Precision Decay-Pion Spectroscopy of Hyperhydrogen

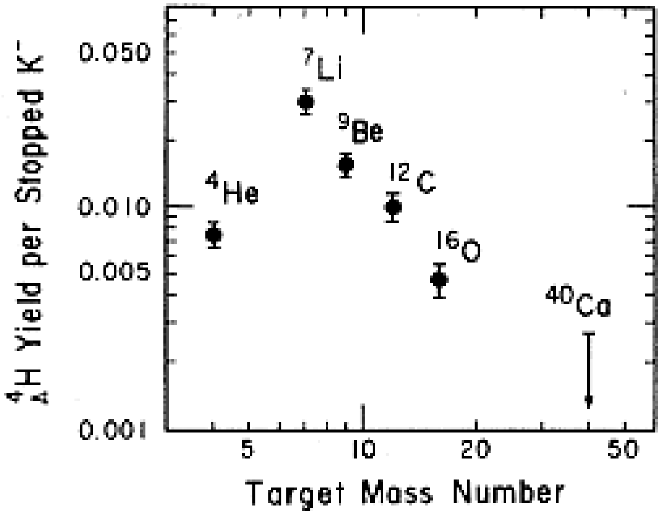
Patrick Achenbach

U Mainz

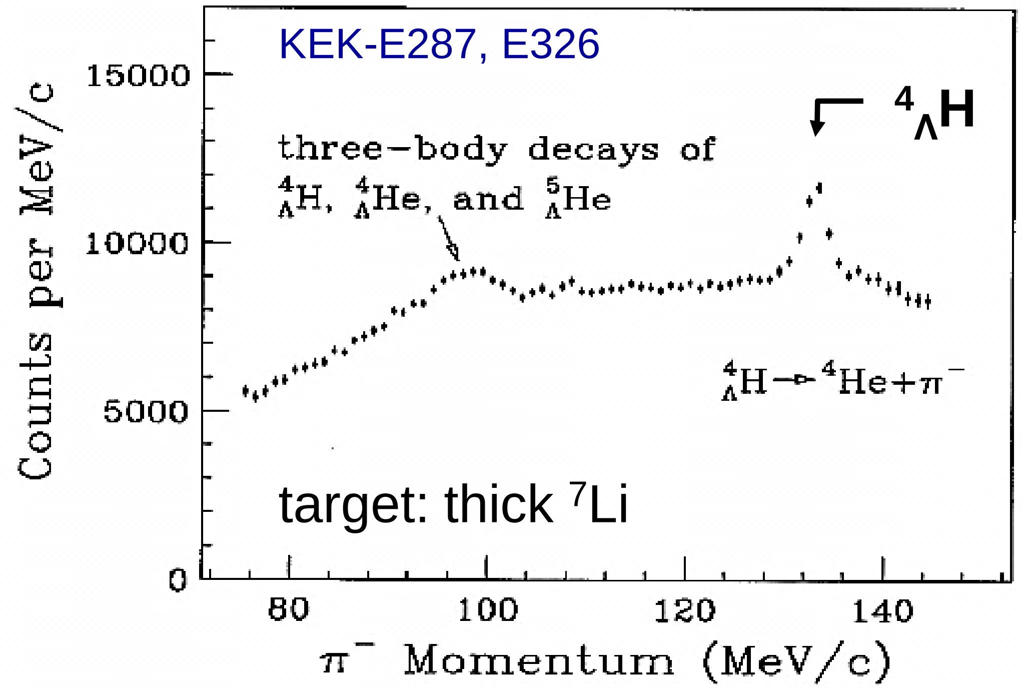
Sept. 2o14

Experimental Considerations

Formation of hyperhydrogen on light nuclei



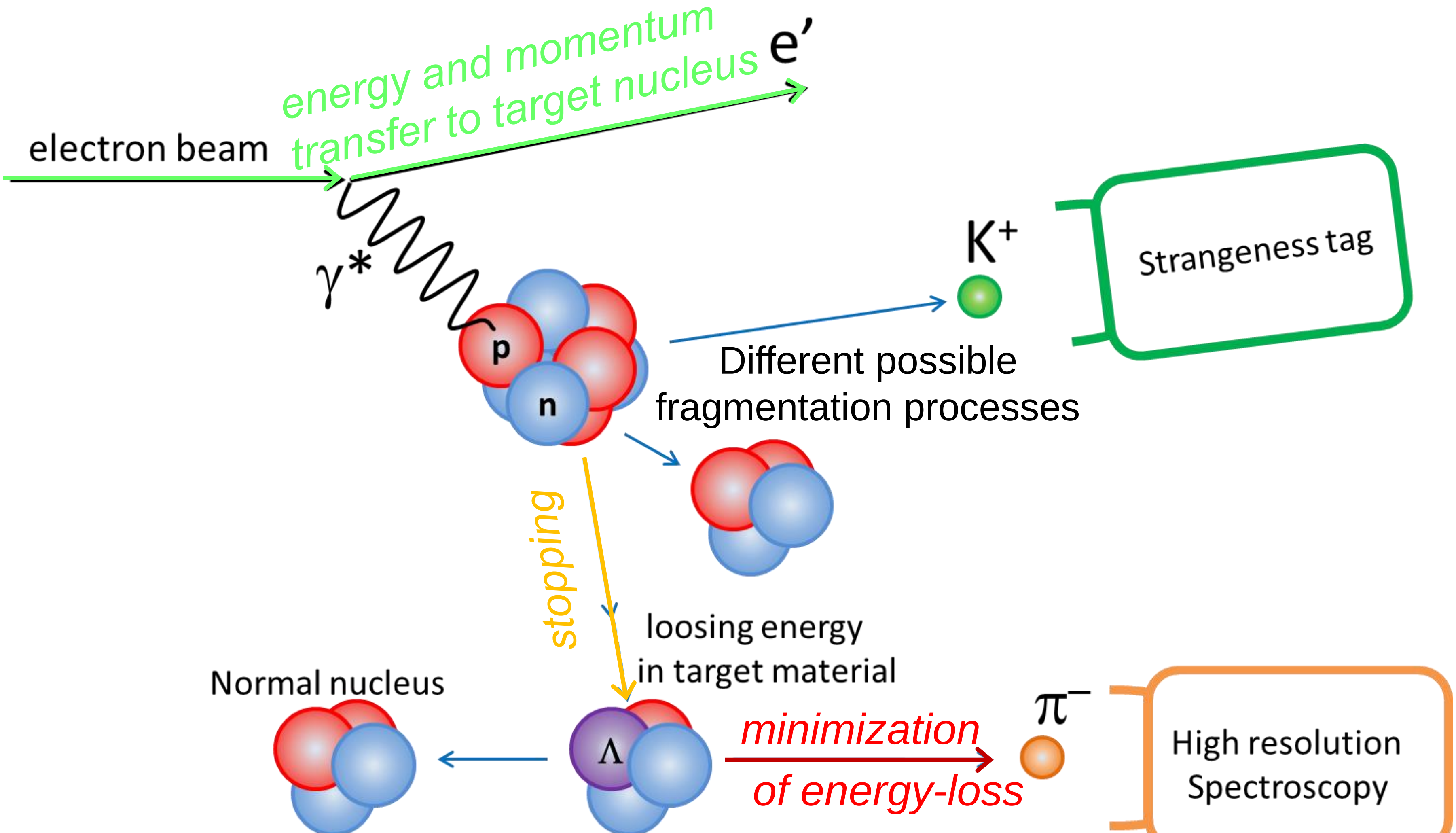
target dependence



- first detection of hyperfragments in a spectrometer
- limited momentum resolution

[H. Tamura et al. Phys. Rev. C 40 (1989)]

