High precision study of wide variety of light hypernuclei via decay pion spectroscopy

The University of Tokyo

Sho Nagao

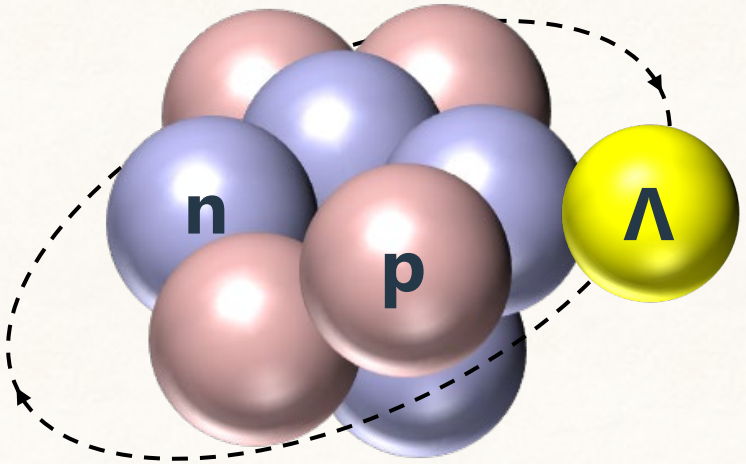
on behalf of

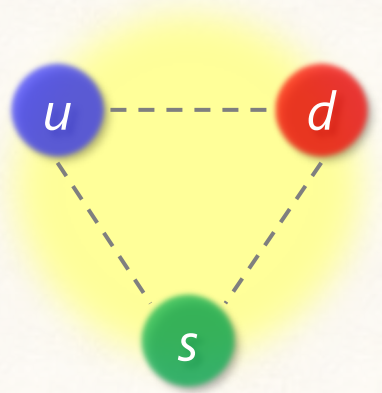
JLab hypernuclear collaboration

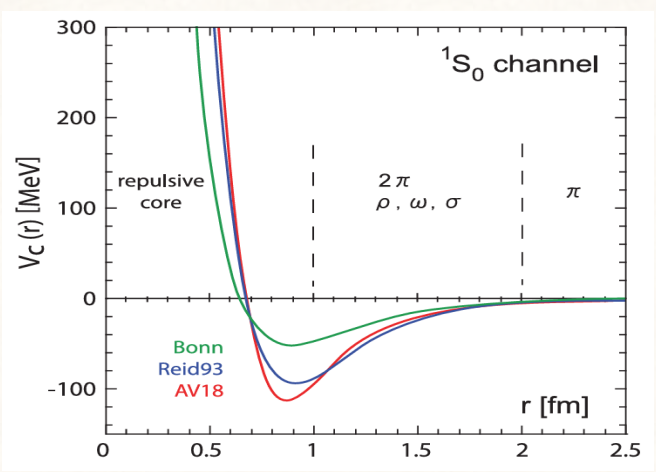
2025 Summer Hall A/C Collaboration Meeting

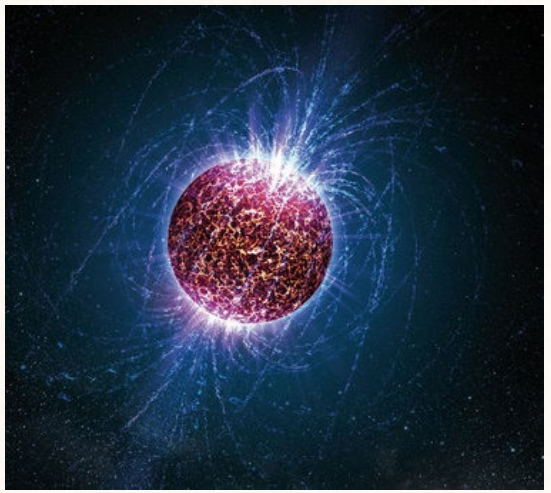
Hypernucleus

"strangeness" many-body system at low-energy limit



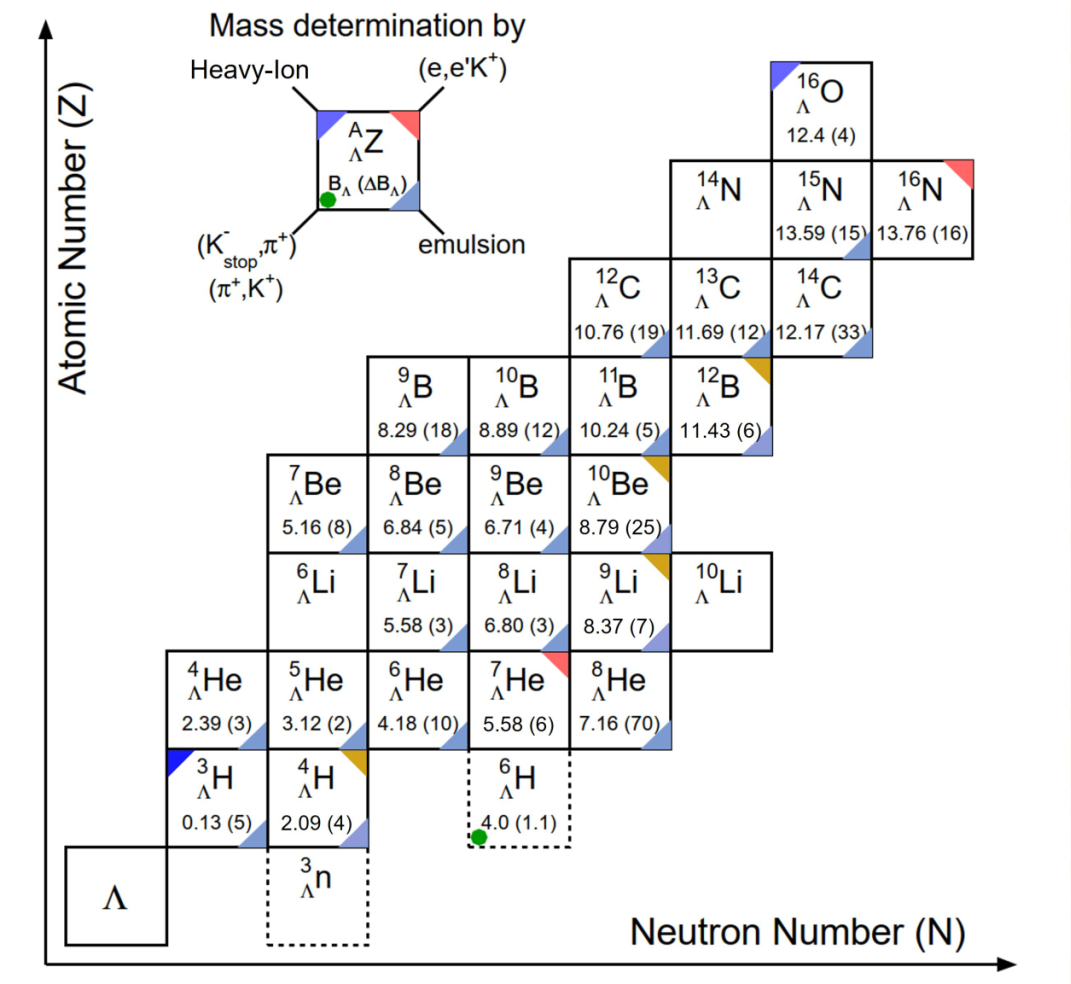






Λ hypernucleus as a Lambda bound many-body system

Hypernuclear Chart (S=−1, up to p-shell)



NOTE: B_Λ from hypernuclei database [https://hypernuclei.kph.uni-mainz.de/]

Precise Measurement of Λ Binding Energy

Study of NN and BB interaction

$$B_\Lambda = M_{core} + M_\Lambda - M_{HYP}$$

Core Mass — Λ Mass — Hypernucleus Mass

High-resolution spectroscopy available

Weakly interacting Λ and N
→ τ(g.s) ~ 200 ps, Γ(e.x above Sn) < 100 keV

Good probe for ΛN interaction / (Hyper)nuclear structure

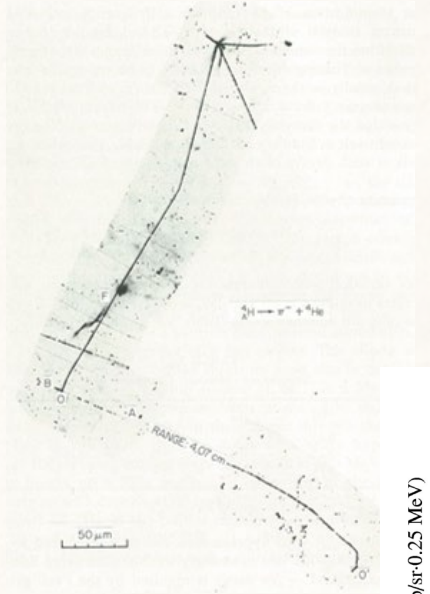
Mass, Isospin dependence etc. provide important information about effective ΛN/ΛNN interaction

Light hypernuclei that can be applied for precise calculations are useful probes thanks to the recent progress of theories

Possible to approach changes of nuclear structure and deformation using Λ as a probe

Determination of Lambda binding energy

1970's **Emulsion** **Accuracy = 50 ~ several 100 keV**
Resolution = several MeV

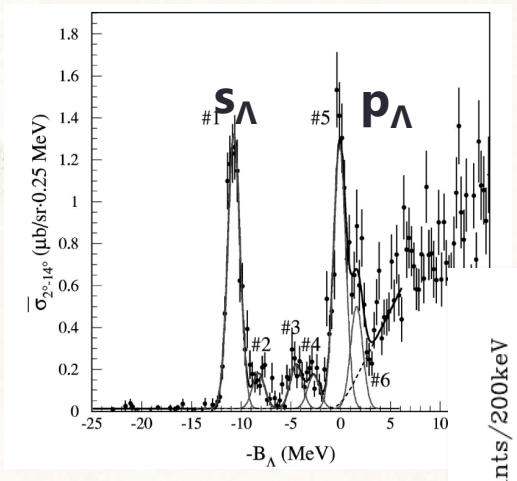


Walter H. Barkas, Nuclear Research Emulsions (1973)

1990's **$(K^-,\pi^-)/(\pi^+,K^+)$ Spec.** **γ-ray spectroscopy**

500 keV
a few MeV

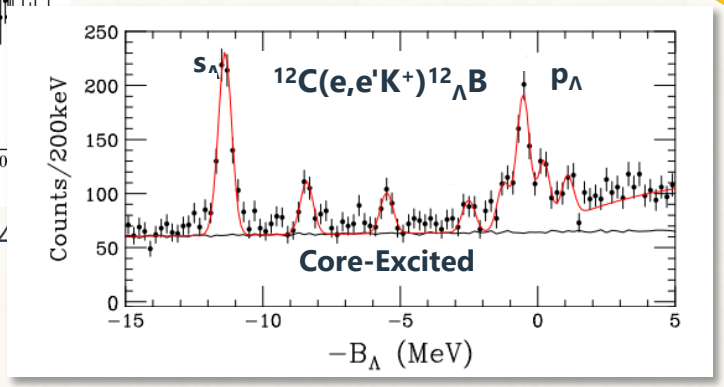
100 keV
0.5 MeV



H.Hotch et al., PRC 64 (2001) 044

2000's **$(e,e'K^+)$ Spec.**

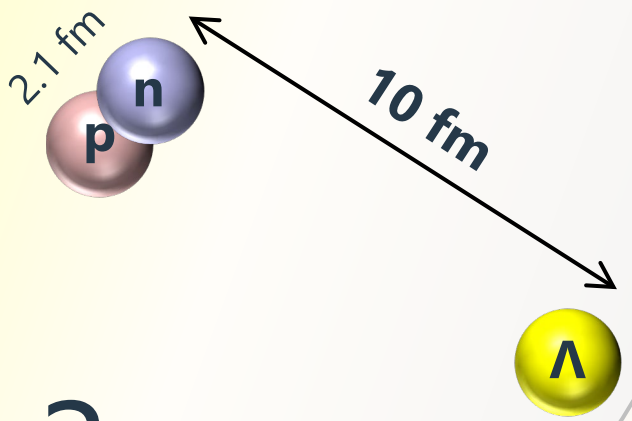
<100 keV
0.1 MeV



PRC90 (2014) 034320.

2010's **Decay Pion Spec.**
HI collision

Hypertriton (Z=1, n=1, L=1 system)



$^{3}_{\Lambda}H$

- Lightest system with nucleons and Lambda
- **$J^P = 1/2^+$**
- T = 0
- Lambda binding energy

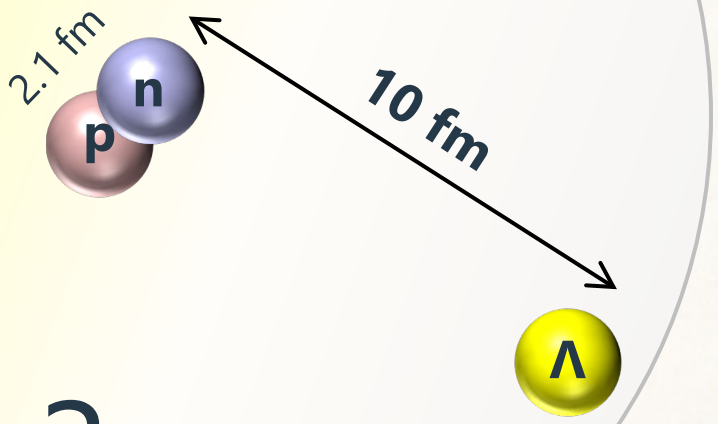
  $B_\Lambda = 130 \pm 50(\text{stat.})$ keV
  [M. Juric et al., NPB52(1973)1.]

