Hypernuclear decay pion spectroscopy at MAMI, Germany

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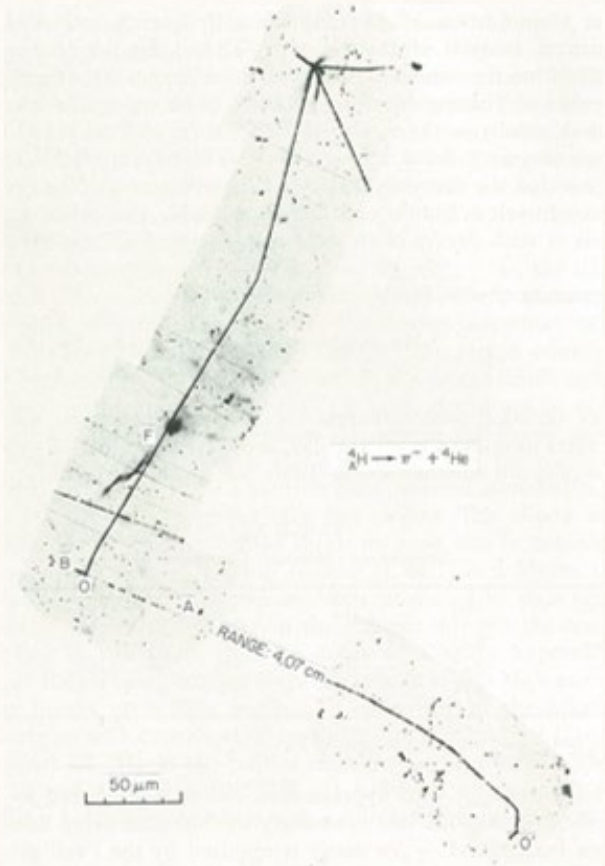
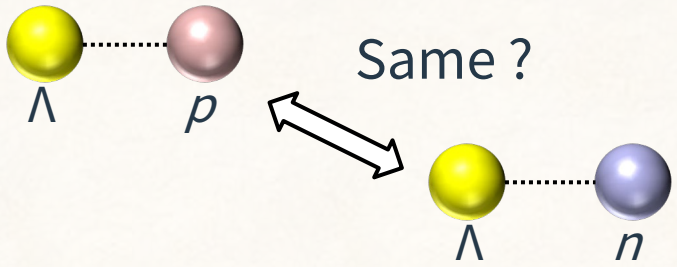
Physics Motivation

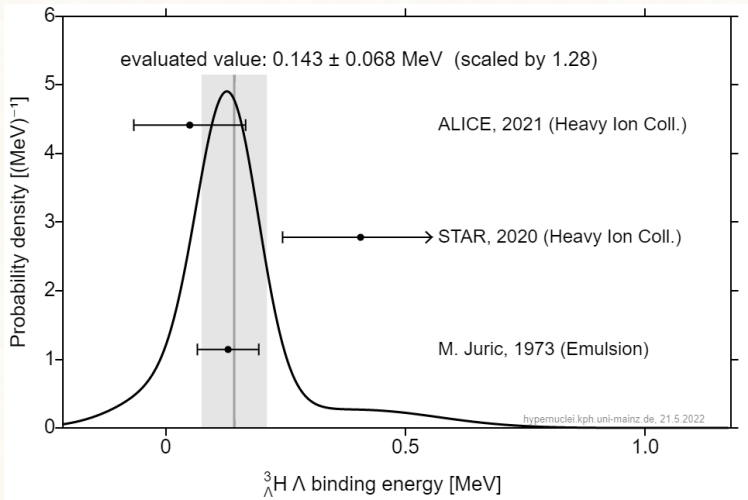
Emulsion track of ${}^{4}_{\Lambda}\mathrm{H}$



Walter H. Barkas, Nuclear Research Emulsions (1973)

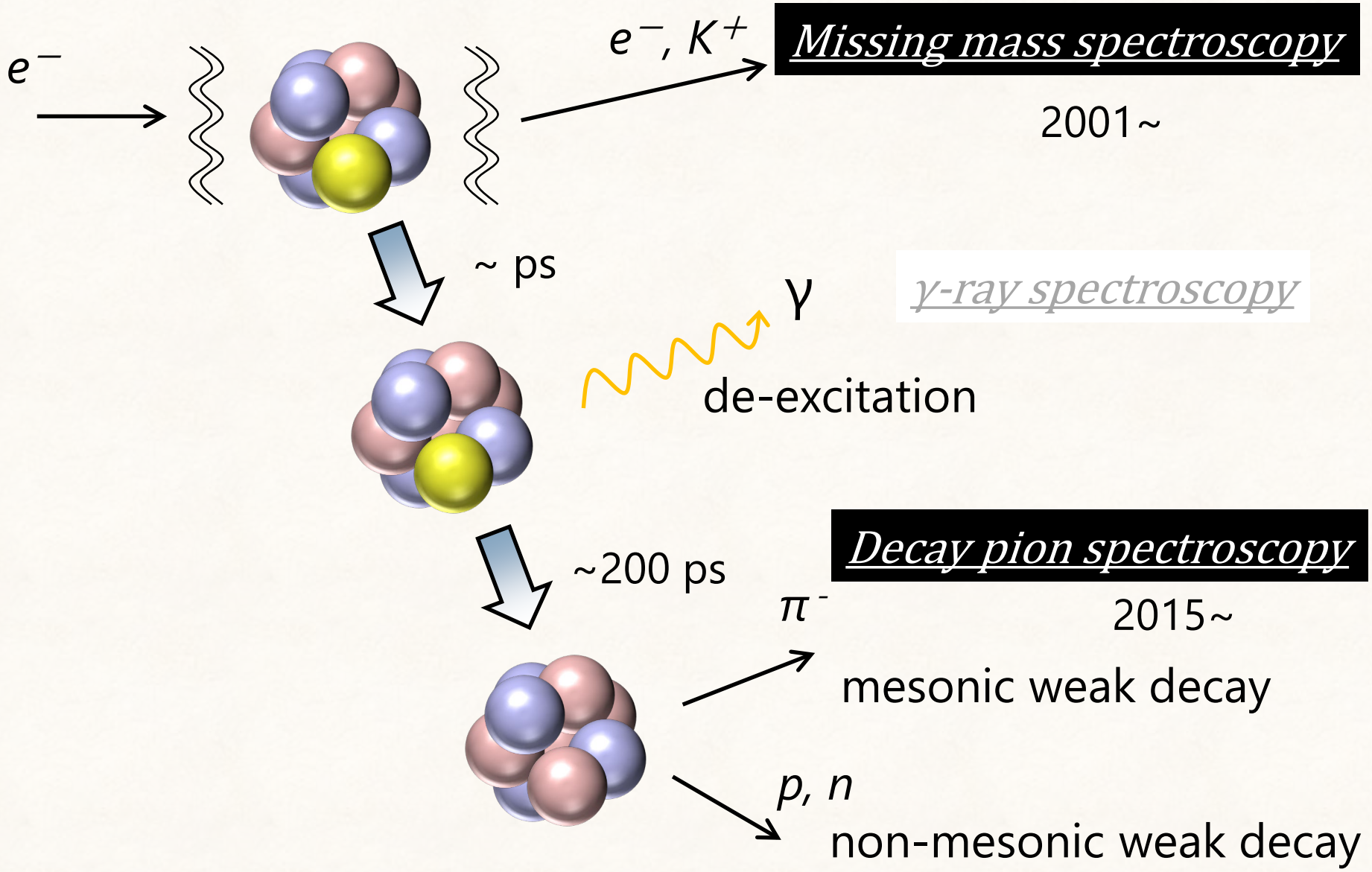
- Λ binding energies of Λ hypernuclei play an important rule to understand ΛN interaction nuclear medium. Light hypernuclei is one of the good probe thanks to precise calculations and data.
- Λ binding energy of hypernuclei provided by Emulsion in 1960-70's with a few 10 - several 100 keV precision and 50 keV systematic? .
- Inconsistency have appeared because of recent progresses of few-body calculation and new data, for example, Charge Symmetry Breaking Effect, Hypertriton Lifetime-BindingEnergy puzzle etc.
- Since exp. data do NOT have enough accuracy, much more accurate data are important discussing above items.





