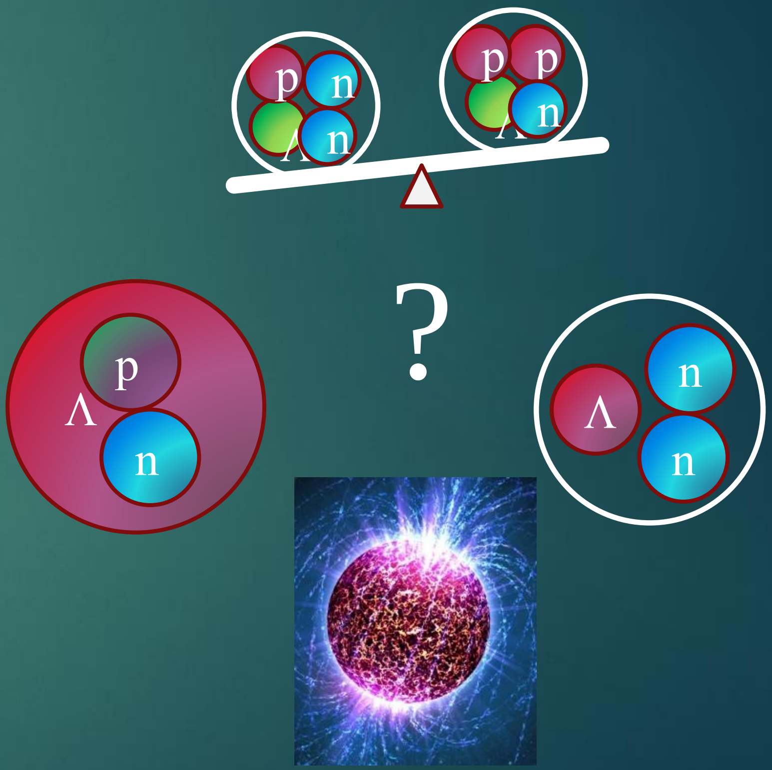
Second EMMI Workshop @ Torino, Italy

Electro-photo production of Λ hypernuclei and perspecitves



SATOSHI N. NAKAMURA

TOHOKU UNIVERSITY

08 November 2017

History of Experimental Study on Hypernuclei

1953 discovery of hypernucleus (emulsion with cosmic-ray, by Danysz and Pniewski)

1970s CERN, BNL Counter experiments
with Kaon beam

1980s BNL-AGS, KEK-PS Counter experiments
with K/π beam

1998- γ-spectroscopy with Hyperball

FINUDA at DAΦNE

$\Phi \rightarrow K^{+}K^{-}$ (49%)

2000~

(e,e'K^{+}) spectroscopy @ JLab

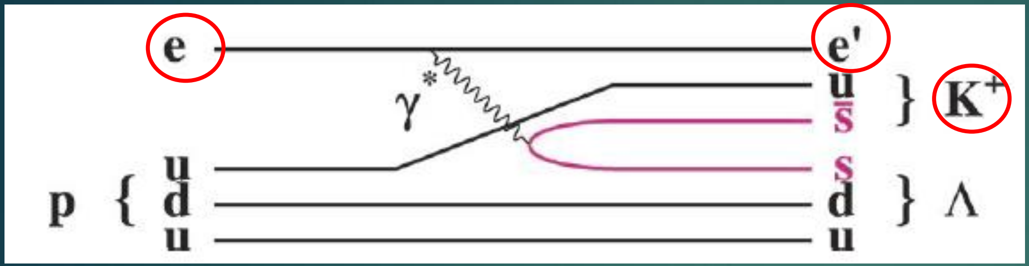
Z(e^{-},e'K^{+})$_{\Lambda}$(Z–1) reaction

Meson beam experiments at J-PARC

Decay π @ Mainz

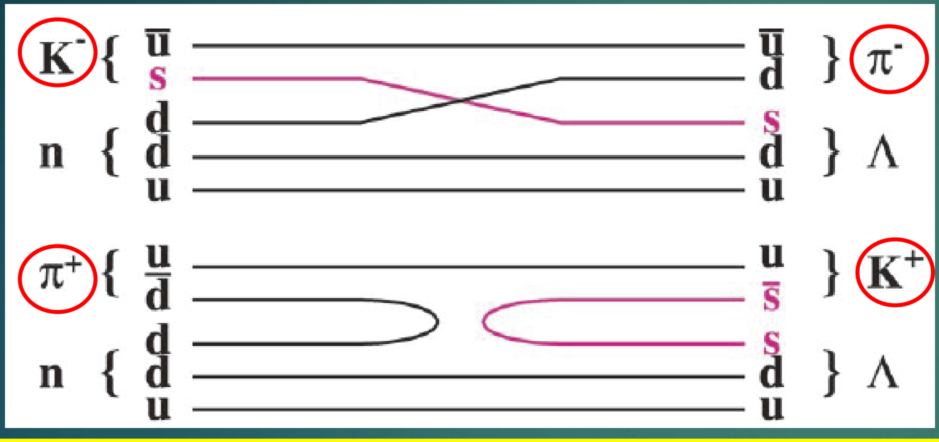
HI-Beams @ GSI, RHIC, LHC

(e,e'K$^+$) vs. others



(e,e'K$^+$)
Excellent mass resolution
(~ 0.5 MeV)

Absolute energy calibration
p(e,e'K$^+$) Λ, Σ^0



(K$^-$, π^-)

(π^+, K$^+$)
1-2 MeV resolution
Normalized to $^{12}{}_{\Lambda}$C mass

γ-ray spectroscopy
Super high resolution (a few keV)
But only **level spacing** measurable

decay π
Excellent mass resolution (~0.1 MeV)
But only **mass of ground state of light HY**

HI beam spectroscopy
Exotic light hypernuclei (p, n rich)
Invariant mass, a few MeV resolution

Hypernuclear experiments at JLab

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

E94-107 (2004-5)
Two HRSs + SC Septum
Λ, Σ^0, ${}^{9}_{\Lambda}$Li, ${}^{12}_{\Lambda}$B, ${}^{16}_{\Lambda}$N

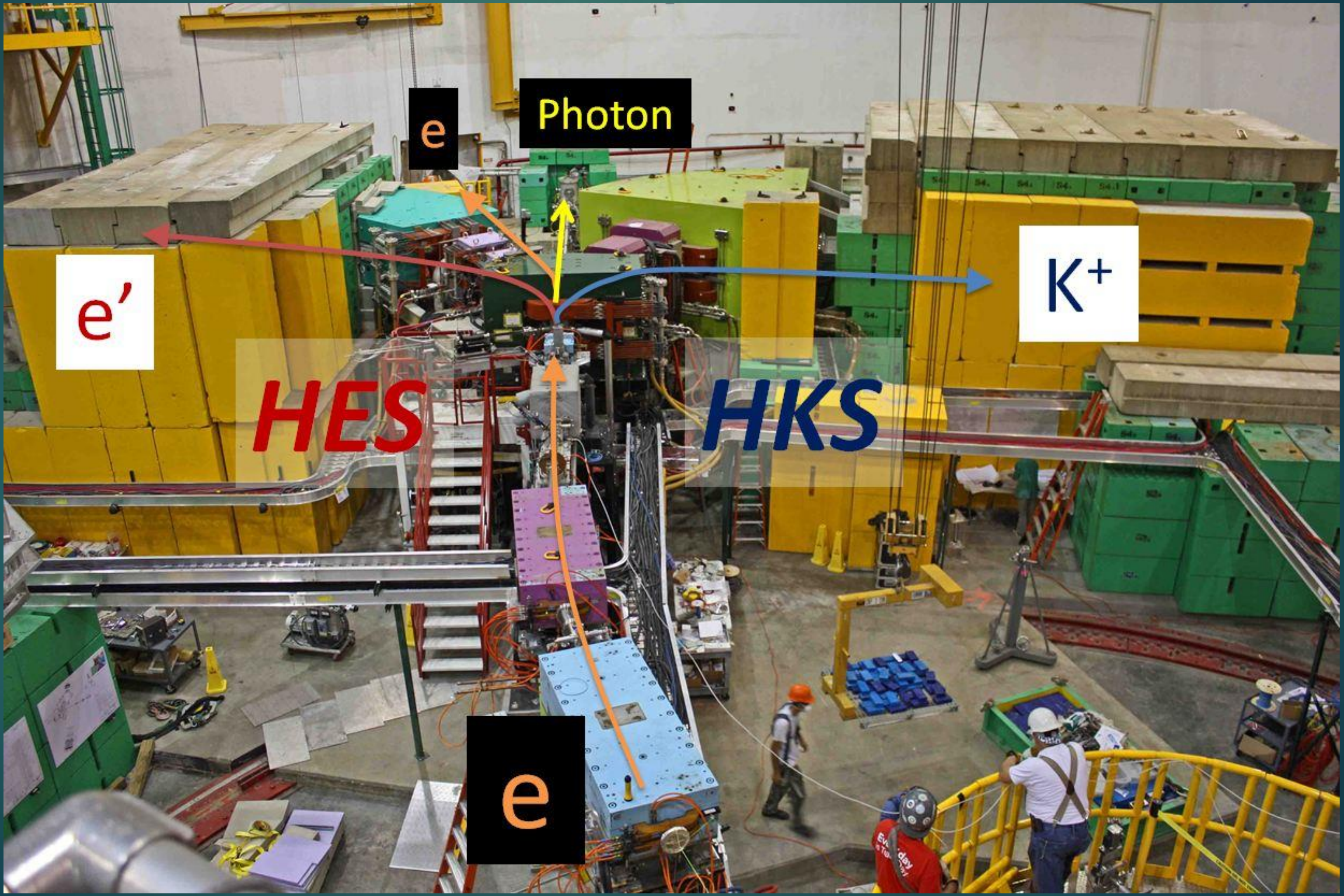
Light Hypernuclei

E05-115 (2009) :
HKS+HES, new Chicane beamline, Splitter
Λ, Σ^0, ${}^{7}_{\Lambda}$He , ${}^{12}_{\Lambda}$B, ${}^{52}_{\Lambda}$V

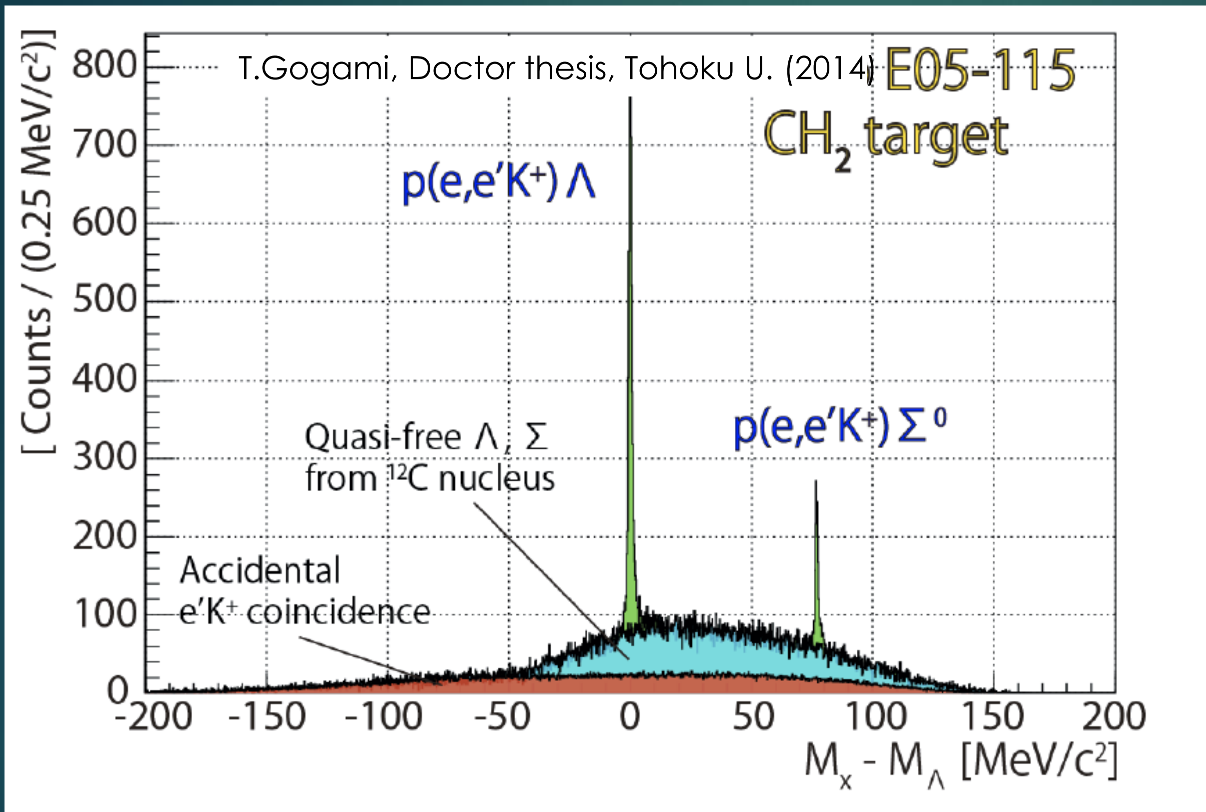
Light to medium-heavy Hypernuclei

Hypernuclear study with the (e,e’K⁺) reaction

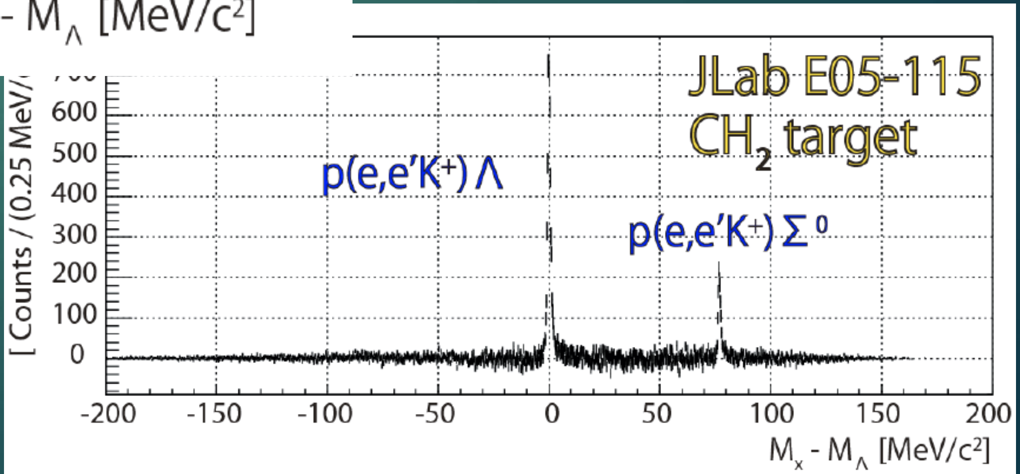
Initiated and established at **JLab**



p(e,e'K⁺)Λ, Σ^0: Elementary Process



CH$_2$ Target



T. Gogami et al.
arXiv:1709.05682
Submitted to NIM-A

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

0.5 MeV (FWHM)

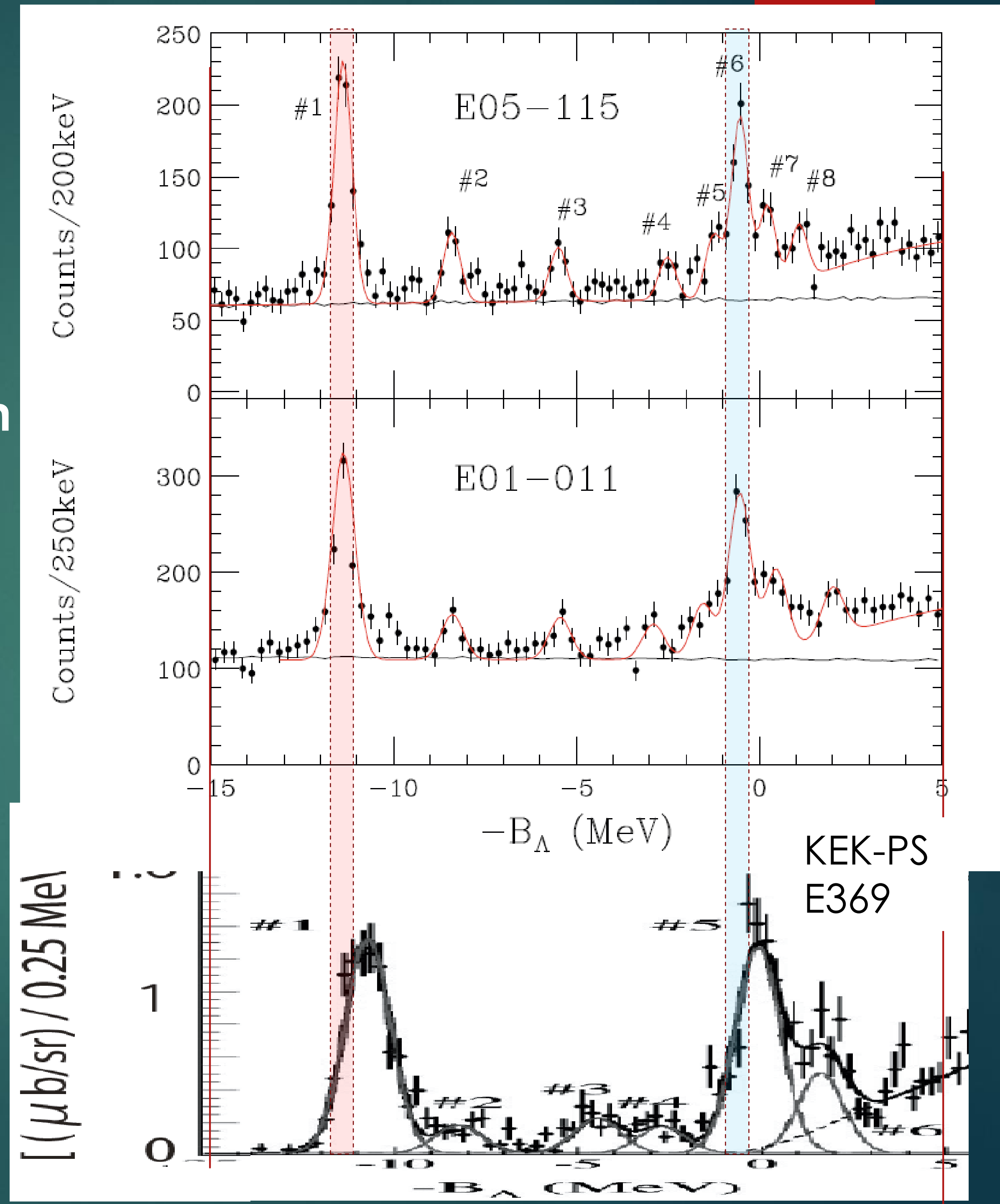
Absolute MM calibration

0.7 MeV (FWHM)

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

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. ${}^{12}_{\Lambda}C \to \pi^- + p + {}^{4}He + {}^{7}Be$	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 ${}^{12}_{\Lambda}C$: ($\pi^-{}^{12}N$), ($\pi^- p {}^{11}C$), ($\pi^- p {}^{3}He {}^{4}He {}^{4}He$) and ($\pi^- p {}^{4}He {}^{7}Be$). 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**

