High-Precision Measurement of the Hypertriton Mass

motivation, ideas, concepts, experimental limitations, …

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The story from hypernuclear halos to optical interferences

– a hypernuclear halo system

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– the puzzle of its lifetime vs B_Λ

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– emulsion data limitations

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– need for new precision measurements

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– decay-pion spectroscopy at MAMI

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– limitation by absolute beam energy precision

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– interferometry of optical undulator radiation

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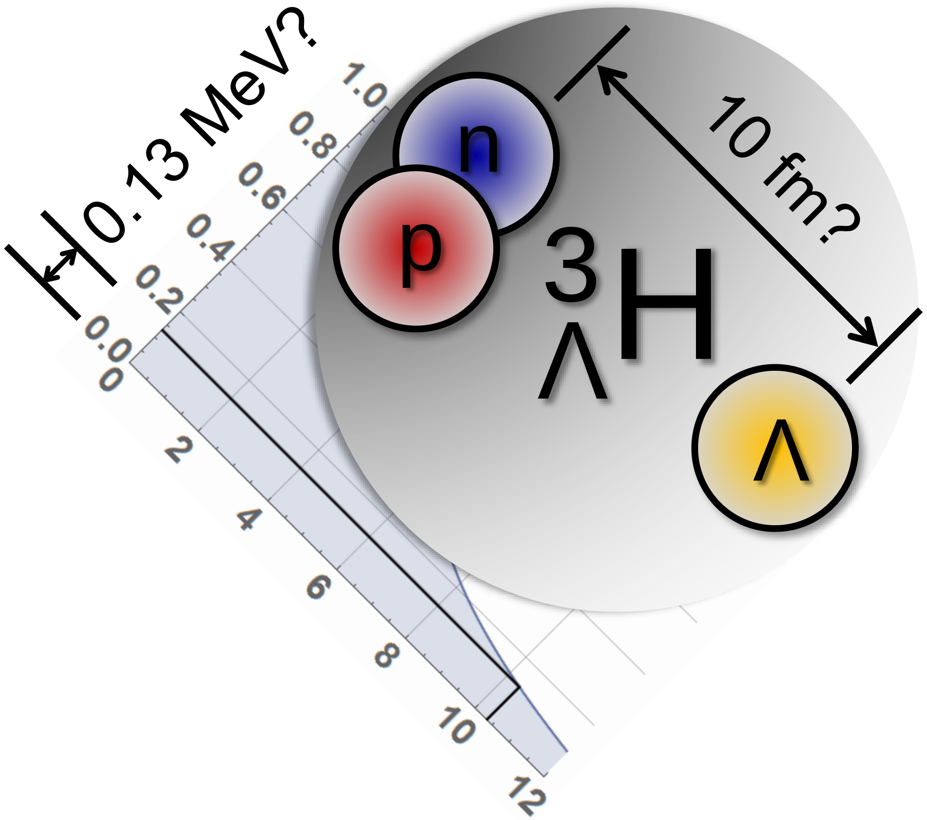
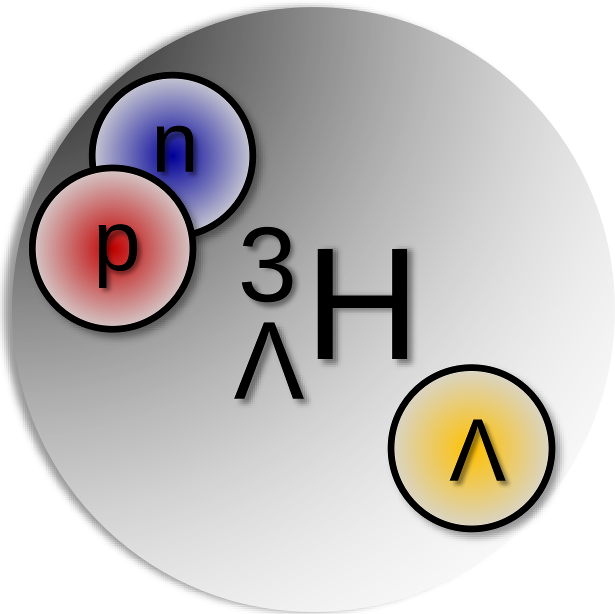
– ongoing activities and future projects

A hypernuclear halo system



The Λ-hypernuclear three-body system

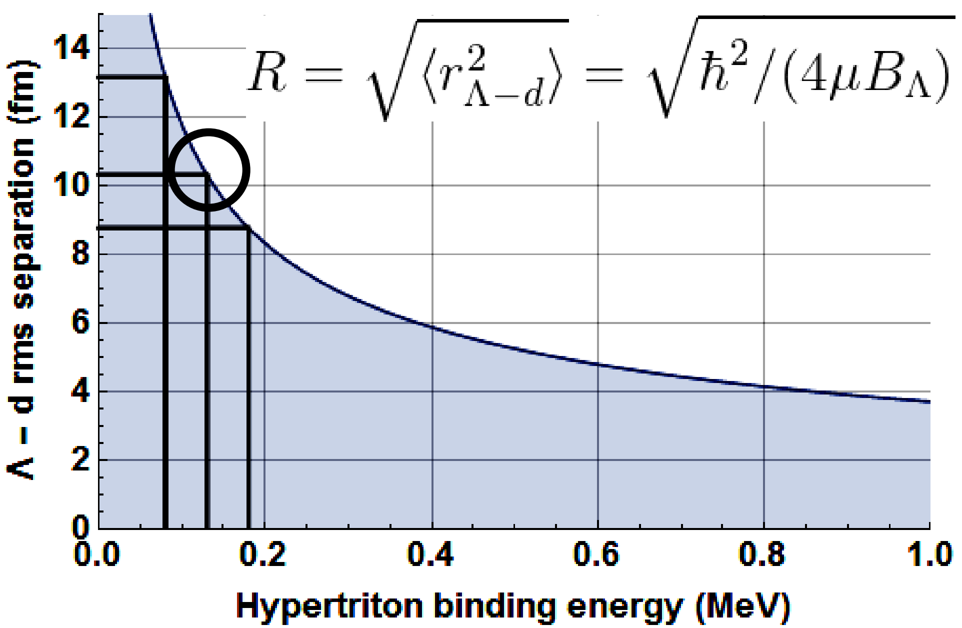
the hypertriton

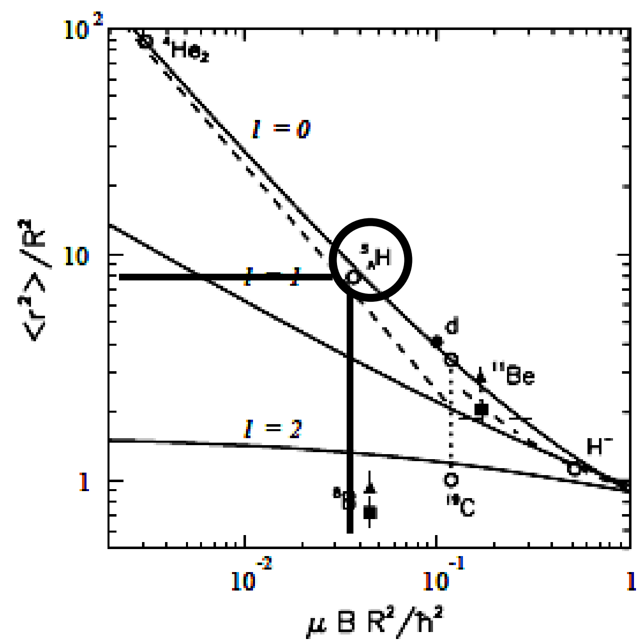


- lightest hypernuclear bound state: $S = -1$, $J^P = ½^+$, $T = 0$
- simplest system in which Λ particle interacts with nucleons at low energy
- Λ separation = binding energy B_Λ = 130 ± 50 (stat.) ± 50 (syst.) keV
- short ranges of NN and ΛN interactions & small total binding energy (~2.3 MeV) imply *S* states for relative motions and very loose structure
- mesonic weak decay (MWD) is expected to dominate over non-MWD

Hypertriton as a halo system

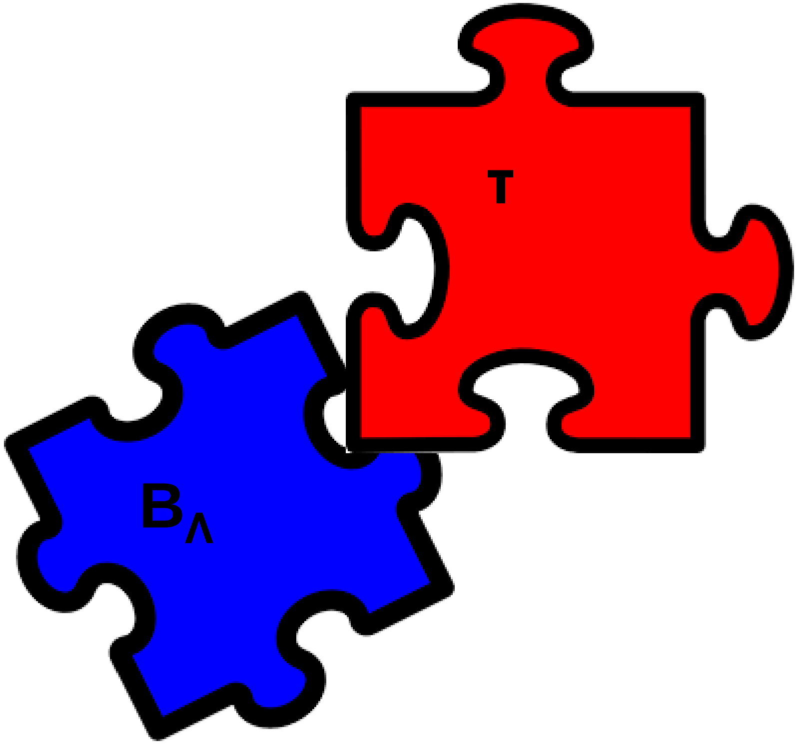
- 1n & 2n halos known for small n separation energies near dripline
- universal scaling relations derived for nuclear systems with low binding
- hypertriton effective two-body *dΛ* system (?)
- in hypertriton no centrifugal barrier, no Coulomb repulsion
- when pair of particles is close, the third particle is, on average, far away
- for a spatially extended nuclear state (compared to core size) most of wave function tunneled into classically forbidden region



