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

Run Group Addition E12-20-013A/E12-15-008A

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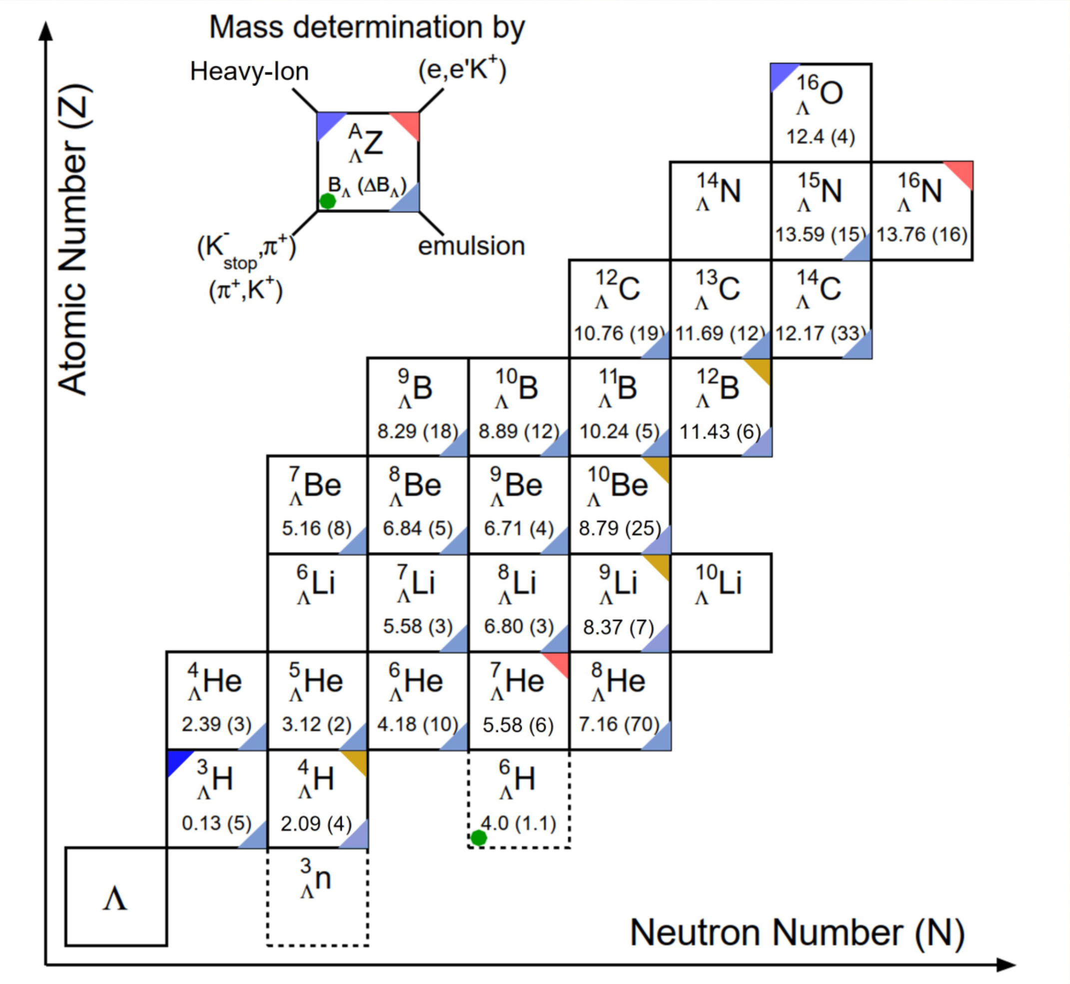
on behalf of JLab hypernuclear collaboration

July 11, 2024

Hypernuclear Λ binding energies

Hypernuclear Chart (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*

Good probe investigating ΛN interaction

Mass, Isospin dependence etc...

Light hypernuclei as useful probes thanks to precise calculations.

Precise B_Λ(g.s & e.x) with the (e,e'K+) experiment

Missing mass spectroscopy of

$^{40,48}_{\Lambda}$K, $^{208}_{\Lambda}$Pb

(E12-15-008 / E12-20-013)

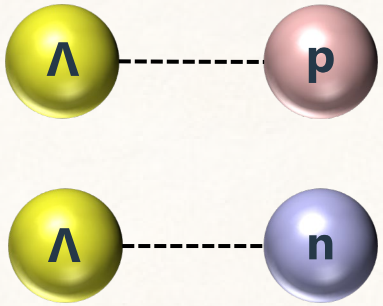
(PR12-24-013 / PR12-24-003)

$^{6}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{11}_{\Lambda}$Be, $^{12}_{\Lambda}$C, $^{27}_{\Lambda}$Mg

(PR12-24-004 / PR12-24-011)

High precision data provide

Key information of ΛN CSB effect

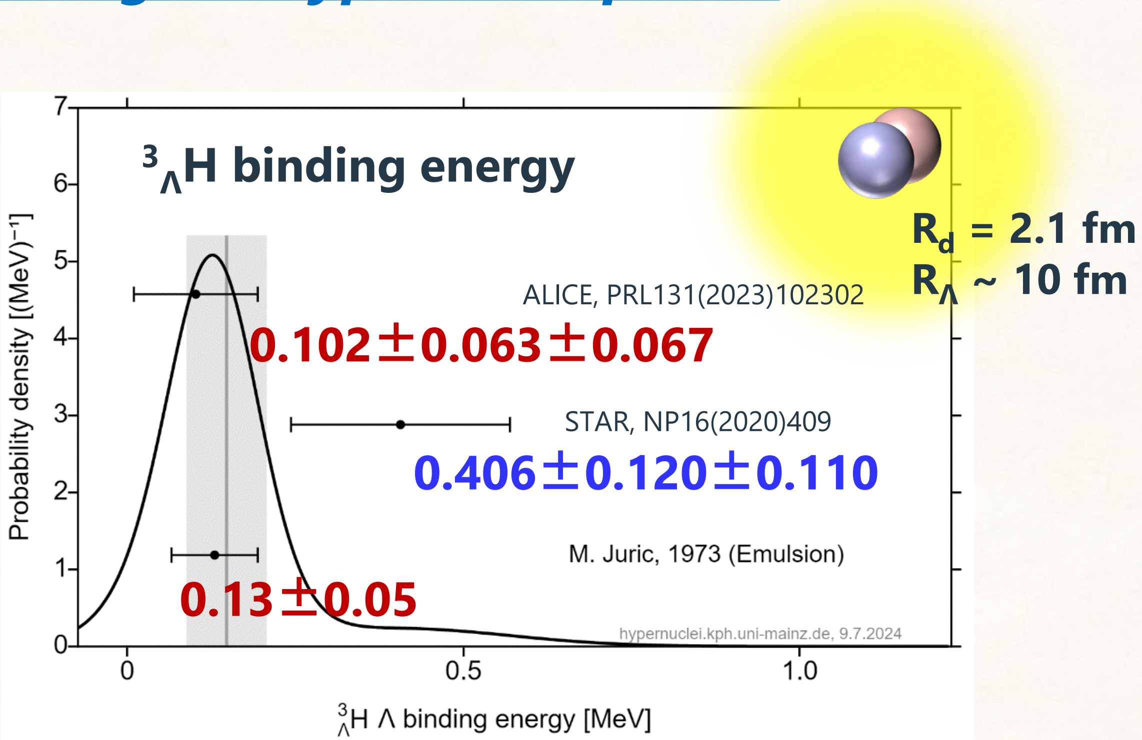


Larger difference than pp & nn

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

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

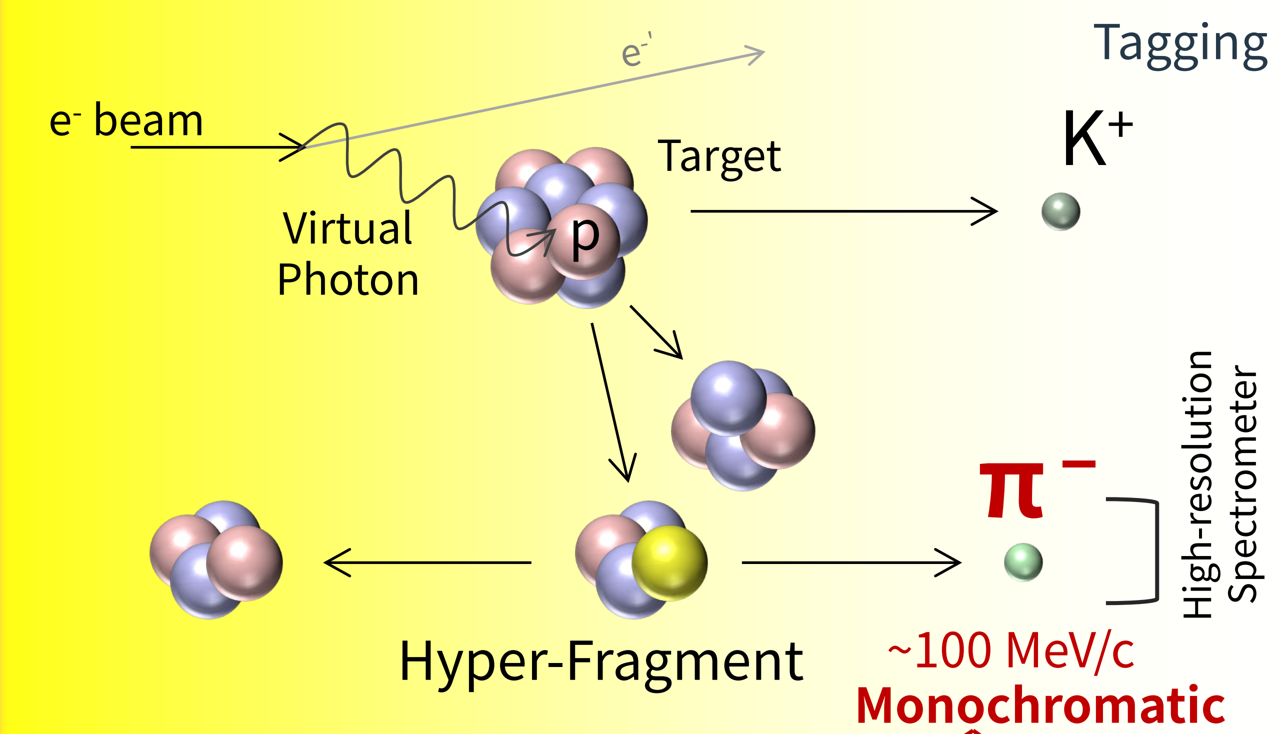
Resolving the hypertriton puzzle



- Weakly Λ bound system in deuteron
- Deep/Shallow B_Λ and Long/Short life ??
- Most important input

Decay Pion Spectroscopy (DPS)

High-resolution, High-precision mass spectroscopy



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

No effect from Beam energy spreading, stability etc.