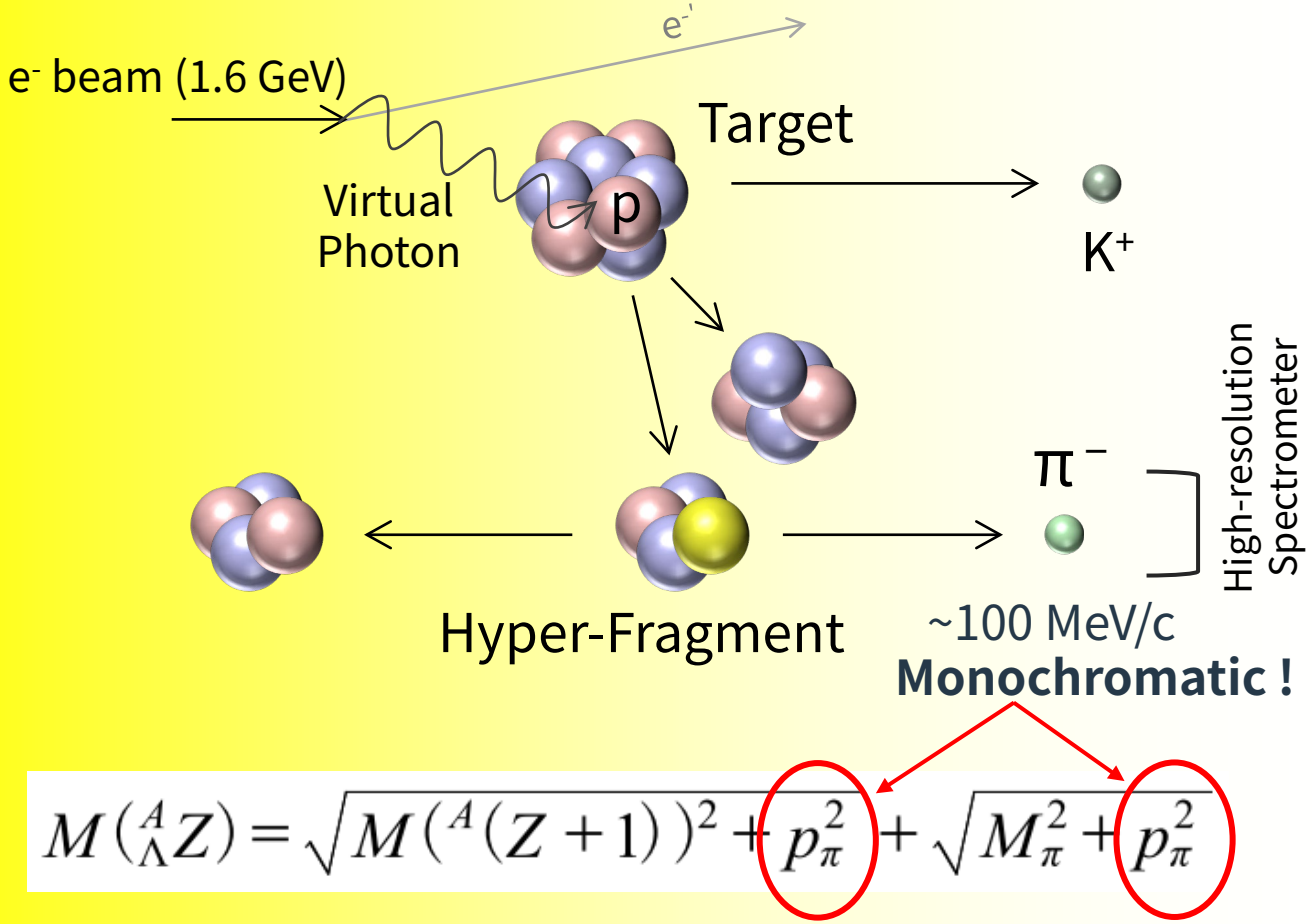
Hypernuclei database (https://hypernuclei.kph.uni-mainz.de/)

Hypernuclear Formation - Decay



Experimental Principle

Decay Pion Spectroscopy



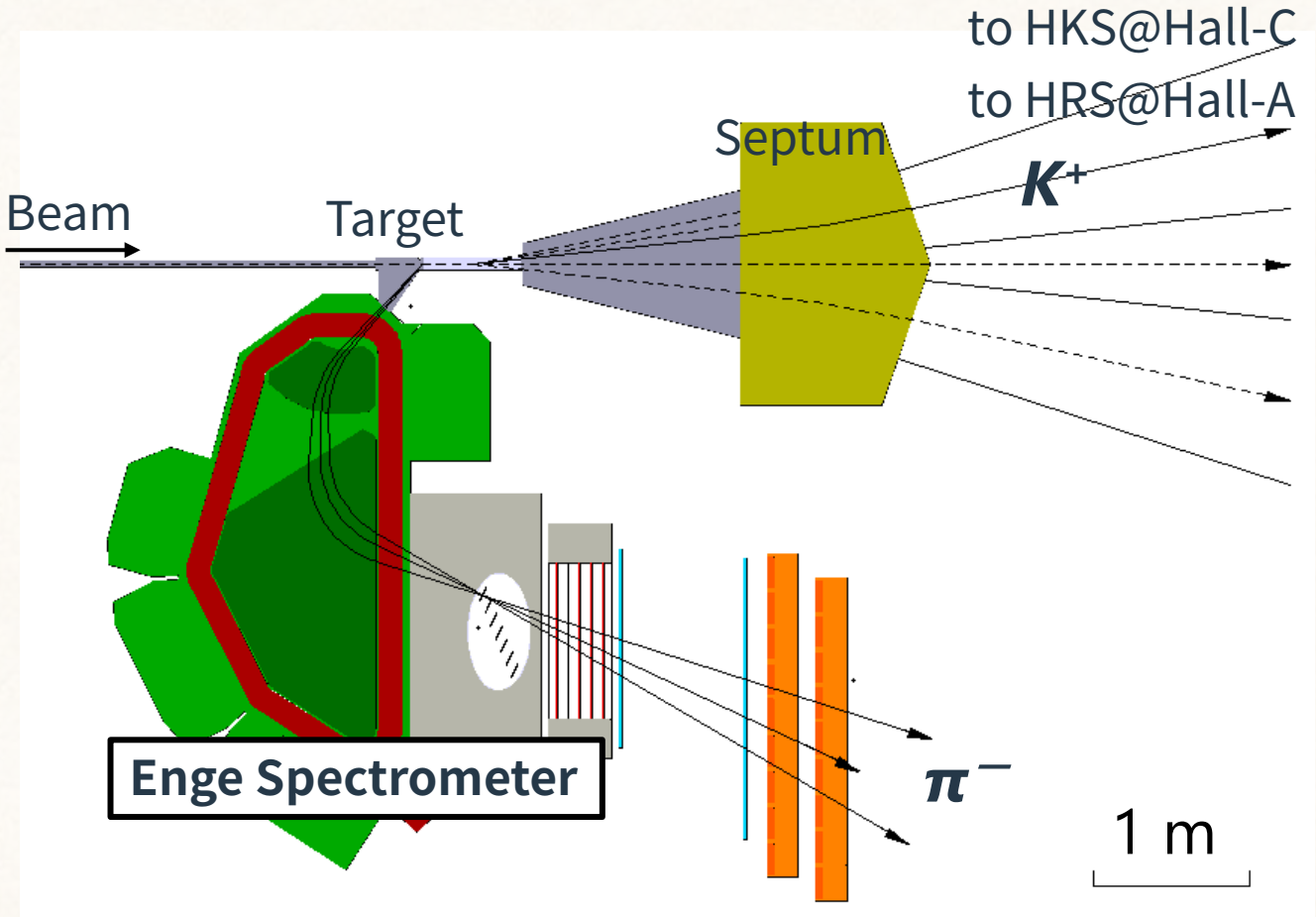
$$M\left({}^{A}_{\Lambda}Z\right) = \sqrt{M\left({}^{A}(Z+1)\right)^2 + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2}$$

