HIRSCHEGG2015 NUCLEAR STRUCTURE AND REACTIONS :
WEAK, STRANGE AND EXOTIC
14TH JANUARY 2015

Study of Lambda hypernuclei with electron beams

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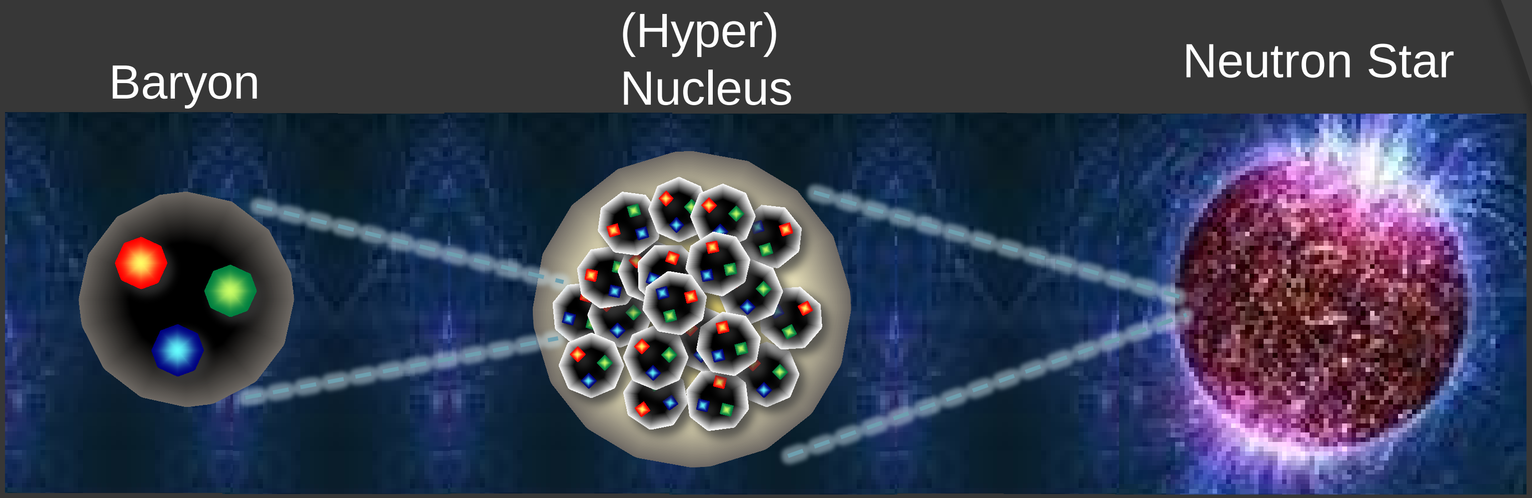
JLab HKS-HES
Mainz A1 hypernuclear
Collaborations

JLab E05-115 collaboration, 2009, JLab Hall-C

Quantum Many-body System bound by the Strong Int.



10^{-15} m 10^{4} m

Pictures from H.Ohnishi

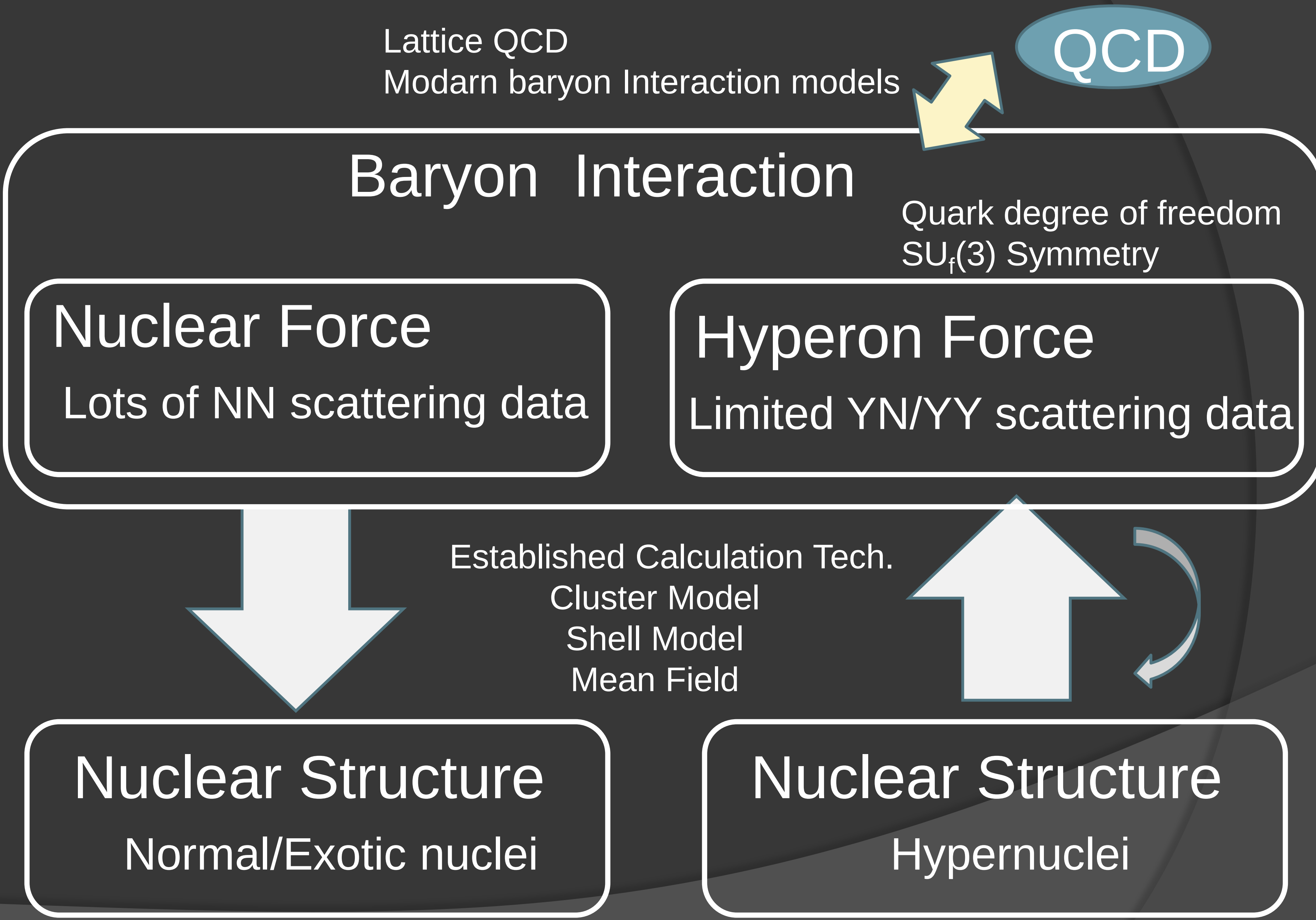
Spectroscopy of Hypernuclei

NN scat.

Obs. 2 $M_\odot$
Hyperon Puzzle

LQCD

Baryon Interaction

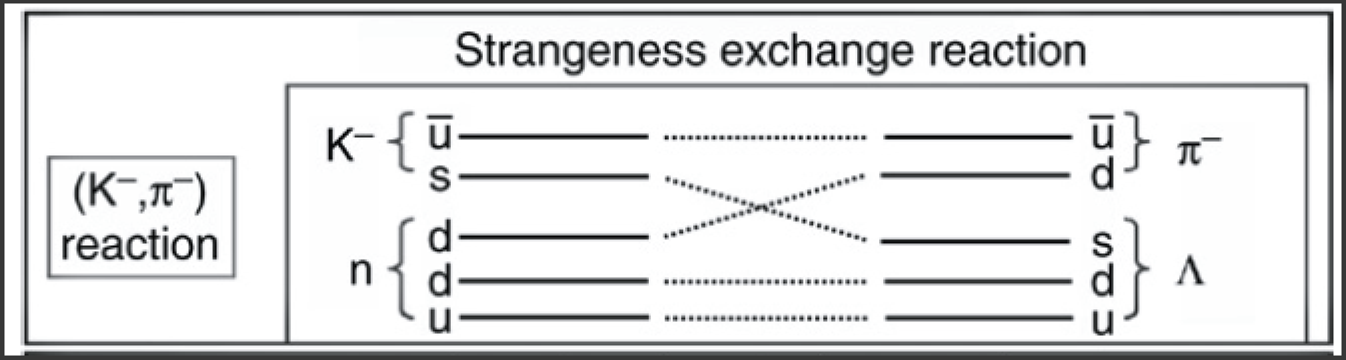

Lattice QCD
Modarn baryon Interaction models
QCD
Baryon Interaction
Quark degree of freedom
$SU_f(3)$ Symmetry
Nuclear Force
Lots of NN scattering data
Hyperon Force
Limited YN/YY scattering data
Established Calculation Tech.
Cluster Model
Shell Model
Mean Field
Nuclear Structure
Normal/Exotic nuclei
Nuclear Structure
Hypernuclei

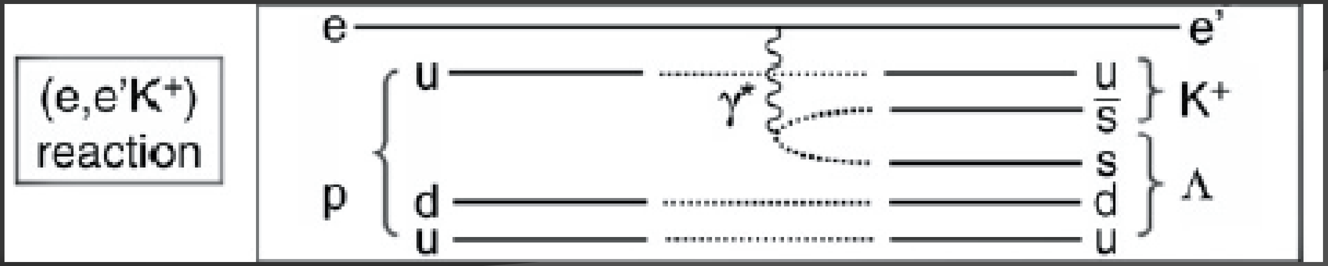
Production of Hypernuclei

s-quark exchange
s,sbar pair creation

(K^-,π^-)

(π^+,K^+), ($e,e'K^+$)





Characteristics of (e,e'K) HY study

- Electromagnetic production
- Convert Proton to Lambda :

  Mirror to well studied HY by (π,K), (K, π)

  Absolute energy calibration

  with **$p(e,e'K^+)\Lambda, \Sigma^0$**

- High quality primary beam

  High energy resolution (< 1MeV)

  Thin enriched target

Challenge of (e,e'K) HY Study

- Huge e' Background due to
  Bremsstrahlung and Mϕller scattering
  Signal/Noise, Detector

- Less Hypernuclear Cross Section
- Coincidence Measurement (e', K^+)
  Limited Statistics
  DC beam is necessary

High Quality Electron Beam is Essential !

Three generation experiments at Hall-C

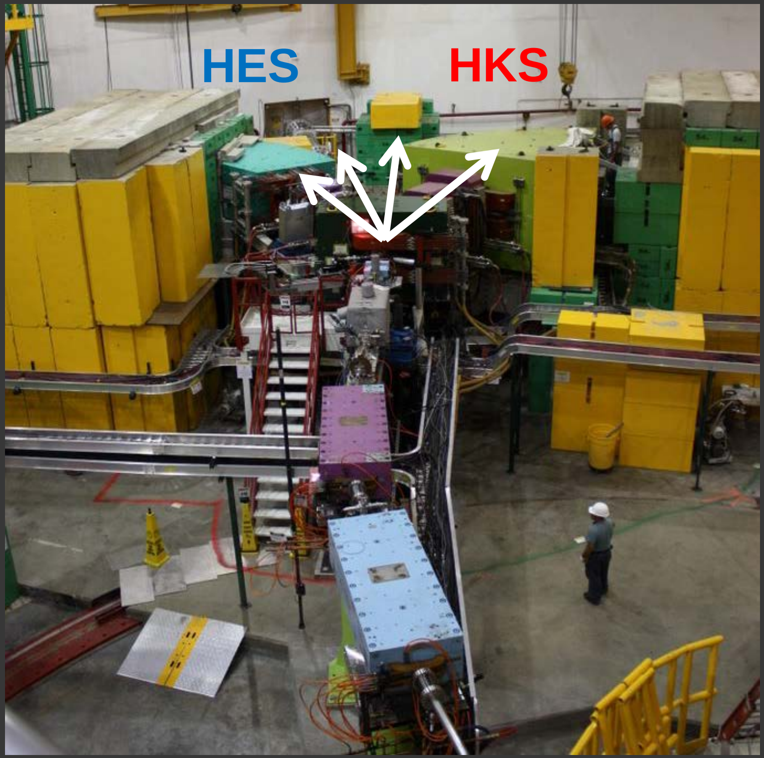
E89-009 (2000) : Existing spectrometers,

SOS + Enge **Proof of Principle**

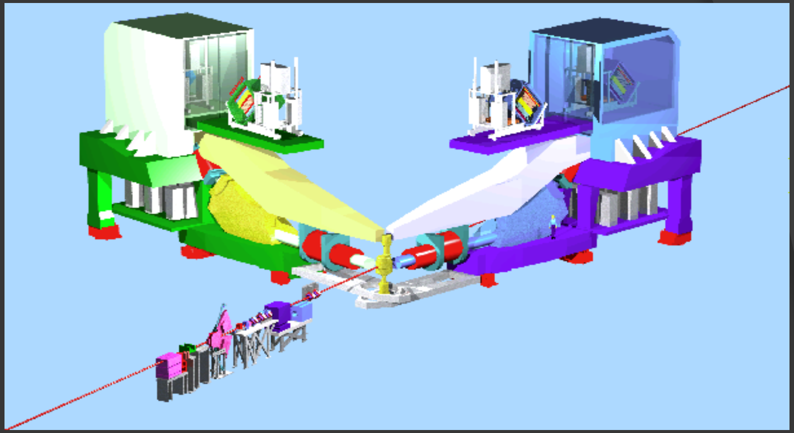
E01-011 (2005) : Construction of HKS,
Tilt Method
Λ, Σ^0, ${}^{7}_{\Lambda}$He, ${}^{12}_{\Lambda}$B, ${}^{28}_{\Lambda}$Al
Light Hypernuclei

E05-115 (2009) : HKS+HES,
new Beamline, Splitter
Λ, Σ^0, ${}^{7}_{\Lambda}$He , ${}^{12}_{\Lambda}$B, ${}^{52}_{\Lambda}$V
Light to medium-heavy Hypernuclei

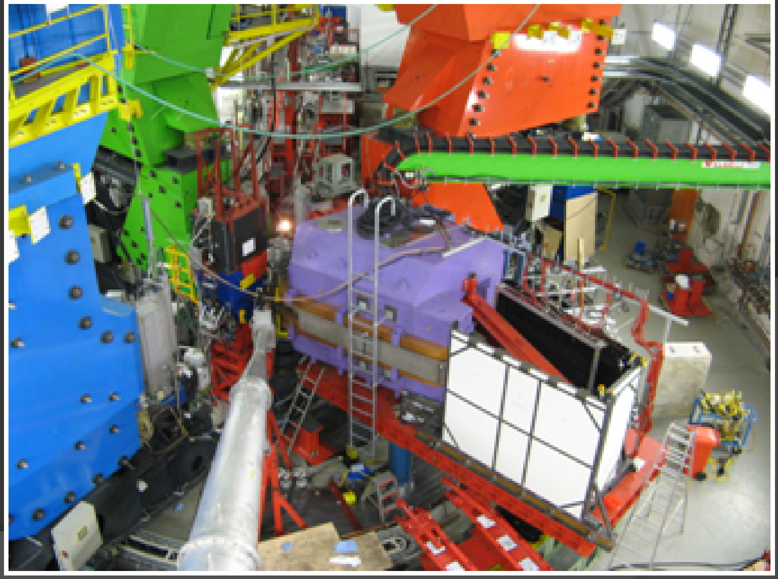
Facilities for (e,e'K$^+$) HY study



JLab Hall-C
HNSS (2000)
HKS (2005)
HKS+HES (2009)

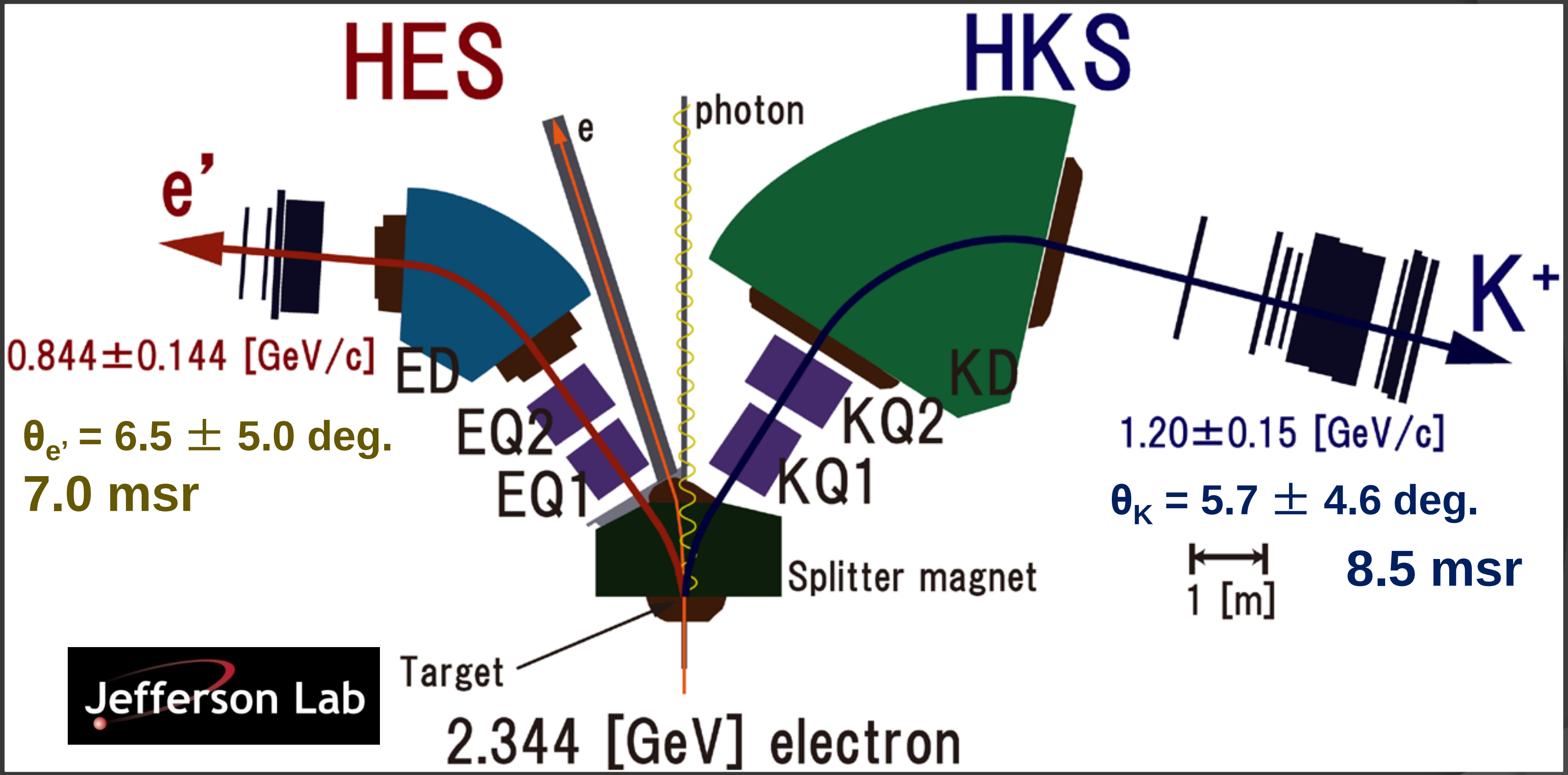


JLab Hall-A HRS+HRS (2004)



