High-resolution hypernuclear decay pion spectroscopy at MAMI and future

Contents

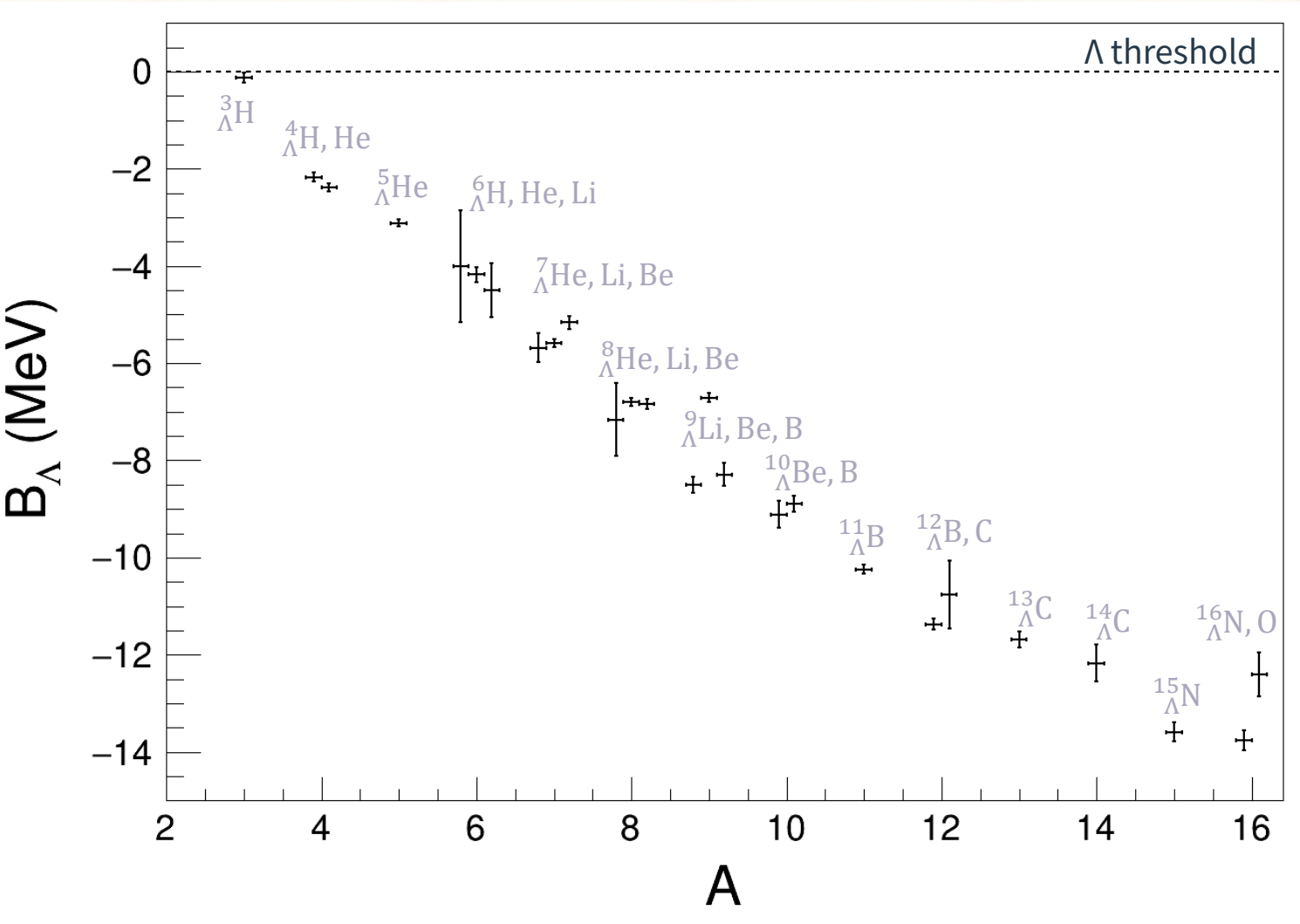
- Principle, Status, Future of the Decay Pion Spectroscopy
  - at MAMI
  - at JLab

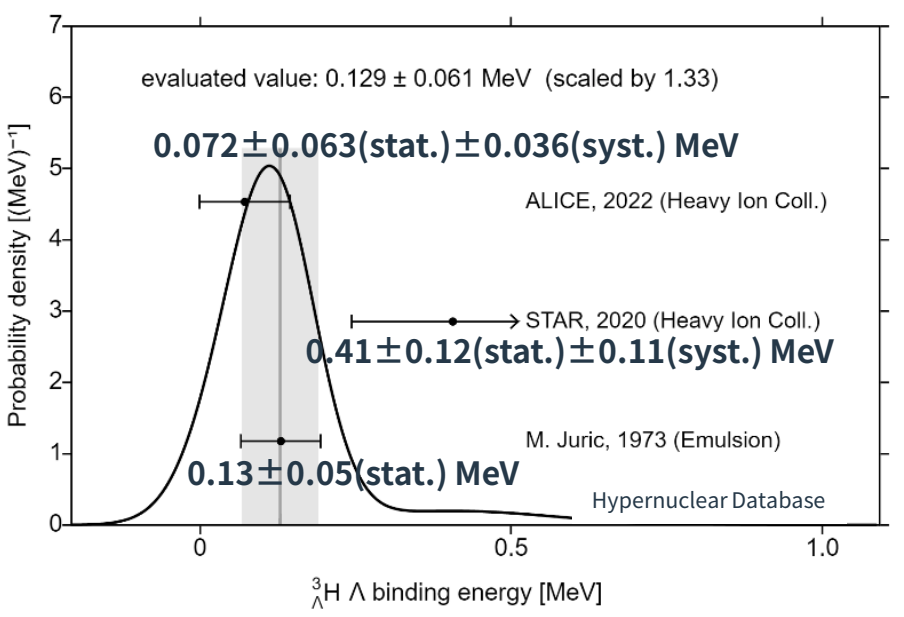
The University of Tokyo

Sho Nagao

2023/06/08

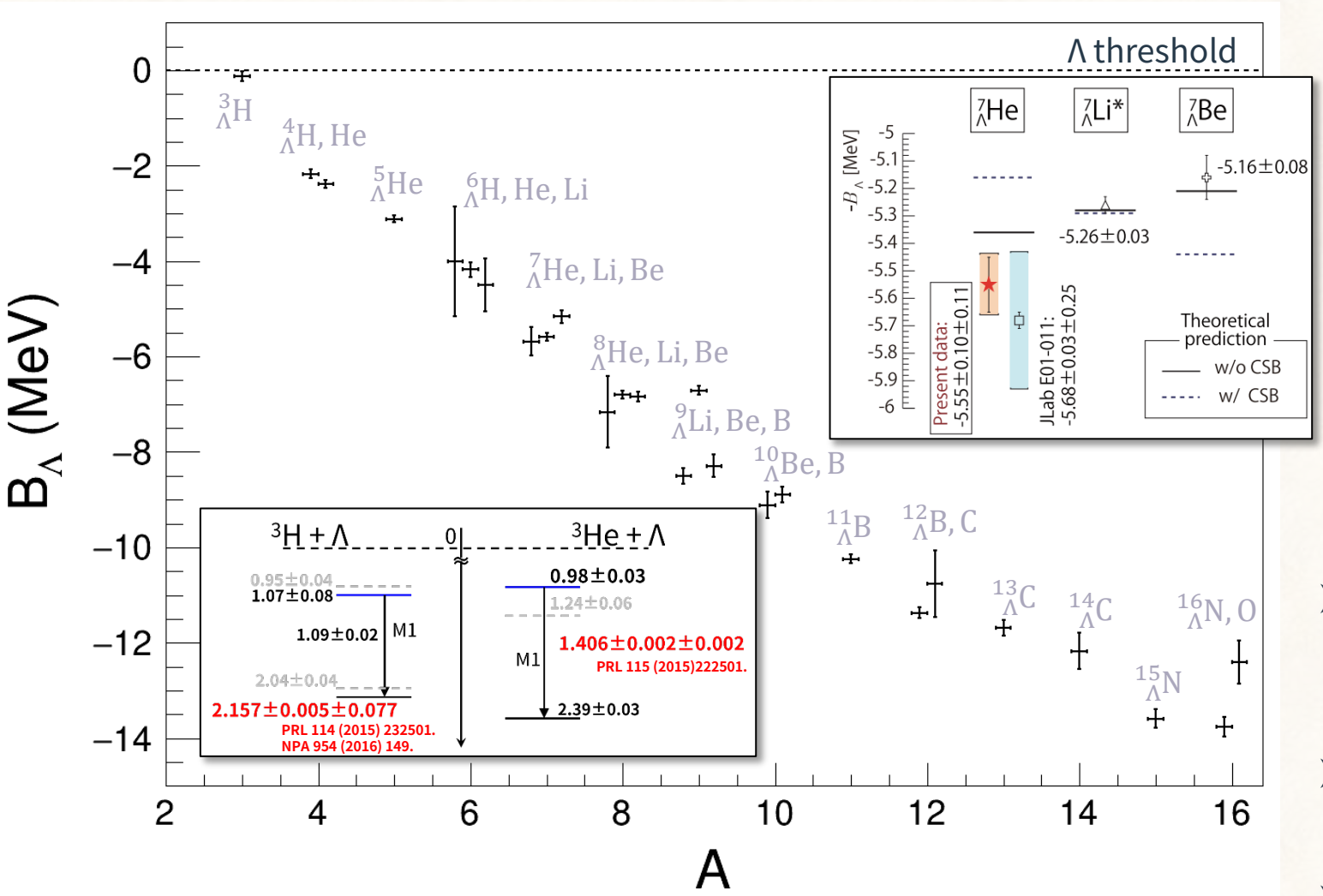
Λ binding energy of light hypernuclei

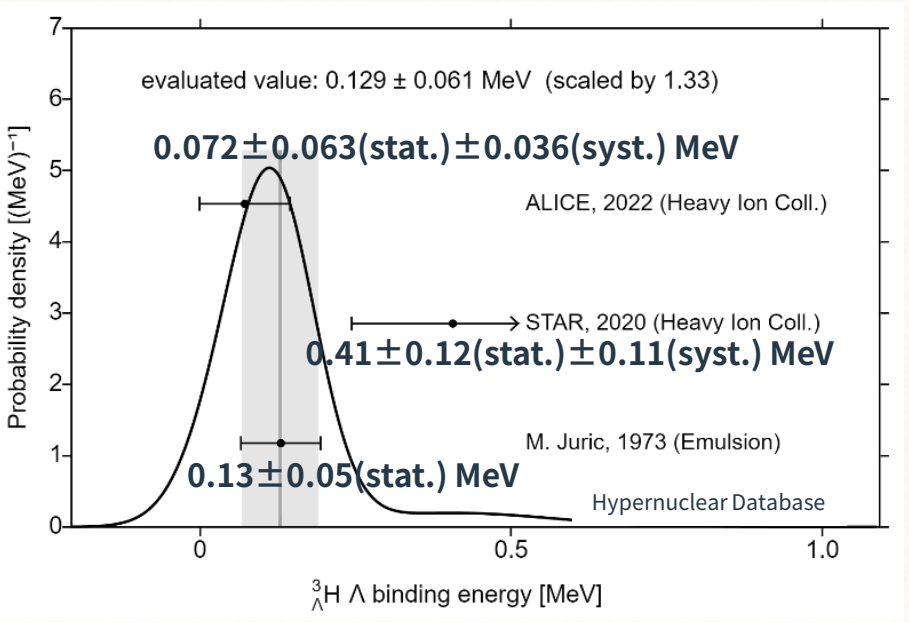




- Λ binding energies by the emulsion, missing-mass, invariant-mass spectroscopies
- Discussion about $^{3}_{\Lambda}$H puzzle, CSB, ΛN-ΣN coupling effect etc...
- Accurate data open further discussions

