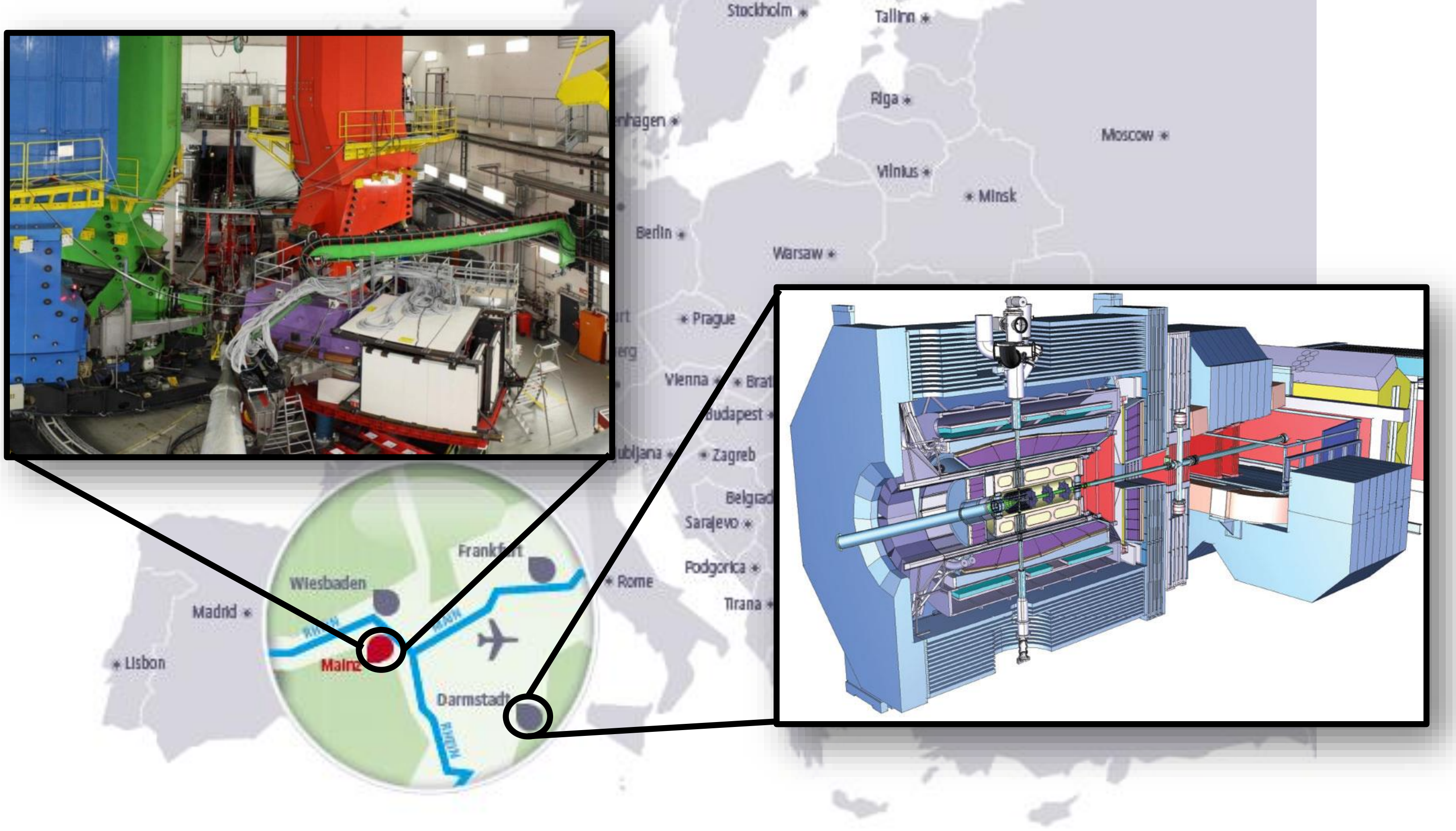
Solving puzzles in hypernuclear physics at MAMI and PANDA

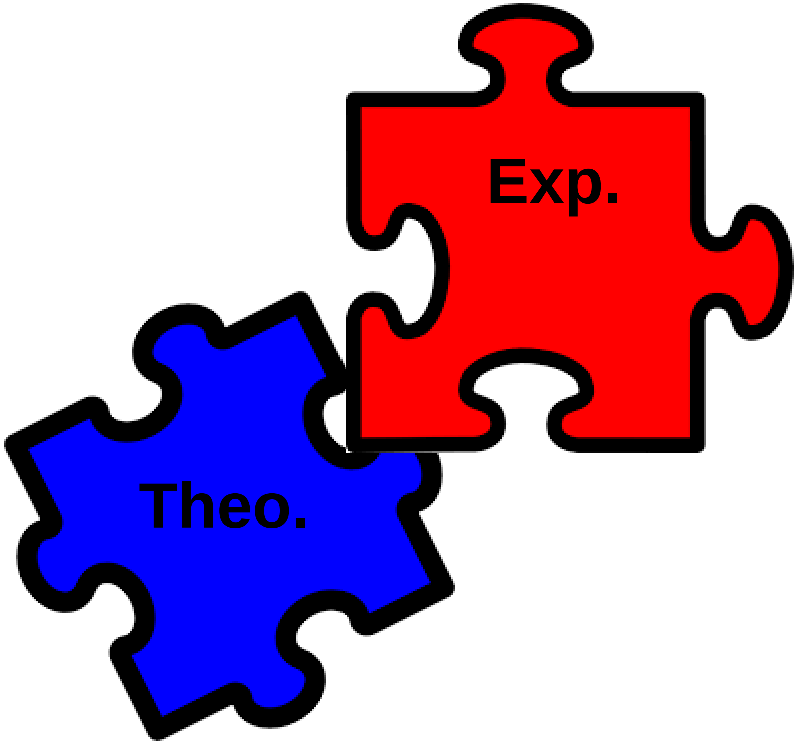


Patrick Achenbach

U Mainz

October 2o16

Light Λ hypernuclei and the puzzle of charge symmetry breaking



The world as we know it relies on charge symmetry breaking

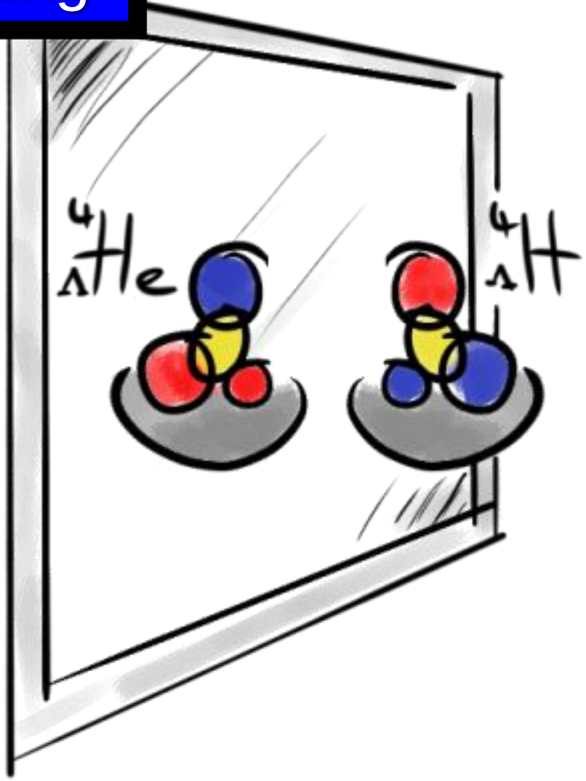
Charge independence: strong force independent of nucleon isospin state

$$(F_{\text{p-p}} = F_{\text{n-n}} = F_{\text{p-n}})$$

Charge symmetry: strong force independent of nucleon isospin exchange

$$(F_{\text{p-p}} = F_{\text{n-n}})$$

Coulomb interactions are rather ineffective in breaking the isospin symmetries in nuclei



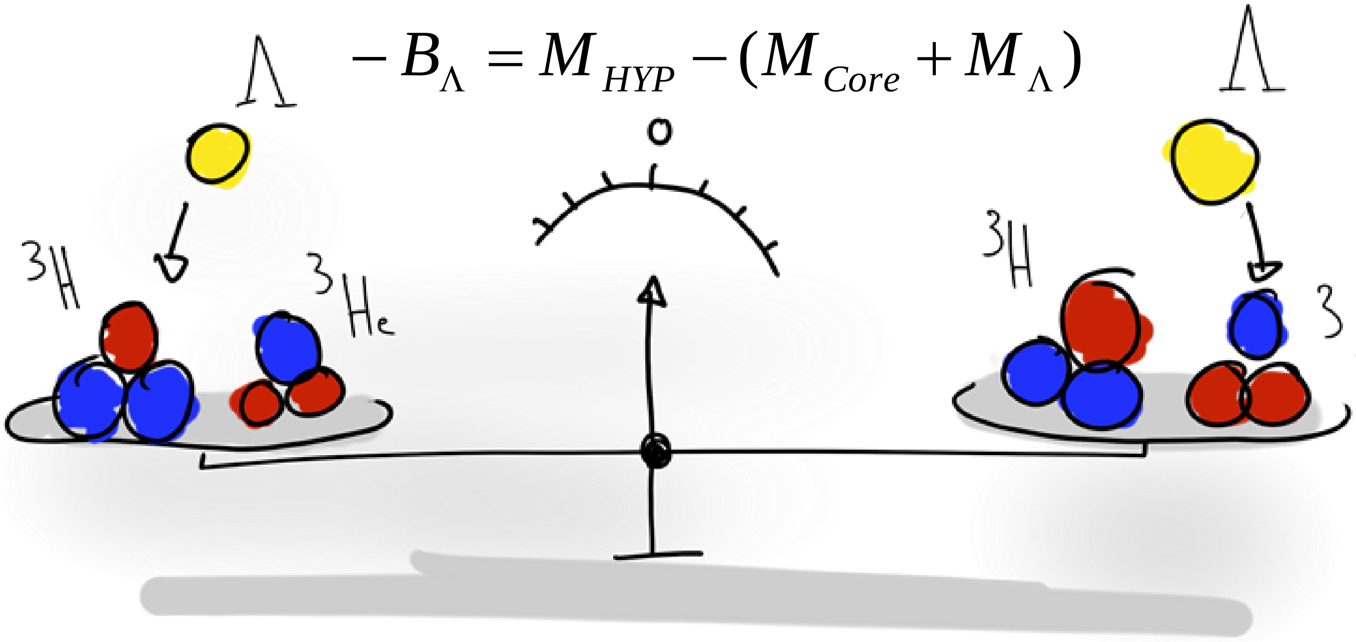
If charge symmetry would be satisfied in nuclear two-body force…

… mirror hypernuclei would have (nearly) identical mass
… protons would be heavier than neutrons because of electrostatic repulsion
… no free protons would have survived the primordial nucleosynthesis
… the Sun and the stars would have no slow-burning fuel

Charge symmetry in light hypernuclei

Opportunity to study strong force symmetries with Λ as neutral probe

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



Λ hyperon has no isospin and no charge →

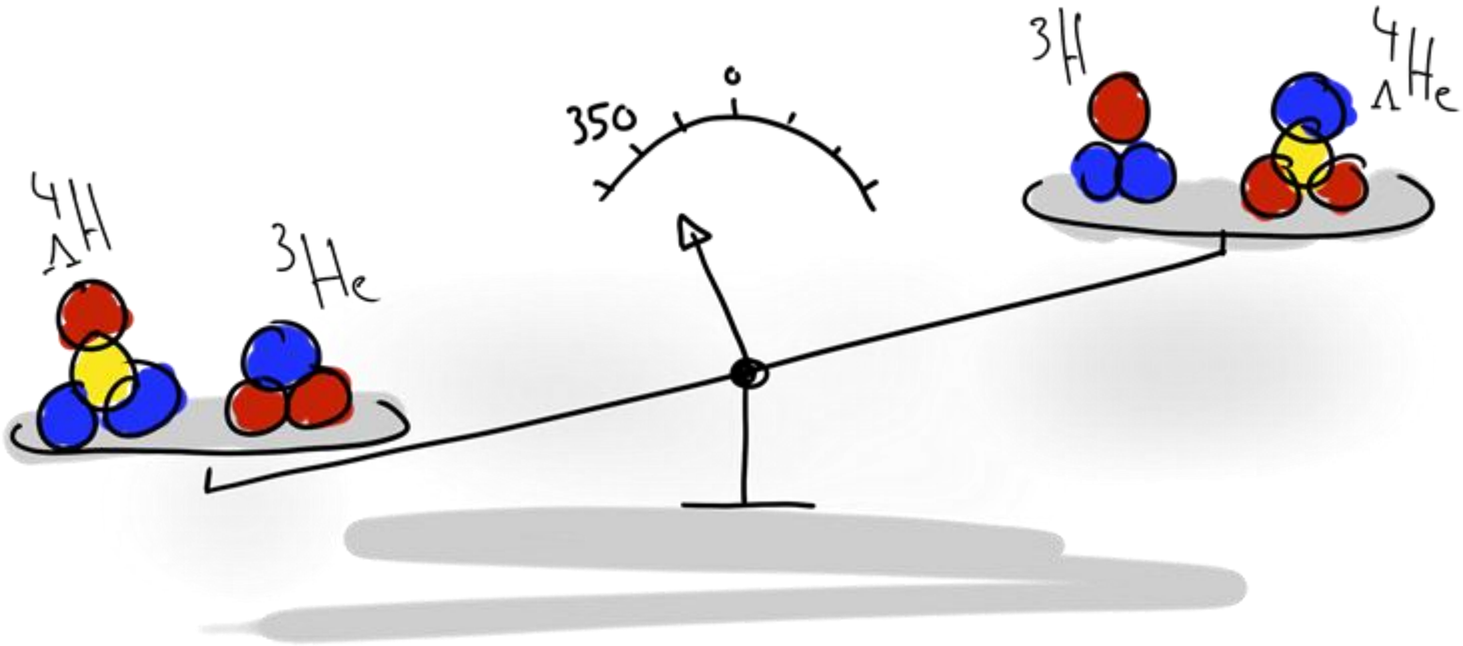
Λ binding in mirror hypernuclei directly tests charge symmetry

$$F_{\Lambda\text{-}p} = F_{\Lambda\text{-}n} \rightarrow B_\Lambda({}_\Lambda{}^AZ) = B_\Lambda({}_\Lambda{}^AZ{+}1)$$

