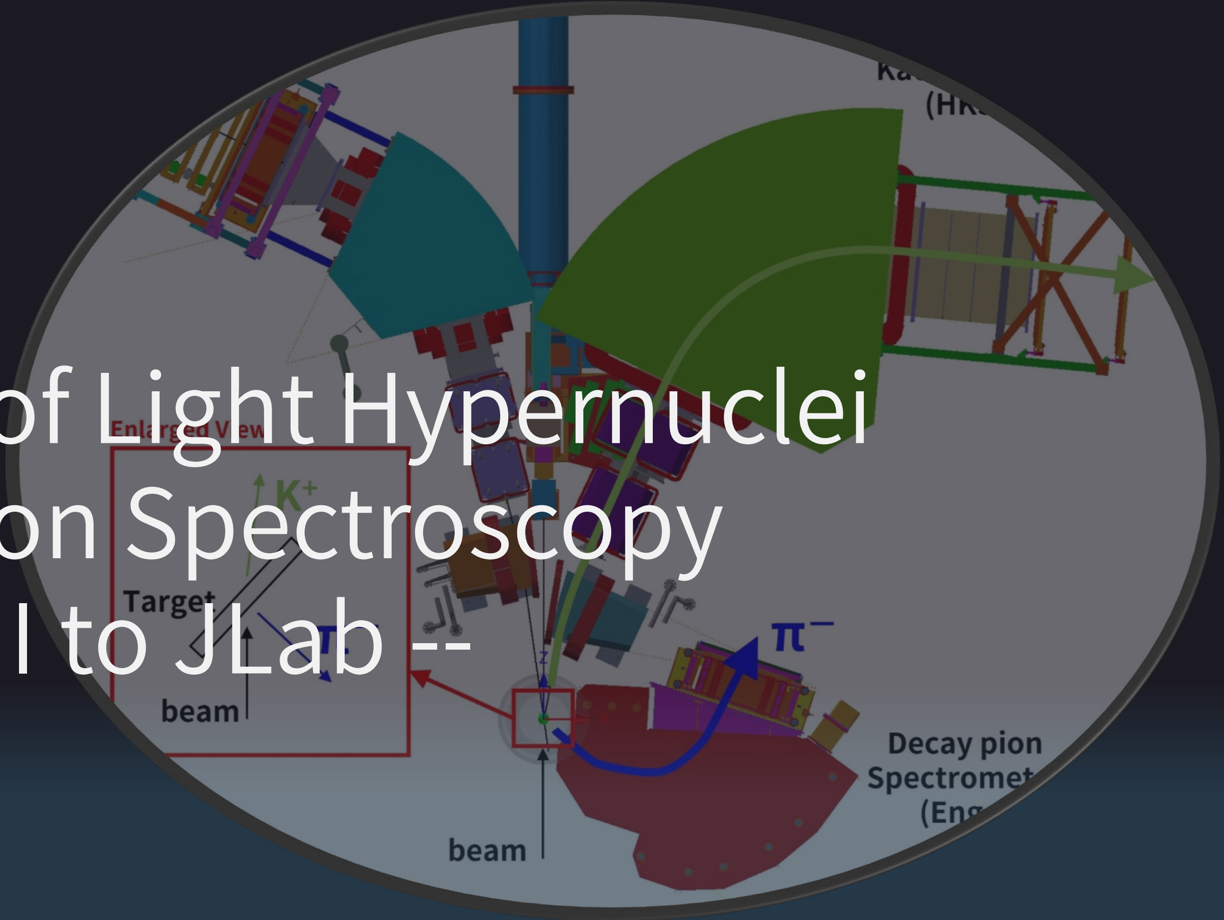



Mass Determination of Light Hypernuclei with the Decay Pion Spectroscopy -- from MAMI to JLab --

Contents

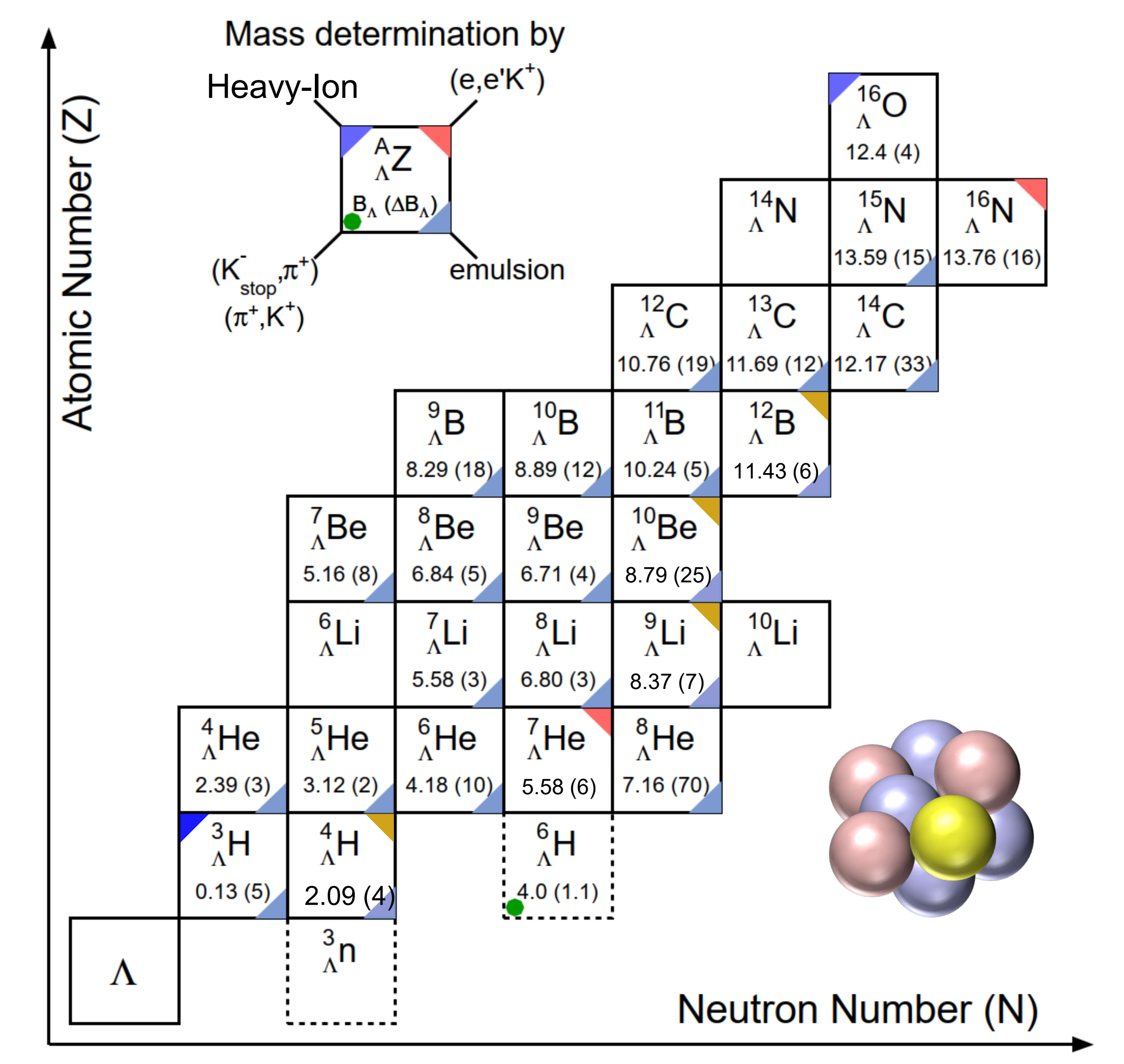
- Hypernuclear Physics
- Decay Pion Spectroscopy
  - Principle
  - Previous Studies (MAMI exp.)
  - DPS at JLab (LOI12-23-011)

The University of Tokyo
Sho Nagao
for the JLab Hypernuclear Collaboration

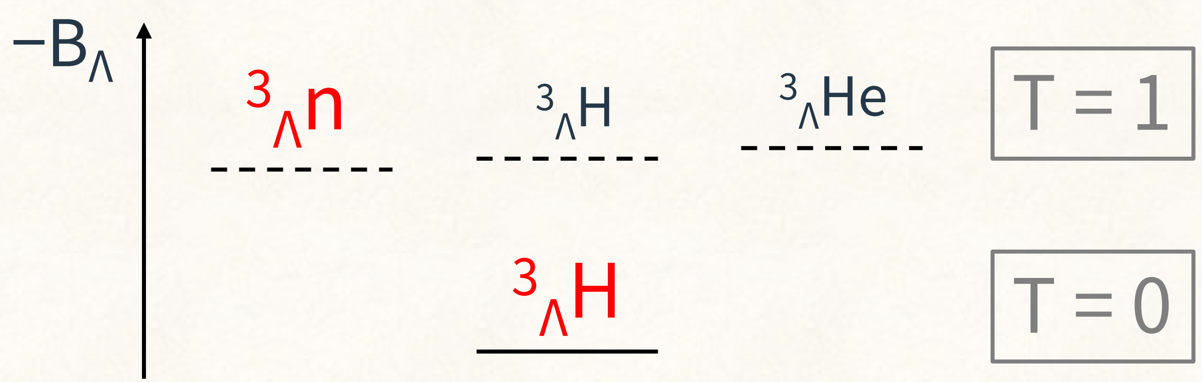
June 30, 2023

Hypernuclei

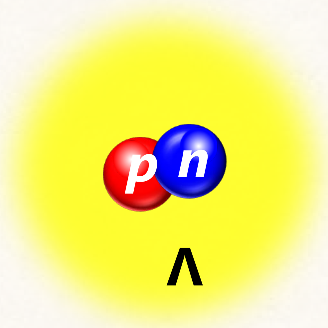
- Few-body system with *strangeness*
- Investigation of YN interaction based on $SU_f(3)$, nuclear structure, impurity effect, and neutron-stars
- Λ binding energies by the emulsion, missing-mass, invariant-mass spectroscopies
- Precise measurement is essential especially for s-, p-shell hypernuclei
- Discussion about ${}^{3}_{\Lambda}H$ puzzle, CSB, ΛN-ΣN coupling effect etc...



Hypertriton Puzzle



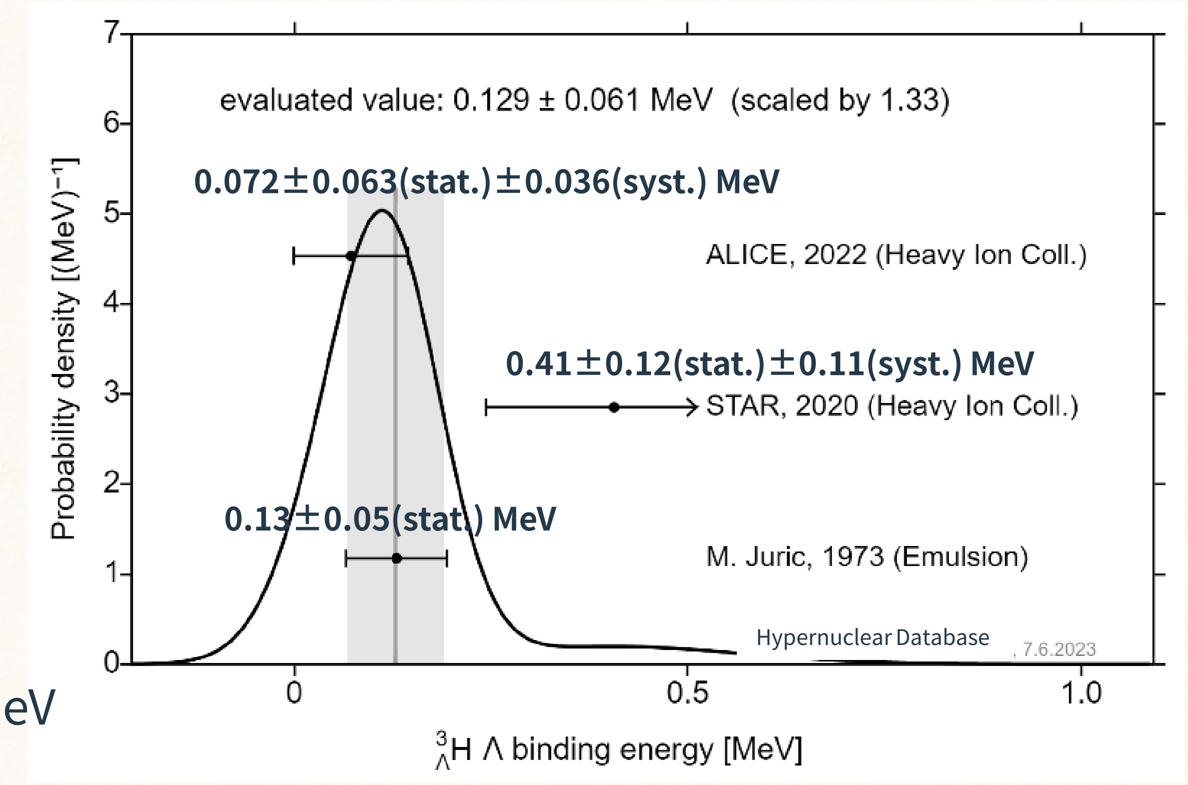
0.13±0.05 MeV [NPB52(1973)1.]



M_Λ (2023) = 1115.683(6)

M_Λ (1973) = 1115.57(3)

0.11 MeV



- Shallow B_Λ
- Similar lifetime to free Λ (263 ps)
- No other A=3 hypernuclei

⇨

- Deeply B_Λ?
- Shorter lifetime?
- Bound or Resonance state of nnΛ

Charge Symmetry Breaking (CSB)

$S = 0$

p *p* *n* *n*

Scattering Length $a_{pp} = -17.3 \pm 0.4$ fm $a_{nn} = -18.6 \pm 0.4$ fm

[arXiv:1703.00519 (2017)]

Small CSB

$S = -1$

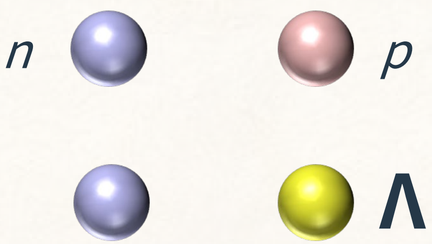
p Λ *n* Λ

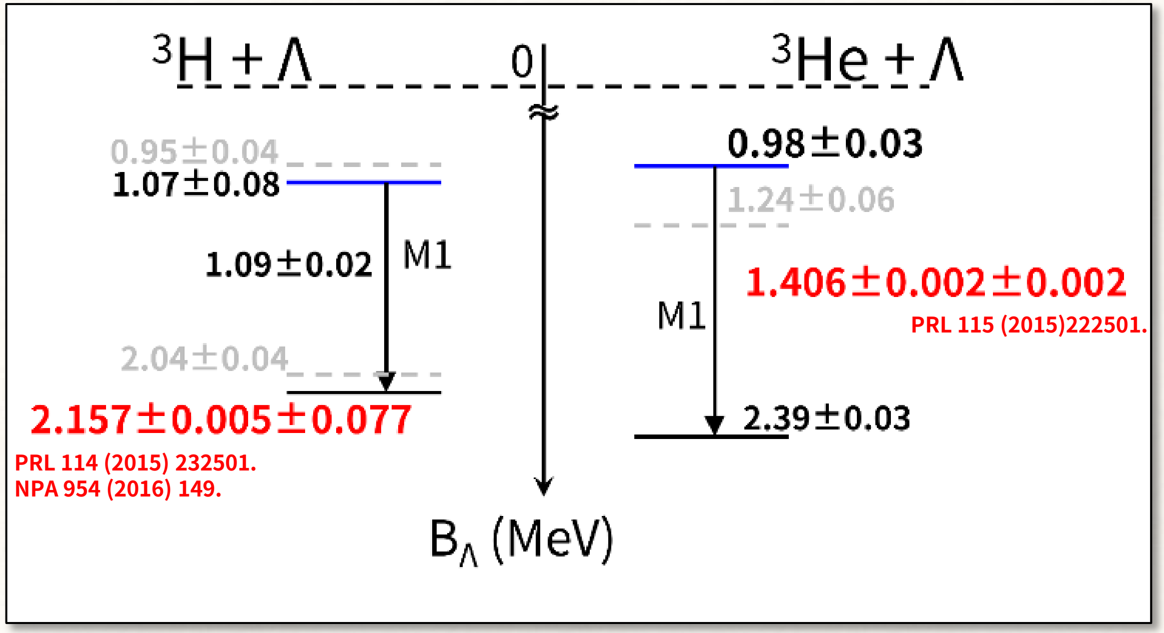
Large or Small ?

Scattering Exp. is difficult

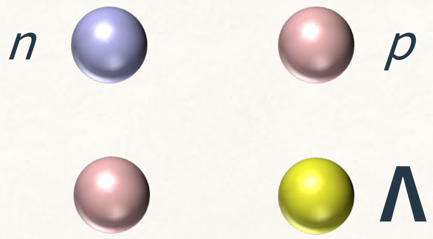
- Good Charge-Symmetry between p-p and n-n
- Good symmetry for iso-mirror nuclei e.g. ^{3}H and ^{3}He
- Small CSB due to quark mass differences
- Charge-Symmetry is large or small with strengeness
- Limited scattering data
- Investigation of CSB with iso-mirror hypernuclei

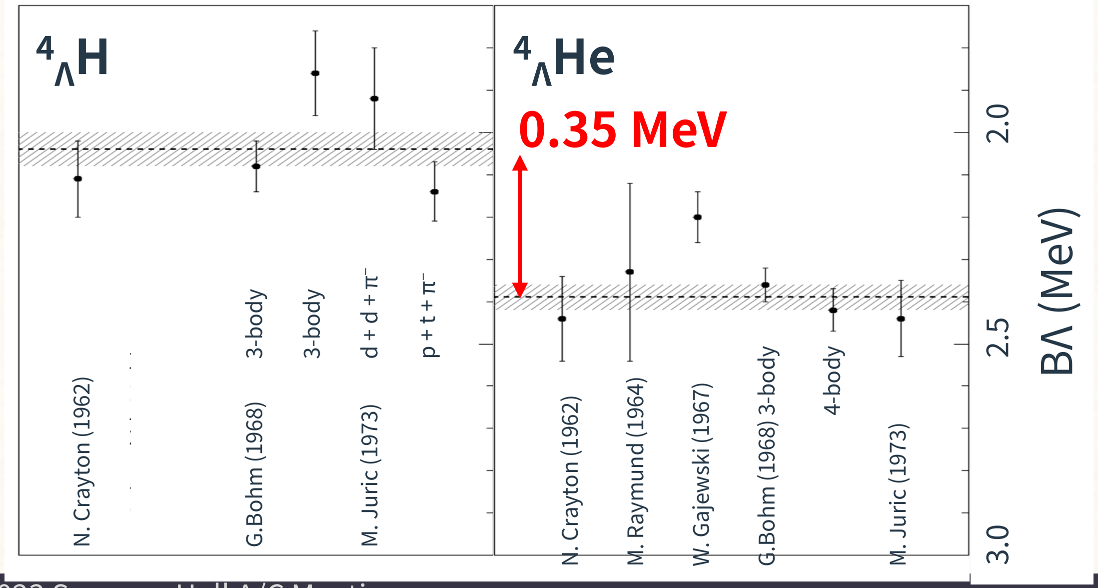
$^4_\Lambda$H (I = −1/2)