Λ binding energy of light hypernuclei





- Λ binding energies by the emulsion, missing-mass, invariant-mass spectroscopies
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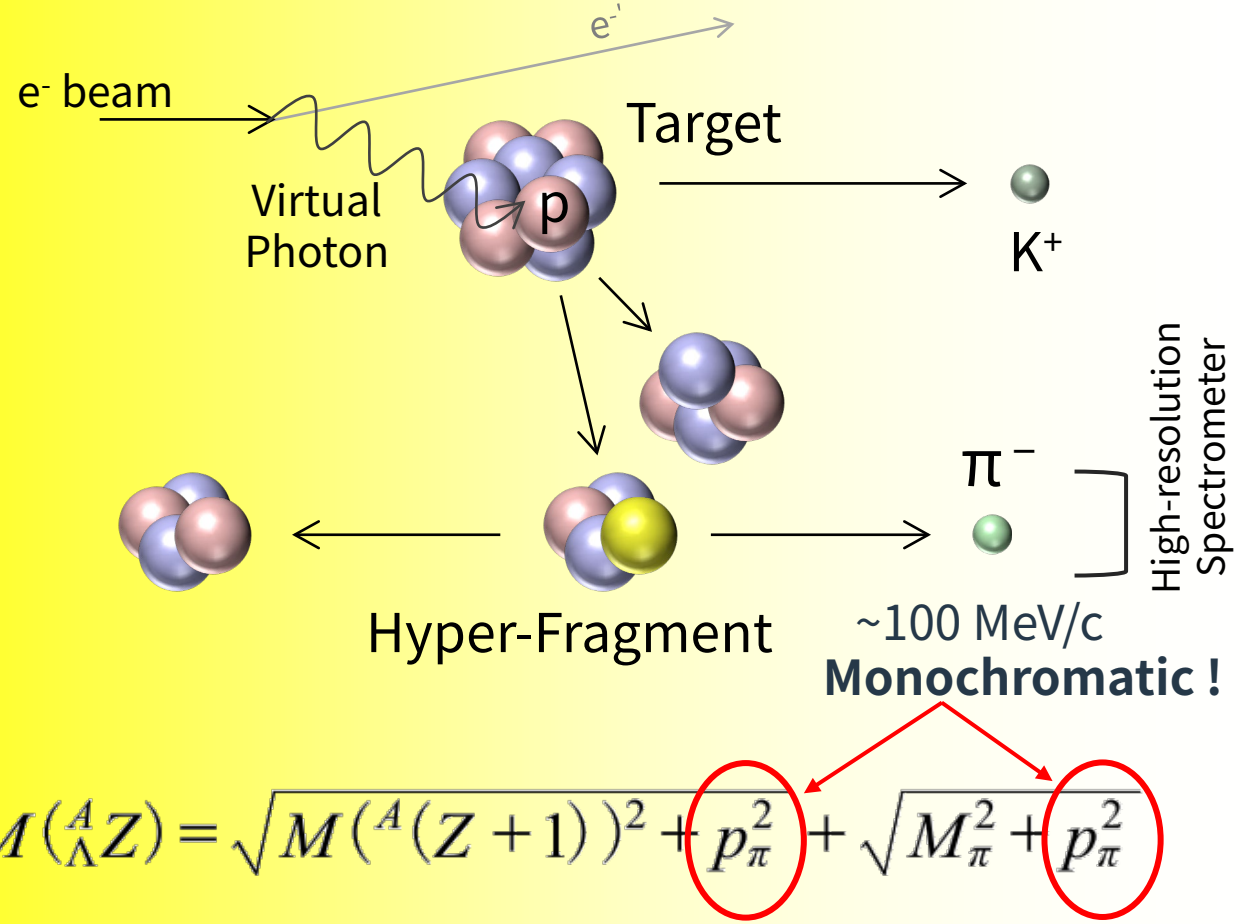
Higher-resolution mass spectroscopy

Decay Pion Spectroscopy



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

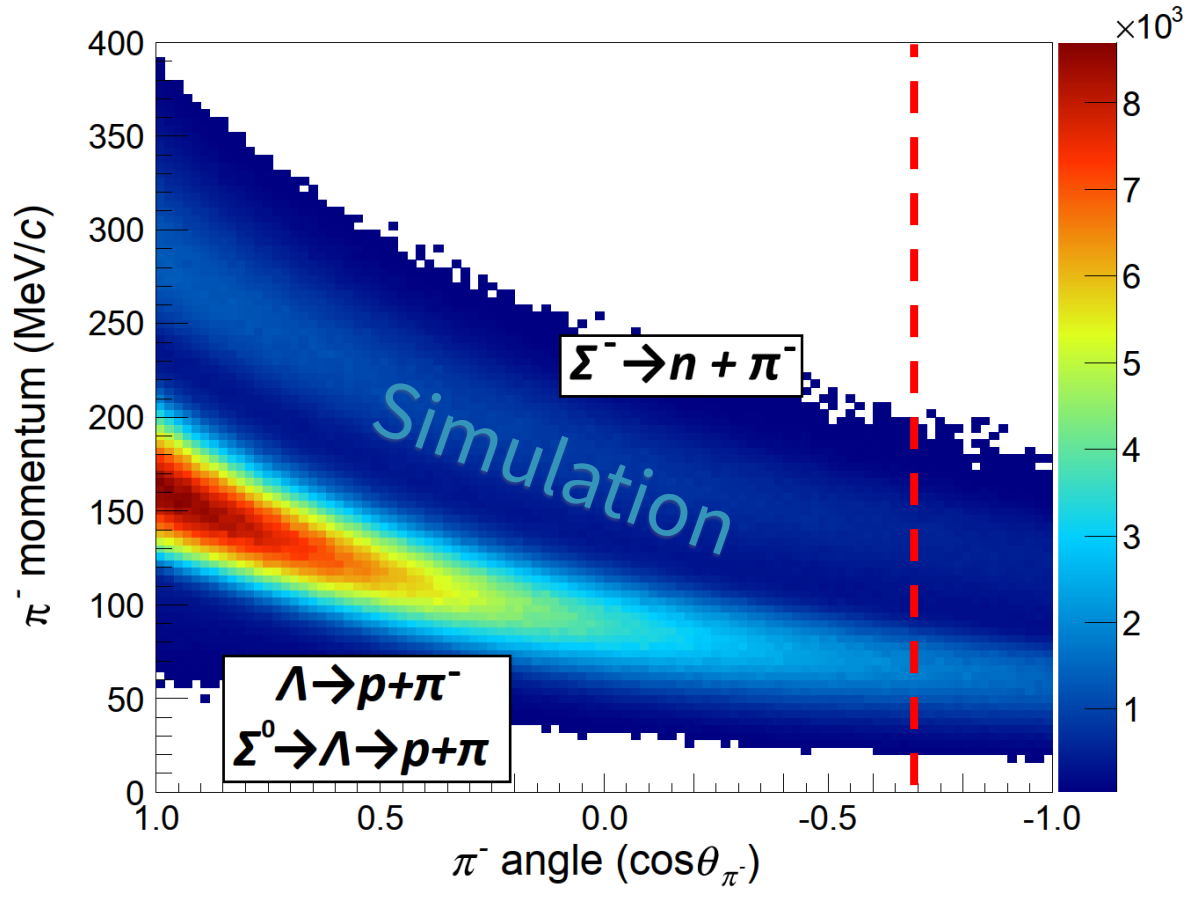
- High-resolution & High-precision hypernuclear mass spectroscopy
  - Stopping in a target
  - Two-body decay with π^- & nucleus
    → hypernuclear ground-state
- Momentum resolution $\Delta p \sim 0.1$ MeV/c
- Mass precision $\Delta M \sim 0.01$ MeV/c^2
- Good calibration sources
- Tagging Kaon

