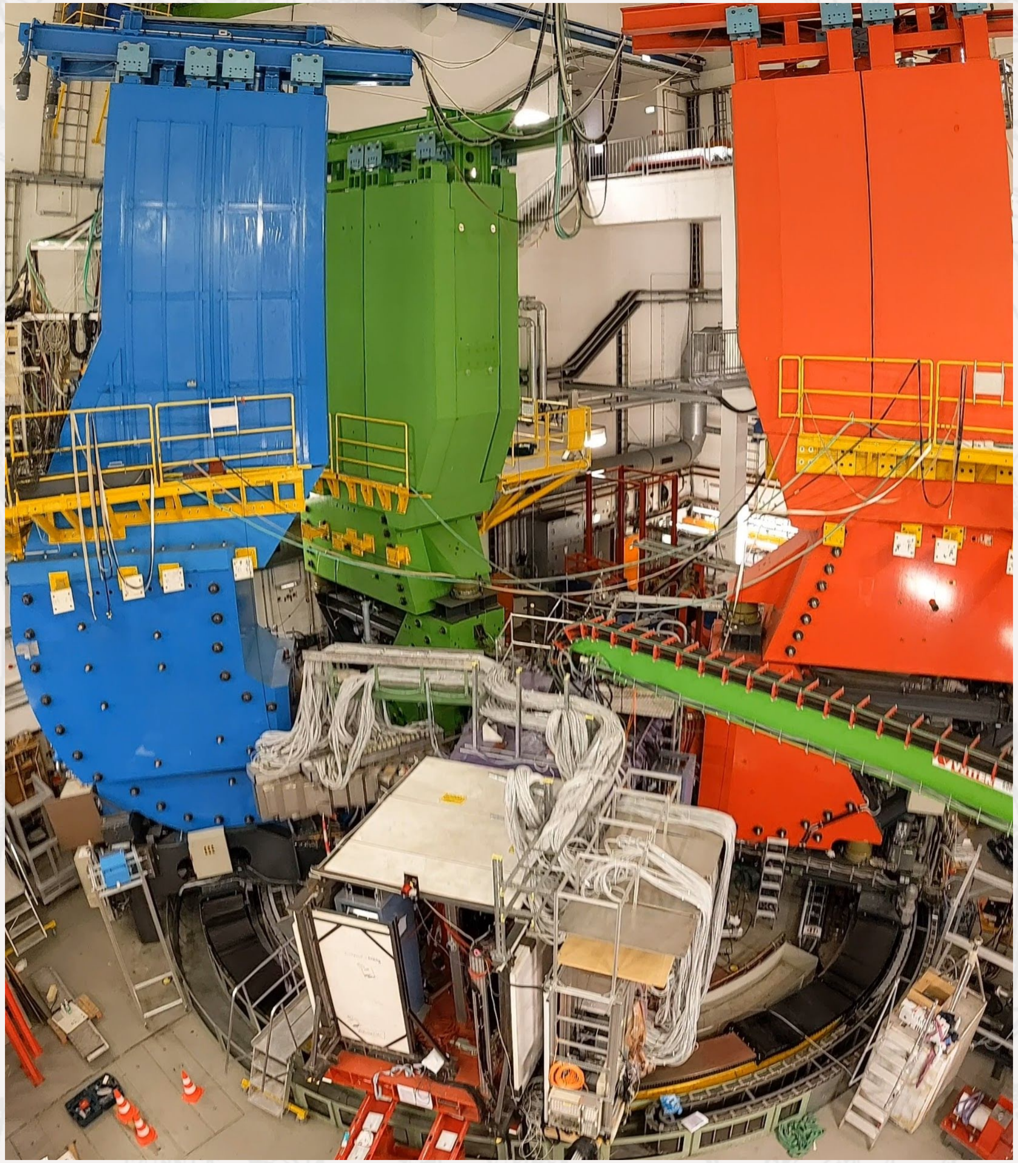
"Workshop of Electro- and Photoproduction of Hypernuclei and Related Topics 2024" (WEPH RE:2024)

Analysis status of decay pion spectroscopy for measurement of hypertriton binding energy at MAMI

Ryoko Kino Tohoku Univ.

for the A1 hypernuclear Collaboration

October 17th, 2024

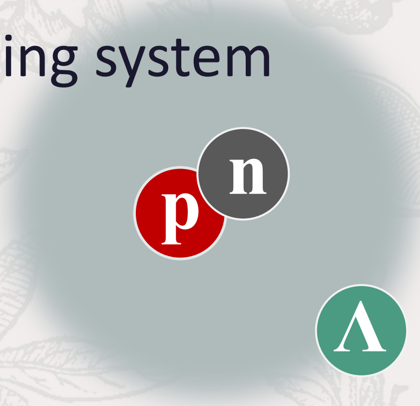


Nuclear Physics Institute, Czech Academy of Sciences + Online (Zoom)

Λ Binding Energy of Hypertriton

Hypertriton – a benchmark in hypernuclear physics

d-Λ binding system



Shallow binding?
or
Deeply bounded?

- Still large experimental uncertainties:

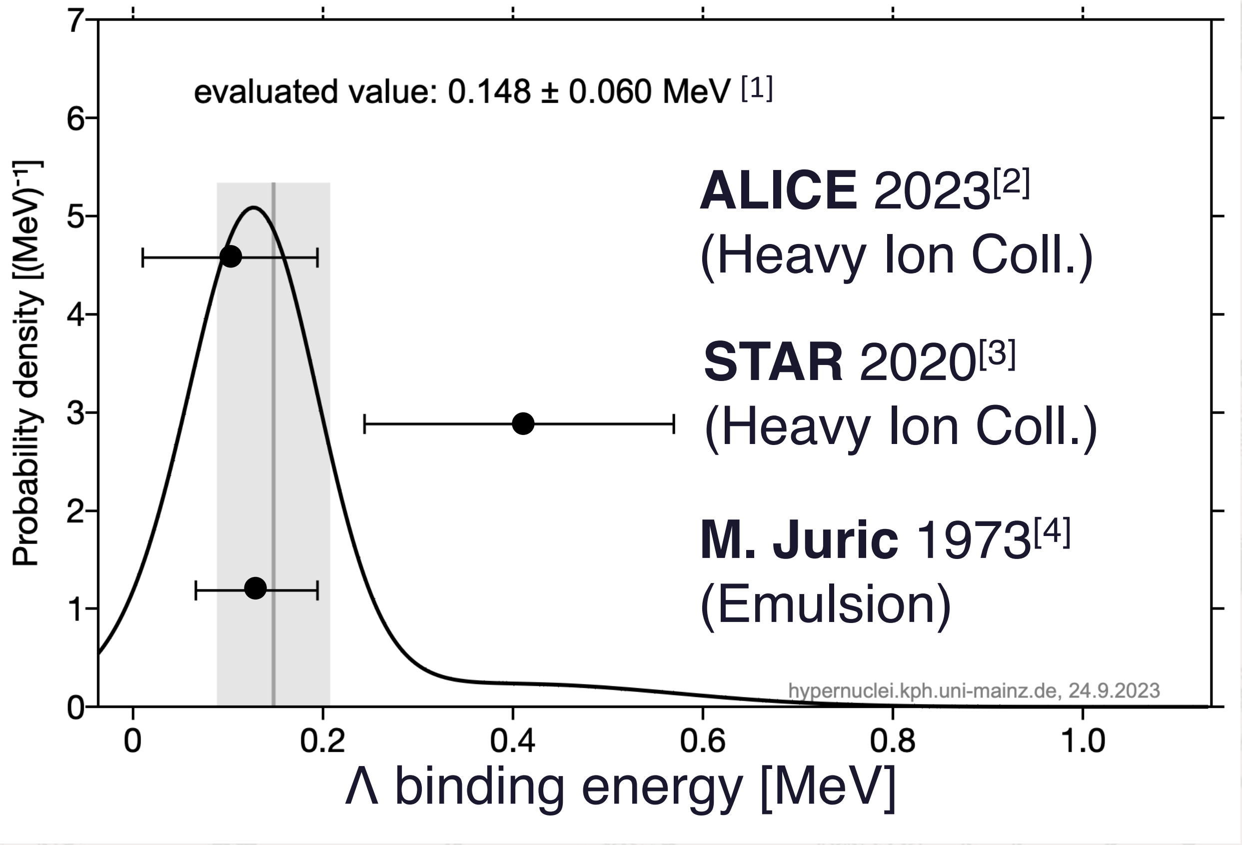
  STAR 2020 : $0.41 \pm 0.12_{(stat.)} \pm 0.11_{(syst.)}$ MeV

