SPICE: Strange hadrons as a Precision tool
for strongly InteraCting systEms

Progress in mass measurement of light hypernuclei and high-precision spectrometer calibration method at MAMI

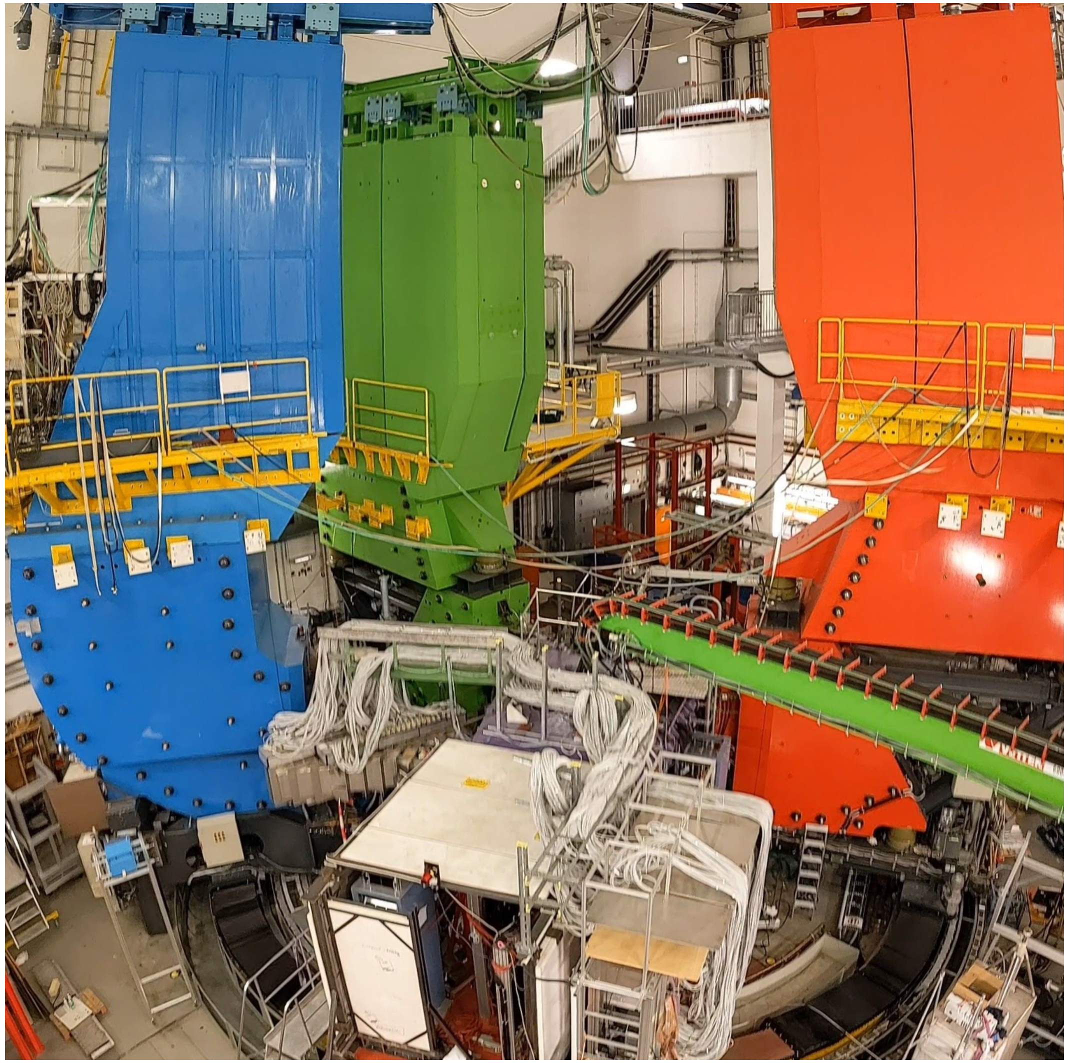
Ryoko Kino   Tohoku Univ.

for the A1 hypernuclear Collaboration

TOHOKU UNIVERSITY   GPPU 宇宙創成物理学国際共同大学院   東京大学 THE UNIVERSITY OF TOKYO   JG|U   STRONG 2020   A1

May 15, 2024

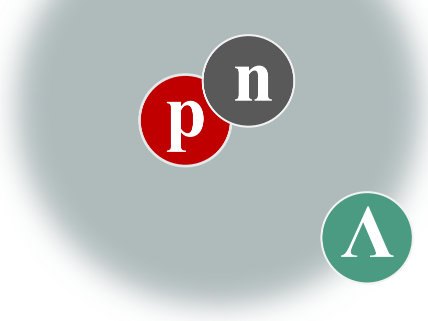
*ECT**
European Centre for Theoretical studies in nuclear physics and related areas
Trento, Italy



Λ Binding Energy of Hypertriton

Hypertriton – a benchmark in hypernuclear physics

d-Λ binding system



Shallow binding?
or
Deeply bounded?

- Still large experimental uncertainties:

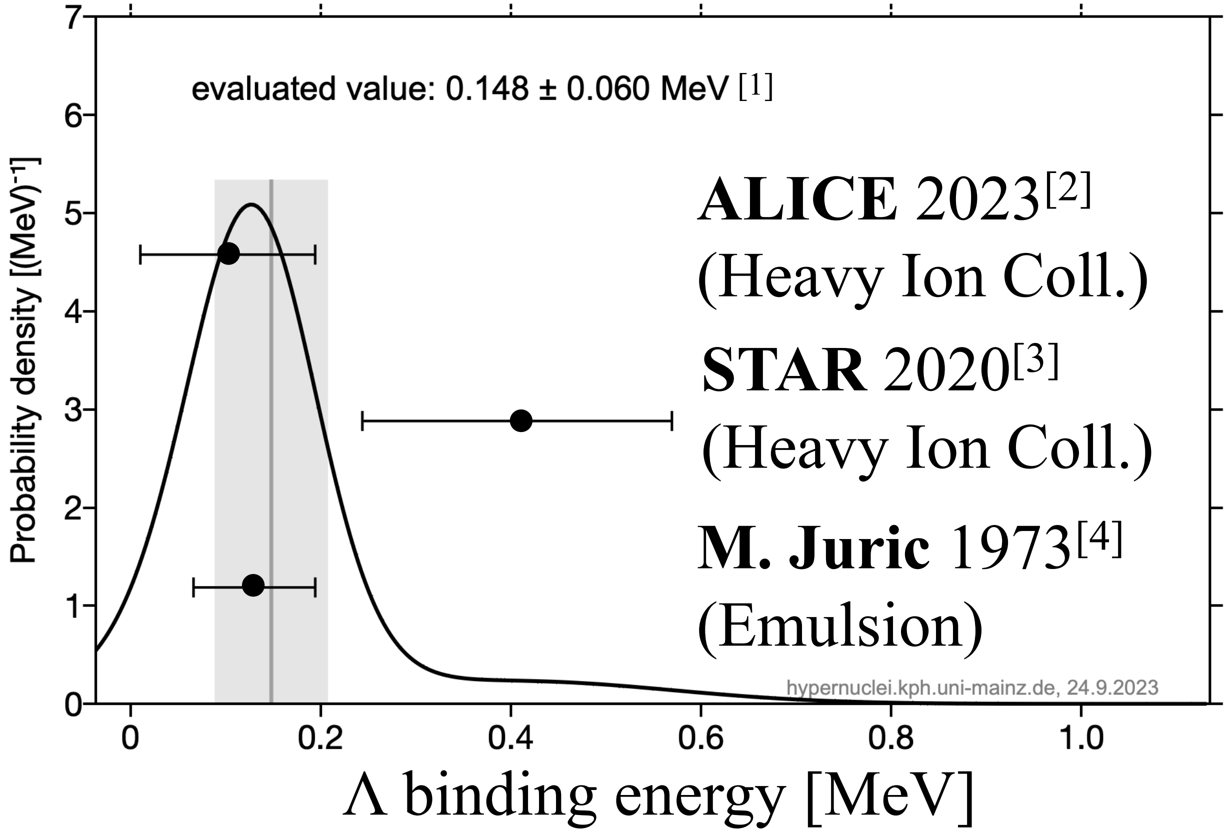
  STAR 2020 : $0.41 \pm 0.12_{(stat.)} \pm 0.11_{(syst.)}$ MeV