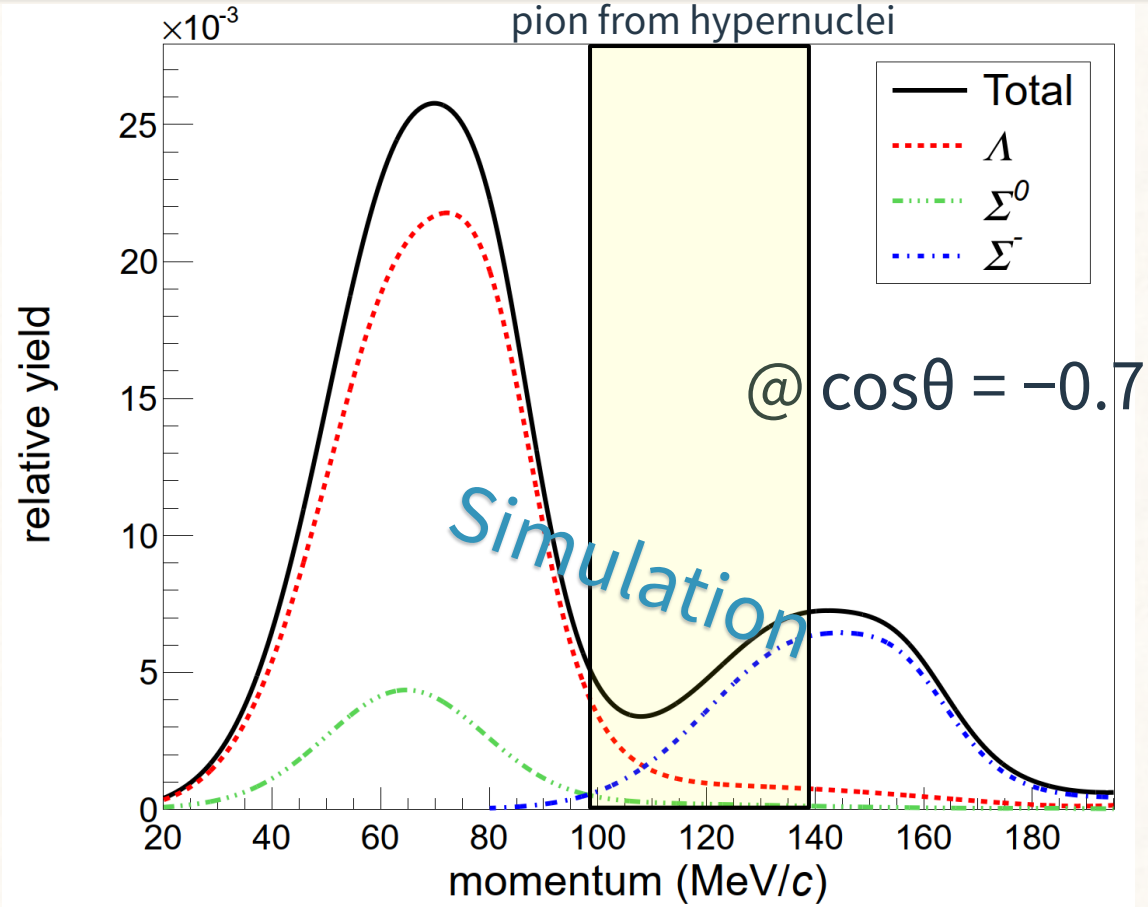
List of decay pion candidates

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

- 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

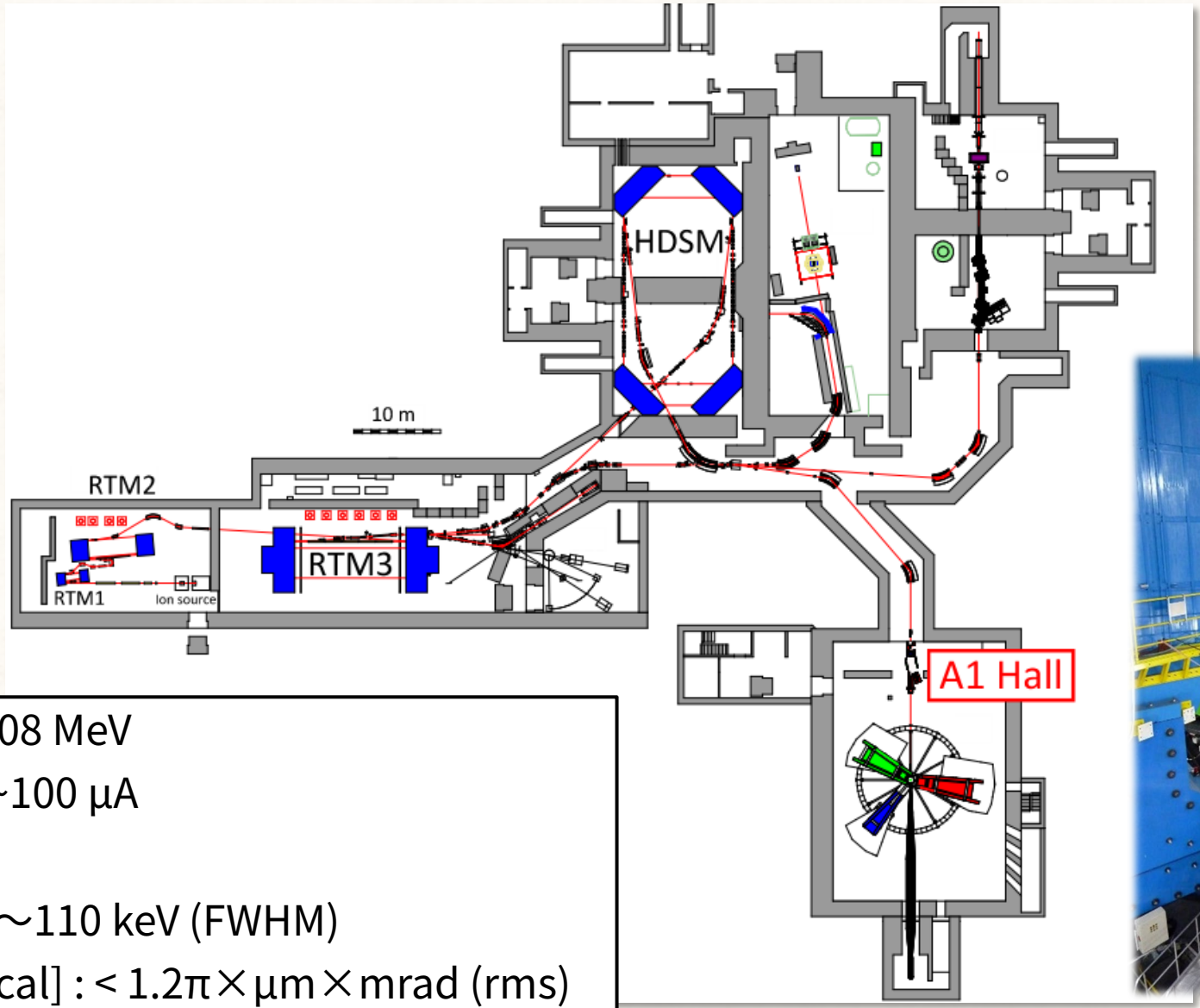
Background sources

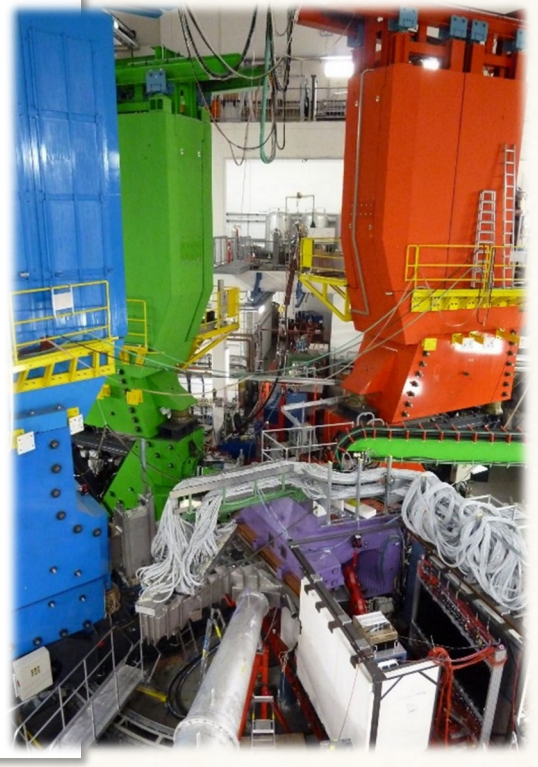




- Major background source of π^- from in-flight hyperon decay, especially from $\Sigma^- \rightarrow n + \pi^-$
- Most of π^- backgrounds go to the forward angles
- Decay pion measurement at the backward angles helps getting better S/N

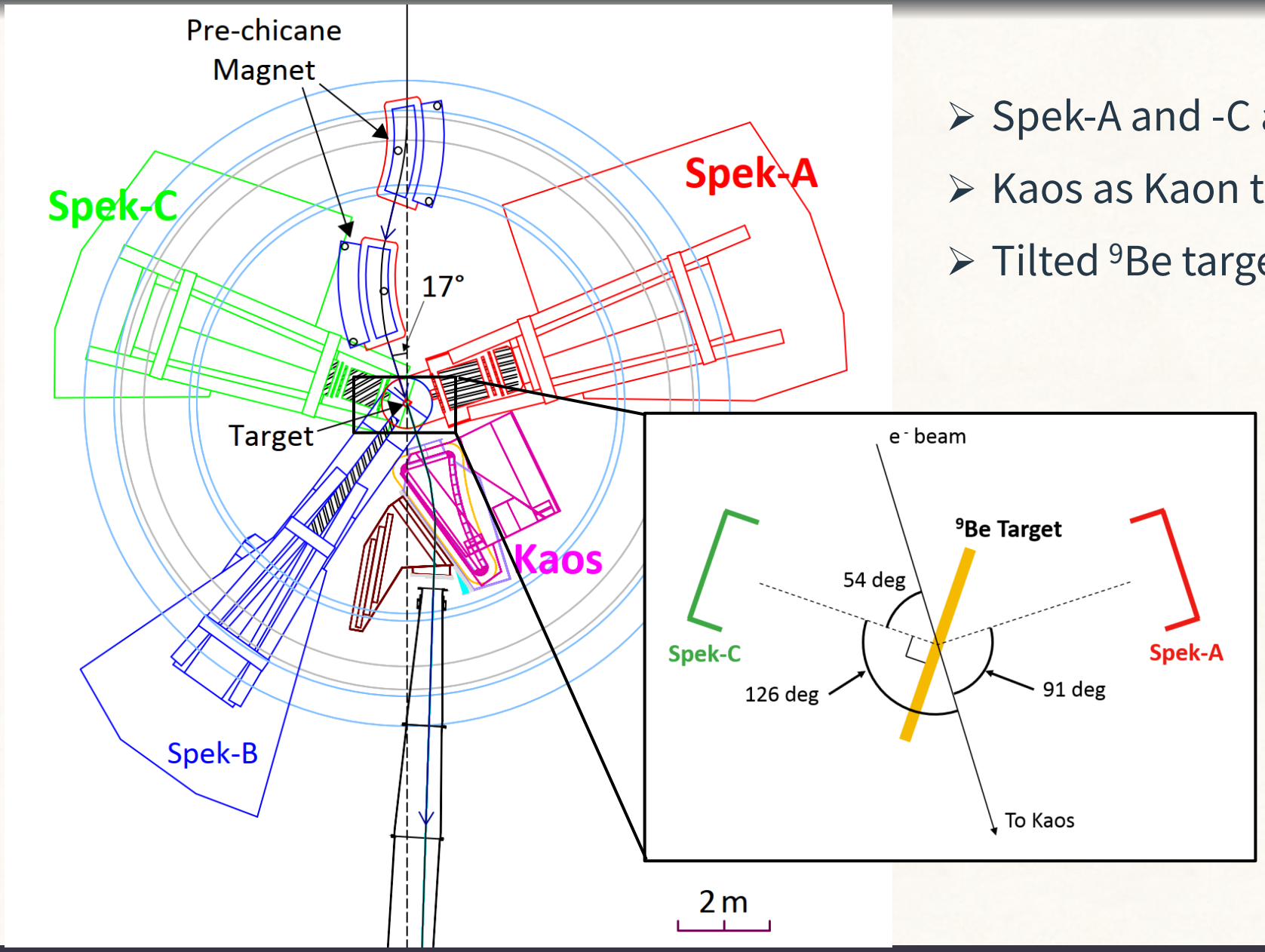
Mainz Microtron (MAMI)



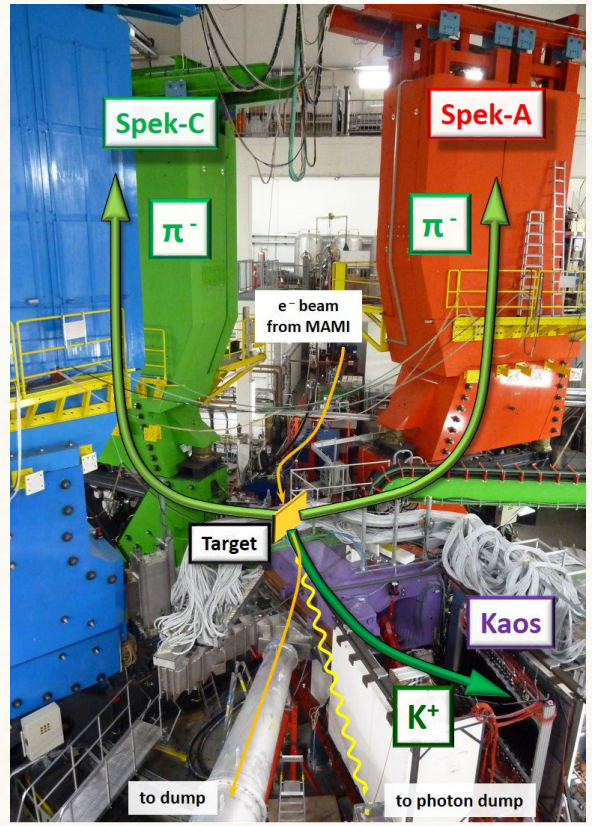


- Beam energy : Max. 1508 MeV
- Beam intensity : Max. ~100 μA
- Duty factor : 100%
- Energy resolution : ΔE～110 keV (FWHM)
- Beam emittance [vertical] : < 1.2π×μm×mrad (rms)

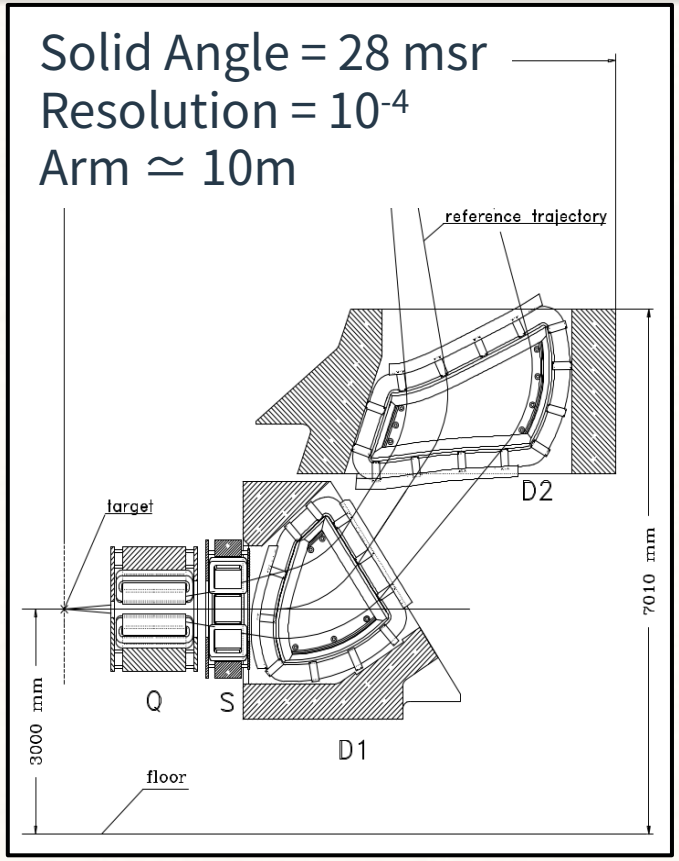
Setup of A1-Hall MAMI

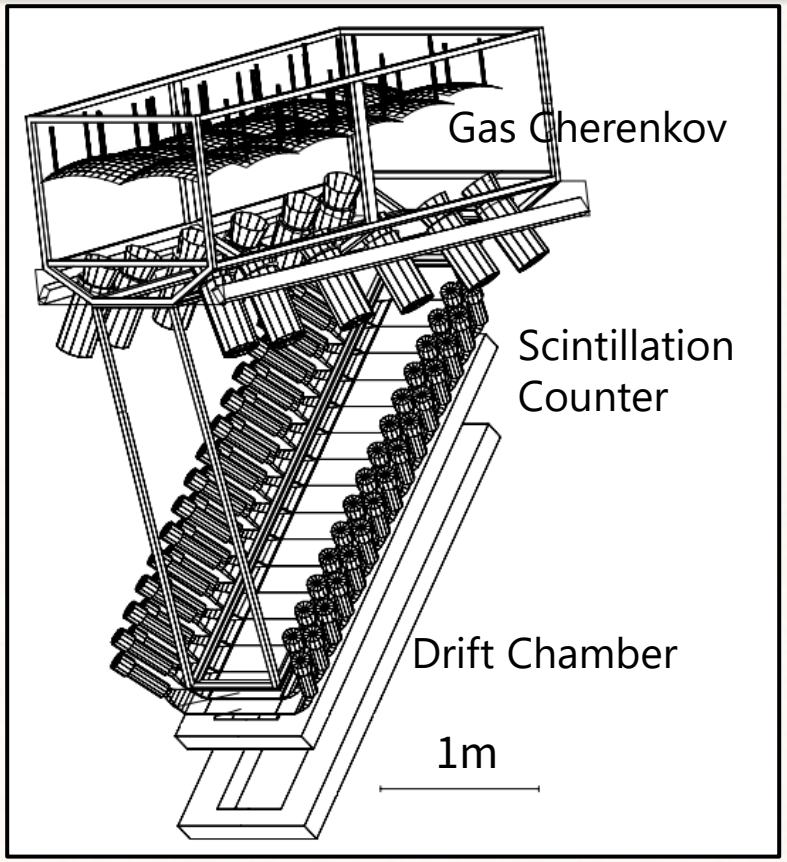


- Spek-A and -C as pion spectrometers
- Kaos as Kaon tagger
- Tilted ^{9}Be target (0.125 mm thick)