  ALICE 2023 : $0.10 \pm 0.06_{(stat.)} \pm 0.07_{(syst.)}$ MeV

- Need to clarify with the lifetime

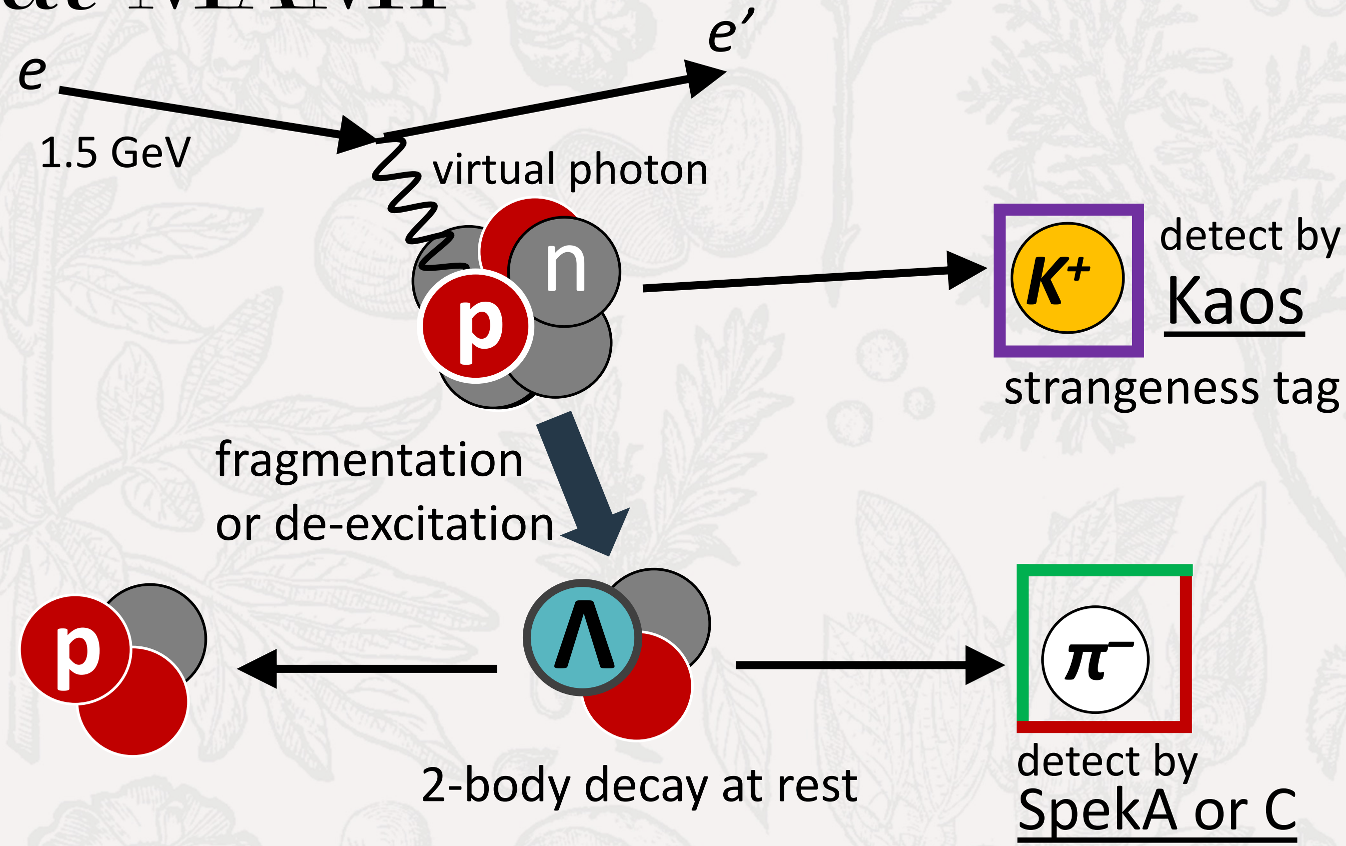
→ Decay-pion spectroscopy at MAMI

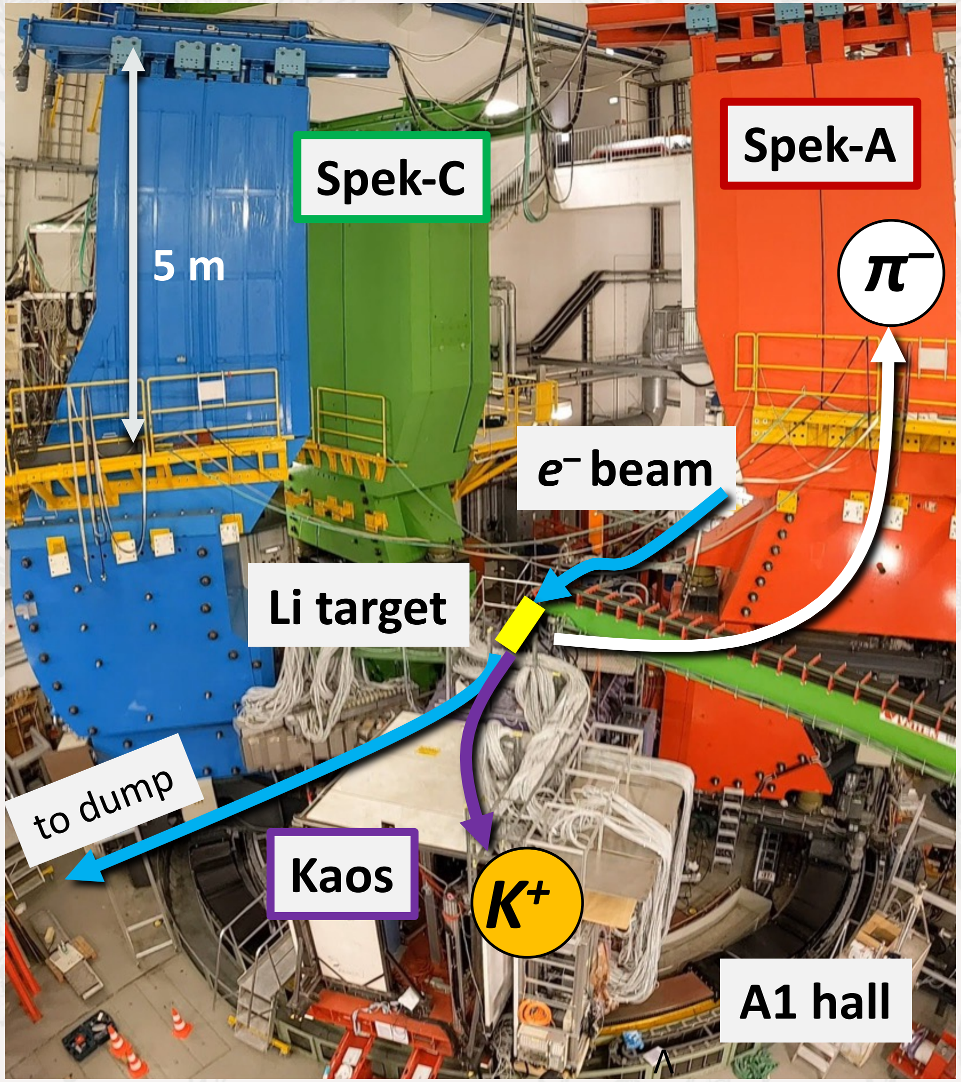
[1] Hypernuclear database (https://hypernuclei.kph.uni-mainz.de/)
P. Eckert *et al.*, Suplemento de la Revista Mexicana de Fisica 3 0308069 (2022) 1-6



[2] S. Acharya *et al.*, Phys. Rev. Lett. 131(2023), 102302
[3] STAR, Nature Phys. 16 (2020) 4, 409-412 [4] M. Juric, Nucl. Phys. B 52, 1 (1973) 1-30

Decay-pion spectroscopy at MAMI





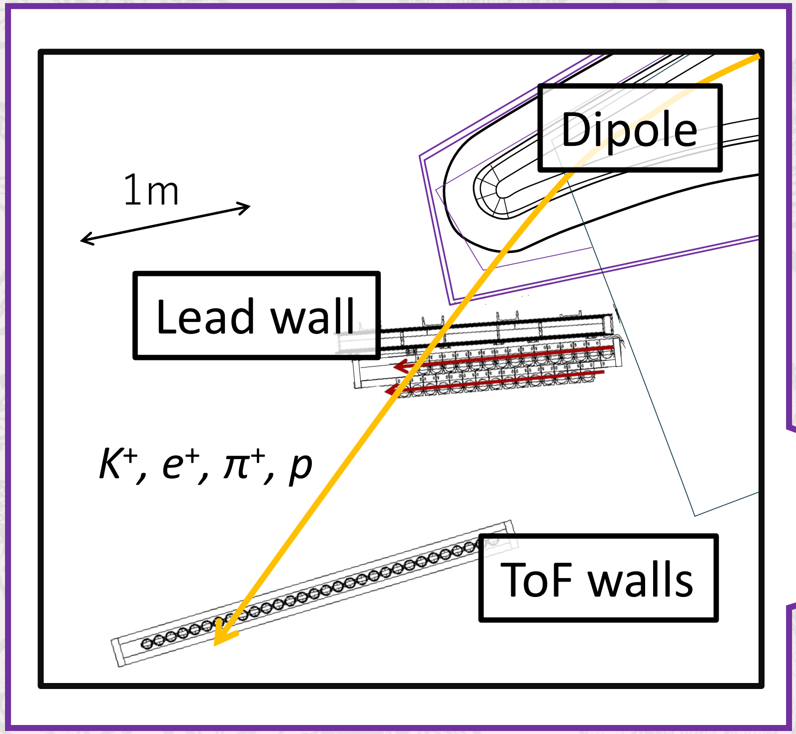
$$m({}^{A}_{\Lambda}Z) = \sqrt{m({}^{A}(Z+1))^2 + p_\pi^2} + \sqrt{m_\pi^2 + p_\pi^2}$$