Principle

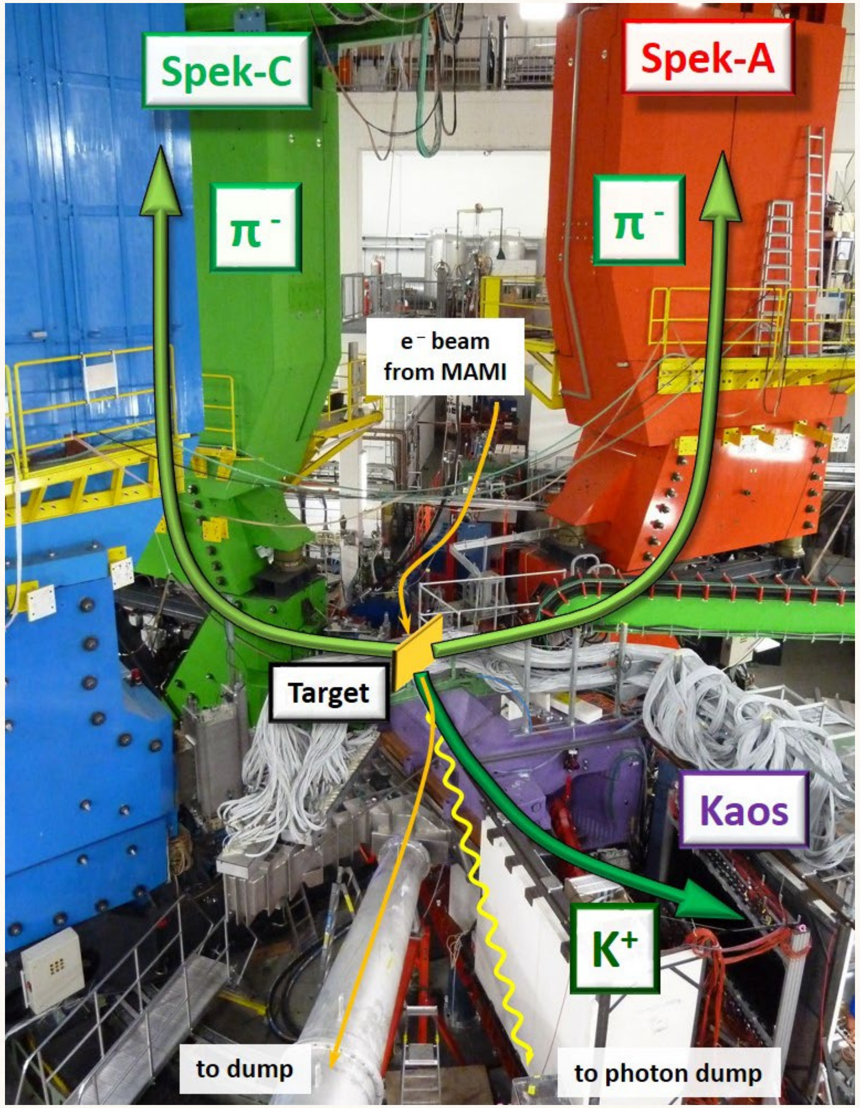
- Measurement of **monochromatic decay pion**
  - from hypernuclei **stopped** in the target
  - emitting pion in **two-body decay**

    (e.g. ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^-$)
  - B_Λ must be approximately known

    (hypernuclear ID is performed by the pion momentum)
- **Tagging K⁺** for background suppression from non-strangeness production

Previous Experiment at MAMI

Proof of Principle at MAMI

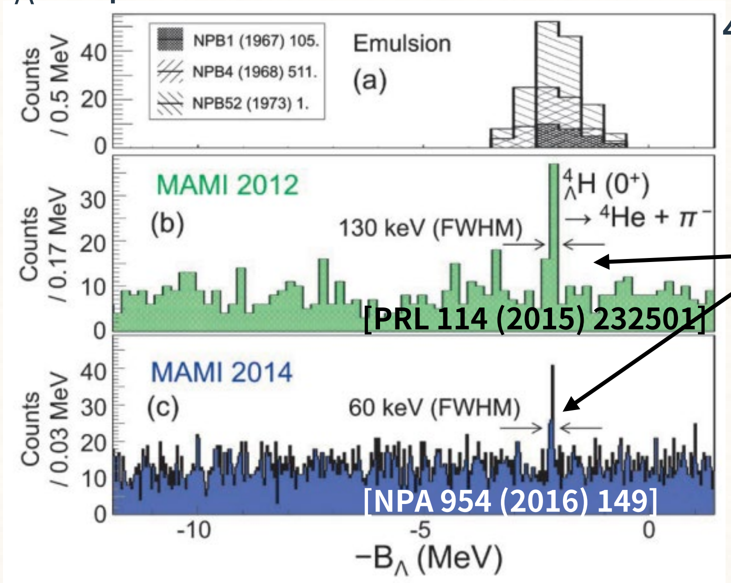


Experimental Feasibility

5 keV (stat.) & 77 keV (syst.) at MAMI exp.

PRL 114 (2015) 232501
NPA 954 (2016) 149]

$^4_\Lambda$H Spectrum

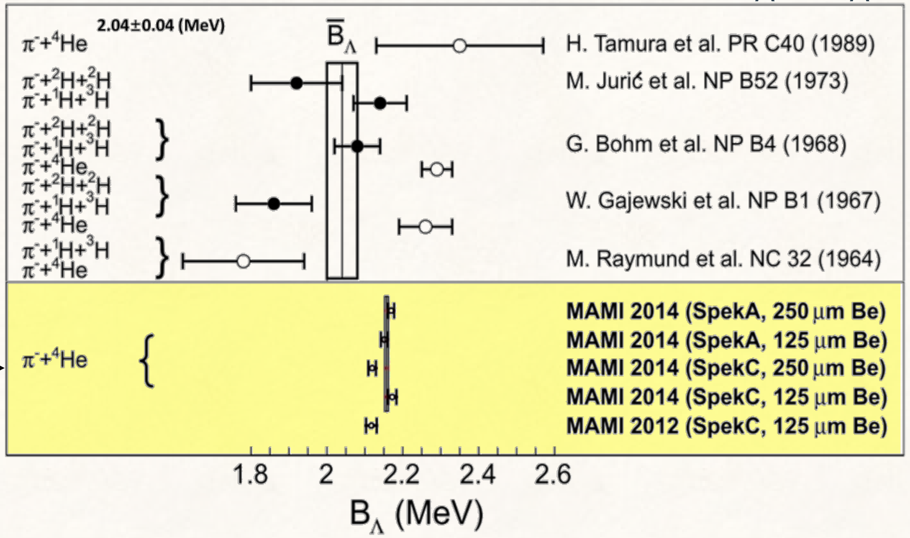


$^4{}_\Lambda$H peak by Emulsion

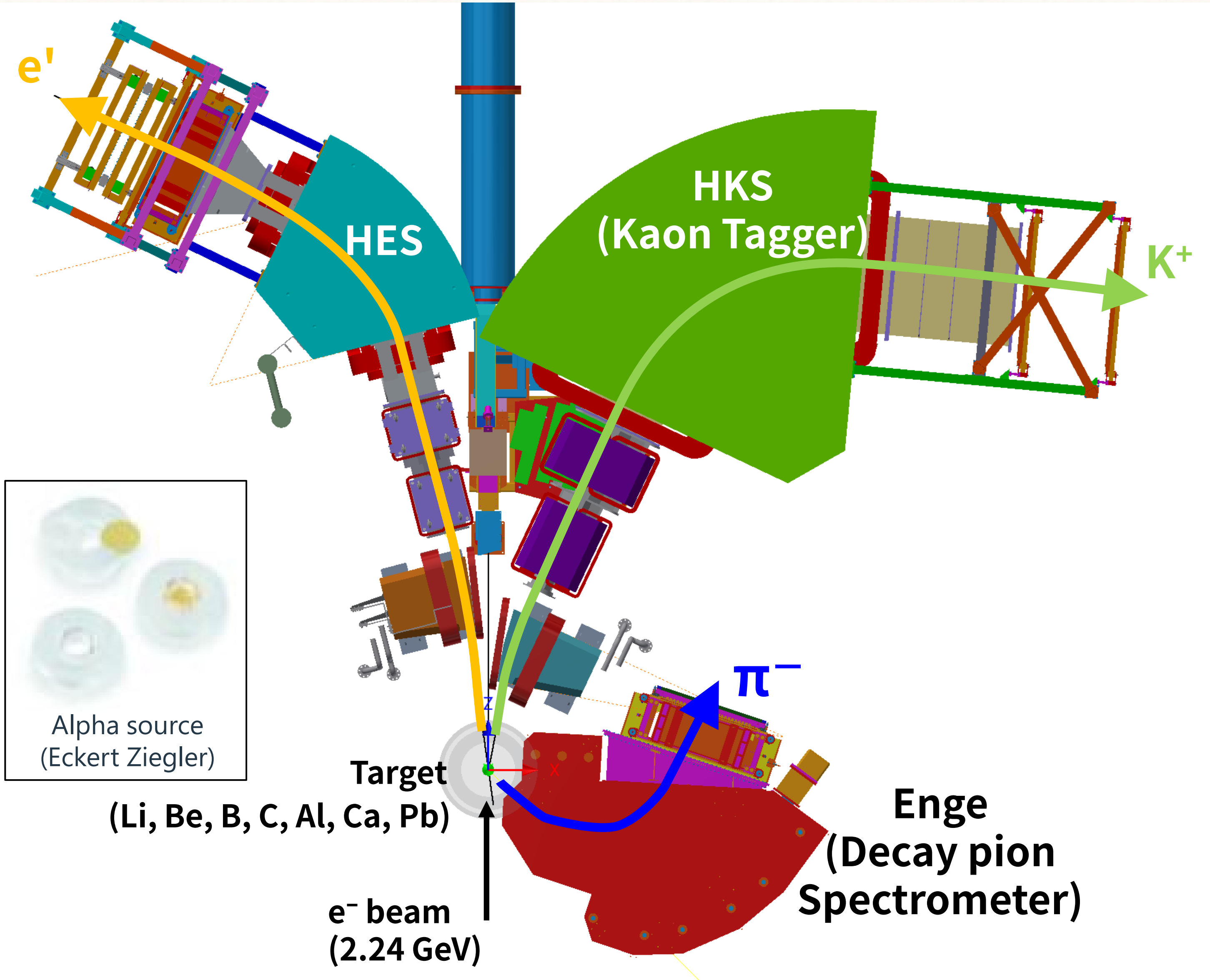
DPS at MAMI w/ ^{9}Be foil

Word Data of $^4{}_\Lambda$H B_Λ

MAMI results →



Proposed experiment



Setup

- **Parallel exp.** with proposed (e,e'K$^+$) exp.
- "Enge" for decay pion measurement
- "HKS" for K$^+$ tagger
- **"K$^+$ & π^-" coin. exp.** with HKS and Enge

Advantage

- **30 times yield** per time thanks to higher CEBAF beam
- Background less thanks to better KID
- Another data **without additional beamtime**

Others

- Compatible setup with the (e,e'K$^+$) target ladder for Enge@150deg.
- Possible installation plan by the engineering group
- Low radiation level & a few 10 kHz single rate
- Mixed nuclides (Eckert & Ziegler) through RadCon
- Calibration **w/o beams （~10 keV systematic）**

Expectation

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

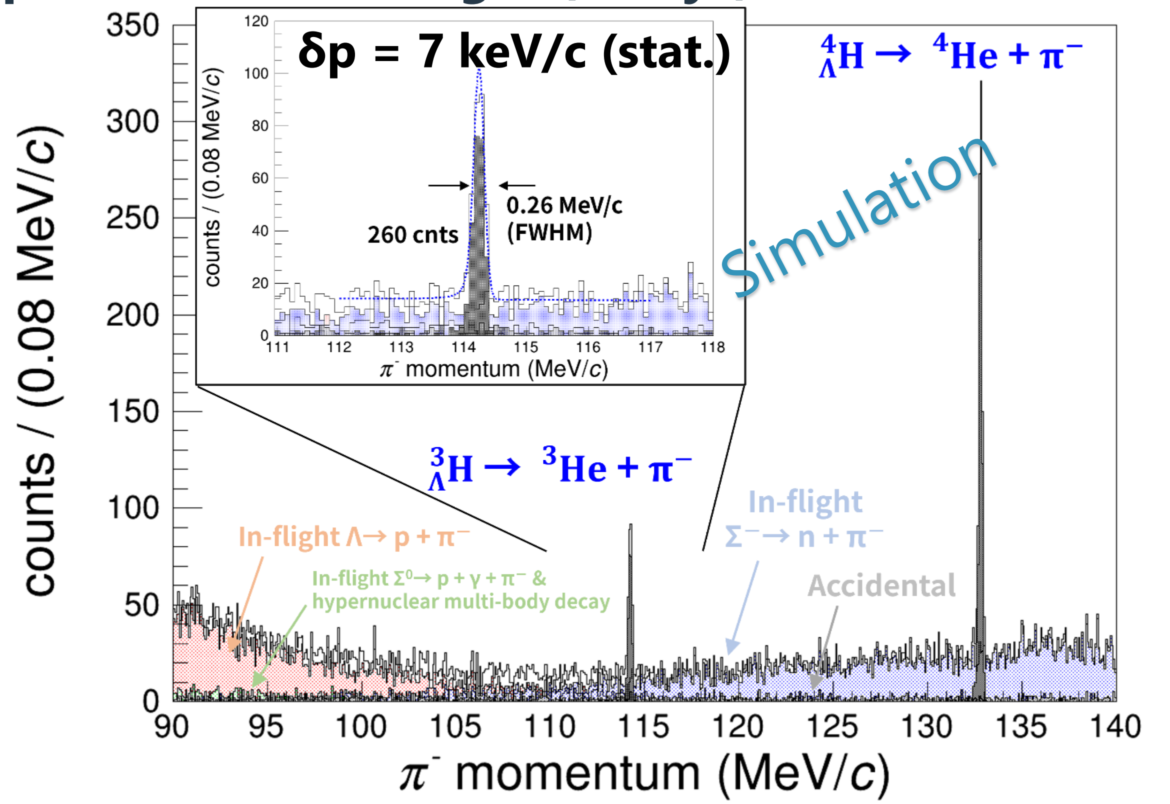
×30

AMD calc.
[Y.Nara, PLB346(1995)217.]
[A.Kawachi, Dthesis, U-Tokyo(1997)]

shell-model calc.
[T.Motoba, PTPS 117(1994)477]

Monte-Carlo

Expected with ^{6}Li target (5 days)



- Low background from Λ/Σ & in-flight, multi-body hypernuclei
- Low accidental
- Clear peak from $_\Lambda$H
- **δB_Λ = 5 keV (stat.)**
- Pion from p-shell hypernuclei with ^{9}Be, ^{12}C target

NOTE: δp ~ σ / √N = 0.26/2.35 / √260 ~ 0.007 MeV/c

Summary

Physics Motivation and Goals

ΛN interaction properties and hypernuclear structure have been discussed with the Λ binding energies of variety of hypernuclei.