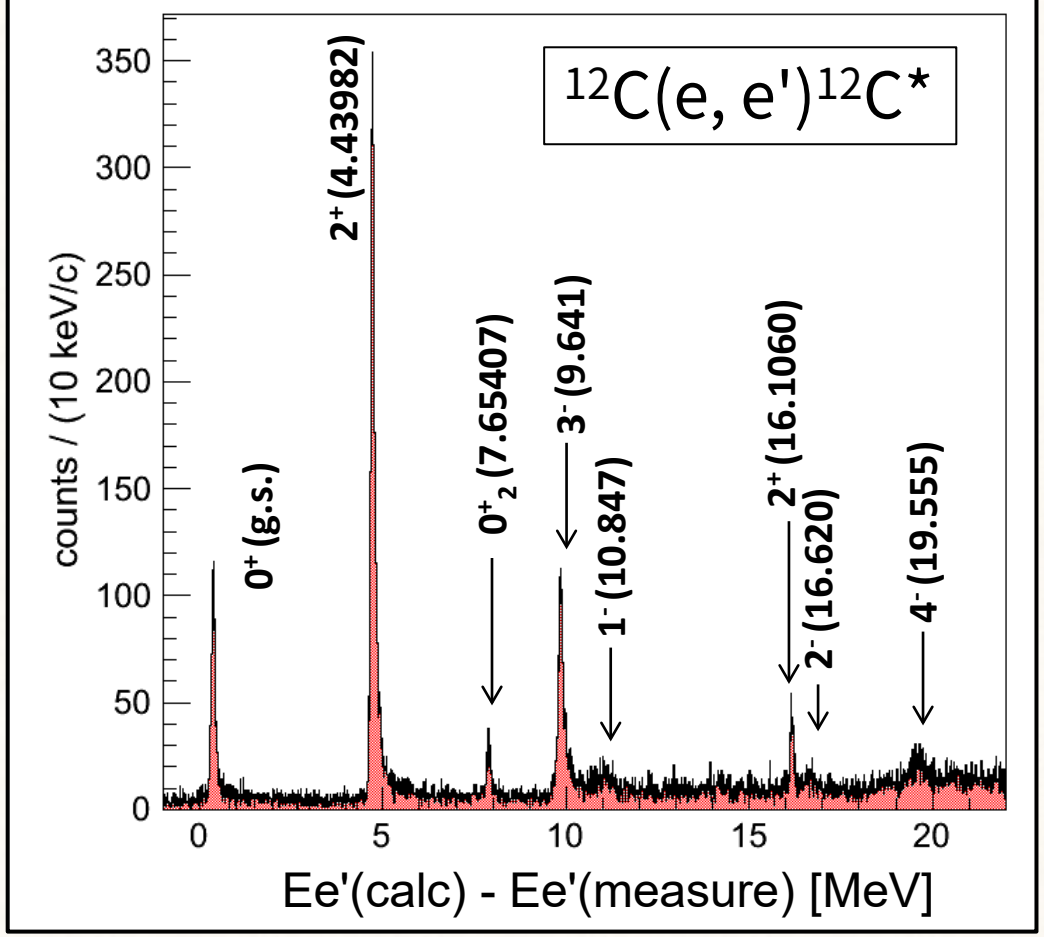


Decay Pion Spectrometer (Spek-A, -C)



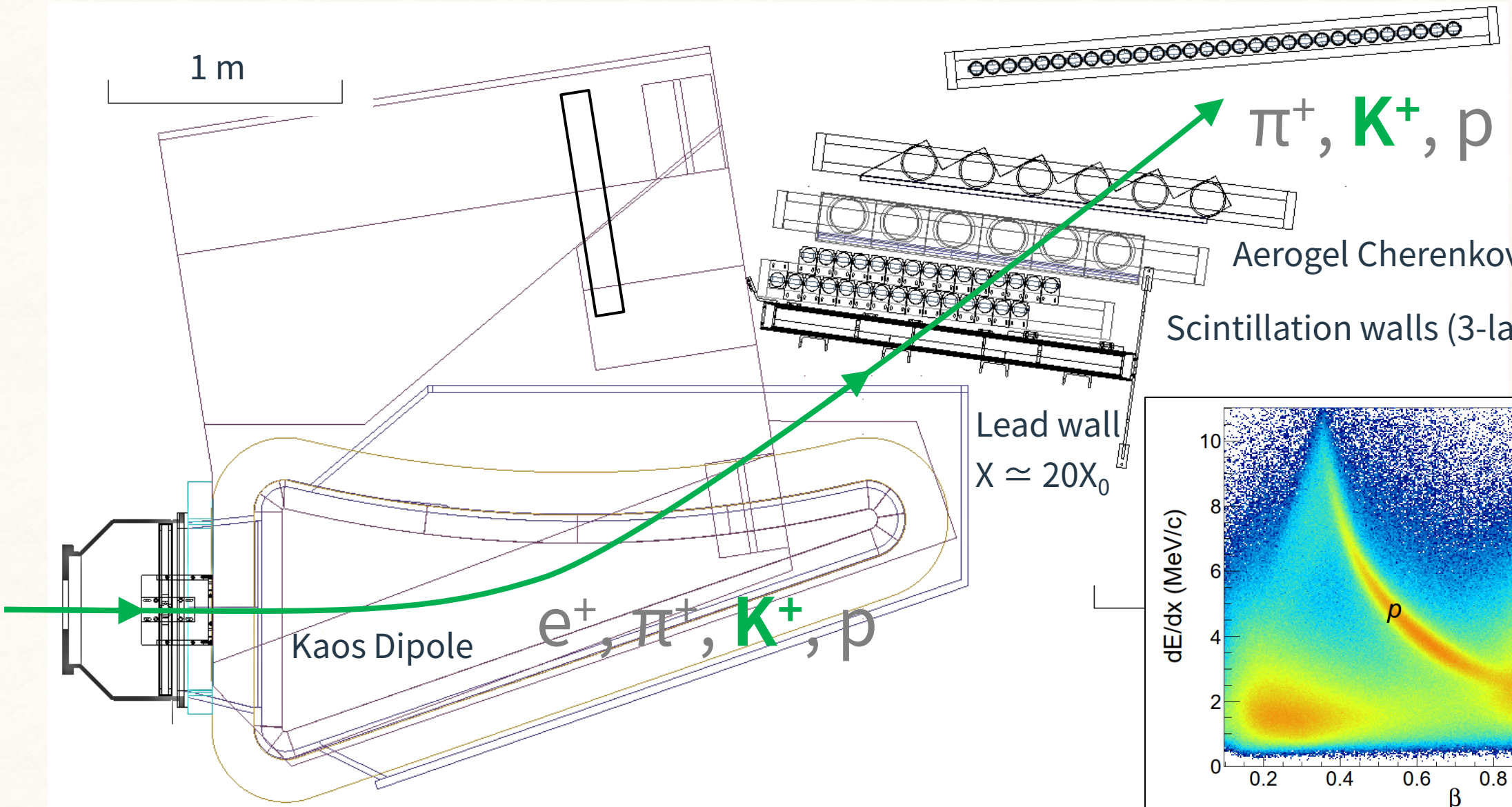


$$E_{e'} = \frac{E_e}{1 + E_e/M_{tar}(1 - \cos\theta_e)}$$

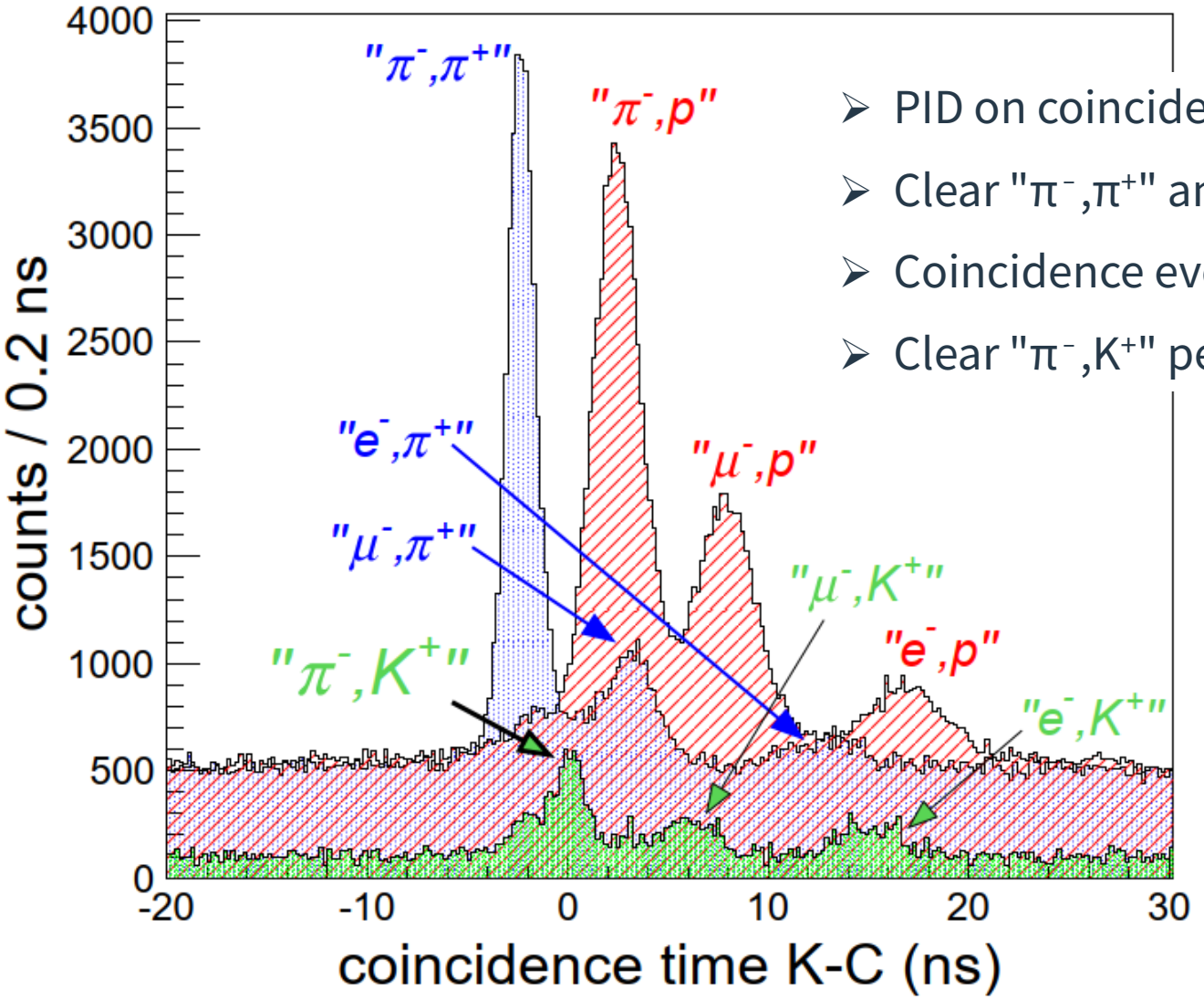


- High-resolution spectrometers
- Momentum calibration with elastic-scattered electrons
- 0.1 MeV/c accuracy ← uncertainty of E_e

Kaon Tagger (Kaos)



