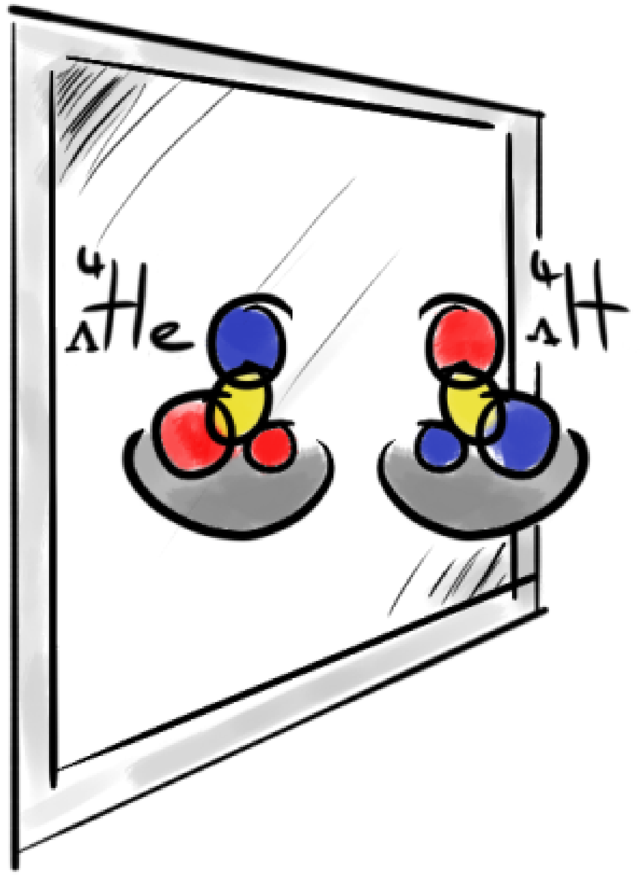
Light Hypernuclei –
A Testbed for Charge Symmetry Breaking



Patrick Achenbach

U Mainz

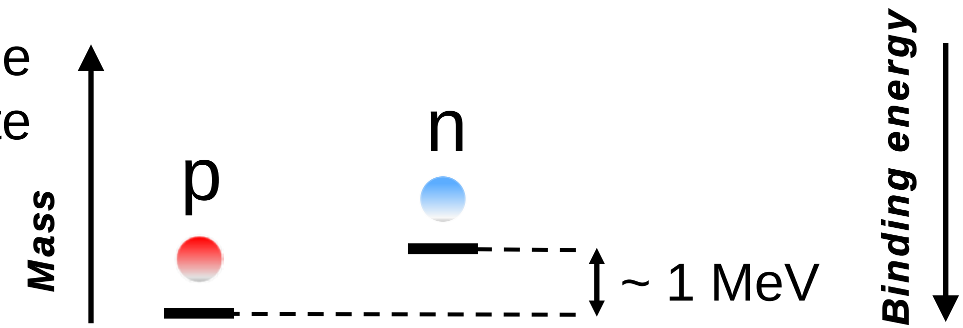
Sept. 2o18

Living in a charge symmetry breaking world

charge symmetry in strong interaction:
interchange of *u* and *d* quarks: $\Delta(m_u - m_d)/M \sim 0.1\ \%$

The nucleon: one particle of two almost degenerate charge (isospin) states:

$\Delta(m_n - m_p)/M \sim 0.1\ \%$



If charge symmetry would be satisfied in nuclear systems …

… protons would be heavier than neutrons because of electrostatic repulsion

… free protons would decay into neutrons

… big bang nucleosynthesis would have proceeded along different paths

… a fundamentally different universe would have been produced

… the Sun and the stars would have no slow-burning fuel

[C. J. Hogan, PRD 74, 123514 (2006)]

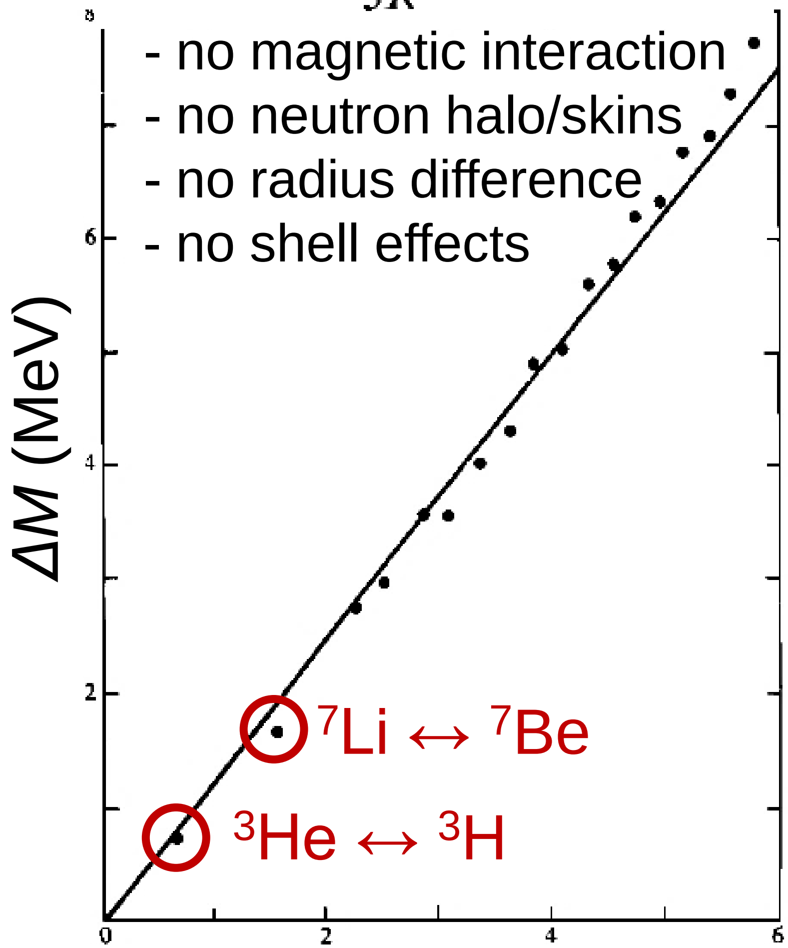
… the Sun would be dark by now and we would not be here in Bologna

Charge symmetry breaking has significant impact on all of us!

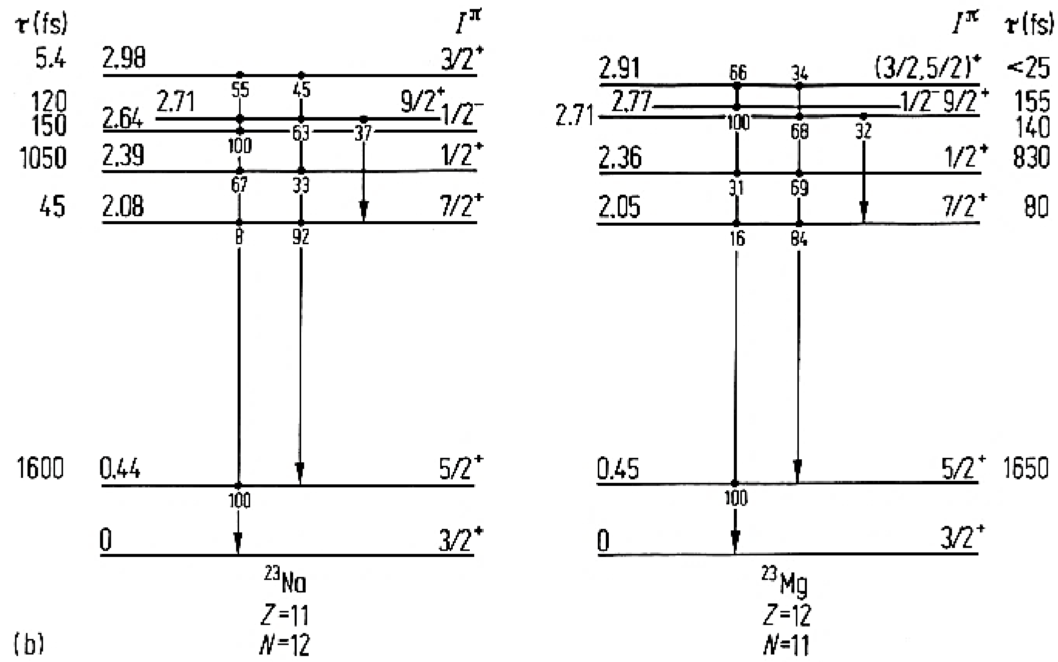
Manifestation of charge symmetry

$$\Delta M = (Z_1 - 1)\frac{6e^2}{5R} + (M_H - M_n)c^2$$

- no magnetic interaction
- no neutron halo/skins
- no radius difference
- no shell effects



[Gleit et al. Nuclear Data Sheets 5 (1963)]



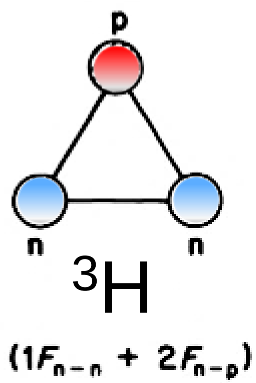
[Endt & van der Leun, NPA 310 (1978), 67]

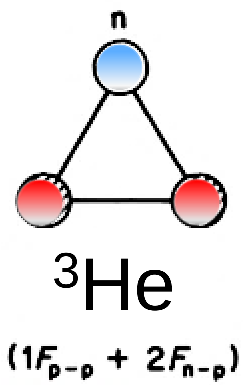
symmetry in masses, binding energies and level schemes of mirror nuclei, with proton and neutron states exchanged

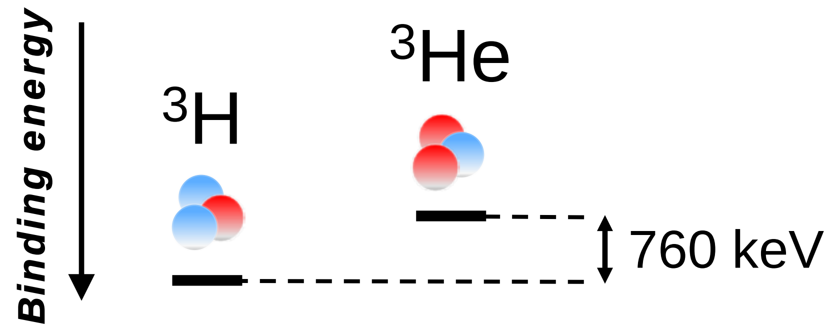
Charge symmetry in light nuclei

Charge symmetry: strong force independent of nucleon isospin exchange ($F_{p\text{-}p} = F_{n\text{-}n}$)