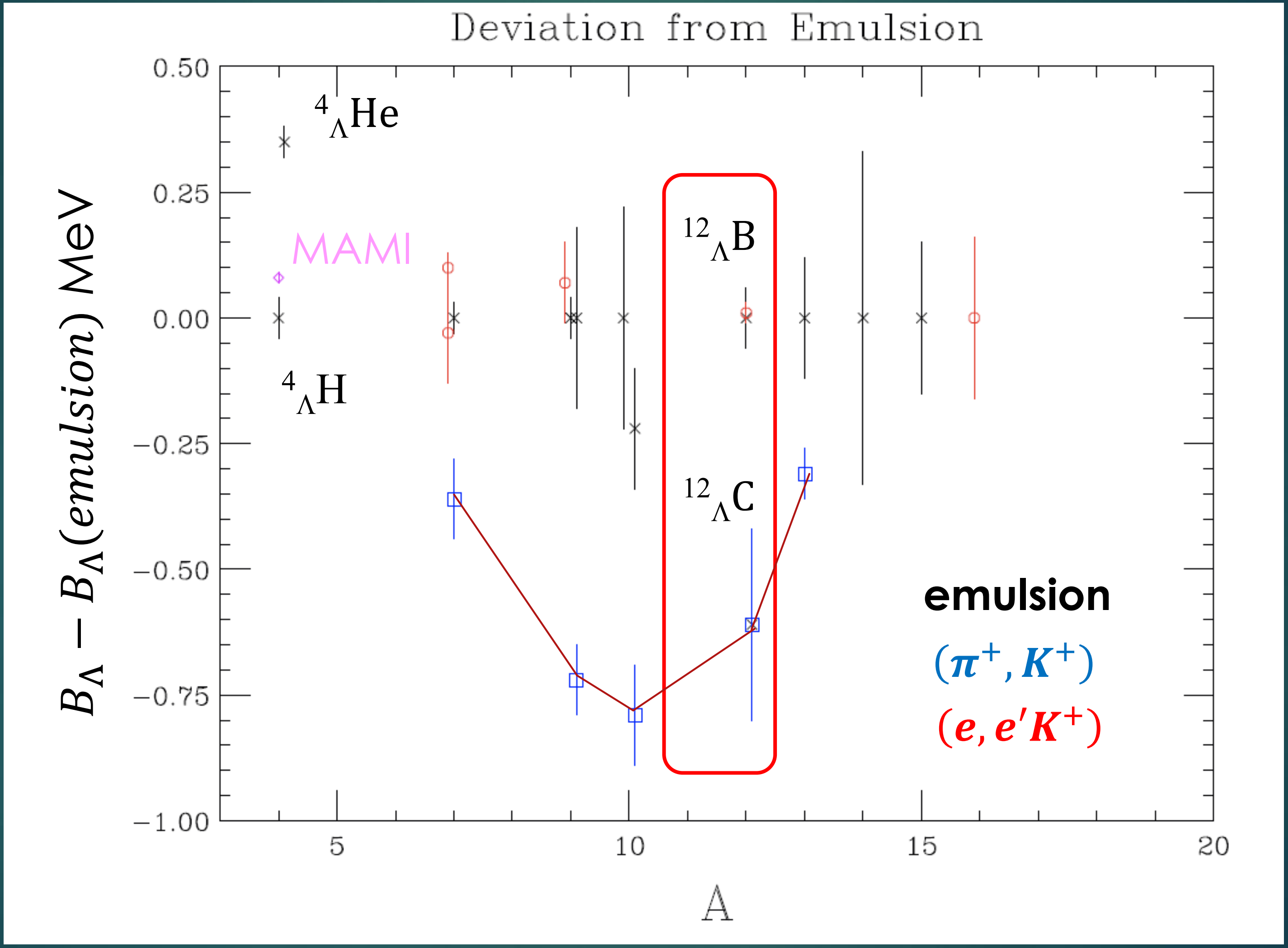
Statistical error only

Reference for all (π, K) B_Λ data:

B_Λ (${}^{12}_{\Lambda}$Cg.s.) = 10.76 +-0.19MeV

Sys. Error ~ 0.04 MeV

Remove apparent A dependence



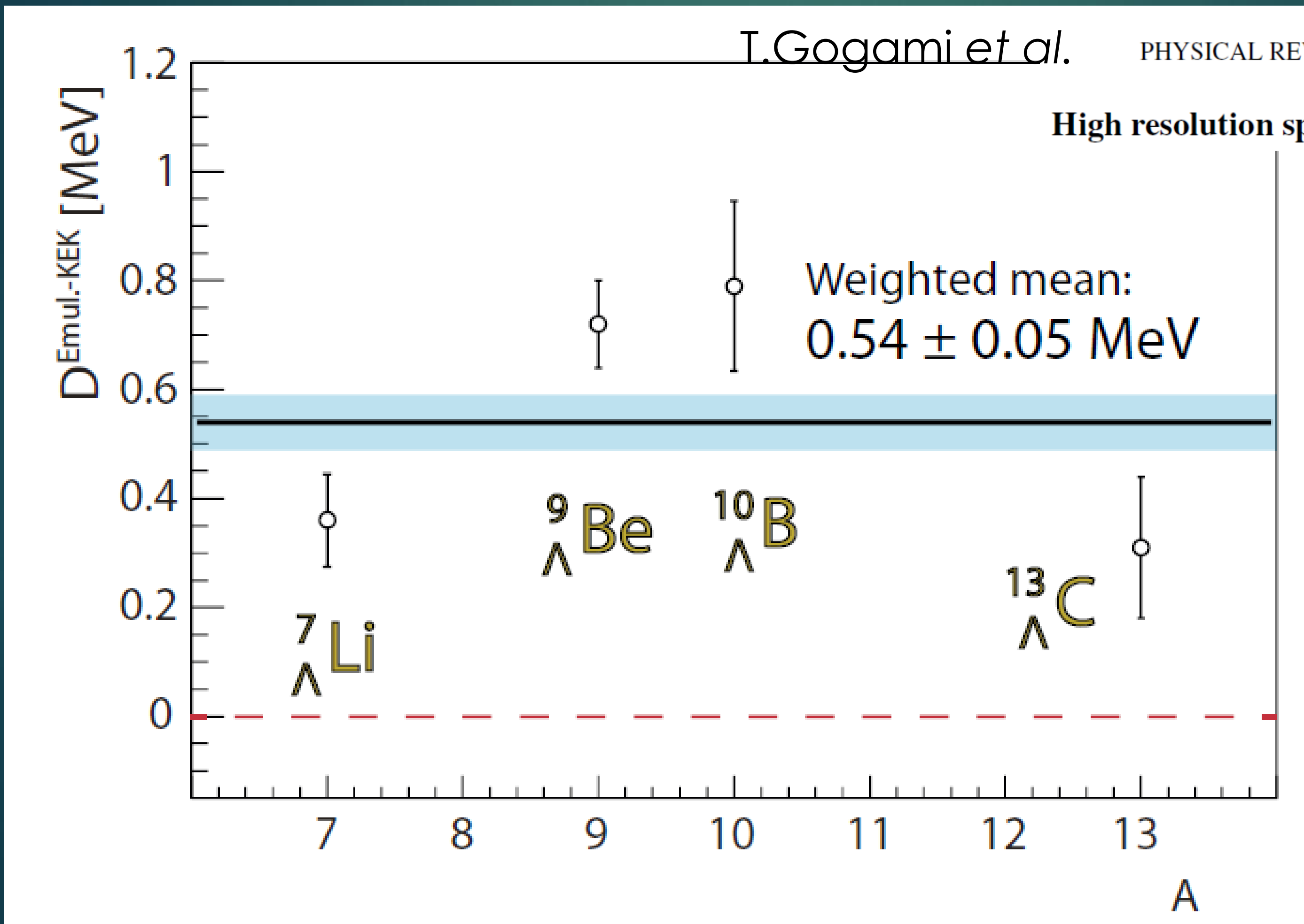
Possible shift of $^{12}_{\Lambda}\mathrm{C}_{gs}$ B_{Λ}

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

T.Gogami *et al.*

PHYSICAL REVIEW C **93**, 034314 (2016)

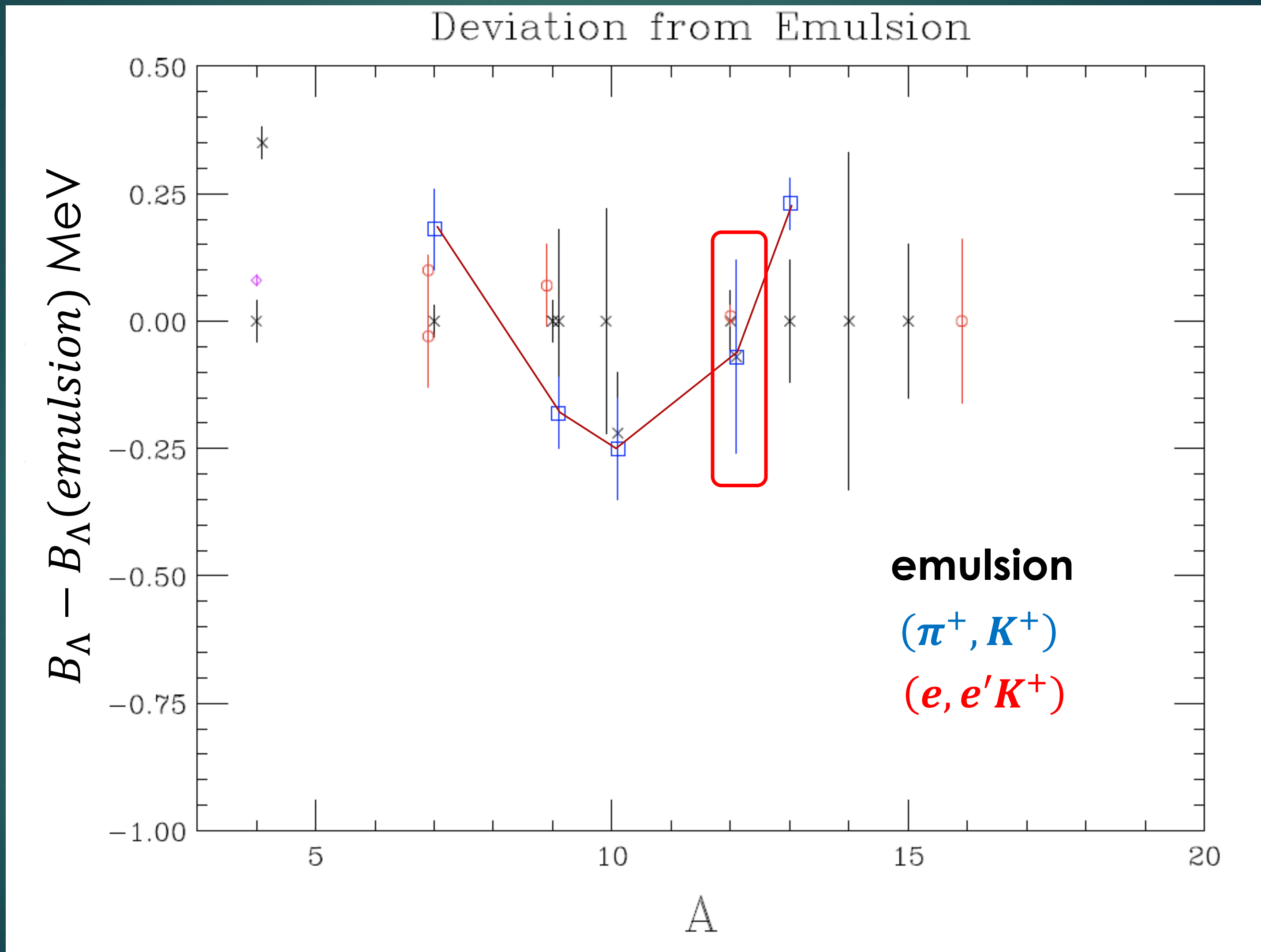
High resolution spectroscopic study of $^{10}_{\Lambda}\mathrm{Be}$



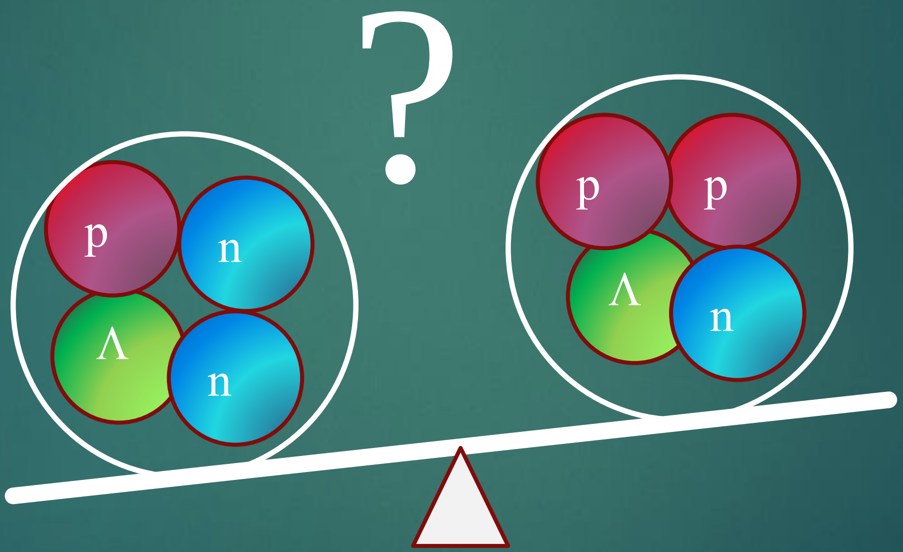
$^{10}{}_{\Lambda}\mathrm{B}$-$^{10}{}_{\Lambda}\mathrm{Be}$ =-0.50MeV

Should be 0

Shift $^{12}_{\Lambda}C_{gs}$ B_{Λ} by 0.54 MeV



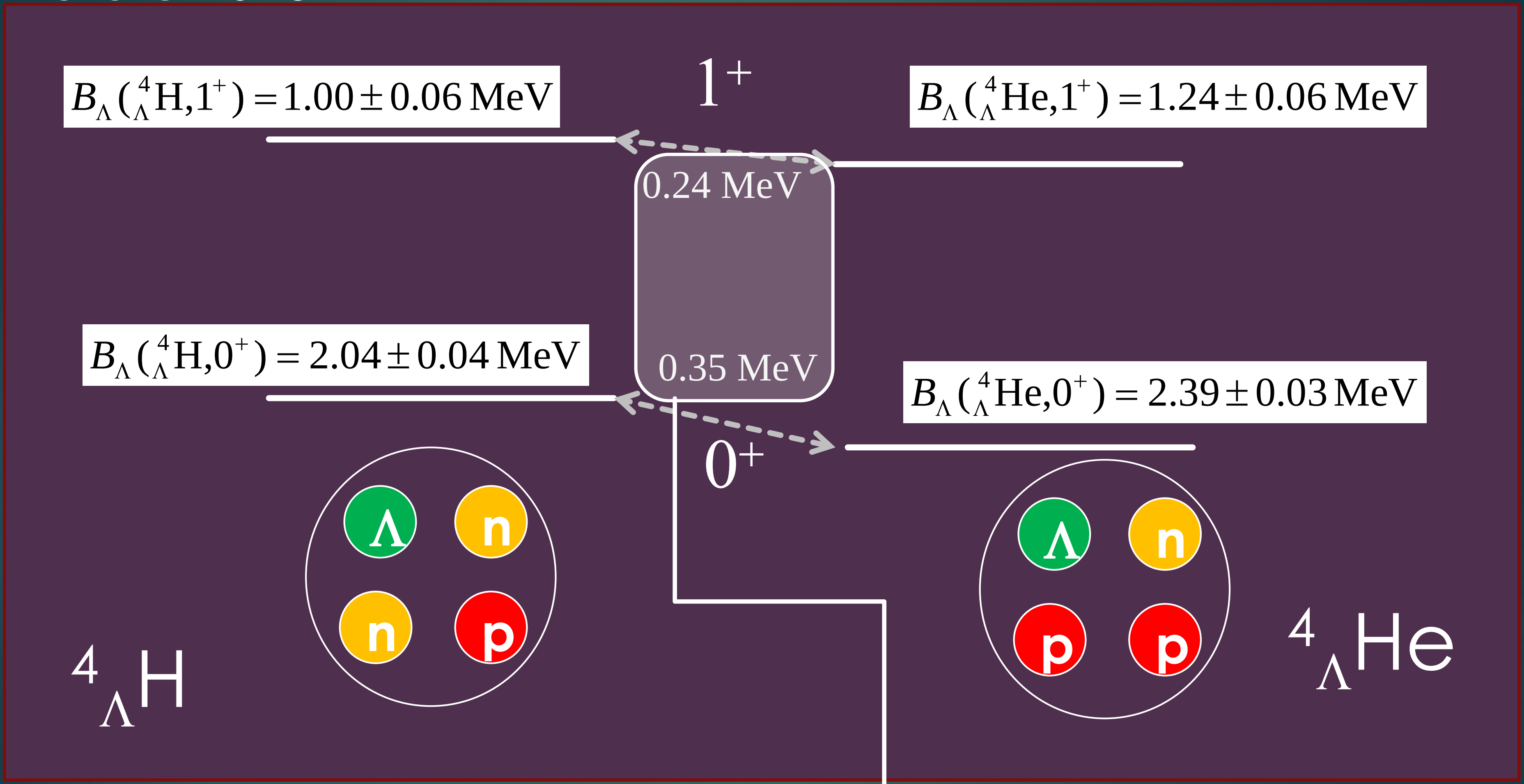
Charge Symmetry Breaking of the ΛN interaction



A=4 system

Data from
Emulsion
NaI γ-ray

Before 2015



Coulomb effect is very small.