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

- Need to clarify with the lifetime

→ Decay-pion spectroscopy at MAMI

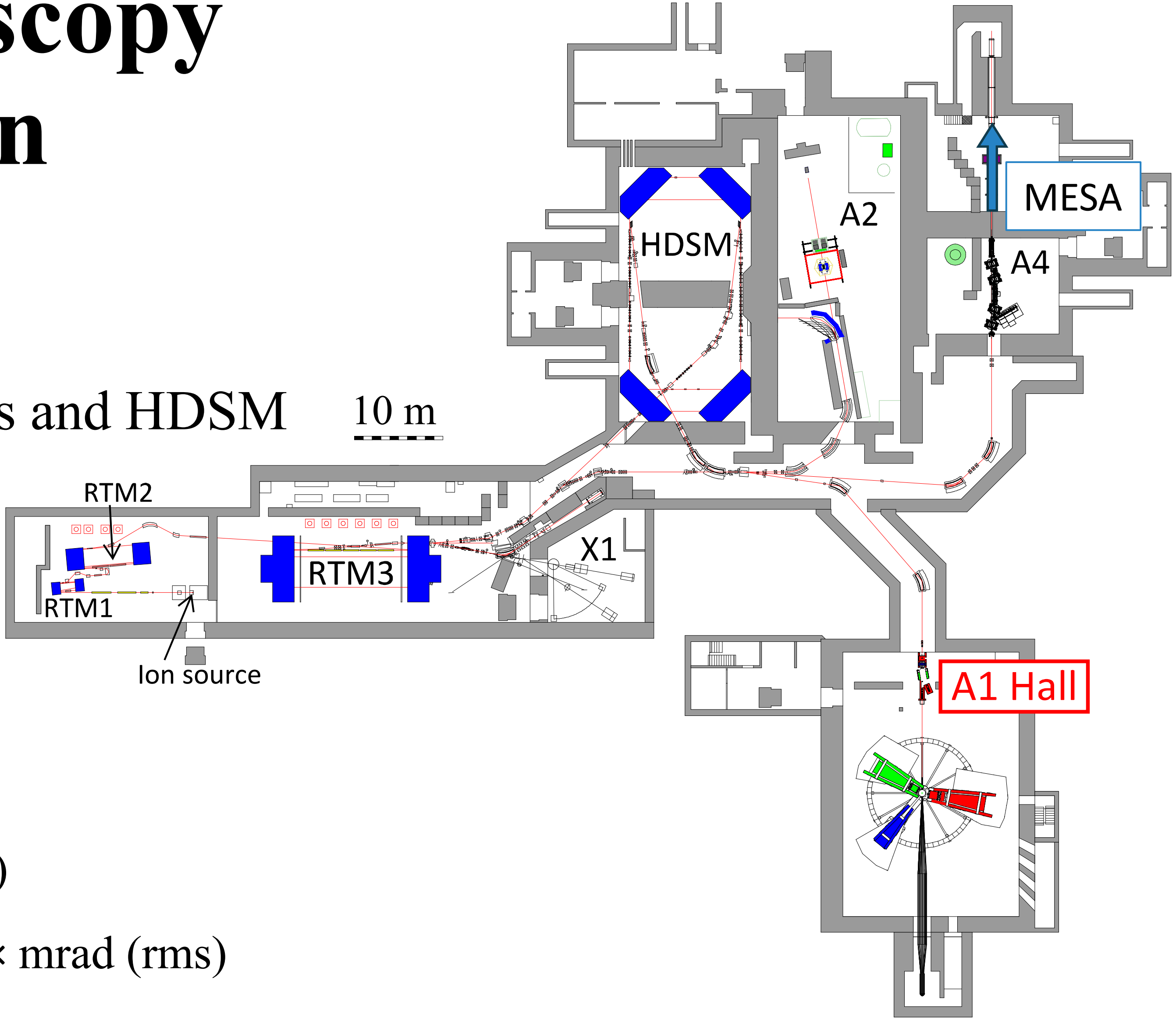
[1] Hypernuclear database (https://hypernuclei.kph.uni-mainz.de/)
P. Eckert *et al.*, Suplemento de la Revista Mexicana de Fisica 3 0308069 (2022) 1-6



[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

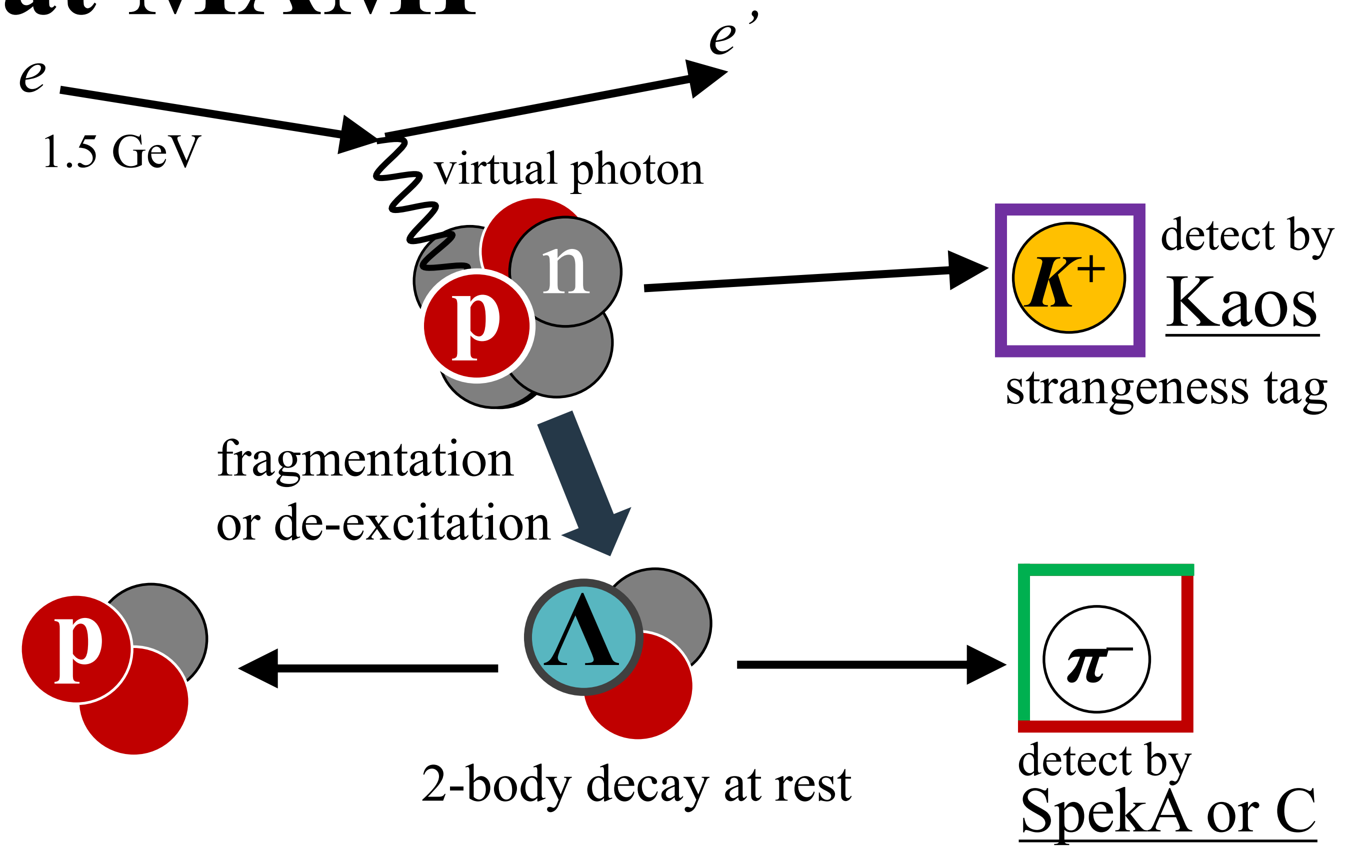
Decay-pion spectroscopy at MAinz-MIcrotron

