C$ likely to have shifted around 0.5 MeV

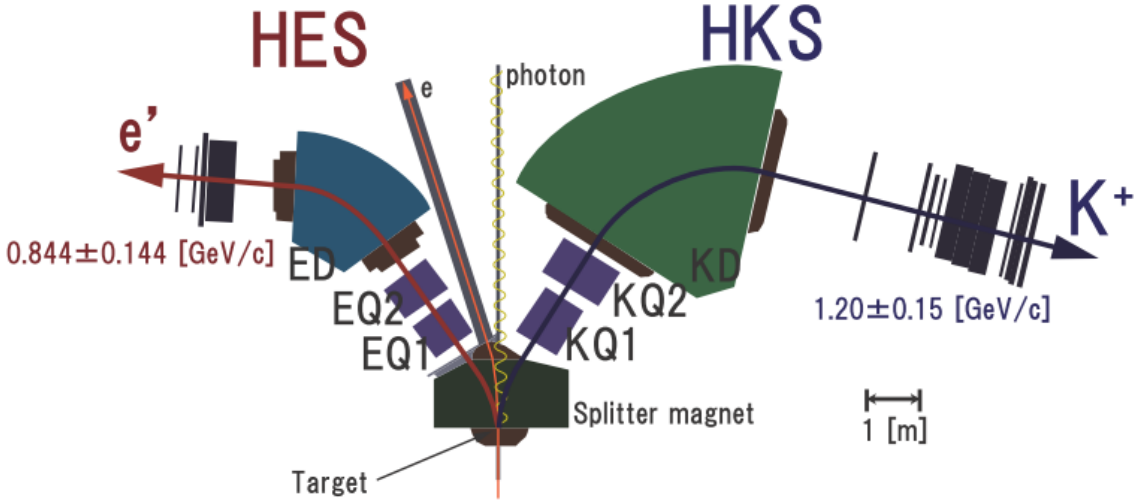
JLab CEBAF & (e,e'K$^+$) missing mass spectroscopy

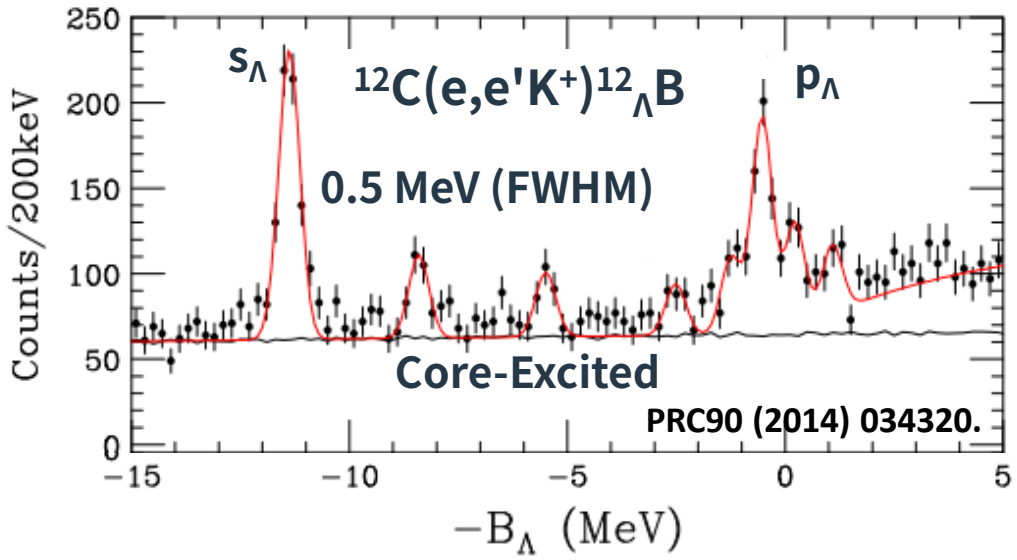
Continuous Electron Beam Accelerator Facility (CEBAF)



- 12 GeV (max.)
- ~ 200 μA
- 2-ns bunches
- 2 μm·mrad
- $\Delta E/E = 2 \times 10^{-5}$

Exp. Setup of JLab Hall-C experiment





Overview of Hypernuclear Exp. @JLab

2000 — $^{12}_{\Lambda}\mathrm{B}$ — $^{12}\mathrm{C}(e,e'K^+)^{12}_{\Lambda}\mathrm{B}$ *PRL90 (2000) 232502.*

HKS Const. Tilt Method

2005 — $^{9}_{\Lambda}\mathrm{Li}$, $^{12}_{\Lambda}\mathrm{B}$, $^{16}_{\Lambda}\mathrm{N}$ *PRL103 (2009) 202501. NPA835 (2010) 129.*

$^{7}_{\Lambda}\mathrm{He}$, $^{12}_{\Lambda}\mathrm{B}$, $^{28}_{\Lambda}\mathrm{Al}$ *PRL110 (2013) 012502. JPS Conf. Proc. 17, (2017) 011002.*

HES Const.

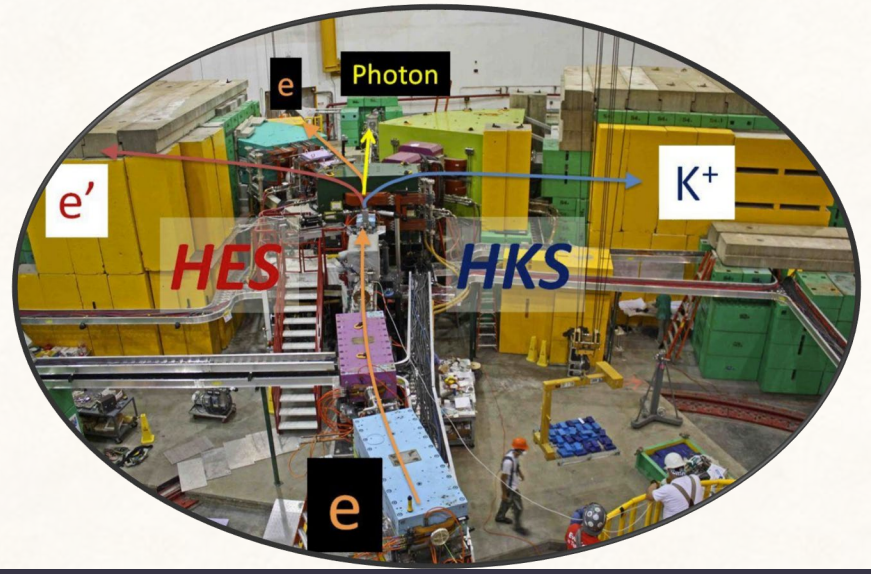
2009 — $^{7}_{\Lambda}\mathrm{He}$, $^{9}_{\Lambda}\mathrm{Li}$, $^{10}_{\Lambda}\mathrm{Be}$, $^{12}_{\Lambda}\mathrm{B}$, $^{52}_{\Lambda}\mathrm{V}$ *PRC73 (2006) 044607. PRC90 (2014) 034320. PRC93 (2016) 034314. PRC94 (2016) 021302. PRC103 (2021) L041301.*

12 GeV Upgrade

2018 — $^{3}_{\Lambda}n$ *PTEP, Vol2022, (2022) 013D01. PRC105 (2022) L051001.*

PCS Const.

2026-27 ?? — $^{3}_{\Lambda}\mathrm{H} - {}^{208}_{\Lambda}\mathrm{Tl}$



Proposed Experiments

^{40,48}Ca(e,e'K$^+$)$^{40,48}_{\Lambda}$K (Approved)

An isospin dependence study of the ΛN interaction through the high precision spectroscopy of Λ-hypernuclei with electron beam

^{208}Pb(e,e'K$^+$)$^{208}_{\Lambda}$Tl (Approved)

Studying Λ interactions in nuclear matter with the ^{208}Pb(e,e'K$^+$)$^{208}_{\Lambda}$Tl reaction

^{6}Li, ^{9}Be, ^{11}B(e,e'K$^+$)$^{6}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{11}_{\Lambda}$Be