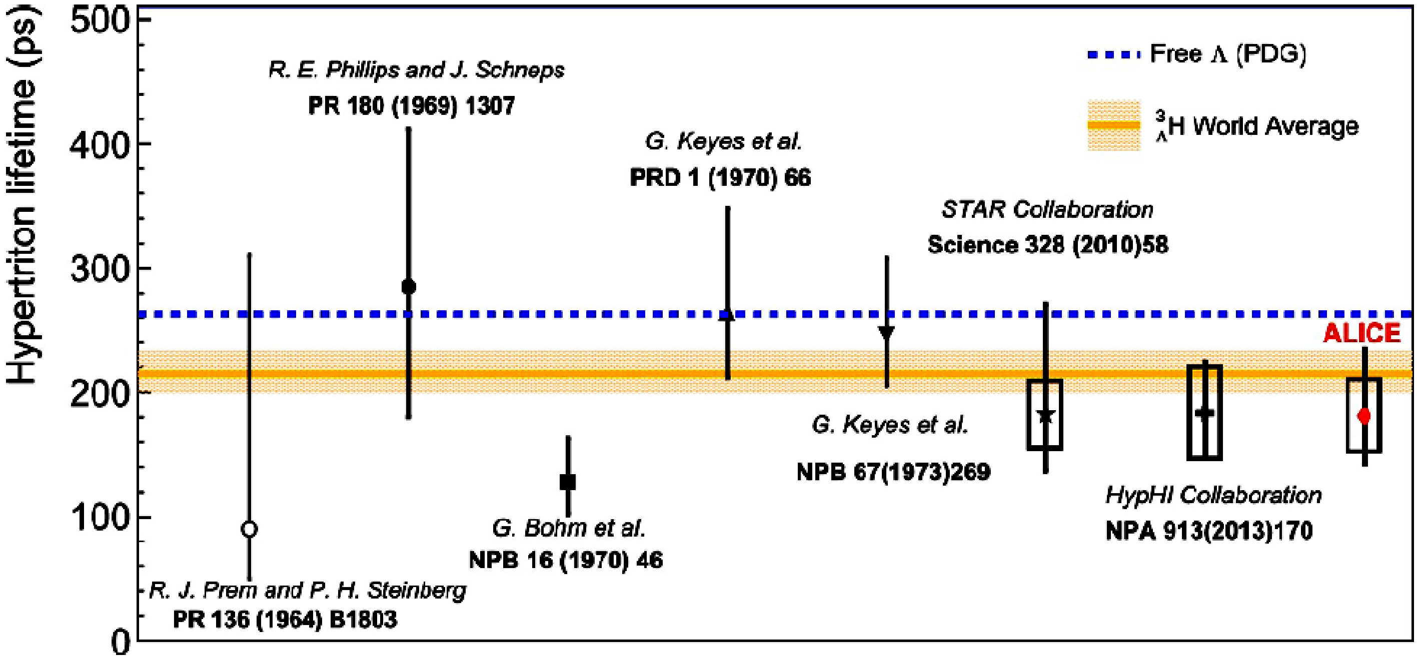


[Riisager et al., Europhys. Lett. 49 (2000)]

The puzzle of its lifetime vs B_Λ



$^{3}_{\Lambda}$H lifetime measurements



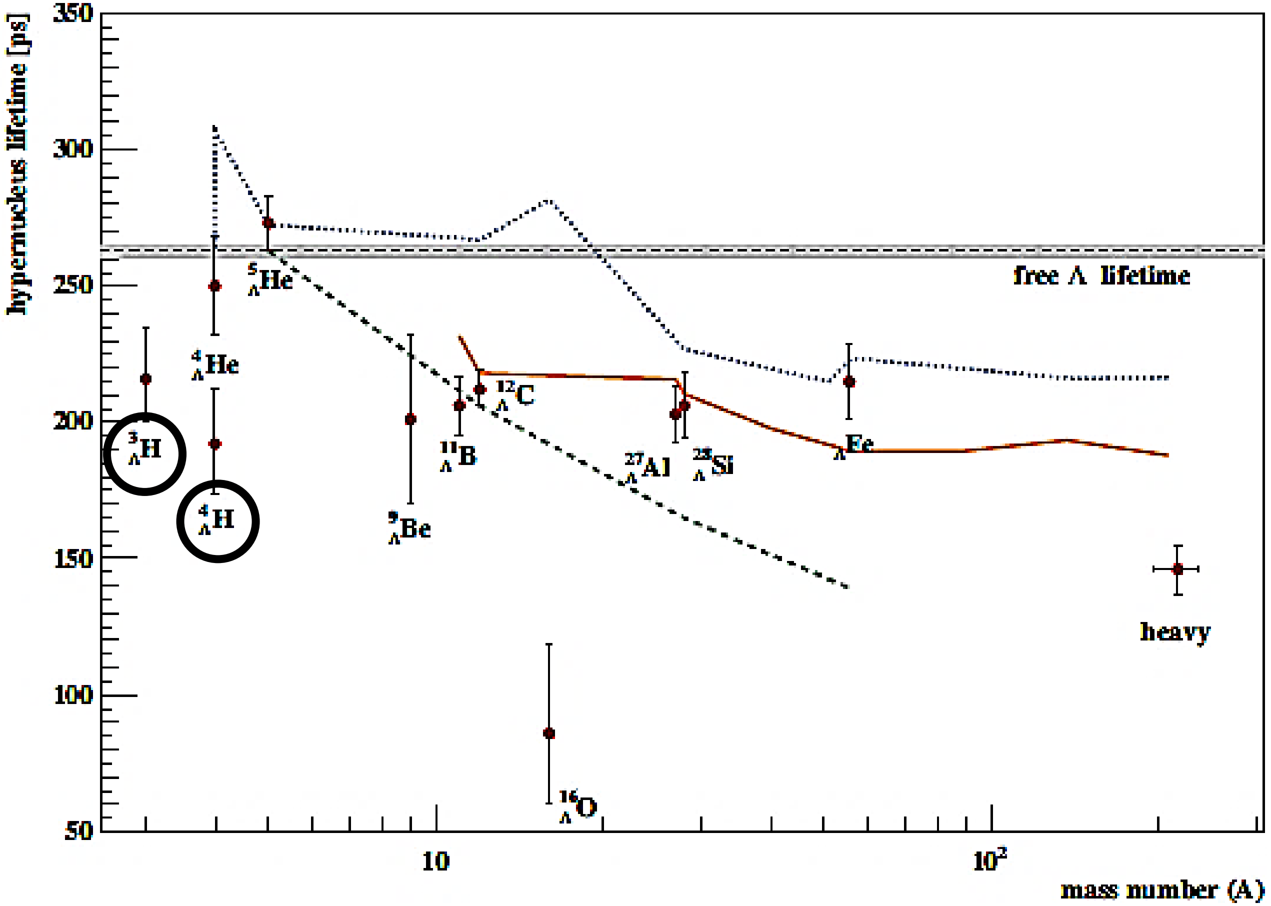
[ALICE Collab. PLB 754 (2016)]

– lifetimes of light ($A \leq 4$) hypernuclei expected to be similar to free Λ, if Λ in the hypernucleus is weakly bound
– hypernuclear lifetimes are not known as precisely as the Λ lifetime
– world average of $^{3}_{\Lambda}$H lifetime measurements $\tau = 215\ ^{+18}_{-16}$ ps
– comparison with $\tau_\Lambda = 263.2 \pm 2$ ps

values from heavy ion experiments are surprisingly small

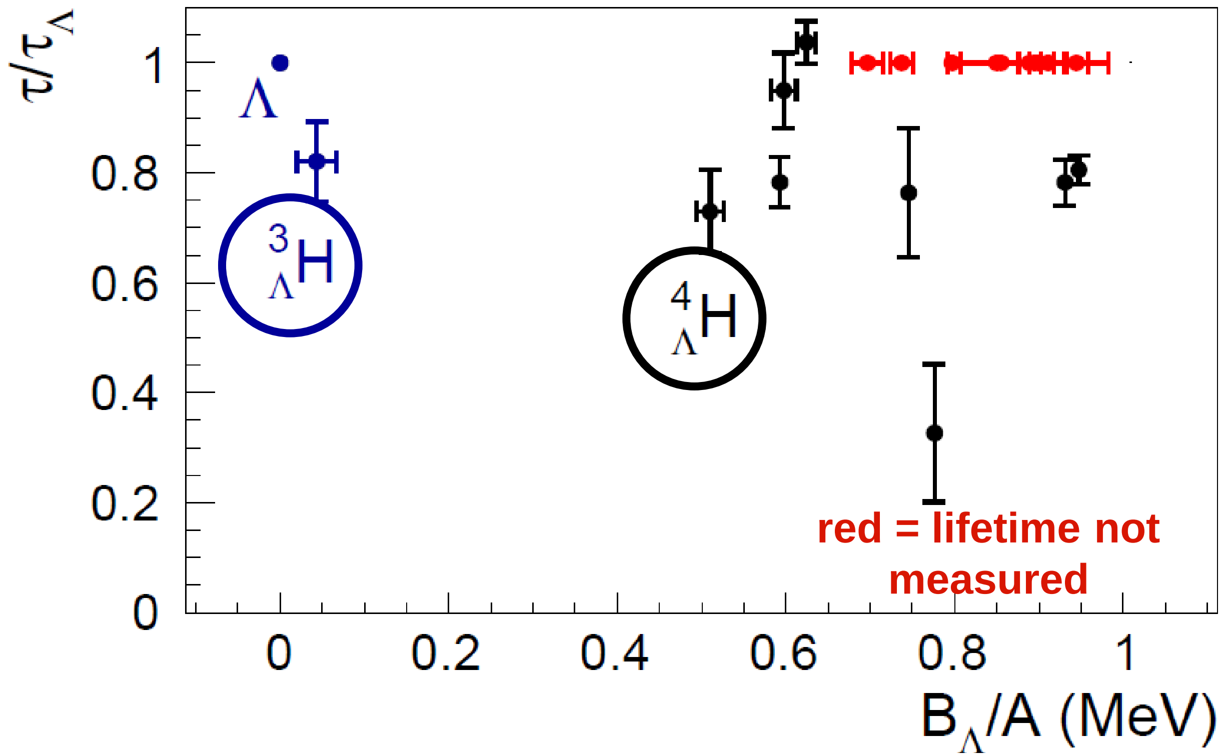
Other hypernuclear lifetimes

– only ~ 10 hypernuclear lifetimes known
– theoretical predictions are scattered over a large range
– calculations hyperhydrogen lifetimes predict no more than 10% deviation