Charge symmetry breaking in nuclear two-body forces …







… can be studied in mirror nuclei

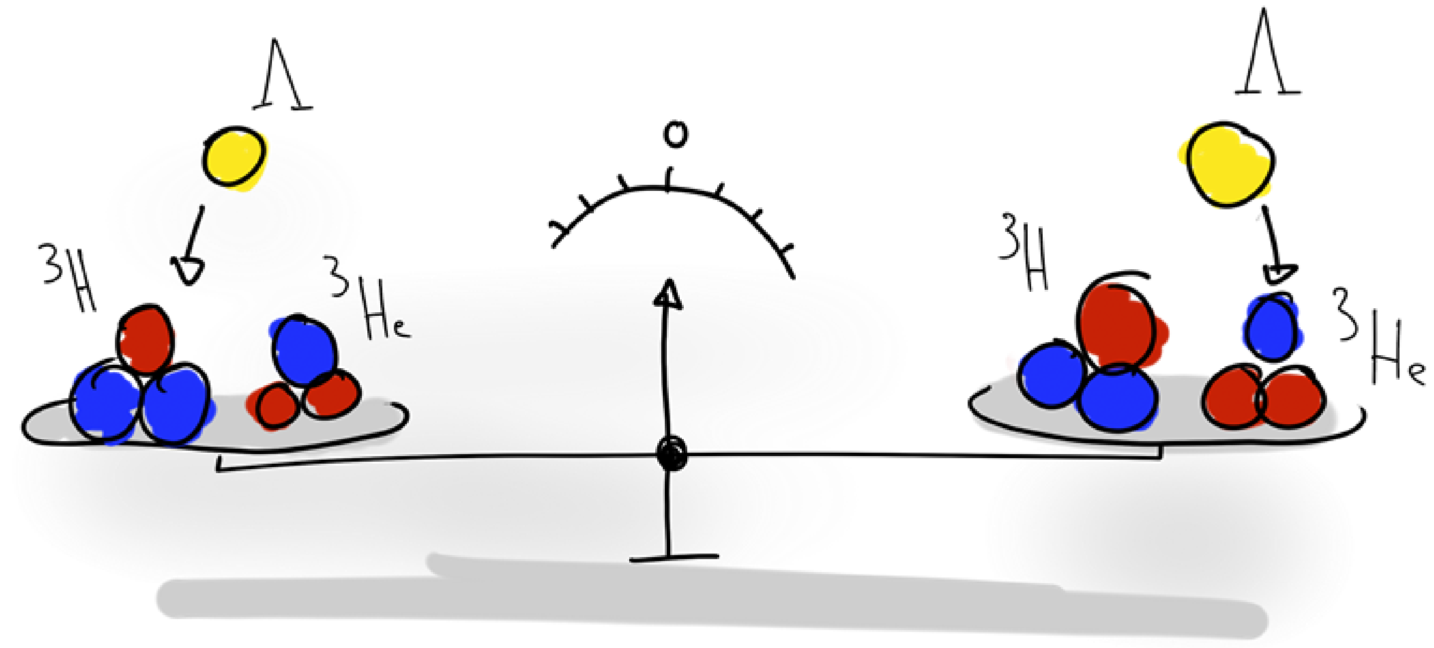
… after correcting for electromagnetic effects of order 1 MeV

… is very small: only ~ 80 keV for ^{3}H - ^{3}He: $\Delta B_{CSB}/B \sim 0.1\ \%$

… can be calculated rather accurately [R. Machleit *et al.*, PRC 63, 034005 (2001)]

Charge symmetry in light hypernuclei

Study of charge symmetry with a neutral probe



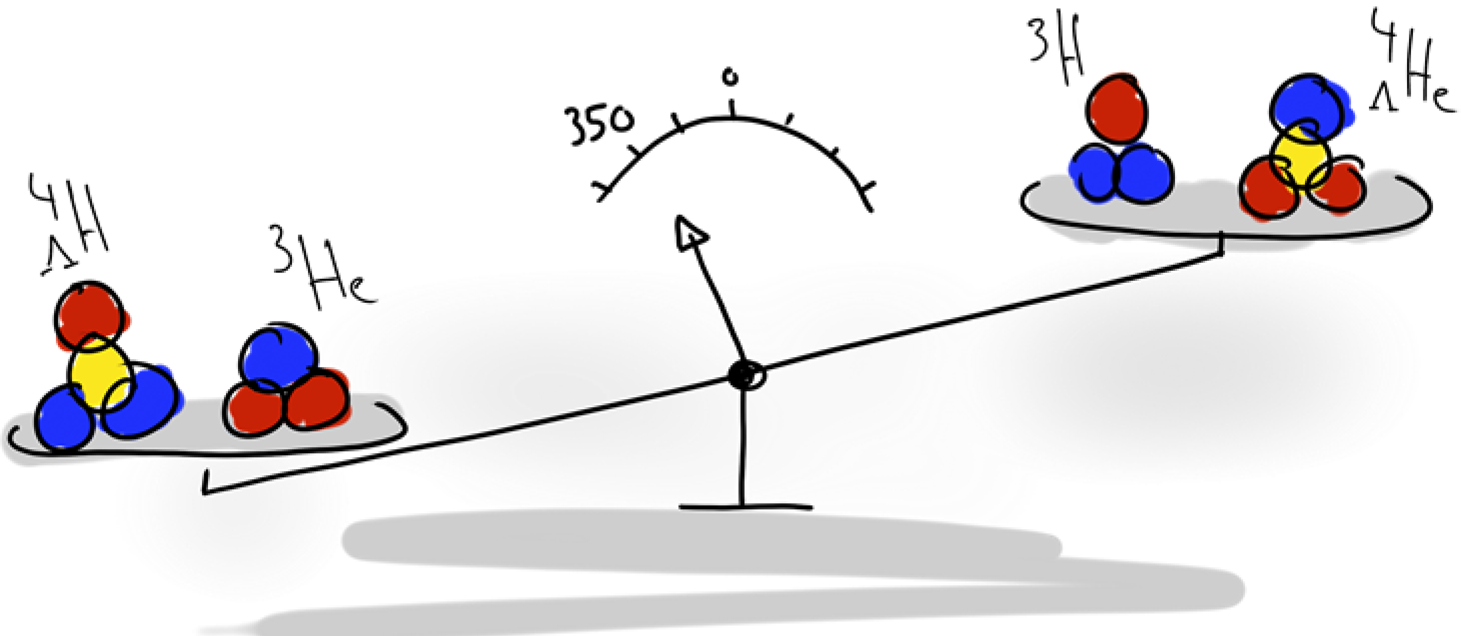
$$-B_{\Lambda} = M_{HYP} - (M_{Core} + M_{\Lambda})$$

Λ hyperon: no isospin and no charge

if $F_{\Lambda\text{-}p} = F_{\Lambda\text{-}n}$ then $B_{\Lambda}({}_{\Lambda}^{A}Z) = B_{\Lambda}({}_{\Lambda}^{A}Z{+}1)$

Large charge symmetry breaking in $A = 4$

$^{4}_{\Lambda}$H - $^{4}_{\Lambda}$He ground state difference exceptionally large > 300 keV

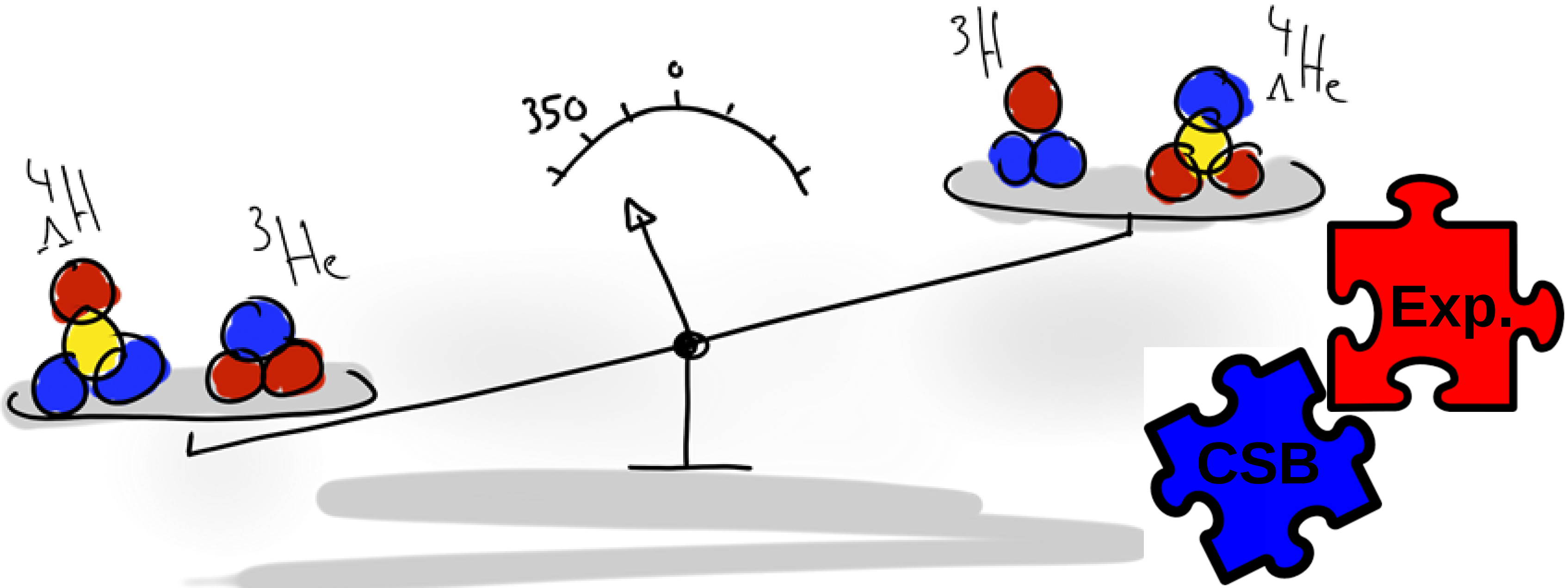


$M(^{4}_{\Lambda}\mathrm{H}) =$	3922.56	$B_{\Lambda}(^{4}_{\Lambda}\mathrm{H}) =$	2.04
$M(^{4}_{\Lambda}\mathrm{He}) =$	3921.68	$B_{\Lambda}(^{4}_{\Lambda}\mathrm{He}) =$	2.39
$\Delta M^{4}_{\Lambda} =$	−0.88	$\Delta B^{4}_{\Lambda} =$	0.35

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

Large charge symmetry breaking in *A = 4*

$^4_\Lambda$H - $^4_\Lambda$He ground state difference $\Delta B/B$ ~ 1 %



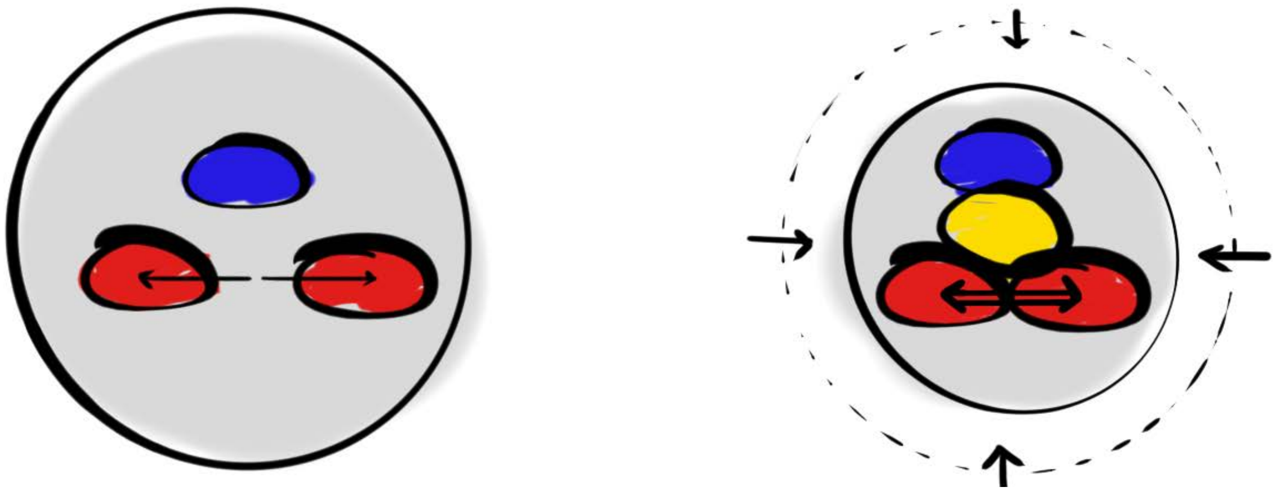
- CSB difference about 5 times larger than in ^{3}H - ^{3}He system
- quite remarkable, considering the weaker ΛN interaction
- Λp interaction stronger than Λn interaction
- What is the source of such a strong violation of charge symmetry?