Study of charge symmetry breaking in p-shell hypernuclei

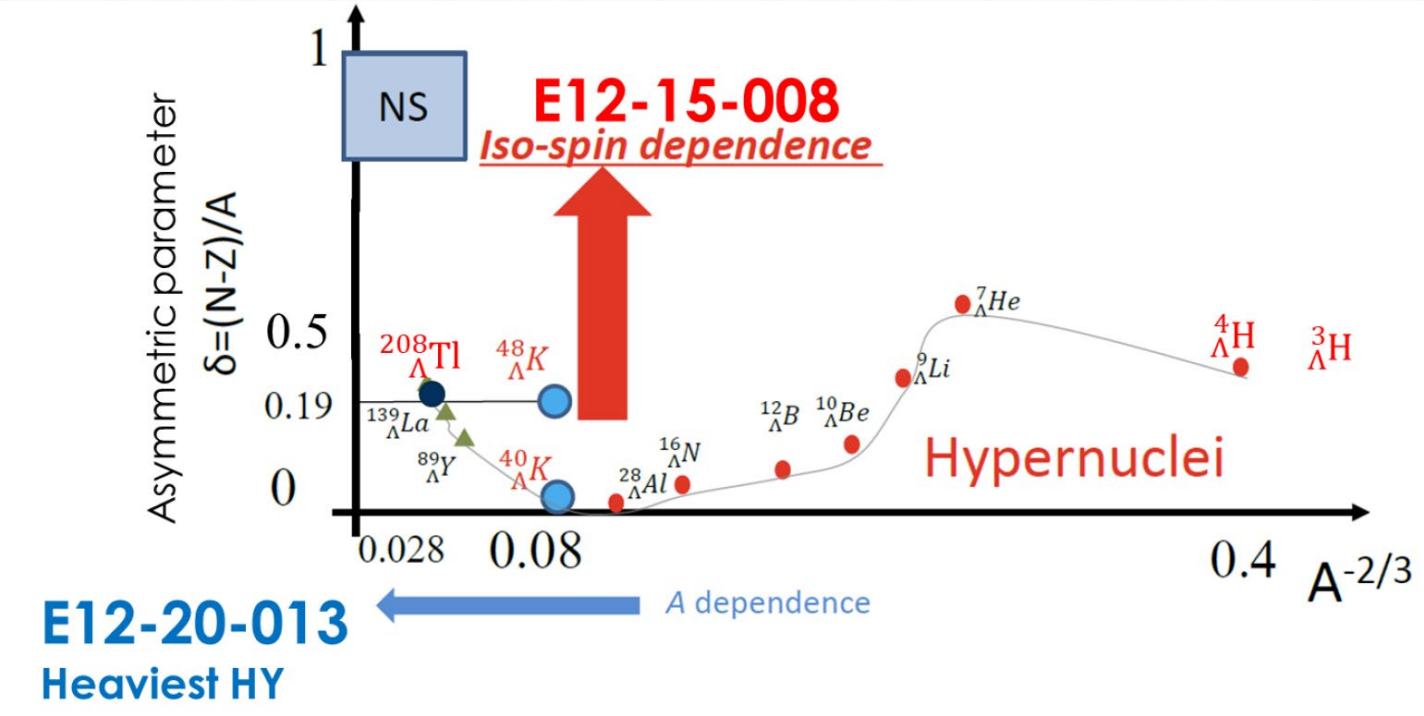
^{27}Al(e,e'K$^+$)$^{27}_{\Lambda}$Mg

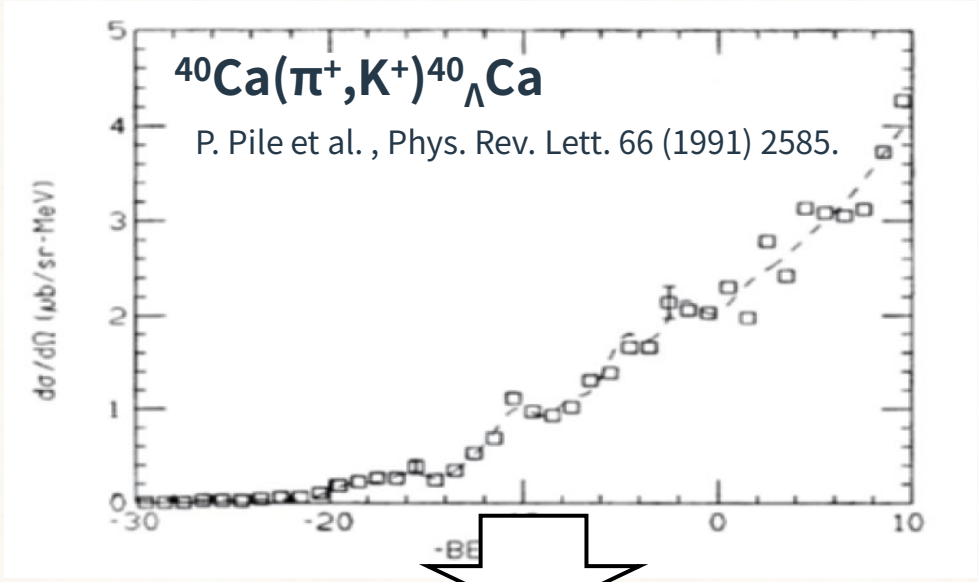
Study of a triaxially deformed nucleus using a Lambda particle as a probe

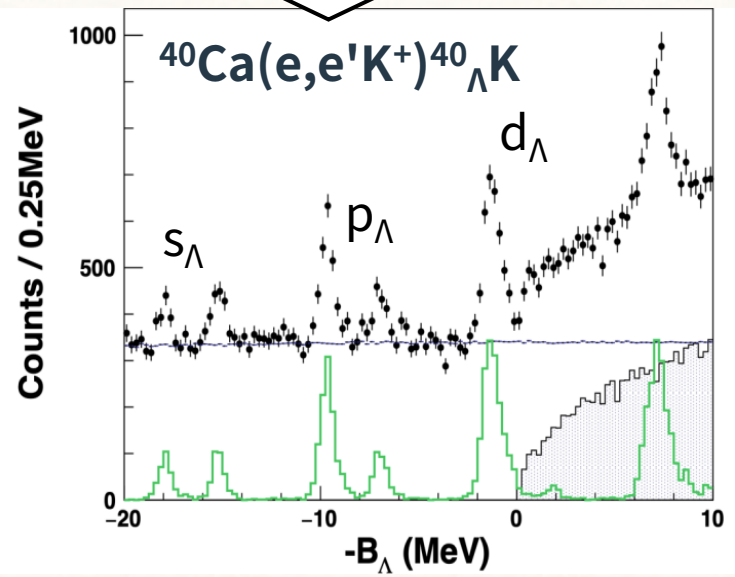
s-, p-shell hypernuclei with Decay Pion Spectroscopy

High-resolution spectroscopy of light hypernuclei with the decay pion spectroscopy

Hypernuclear Isotopes ($^{40,48}_{\Lambda}$K)







Study of effective ΛN interaction to support 2⊙ NS

Mass dependence

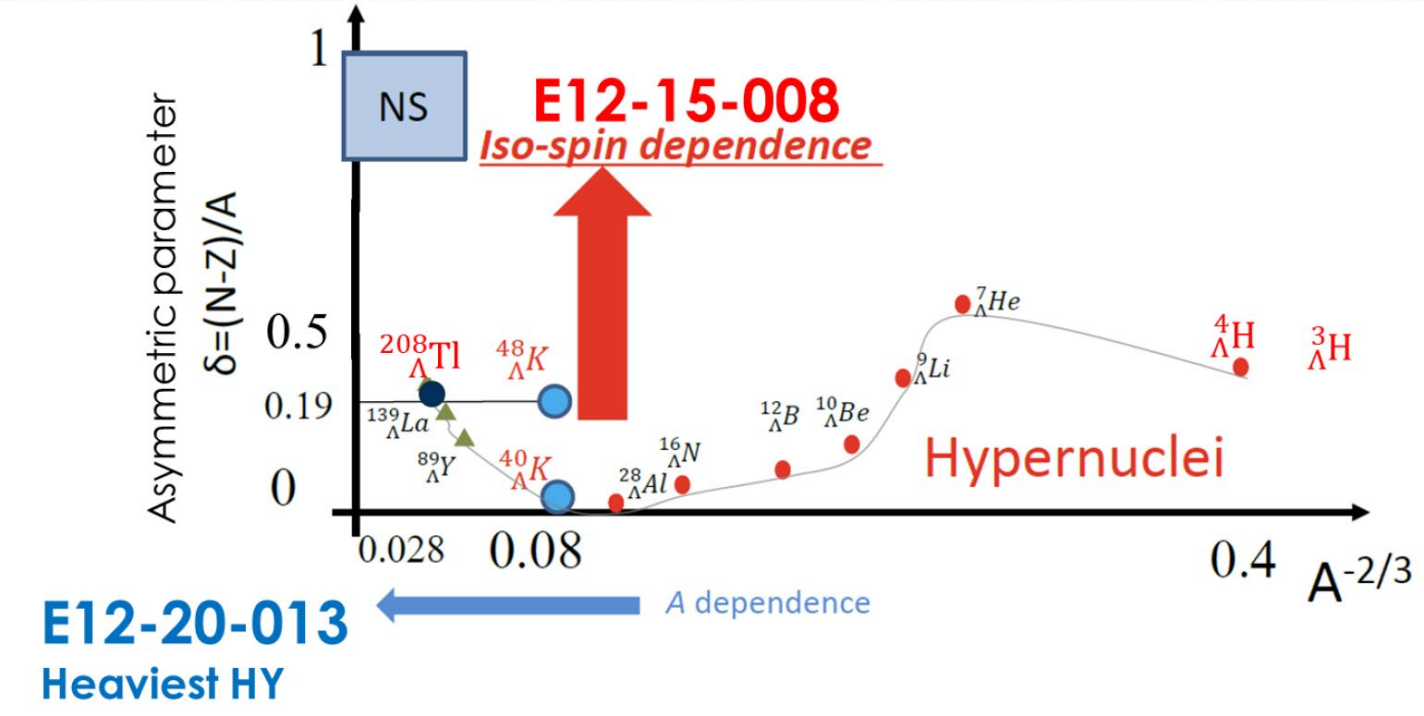
Poor data quality

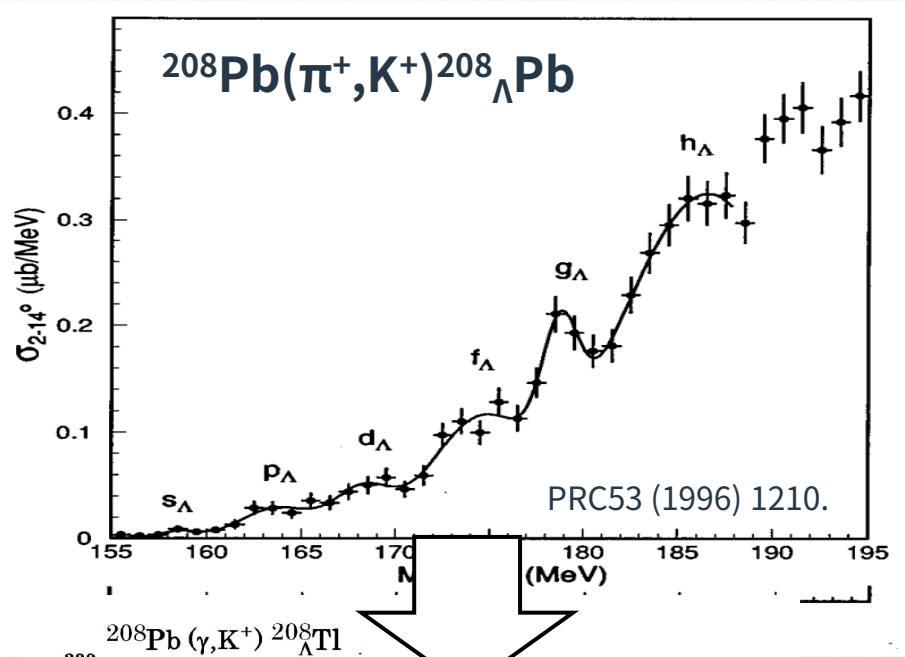
Isotope dependence

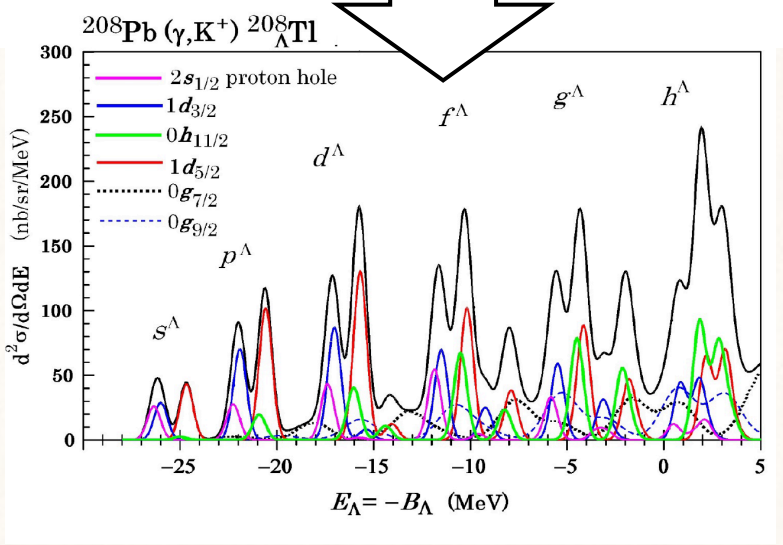
No data for A>12

⇨ **High-resolution Spectroscopy**

Super-Heavy hypernuclei ($^{208}_{\Lambda}$Tl)