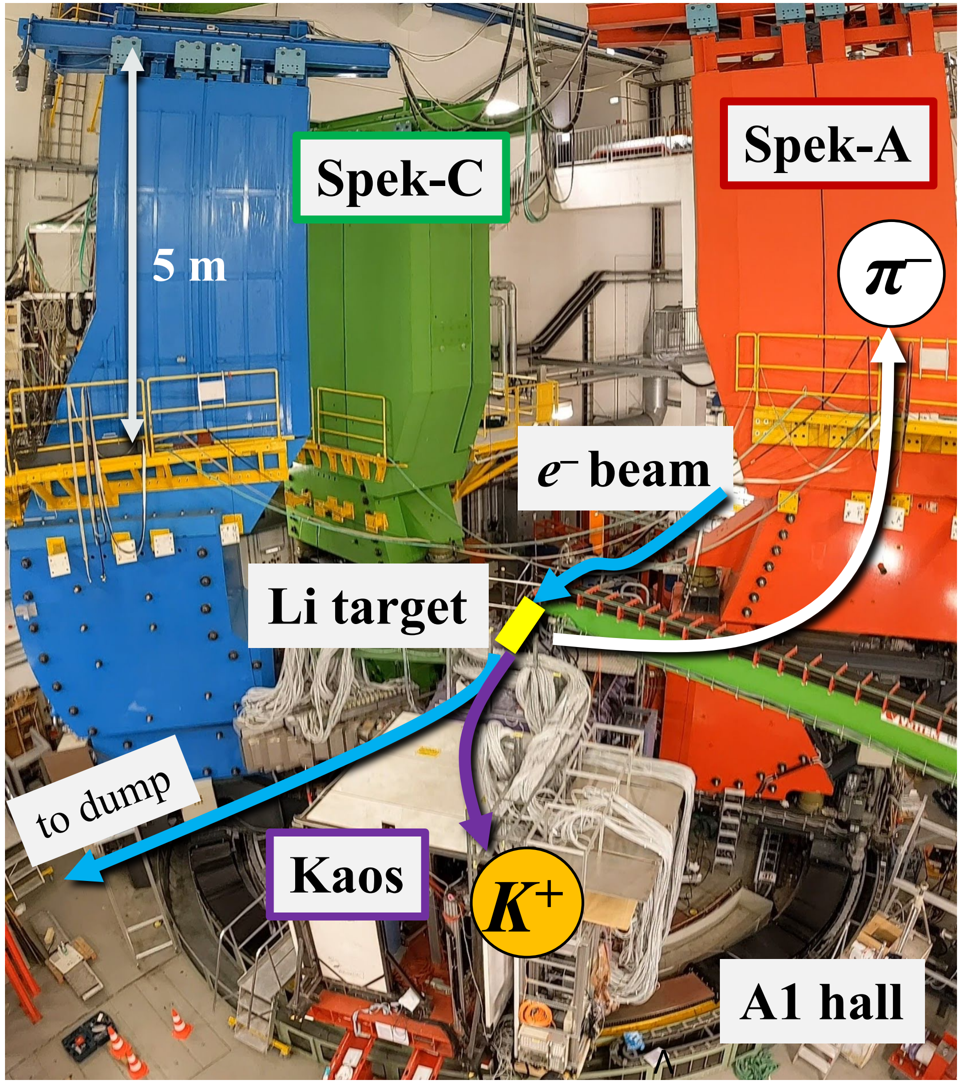
- continuous electron accelerator
- accelerates up to 1.5 GeV
  with three Race-Track-Microtrons and HDSM



- Beam energy: Max.1508 MeV
- Beam intensity: Max.~100 μA
- Duty factor: 100%
- Energy resolution: ΔE~110 keV(FWHM)
- Beam emittance [vertical]: < $1.2\pi \times \mu m \times$ mrad (rms)

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

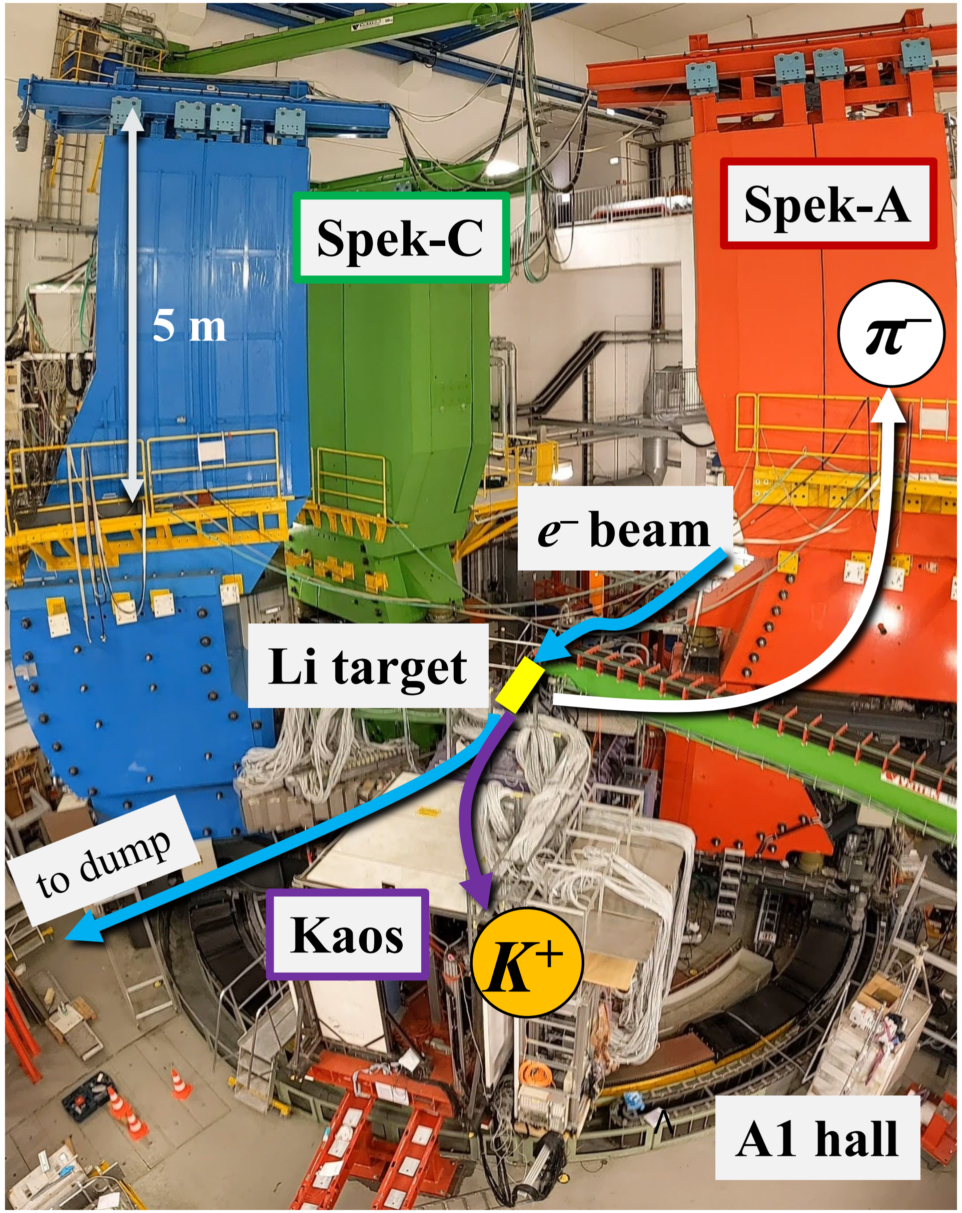
Magnetic spectrometer A & C Measuring pion momentum

- Offer high momentum resolution of $\Delta p/p \sim 10^{-4}$
- Large solid angle (28 msr), angular range (15° – 160°), and momentum acceptance (20 – 25%)
  → long- target acceptance (50 mm)

Kaos Detection of Kaons
→ Identify hyperon production events

- Short central orbital length (~ 6.4 m)
  → Suitable for short-live kaons ($c\tau \sim 3.7$ m)
- Wide momentum acceptance → High yield of kaons

Coincidence events: Kaos ∩ (A ∪ C)



Previous experiment of Decay-pion spectroscopy

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

  $B_{\Lambda} = 2.12 \pm 0.01\ (\mathrm{stat.}) \pm 0.09\ (\mathrm{syst.})\ \mathrm{MeV}$ (2012)