- Stopped hypernucleus emits monochromatic charged-pion with 2-body weak-decay
- Mass of parents hypernucleus can be deduced from the pion momentum only
- Precise measurement of monochromatic pion from hypernuclear weak-decay
- High-resolution spectroscopy could be achieved for hypernuclear ground-state

Method	p	Δp/p	ΔM
HI col.	0.3 GeV/c	10^{-2}	5 MeV
(e,e'K⁺)	1 GeV/c	10^{-4}	0.5 MeV
DPS	0.1 GeV/c	10^{-4}	**0.1 MeV**

First Proposal at JLab

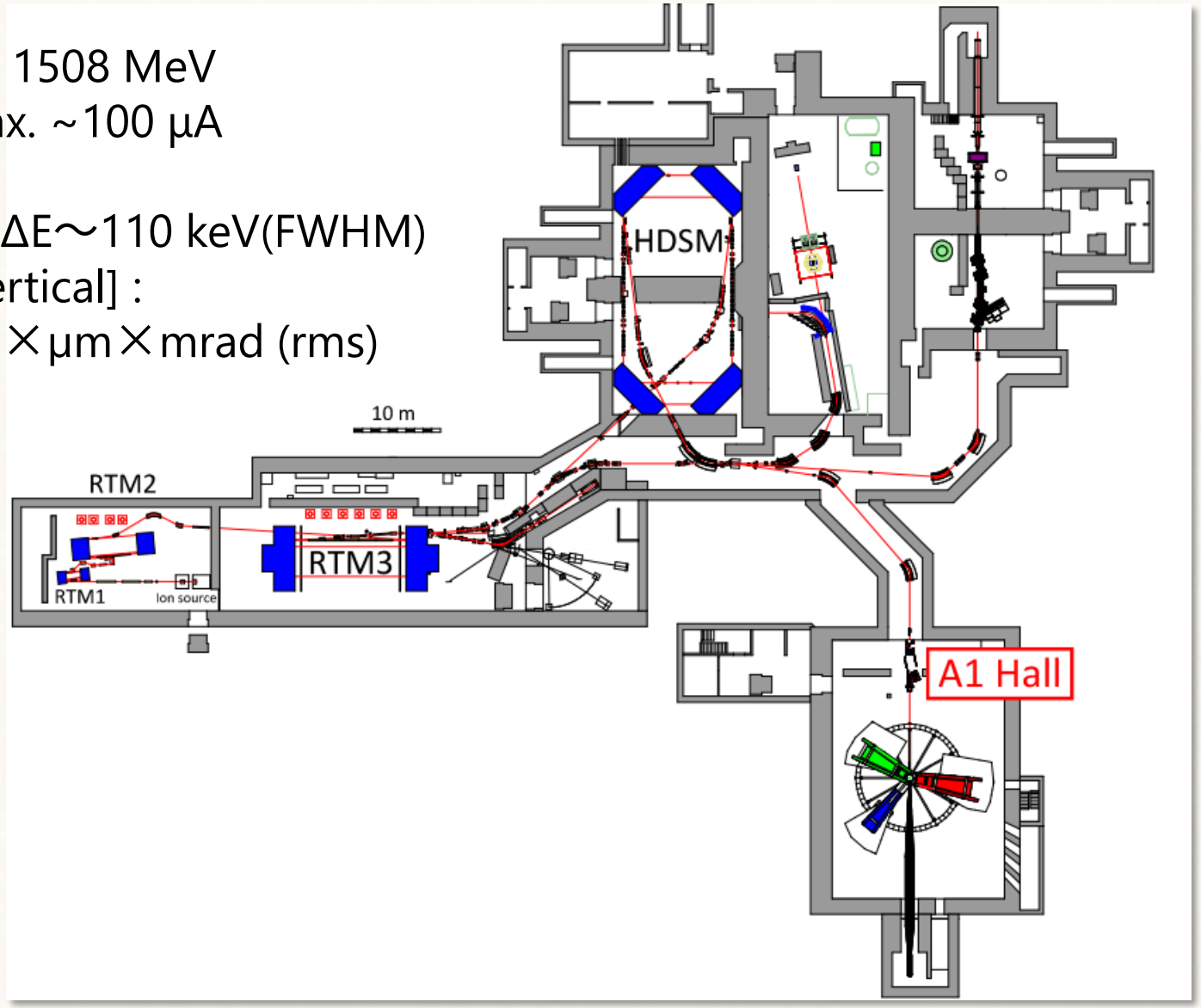
The first proposal was submitted as E08-012 "Study of Light Hypernuclei by Pionic Decay at JLab" by L.Tang *et al.*



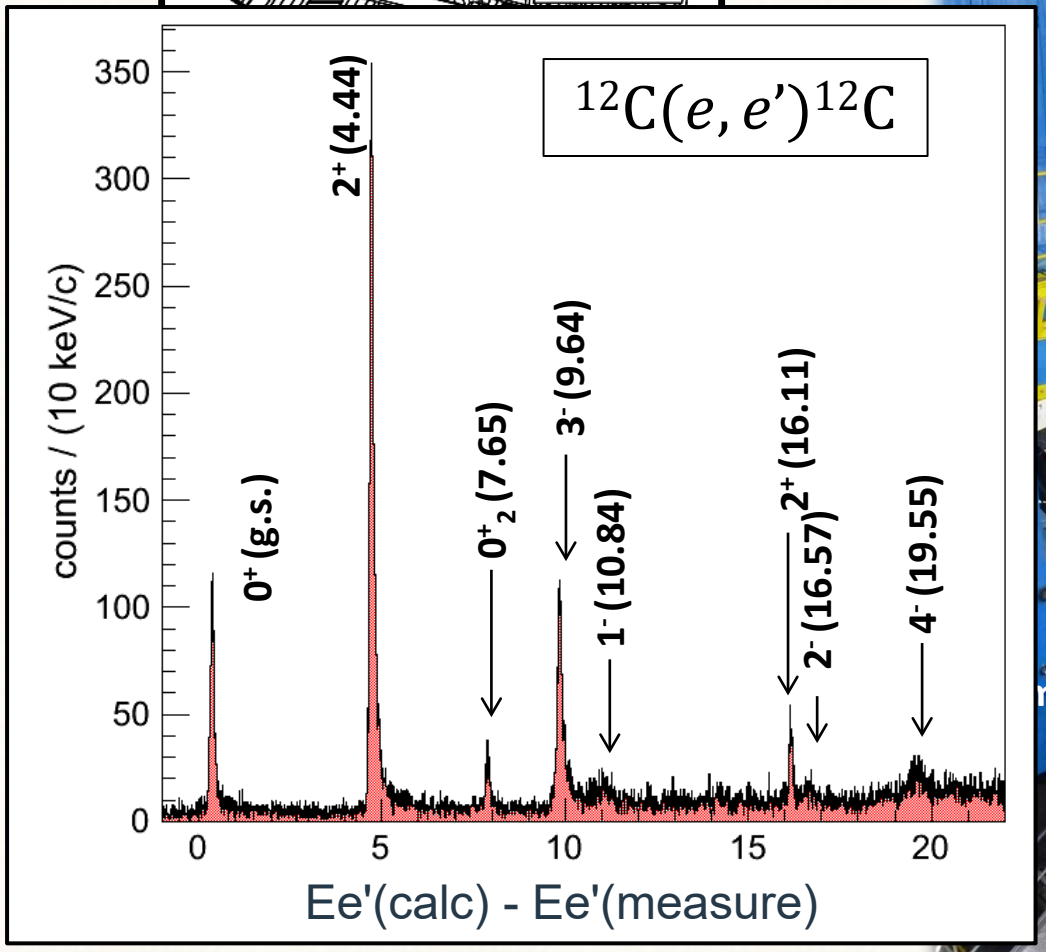
- Enge as π^- spectrometer
- HKS as K^+ tagger (or HRS@Hall-A)
- Both spectrometers were used on the hypernuclear experiment (E01-011), in ESB now.
- We could not run at JLab because 12 GeV upgrade project started from 2011