Mainz MAMI-C A1 KaoS (2008-)

JLab E05-115 (Hall-C) setup



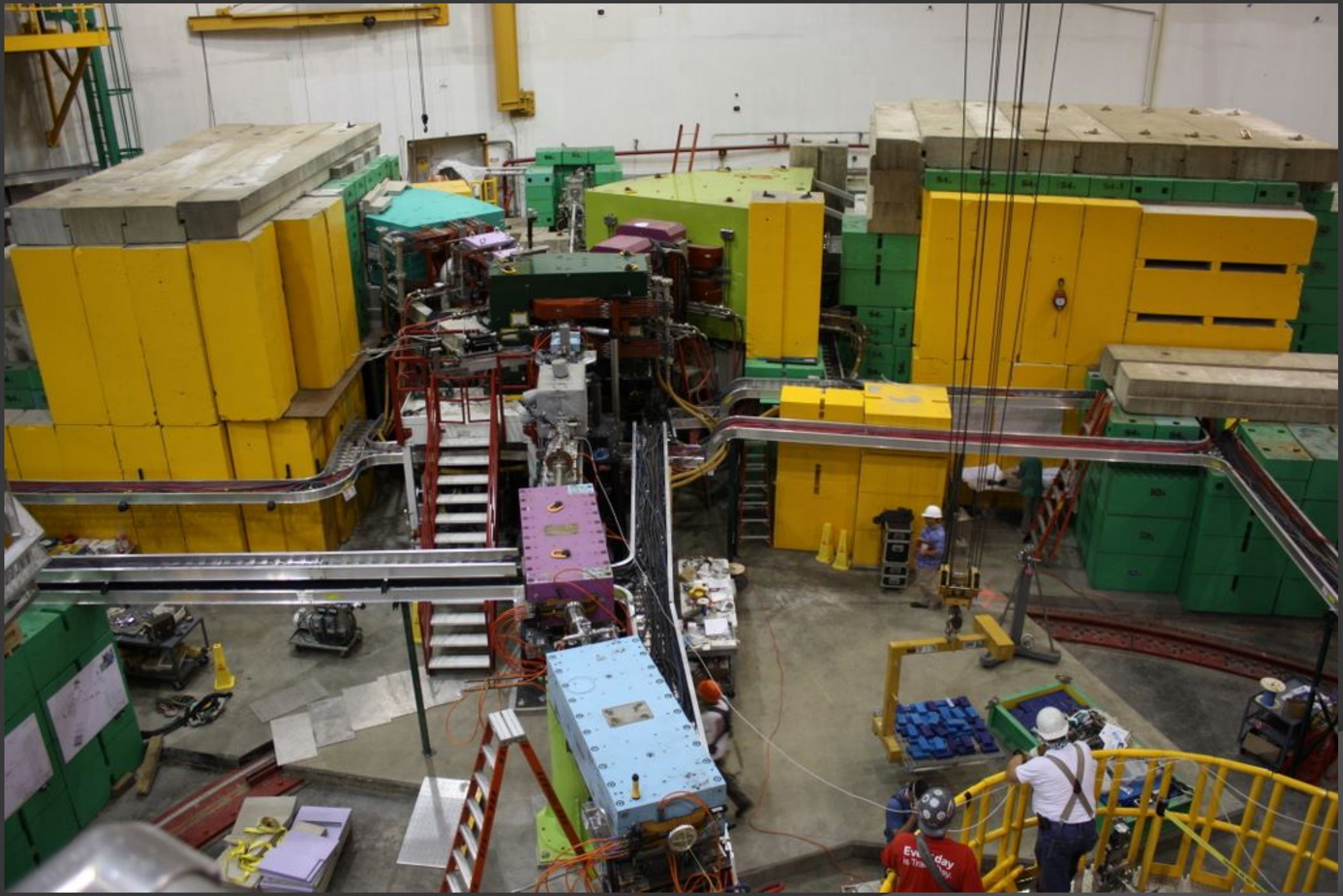
$\Delta p/p \sim 2 \times 10^{-4}$

$P_K, P_e' : measure$

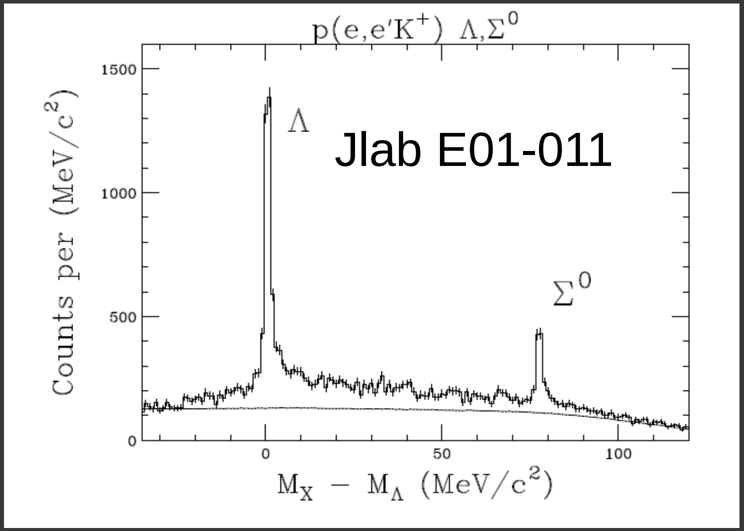
$E_e, m_A : known$

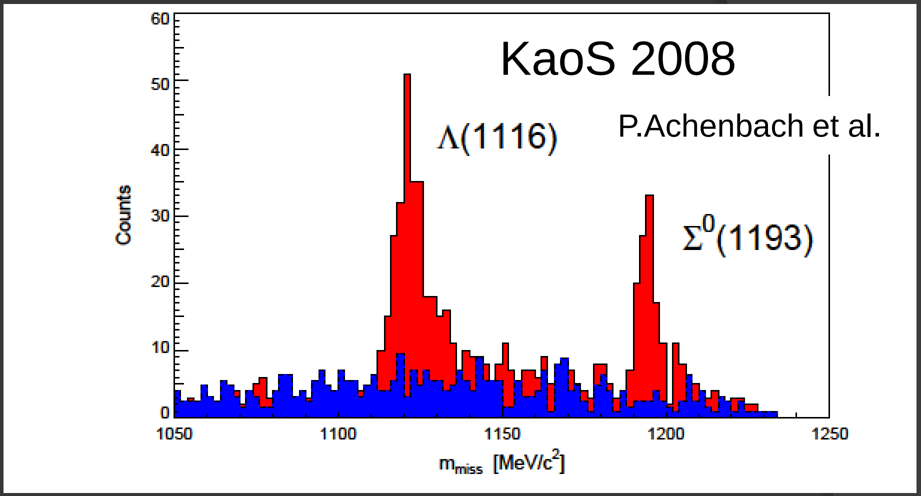
$m_{HY} : deduced\ as\ Missing\ Mass$

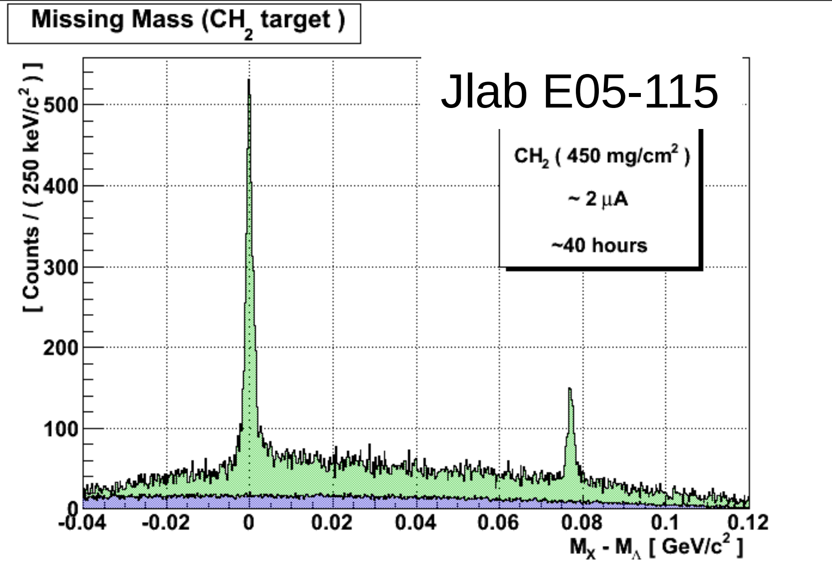
JLab E05-115 (Hall-C) setup

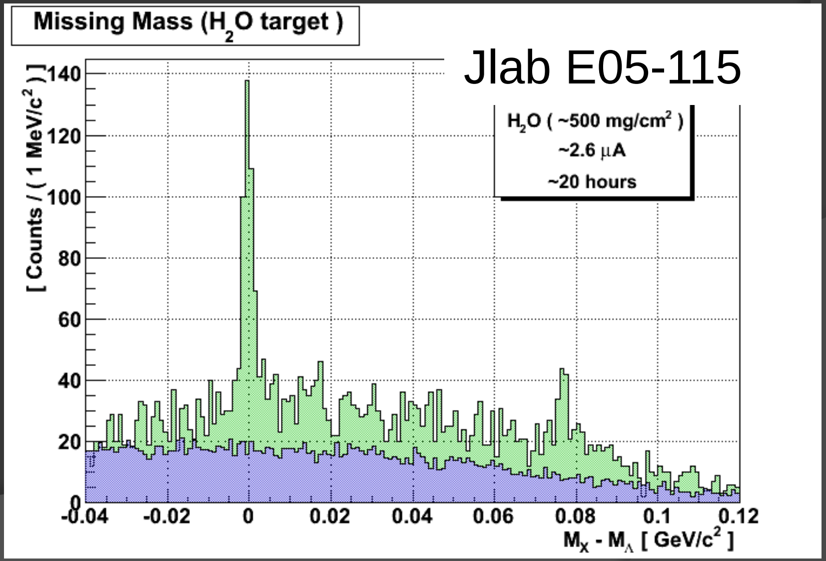


p(e,e'K$^+$)Λ, Σ^0: Elementary Process









$^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$

0.54 MeV (FWHM)

Absolute MM calibration

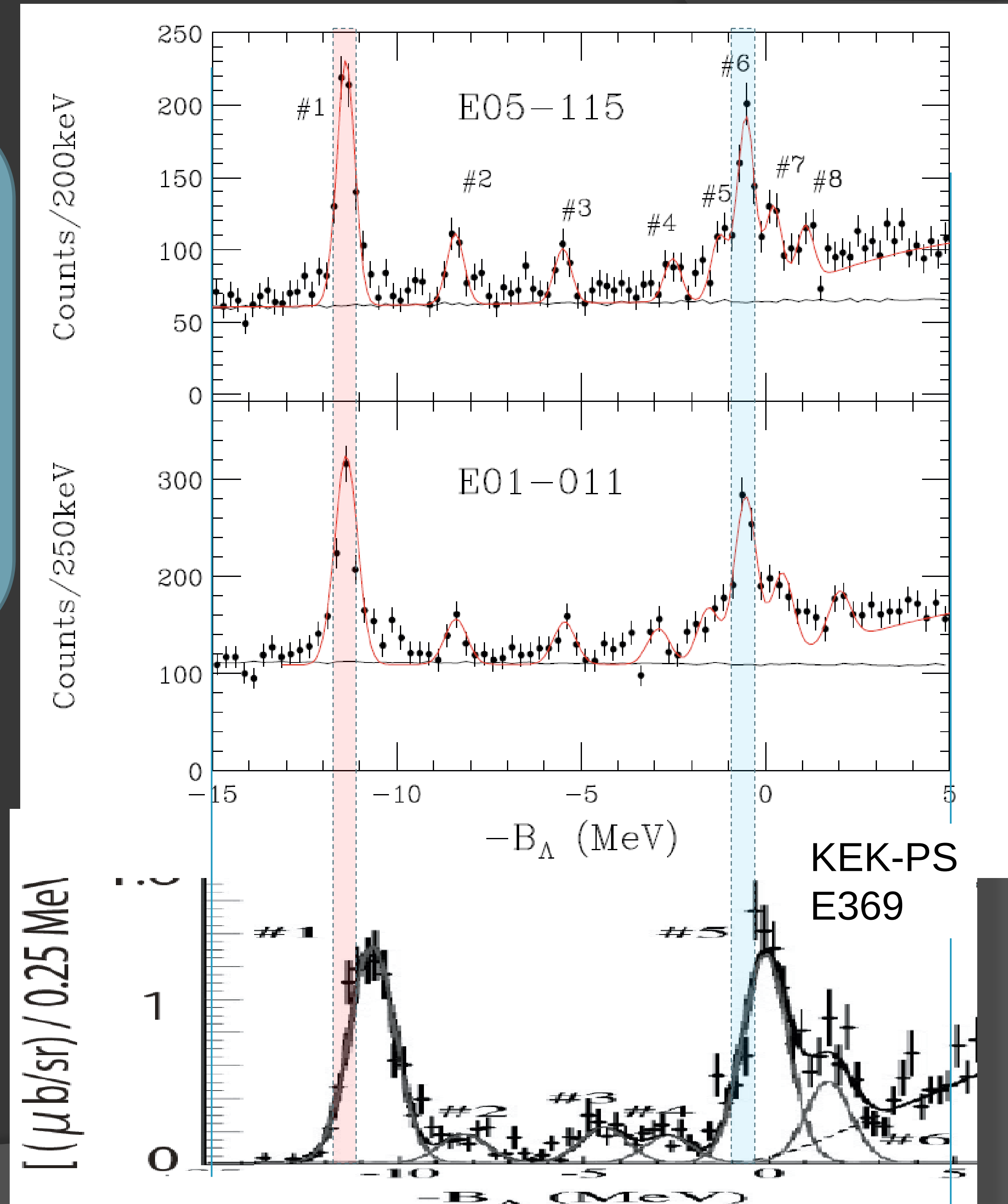
0.71 MeV (FWHM)

L.Tang, C.Chen, T.Gogami *et al.* Phys. Rev. C **90** (2014) 034320.

$^{12}C(\pi^+,K^+)^{12}{}_{\Lambda}C$

1.45 MeV (FWHM)

$^{12}{}_{\Lambda}C_{gs}$ energy from emulsion



$^{12}{}_{\Lambda}C$ emulsion data

Nuclear Physics A484 (1988) 520–524

TABLE 1 [a])

Decay mode	Range of the hypernucleus (μm)	B_{Λ} (as $^{12}_{\Lambda}C$) (MeV)	Ref.
1. $^{12}_{\Lambda}C \to \pi^- + {}^{12}N(g.s.)$	—	11.14 ± 0.57	[4]
2. $^{12}_{\Lambda}C \to \pi^- + p + {}^4He + {}^7Be$	3.0 ± 0.8	10.45 ± 0.33	[3]
3. $^{12}_{\Lambda}C \to \pi^- + p + {}^{11}C$	4.3 ± 0.7	10.50 ± 0.47	[3]
4.	3.5 ± 0.4	10.65 ± 0.33	[1,2]
5.	3.5 ± 0.5	10.85 ± 0.44	[1,2]
6.	3.4 ± 0.5	11.59 ± 0.45	[1,2]
7.	3.2 ± 0.4	15.67 ± 0.50	[1,2]

^{11}C (3/2-) : Ex = 4.8MeV

situation is not the case for π^- mesonic decay modes of $^{12}_{\Lambda}C$: ($\pi^{-12}N$), ($\pi^- p^{11}C$), ($\pi^- p^3He^4He^4He$) and ($\pi^- p^4He^7Be$). Every one of these decay topologies is easily confused with those of other hypernuclei.

The value obtained for B_{Λ} of $^{12}_{\Lambda}C$, (10.80 ± 0.18) MeV

Statistical errors quoted, systematic errors (~0.04 MeV) reduced by measuring M_{Λ} in same emulsion stack.

Nuclear Physics A547 (1992) 369

$^{12}_{\Lambda}C$	**10.76 ± 0.19**

Statistical error only

Reference for all (π, K) B_{Λ} data:

B_{Λ} ($^{12}{}_{\Lambda}C$g.s.) = 10.76 +-0.19MeV

$^{12}_{\Lambda}B$ emulsion data

Nuclear Physics B52 (1973) 1–30.

