京大・原子核理論研究室セミナー

JLabにおけるラムダハイパー核分光の新しい結果と今後の展望

京大・原ハド

後神 利志 (Toshiyuki Gogami)

令和 3 年 (西暦 2021 年) 10 月 29 日

GRADUATE SCHOOL OF SCIENCE
FACULTY OF SCIENCE
KYOTO UNIVERSITY

科研費 KAKENHI

SPIRITS
SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

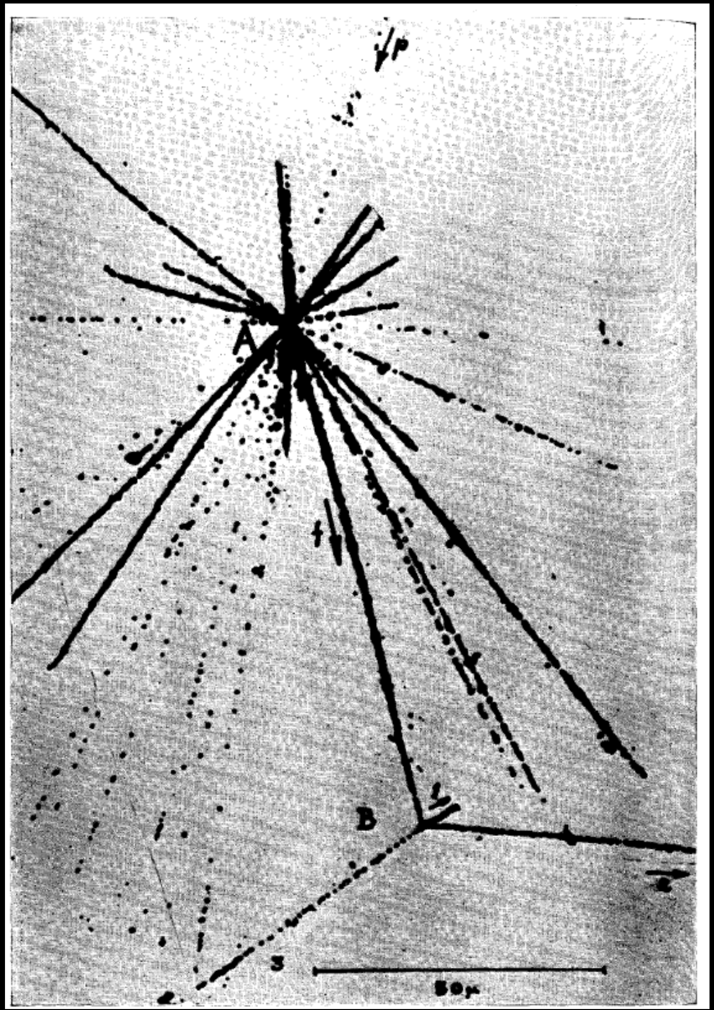
1. Introduction
2. Experiments
   - A few of light hypernuclei (Hall C 2009)
   - $nn\Lambda$ **search** (Hall A 2018)
   - Future projects (Hall A or C 2024?)
3. Summary

Jefferson Lab
Thomas Jefferson National Accelerator Facility

THE FIRST HYPERNUCLUS

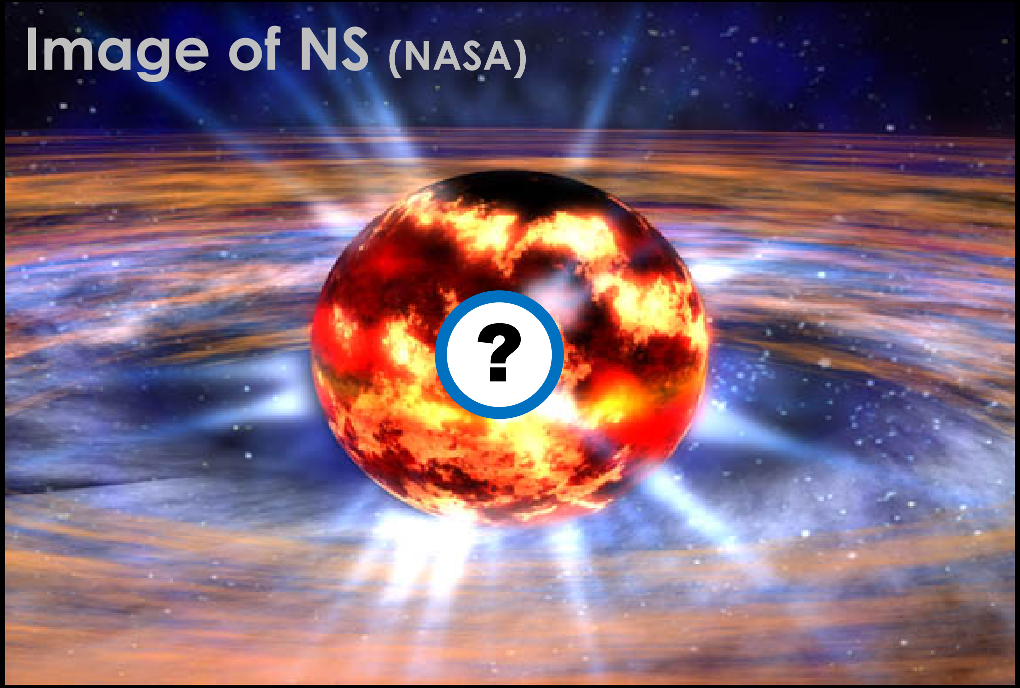
A.K. Wroblewski,
Acta Physica Polonica B 35, 3 (2004).

The fist Λ hypernucleus in history



M. Danysz & J. Pniewski, Phil. Mag. Ser. 7, 44, 14 (1953).

HYPERONS IN NATURE



Astronomical observation

- space observation
- gravitational wave

What's inside ?

- ☐ Strange Hadrons?
- ☐ Quark matter?
- ☐ Meson condensate?

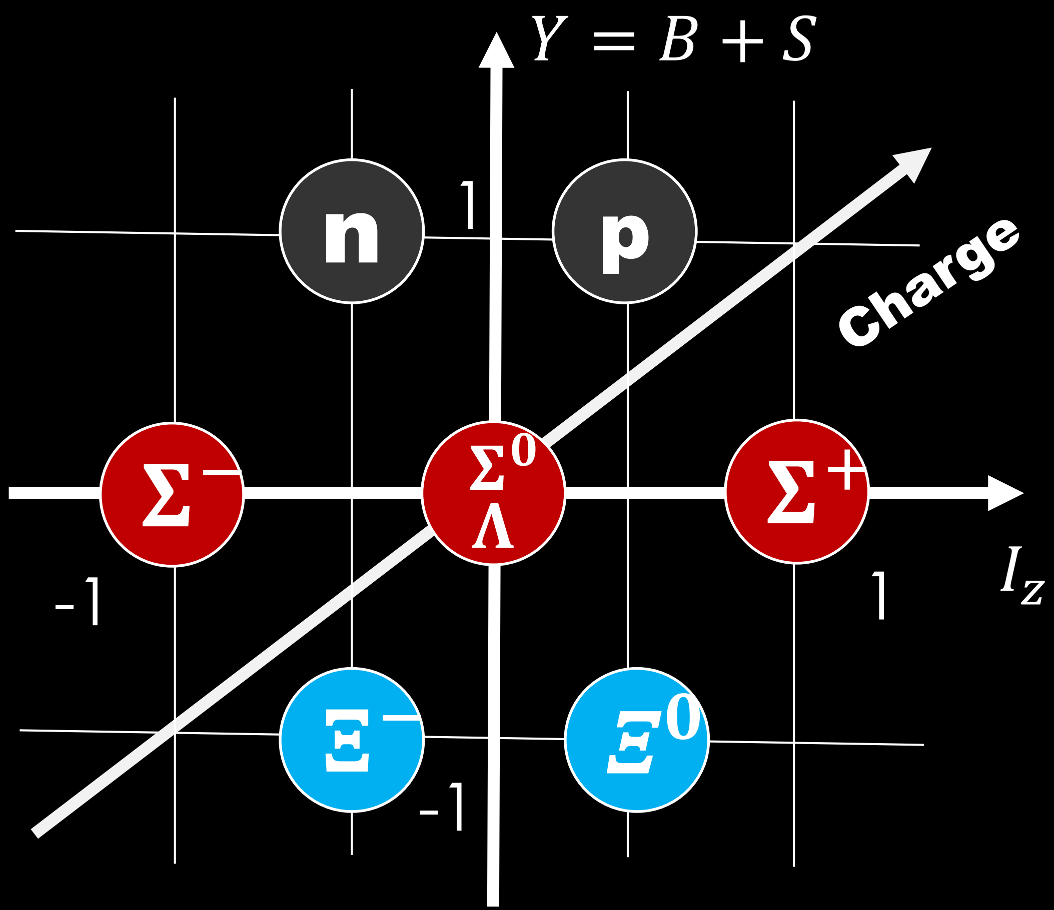
<u>Hyperons make a NS softer</u>

→ $\geq 2M_{\odot}$ is hard to support by only 2BF

→Multi body repulsive forces may play a role

More precise studies on the strange BB/BBB interactions are needed

STUDY ON BARYON INTERACTION (BB INT.)



Baryon Octet $J^\pi = \frac{1}{2}^+$

Nuclear Sector (NN)

- Rich data of scattering experiment
- Nuclear data > 3000

Strangeness Sector (ΛN, ΣN, ΞN etc.)

- Scarce data of scattering experiment
- Hypernuclear data ~ only 40 !!

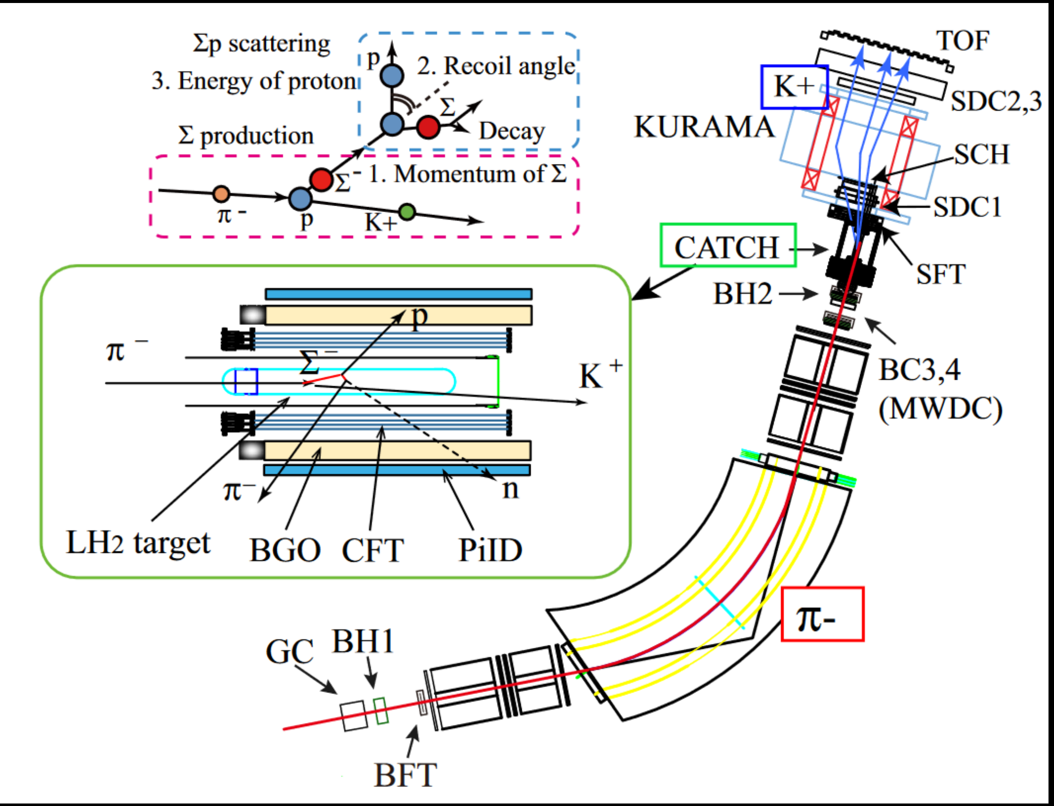
Available facilities for HN experiments:

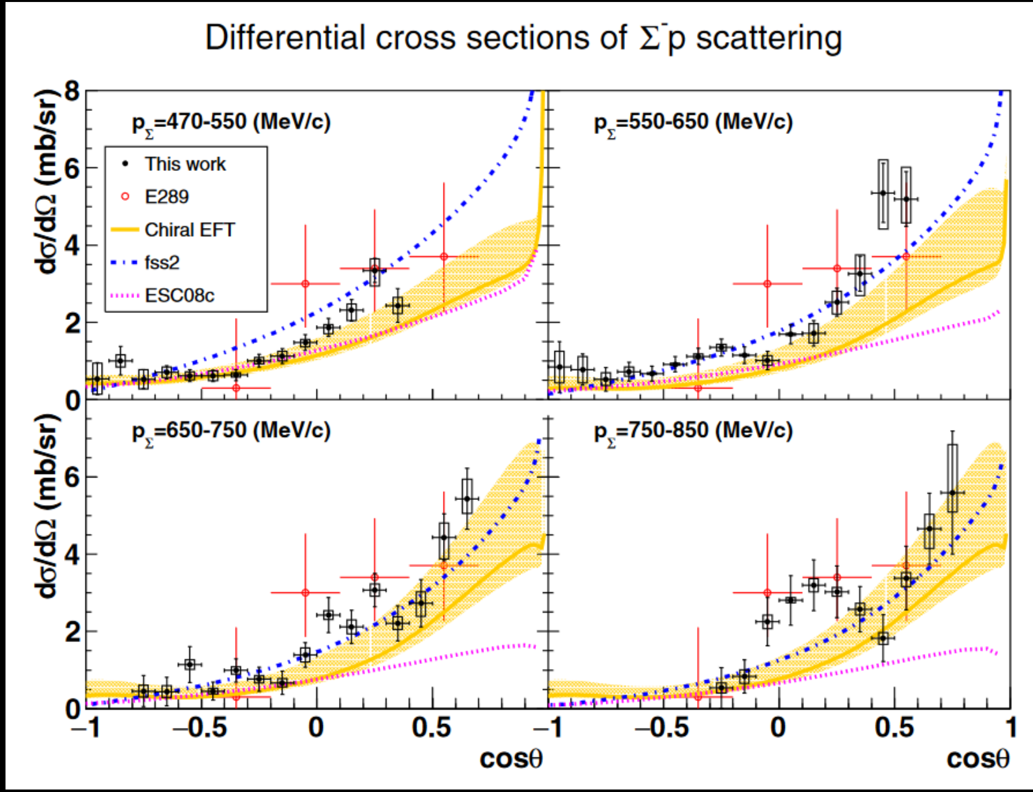
- $S = -1$: CERN, RHIC, GSI, J-PARC, MAMI, **JLab**
- $S = -2$: J-PARC, FAIR

$\Sigma^{-}p$ scattering (J-PARC E40)

K. Miwa et al., PRC 104, 045204 (2021)

昨日公開



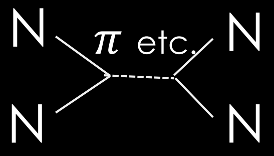


HOW TO INVESTIGAE THE BB INTERACTION

Method A

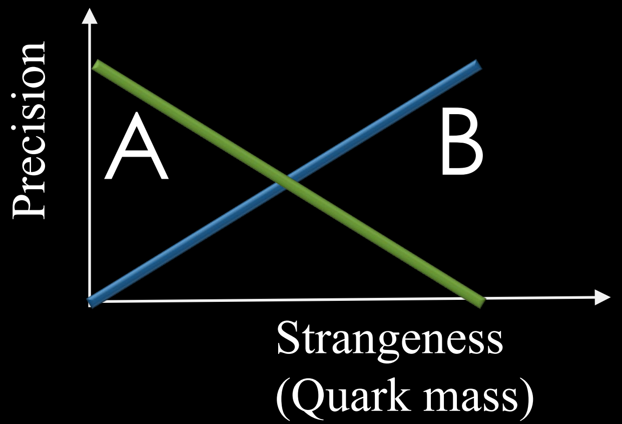
Data
- Scattering experiment
- (hyper)nuclear spectroscopy
- Phemtoscopy (ALICE, PRL123, 112002 (2019))

Phenomenological Theories
- Meson exchange model
- Effective field theory
- Quark cluster model etc.



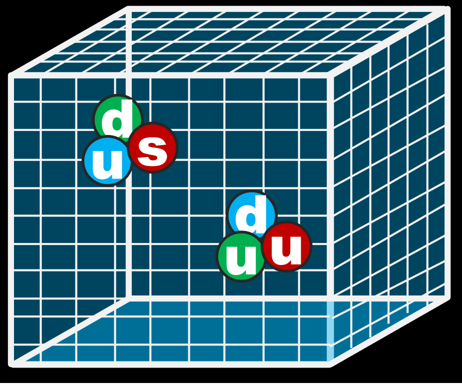
H. Yukawa (Kyoto Univ.)
Novel Prize 1949

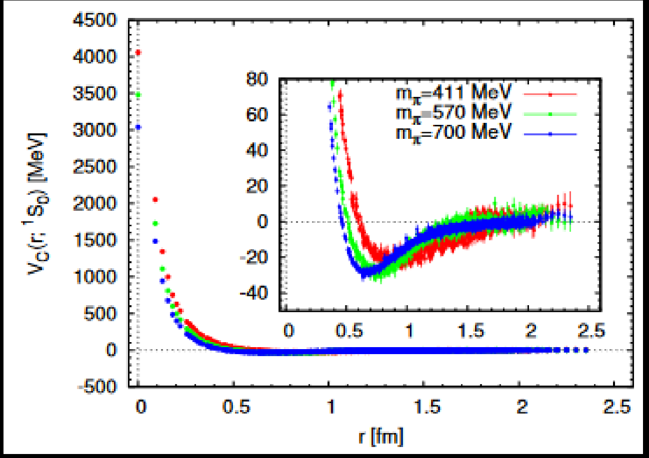
Complementary



Method B

Lattice QCD
(First principle calc.)





arXiv:2003.10730v2 [hep-lat] 12 Jul 2020

BB interaction (Strong force)

Typical options for hypernuclear measurement

Production measurement

Missing mass spectroscopy

- ✓ (π^+,K^+) @J-PARC
- ✓ (K^-,π^-) @J-PARC
- ✓ $(e,e'K^+)$ @JLab

⇨ **Mass**, production mechanism

Better precision!

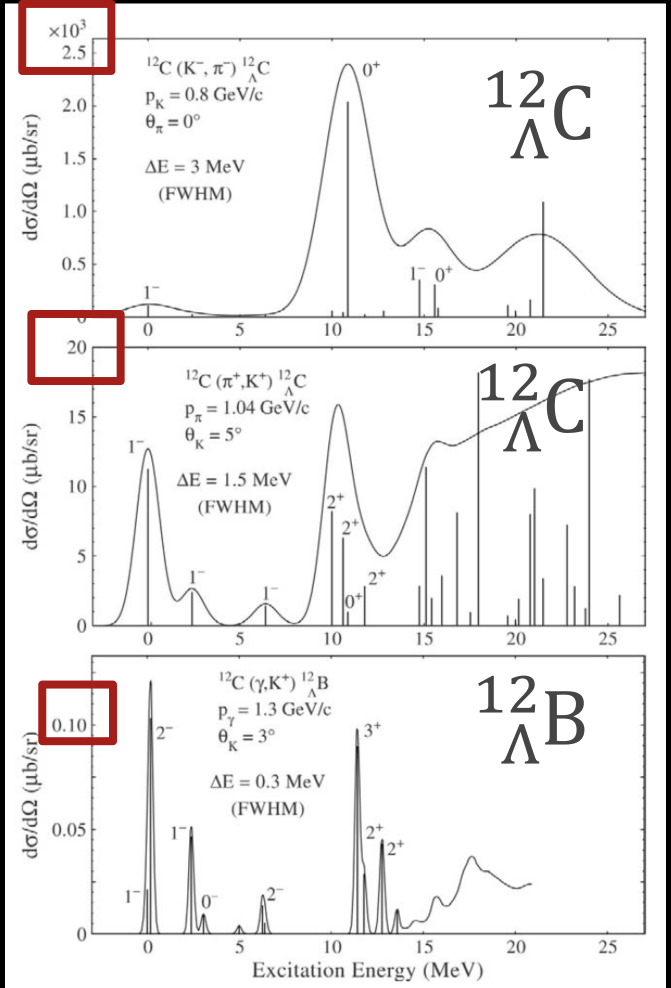
Decay particle measurements

- Emulsion @J-PARC
- Invariant mass spectroscopy @GSI
- γ-ray spectroscopy @ J-PARC
- Decay π spectroscopy @MAMI
- (femtoscopy @CERN)

⇨ Mass, Lifetime, decay mechanism

DRAWBACK AND ADVANTAGE

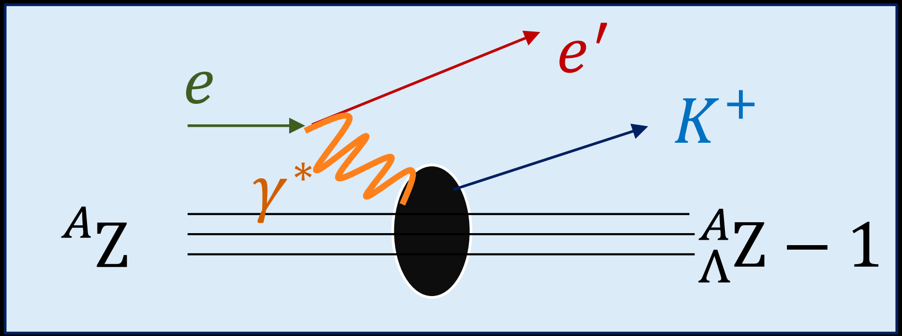
Hypernuclei from ^{12}C



(K^-, π^-)

(π^+, K^+)

$(e, e'K^+)$

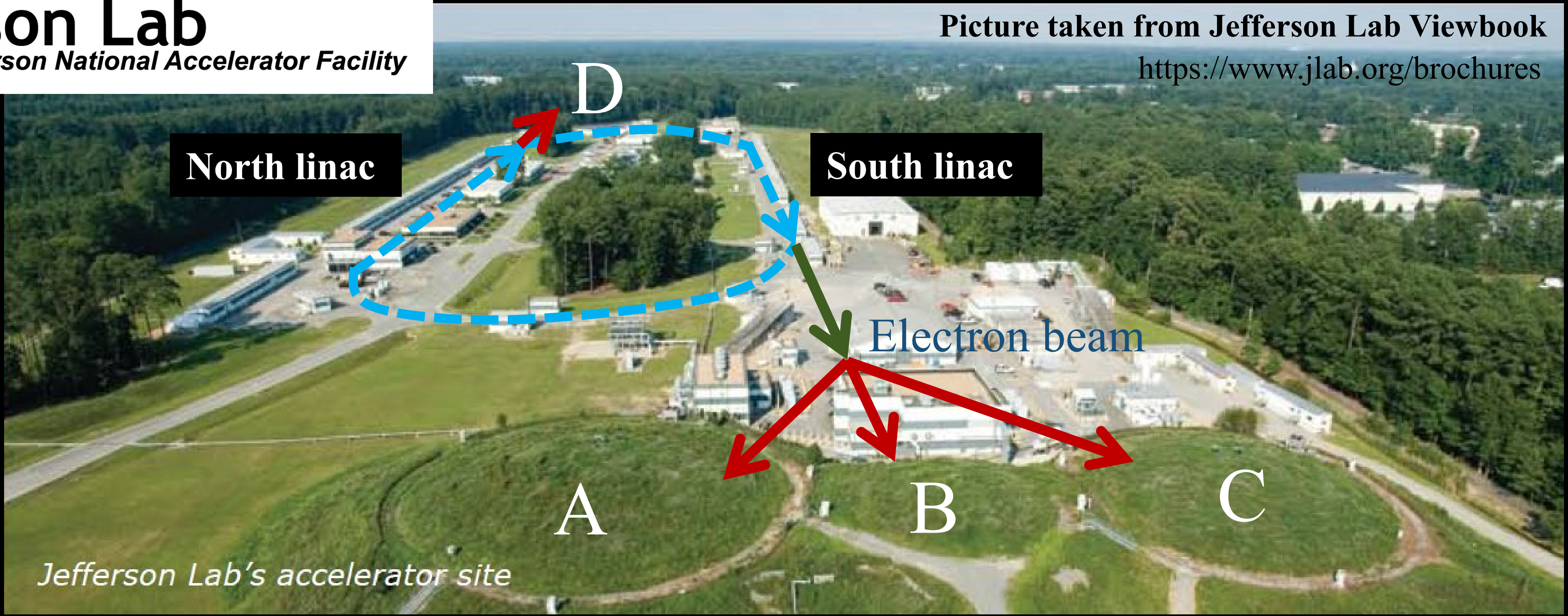


- High resolution (< 1 MeV) ◎
- Production of mirror nuclei ◎
- Large spin flip amplitude △
- Very small cross section ×
- Huge EM backgrounds ×
- e' and K⁺ coincidence ×

➡ Good but difficult!

