Decay Pion Spectroscopy of Lambda Hypernuclei at Jefferson Lab

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

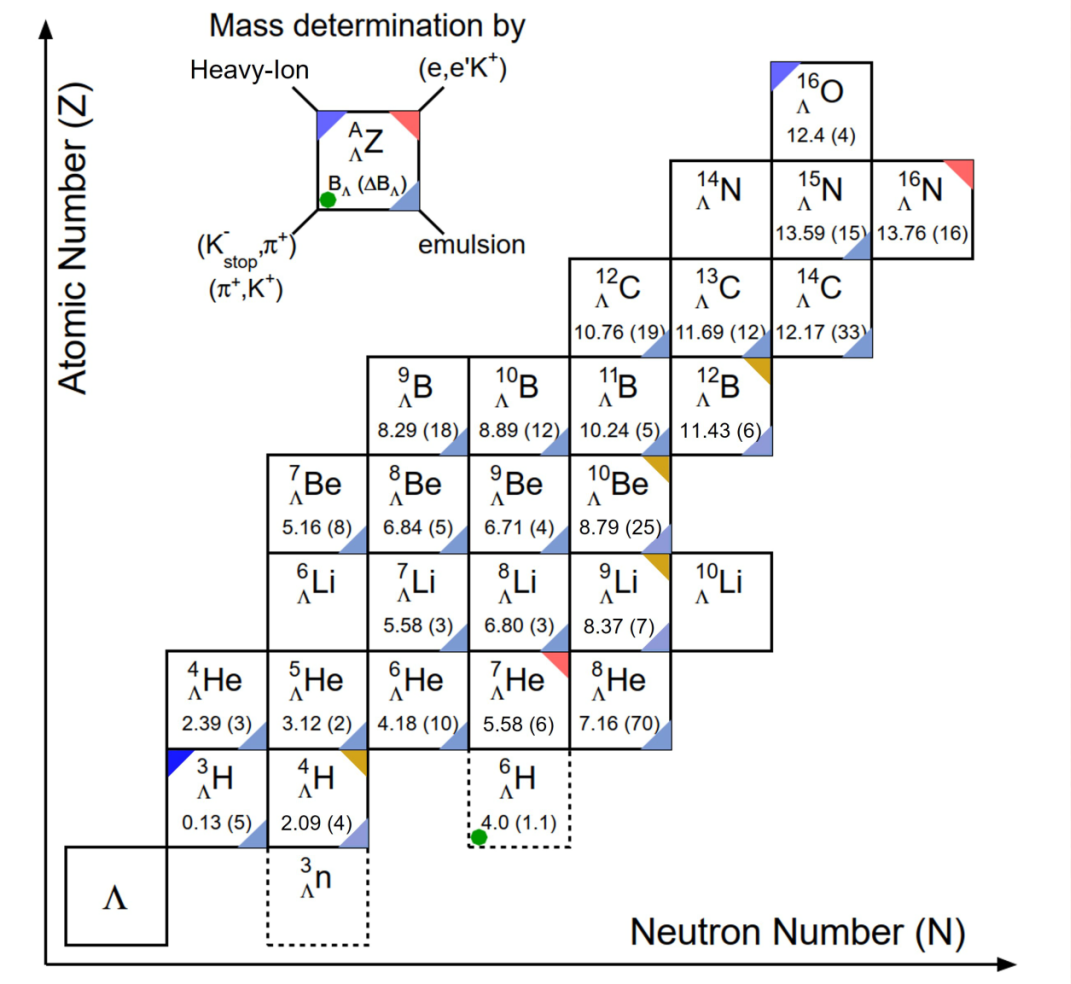
(Run group proposal, simultaneous run with (e,e'K^+))

The University of Tokyo

Sho Nagao

Λ hypernucleus as a Lambda bound multi-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

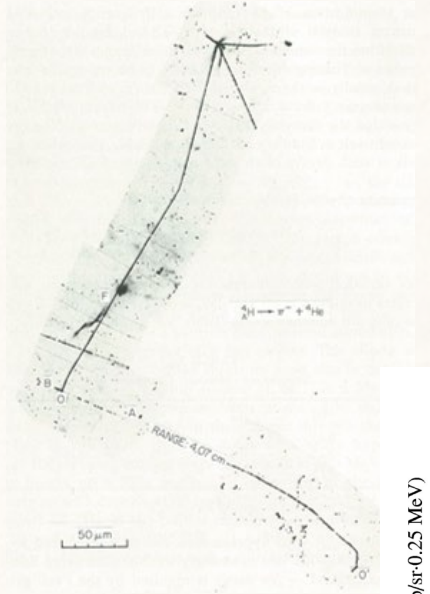
Mass, Isospin dependence etc. provide important information about effective ΛN/ΛNN interaction

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

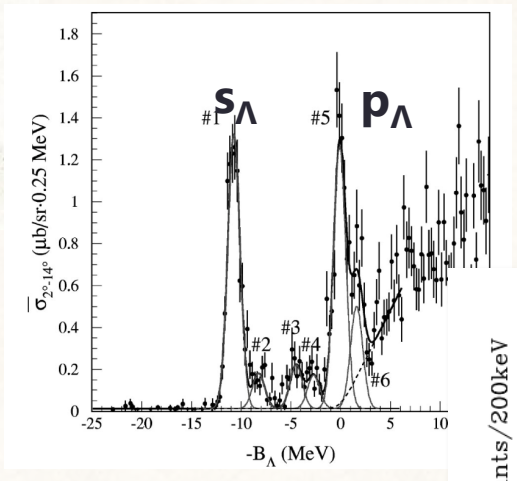


Walter H. Barkas, Nuclear Research Emulsions (1973)

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

500 keV
a few MeV

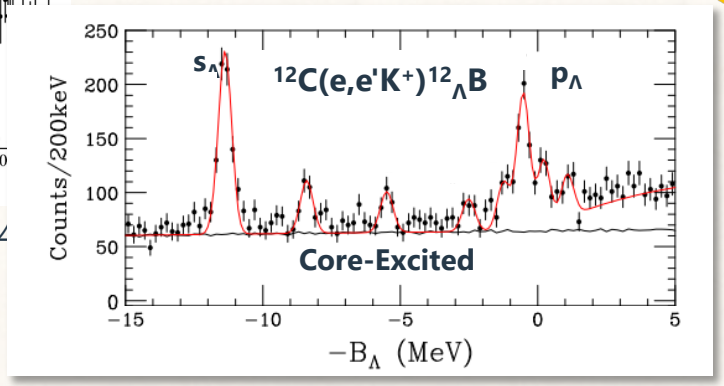
100 keV
0.5 MeV



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

2000's **(e,e'K⁺) Spec.**

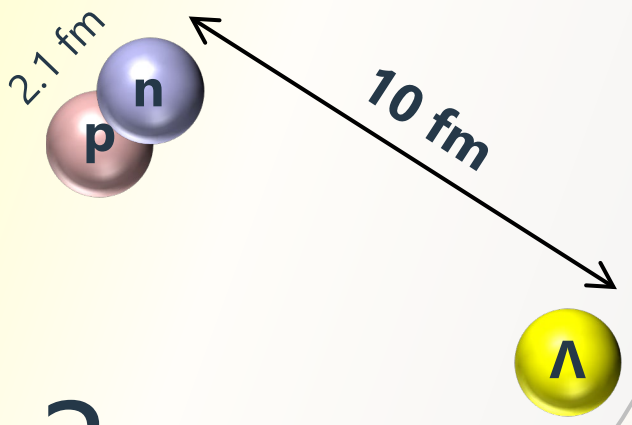
<100 keV
0.1 MeV



PRC90 (2014) 034320.

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

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



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

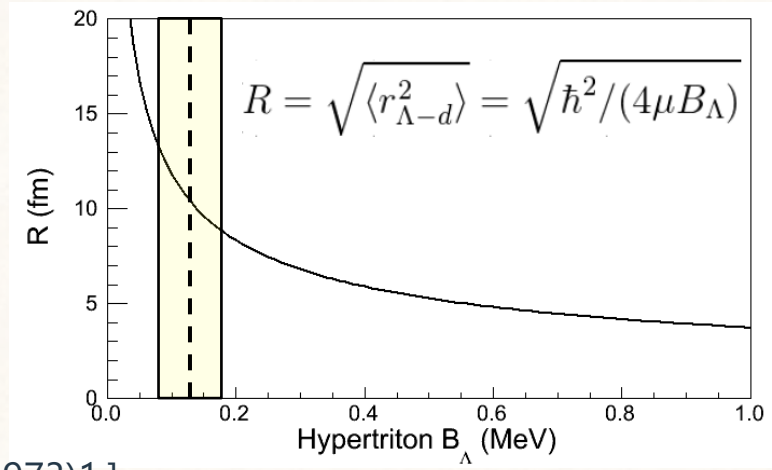
- Lightest system with nucleons and Lambda
- $J^P = 1/2^+$
- T = 0
- Lambda binding energy

  B_Λ = 130±50(stat.) keV

  [M. Juric et al., NPB52(1973)1.]