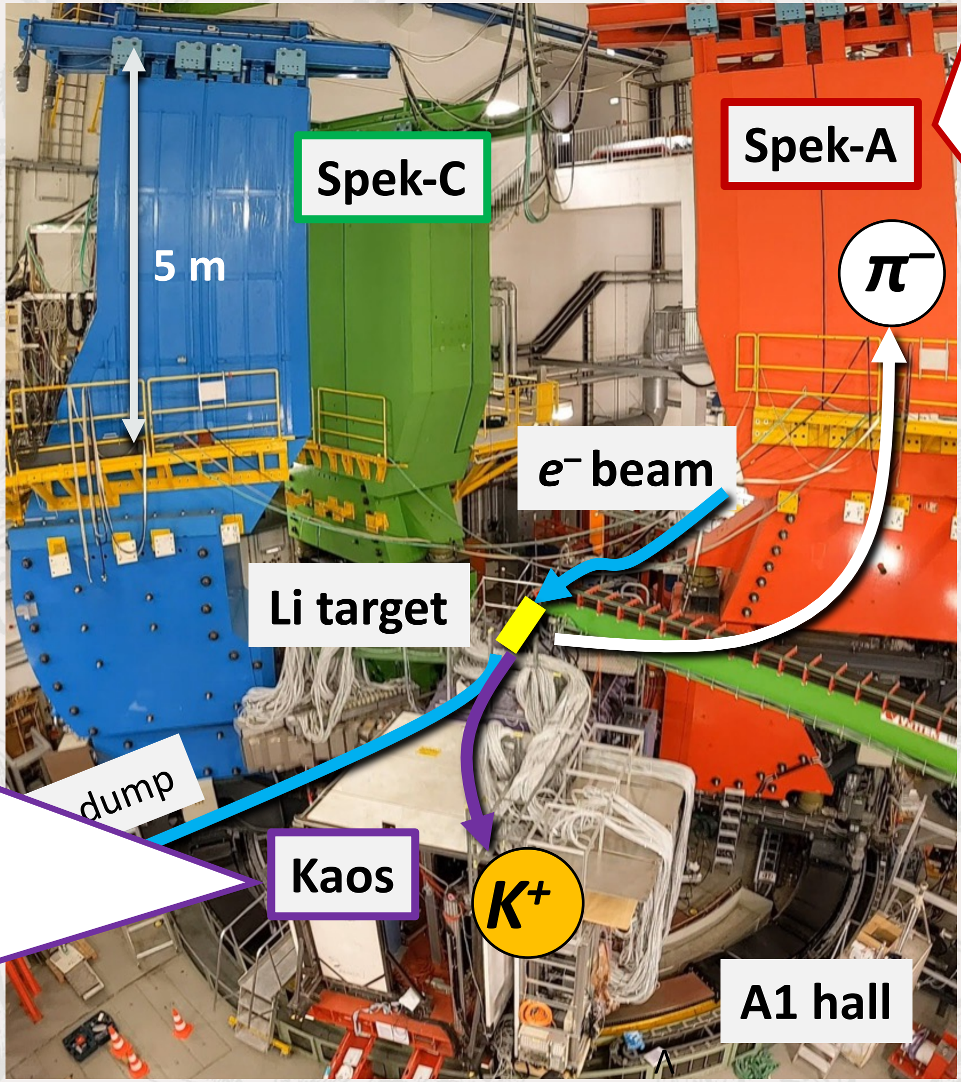
monochromatic momentum
→ high precision will be expected

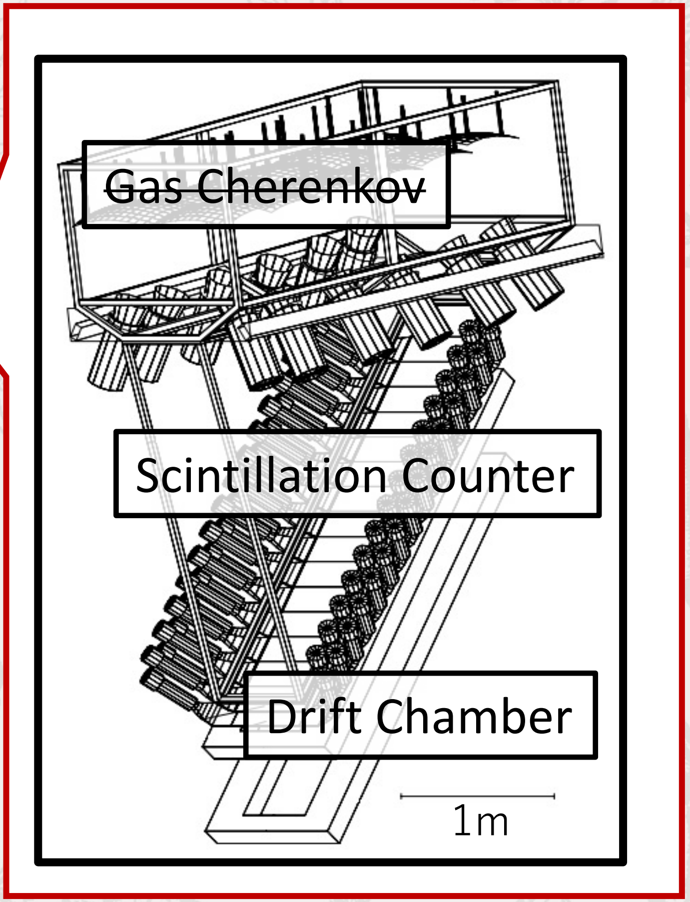
Decay-pion spectroscopy at MAMI

Kaon tagger

- Short orbital length (~ 6.4 m)
- Wide momentum acceptance







Measuring pion momentum

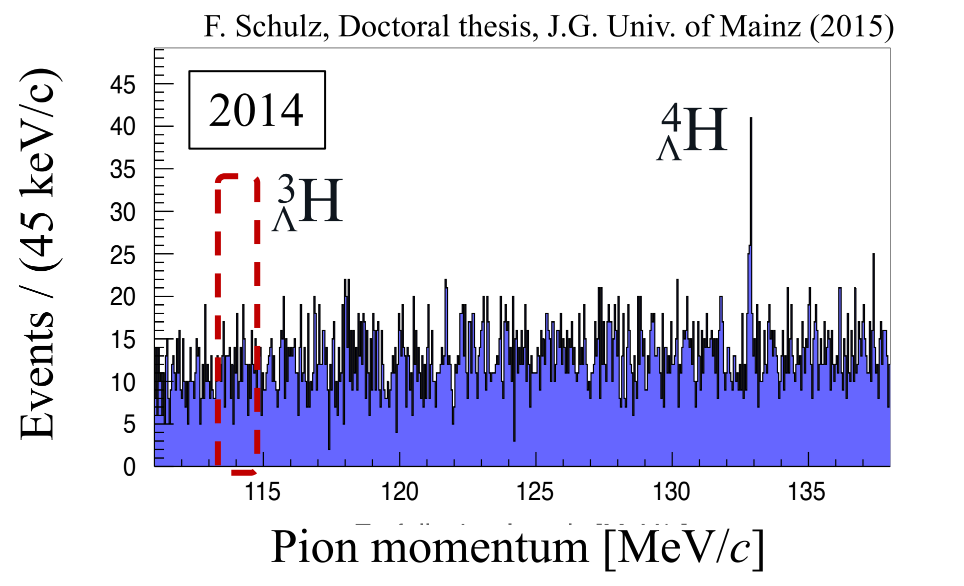
- Resolution: $\Delta p/p$ ~10^{-4}
- Long target acceptance (50 mm)

Previous experiment of Decay-pion spectroscopy

- Two body decays of hypernuclei:
  $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ @ 114 MeV/c
  $^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$ @ 133 MeV/c

- Result of $^{4}_{\Lambda}\mathrm{H}$ from the previous experiment

  $B_{\Lambda} = 2.157 \pm 0.005$ (stat.) $\pm$ **0.077** (syst.) MeV (2014)



New experiment

1. Increase the yield of $^{3}_{\Lambda}\mathrm{H}$ ➡ The new Lithium target system
2. Suppress systematic errors ➡ High-precision beam energy measurement

1. New Lithium target design

- From Beryllium to Lithium
- **Less background** as ^{9}Be

  No hyper-helium with similar decay pion momenta:

  $^{8}_{\Lambda}$He: 116.47 [MeV/c]

  ($^{3}_{\Lambda}$H: 114.3 MeV/c)