Study of effective ΛN interaction to support 2⊙ NS

Mass dependence

Poor data quality

Isotope dependence

No data for A>12

⇨ **High-resolution Spectroscopy**

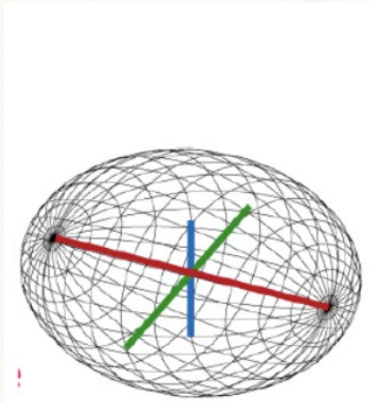
CSB in p-shell

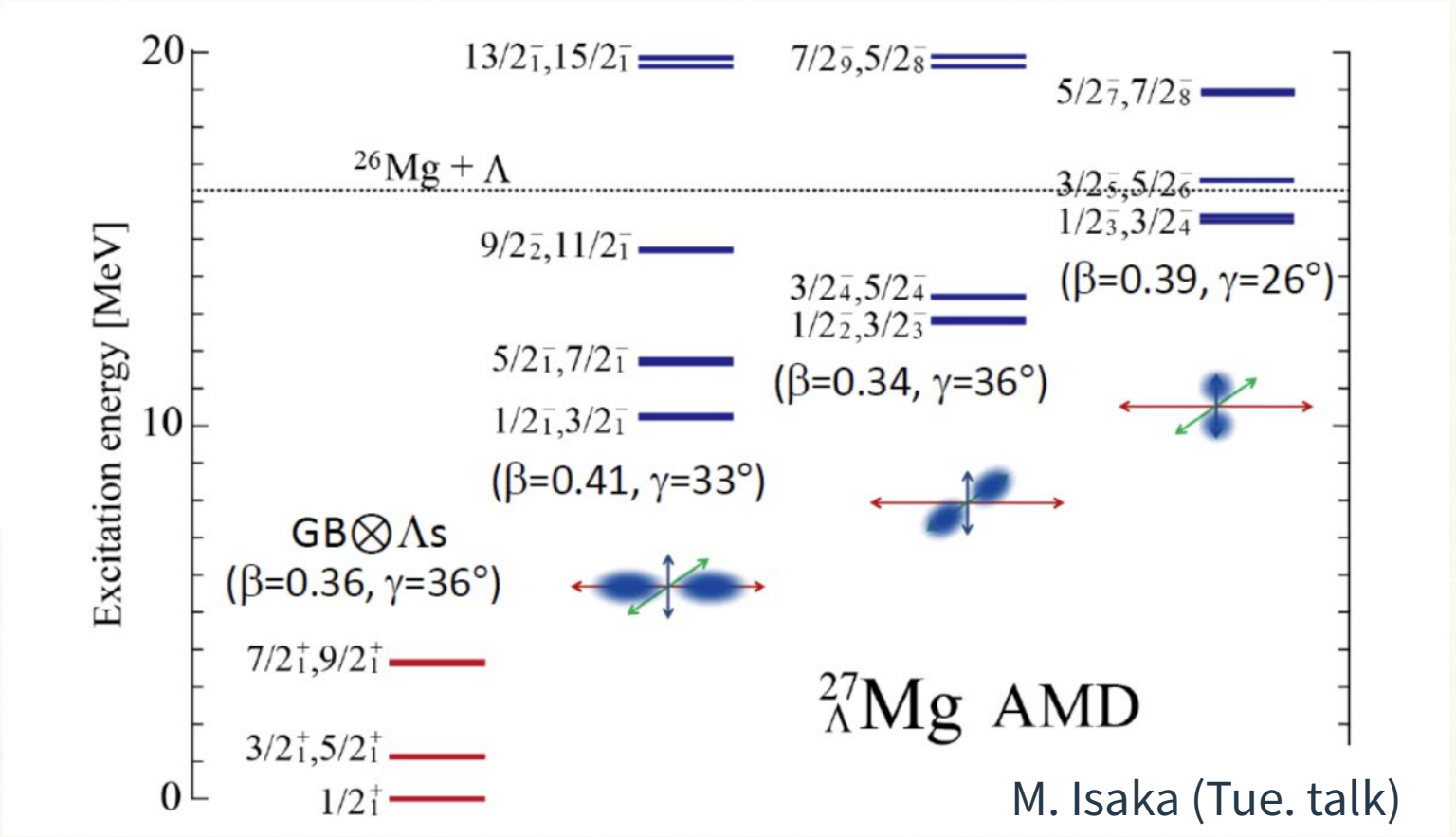
Electron-beam experiment at JLab — Emulsion experiment
Hadron-beam experiment at J-PARC — γ-ray experiment

	Hypernucleus		T<0	T=0	T>0	CSB study: Now	CSB study: New JLab	CSB study: J-PARC
s-shell	dNΛ	(0^+)	${}^{4}_{\Lambda}$H		${}^{4}_{\Lambda}$He	○	○	○
		(1^+)	${}^{4}_{\Lambda}$H (new)		${}^{4}_{\Lambda}$He	△	●	●
p-shell	αNΛ		${}^{6}_{\Lambda}$He (new)		${}^{6}_{\Lambda}$Li (new)			●
	αNNΛ		${}^{7}_{\Lambda}$He	${}^{7}_{\Lambda}$Li*	${}^{7}_{\Lambda}$Be	○	○	○
	αdNΛ		${}^{8}_{\Lambda}$Li		${}^{8}_{\Lambda}$Be	○	○	○
	αdNNΛ		${}^{9}_{\Lambda}$Li (new)	${}^{9}_{\Lambda}$Be	${}^{9}_{\Lambda}$B		●	●
	ααNΛ		${}^{10}_{\Lambda}$Be		${}^{10}_{\Lambda}$B (new)			●
	ααNNΛ		${}^{11}_{\Lambda}$Be (new)	${}^{11}_{\Lambda}$B (new)	${}^{11}_{\Lambda}$C		●	●
	ααdNΛ		${}^{12}_{\Lambda}$B		${}^{12}_{\Lambda}$C (new)			●

→ T.Gogami (Fri. talk)

Triaxial Deformed Nucleus ($^{27}_{\Lambda}$Mg)





- Study of triaxial deformed nuclei by using Λ as a probe
- Different overlap between p-shell Λ and nucleons results in different B_Λ
- High-resolution spectroscopy is able to measure the difference of $^{27}_{\Lambda}$Mg structure

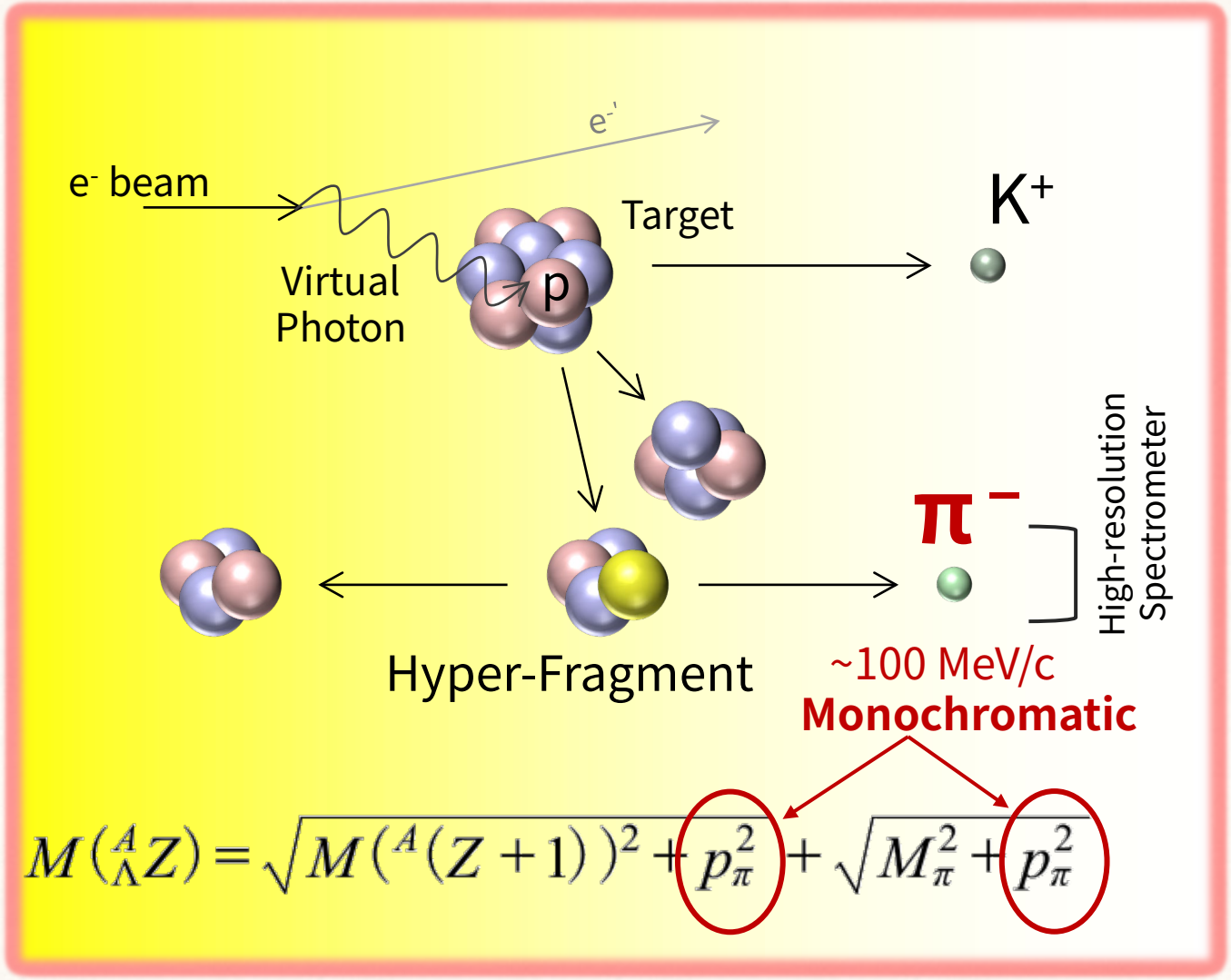
Decay Pion Spectroscopy @ JLab

High-resolution spectroscopy
of light hypernuclei with the decay-pion spectroscopy

Spectroscopy of p-shell hypernuclei with high accuracy

Decay Pion Spectroscopy

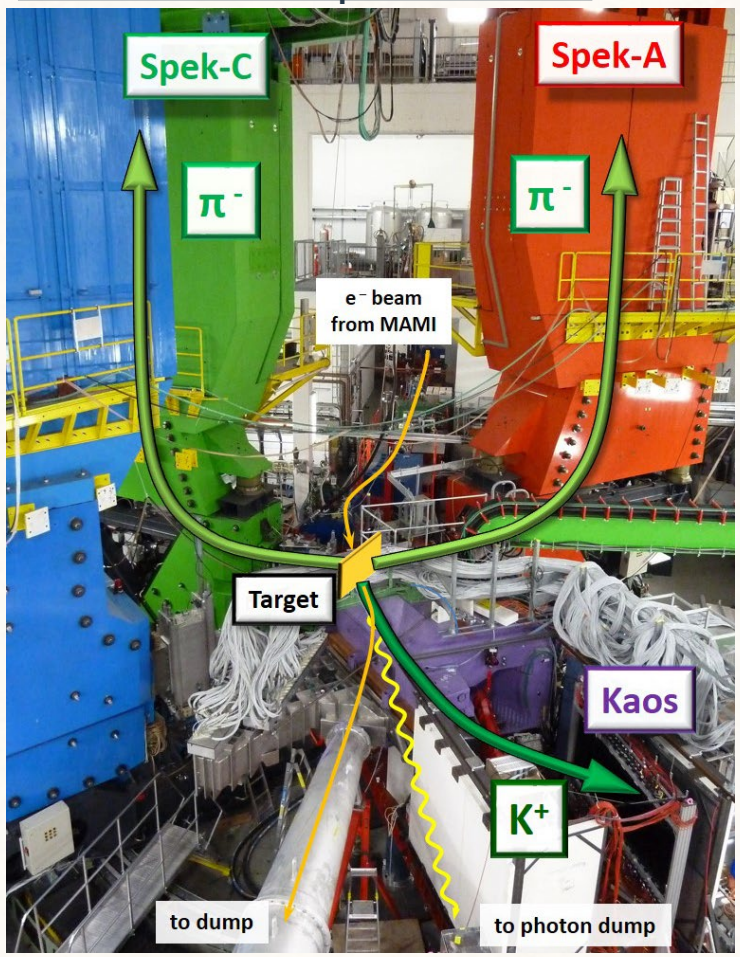
High-resolution, High-precision mass spectroscopy