  Loosely bound system

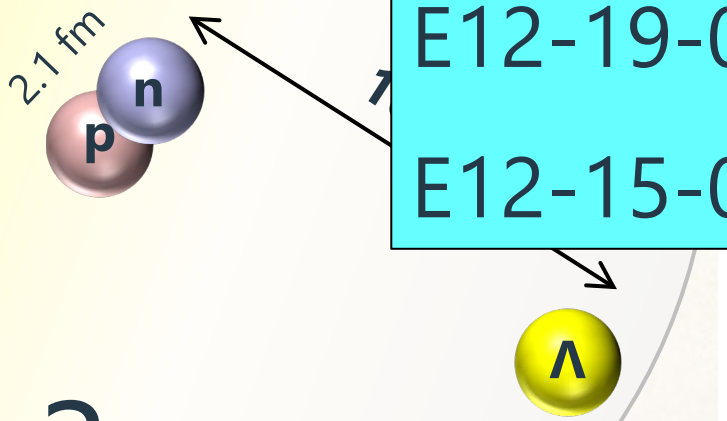
  Lambda halo nucleus



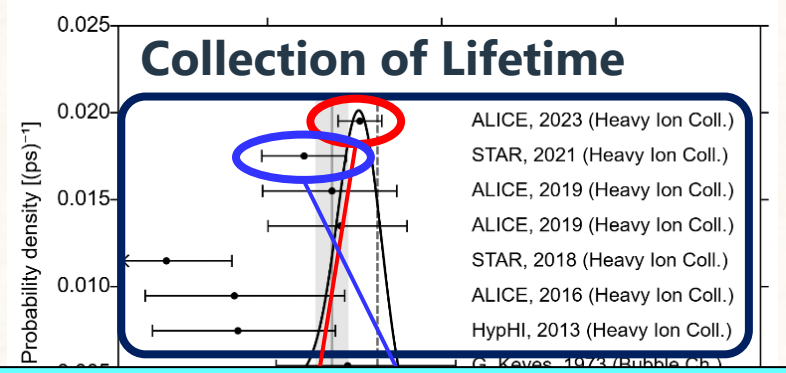
- Mesonic Weak Decay (MWD) dominant

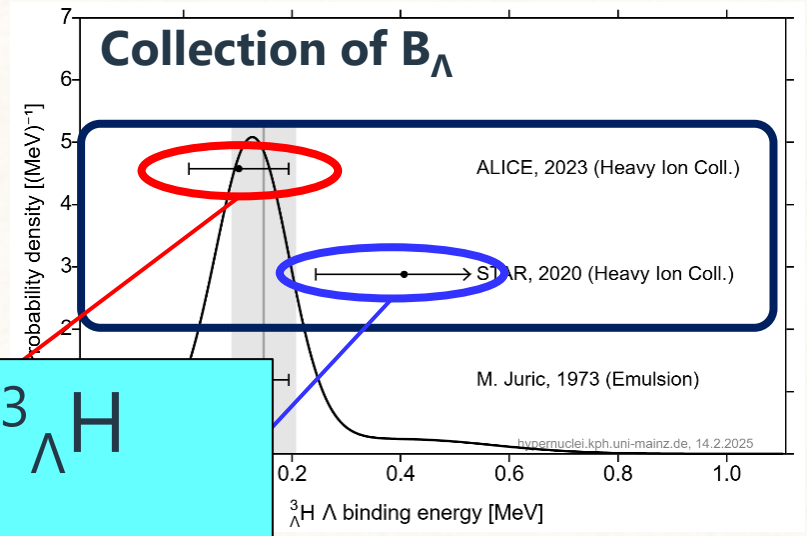
  Similar lifetime to free-Lambda (263.4 ps) ??

Hypertriton Puzzle



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

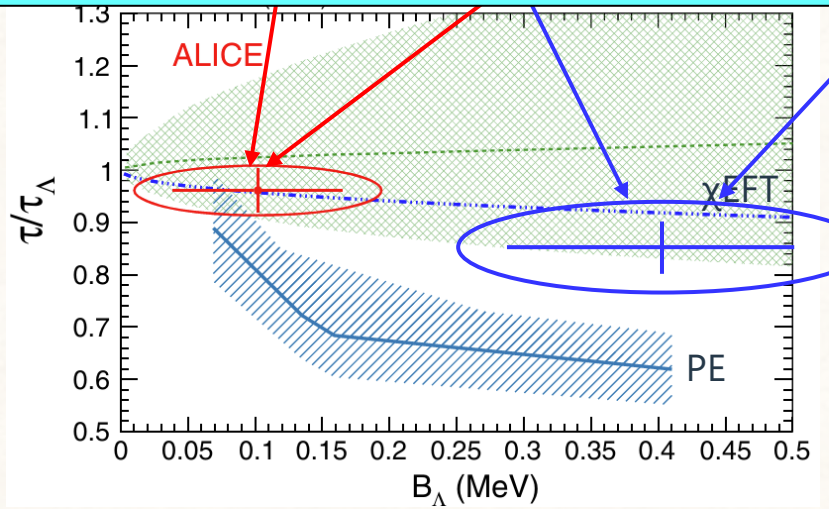




se [https://hypernuclei.kph.uni-mainz.de/]

E12-19-002 $^{3}He(e,e'K^{+})^{3}_{\Lambda}H$

E12-15-008A Decay Pion Spec.



[ALICE collaboration, PRL131 (2023) 102302]

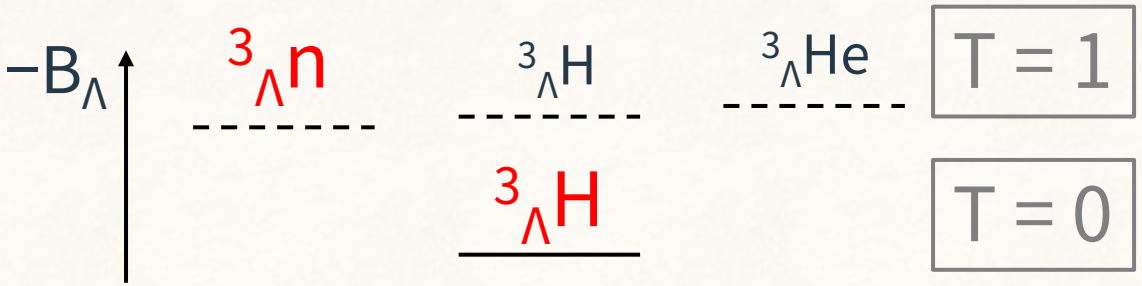
Recent HI exp. have measured τ & B_Λ with invariant mass

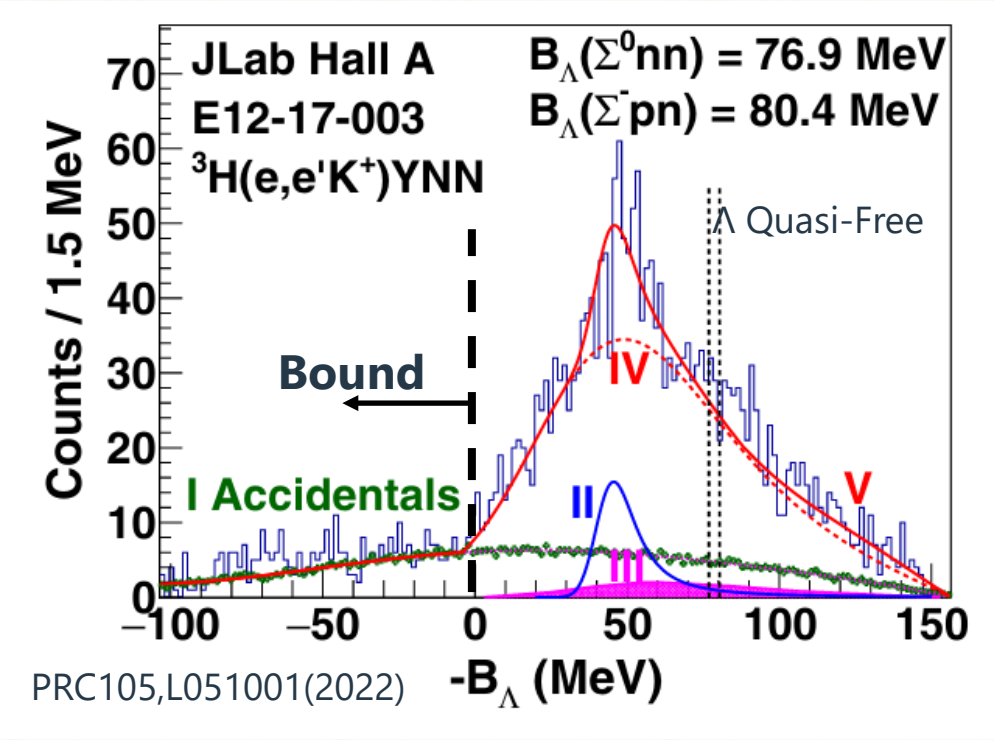
Some results mentioned short τ & deep B_Λ picture, but subsequent result shows different

Measurement with the different approach is important

Related topics

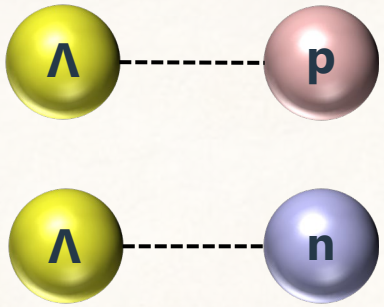
Existence of other A=3 system





PRC105,L051001(2022)