Large charge symmetry breaking in $A = 4$

Coulomb energy effect for a bound neutral particle:

shrinking of hypernucleus as compared to core

→ change in electrostatic repulsion of protons in core



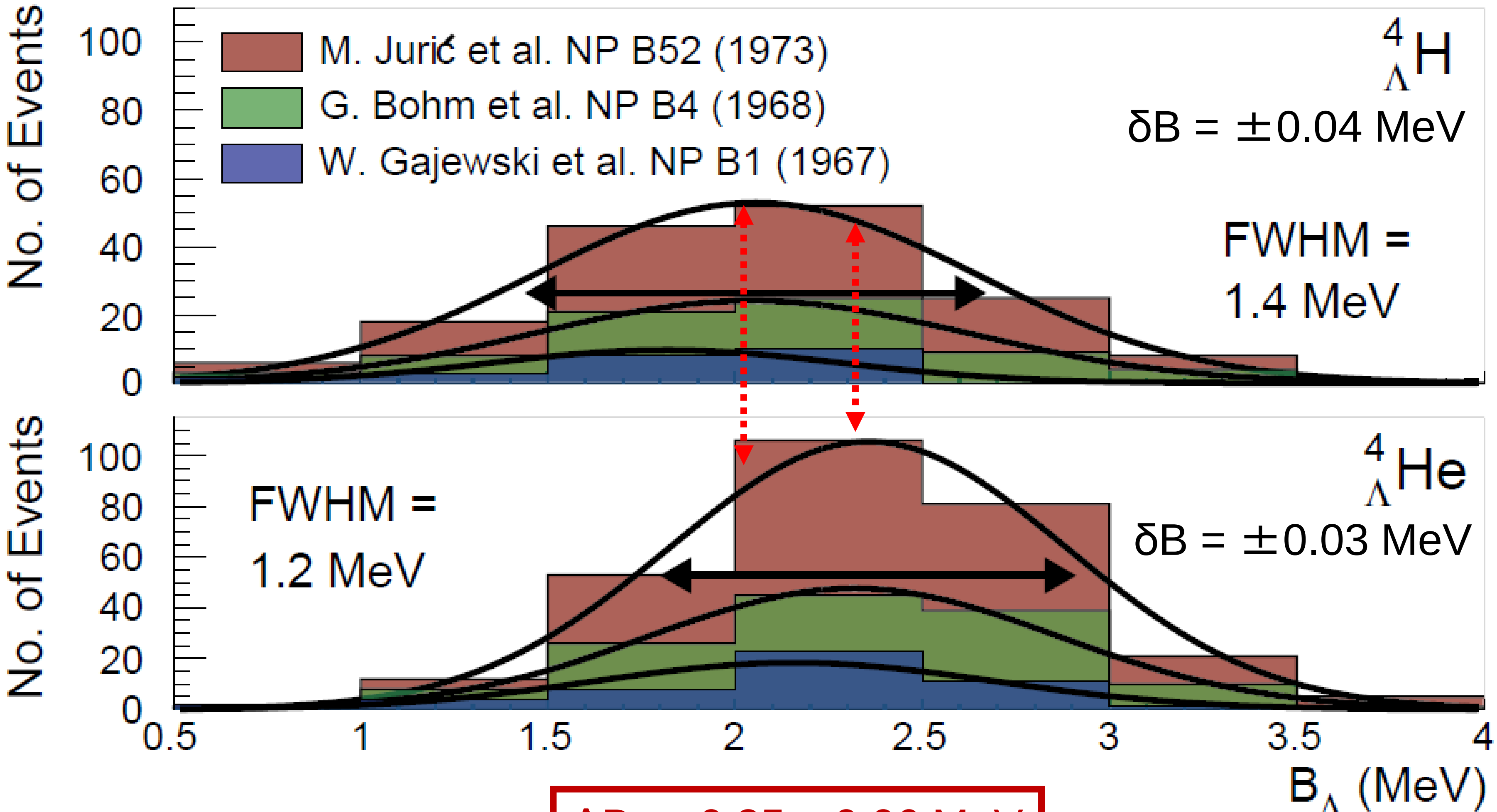
^{3}He $\qquad$ $^{4}_{\Lambda}He$

- $^{4}_{\Lambda}H$ - $^{4}_{\Lambda}He$ Coulomb correction < 50 keV in <u>opposite</u> direction
- overcompensation by a factor 7 due to strong interaction CSB

[A. R. Bodmer and Q. N. Usmani, PRC 31, 1400 (1985)]

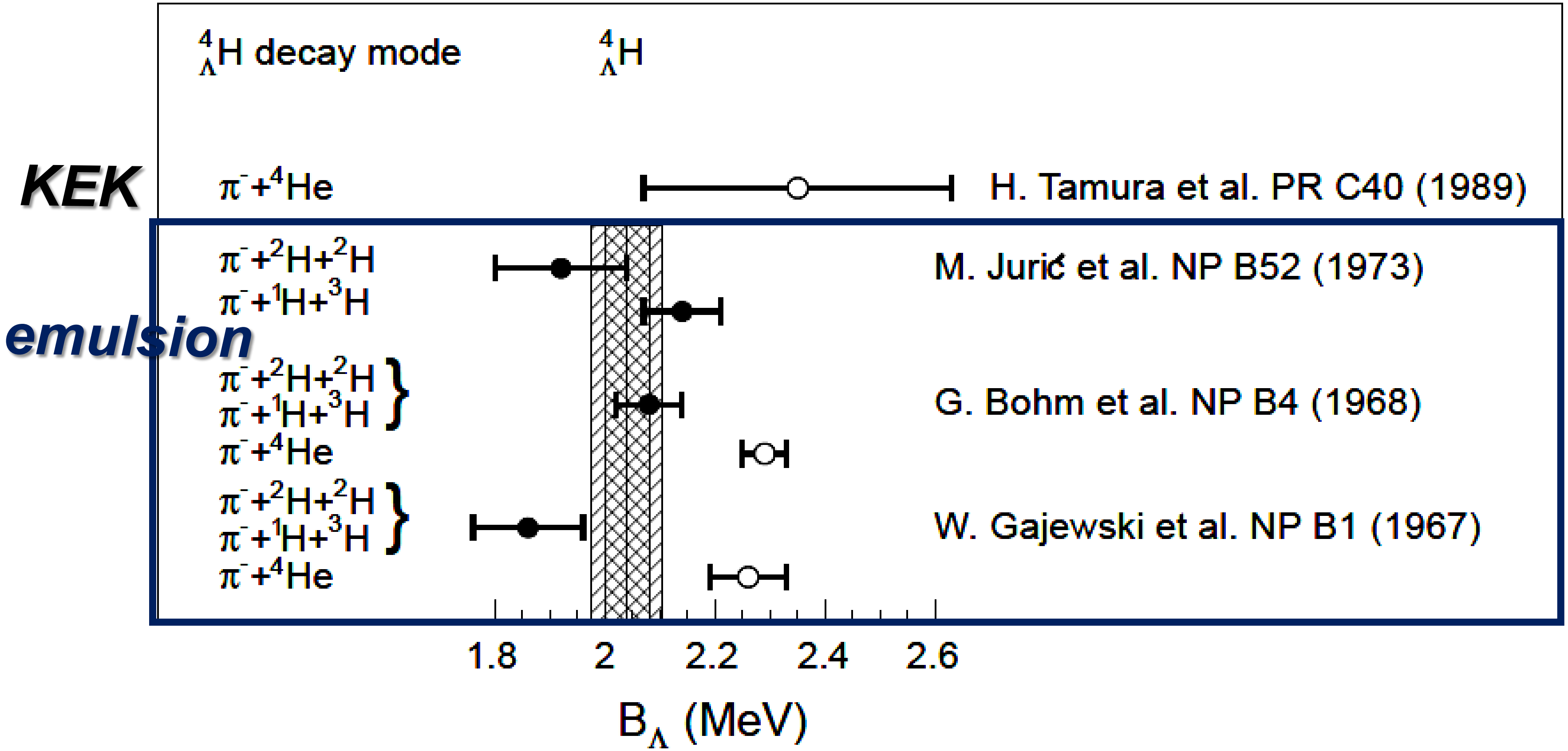
Emulsion results on $_{\Lambda}^{4}H$ and $_{\Lambda}^{4}He$

155 events for hyperhydrogen, 279 events for hyperhelium



$\Delta B_{\Lambda} = 0.35 \pm 0.06$ MeV

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



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

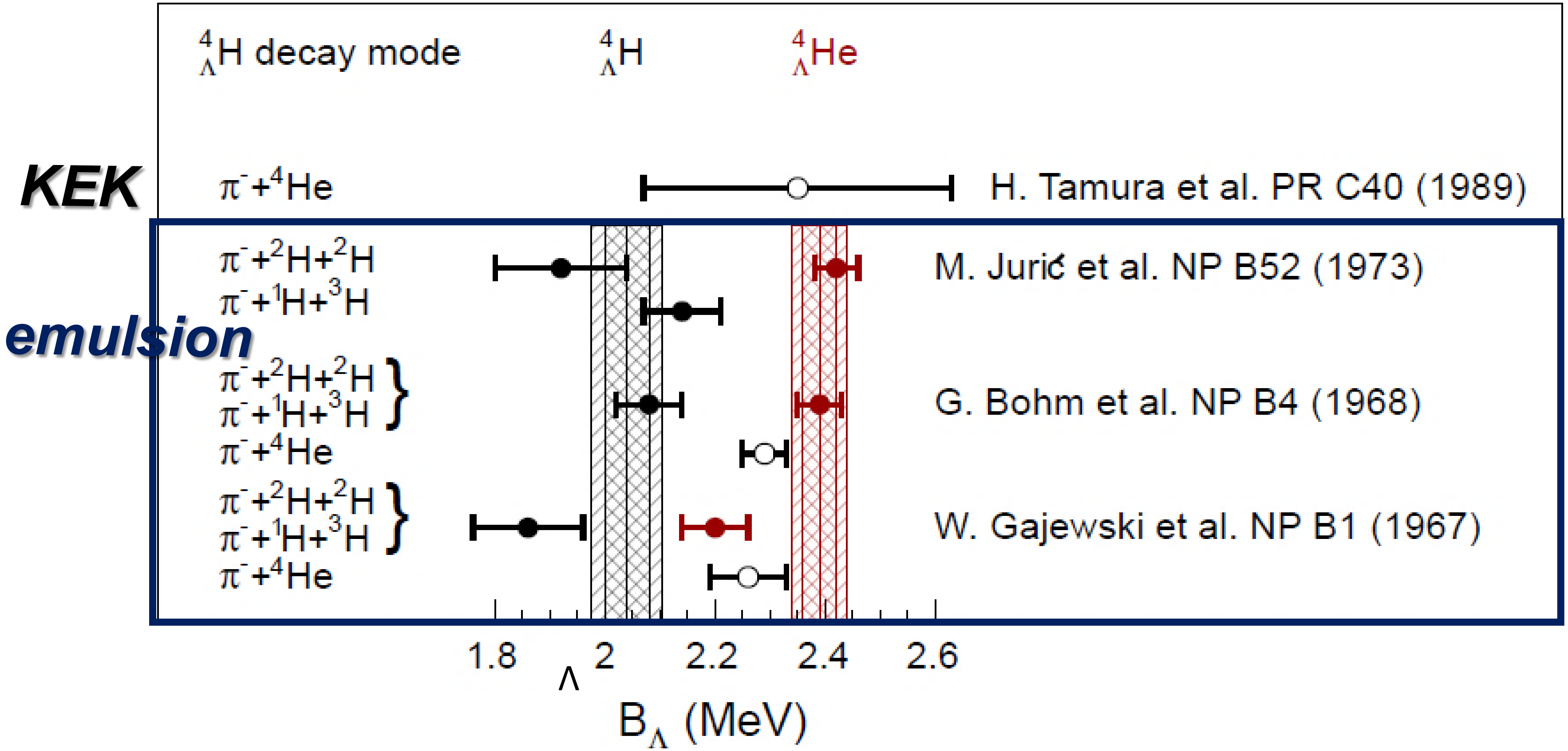
$${}_{\Lambda}^{4}H \xrightarrow{decay} \pi^- + {}^2H + {}^2H: B = 1.92 \pm 0.12 \text{ MeV}$$