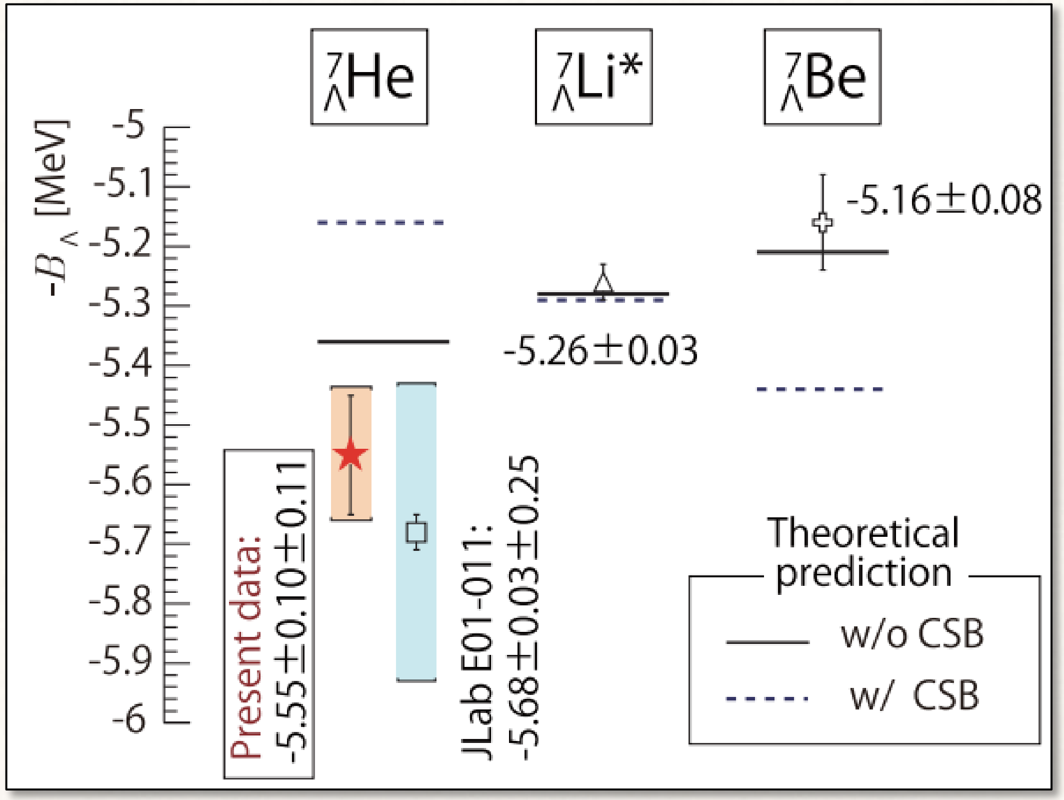
$^4_\Lambda$He (I = +1/2)





- Large CSB on A=4 hypernuclei in Emulsion
- Not included 2-body decay mode
- M_Λ has 0.11 MeV difference
- Recent update with DPS and γ-ray

CSB on A=7 system



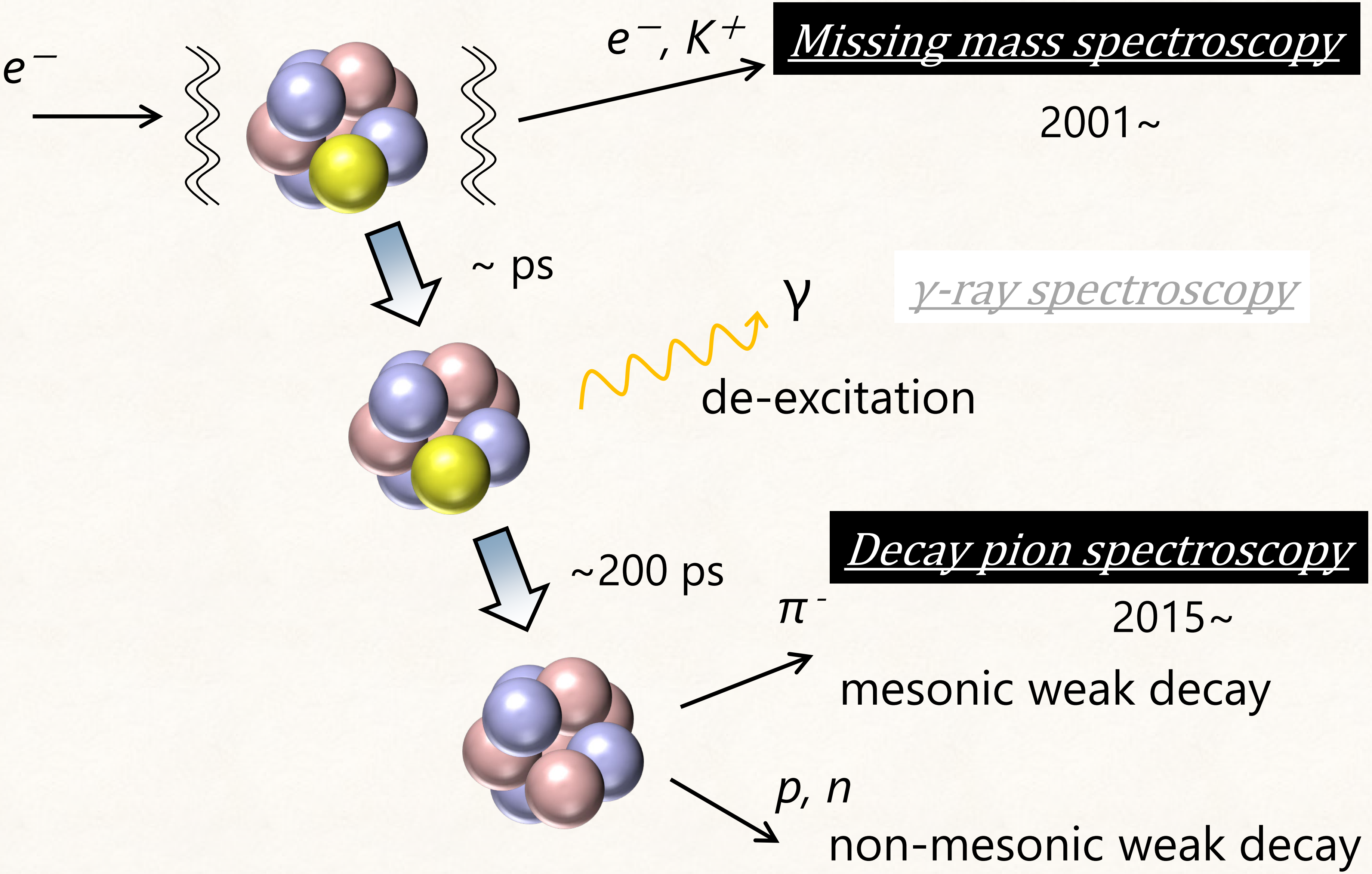
[T. Gogami et al., PRC94 (2016) 021302(R).

- No observation of large CSB on p-shell hypernuclei
- Measurement with <100 keV accuracy is essential

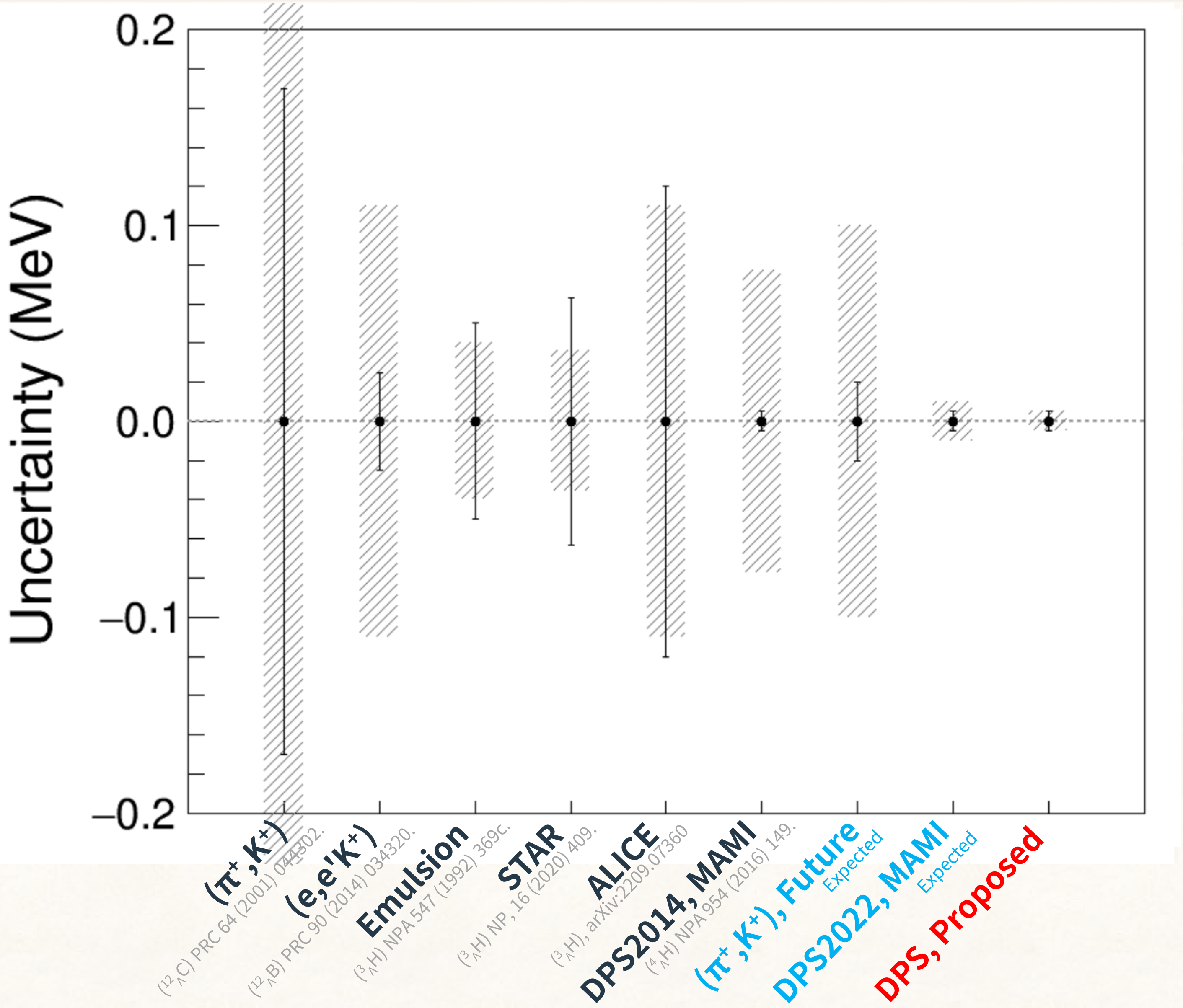
Recent work of ChiralEFT [PRC107 (2023) 024002]

		ΔT	ΔV_{NN}	ΔB_Λ
${}^{7}_{\Lambda}$Be - ${}^{7}_{\Lambda}$Li*	NLO13	7	−24	−17
	NLO13-CSB	8	−24	−40
	NLO19	6	−40	−34
	NLO19-CSB	6	−41	−35
	Hiyama [13]		−70	150
	Gal [37]	3	−70	−17
	Experiment [6]			−100 ± 90
${}^{7}_{\Lambda}$Li* - ${}^{7}_{\Lambda}$He	NLO13	8	−13	−5
	NLO13-CSB	7	−14	−31
	NLO19	5	−22	−17
	NLO19-CSB	5	−21	−16
	Hiyama [13]		−80	130
	Gal [38]	2	−80	−28
	Experiment [6]			−20 ± 230[a] −50 ± 190
${}^{8}_{\Lambda}$Be - ${}^{8}_{\Lambda}$Li	NLO13	12	8	16
	NLO13-CSB	12	7	178
	NLO19	7	−11	−6
	NLO19-CSB	6	−11	143
	Hiyama [13]		40	160
	Gal [37]	11	−81	49
	Experiment [4]			40 ± 60

Hypernuclear Formation - Decay



B_Λ Accuracy



(e,e'K+)

Unique exp. technique to measure B_Λ from light to heavy hypernuclei precisely

Sensitivity of Excitation, Resonance states

Heavy-Ion

Established method recently

s-shell hypernuclear g.s. only

Decay Pion Spectroscopy

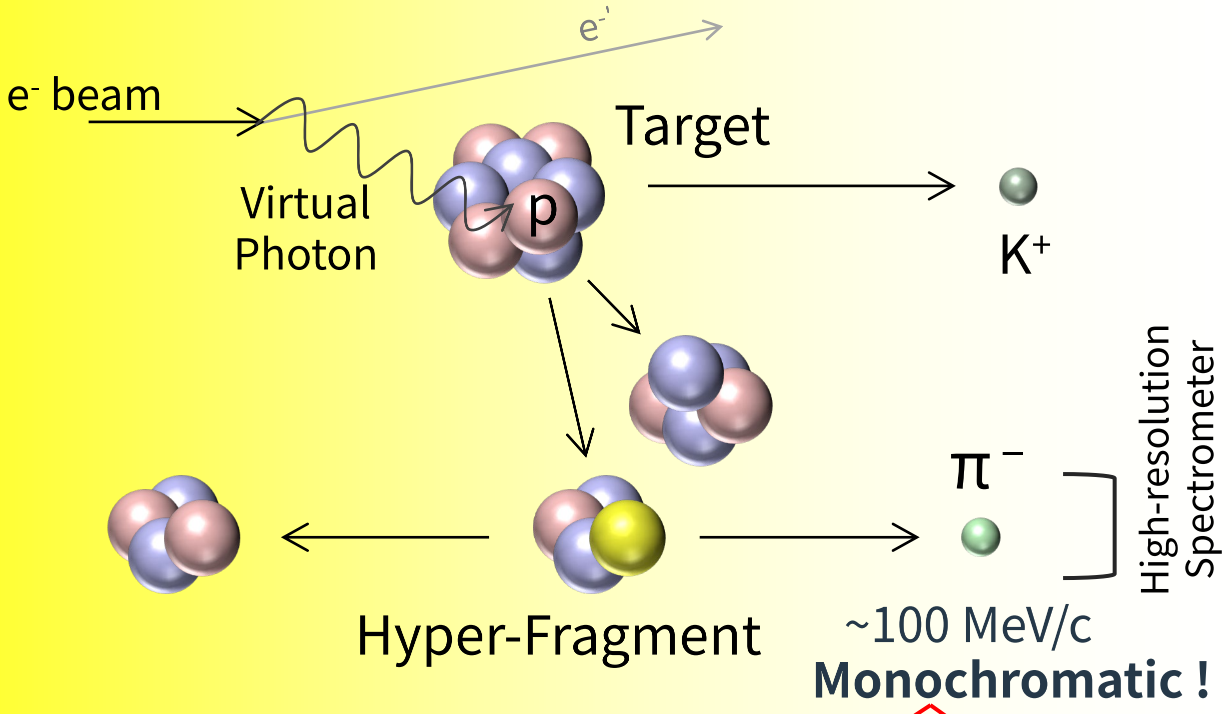
Extreme high precision exp.

s-, p-shell hypernuclear g.s.

possibility of <10 keV accuracy

Higher-resolution mass spectroscopy

Decay Pion Spectroscopy



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

- High-resolution & High-precision hypernuclear mass spectroscopy
  - Stopping in a target
  - Two-body decay with π^- & nucleus
    → hypernuclear ground-state
- Momentum resolution Δp ~ 0.1 MeV/c
- Mass precision ΔM ~ 0.01 MeV/c^2
- Good calibration sources
- Tagging Kaon

List of decay pion candidates

Hypernuclei	Decay mode	p_{π^-} (MeV/c)
${}^{3}_{\Lambda}$H	^{3}He + π^-	114.4
${}^{4}_{\Lambda}$H	^{4}He + π^-	133.0
${}^{6}_{\Lambda}$H	^{6}He + π^-	135.3
${}^{7}_{\Lambda}$He	^{7}Li + π^-	114.8
${}^{7}_{\Lambda}$Li	^{7}Be + π^-	108.1
${}^{8}_{\Lambda}$He	^{8}Li + π^-	116.5
${}^{8}_{\Lambda}$Li	2α + π^-	124.2
${}^{8}_{\Lambda}$Be	^{8}B + π^-	97.2
${}^{9}_{\Lambda}$Li	^{9}Be + π^-	121.3
${}^{9}_{\Lambda}$B	^{9}C + π^-	96.8
${}^{10}_{\Lambda}$B	^{10}C + π^-	100.5
${}^{11}_{\Lambda}$B	^{11}C + π^-	86.5
${}^{12}_{\Lambda}$B	^{12}C + π^-	115.9
${}^{12}_{\Lambda}$C	^{12}N + π^-	91.5
${}^{13}_{\Lambda}$C	^{13}N + π^-	92.3
${}^{14}_{\Lambda}$C	^{14}N + π^-	101.2
${}^{15}_{\Lambda}$N	^{15}O + π^-	98.4
${}^{16}_{\Lambda}$N	^{16}O + π^-	106.2

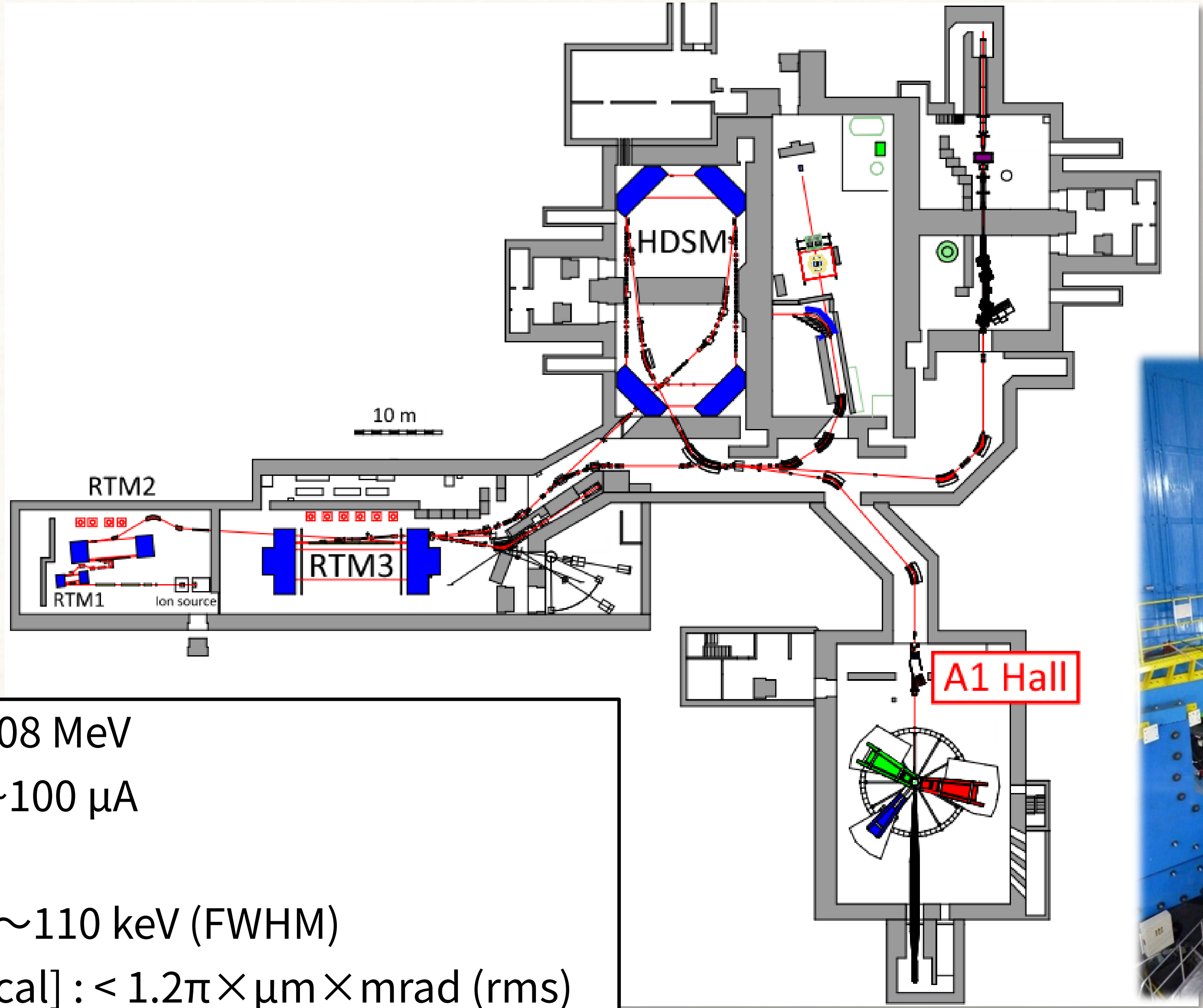
^{6}Li target
^{7}Li target
^{9}Be target
^{12}C target

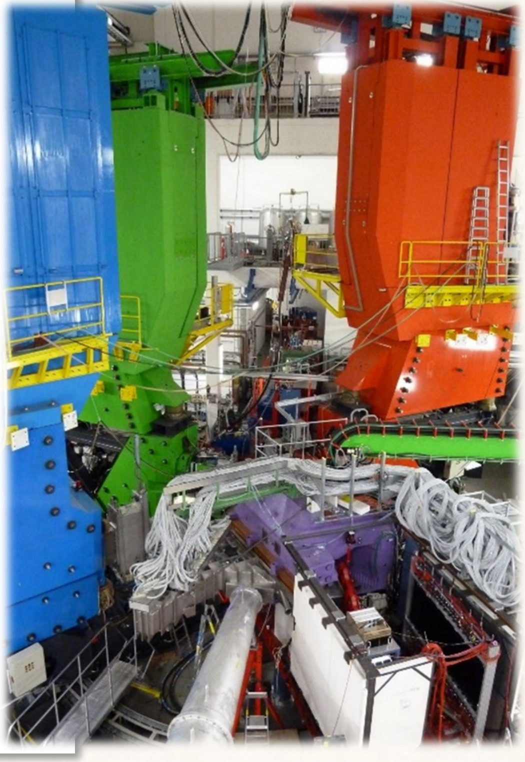
- Momentum of 100-130 MeV/c
- Emitting π^- from neutron-rich hypernuclei
- Decay prob. are measured and calculated
  [NPA754(2005)157c, PLB681(2009)139, PTPS117(1994)477.]
- Dependence on parent hypernuclei
- Some decay pion momenta are very close
- Identification by changing the target

Decay Pion Spectroscopy

- New determination of $B_\Lambda(^4_\Lambda H)$ at MAMI
- From MAMI to JLab
- LOI12-23-011 (parallel exp. to $(e,e'K^+)$ exp.)