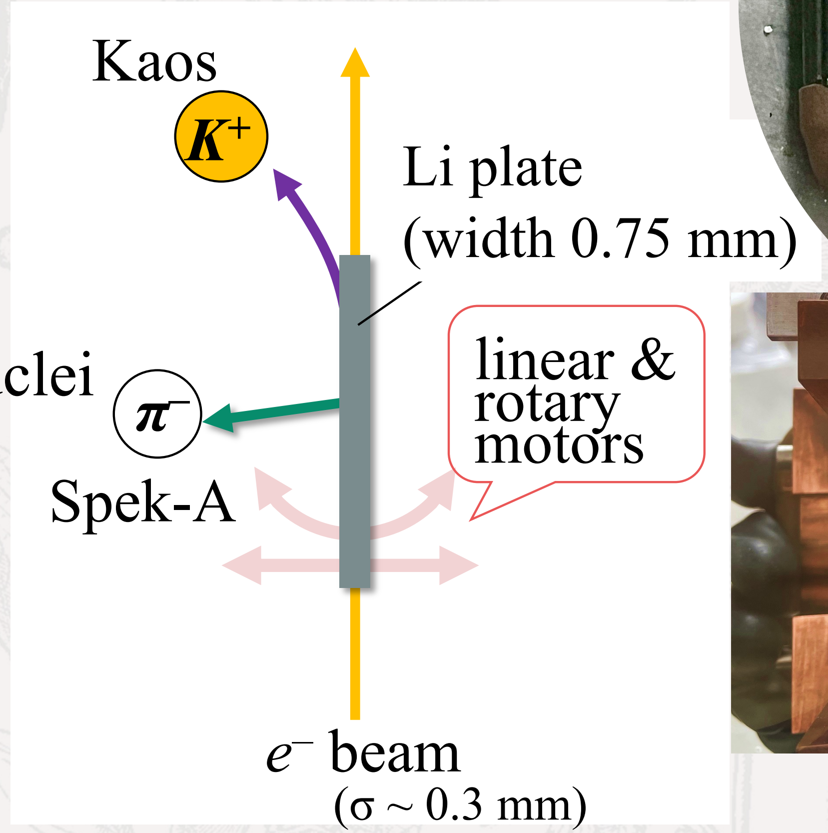
- **Maximized rate** of hypernuclei

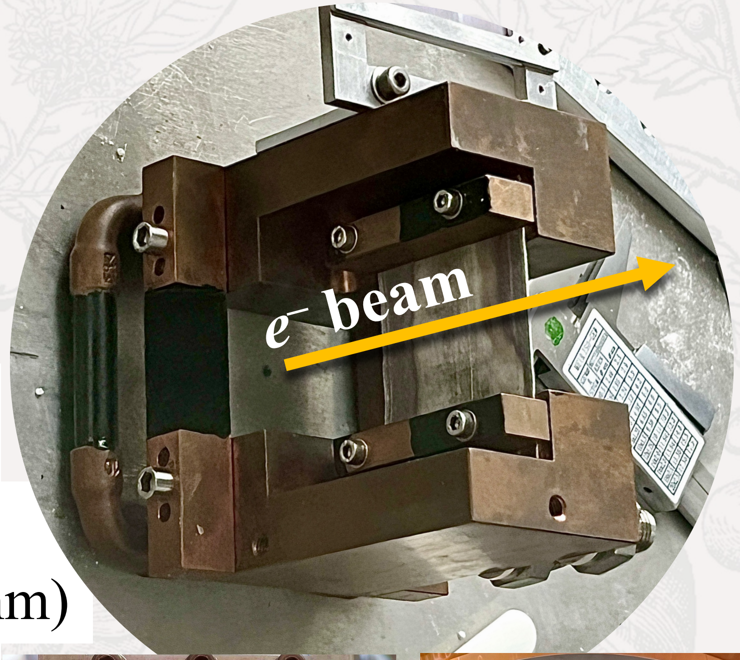
  Beam direction – 45 mm long

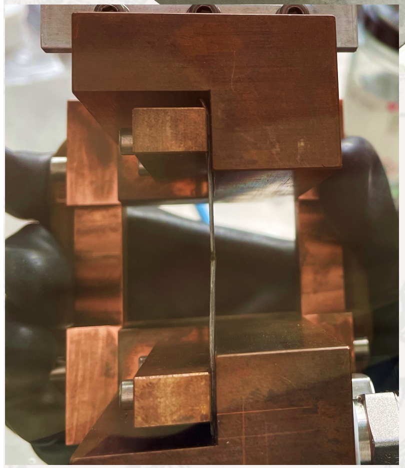
^{9}Be 27mg/cm^2, ~40 μA

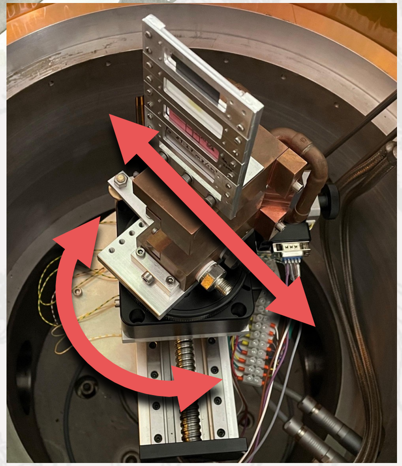
~100 times thicker

^{7}Li **2403** mg/cm^2, ~1 μA









2. Suppression of systematic error

Spectrometer momentum calibration
Established elastic electron scattering

- Relative resolution: 2×10^{-4}

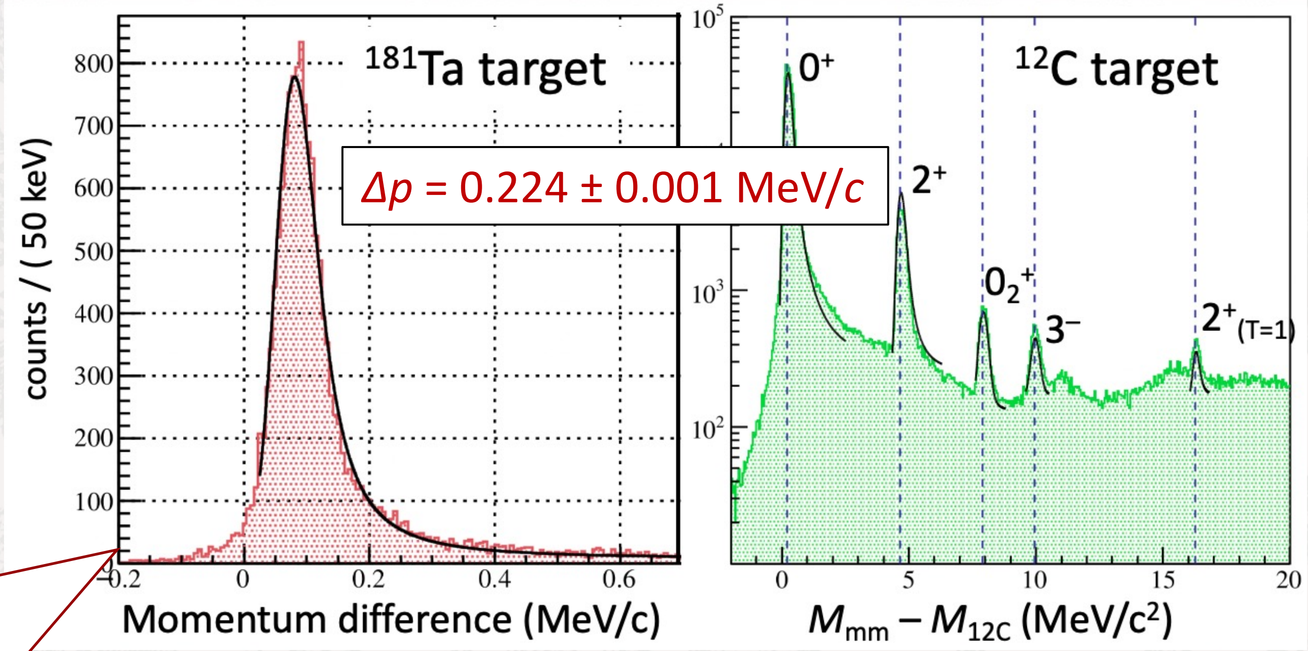
Momentum difference

(p_{m} : measured value)

$$= p_{\mathrm{calc}} - p_m$$

$$\simeq \frac{E_b}{1 + E_b/M_t(1 - \cos\theta_m)} - p_m$$

($m_e^2 << 1$)



e^- beam energy;
± 160 keV uncertainty

systematic error of $B_\Lambda(^4_\Lambda\mathrm{H})$
= 77 keV (2016)

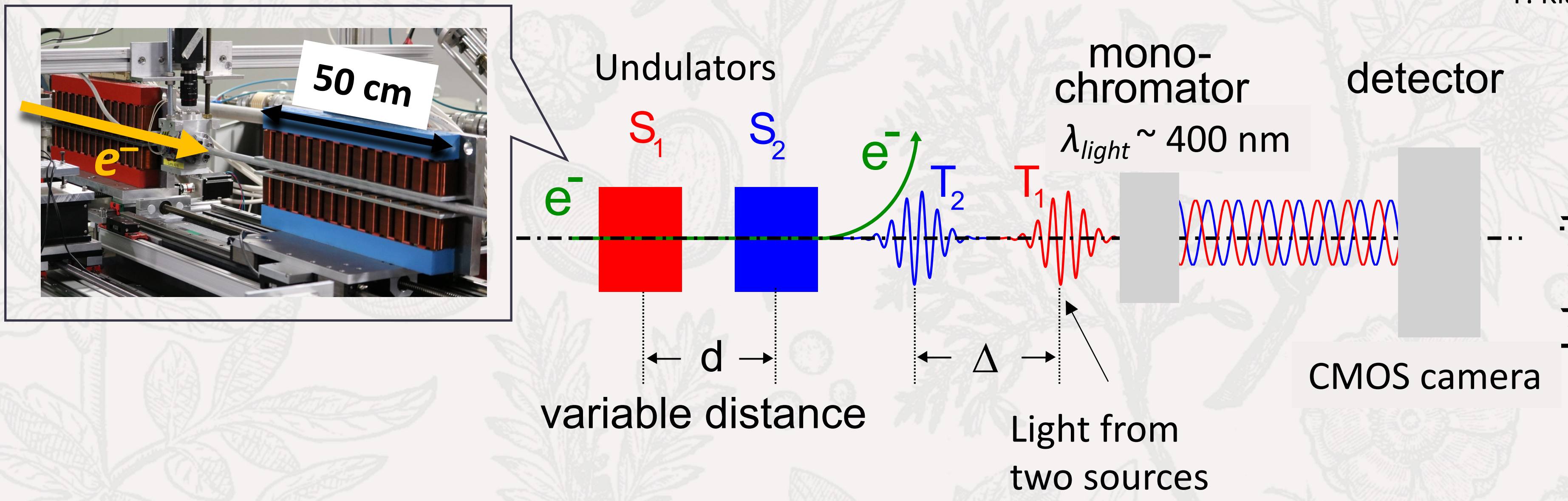
For low energy measurement with high accuracy
($\Delta E/E$ ~ 20 keV)