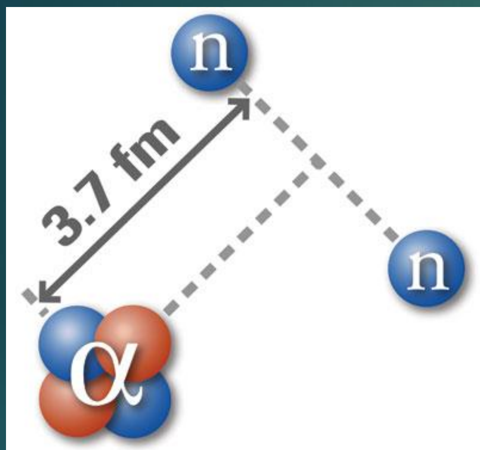
$$-\Delta B_c = 0.050 \pm 0.02 \text{ MeV},$$

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

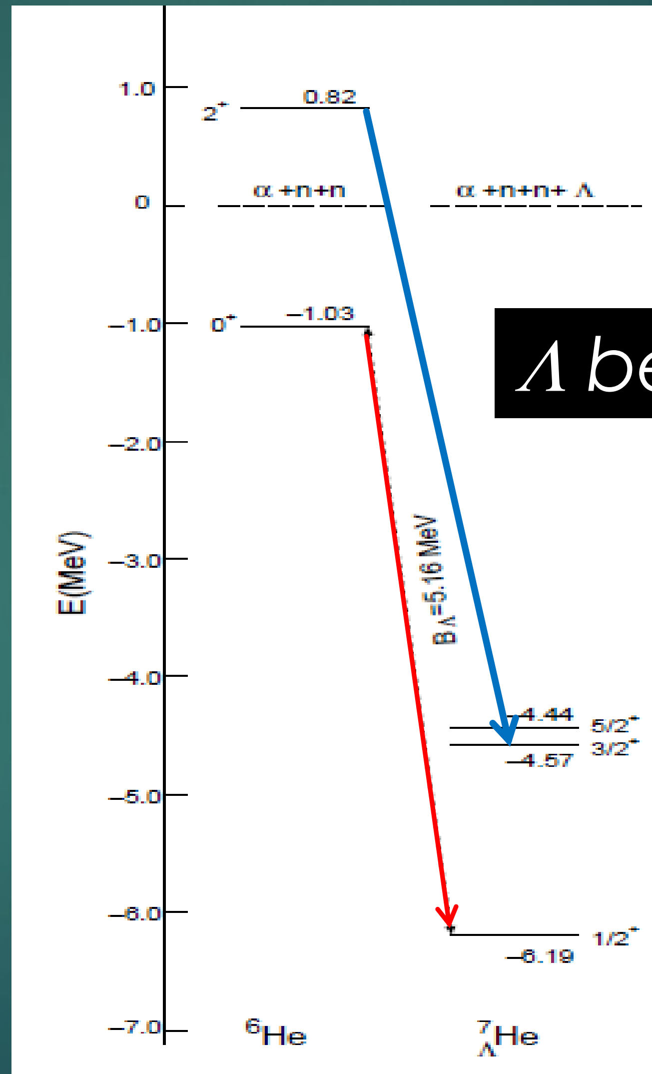
Charge Symmetry Breaking

cf) B(^{3}H)-B(^{3}He)-ΔB_c ~ 70 keV

$^{7}_{\Lambda}$He = ^{6}He + Λ



^{6}He : 2n halo

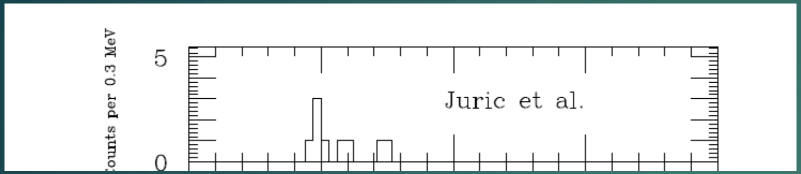


Λ behaves like glue

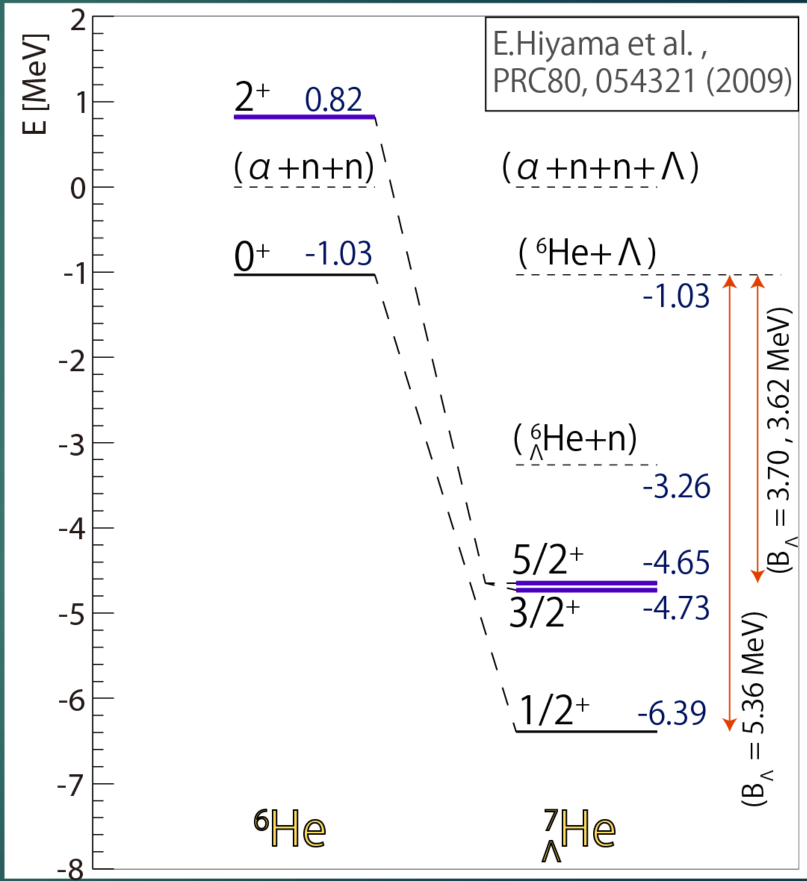
E.Hiyama et al. PRC 80, 054321 (2009)

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

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

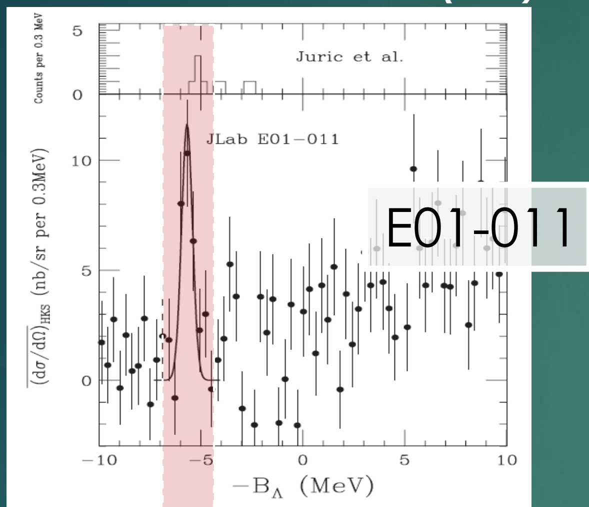


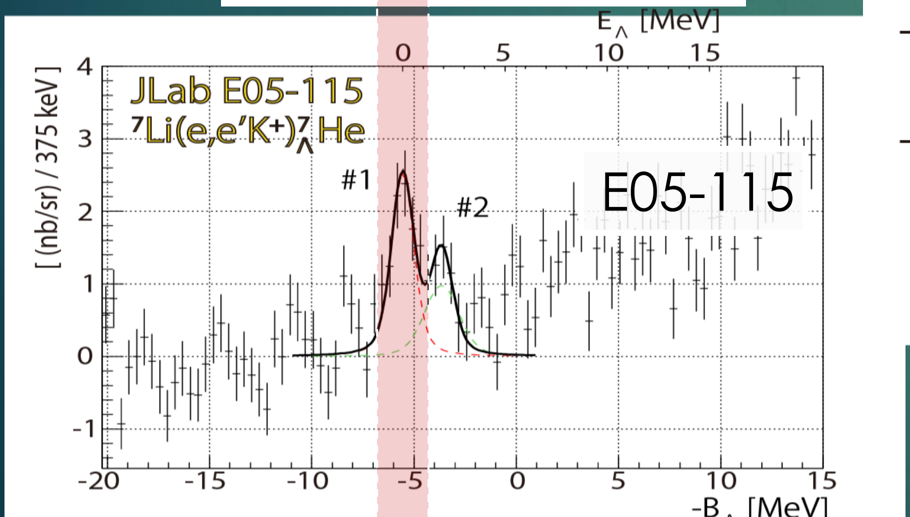
No B_Λ was obtained.



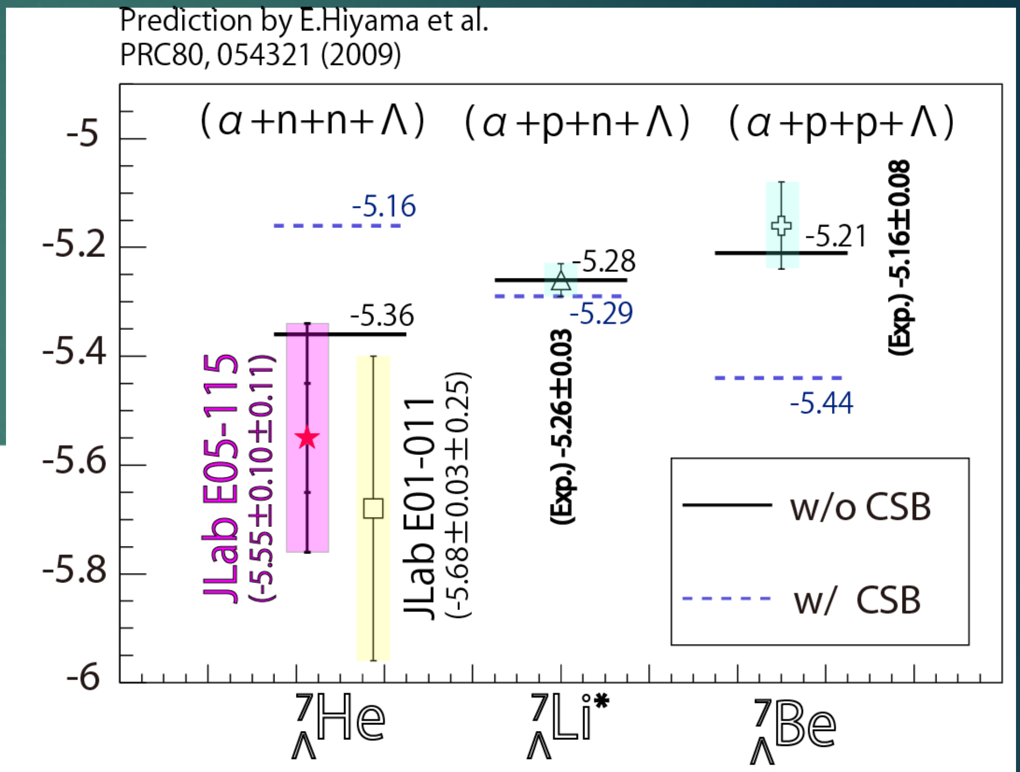
CSB interaction test in A=7 iso-triplet comparison

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

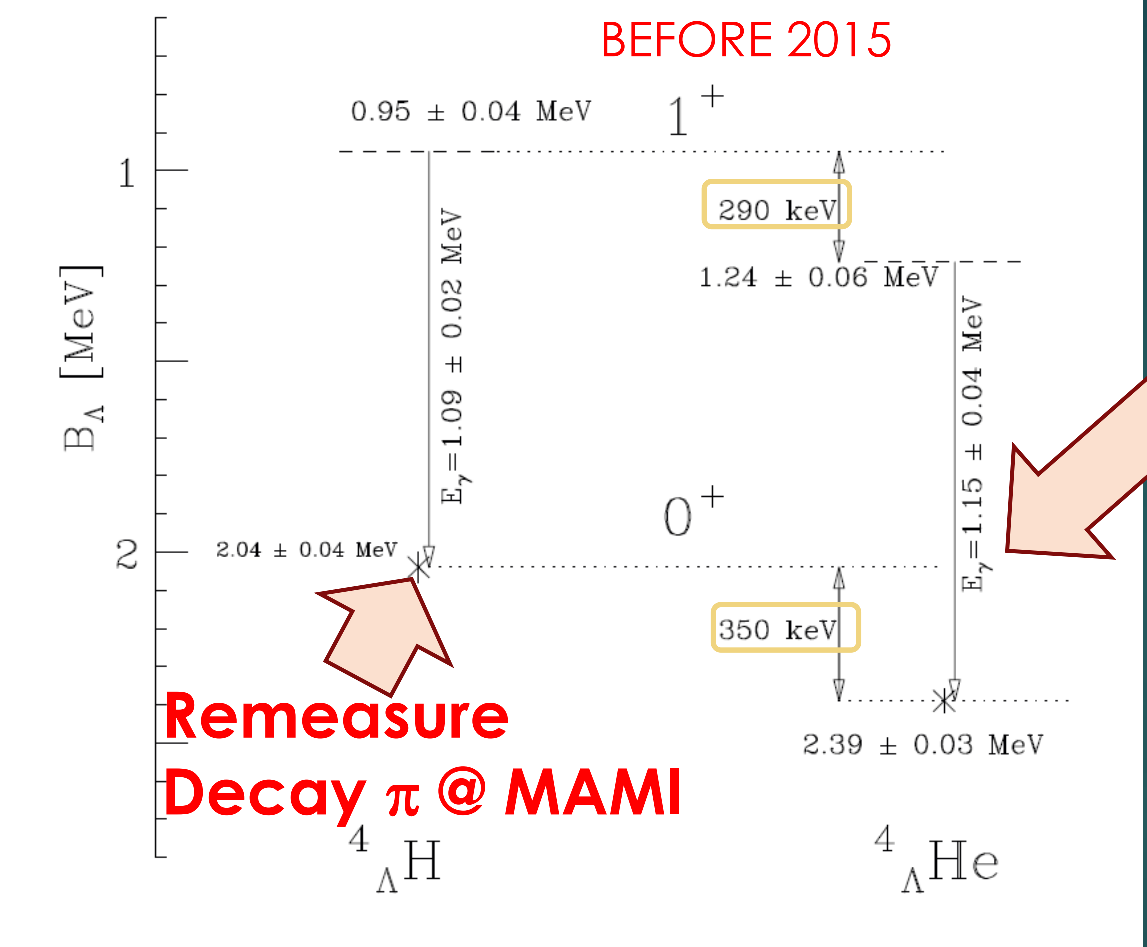




T.Gogami et al. PRC 94 021302(R) (2016)