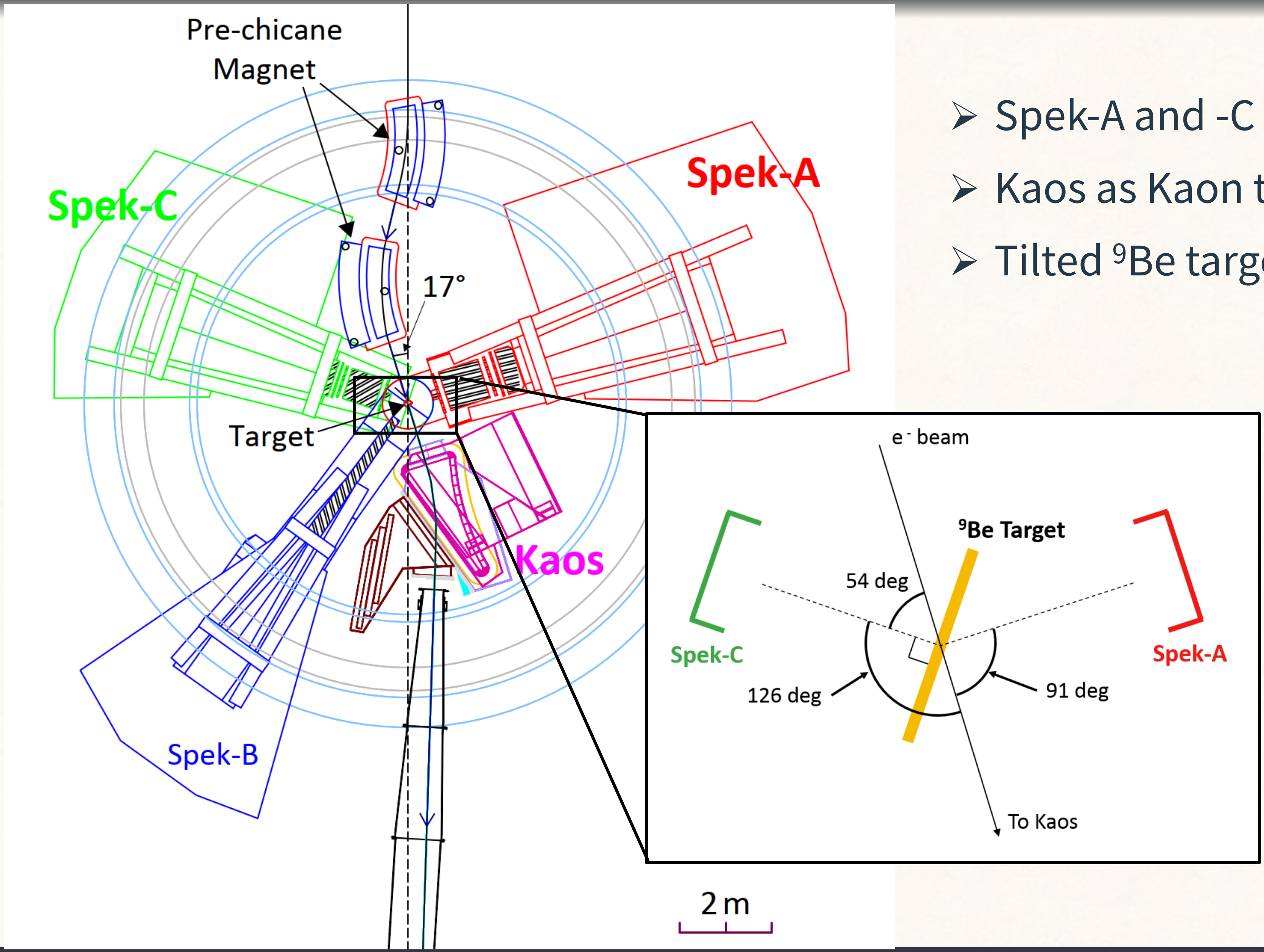
Mainz Microtron (MAMI)



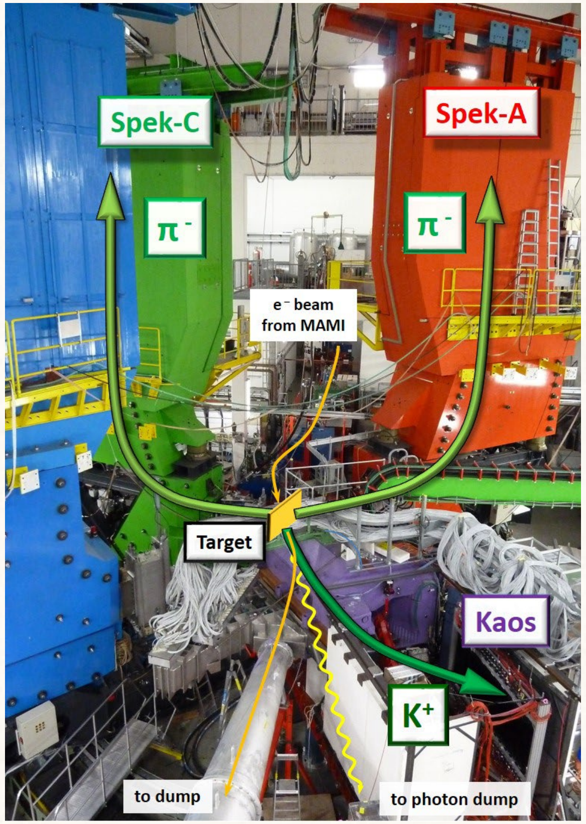


- Beam energy : Max. 1508 MeV
- Beam intensity : Max. ~100 μA
- Duty factor : 100%
- Energy resolution : ΔE∼110 keV (FWHM)
- Beam emittance [vertical] : < 1.2π×μm×mrad (rms)

Setup of A1-Hall MAMI

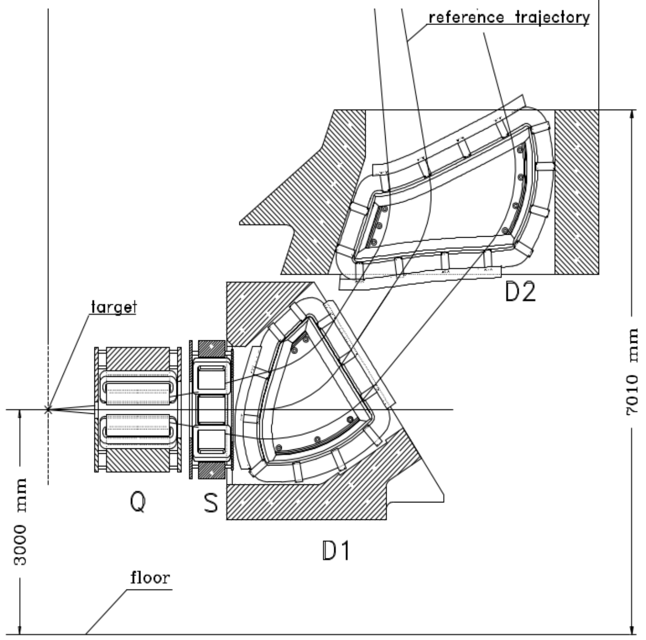


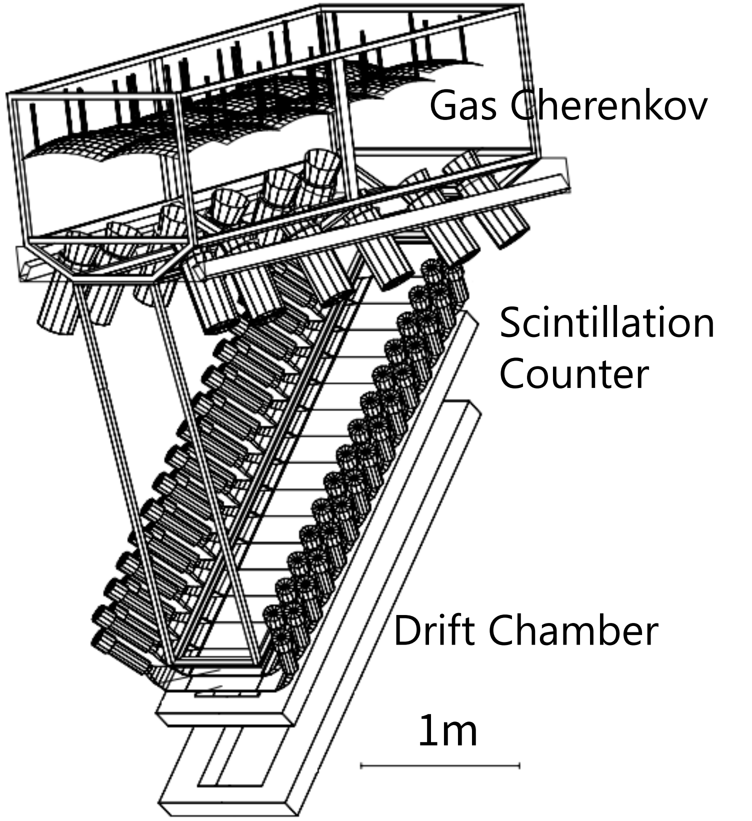
- Spek-A and -C as pion spectrometers
- Kaos as Kaon tagger
- Tilted ^{9}Be target (0.125 mm thick)



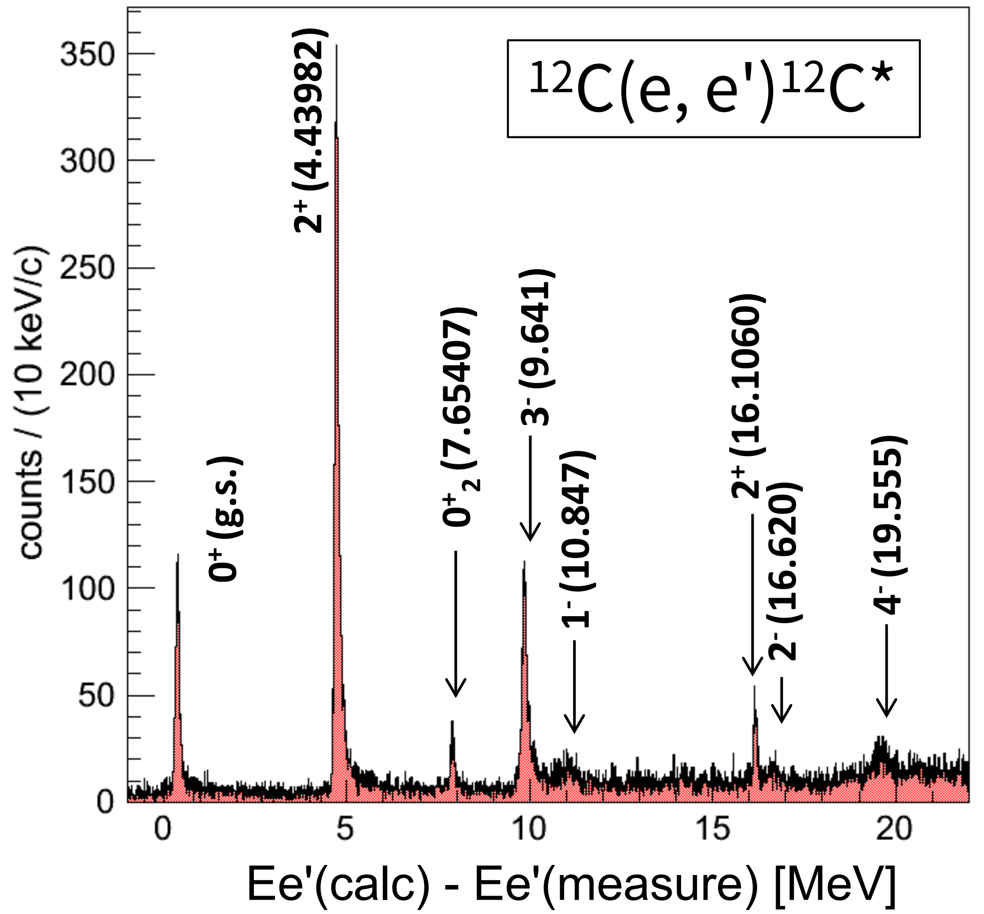
Decay Pion Spectrometer (Spek-A, -C)

Solid Angle = 28 msr
Resolution = 10^{-4}
Arm ≃ 10m



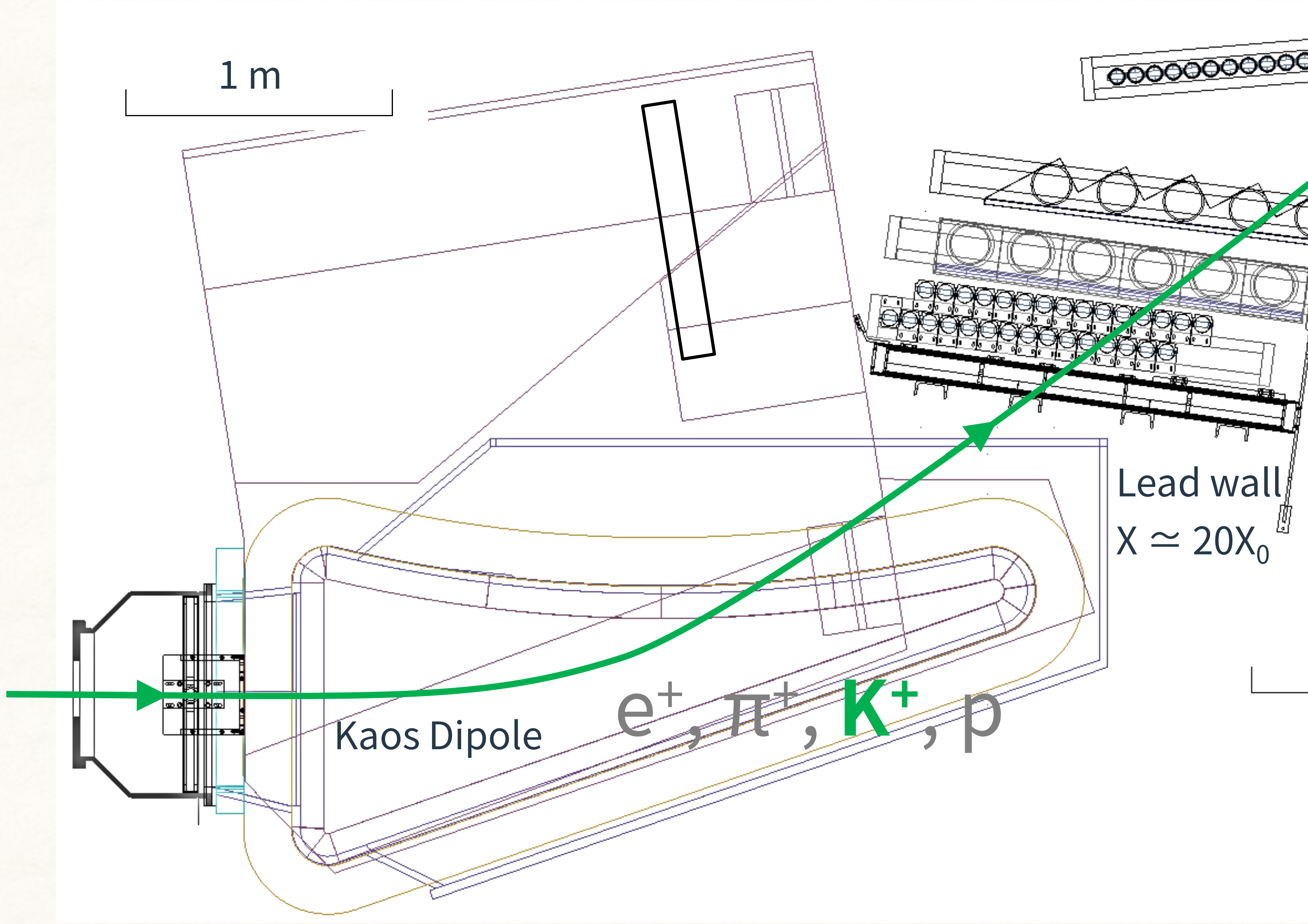


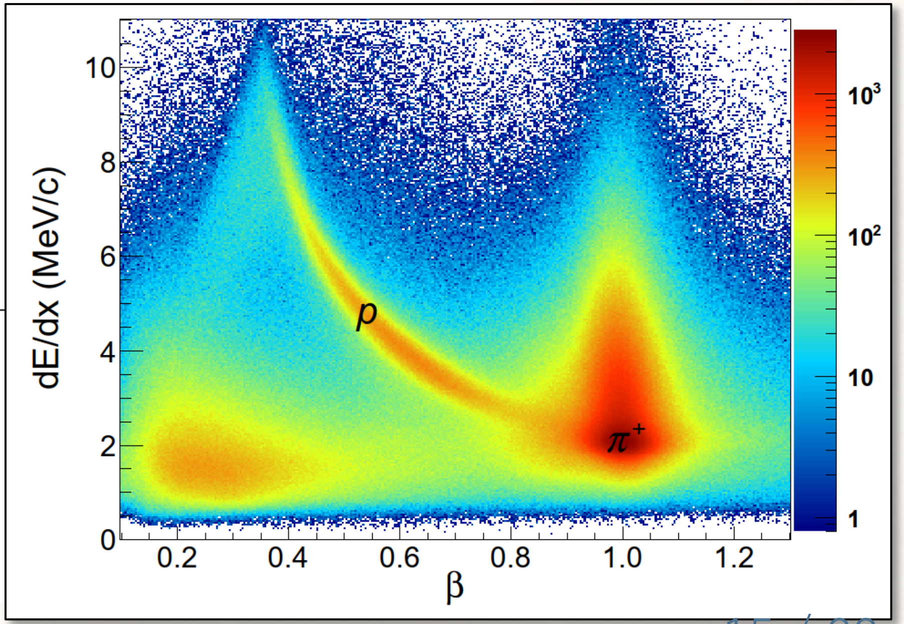
$$E_{e'} = \frac{E_e}{1 + E_e/M_{tar}(1 - \cos\theta_e)}$$