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

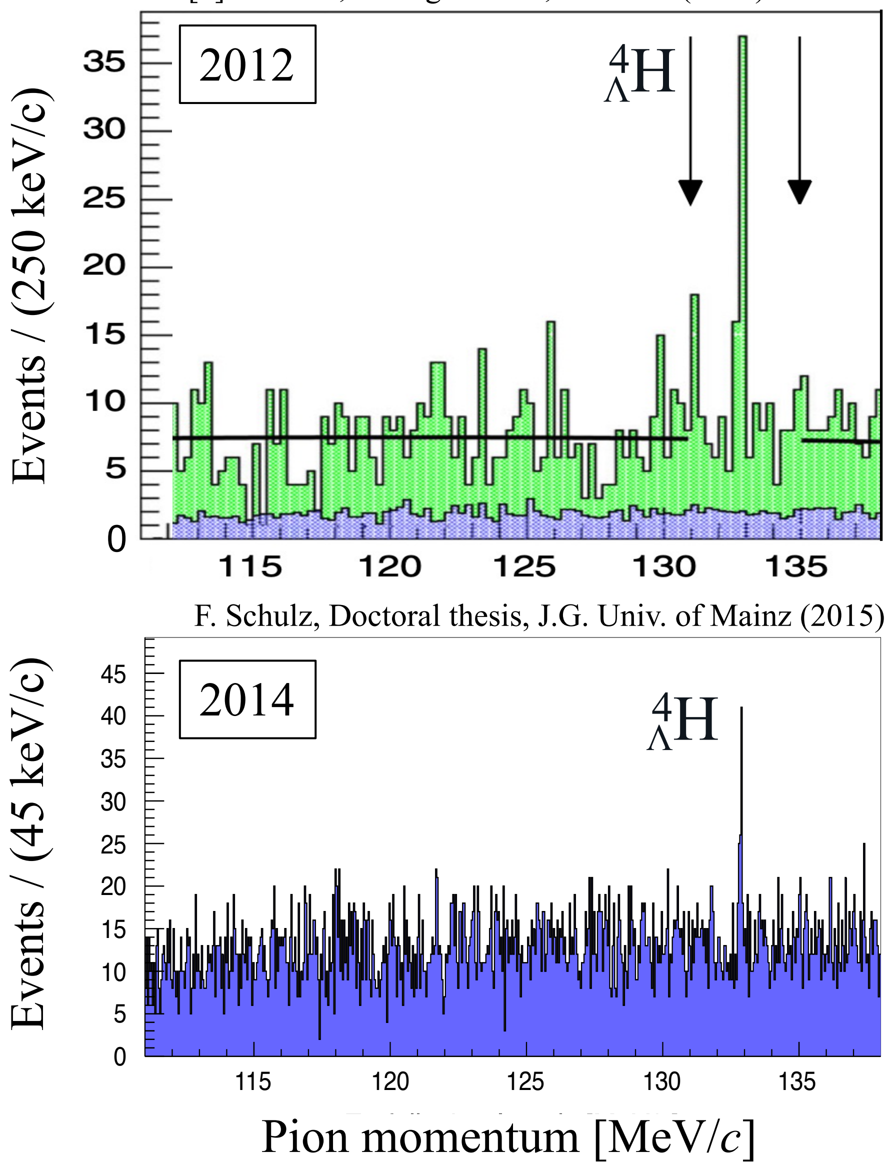
- Two body decays of hypernuclei:

  ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ @ 114 MeV/c

  ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$ @ 133 MeV/c

[8] A. Esser, S. Nagao *et al.*, PRL 114 (2015) 232501.

F. Schulz, Doctoral thesis, J.G. Univ. of Mainz (2015)



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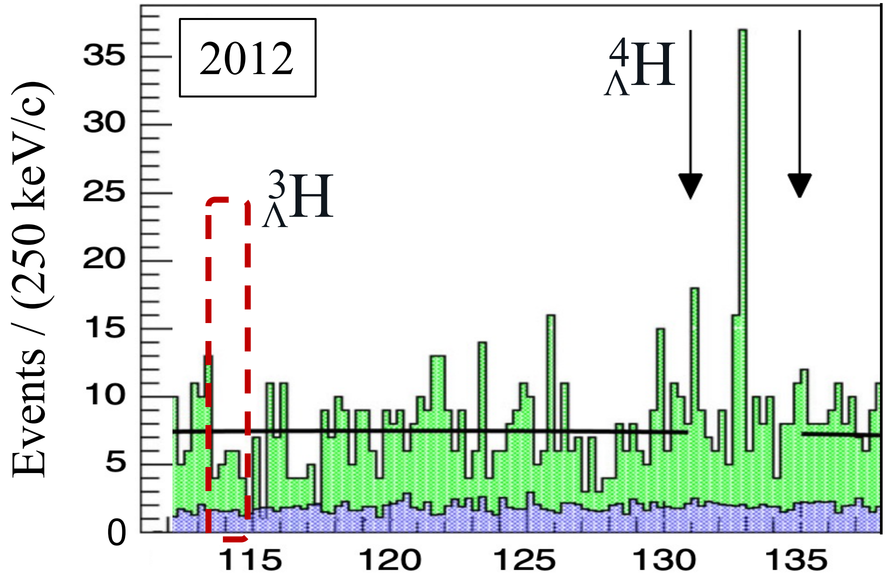
We need to…

- ❑ Ensure the yield of ${}^{3}_{\Lambda}\mathrm{H}$
- ❑ Suppress systematic errors

A. Esser, S. Nagao *et al.*, PRL 114 (2015) 232501.



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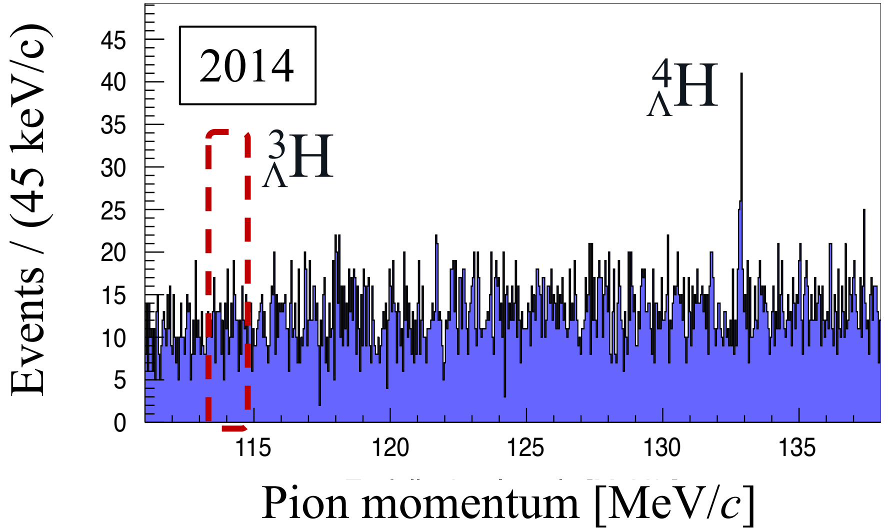

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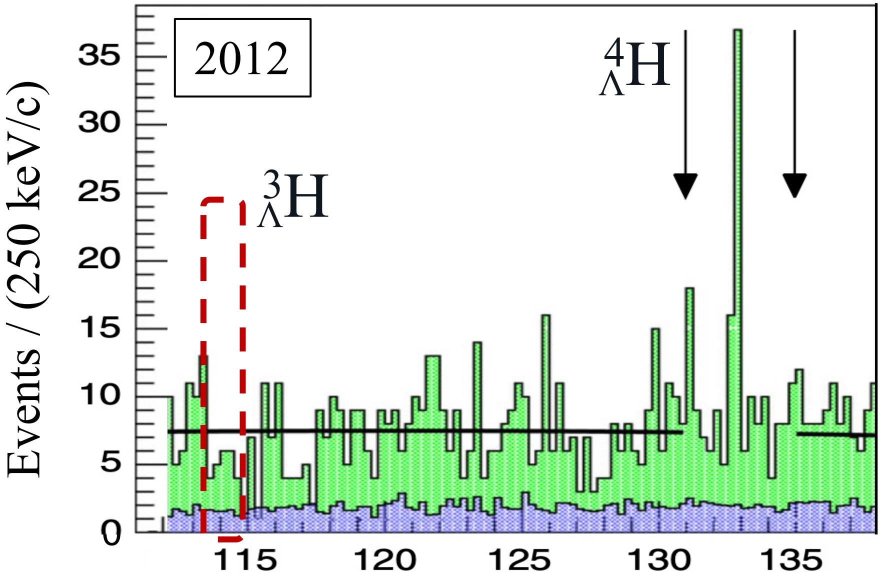