A NEW DETERMINATION OF THE BINDING-ENERGY VALUES OF THE LIGHT HYPERNUCLEI ($A \leqslant 15$)

		(# of events)	
$^{12}_{\Lambda}B$	$\pi^- + {}^4He + {}^4He + {}^4He$	61	11.45 ± 0.07

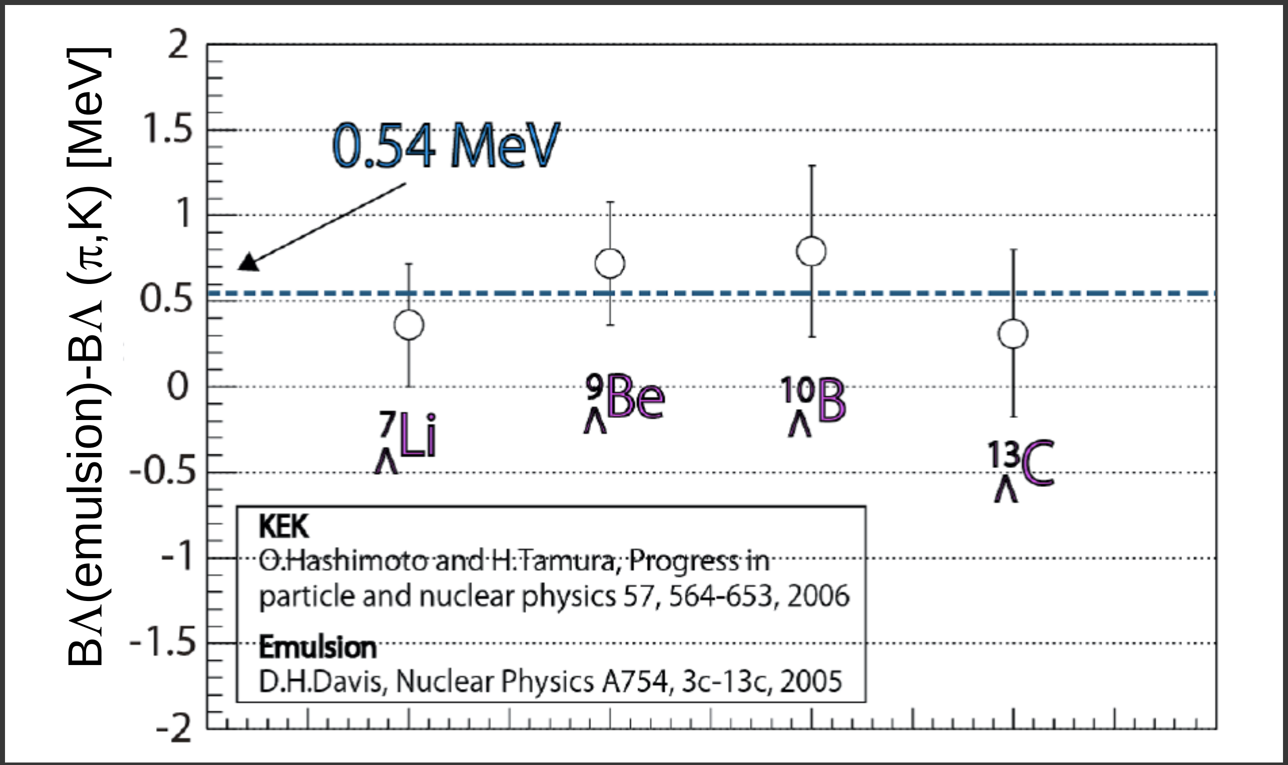
B_{Λ} ($^{12}_{\Lambda}B$g.s.) = 11.45 +-0.07 MeV Emulsion Result (M.Juric et al.)

B_{Λ} ($^{12}_{\Lambda}B$g.s.) = 11.38 +- 0.02 (stat) MeV (JLab E05-115)

Totally independent measurement

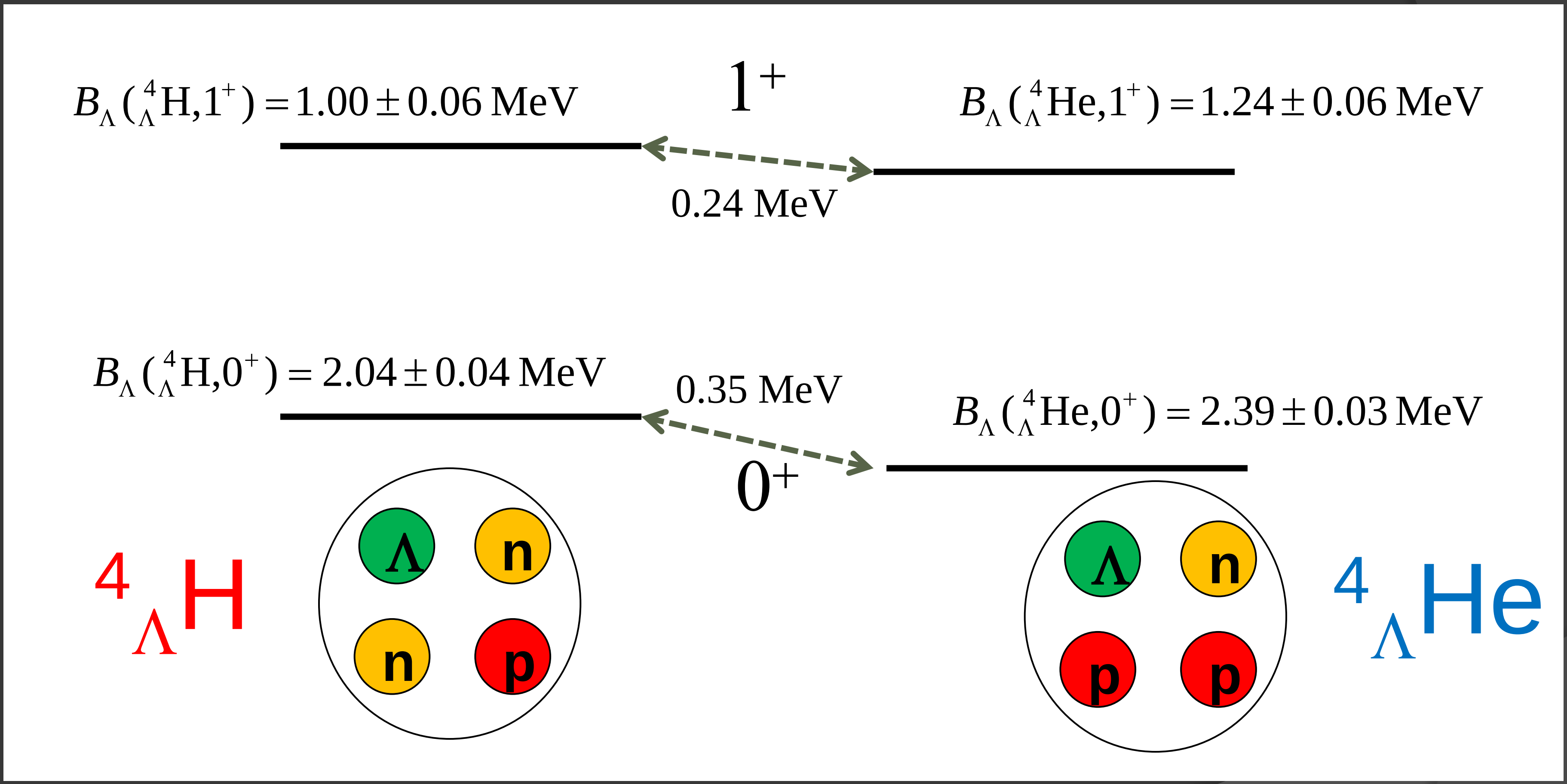
Possible shift of $^{12}_{\Lambda}C_{gs}$ B_{Λ}

$^{12}_{\Lambda}C - ^{12}_{\Lambda}B$	-0.57 ± 0.19 $-0.62 \pm 0.19 \pm 0.11$	$^{12}_{\Lambda}C$: 6 events, $^{12}_{\Lambda}B$: 87 events present data for $^{12}_{\Lambda}B$



T. Gogami, Doctor thesis, (2014) Tohoku U.

Charge Symmetry Breaking Effect of ΛN interaction



Coulomb effect is small.

$$-\Delta B_c = 0.050 \pm 0.02 \text{ MeV},$$

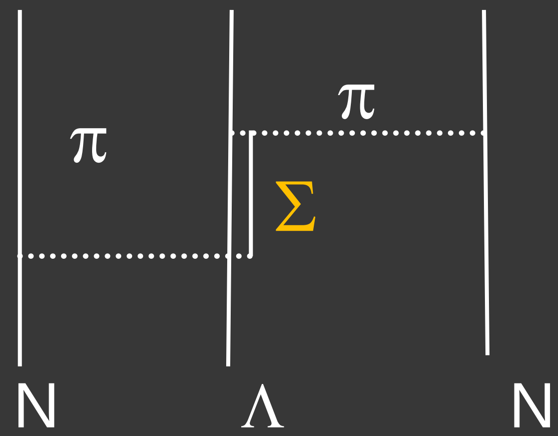
$$-\Delta B_c^* = 0.025 \pm 0.015 \text{ MeV}$$

Charge Symmetry Breaking

cf) B(^{3}H)-B(^{3}He)-ΔB_c = 764-693 = 71 keV

Three-body ΛNN force

Modern ChPT-NLO calculation predicts 3NF effect is < 100keV but
NLO calculation cannot explain experimental results for A=4, T=1/2, hypernuclei.
(Nogga, HYP2012)



ΛΣ mass difference ~ 80 MeV < NΔ mass difference ~ 300MeV

$M(\Sigma^+) < M(\Sigma^0) < M(\Sigma^-)$, $\Delta M(\Sigma^- - \Sigma^+)$~8MeV

Consistent ~~understanding of 0^+, 1^+ of ${}^4_\Lambda$H, ${}^4_\Lambda$He~~

Phenomenological potential :

A.R.Bodmer&Q.N.Usmani, PRC 31(1985)1400.

$$V^{CSB} = -\tau_3 T_\pi^2 \tfrac{1}{8}[(0.568\Delta B_\Lambda + 0.756\Delta B_\Lambda^*) + (0.568\Delta B_\Lambda - 0.756\Delta B_\Lambda^*)\sigma_\Lambda \cdot \sigma_N]$$

B_Λ of light hypermultiplets

$^{4}_{\Lambda}$H

$B_\Lambda(^{4}_{\Lambda}\mathrm{H}) = 2.04 \pm 0.04\ \mathrm{MeV}$

67 events

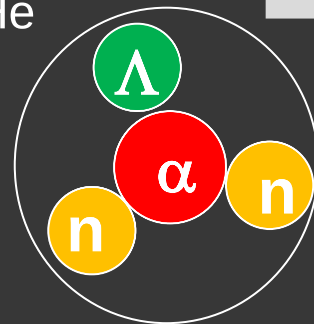
$^{4}_{\Lambda}$He

$B_\Lambda(^{4}_{\Lambda}\mathrm{He}) = 2.39 \pm 0.03\ \mathrm{MeV}$

98 events

$^{7}_{\Lambda}$He

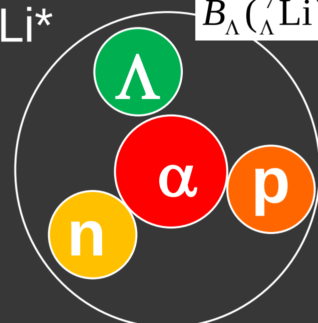
No reported B_Λ



$^{7}_{\Lambda}$Li*

$B_\Lambda(^{7}_{\Lambda}\mathrm{Li}^*) = 5.26 \pm 0.03\ \mathrm{MeV}$

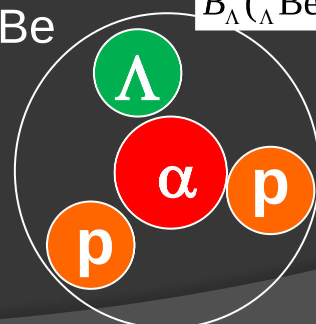
167 events



$^{7}_{\Lambda}$Be

$B_\Lambda(^{7}_{\Lambda}\mathrm{Be}) = 5.16 \pm 0.08\ \mathrm{MeV}$

15 events



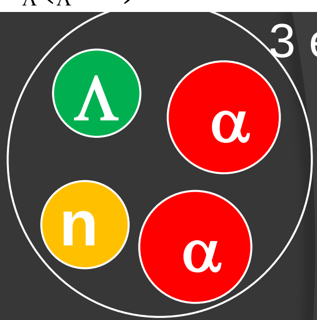
Exp. Data : Emulsion

Nuclear Physics B52 (1973) 1–30.

$^{10}_{\Lambda}$Be

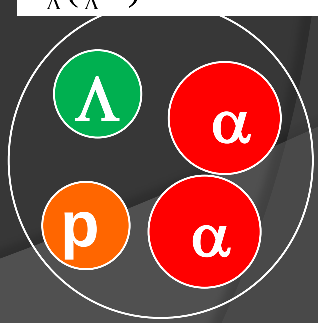
$B_\Lambda(^{7}_{\Lambda}\mathrm{Li}^*) = 9.11 \pm 0.22\ \mathrm{MeV}$

3 event



$^{10}_{\Lambda}$B

$B_\Lambda(^{10}_{\Lambda}\mathrm{B}) = 8.89 \pm 0.12\ \mathrm{MeV}$

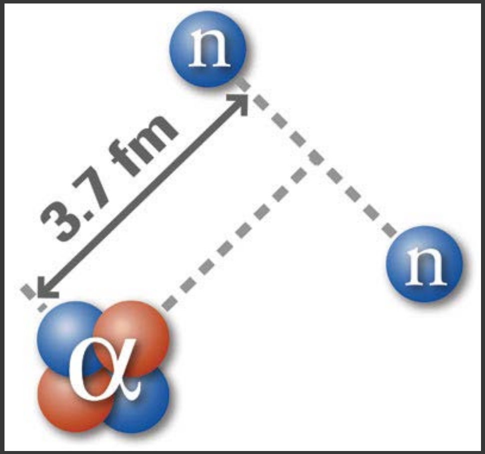


10 events

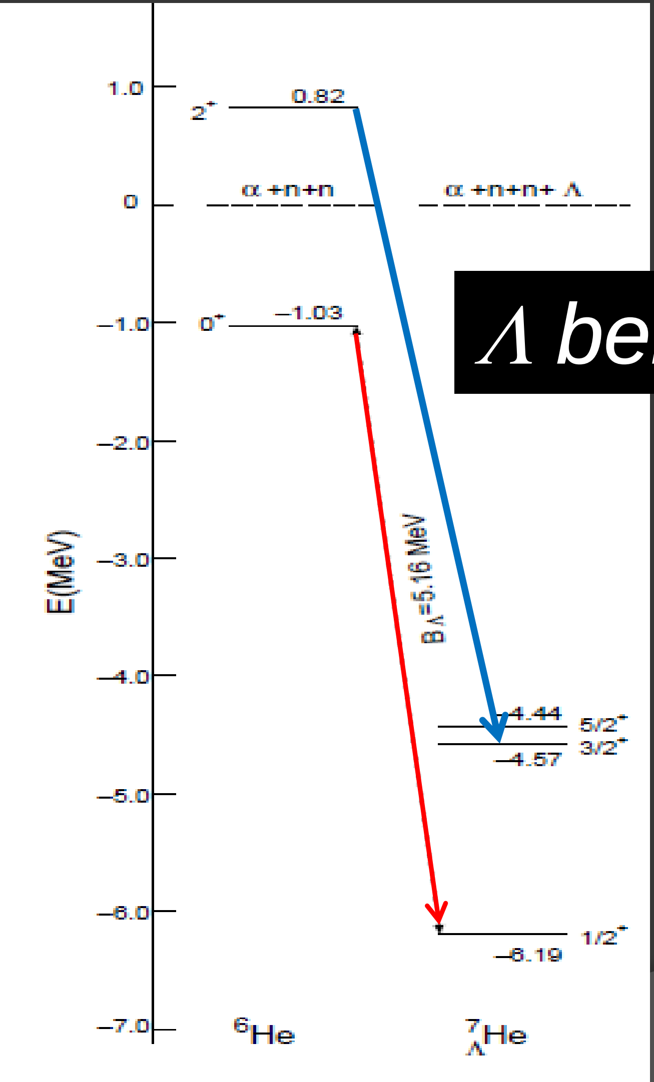
Experimental B_Λ ➡ Δ_{CSB}

Hiyama *et al.* *PRC 80.054321*
PTP 128 (2012) 105..