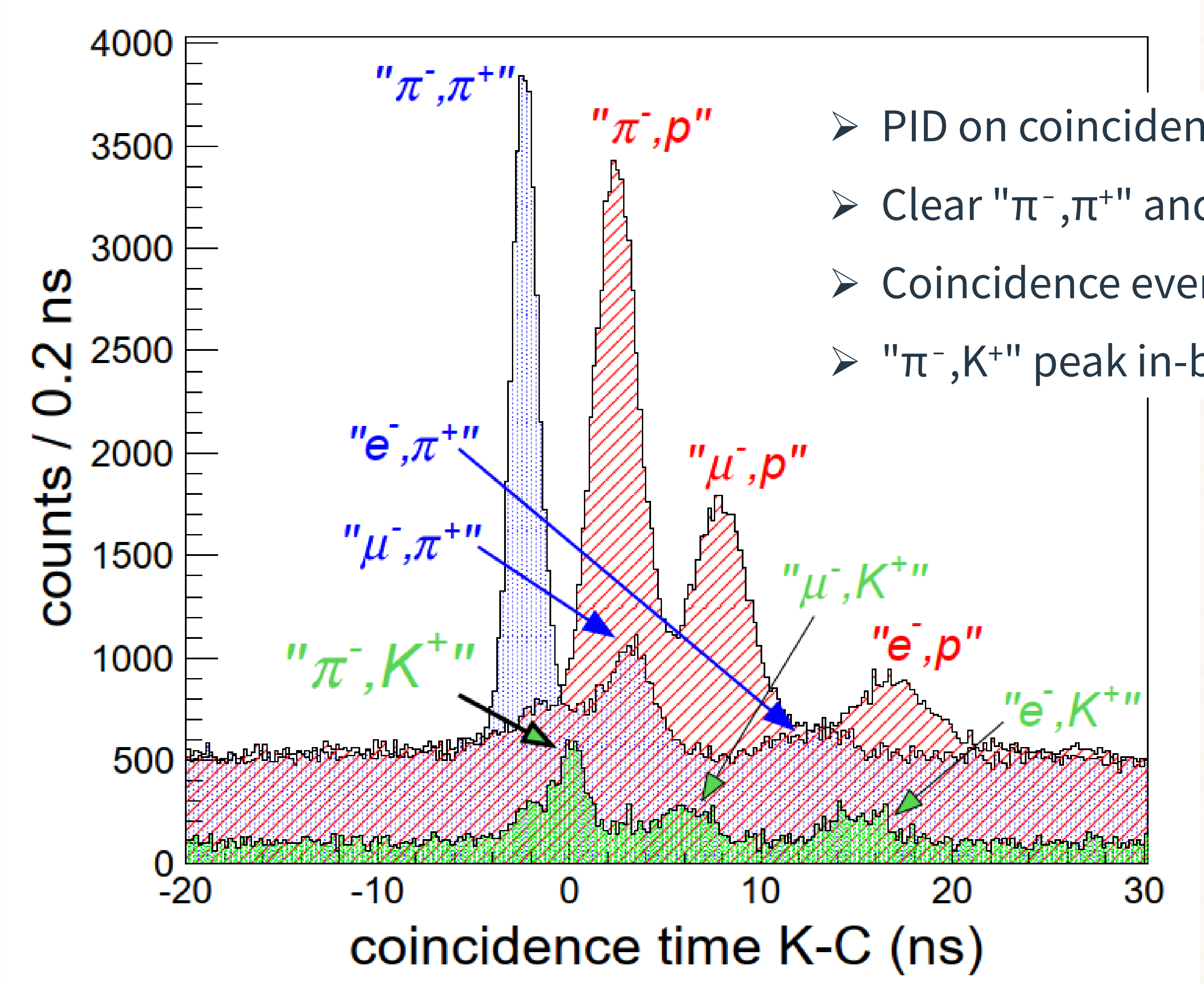
- High-resolution spectrometers
- Momentum calibration with elastic-scattered electrons
- 0.1 MeV/c accuracy ← uncertainty of E_e

Kaon Tagger (Kaos)



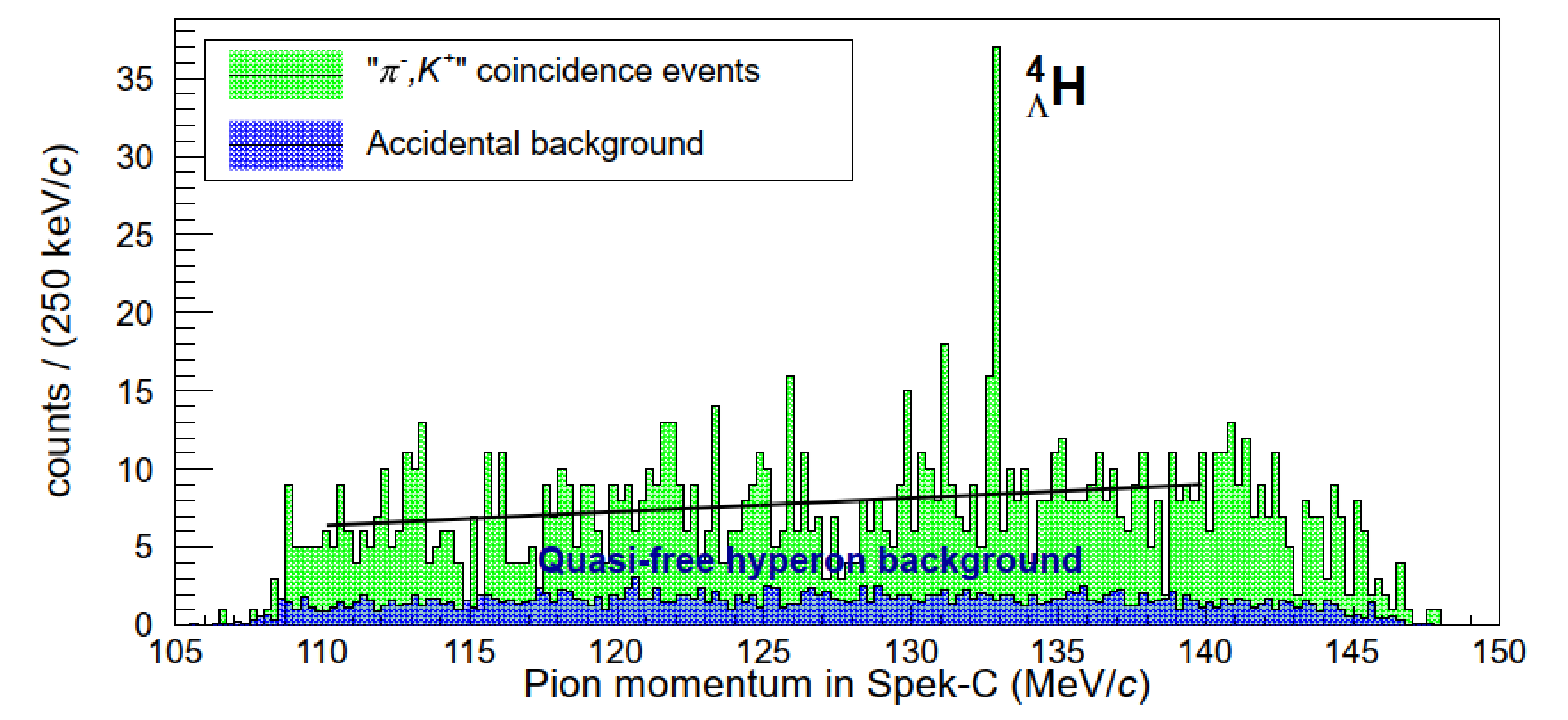


PID on coincidence time spectrum



- PID on coincidence time at the target between Kaos & Spek-A, -C
- Clear "π^-,π^+" and "π^-,p" coincidence peak with PID cuts of Kaos
- Coincidence events with μ^- and e^-
- "π^-,K^+" peak in-between

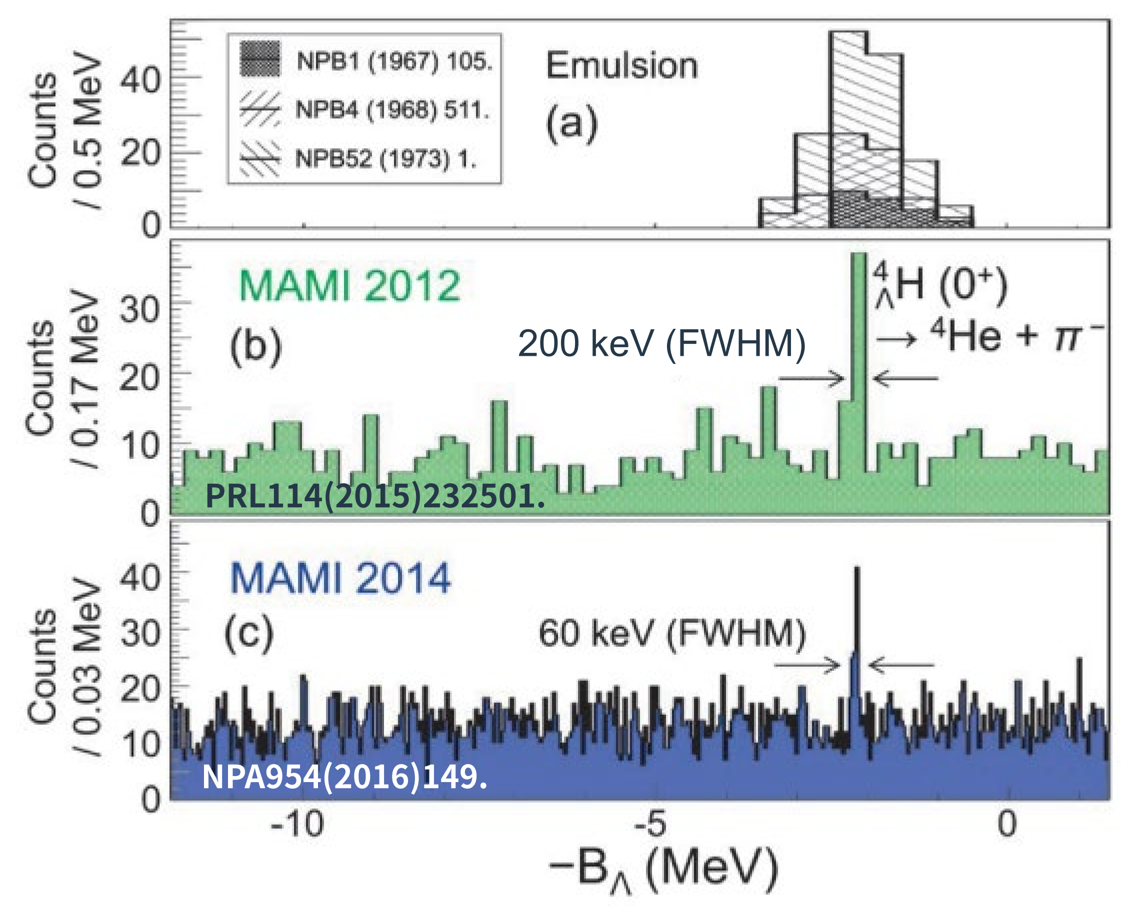
Pion Momentum Distribution (MAMI)

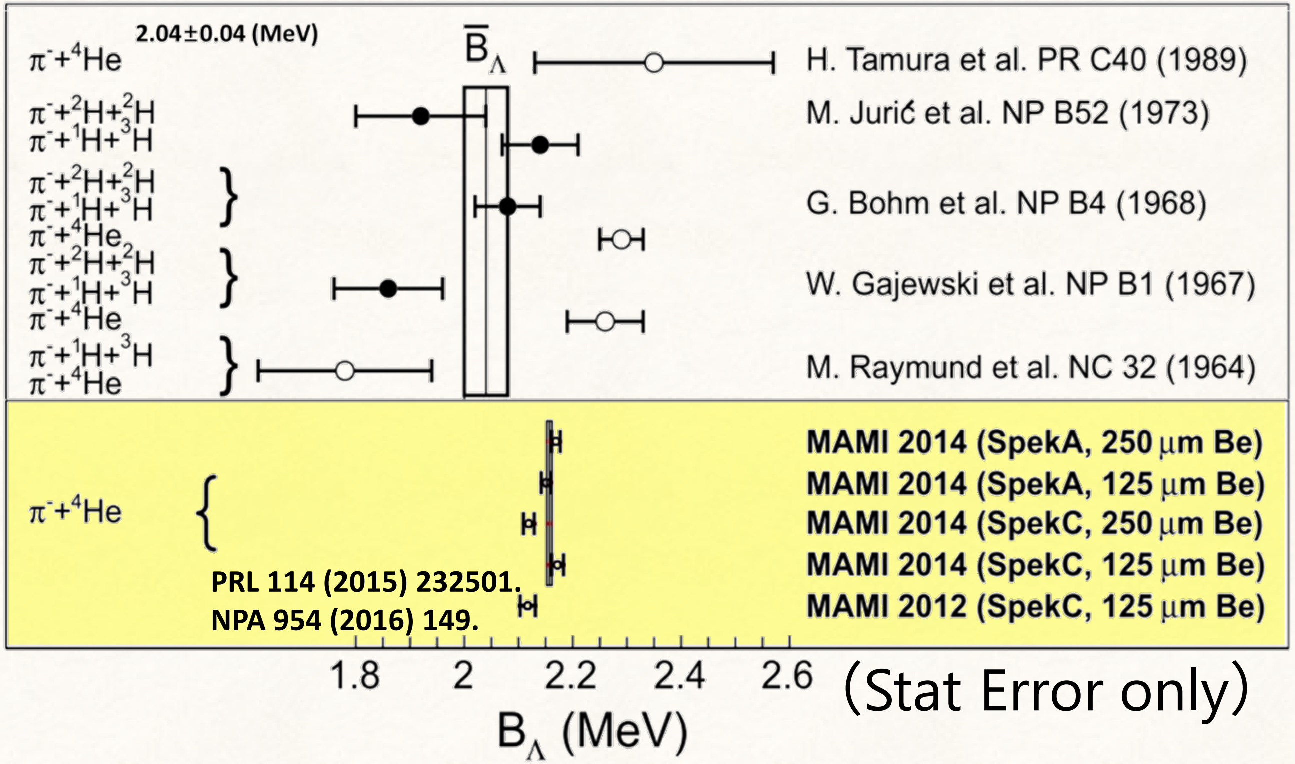


Latest results of $^{4}_{\Lambda}H$

$$B_\Lambda\ (\text{MAMI 2012}) = 2.12 \pm 0.01 \pm 0.09\ (\text{MeV})$$
$$B_\Lambda\ (\text{MAMI 2014}) = 2.157 \pm 0.005 \pm 0.077\ (\text{MeV})$$

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





(Stat Error only)

Decay Pion Spectroscopy @ JLab

LOI12-23-011
High-resolution spectroscopy
of light hypernuclei with the decay-pion spectroscopy

> 30 times hypernuclear yields per unit time
<10 keV systematics

Motivation

Good B_Λ determination of ${}^{4}_{\Lambda}H$ at the MAMI experiments

Expecting a new determination for ${}^{3}_{\Lambda}H$ with the Li target experiment

~1/10 yields of decay-pions from other A>4 hypernuclei

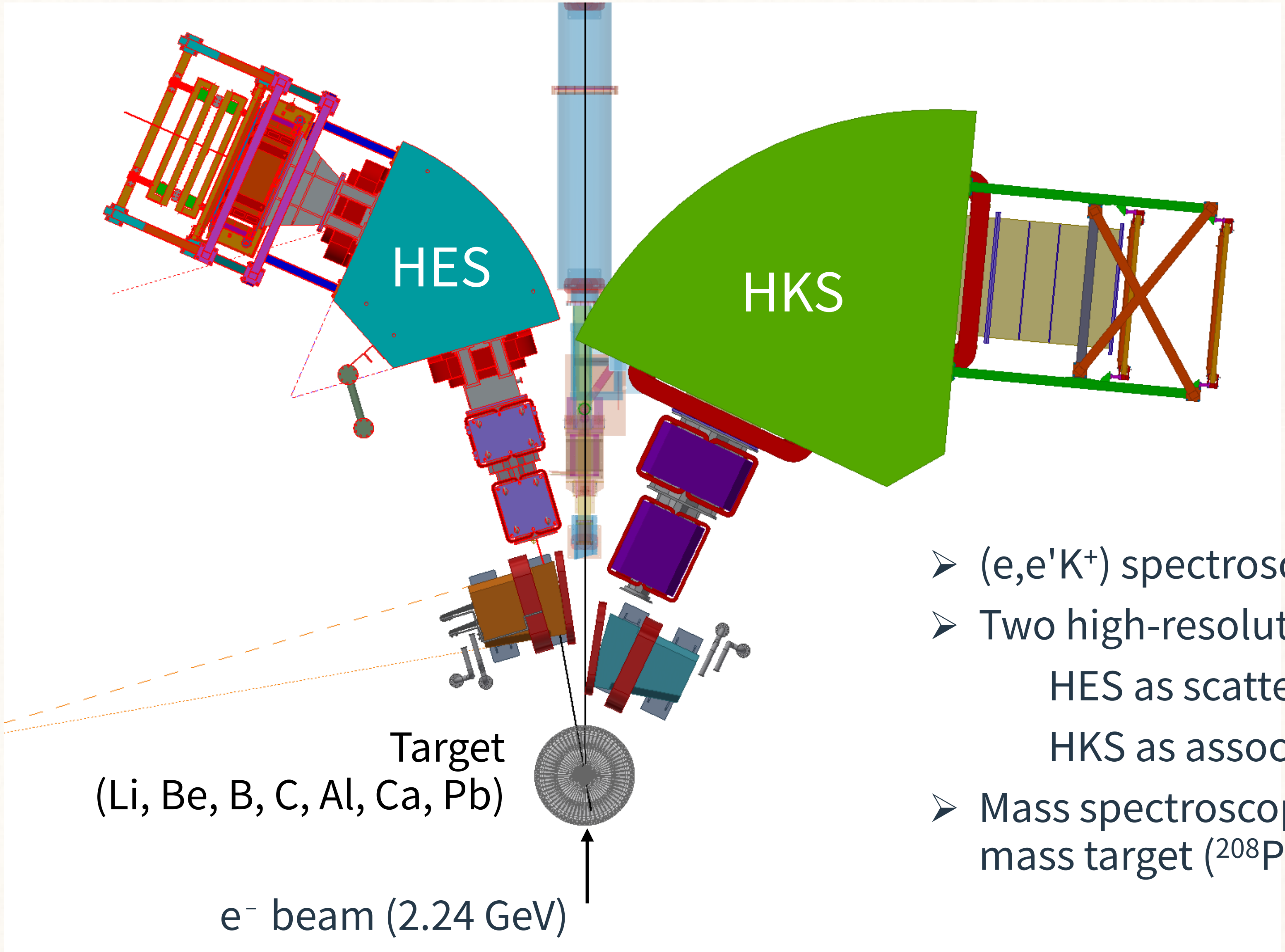
Needs of experiments with much higher statistics

Limitation of .....