Hypernuclear decay-pion spectroscopy in counter experiments



two-body decay at rest ⇒ mono-energetic pions

Hypernuclear ground-state masses

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

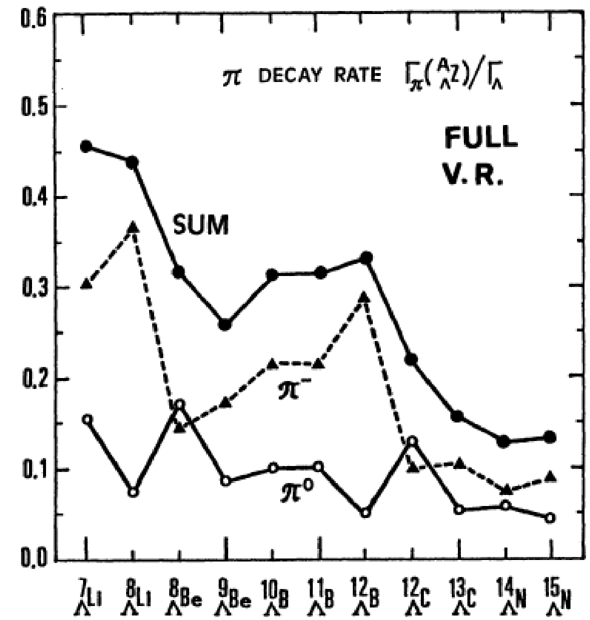
⇨ pion momentum resolution ~ 100-150 keV/c
→ mass resolution ~100 keV/c^2 (FWMH)

9 accessible isotopes with ^{9}Be from $^3_\Lambda$H, $^4_\Lambda$H, …, to $^9_\Lambda$Li:

^{3}He + p + π^-
p + ^{4}He + π^-
^{3}He + π^-
^{4}He + π^-

	$^6_\Lambda$Li	$^7_\Lambda$Li	$^8_\Lambda$Li	$^9_\Lambda$Li
$^4_\Lambda$He	$^5_\Lambda$He	$^6_\Lambda$He	$^7_\Lambda$He	$^8_\Lambda$He
$^3_\Lambda$H	$^4_\Lambda$H		$^6_\Lambda$H	

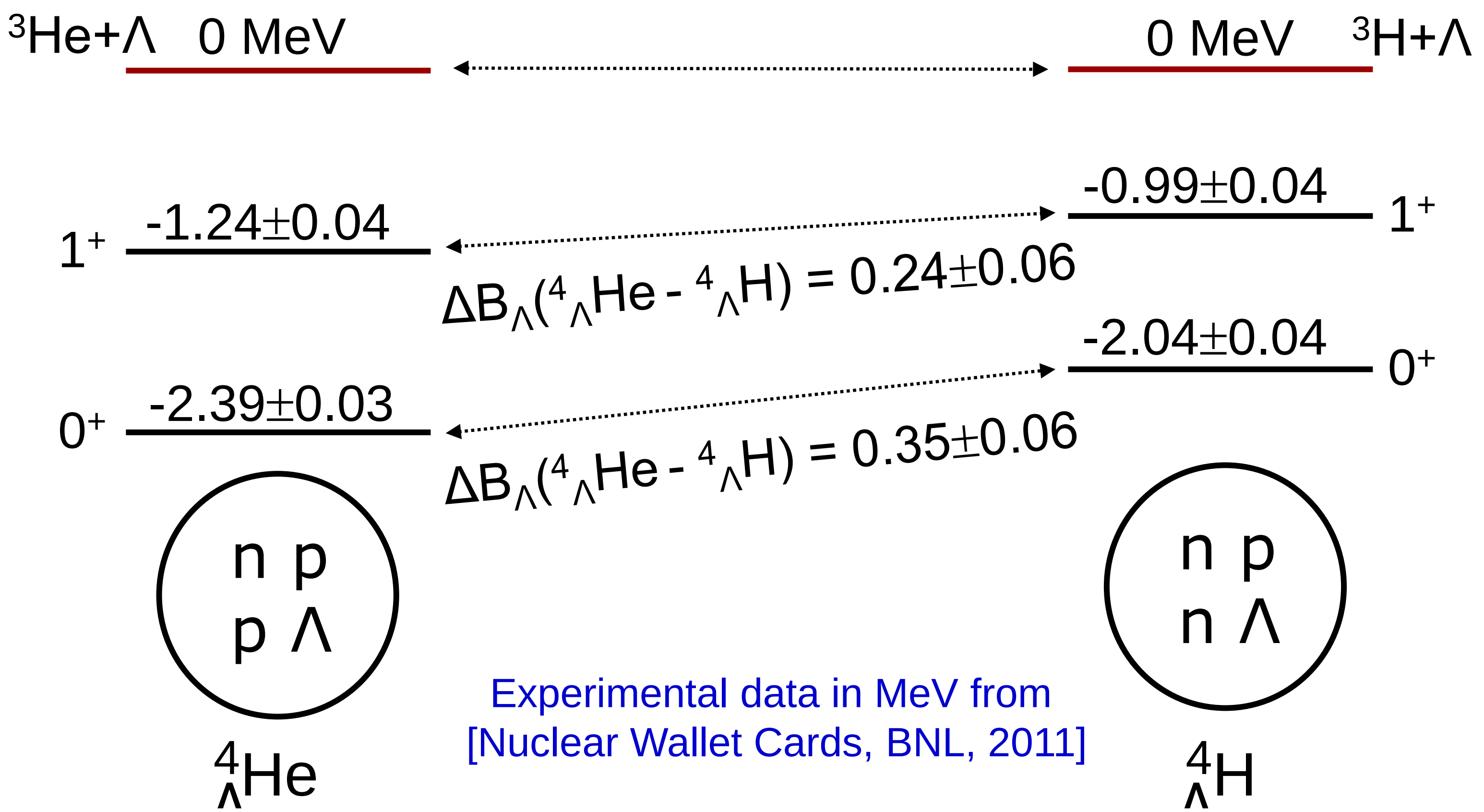
red: inaccessible by MM
gray: no two-body decay



[T. Motoba & K. Itonaga, PTPS 117 (1994)]