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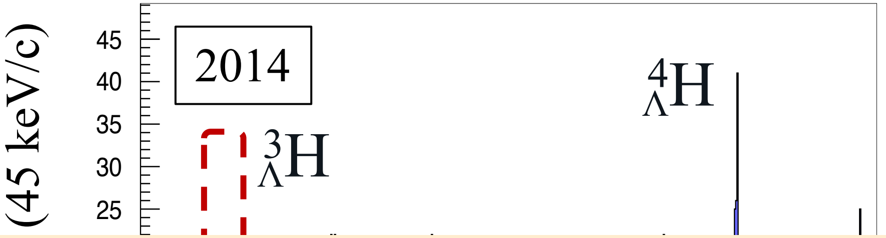


New experiment

- ❑ Ensure the yield of ${}^{3}_{\Lambda}$H → The new Lithium target system
- ❑ Suppress systematic errors → High-precision beam energy measurement

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)

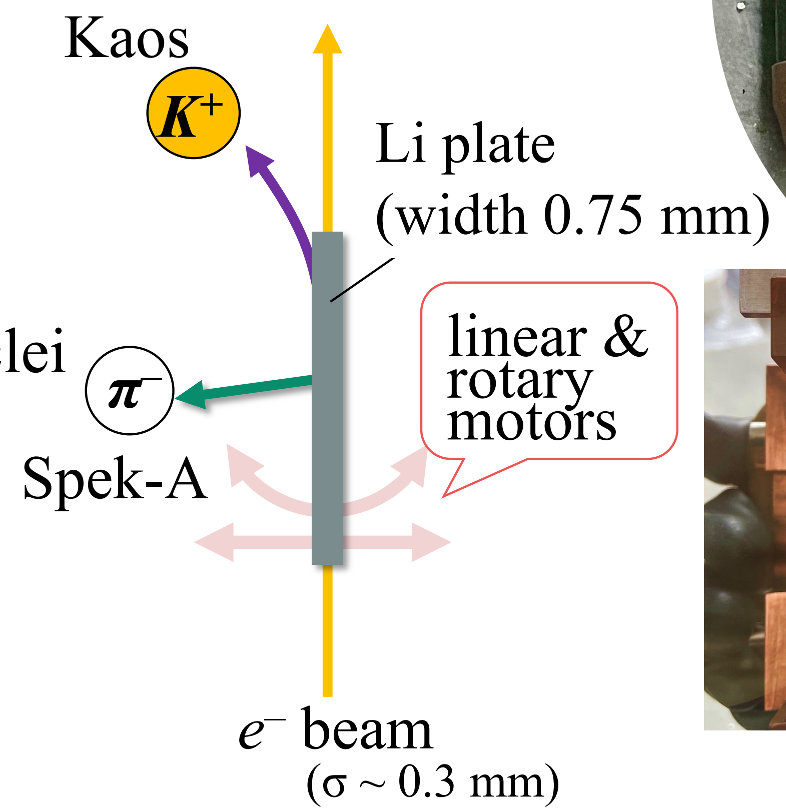
- **Maximized rate** of hypernuclei

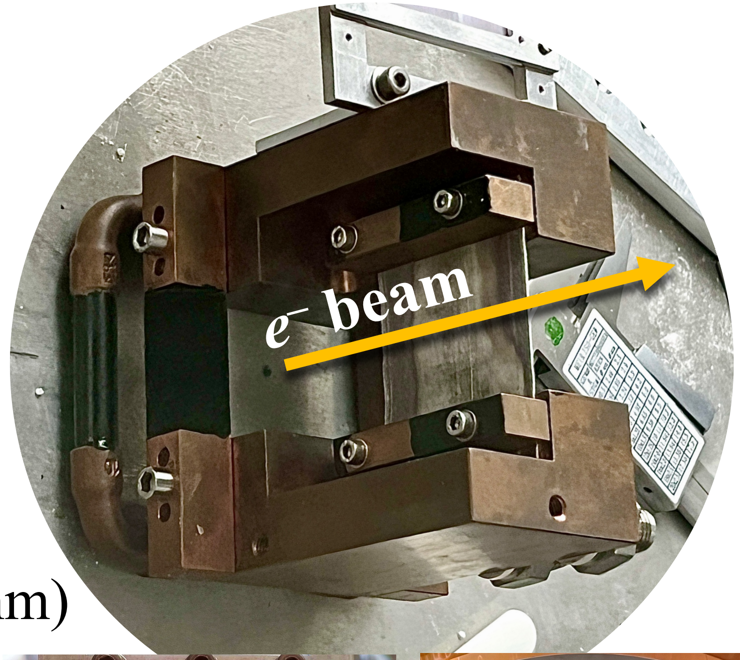
  Beam direction – 45 mm long

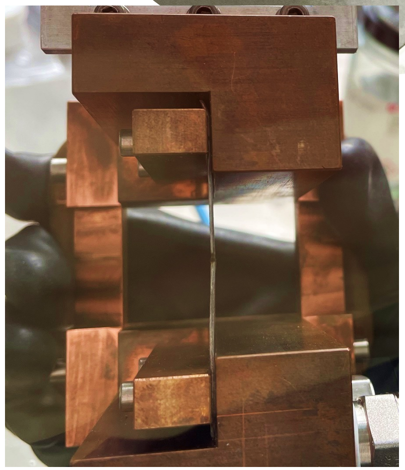
^{9}Be 27mg/cm^{2}, ~40 μA

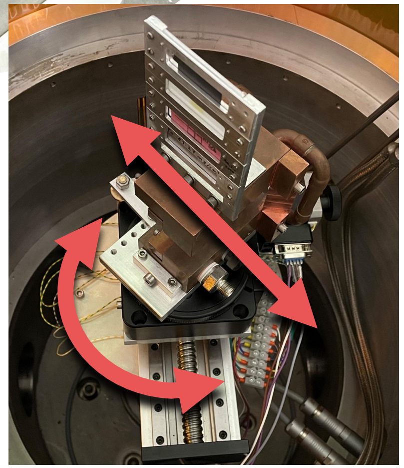
~100 times thicker

^{7}Li **2403** mg/cm^{2}, ~1 μA







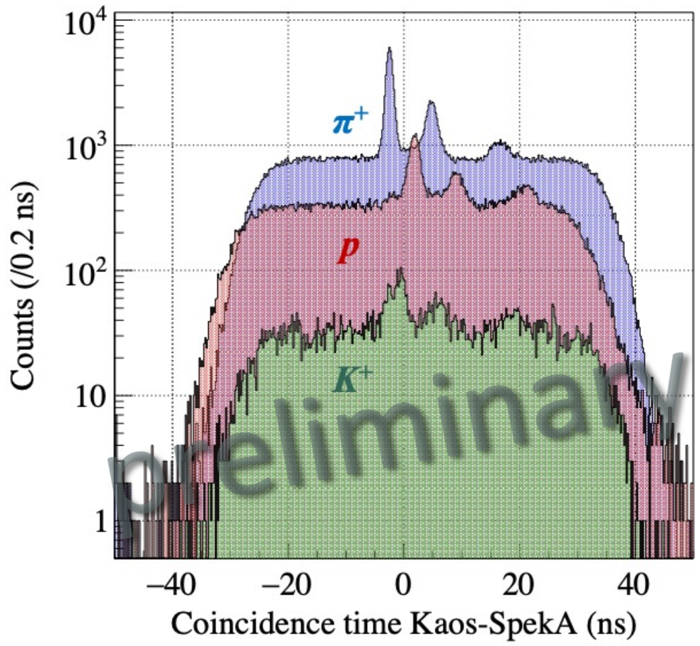


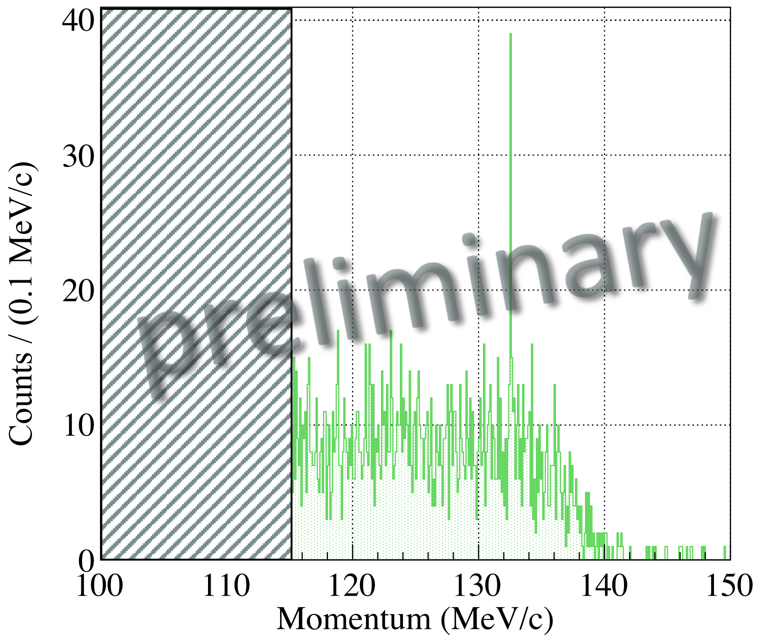