Hypertriton puzzle, **ΛN Charge Symmetry Breaking**, and **Σ mixing effect** hypernuclear medium have been discussed, and are still open question.

Precise measurements of the Λ binding energies will resolve these problems.

The decay pion spectroscopy is possible to measure the B_Λ on **more various hypernuclei** via the fragmentation accurately.

Proposing Decay Pion Spectroscopy

Pion momentum measurement in Enge together with K^+ tagging in HKS will find peaks of **monochromatic two-body decay pions** from hyperfragments.

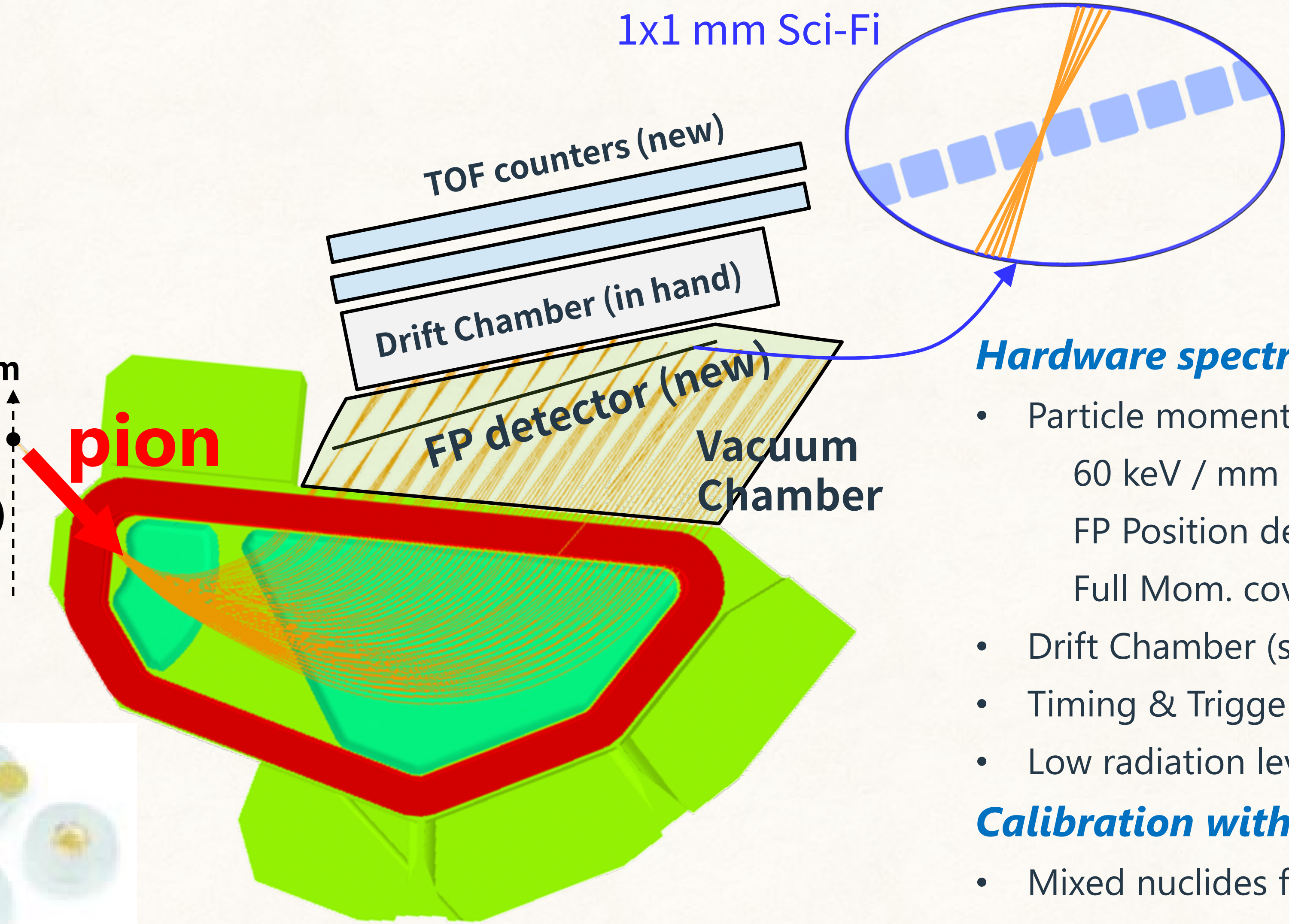
Targets, beamtime, and data taking will be shared with the $(e,e'K^+)$ experiments.

Once we successfully find a decay pion peak and identify the parent hypernucleus, new B_Λ determination will be possible with an **accuracy of ~10 keV**.

This excellent measurement will renovate the hypernuclear data from the 1960s.

Backup

Pion Spectrometer "Enge"



Alpha source PM-Type
(Eckert & Ziegler)

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 KDC) for reconstruction to the target
- Timing & Trigger detector
- Low radiation level & a few 10 kHz single rate

Calibration with α-sources

- Mixed nuclides from Eckert & Ziegler through RadCon
- Possible calibration **without beams** （**~10 keV systematic**）

Possible hypernuclei & Decay pion momenta (up to A=16)

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 ${}^{8}\mathrm{B}$(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 ${}^{12}\mathrm{N}$(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	

^{6}Li target

^{7}Li target

^{9}Be target

^{11}B target

^{12}C target

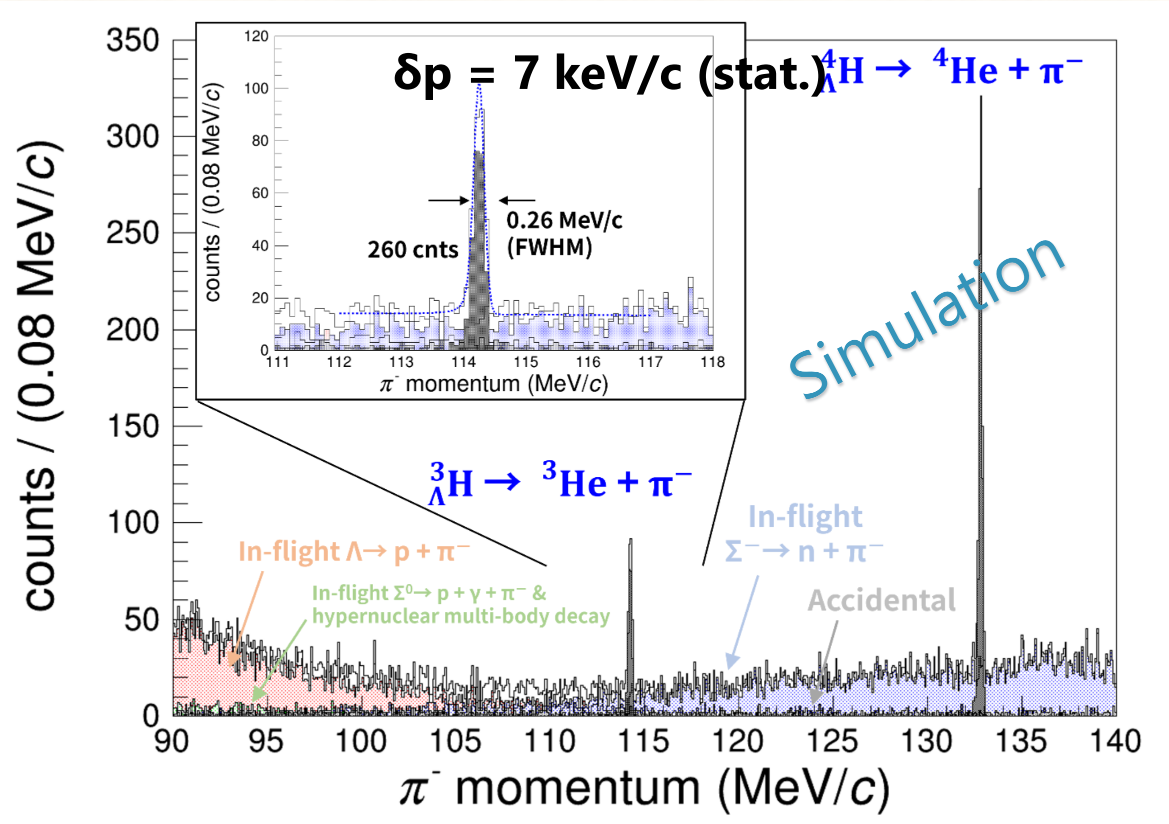
^{16}O target

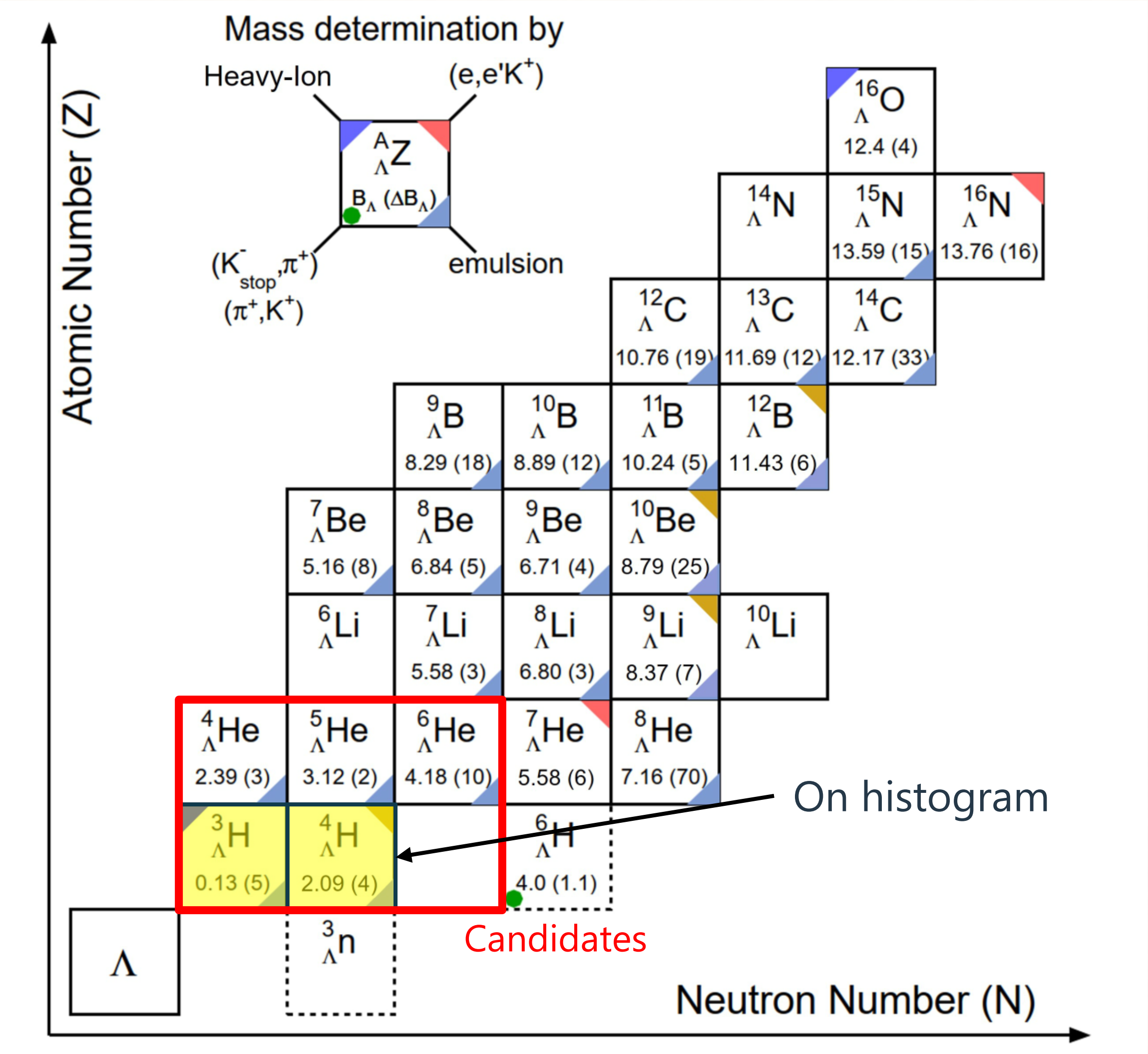
$$M\left({}^{A}_{\Lambda}Z\right) = \sqrt{M\left({}^{A}(Z+1)\right)^2 + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2}$$