  Loosely bound system

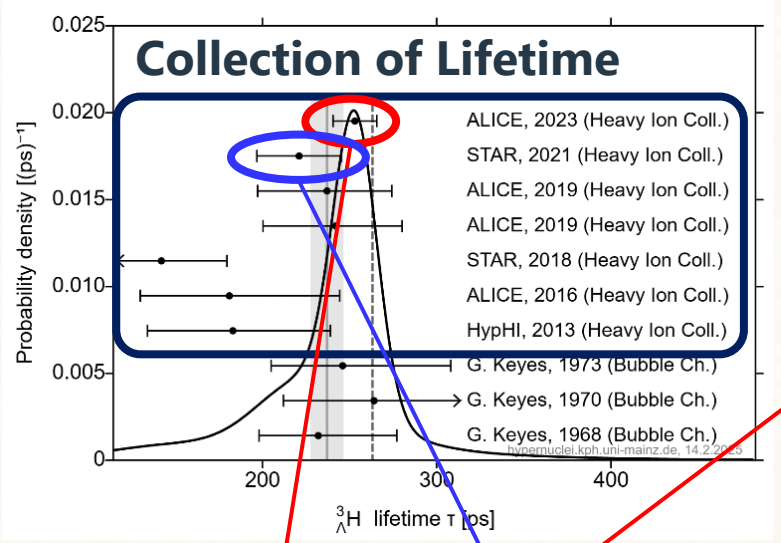
  Lambda halo nucleus
- Mesonic Weak Decay (MWD) dominant

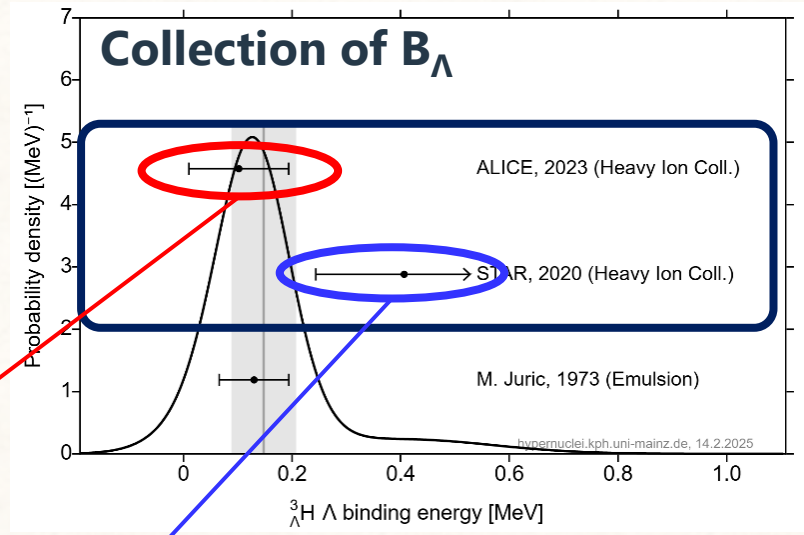
  Similar lifetime to free-Lambda (263.4 ps) ??

Hypertriton (Z=1, n=1, L=1 system)

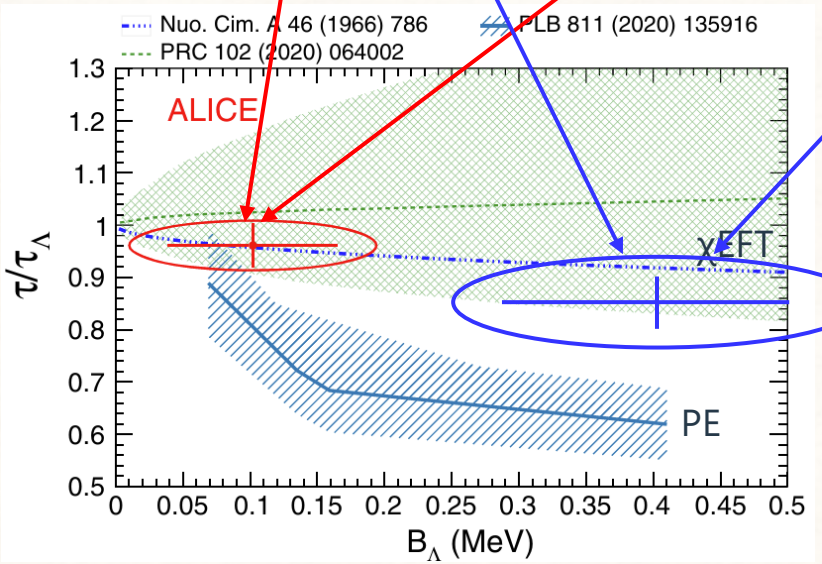


$^{3}_{\Lambda}H$





hypernuclei database [https://hypernuclei.kph.uni-mainz.de/]



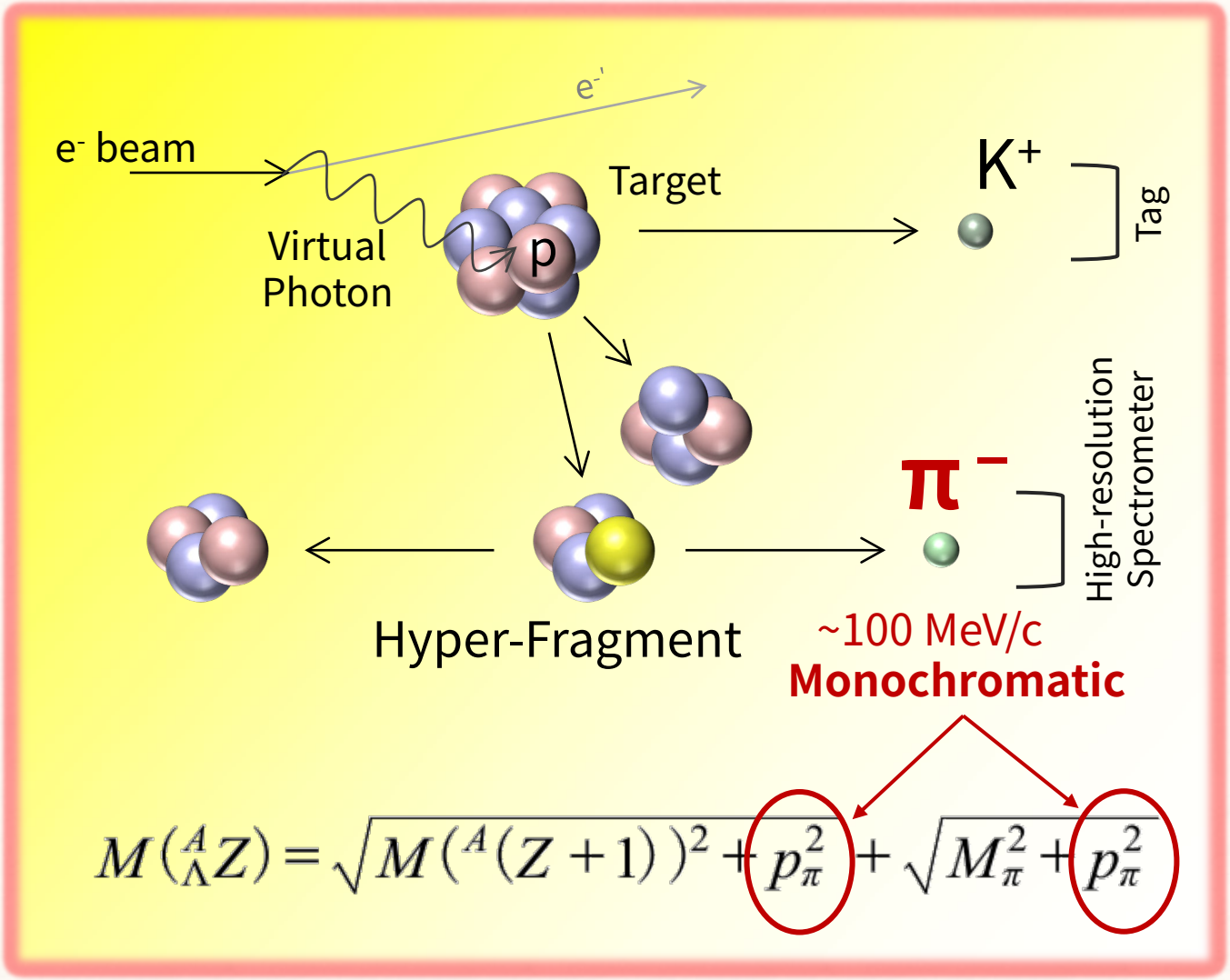
[ALICE collaboration, PRL131 (2023) 102302]

Λ binding energy
Shallow? ⇔ Deep?

Lifetime
Long? ⇔ Short?

What is the right description?
⇒ High precision data is necessary !!

Decay Pion Spectroscopy Technique



Hypernuclear Mass Spectroscopy with

FWHM ~ 100 keV

Stat. Error < 10 keV

Systematic ~ 10 keV

Principle

- Measurement of **mono. decay pion** from hypernuclei **stopped** in the target emitting pion in **two-body decay** (e.g. $^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$)
  Hyp. ID from known (or expected) B_Λ
- **Tagging K^+** for background suppression from non-strangeness production

Possible hypernuclei & Expected Pion Momenta

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

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

M(α)	= 3727.3794118(11)	MeV/c²
M(π)	= 139.57039(18)	MeV/c²
p(π)	= 133.03(6)	MeV/c
M(${}^{4}_{\Lambda}$H)	= 3922.56(4)	MeV/c²

Specific decay pion momentum each hypernucleus

Well known daughter particle masses

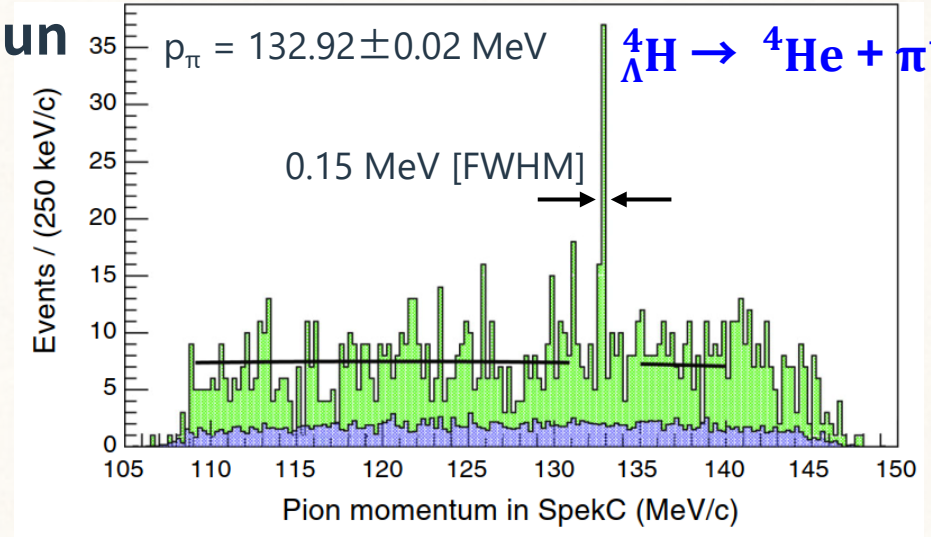
Precise pion momentum → Precise hypernuclear ground-state mass