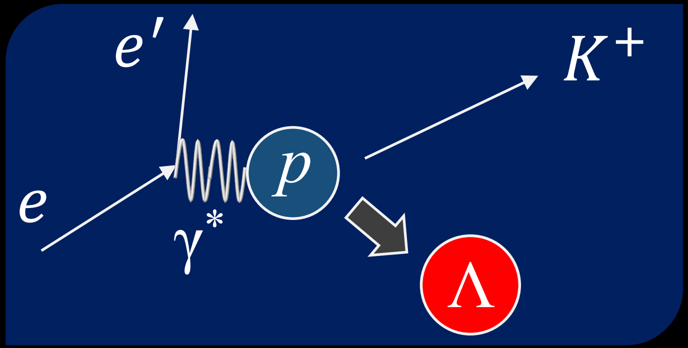
TG et al., Nucl. Instrum. Methods., Phys. Res. A 900, 69—83 (2018)

CEBAF AT JEFFERSON LAB

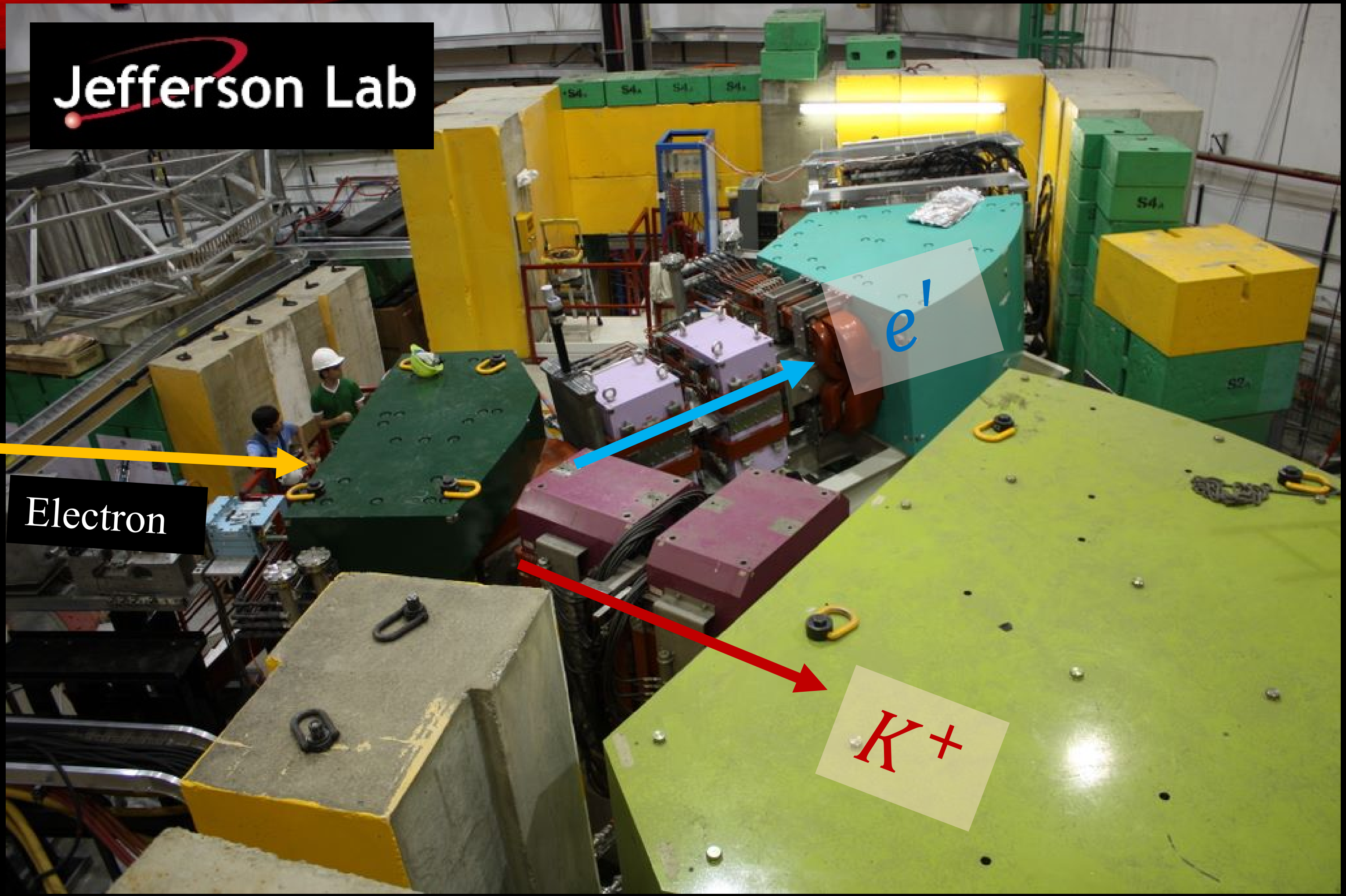


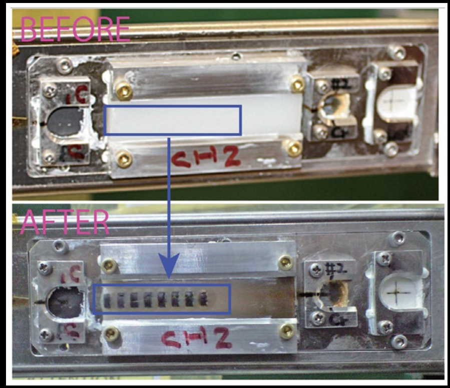
Continuous electron beam facility (CEBAF)

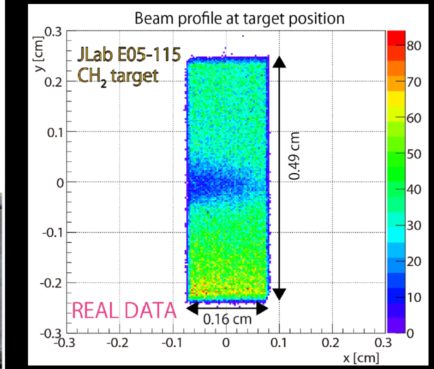
- ✓ 12 GeV at maximum
- ✓ 100 μA (> 600 THz)
- ✓ 2 or 4-ns interval bunches
- ✓ Emittance of 2 μm·mrad
- ✓ Energy spread ($^{\Delta E}/_{E} < 5 \times 10^{-5}$ rms)

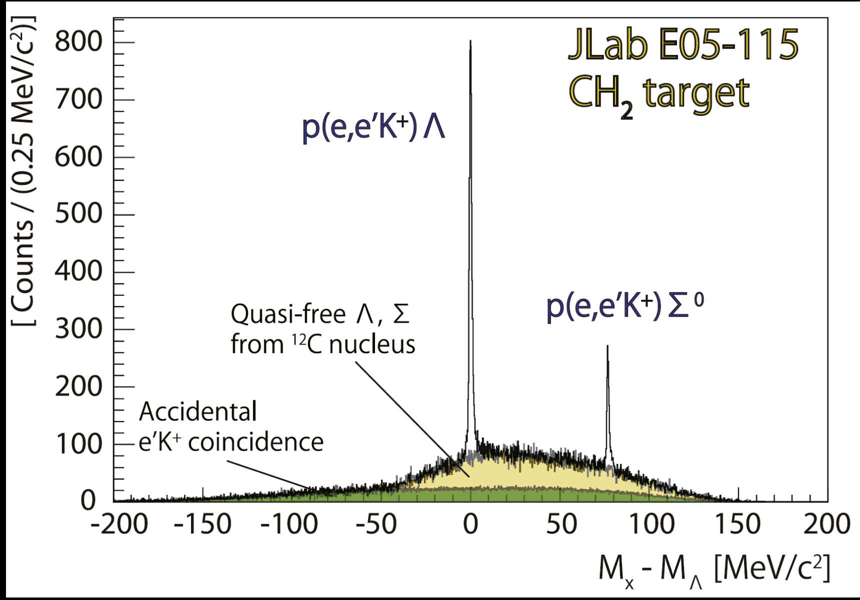


Experimental setup





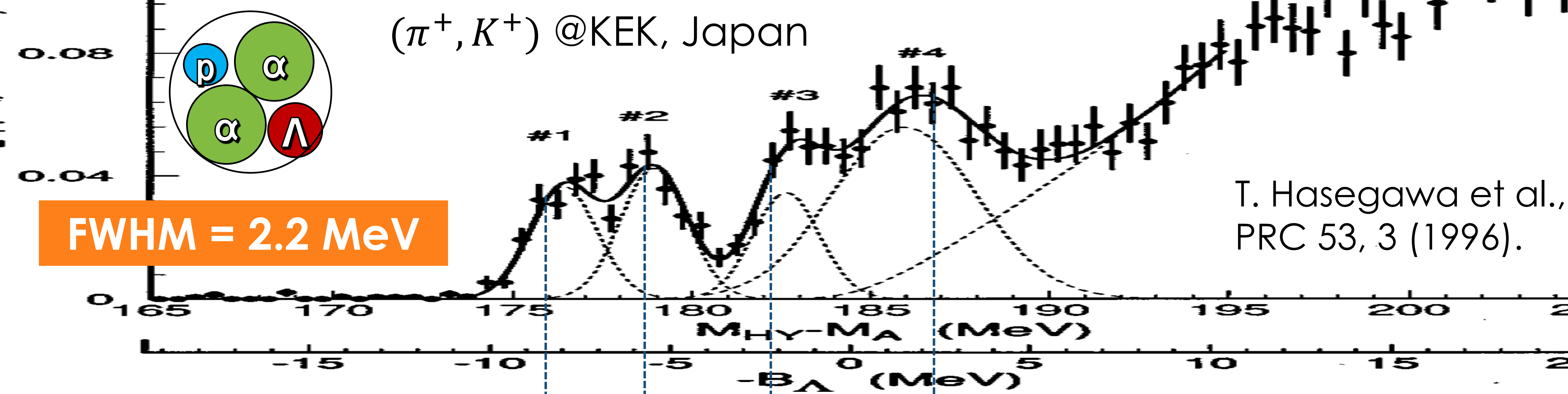




- ✓ High resolution
- ✓ High accuracy

- TG et al., Nucl. Instrum Methods. Phys. A 729, 816—824 (2013)
- Y. Fujii et al., Nucl. Instrum Methods. Phys. A 795, 351—363 (2015)

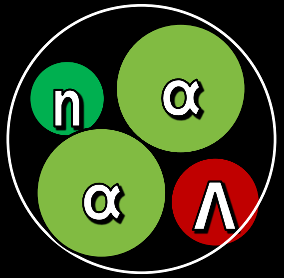
(π^+, K^+) @KEK, Japan



T. Hasegawa et al.,
PRC 53, 3 (1996).

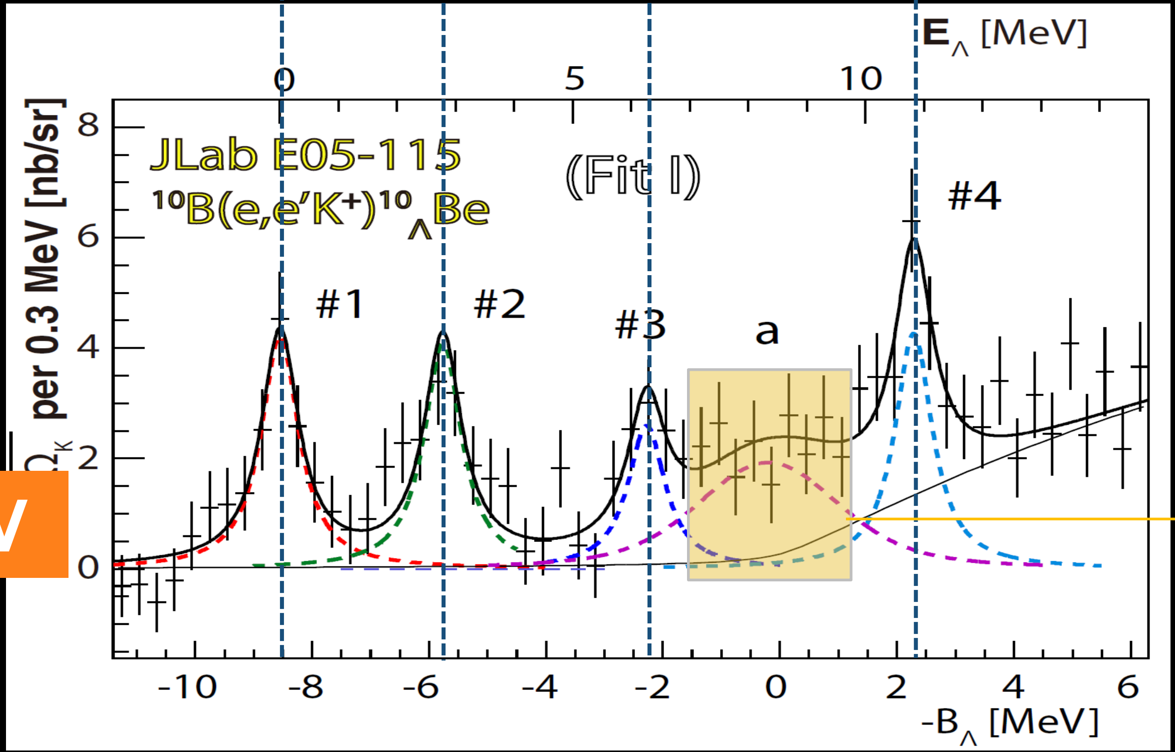
FWHM = 2.2 MeV

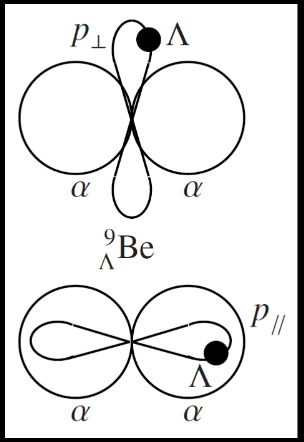
$^{10}_{\Lambda}\mathrm{Be}$



FWHM = 0.8 MeV

TG et al.,
PRC 93, 034314 (2016).