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

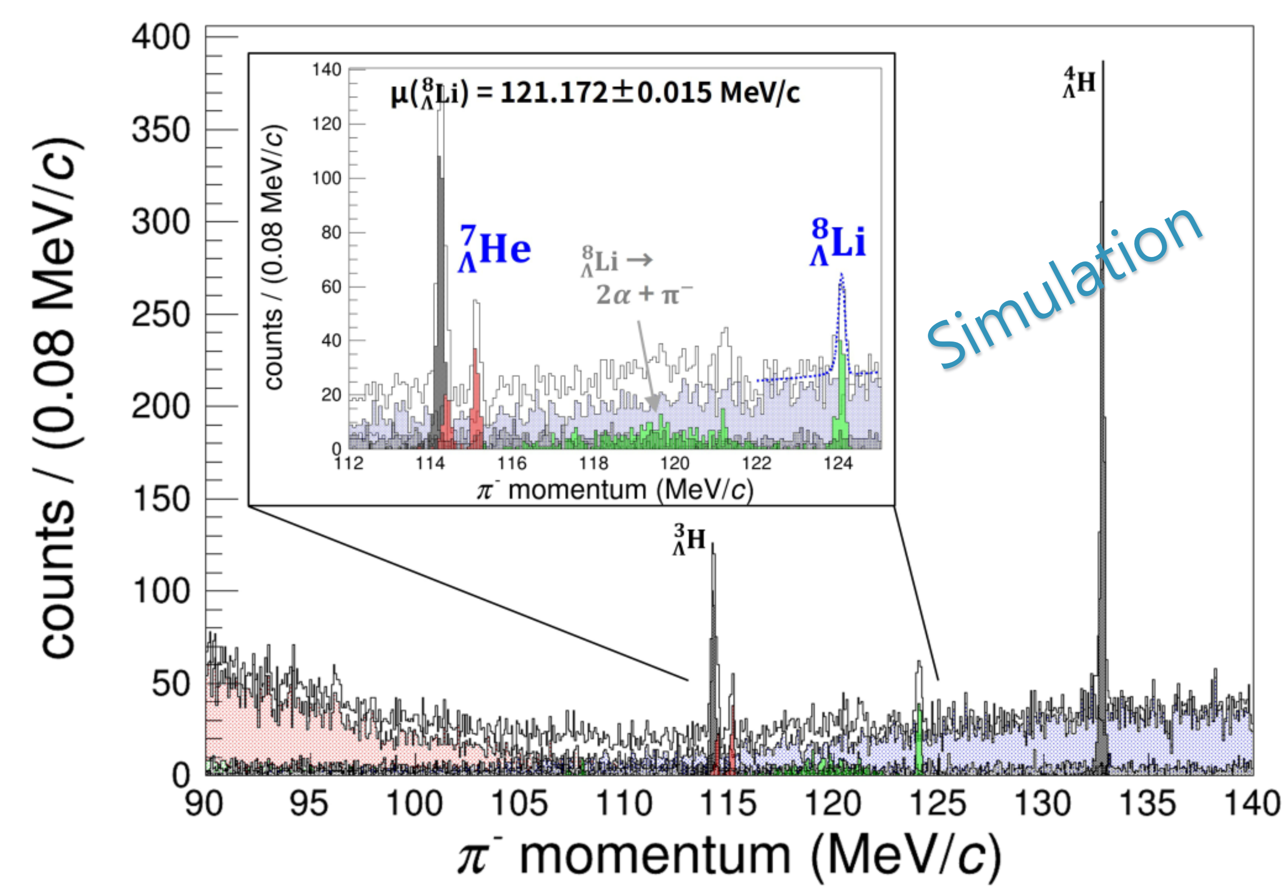
$M(\alpha)$	=	3727.3794118(11)	MeV/c^2
$M(\pi)$	=	139.57039(18)	MeV/c^2
$M({}^{4}_{\Lambda}\mathrm{H})$	=	3922.56(4)	MeV/c^2
$p(\pi)$	=	133.03(6)	MeV/c

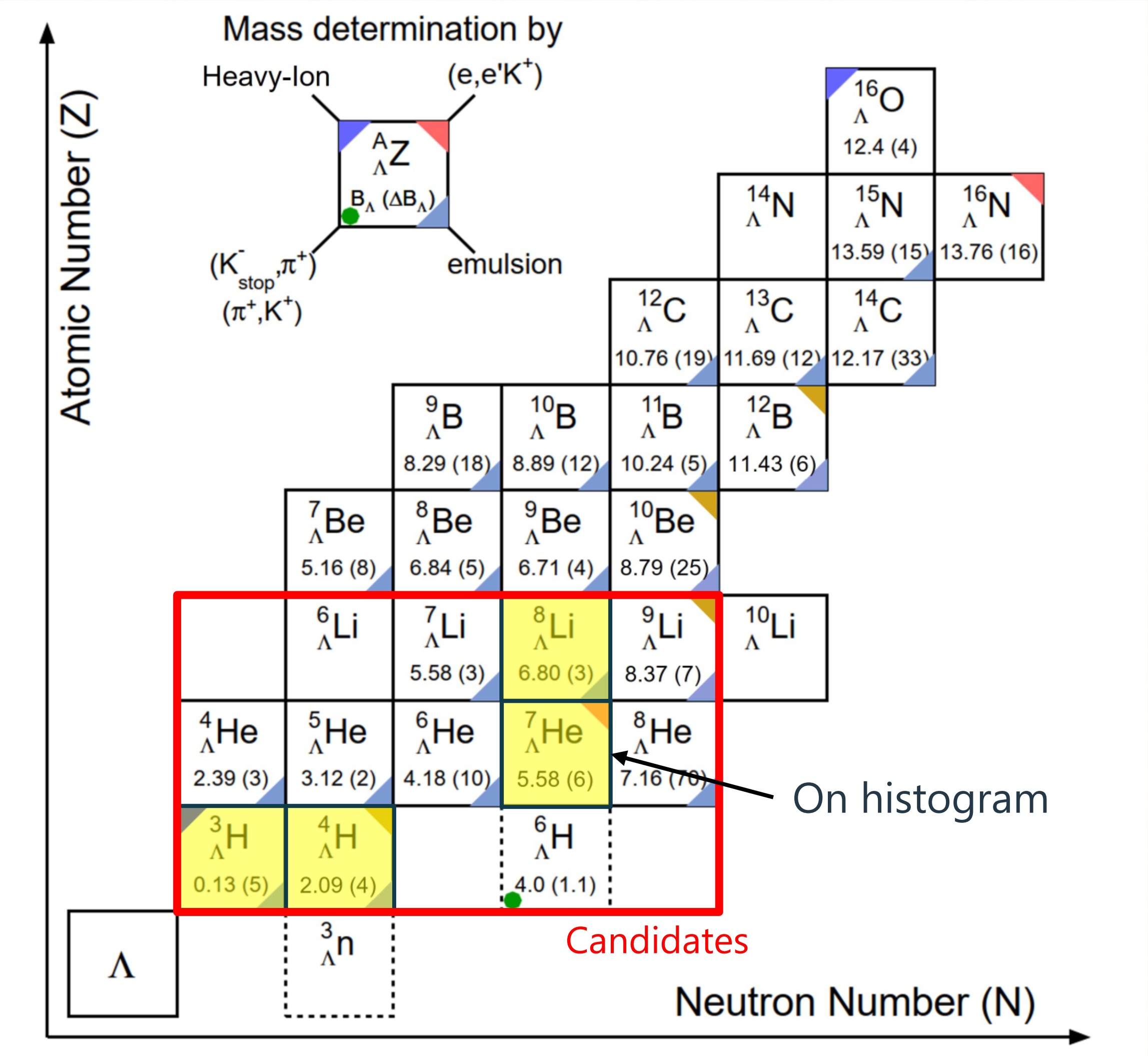
Expectation (^{7}Li target)