Key information of ΛN CSB effect

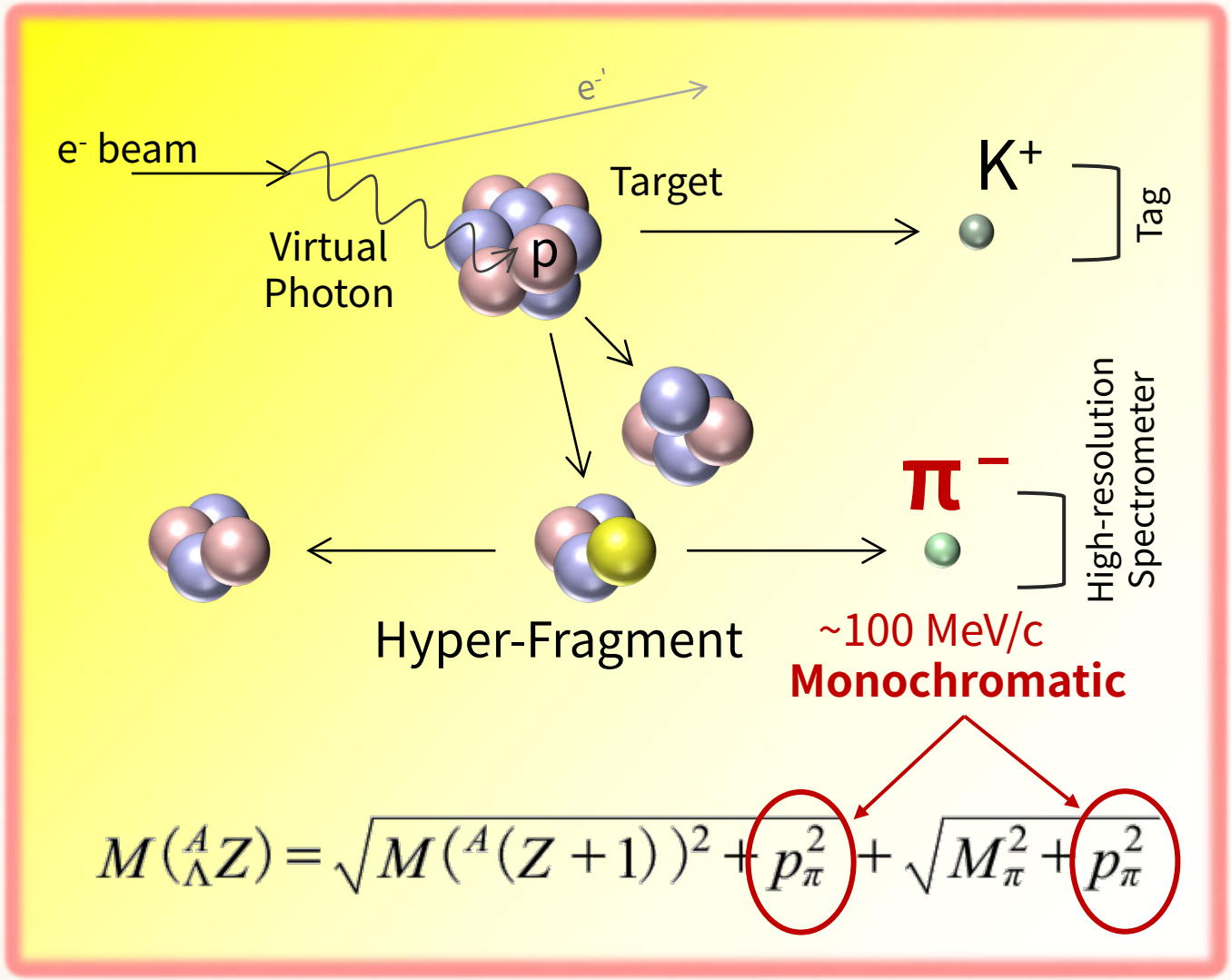


Larger difference than pp & nn

Hypernuclides	ΔB_Λ(Exp) (keV)	Hiyama [PTP128(2012)105]	Gal [PLB744(2015)352]	NLO13 [PRC107(2023)024002]	NLO19 [FBsyst.672(2021)105]
${}^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$	300 ± 60		226	252(43)	238(10)
${}^{7}_{\Lambda}\mathrm{Li}^{*} - {}^{7}_{\Lambda}\mathrm{He}$	-320 ± 140	130(-60)	-17	-31(-5)	-16(-17)
${}^{8}_{\Lambda}\mathrm{Be} - {}^{8}_{\Lambda}\mathrm{Li}$	40 ± 80		49	178(16)	146(-6)
${}^{9}_{\Lambda}\mathrm{B} - {}^{9}_{\Lambda}\mathrm{Li}$	-160 ± 210		-54		
${}^{10}_{\Lambda}\mathrm{B} - {}^{10}_{\Lambda}\mathrm{Be}$	100 ± 300	20(-180)	-136		
${}^{11}_{\Lambda}\mathrm{B}^{*} - {}^{11}_{\Lambda}\mathrm{Be}$	N/A				

- Large symmetry breaking of Λp-Λn
- Under discussion of its origin (Σ mixing?)
- Necessity of systematic studies

Decay Pion Spectroscopy



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 & Decay pion momenta (up to A=16)

Decay pion from a hypernucleus has specific momentum

Daughter nucleus mass is well known usually

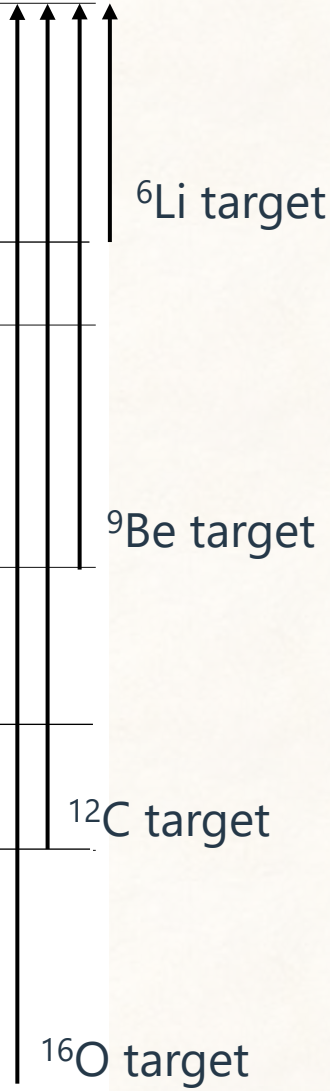
Possible hypernuclei (hyperfragments) depend on the target nucleus

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

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

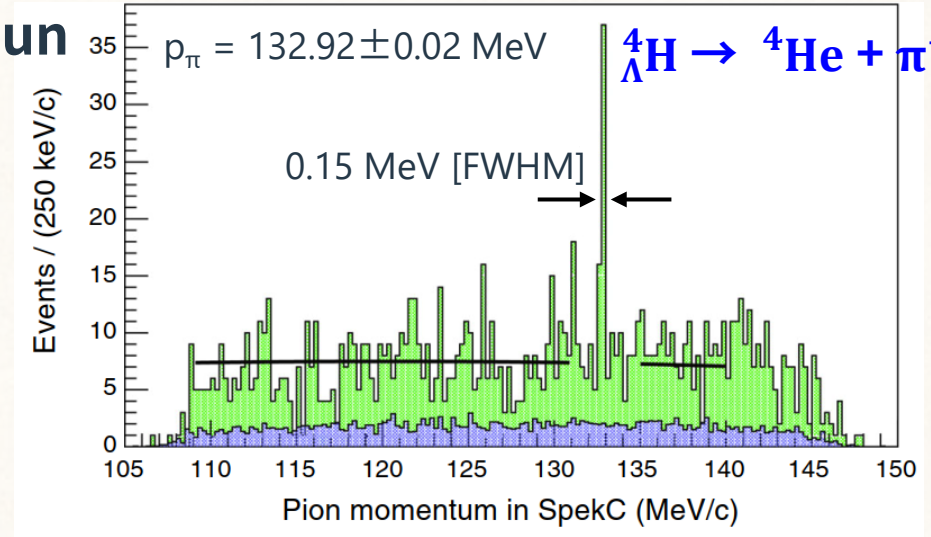
M(α)	= 3727.3794118(11)	MeV/c²
M(π)	= 139.57039(18)	MeV/c²
M(${}^{4}_{\Lambda}$H)	= 3922.56(4)	MeV/c²
p(π)	= 133.03(6)	MeV/c

Hypernuclei	Decay mode	p_{π^-} (MeV/c)	comments
${}^{3}_{\Lambda}\mathrm{H}$	${}^{3}\mathrm{He} + \pi^-$	114.37	
${}^{4}_{\Lambda}\mathrm{H}$	${}^{4}\mathrm{He} + \pi^-$	133.03	
~~${}^{4}_{\Lambda}\mathrm{He}$~~	~~${}^{4}\mathrm{Li} + \pi^-$~~	~~98.17~~	Impossible 2-body decay
~~${}^{5}_{\Lambda}\mathrm{He}$~~	~~${}^{5}\mathrm{Li} + \pi^-$~~	~~99.26~~	Impossible 2-body decay
${}^{6}_{\Lambda}\mathrm{H}$	${}^{6}\mathrm{He} + \pi^-$	135.27	
${}^{6}_{\Lambda}\mathrm{He}$	${}^{6}\mathrm{Li} + \pi^-$	108.48	
~~${}^{6}_{\Lambda}\mathrm{Li}$~~	~~${}^{6}\mathrm{Be} + \pi^-$~~	-	No B_Λ data, above Sp
${}^{7}_{\Lambda}\mathrm{He}$	${}^{7}\mathrm{Li} + \pi^-$	115.10	
${}^{7}_{\Lambda}\mathrm{Li}$	${}^{7}\mathrm{Be} + \pi^-$	108.11	
~~${}^{7}_{\Lambda}\mathrm{Be}$~~	~~${}^{7}\mathrm{C} + \pi^-$~~	~~95.90~~	Impossible 2-body decay
${}^{8}_{\Lambda}\mathrm{He}$	${}^{8}\mathrm{Li} + \pi^-$	116.47	
${}^{8}_{\Lambda}\mathrm{Li}$	${}^{8}\mathrm{Be} + \pi^-$	124.20	
${}^{8}_{\Lambda}\mathrm{Be}$	${}^{8}\mathrm{B} + \pi^-$	97.19	No ^{8}B(g.s) decay
${}^{9}_{\Lambda}\mathrm{Li}$	${}^{9}\mathrm{Be} + \pi^-$	121.31	
${}^{9}_{\Lambda}\mathrm{Be}$	${}^{9}\mathrm{B} + \pi^-$	96.98	
${}^{9}_{\Lambda}\mathrm{B}$	${}^{9}\mathrm{C} + \pi^-$	96.82	
${}^{10}_{\Lambda}\mathrm{Li}$	${}^{10}\mathrm{Be} + \pi^-$	-	No B_Λ data
${}^{10}_{\Lambda}\mathrm{Be}$	${}^{10}\mathrm{B} + \pi^-$	104.41	
${}^{10}_{\Lambda}\mathrm{B}$	${}^{10}\mathrm{C} + \pi^-$	100.49	
${}^{11}_{\Lambda}\mathrm{B}$	${}^{11}\mathrm{C} + \pi^-$	86.54	
${}^{12}_{\Lambda}\mathrm{B}$	${}^{12}\mathrm{C} + \pi^-$	115.87	
${}^{12}_{\Lambda}\mathrm{C}$	${}^{12}\mathrm{N} + \pi^-$	91.48	No ^{12}N(g.s) decay
${}^{13}_{\Lambda}\mathrm{C}$	${}^{13}\mathrm{N} + \pi^-$	92.27	
${}^{14}_{\Lambda}\mathrm{C}$	${}^{14}\mathrm{N} + \pi^-$	101.20	
${}^{14}_{\Lambda}\mathrm{N}$	${}^{14}\mathrm{O} + \pi^-$	-	No B_Λ data
${}^{15}_{\Lambda}\mathrm{N}$	${}^{15}\mathrm{O} + \pi^-$	98.40	
${}^{16}_{\Lambda}\mathrm{N}$	${}^{16}\mathrm{O} + \pi^-$	106.23	
${}^{16}_{\Lambda}\mathrm{O}$	${}^{16}\mathrm{F} + \pi^-$	86.54	