$^{7}_{\Lambda}He = {}^{6}He + \Lambda$



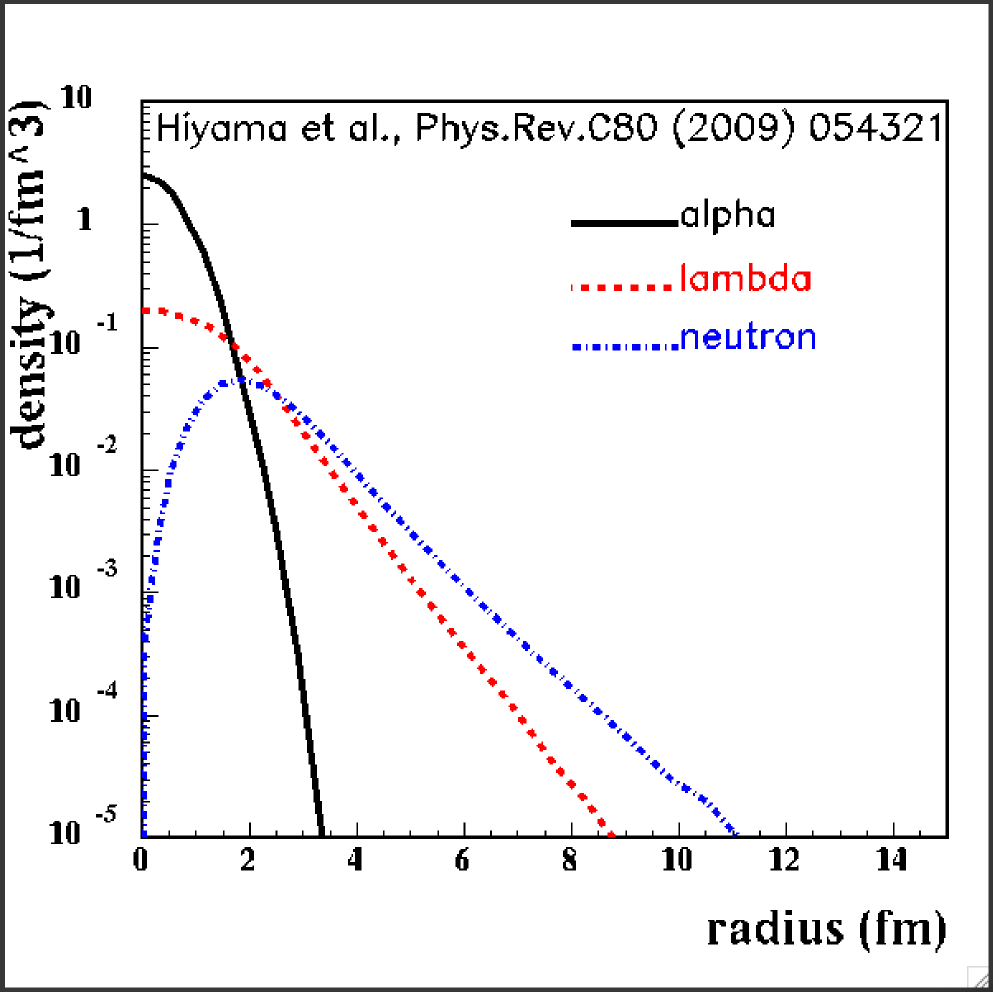
^{6}He : 2n halo

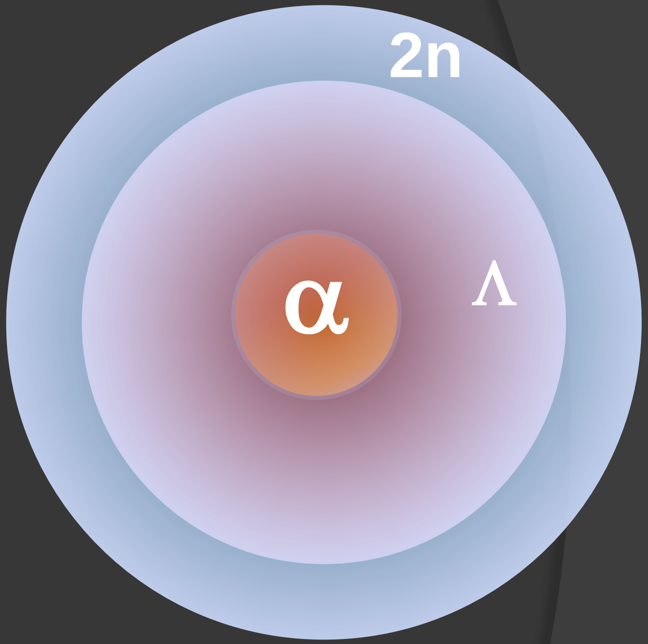


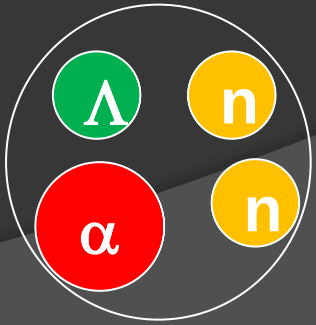
Λ behaves like glue

E.Hiyama et al. PRC 80, 054321 (2009)

$^{7}{}_{\Lambda}$He Density Distributions

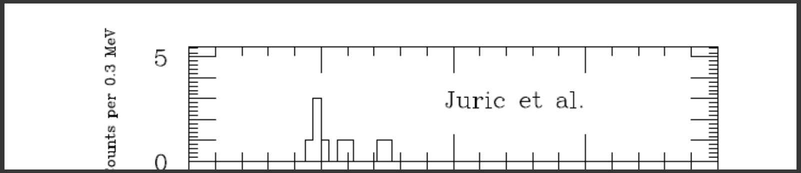




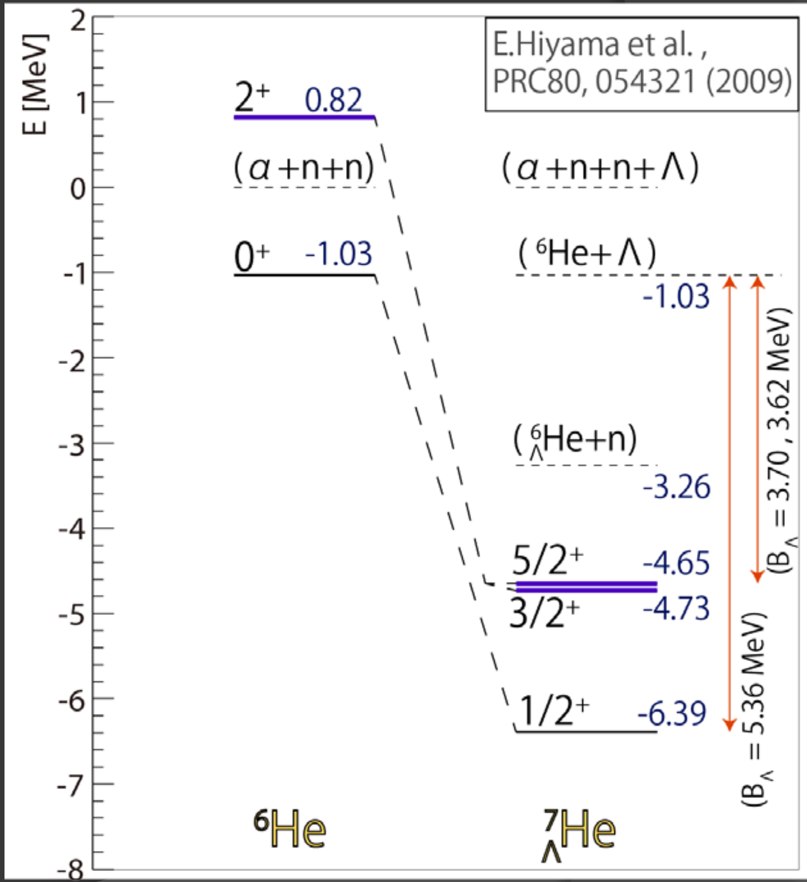


$^{7}_{\Lambda}$He spectrum

Juric et al., Nucl. Phys. A484 (1988) 520

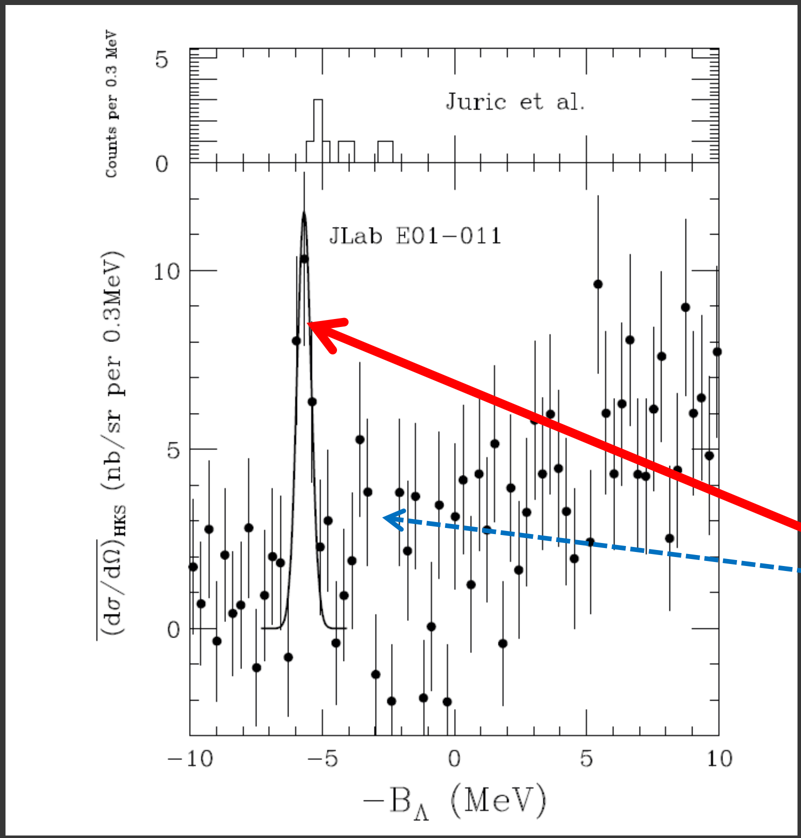


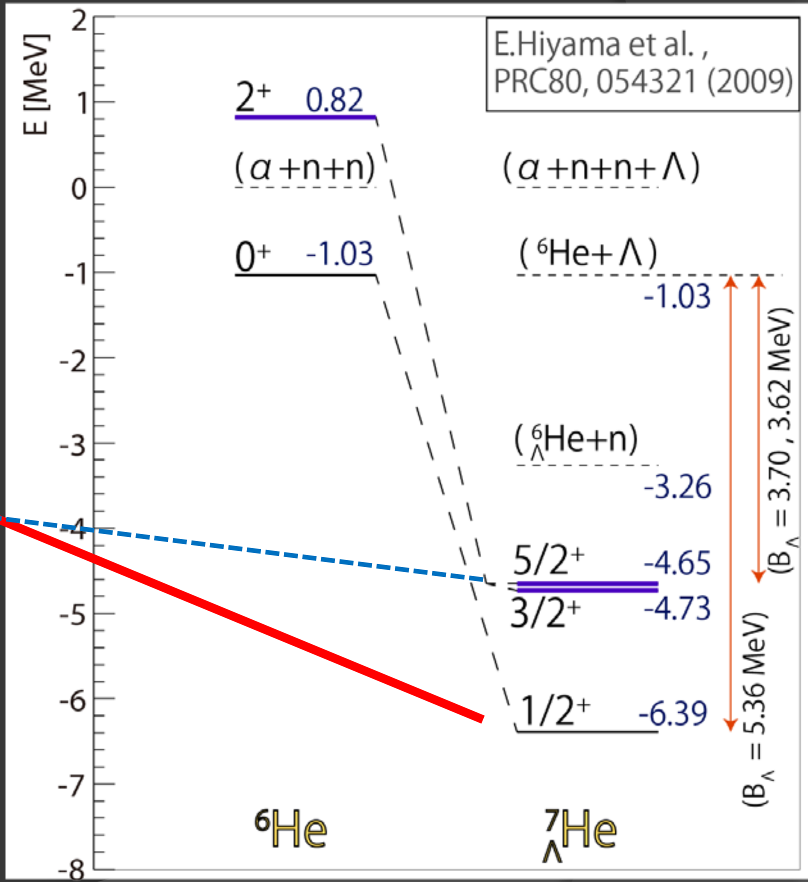
No B_{Λ} was obtained.



$^{7}_{\Lambda}$He spectrum of E01-01

SNN et al., PRL 110, 012502 (2013)

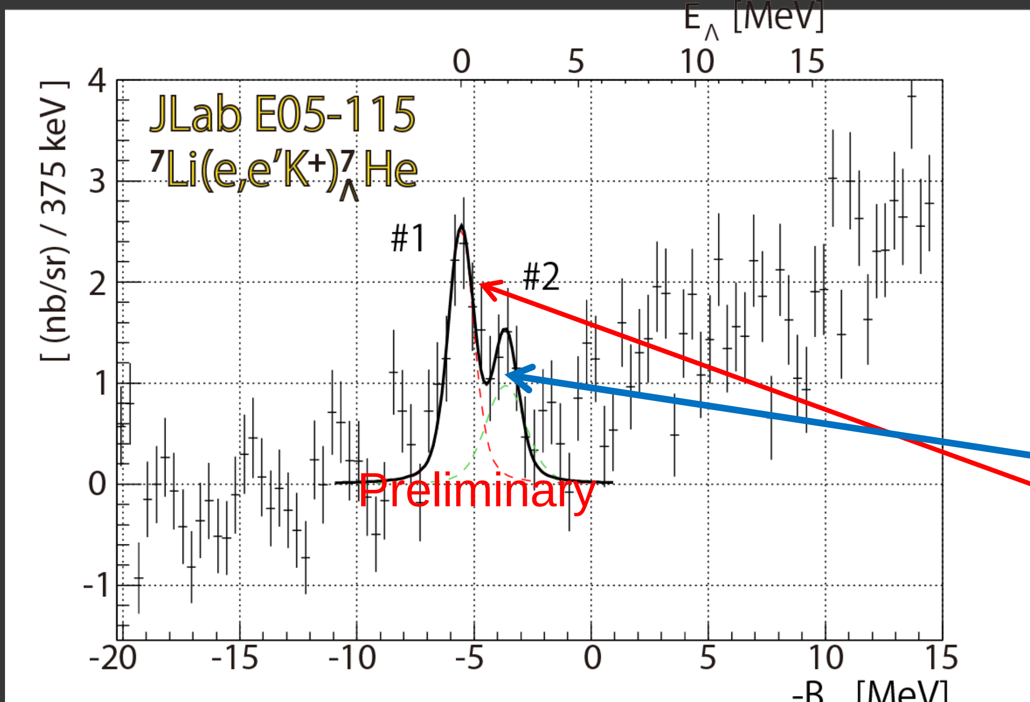


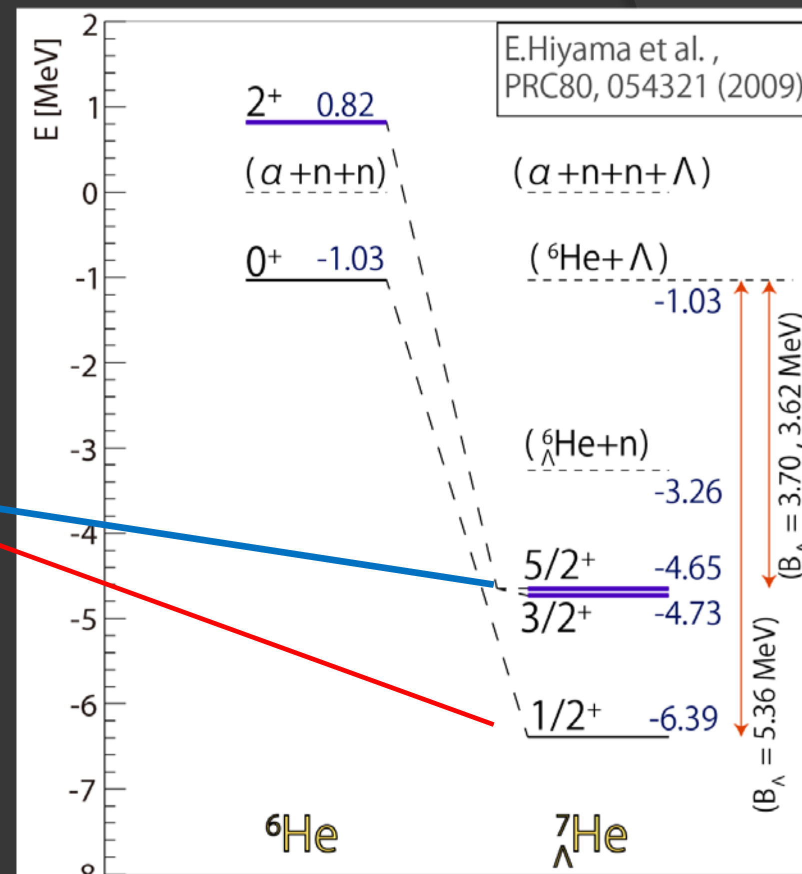


E01-011(HKS) 90 counts

$^{7}_{\Lambda}$He spectrum of E05-115

T.Gogami, Doctor Thesis (2014) Tohoku Univ.