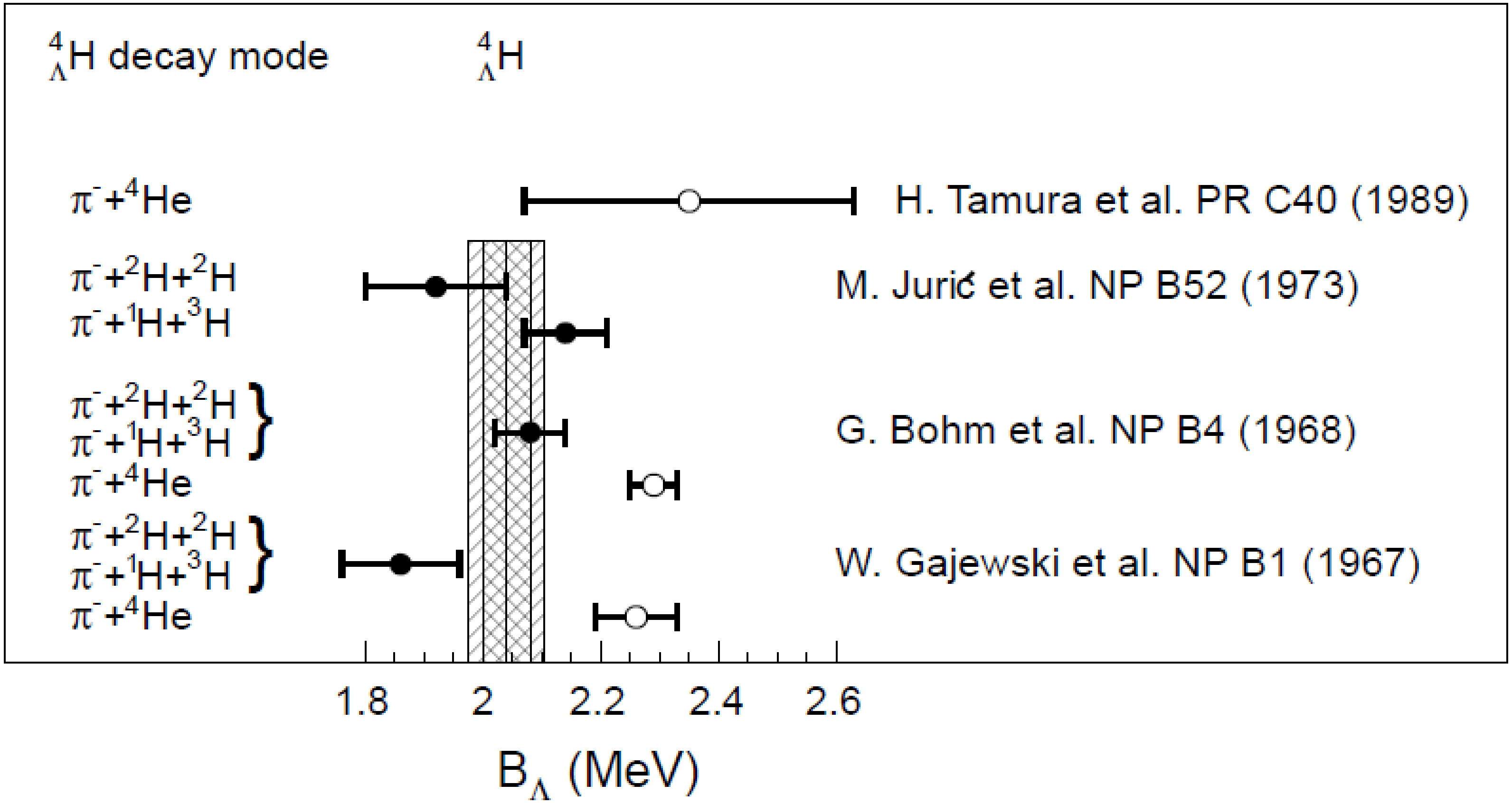
The Mass A = 4 System

The A = 4 isospin doublet



- Nucleon-hyperon interaction can be studied by strange mirror pairs
- Coulomb corrections are < 50 keV for the $^4_\Lambda$H - $^4_\Lambda$He pair

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



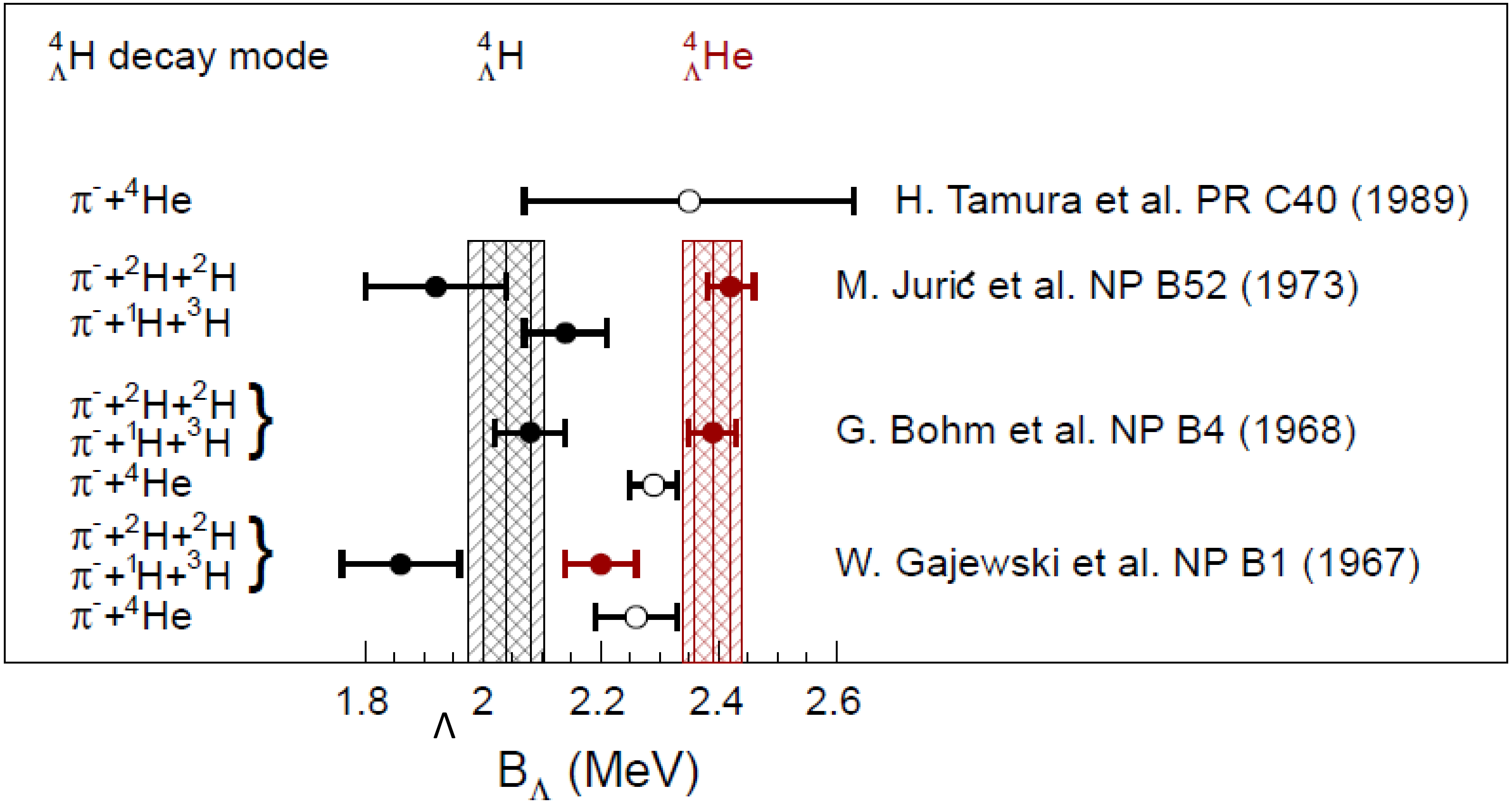
$^4_\Lambda H \xrightarrow{decay} \pi^- + {}^1H + {}^3H$: $B = 2.14 \pm 0.07$ MeV

$^4_\Lambda H \xrightarrow{decay} \pi^- + {}^2H + {}^2H$: $B = 1.92 \pm 0.12$ MeV

} 0.22 MeV difference

Total: $B = 2.08 \pm 0.06$ MeV [M. Juric et al. NP B52 (1973)]