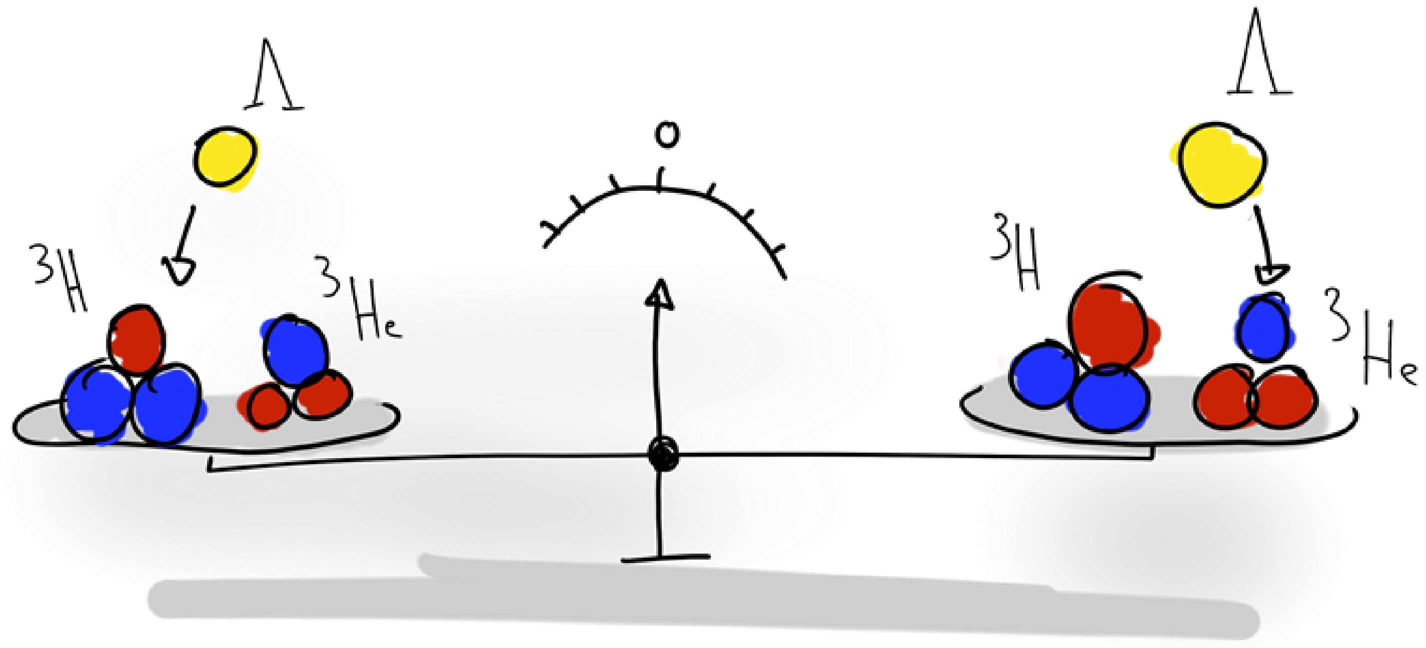
[E. Botta et al. Riv. N. Cim. 38 (2015)]

Scaled lifetime vs scaled B_Λ



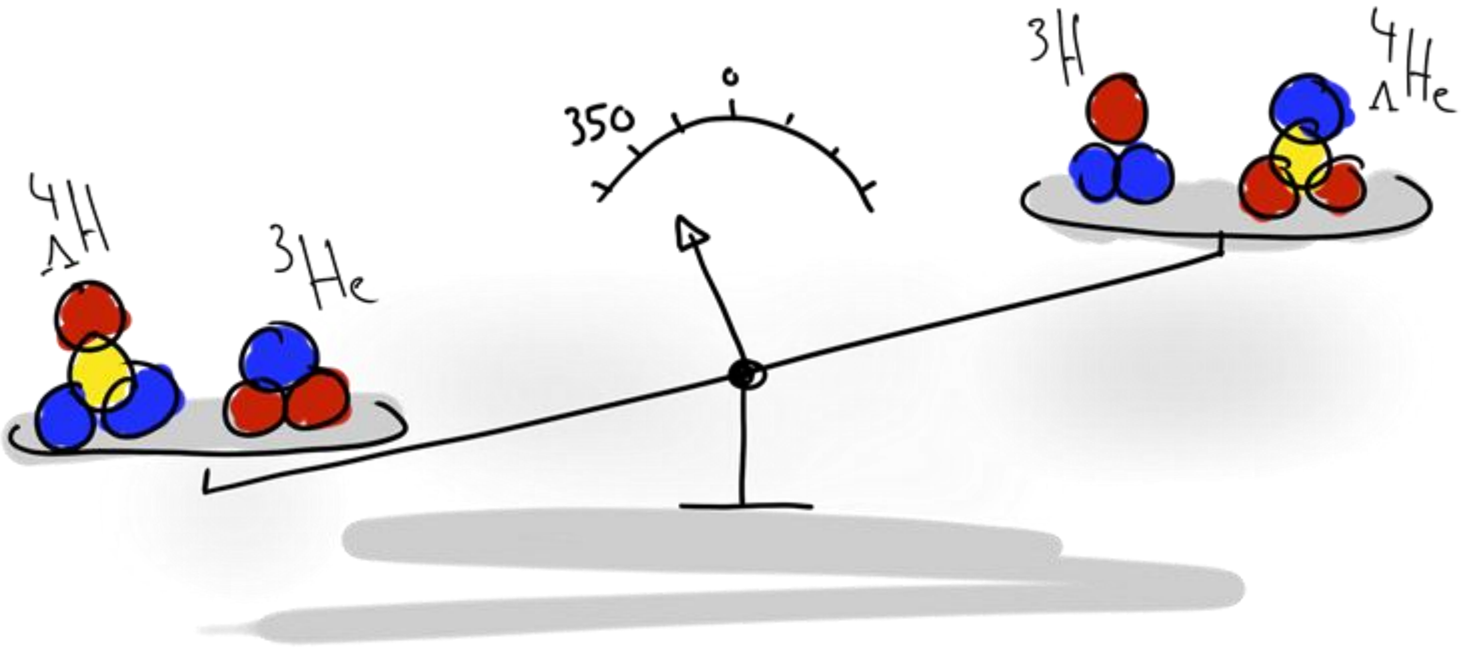
- small Λ binding energy implies extended wave function → lifetime puzzle connected to precision of B_Λ measurement
- unique location of ${}^{3}_{\Lambda}$H compared to all other known hypernuclei
- lifetime of hydrogen hyperisotopes ~ 30% shorter with respect to Λ
- B_Λ of ${}^{4}_{\Lambda}$H ~15% smaller with respect to ${}^{4}_{\Lambda}$He
- strong charge symmetry breaking only in light hypernuclear systems

Charge symmetry in light hypernuclei



$$-B_{\Lambda} = M_{HYP} - (M_{Core} + M_{\Lambda})$$

Charge symmetry in light hypernuclei

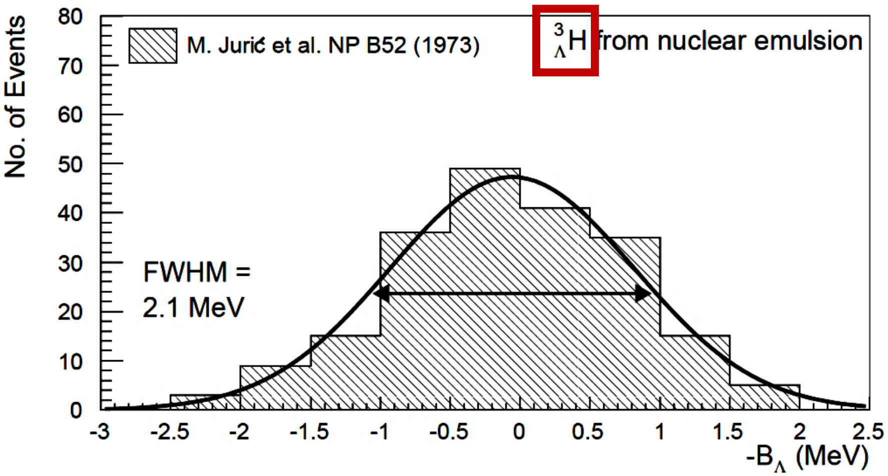


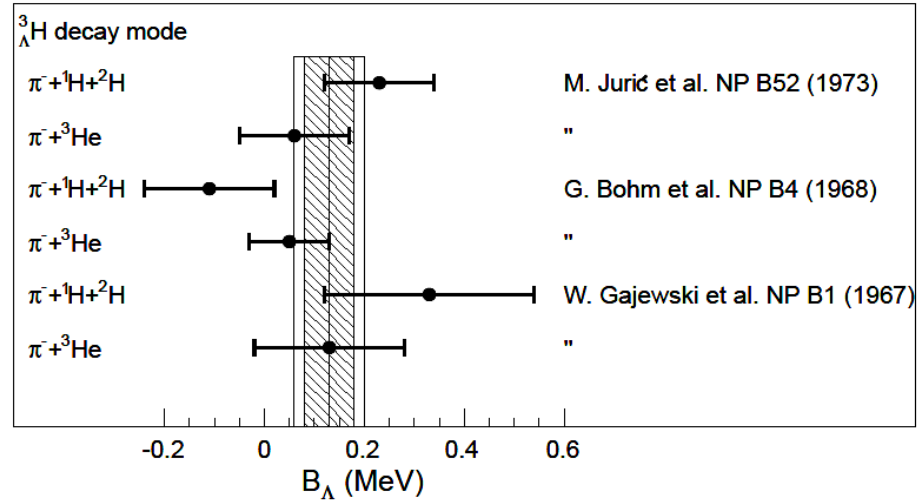
$$-B_\Lambda = M_{HYP} - (M_{Core} + M_\Lambda)$$

Emulsion data limitations

The emulsion data for $^{3}_{\Lambda}$H

only about 200 analyzed events from emulsion:





these data (from 2 decay modes): only source of binding energy information

$$^{3}_{\Lambda}\mathrm{H} \xrightarrow{\text{decay}} \pi^- + {}^3\mathrm{He}: \quad B_\Lambda = 70 \pm 60 \text{ keV}$$