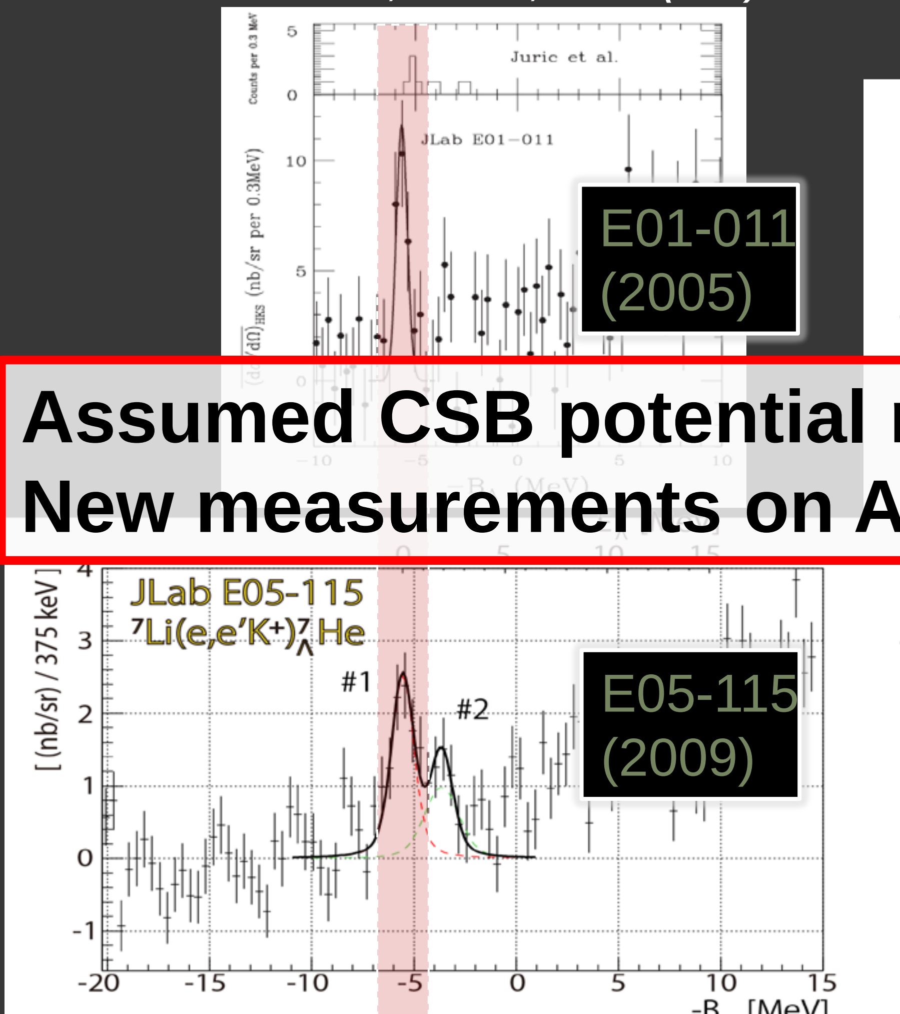


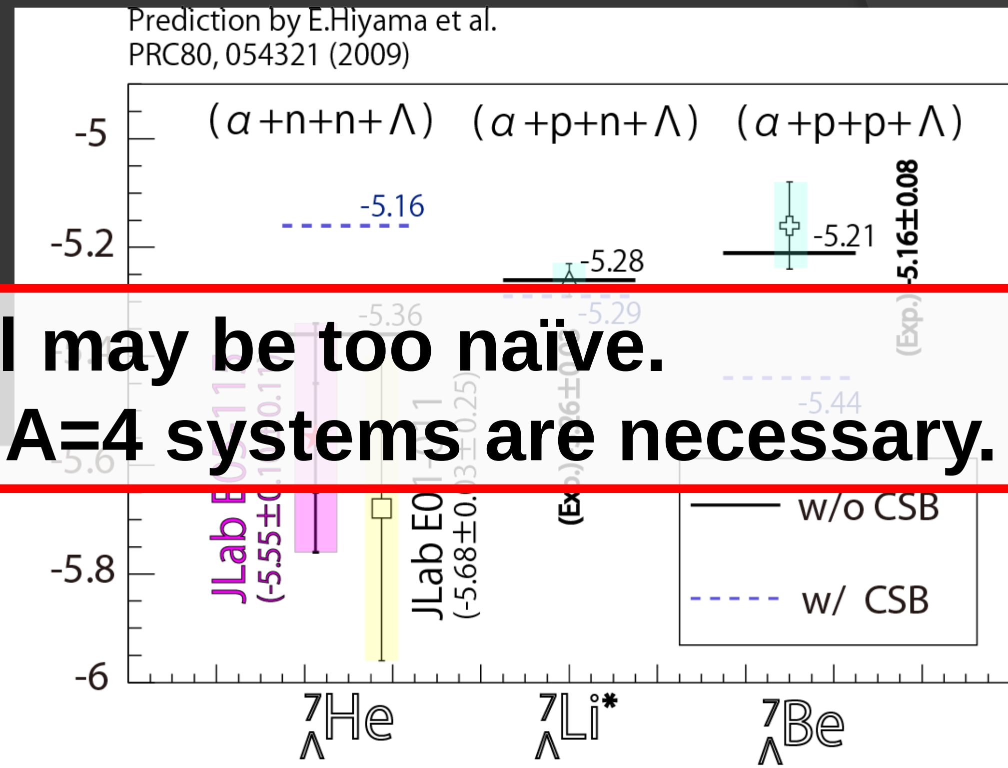
E01-011(HKS) 90 counts

E05-115(HKS-HES) >500 counts

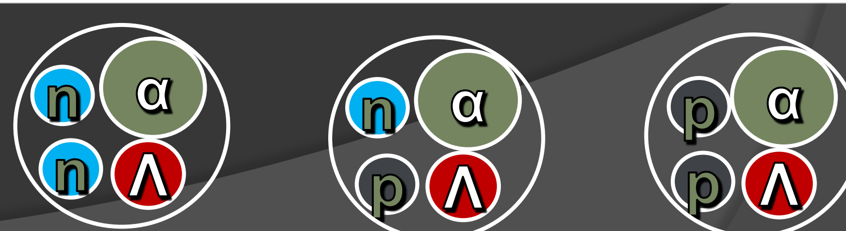
CSB interaction test in A=7 iso-triplet comparison

SNN et al., PRL 110, 012502 (2013)



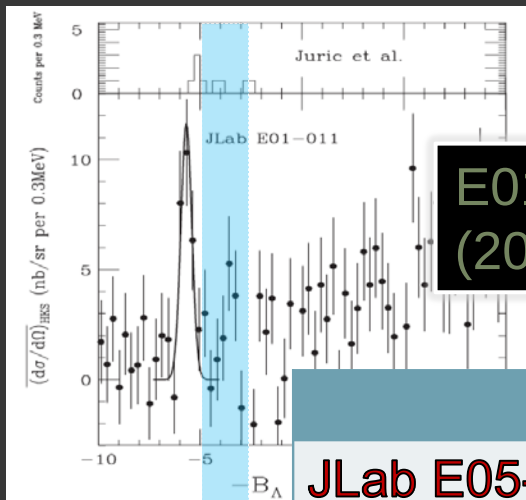


Assumed CSB potential may be too naïve.
New measurements on A=4 systems are necessary.

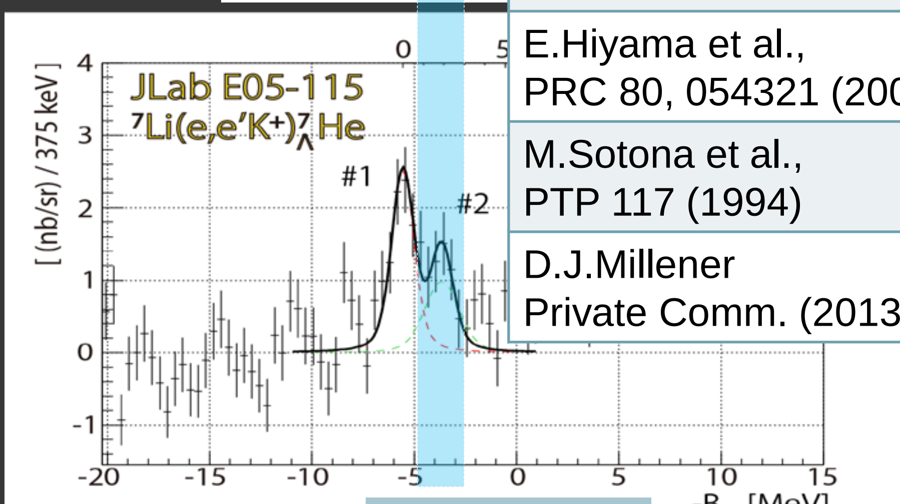


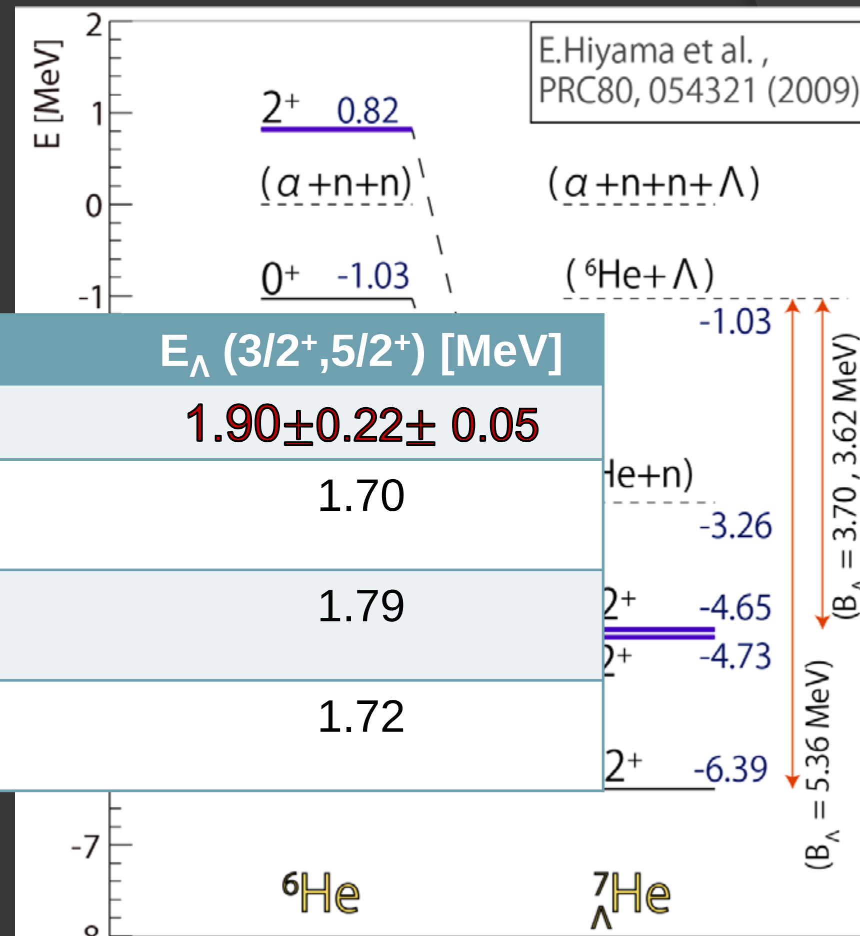
T.Gogami, Doctor Thesis (2014) Tohoku Univ.

CSB interaction test in A=7 iso-triplet comparison



E01-011 (2005)



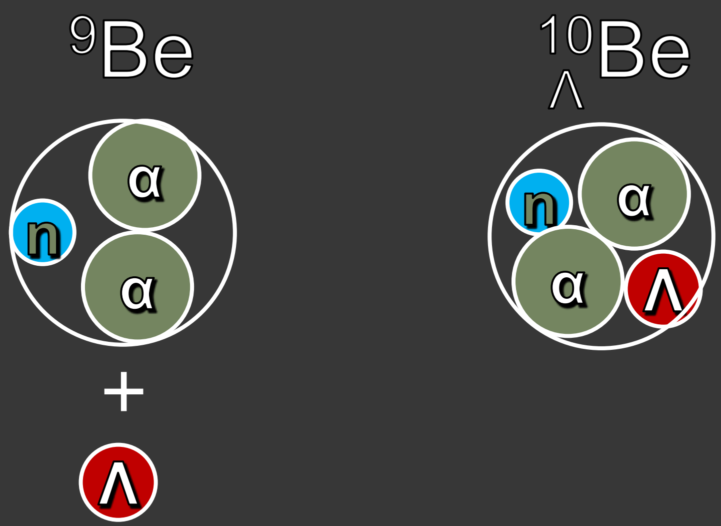


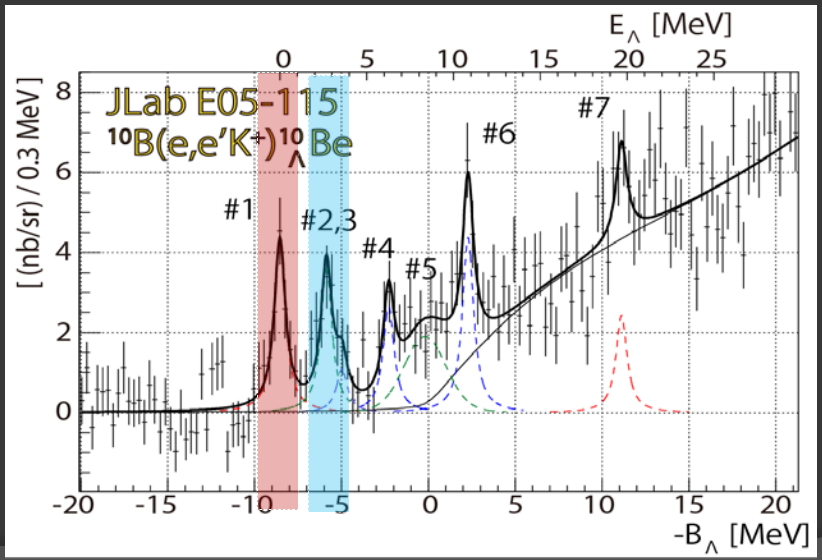
	E_Λ ($3/2^+$,$5/2^+$) [MeV]
JLab E05-115	1.90±0.22± 0.05
E.Hiyama et al., PRC 80, 054321 (2009)	1.70
M.Sotona et al., PTP 117 (1994)	1.79
D.J.Millener Private Comm. (2013)	1.72

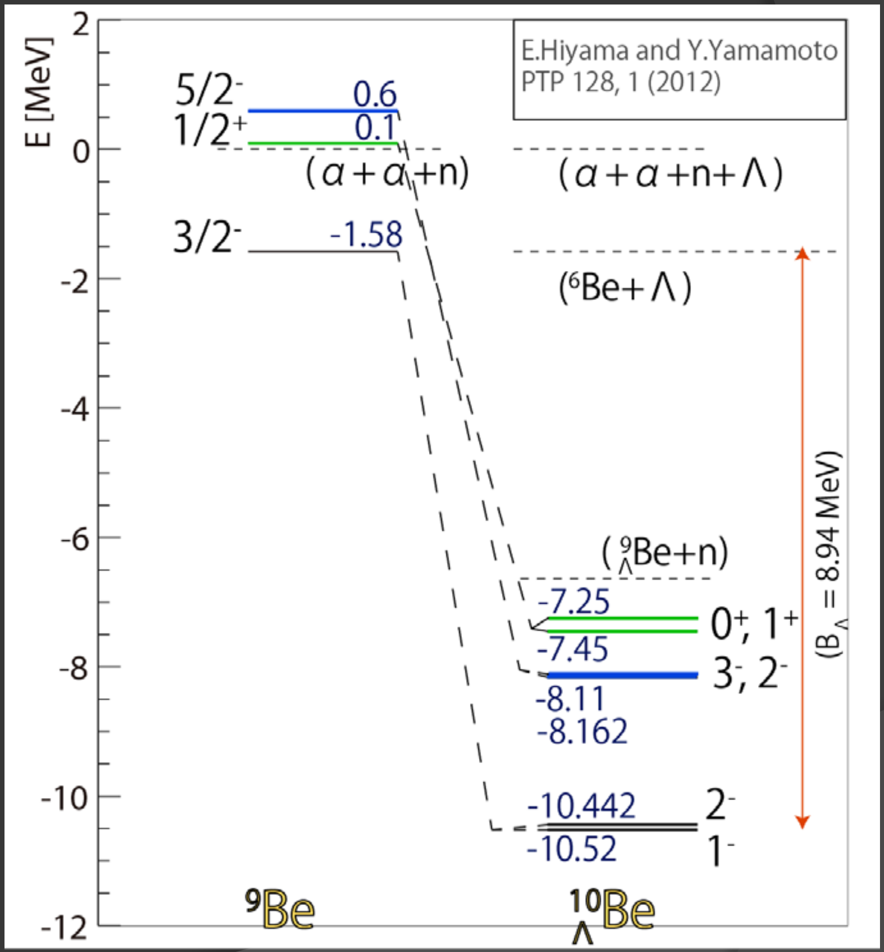
$3/2^+$, $5/2^+$

T.Gogami, Doctor Thesis (2014) Tohoku Univ.

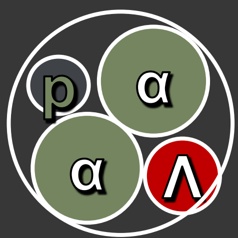
$^{10}B(e,e'K^+)^{10}{}_{\Lambda}Be$



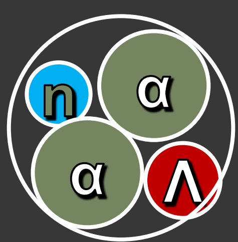




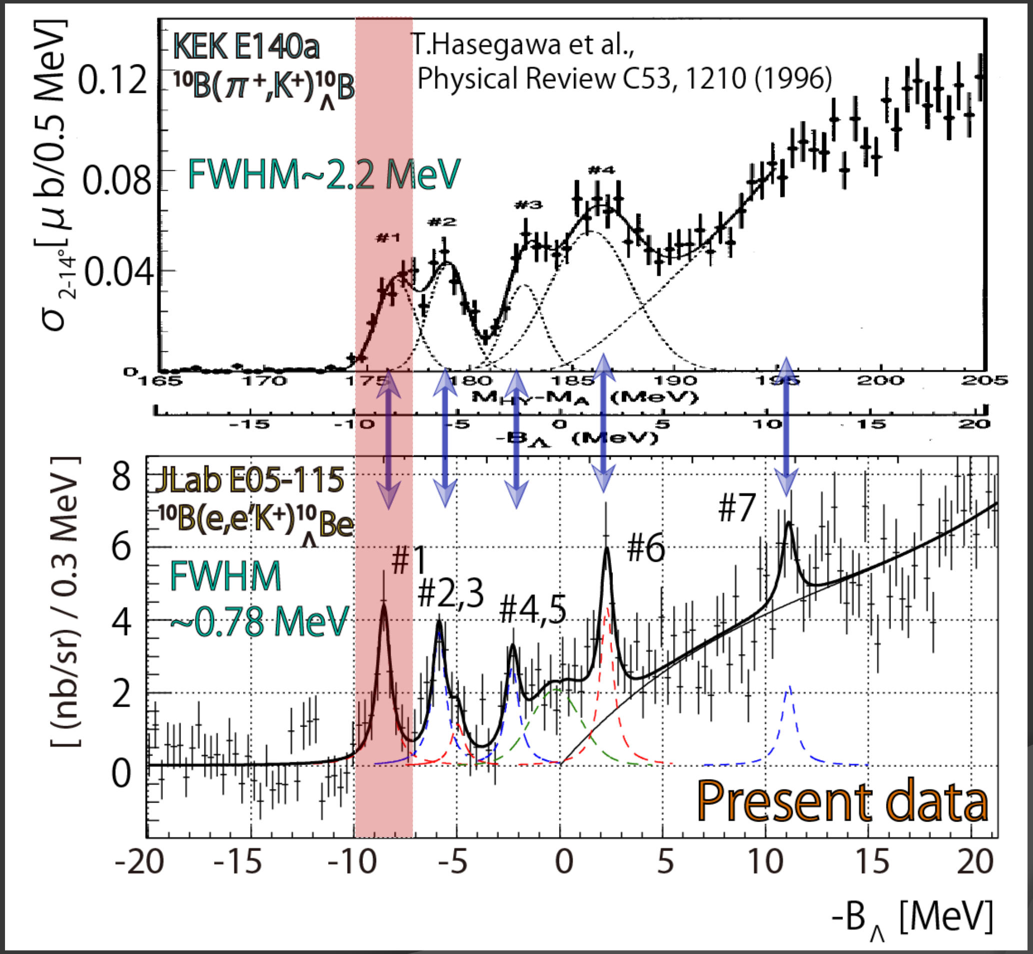
$^{10}_{\Lambda}$B and $^{10}_{\Lambda}$Be