- K^+ identification
- DAQ rate
- Does level in the Hall

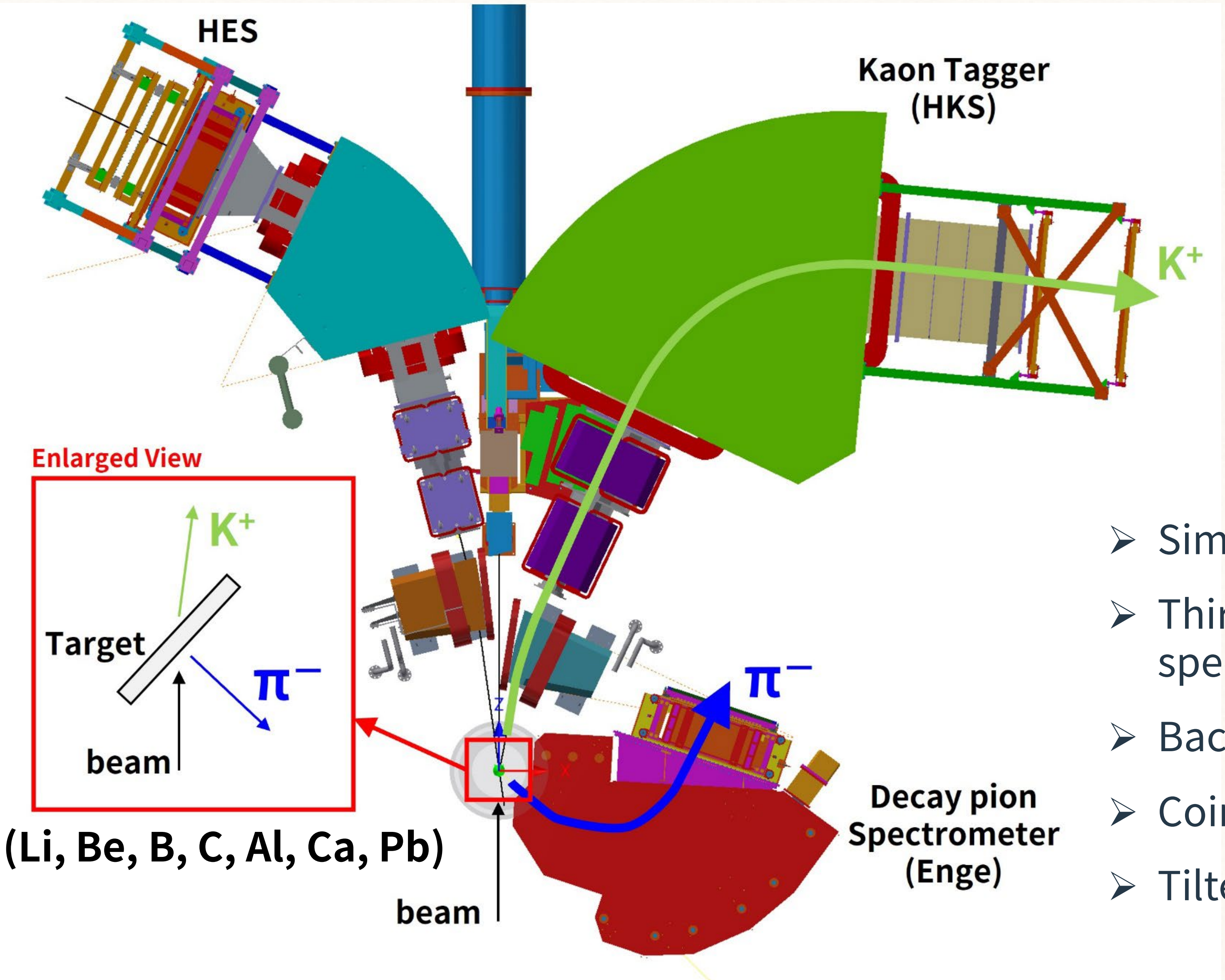
→ DPS at JLab

(e,e'K$^+$) spectroscopy at JLab (E12-15-008, E12-20-013)



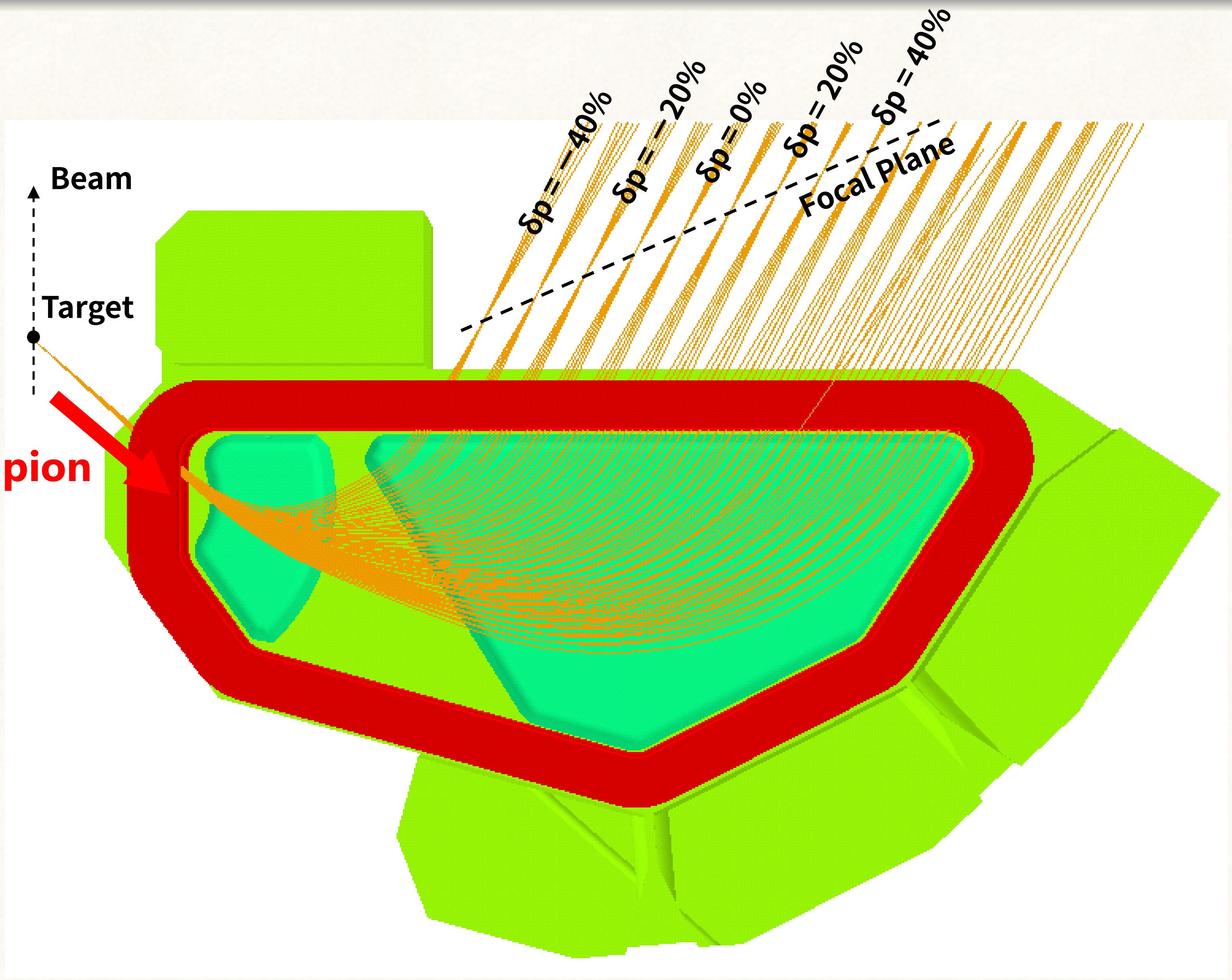
- (e,e'K$^+$) spectroscopies at JLab Hall-C
- Two high-resolution spectrometers
  - HES as scattered electrons
  - HKS as associated Kaons
- Mass spectroscopies of a light-mass target (^{6}Li) to a heavy-mass target (^{208}Pb)

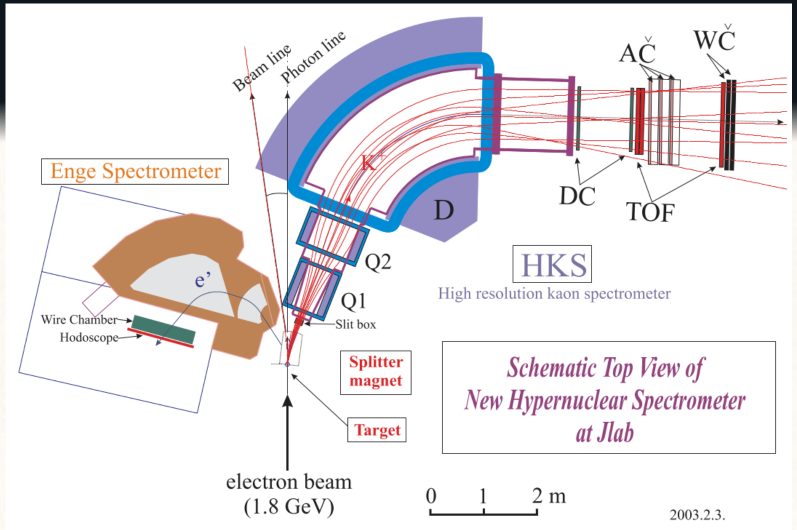
Additional pion spectrometer Enge



- Similar concept to MAMI exp.
- Third spectrometer (Enge) as a decay-pion spectrometer
- Background suppression by tagged K^+
- Coincidence measurement of "π^-, K^+"
- Tilted targets

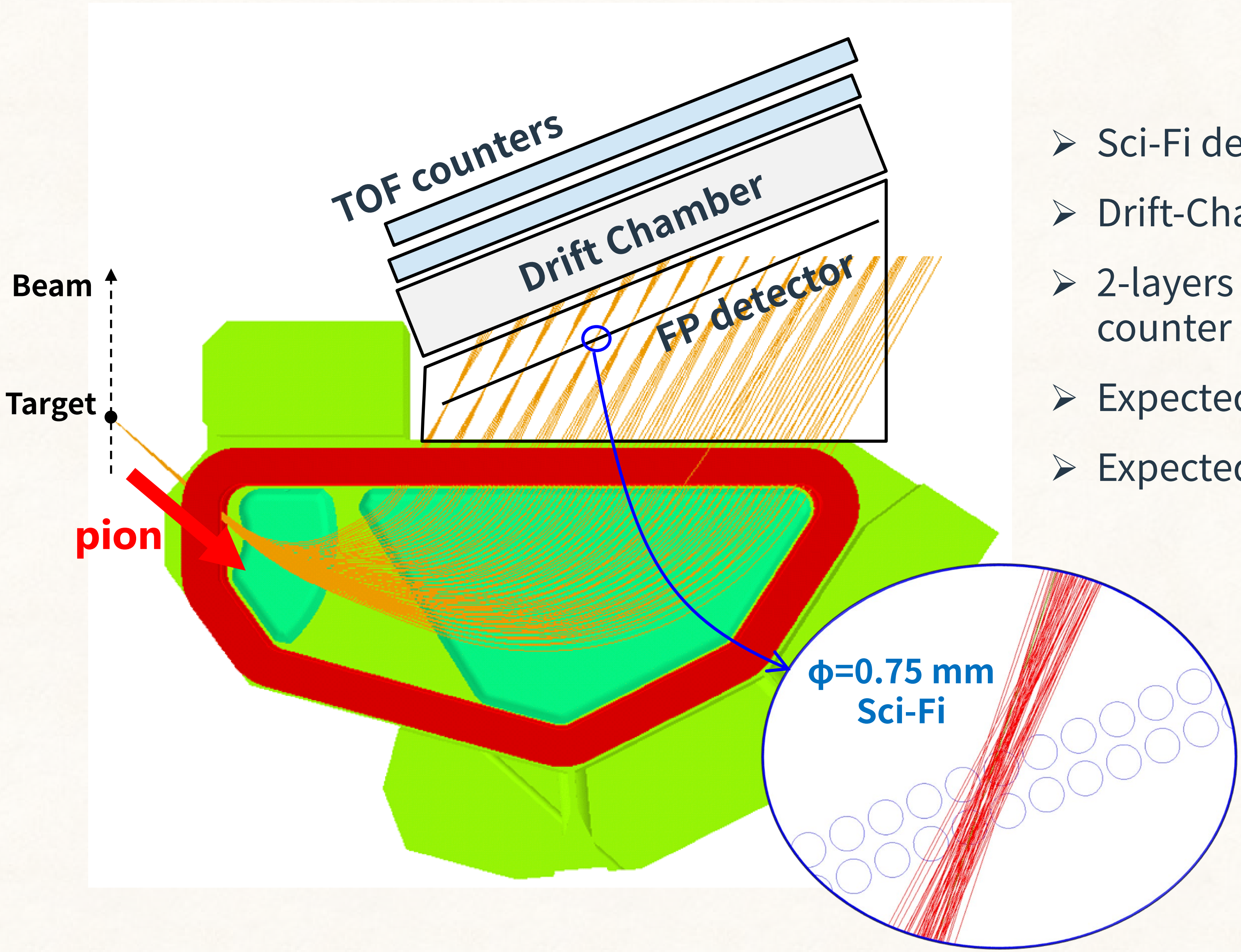
Pion spectrometer





- Split-pole magnet @JLab storage
- Hardware spectrometer
- Position at FP = Momentum
- Good momentum resolution
  $\Delta p/p = 4 \times 10^{-4}$
- Wide momentum bite
  p = 70 - 170 MeV/c
- Dark Spectrometer
  $\Delta\Omega = 4$ msr

Detectors of Enge

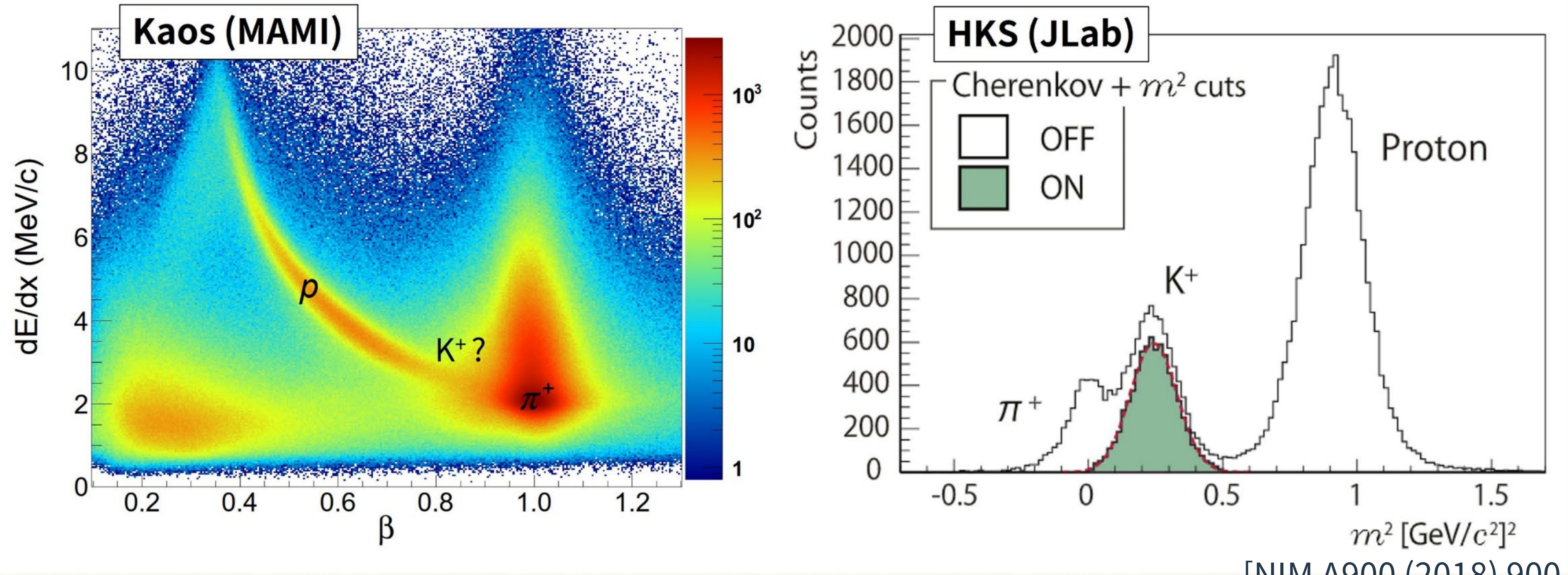


- Sci-Fi detector for momentum measurement
- Drift-Chamber for target reconstruction
- 2-layers of TOF countersfor Trigger and Timing counter
- Expected single-rate: several 10 kHz
- Expected DAQ rate: 100 Hz

Advantage of DPS at JLab

- **Capability of better**
  - Kaon Identification of HKS detectors (2-layers AC → 3-layers AC & 2-layers WC)
  - DAQ Max. Rate (several 100 Hz → several kHz) & Does Limit

    Higher beam current (20 → 50 μA) & Thicker target (40 → 150 mg/cm^2) → ×9 Gain Factor



[NIM A900 (2018) 900.]

Advantage of DPS at JLab

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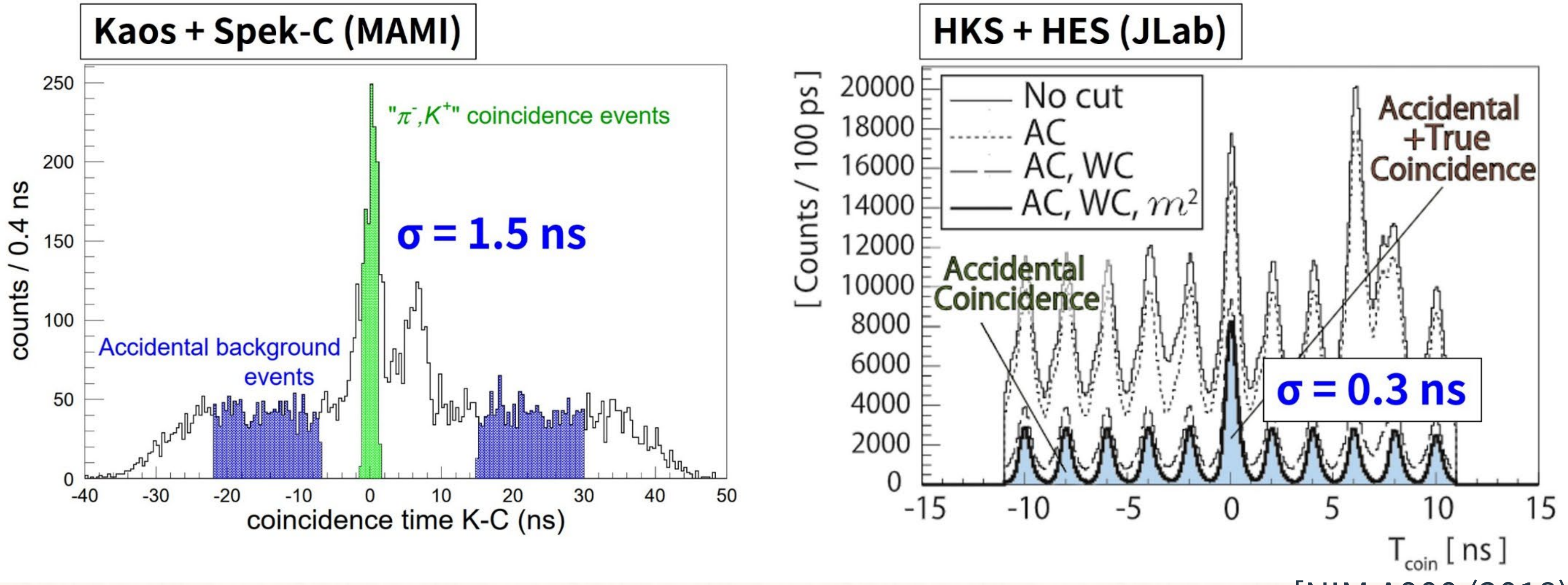

[NIM A900 (2018) 900.]