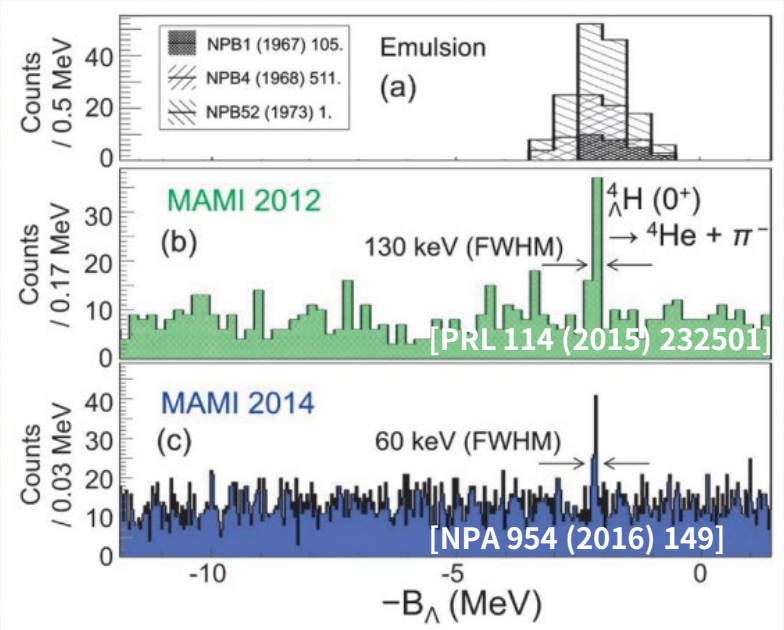
- Measurement of two-body decay pions
- Kaon Tagging
- Thin Target
  → High-Resolution
- Precise Momentum Calibration
  → Accurate mass
- Available for
  Charged, Two-Body Decay & π^- MWD

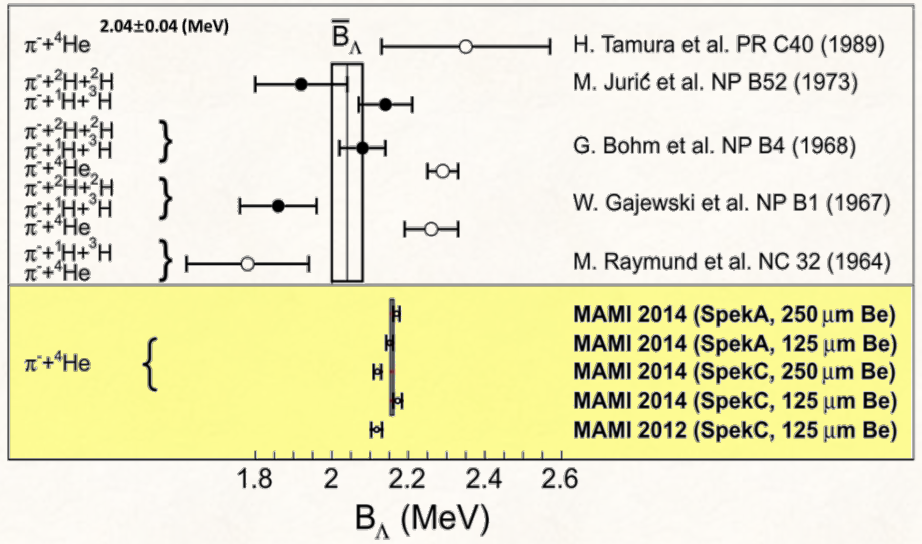
Previous Experiment at MAMI

Proof of Principle at MAMI



- Pion measurement with spectrometers at the backward angles
- First observation of ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$
- N ~ 40, Resolution ~ 100 keV, Precision ~ 5 keV
- ${}^{3}_{\Lambda}\mathrm{H}$ analysis is on going from 2022 data (R.Kino, Wed. talk)





$$M\left({}^{A}_{\Lambda}Z\right) = \sqrt{M\left({}^{A}(Z+1)\right)^2 + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2}$$

What's new??