Large charge symmetry breaking in *A = 4*

$^4_\Lambda$H - $^4_\Lambda$He binding energy difference exceptionally large > 300 keV

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



- Charge symmetry breaking 5 times larger than in ^{3}H - ^{3}He system
- Λp interaction stronger than Λn interaction

Observations not consistently reproduced by theory before 2015

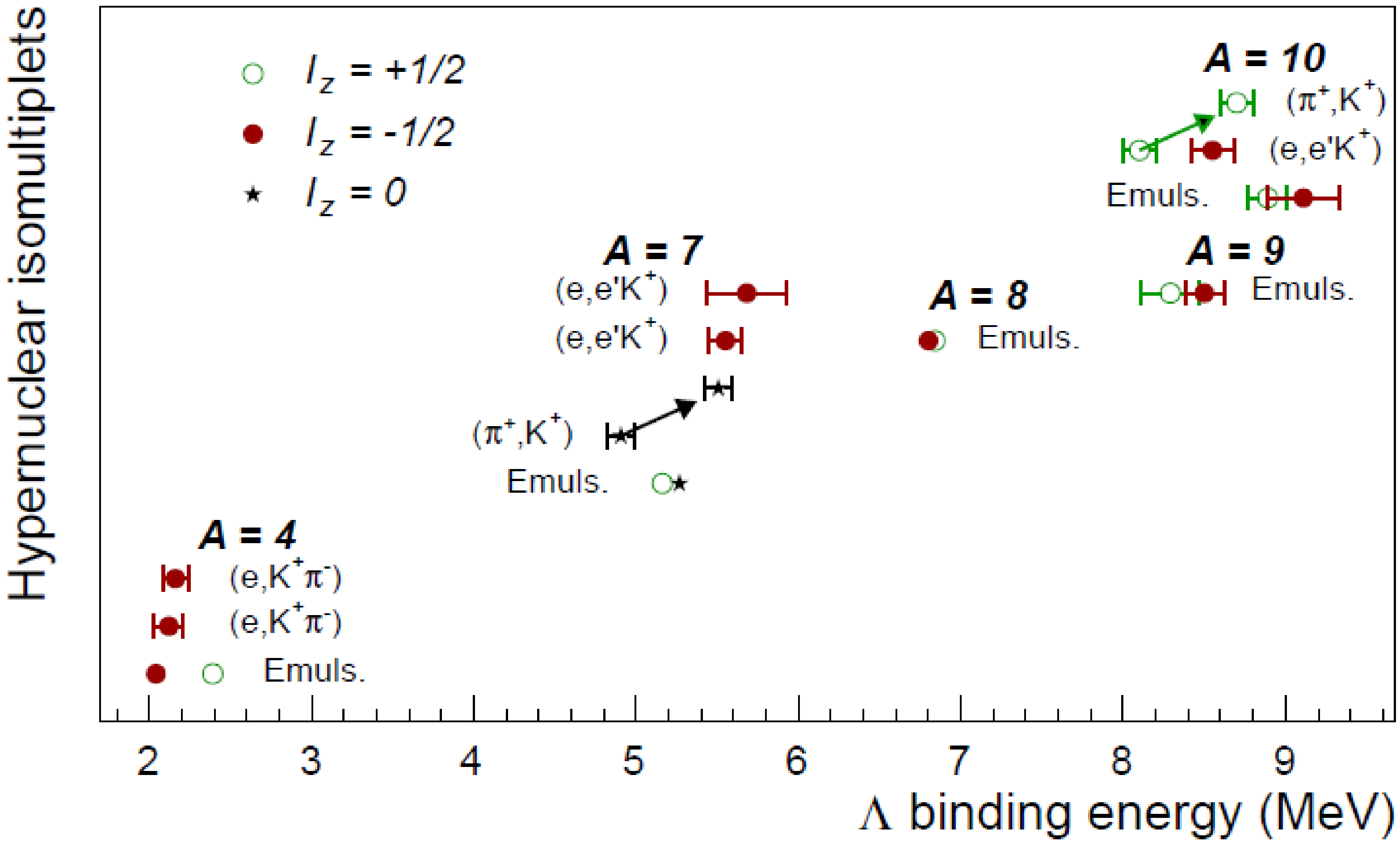
[A. Nogga, NP A 914,140 (2013)]

The *A* = *4* CSB puzzle

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

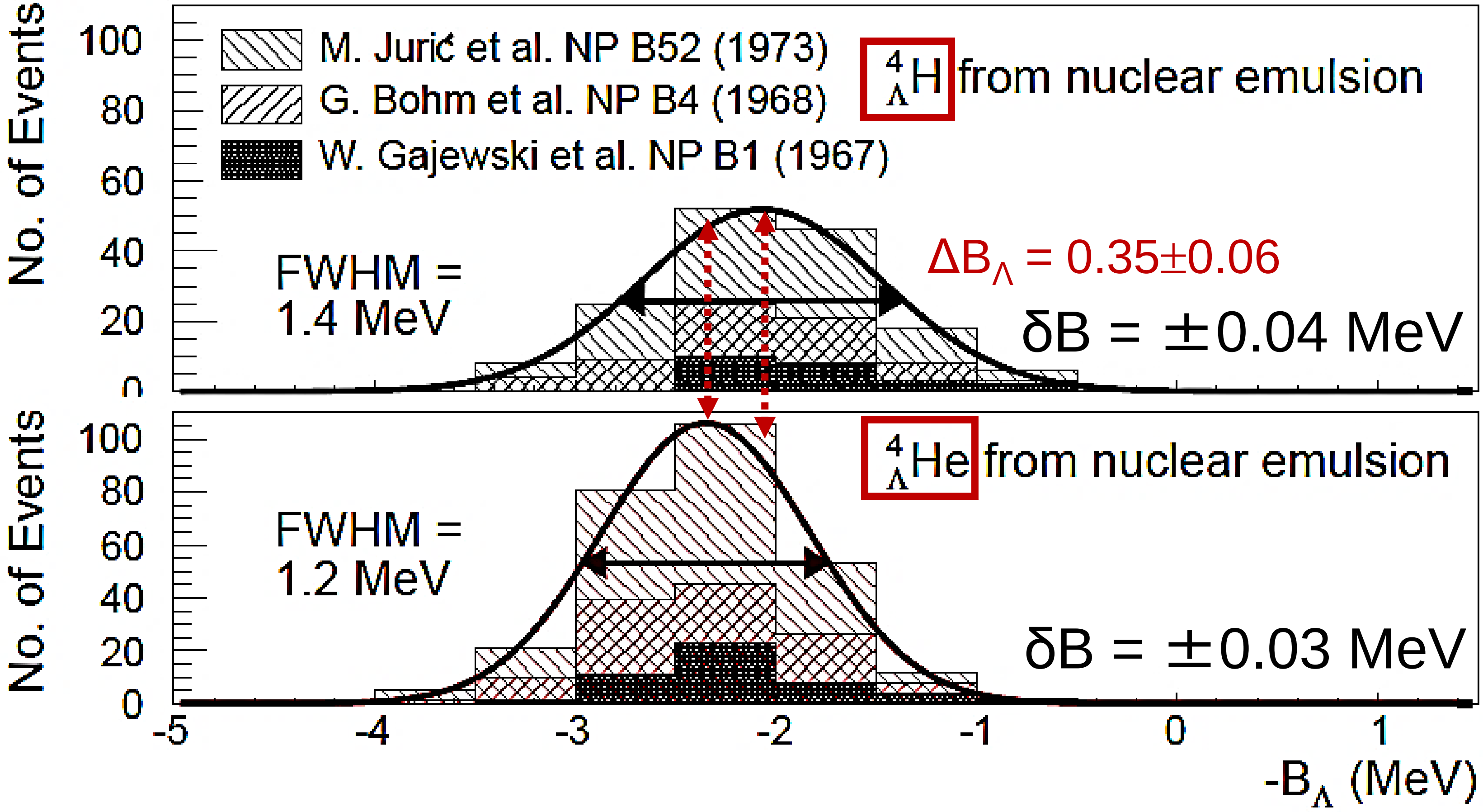
- calculations since decades fail to explain large ΔB_Λ
- coupled channel calculation using SC89 fails to bind excited state

World data on *A* ≤ *10* systems



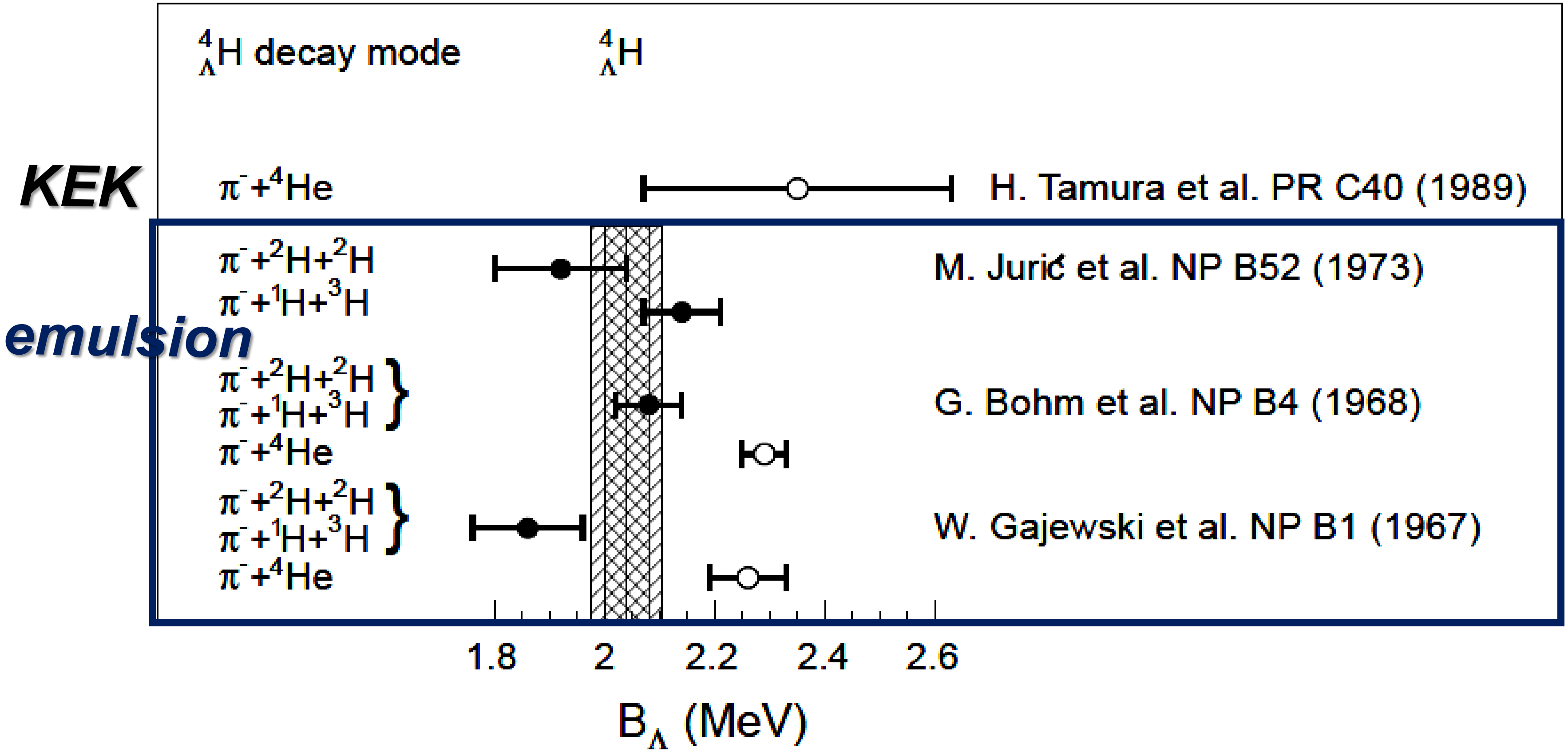
- clearest signature of charge symmetry breaking in *A* = *4* system
- weak indications of charge symmetry breaking in *A* ≠ *4* systems