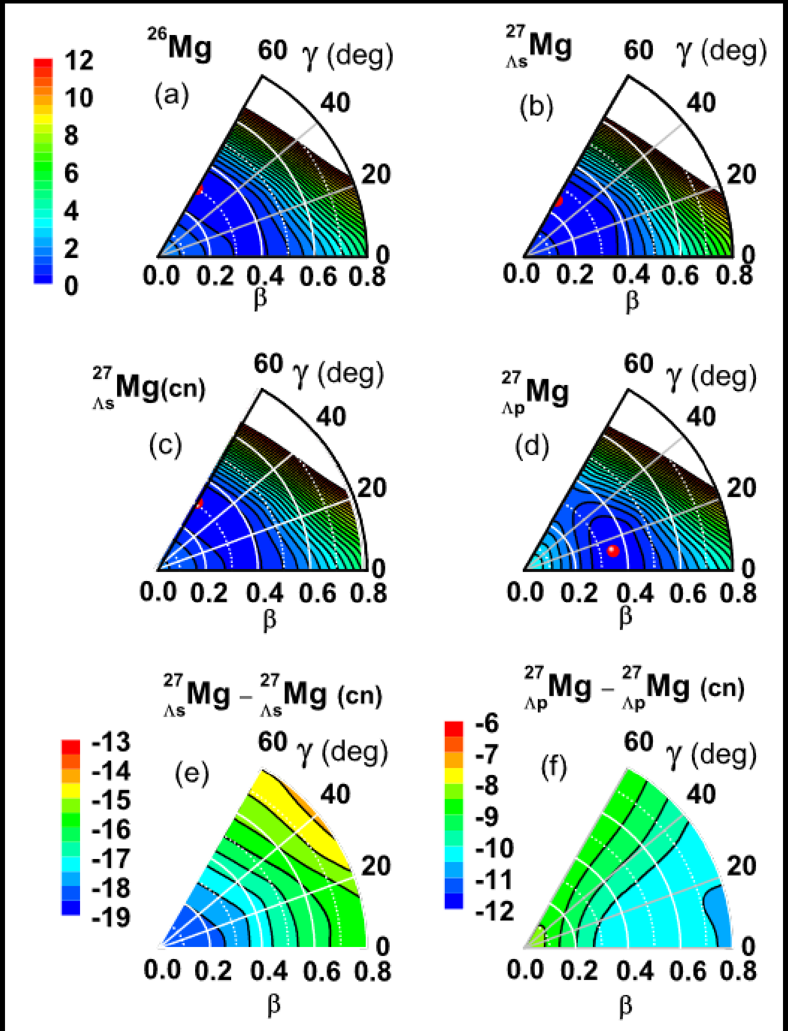


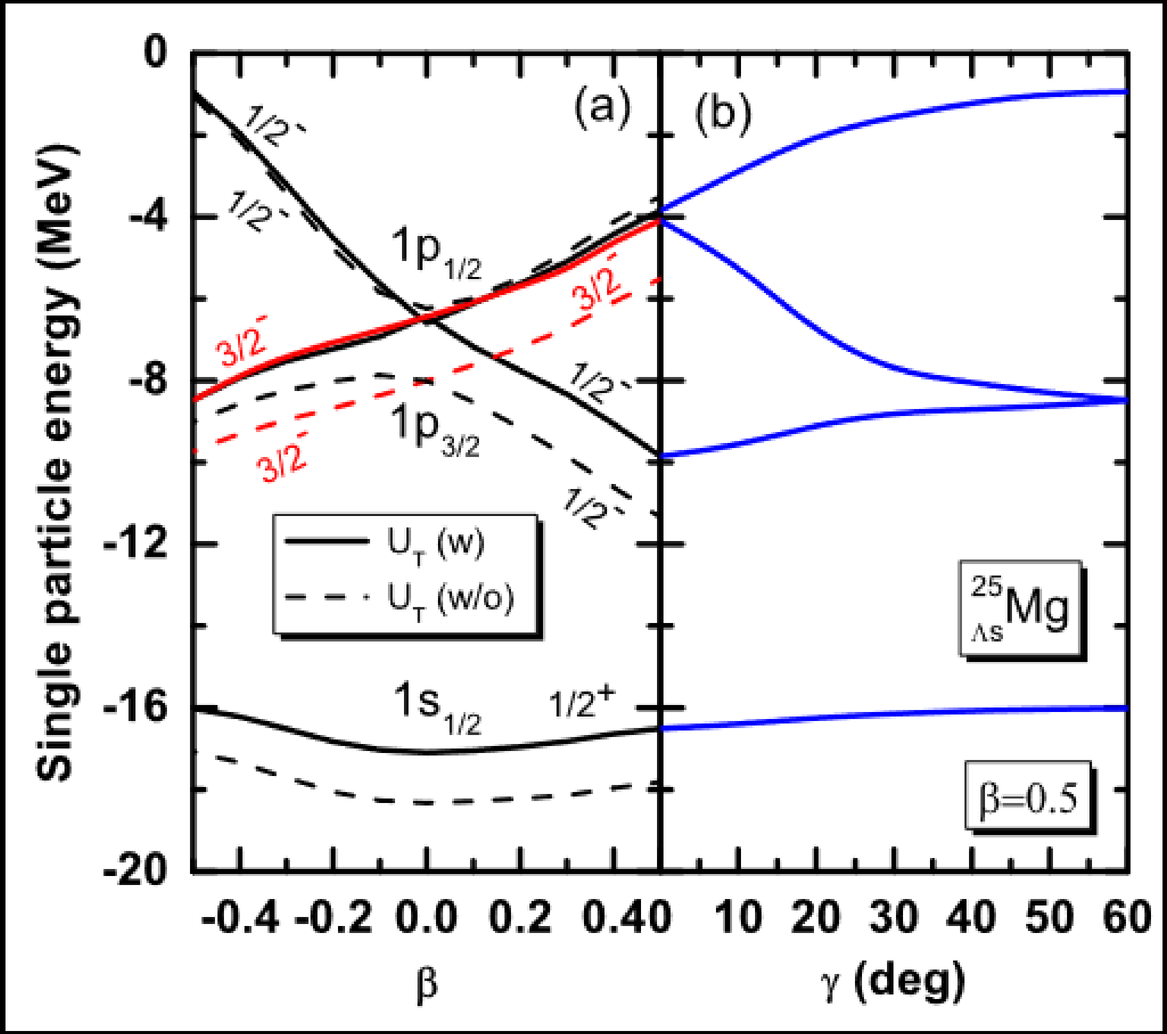
A. Umeya *et al.*, *J. Phys.: Conf. Ser.* **1643** 012110 (2020).

DEFORMATION EFFECT

Triaxial RMS:

W. X. Xue, J. M. Yao, K. Hagino, Z. P. Li,1 H. Mei, and Y. Tanimura, PRC 91, 024327 (2015)

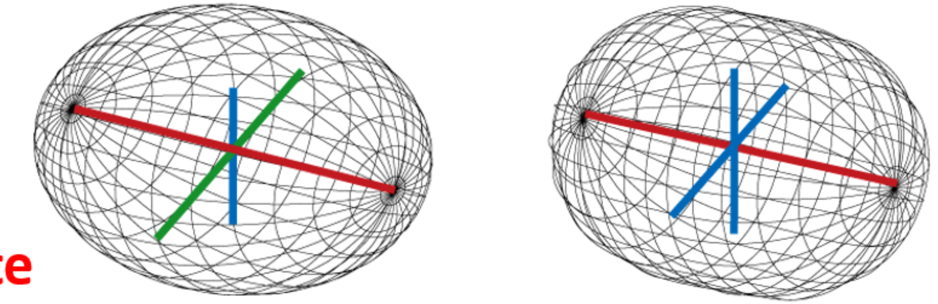




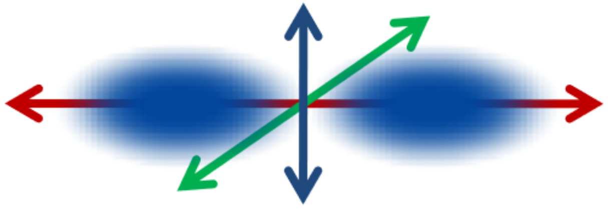
Triaxial deformation

If ^{26}Mg is triaxially deformed nuclei

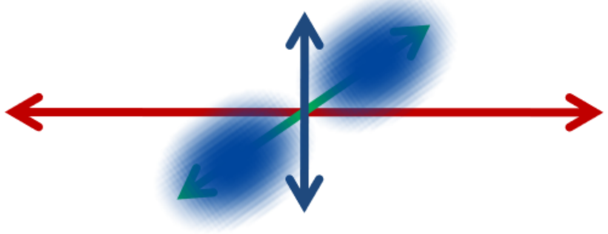
→ *p*-states split into 3 different state



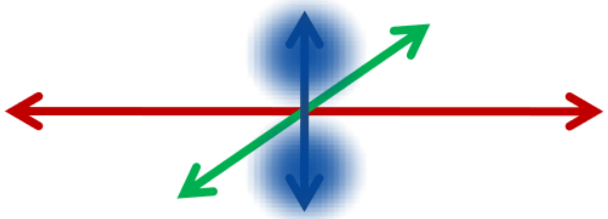
Triaxial deformation　　Prolate deformation



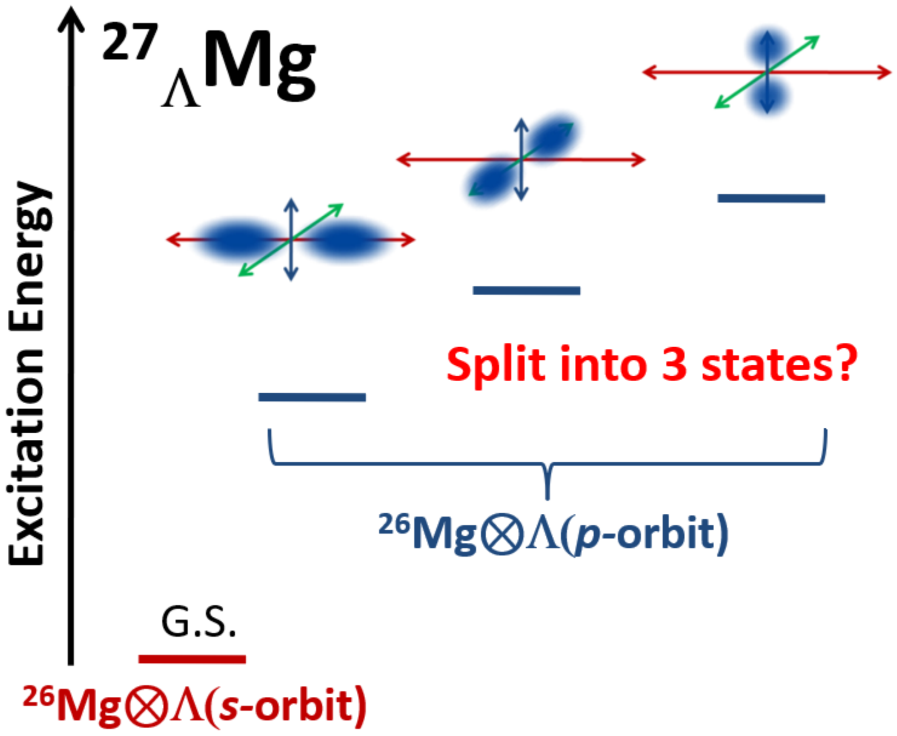
Large overlap leads to deep binding



Middle



Small overlap leads to shallow binding



Observing the 3 different *p*-states is strong evidence of triaxial deformation

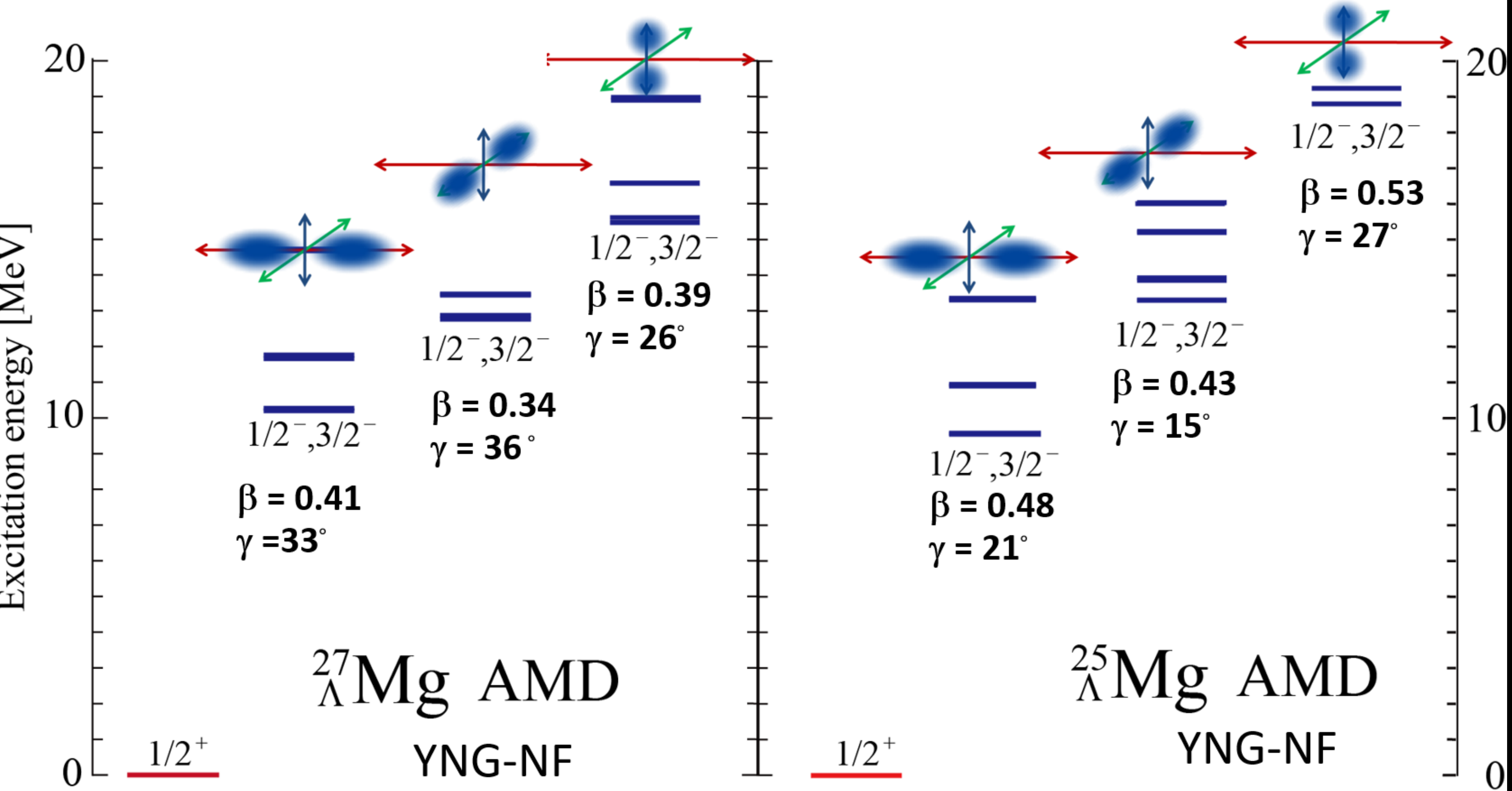
Our (first) task: To predict the level structure of the *p*-states in $^{27}{}_{\Lambda}$Mg