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



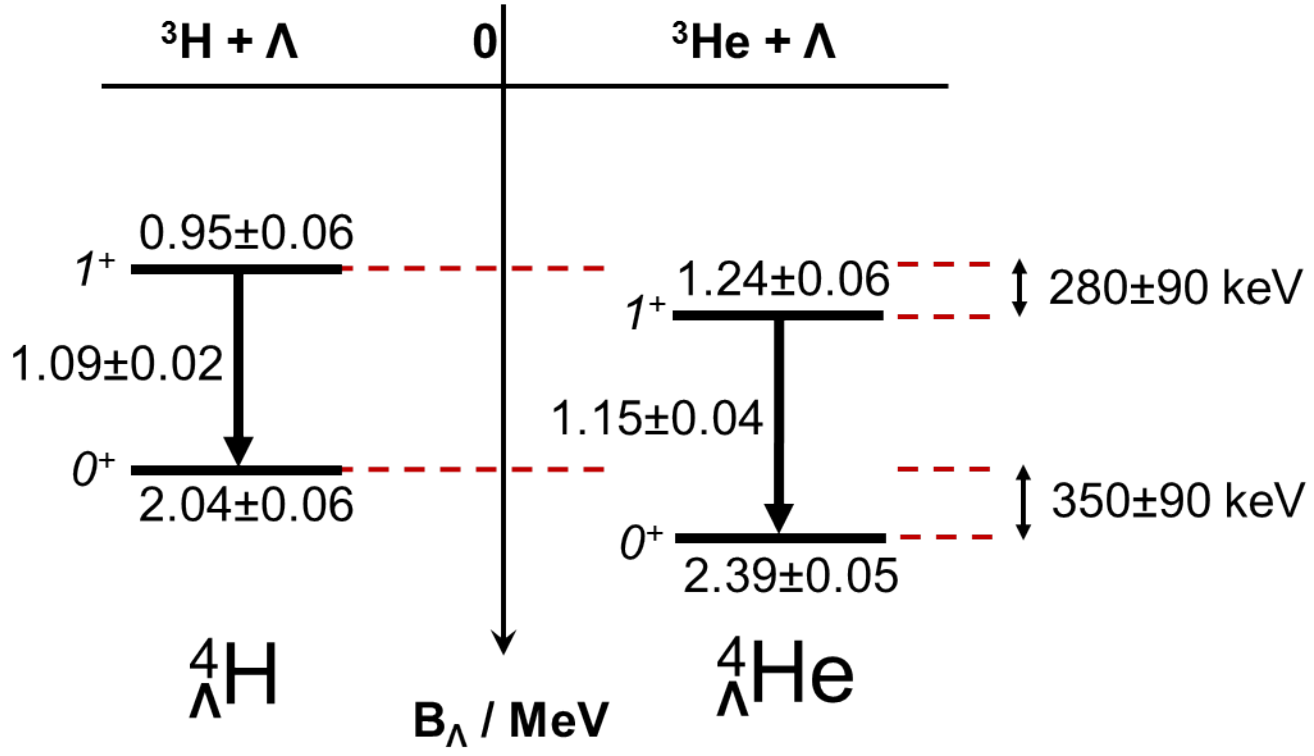
$$^4_\Lambda\mathrm{He} \xrightarrow{\text{decay}} \pi^- + {}^1\mathrm{H} + {}^3\mathrm{He}: B = 2.42 \pm 0.05 \text{ MeV}$$

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

0.02 MeV difference

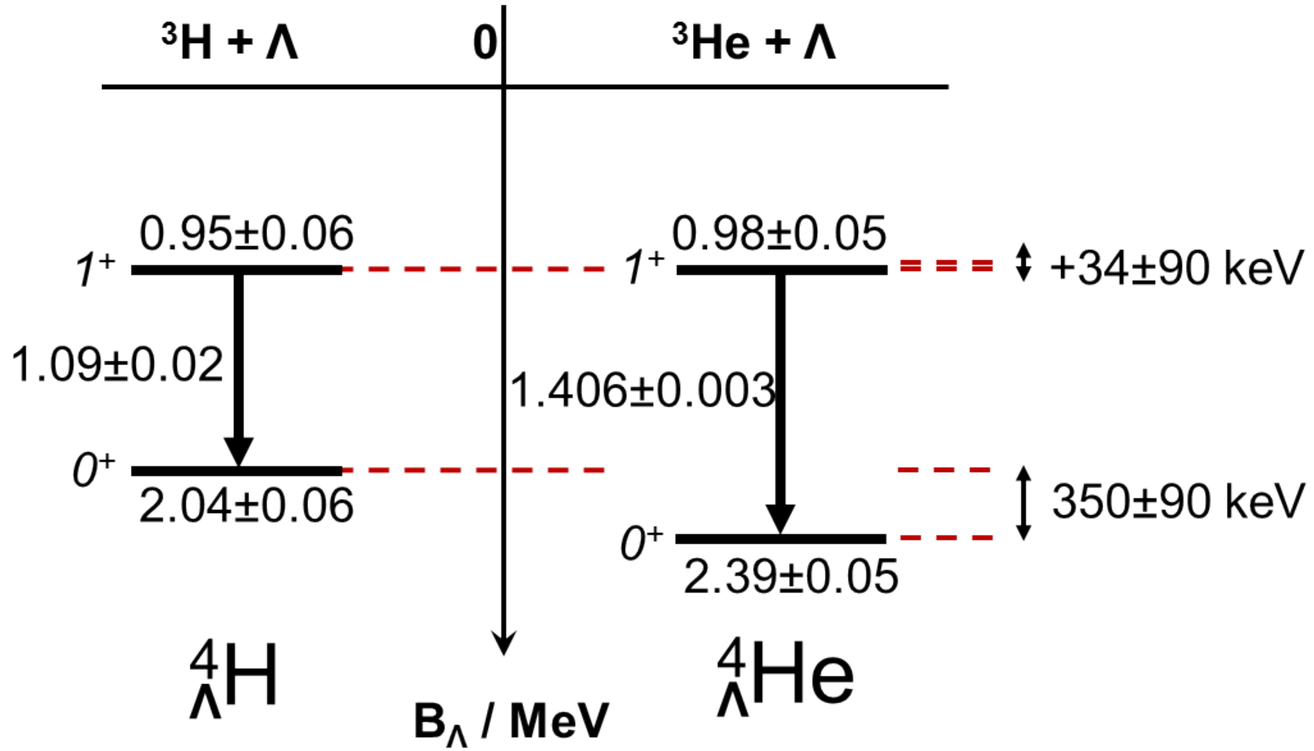
Total: $B = 2.42 \pm 0.04$ MeV [M. Juric et al. NP B52 (1973)]

The A = 4 level schemes (before 2015)



- charge symmetry breaking only if emulsion data is correct
- <u>spin-independent</u> charge symmetry breaking

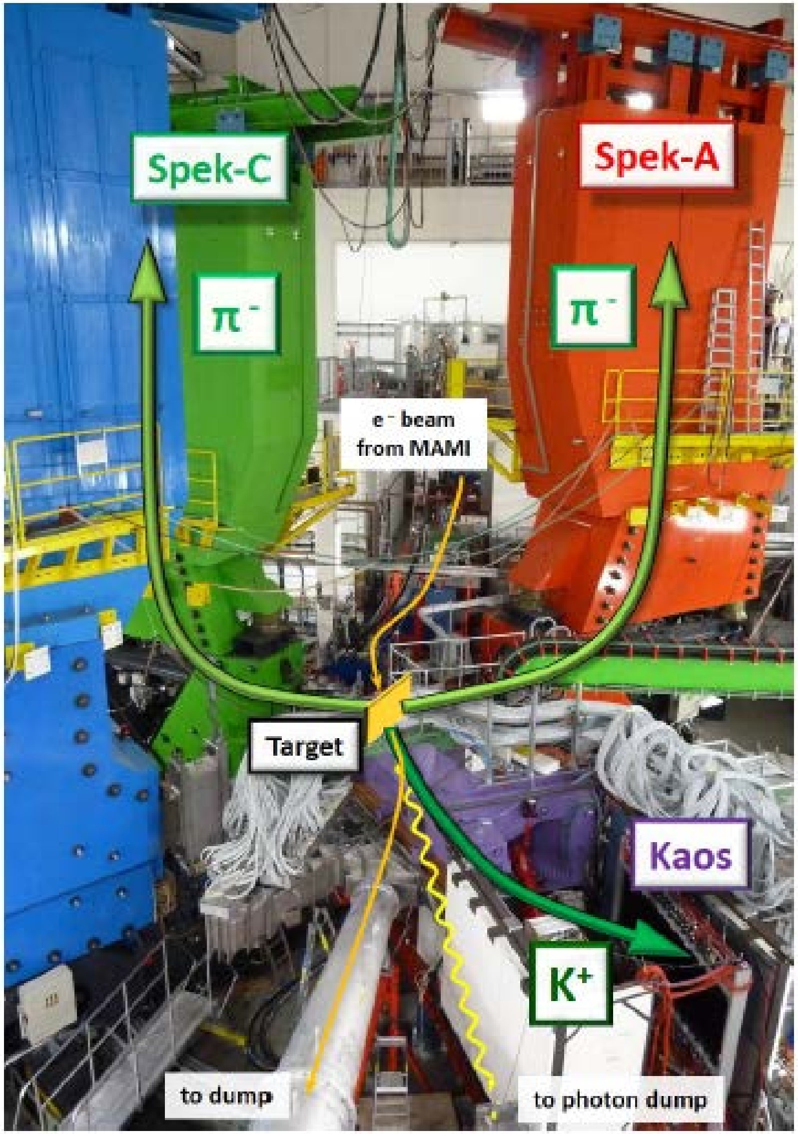
The A = 4 level schemes (in 2015)