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

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

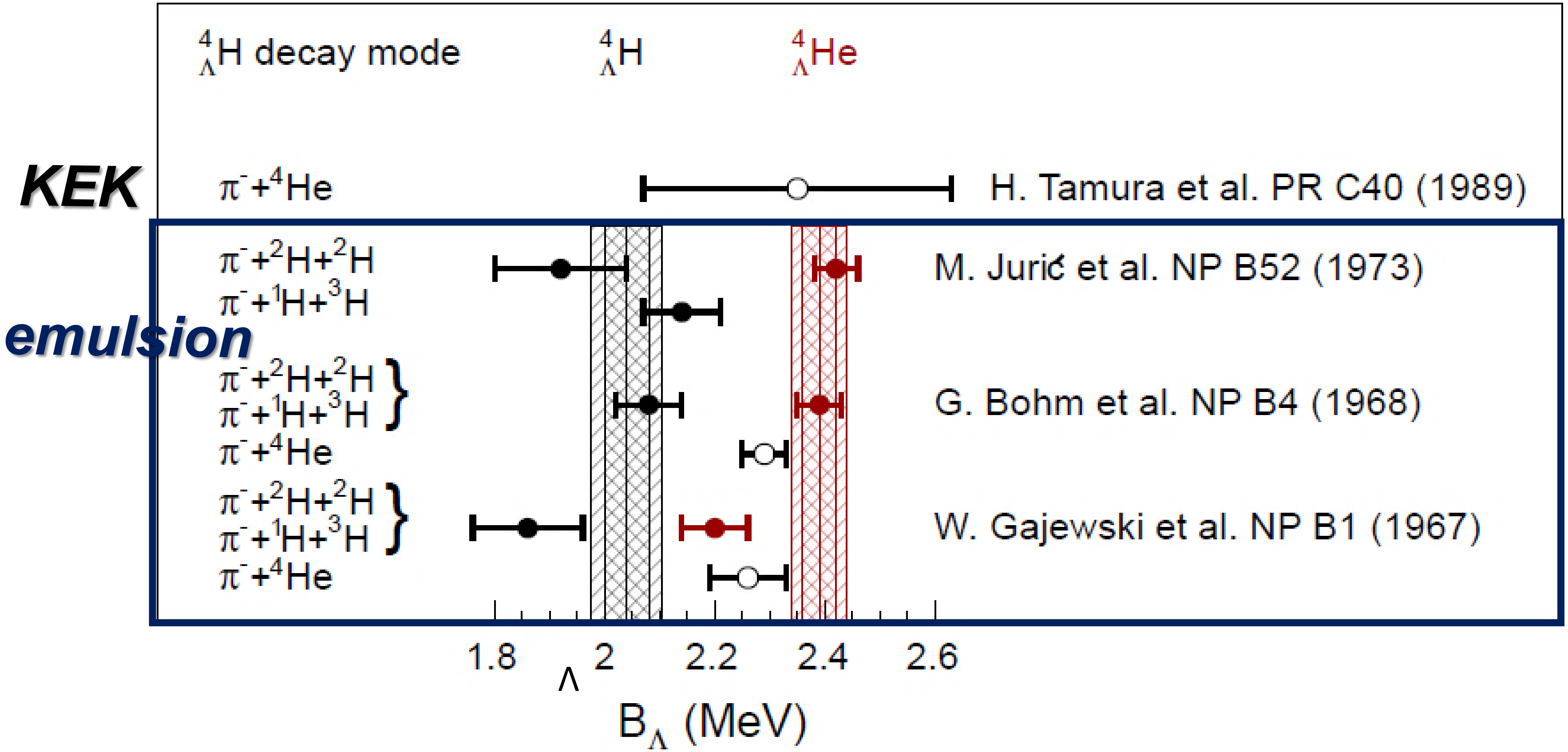


$$\left.\begin{array}{l} {}_{\Lambda}^{4}\mathrm{H} \xrightarrow{\text{decay}} \pi^- + {}^1\mathrm{H} + {}^3\mathrm{H}: B = 2.14 \pm 0.07\ \mathrm{MeV} \\ {}_{\Lambda}^{4}\mathrm{H} \xrightarrow{\text{decay}} \pi^- + {}^2\mathrm{H} + {}^2\mathrm{H}: B = 1.92 \pm 0.12\ \mathrm{MeV} \end{array}\right\} 0.22\ \mathrm{MeV\ difference}$$

$$\text{Total: } B = 2.08 \pm 0.06\ \mathrm{MeV}$$

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

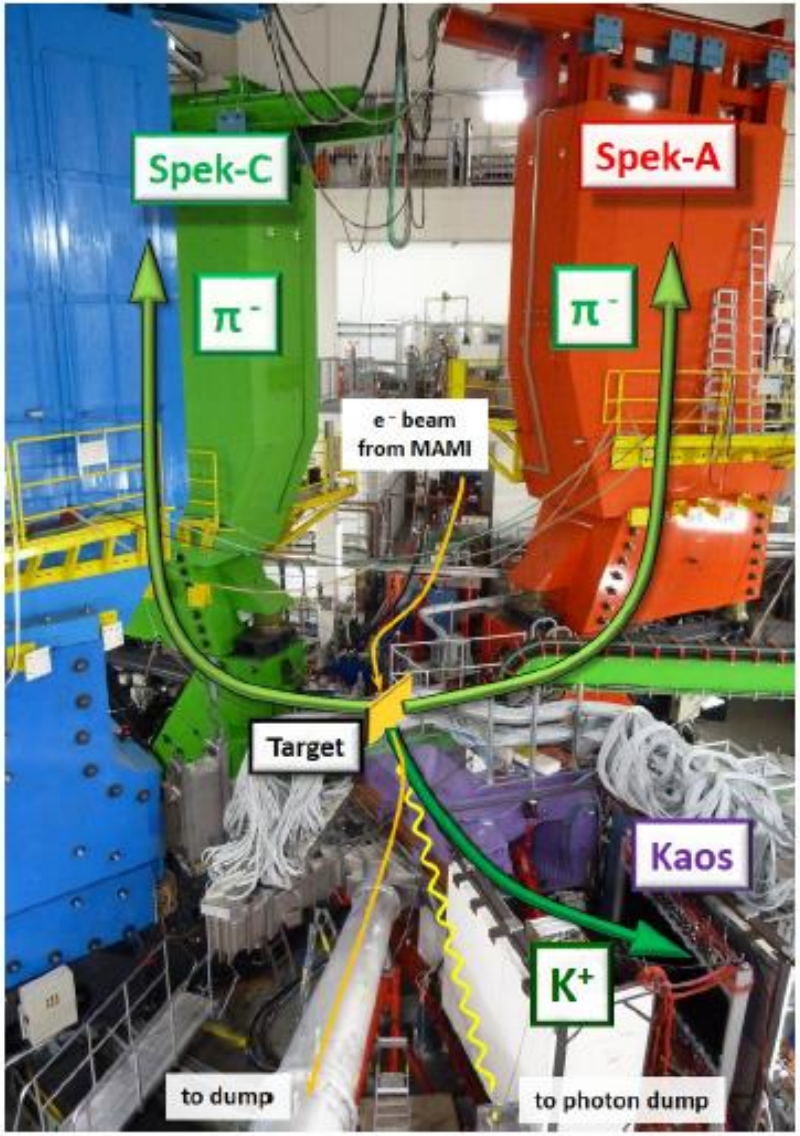
World data on *A* = *4* system

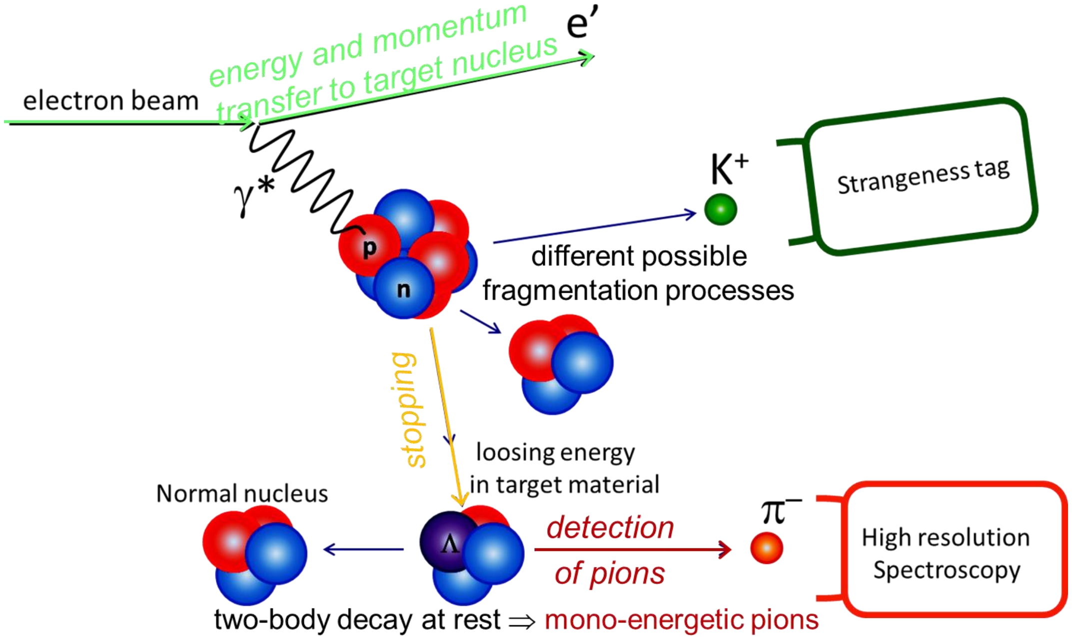


$$\left.\begin{array}{l} {}^{4}_{\Lambda}\mathrm{He} \xrightarrow{\text{decay}} \pi^- + {}^1\mathrm{H} + {}^3\mathrm{He}: B = 2.42 \pm 0.05\ \mathrm{MeV} \\ {}^{4}_{\Lambda}\mathrm{He} \xrightarrow{\text{decay}} \pi^- + 2\,{}^1\mathrm{H} + {}^2\mathrm{H}: B = 2.44 \pm 0.09\ \mathrm{MeV} \end{array}\right\} \text{0.02 MeV difference}$$

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

Hyperfragment decay-pion spectroscopy with electron beams

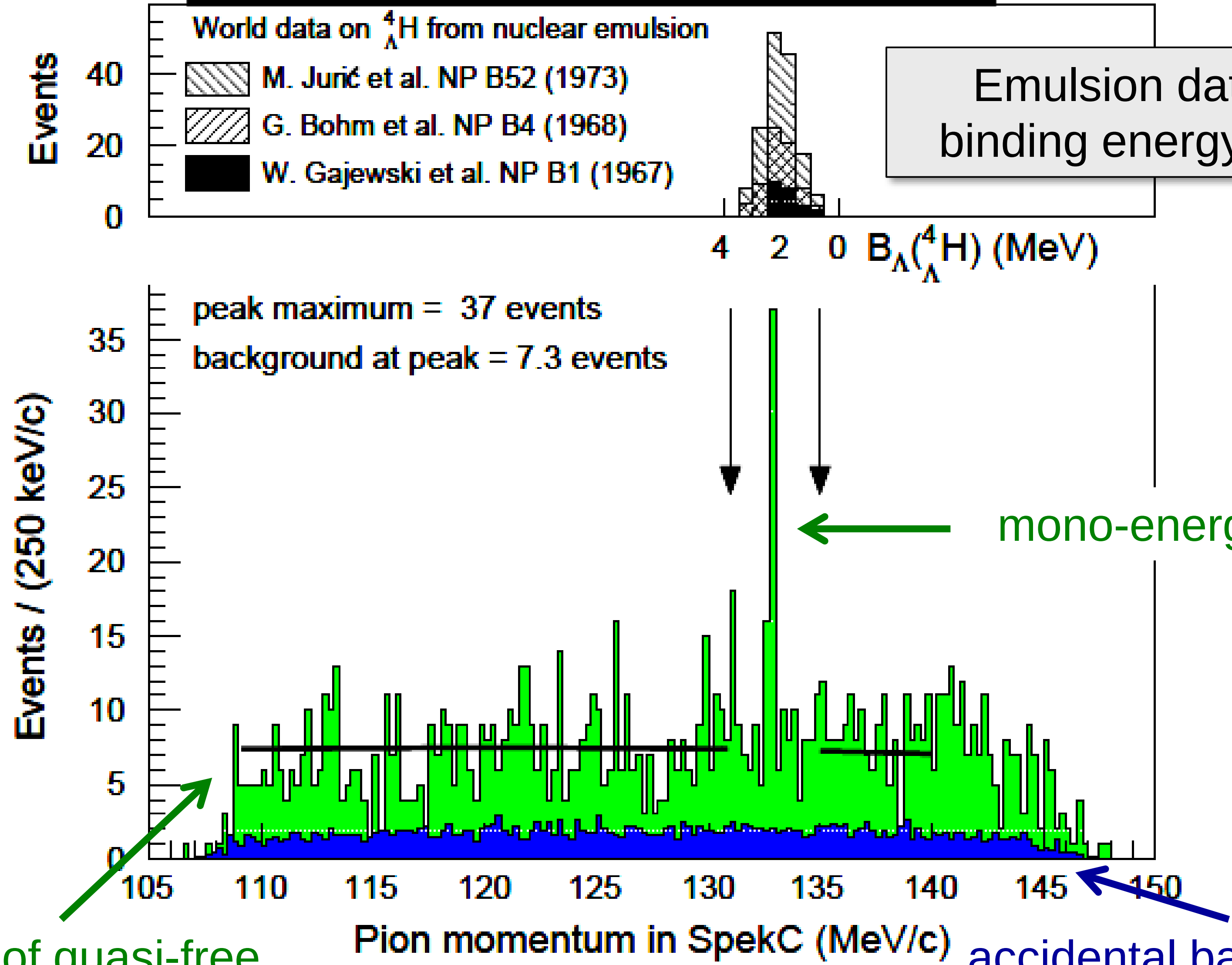




$$M_{\mathrm{HYP}} = \sqrt{M_{\mathrm{ncl}}^2 + p_{\pi^-}^2} + \sqrt{M_{\pi^-}^2 + p_{\pi^-}^2}$$