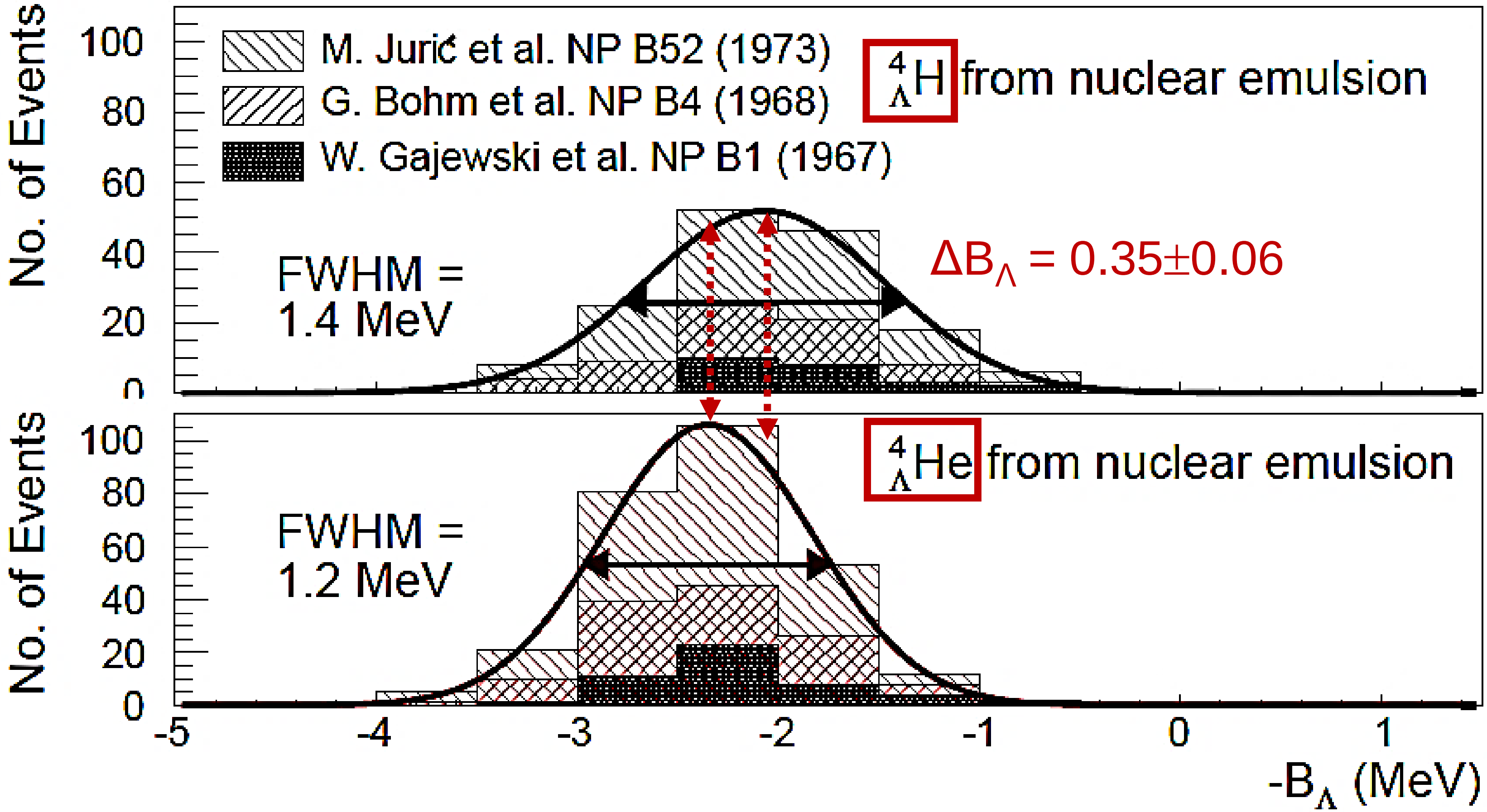
$$^{3}_{\Lambda}\mathrm{H} \xrightarrow{\text{decay}} \pi^- + {}^1\mathrm{H} + {}^2\mathrm{H}: \quad B_\Lambda = 120 \pm 80 \text{ keV}$$

} 50 keV difference

$$\text{Total: } B_\Lambda = 130 \pm 50 \text{ keV}$$

[M. Juric et al. NP B52 (1973)]

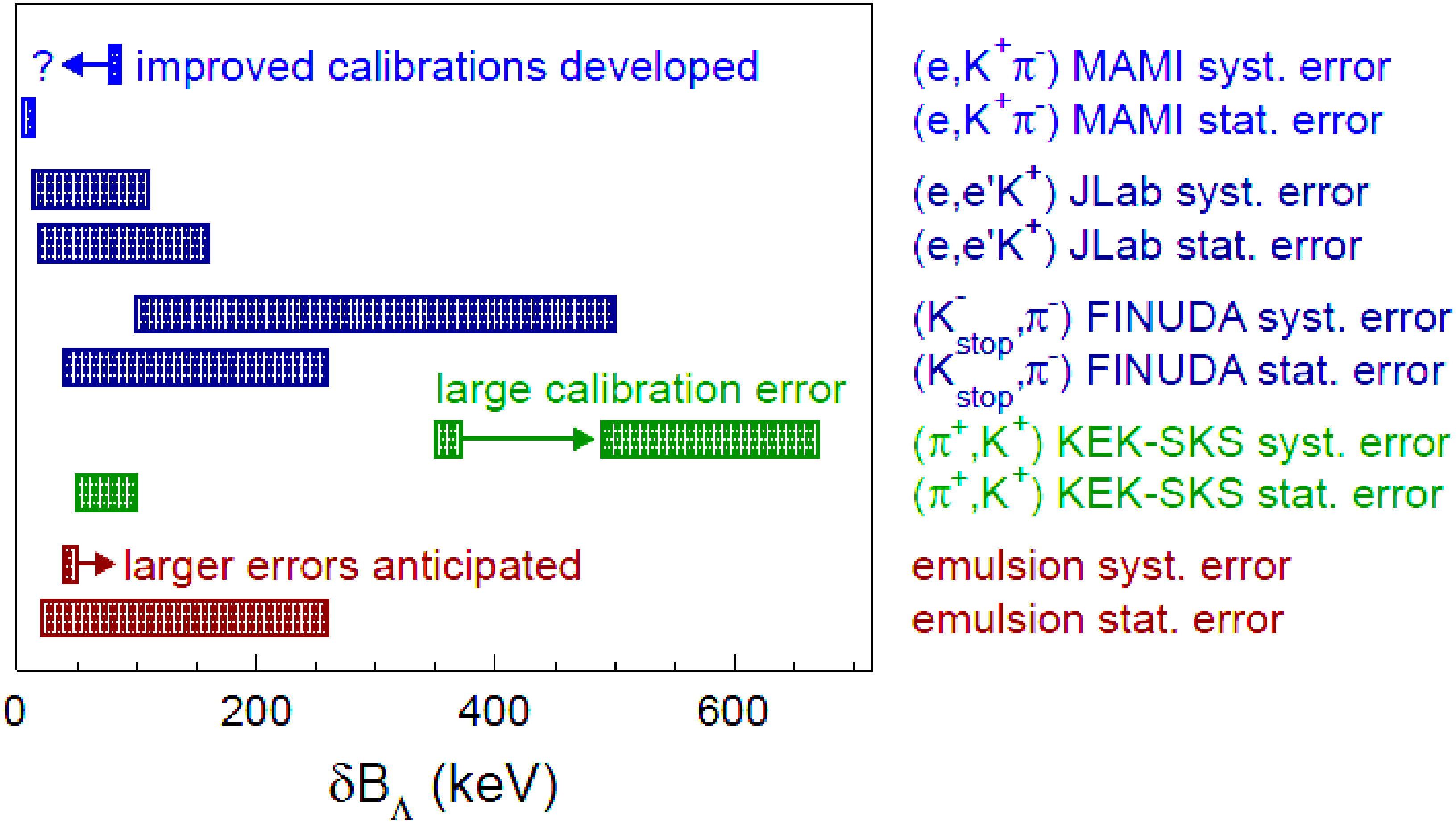
Emulsion results on $_{\Lambda}^{4}H$ and $_{\Lambda}^{4}He$



- only three-body decay modes used for hyperhydrogen
- 155 events for hyperhydrogen, 279 events for hyperhelium

Need for new precision measurements

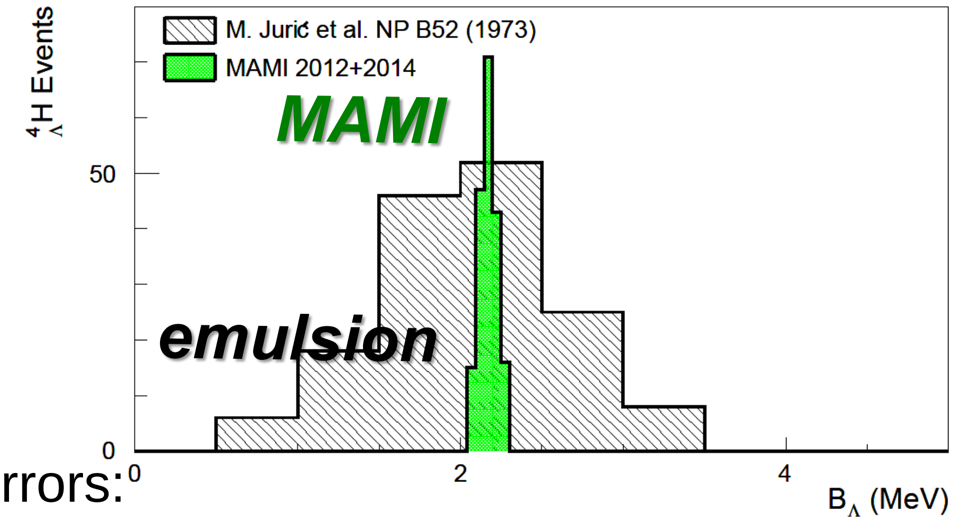
Errors on binding energy by method



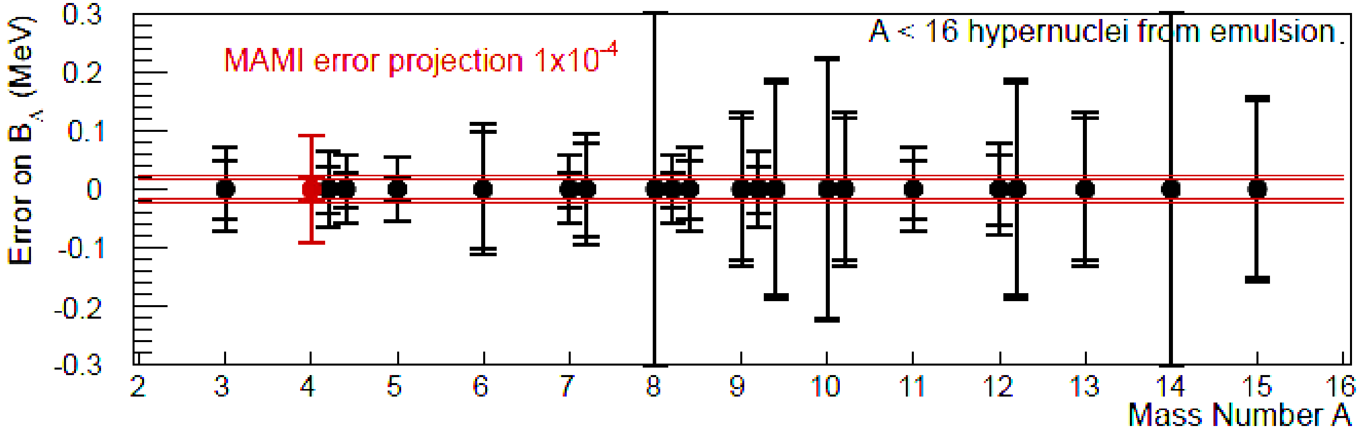
- goal of calibrations is syst. error comparable to stat. error < 20 keV
- decay-pion spectroscopy will be the most precise method of all