World data on $A = 4$ system



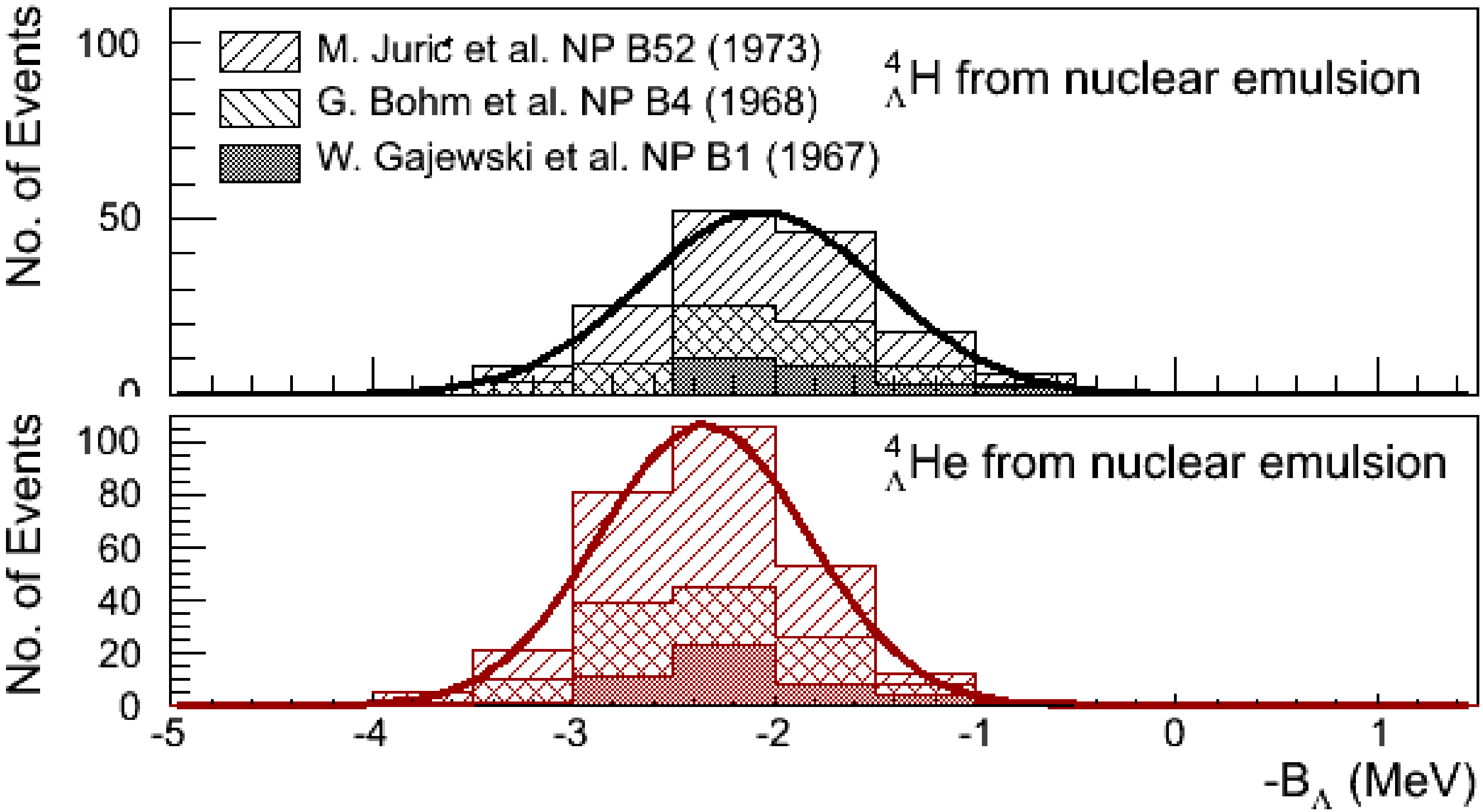
$^4_\Lambda He \xrightarrow{decay} \pi^- + {}^1H + {}^3He$: B = 2.42 ±0.05 MeV

$^4_\Lambda He \xrightarrow{decay} \pi^- + 2\,{}^1H + {}^2H$: B = 2.44 ±0.09 MeV

0.02 MeV difference

Total: B = 2.42 ±0.04 MeV [M. Juric et al. NP B52 (1973)]

World data on $A = 4$ system



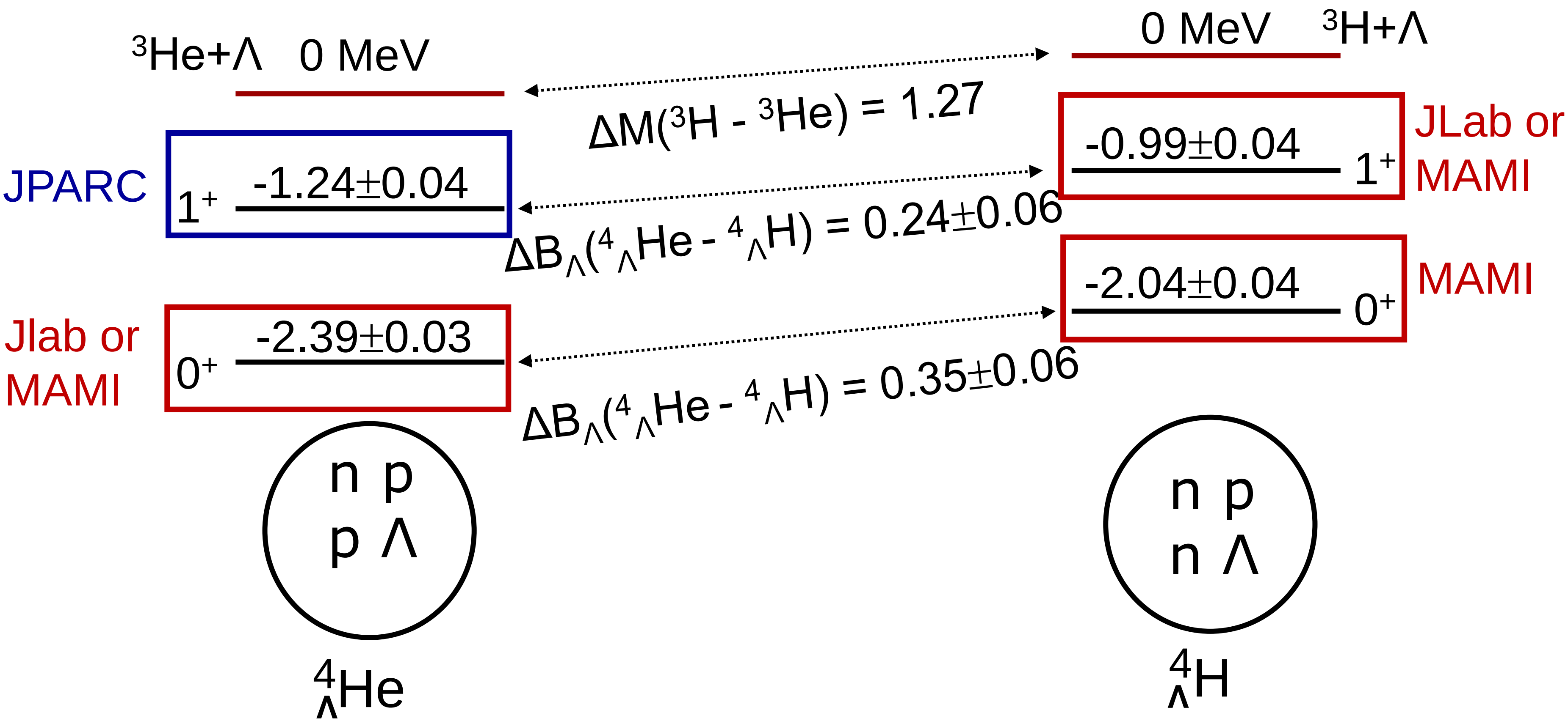
- Only three-body decay modes used for hyperhydrogen
- Systematic errors of > 0.04 MeV not included [D. Davis]
- 155 events for hyperhydrogen, 279 events for hyperhelium

Modern calculations on A = 4 system

Calculation	Interaction	$B_\Lambda(^4_\Lambda H_{gs})$	$B_\Lambda(^4_\Lambda He_{gs})$	ΔB_Λ $(^4_\Lambda He - ^4_\Lambda H)$
A. Nogga, H. Kamada and W. Gloeckle, PRL 88, 172501 (2002)	SC97e	1.47	1.54	0.07
	SC89	2.14	1.80	0.34
H. Nemura. Y. Akaishi and Y. Suzuki, PRL 89, 142504 (2002)	SC97d	1.67	1.62	-0.05
	SC97e	2.06	2.02	-0.04
	SC97f	2.16	2.11	-0.05
	SC89	2.55	2.47	-0.08
E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yama PRC 65, 011301 (R) (2001)	AV8	2.33	2.28	-0.05
World data average		2.04±0.04	2.39±0.03	0.35±0.06