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

Decay-pion spectrum



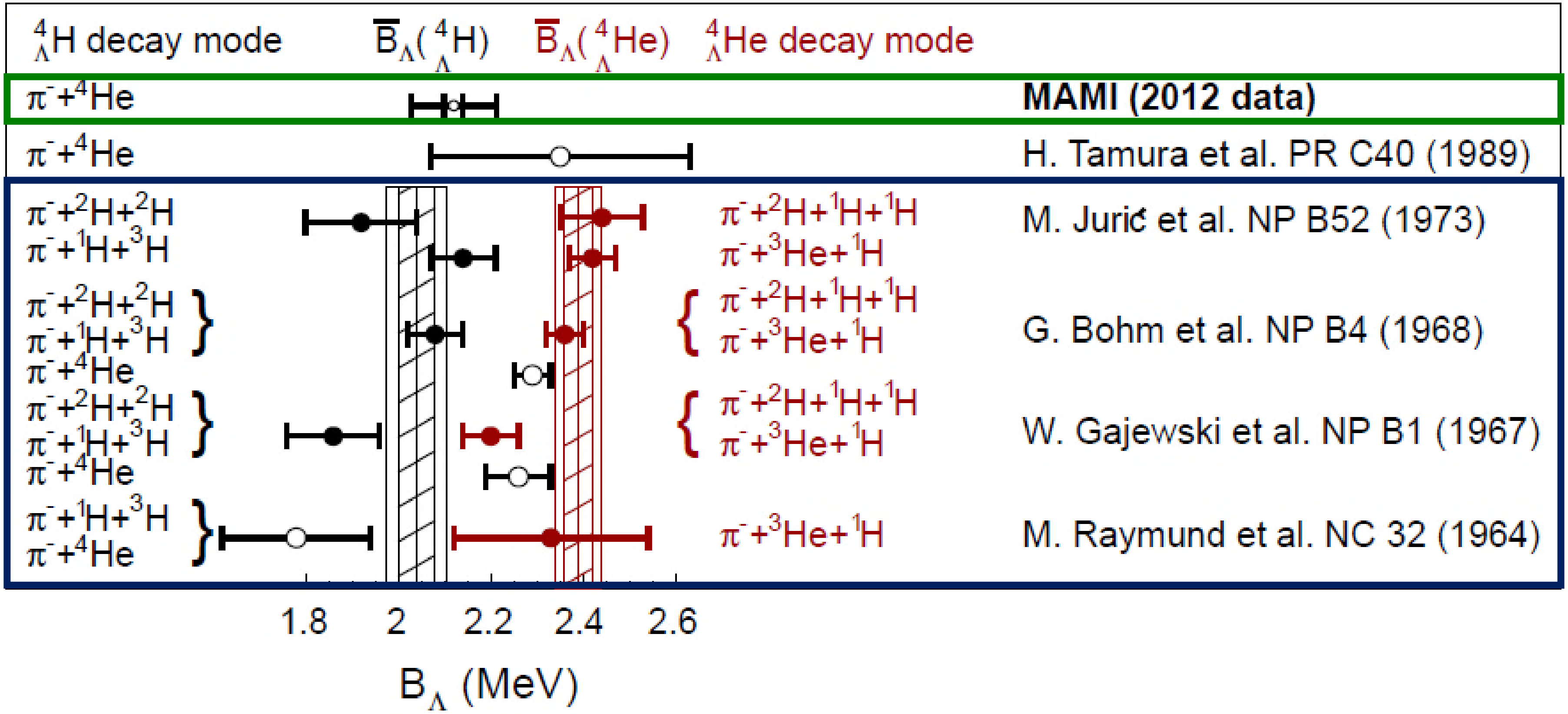
Emulsion data on binding energy scale

mono-energetic pions

decays of quasi-free produced hyperon

accidental background reactions

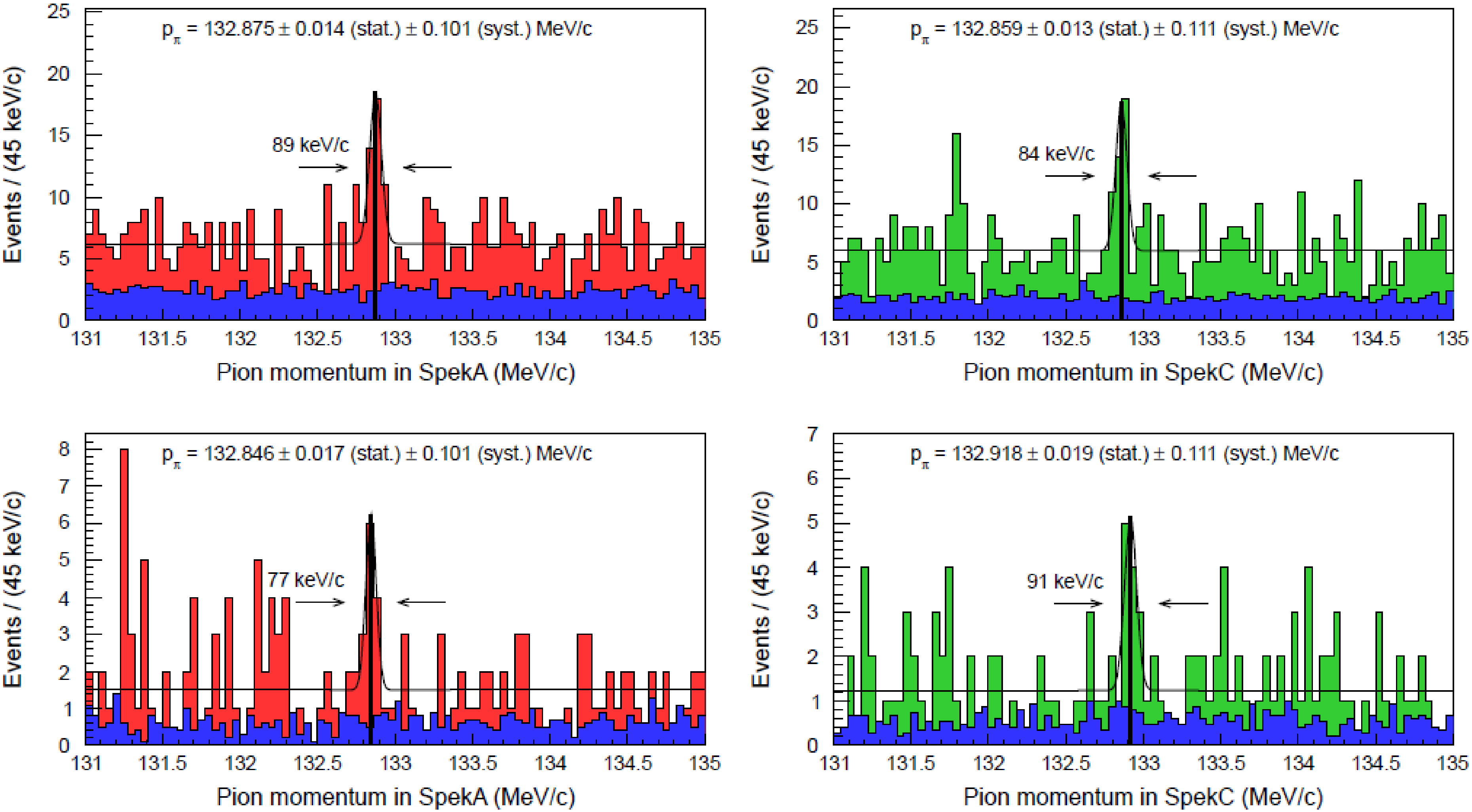
World data on *A* = *4* system



MAMI 2012 experiment Λ binding energy of $_\Lambda{}^4$H:
B_Λ = 2.12 ± 0.01 (stat.) ± 0.09 (syst.) MeV

A. Esser et al. (A1 Collaboration), PRL 114, 232501 (2015)

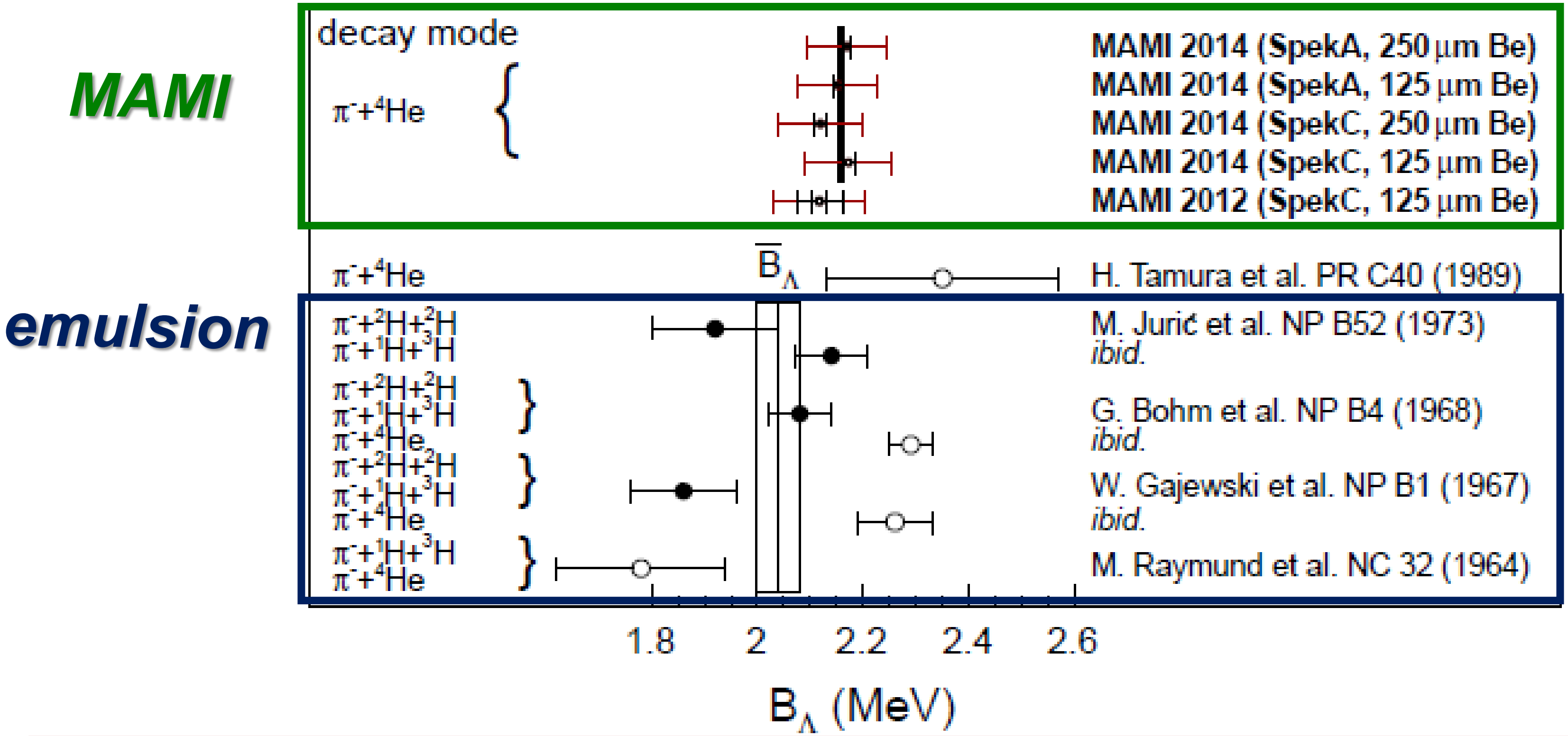
Systematic studies of the decay-pion line



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

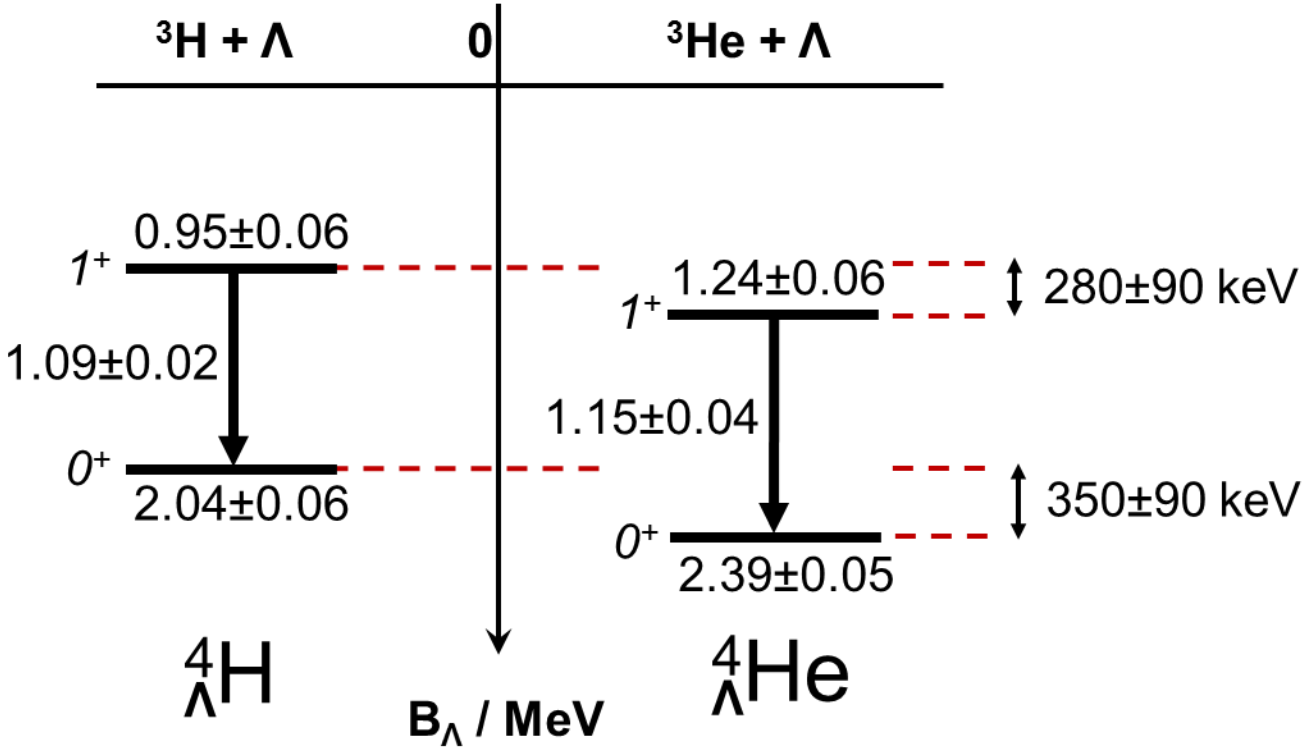
World data on $^4_\Lambda$H mass

outer error bars correlated from calibration



	$B_\Lambda(^4_\Lambda\mathrm{H})$ (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 2012:	2.12 ± 0.01 ± 0.08 ± 0.03 MeV	[P. Achenbach et al., JPS (2016)]
MAMI 2014:	2.16 ± 0.01 ± 0.08 MeV	[F. Schulz et al., NPA 954 (2016)]