PID on coincidence time spectrum

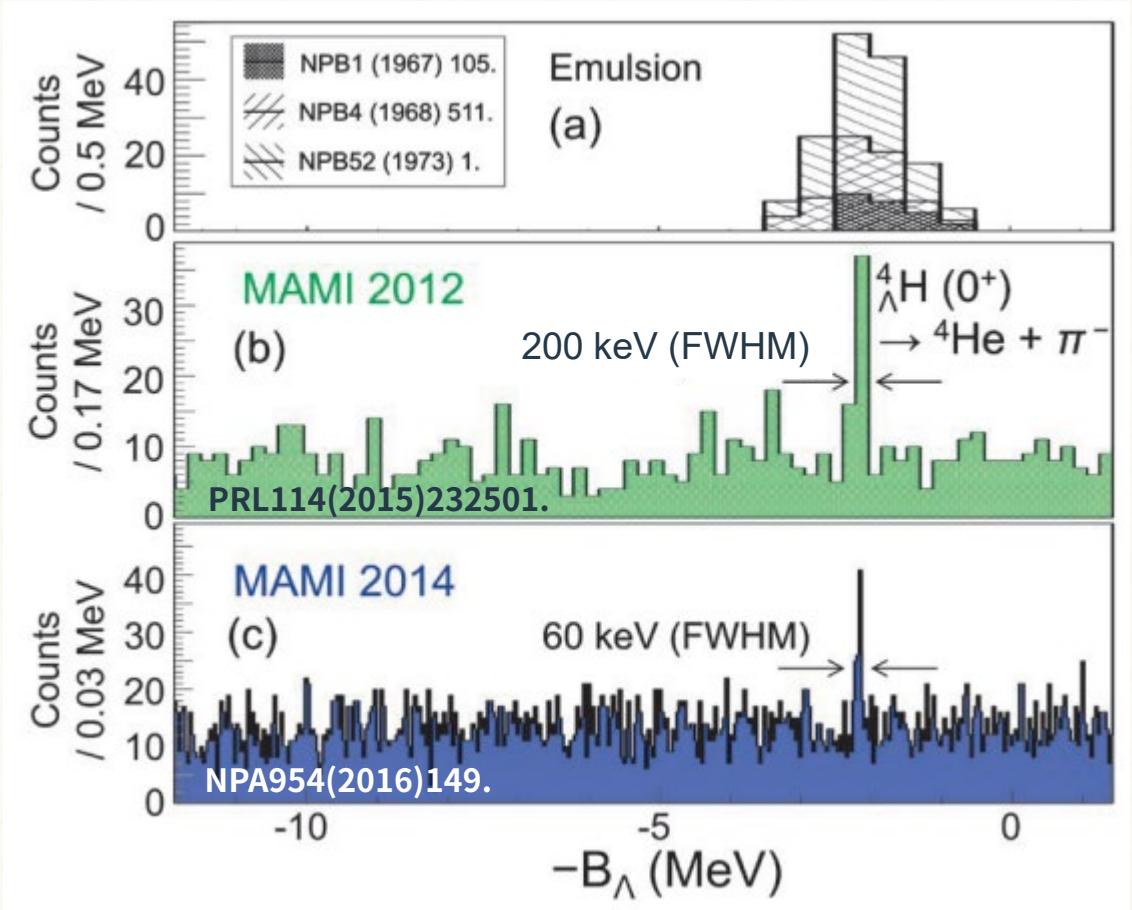


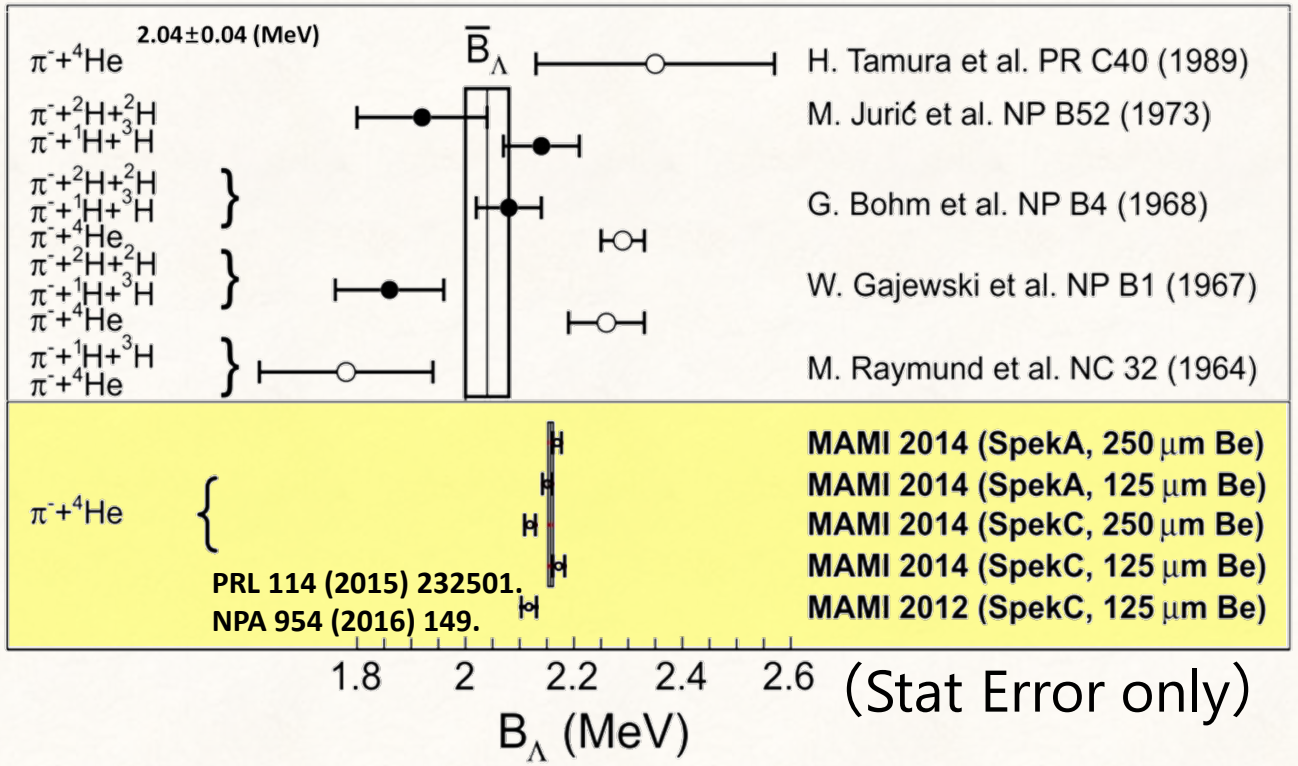
- PID on coincidence time at the target between Kaos & Spek-A, -C
- Clear "π^-,π^+" and "π^-,p" coincidence peak with PID cuts of Kaos
- Coincidence events with μ^- and e^-
- Clear "π^-,K^+" peak in-between

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.]

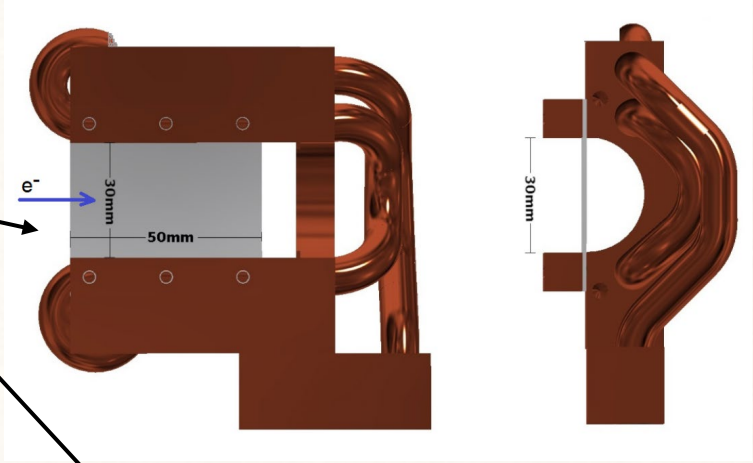




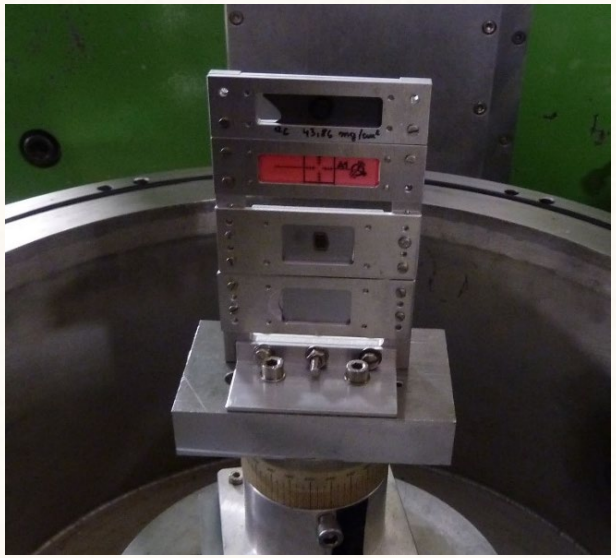
(Stat Error only)

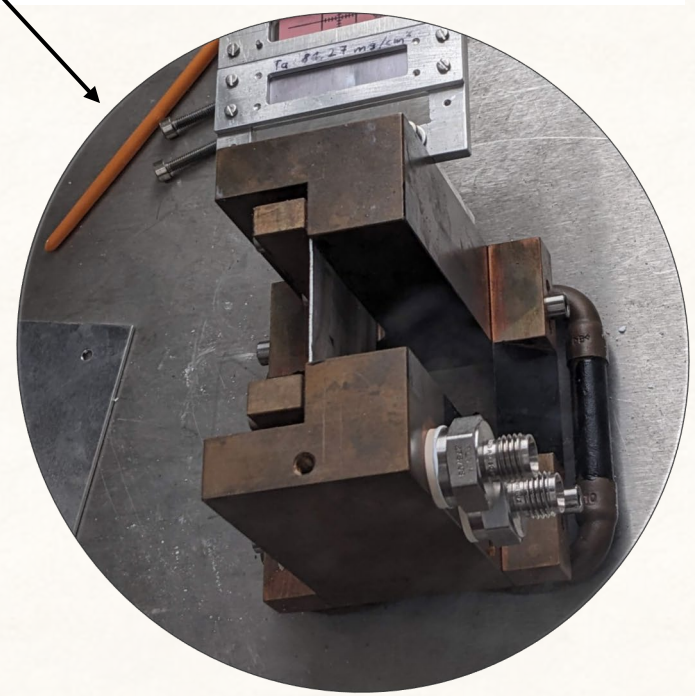
Update experiment for $^{3}_{\Lambda}$H measurement