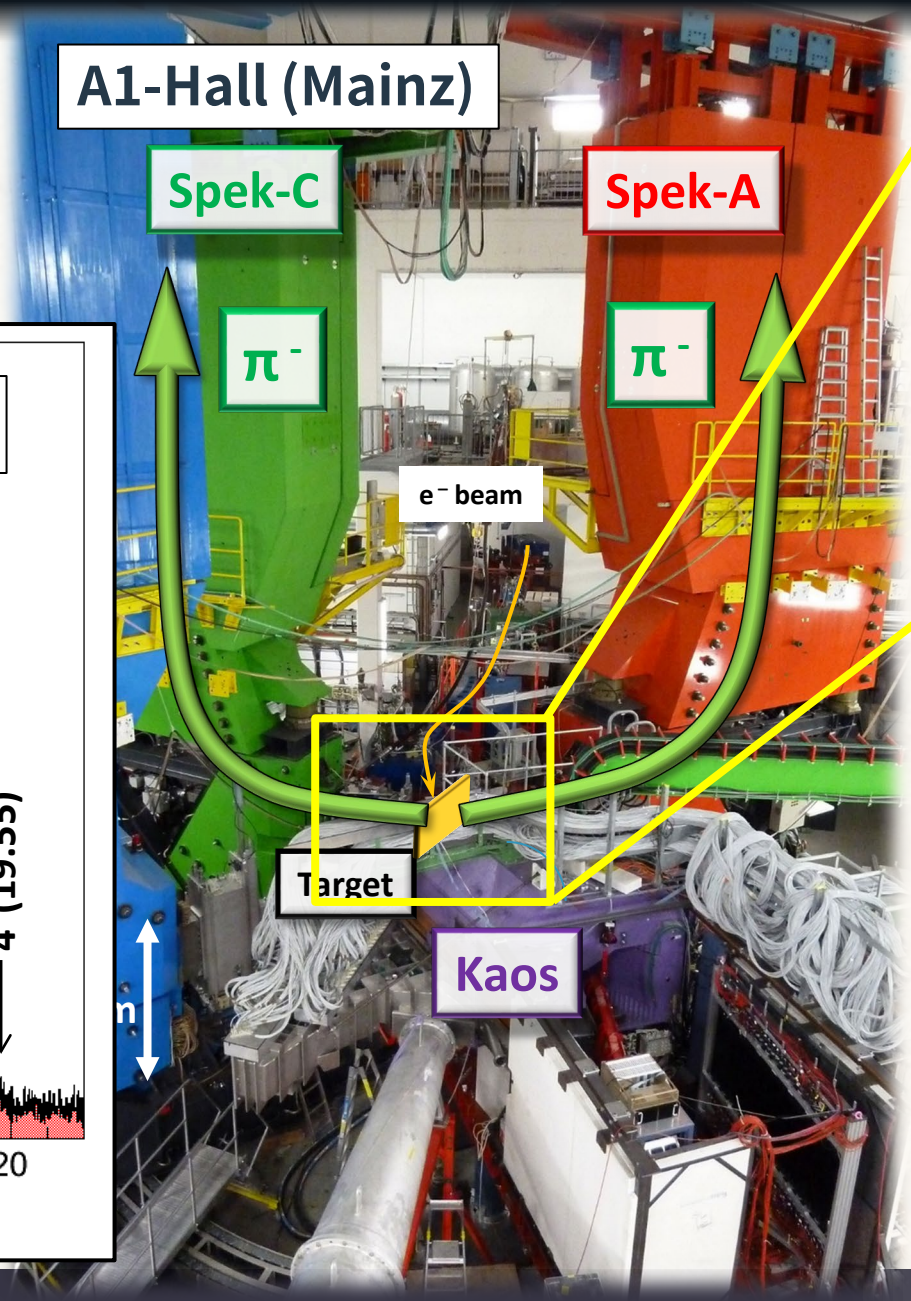
Mainz Microtron (MAMI)

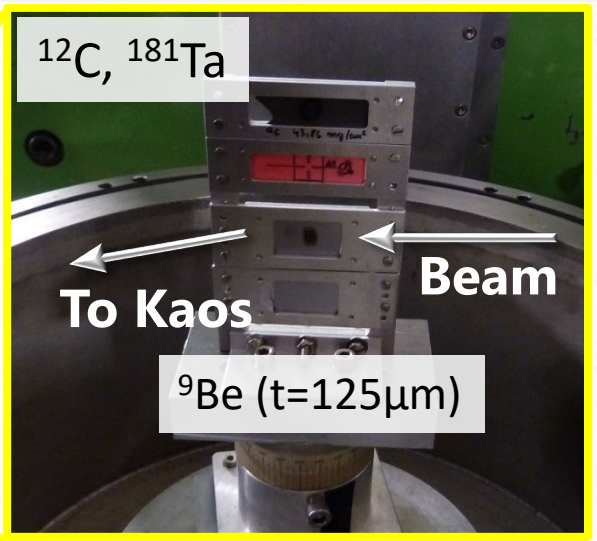
- **Beam energy** : Max. 1508 MeV
- **Beam intensity** : Max. ~100 μA
- **Duty factor** : 100%
- **Energy resolution** : ΔE～110 keV(FWHM)
- **Beam emittance** [vertical] :
  < 1.2π×μm×mrad (rms)