法政大・井坂さんのスライドより (2015)

Results: Comparison with $^{25}{}_{\Lambda}$Mg

- **3 *p*-states appear both in $^{25}{}_{\Lambda}$Mg and $^{27}{}_{\Lambda}$Mg**
- **Difference in energy difference among *p*-states**

→ One of the reasons: difference of the deformations



法政大・井坂さんのスライドより (2015)

CHARGE SYMMETRY BREAKING (CSB)

*1) T. O. Yamamoto *et al.* (J-PARC E13 Collaboration), Phys. Rev. Lett. 115, 222501 (2015)
*2) A. Esser *et al.* (A1 Collaboration), Phys. Rev. Lett. 114, 232501 (2015).

^{3}He ^{3}H

$\Delta B = 0.76384\ (26)$*1) MeV
$\Delta B_{\text{Coulomb}} = 0.683$*2) MeV

⇨ ***0.081 MeV***

*1) J.H.E.Mattauch *et al., Nucl. Pys.* **67**, 1 (1965).
*2) R.A.Brandenburg, S.A.Coon *et al.*, *NPA***294,** 305 (1978).

$^4_\Lambda$He

$^4_\Lambda$H

^{3}He+Λ		^{3}H+Λ	
-0.98*1)	1^+	-0.95	1^+
-2.39	0^+	-2.12*2)	0^+

0.03±0.05 MeV

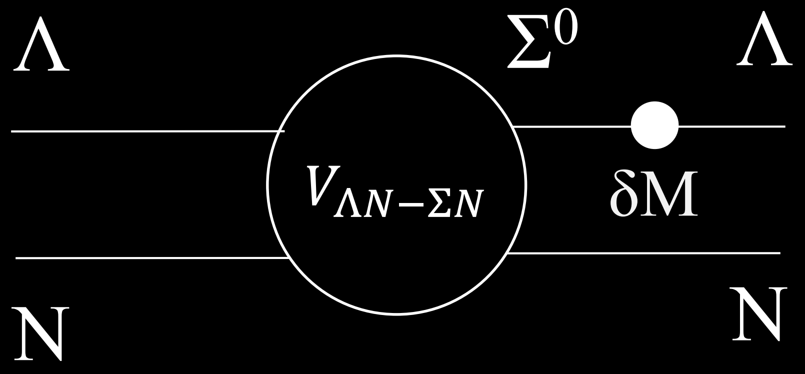
0.27±0.06 MeV

⇨ ***≈0.4 MeV w/ correction***

- Five times larger effect
- Spin dependent

ΛN-ΣN COUPLING

A. Gal, Phys. Lett. B 744, 352 (2015)



$$\langle N\Lambda|V_{CSB}|N\Lambda\rangle = -0.0297\tau_{Nz}\frac{1}{\sqrt{3}}\langle N\Sigma|V_{CS}|N\Lambda\rangle$$

$\Delta E(0+) = 266$ keV
$\Delta E(1+) = 39$ keV

ΛN-ΣN COUPLING

A. Gal, Phys. Lett. B 744, 352 (2015)

What about other systems such as the p-shell region?

$$\ldots|N\Lambda\rangle = -0.0297\,\tau_{Nz}\,\frac{1}{\sqrt{3}}\langle N\Sigma|V_{CS}|N\Lambda\rangle$$

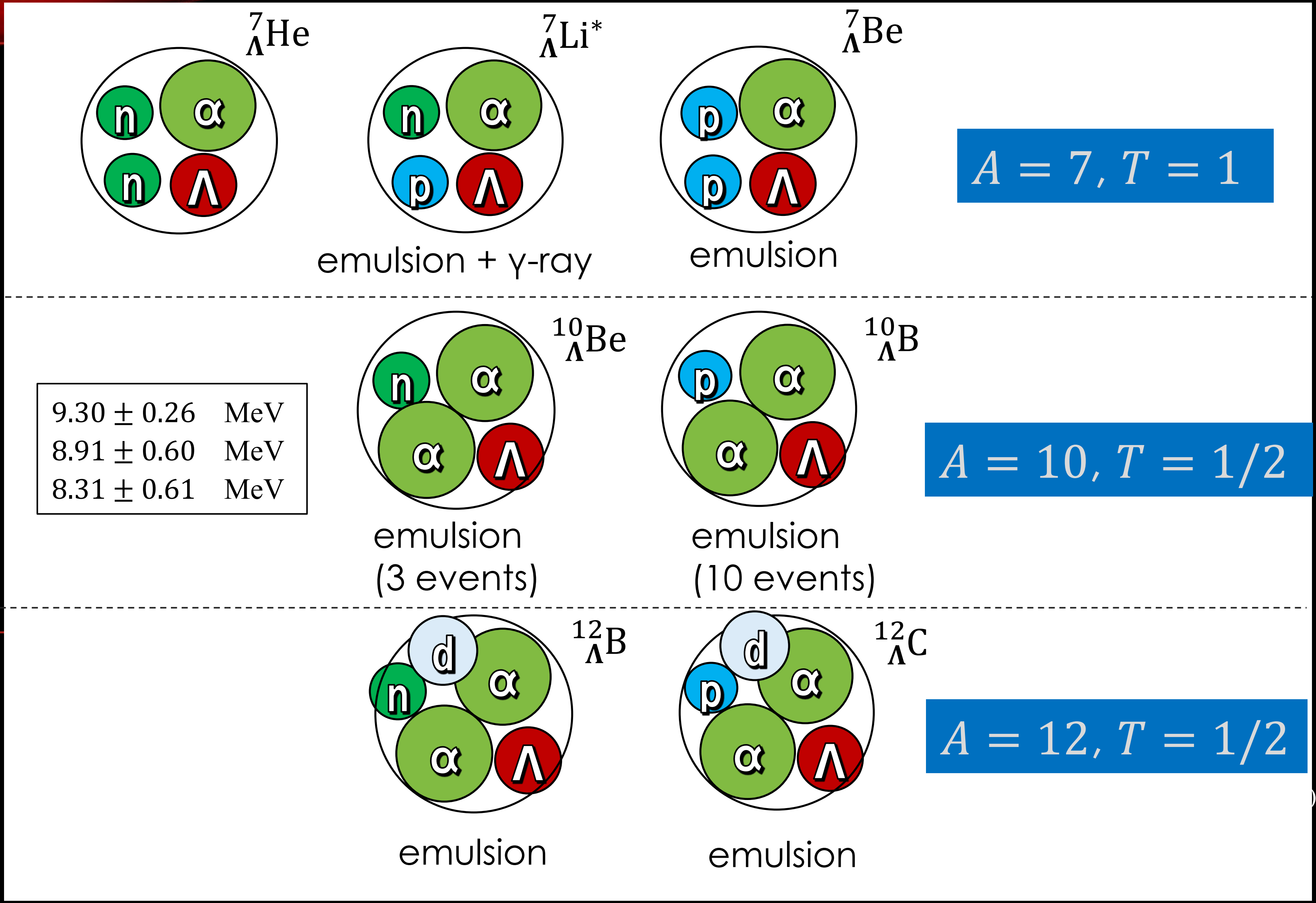
p-shell → matrix elements are **smaller** compared to those for s-shell by a factor of 2

(The matrix elements are determined to reproduce γ-ray transition energies;
D.J. Millener, Nucl. Phys. A 881, 298—309 (2012))

Charge symmetry breaking (CSB) in the p-Shell hypernuclei

A. Gal et al., J. Phys.: Conf. Ser. 966 012006 (2018)

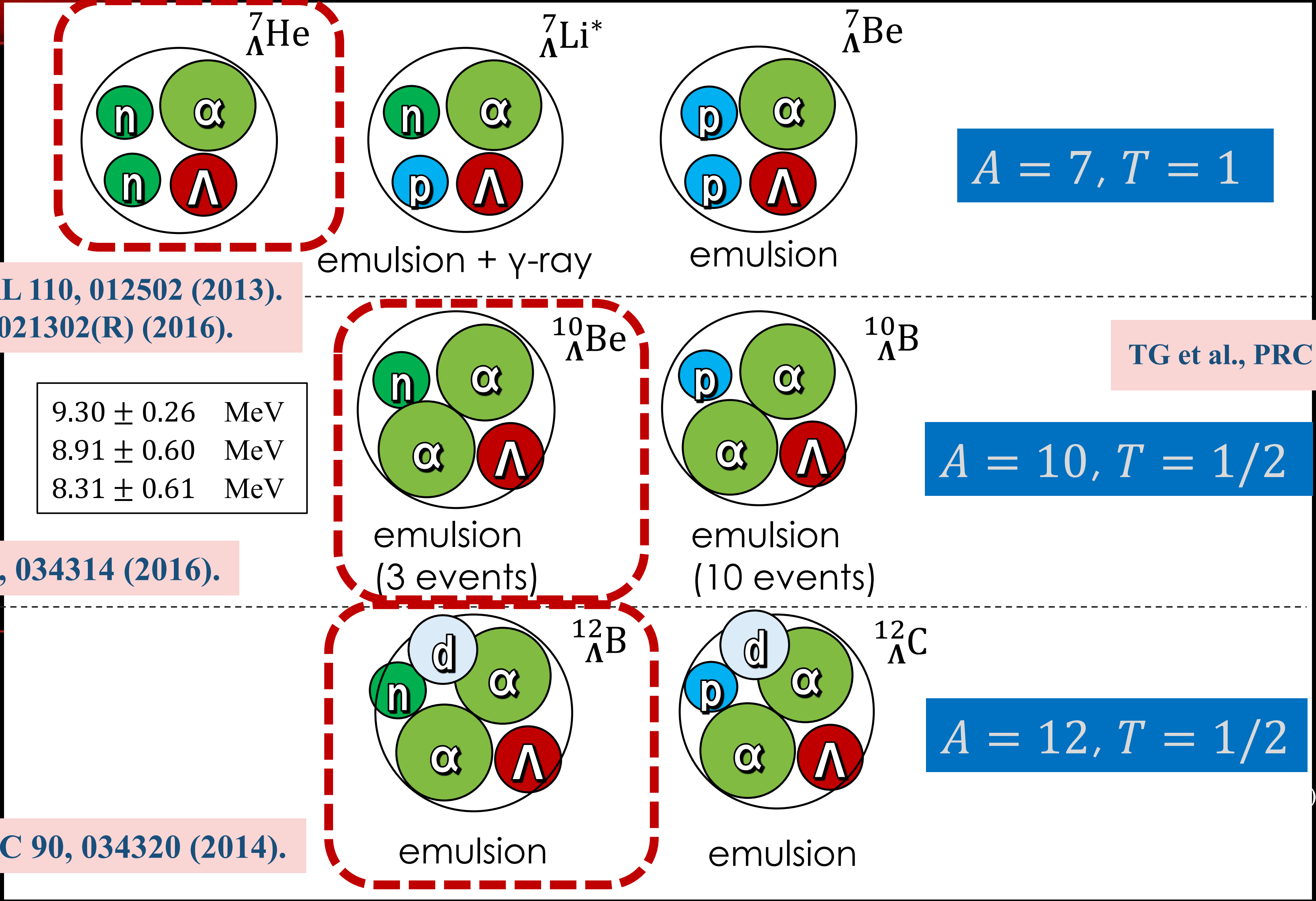
Expected difference



15—30 keV

136 keV

Charge symmetry breaking (CSB) in the p-Shell hypernuclei



S.N.Nakamura, PRL 110, 012502 (2013).
TG et al., PRC 94, 021302(R) (2016).

9.30 ± 0.26	MeV
8.91 ± 0.60	MeV
8.31 ± 0.61	MeV

TG et al., PRC 93, 034314 (2016).