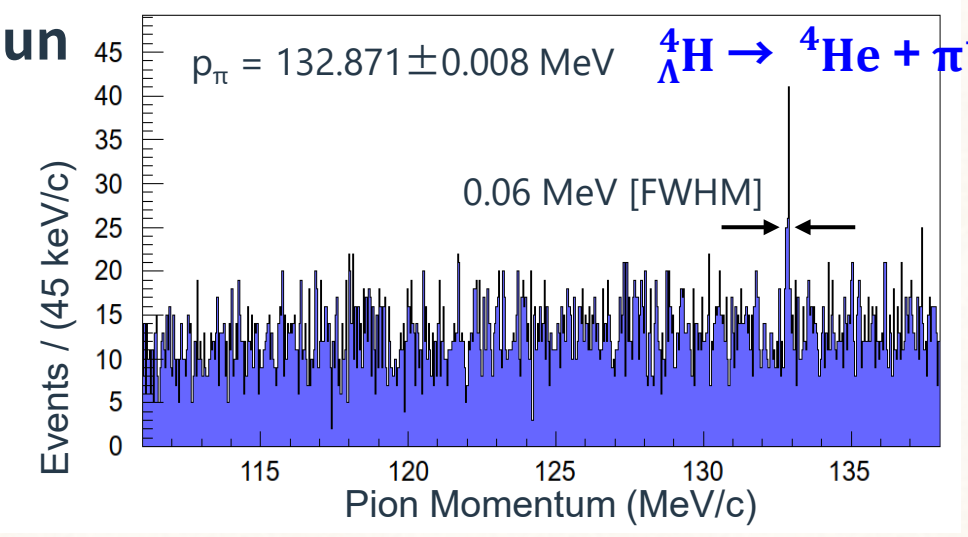


$^{4}_{\Lambda}$H peak in DPS (MAMI)

2012 Run



2014 Run



Hypernuclear production with ^{9}Be target

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

Excellent peak resolution thanks to

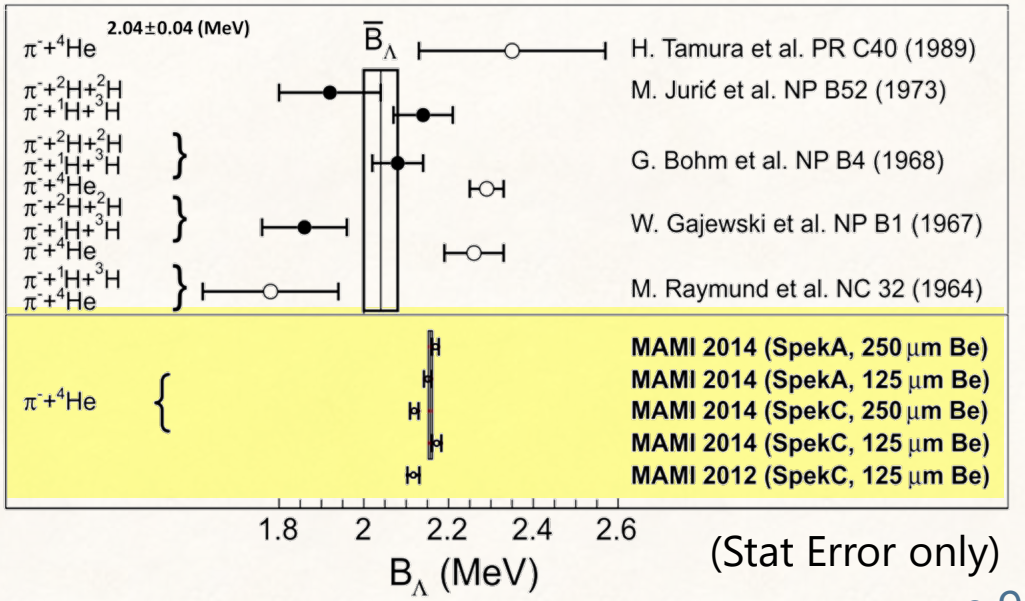
high-resolution spectrometer & thin target

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

[PRL 114 (2015) 232501.]

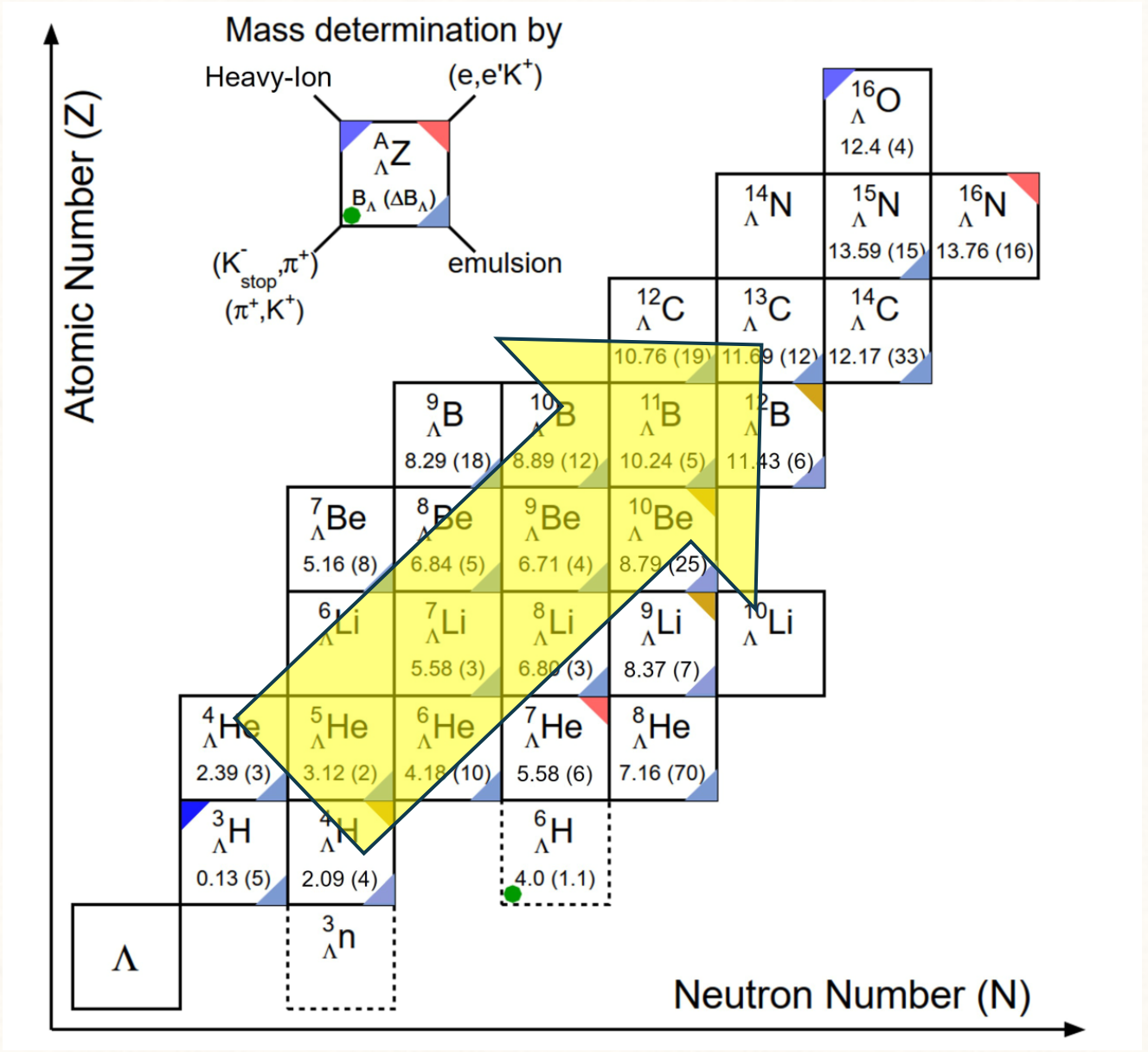
$$B_\Lambda\,(\text{MAMI 2014}) = 2.157 \pm 0.005 \pm 0.077\ (\text{MeV})$$

[NPA 954 (2016) 149.]