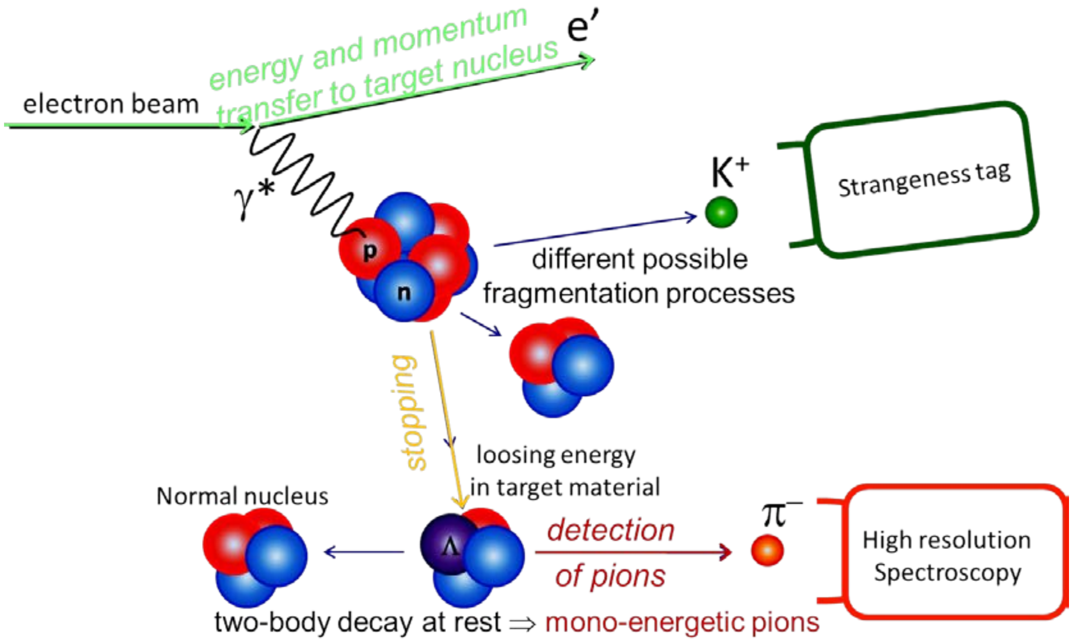


- observation of charge symmetry breaking in γ-ray spectroscopy
- <u>spin-dependent</u> charge symmetry breaking

[T. O. Yamamoto, PRL 115 (2015) 222501]

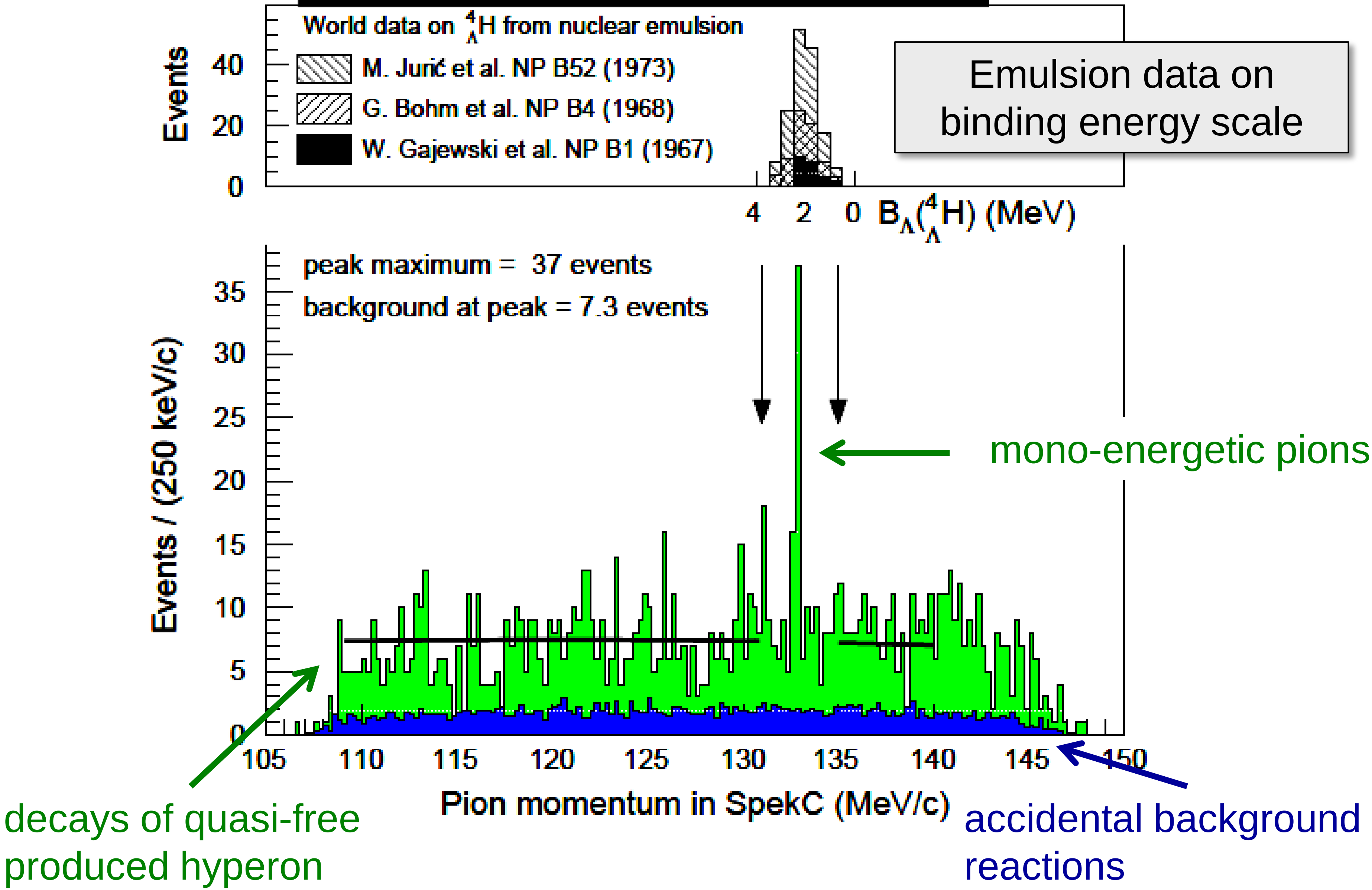
Hyperfragment decay-pion spectroscopy with electron beams



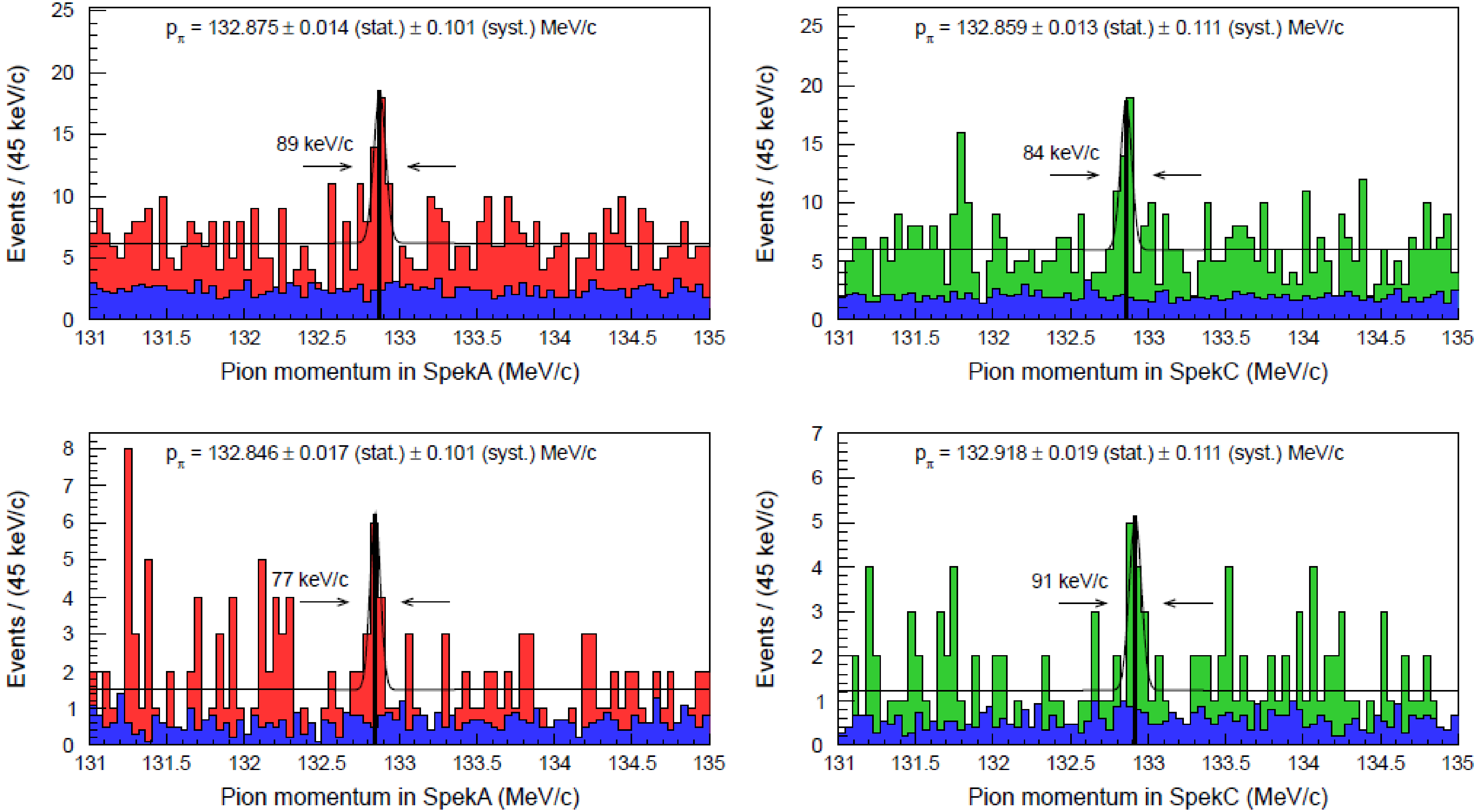


$$M_{\mathrm{HYP}} = \sqrt{M_{\mathrm{ncl}}^2 + p_{\pi^-}^2} + \sqrt{M_{\pi^-}^2 + p_{\pi^-}^2}$$