The A = 4 level schemes (before 2015)

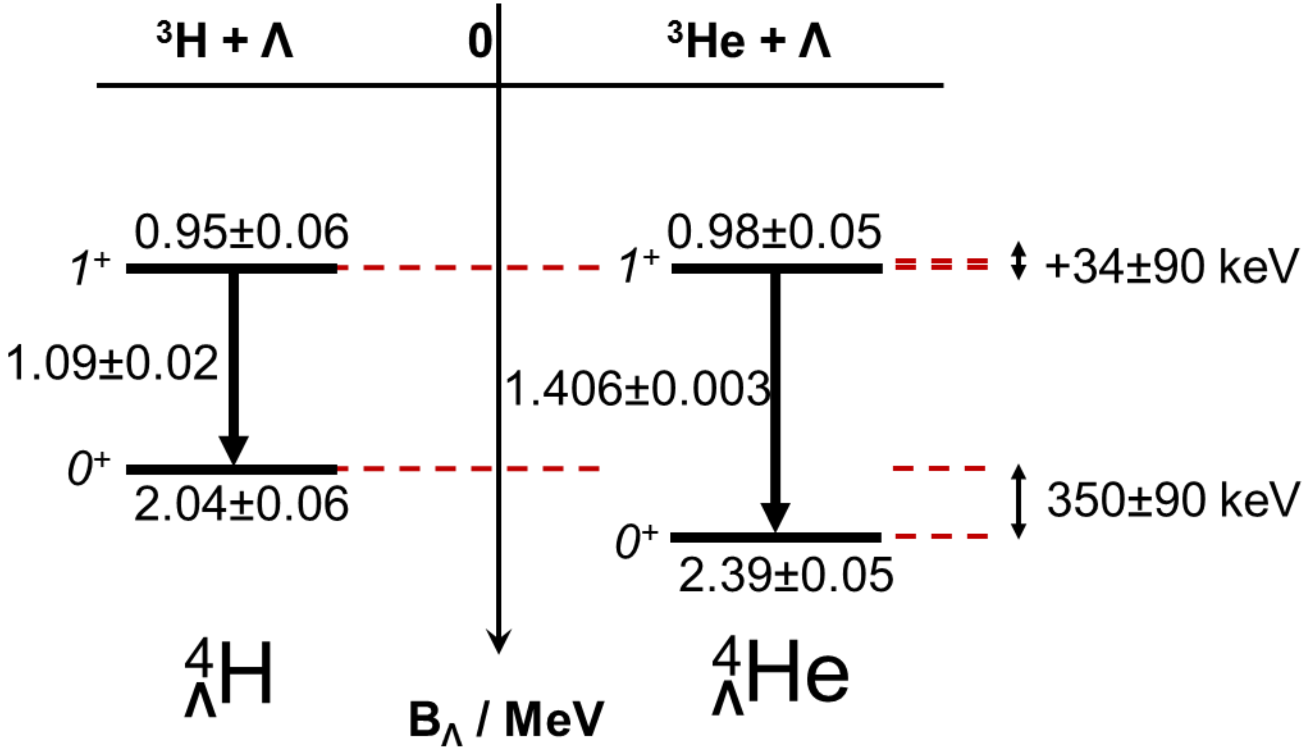


ΔB_Λ (1+ ex. st.) = 280 ± 90 keV *(emulsion + old γ-ray data)*

ΔB_Λ (0+ gr. st.) = 350 ± 90 keV *(emulsion data)*

- charge symmetry breaking only if emulsion data is correct
- spin-independent charge symmetry breaking likely

The *A* = 4 level schemes (as of 2015)



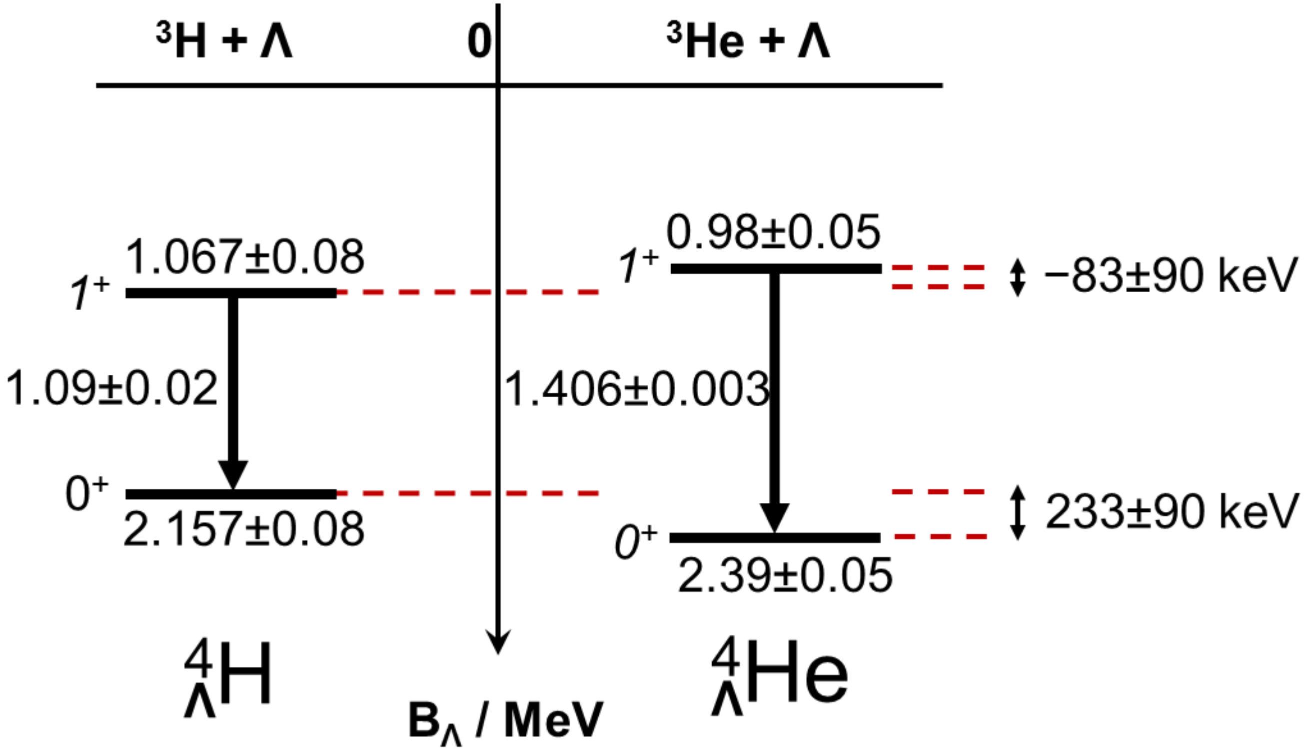
ΔB_Λ (1+ ex. st.) = +34 ± 90 keV *(emulsion + new γ-ray data)*

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

ΔB_Λ (0+ gr. st.) = 350 ± 90 keV *(emulsion data)*

- observation of charge symmetry breaking in γ-ray spectroscopy
- spin-dependent charge symmetry breaking

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



ΔB_Λ (1+ ex. st.) = −83 ± 90 keV *(MAMI + emulsion + new γ-ray data)*

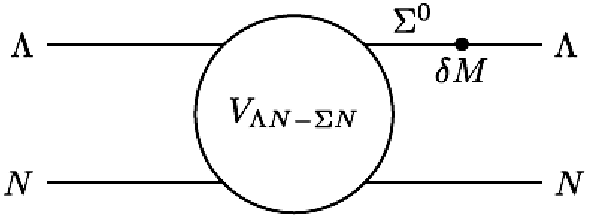
[F. Schulz et al., NPA 954 (2016)]

ΔB_Λ (0+ gr. st.) = 233 ± 90 keV *(MAMI + emulsion data)*

- CSB considerably stronger than in other hyper- or ordinary nuclei
- CSB possibly changing sign between ground and excited states

Consistent experimental data with latest theory

latest 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 model YN potential

ΔB_Λ (0+ gr. st.) = +226/266 keV
ΔB_Λ (1+ ex. st.) = +30/39 keV

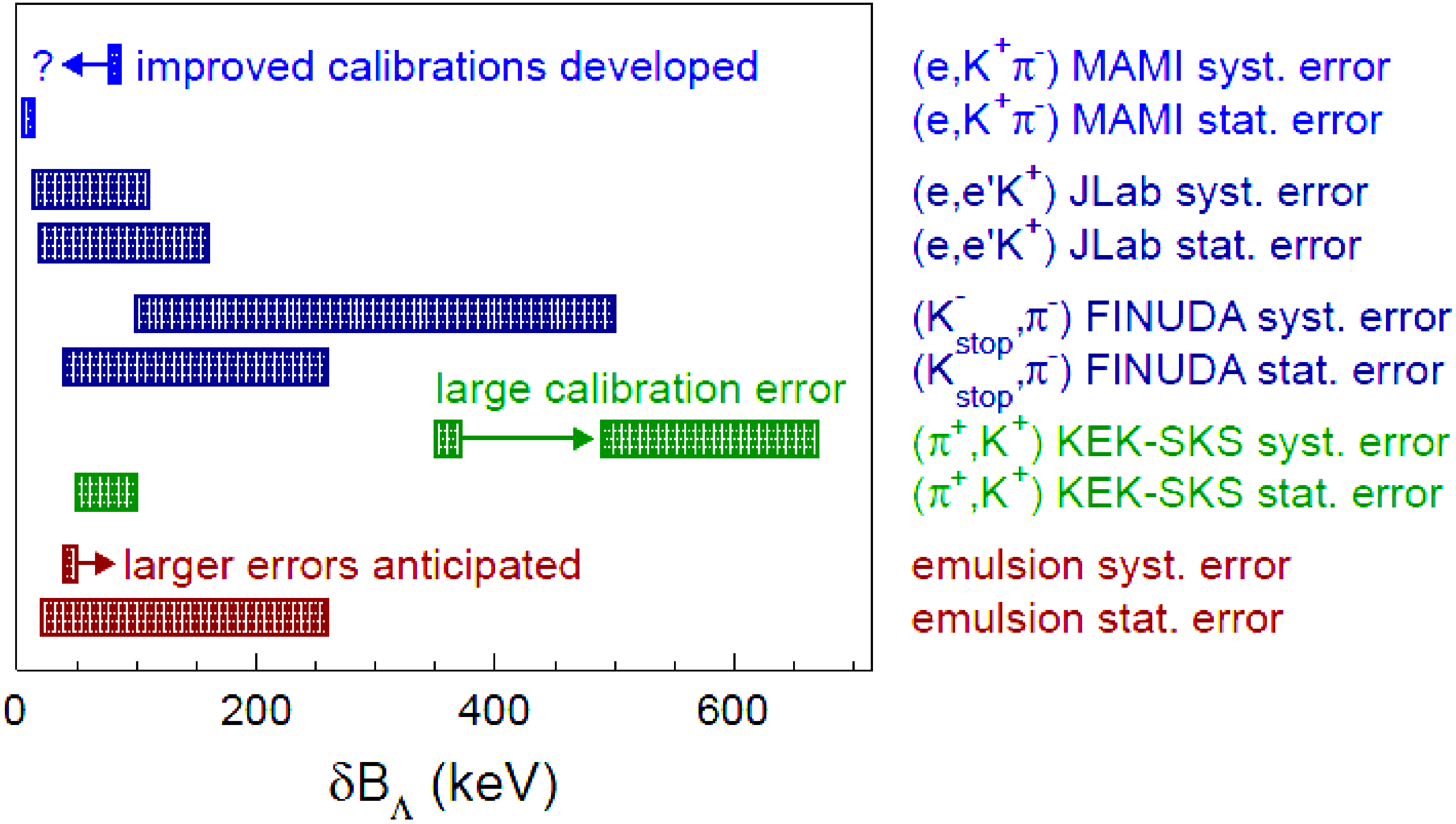
[A. Gal, PLB 744, 352 (2015)]

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)]