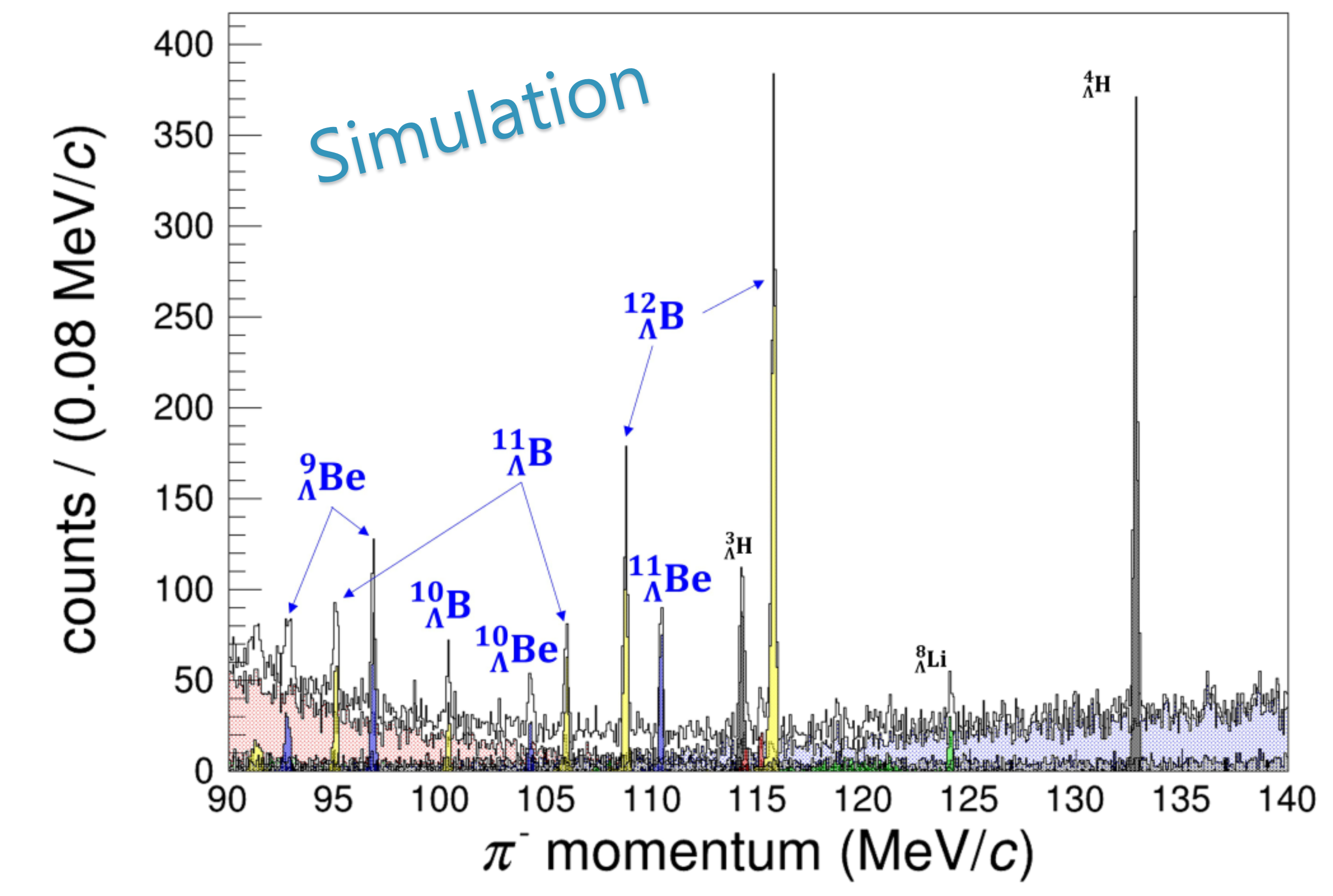


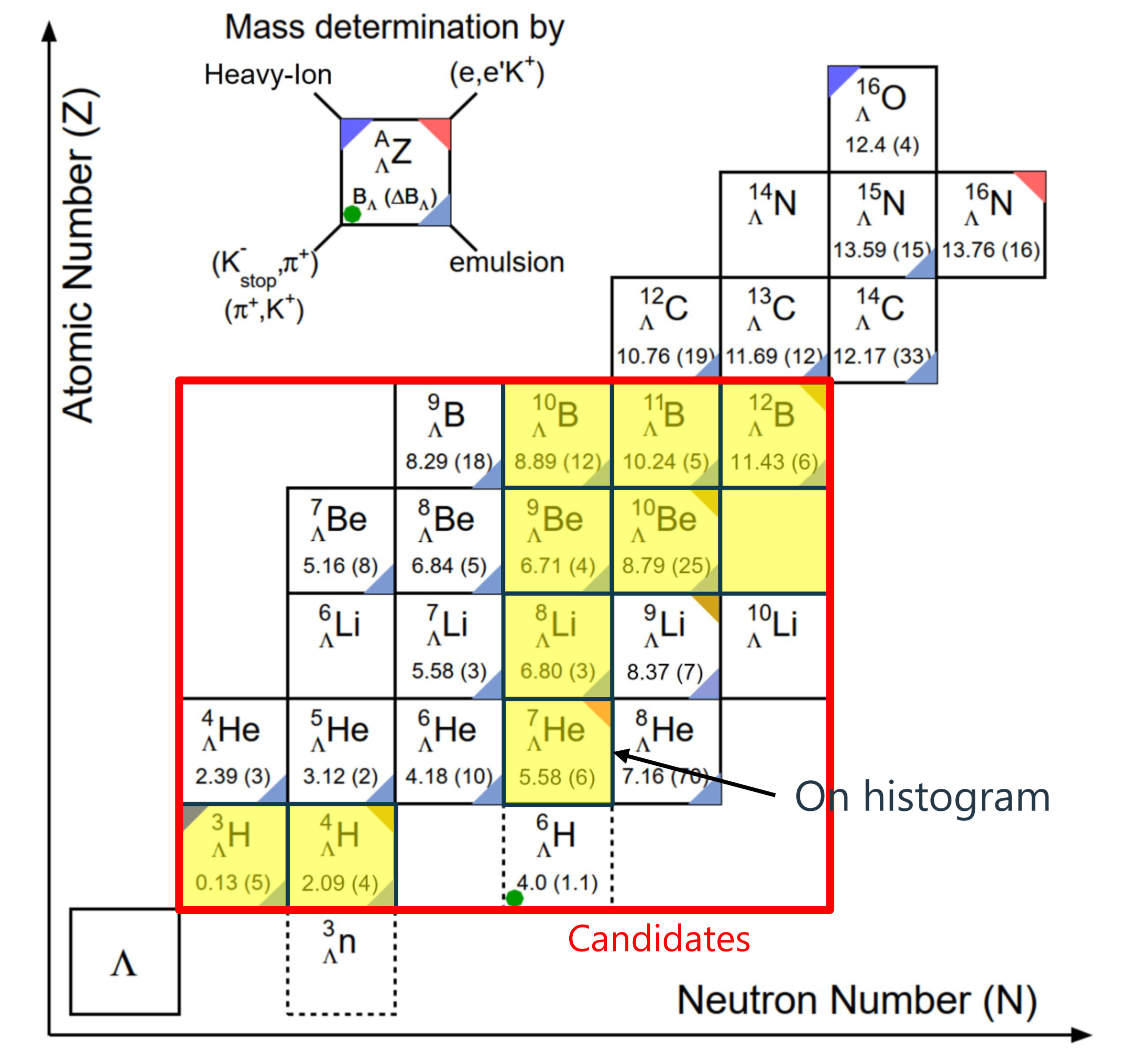
Expectation (^{9}Be target)



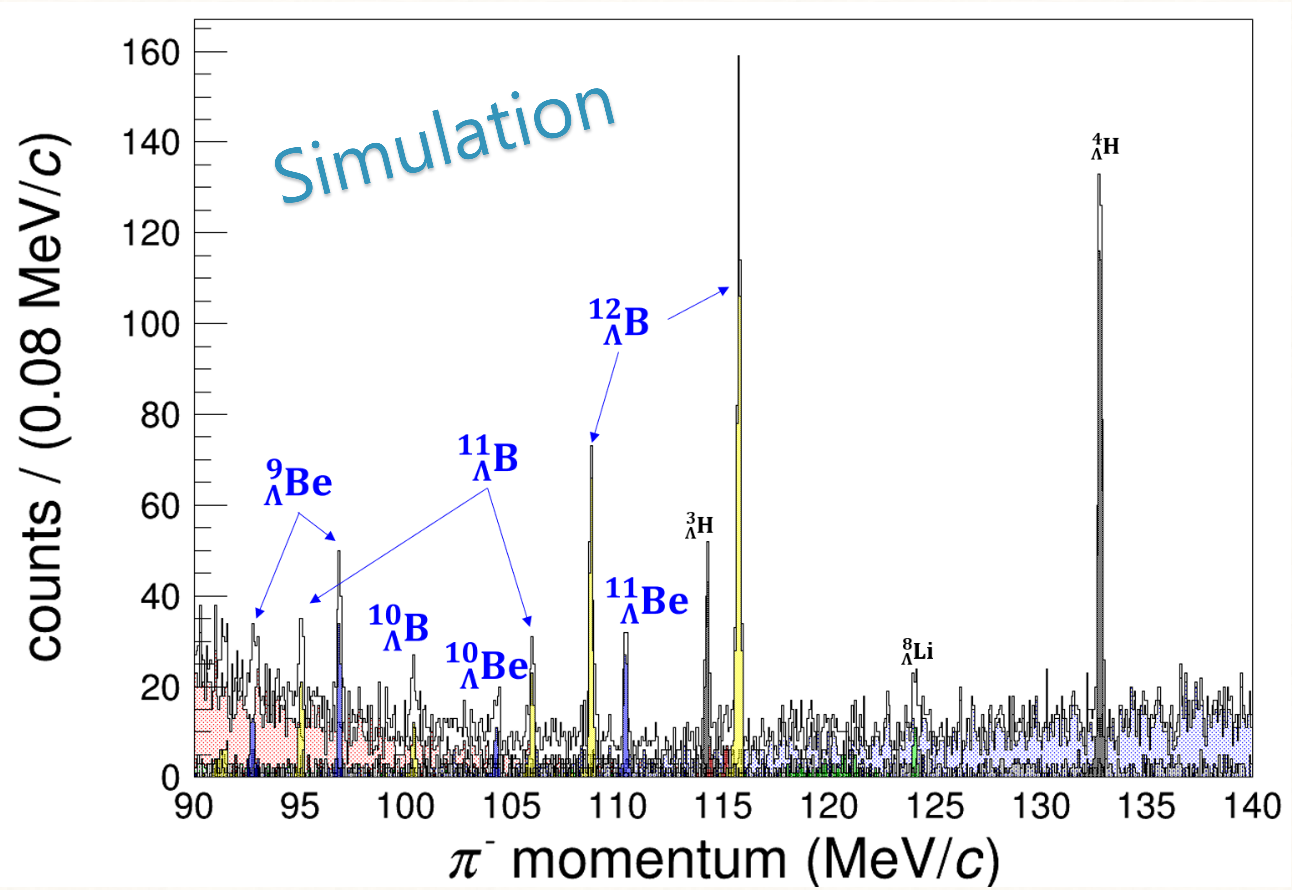


Expectation (^{12}C target)

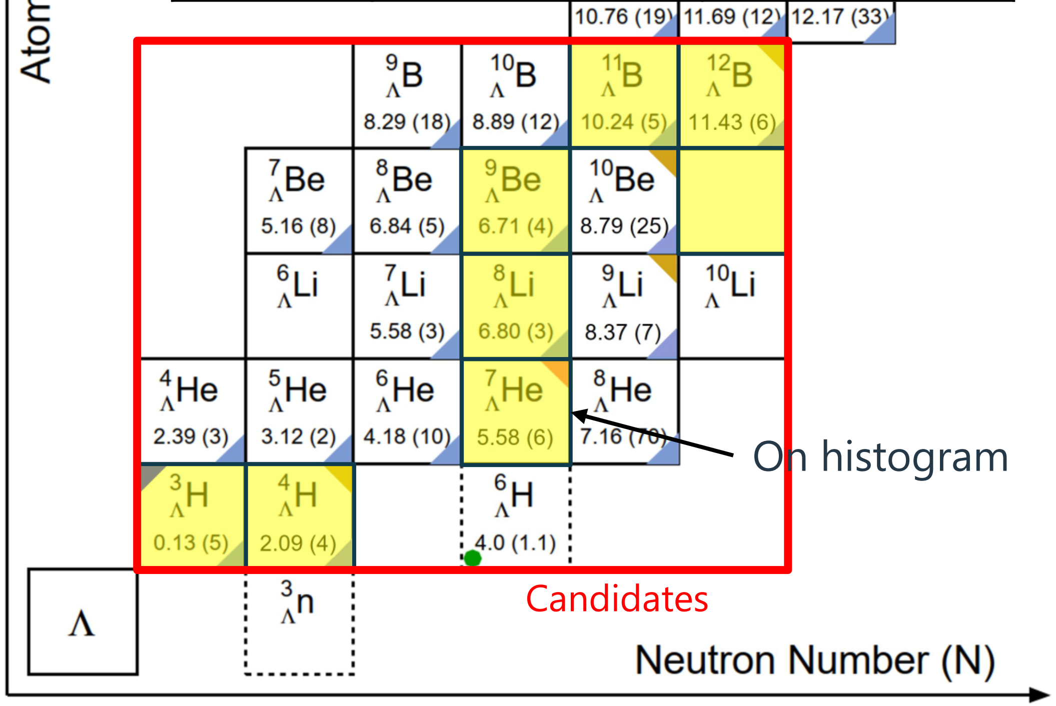




Expected (^{12}C target, no-add beamtime)

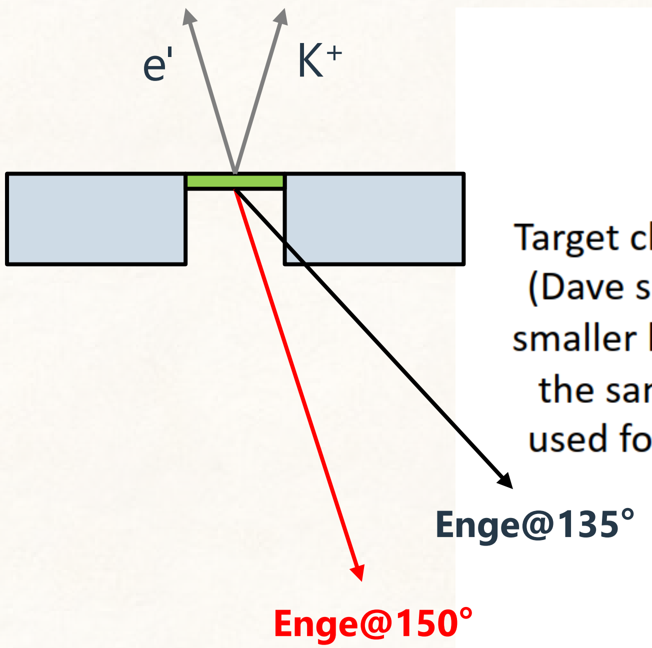


Nuclides	Significance (σ)	Precision (keV)
$^{3}_{\Lambda}$H	>10 → **8.4**	4.9 → **8.2**
$^{4}_{\Lambda}$H	>10 → **>10**	5.3 → **5.2**
$^{9}_{\Lambda}$Be	10 → **7.3**	5.2 → **9.1**
$^{10}_{\Lambda}$Be	6.0 → **3.8**	9.7 → **16**
$^{11}_{\Lambda}$Be	10 → **6.8**	5.8 → **10**
$^{10}_{\Lambda}$B	6.1 → **4.1**	10 → **15**
$^{11}_{\Lambda}$B	9.4 → **6.9**	6.2 → **10**
$^{12}_{\Lambda}$B	>10 → **>10**	4.1 → **5.0**