Decay Pion Spectroscopy @JLab will be

Higher luminosity & Less background

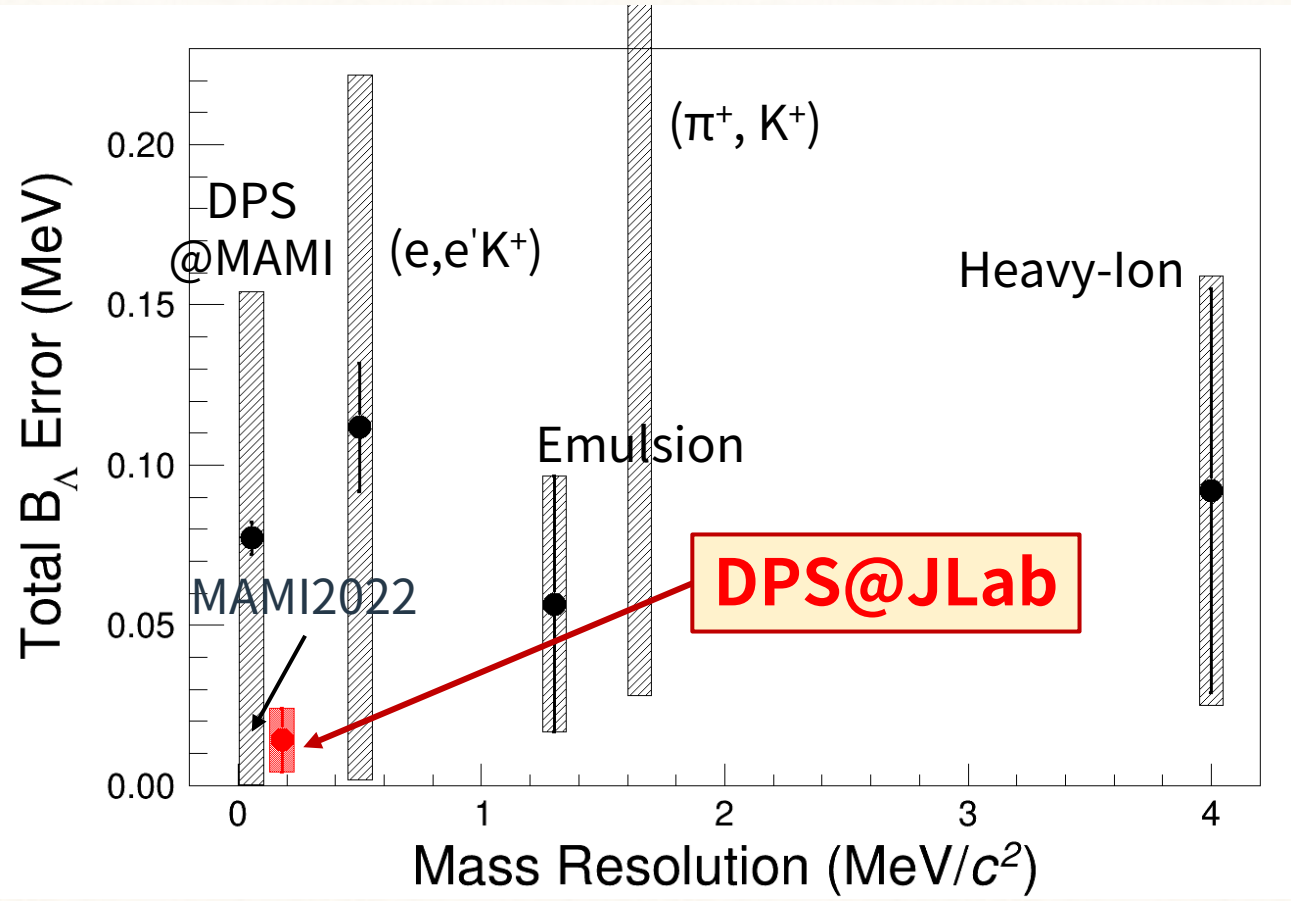
→ Expansion to p-shell hypernuclei

New calibration method

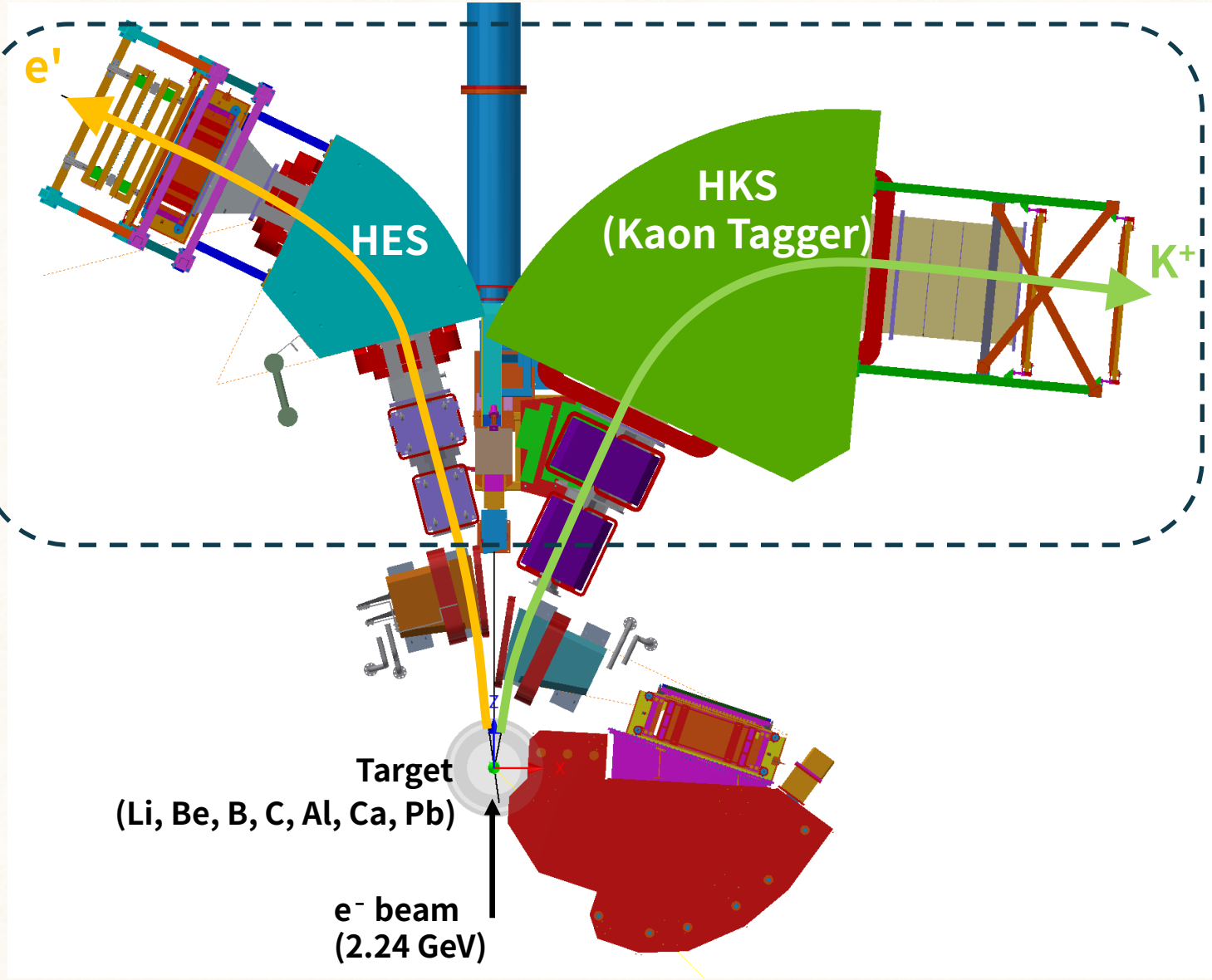
→ Better accuracy

Heavy targets (Al, Ca, Pb targets)

→ sd-shell ???



Setup Overview



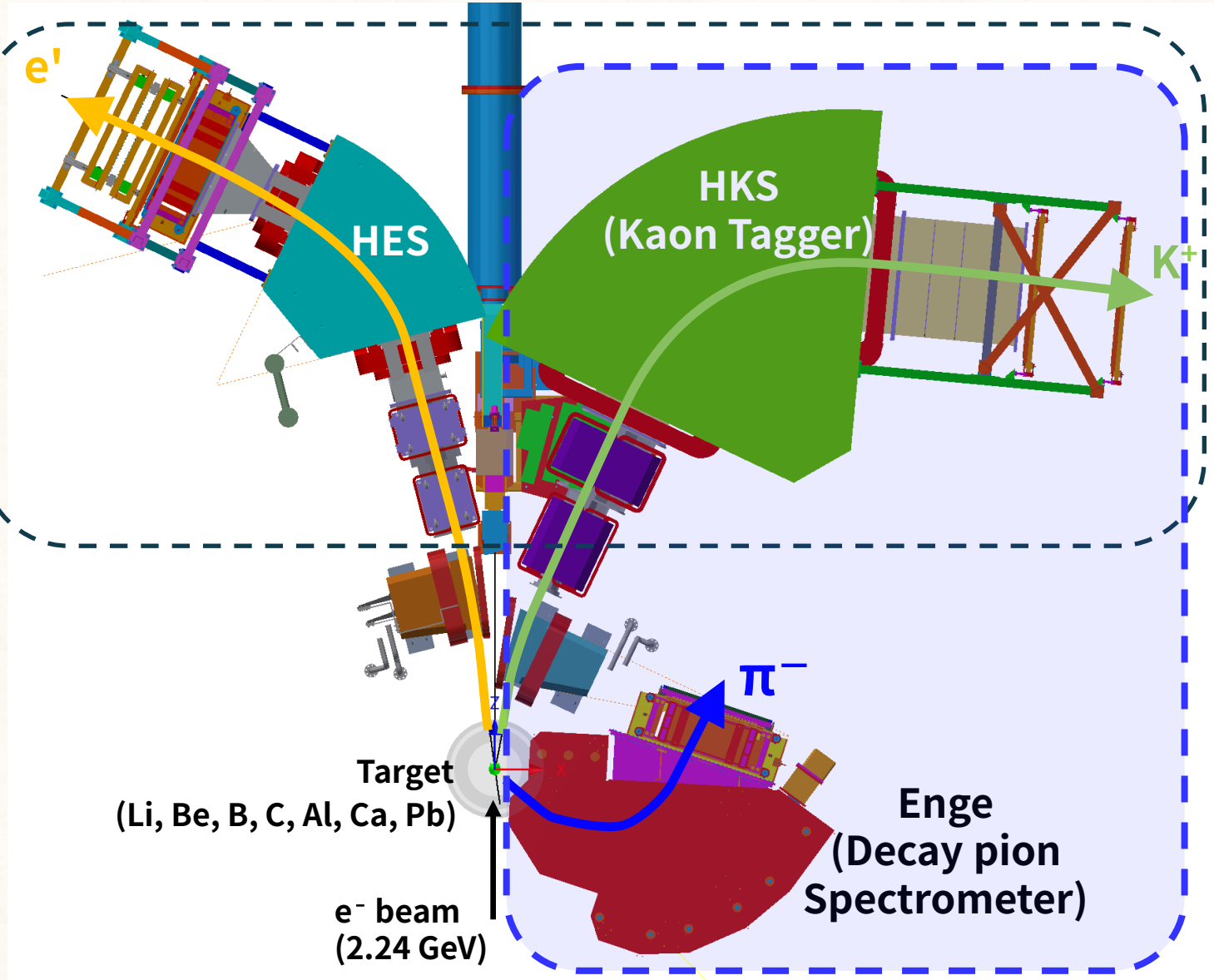
Proposed (e,e'K⁺)

- Medium-heavy $_{\Lambda}$K isotopes (E12-15-008)
- Super-heavy $^{208}_{\Lambda}$Tl (E12-20-013)
- CSB in p-shell (LOI12-23-013)
- Triaxial Deformation (LOI12-23-016)

High-resolution spectroscopy with HKS⊗HES

Will be scheduled for 2026-2027

Setup Overview



Proposed (e,e'K⁺)

- Medium-heavy $_{\Lambda}$K isotopes (E12-15-008)
- Super-heavy $^{208}_{\Lambda}$Tl (E12-20-013)
- CSB in p-shell (LOI12-23-013)
- Triaxial Deformation (LOI12-23-016)