Hyper-fragment candidates from ^{12}C target

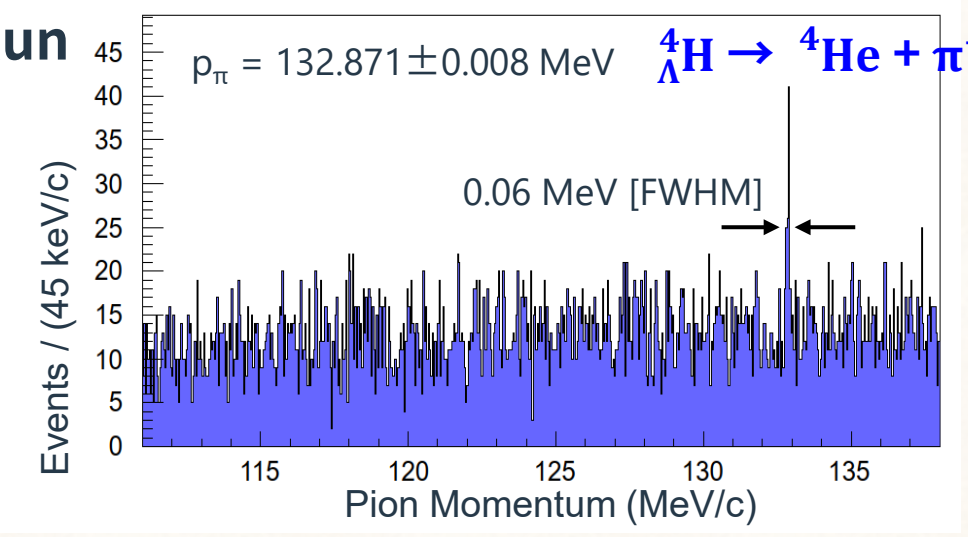
Hypernuclei	Decay mode	p_{π^-} (MeV/c)	comments
${}^{3}_{\Lambda}$H	^{3}He + π^-	114.37	
${}^{4}_{\Lambda}$H	^{4}He + π^-	133.03	
~~${}^{4}_{\Lambda}$He~~	~~^{4}Li + π^-~~	~~98.17~~	Impossible 2-body decay
~~${}^{5}_{\Lambda}$He~~	~~^{5}Li + π^-~~	~~99.26~~	Impossible 2-body decay
${}^{6}_{\Lambda}$H	^{6}He + π^-	135.27	
${}^{6}_{\Lambda}$He	^{6}Li + π^-	108.48	
~~${}^{6}_{\Lambda}$Li~~	~~^{6}Be + π^-~~	-	No B_Λ data, above Sp
${}^{7}_{\Lambda}$He	^{7}Li + π^-	115.10	
${}^{7}_{\Lambda}$Li	^{7}Be + π^-	108.11	
~~${}^{7}_{\Lambda}$Be~~	~~^{7}C + π^-~~	~~95.90~~	Impossible 2-body decay
${}^{8}_{\Lambda}$He	^{8}Li + π^-	116.47	
${}^{8}_{\Lambda}$Li	^{8}Be + π^-	124.20	
${}^{8}_{\Lambda}$Be	^{8}B + π^-	97.19	No ^{8}B(g.s) decay
${}^{9}_{\Lambda}$Li	^{9}Be + π^-	121.31	
${}^{9}_{\Lambda}$Be	^{9}B + π^-	96.98	
${}^{9}_{\Lambda}$B	^{9}C + π^-	96.82	
${}^{10}_{\Lambda}$Li	^{10}Be + π^-	-	No B_Λ data
${}^{10}_{\Lambda}$Be	^{10}B + π^-	104.41	
${}^{10}_{\Lambda}$B	^{10}C + π^-	100.49	
${}^{11}_{\Lambda}$B	^{11}C + π^-	86.54	
${}^{12}_{\Lambda}$B	^{12}C + π^-	115.87	

$^{4}_{\Lambda}$H peak in DPS (MAMI)

2012 Run



2014 Run



Hypernuclear production with ^{9}Be target

Two-body decay peak from $^{4}_{\Lambda}$H

Excellent peak resolution thanks to

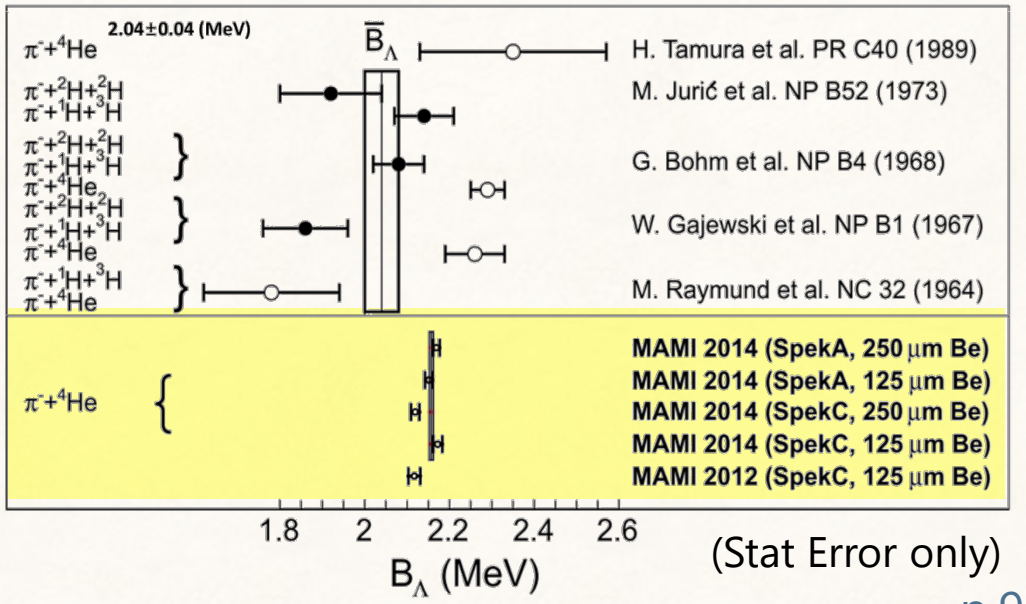
high-resolution spectrometer & thin target

$$B_\Lambda\,(\text{MAMI 2012}) = 2.12 \pm 0.01 \pm 0.09\ (\text{MeV})$$

[PRL 114 (2015) 232501.]

$$B_\Lambda\,(\text{MAMI 2014}) = 2.157 \pm 0.005 \pm 0.077\ (\text{MeV})$$

[NPA 954 (2016) 149.]



(Stat Error only)

Latest results of hypertriton data (MAMI)

Subsequence exp. was done in 2022

Different target (Be → Li 2.7 g/cm^2)

Total Charge = 1.074 C (1 μA x 12 days)

Finding two peaks on pion spectrum

$^4_\Lambda$H → ^{4}He+π$^-$ (~133 MeV/c)

$^3_\Lambda$H → ^{3}He+π$^-$ (~114 MeV/c)

Reliable peak resolution FWHM ~ 100 keV/c

Statistical error ~ 10 keV/c

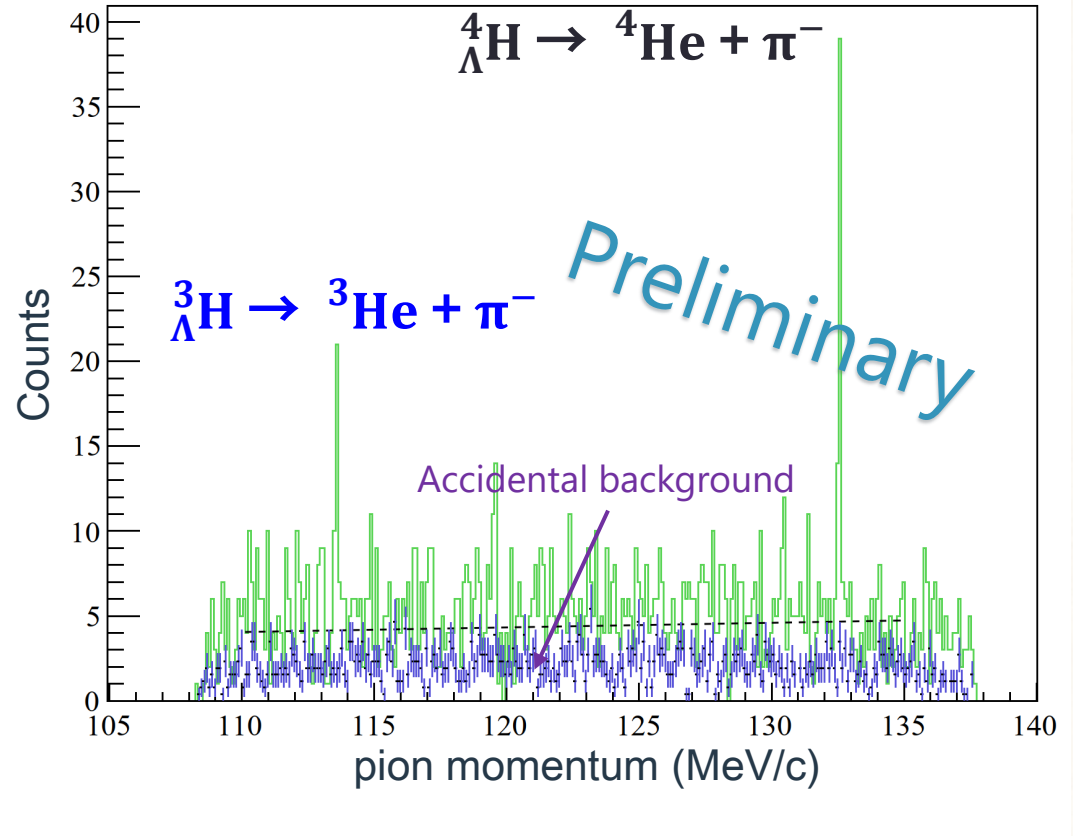
Pion Yield: $^4_\Lambda$H : $^3_\Lambda$H = 3 : 1

Ongoing calibration

Evaluating absolute momentum and linearity with e-N scattering data

e$^-$ beam measurement which is newly developed "undulator radiation interferometry" method

Expected accuracy δB_Λ ~ a few tens keV



NOTE: Momentum calibration result is NOT applied

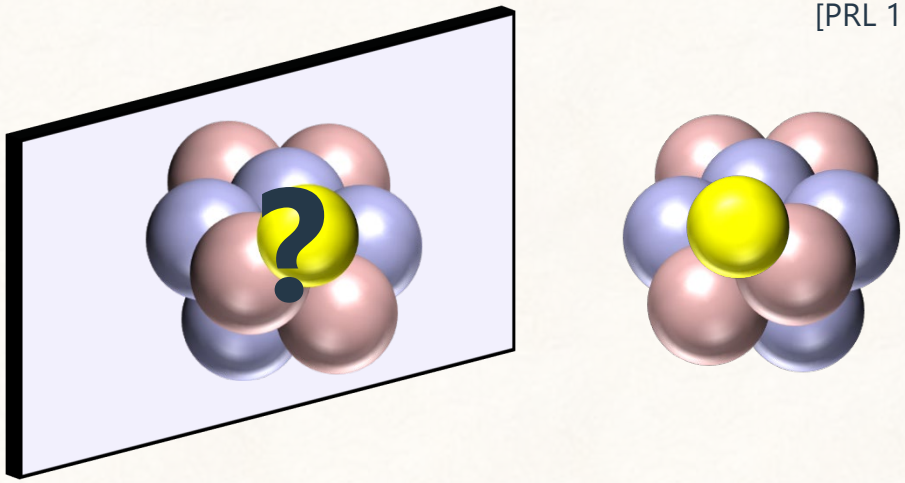
Beyond s-shell hypernuclei

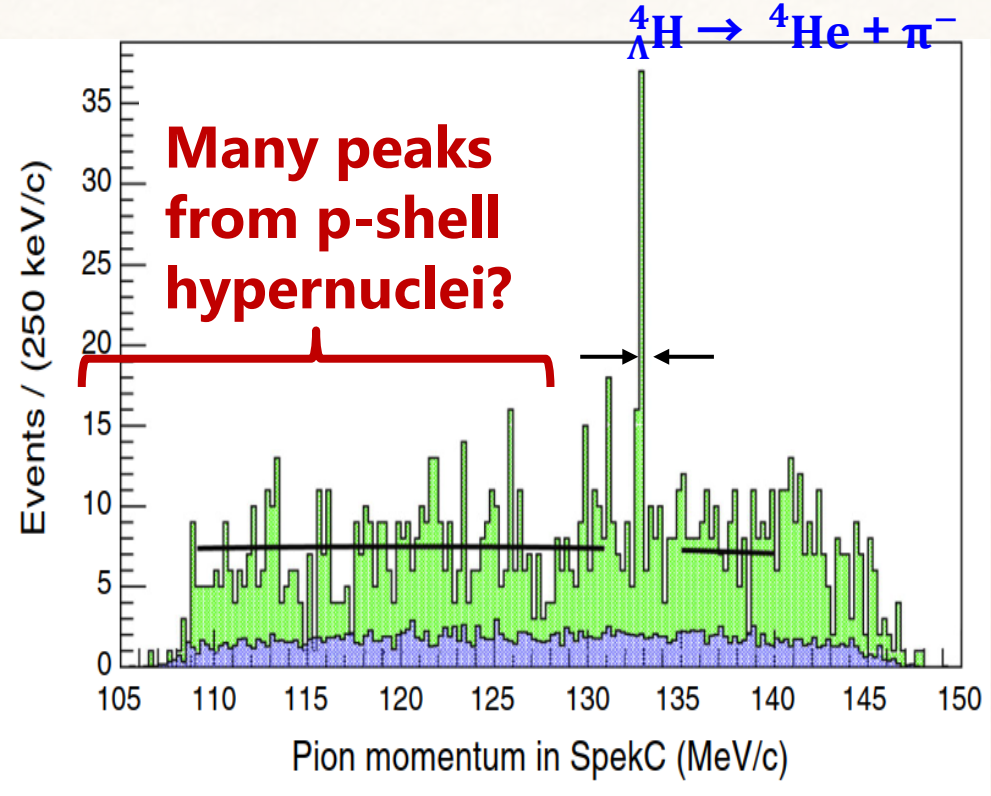
Charge Symmetry on p-shell

Different interaction between Λp & Λn (Isospin rotation)

Larger ΛN CSB effect in s-shell hypernuclei

[PRL 114 (2015) 232501]
[PRL 115(2015) 222501]





Σ mixing effect

Particularly essential effect on neutron-rich hypernuclei

Super-heavy Hydrogen, Helium

Limit of nuclear existence, coupling to heavy hydrogen, helium, 4n-state in NN sector

⇒ Much better statistics is essential !