$^{10}_{\Lambda}$B

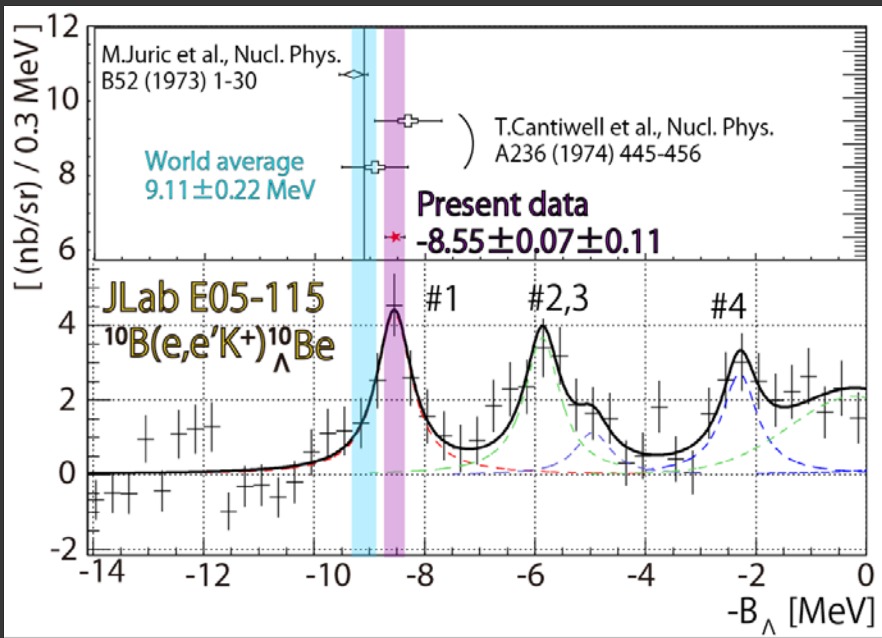


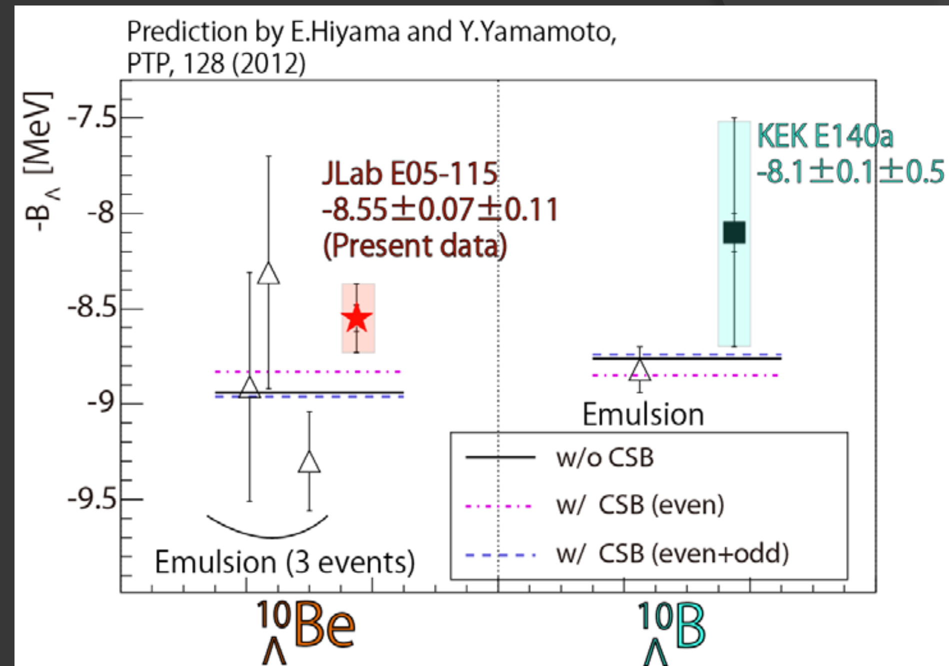
$^{10}_{\Lambda}$Be



T.Gogami, Doctor Thesis (2014) Tohoku Univ.

Comparison of the ground states (A=10)



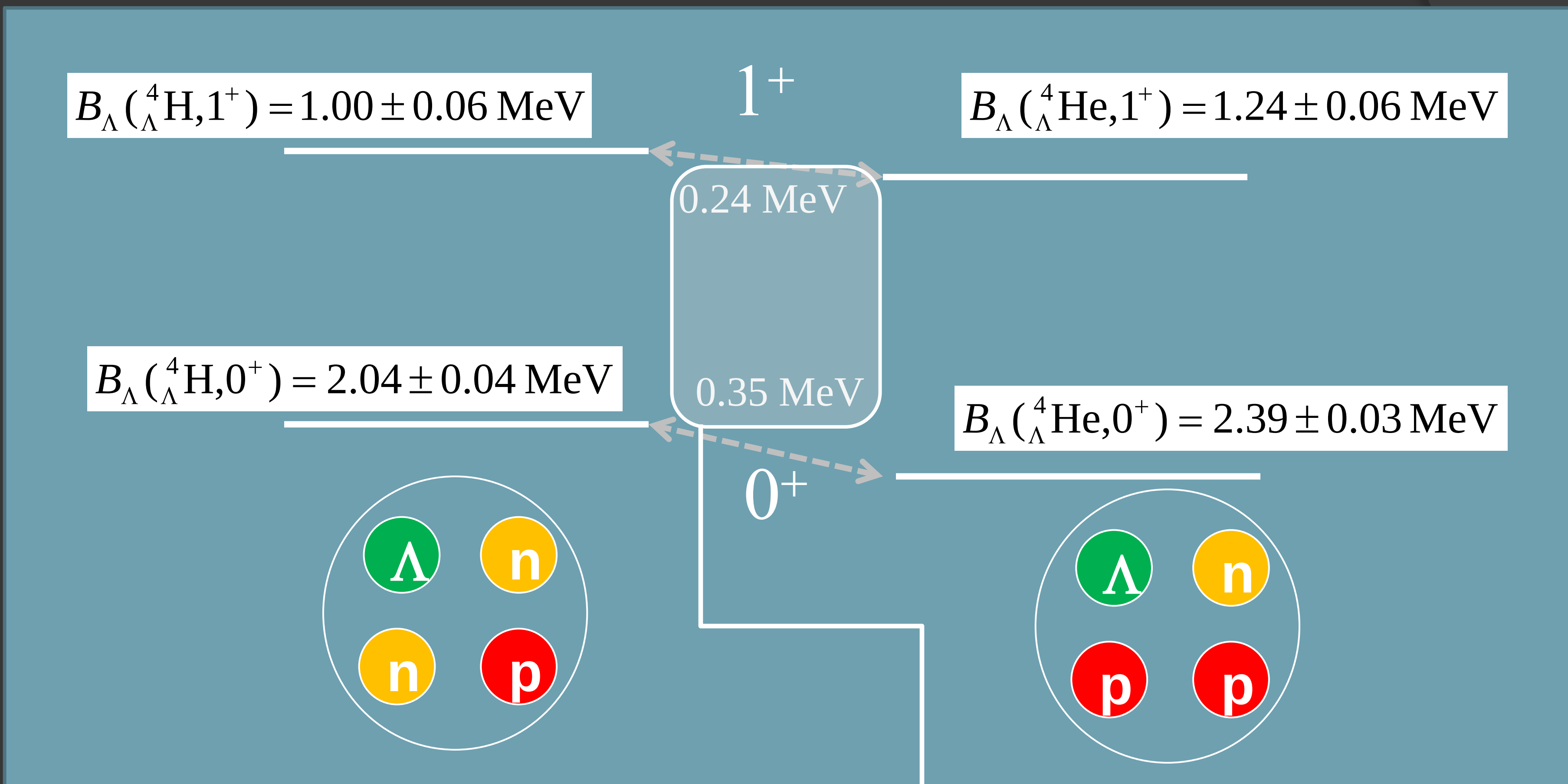


$$
\begin{aligned}
& B_\Lambda(^{10}_{\Lambda}\mathrm{Be}) - B_\Lambda(^{10}_{\Lambda}\mathrm{B}) \\
= \; & 0.45 \pm 0.12(\mathrm{stat.}) \pm 0.61(\mathrm{sys.})\ \mathrm{MeV}\ \ (\mathrm{JLab} - \mathrm{KEK}), \\
& -0.27 \pm 0.07(\mathrm{stat.}) \pm 0.23(\mathrm{sys.})\ \mathrm{MeV}\ \ (\mathrm{JLab} - \mathrm{emulsion}),
\end{aligned}
$$

⟺

CSB(even) on : 20 keV
CSB off: -180 keV

A=4 system
CSB ΛN potential



A.R.Bodmer&Q.N.Usmani, PRC 31(1985)1400.

Coulomb effect is very small.

$$-\Delta B_c = 0.050 \pm 0.02 \text{ MeV},$$
$$-\Delta B_c^* = 0.025 \pm 0.015 \text{ MeV}$$

$$V^{CSB} = -\tau_3 T_\pi^2 \tfrac{1}{8}[(0.568\Delta B_\Lambda + 0.756\Delta B_\Lambda^*) + (0.568\Delta B_\Lambda - 0.756\Delta B_\Lambda^*)\sigma_\Lambda \cdot \sigma_N]$$

$^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He emulsion data

Nuclear Physics B52 (1973) 1–30.

A NEW DETERMINATION OF THE BINDING-ENERGY VALUES OF THE LIGHT HYPERNUCLEI ($A \leqslant 15$)

Emulsion Result (M.Juric et al.)

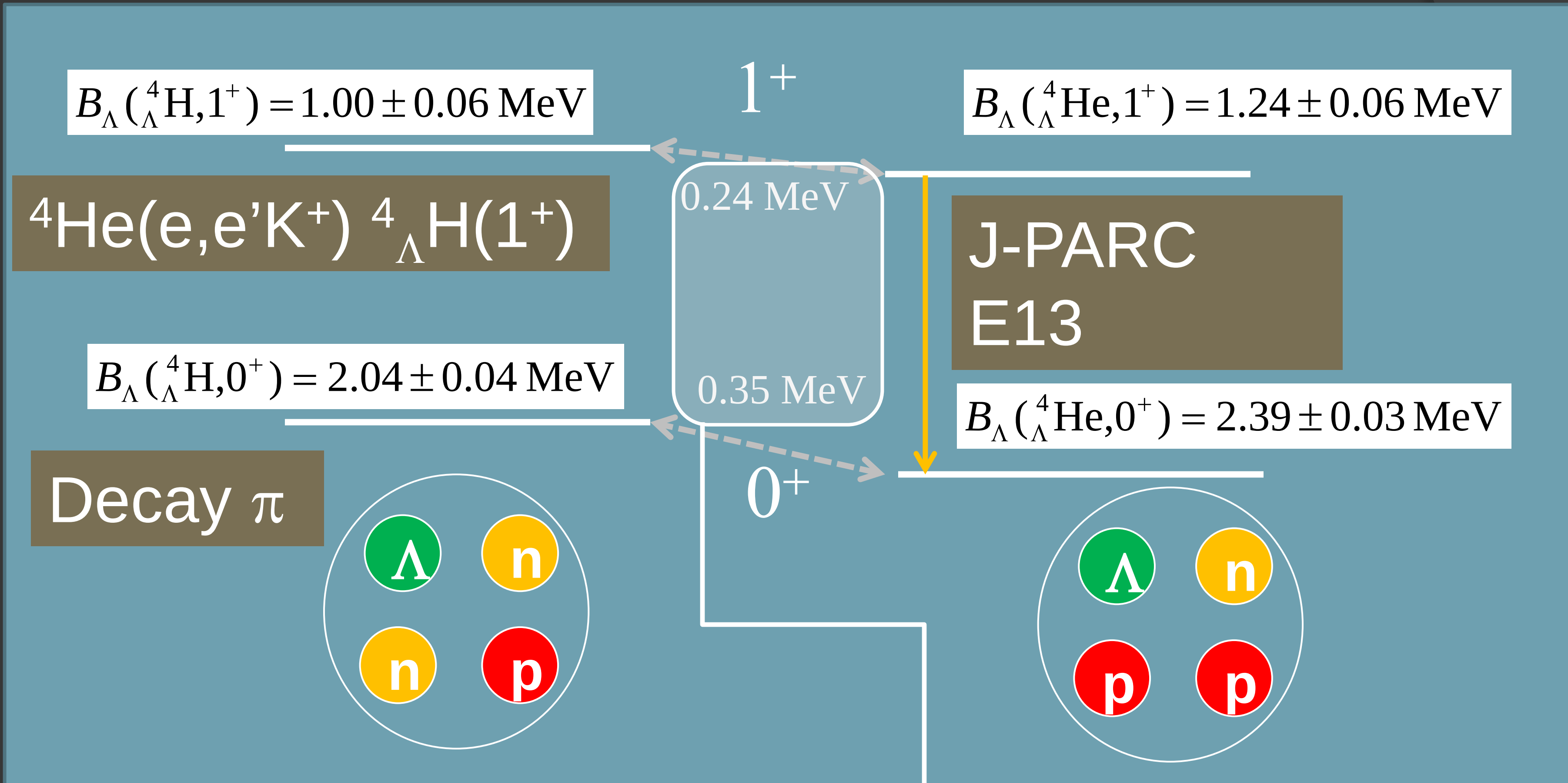
		(# of events)	B_{Λ} (MeV)
$^{4}_{\Lambda}$H	$\pi^- + {}^1H + {}^3H$	56	2.14 ± 0.07
	$\pi^- + {}^2H + {}^2H$	11	1.92 ± 0.12
	total	67	2.08 ± 0.06
$^{4}_{\Lambda}$He	$\pi^- + {}^1H + {}^3He$	83	2.42 ± 0.05
	$\pi^- + {}^1H + {}^1H + {}^2H$	15	2.44 ± 0.09
	total	98	2.42 ± 0.04

$$2.14 \pm 0.07$$
$$1.92 \pm 0.12$$

$\longrightarrow$ $\Delta = 0.22\ MeV$

$$CSB = 0.35\ MeV$$

A=4 system
CSB ΛN potential



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Future Plans at JLab

Possible Future Programs @ JLab & MAMI

1. Elementary Λ, Σ^0

Reliable data $^1H(e,e'K^+)\Lambda$, Σ^0 in low Q^2

2. Few-body $^{6,7}Li(e,e'K)^6{}_\Lambda He$, $^7{}_\Lambda He$

$^2d(e,e'K^+)$ [ΛN], $^3t(e,e'K)[nn\Lambda]$ Exotic bound state, ΛN int.

$^4He(e,e'K^+)^4{}_\Lambda H(1^+)$ ΛN CSB

3. Medium-heavy $^{19}F(e,e'K)^{19}{}_\Lambda O$

$^{40,44,48}Ca(e,e'K^+)$ $^{40,44,48}{}_\Lambda K$ Λ's S.E., iso-spin

$^{27}Al(e,e'K^+)$ $^{27}{}_\Lambda Mg$ Tri-axial deformation

4. Heavy

$^{208}Pb(e,e'K^+)$ $^{208}{}_\Lambda Tl$ Λ in heaviest nucleus

5. Decay π

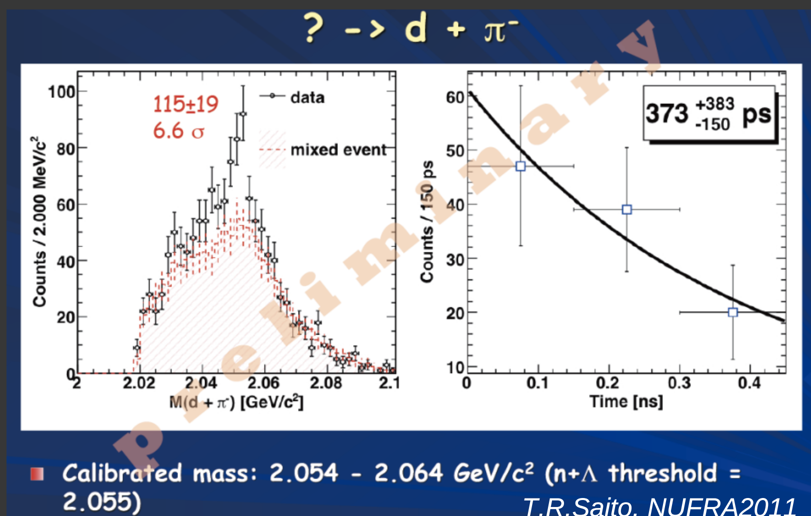
Weak decay of light hyper-fragments

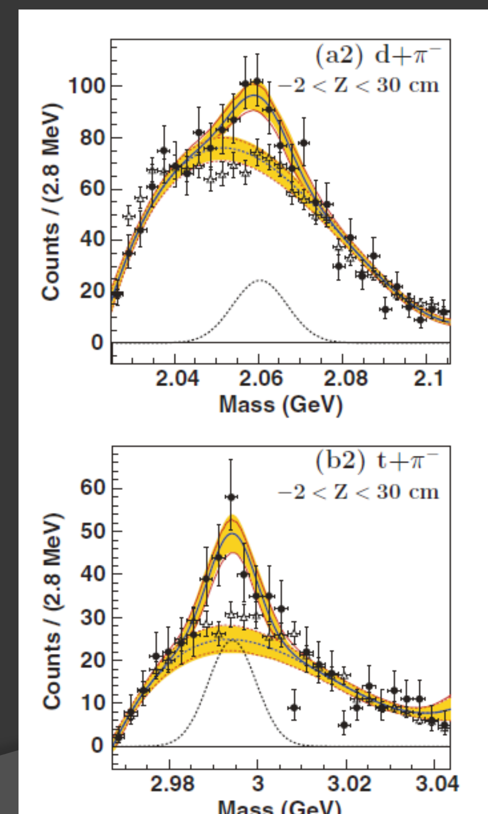
Few-body physics with strangeness

Search of [nΛ] bound state and study of n-Λ interaction through FSI.