Decay-pion spectrum



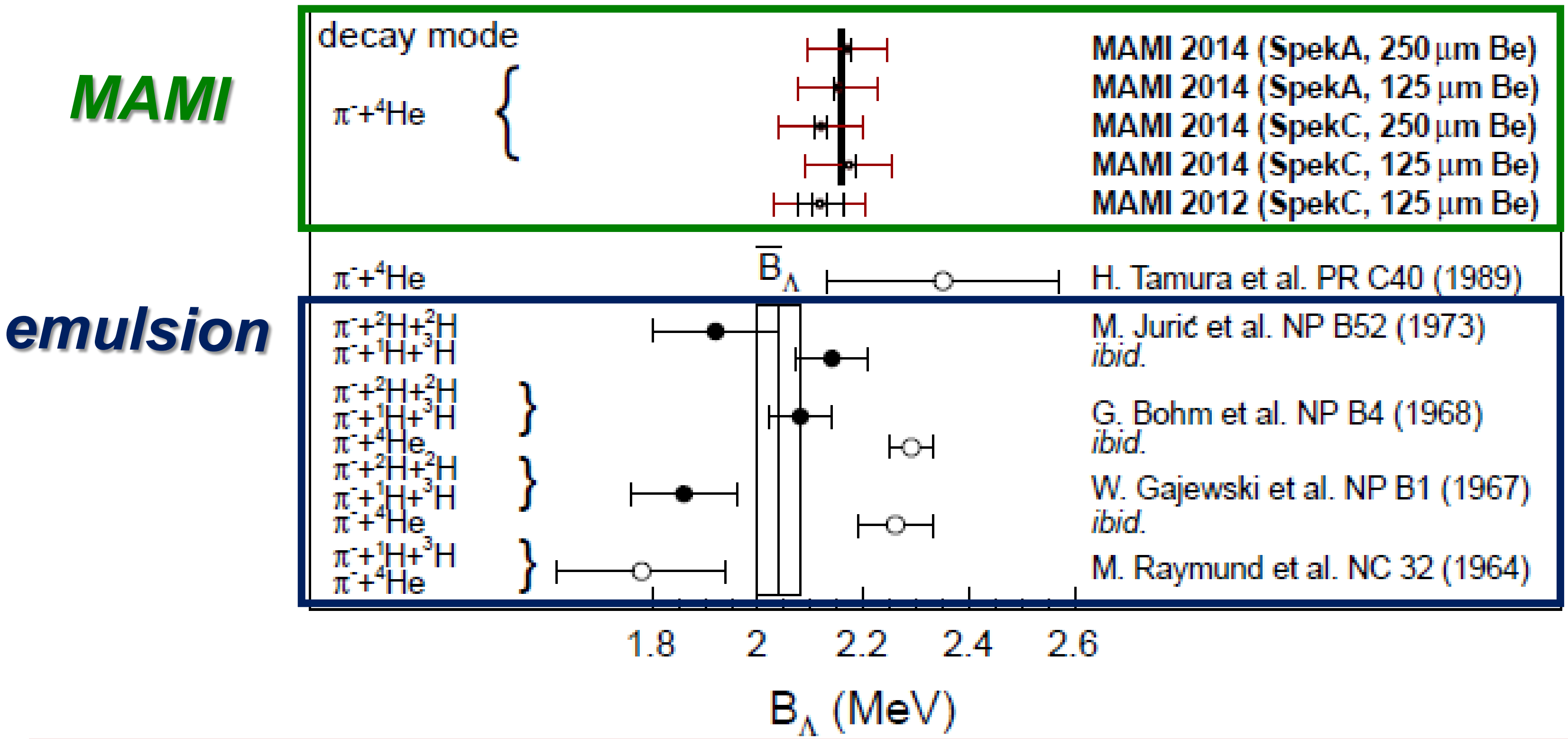
Systematic studies of the decay-pion line



- consistent result for $B_\Lambda({}^4_\Lambda H)$ from MAMI 2012 and MAMI 2014
  independent measurement in two specs, two targets, two beam-times

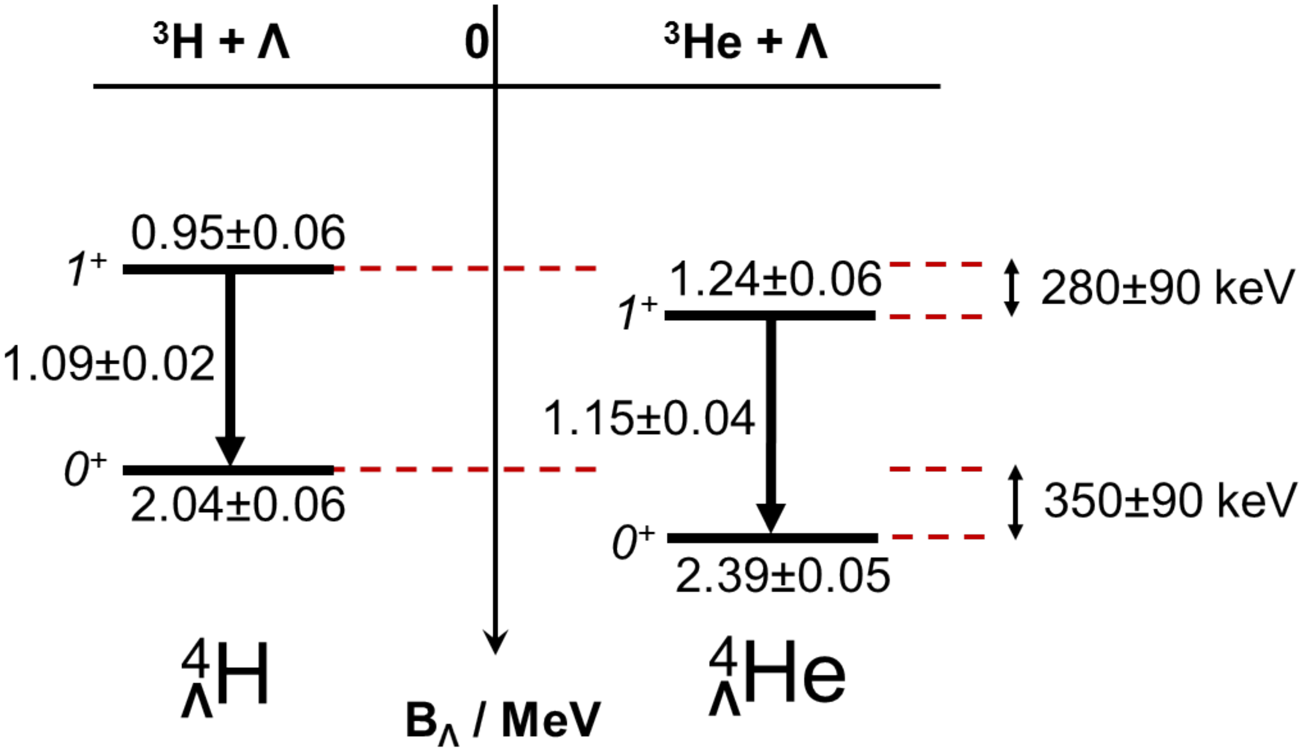
World data on $^4_\Lambda H$ mass

outer error bars correlated from calibration



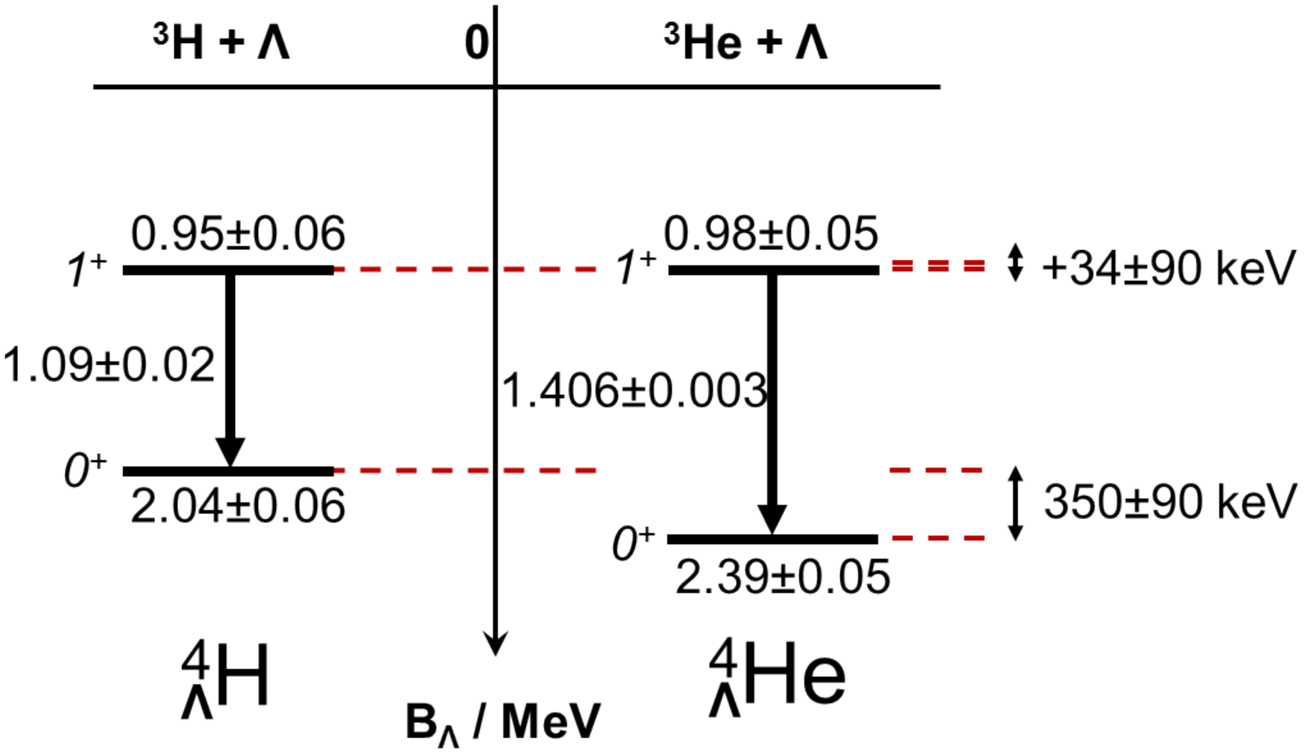
	$B_\Lambda(^4_\Lambda H)$ (stat.) (syst.)	
emulsion:	2.04 ± 0.04 ± 0.05 MeV	[M. Juric et al. NP B52 (1973)]
MAMI 2012:	2.12 ± 0.01 ± 0.08 ± 0.03 MeV	[A. Esser et al., PRL 114 (2015)]
MAMI 2014:	2.16 ± 0.01 ± 0.08 MeV	[F. Schulz et al., NPA (2016)]

Current knowledge on CSB in the *A* = 4 system



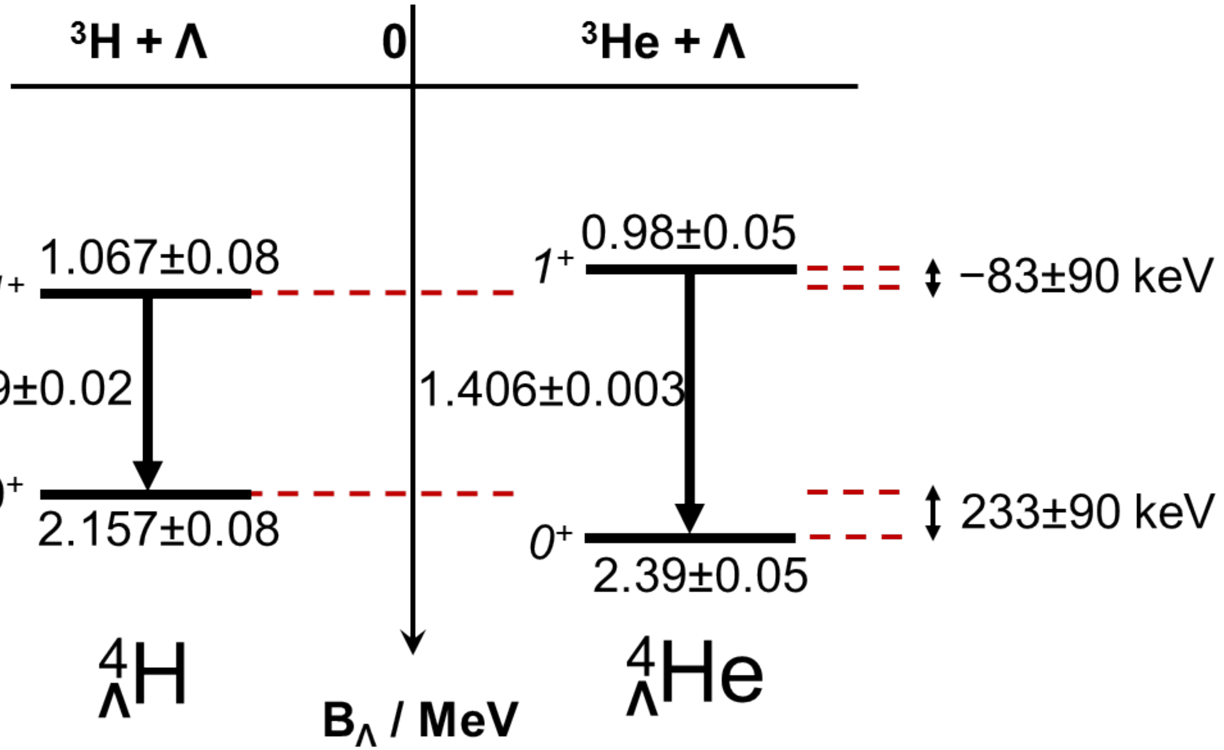
ΔB_Λ (1+ ex. st.) =	280 ± 90 keV	*(emulsion + old γ-ray data)*
ΔB_Λ (0+ gr. st.) =	350 ± 90 keV	*(emulsion data)*