Hypernuclear project at Jefferson Lab Hall-C

s-, p-shell hypernuclei with Decay Pion Spectroscopy **E12-15-008A / E12-20-013A**

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

^{6}Li, ^{9}Be, ^{11}B(e,e'K^{+})$^{6}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{11}_{\Lambda}$Be **E12-24-004**

Study of charge symmetry breaking in p-shell hypernuclei

^{27}Al(e,e'K^{+})$^{27}_{\Lambda}$Mg **E12-24-011**

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

>1 year run

$^{40, 48}$Ca(e,e'K^{+})$^{40, 48}_{\Lambda}$K **E12-15-008 / E12-24-013**

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

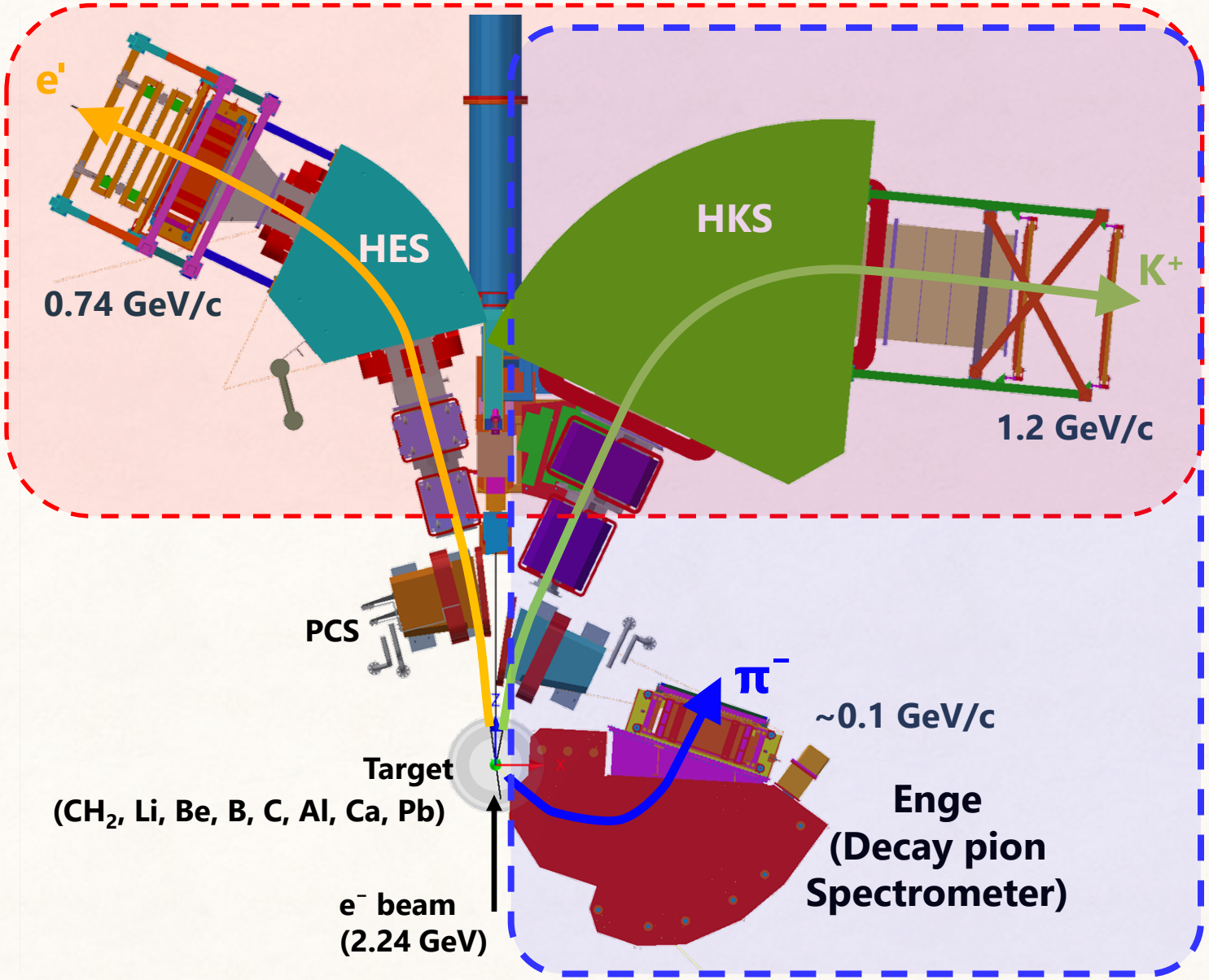
^{208}Pb(e,e'K^{+})$^{208}_{\Lambda}$Tl **E12-20-013 / E12-24-003**

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

Goal of DPS experiment @JLab

- **New Determination of B_Λ (δB_Λ~10 keV) for several s- p-shell hypernuclei**
- **Experimental challenge to heavier sd-shell hypernuclei**
- **Lifetime Measurement**
- **Spin-Parity Assignment**

New Experiment at Jefferson Lab.



(e,e'K⁺) Program

"e', K⁺" coincidence with HES & HKS

New separation magnets (PCS) for better S/N

g.s & e.x B_Λ up to A=6 ~ **208**

with **<100 keV accuracy**

Simulations Data Taking

Decay Pion Program

"π⁻, K⁺" coincidence with Enge & HKS

Parallel Experiment with

(HES ⊗ HKS) ⊕ (Enge ⊗ HKS)

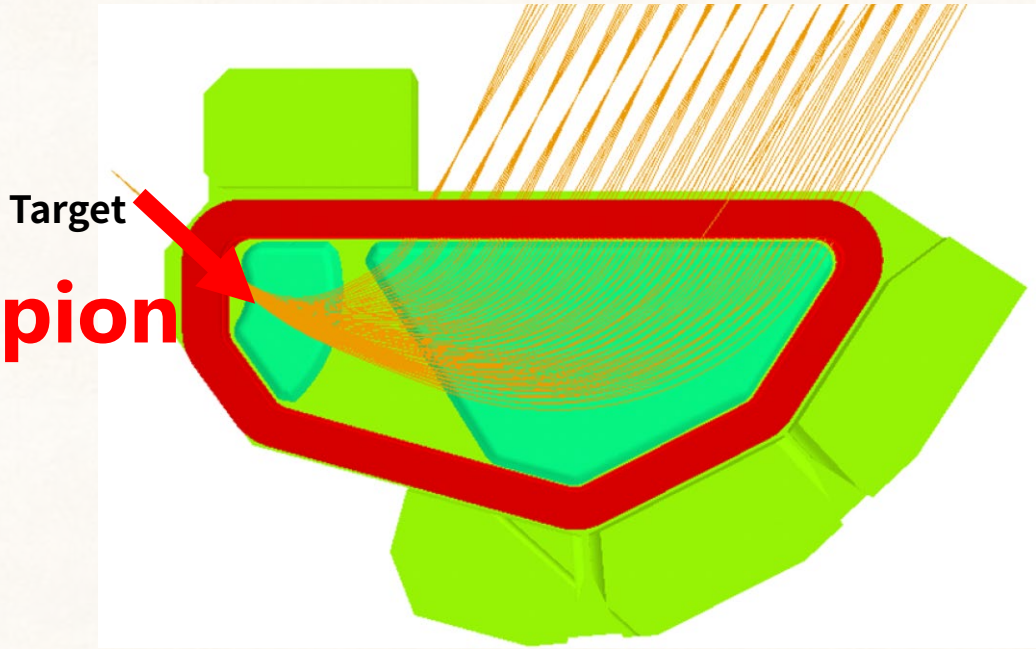
g.s B_Λ of **s-**, **p-**, (sd-) **shell**

with **~10 keV accuracy**

> 30 times stat. per unit time

Decay Pion Spectrometer "Enge"

Type	Hardware spectrometer
Central Momentum	~ 110 MeV/c
Momentum bite	+/- 30%
Dispersion	1.53 cm/(MeV/c)
Momentum Resolution	10^{-3} (FWHM)
Solid Angle	4 msr



Δp/p ~ 10^{-3} momentum resolution

- Peak separation, Better S/N
- Measurement from position info. at focal-plane
- Angular information for target reconstruction

A few 10 keV/c momentum calibration

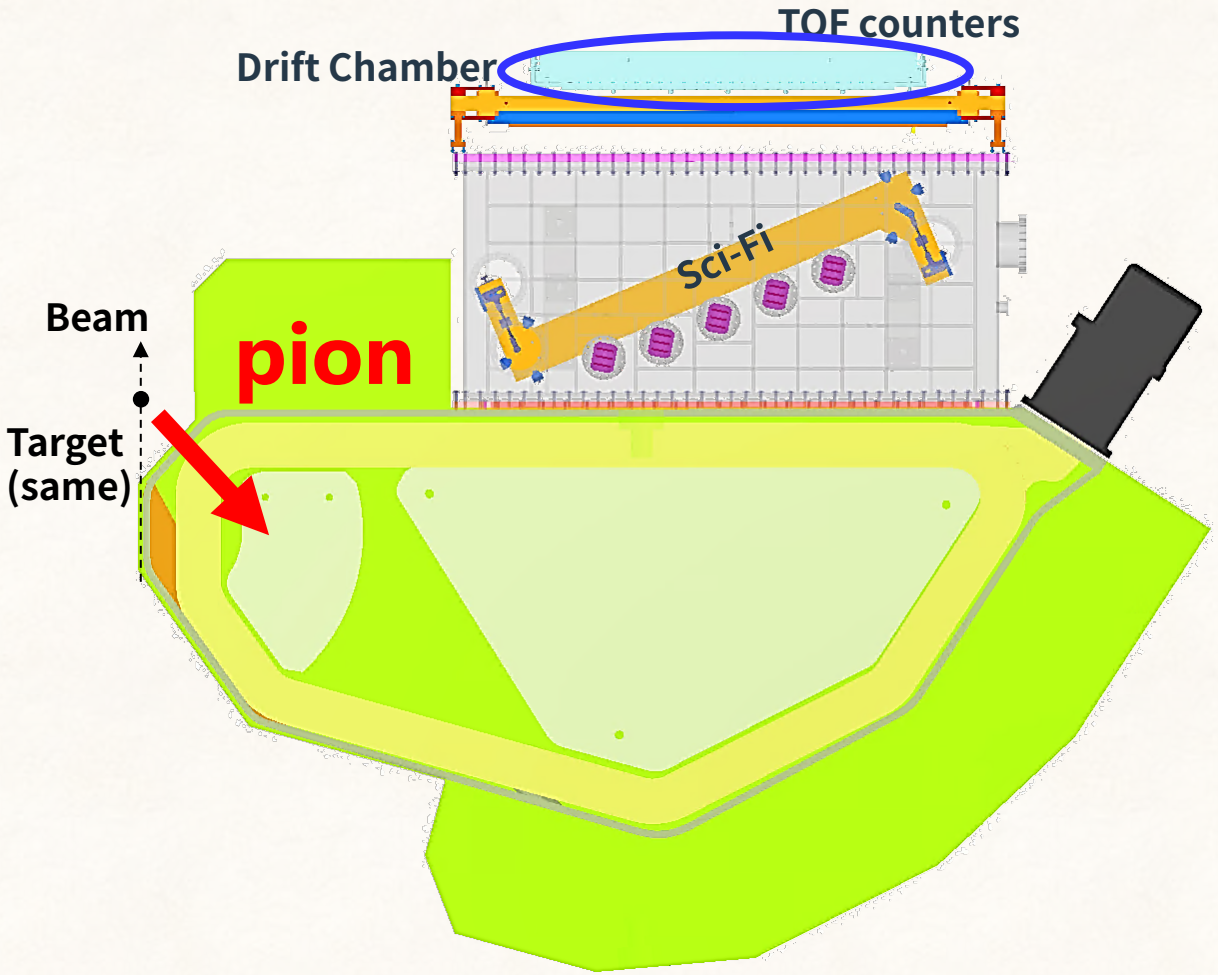
- With alpha-sources (~ 100 MeV/c/q) @target
- Detection of well-known momenta alpha-particles at focal-plane in vacuum

σ~100 ps target time reconstruction

- Suppression of accidental coincidence background
- Particle identification (π / μ / e)
- Lifetime measurement

→ Good start time counter (σ~100 ps)
position (σ~350 μm) & angle (σ~6.7 mrad) information