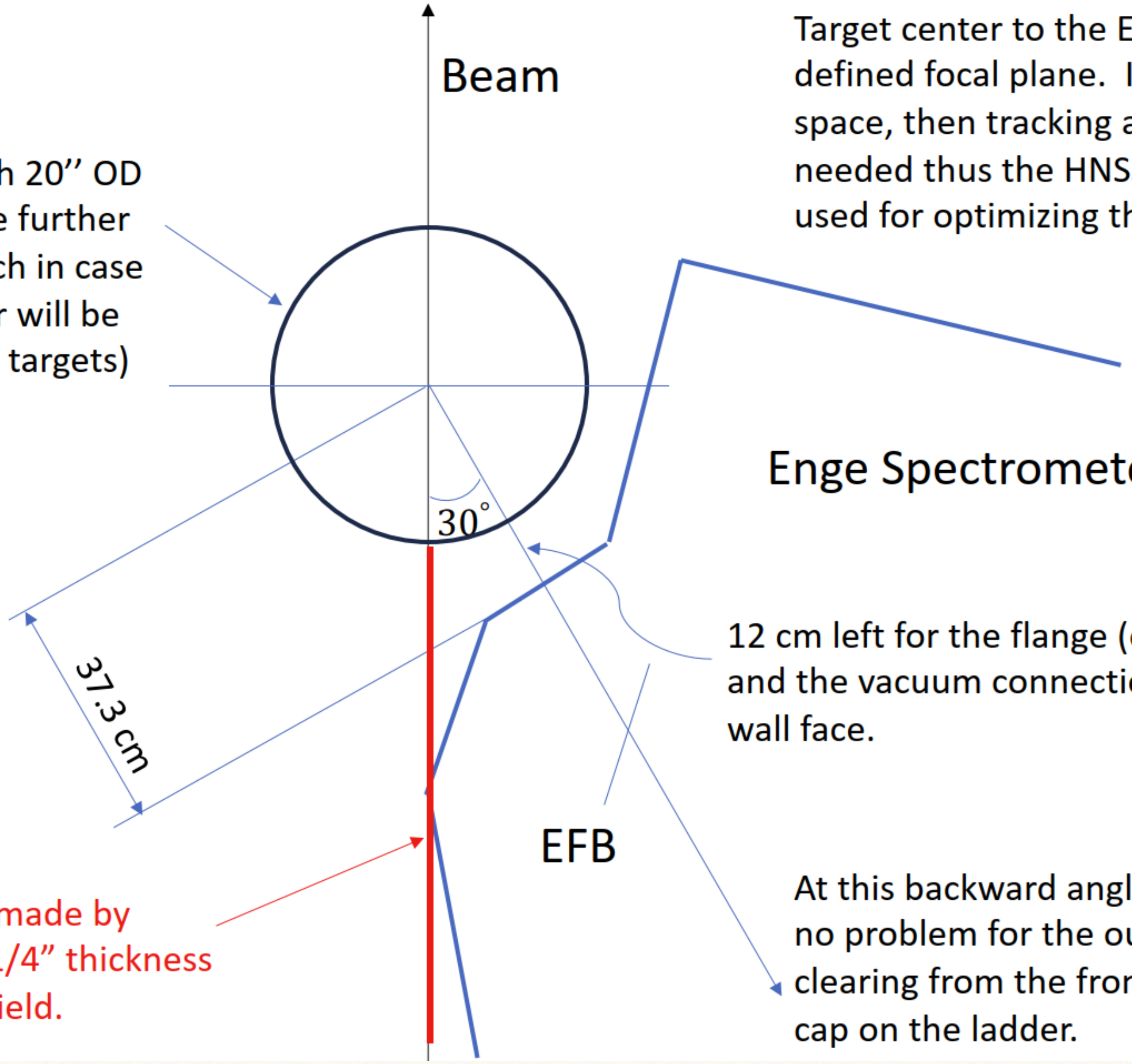


- ➢ Not enough statistics for A=10 hypernuclei
- ➢ No beam raster data on ^{12}C for the ^{6}Li run
- ➢ No thinner ^{12}C runs for dE correction

Target & Enge Geometry



Target chamber with 20'' OD (Dave said it can be further smaller but not much in case the same chamber will be used for future gas targets)



Target center to the EFB: 72 cm for a well defined focal plane. If backup Enge for more space, then tracking and its matrices are needed thus the HNSS sieve slit has to be used for optimizing the angular matrices.

Enge Spectrometer outline

12 cm left for the flange (on the target chamber) and the vacuum connection to the Enge vacuum wall face.

5' long beam pipe made by regular steel with 1/4" thickness to fully shield the field.

At this backward angle, there should be no problem for the outgoing pions clearing from the front target holding cap on the ladder.

alpha-source and calibration

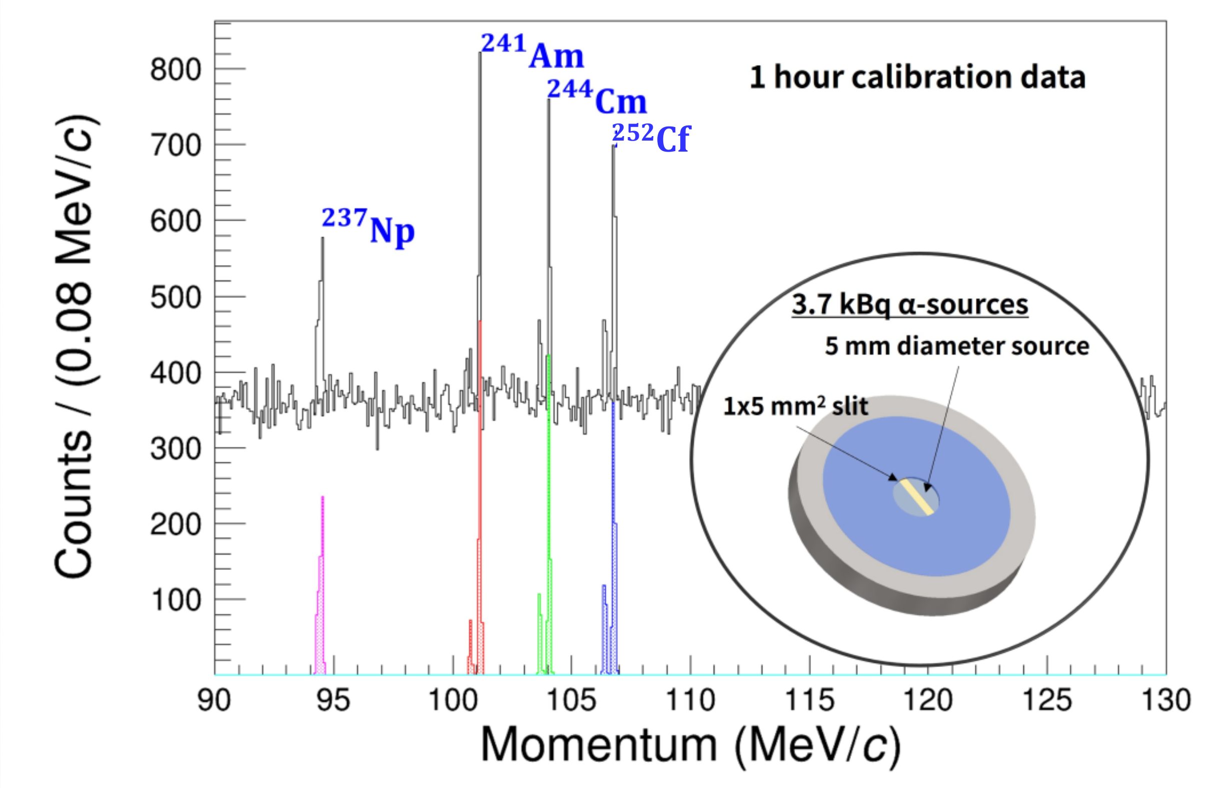
Alpha source PM-Type
(Eckert & Ziegler)

Plastic holder with removable alpha foil

- Holder: 1" diameter
- Foil: 11.1 mm diameter
- Active: 5.0 mm diameter

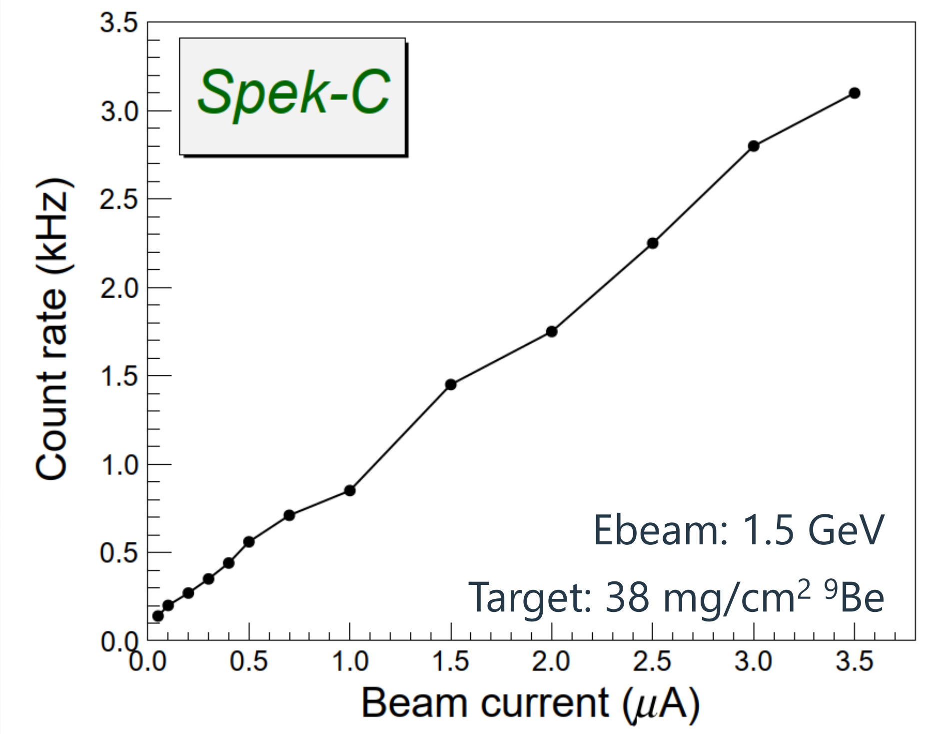
3-mixed source
^{241}Am, ^{244}Cm, and ^{252}Cf (or ^{239}Pu)
is available

Mounting the foil into the custom designed target holder with 1x5 mm^2 slit



Expected Rate of Enge

Single Rate of pion spectrometer



MAMI: 1 kHz / μA w/ Spek-C (28 msr, 120 deg)

JLab: x 3 thicker target, 50 μA

w/ Enge (4 msr, 150 deg)

→ a few tens kHz single rate

$$\mathcal{R}_{\mathrm{Enge}} = 1\ (\mathrm{kHz}/\mu\mathrm{A}) \times \mathrm{I}\ \frac{N_t}{2.6 \times 10^{21}} \mathrm{A}^{0.86}\ \frac{\Delta\Omega_{Enge}}{28\ \mathrm{msr}} \frac{\varepsilon_{decay}}{0.25},$$

$$\mathcal{R}^{\mathrm{ana}}_{\mathrm{HKS}} = \mathcal{R}_{\pi^+}\ \varepsilon_{\pi^+} + \mathcal{R}_{K^+}\ \varepsilon_{K^+} + \mathcal{R}_p\ \varepsilon_p,$$

$$\mathcal{R}^{\mathrm{ana}}_{\mathrm{HKS}} = \mathcal{R}_{\pi^-}\ \varepsilon_{\pi^-},$$

$$\mathcal{R}_{\mathrm{Spectrum}} = \mathcal{R}^{\mathrm{ana}}_{\mathrm{HKS}} \times \mathcal{R}^{\mathrm{ana}}_{\mathrm{Enge}} \times T_{\mathrm{window}},$$

Target	$\mathcal{R}_{\mathrm{HKS}}$ (kHz)	$\mathcal{R}_{\mathrm{Enge}}$ (kHz)	$\mathcal{R}_{\mathrm{Trigger}}$ (Hz)	$\mathcal{R}_{\mathrm{Spectrum}}$ (Hz/MeV)
^{6}Li	45	20	90	5.6×10^{-6}
^{9}Be	25	21	50	3.0×10^{-6}
^{12}C (Graphite)	41	20	80	5.2×10^{-6}
^{27}Al	54	31	170	1.0×10^{-5}
^{40}Ca	52	31	160	9.5×10^{-6}
^{208}Pb	20	15	30	1.9×10^{-6}