With precise spectroscopy details of *NY*-interaction can be inferred

The A = 4 isospin doublet



- $^4_Λ$H g.s. re-measured at MAMI in pion-decay spectroscopy
- $^4_Λ$He g.s. can possibly be re-measured in pion-decay spectroscopy
- $^4_Λ$H ex.s. can possibly be re-measured in He(e,e'K)H spectroscopy
- $^4_Λ$He ex.s. can be re-measured in γ-ray spectroscopy at JPARC

Experiments at MAMI

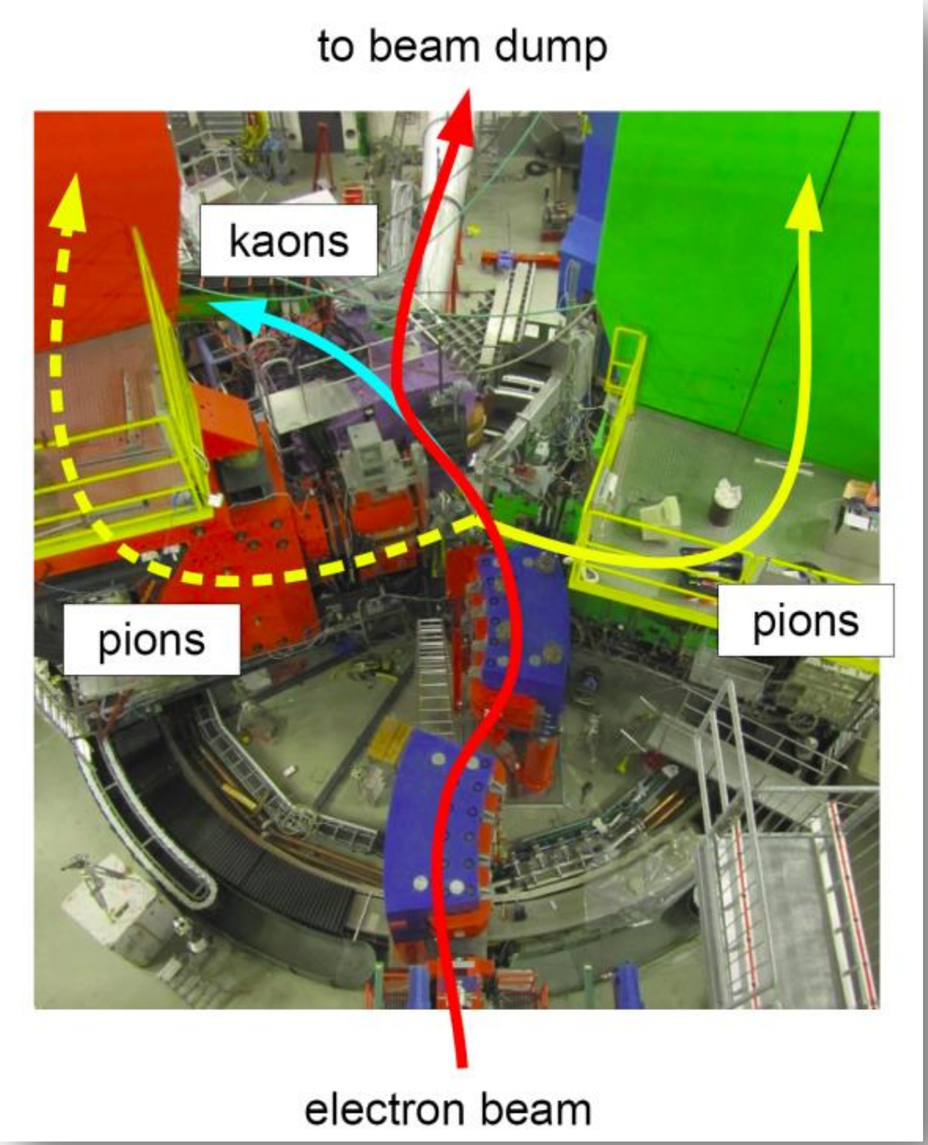
Decay-pion spectroscopy at MAMI

Primary Beam	
Energy	1.5 GeV

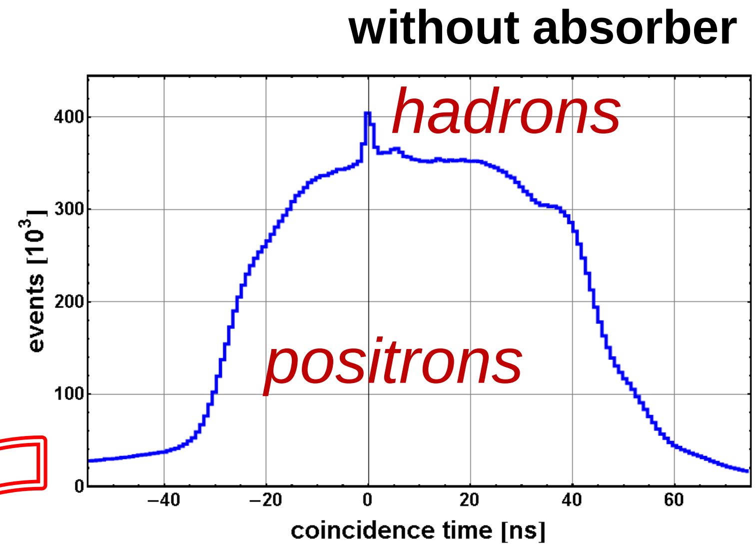
Target	
Material	^{9}Be
Thickness	125 μm
Tilt angle	54 deg

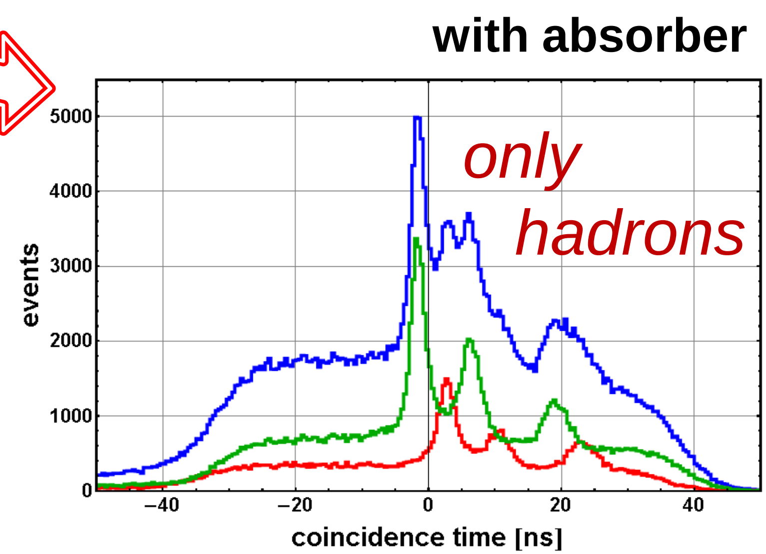
Kaos	
Cent. Mom	+900 MeV/c
Detector	MWPC, TOF, AC