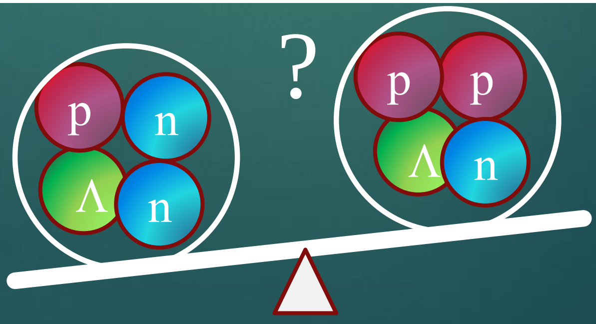
Large CSB for A=4 hypernuclei



Large CSB

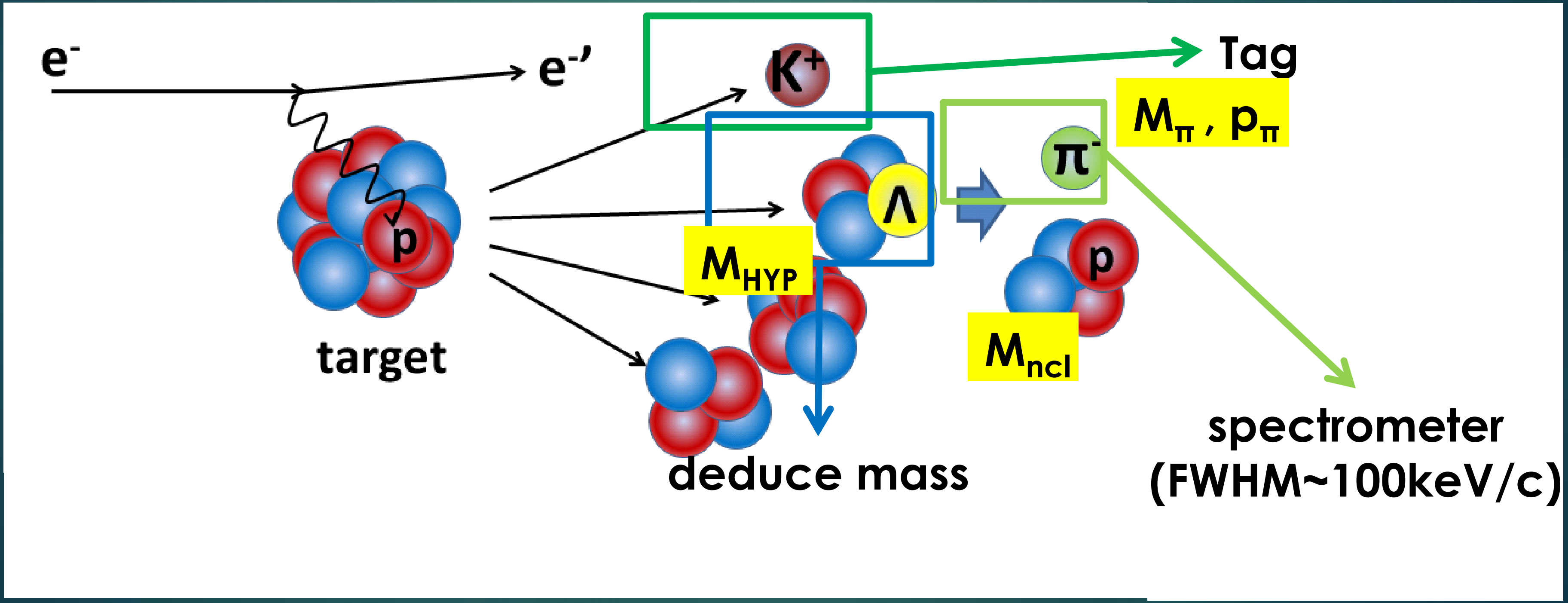
Remeasure
HY ball@J-PARC

Large CSB

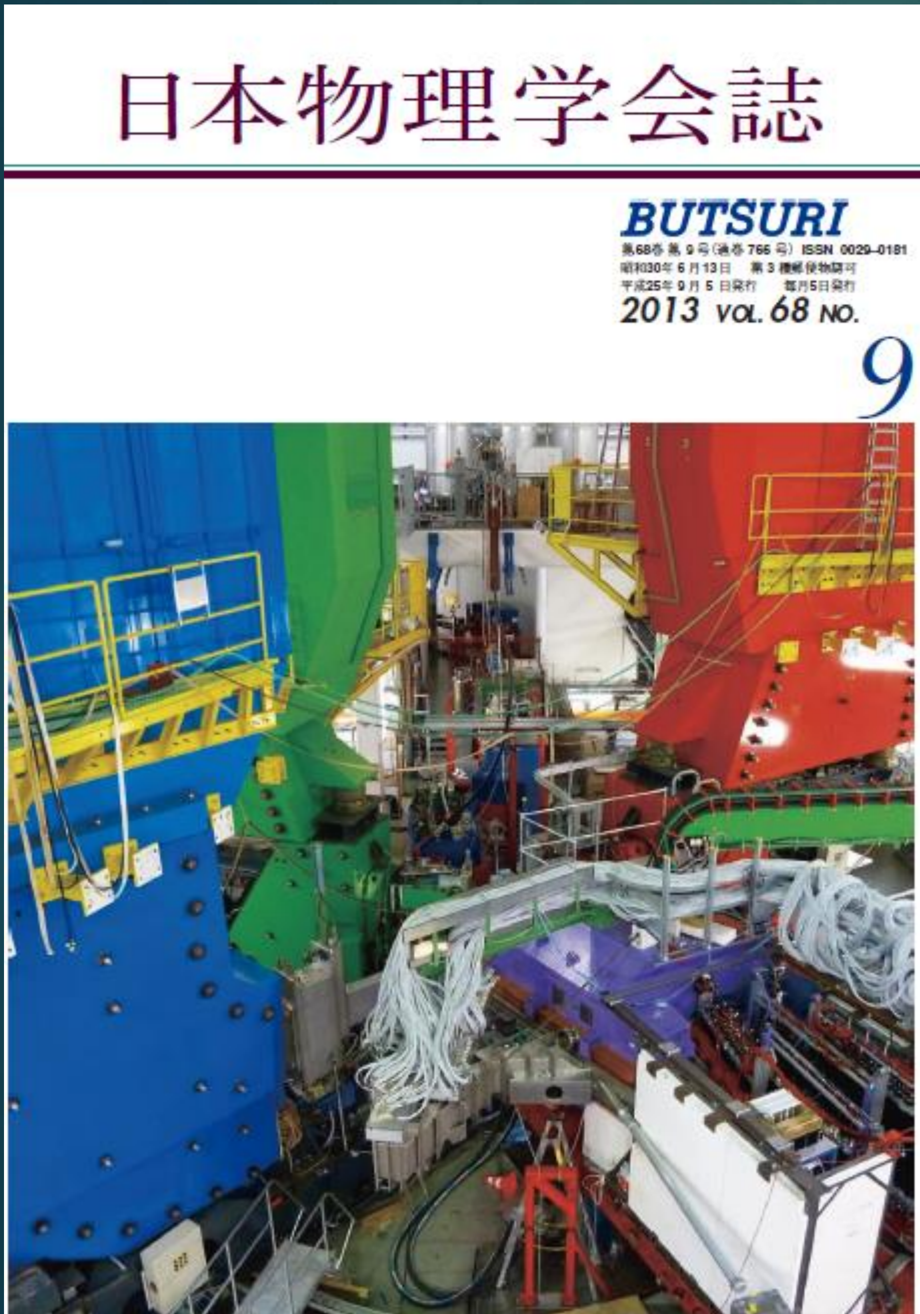


Decay π Spectroscopy of electro-produced hypernuclei

Study of ${}^{4}_{\Lambda}H$ ground state



Kaos at MAMI-C (Mainz Univ.)



Beam

Energy	1.5 GeV

Target

Material	^{9}Be
Thickness	125 μm (54° tilted)

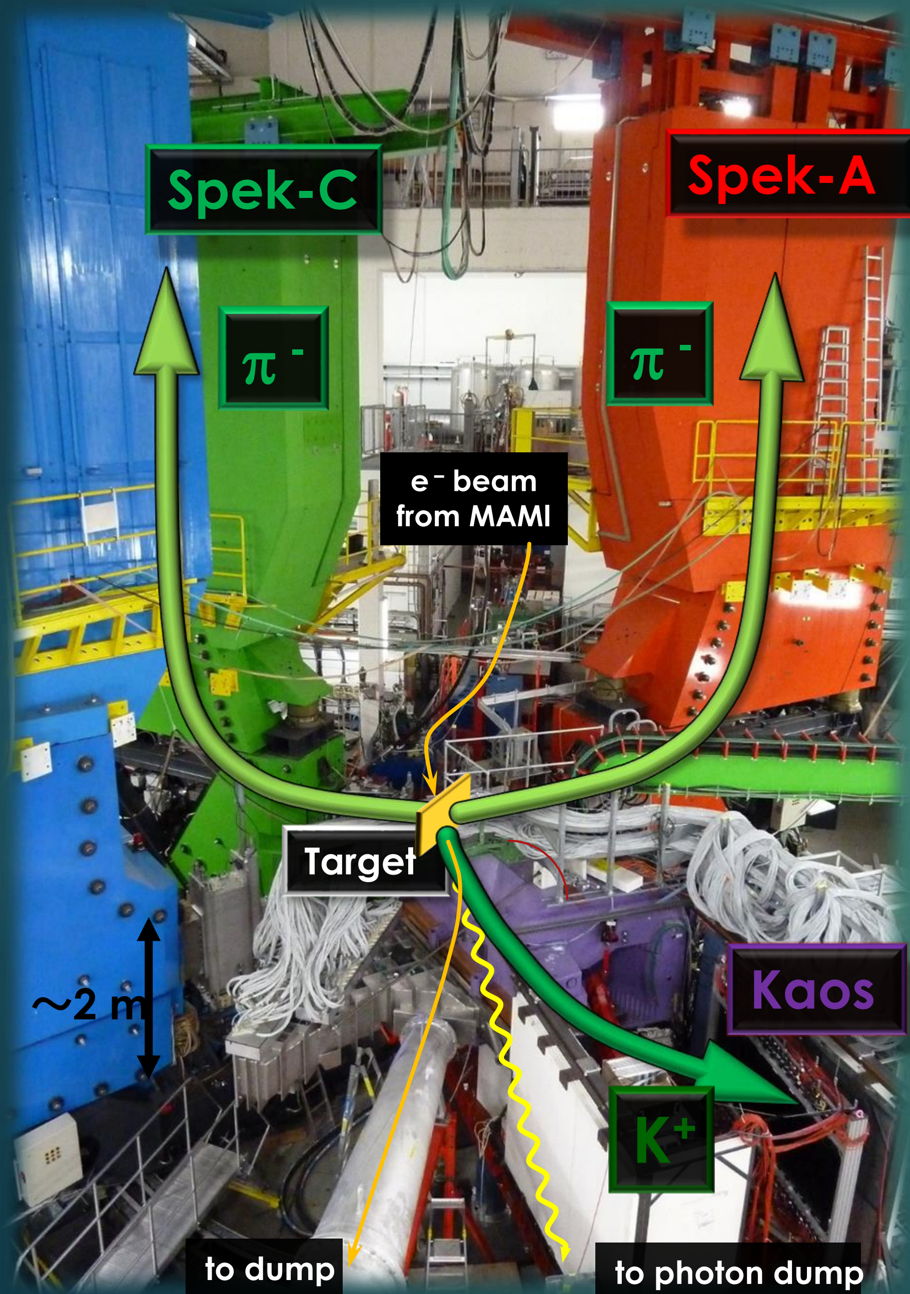
Kaos (Kaon tagger)

Cent.Mom	+900 MeV/c
Solid angle	~ 15 msr
K^{+} survival ratio	~ 40%

Spek-A, C (Pion spectrometer)

Cent.Mom	Spek-A = -115 MeV/c Spek-C = -125 MeV/c
Mom. res	$\Delta p/p < 10^{-4}$

Kaos at MAMI-C (Mainz Univ.)



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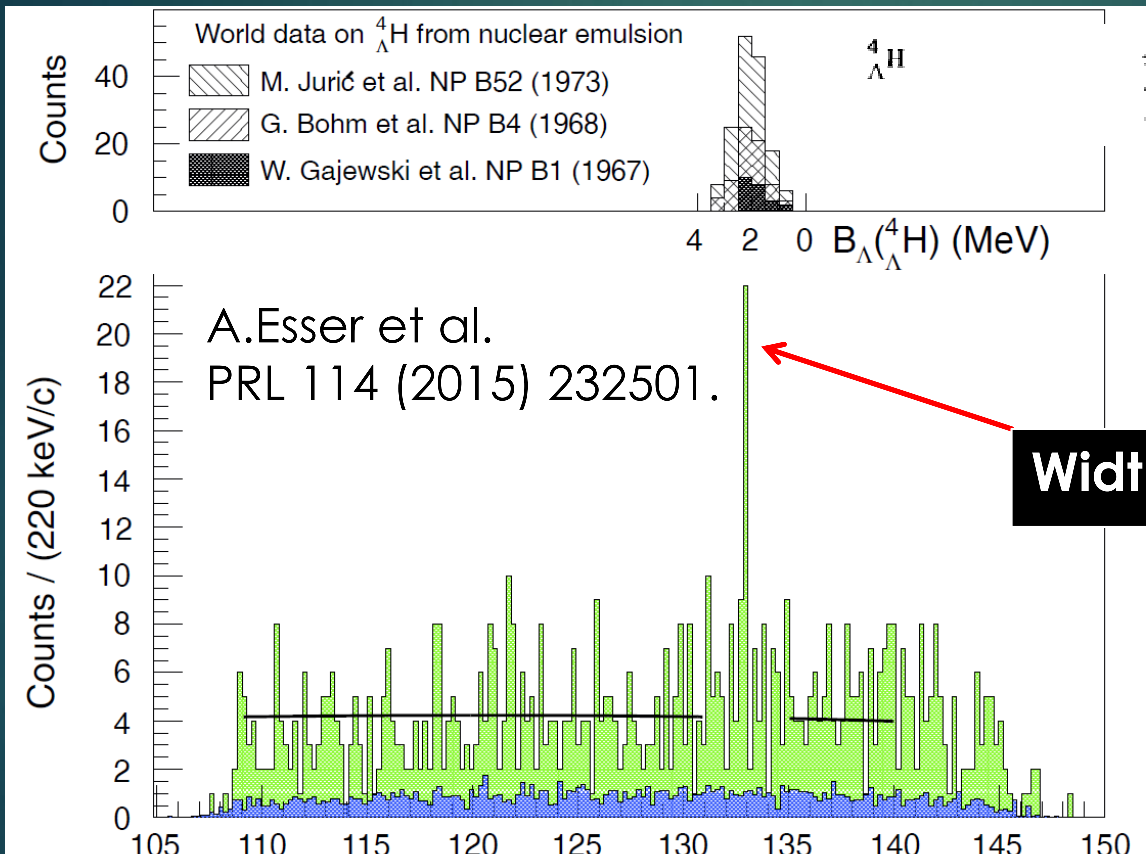
Cent.Mom	Spek-A = -115 MeV/c Spek-C = -125 MeV/c
Mom. res	$\Delta p/p < 10^{-4}$

π^- spectrum tagged by K^+



Pion momentum (MeV/c)

Kaos + Spek-C (2011-2012, 2014)

$\pi^- + {}^1H + {}^3H$	56	2.14 ± 0.07
$\pi^- + {}^2H + {}^2H$	11	1.92 ± 0.12
total	67	2.08 ± 0.06

2ch Δ = 0.22 MeV

Claimed Sys.E = 0.05 MeV

Stat. Limit

Width 230 keV/c (FWHM)

$B_\Lambda = 2.12 \pm 0.01 \pm 0.09$ MeV

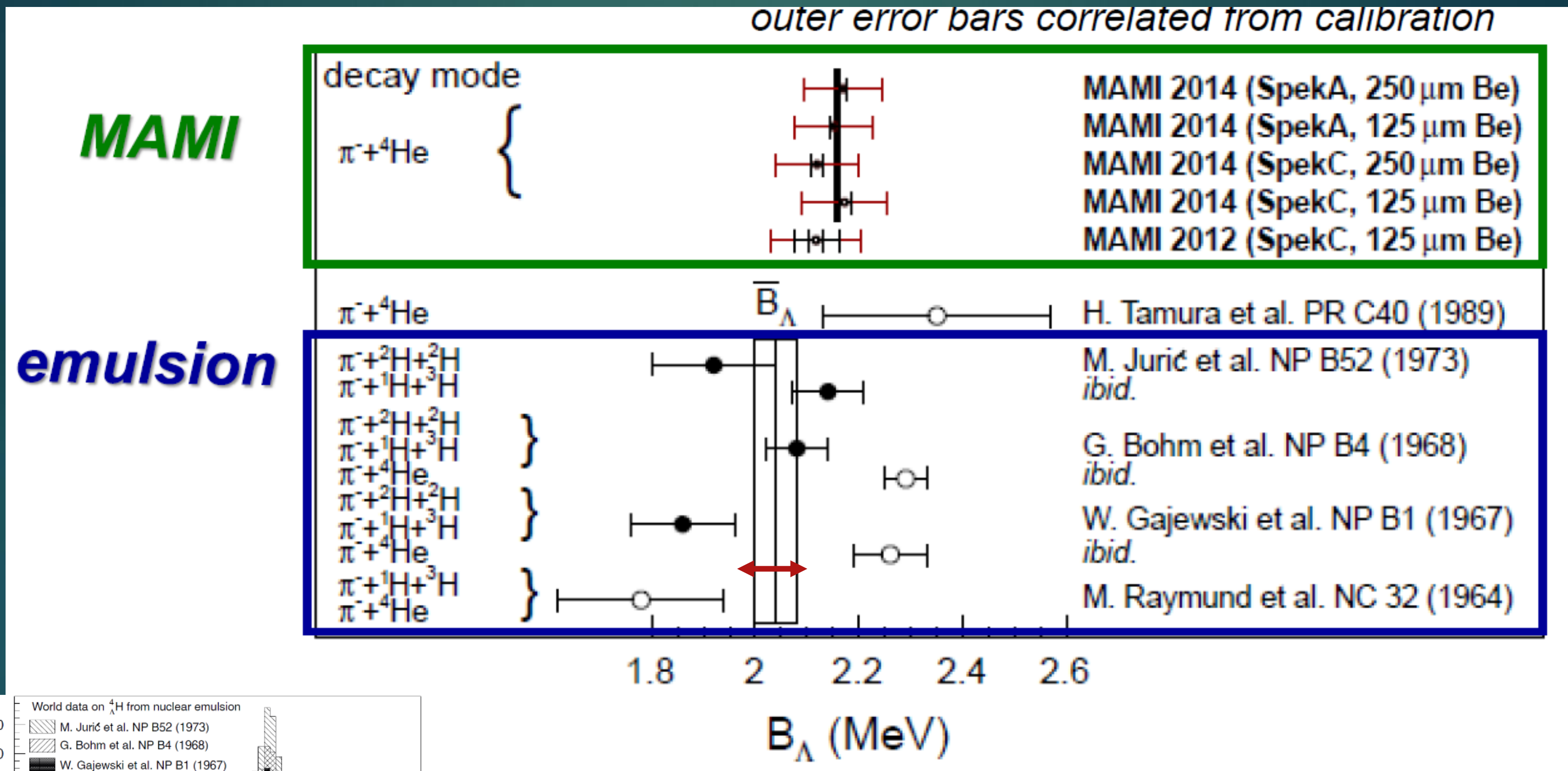
$B_\Lambda = 2.157 \pm 0.005 \pm 0.077$ MeV

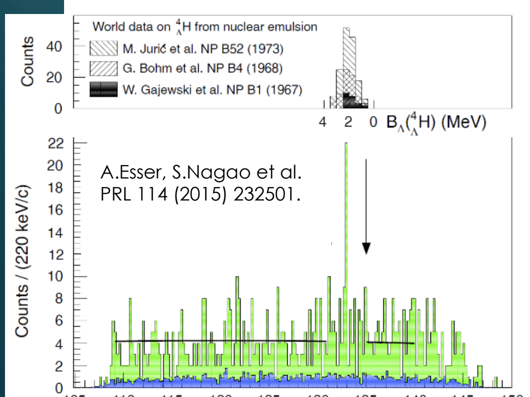
F.Schultz et al. NPA954 (2016)149.

Sys. Limit to be improved.