New Li Target



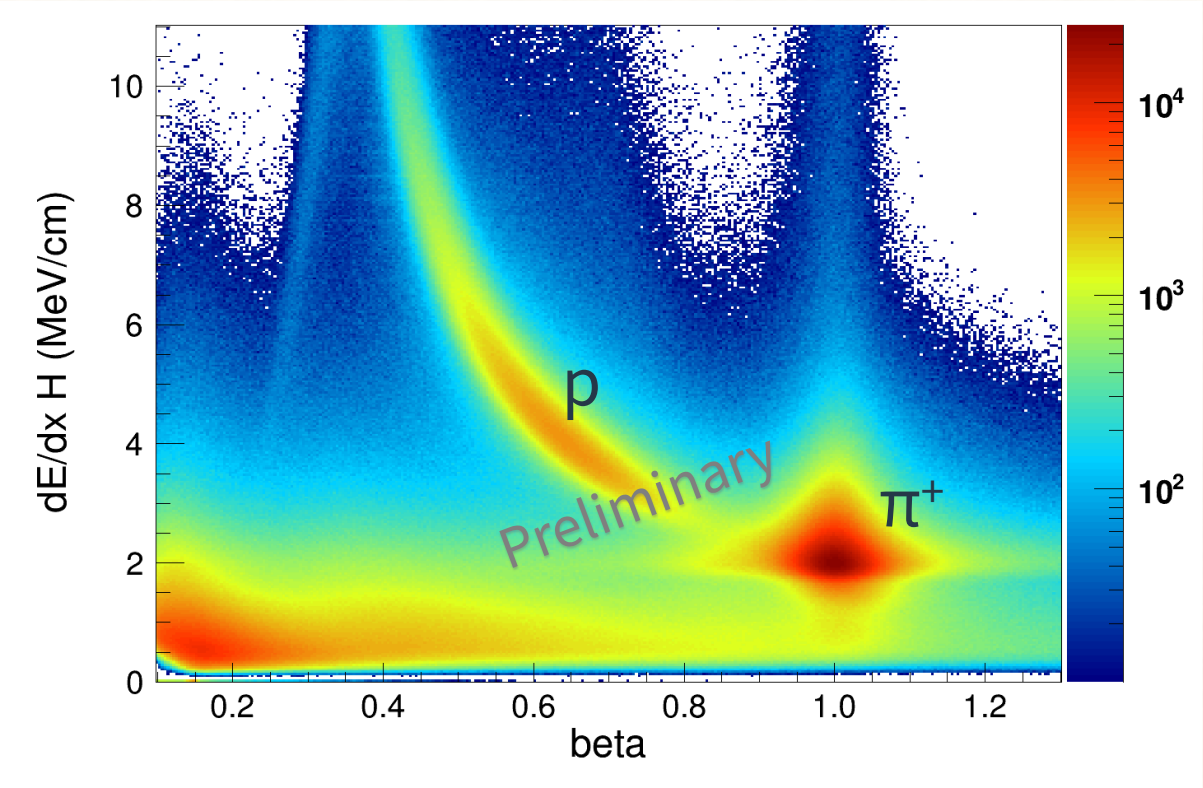
↓ OLD ^{9}Be target

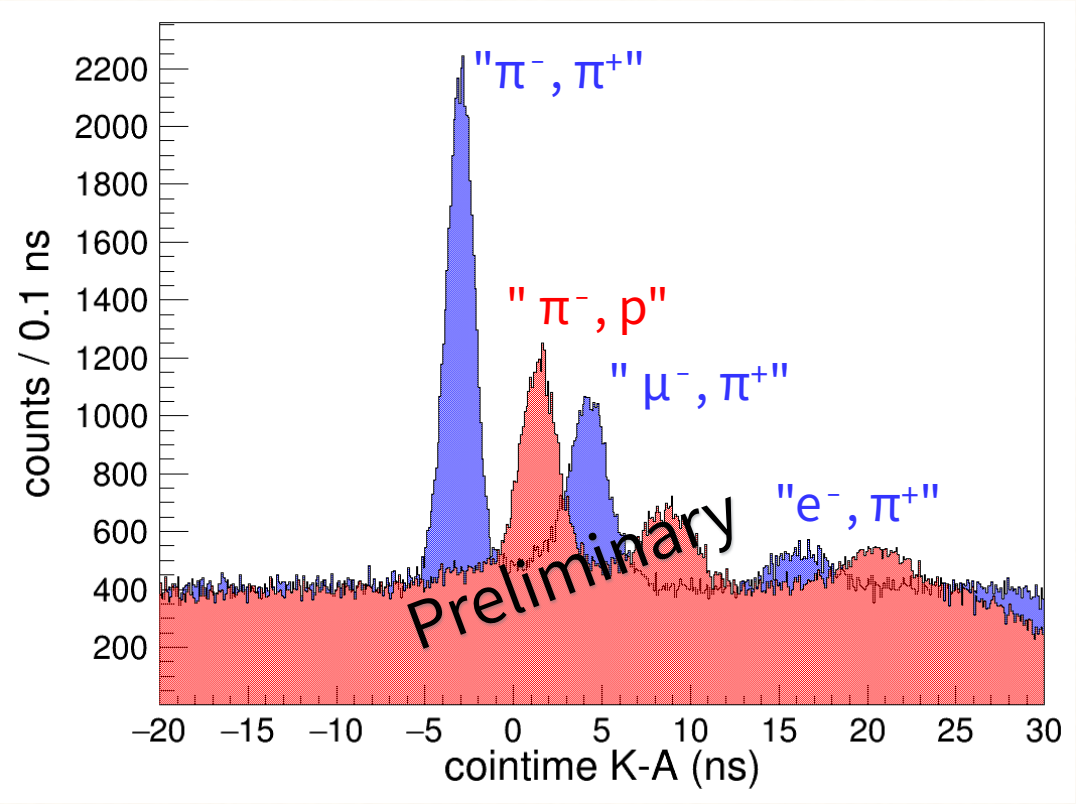




- Update experiment with a new Li target
- Better $^{4}_{\Lambda}$H hypernuclear yield according to (K^{-}_{stop}, π^{-}) experiment
- New 90 deg tilted Li target with a thickness of 2700 mg/cm^{2}
- Better yield and Lower does level thanks to thick-target and low-current
- Data taking in 2022

Preliminary Results



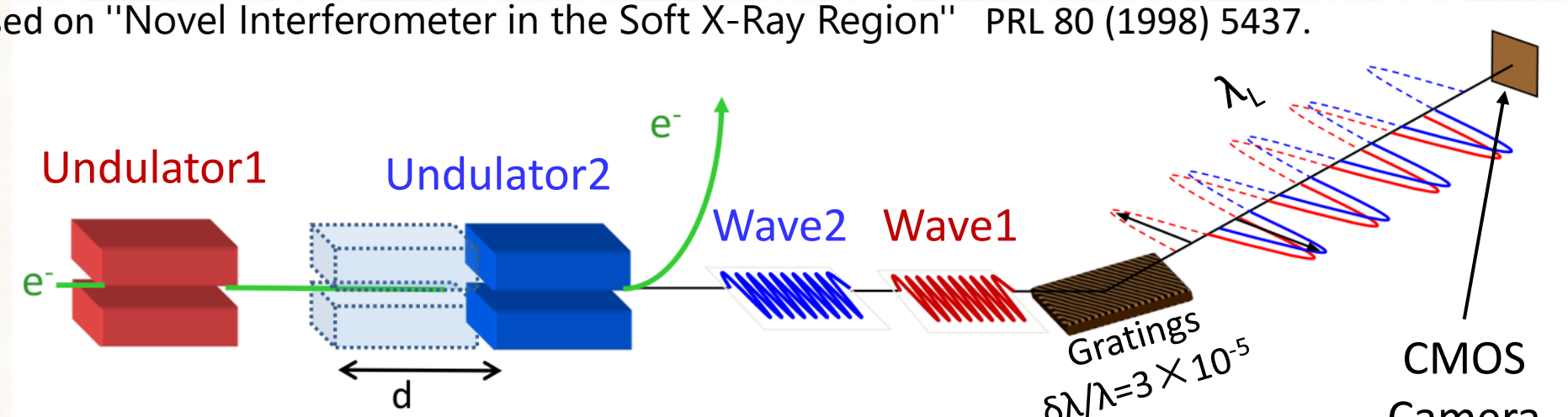


- Similar performance to the past experiments
- Better no. coincidence peak
- Good π^+ and p ID in Kaos
- Expecting hypernuclear events between "π^-, π^+" and "π^-, p"

Towarding 10 keV Accuracy

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

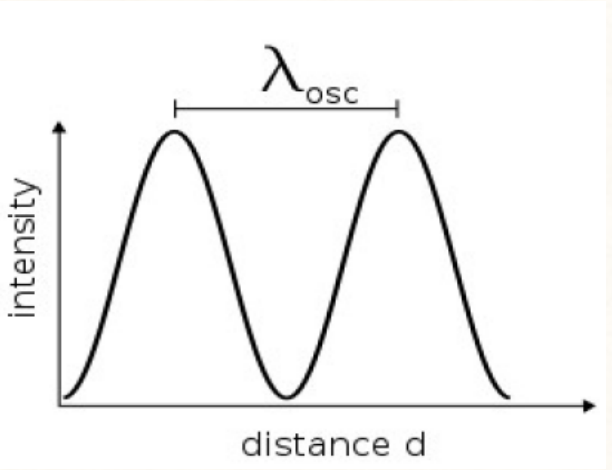
Based on "Novel Interferometer in the Soft X-Ray Region" PRL 80 (1998) 5437.