Spek-A, C	
Cent. Mom	- 115/ -125 MeV/c
Detector	DC, TOF, GC



Kaos spectrometer changed into zero-degree tagger

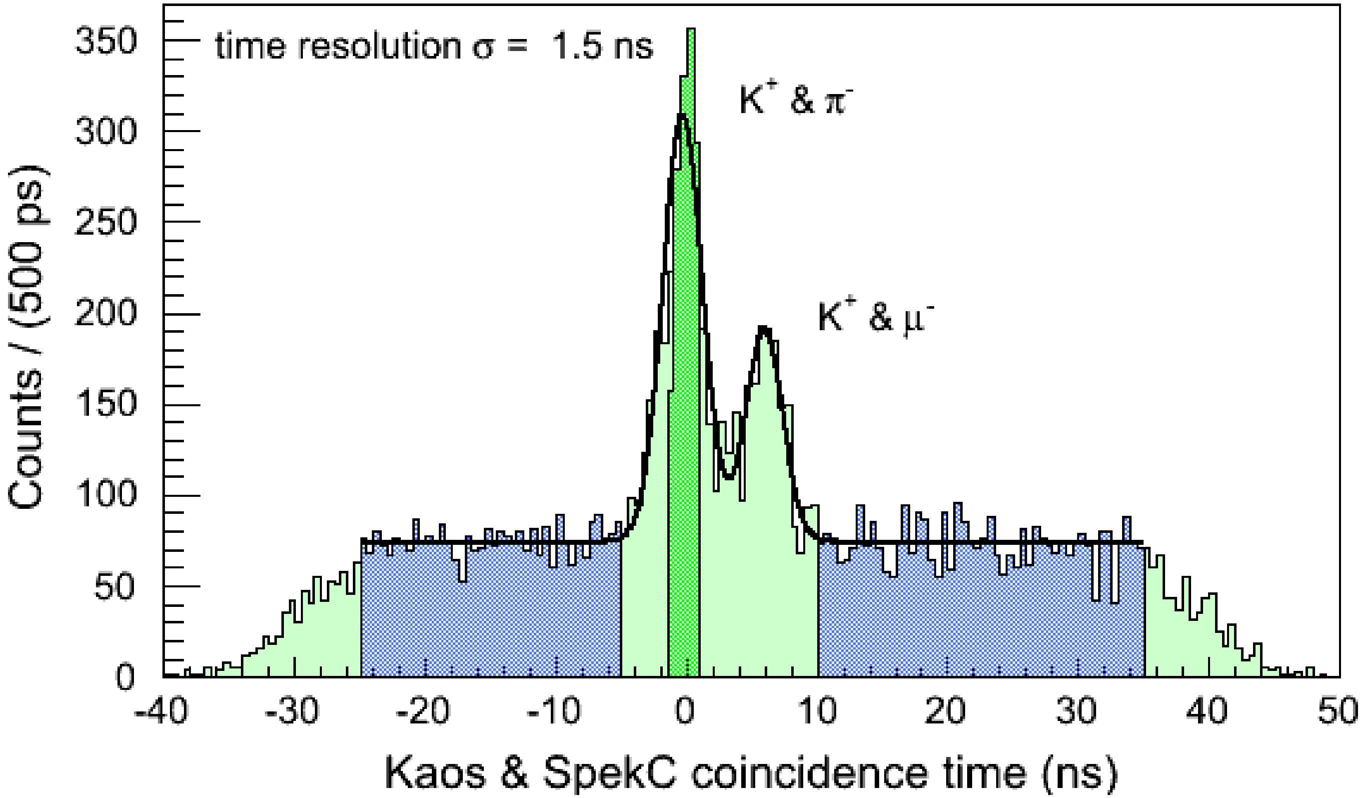




- Suppression of large positron flux with 25 X_0 lead absorber wall
- Much cleaner spectra for all hadrons

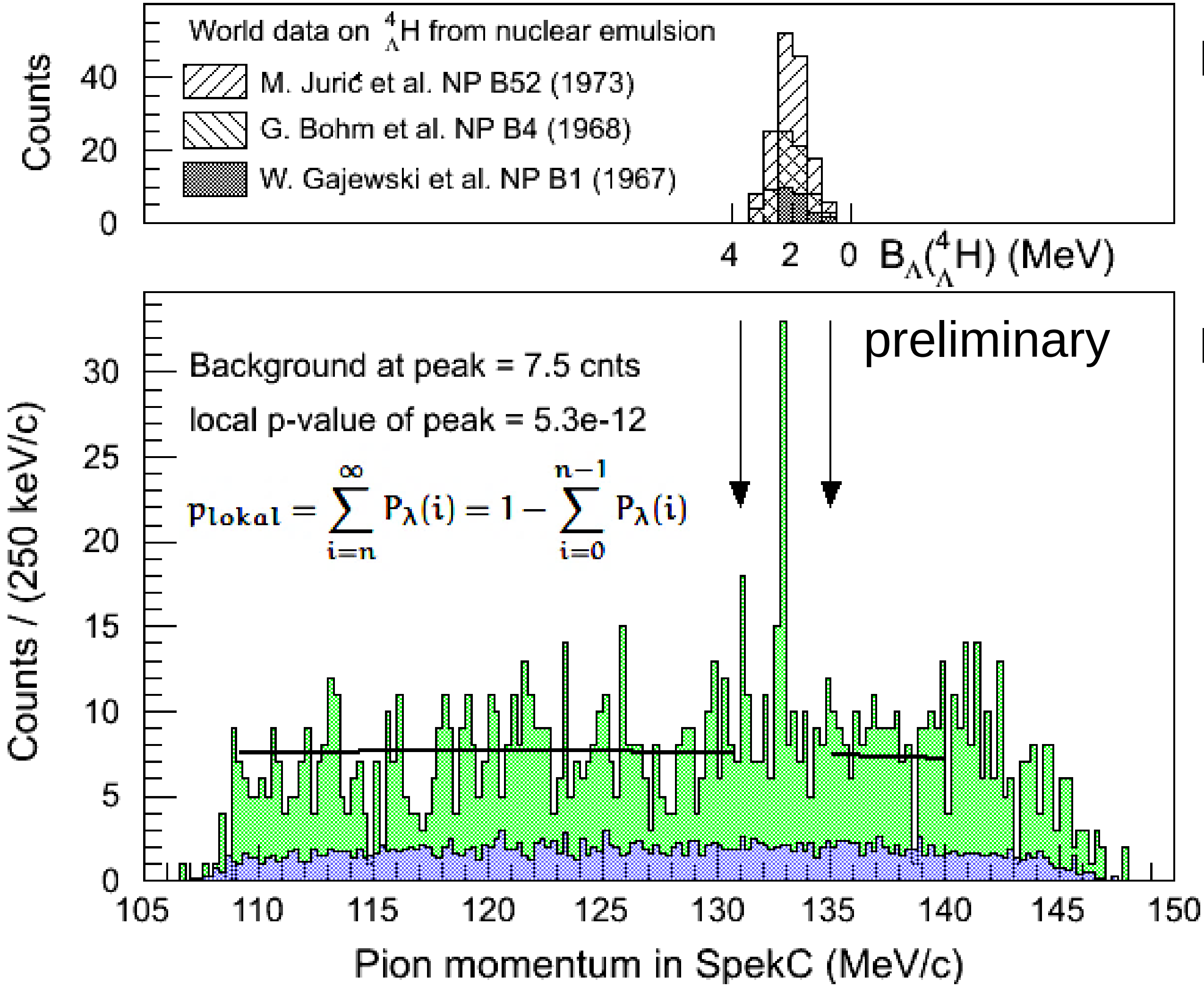
Reaction identification

with cut on gas Cherenkov signal for electron rejection



- established clean tag on strangeness production at zero-degree
- decay-pion detection with Spectrometer A & C (dp/p <10^{-4})
- more than 1000 pion-kaon-coincidences from weak decays of hyperons