Decay π vs Emulsion

P.Achenbach, ASTRA2017



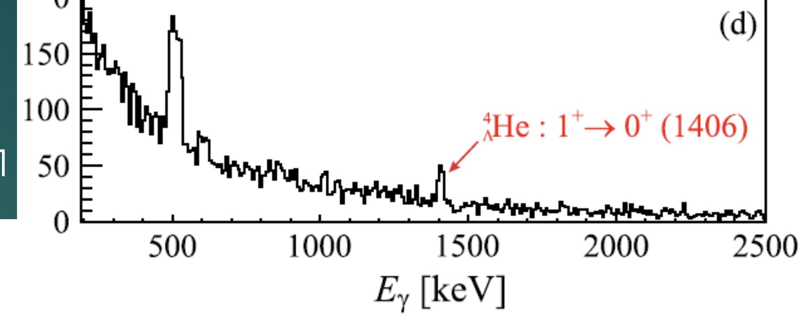


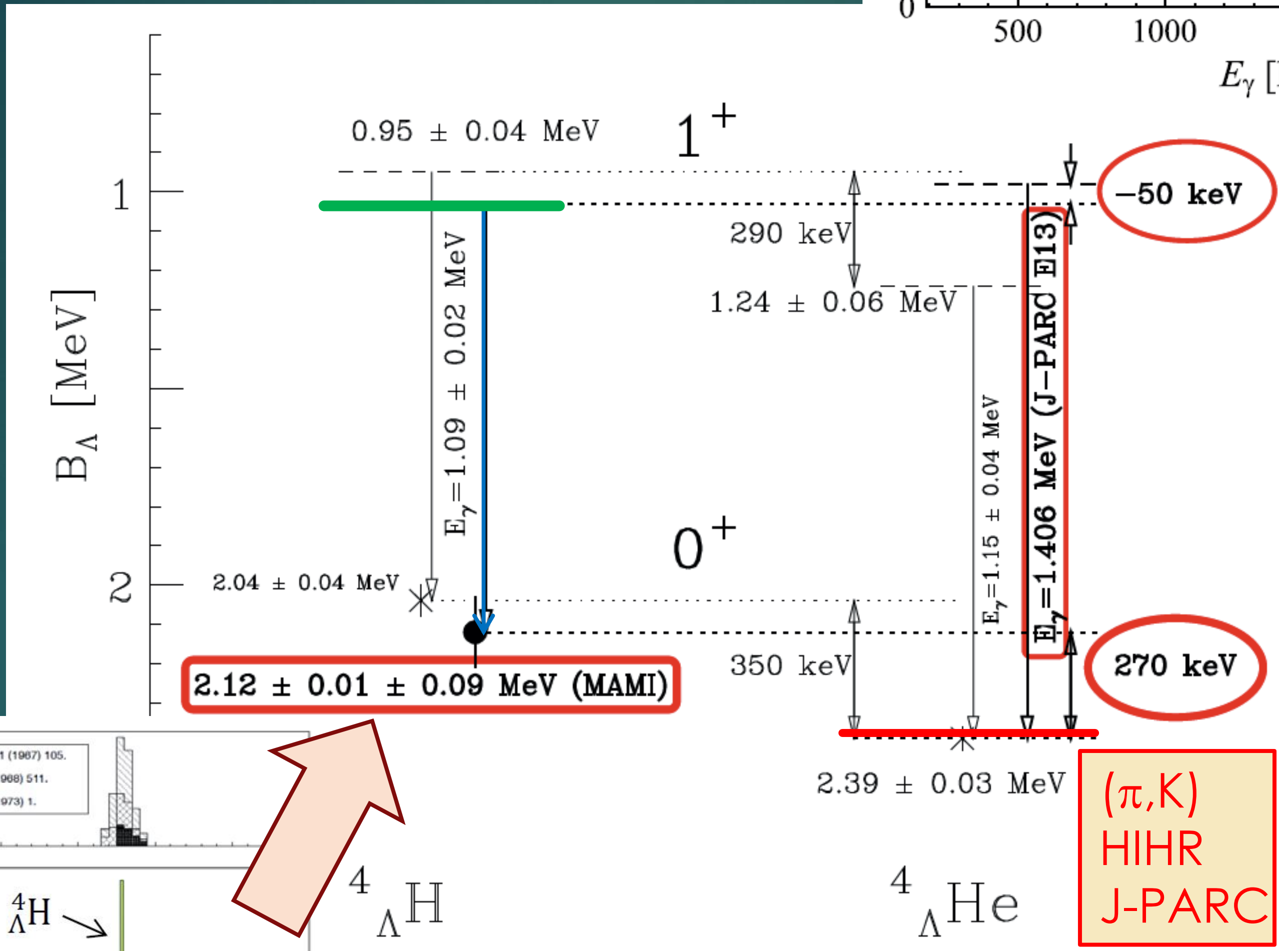
Emulsion : Stat 40 keV, Sys. 50 keV

Decay π : Stat 10 keV, Sys. 90 keV

New Measurements published in 2015

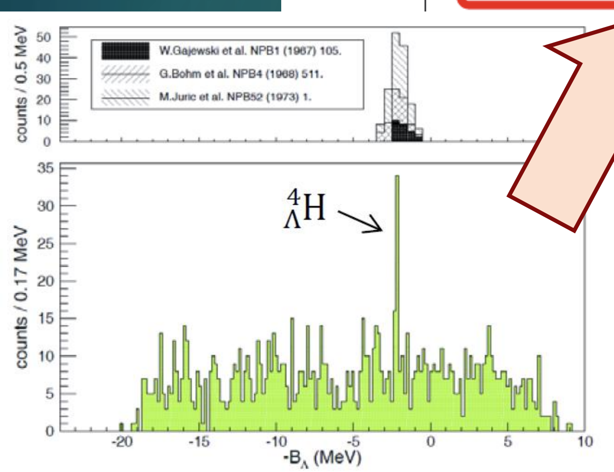
T.O.Yamamoto *et al*. PRL 115 222501





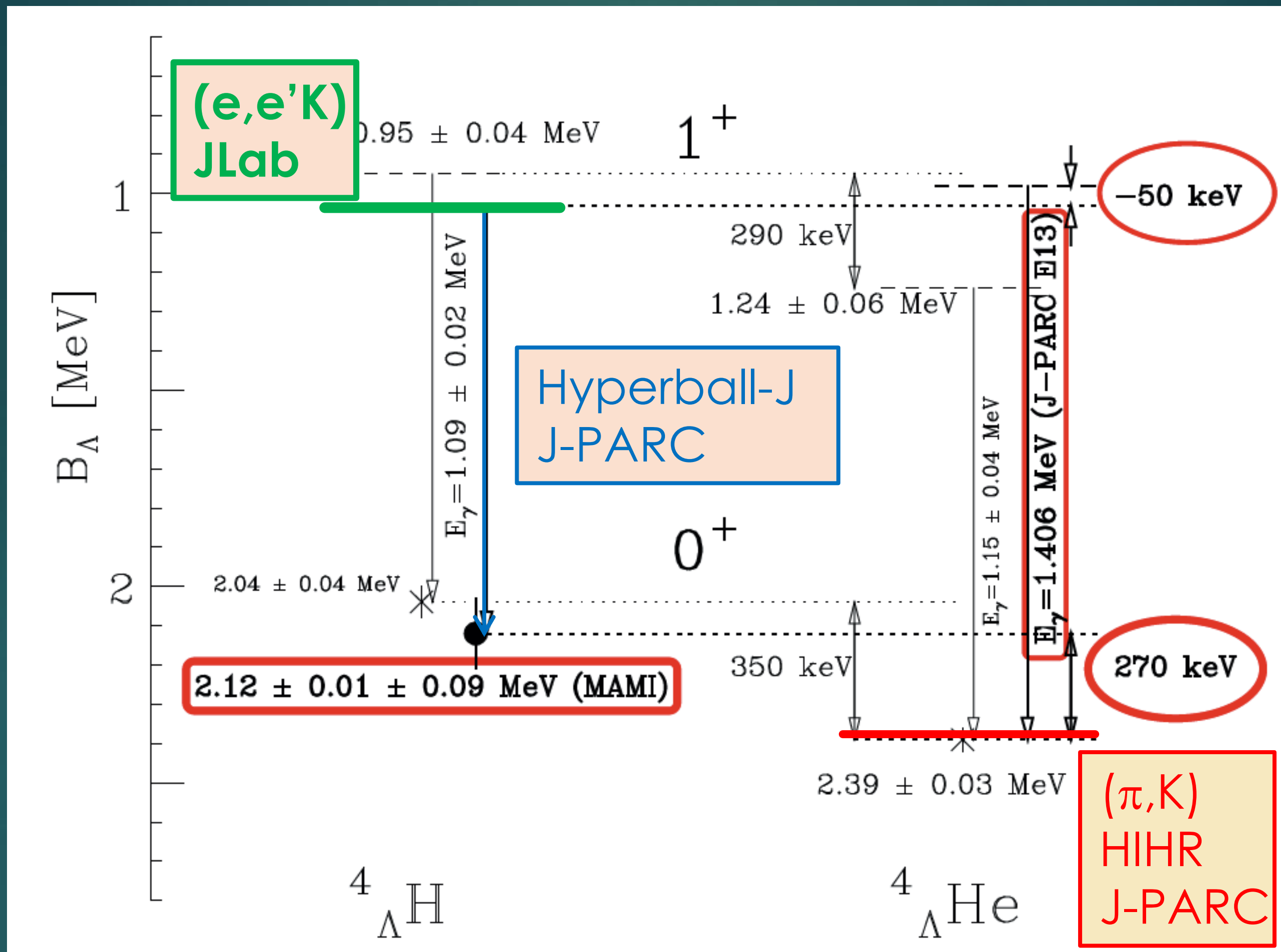
Small CSB

Large CSB



A.Esser *et al.* PRL 114 232501

CSB for A=4 hypernuclei : ***Future*** Measurements



Small CSB

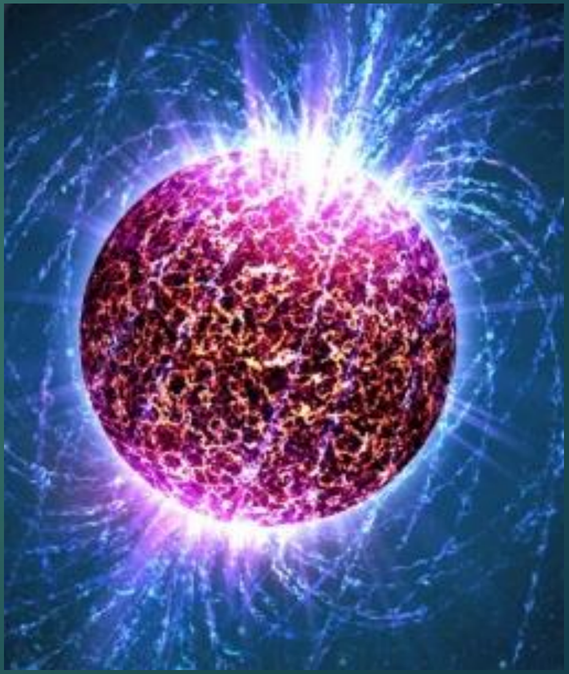
Large CSB

A.Gal
PLB744 (2015)352

Λ-Σ coupling is a key

Future Plan

Isospin dependence of the ΛNN interaction and Hyperon Puzzle

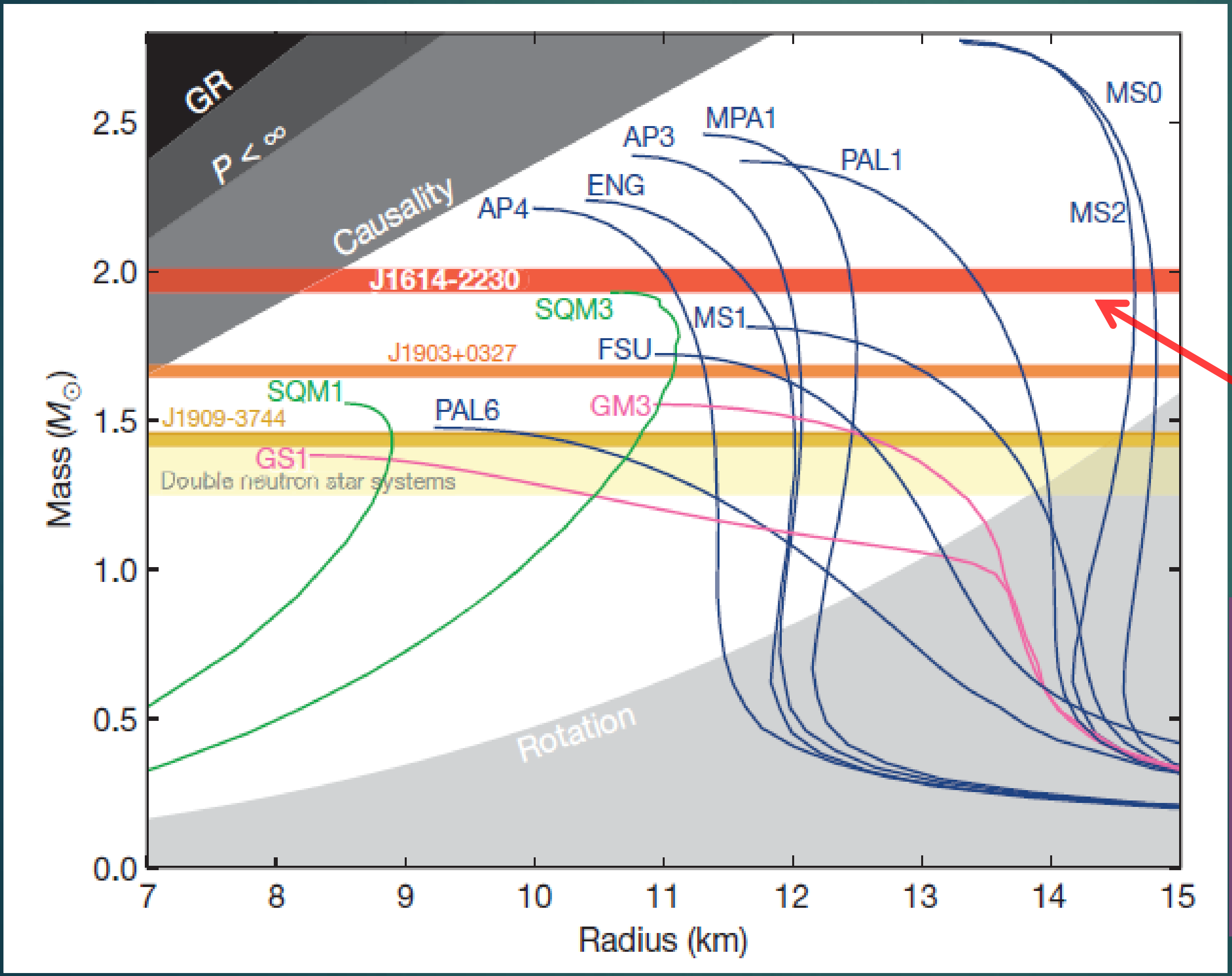


Two solar mass neutron stars

Hyperon Puzzle

Based on our knowledge on Baryonic Force:

Hyperon should appear at high density (ρ=2~3ρ_0)