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

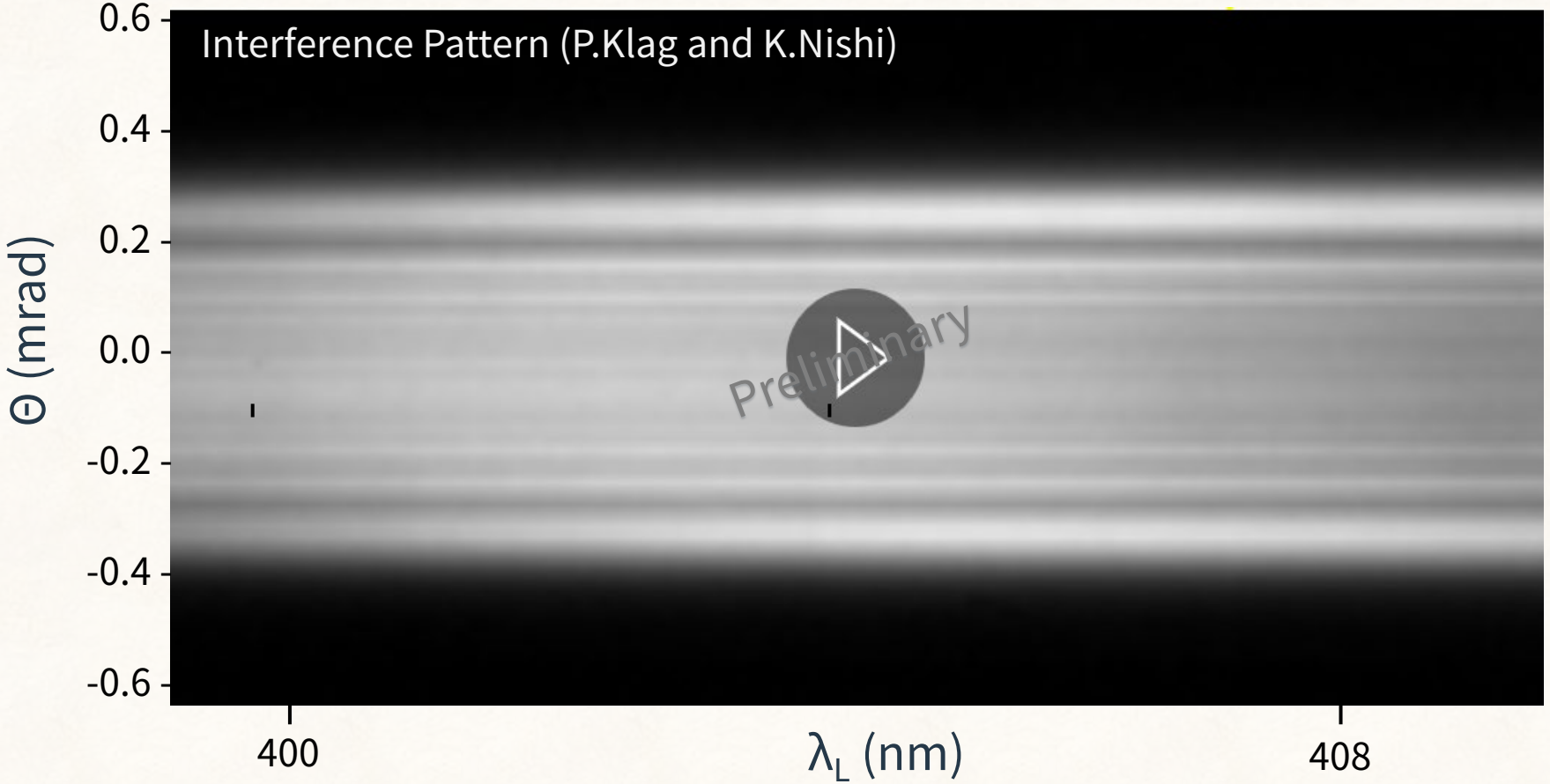
Lorenz factor

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

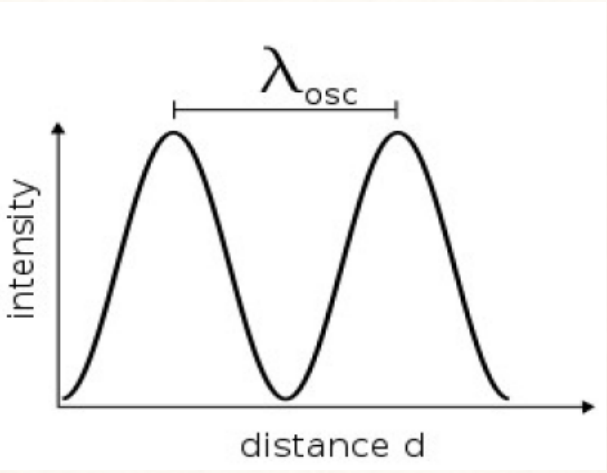


Toward much more Accurate measurement

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

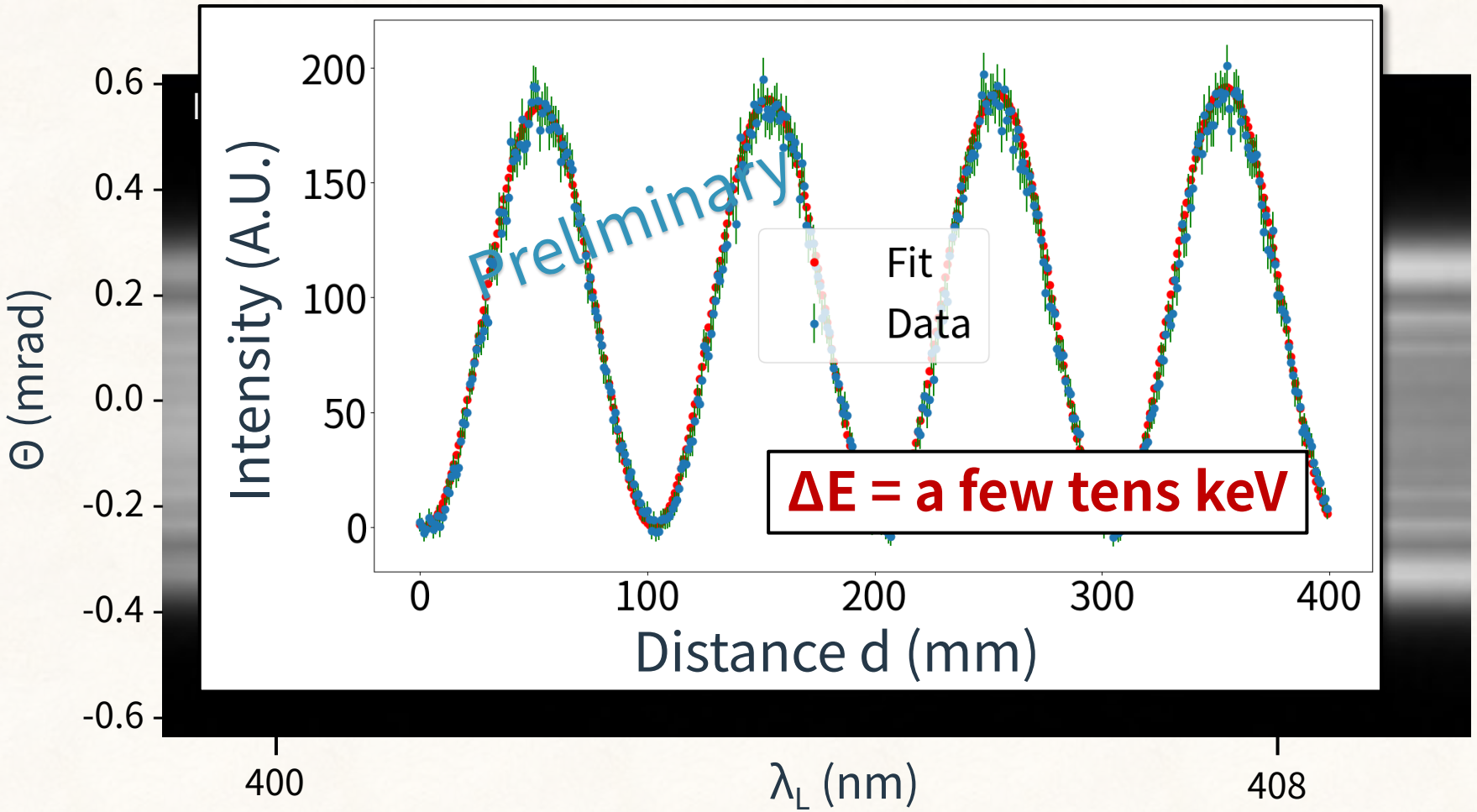


$$\gamma = \sqrt{\lambda_{osc}(\Theta)/2\lambda_L}$$

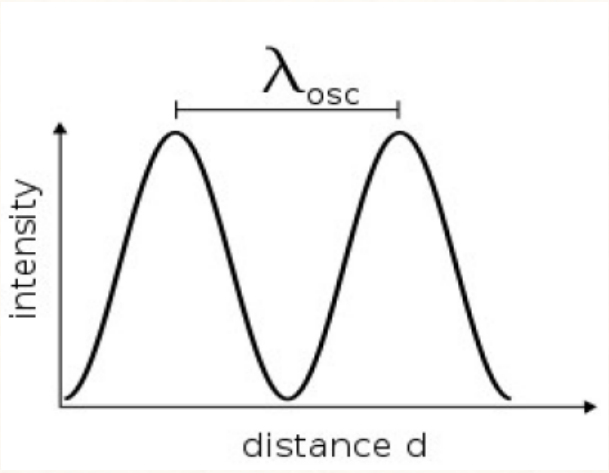


Toward much more Accurate measurement (DPS)

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



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



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

keV systematics **note: ΔM_Λ =6 keV**

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

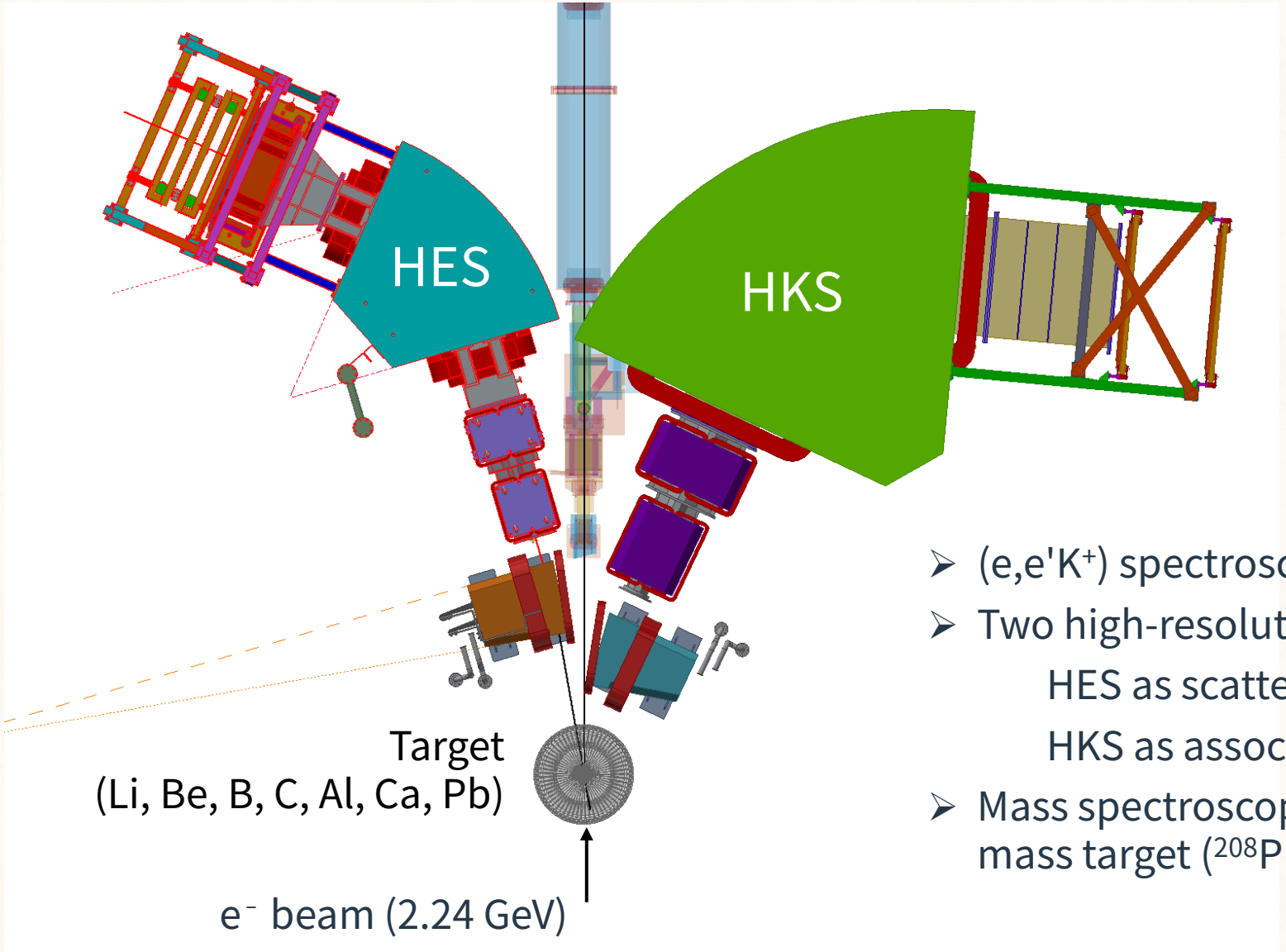
Needs of experiments with much higher statistics

Limitation of .....