High-resolution spectroscopy with HKS⊗HES

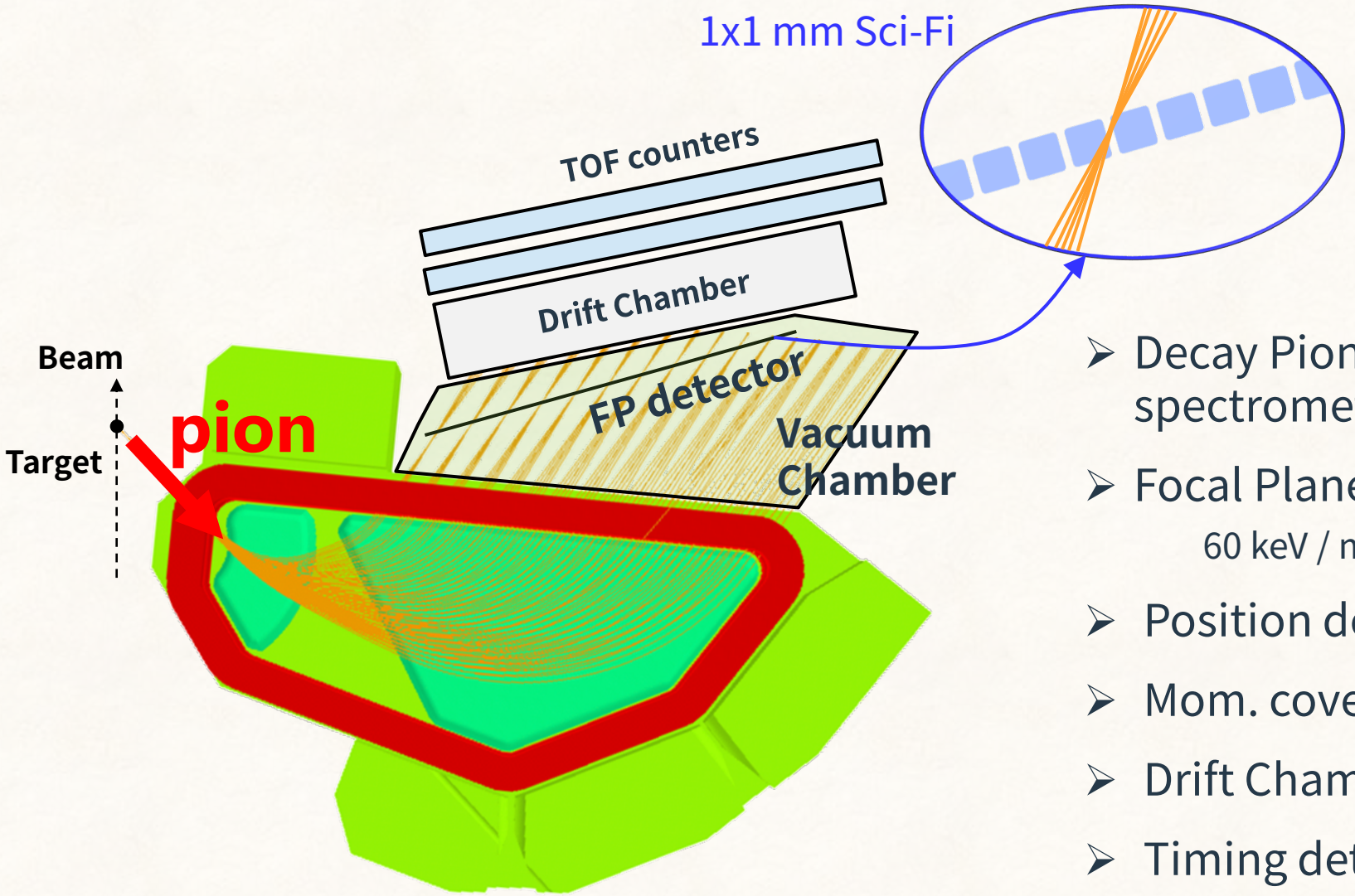
Will be scheduled for 2026-2027

Another Spectrometer "Enge" for decay pion measurement

DPS with HKS⊗Enge

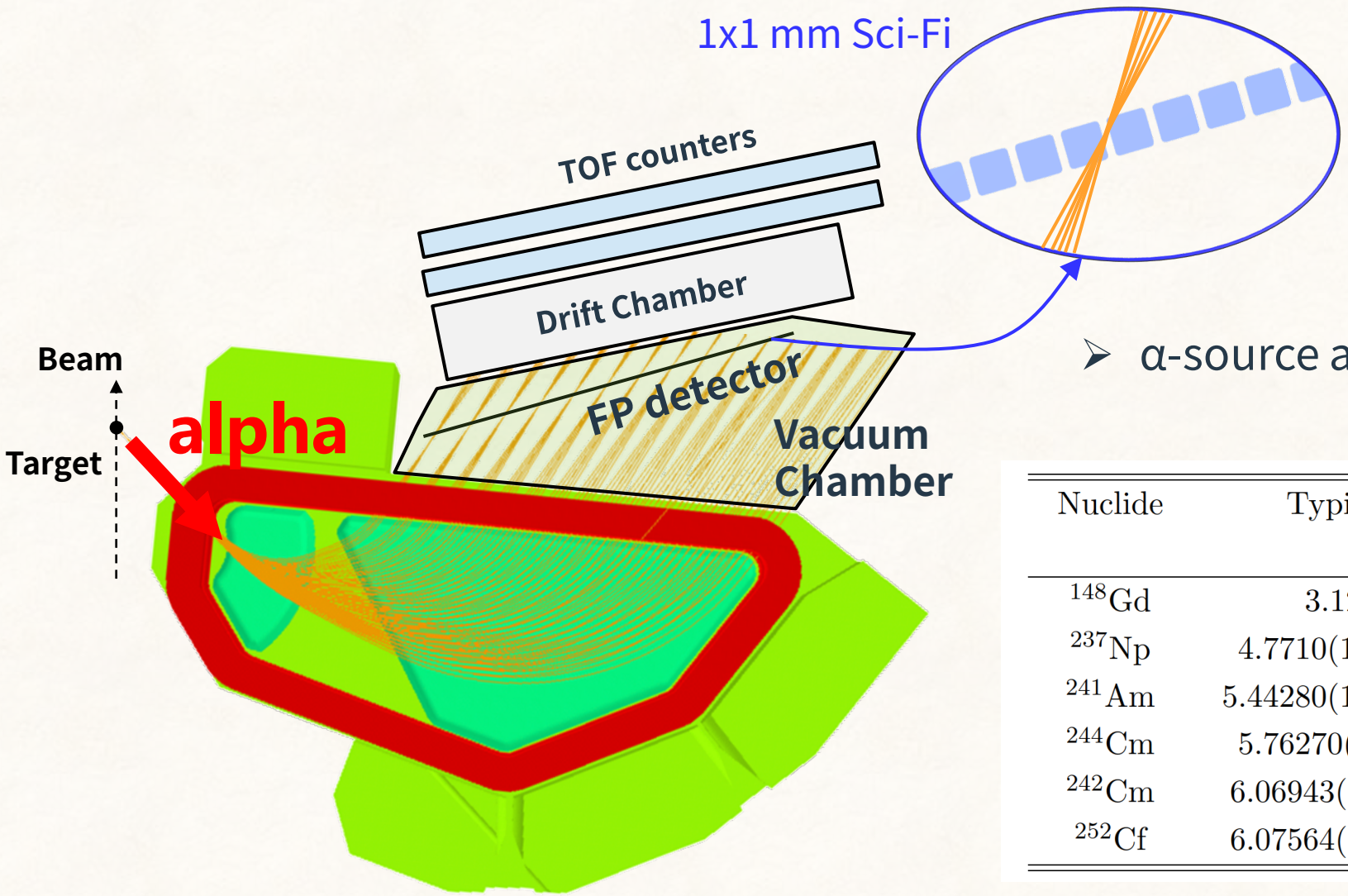
Parallel exp. with (e,e'K⁺)

Pion Spectrometer "Enge"



- Decay Pion Spectrometer as Hardware spectrometer Enge
- Focal Plane position = Pion Momentum
  60 keV / mm Dispersion
- Position detector in vacuum
- Mom. coverage 70 ~150 MeV/c
- Drift Chamber for angular measurement
- Timing detector

Pion Spectrometer "Enge"



- α-source at target for momentum calib.

Nuclide	Typical Energy (MeV)	Momentum (MeV/c/q)
^{148}Gd	3.128787(24)	77.03415(29)
^{237}Np	4.7710(15), 4.7880(15)	94.326(15), 94.494(15)
^{241}Am	5.44280(13), 5.48556(12)	100.7526(12), 101.1479(11)
^{244}Cm	5.76270(3), 5.80482(5)	103.6734(3), 104.0519(4)
^{242}Cm	6.06943(12), 6.11272(8)	106.3990(11), 106.7781(7)
^{252}Cf	6.07564(11), 6.11810(4)	106.4534(10), 106.8251(4)

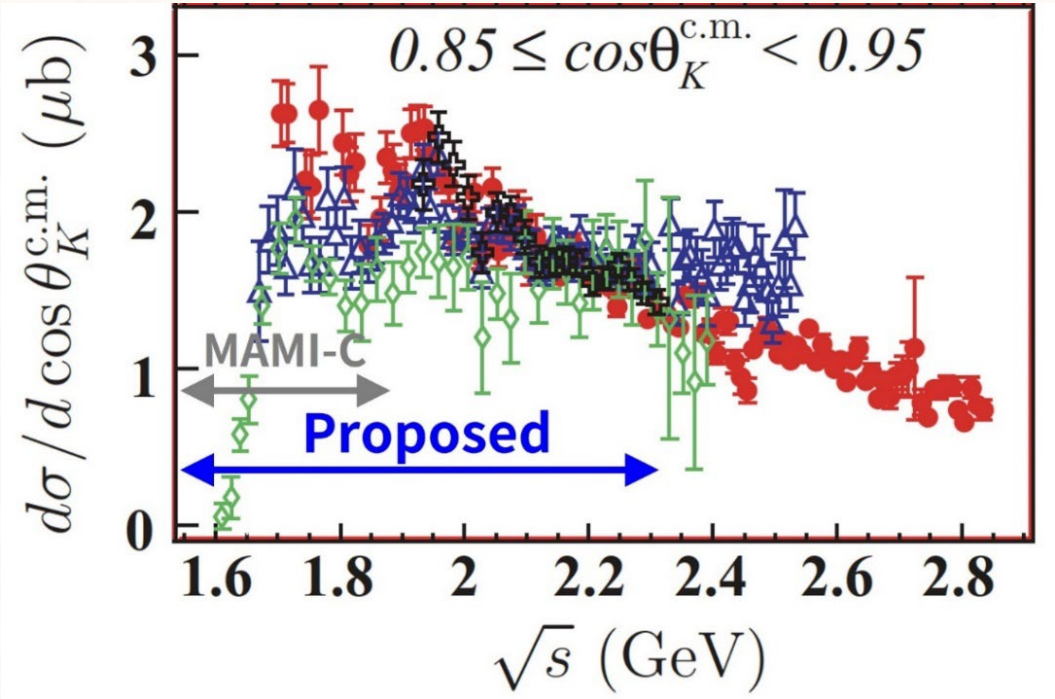
~30 times yield

$$N_{HYP} = N_\Lambda R_{F.P} R_{stop} \Gamma_{\pi^-} \Delta\Omega_{\pi^-} \varepsilon_{\pi^-}^{decay} \varepsilon_{\pi^-}^{det}$$

↑ ×30

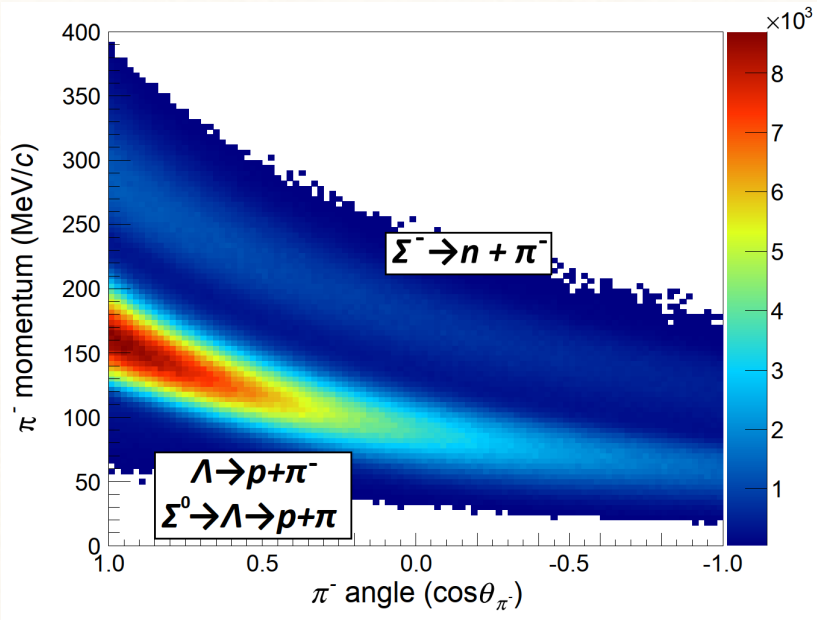
Monte-Carlo

p(γ,K⁺)Λ Cross Section



[CLAS, Phys. Rev. C 81 (2010) 025201.]

- Much better luminosity thanks to higher beam energy and intensity
- Background reduction from in-flight hyperons

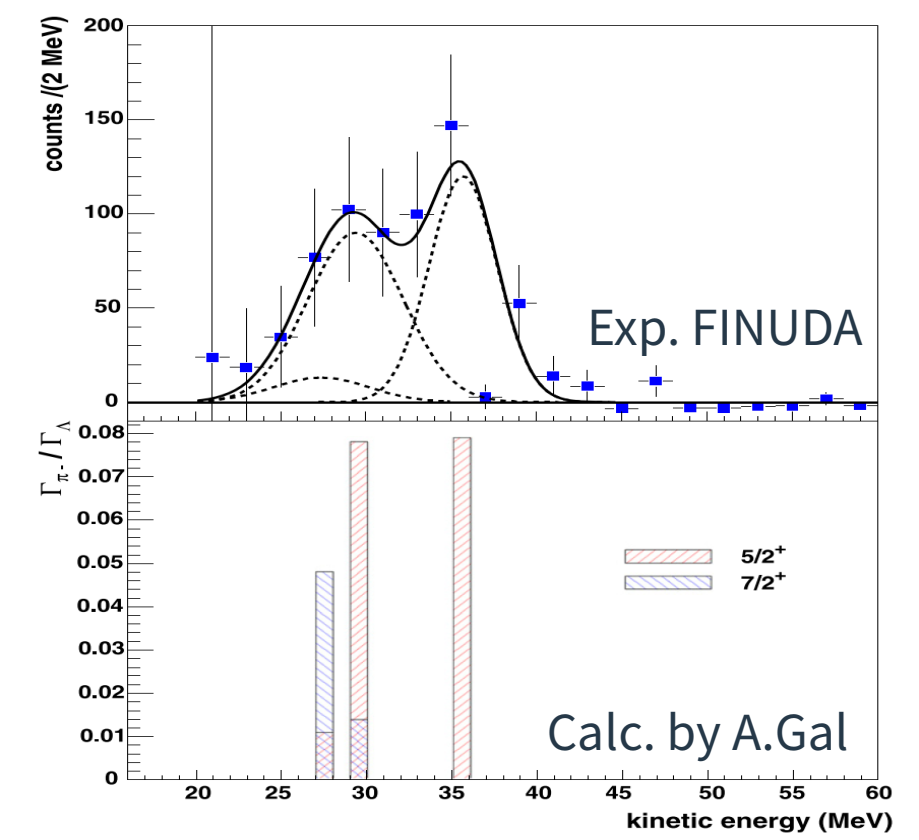


Spin assignment from decay width

$$N_{HYP} = N_\Lambda \, R_{F.P} \, R_{stop} \, \Gamma_{\pi^-} \, \Delta\Omega_{\pi^-} \, \varepsilon_{\pi^-}^{decay} \, \varepsilon_{\pi^-}^{det}$$