High-precision mass measurements at MAMI

requirements: calibration and beam energy with $O(10^{-4})$ precision



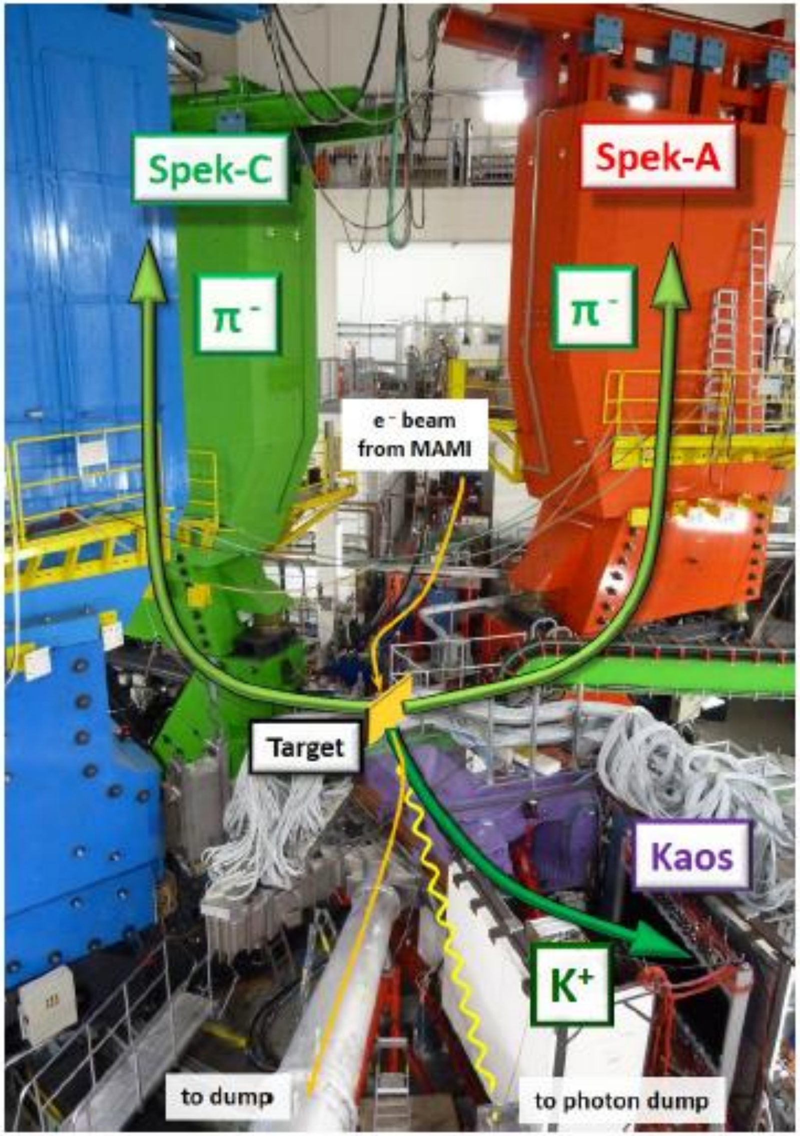
projected error compared to emulsion errors:

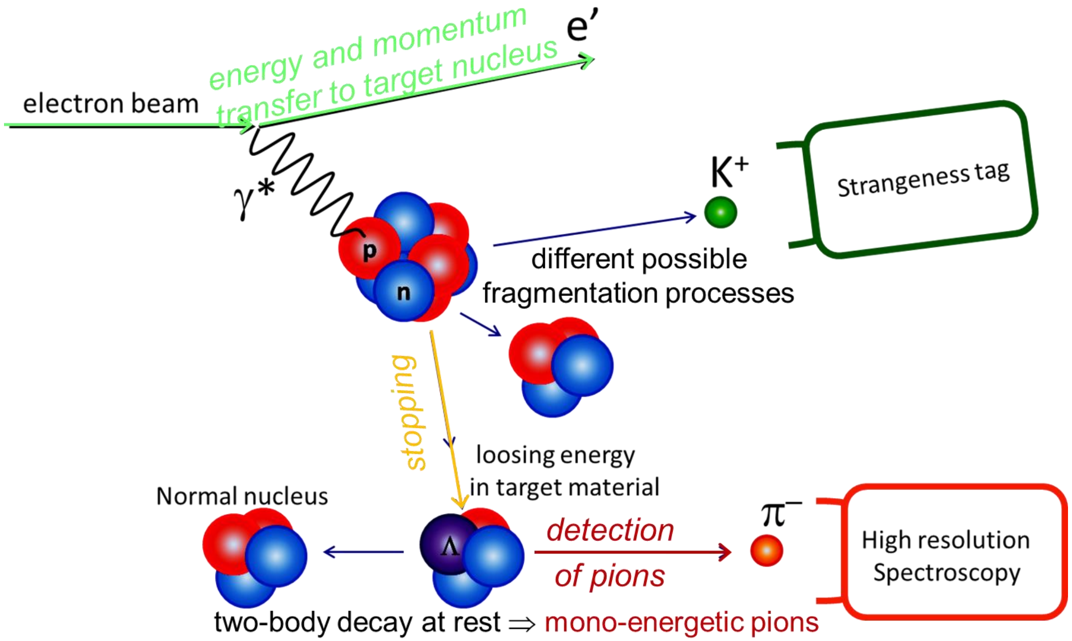


binding energies of light hyperisotopes could be measured with improved precision by decay-pion spectroscopy

Decay-pion spectroscopy at MAMI

Hyperfragment decay-pion spectroscopy with electron beams

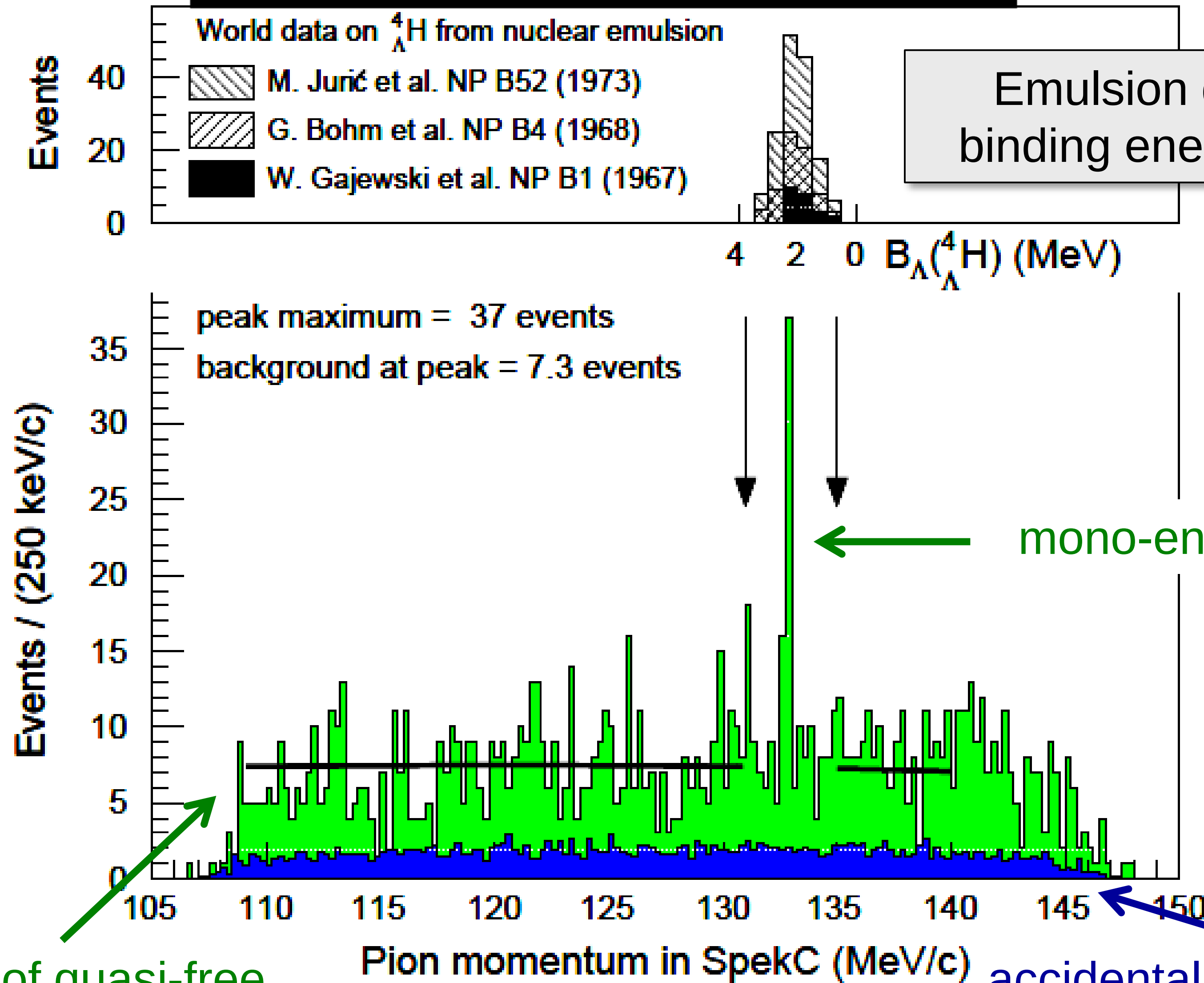




$$M_{\mathrm{HYP}} = \sqrt{M_{\mathrm{ncl}}^2 + p_{\pi^-}^2} + \sqrt{M_{\pi^-}^2 + p_{\pi^-}^2}$$

Hypernuclear experiments at MAMI done in Collaboration with Tohoku University (S.N.N. Nakamura et al.)