A1 Hall at MAMI

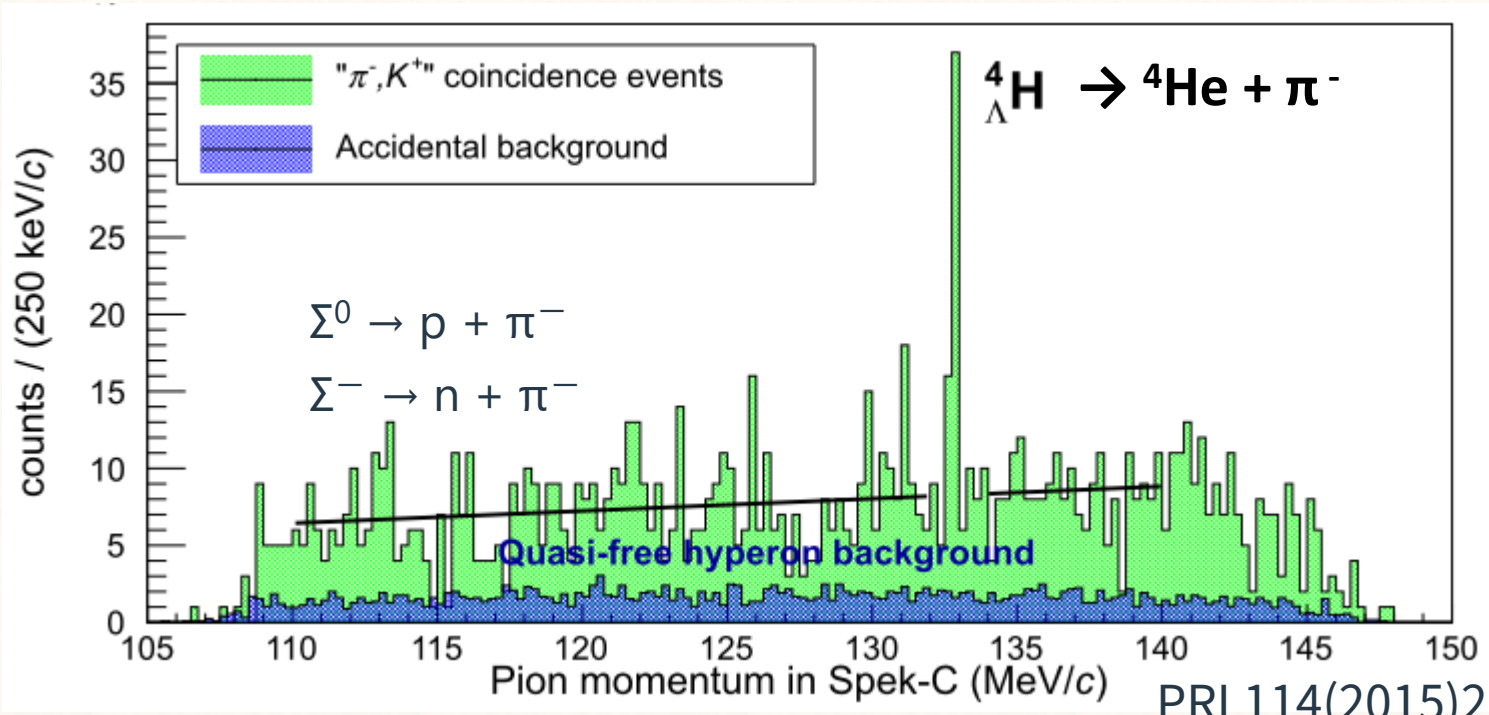






Observation of monochromatic pion from $^{4}_{\Lambda}$H

Momentum distribution on Spek-C

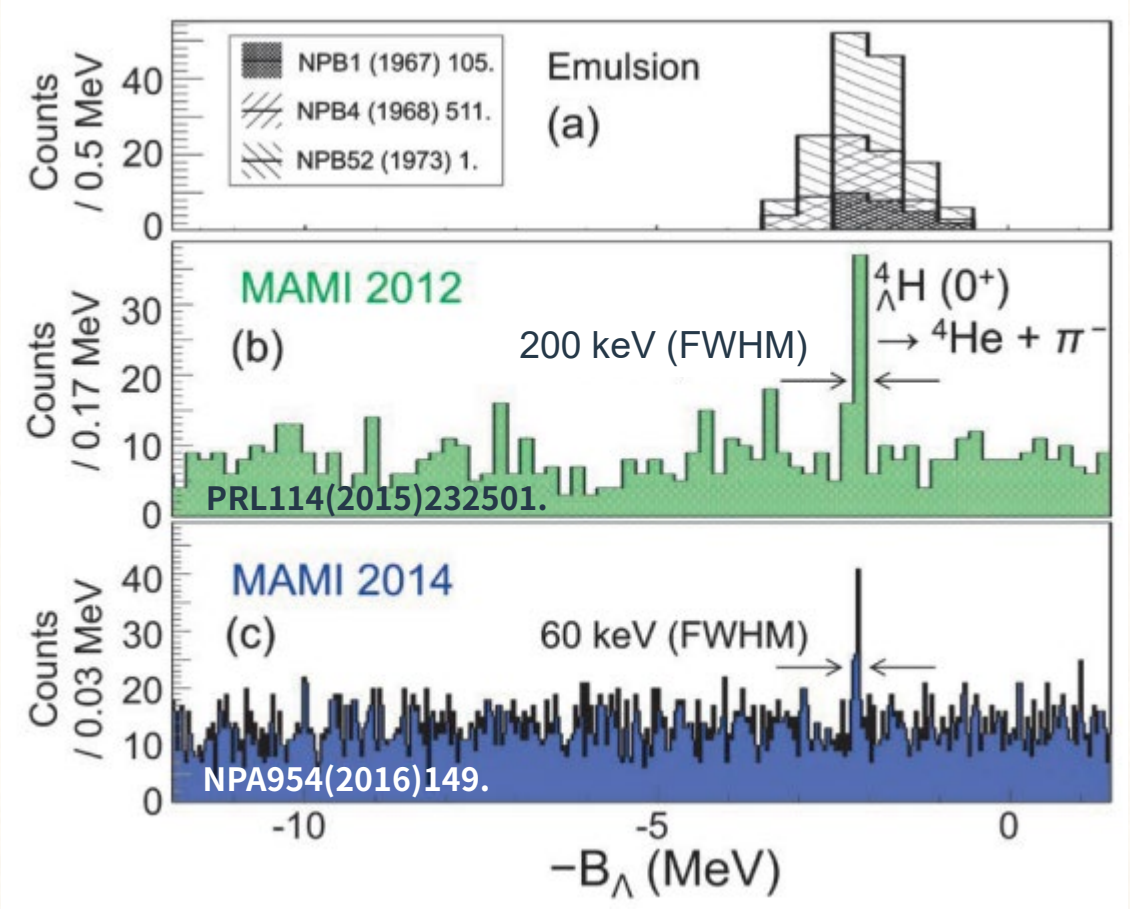


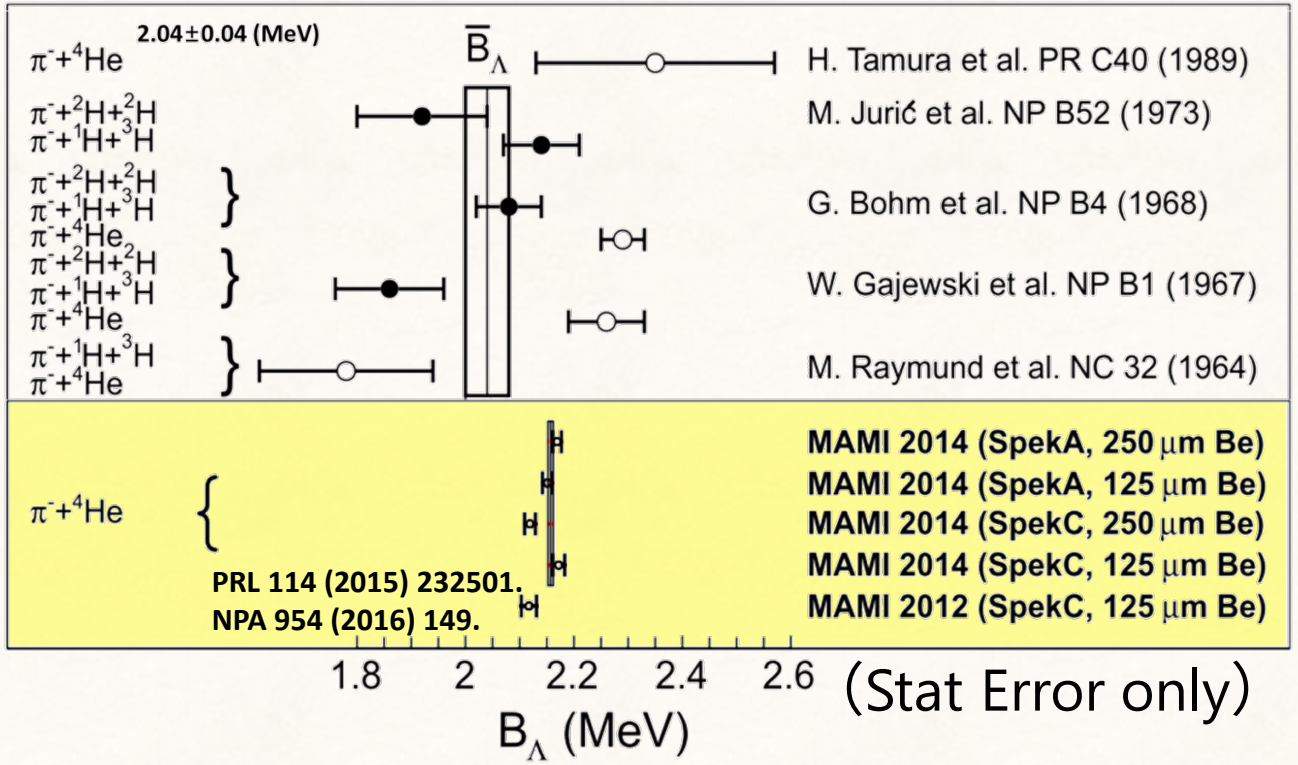
PRL114(2015)232501.