Too Soft EOS

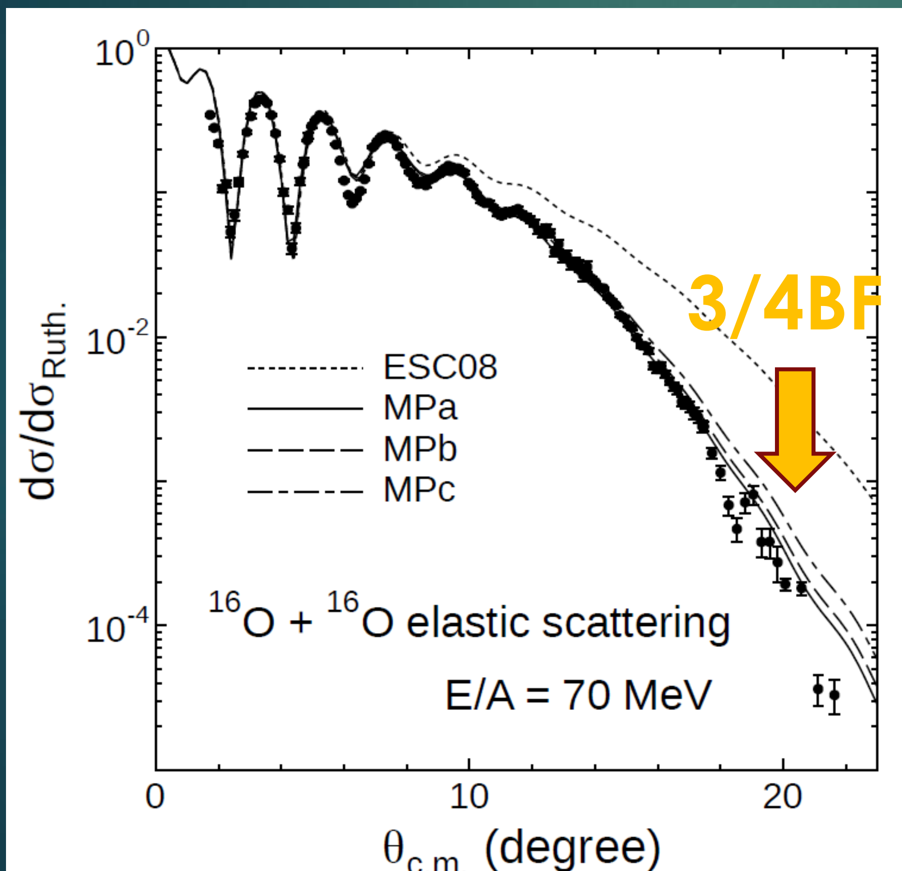
Contradict to observation

2 M_{solar} Neutron Stars

Hyperon Puzzle :
One of most important issues to be solved in nuclear physics

EOS of nuclear matter

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



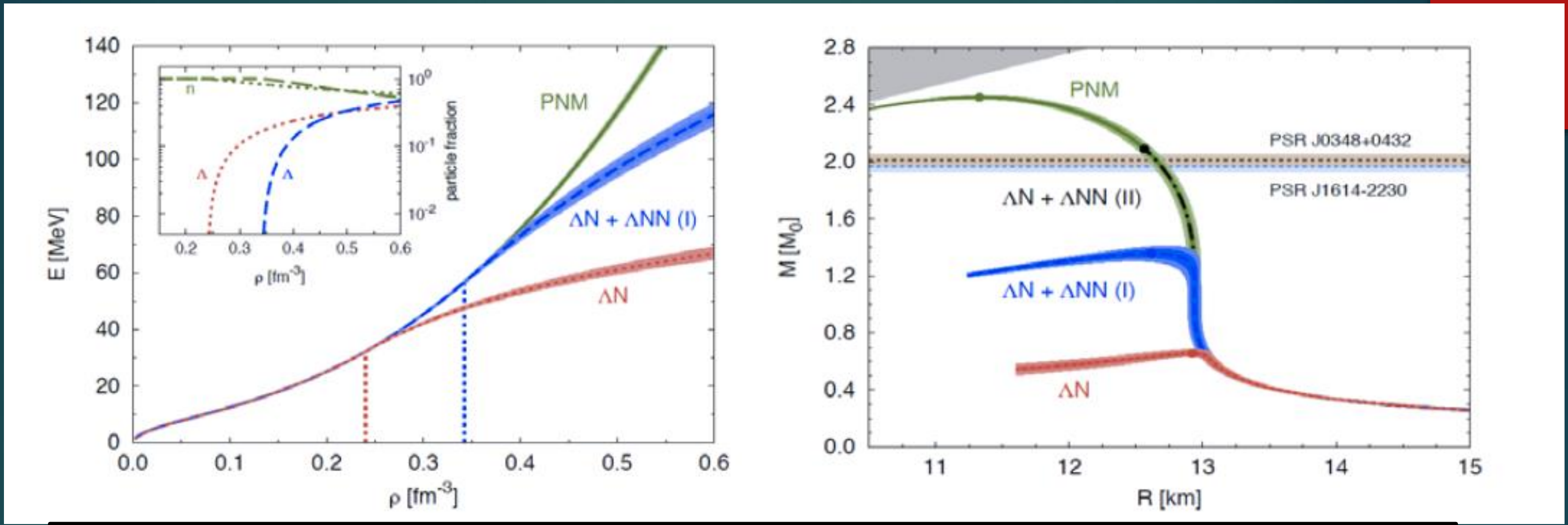
Higher density

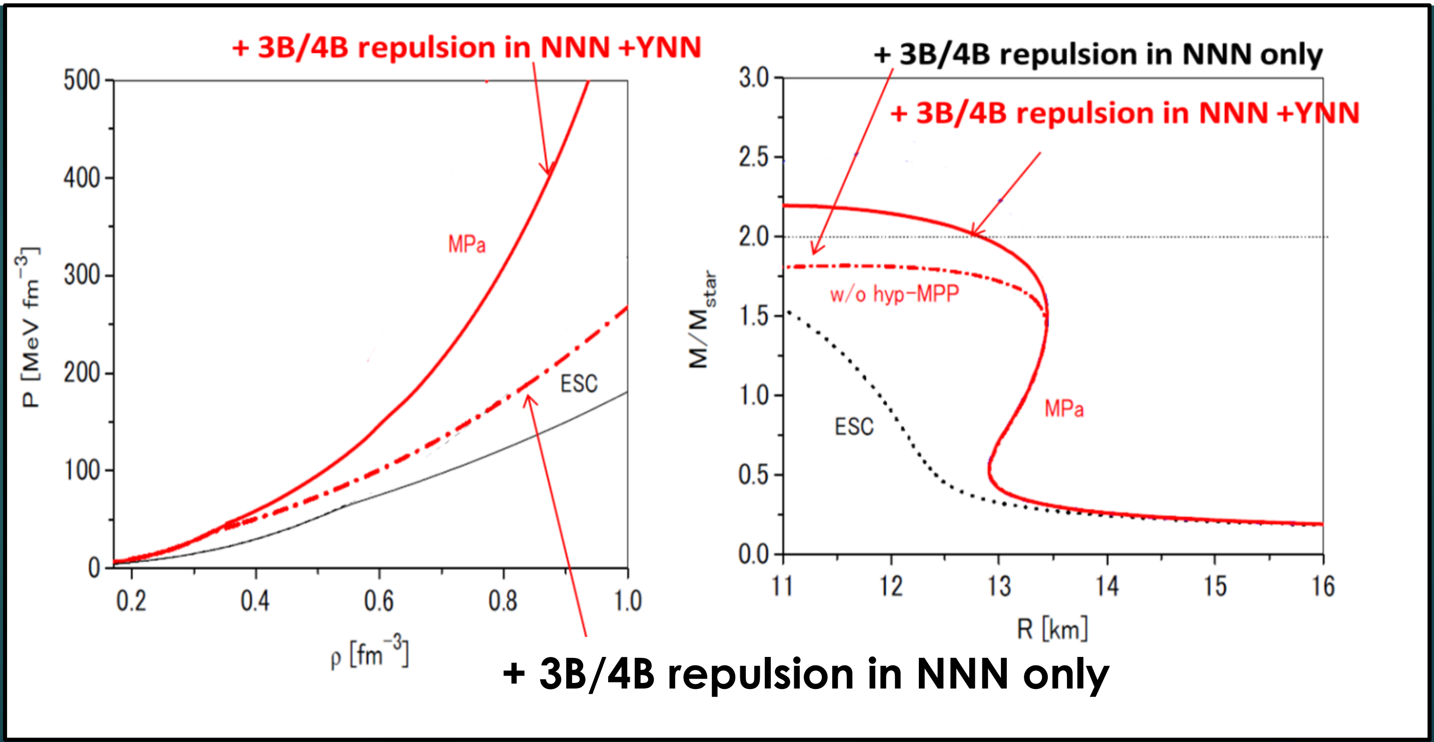
3B/4BF play key roles

Promising scenario to solve Hyp. Puzzle
Repulsive 3B/4B force in YN sector

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

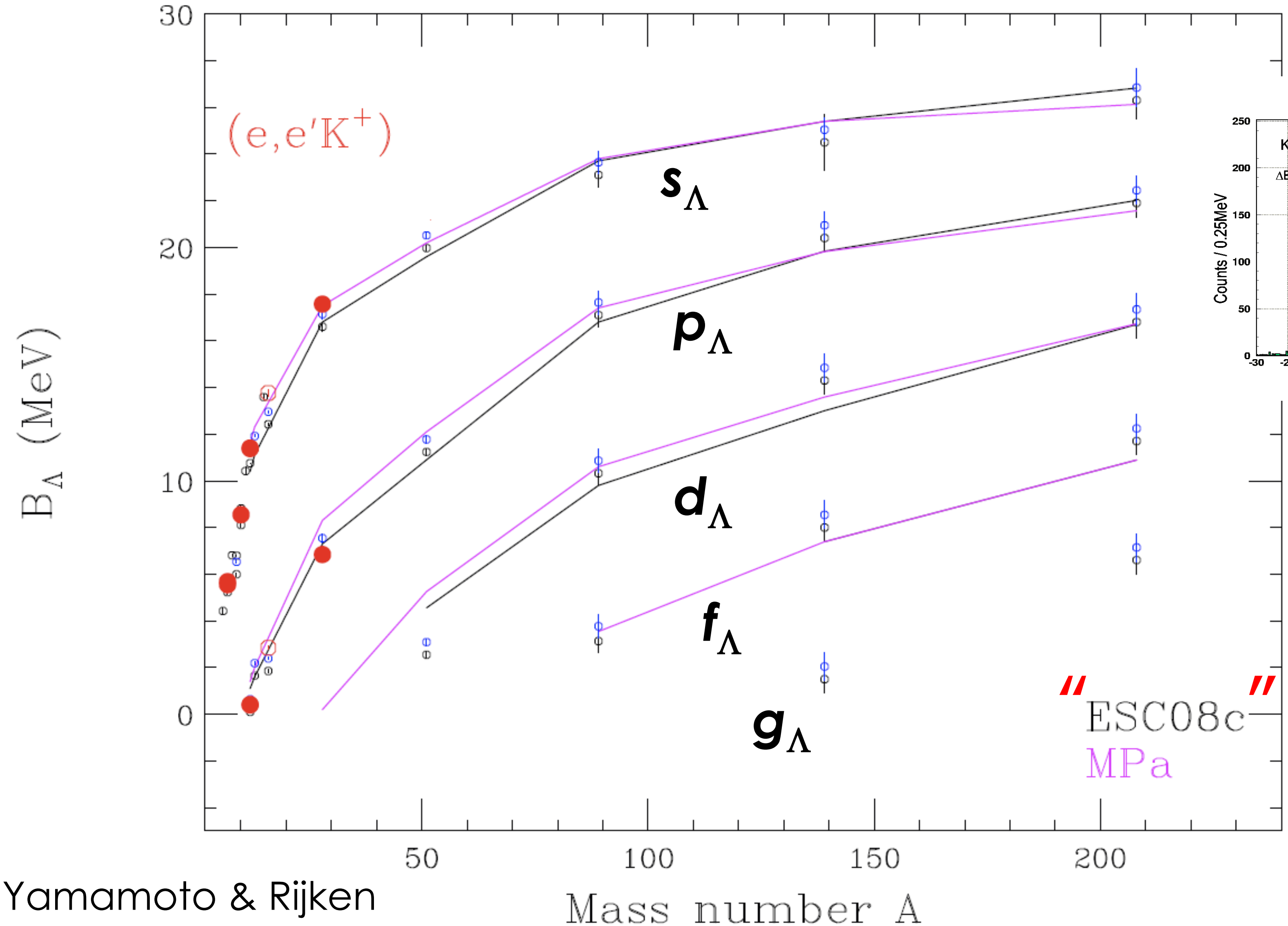
AFDMC by Lonardoni et al.



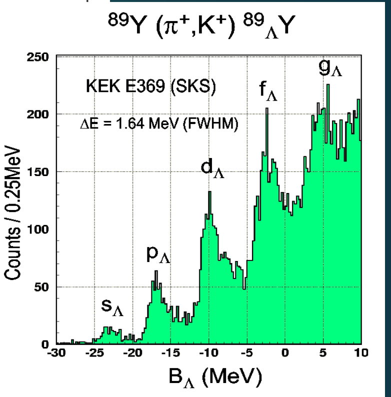


ESC08c + 3B/4B RF : G-Matrix Calc. by Yamamoto, Rijken et al.

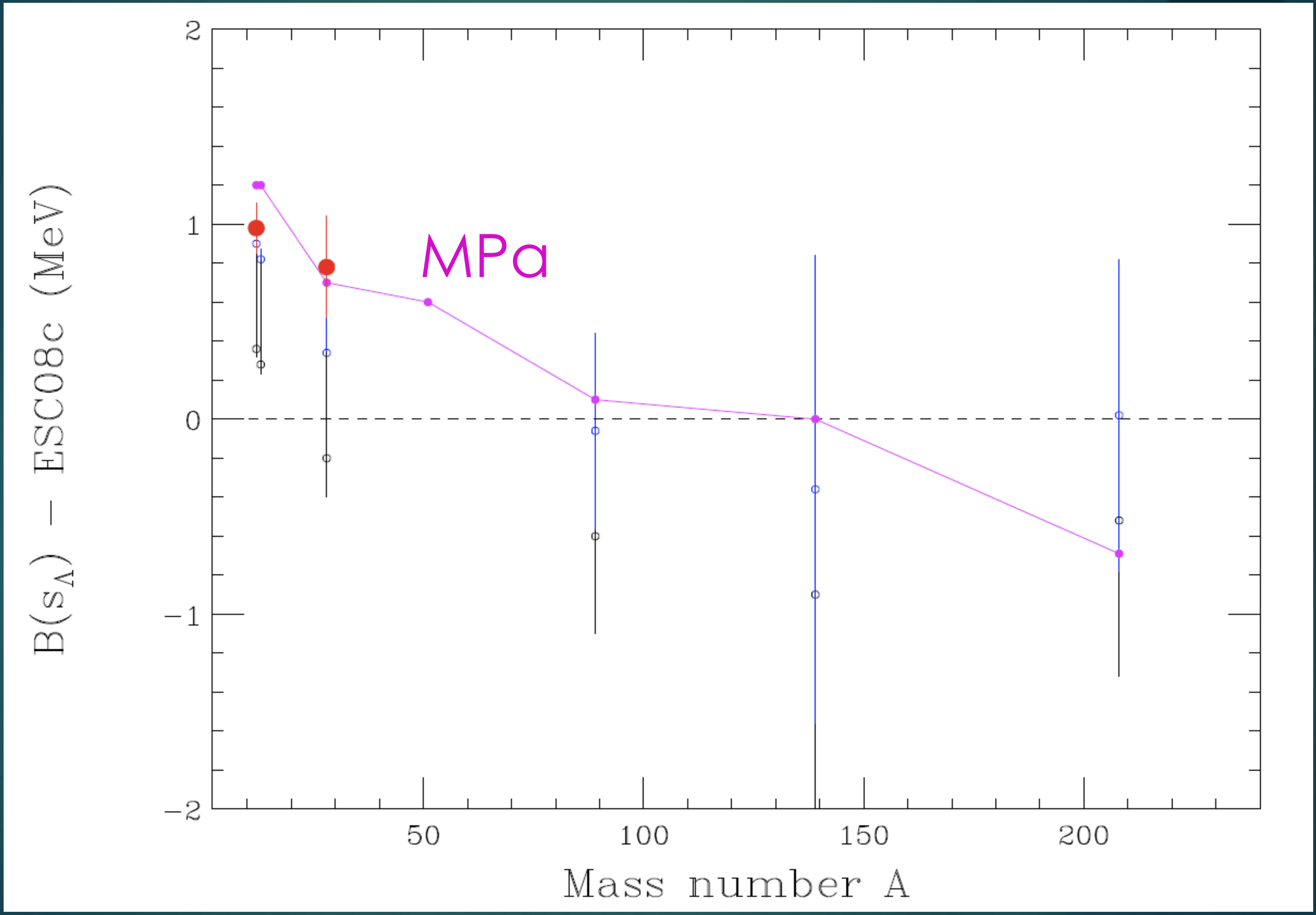
B_Λ study for wide A range



Yamamoto & Rijken



3B/4B effects for B_Λ



Special features of NS

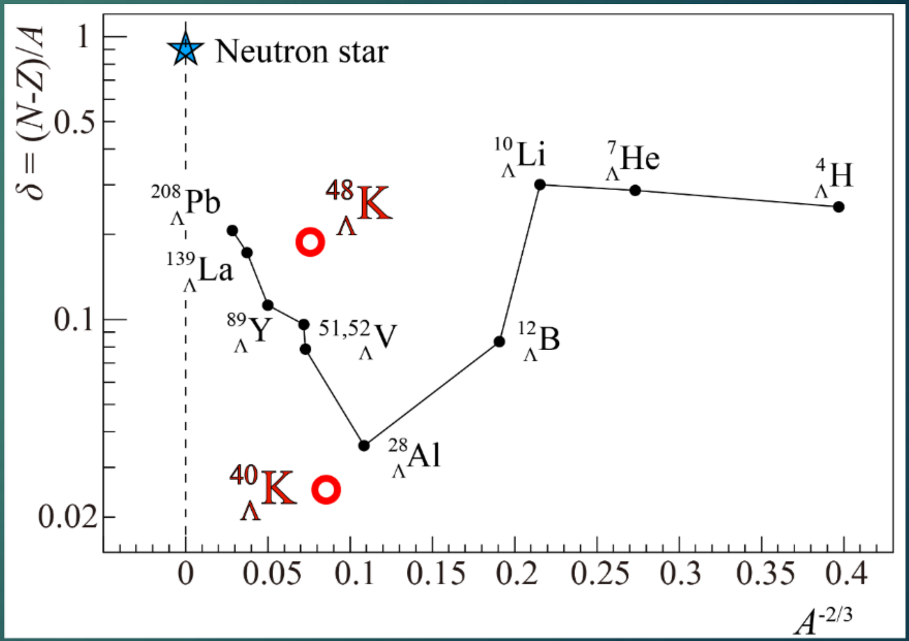
Mass No. $A \rightarrow \infty$

Extrapolate from various data

A=1 (elementary) ELPH, A<12 MAMI, JLab, 12≤A JLab

Isospin Asymmetry

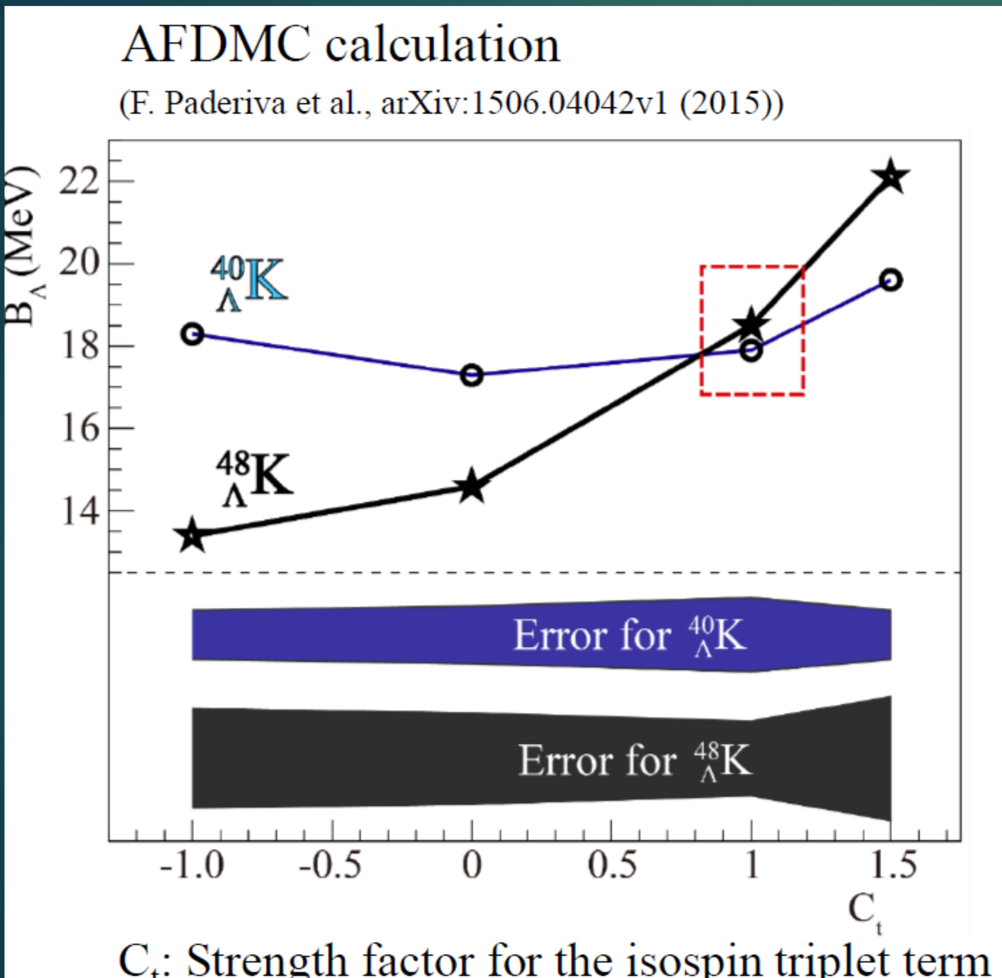
$$\delta = \frac{N - Z}{A} \sim 1$$



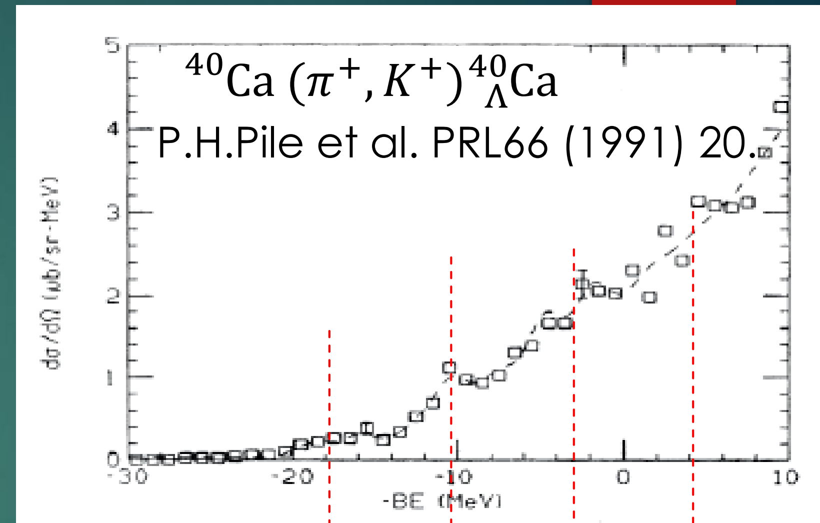
No isospin dep. data for med-heavy Hyp.Nucl.