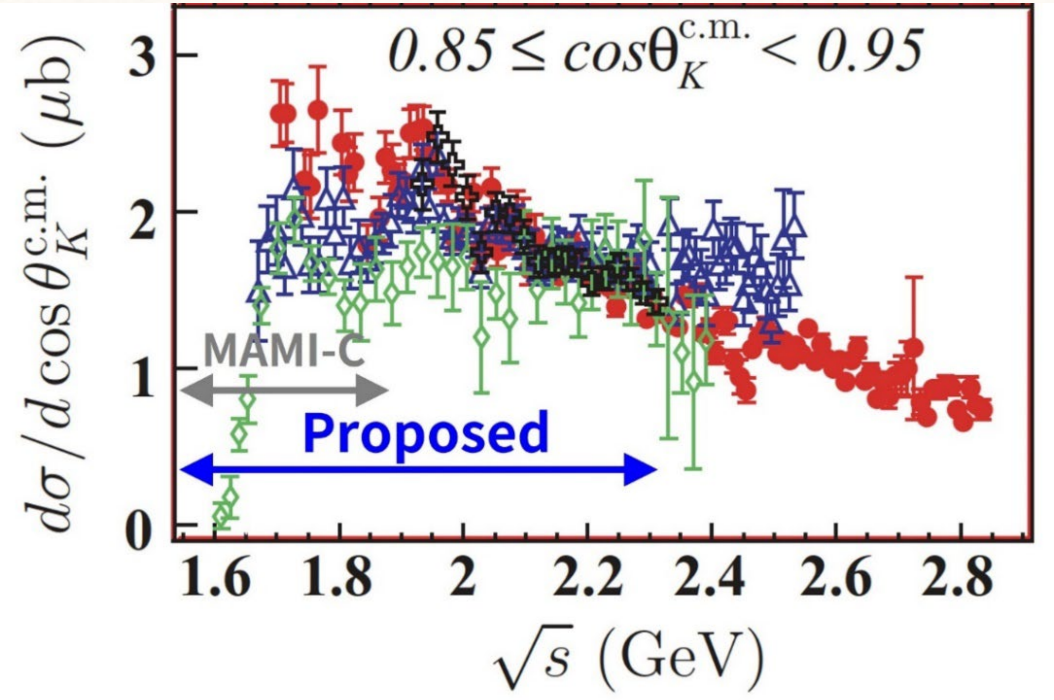
~30 times yield

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

↑ ×30

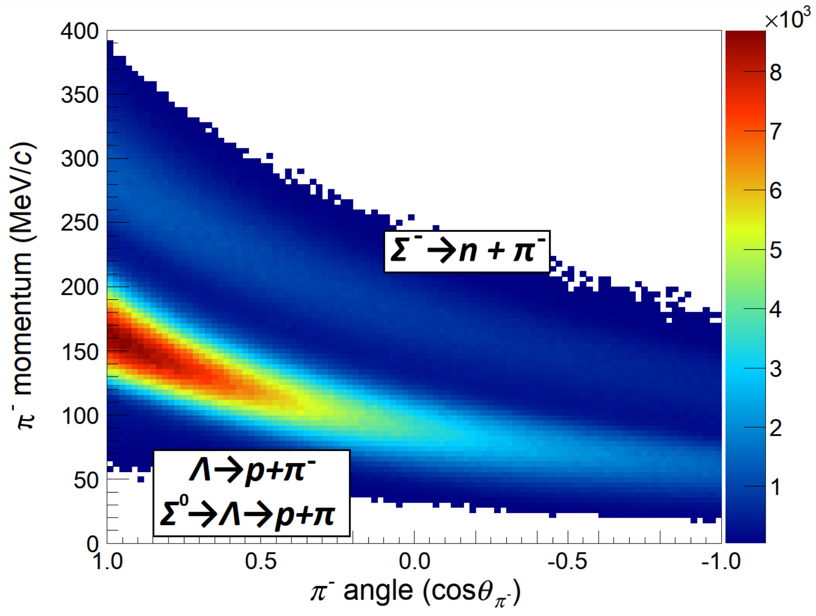
Monte-Carlo

p(γ,K⁺)Λ Cross Section

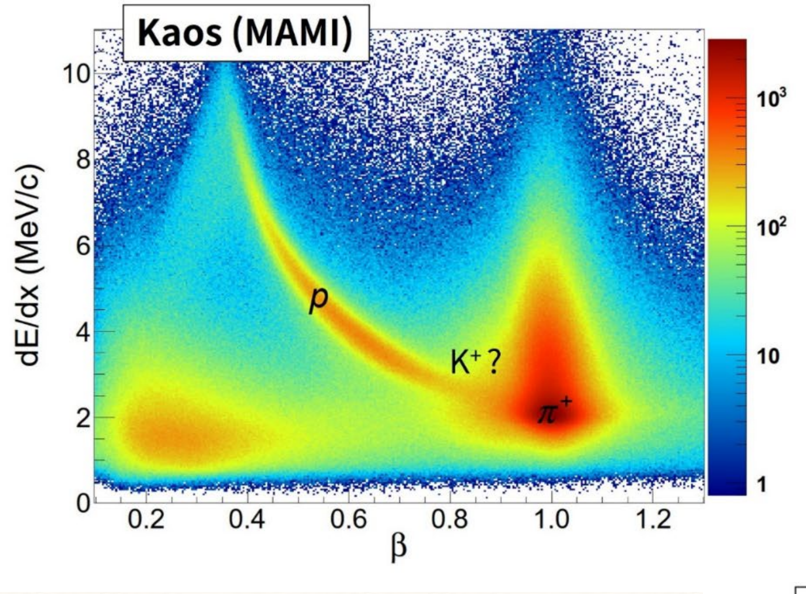


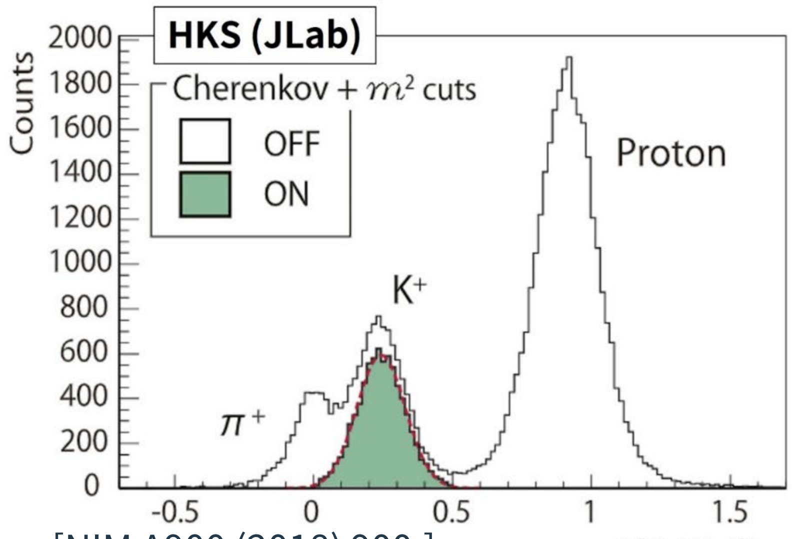
[CLAS, Phys. Rev. C 81 (2010) 025201.]

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

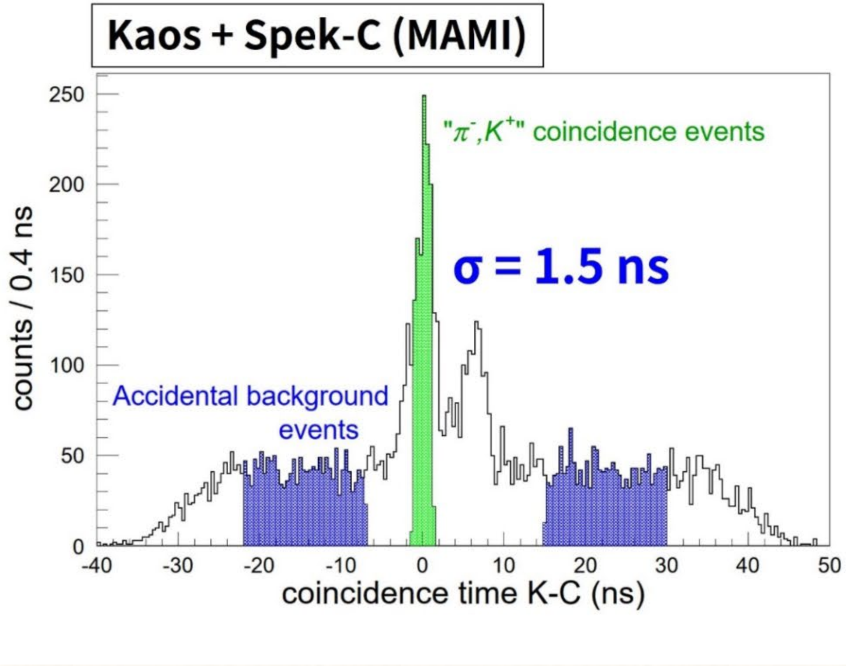


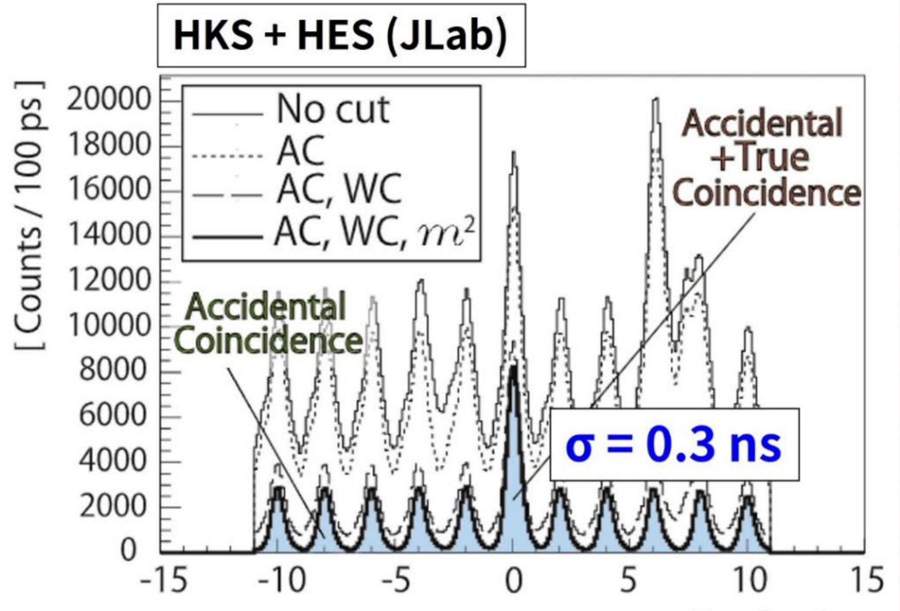
PID performance





[NIM A900 (2018) 900.]