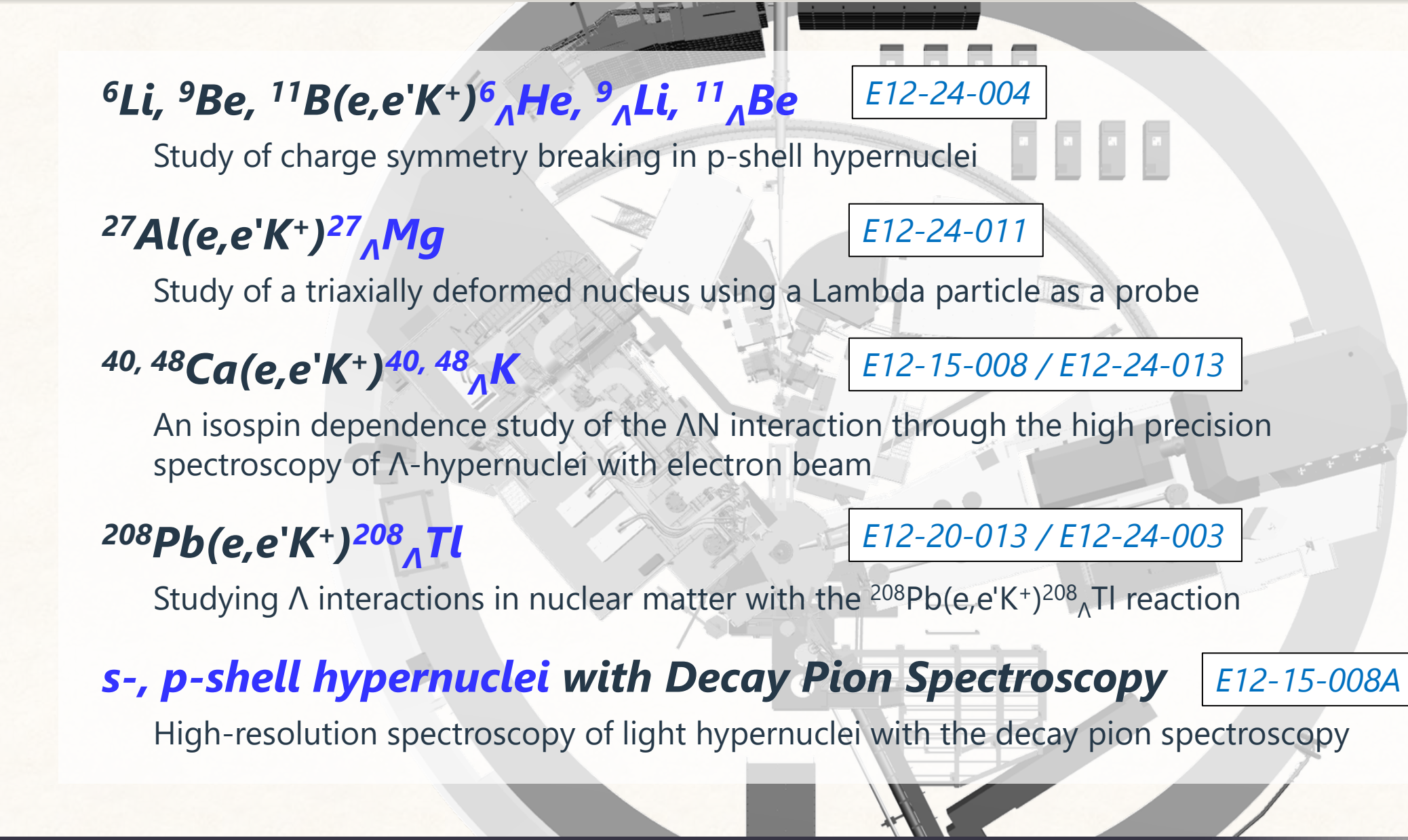


(Stat Error only)

from "s-" to "p-" "sd-"


Mass determination by
Heavy-Ion
(e,e'K+)
AZ Λ
BΛ (ΔBΛ)
(K-stop,π+)
(π+,K+)
emulsion
Atomic Number (Z)
Neutron Number (N)
16O Λ 12.4 (4)
14N Λ
15N Λ 13.59 (15)
16N Λ 13.76 (16)
12C Λ 10.76 (19)
13C Λ 11.69 (12)
14C Λ 12.17 (33)
9B Λ 8.29 (18)
10B Λ 8.89 (12)
11B Λ 10.24 (5)
12B Λ 11.43 (6)
7Be Λ 5.16 (8)
8Be Λ 6.84 (5)
9Be Λ 6.71 (4)
10Be Λ 8.79 (25)
6Li Λ
7Li Λ 5.58 (3)
8Li Λ 6.80 (3)
9Li Λ 8.37 (7)
10Li Λ
4He Λ 2.39 (3)
5He Λ 3.12 (2)
6He Λ 4.18 (10)
7He Λ 5.58 (6)
8He Λ 7.16 (70)
3H Λ 0.13 (5)
4H Λ 2.09 (4)
6H Λ 4.0 (1.1)
Λ
3n Λ

Hypernuclear project at Jefferson Lab Hall-C



^{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

$^{40,\,48}$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

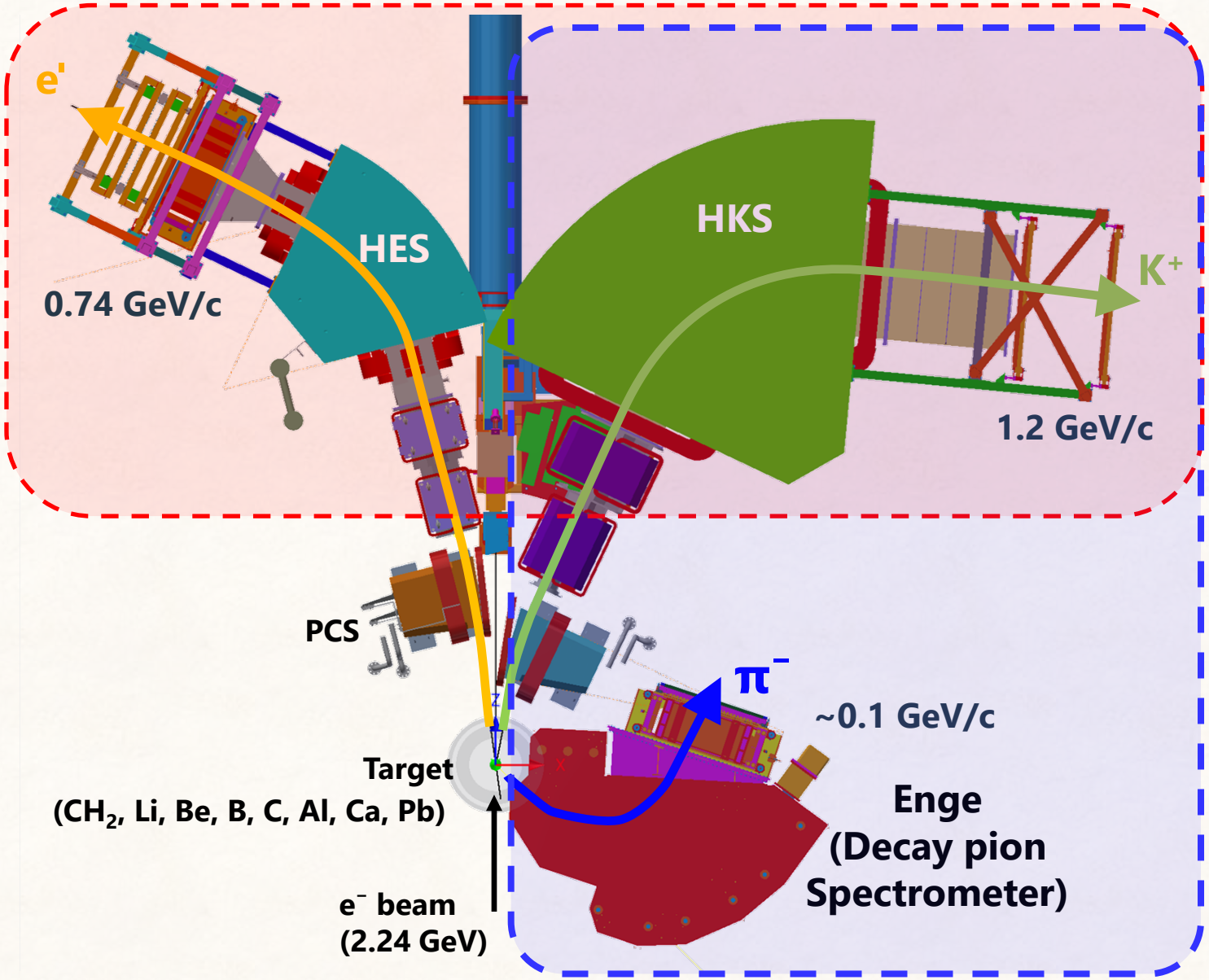
^{208}Pb(e,e'K^{+})$^{208}_{\Lambda}$Tl — *E12-20-013 / E12-24-003*

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

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

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**

Decay Pion Program

"π⁻, K⁺" coincidence with Enge & HKS

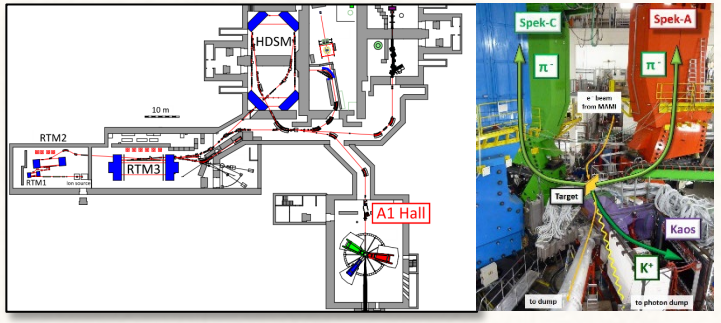
Parallel Experiment with

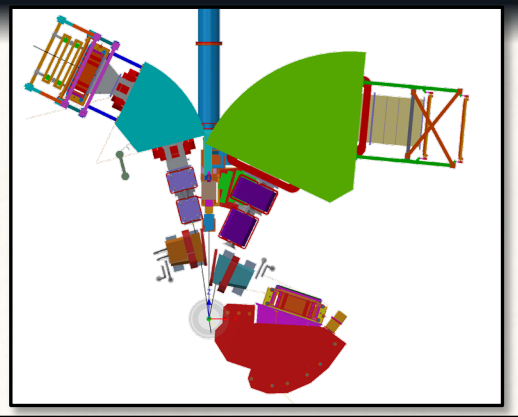
(HES ⊗ HKS) ⊕ (Enge ⊗ HKS)