Established lightest hypernyclei = $^{3}_{\Lambda}$H

Hyp-HI experiment at GSI   a structure in d + π^- , t + π^- invariant mass





C.Rappold et al. PRC88, 041001(R) (2013)

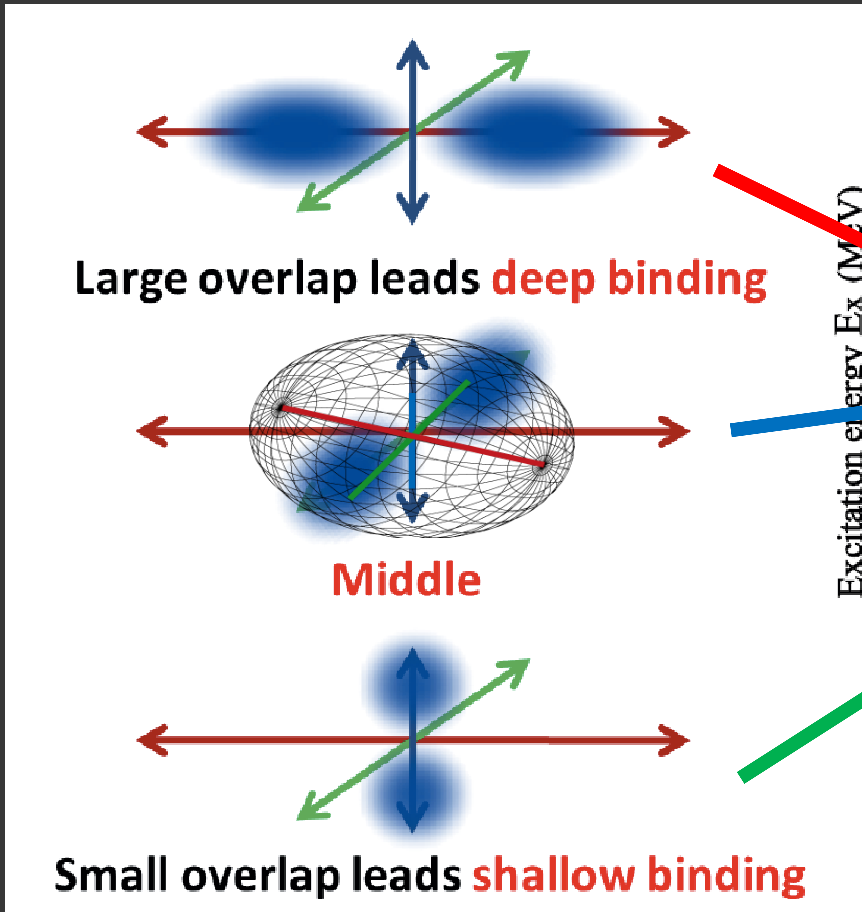
Indication of a nΛ , nnΛ bound state ?

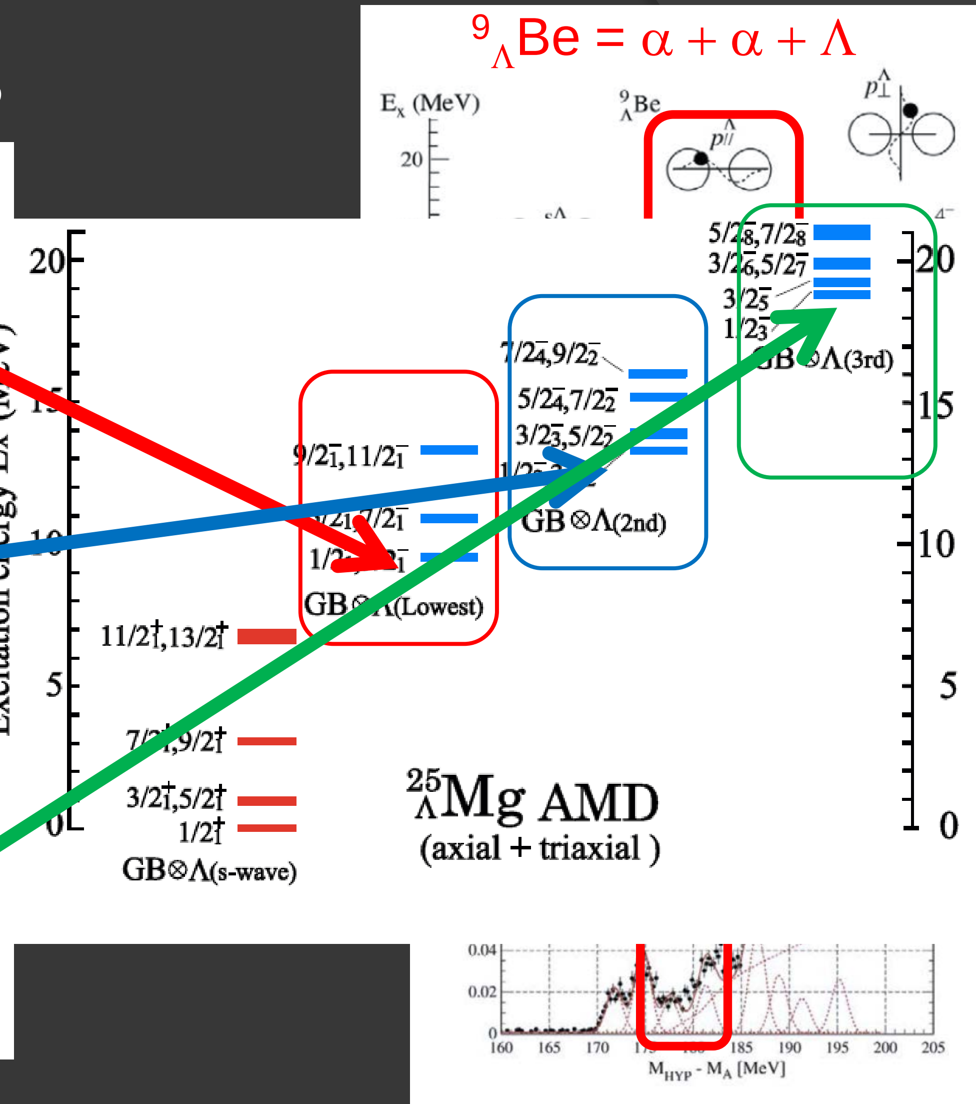
^{2}d(e,e'K$^+$)[nΛ]

^{3}t(e,e'K$^+$)[nnΛ]

Direct method to search these exotic systems.

^{27}Al (e,e'K$^+$) $^{27}{}_{\Lambda}$Mg





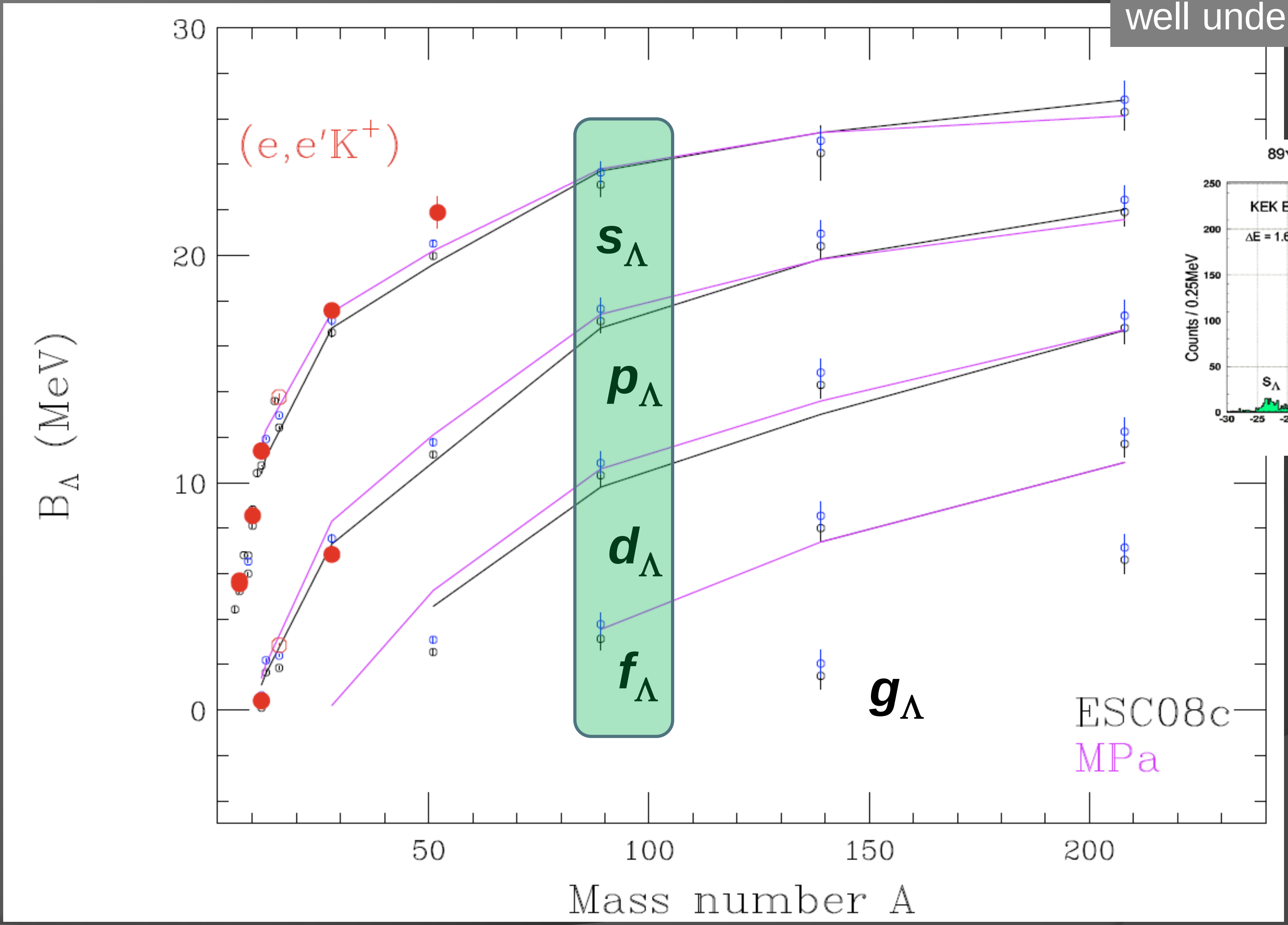
M.Isaka

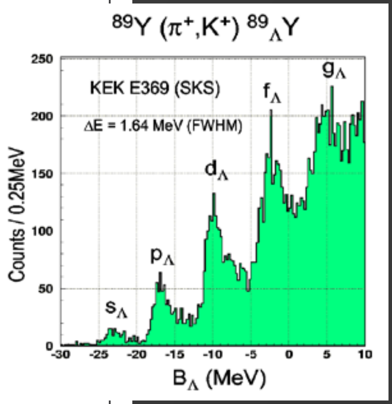
Tri-axially deformed ^{26}Mg core + Λ in p-shell

Totally new method to study shape of nucleus with Λ!

Mass dependence of B_Λ

General tendency is well understood.



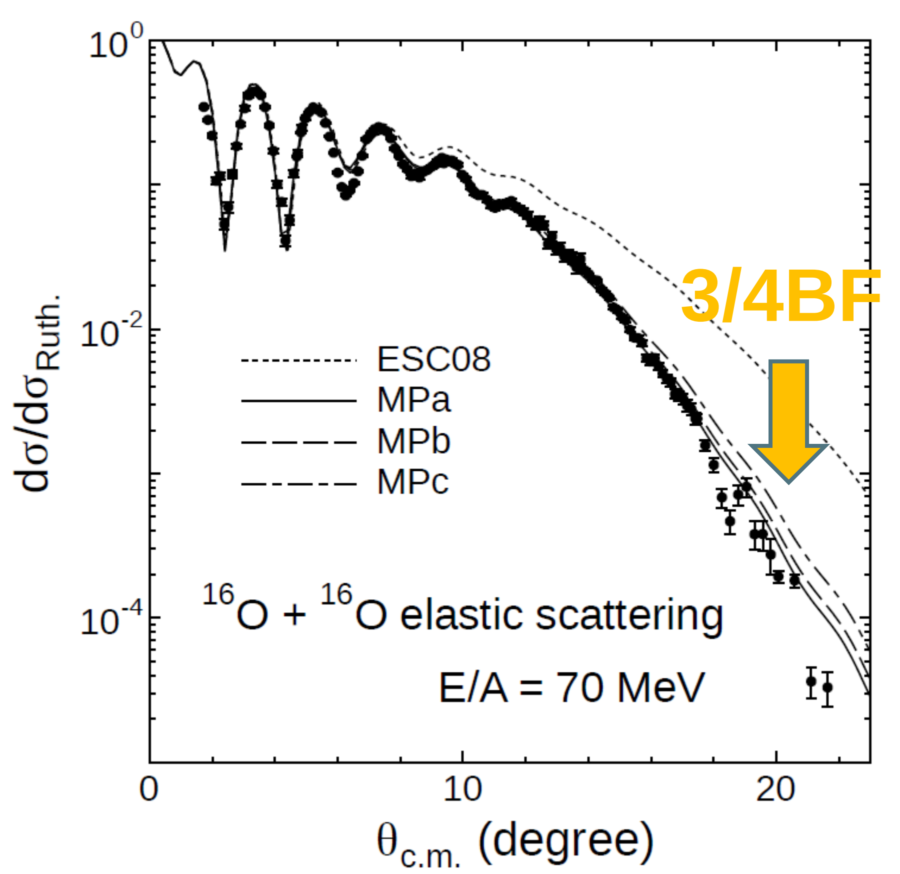


Lines: Calc. by Yamamoto & Rijken

EOS of nuclear matter with hyperons

To solve hyperon puzzle

Microscopic nuclear force model @ $\rho_0 \rightarrow 2\rho_0$

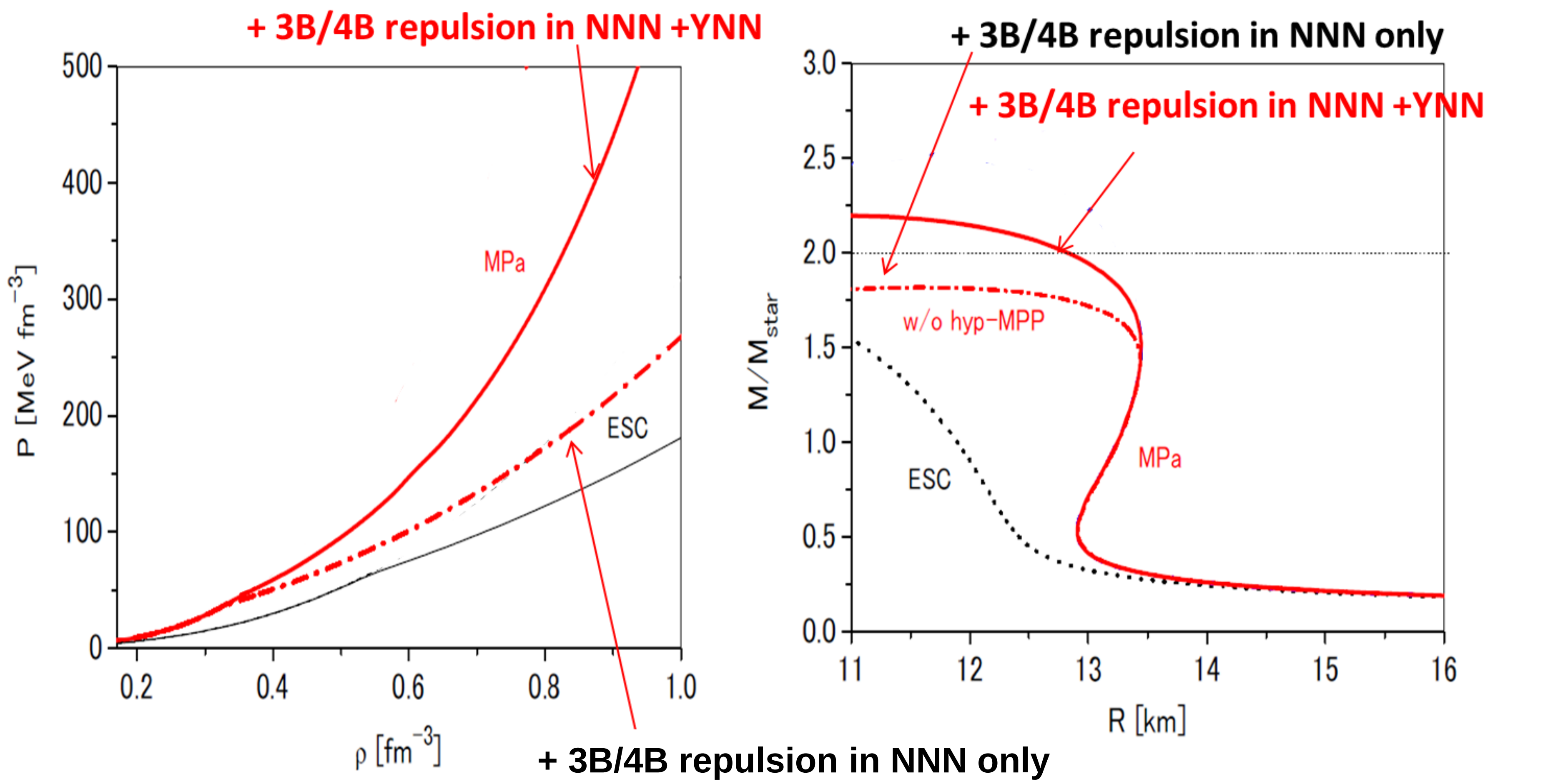


Density dependence with hyperons

Importance of 3B/4BF

Furumoto, Sakuragi, Yamamoto, PRC 79 (2009) 0011601(R)