Hyperhydrogen peak search

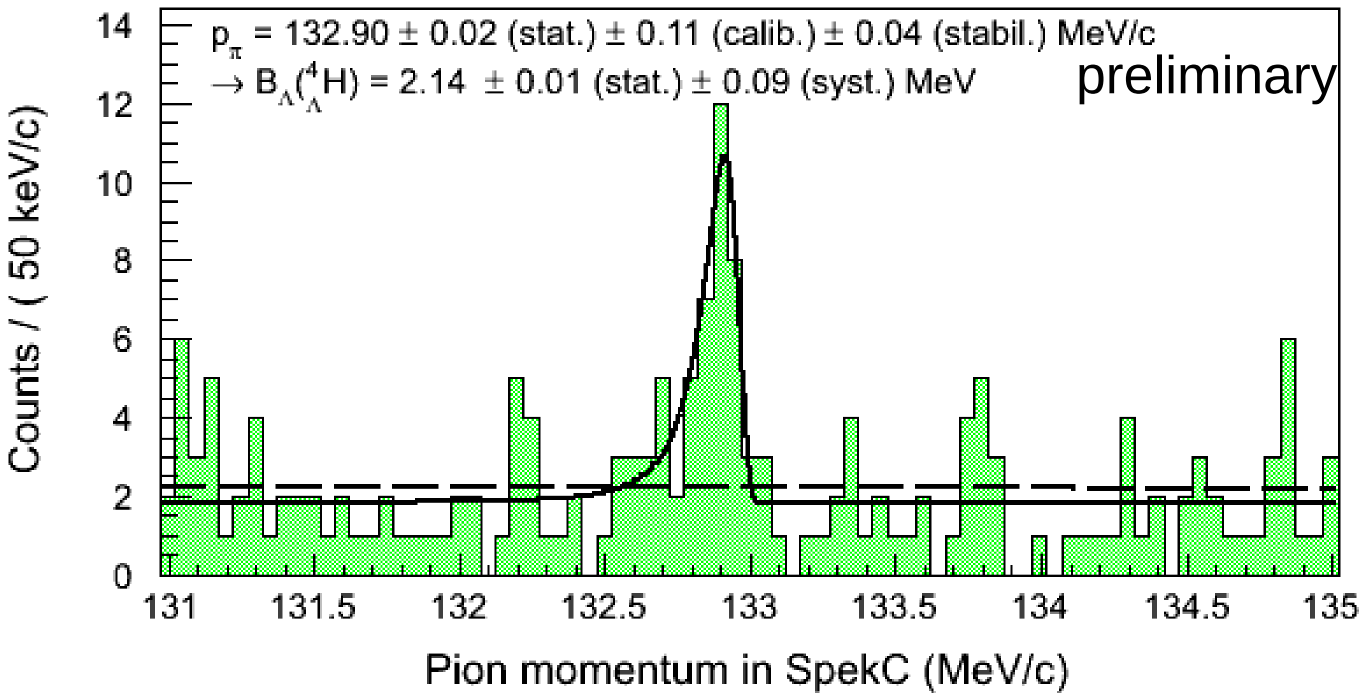


Emulsion data

MAMI data

local excess observed inside the hyperhydrogen search region

Binding energy extraction



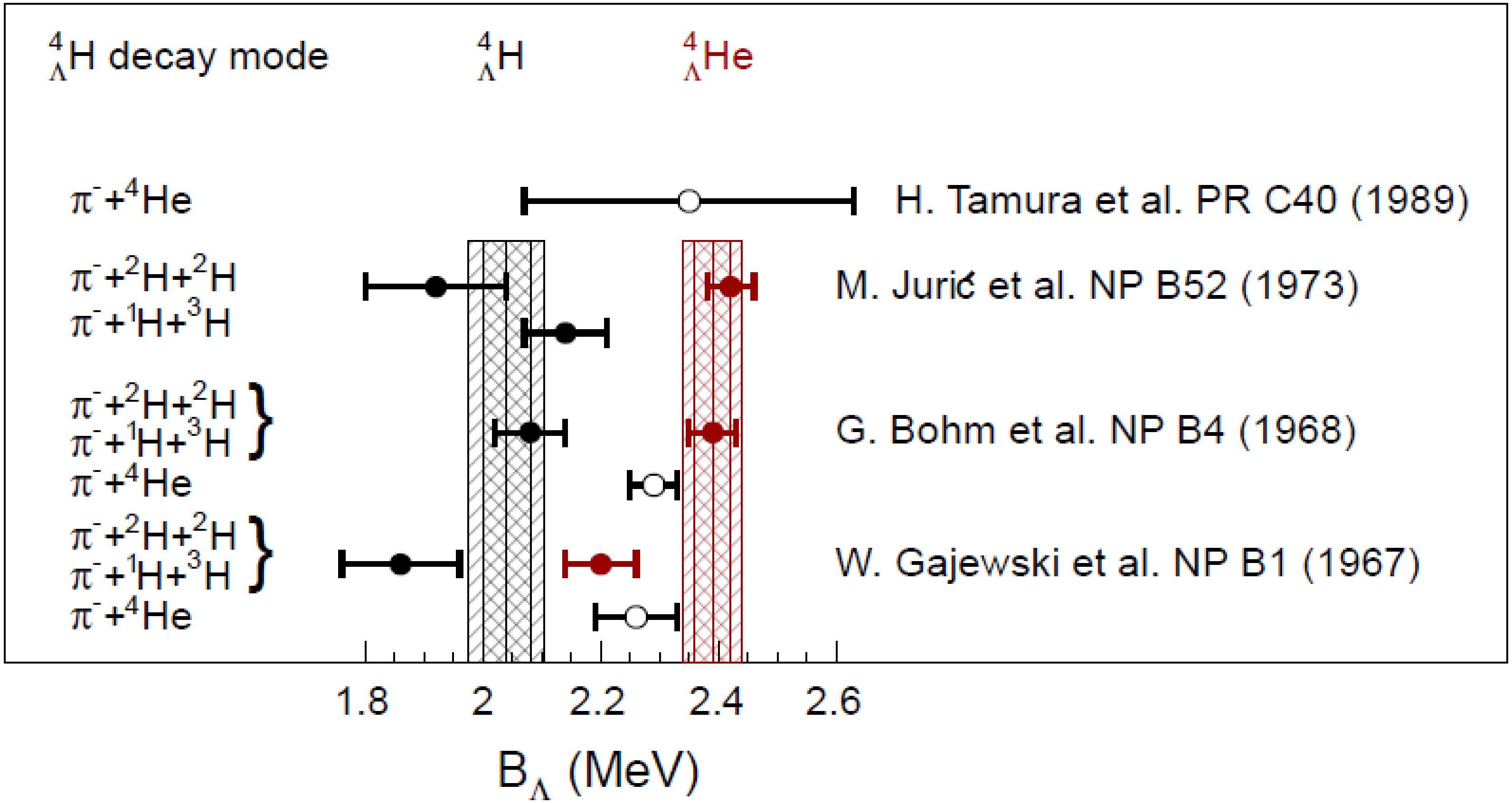
$$M(^4_\Lambda\mathrm{H}) = \sqrt{M^2(^4\mathrm{He}) + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2} \quad \text{and}$$

$$B_\Lambda = M(^3\mathrm{H}) + M_\Lambda - M(^4_\Lambda\mathrm{H}) \quad \text{with c} = 1$$