Decay-pion spectrum



Emulsion data on binding energy scale

mono-energetic pions

decays of quasi-free produced hyperon

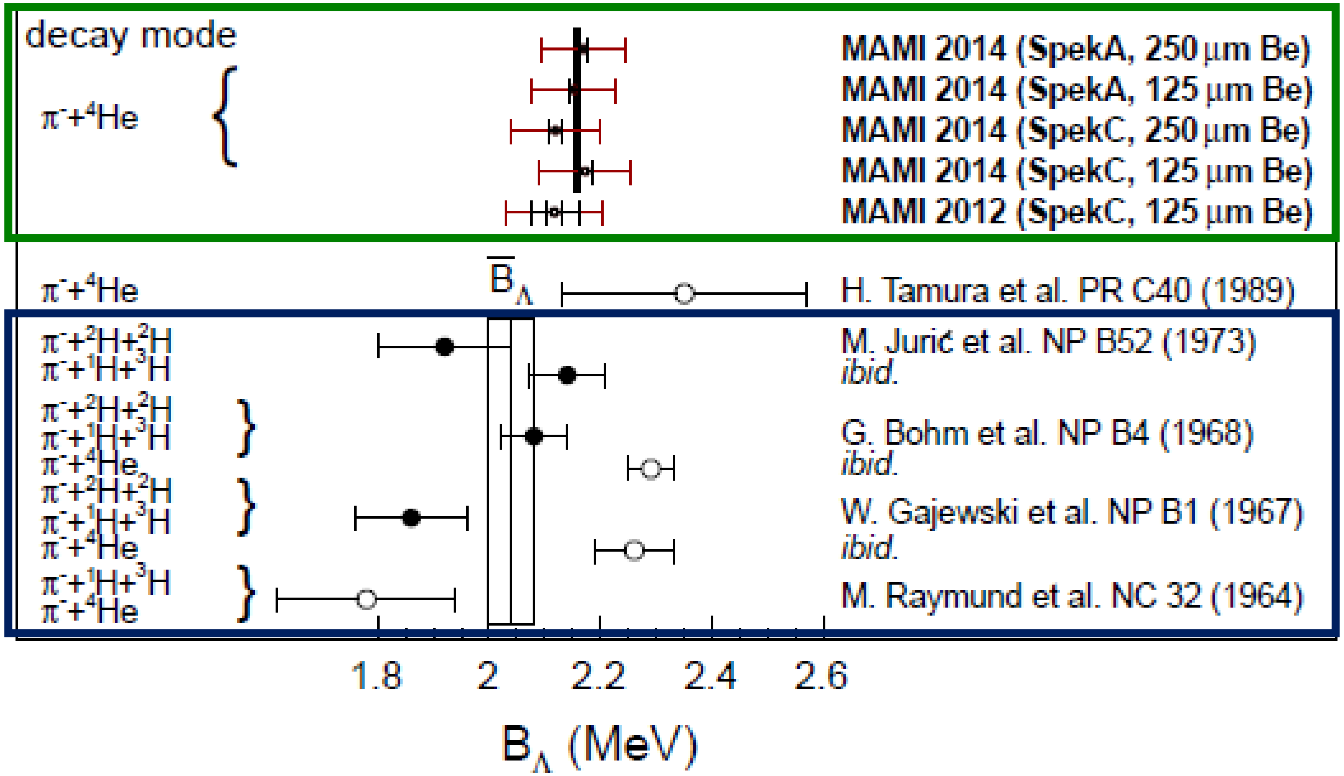
accidental background reactions

World data on $^{4}_{\Lambda}H$ mass

outer error bars correlated from calibration

MAMI

emulsion

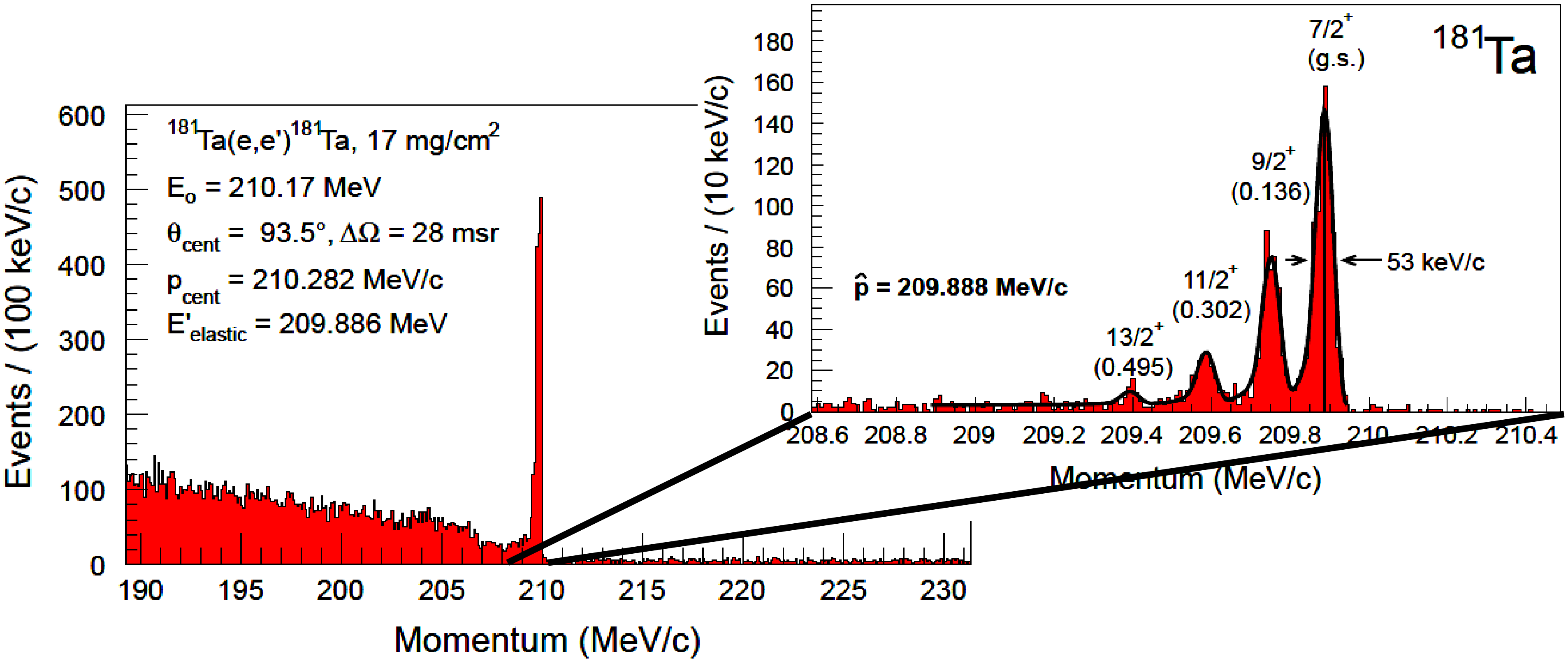


	$B_{\Lambda}(^{4}_{\Lambda}H)$	(stat.)	(syst.)	
emulsion:	2.04	± 0.04	± 0.05 MeV	[M. Juric et al. NP B52 (1973)]
MAMI 2012:	2.12	± 0.01	± 0.09 MeV	[A. Esser et al., PRL 114 (2015)]
MAMI 2014:	2.16	± 0.01	± 0.08 MeV	[F. Schulz et al., NPA (2016)]

Limitation by absolute beam energy precision

Absolute momentum calibration

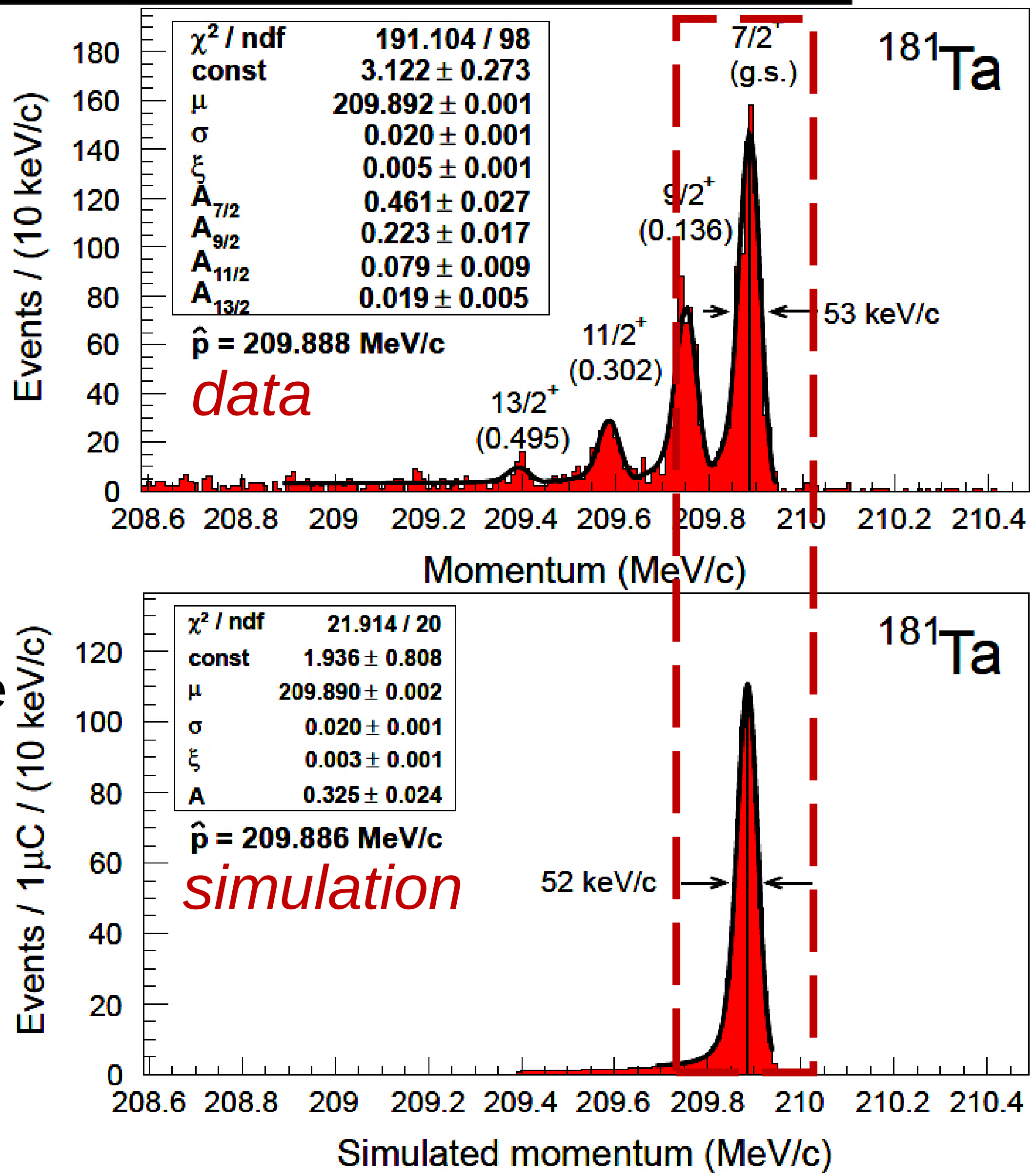
scattering off thin tantalum foil



- spectrometer FWHM of 53 keV/*c* → $\delta p/p \sim 2 \cdot 10^{-4}$
- beam energy absolute accuracy δp_{beam} ± 160 keV/*c* → $\delta E/E \sim 7 \cdot 10^{-4}$
- repeated calibrations at different momenta reveal δp_{calib} ~ 5 keV/*c*

Simulation of scattering process and spectrometer

comparison of
simulation *vs.* data
reveals highest precision

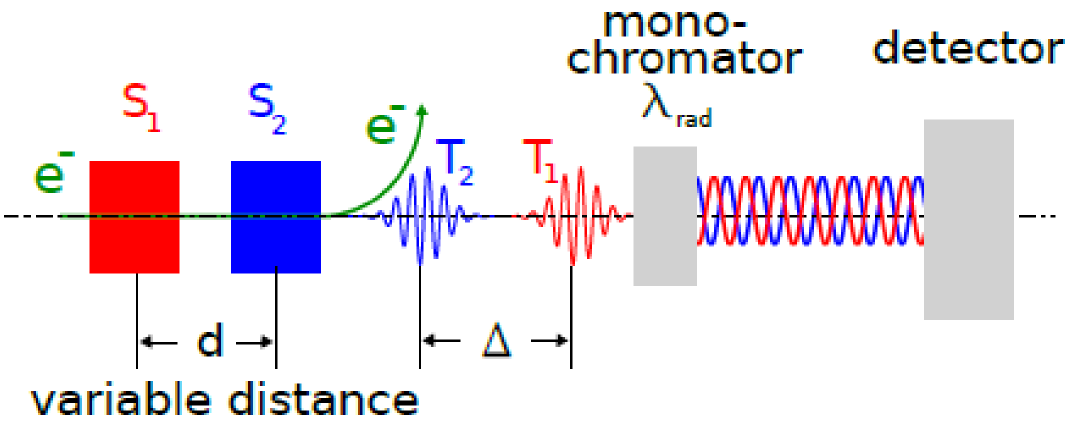


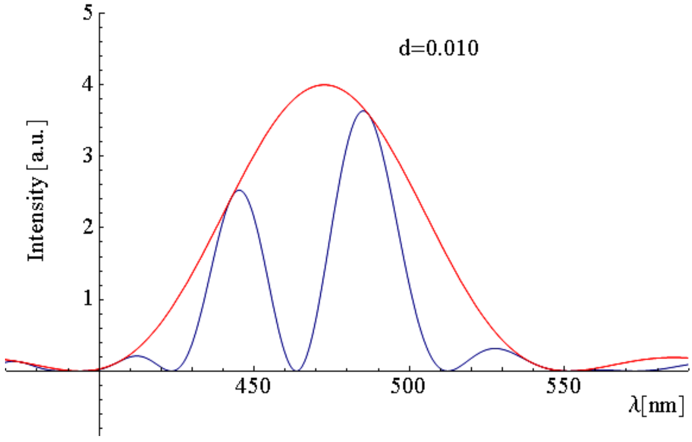
Monte Carlo code for
…**energy-loss** of incoming beam,
…reaction **vertex distribution**,
…**reaction kinematics**, and
…**energy-loss** of outgoing particle
→ shape & width well reproduced

calibration fixed at relative momentum closest to decay-pion line of $^{4}_{\Lambda}H$, data here shifted 7%
→ difference of only 2 keV/c