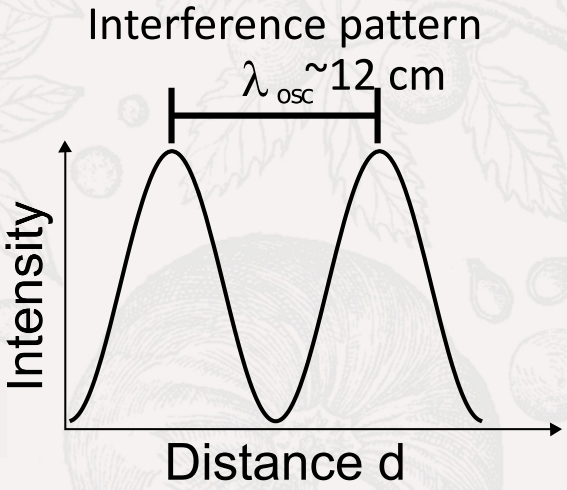
Undulator interference method

Interference of undulator radiation

K. Nishi, JPS2024 16aB111-8

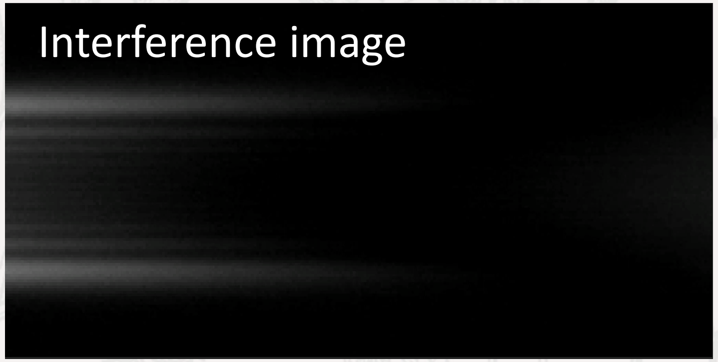
P. Klag *et al.*, NIM A 910 (2018) 147–156





- Synchrotron radiation from two undulators
- Phase difference related to the Lorentz factor of the electron beam
- Interference intensity period λ_{osc}: measured with a CMOS camera
- Calculate beam energy:

$$\gamma = \sqrt{\frac{\lambda_{osc}}{2\lambda_{light}}}$$



Interference of undulator radiation

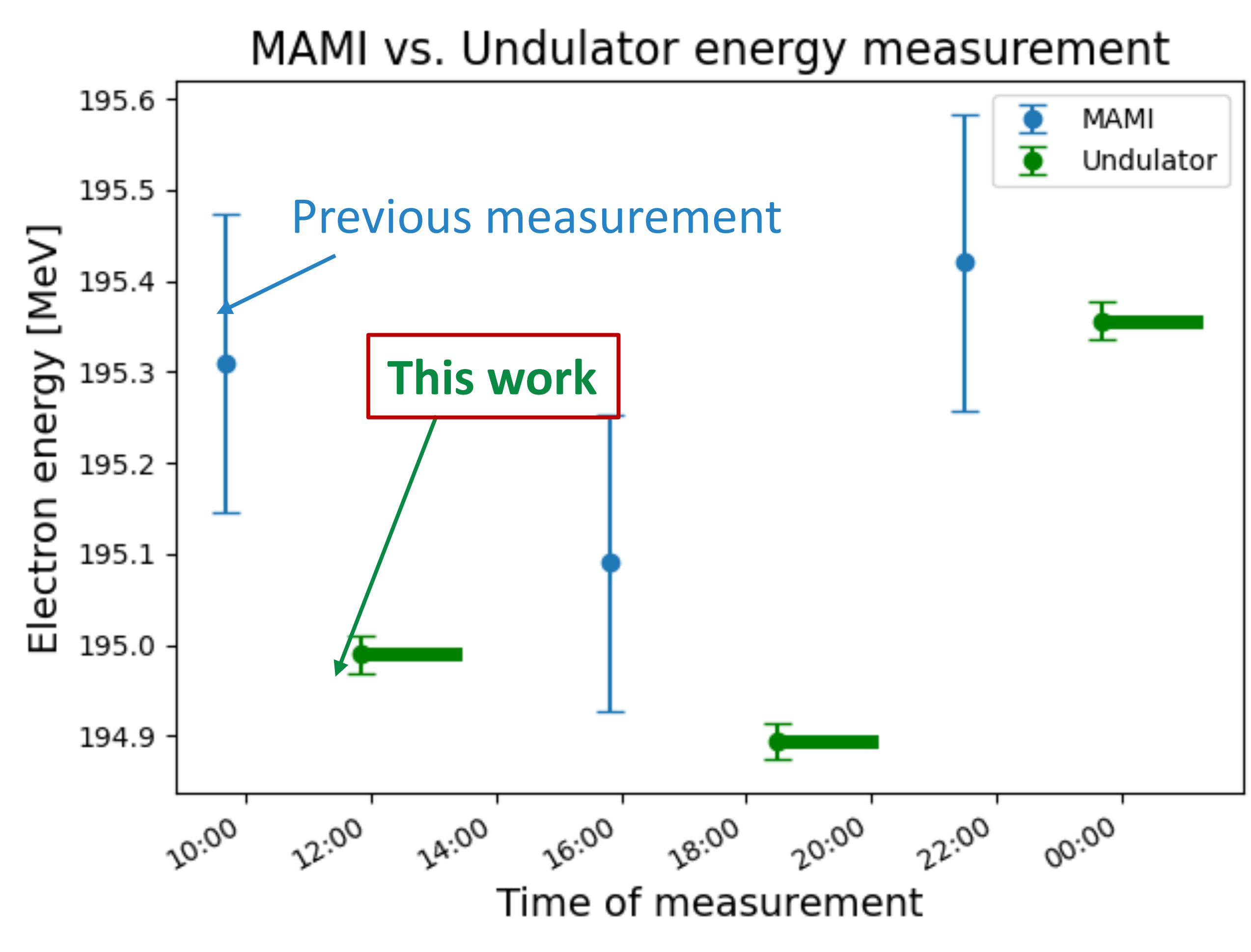
Relativistic γ via undulator eq.:

$$\gamma = \sqrt{\frac{\lambda_{osc}}{2\lambda_{light}}}$$

The accuracy of gamma depends on:

- Length measurement
- Monochromator-calibration
- Optical alignment

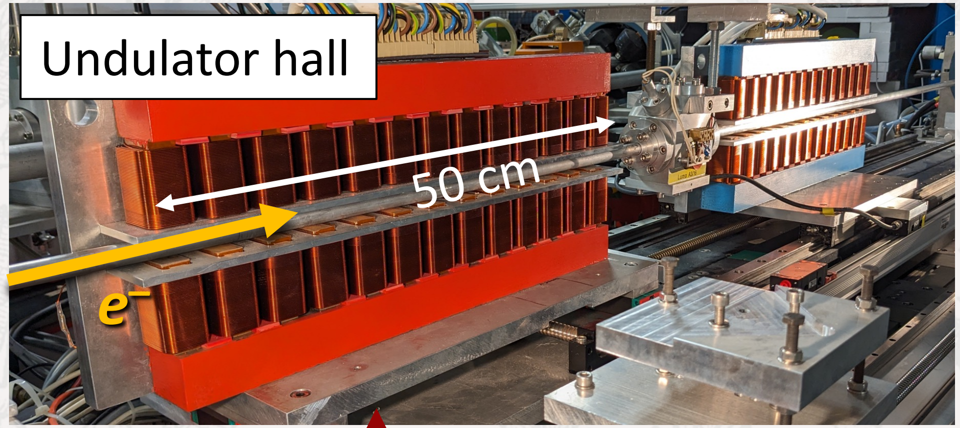
→ The precision of
$\Delta E/E$ ~ 18 keV (/200 MeV) is possible
10 times accurate!



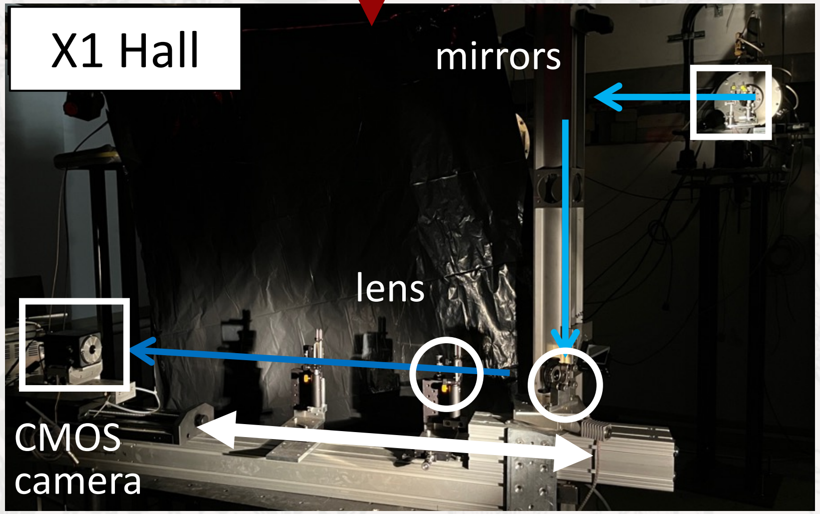
P. Klag, Ph.D. thesis, JGU Mainz (2024)

➡ The final systematic error will be less than ΔB_Λ ~10 keV!