Advantage of DPS at JLab

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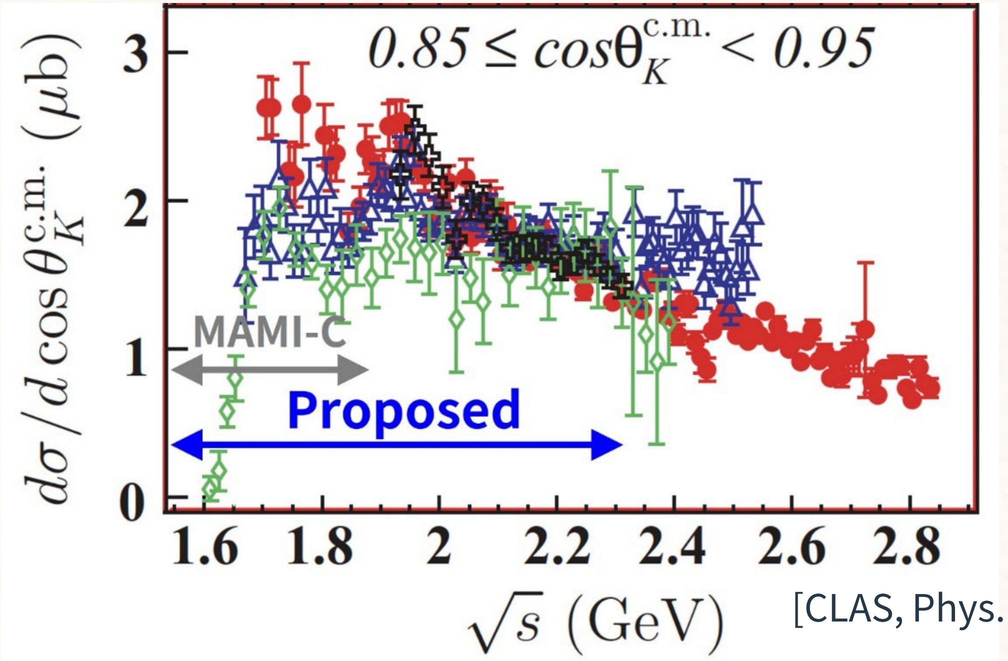
  - DAQ Max. Rate (several 100 Hz → several kHz) & Does Limit
    Higher beam current (20 → 50 μA) & Thicker target (40 → 150 mg/cm^2) → ×9 Gain Factor
- **Higher beam energy**
  - Increasing no. virtual photons associated Λ production (×5 Gain Factor)



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

Advantage of DPS at JLab

➢ Capability of better

- Kaon Identification of HKS detectors (2-layers AC → 3-layers AC & 2-layers WC)
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  Higher beam current (20 → 50 μA) & Thicker target (40 → 150 mg/cm^2) → ×9 Gain Factor

➢ Higher beam energy

- Increasing no. virtual photons associated Λ production (×5 Gain Factor)

➢ Data taking with several targets (Li ~ Pb)

- Parallel experiment with proposed (e,e'K$^+$)
- Identification of parent hypernucleus

➢ Off-beam momentum calibration

- Momentum calibration with α-sources

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)

Advantage of DPS at JLab

- **Capability of better**
  - Kaon Identification of HKS detectors (2-layers AC → 3-layers AC & 2-layers WC)
  - DAQ Max. Rate (several 100 Hz → several kHz) & Does Limit
    Higher beam current (20 → 50 μA) & Thicker target (40 → 150 mg/cm^2) → ×9 Gain Factor
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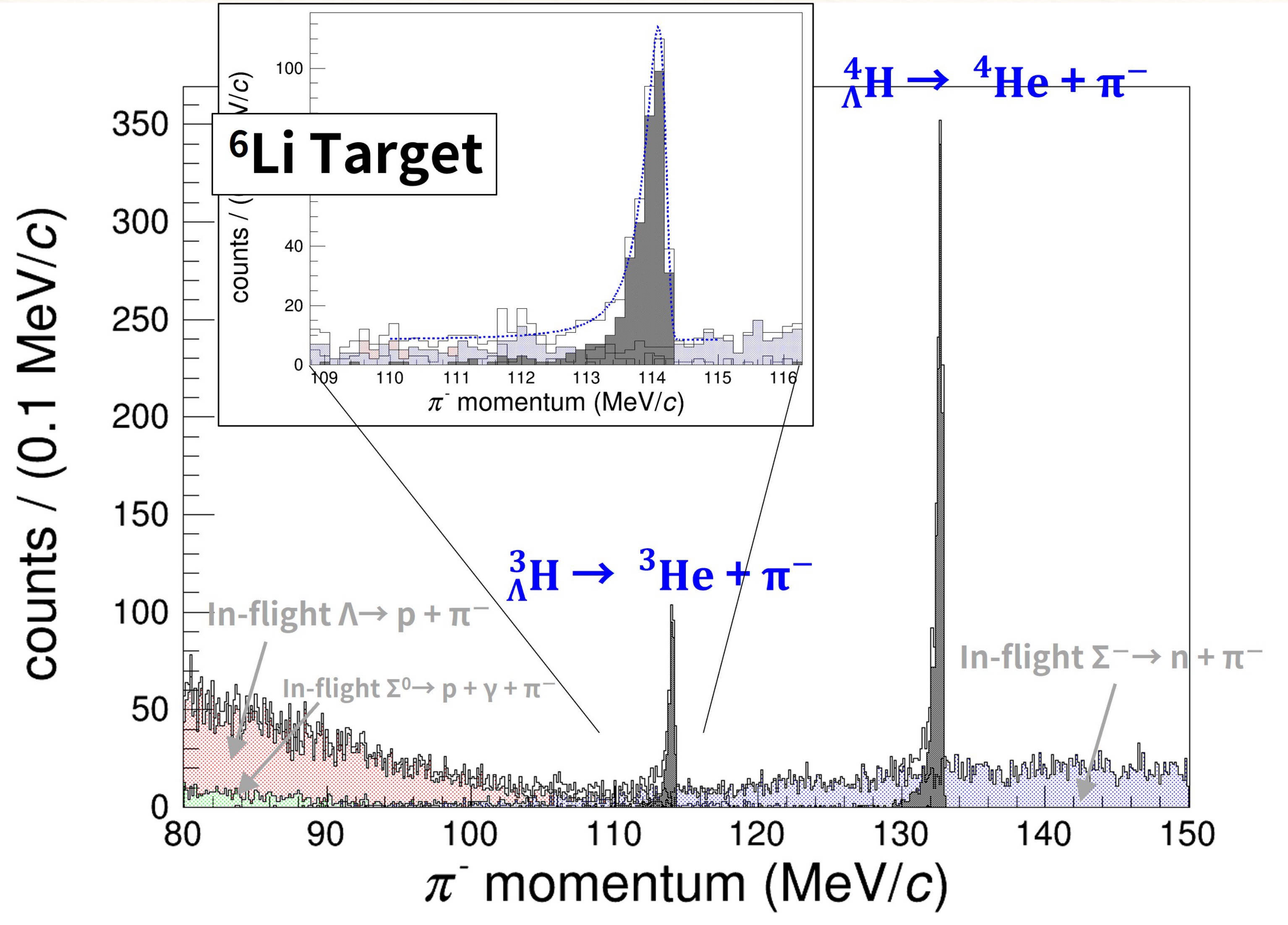
^{244}Cm	5.76270(3), 5.80482(5)	103.6734(3), 104.0519(4)

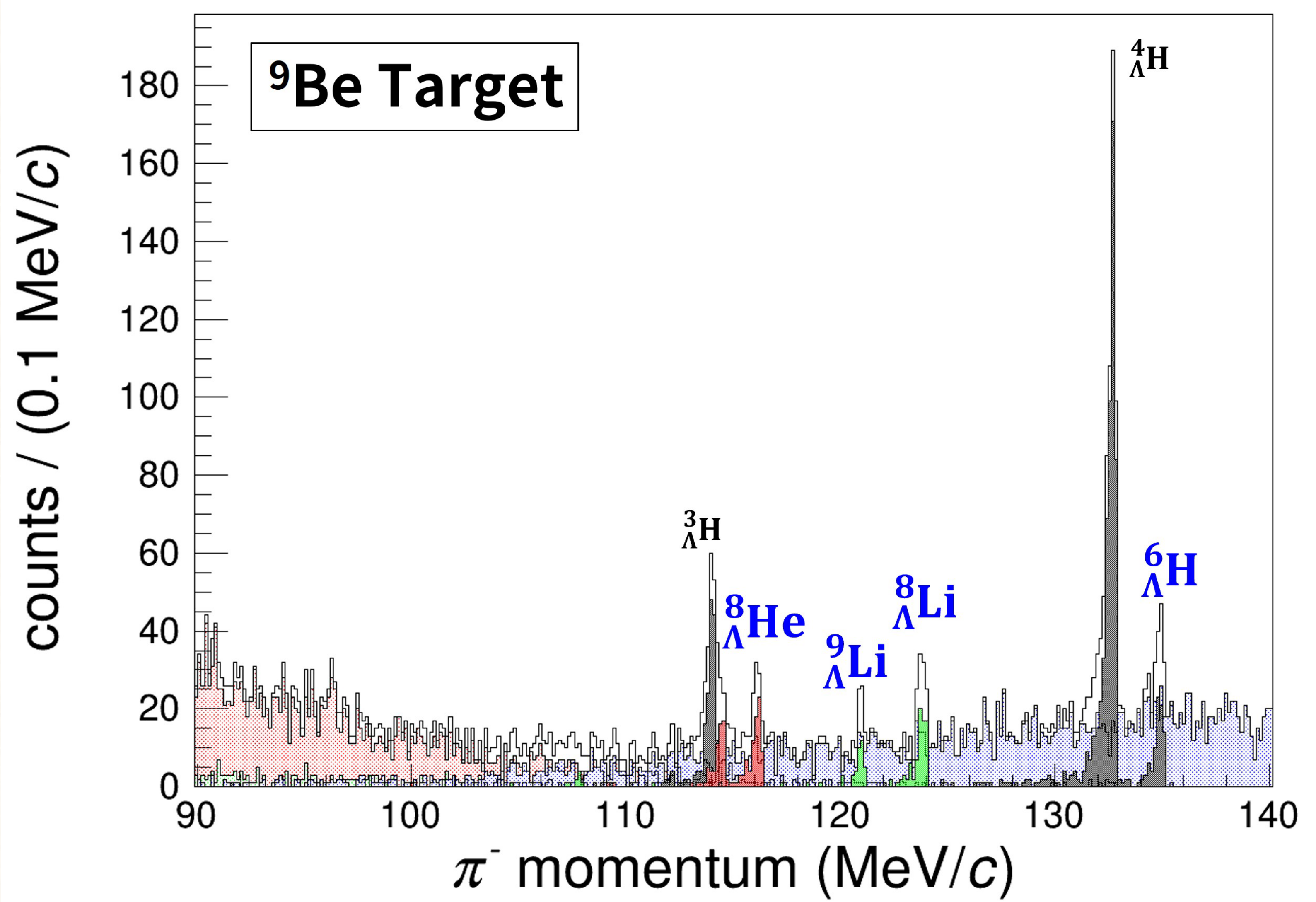
> 30 times hypernuclear yields per unit time

<10 keV systematics

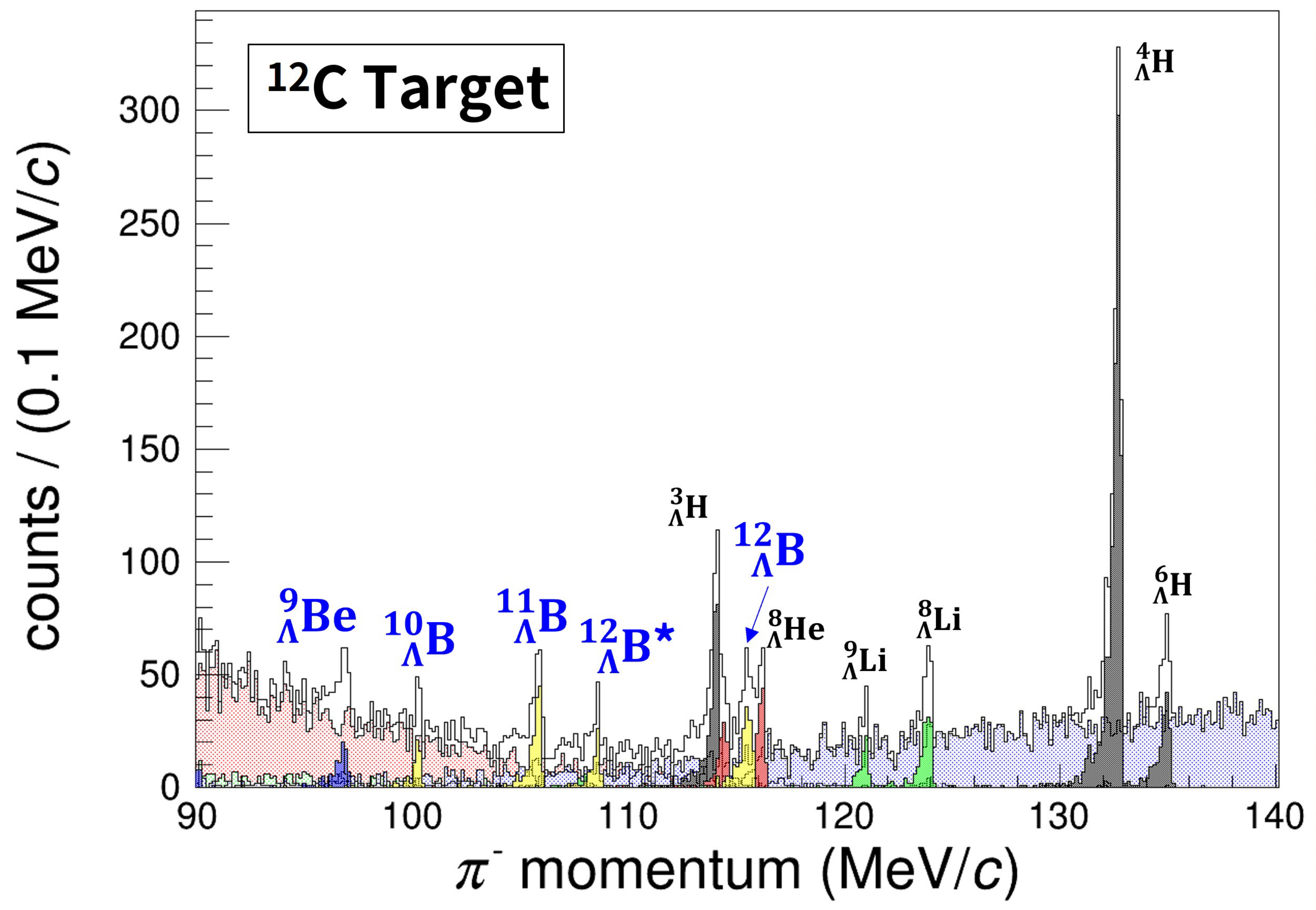
Expected (^{6}Li target)



Expected (^{9}Be target)



Expected (^{12}C target)



Summary

- **Λ binding energies measurement with the decay pion spectroscopy**

  DPS started and has developed at MAMI Mainz

  First observation of decay-pion from $^{4}_{\Lambda}$H

  $B_{\Lambda}(^{4}_{\Lambda}\text{H g.s}) = 2.157 \pm 0.005 \pm 0.077$ (MeV) from MAMI2014

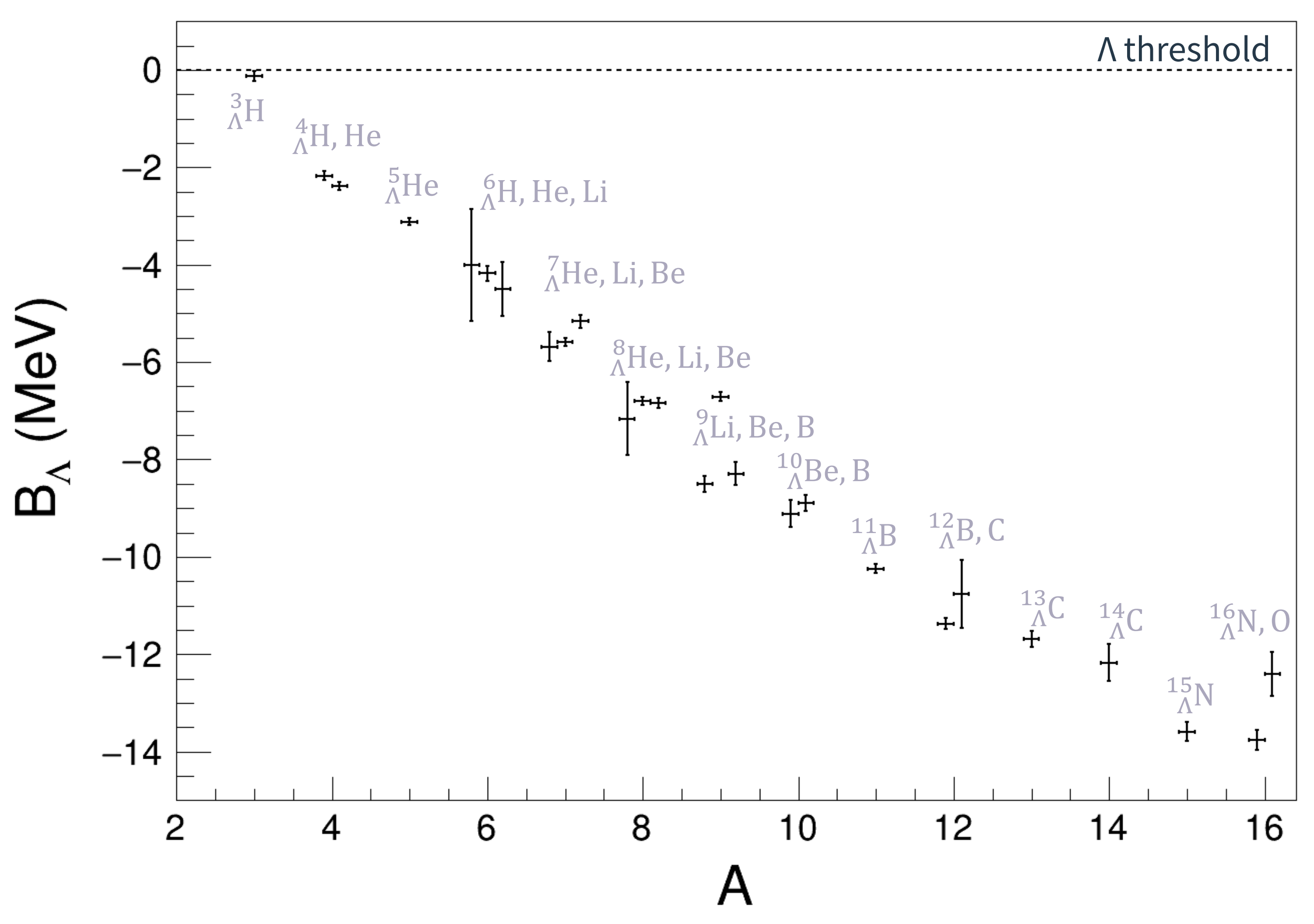
- **New stage of the decay pion spectroscopy at JLab (LOI12-23-011)**

  Parallel experiment with the proposed (e,e'K^{+}) experiments

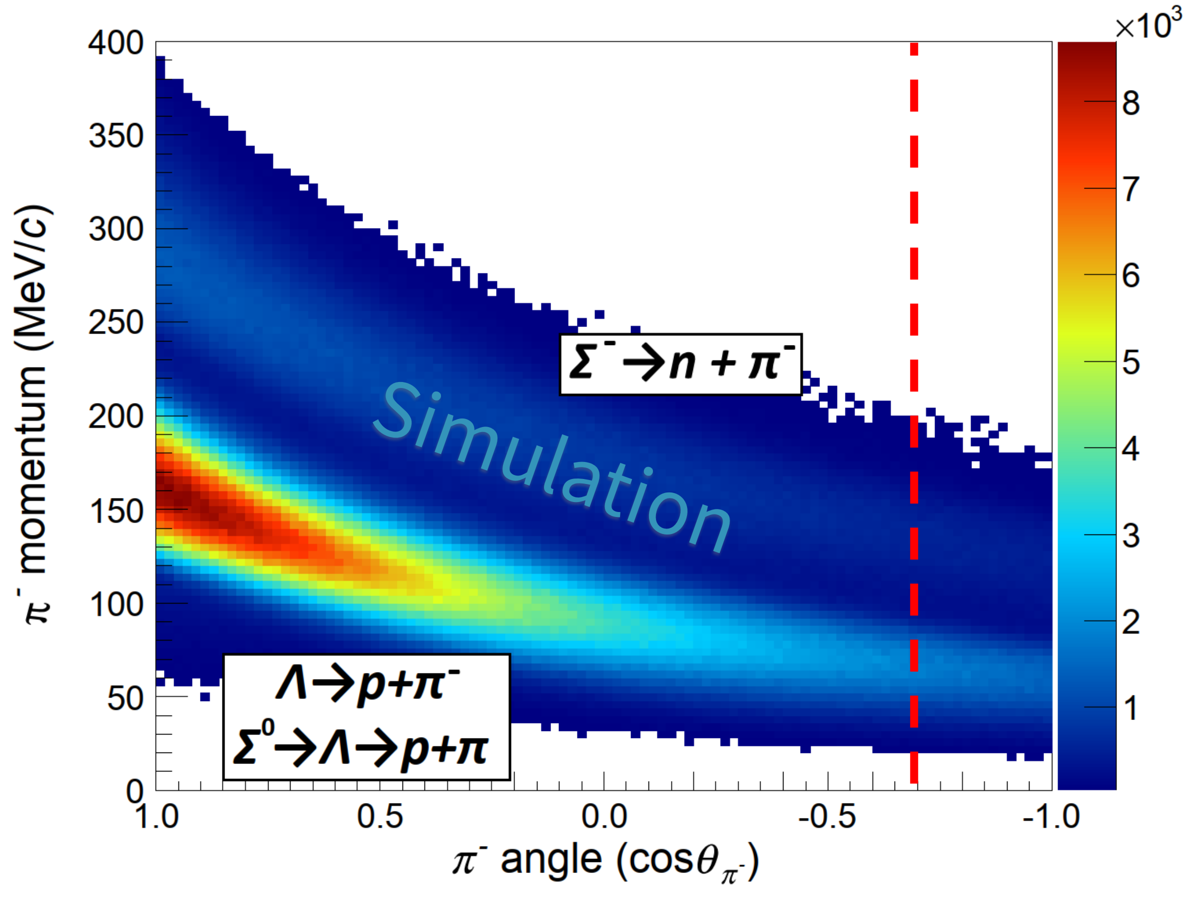
  Third spectrometer Enge as a decay pion spectrometer