Enge Detectors



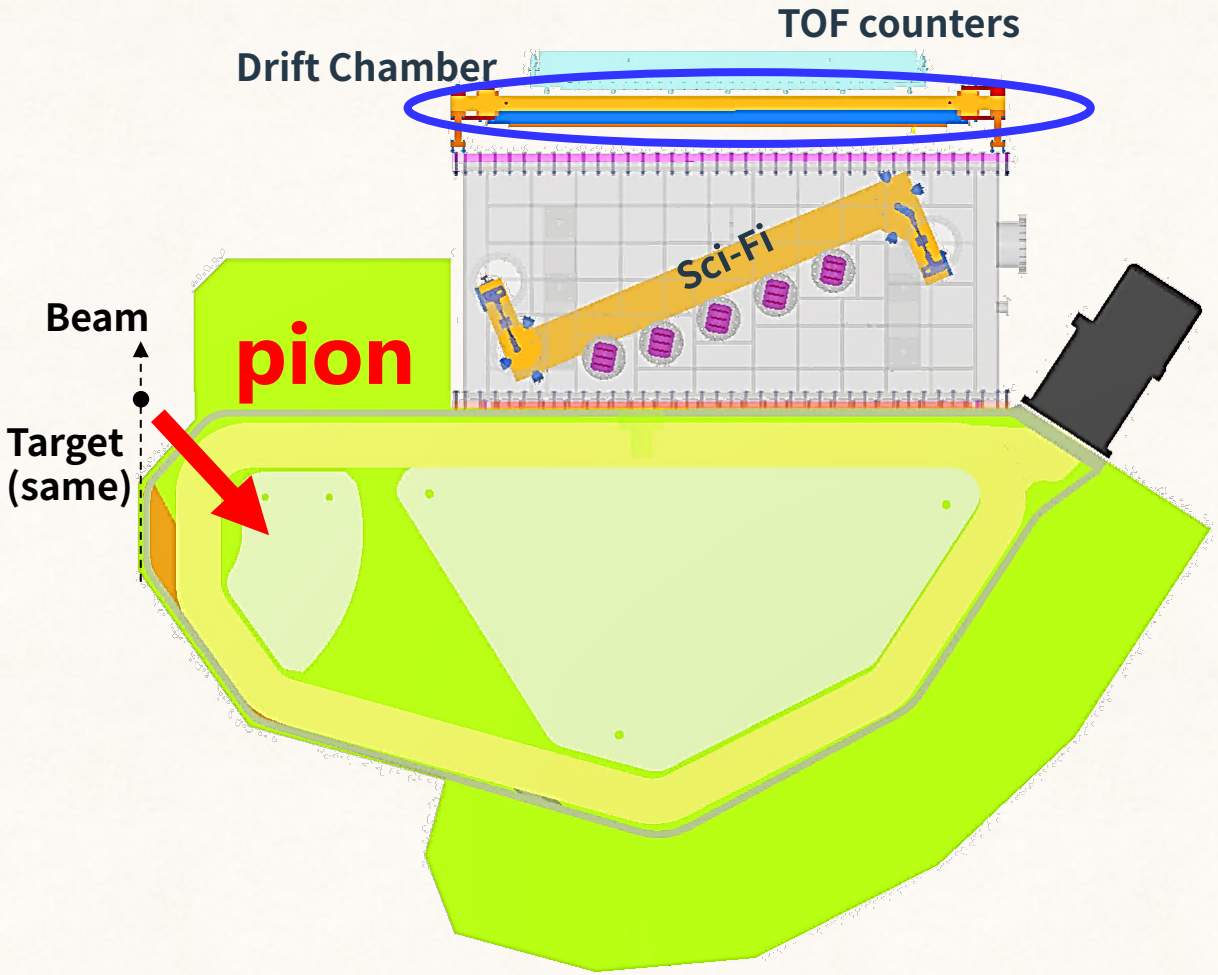
TOF counter

Timing measurement & Trigger Timing

2 Layer of plastic scintillator paddles (48 ch)

Scintillator paddles in ESB

Enge Detectors



TOF counter

Timing measurement & Trigger Timing

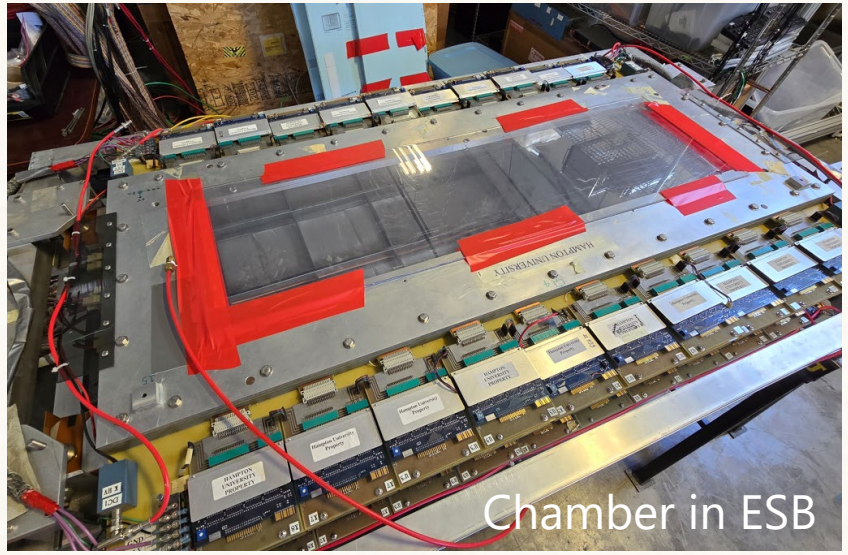
2 Layer of plastic scintillator paddles (48 ch)

Drift Chamber

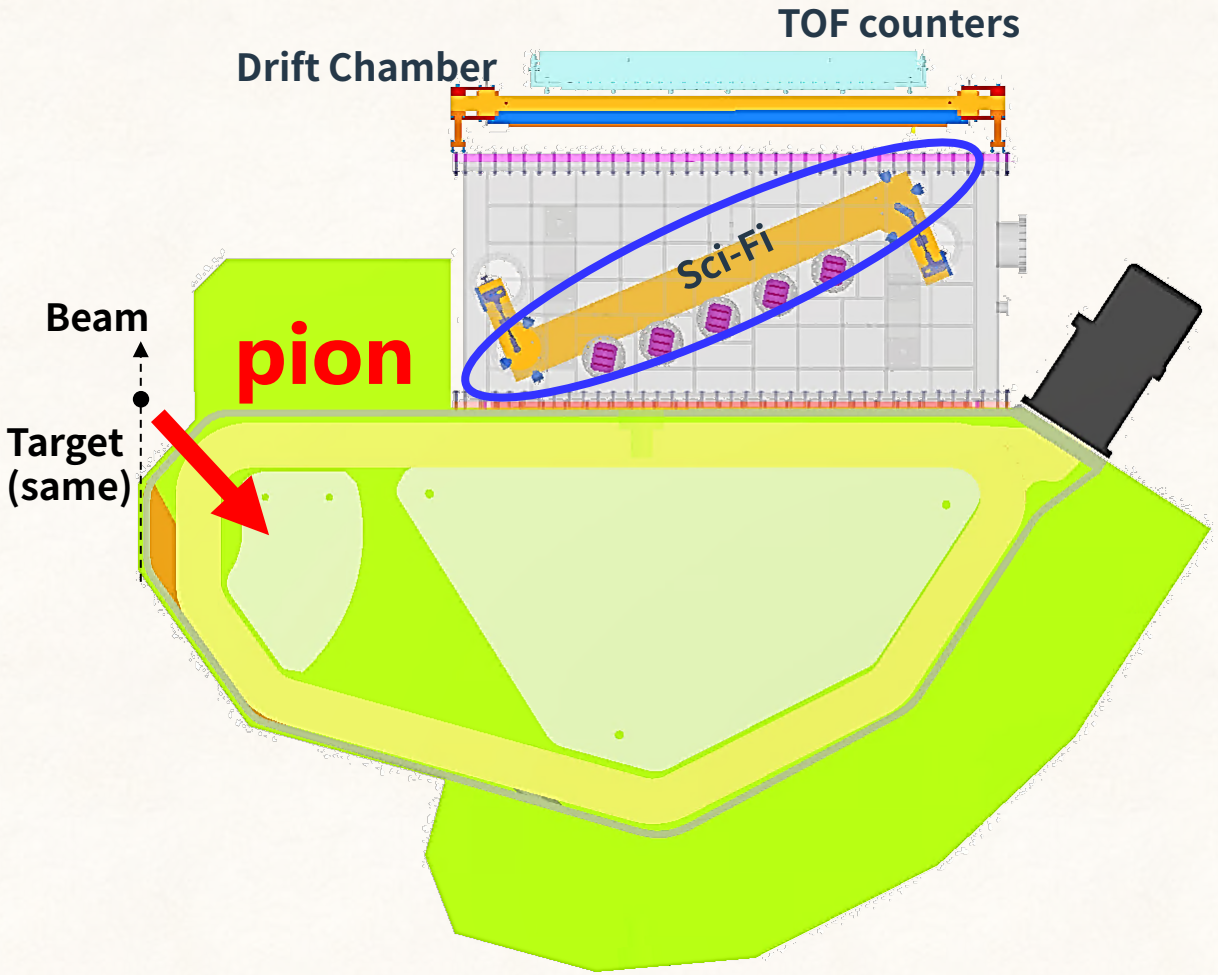
Tracking for angular measurement

→ Reconstruction to our target

Same as HKS Drift Chamber



Enge Detectors



TOF counter

Timing measurement & Trigger Timing

2 Layer of plastic scintillator paddles

Drift Chamber

Tracking for angular measurement

→ Reconstruction to our target

Same as HKS Drift Chamber

Focal Plane Scintillating Fiber Detector (New)

1x1 mm Sci-Fi in vacuum (832 ch)

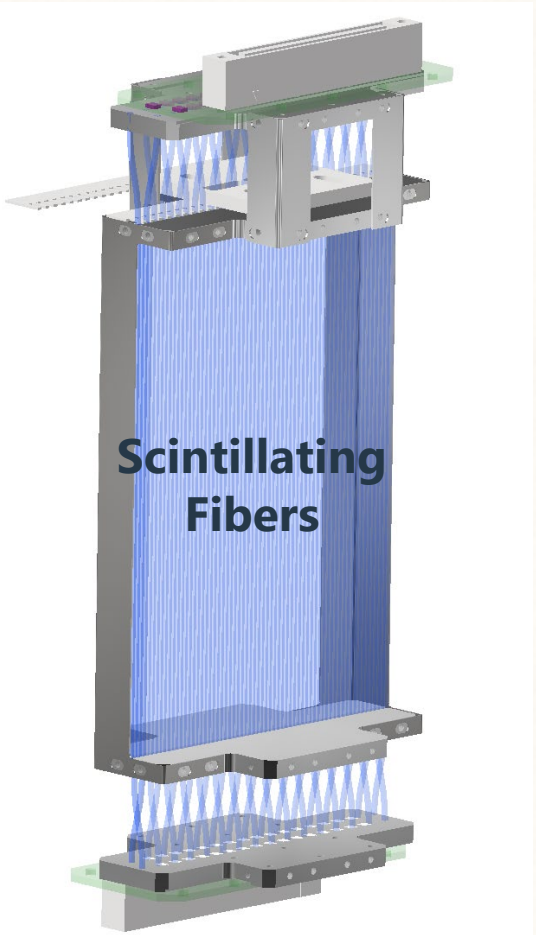
80 keV/c LSB

SiPM photon counter

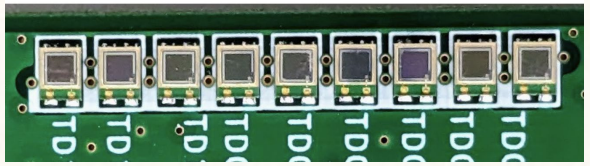
Wide mom. coverage (78 ~ 140 MeV/c)

Enge Detectors

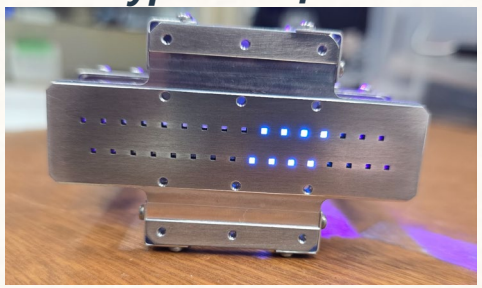
64 ch Sci-Fi Assembly



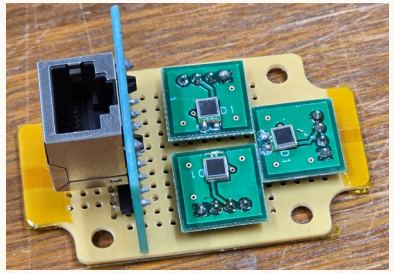
SiPM board



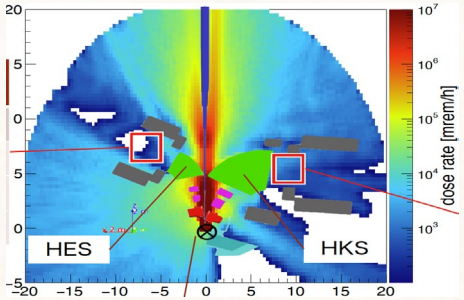
Prototype Fiber frame & Fibers



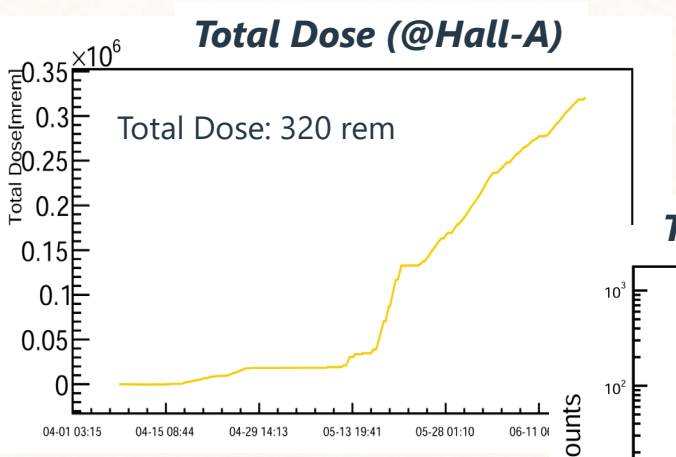
Test box for radiation test (@ Hall-A)