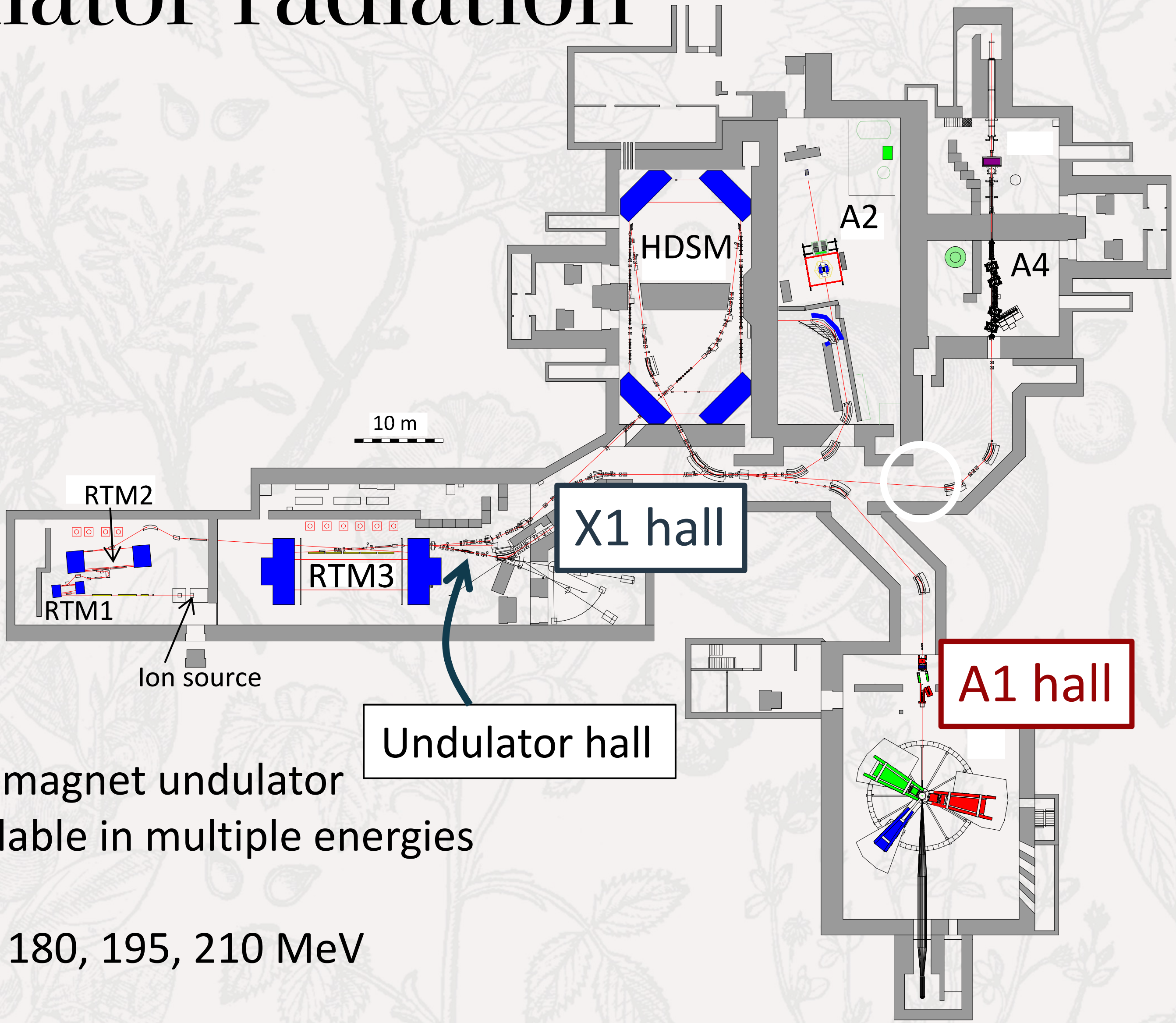
Interference of undulator radiation



10 m



K. Nishi, JPS2024 16aB111-8



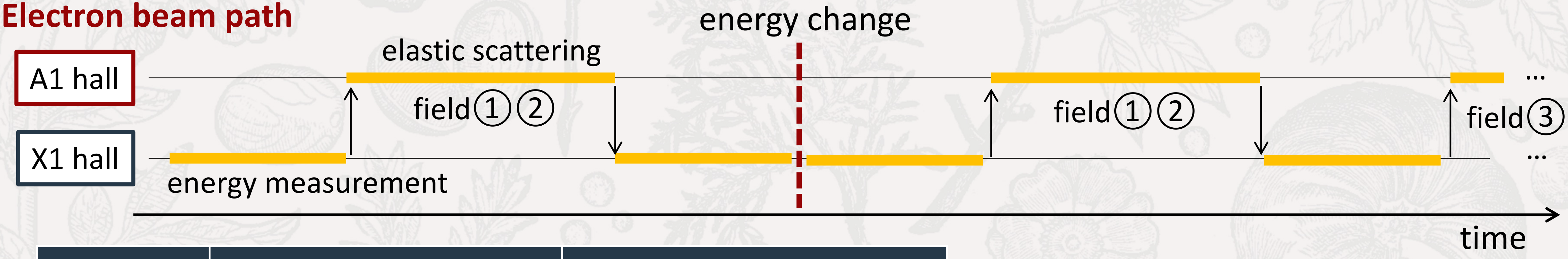
electromagnet undulator
→ available in multiple energies

E_{beam} = 180, 195, 210 MeV

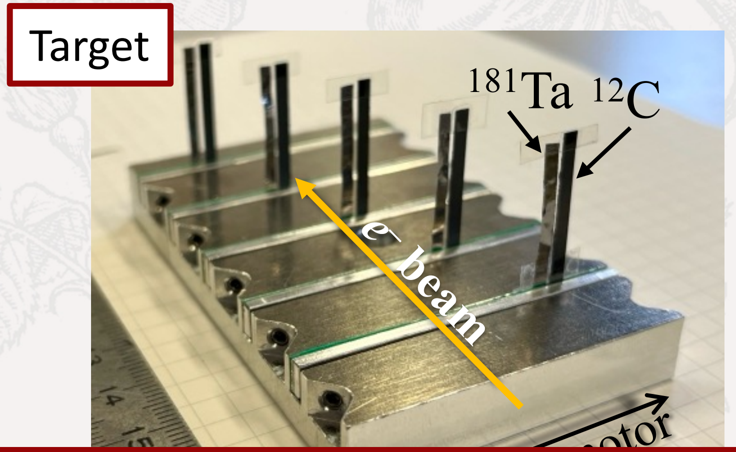
Summary of the spectrometer calibration experiment

Beamtime: March 19th – April 8th, April 29th – May 6th, 2024

Electron beam path



E_b (MeV)	Target	No. of Mom. sets	
		SpekA	SpekC
180	^{181}Ta × 5 & ^{12}C × 5	4	10
195	^{181}Ta × 5 & ^{12}C × 5	3	7
210	^{181}Ta × 5 & ^{12}C × 5	5	11
225	^{181}Ta × 5 & ^{12}C × 5	0	11



Quite enough data sets than the previous experiment & suppressed systematic errors!

Status of the experiment

Experiment

Commissioning run

Physics run

Run time: 541 hours
Beam charge: ~1.08 C
Momentum setting:
covering ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$
Target: Lithium, 2403 mg/cm^2

Spectrometer calibration
(Electron elastic scattering)

Target: ^{181}Ta, ^{12}C, multi-foil
Beam energy: 180 – 420 MeV
Combined with the undulator interference method

FY2022 → **FY2023** → **FY2024** → **FY2025**

Analysis

Physics data analysis

- ✓ Parameter adjustment
- ✓ Particle tracking
- ❑ Particle identification
- ❑ (matrix tuning)