Status of the experiment and data analysis

Items	Status
✓ Parameter adjustment	done
✓ Particle tracking	done
❑ Particle identification via Kaos	In progress
❑ Momentum calibration of SpekA&C	Data-taking has done last week!

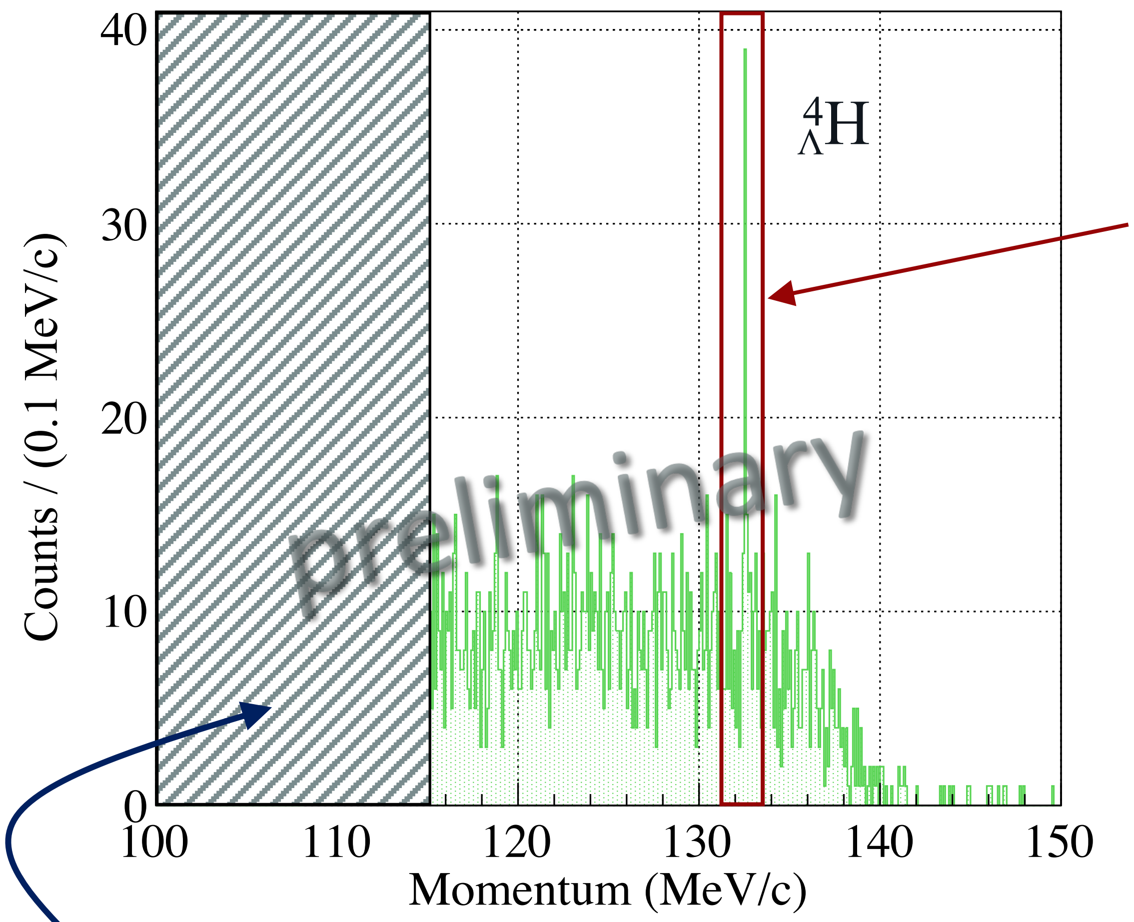
Data info:
Taken on Sept. – Oct., 2022
Run time: 541 hours
Beam charge: ~1.08 C

Momentum setting:
covering $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$
Target: Lithium, 2403 mg/cm^2



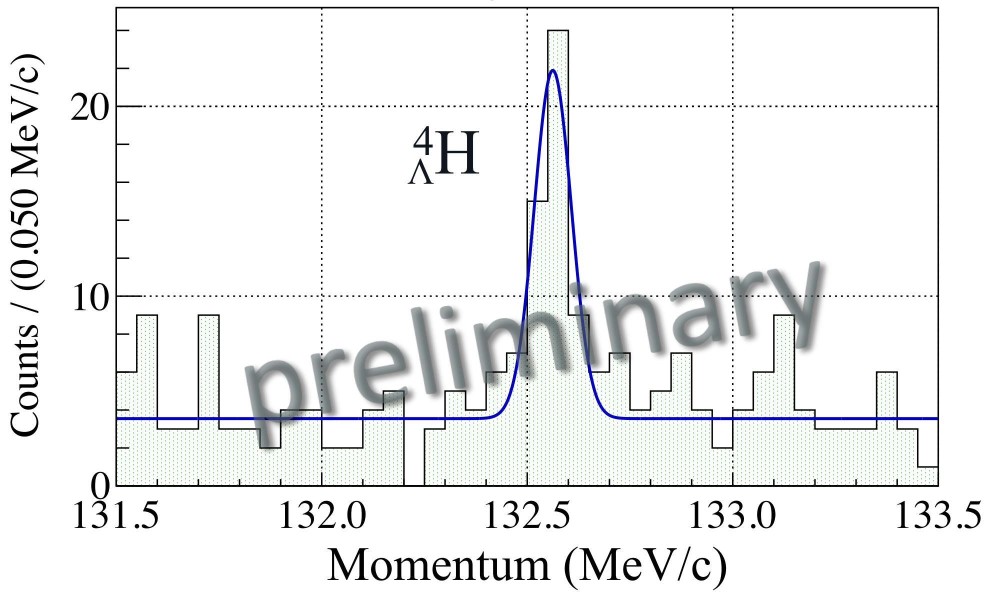


Latest pion momentum distribution



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

Gaussian fitting



$p_{\pi} = 132.54 \pm 0.008$ (MeV/c)
$\sigma = 0.045 \pm 0.015$ (MeV/c)

(2014: $p_{\pi} = 132.92$ (MeV/c))