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

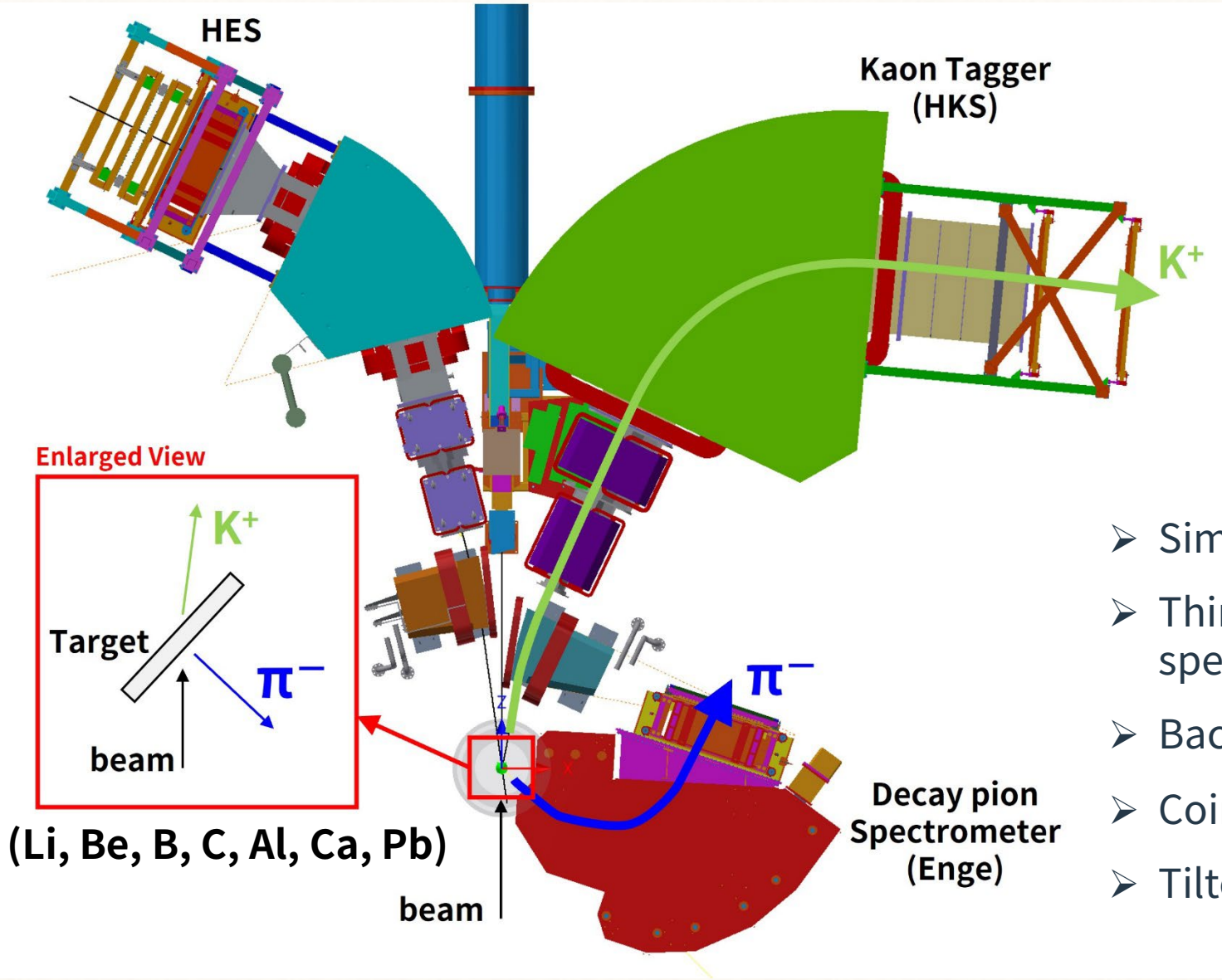
→ DPS at JLab

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



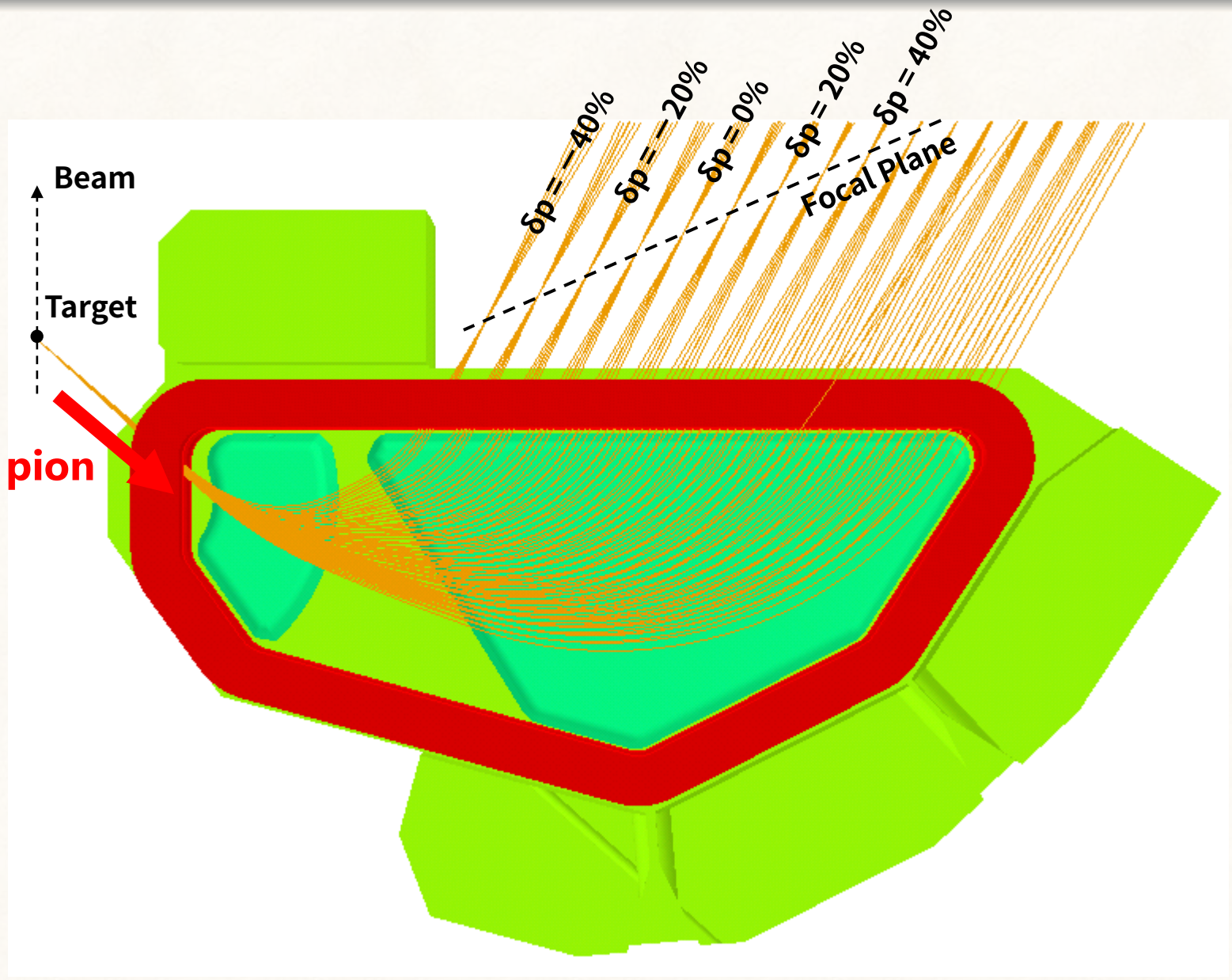
- (e,e'K^+) spectroscopies at JLab Hall-C
- Two high-resolution spectrometers
  - HES as scattered electrons
  - HKS as associated Kaons
- Mass spectroscopies of a light-mass target (^{6}Li) to a heavy-mass target (^{208}Pb)

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



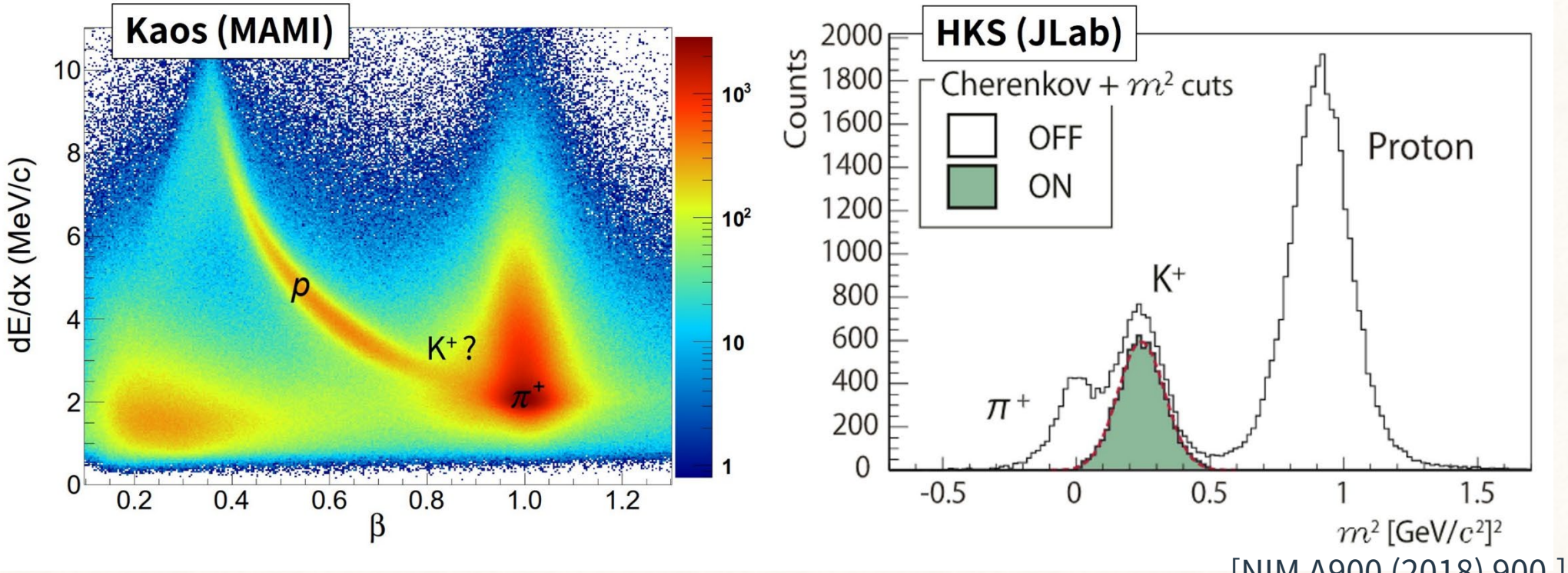
- Split-pole magnet @JLab storage
- Hardware spectrometer
- Position at FP = Momentum
  FP detector (Sci-Fi)
- Good momentum resolution
  $\Delta p/p = 4 \times 10^{-4}$
- Wide momentum bite
  p = 70 - 170 MeV/c
- Dark Spectrometer
  $\Delta\Omega$ = 4 msr

Advantage of DPS at JLab

➢ Capability of better

- Kaon Identification of HKS detectors (2-layers AC → 3-layers AC & 2-layers WC)
- DAQ Rate (several 100 Hz → several kHz) & Does Limitation

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



[NIM A900 (2018) 900.]

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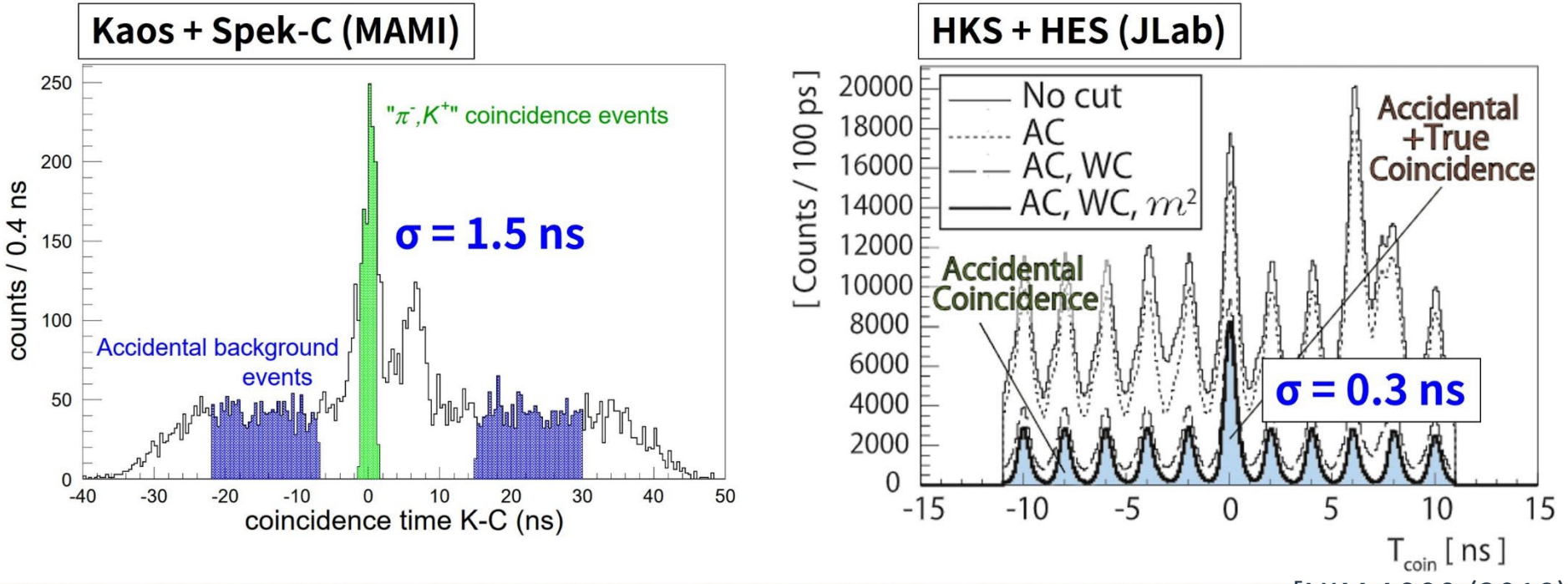

[NIM A900 (2018) 900.]

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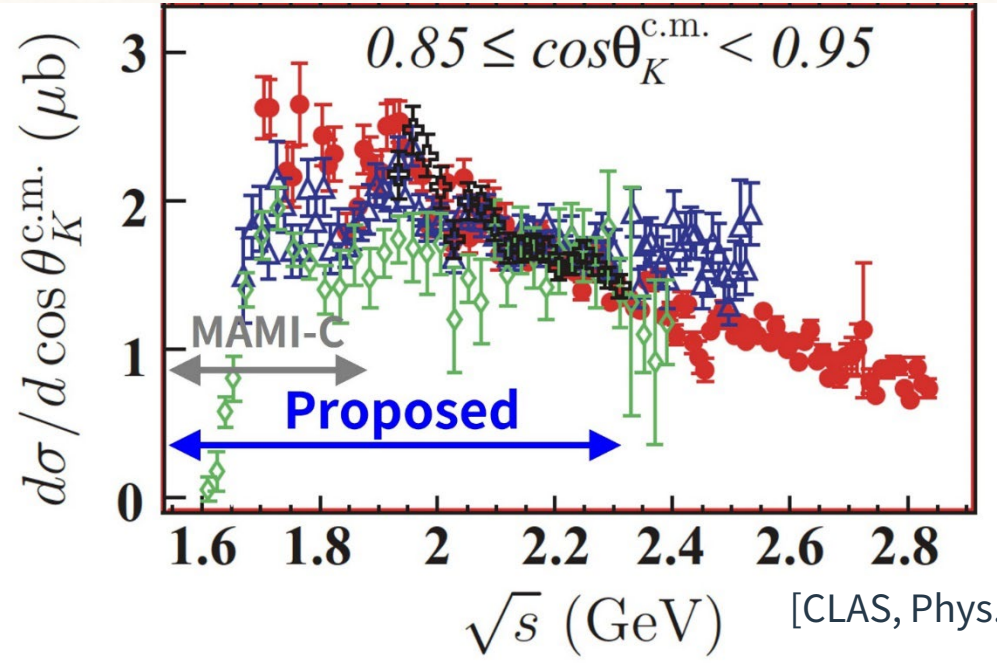
➢ Higher beam energy

- Increasing no. virtual photons associated Λ production (5 times)



[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)
  - DAQ Rate (several 100 Hz → several kHz) & Does Limitation
    Higher beam current (20 → 50 μA) & Thicker target (40 → 150 mg/cm^2)
- **Higher beam energy**
  - Increasing no. virtual photons associated Λ production (5 times)
- **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**
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> 30 times hypernuclear yields per unit time

keV systematics **note: ΔM_Λ =6 keV**

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
  - $B_{\Lambda}(^{4}_{\Lambda}\mathrm{H}\ \mathrm{g.s}) = 2.157 \pm 0.005 \pm 0.077$ (MeV) from MAMI2014
  - Upgrade experiment with a new Li target
  - New technique for beam energy measurement → 10 keV accuracy
- **New stage of the decay pion spectroscopy at JLab**
  - 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
  - We submitted LoI in PAC51