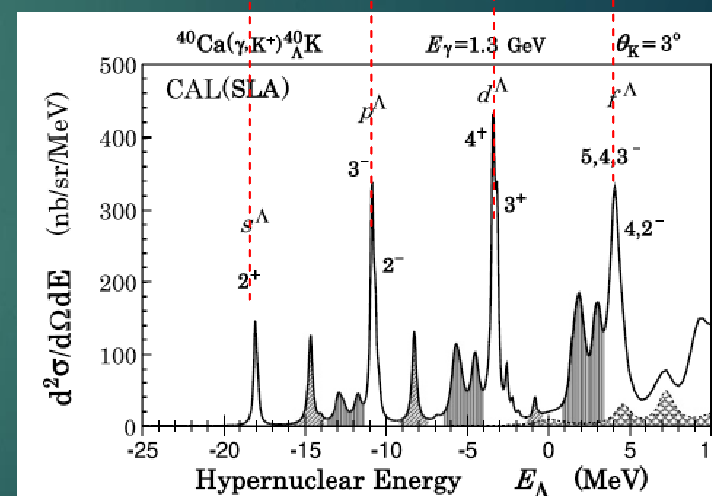
Phenomenological 3 BRF+AFDMC

$$\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j = -3P^{\mathrm{T}=0} + \mathrm{C_T}\, P^{\mathrm{T}=1}$$



^{40}Ca(e ,e′K$^+$)$^{40}{}_{\Lambda}$K and , ^{48}Ca(e, e′K$^+$)$^{48}{}_{\Lambda}$K

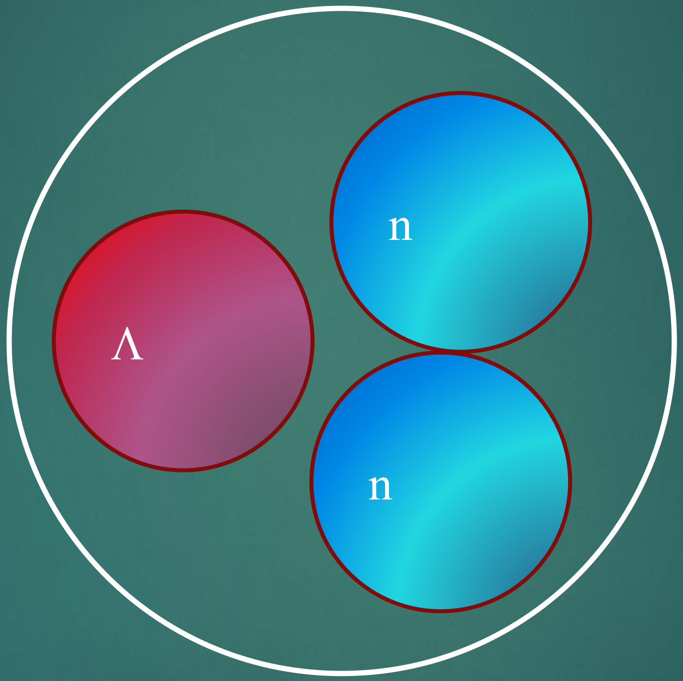




T.Motoba et al., PTPsuppl. 185 (2010)224.

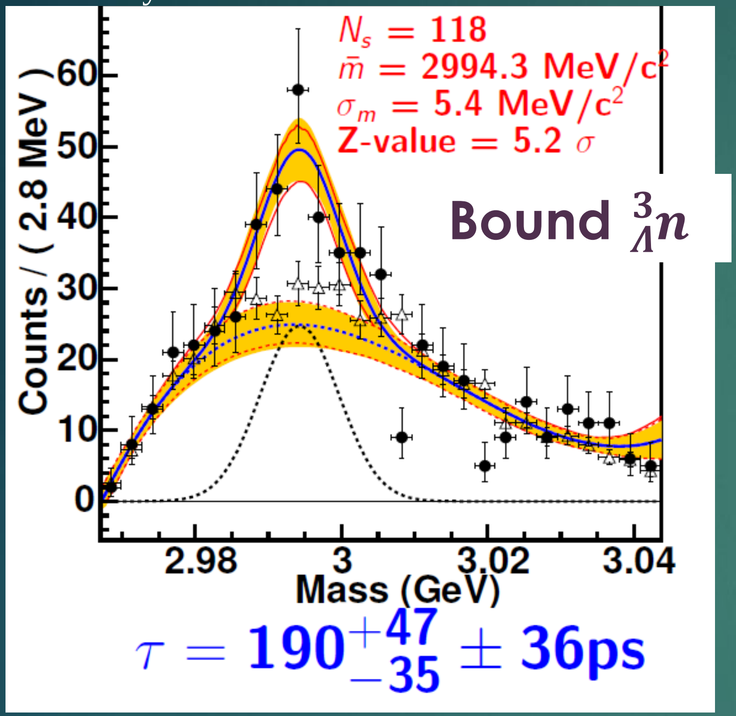
JLab E12-15-008 Grade A Approved

$nn\Lambda$ state exists?



nnΛ state exists?

C. Rappold et al. (HypHI Collaboration), Phys. Rev. C 88, 041001(R) (2013).
Talk by C.R. at EMMI2

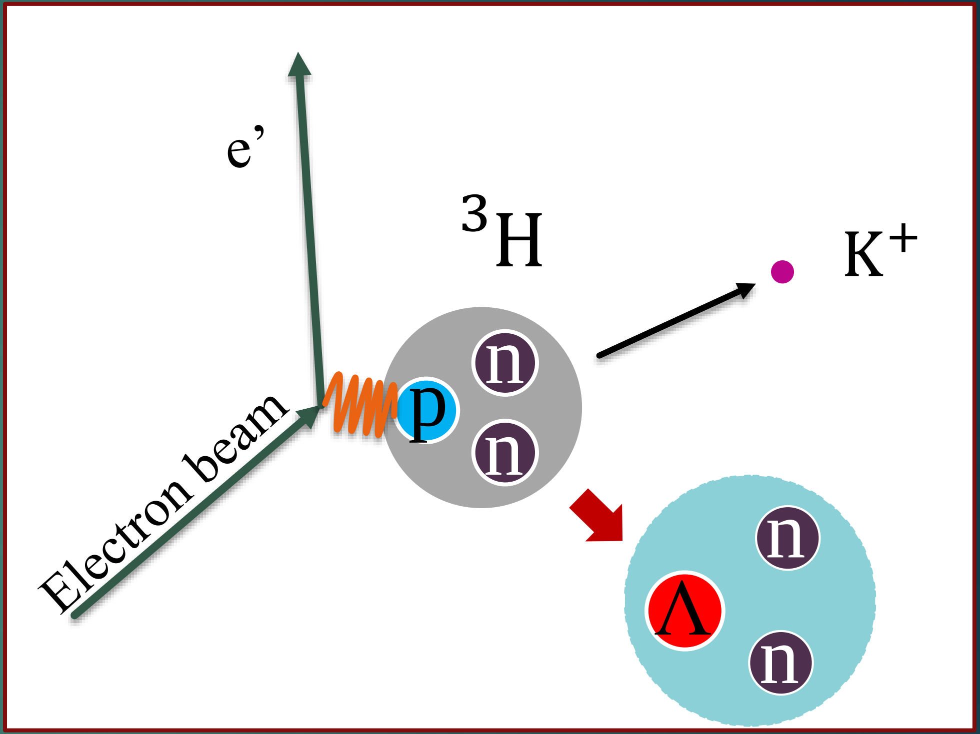


Bound ${}^{3}_{\Lambda}n$ ***cannot be reproduced:***

E. Hiyama et al., Phys. Rev. C 89, 061302(R) (2014)
A. Gal et al., Phys. Lett. B 736, 93–97 (2014)

Resonance nnΛ may exist:

I.R.Afnan et al., PRC 92, 054608 (2015)
H. Kamada et al., EPJ Web Conf. 113, 07004 (2016)



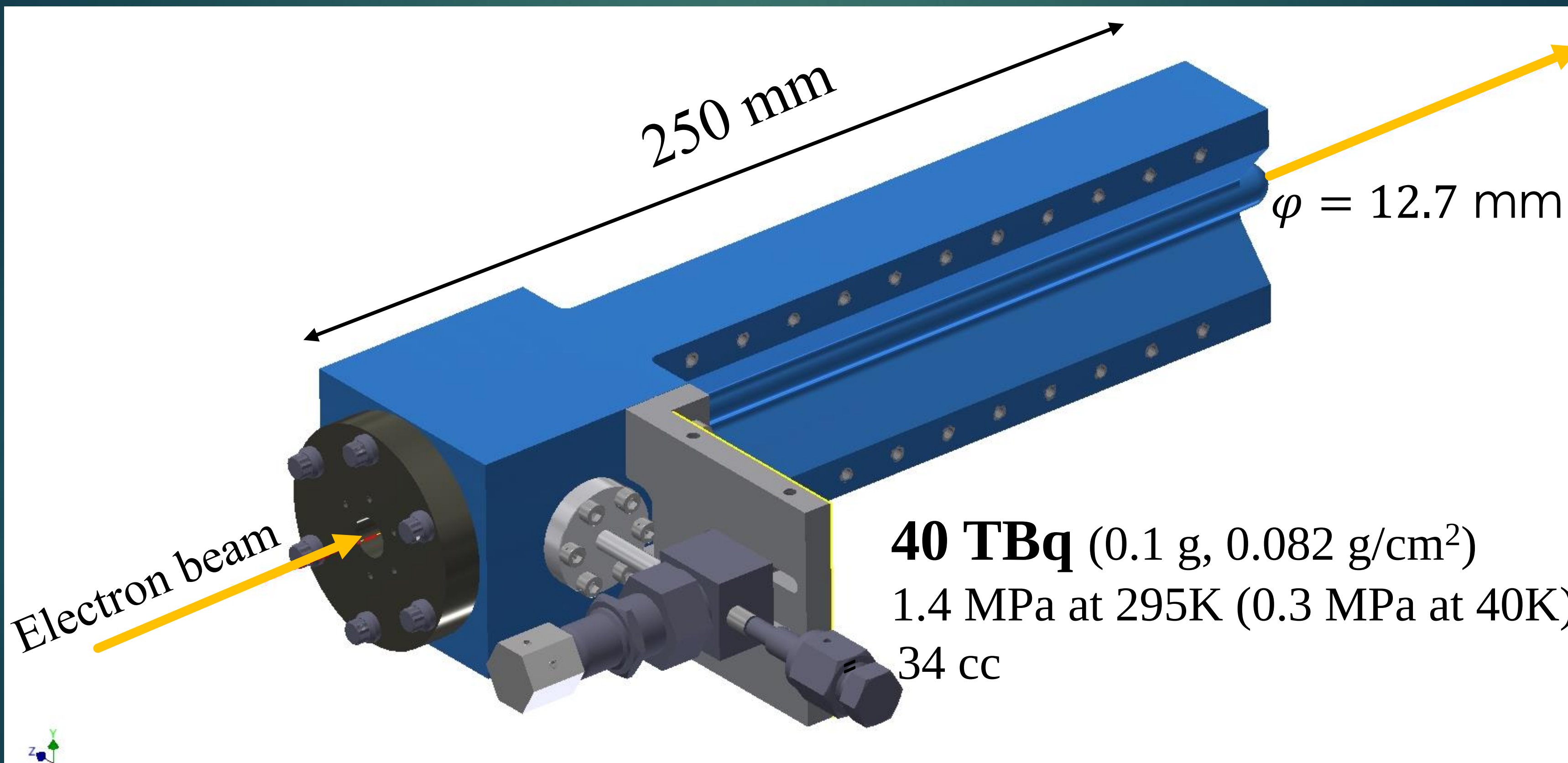
$^{3}\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{K}^{+})nn\Lambda$

Detectable both bound and resonance states

E12-17-003; JLab PAC45 approved with A-, high impact

Target cell of tritium gas

Cell material:
Al alloy (ASTM B209 AL 7075-T651)



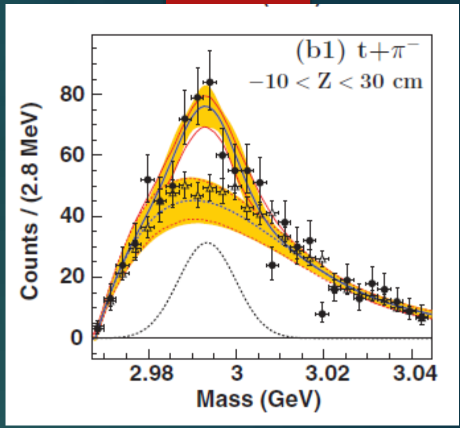
Dave Meekins (JLab, 2015).

Typical Checking Source for Detector Test :
3.7 MBq

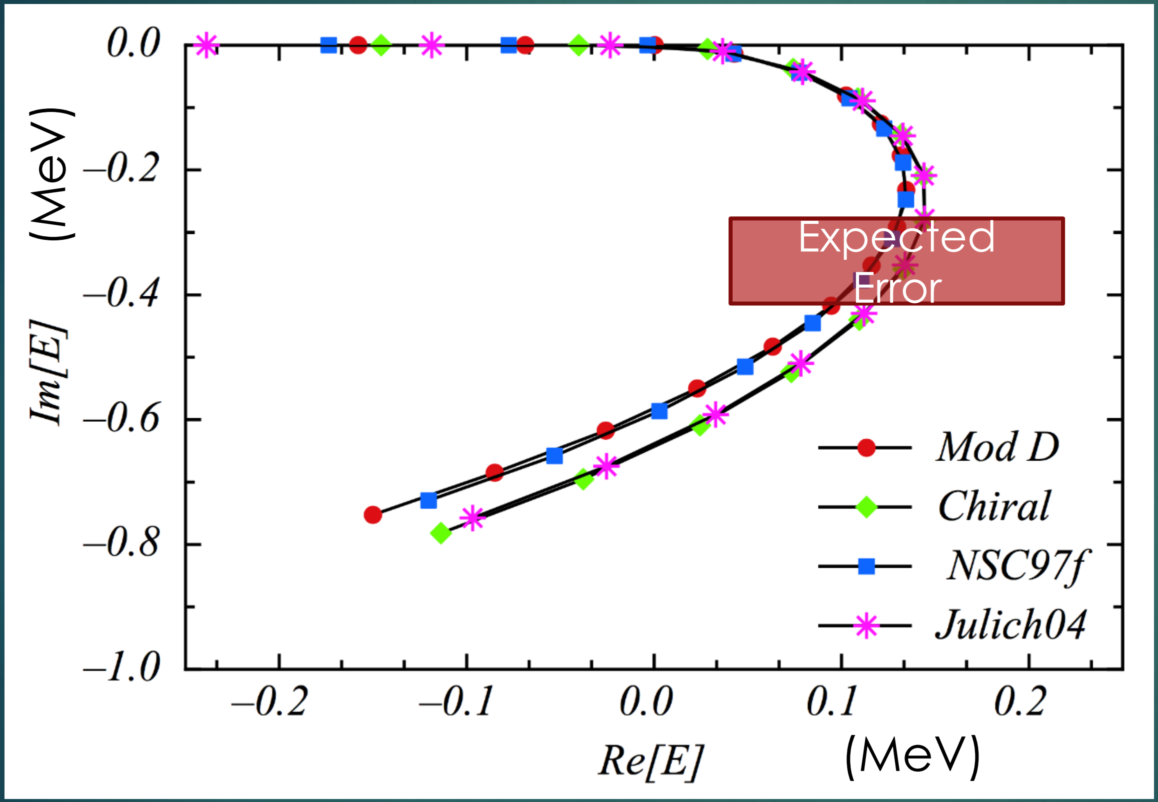
$\times 10^6$

JLab E12-17-003
Λn interaction study by inverstigation of Λnn resonance

Jlab PAC45 approved as "High-Impact" exp. (June 2017)

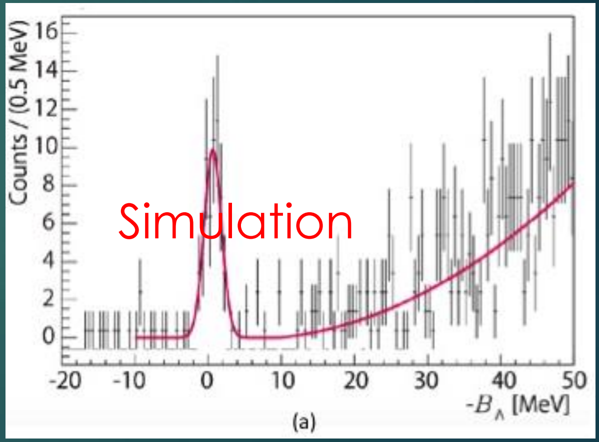


C.Rappold et al.
PRC 88041001(R) (2013)