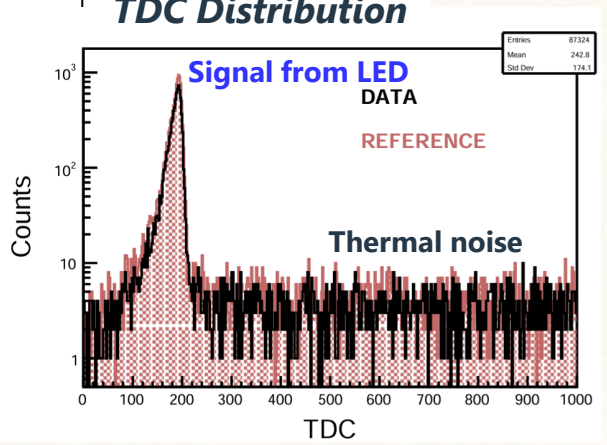
Dose simulation



Total Dose (@Hall-A)

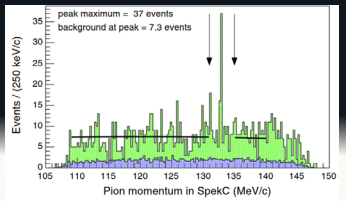


TDC Distribution



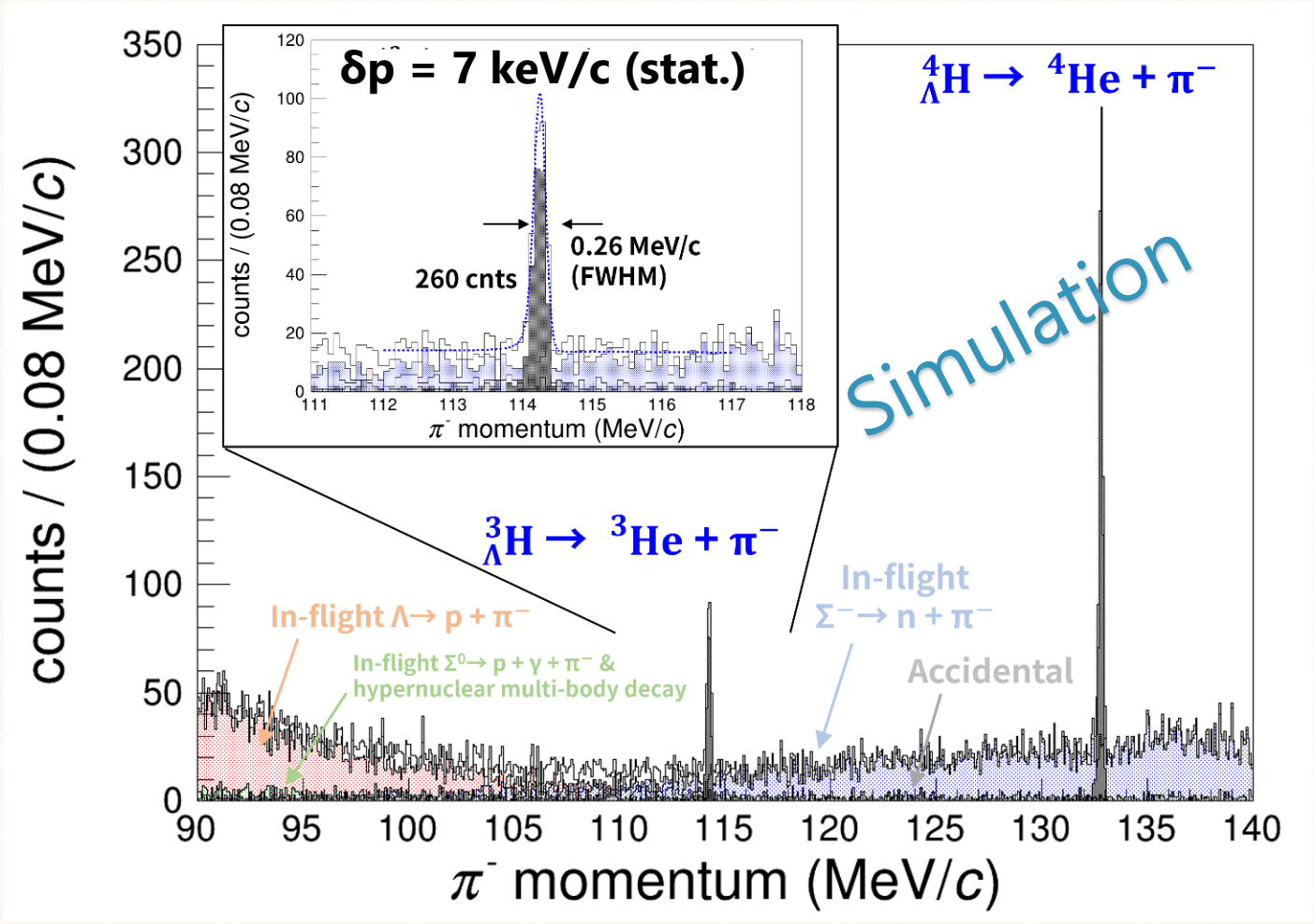
Focal Plane Scintillating Fiber Detector (New)

- 1x1 mm Sci-Fi in vacuum (832 ch)
- 80 keV/c LSB
- SiPM photon counter
- Wide mom. coverage (78 ~ 140 MeV/c)



Expected Spectrum from Simulation

Expected on ^{6}Li target



Monte-Carlo simulation by

- ✓ Spec. Resolution
- ✓ Hyperfragment yield
- ✓ π^- branching ratio
- ✓ Background from QF hyperons
- ✓ Accidental Background

Simplest spectrum

Clear peak from $^{4}_{\Lambda}$H, $^{3}_{\Lambda}$H

FWHM = 260 keV/c

Low QF background

Low accidental

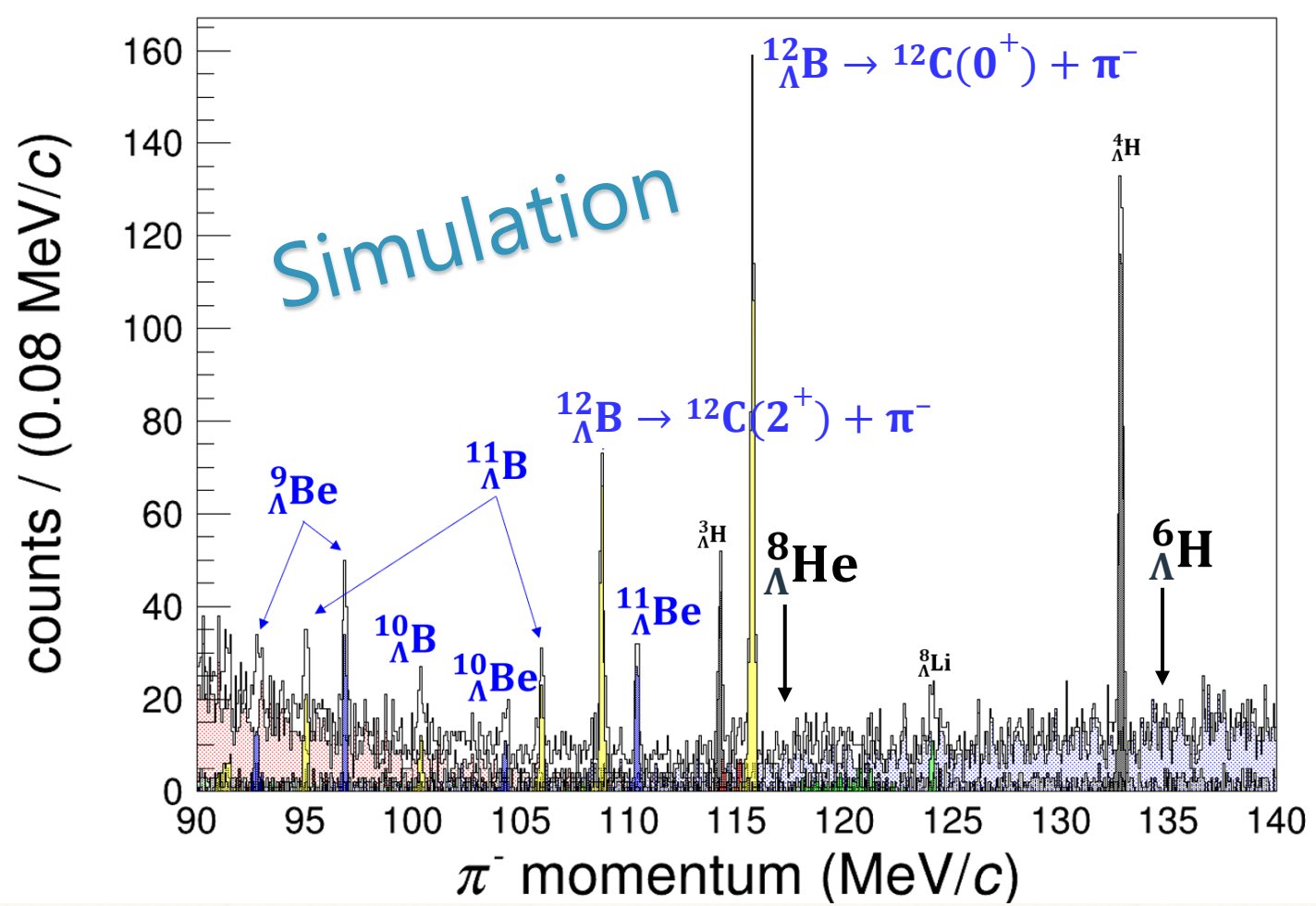
δB_{Λ} = several keV (stat.)

N($^{4}_{\Lambda}$H) @MAMI = 40 cnt / 2 weeks

N($^{4}_{\Lambda}$H) @JLab = 600 cnt / 1 weeks

Expected Spectrum from Simulation

Expected on ^{12}C target



Clouded spectrum, but separable

$^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$: Reference peak

$^{12}_{\Lambda}B$: Directly produced hyp.

Large cross-section, branching ratio

2-peaks from different daughter

→ Spin-Parity assignment

$^{10,11}_{\Lambda}Be$, $^{10,11}_{\Lambda}B$

Isospin partner hyp.

Good for p-shell CSB study

$^{9}_{\Lambda}Be$

Many $^{9}B+\pi^-$ decay in emulsion

$^{8}_{\Lambda}Li$

Famous $^{8}Be+\pi^-$ decay channel

Summary

Lambda hypernuclei as a multi-body system with strangeness

High-resolution spectroscopy available thanks to narrow width of hypernuclear state

Investigation of ΛN interaction nuclear medium / (hyper)nuclear structure possible

More precise discussion on going thanks to recent progress of both experiment and calculation

High-resolution spectroscopy of electro-produced hypernuclei

Decay Pion Spectroscopy

Novel technique for B_Λ measurement from Decay Pion momentum measurement

Excellent resolution (FWHM ~ 100 keV) and precision (δB_Λ ~ 10 keV)

Measurement of hypernuclear ground-state started at MAMI, Germany

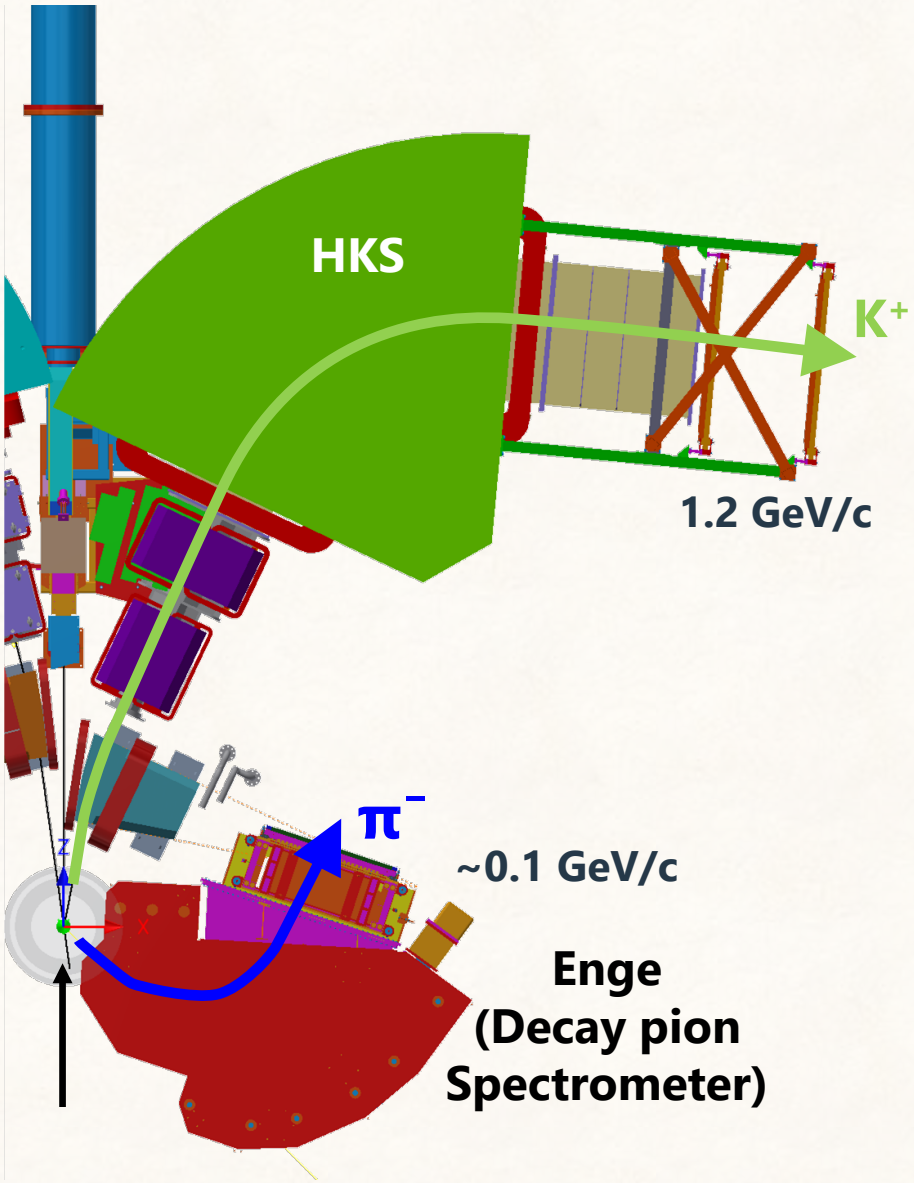
Improving hyp. yield ~30 times thanks to better beam intensity & PID etc.