Errors on binding energy by method

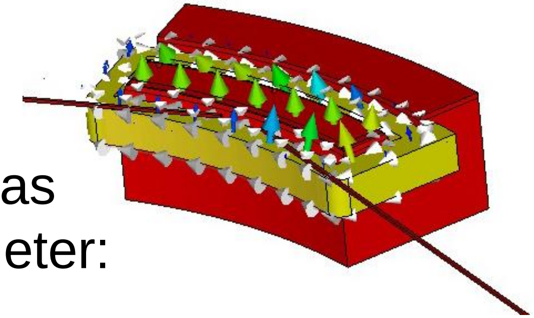


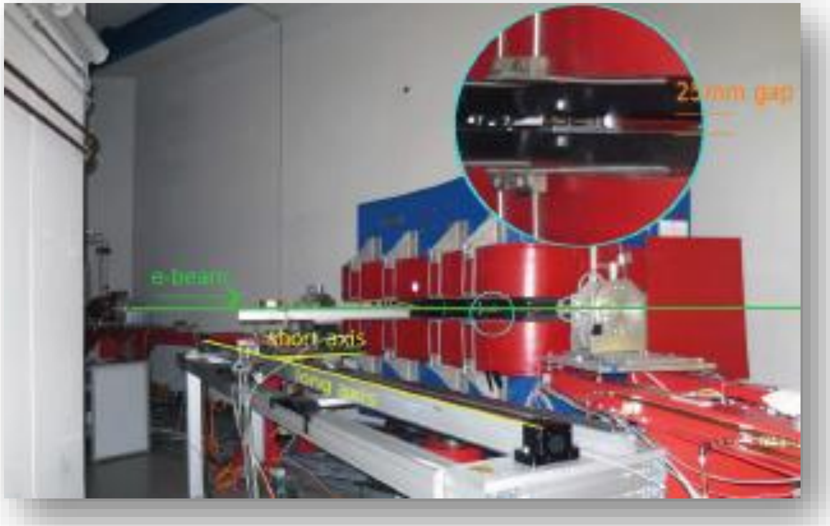
- goal of calibrations is syst. error comparable to stat. error < 20 keV
- decay-pion spectroscopy will be the most precise method of all

Reducing the systematic error

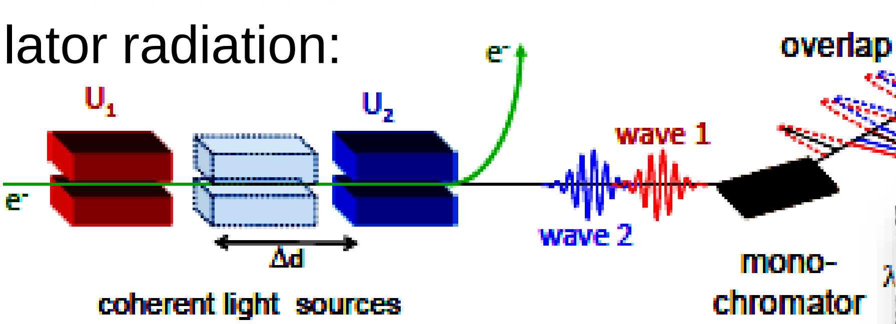
MAMI energy measurement
with $O(10^{-4})$ precision

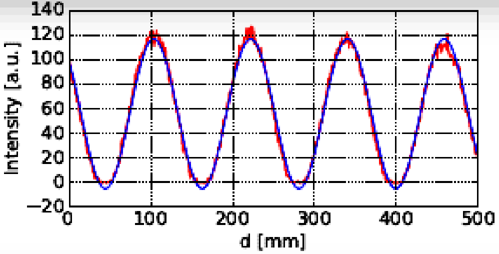
1) by a dipole used as beam-line spectrometer:





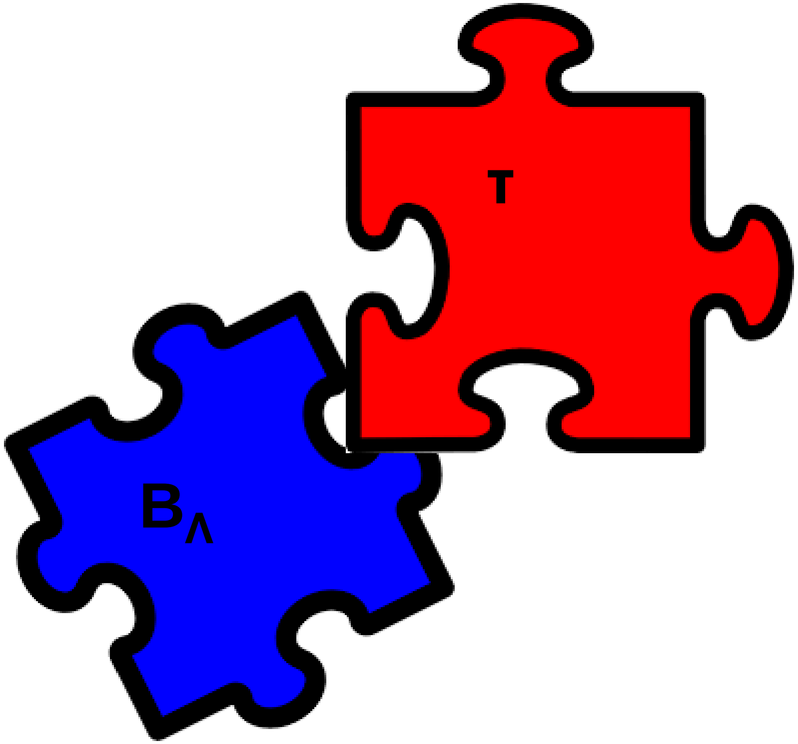
2) by interference of undulator radiation:





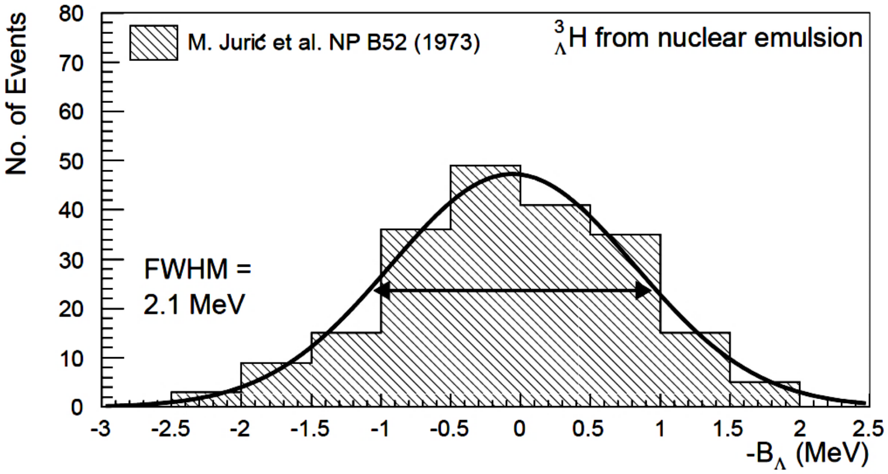
$$\gamma_{beam}^2 = \frac{1}{2}\frac{\lambda_{osc}}{\lambda_{rad}}$$

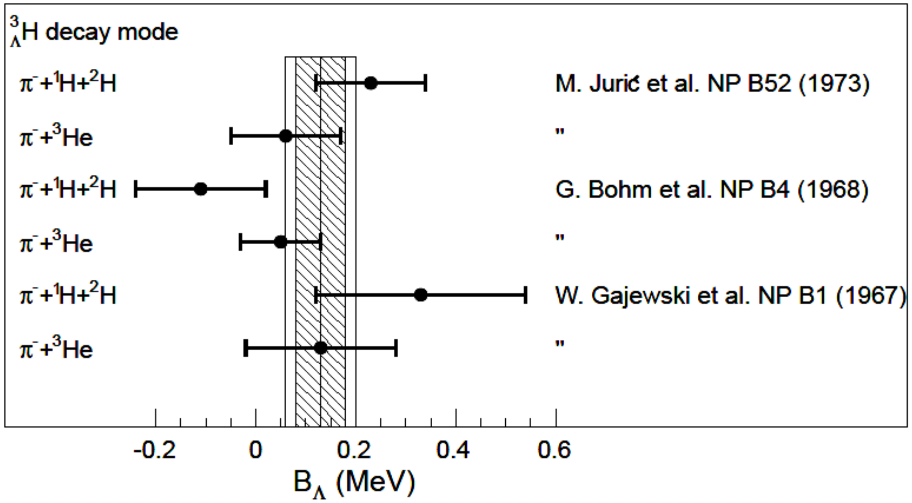
The lightest Λ hypernucleus and the puzzle of lifetime



The quest for $^3_\Lambda$H

only about 200 analyzed events from emulsion:





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

$$\left.\begin{array}{l} ^3_\Lambda\mathrm{H} \overset{\text{decay}}{\longrightarrow} \pi^- + {}^3\mathrm{He}: \quad B = 0.07 \pm 0.06\ \mathrm{MeV} \\ ^3_\Lambda\mathrm{H} \overset{\text{decay}}{\longrightarrow} \pi^- + {}^1\mathrm{H} + {}^2\mathrm{H}: B = 0.12 \pm 0.08\ \mathrm{MeV} \end{array}\right\} \text{0.05 MeV difference}$$

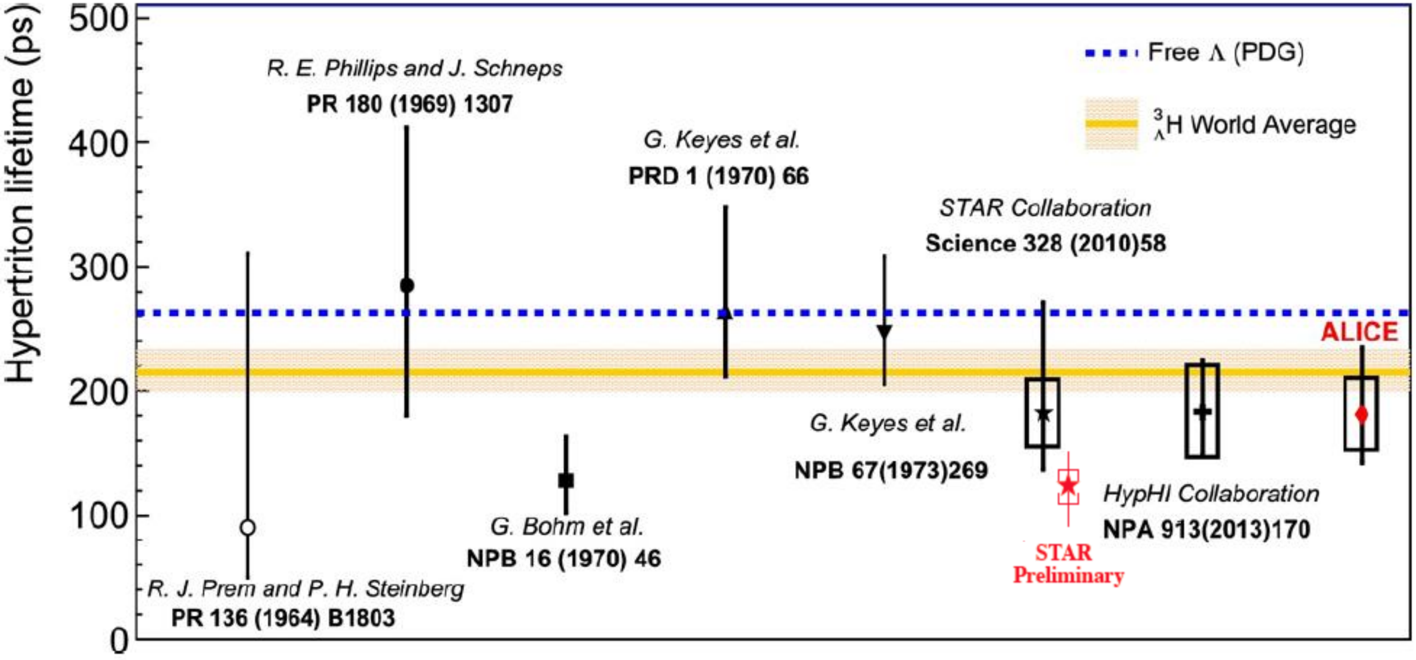
$$\text{Total: } B = 0.13 \pm 0.05\ \mathrm{MeV}$$

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

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

Small Λ binding energy implies extended wave function → hypernucleus lifetime should be comparable to free Λ lifetime

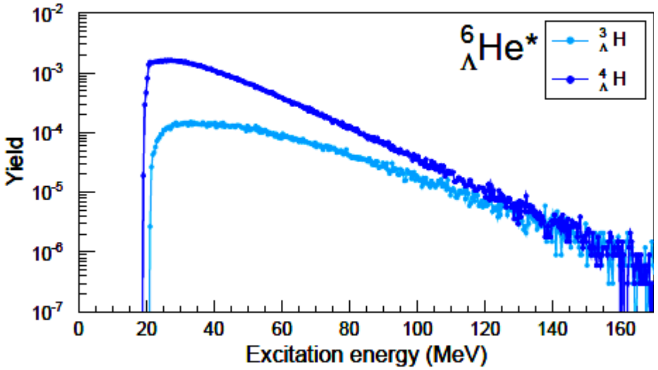
all calculations of lifetime predict no more than 10% deviation