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

with **~10 keV accuracy**

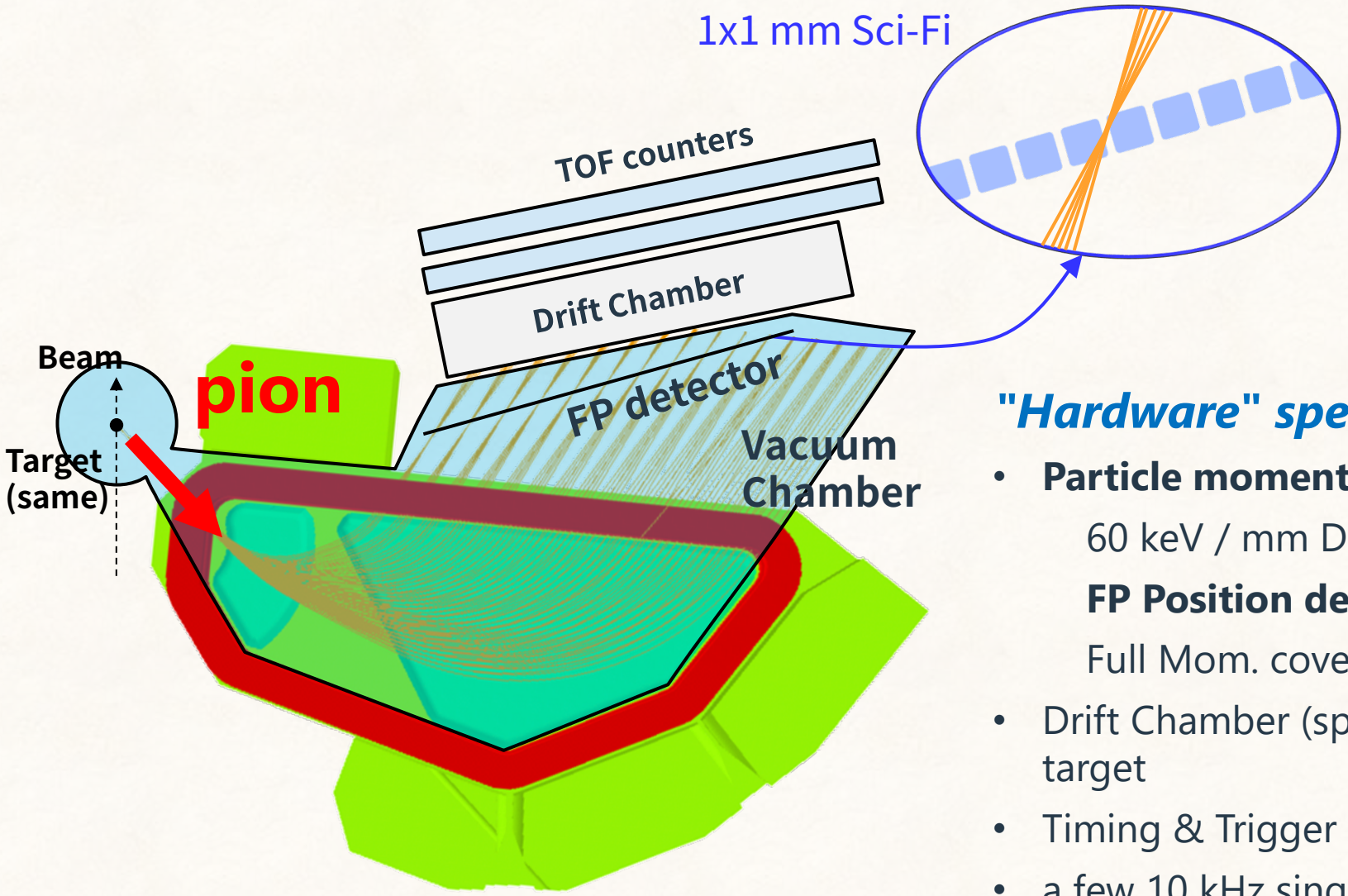
Characteristics of DPS at JLab





	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**
Beamtime	~ 2 weeks	~ 1 year	**Better yield**
K^+ Tag Efficiency	~20%	~80%	**Better PID, S/N**
π^- angle	90~120 deg	150 deg	
π^- mom. resolution	$<1\times10^{-3}$ (FWHM)	2×10^{-3} (FWHM)	
mom. coverage	110 ~ 135 MeV/c	70 ~ 150 MeV/c	**Covered Entire region**
"K^+,π^-" time resolution	2000 ps	< 200 ps	**Lifetime measurement**

Pion Spectrometer Enge



"Hardware" spectrometer Enge

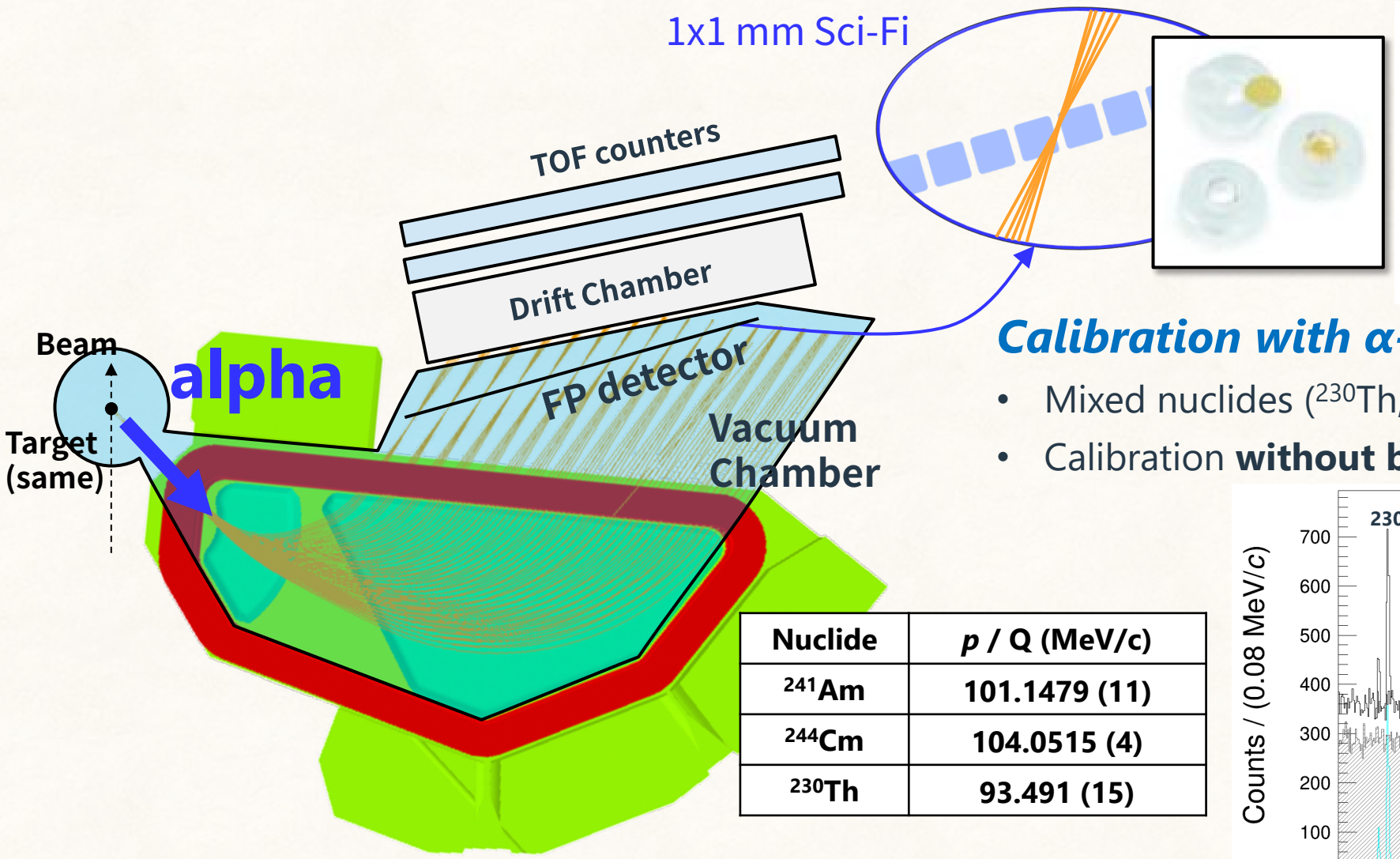
- **Particle momentum from Focal Plane position**

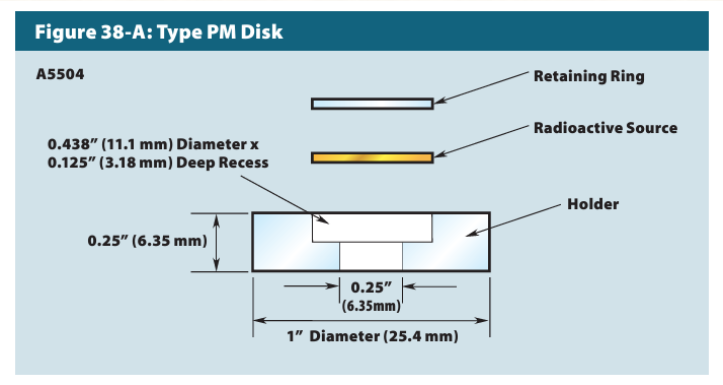
  60 keV / mm Dispersion

  FP Position detector (Scinti+SiPM) in vacuum

  Full Mom. coverage from decay pions (70 ~150 MeV/c)
- Drift Chamber (spare HKS DC) for reconstruction to the target
- Timing & Trigger detector
- a few 10 kHz single rate