Interferometry of optical undulator radiation

Novel absolute beam energy measurements

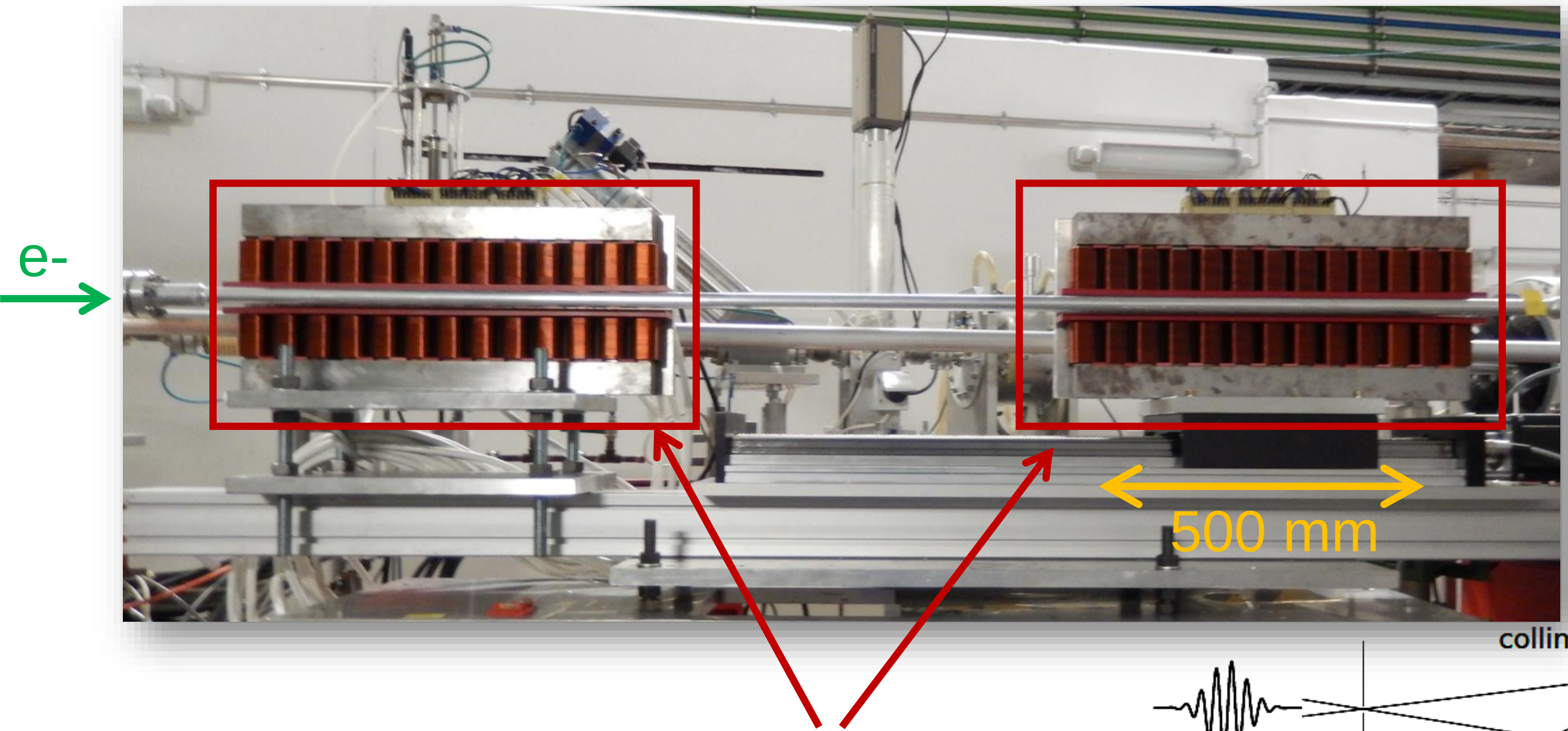




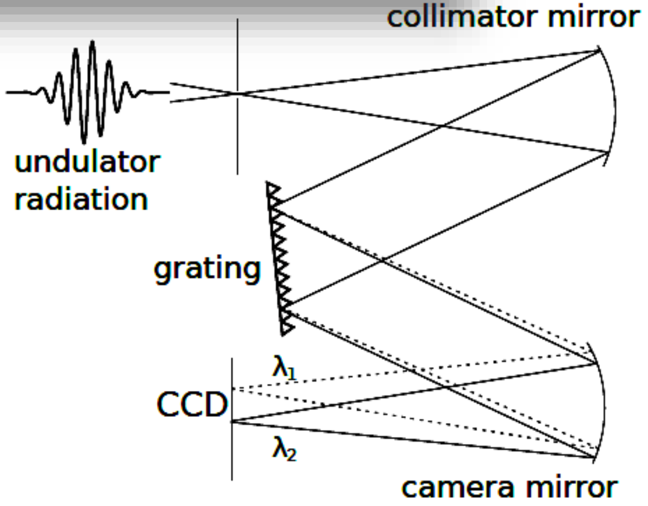
- two spatially separated sources of coherent synchrotron light
- two separated wave trains show interference in optical detector
- monochromator serves as Fourier analyzer of wave trains
- intensity for a selected wavelength shows a periodical variation
- intensity oscillation length directly related to beam energy

$$\gamma^2_{\mathrm{beam}} = \frac{\lambda_{\mathrm{osc}}}{2\lambda_{\mathrm{rad}}}$$

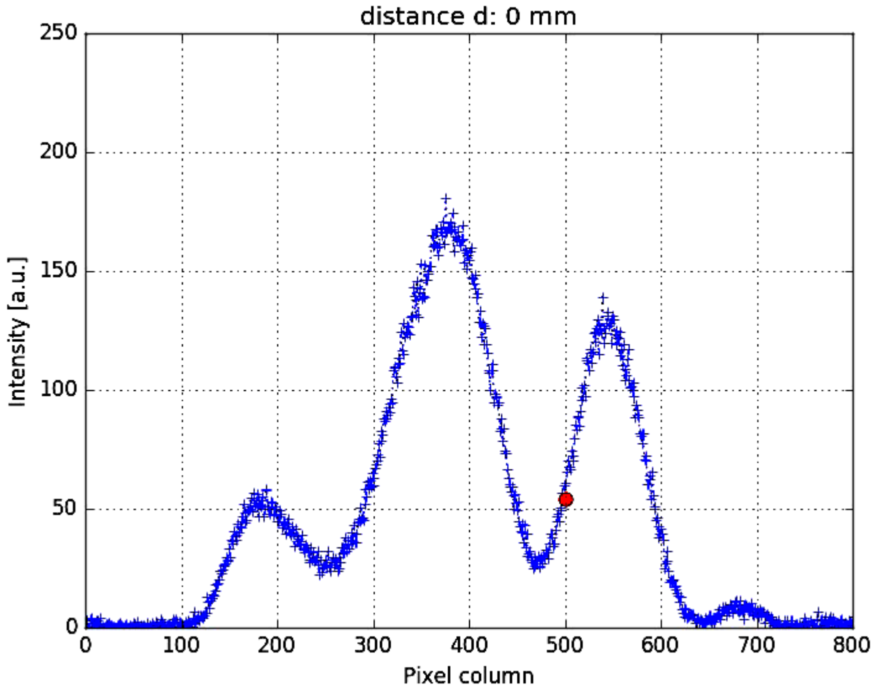
Pioneering run with undulator setup at MAMI



- two 50 cm long undulators
- variable distance of 500 mm
- monochromator and CCD system



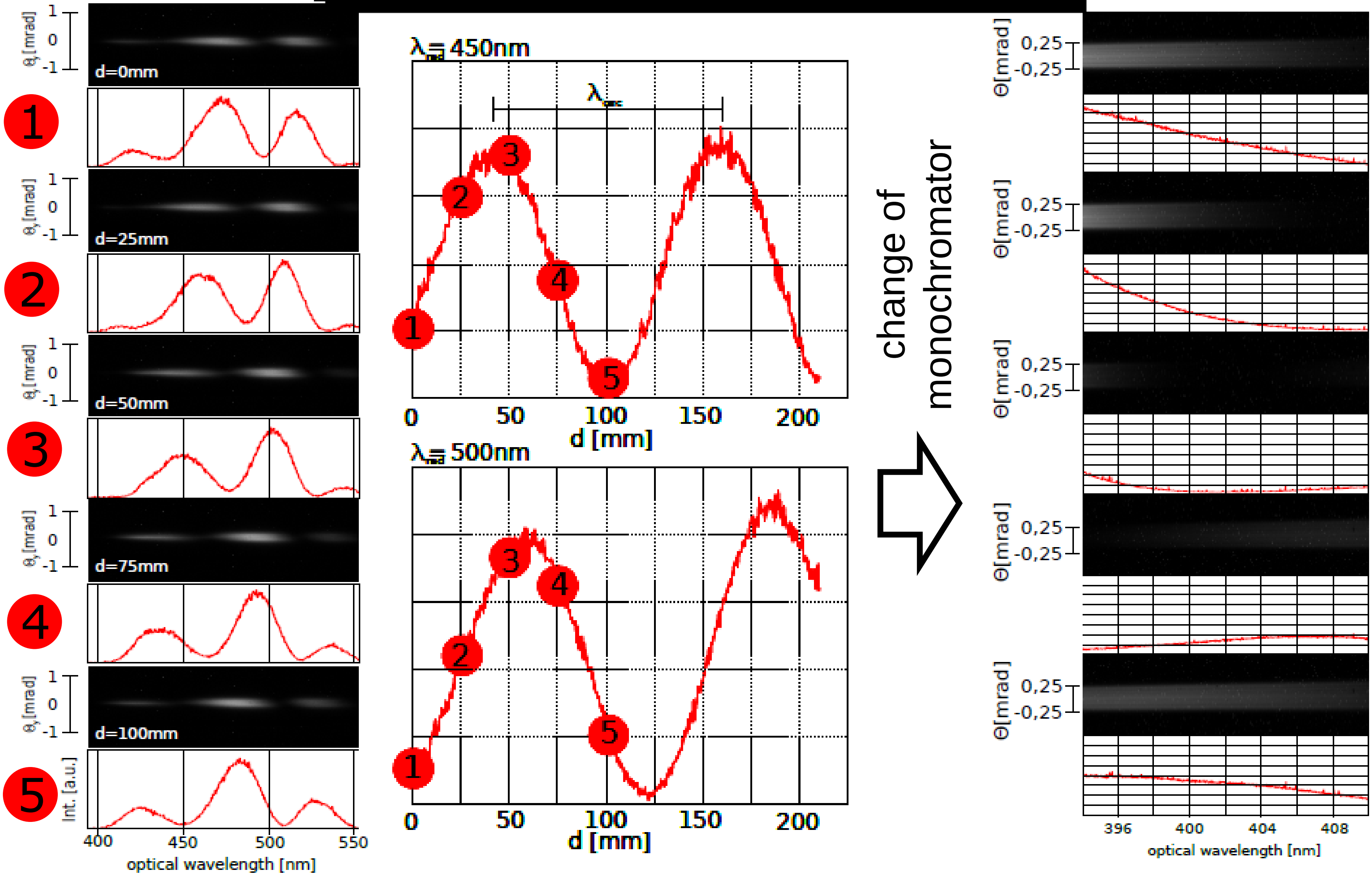
Evolution of synchrotron spectrum with distance