- The first observation of decay pions from $^{4}_{\Lambda}$H on continuous background through this method
- Background shape could be reproduced with Quasi-Free Σ decays
- Peak resolution of 200 keV (FWHM)
- p = 132.92±0.02(stat.) MeV/c

Best resolution & Best precision

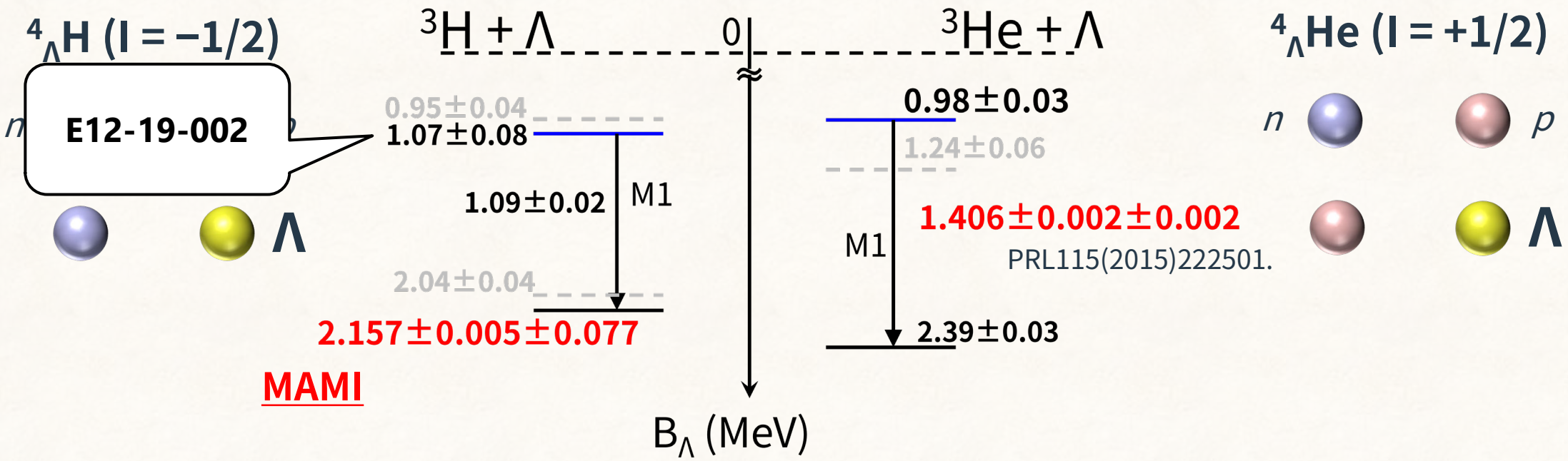
$$B_\Lambda\,(\text{MAMI 2012}) = 2.12 \pm 0.01 \pm 0.09\ (\text{MeV})$$
$$B_\Lambda\,(\text{MAMI 2014}) = 2.157 \pm 0.005 \pm 0.077\ (\text{MeV})$$





(Stat Error only)

Latest A = 4 Level Scheme



$$\Delta B^{CSB}(^4_\Lambda He(1^+) - {}^4_\Lambda H(1^+)) = +0.29 \rightarrow -0.09 \text{ MeV}$$

$$\Delta B^{CSB}(^4_\Lambda He(0^+) - {}^4_\Lambda H(0^+)) = +0.35 \rightarrow 0.23 \text{ MeV}$$

NOTE: ΔB(^{3}He - ^{3}H) ~ −0.07 MeV

Large ΔB^{CSB} exists for the ground state though ΔB^{CSB} becomes smaller.

M1 transitions have large difference → ΛN CSB has spin-dependent

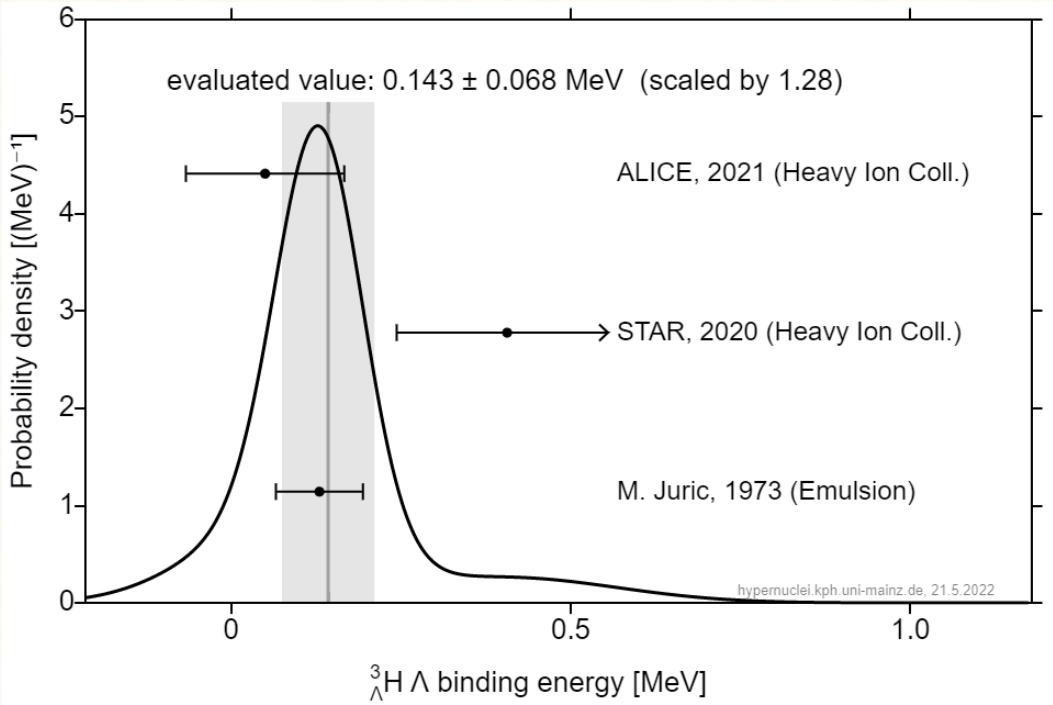
→ CSB problem became much more complex

On going project

We successfully observed decay-pion from ${}^{4}_{\Lambda}\mathrm{H}$.....