Pion Spectrometer Enge

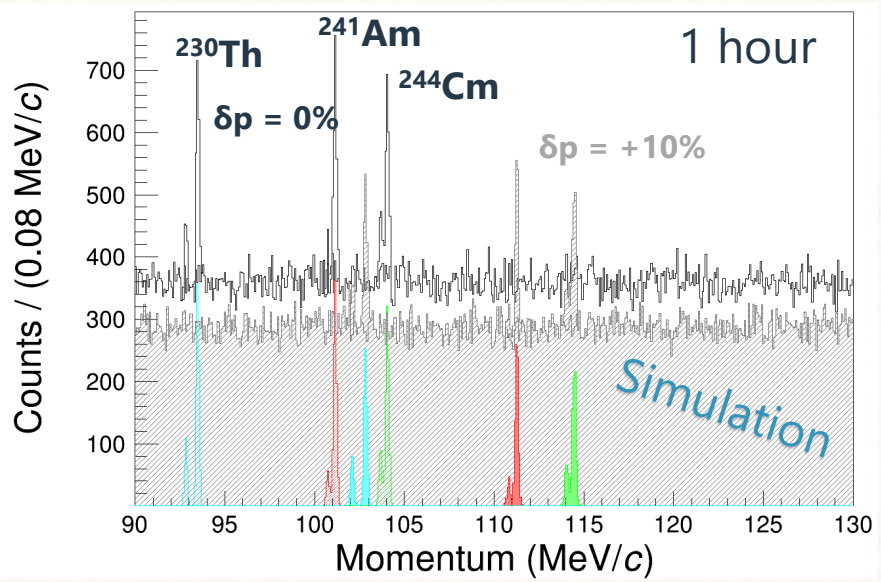




Calibration with α-sources

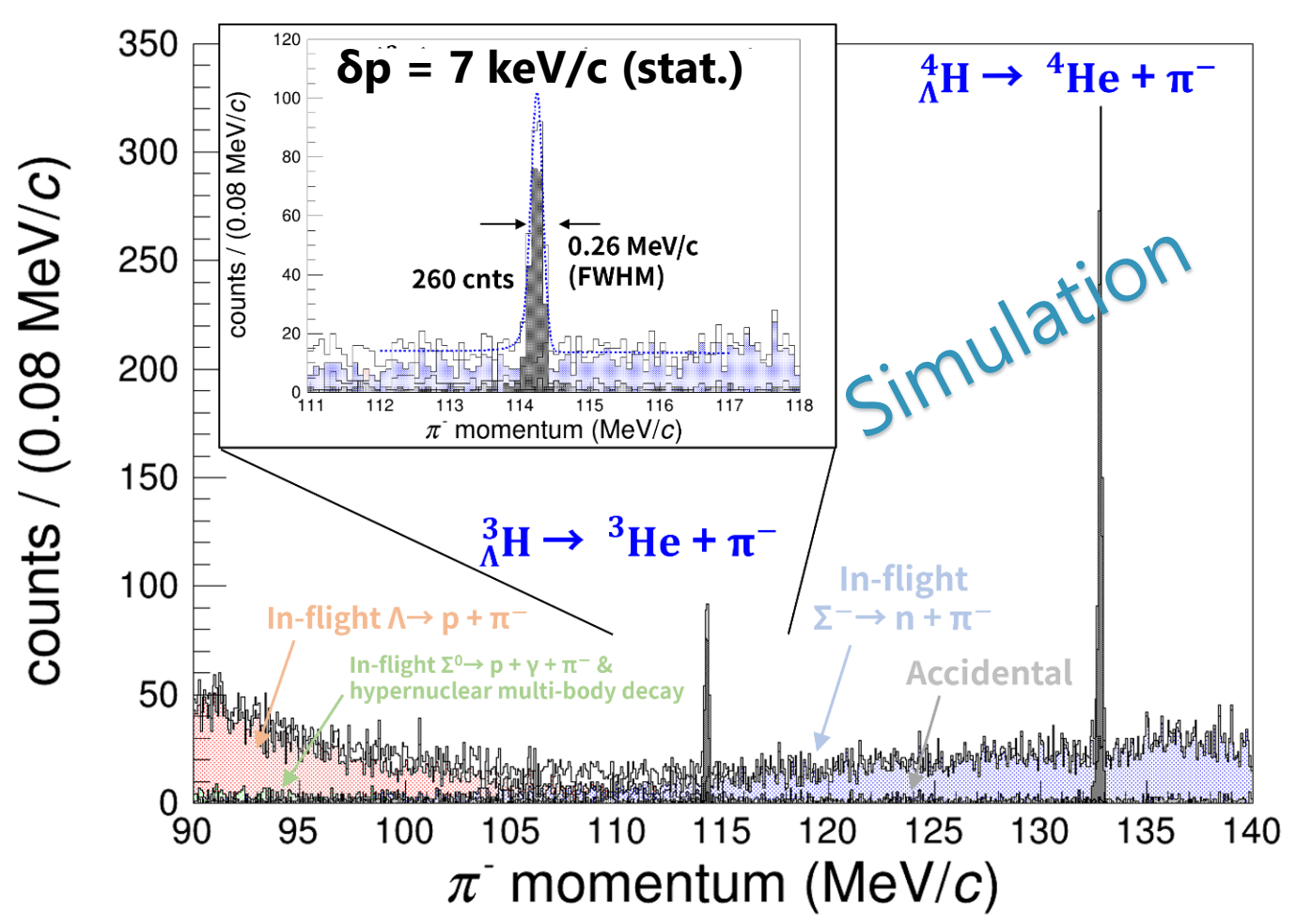
- Mixed nuclides (^{230}Th, ^{241}Am, ^{244}Cm) [Eckert & Ziegler]
- Calibration **without beams（~10 keV systematic）**

Nuclide	*p* / Q (MeV/c)
^{241}Am	101.1479 (11)
^{244}Cm	104.0515 (4)
^{230}Th	93.491 (15)



Expected Spectrum

Expected on ^{6}Li target



Monte-Carlo simulation by

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

Simplest spectrum

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

FWHM = 260 keV/c

Low QF background

Low accidental

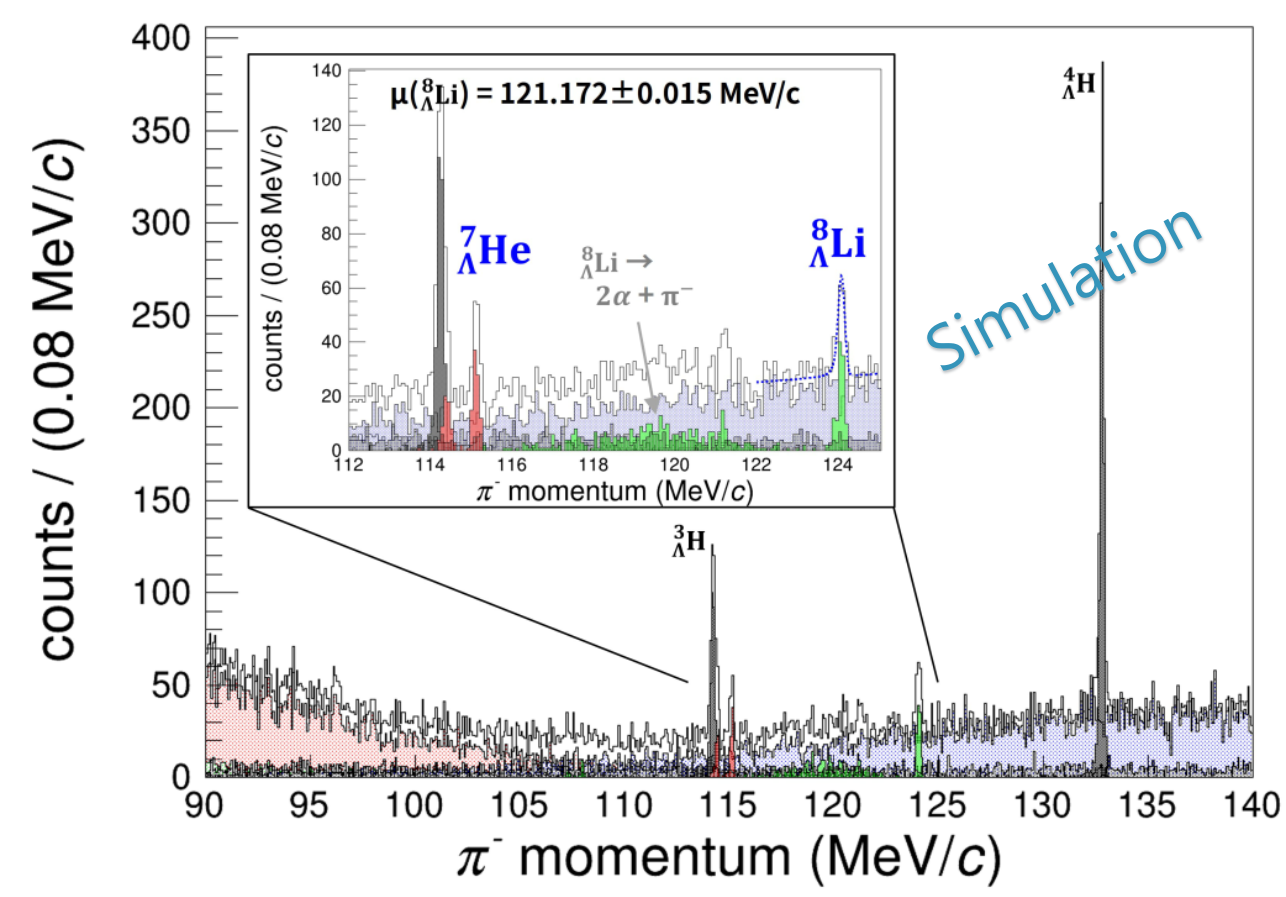
δB_Λ = several keV (stat.)