Current knowledge on CSB in the *A* = 4 system



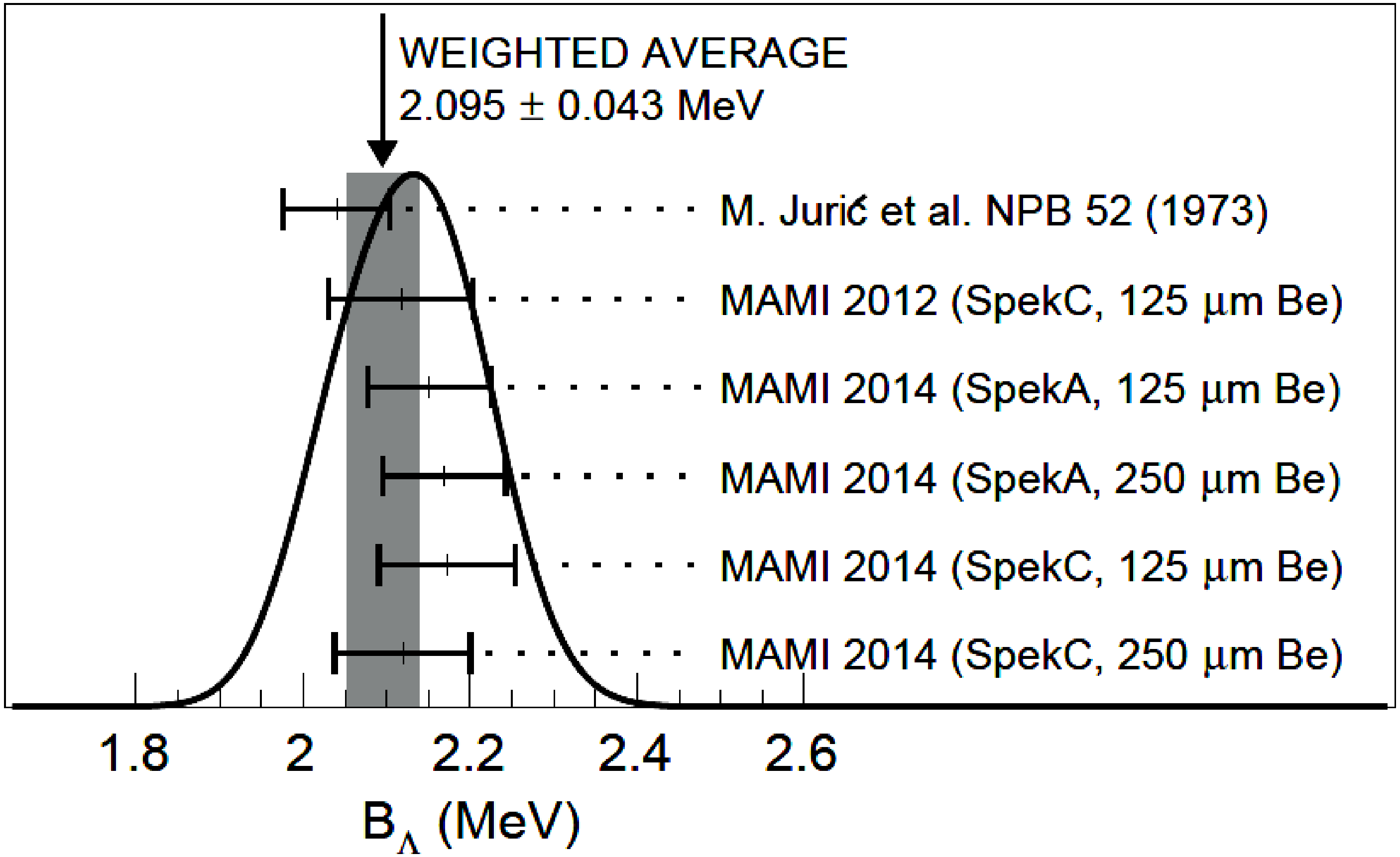
ΔB_Λ (1+ ex. st.) =	280 ± 90 keV	*(emulsion + old γ-ray data)*
	+34 ± 90 keV	*(emulsion + new γ-ray data)*
ΔB_Λ (0+ gr. st.) =	350 ± 90 keV	*(emulsion data)*

Current knowledge on CSB in the *A* = 4 system



ΔB_Λ (1+ ex. st.) =	280 ± 90 keV	*(emulsion + old γ-ray data)*	
	+34 ± 90 keV	*(emulsion + new γ-ray data)*	
	−83 ± 90 keV	*(MAMI + emulsion + new γ-ray data)*	↕ + → –
ΔB_Λ (0+ gr. st.) =	350 ± 90 keV	*(emulsion data)*	
	233 ± 90 keV	*(MAMI + emulsion data)*	↕ ~ 2/3

Combination of all experimental results



inclusion of correlations according to PDG procedure:

– modified systematic errors for each measurement

– treated as independent and averaged in the usual way with other data

Microscopic calculations

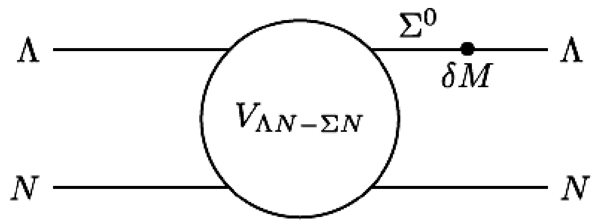
Calculation	NY interaction	$B_\Lambda(^4_\Lambda H)$ (MeV)	$B_\Lambda(^4_\Lambda He)$ (MeV)	ΔB_Λ ($^4_\Lambda He - ^4_\Lambda H$)
A. Nogga, H. Kamada and W. Gloeckle, PRL 88, 172501 (2002)	$SC97_e$	1.47	1.54	75
	SC89	2.14	1.80	–340
H. Nemura. Y. Akaishi and Y. Suzuki, PRL 89, 142504 (2002)	$SC97_d$	1.67	1.62	–50
	$SC97_e$	2.06	2.02	–40
	$SC97_f$	2.16	2.11	–50
	SC89	2.55	2.47	–80
E. Hiyama et al., PRC 65, 011301 (2001)	AV8	2.33	2.28	–50
Gazda, Gal, NPA 954, 161 (2016)	LO χEFT			–10 ± 30
Nogga et al., NPA 914 (2013)	NLO χEFT			46
Gazda, Gal, PRL 116, 122501 (2016)	NLO χEFT			180 ± 130

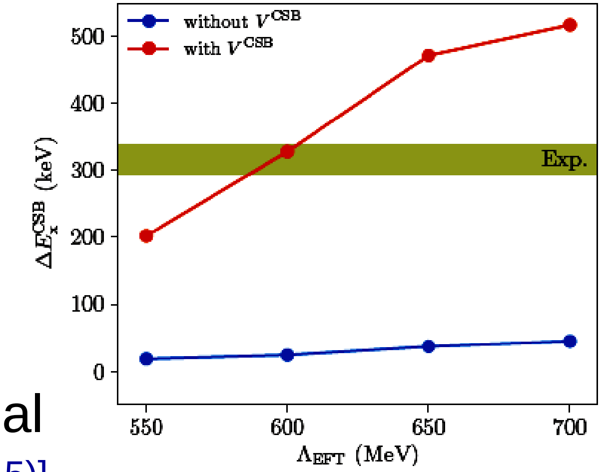
until recently, no calculation was able to consistently reproduce ΔB_Λ values

Latest theory predictions with chiral interactions

chiral effective models with central force ΛN-ΣN coupling

→ mixing of *I* = 0 and *I* = 1 hyperons leads to long-range pion exchanges





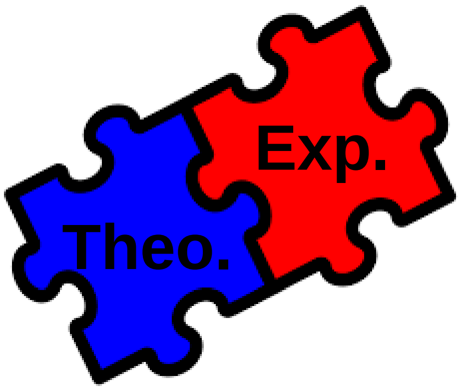
based on OBE Nijmegen NSC97 YN potential

[A. Gal, PLB 744, 352 (2015)]

ΔB_Λ (0+ gr. st.) = +226/266 keV

ΔB_Λ (1+ ex. st.) = +30/39 keV

based on LO chiral EFT Bonn-Jülich YN potential



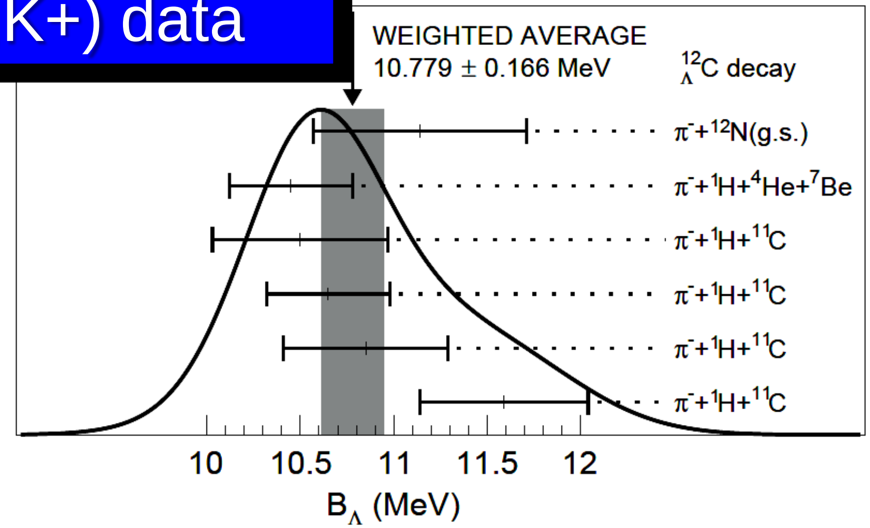
ΔB_Λ (0+ gr. st.) = +180 ± 130 keV

ΔB_Λ (1+ ex. st.) = –200 ± 30 keV

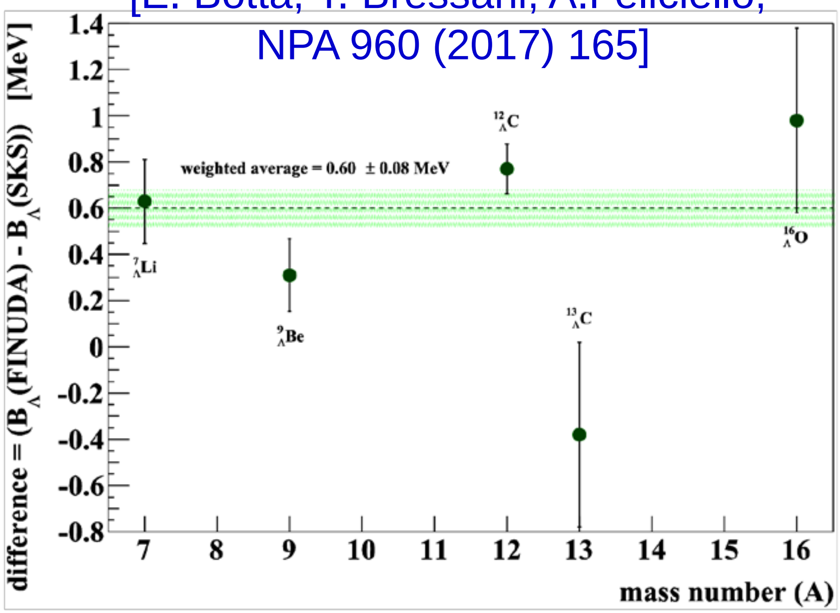
[D. Gazda, A. Gal, PRL 116, 122501 (2016)]
[D. Gazda, A. Gal, NPA 954, 161 (2016)]