L. Tang et al., PRC 90, 034320 (2014).

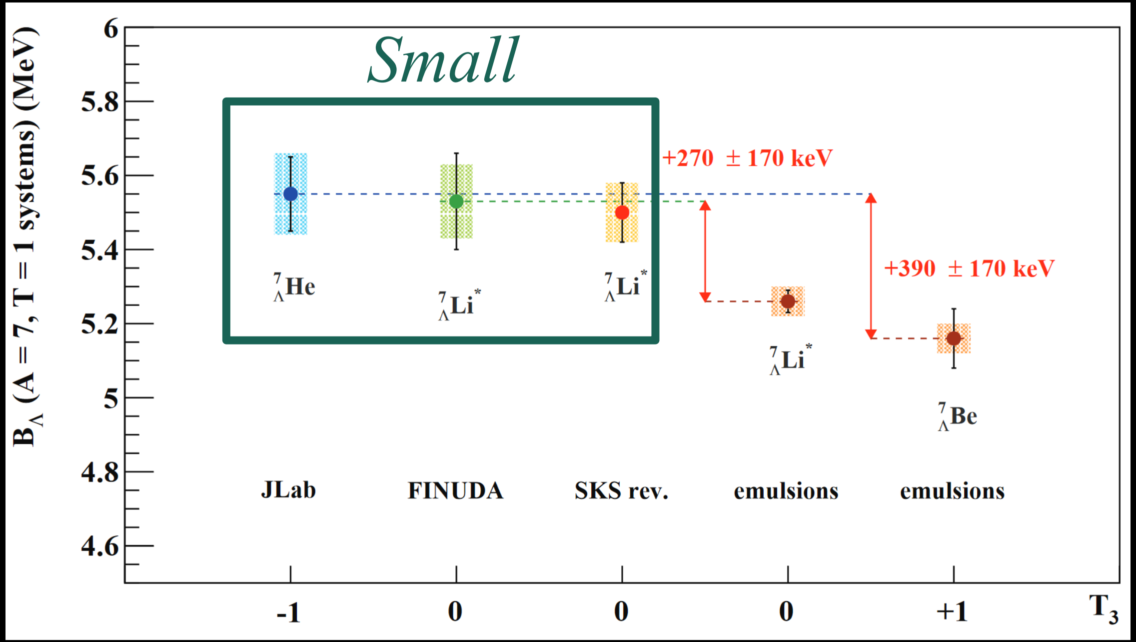
$^{9}_{\Lambda}$Li vs. $^{9}_{\Lambda}$B

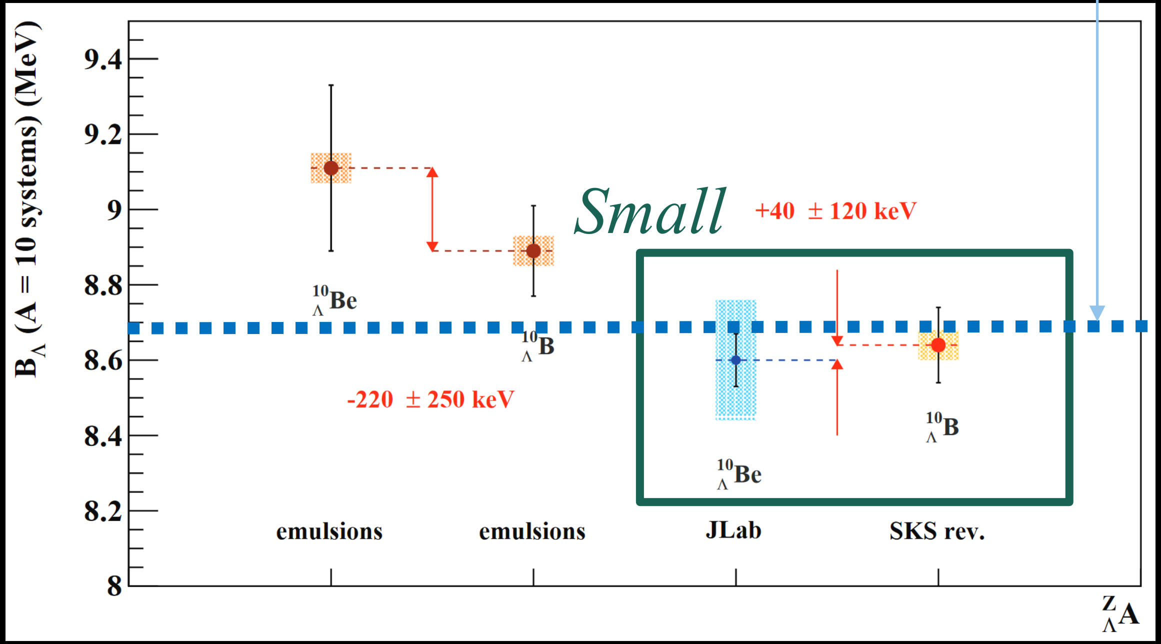
TG et al., PRC 103, L041301 (2021)

RESULTS

Y. Kanada, PRC97, 034324 (2018);
ESC08a (DI)

E. Botta, AIP Conference Proceedings 2130, 030003 (2019)



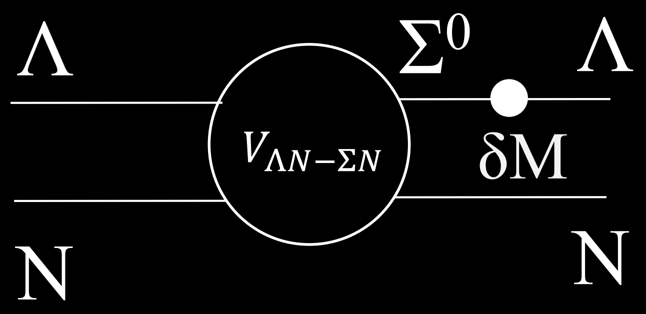


- CSB seems to be small in p-shell when counting experiments' data are used
- Double check is awaited for emulsion data → J-PARC E07 (data were taken)

BASIC INFORMATION FOR THE ΛN CSB STUDY: ${}^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$

Explicit inclusion of Σ

A. Gal, Phys. Lett. B 744, 352 (2015)



$$\langle N\Lambda|V_{CSB}|N\Lambda\rangle = -0.0297\tau_{Nz}\frac{1}{\sqrt{3}}\langle N\Sigma|V_{CS}|N\Lambda\rangle$$

Phenomenological potential

E. Hiyama et al., Phys. Rev. C **80**, 054321 (2009).
M. Isaka et al., Phys. Rev. C 101, 024301 (2020).

$$V_{\Lambda N}^{\mathrm{CSB}}(r) = -\frac{\tau_z}{2}\left[\frac{1+P_r}{2}\left(v_0^{\mathrm{even,CSB}} + \sigma_\Lambda\cdot\sigma_N v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{even,CSB}}\right)e^{-\beta_{\mathrm{even}}r^2} + \frac{1-P_r}{2}\left(v_0^{\mathrm{odd,CSB}} + \sigma_\Lambda\cdot\sigma_N v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{odd,CSB}}\right)e^{-\beta_{\mathrm{odd}}r^2}\right]$$

Basic Input

JLab → $B_\Lambda({}^{4}_{\Lambda}\mathrm{H};\ 1^{+})$

A=4 → **CSB interaction** →

A=5 HKS, PRL 110, 012502 (2013)

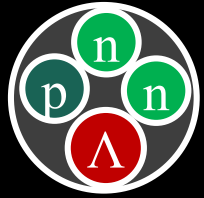
A=7 HKS, PRC 94, 021302(R) (2016)

A=9 Hall A, PRC 91,034308 (2015)
HKS, PRC103, L041301 (2021)

A=10 HKS, PRC 93, 034314 (2016)

… HKS, PRC 90, 034320 (2014) …

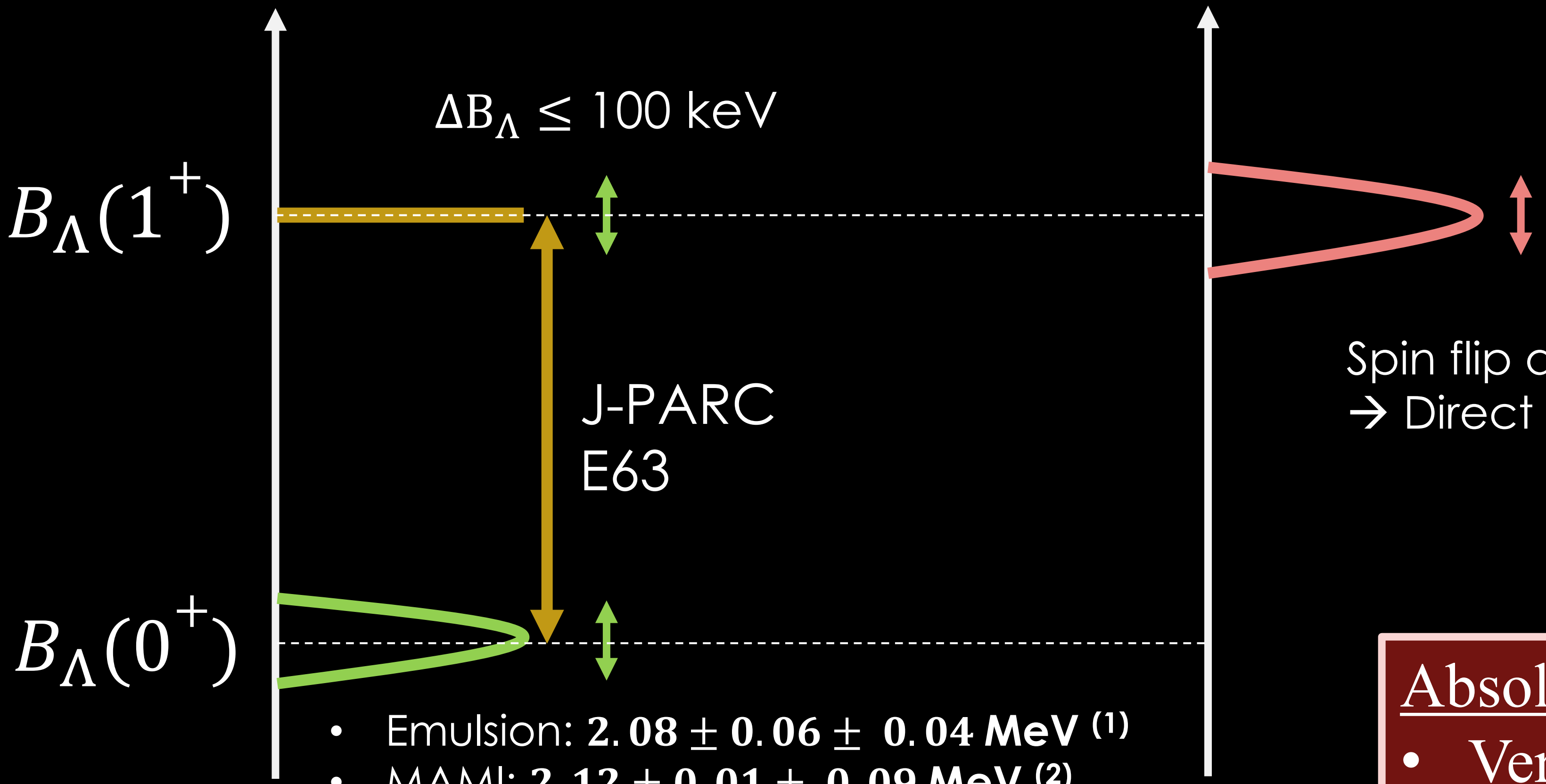
HOW WE CONFIRM THE $B_\Lambda({}^4_\Lambda\mathrm{H};\ 1^+)$



Conventional way

JLab E12-19-002

Fully approved by JLab PAC (2021)



$\Delta B_\Lambda^{total} \lesssim 60$ keV (2 days)

Spin flip amplitude is large
→ Direct production of 1^+ state

- Emulsion: $\mathbf{2.08 \pm 0.06 \pm 0.04}$ **MeV** (1)
- MAMI: $\mathbf{2.12 \pm 0.01 \pm 0.09}$ **MeV** (2)