- Other Hypernucleus
- Better accuracy

${}^{3}_{\Lambda}\mathrm{H}$ world data

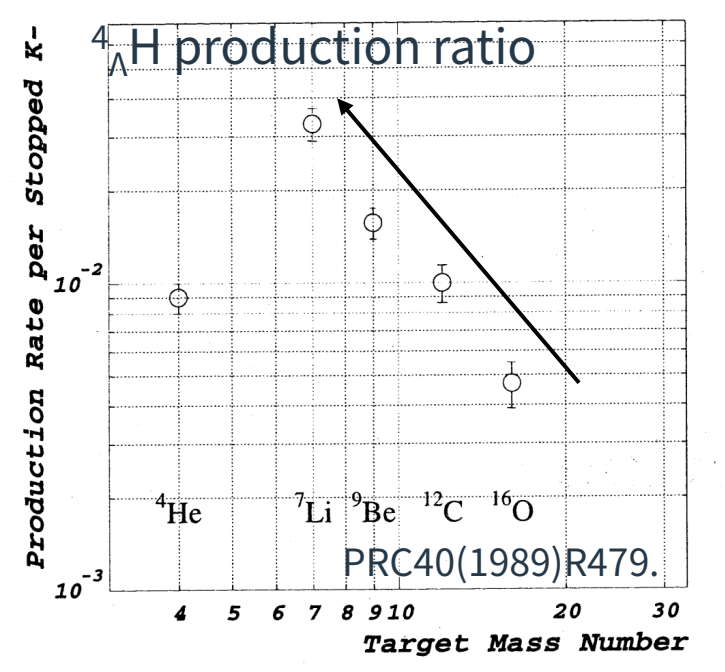


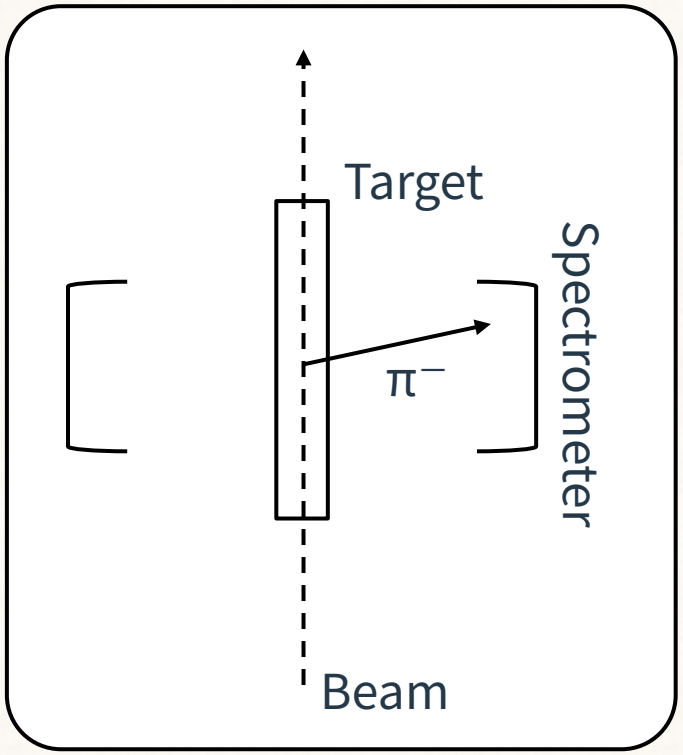
New Target

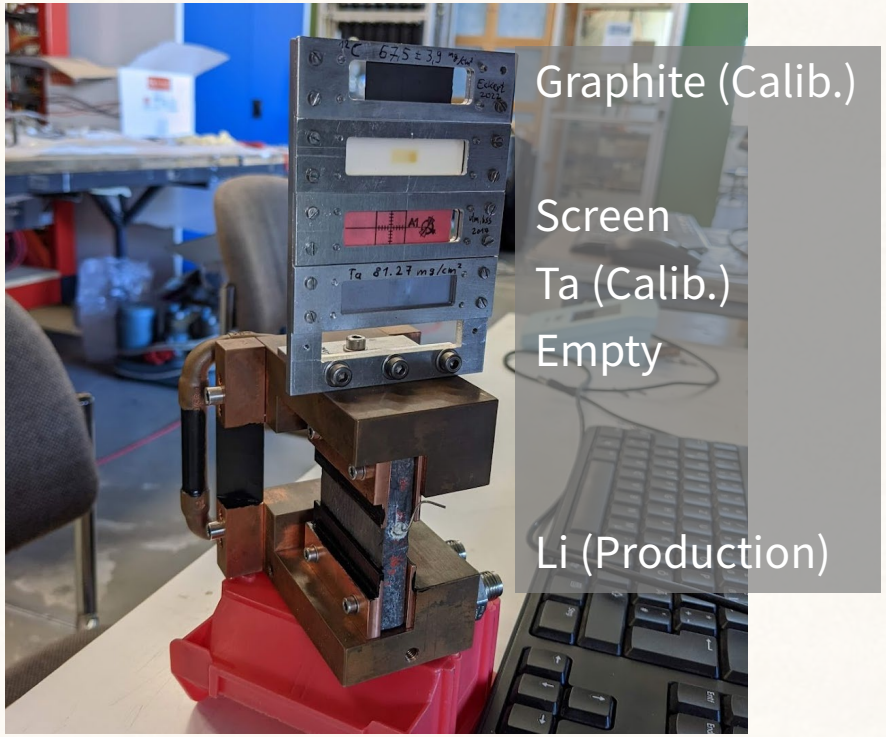
- Hyper-fragments more efficient
- Experiment with low mass target would be fine
- Be → Li

- Lower air dose by using lower beam current
- 90 deg tilted target
- Maximize hyper yield
- Minimize struggling

- New 90 deg tilted Li target
- Last : ^{9}Be 47mg/cm^2 40 μA
- New: Li 2700 mg/cm^2 0.5 μA



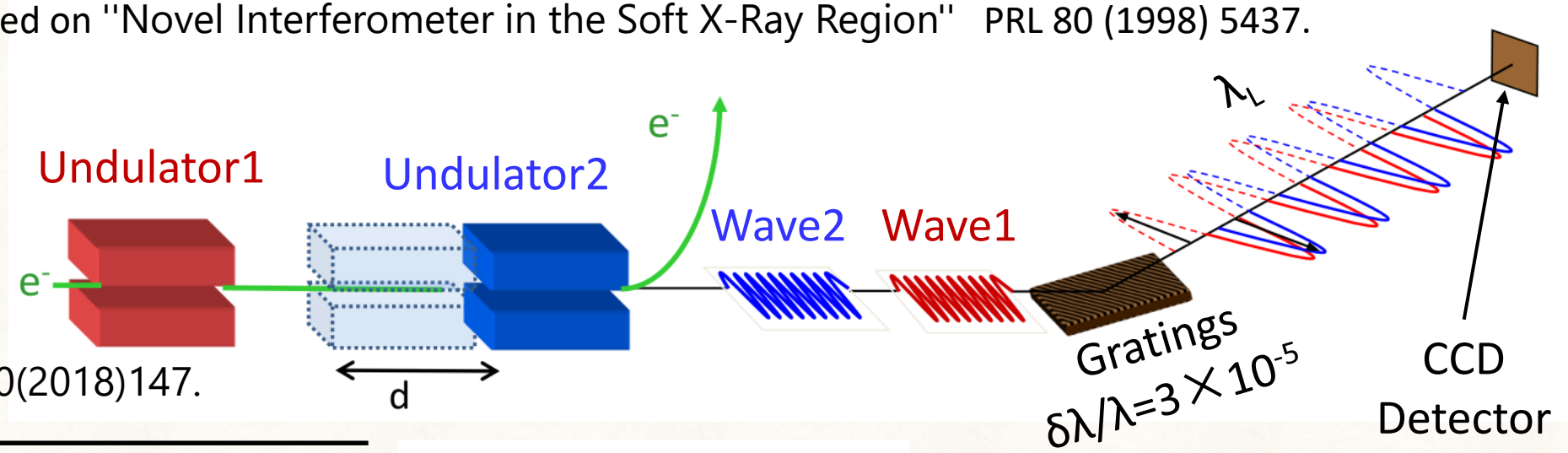




New Beam-Energy Measurement

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.



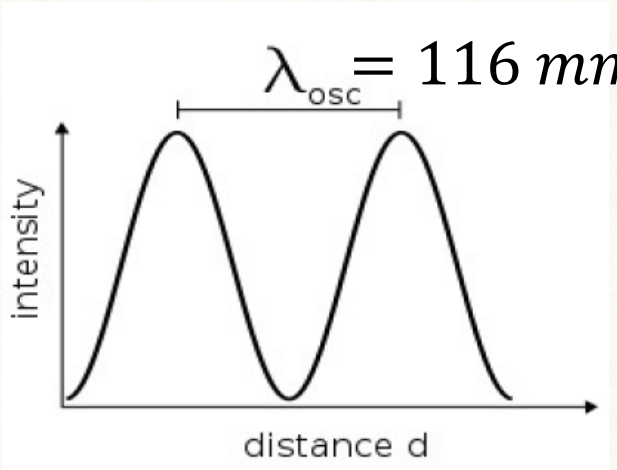
NIMA 910(2018)147.