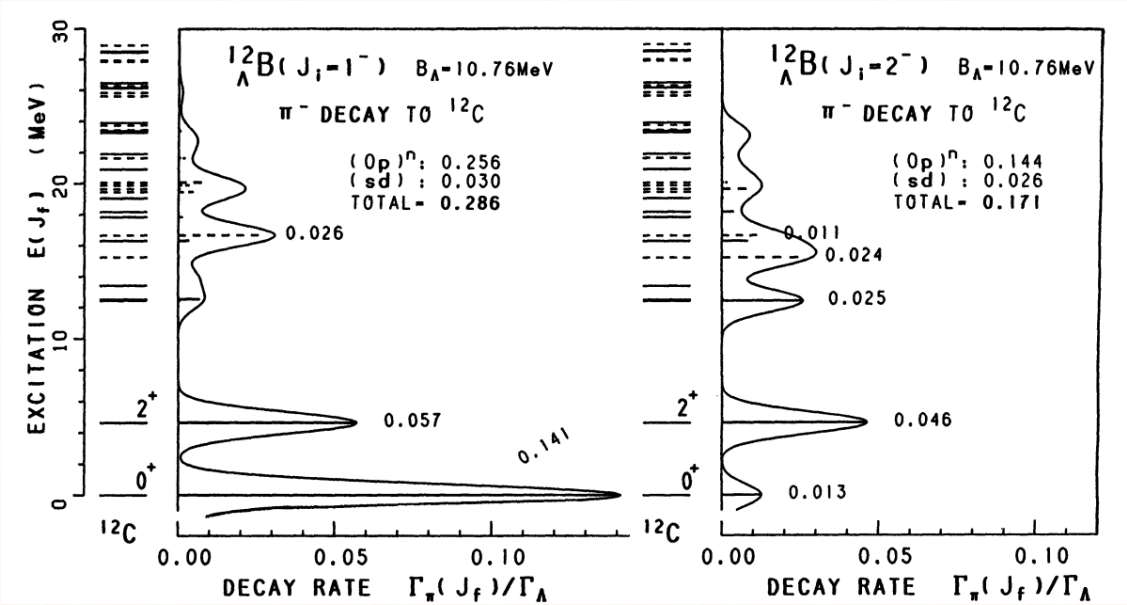
Monte-Carlo

$^{11}_{\Lambda}B \rightarrow {}^{11}C + \pi^-$ decay pion energy



FINUDA, Phys. Lett. B681 (2009) 139

- Decay width calc. well reproduced exp. data (T. Motoba and K. Itonaga, PTPS117(1994)477.)
- Large Γ_π dependence on SPIN of parent hypernuclei

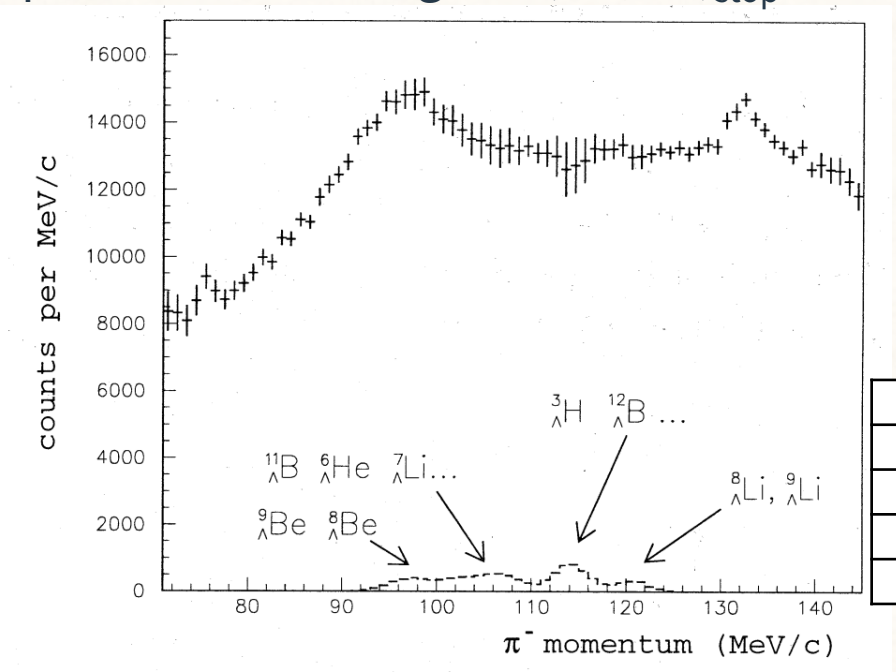


Hypernuclear formation probability

$$N_{HYP} = N_{\Lambda} R_{F.P} R_{stop} \Gamma_{\pi^-} \Delta\Omega_{\pi^-} \varepsilon_{\pi^-}^{decay} \varepsilon_{\pi^-}^{det}$$

Monte-Carlo

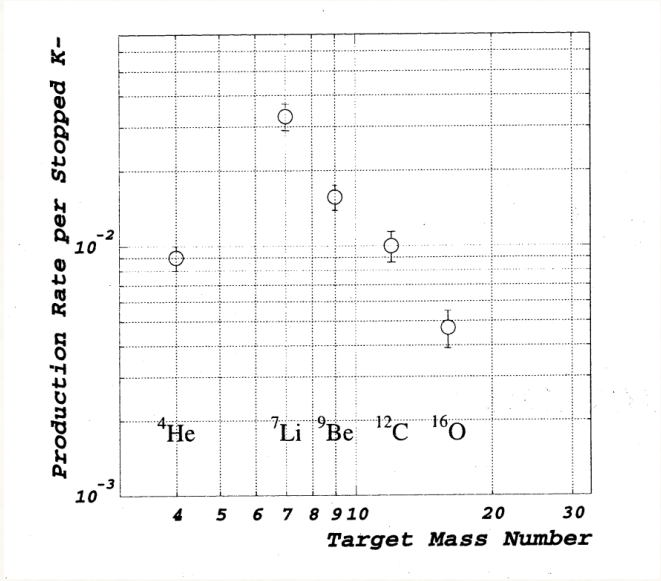
π^- spectrum of ^{12}C target @$(K^-,\pi^-)_{stop}$



Hyp.	RFP(%)
$^4_\Lambda$H	1.1
$^9_\Lambda$Be	0.94
$^{10}_\Lambda$B	0.20
$^{11}_\Lambda$B	0.53

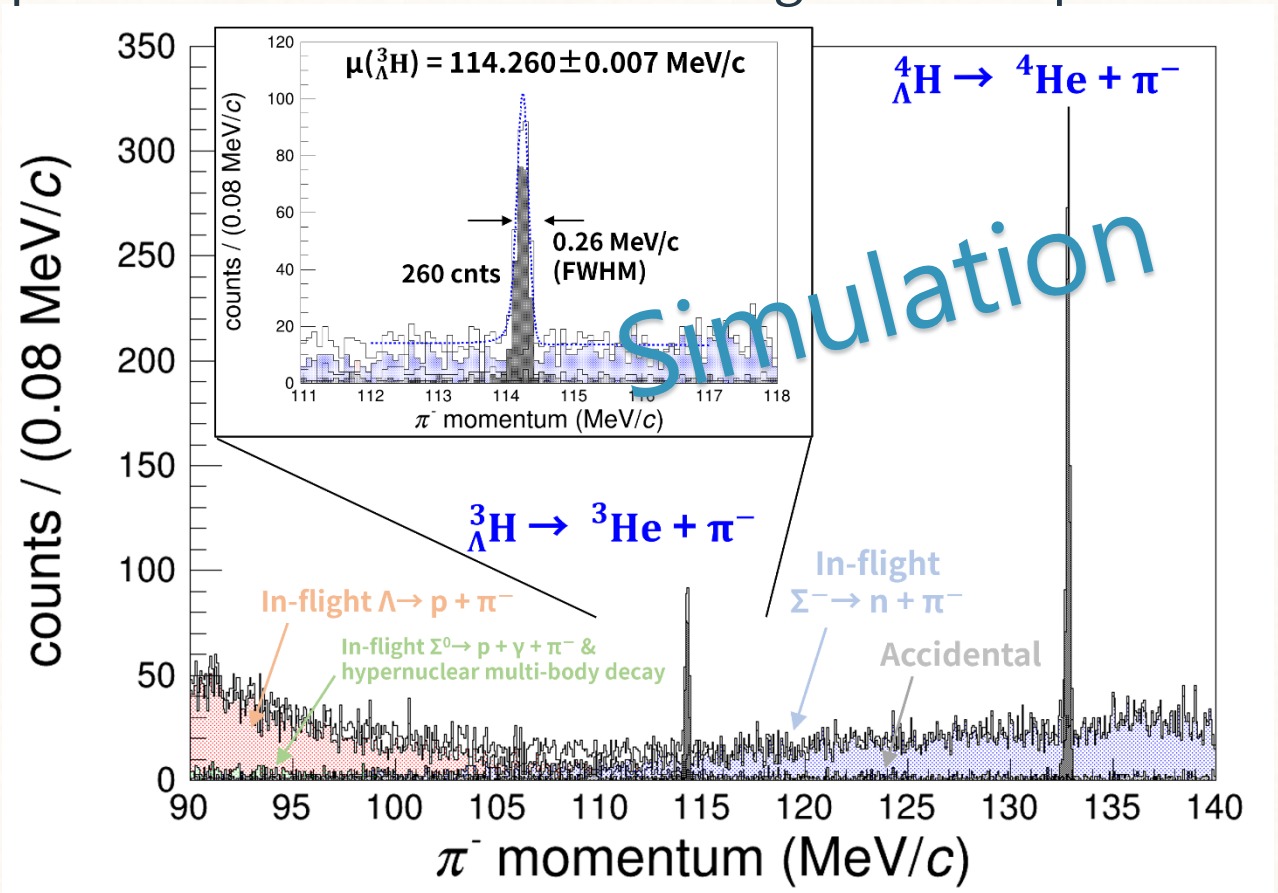
A. Kawachi (1992) Ph.D thesis, U-Tokyo

- A^{-2} dependence of $^4_\Lambda$H Form. Prob. (H.Tamura, PRC40(1989)R479)
- 1.57% @$(K^-,\pi^-)_{stop}$, 1% @MAMI for ^{9}Be target
- Prediction by AMD on ^{12}C target