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

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

Expected Spectrum

Expected on ^{9}Be target



Additional peaks

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

$^{7}_{\Lambda}$He

Isospin partner of A=7 system

Charge Symmetry Breaking on p-shell

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

→ ^{8}Be + π^{-}

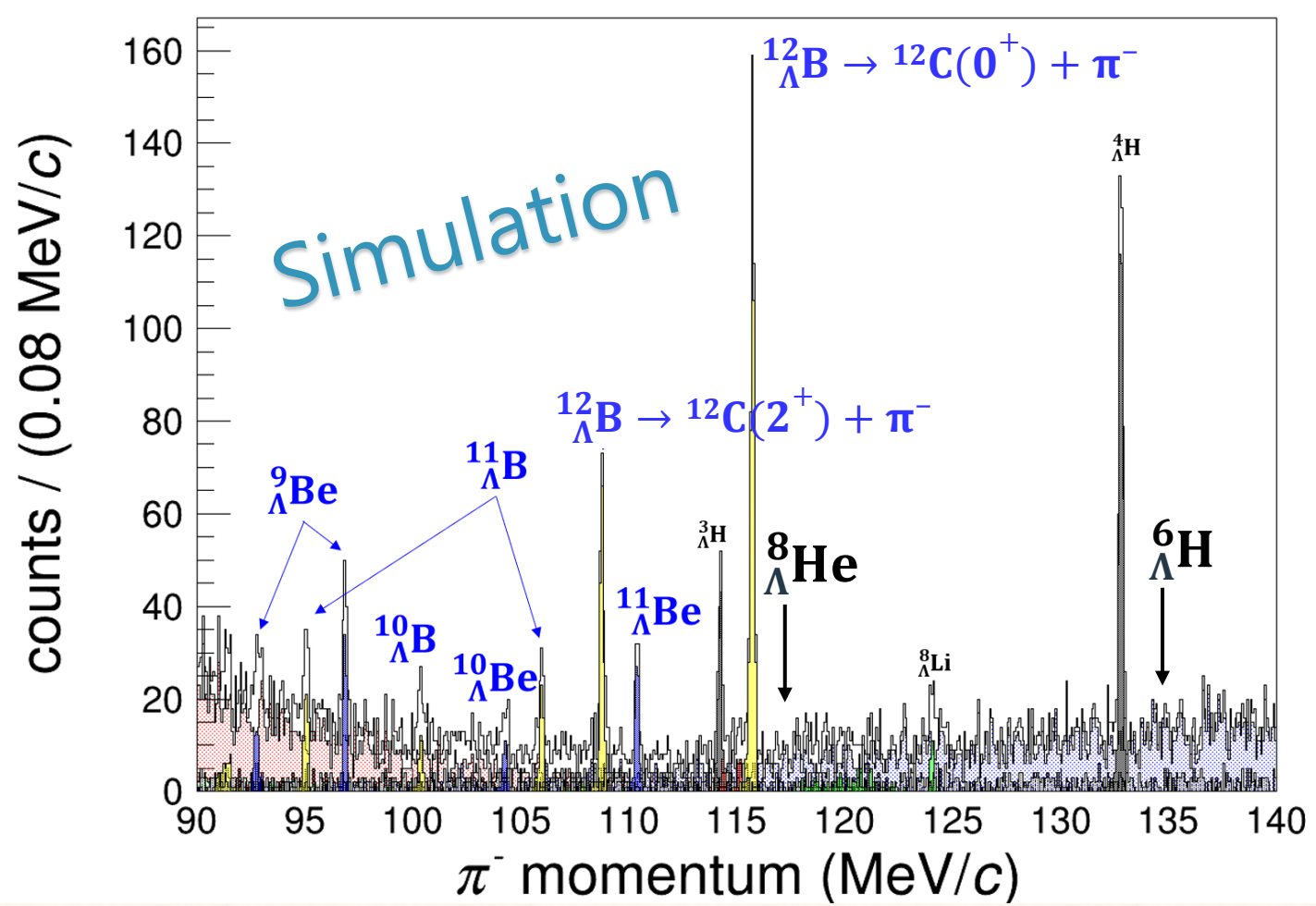
CSB on A=8 system

$^{6}_{\Lambda}$H

Evidence of super heavy hydrogen

Expected Spectrum

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

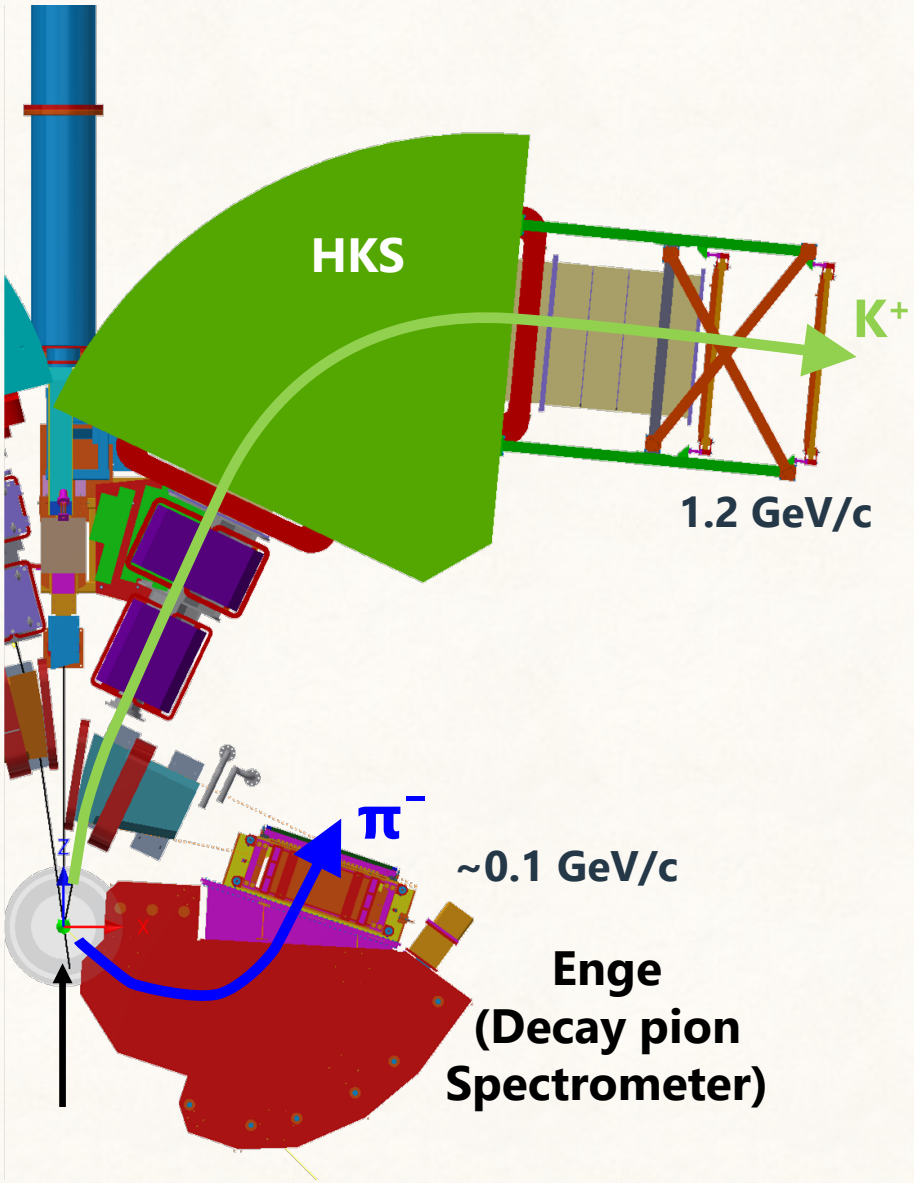
$^{9}_{\Lambda}Be$

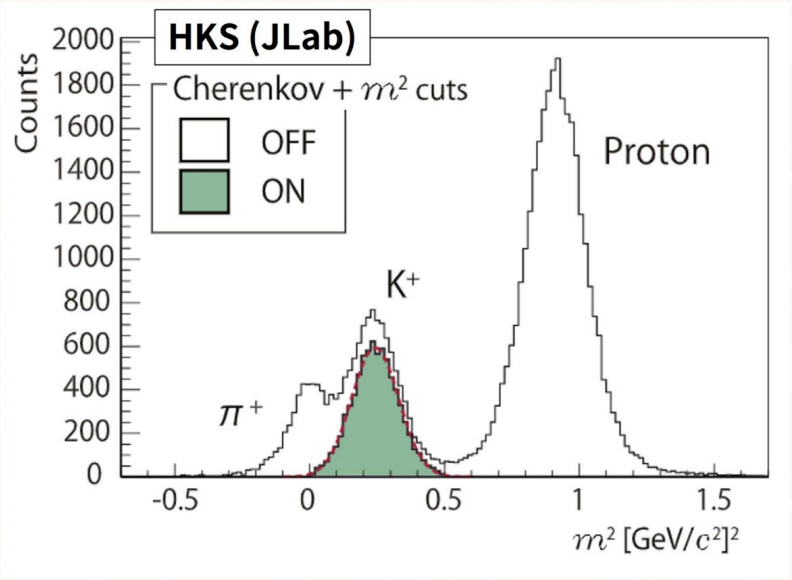
Many $^{9}B+\pi^-$ decay in emulsion

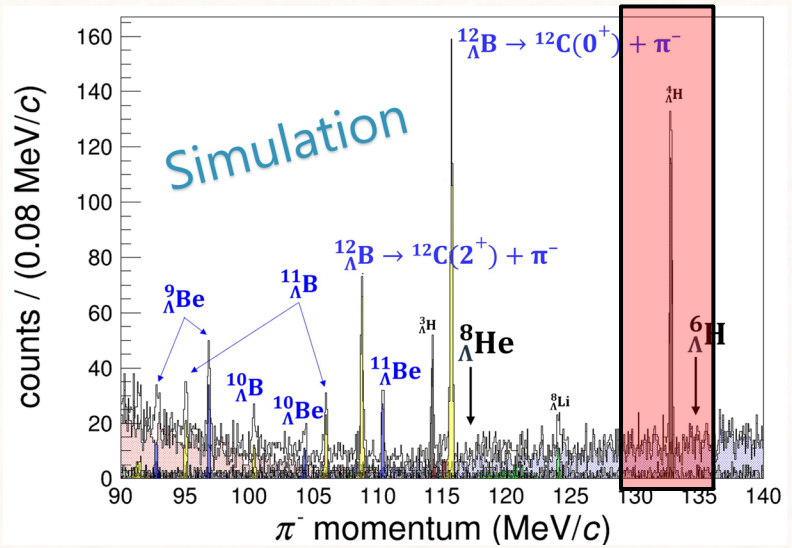
$^{8}_{\Lambda}Li$

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

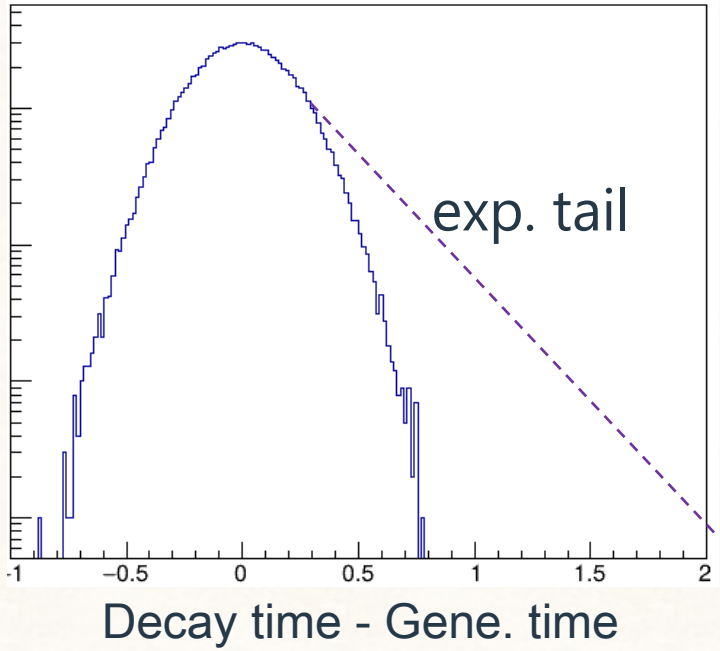
Lifetime measurement (by product)







K^+ time = Generate time



π^- time = Decay time

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