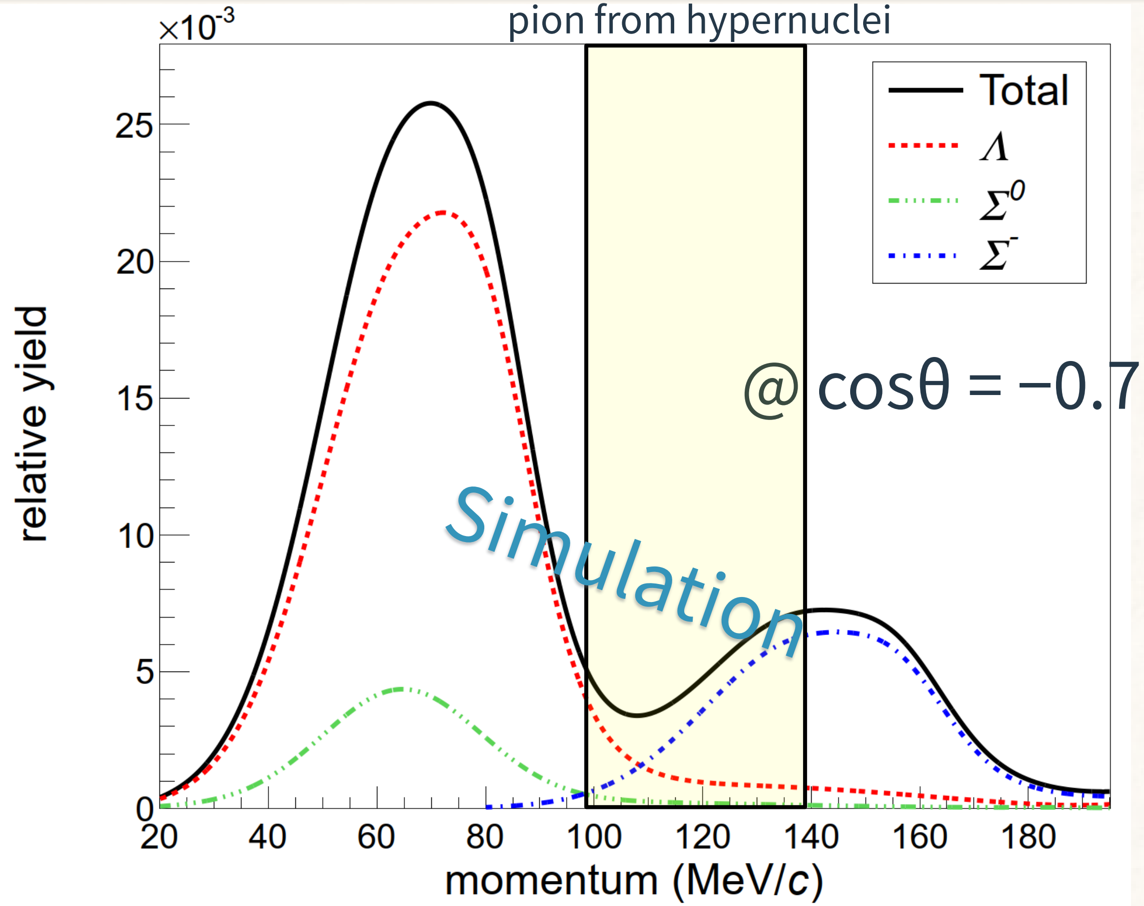
  Expecting much better hypernuclear yield and Excellent accuracy

Λ binding energy of light hypernuclei



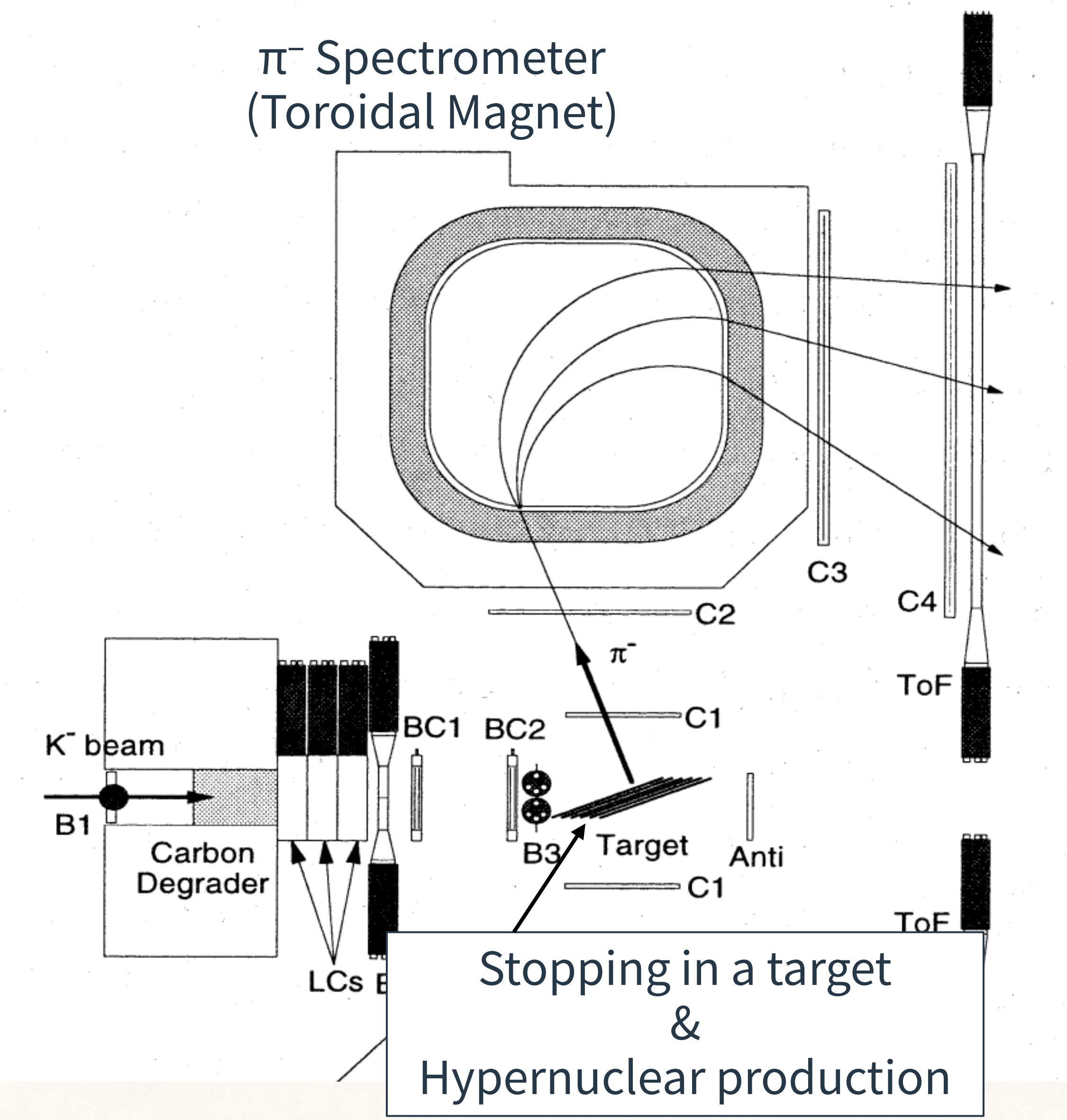
Background sources

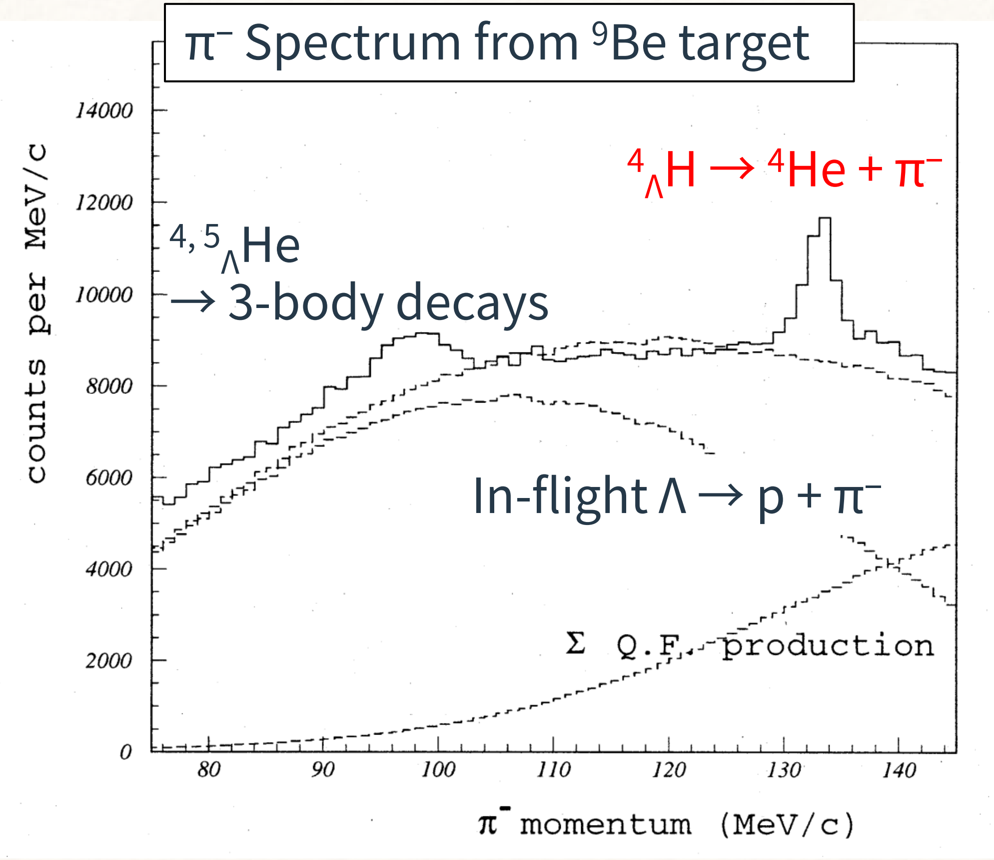




- Major background source of π^- from in-flight hyperon decay, especially from $\Sigma^- \rightarrow n + \pi^-$
- Most of π^- backgrounds go to the forward angles
- Decay pion measurement at the backward angles helps getting better S/N

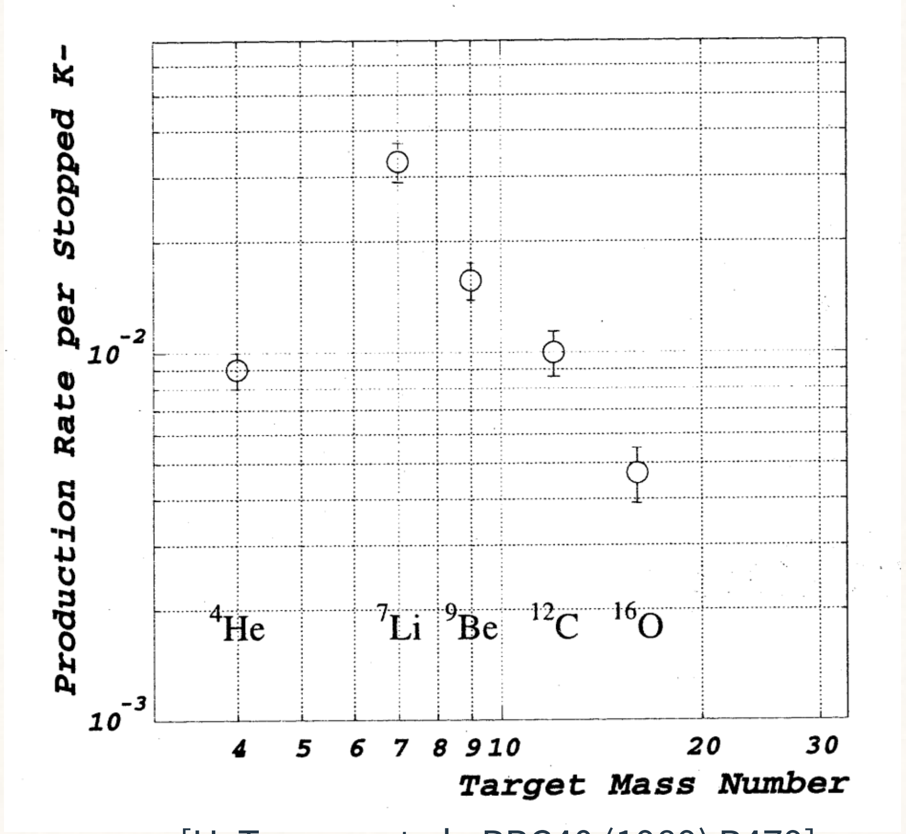
DPS with (K^-_{stop}, π^-) [A. Kawachi Ph.D thesis, U-Tokyo]



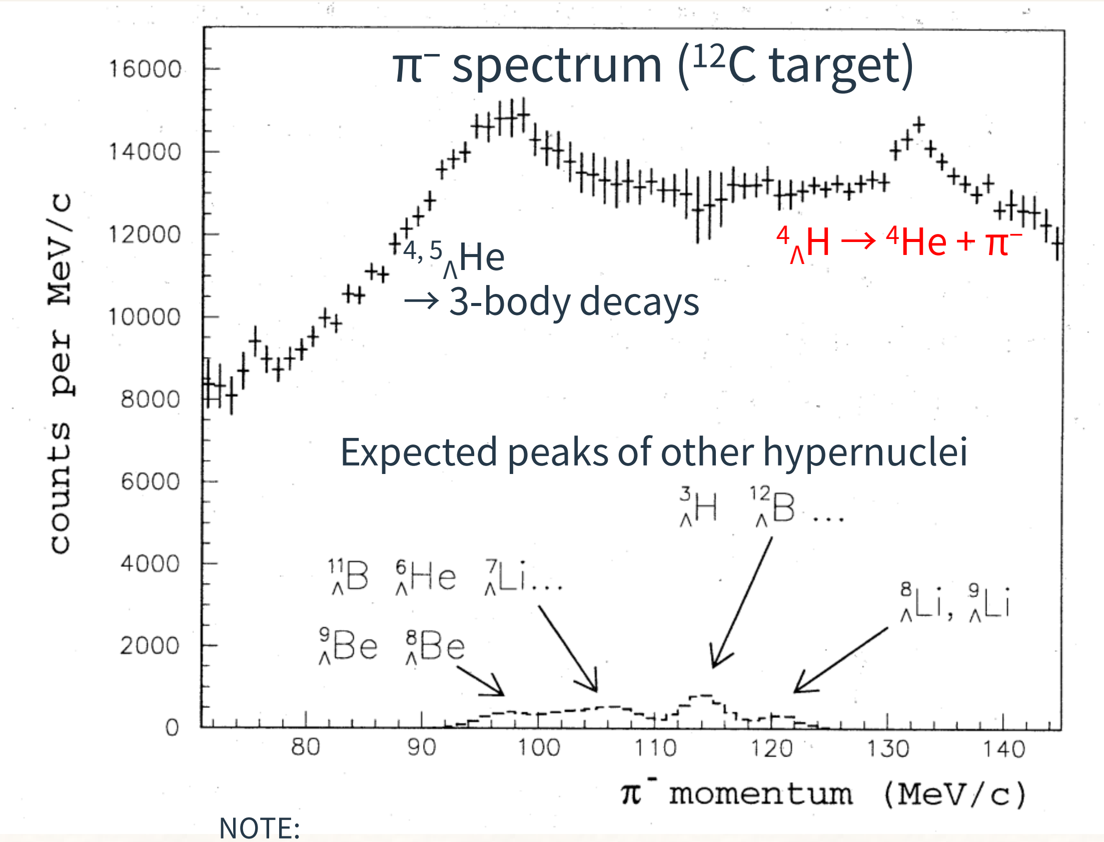


- Observation of 2-body π^- decay peak from ${}^4_\Lambda H$
- Continuum of 3-body decay from ${}_\Lambda He$
- Large π^- background from in-flight Λ

DPS with (K^-_{stop}, π^-) [H. Tamura et al., Phys. Rev. C40 (1989) R479, A. Kawachi Ph.D thesis, U-Tokyo]



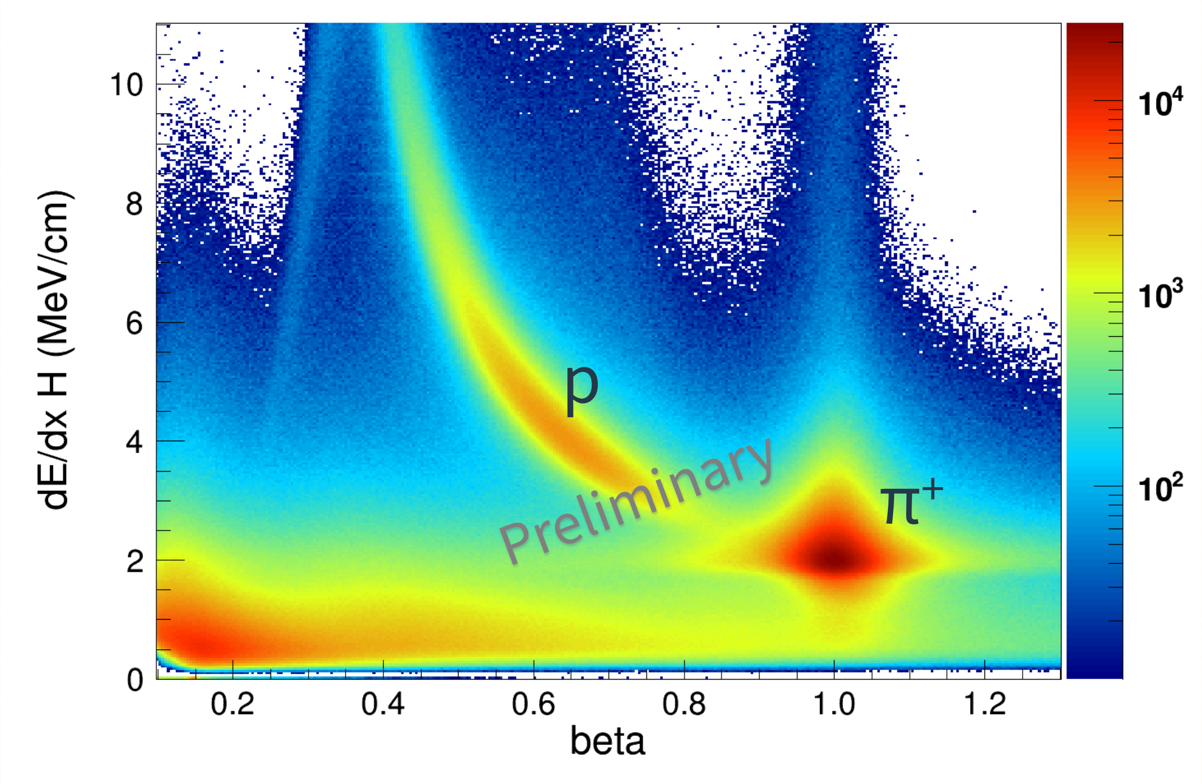
[H. Tamura et al., PRC40 (1989) R479]

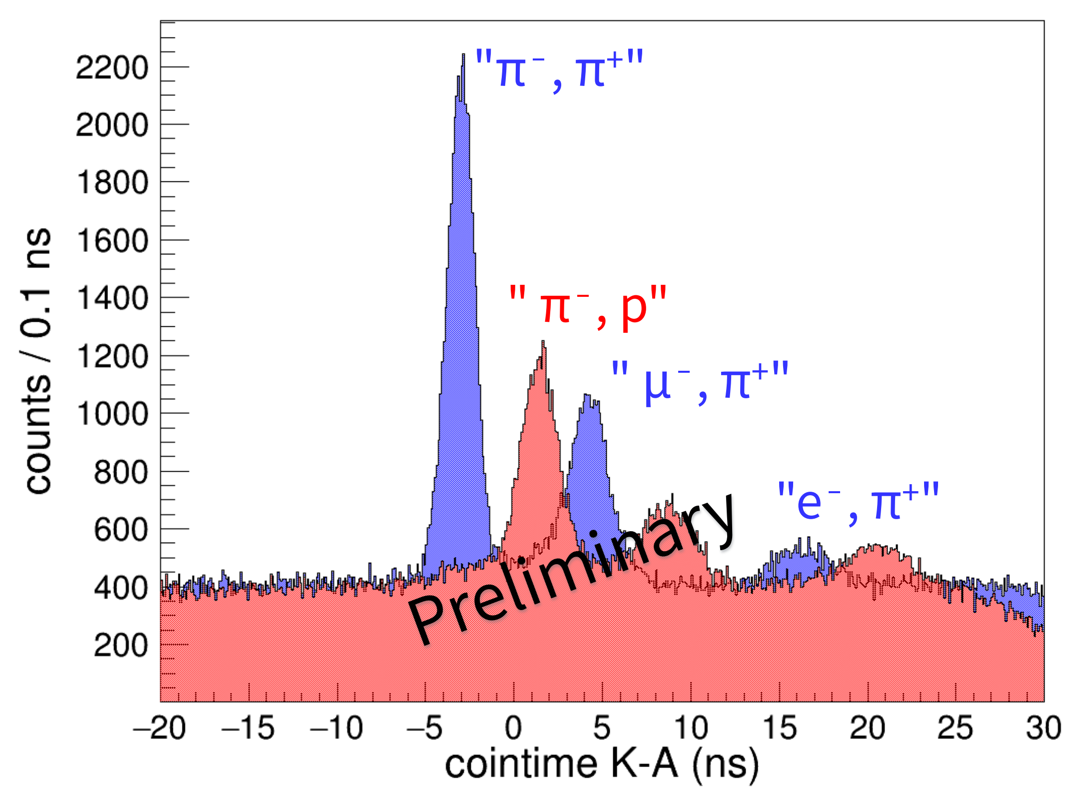


NOTE:
Calculated production rates by AMD calc.
π^- branching ratio by shell model calc [NPA 489 (1988) 683.]