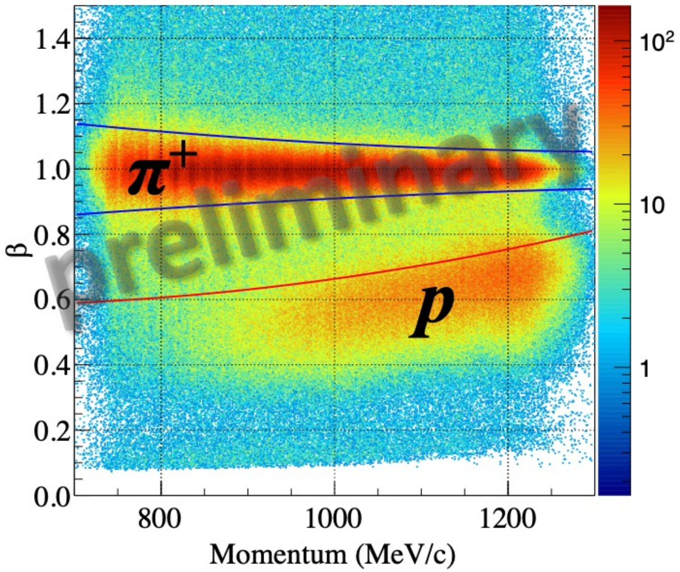
Calibration data analysis

- ✓ Peak fitting
- ❑ Calibration factor estimation
- ❑ Peak shape study

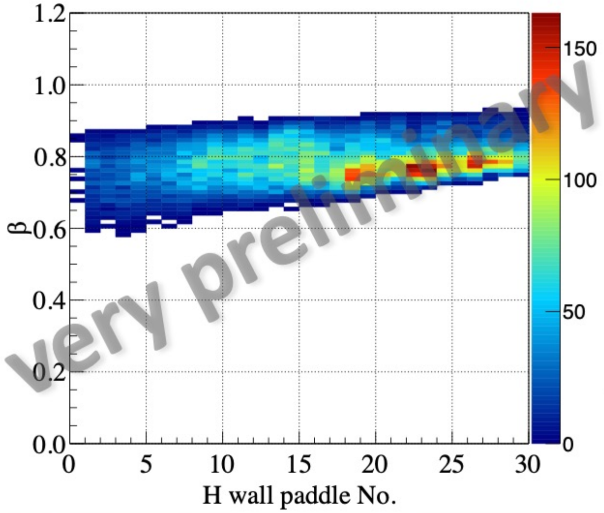
the undulator interference

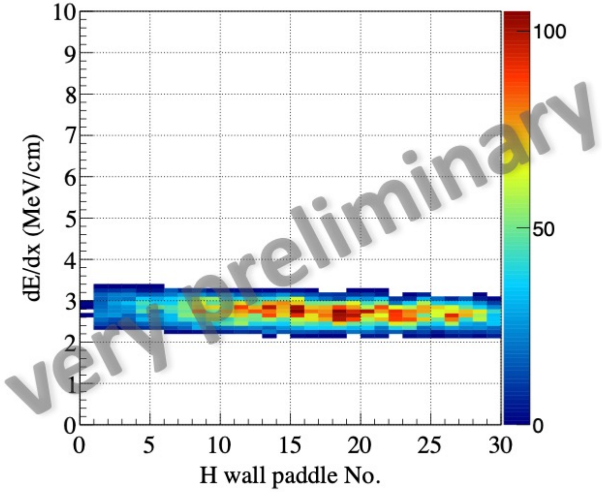
Particle identification

Clearly identify ▶
Protons and Pions BG



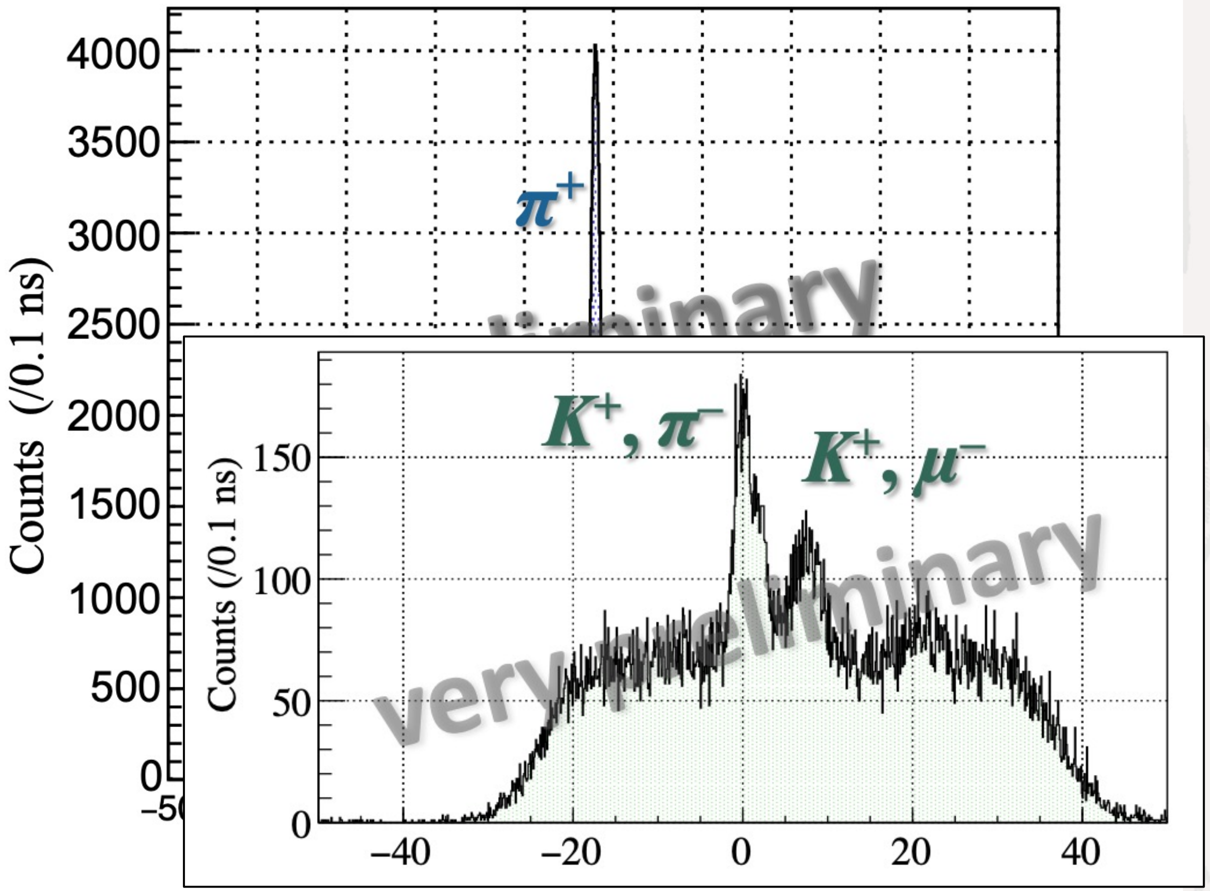
Selected Kaons ▼



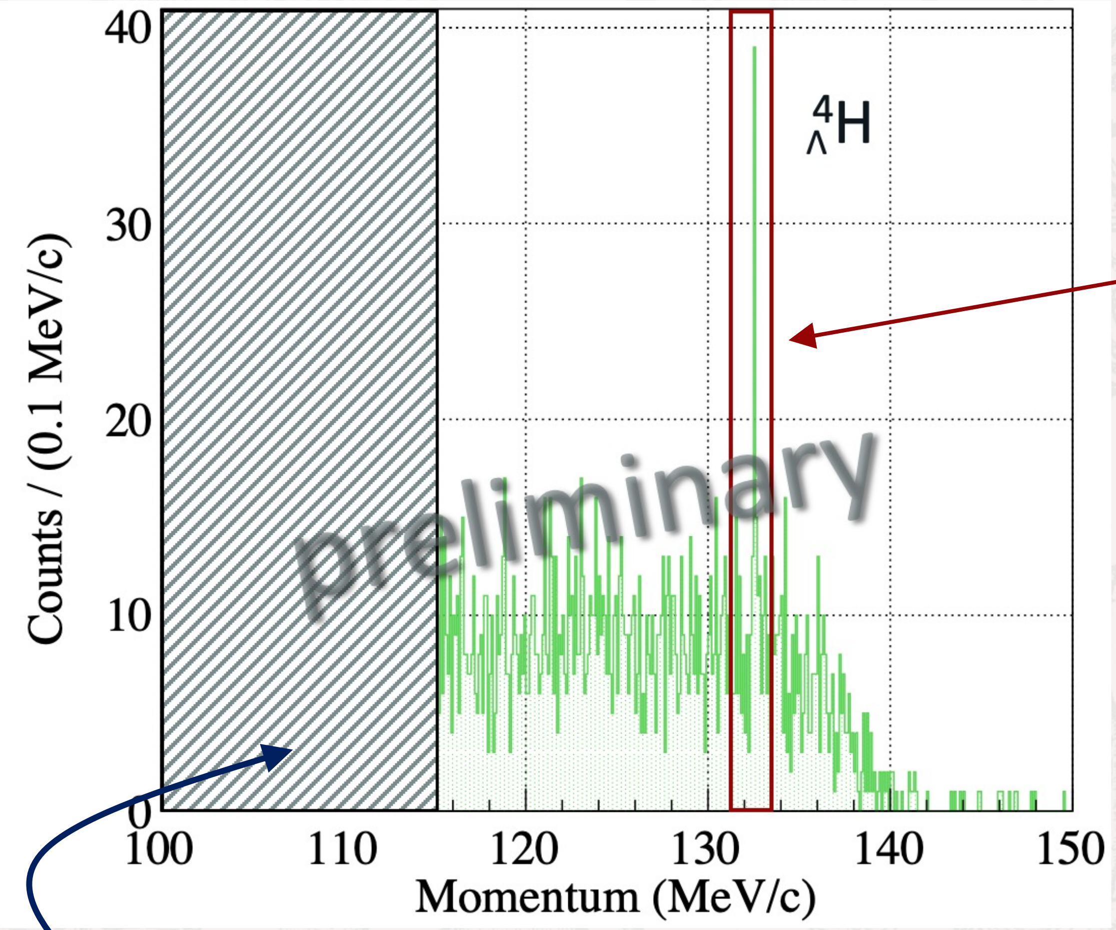


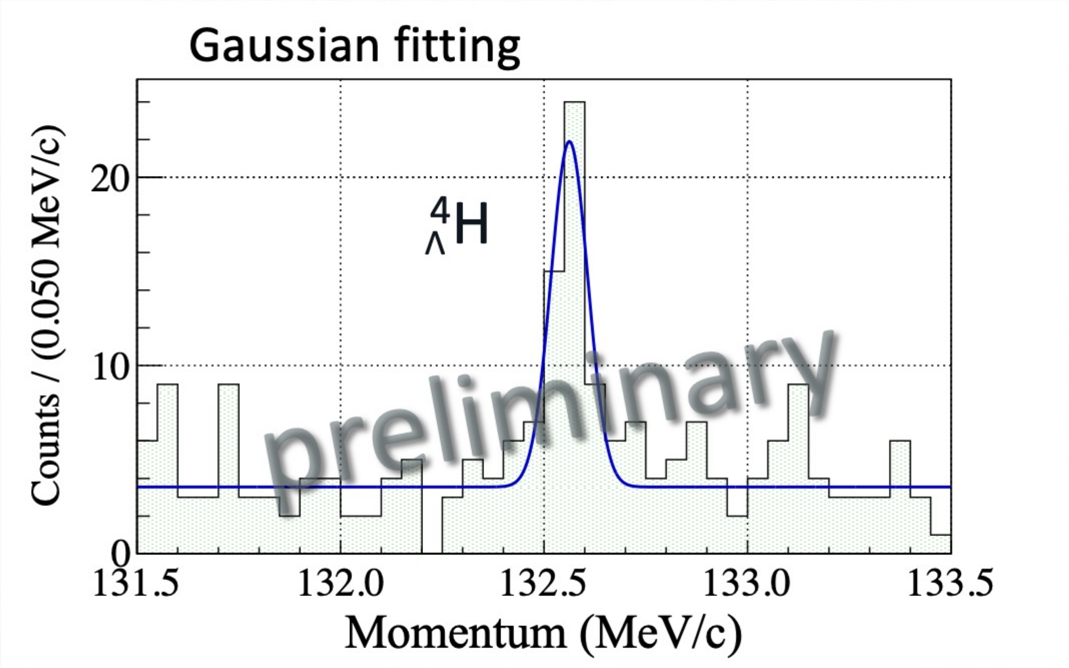
Coincidence between Pion & Kaon spectrometers

$(= t_{\mathrm{spekA}} - t_{\mathrm{KAOS}})$



Pion momentum distribution





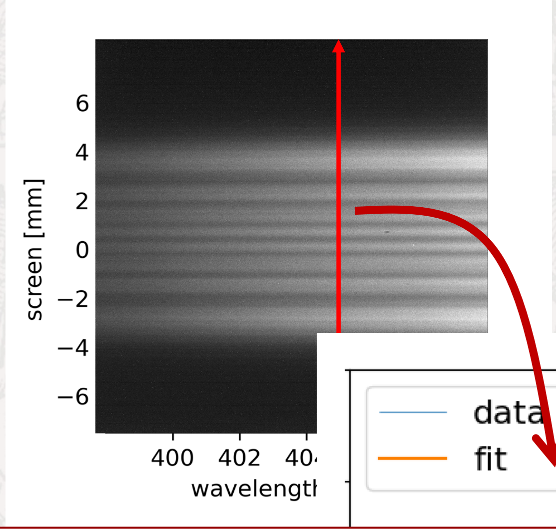
p_π = 132.65 ± 0.008 (MeV/c) ← to be calibrated!

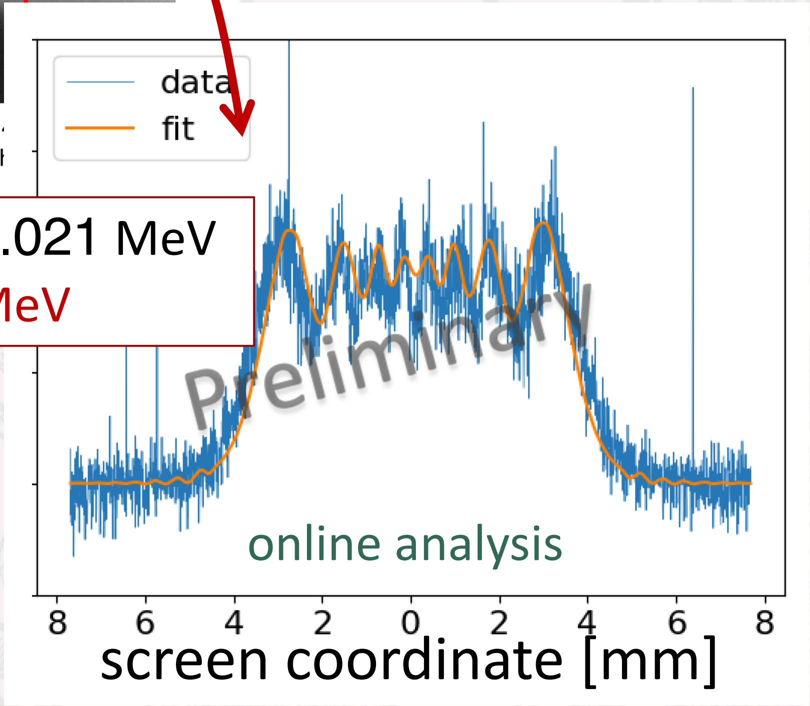
σ = 0.05 ± 0.01 (MeV/c)

(2014: p_π = 132.92 (MeV/c))