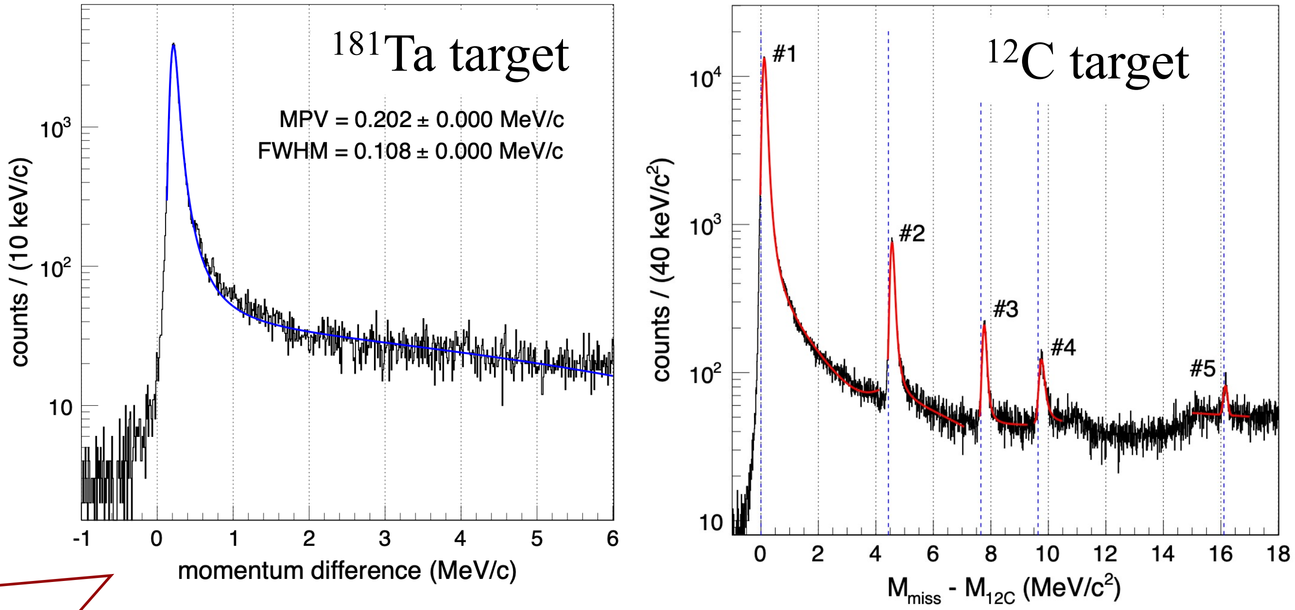
Momentum calibration will be done!

Spectrometer momentum calibration

S. Nagao, Doctoral thesis, Tohoku Uni (2016)

Established elastic electron scattering

- Relative resolution: 2×10^{-4}



Momentum difference

(p_m : measured value)

$$= p_{calc} - p_m$$

$$= \sqrt{\left(\frac{E_b}{1 + E_b/M_t(1-\cos\theta_m)}\right)^2 - m_e^2} - p_m$$

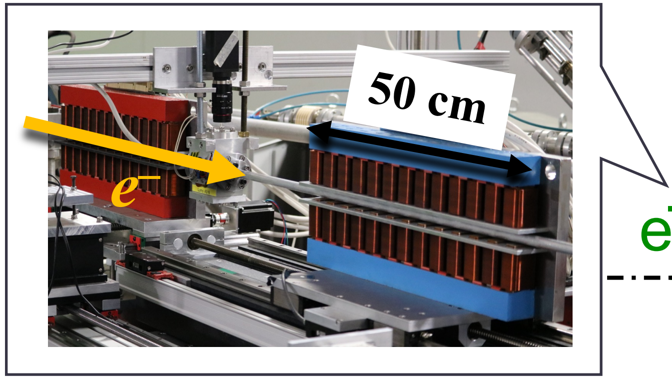
± 160 keV uncertainty ➡ systematic error of $B_\Lambda(^4\mathrm{H})$ = 77 keV (2016)

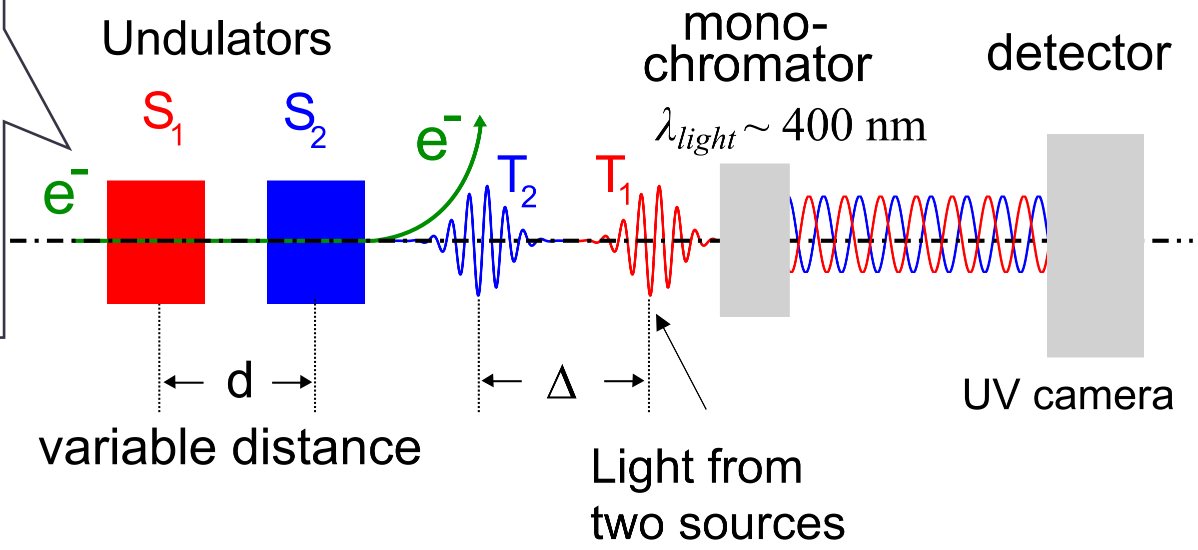
For low energy measurement with high accuracy ($\Delta E/E \sim 20$ keV)

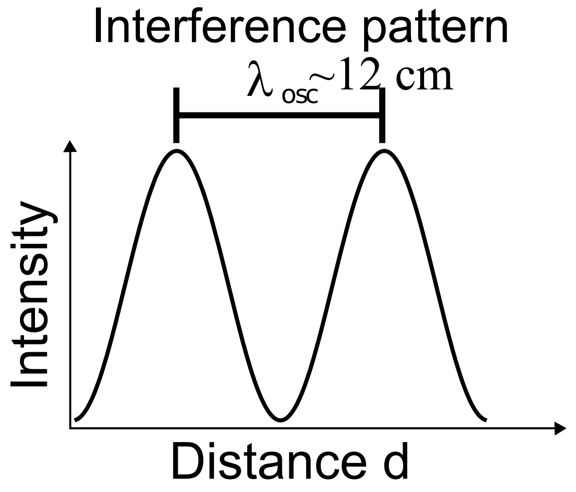
➡ Undulator interference method

Interference of undulator radiation

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:

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

Beam energy measurement

Relativistic γ via undulator eq.:

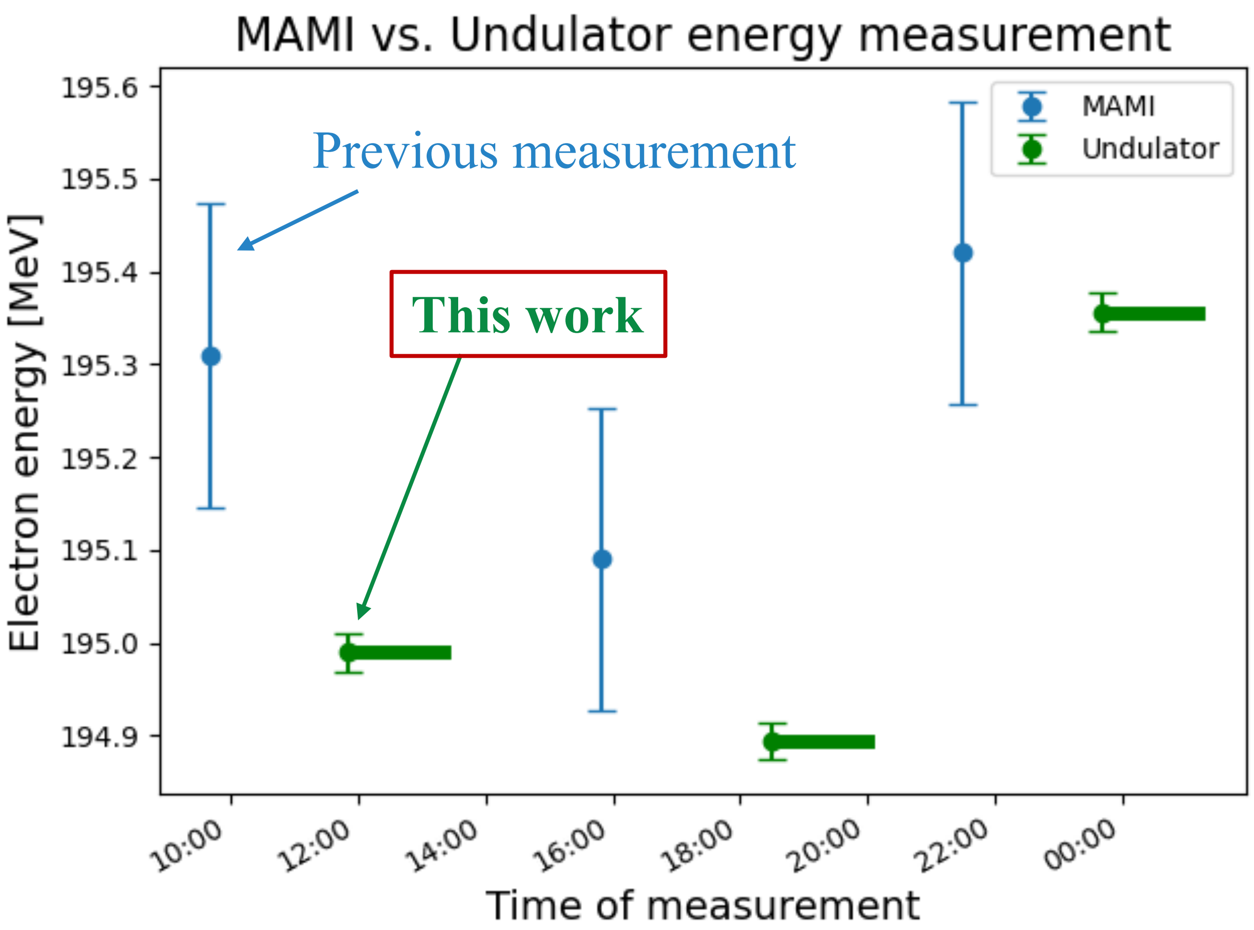
$$\gamma = \sqrt{\frac{\lambda_{osc}}{2\lambda_{light}}}$$

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!

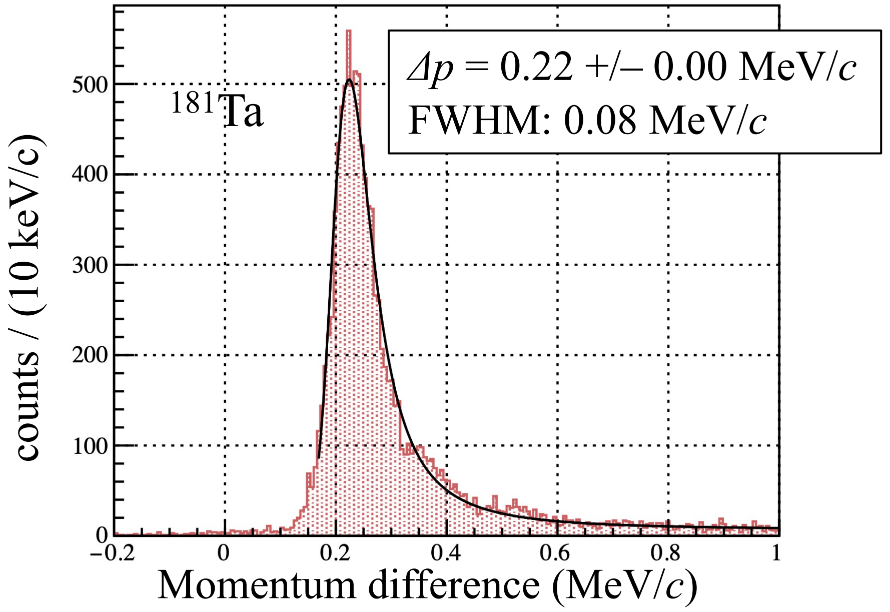
Figure from P. Klag, Ph.D. thesis, JGU Mainz (in preparation)

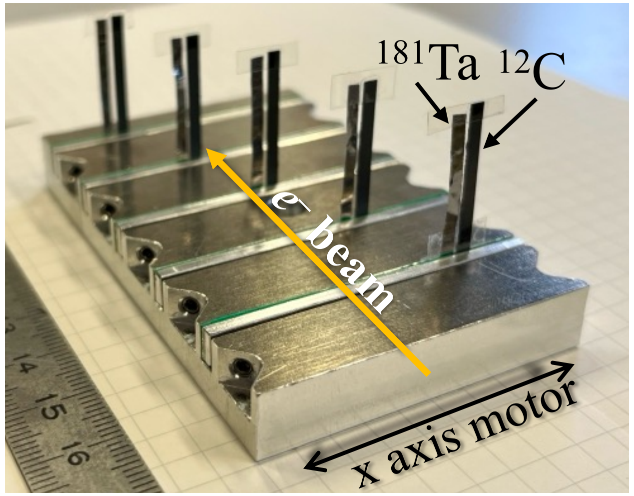


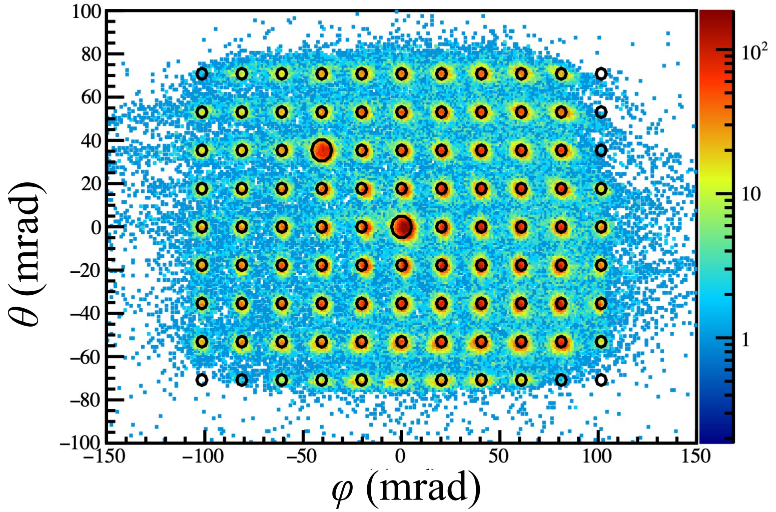
The final systematic error will be less than ΔB_{Λ} ~10 keV!

Summary of the spectrometer calibration experiment

- Beamtime: March 19th – April 8th, April 29th – May 6th, 2024
- Spectrometer angle: 54 deg → yield: 10^4 counts (/min/μA)
- Beam Energy: 5 sets (180, 195, 210, 225, and 420 MeV)
- Multi-foil targets: ^{181}Ta, ^{12}C
- Mom. setting: covering both $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H ($^{3}_{\Lambda}$H: $\delta p \sim -7\%$, $^{4}_{\Lambda}$H: $\delta p \sim +9\%$)
- Combined with beam energy measurement via undulator interference

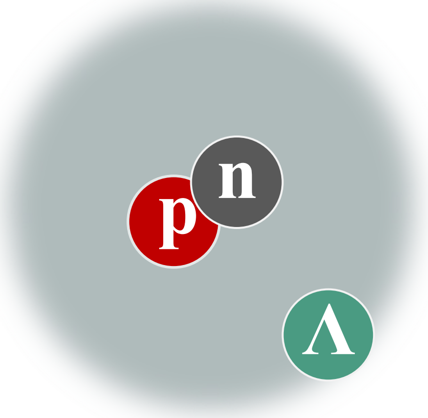






Quite enough data sets than the previous experiment & suppressed systematic errors!

Summary



- Measuring B_Λ of Hypertriton by Decay-pion spectroscopy at MAMI
- Updates from the previous experiments
  - Lithium long targeting system
  - Momentum calibration method combined with undulator interferometry
- Analysis status
  - Particle ID: now ongoing, Absolute momentum will be calibrated

Our goal: total error of < 10 keV in Λ binding energy!