- Target mass dependence on production rate of ${}^4_\Lambda H$
- No peaks from other hypernuclei
- Decay pion peaks from several hypernuclei are expected (several times less than ${}^4_\Lambda H$)
- Background suppression and High-resolution is essential

Preliminary Results of 2022 exp. (New Li target)





- Similar performance to the past experiments
- Better no. coincidence peak
- Good π^+ and p ID in Kaos
- Expecting hypernuclear events between "π^-, π^+" and "π^-, p"

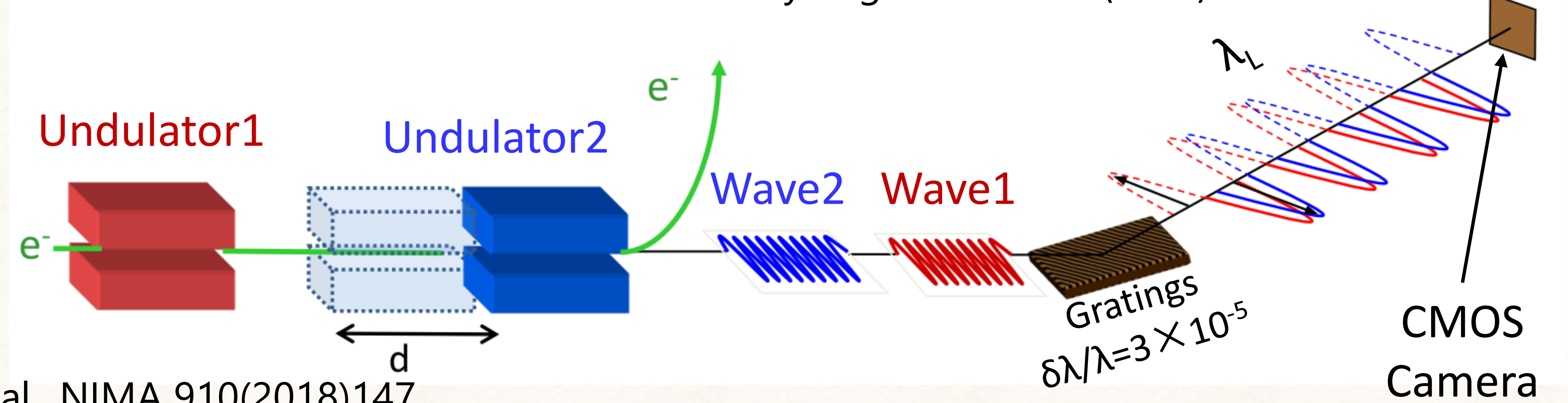
Uncertainties

	Uncertainty
Mag. Field Stability	< 10 keV
Beam Energy in Spec. Calib. run	70 keV
Beam Position	10 keV
Energy Loss Correction	< 10 keV
Total	77 keV

Towarding 10 keV Accuracy

Accuracy of beam energy for elastic-scattering measurement limits our systematics

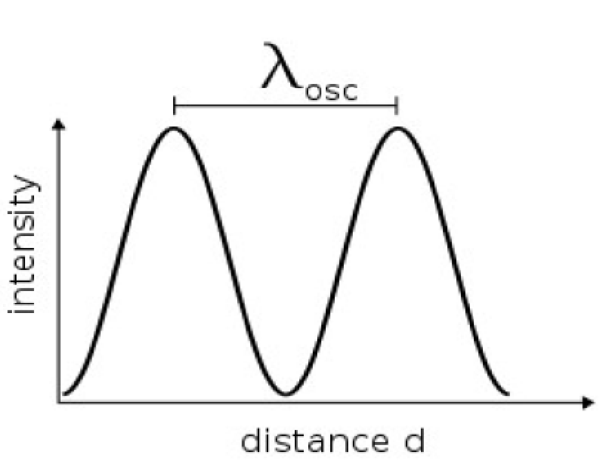
Based on "Novel Interferometer in the Soft X-Ray Region" PRL 80 (1998) 5437.



P. Klag et al., NIMA 910(2018)147.

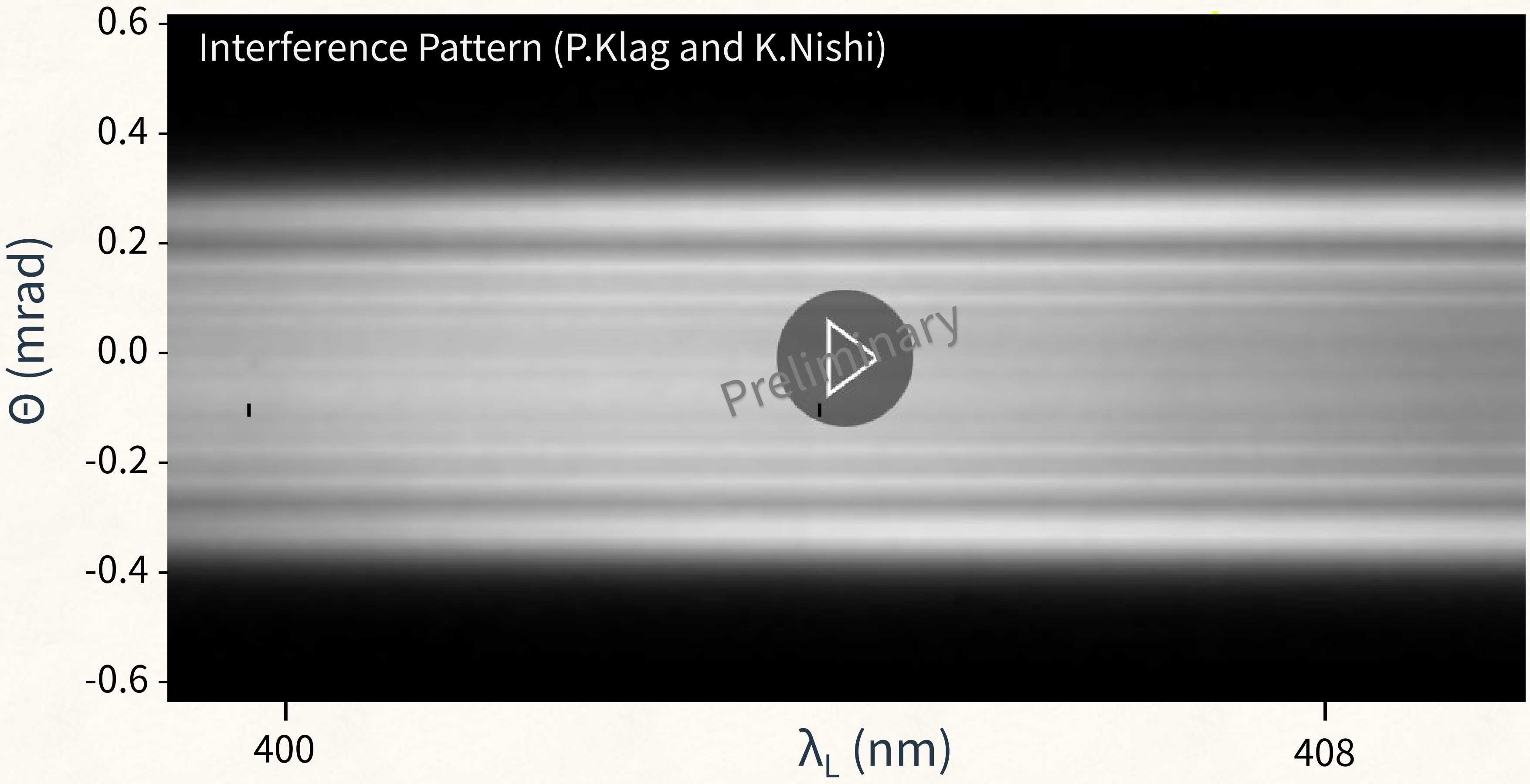
Lorenz factor

$$\gamma = \sqrt{\lambda_{osc}(\Theta)/2\lambda_L}$$

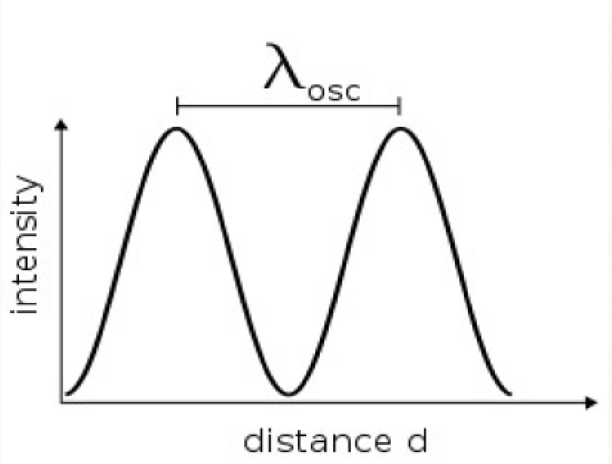


Toward much more Accurate measurement

Accuracy of beam energy for elastic-scattering measurement limits our systematics

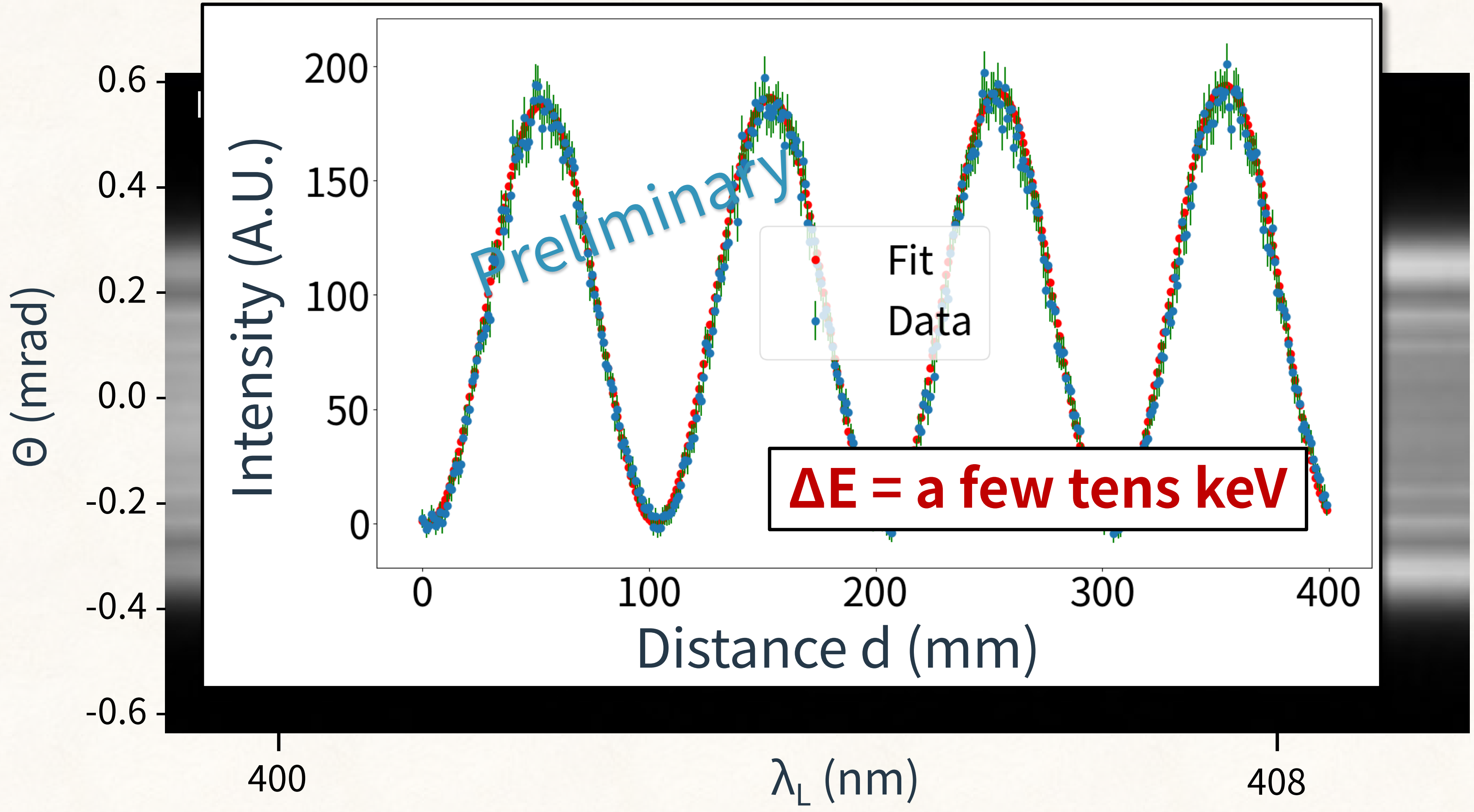


$$\gamma = \sqrt{\lambda_{osc}(\Theta)/2\lambda_L}$$

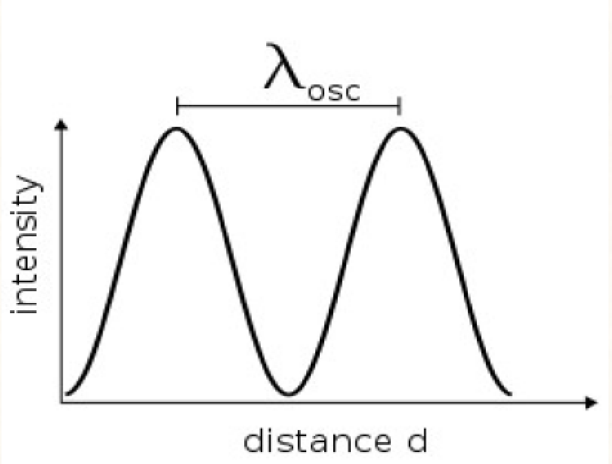


Toward much more Accurate measurement (DPS)

Accuracy of beam energy for elastic-scattering measurement limits our systematics

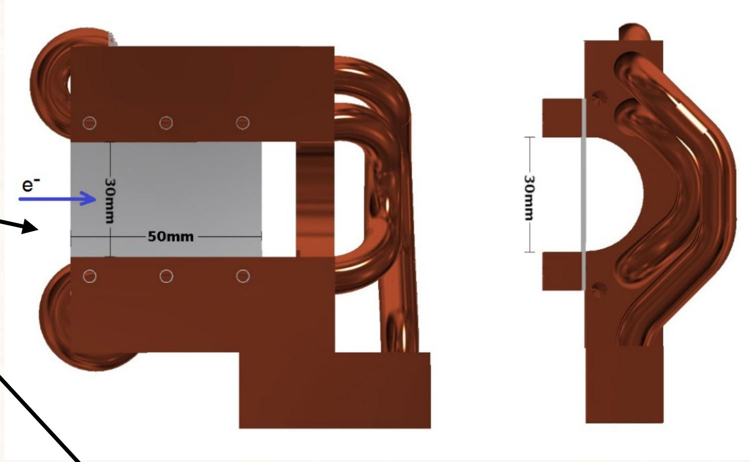


$$\gamma = \sqrt{\lambda_{osc}(\Theta)/2\lambda_L}$$

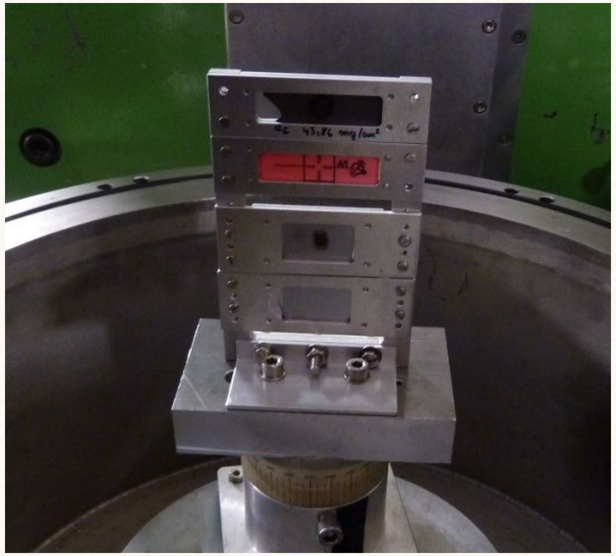


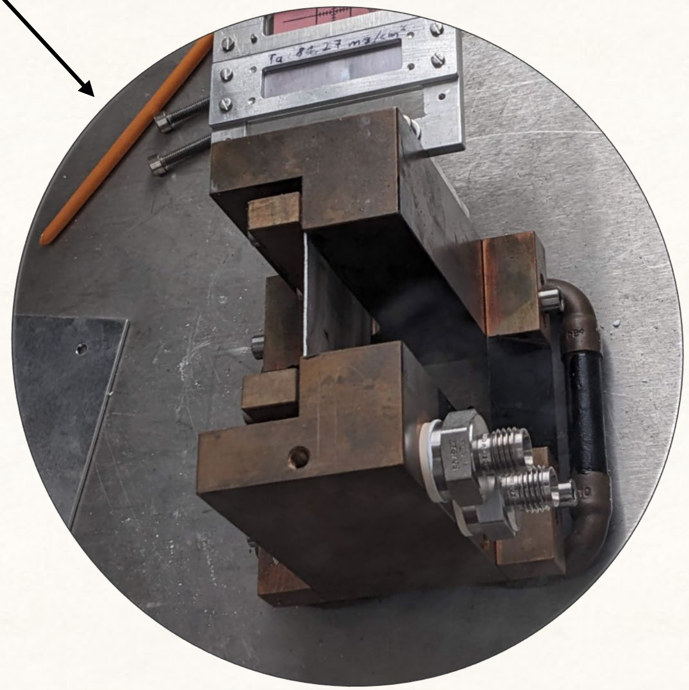
Update experiment for $^{3}_{\Lambda}H$ measurement

New Li Target



↓ OLD ^{9}Be target





- Update experiment with a new Li target
- Better $^{4}_{\Lambda}H$ hypernuclear yield according to (K^{-}_{stop}, π^{-}) experiment
- New 90 deg tilted Li target with a thickness of 2700 mg/cm^2
- Better yield and Lower does level thanks to thick-target and low-current
- Data taking in 2022

Yield Gain summary

Table 5: Hypernuclear yield gain (^{9}Be target).

Item		MAMI	JLab	Yield Gain
Kinematics	Beam Current (μA)	20	50	2.5
	Int. VP Flux (A.U.)	2.9	13.5	4.7
	Thickness (mg/cm^2)	39	150	3.7
	$^{4}_{\Lambda}$H Stop. Prob. (%)	42	81	1.9
	$^{4}_{\Lambda}$H Form. Prob. (%)	1	1	1.0
	Sub Total			**81**
K^+ Tagger	Solid Angle (msr)	17	8.3	0.49
	Survival Ratio (%)	40	30	0.74
	K^+ ID Eff. (%)	48	81	1.7
	Lead-wall Eff. (%)	50	100	2
	Sub Total			**1.2**
π^- Spec.	Solid Angle (msr)	28	4	0.14
	Survival Ratio (%)	32	51	1.6
	π^- ID Eff. (%)	90	90	1.0
	Sub Total			**0.23**
Others	CoinTime Eff. (%)	68	90	1.3
	DAQ Eff. (%)	87	90	1.0
Total				**31**