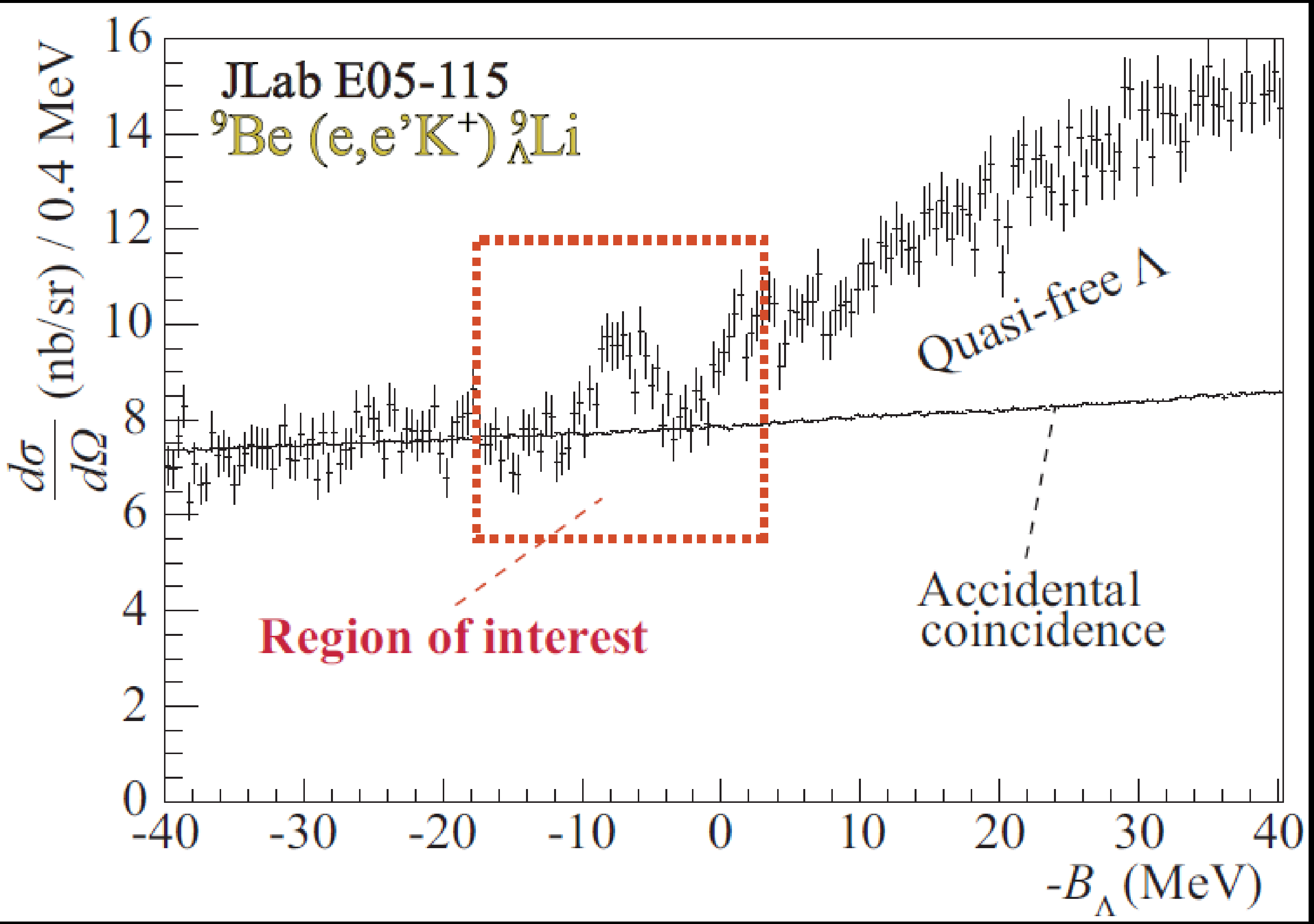
<u>Absolute Energy Measurement:</u>
- Very unique (direct meas.)
- Complementary with other data

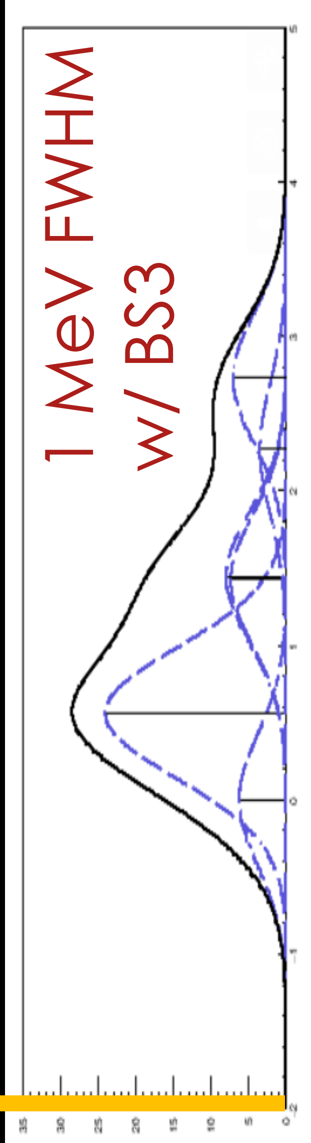
(1) NPB 52, 1-30 (1973)
(2) PRL 114, 232501 (2015)

^{8}Li ⊗ Λ = $^{9}_{\Lambda}$Li (Hyperlithium)

$^{8}\mathrm{Li}(e,e'K^{+})^{9}_{\Lambda}\mathrm{Li}$
P. Bydžovský
(private communication)

TG et al., PRC 103, L041301 (2021)

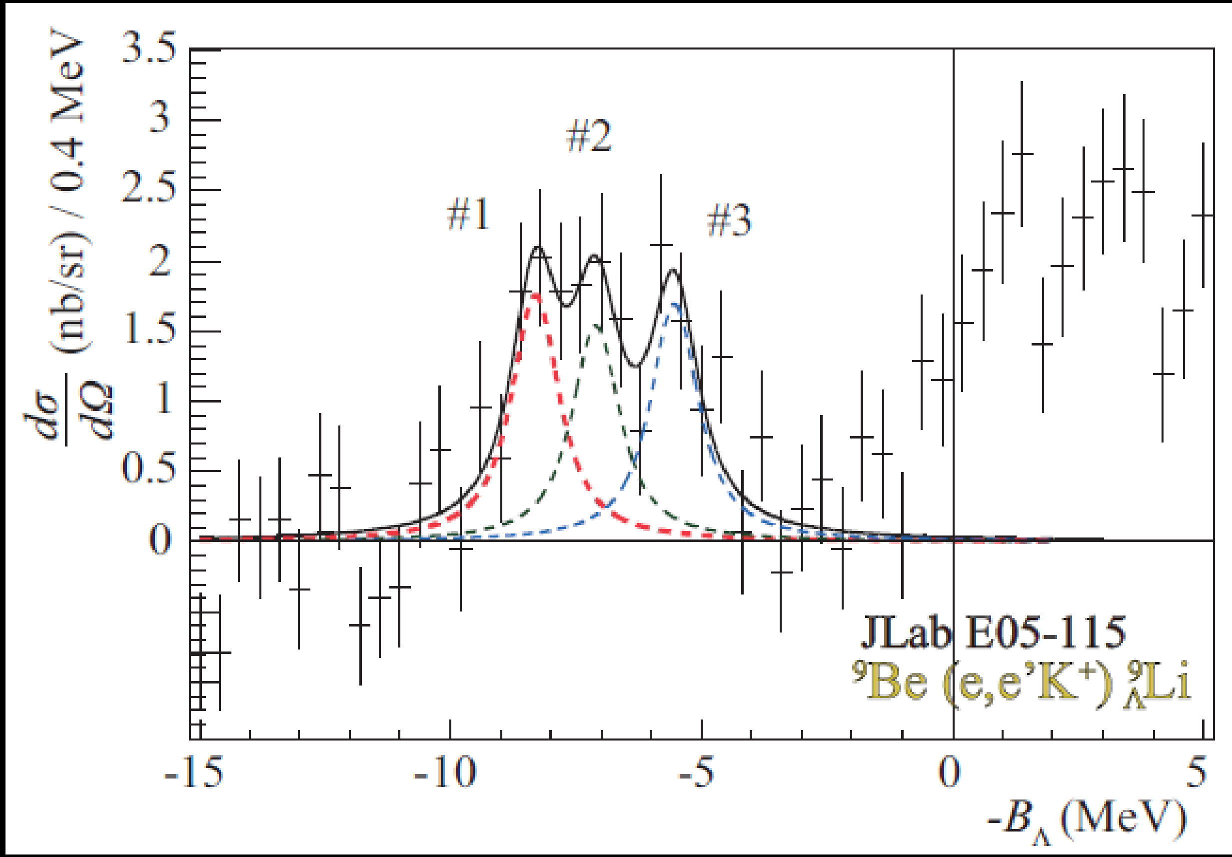


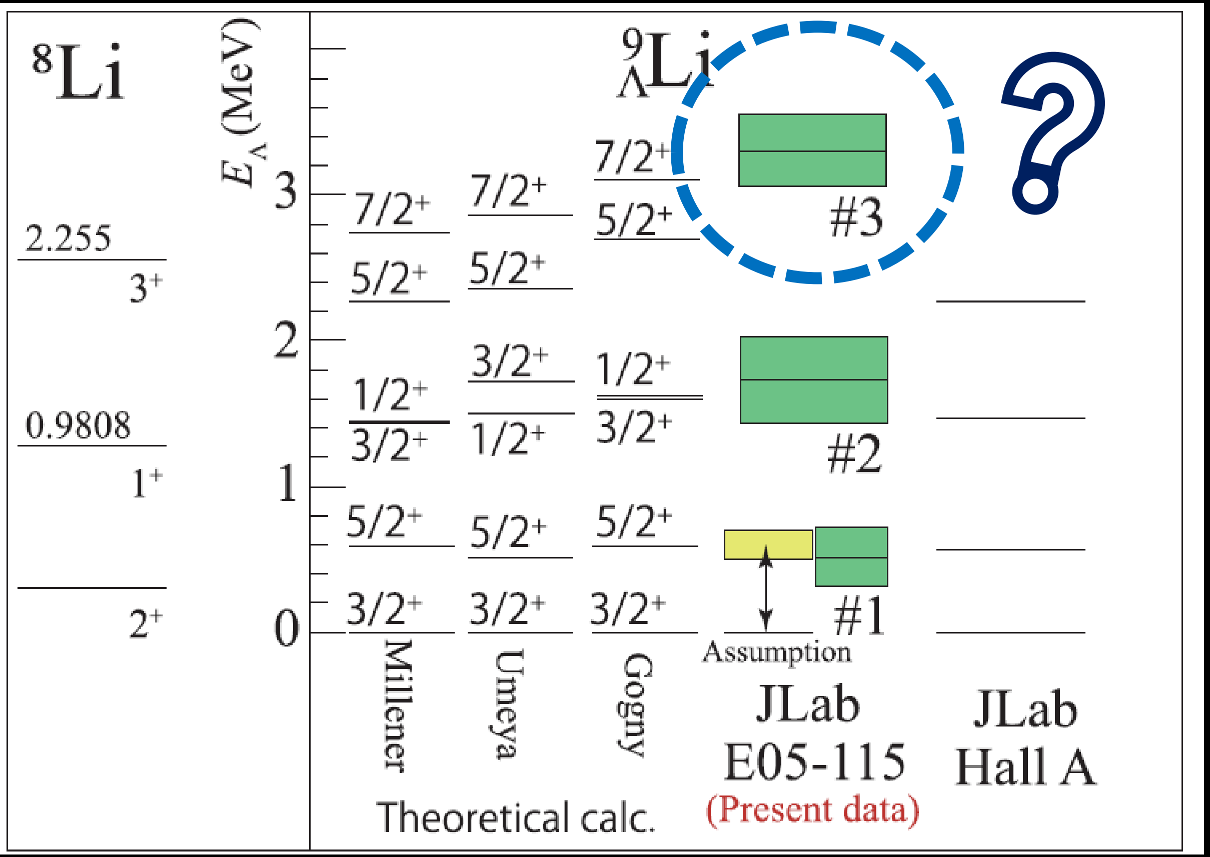


Production rate

Small binding in $^{8}\mathrm{Li}\,(3^{+}) \otimes \Lambda$

HKS Collaboration, PRC 103, L041301 (2021)





CLUSTER STRUCTURE?