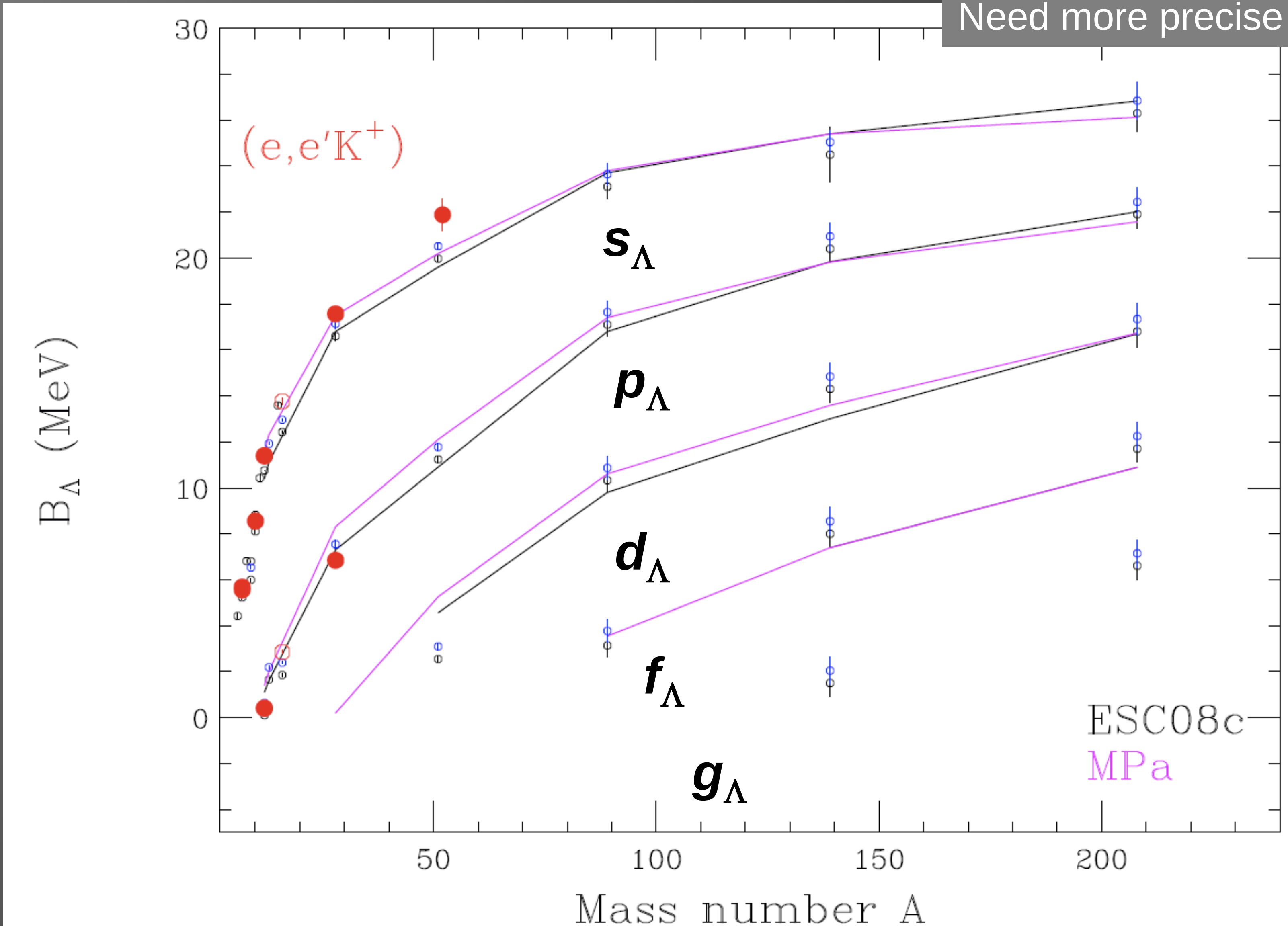
EOS w/3B,4BF & Hyperon Puzzle



Yamamoto & Rijken

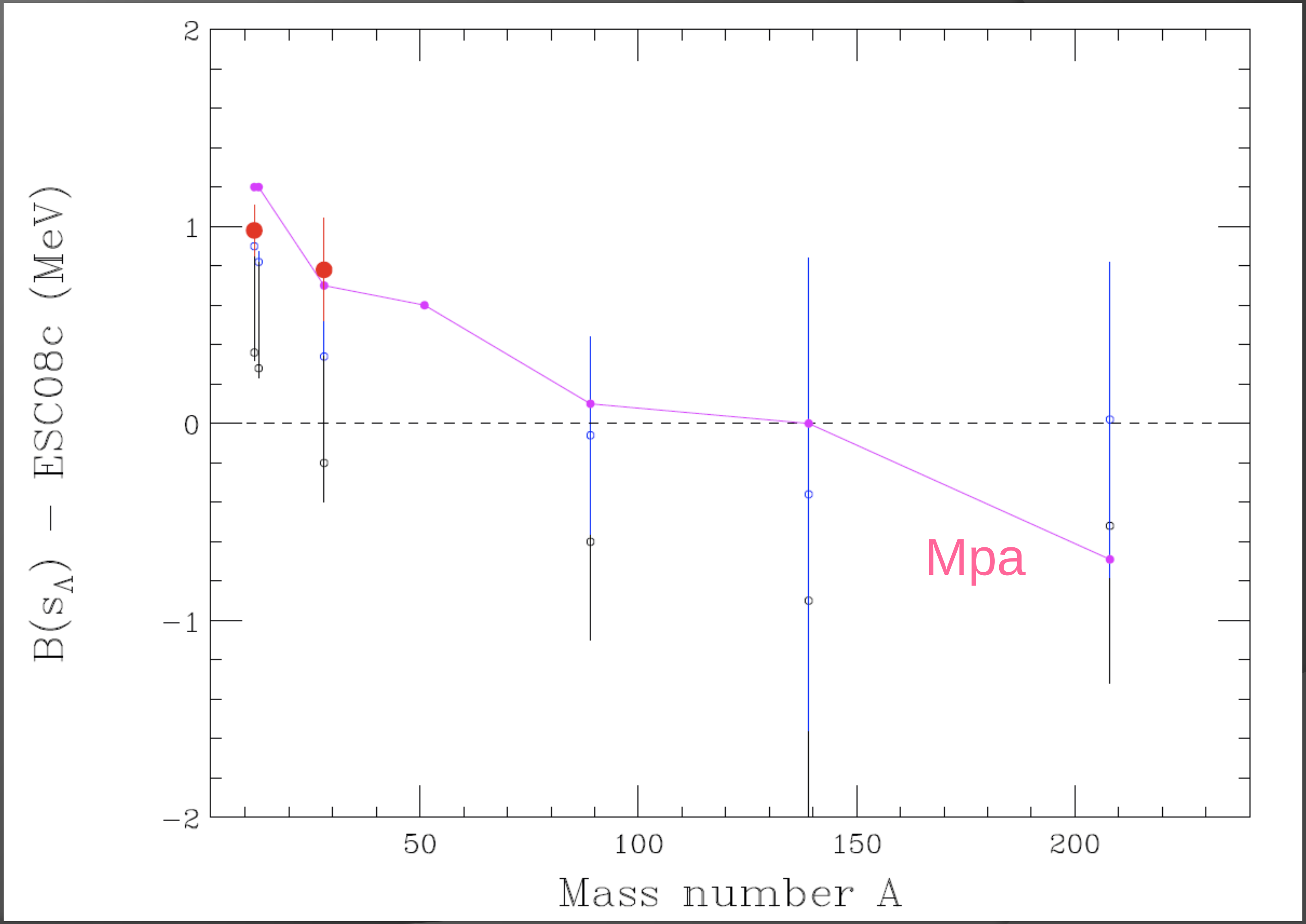
Mass dependence of B_Λ

General tendency understood.
Need more precise data.

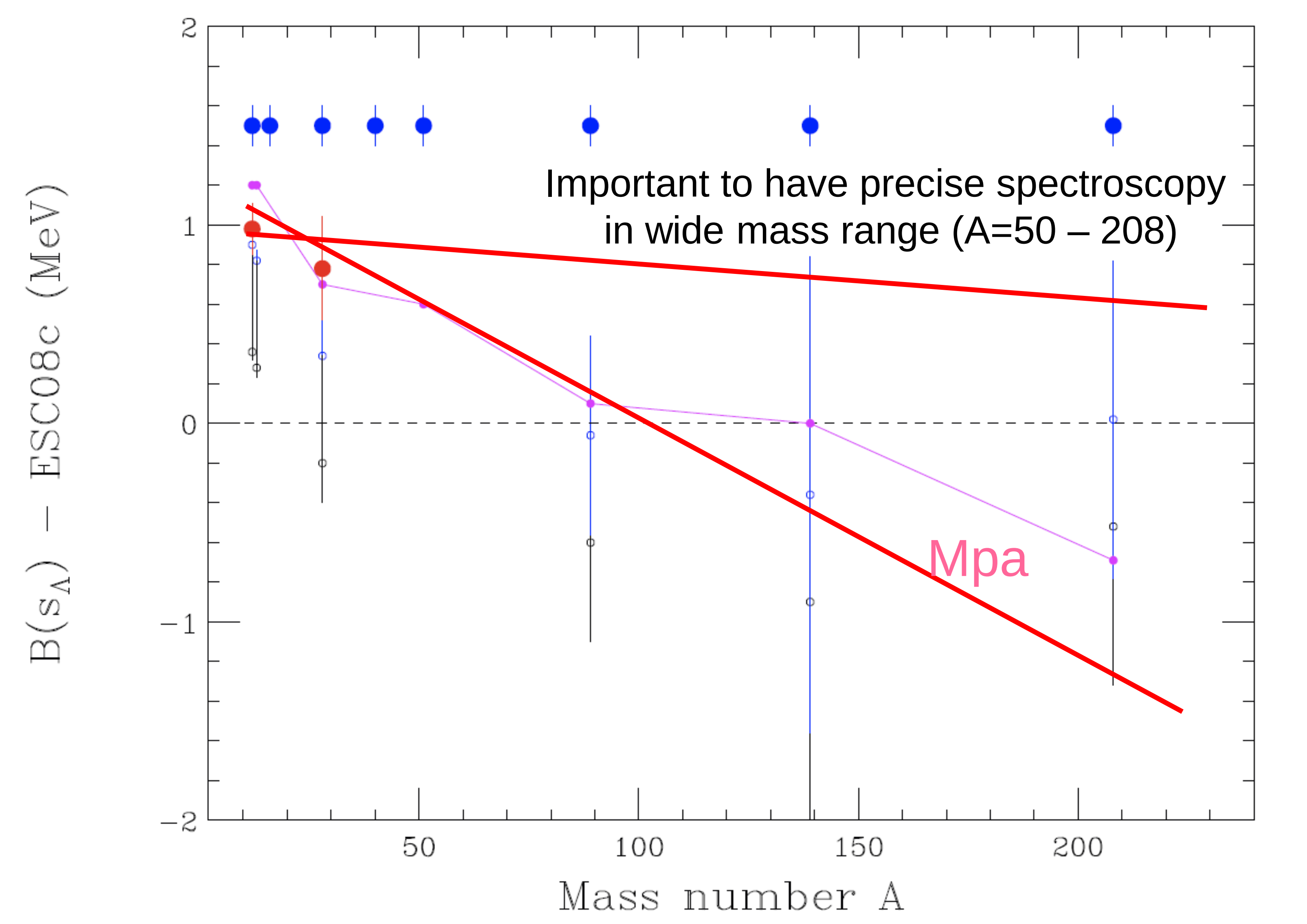


Lines: Calc. by Yamamoto & Rijken

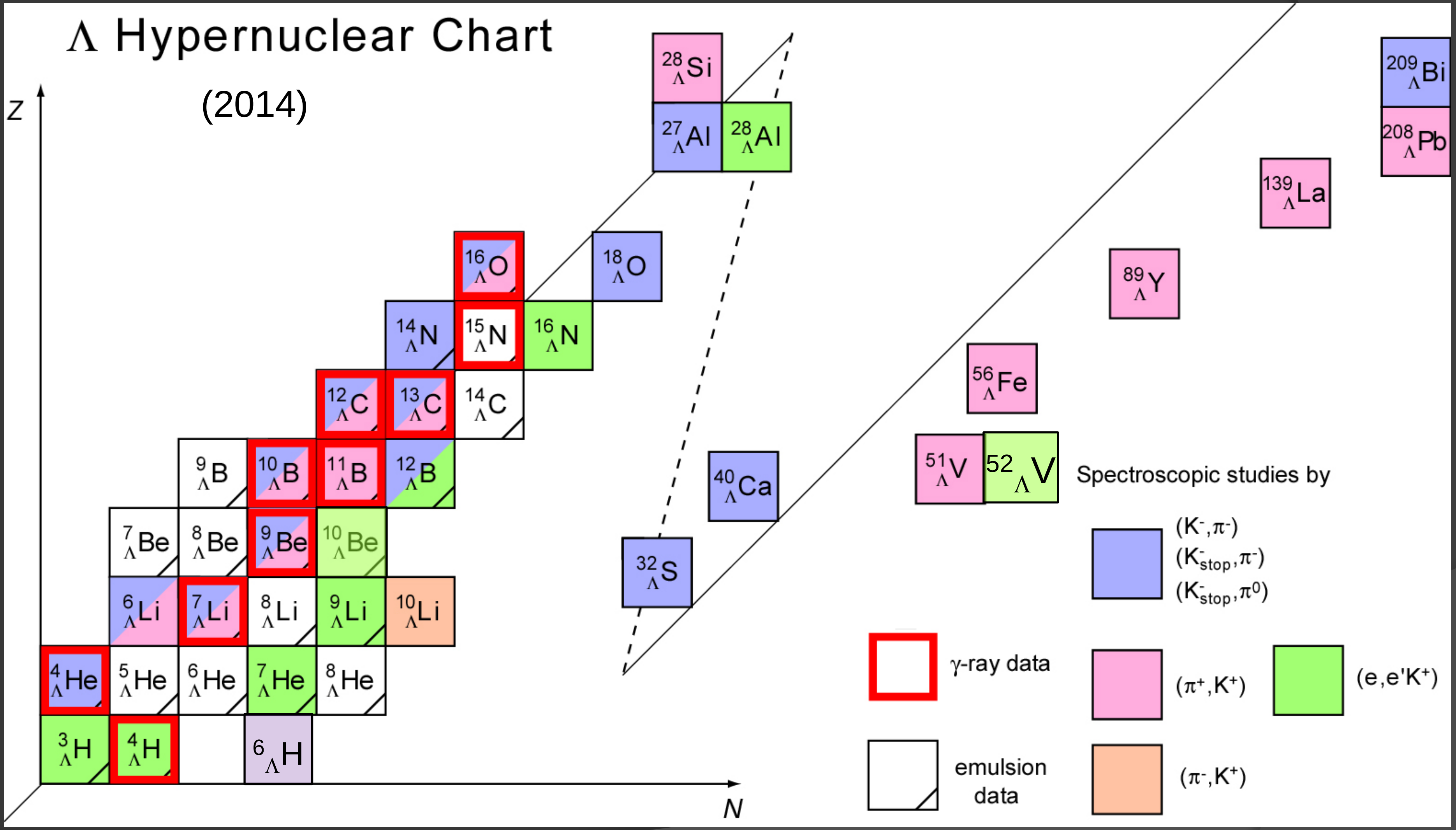
Mass dependence of B_Λ



Mass dependence of B_Λ



Present Status of Λ Hypernuclear Spectroscopy



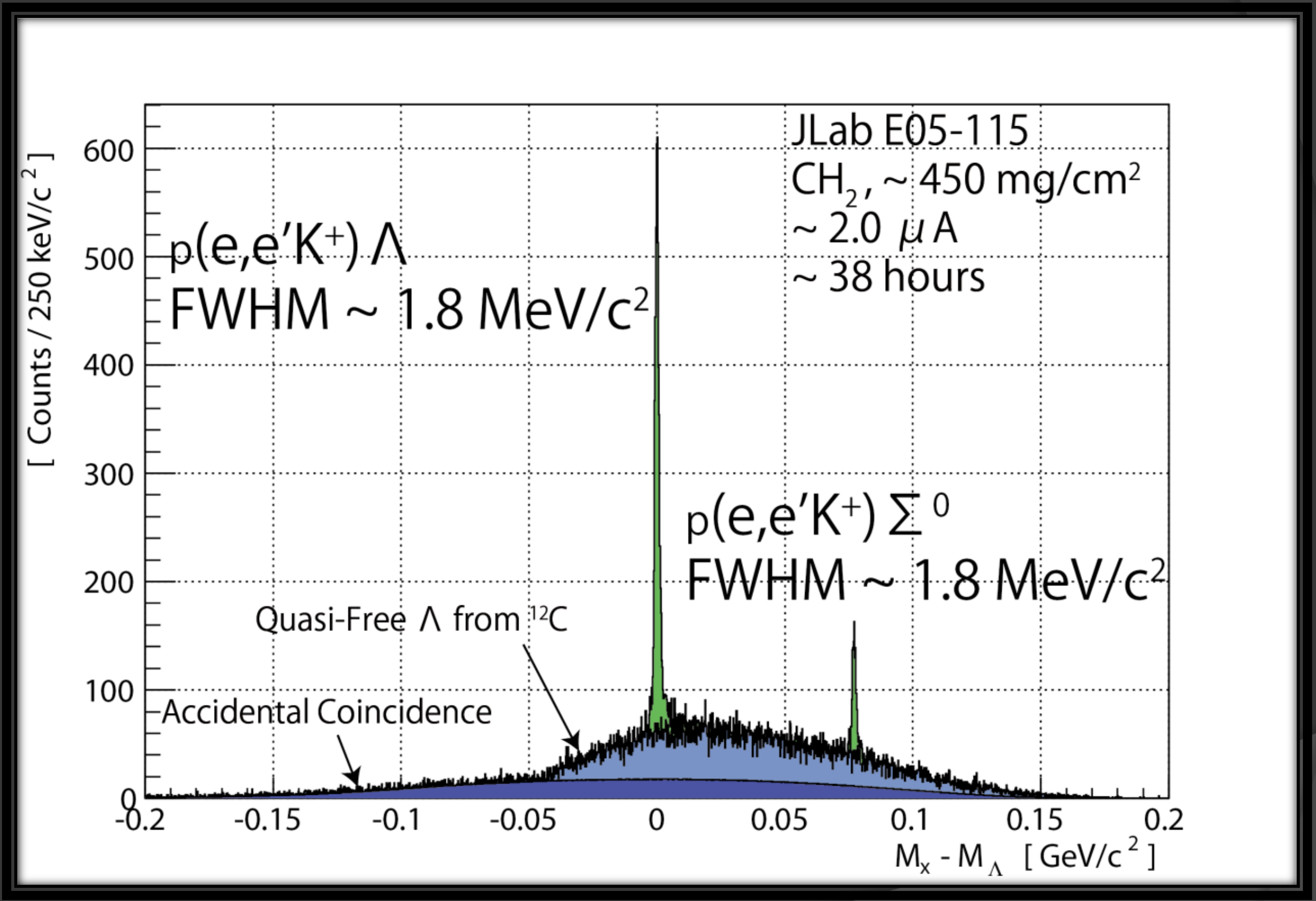
Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Summary

- We have been developing large magnetic spectrometers (HKS, HES) and techniques in the last decade at JLab and (e,e'K$^+$) HY spectroscopy **is** *now established.*
- Best spectroscopy of $^{12}{}_{\Lambda}B$ was performed and absolute binding energy calibration implies a shift (500-600 keV) of $^{12}{}_{\Lambda}C$ emulsion B_{Λ} which is the reference to all (π^+,K$^+$) spectrosopy binding energies.
- Binding energy of $^{7}{}_{\Lambda}He_{gs}$ was determined. Important input for ΛN CSB potential. Excited state of $^{7}{}_{\Lambda}He$ was clearly observed.
- New data on $^{10}{}_{\Lambda}Be_{gs}$ was obtained.

We are designing next programs at JLab.
systematic study of B_{Λ} for wide A range up to 208,
tri-axial deformed HY ,
CSB study with light HY and
elementary study with exotics (nnΛ).

Λ, Σ^0 from polyethylene (CH_2)target



Λ, Σ^0 from CH_2 target