- clean spectra observed at center of radiation cone
- intensity at one wavelength varies periodically
- low counting noise
  ⇨ high statistical precision

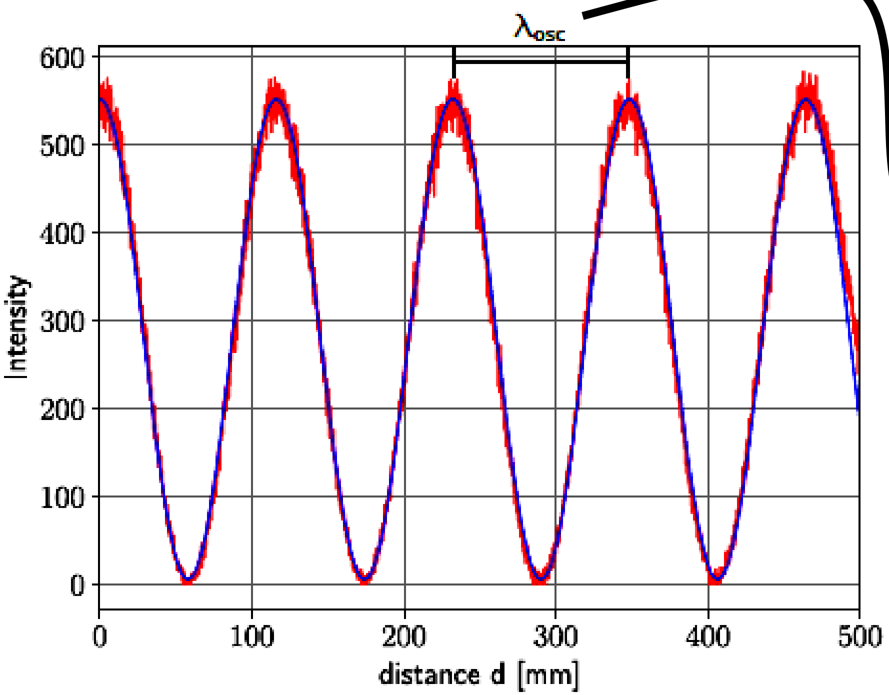
proof of principle demonstrated with this measurement

Proof of principle demonstrated

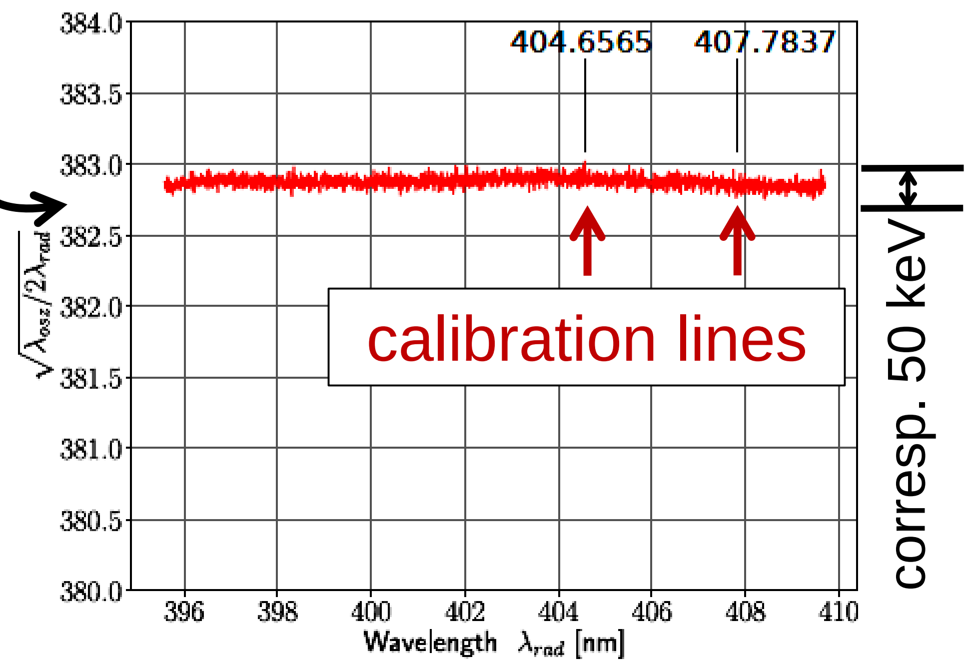


Highest-precision beam energy measurement achieved

intensity oscillation for one selected wavelength:



simultaneous measurement for 2328 wavelengths in CCD:

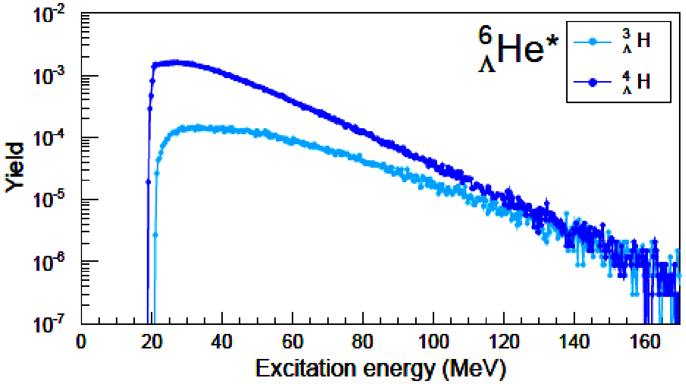


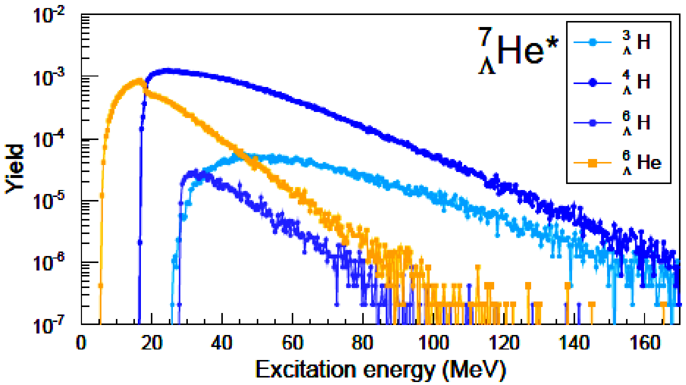
$$\gamma_{\text{beam}} = 382.2 \pm 0.002\ (\text{stat.})\ \pm 1.3\ (\text{syst.}\delta_{\Theta})\ \pm 0.1\ (\text{syst.}\delta_{\lambda})$$

$$E_{\text{beam}} = 194.8 \pm 0.001\ (\text{stat.})\ \pm 0.7\ (\text{syst.}\delta_{\Theta})\ \pm 0.05\ (\text{syst.}\delta_{\lambda})\ \text{MeV}$$

Ongoing activities and future projects

Li: an ideal target for $^{3}_{\Lambda}$H production

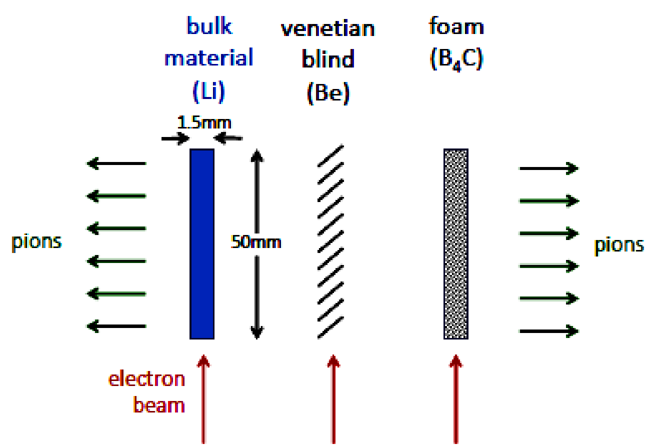


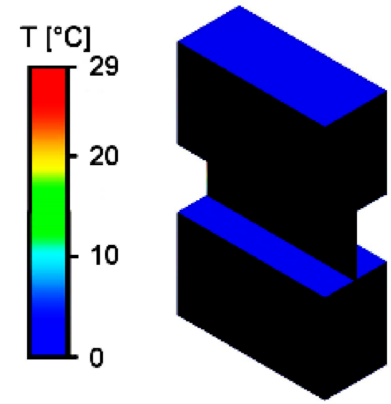


statistical decay simulations:

		^{9}Be target			^{7}Li target	^{6}Li target
hyper-nucleus	π^- momentum (MeV/c)	direct Λ capture $^{9}_{\Lambda}$Li*	Λ+neutron kick out $^{8}_{\Lambda}$Li*	Λ+proton kick out $^{8}_{\Lambda}$He*	direct Λ capture $^{7}_{\Lambda}$He*	direct Λ capture $^{6}_{\Lambda}$He*
$^{3}_{\Lambda}$H	114.37±0.08	0.56	1.18	0.67	1.49	2.48
$^{4}_{\Lambda}$H	132.87±0.06	3.56	3.74	7.51	12.61	8.81
$^{6}_{\Lambda}$H	135.13±1.52	0.03	<0.01	0.23	0.10	–
$^{6}_{\Lambda}$He	108.47±0.18	2.44	1.25	1.47	3.53	–
$^{7}_{\Lambda}$He	$114.97 \pm 0.15_{stat} \pm 0.17_{sys}$	2.12	0.44	1.35	–	–
$^{8}_{\Lambda}$He	116.50 ±1.08	0.04	–	–	–	–
$^{7}_{\Lambda}$Li	108.11 ±0.05	1.54	1.68	–	–	–
$^{8}_{\Lambda}$Li	124.20 ±0.05	0.85	–	–	–	–

possible experiments: 2019/2020





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