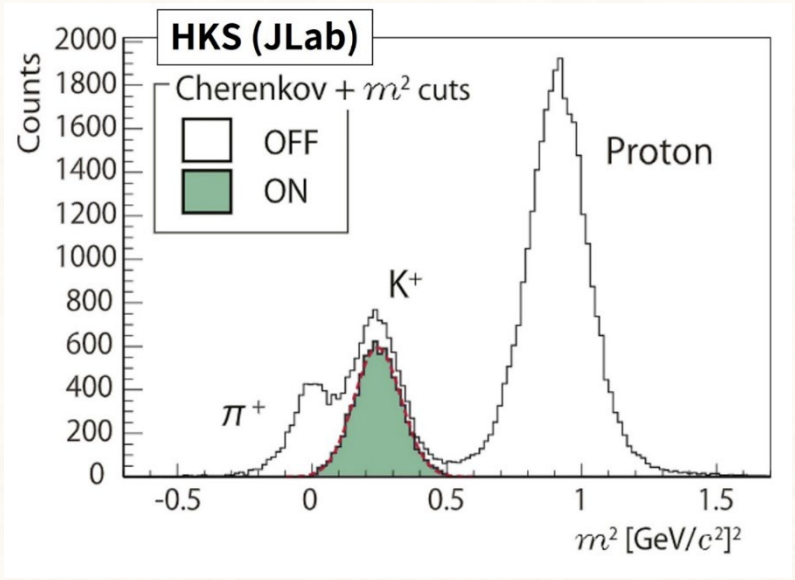
Expecting decay pions from several s-, p-, (sd-) shell hypernuclei

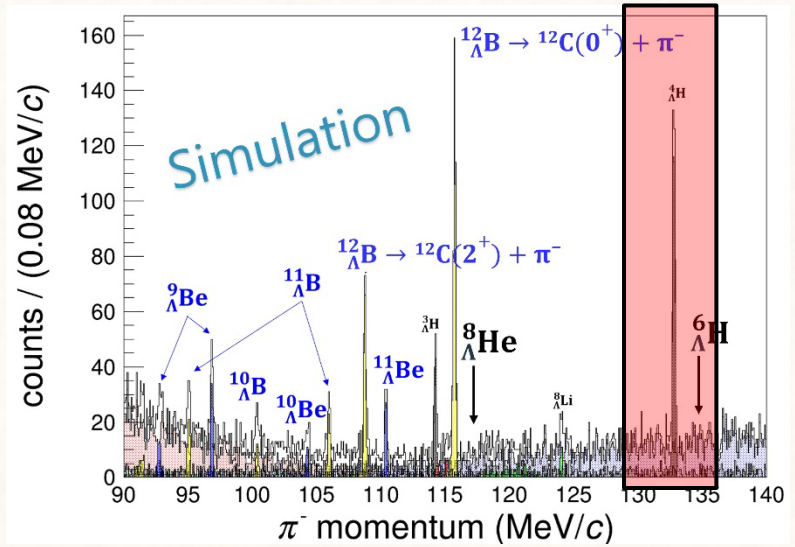
Re-determination of Hypernuclear g.s. Λ binding energies

Please join us !!

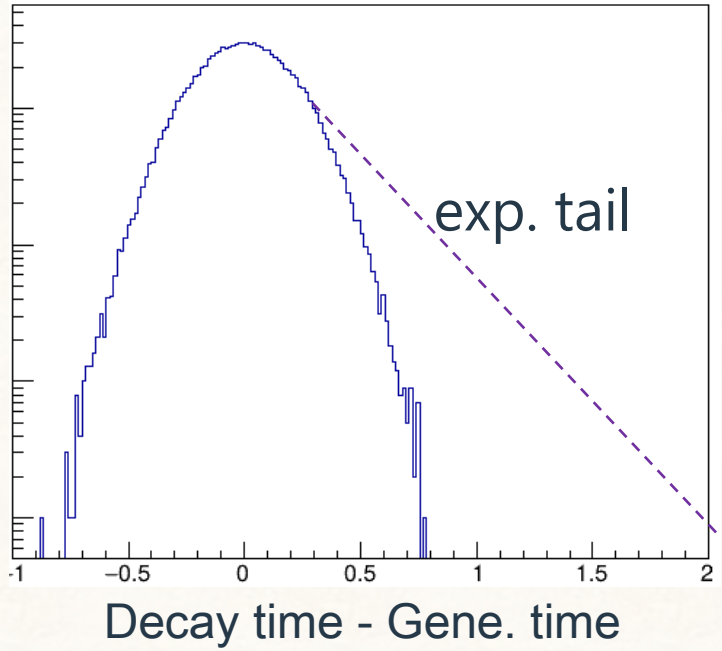
Lifetime measurement (by product)





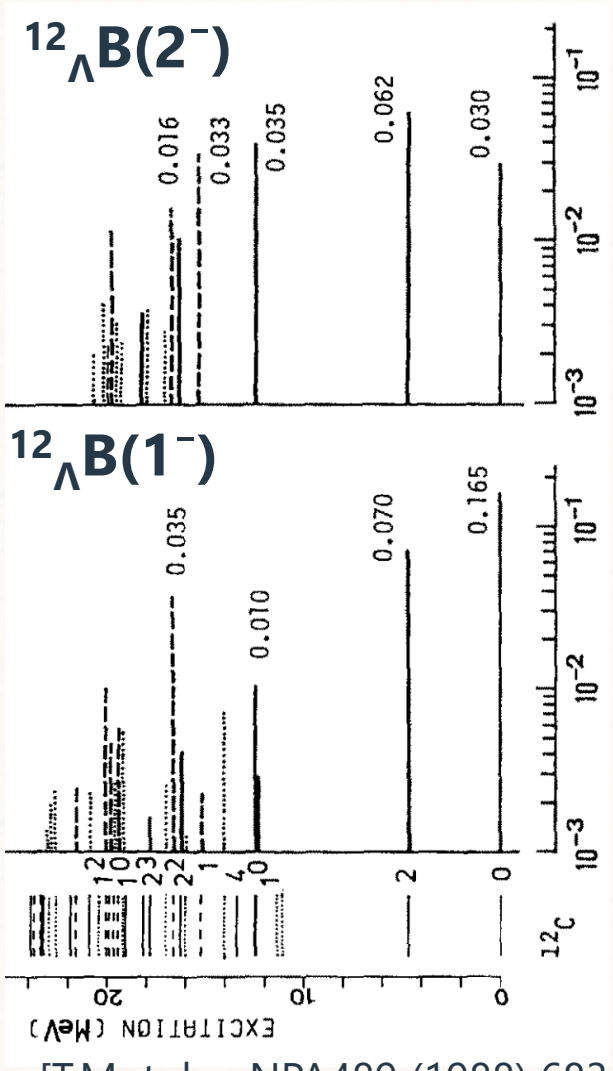


K^+ time = Generate time

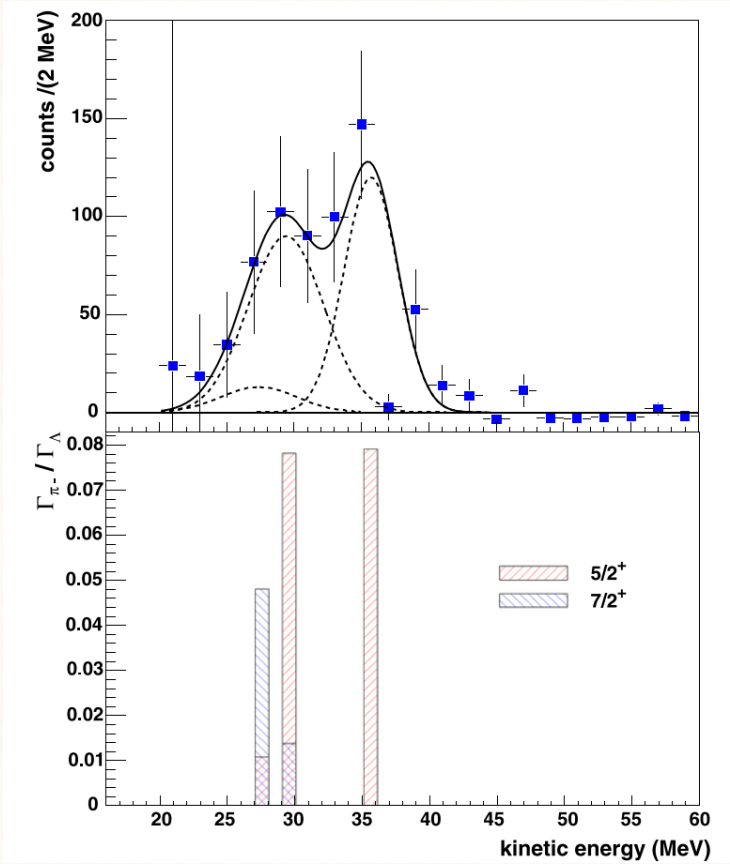


π^- time = Decay time

Possibility of Spin Assignment



[T.Motoba, NPA489 (1988) 683.]



[FINUDA, PLB681 (2009) 139.]

Spin-Parity assignment only for several hypernuclear ground-state

Possibility of spin inversion of the ground state in neutron-rich hypernuclei

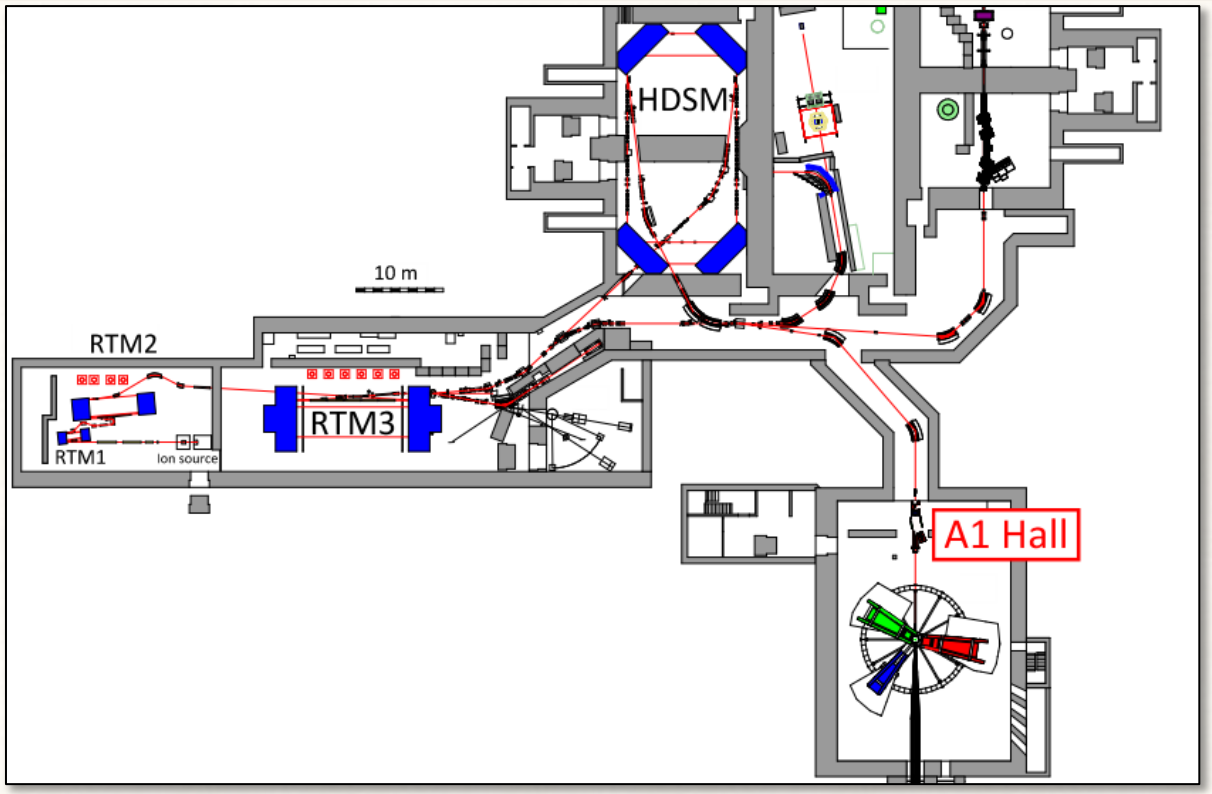
Weak-decay branching-ratio depending on the spin-parity relationship of parent hypernucleus and daughter nucleus