Correction of (π+,K+) data

- normalization of (π+,K+) data to $^{12}{}_{\Lambda}C$ emulsion value
- only 6 recorded events from several decay channels

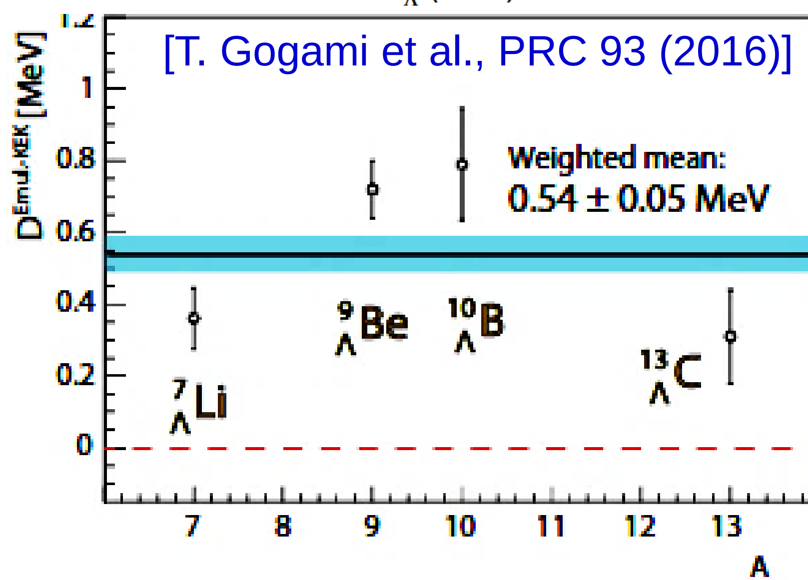


[E. Botta, T. Bressani, A.Feliciello, NPA 960 (2017) 165]



$^{7}{}_{\Lambda}Li$, $^{9}{}_{\Lambda}Be$, $^{12}{}_{\Lambda}C$, $^{13}{}_{\Lambda}C$, $^{16}{}_{\Lambda}O$ to FINUDA

[T. Gogami et al., PRC 93 (2016)]



$^{7}{}_{\Lambda}Li$, $^{9}{}_{\Lambda}Be$, $^{10}{}_{\Lambda}B$, $^{13}{}_{\Lambda}C$ to emulsion

evidence of unreported systematic dependencies in data

Revised CSB values in p-shell hypernuclei

multiplet pair	$\Delta B_\Lambda(A,Z)$ (keV)	experimental sources	Reference
${}^{7}_{\Lambda}\mathrm{Be} - {}^{7}_{\Lambda}\mathrm{Li}^*$	-100 ± 90	emuls. – emuls.	[2, 4]
${}^{7}_{\Lambda}\mathrm{Li}^* - {}^{7}_{\Lambda}\mathrm{He}$	-20 ± 230	FINUDA – $(e,e'K^+)$	[t.w.]
${}^{8}_{\Lambda}\mathrm{Be} - {}^{8}_{\Lambda}\mathrm{Li}$	$+40 \pm 60$	emuls. – emuls.	[2]
${}^{10}_{\Lambda}\mathrm{B} - {}^{10}_{\Lambda}\mathrm{Be}$	-220 ± 250	emuls. – emuls.	[2]
	$+40 \pm 120$	SKS – (e,e',K^+)	[13]
${}^{12}_{\Lambda}\mathrm{C} - {}^{12}_{\Lambda}\mathrm{B}$	-570 ± 190	emuls. – emuls.	[2]
	-230 ± 190	SKS – (e,e',K^+)	[13]
	$+50 \pm 110$	FINUDA – $(e,e'K^+)$	[t.w.]
${}^{16}_{\Lambda}\mathrm{O} - {}^{16}_{\Lambda}\mathrm{N}$	-360 ± 430	FINUDA – $(e,e'K^+)$	[t.w.]

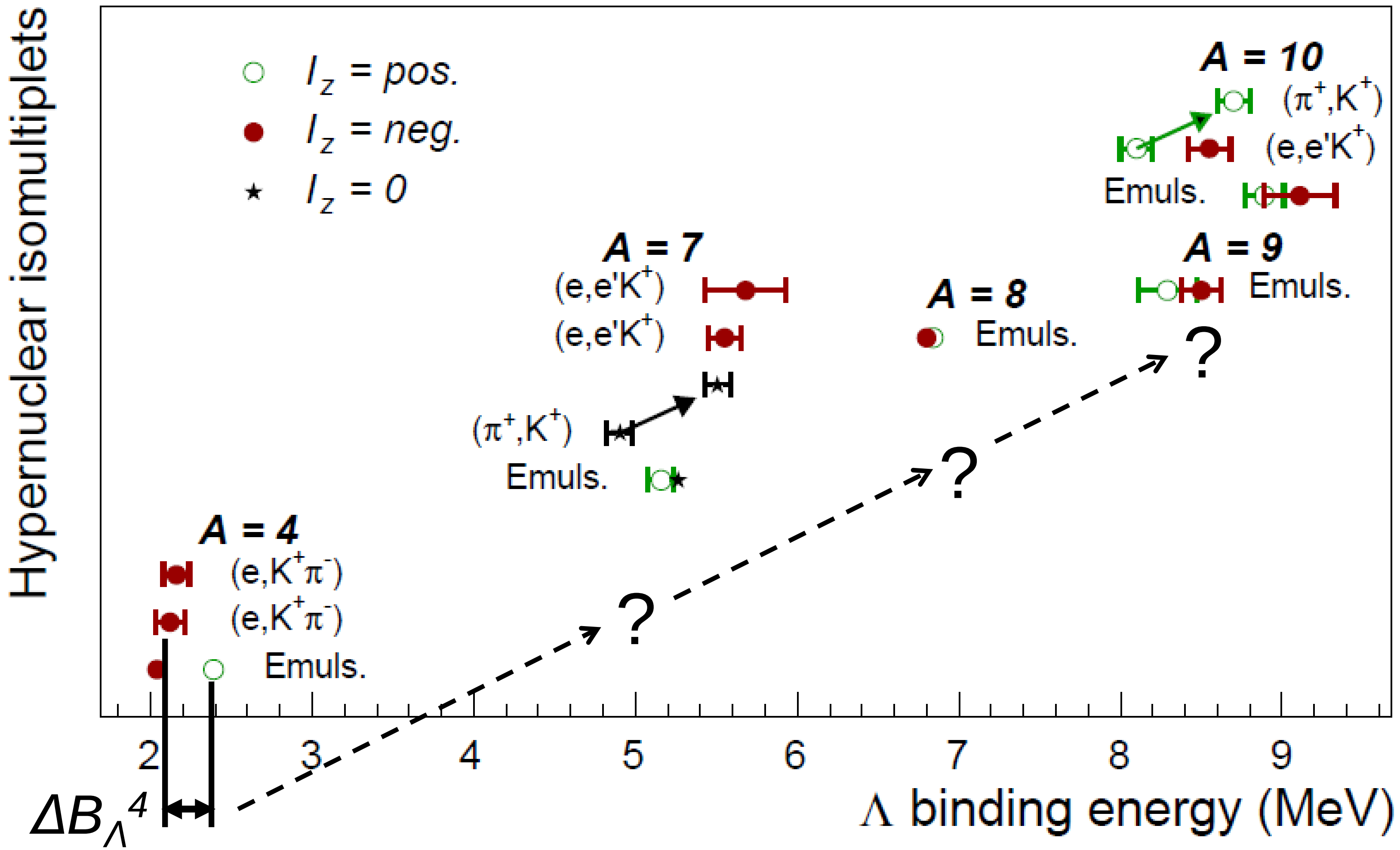
[E. Botta, T. Bressani, A.Feliciello, NPA 960 (2017) 165]

	${}^{7}_{\Lambda}\mathrm{Li}$	${}^{9}_{\Lambda}\mathrm{Be}$	${}^{10}_{\Lambda}\mathrm{B}$	${}^{12}_{\Lambda}\mathrm{C}$	${}^{13}_{\Lambda}\mathrm{C}$	${}^{16}_{\Lambda}\mathrm{O}$
SKS:	5.22(8)	5.99(7)	8.10(10)	10.76	11.38(5)	12.42(5)
emulsion:	5.58(3)	6.71(4)	8.89(12)	10.76(19)	11.69(12)	
SKS + 0.6 MeV:	5.82	6.59	8.70	11.36	11.98	13.02

[A. Gal, E. V. Hungerford, D. J. Millener, Rev. Mod. Phys. 88 (2016) 035004]

Large experimental errors in A = 7 and higher multiplets disguise possible CSB effect in these systems

World data on $A \leq 10$ systems



- clearest signature of charge symmetry breaking in $A = 4$ system
- weak indications of charge symmetry breaking in $A \neq 4$ systems

Unanswered questions

- do we have a complete set of statistical and systematic errors?
- are all of the known errors symmetric?
- are all of the known measurements normally distributed?
- were all used estimators unbiased and consistent?
- were outliers of values treated (and discarded) consistently?
- which data have been superceded or excluded by later experiments?
- were cross-correlated errors considered for combined results?
- were likelihood functions used for combined results?
- which algorithms were used for treating inconsistent or discrepant data?

– comprehensive, regularly updated, and systematic compilation needed
– best option would be to include hypernuclear data in the PDG reviews

Summary

- CSB considerably stronger in hyper- than in ordinary nuclei
  - sizeable charge symmetry breaking effect in *A = 4* recently confirmed by high-precision experiments
  - CSB is strongly spin-dependent ... and possibly changing sign between A = 4 ground and excited states
- limitations of the data on higher mass isomultiplets
  - large experimental (esp. systematic) uncertainties
  - improved database needed
- theoretical description of a large CSB effect
  - effective $\pi\Lambda\Lambda$ coupling in LO χEFT interaction
  - CSB in YN interaction for p-shell nuclei needed

New precision era in hypernuclear physics