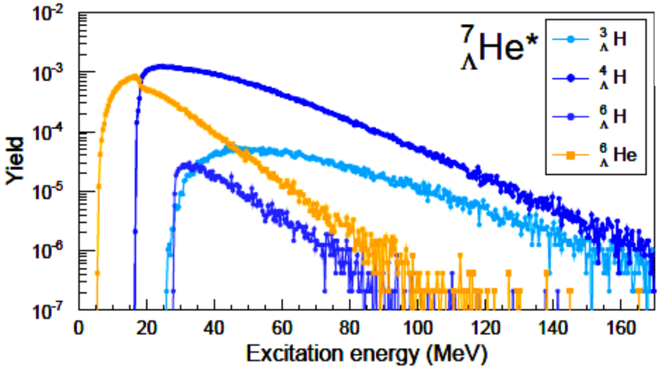


Values from heavy ion experiments are surprisingly small

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

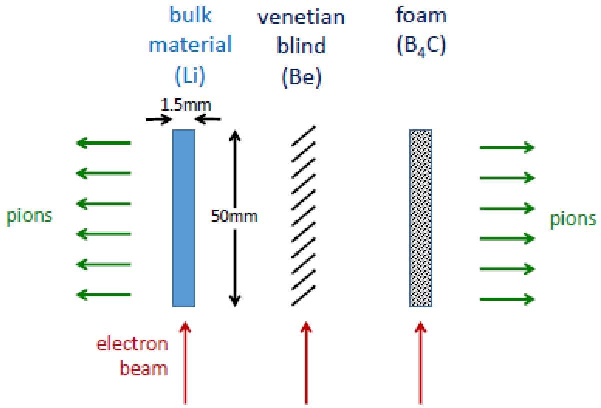
Statistical decay calculations

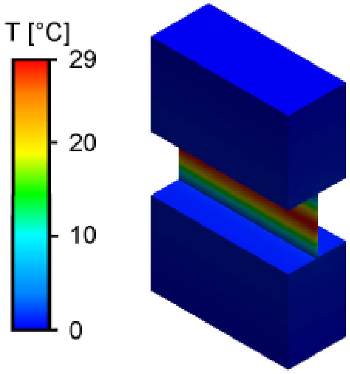




D_C and $P(x)$ in units of 10^{-4}, x in units of mm

	E_x = 20 MeV			E_x = 40 MeV			E_x = 60 MeV		
${}^{6}_{\Lambda}$He*	D_C	$P(0.25)$	$P(1.5)$	D_C	$P(0.25)$	$P(1.5)$	D_C	$P(0.25)$	$P(1.5)$
${}^{3}_{\Lambda}$H	—	—	—	27.	1.4	3.7	17.	1.0	2.1
${}^{4}_{\Lambda}$H	38.	8.1	**17.**	56.	11.	**22.**	20.	3.8	**7.5**
${}^{7}_{\Lambda}$He*	D_C	$P(0.25)$	$P(1.5)$	D_C	$P(0.25)$	$P(1.5)$	D_C	$P(0.25)$	$P(1.5)$
${}^{3}_{\Lambda}$H	—	—	—	9.2	0.4	1.3	8.5	0.5	1.1
${}^{4}_{\Lambda}$H	55.	11.	**23.**	48.	9.3	**18.**	22.	4.1	**8.3**
${}^{6}_{\Lambda}$H	—	—	—	1.3	0.2	0.1	0.3	< 0.1	< 0.1
${}^{6}_{\Lambda}$He	36.	4.8	5.6	6.9	0.9	1.1	1.1	0.1	0.2

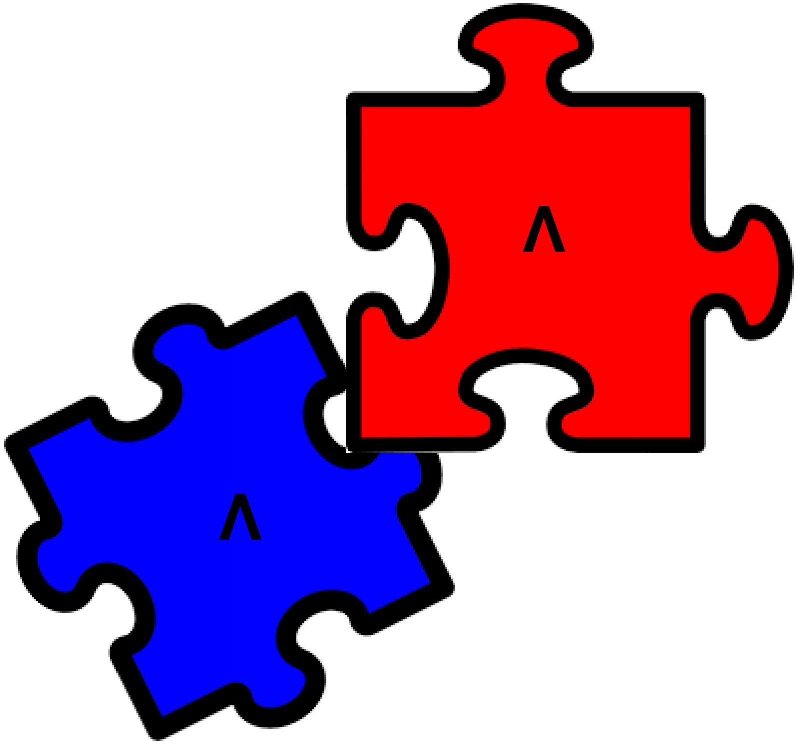




expected excitation energy

- convert proton into Λ ⇒ proton hole state ~ 20 MeV
- kinetic energy of captured Λ: $p_F^2 / 2M_\Lambda$ ~ 20 MeV
- Binding energy of Λ < 10 MeV

Double Λ hypernuclei and the puzzle of ΛΛ interaction

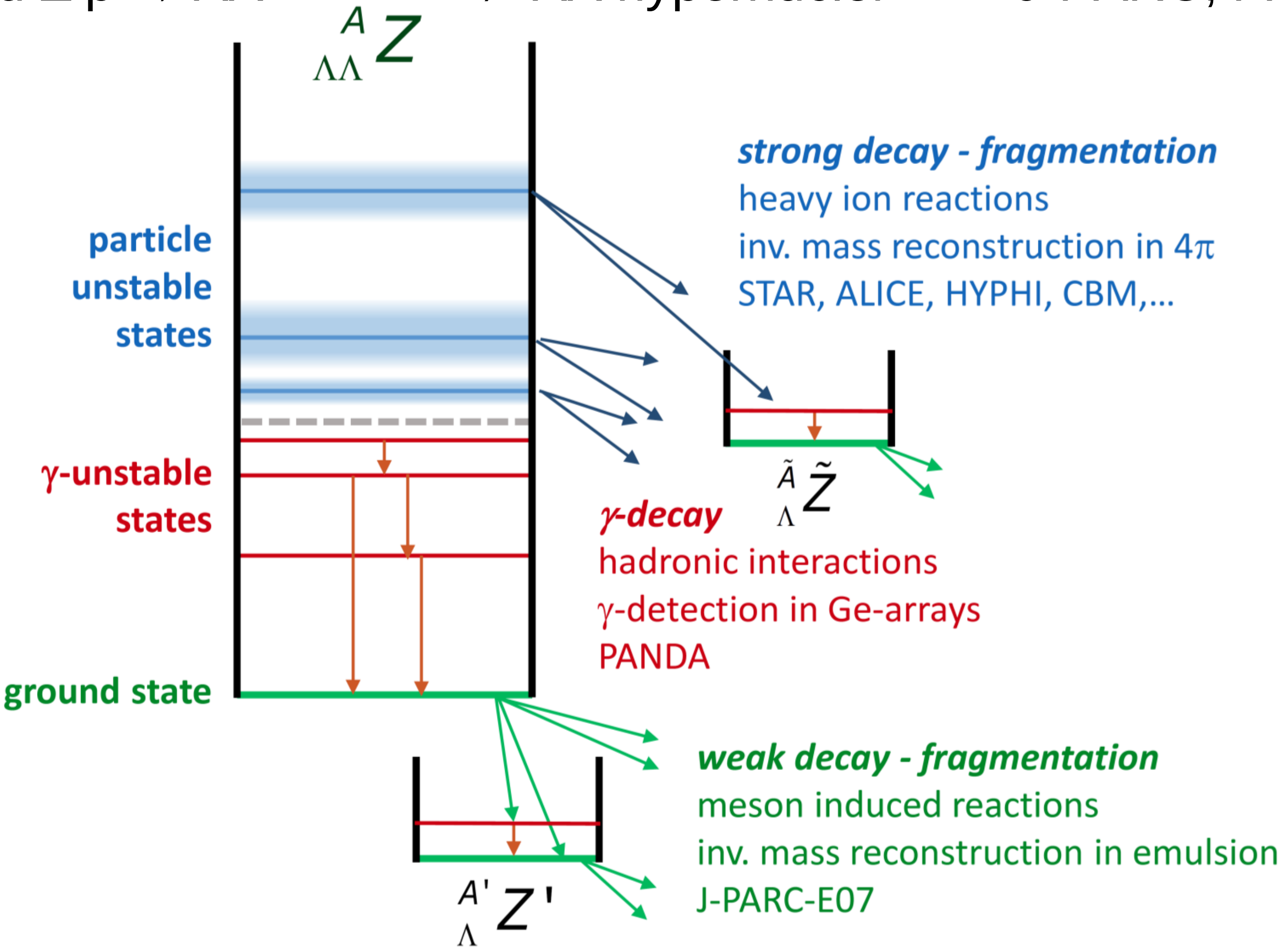


S=-2 systems

missing mass (K^-,K^+) reactions ⇒ Ξ bound state J-PARC

Ξ capture ⇒ Ξ atoms J-PARC, PANDA

Ξ capture and $\Xi^- p \rightarrow \Lambda\Lambda$ ⇒ ΛΛ hypernuclei J-PARC, PANDA, HI



particle unstable states

γ-unstable states

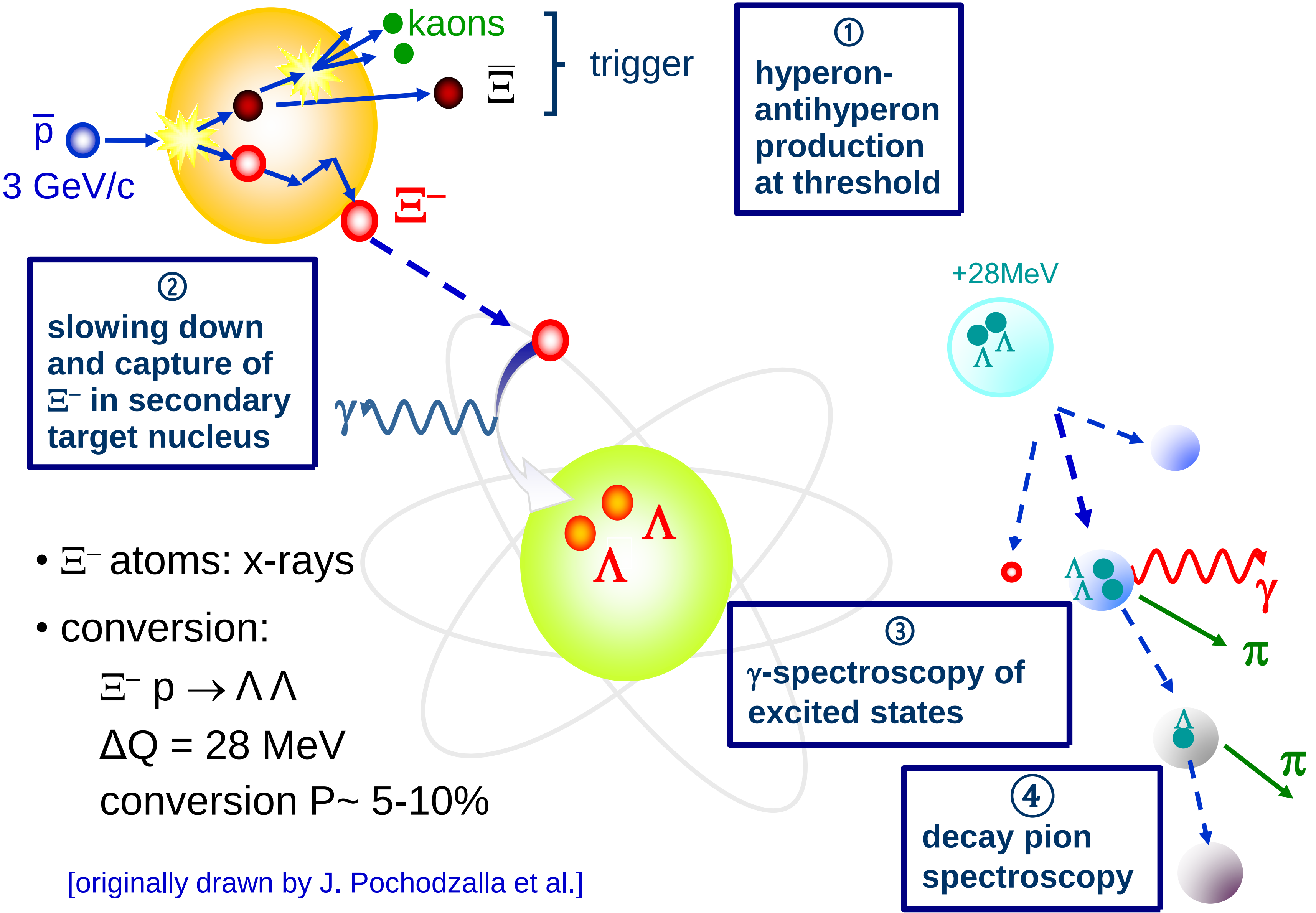
ground state

strong decay - fragmentation
heavy ion reactions
inv. mass reconstruction in 4π
STAR, ALICE, HYPHI, CBM,...