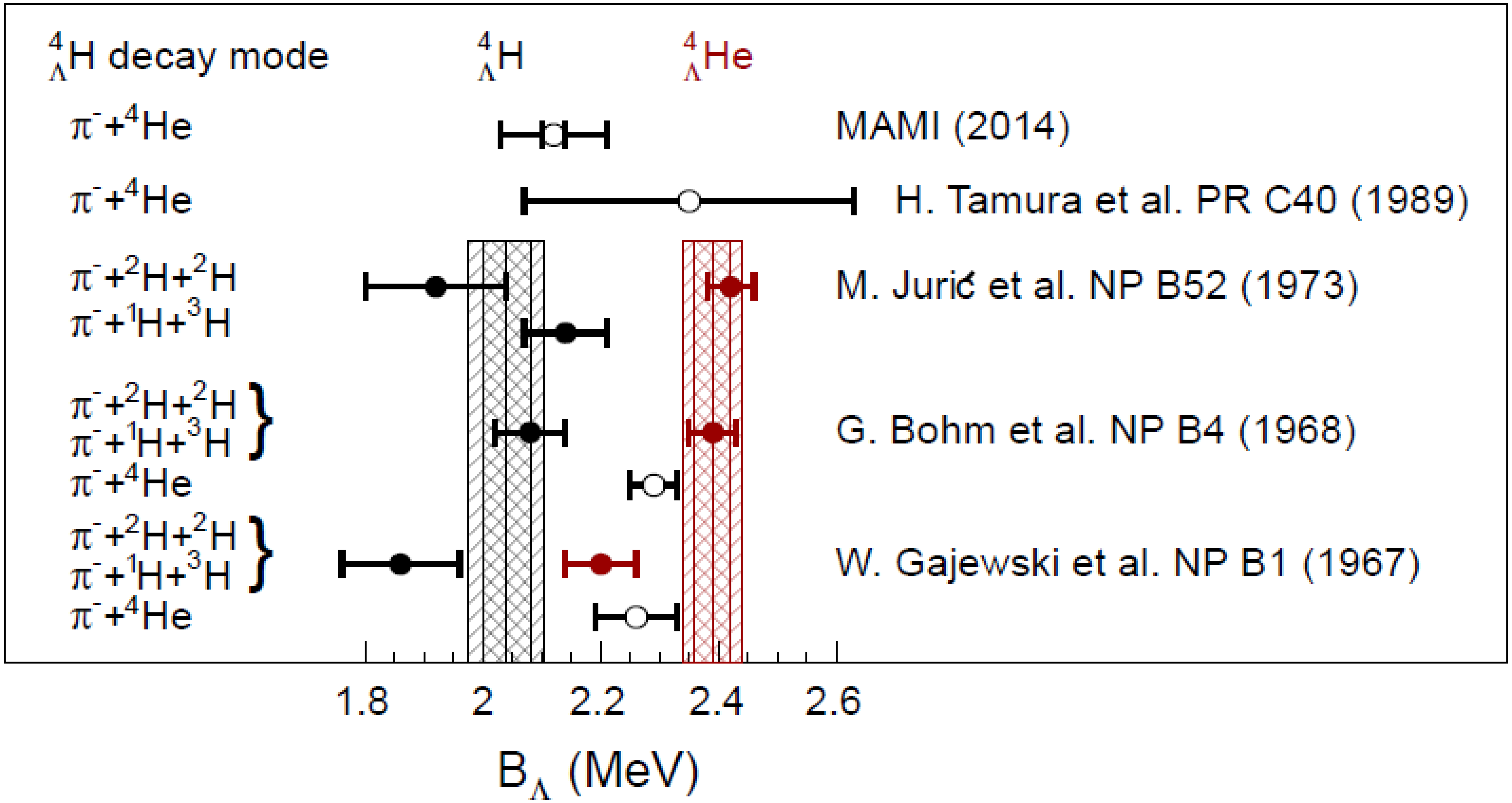
$$S = \sqrt{-2\ln\frac{L(BG)}{L(S+BG)}} = 4.7 \text{ with binned analysis}$$

S ~ 4-5 with unbinned analysis

World data on $A = 4$ system



World data on *A* = *4* system



MAMI experiment confirmed Λ separation energy of ${}_\Lambda^4$H:
$B_\Lambda \sim 2.14 \pm 0.1$ MeV (MAMI 2014 prelim.)

Conclusions

- Decay-pion spectroscopy gives access to masses of light hypernuclei
- Important to understand consistently the *A* = 4 and *A* = 7 systems
- Pioneering experiment followed by experiments with dedicated setup:
  - clean tag on strangeness production at zero-degree
  - clean pion sample from weak decays of hyperons
  - hyperhydrogen-4 identified as the dominant detectable fragment
  - experiment continued with order of magnitude luminosity increase

These are key experiments to get information about charge symmetry breaking (CSB)

Backup

Light hyperisotopes

Hyper-fragment	Bingungsenergie B_Λ [MeV]	Targets	Γ_{π^-}/Γ	Zerfallspion-impuls [MeV/c]	dB_Λ/dp_π	möglicher Zerfallskanal	Resonanz-breite
$^3_\Lambda$H	$0,13 \pm 0.05$ [21]	^{4}He, ^{6,7}Li, ^{9}Be		114,37	0,675	^{3}He + π^-	
$^4_\Lambda$H	$2,04 \pm 0,04$ [21]	^{4}He, ^{6,7}Li, ^{9}Be	$1,00^{+0,18}_{-0,15}$ [22]	133,03	0,725	^{4}He + π^-	
			$\Gamma_{\pi^- {}^4He}/\Gamma = 0,69^{+0,12}_{-0,10}$ [22]				
$^6_\Lambda$H	$4,0 \pm 1,1$ [4]	^{7}Li, ^{9}Be		135,27	0,720	^{6}He + π^-	
$^4_\Lambda$He	$2,39 \pm 0,03$ [21]	^{6,7}Li, ^{9}Be	$0,34 \pm 0,06$ [22]	98,14	0,601	^{3}He + p + π^-	6,03 MeV
$^5_\Lambda$He	$3,12 \pm 0,02$ [21]	^{6,7}Li, ^{9}Be	$0,340 \pm 0,016$ [23]	99,27	0,601	p + ^{4}He + π^-	1,5 MeV
			$0,44 \pm 0,11$ [24]				
			$0,332 \pm 0,069$ [25]				
$^6_\Lambda$He	$4,18 \pm 0,10$ [21]	^{6,7}Li, ^{9}Be		108,48	0,633	^{6}Li + π^-	
$^7_\Lambda$He	$5,68 \pm 0,03 \pm 0,25$ [26]	^{7}Li, ^{9}Be		114,78	0,653	^{7}Li + π^-	
$^8_\Lambda$He	$7,16 \pm 0,70$ [27]	^{9}Be		116,48	0,656	^{8}Li + π^-	
$^6_\Lambda$Li	$5,89 \pm 0,37$ [28]	^{9}Be		101,68	0,607	p + p + ^{4}He + π^-	92 keV
$^7_\Lambda$Li	$5,58 \pm 0,03$ [21]	^{9}Be	$0,353 \pm 0,059$ [25]	108,11	0,629	^{7}Be + π^-	
$^8_\Lambda$Li	$6,80 \pm 0,03$ [21]	^{9}Be		124,20	0,681	^{4}He + ^{4}He + π^-	5,57 eV
$^9_\Lambda$Li	$8,50 \pm 0,12$ [21]	^{9}Be		121,31	0,670	^{9}Be + π^-	

Tabelle 1: Liste der wichtigsten Parameter der möglichen Hyperfragmente an leichten Targets ($A \leq 9$). Aus B_Λ und den in [20] gegebenen Massen gewöhnlicher Kerne sind die Zerfallspionenimpulse berechnet. Die Zerfallsbreiten für π^--Zerfälle (Γ_{π^-}/Γ) sind für die Kerne, für die sie bekannt sind, angegeben. Für $^4_\Lambda$H ist zusätzlich auch die Wahrscheinlichkeit für einen π^--Zweikörperzerfall bekannt. Für alle Hyperfragmente, die in einen ungebundenen Zustand zerfallen, ist der wahrscheinlichste π^--Zerfallskanal angegeben und zusätzlich die Resonanzbreite. Diese stammt aus [29].