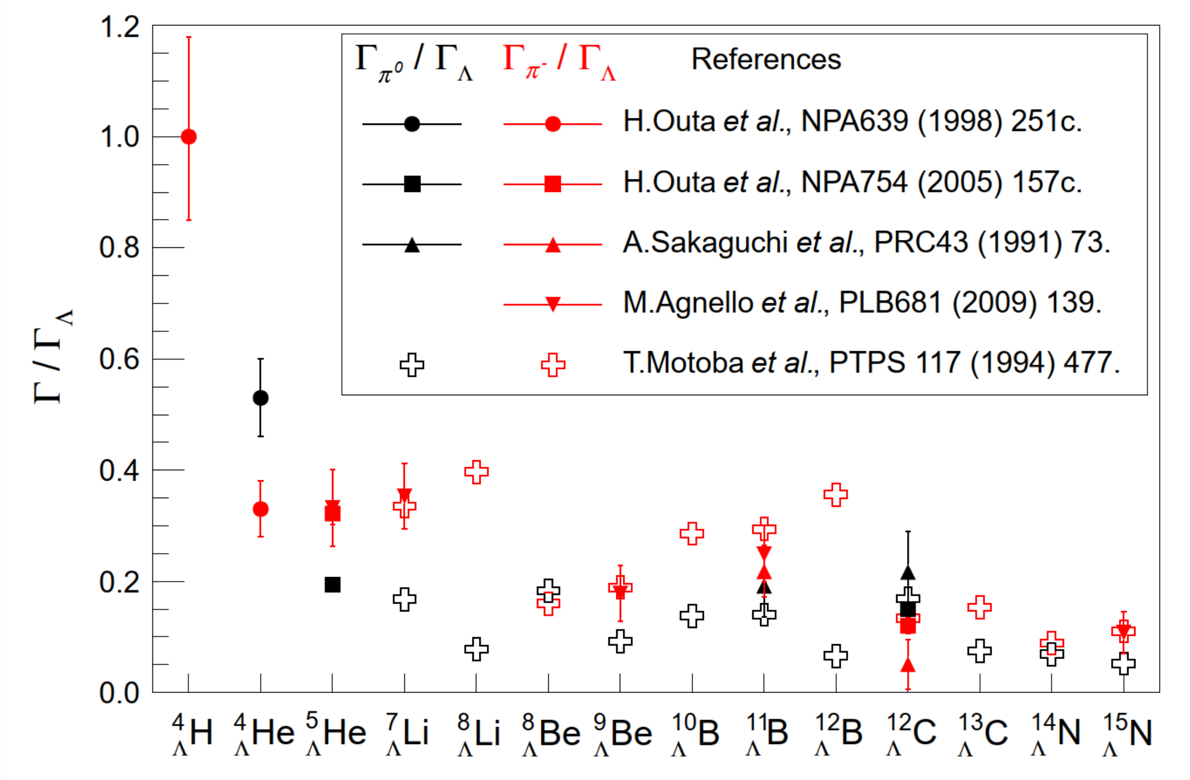


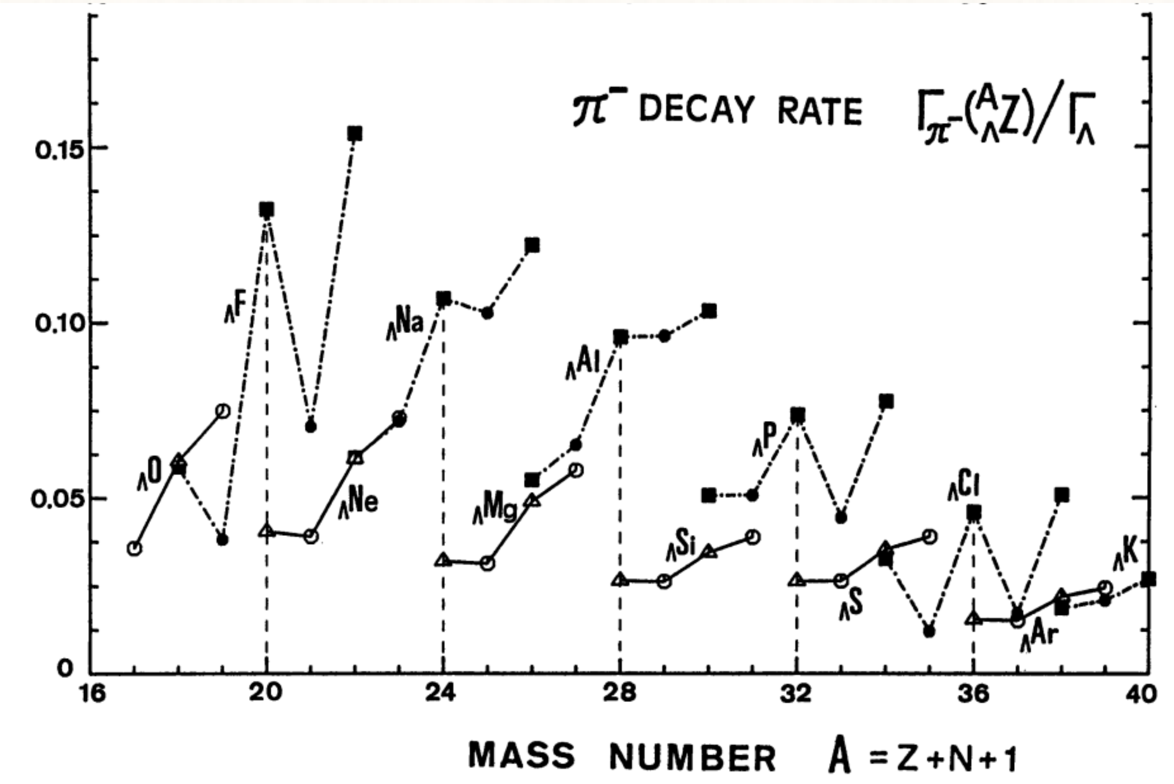
[NIM A900 (2018) 900.]

Pion emission probability

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

Monte-Carlo



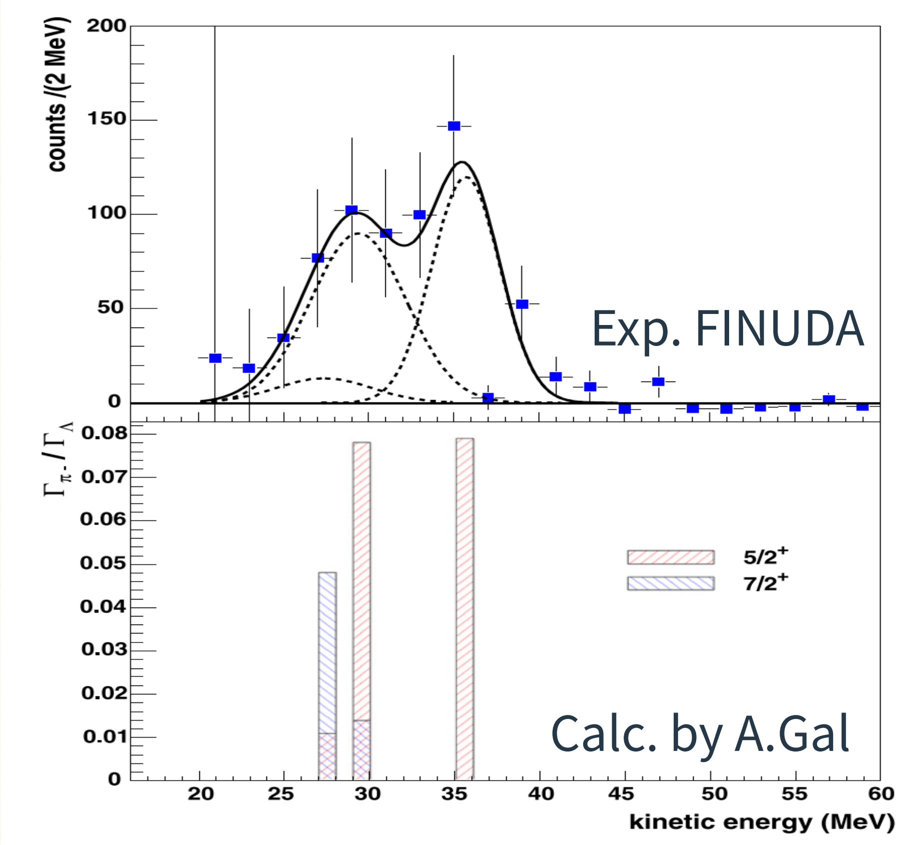


Spin assignment from decay width

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

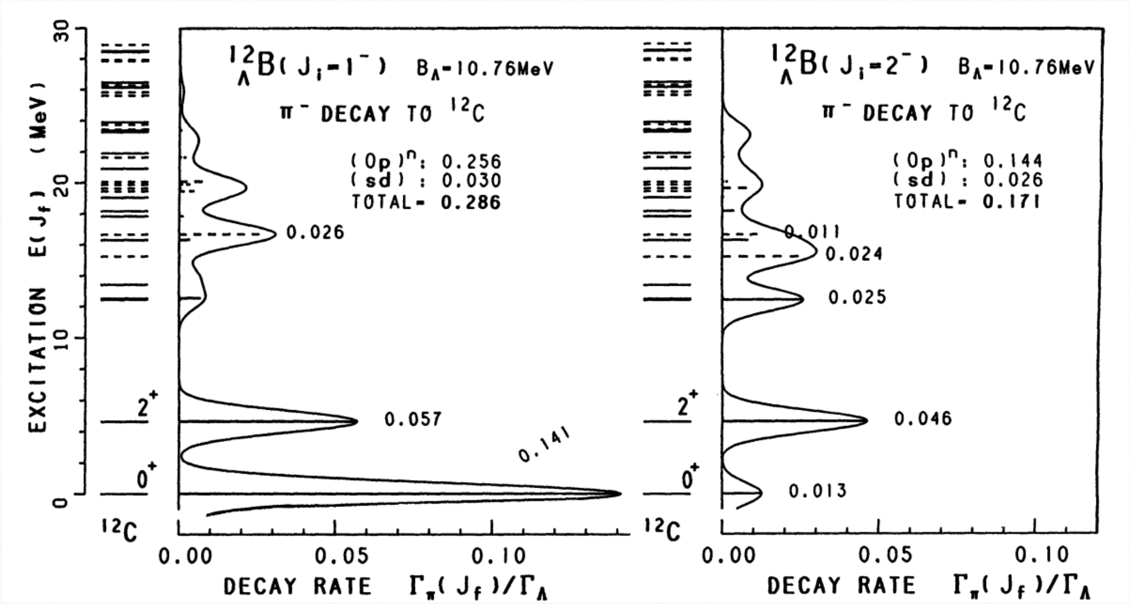
Monte-Carlo

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

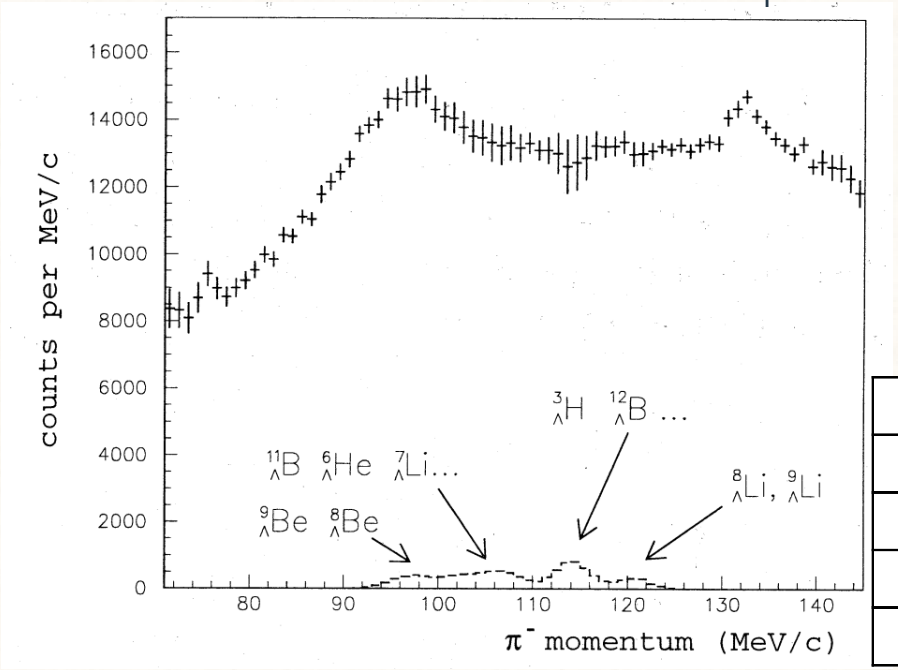


Hypernuclear formation probability

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

Monte-Carlo

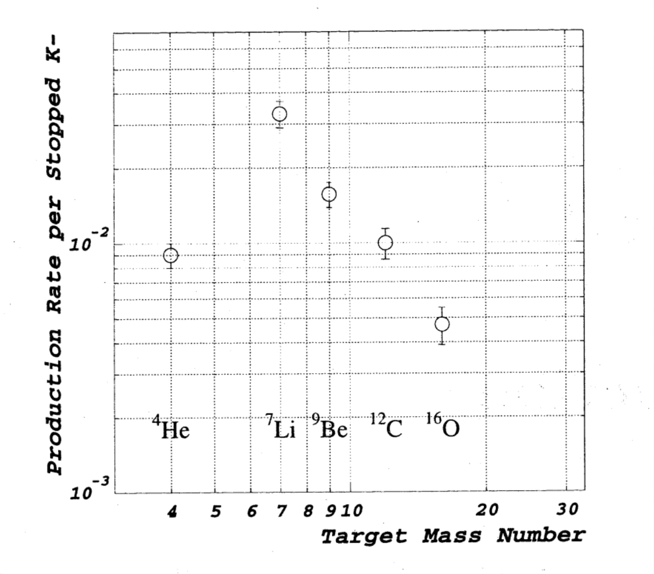
π^- spectrum of ^{12}C target @$(K^-,\pi^-)_{stop}$



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



Proposed (e,e'K$^+$) experiments

Target	Period	Experiment
^{6}Li	5	PR12-24-004
^{9}Be	16	PR12-24-004
^{11}B	3	PR12-24-004
^{12}C	7	E12-15-008 / PR12-24-013
^{27}Al	28	PR12-24-011 / PR12-24-013
^{40}Ca	19	E12-15-008 / PR12-24-013
^{48}Ca	23	E12-15-008 / PR12-24-013
^{208}Pb	42	E12-20-013 / PR12-24-003