pion from $^{3}_{\Lambda}H$ peak appear if $B_\Lambda > 0$ MeV

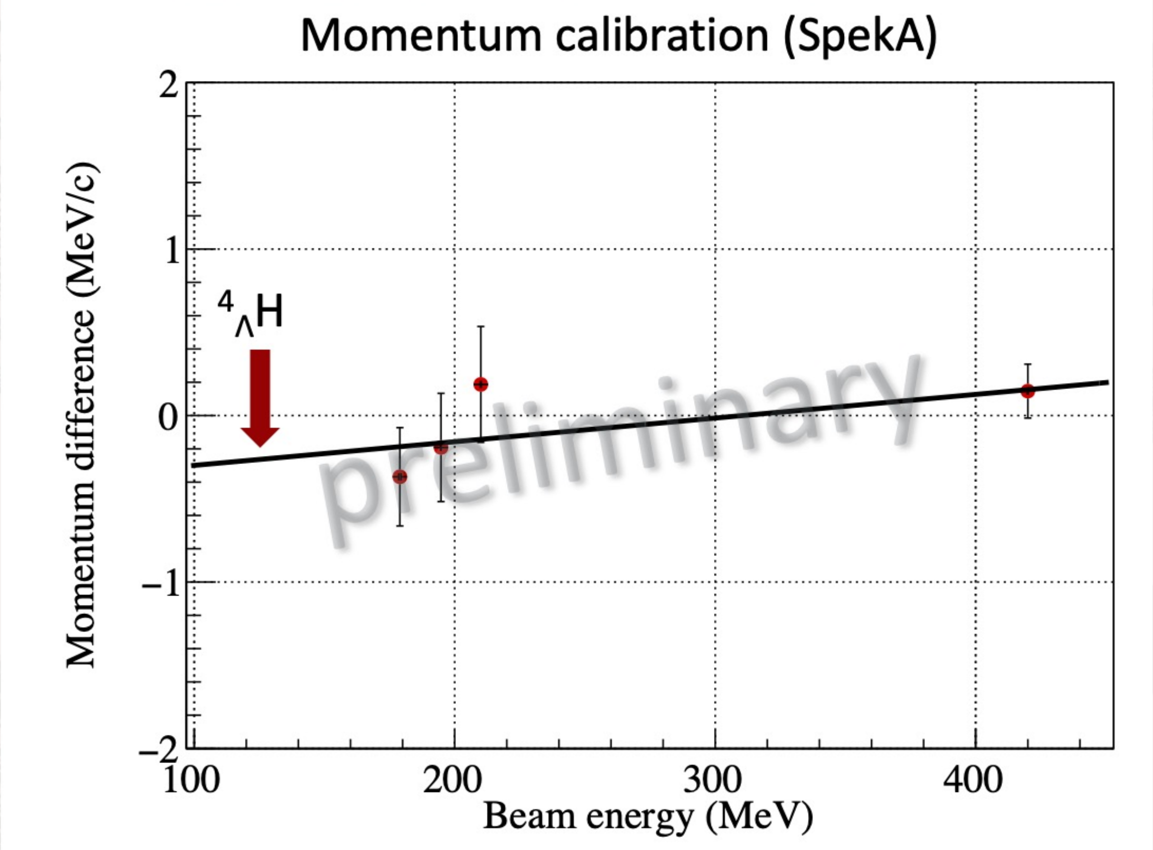
Latest analysis status of the calibration





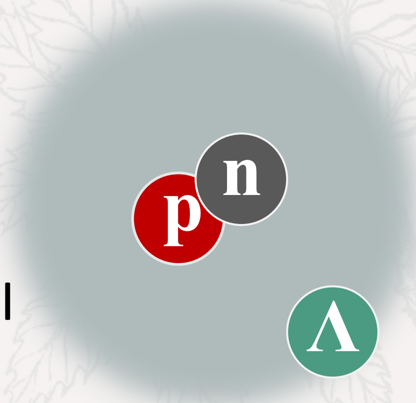
E_b =194.768 ± 0.021 MeV
→ δE_b < 0.010 MeV

K. Nishi, JPS2024
16aB111-8



The analysis is still ongoing:
- Undulator interference
- Scattered electron momentum

Summary



- Measuring B_Λ of s-shell hypernuclei by Decay-pion spectroscopy at MAMI
- Updates from the previous experiments
  - Lithium long targeting system → Increased ${}^{3}_{\Lambda}H$ yield
  - Momentum calibration method combined with undulator interferometry

    → The total error will be suppressed to less than 20 keV
- Analysis status
  - Particle ID is now ongoing, and absolute momentum will be calibrated