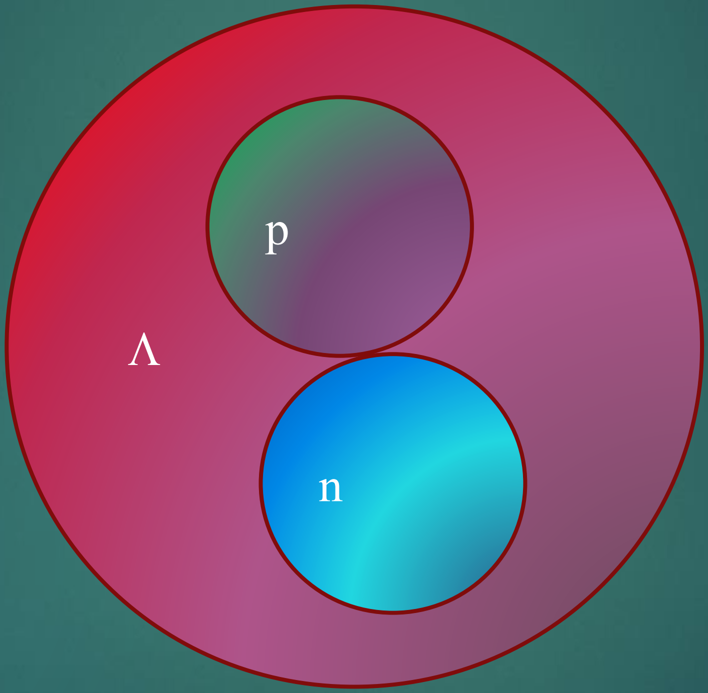
I.R.Afnan and B.F.Gibson, PRC 92, 054608 (2015)

$^{3}T(\mathrm{e},\mathrm{e}'\mathrm{K}^{+})\mathrm{nn}\Lambda$

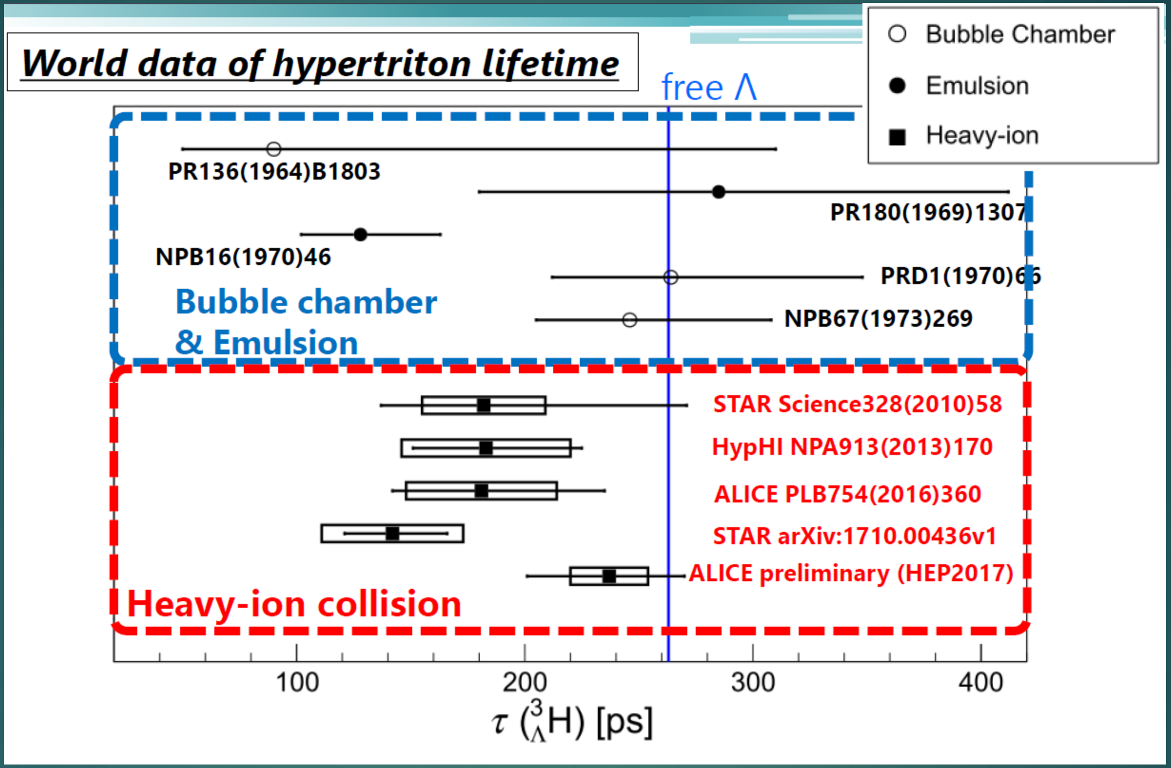


Beamtime is now scheduled 24 Nov. – 17 Dec., 2018.

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



Lifetime measurement of ${}^{3}_{\Lambda}\mathrm{H}$



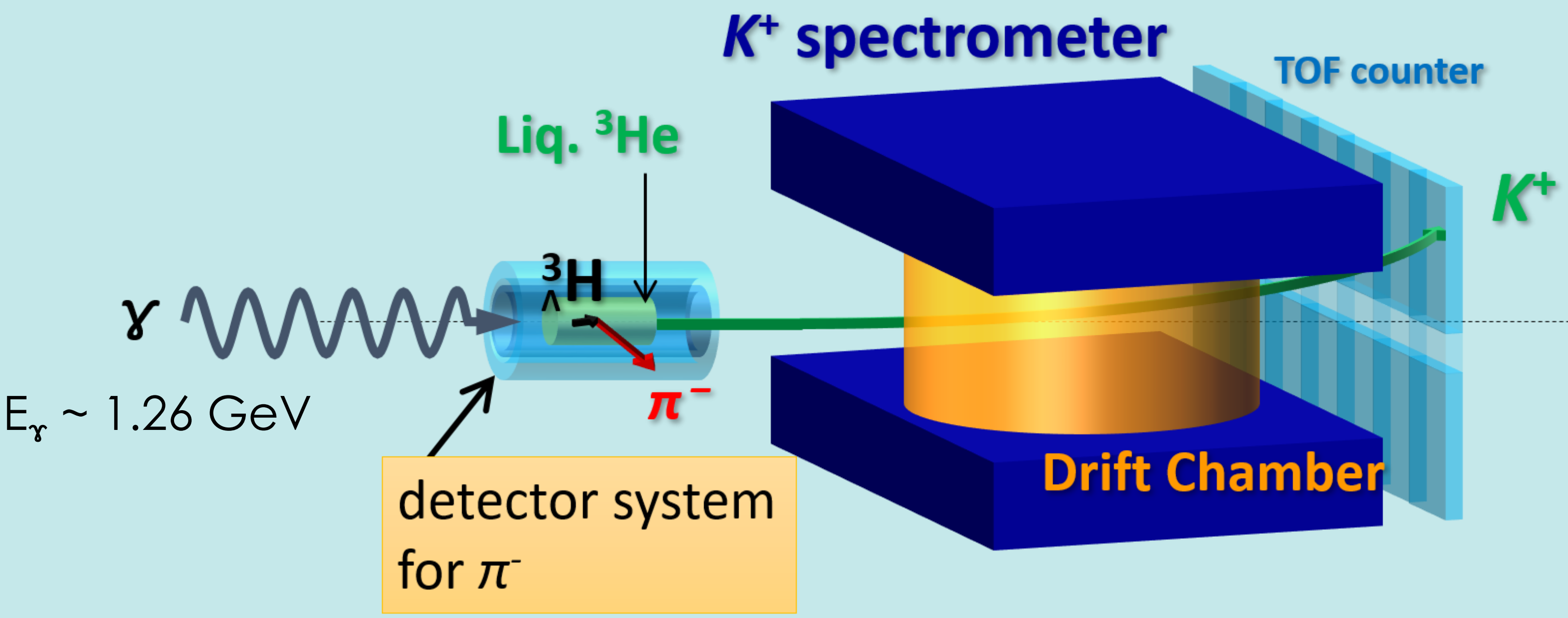
New direct lifetime measurements are planned:

J-PARC: $\pi^{-} + {}^{3,4}\mathrm{He} \rightarrow K^{0} + {}^{3,4}_{\Lambda}\mathrm{H}$ A.Feliciello @ ASTRA2017

ELPH Tohoku : $\gamma + {}^{3,4}\mathrm{He} \rightarrow K^{+} + {}^{3,4}_{\Lambda}\mathrm{H}$

${}^{3}_{\Lambda}$H lifetime measurement at ELPH-Tohoku

$$\gamma + {}^{3,4}\mathrm{He} \rightarrow {}^{3,4}_{\Lambda}\mathrm{H} + K^{+}$$
$${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{X} + \pi^{-}$$

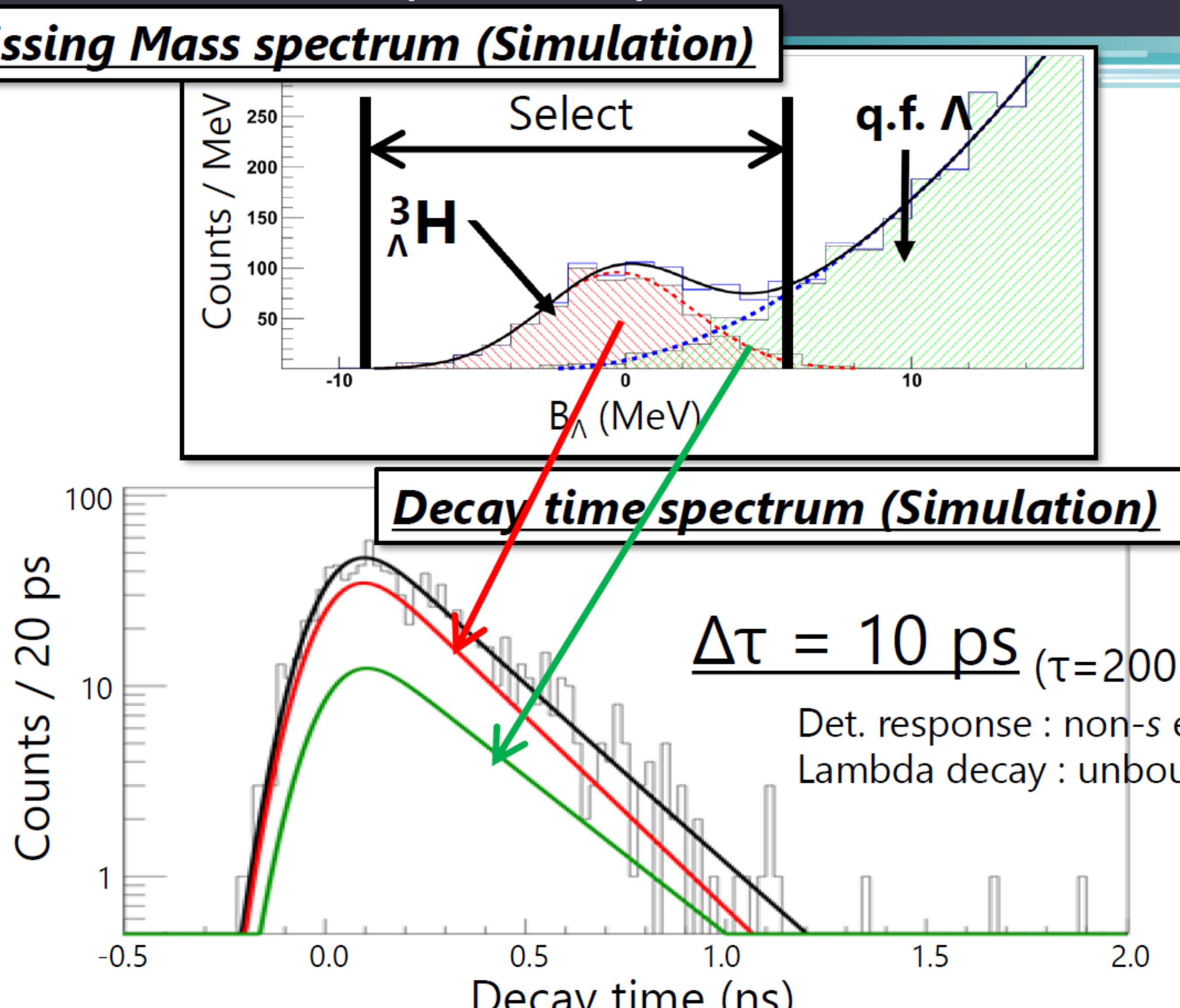


Identify ${}^{3}_{\Lambda}\mathrm{H}$: Missing mass

$$t_{decay} = (t_{TDL} - ToF_{\pi}) - (t_{Tag} + ToF_{\gamma})$$

PoP experiment for Λ lifetime measurement started in this June.

Expected spectrum



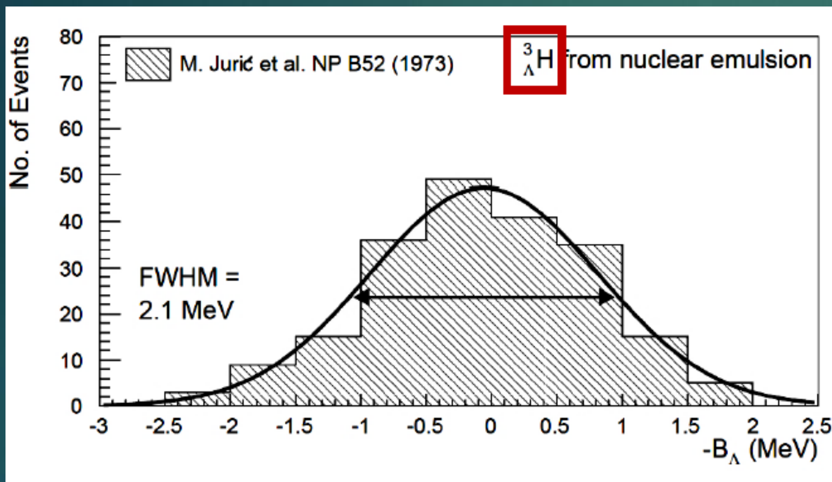
$\Delta\tau$ = 10 ps (τ=200ps)

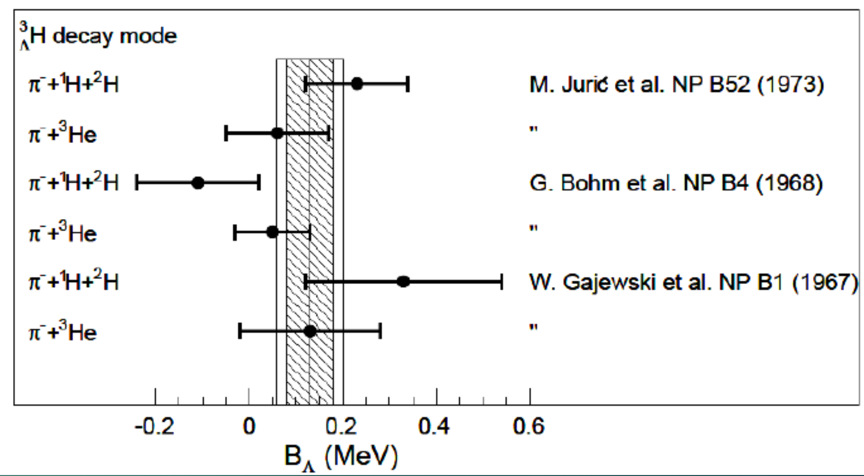
Det. response : non-*s* events

Lambda decay : unbound region

${}^{3}_{\Lambda}$H puzzle may not be lifetime problem

P.Achenbach, ASTRA2017





Decay Channel	# of events	B_Λ
$\pi^- + {}^1\mathrm{H} + {}^2\mathrm{H}$	24	0.23 ± 0.11
$\pi^- + {}^3\mathrm{He}$	58	0.06 ± 0.11
total	82	0.15 ± 0.08

ΛN interaction in the singlet state. Combining the result obtained in this experiment with the data compiled by Bohm et al. [2], reanalysed using the methods and selection criteria defined in the present work, the best estimate for the binding energy of ${}^{3}_{\Lambda}$H is found to be $B_\Lambda = 0.13 \pm 0.05$ MeV.

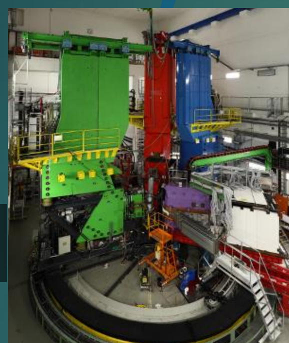
M.Juric et al. NPB52 (1973) 1.

Future HY study with e beams

JLab E12-15-008(e,e'K$^+$)
E12-17-003 (nnΛ)

MAMI-Mainz

Decay π Spectroscopy of electroproduced HY



$^3{}_\Lambda$H Binding E.

Light Hypernuclei

ELPH-Tohoku

Elementary Strangeness photo-production

$^{3,4}{}_\Lambda$H lifetime
(2019-2020 run)

Study of ΛN through nnΛ
(Start Nov. 2018)

First Iso-spin dependence of medium heavy HY w/ best resolution
(Prepare for 2020 run)

Compare experimental results with
Theoretical Predictions of Binding Energies and Cross Sections
Deduce ΛN interaction including many-body forces

Solve Hyperon Puzzle, nnΛ Puzzle, $^3{}_\Lambda$H Puzzle

Summary

Spectroscopy of Lambda hypernuclei with electron beams

⇨ Established at JLab ⇨ Decay π at MAMI

$^{9}_{\Lambda}$Li $^{10}_{\Lambda}$Be $^{12}_{\Lambda}$B $^{16}_{\Lambda}$N ⇨ Abs. B_{Λ} determination sugg.
0.54MeV shift for all (π,K)

Determination of $B_{\Lambda}(^{7}_{\Lambda}He_{gs})$ triggered intensive study for A=4 iso-doublet hypernuclei ($^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He)

⇨ Mainz : Decay π spectroscopy
J-PARC E13 : γ–ray spectroscopy

New experiment for ($^{40}_{\Lambda}$K and $^{48}_{\Lambda}$K) is under prep. to clarify the isospin dependence of 3/4BRF which is necessary to solve Hyperon puzzle.
nnΛ search (JLab E12-17-003) will start Nov. 2018.
Direct measurement of the $^{3}_{\Lambda}$H lifetime is under prep. at ELPH.
$^{3}_{\Lambda}$H binding energy measurement is planned at MAMI.