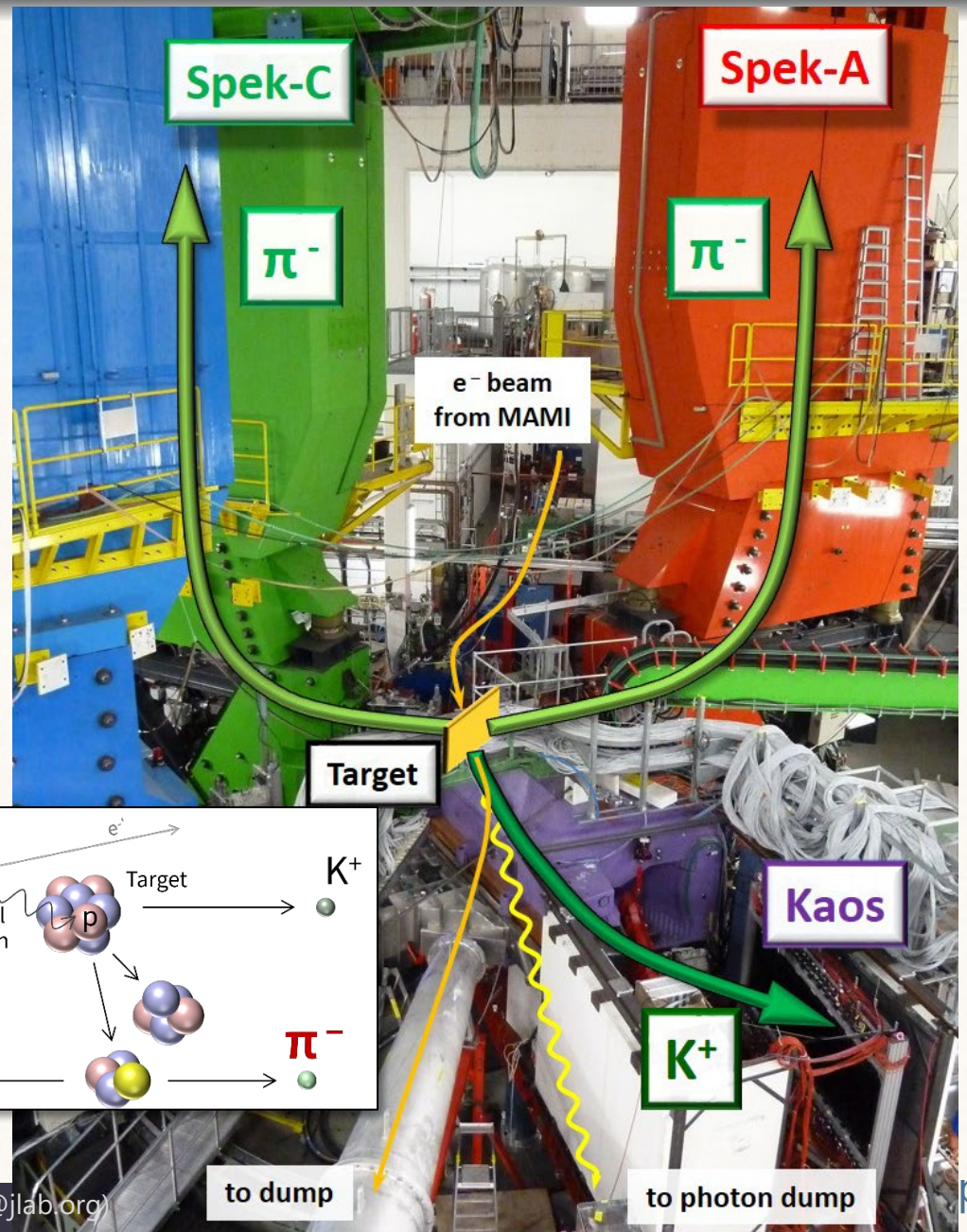
→ spin-parity determination from weak decay branching-ratio

FINUDA exp. has determined spin-parity for several hypernuclei

[FINUDA, PLB681 (2009) 139]
[FINUDA, NPA881 (2012) 322]

Prior experiment at Mainz, Germany

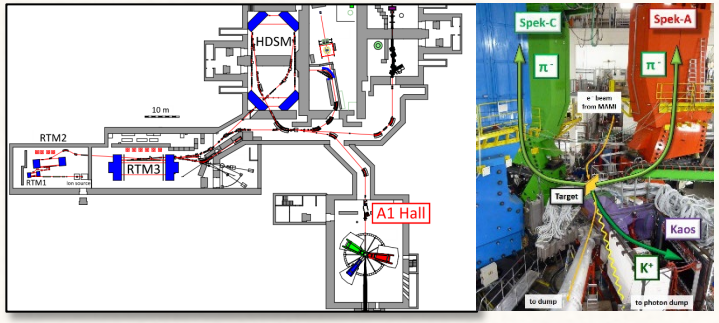


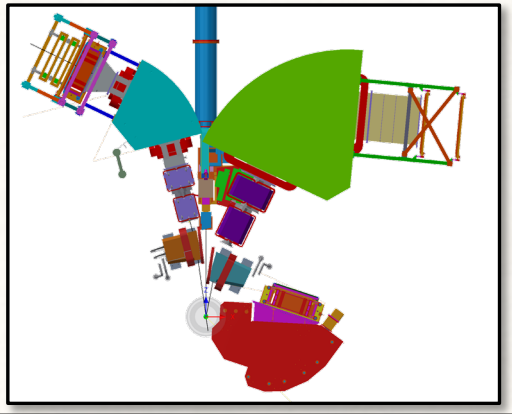


The **MA**inzer **MI**crotron (MAMI)

Beam Emergy:	1.5 GeV max.
Beam Intensity:	100 μA max.
Beam Size:	a few 100 μm
Duty Factor:	100 %

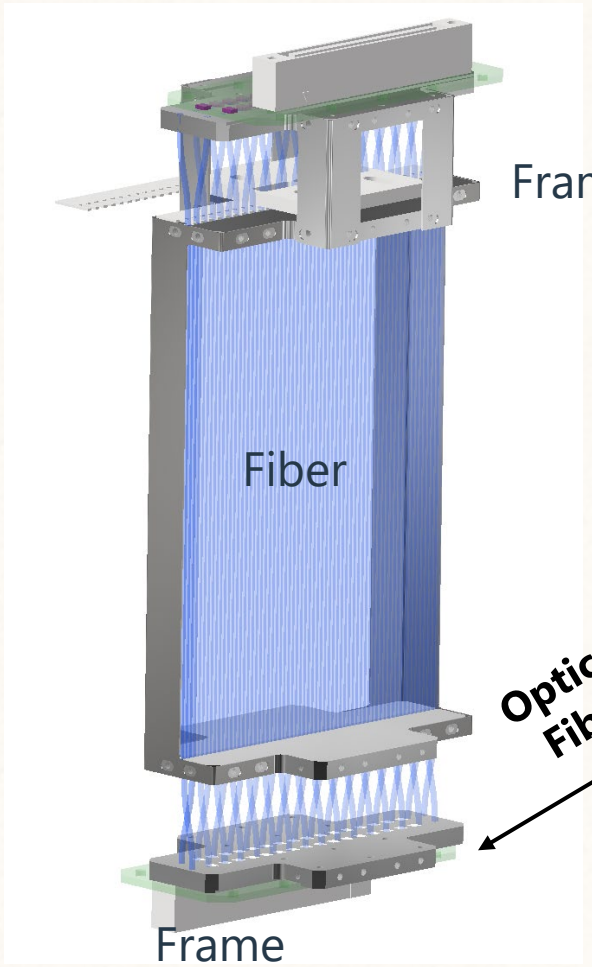
Characteristics of DPS at JLab



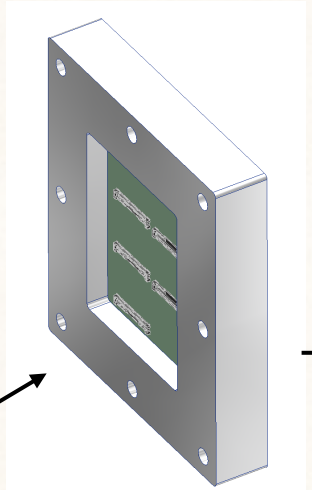


	DPS @MAMI	**DPS @JLab**	
Target	Li / Be (39 mg/cm^2 for Be)	Li / Be / B / C / Al / Ca / Pb (100 ~ 150 mg/cm^2)	**Various hypernuclei**
Beam Energy / Current	1.5 GeV / (20 μA for Be)	2.24 GeV / 50 μA	**Effective Λ production**
K^+ Tag Efficiency	~20%	~80%	**Better PID**
π^- mom. resolution	<1×10^{-3} (FWHM)	2×10^{-3} (FWHM)	
mom. coverage	110 ~ 135 MeV/c	70 ~ 150 MeV/c	**Covered Entire region**
Beamtime	~ 2 weeks	~ 1 year	**Better yield**
"K^+,π^-" time resolution	2000 ps	< 200 ps	**Lifetime measure**

Plan B (Sci-Fi detector)

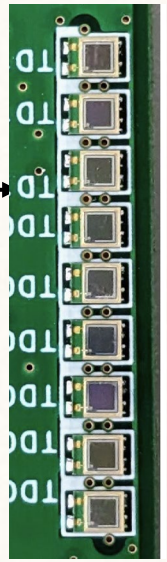


Optical port on chamber



HV ~ +100 V

SiPM



Optical Fiber

EASIROC Test Board on or under the platform

16 ch x 52 modules

LVDS out

34 pin
Flat Cable

VETROC LR-TDC
@ SHMS

alpha-source

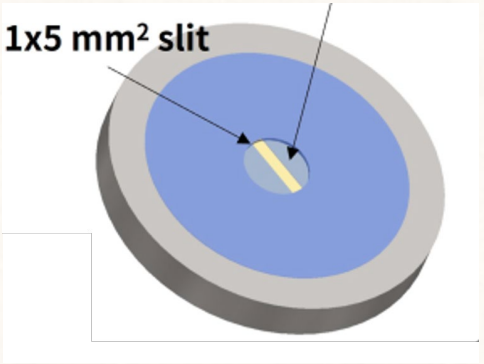
alpha sources available from a vendor "Eckert & Ziegler"

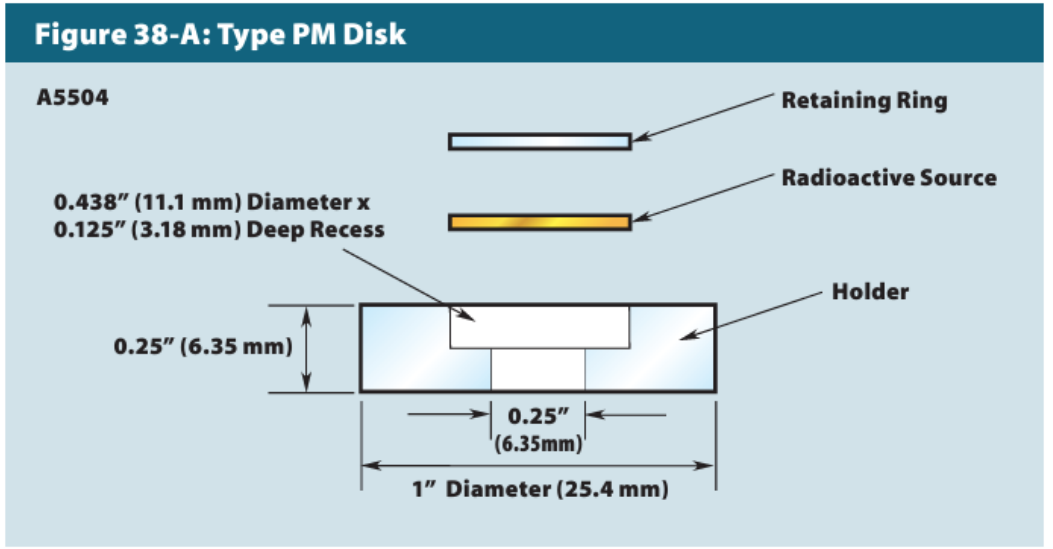
Get AF-type 3-nuclide mixed source through RadCon

- **^{230}Th, ^{241}Am, ^{244}Cm (1~5 kBq each)**
- Φ = 5 mm source area, no cover
- <20 keV resolution (FWHM)
- **Removable** package
- $3,610, 5-6 weeks delivery time

Make special holder to mount to target ladder

- and **1x5 mm^2 slit** to make small source point





Expected alpha-source result