γ-decay
hadronic interactions
γ-detection in Ge-arrays
PANDA

weak decay - fragmentation
meson induced reactions
inv. mass reconstruction in emulsion
J-PARC-E07

Production mechanism and detection strategy at PANDA



① hyperon-antihyperon production at threshold

② slowing down and capture of Ξ^- in secondary target nucleus

③ γ-spectroscopy of excited states

④ decay pion spectroscopy

- Ξ^- atoms: x-rays
- conversion:

  $\Xi^- p \rightarrow \Lambda\Lambda$

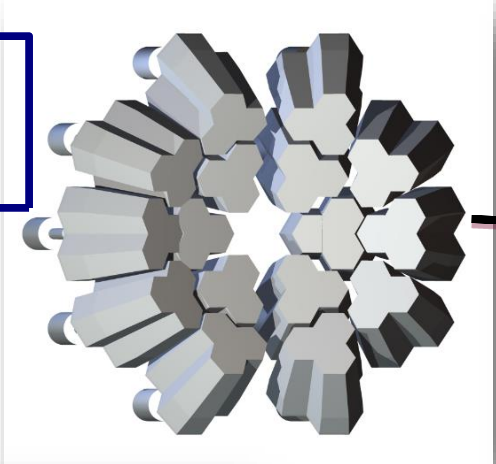
  $\Delta Q = 28$ MeV

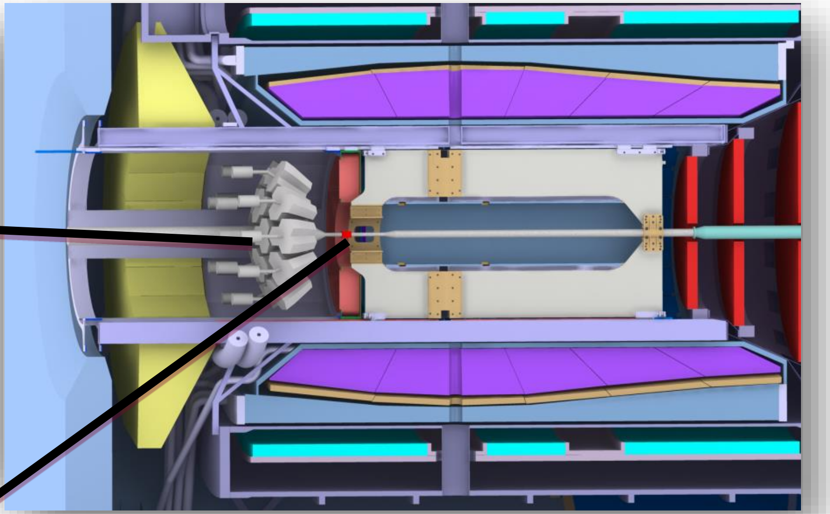
  conversion P~ 5-10%

[originally drawn by J. Pochodzalla et al.]

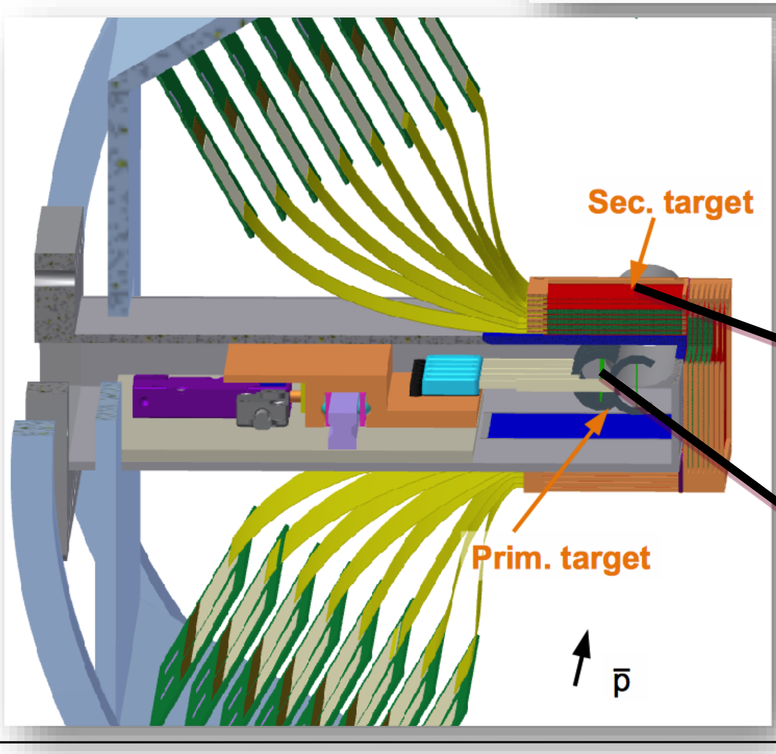
Instrumentation for hypernuclear physics at PANDA

Germanium detector array for hypernuclei spectroscopy



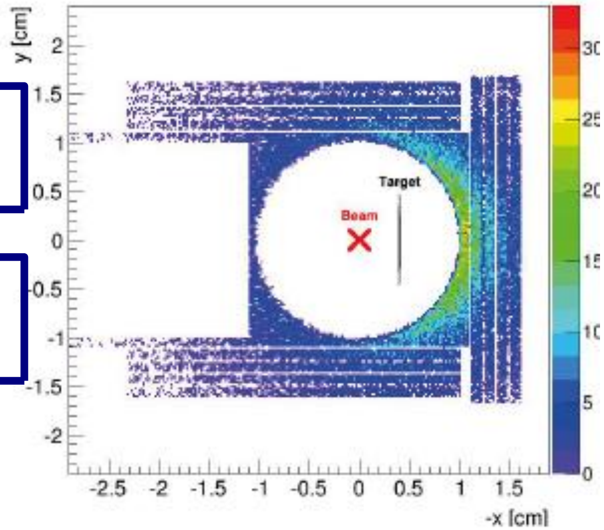


the Panda detector for forward angle particle identification



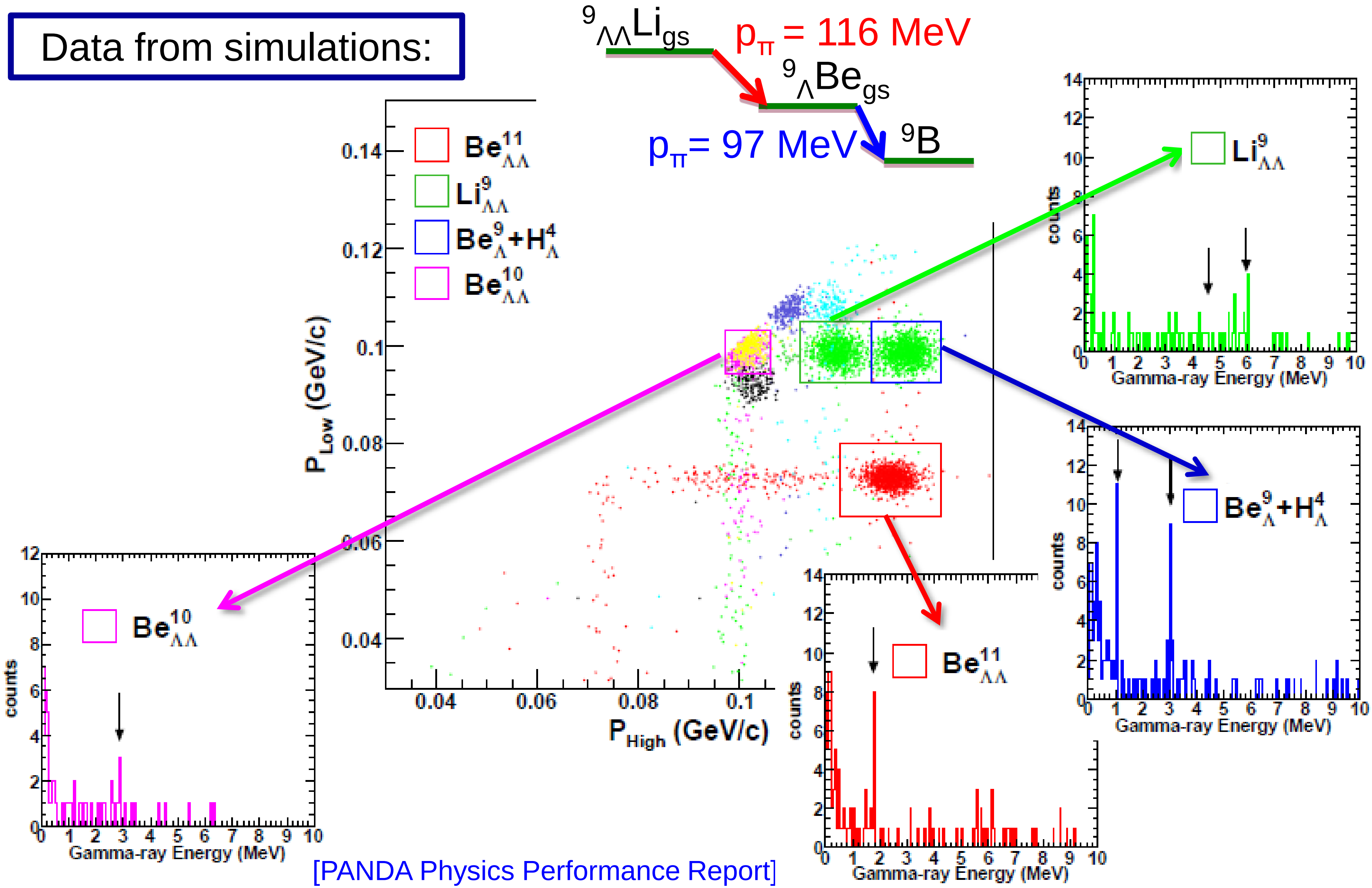
secondary target for hypernuclei formation

primary target for Ξ production



Background suppression by decay pion correlation

Data from simulations:



$^{9}_{\Lambda\Lambda}\mathrm{Li}_{gs}$

$p_\pi = 116$ MeV

$^{9}_{\Lambda}\mathrm{Be}_{gs}$

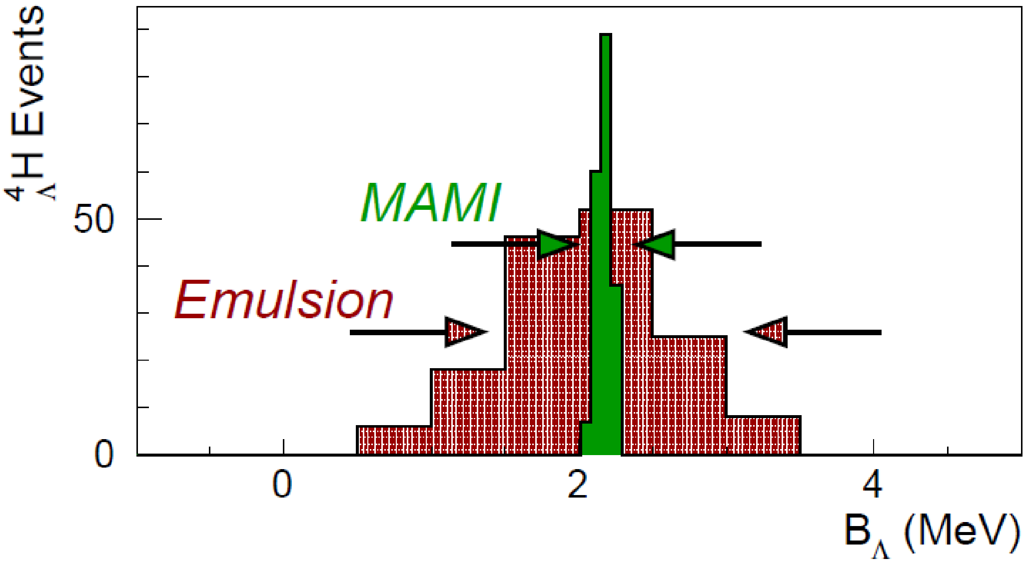
$p_\pi = 97$ MeV

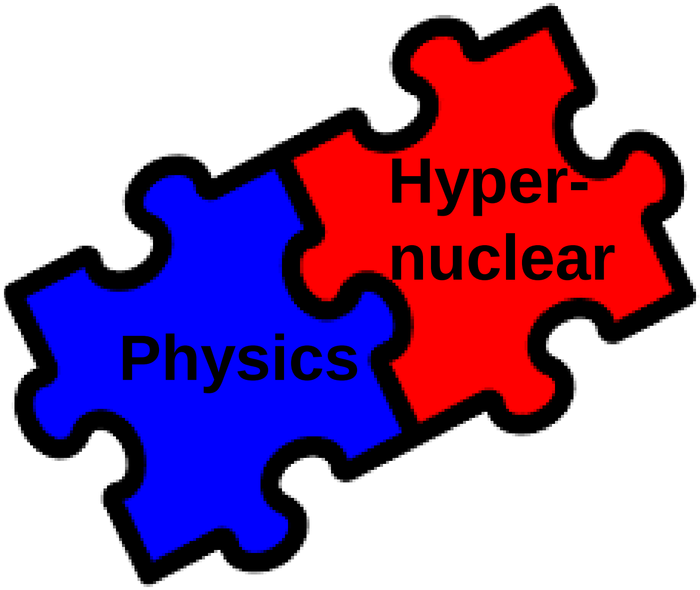
$^{9}\mathrm{B}$

[PANDA Physics Performance Report]

New precision era in hypernuclear physics

1. High-resolution pion spectroscopy has replaced emulsion technique
2. High-purity germanium spectroscopy has replaced NaJ detectors





Hypernuclear physics at MAMI and PANDA is complementary to J-PARC activities