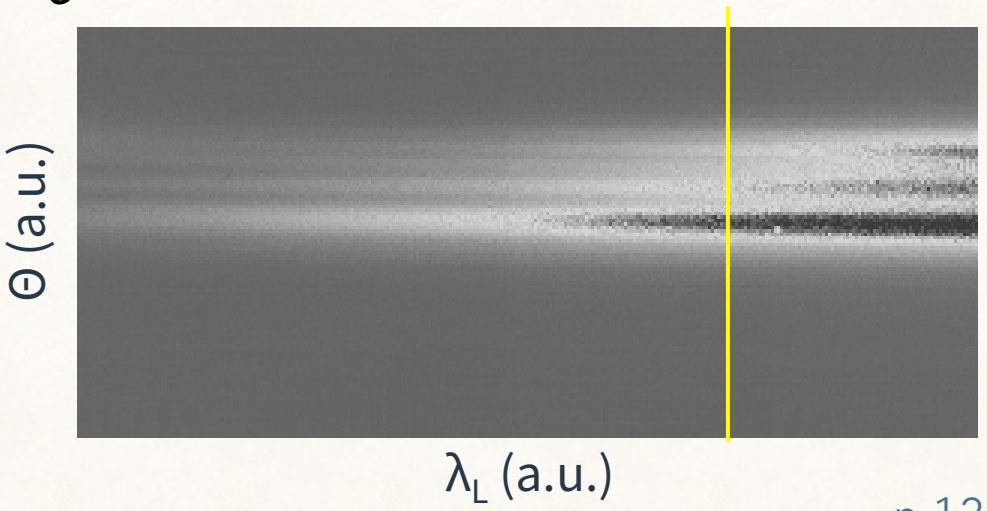
$$\gamma = \sqrt{\lambda_{osc}(\Theta)/2\lambda_L}$$

$\lambda_L = 400\ nm$

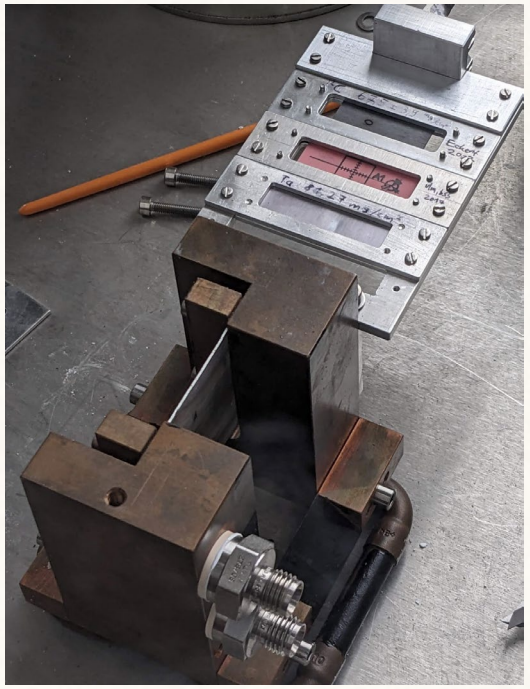
$E = 195\ \mathrm{MeV}$

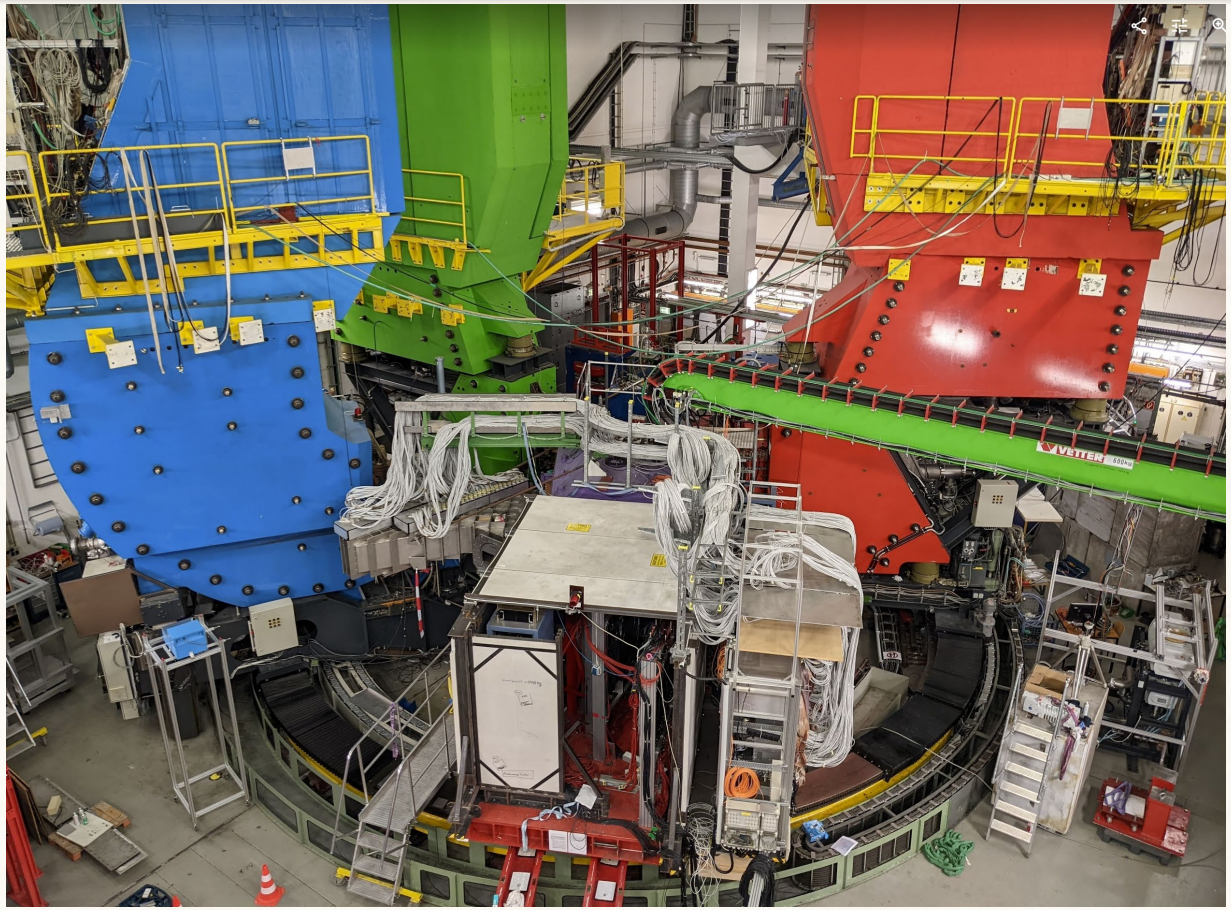
$\gamma = 381$

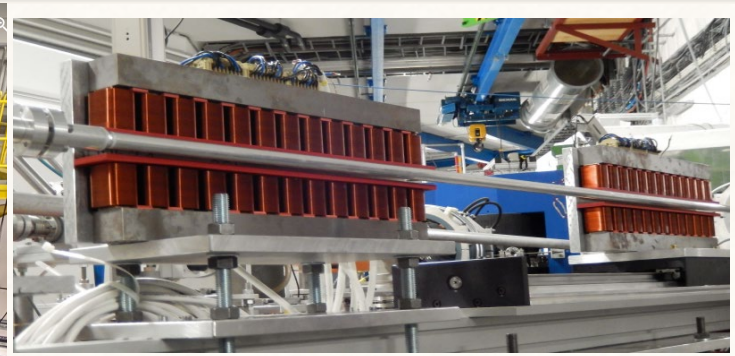




Run in 2022







- Decay pion spectroscopy run in Sept. - Oct 2022 with a new Li target
- Data analysis is ongoing now
- Spectrometer calibration will perform in 2023

Summary

- Hypernuclear measurement
  - Important inputs for ΛN interaction and NS EOS
  - More accurate measurement is necessary especially for light hypernuclei
- Accurate measurement technique "Decay Pion Spectroscopy"
  - Original proposal at JLab, Established at MAMI
- Observation of $^{4}_{\Lambda}$H peak
  - at 132.92±0.02(stat.) MeV/c with a resolution of 0.2 MeV/c (FWHM) @MAMI2012
  - Better precision @MAMI2014 (B_{Λ} = 2.157±0.005±0.077 MeV)
  - Important input discussing CSB effect on A=4 hypernuclear system
- $^{3}_{\Lambda}$H measurement
  - Important measurement resolving hypertriton puzzle
  - Data taking was finished in 2022, Spectrometer calibration will be in 2023