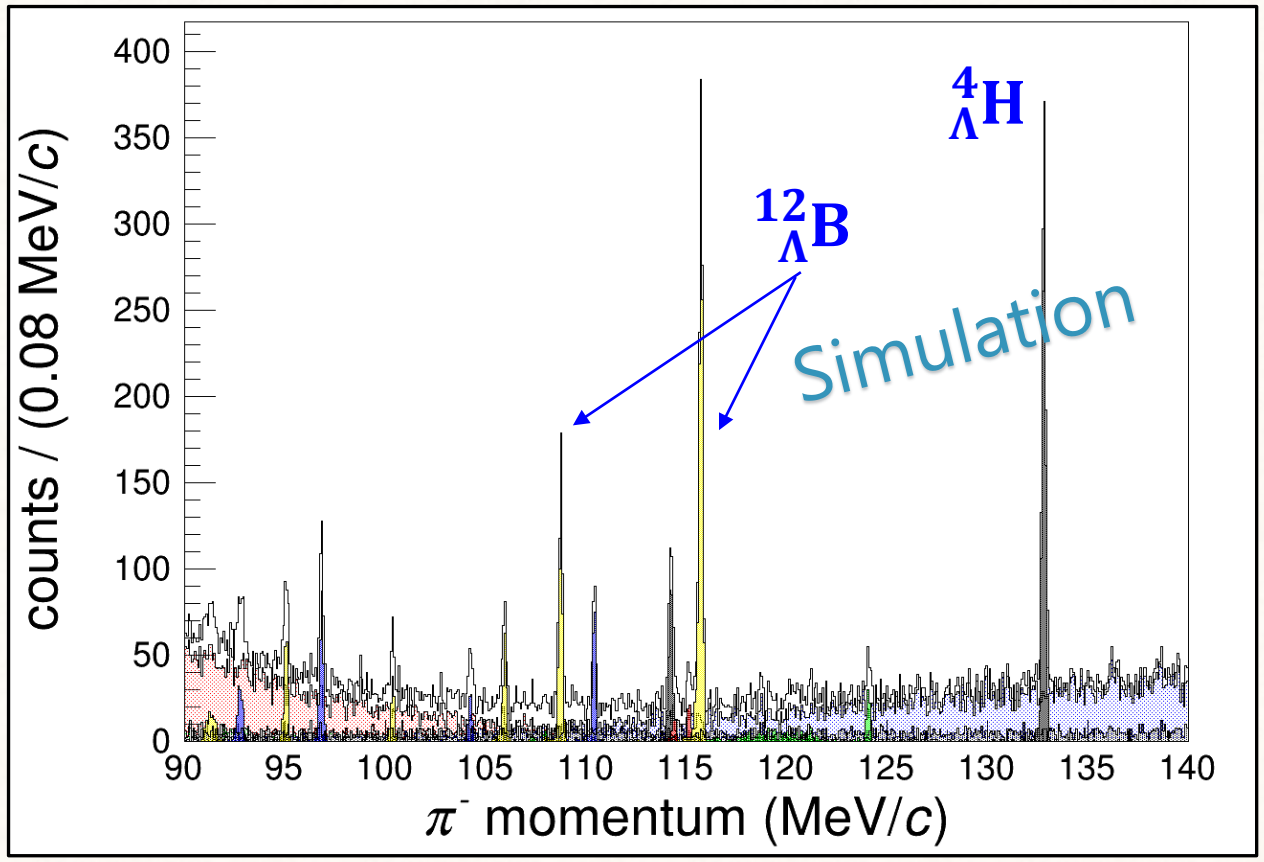
Expected Spectrum (Li target)

- Decay pions of ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H from ^{6}Li target (simplest spectrum)
  - Direct produced ${}^{6}_{\Lambda}$He decays to ${}^{5}_{\Lambda}$He and 3-body final state
- $\Sigma^- \rightarrow n + \pi^-$ as a major background source
- Peak precision of < 10 keV after fitting with a response function



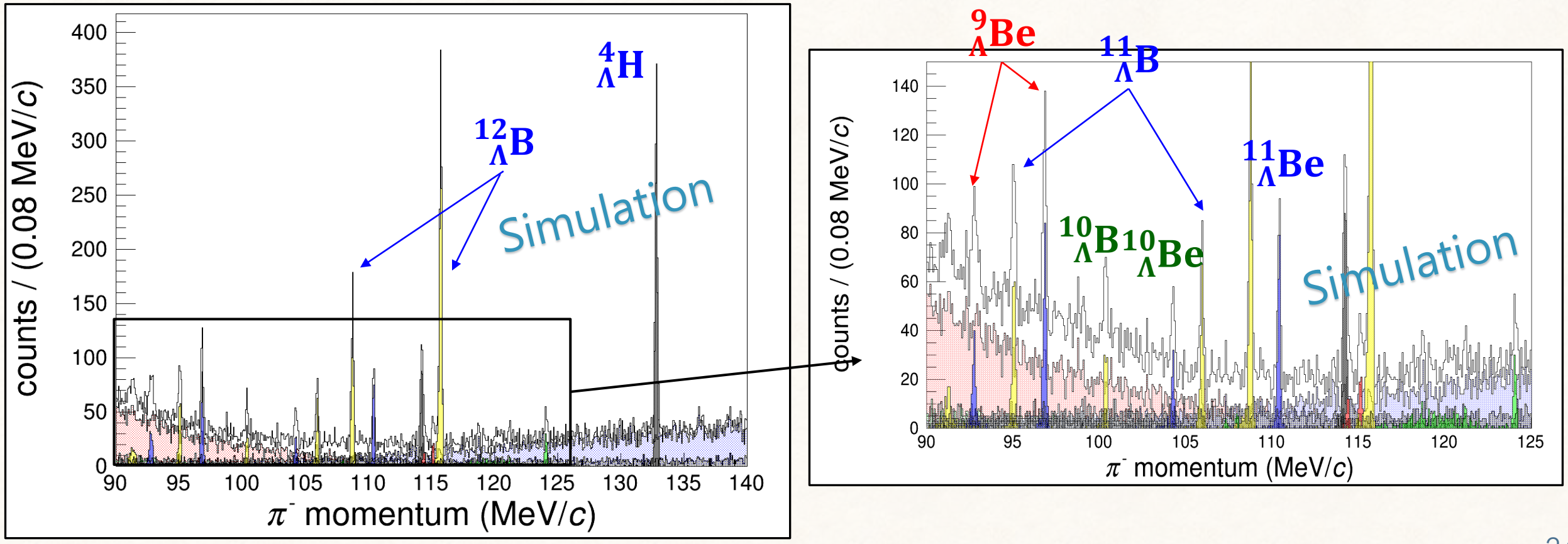
Expected Spectrum (C target)

- Many decay pions from p-shell hypernuclei
- Robust peaks of ${}^{12}_{\Lambda}\mathrm{B} \rightarrow {}^{12}\mathrm{C}(*) + \pi^{-}$
- Interesting hypernuclei about CSB discussion
- Spin determination



Expected Spectrum (C target)

- Many decay pions from p-shell hypernuclei
- Robust peaks of ${}^{12}_{\Lambda}\mathrm{B} \rightarrow {}^{12}\mathrm{C}(*) + \pi^-$
- Interesting hypernuclei about CSB discussion
- Spin determination



Summary

Λ binding energy measurement for wide mass range & good precision

Prospects of JLab hypernuclear project

(e,e'K$^+$) Missing Mass Spectroscopy

$^{6}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{11}_{\Lambda}$Be, $^{27}_{\Lambda}$Mg, $^{40,48}_{\Lambda}$K, $^{208}_{\Lambda}$Tl

Decay Pion Spectroscopy

Parallel exp. with (e,e'K$^+$)

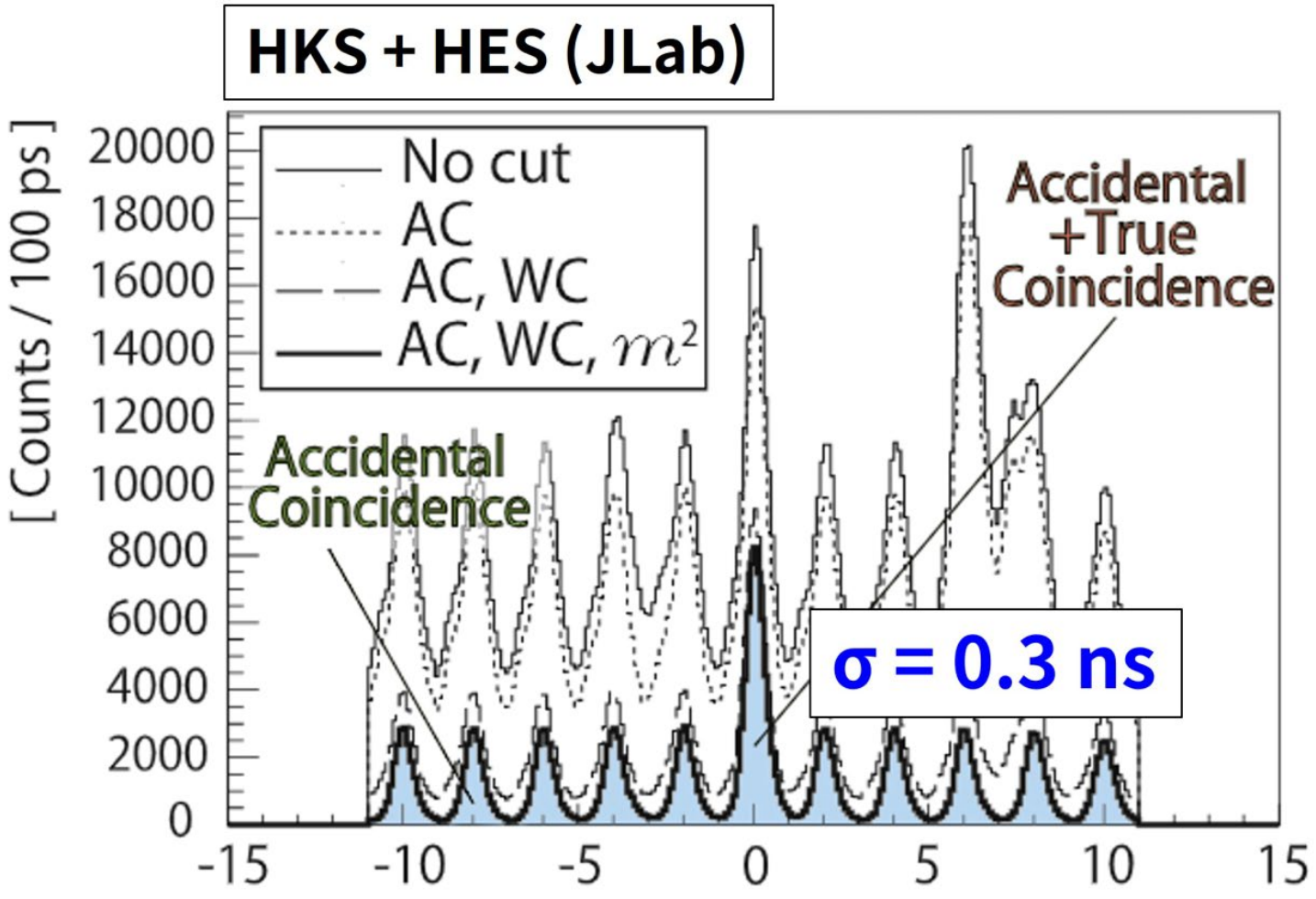
HKS + Enge as Pion Spectrometer

New calibration with alpha-sources

Measurement for s-, p-shell hypernuclei

We submitted proposals, Exp. will run 2026-27.

Time difference of "K, pi"



T.Gogami, Ph.D Thesis

Decay Width of $^{10}_{\Lambda}$B & $^{12}_{\Lambda}$B