H. Stowe and W. Zahn, NPA289, 317—328 (1977)

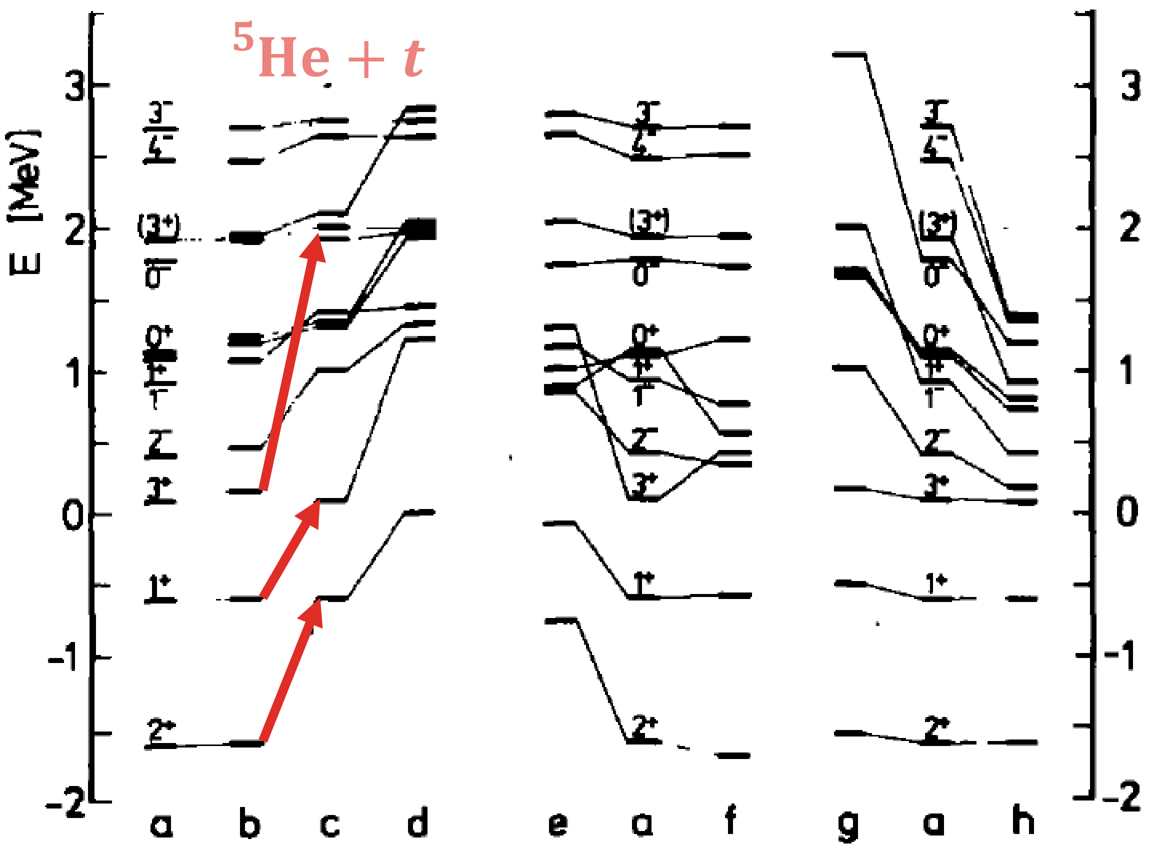
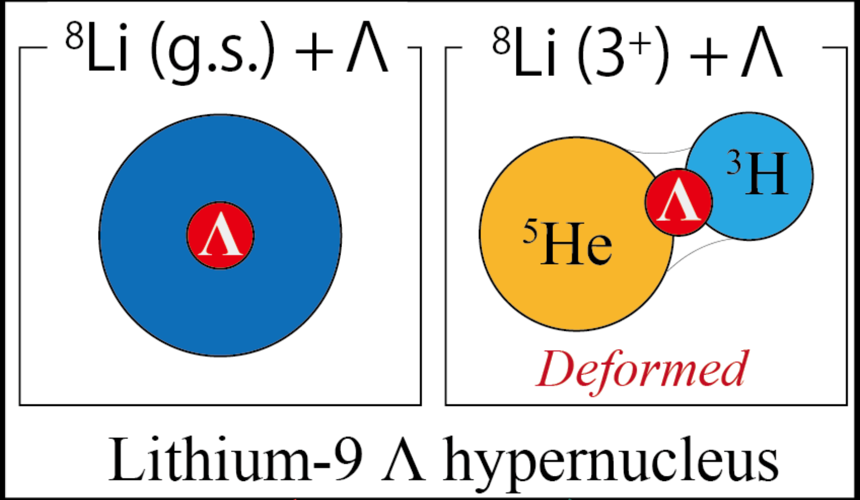
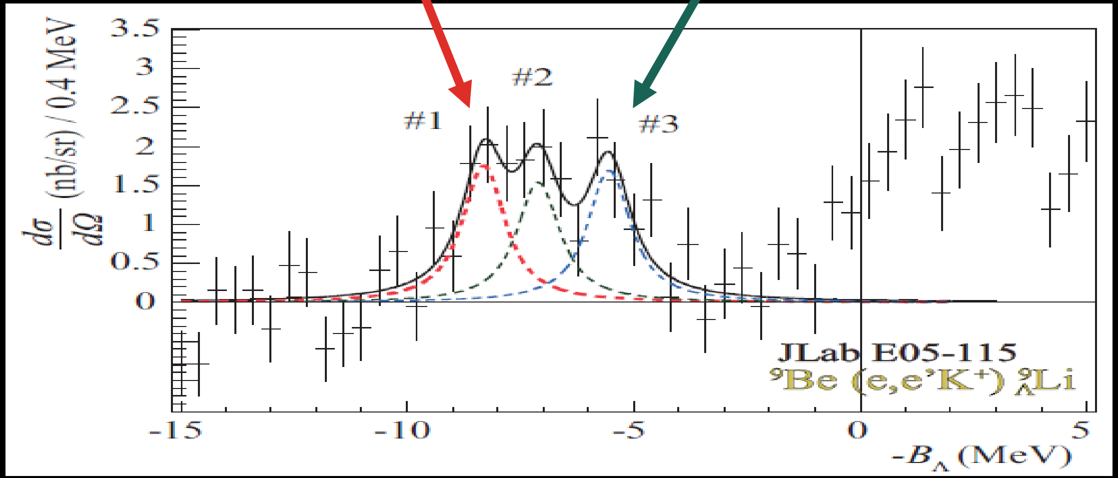


Fig. 4. Results of bound and quasibound state calculations. (a) Full calculation with relative parameters 7–11, (b) same as (a) but without ^{5}He*-t structure, (c) same as (b) but without ^{5}He-t structure, (d) same as (c) but without ^{7}Li*-n structure, (e) same as (a) but with spin-orbit strength 2, (f) same as (a) but with tensor strength 3, (g) same as (a) but with relative parameters 7–10, and (h) same as (a) but with relative parameters 7–12.

Λ probes the core structure

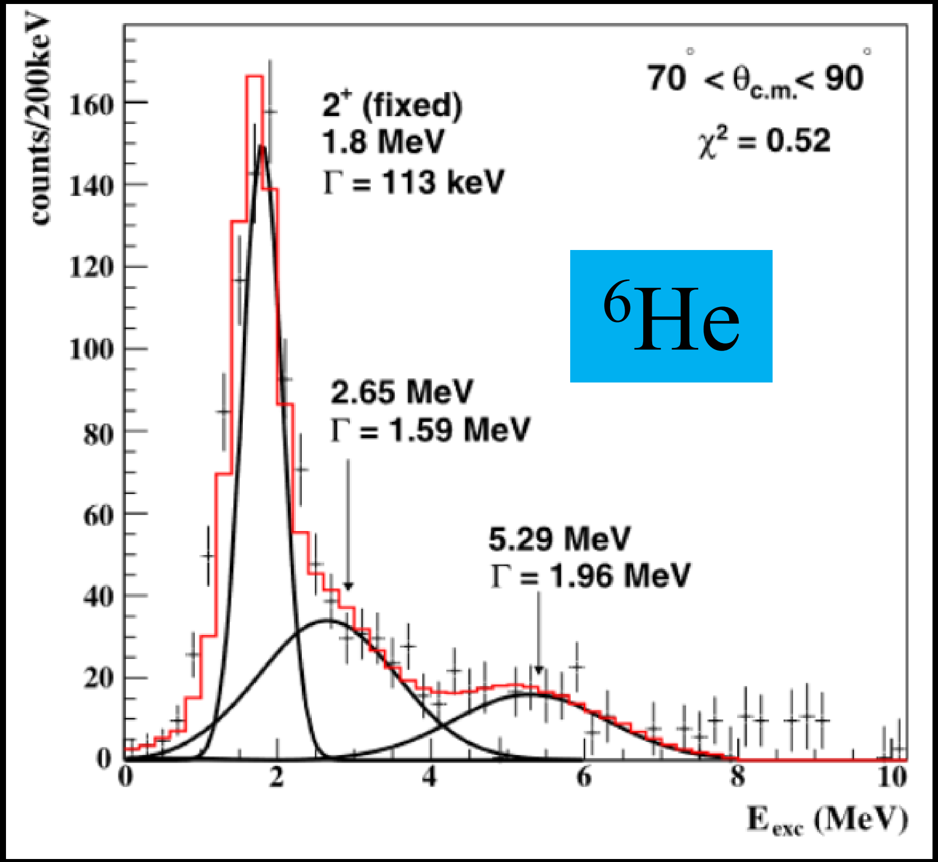




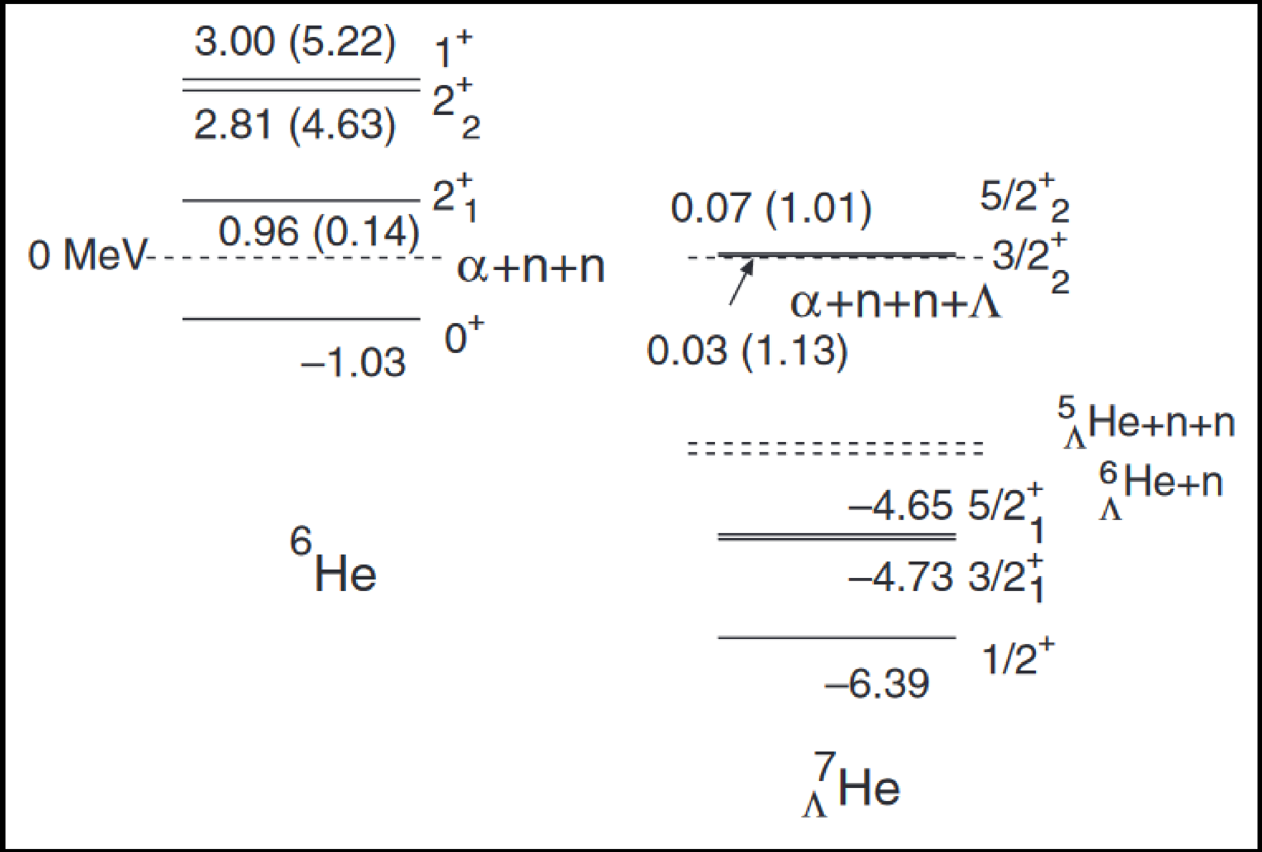
Theoretical calculation is awaited to be compared with the result!!

$^{6}He \otimes \Lambda = {}^{7}_{\Lambda}He$ (Hyperhelium)

$^{8}He(p,t)$ @SPIRAL, GANIL



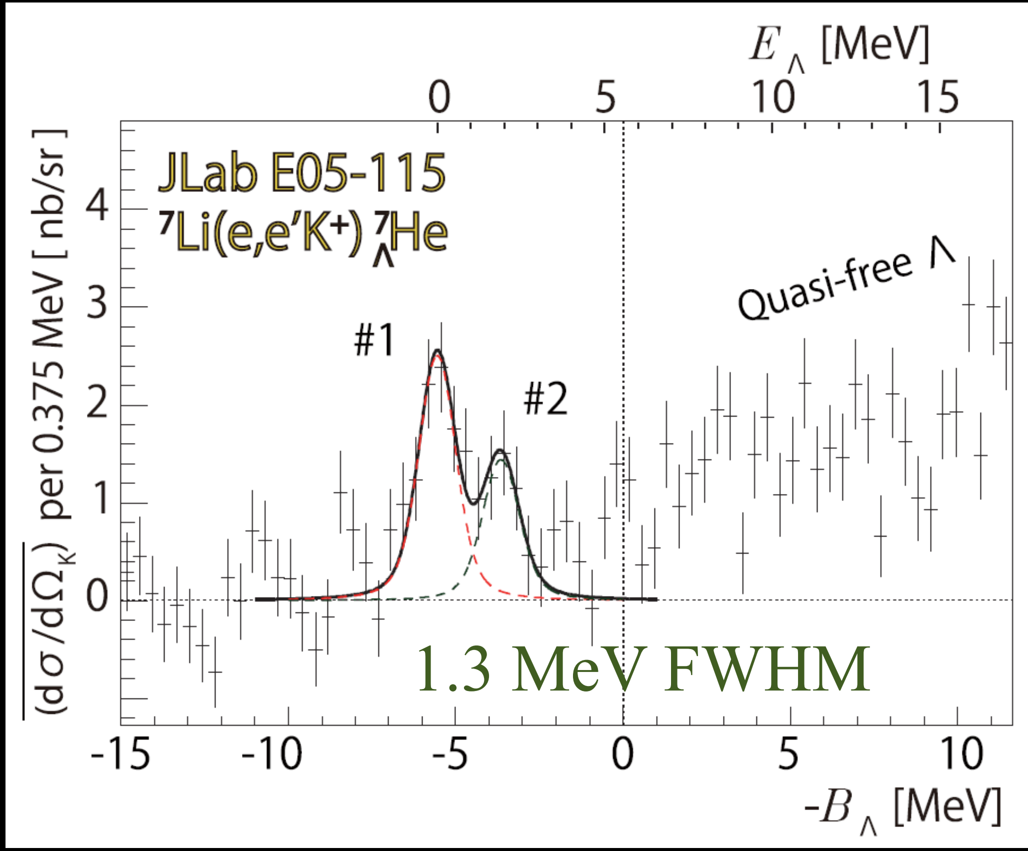
X. Mougeot et al., PLB718, 441—446 (2012)

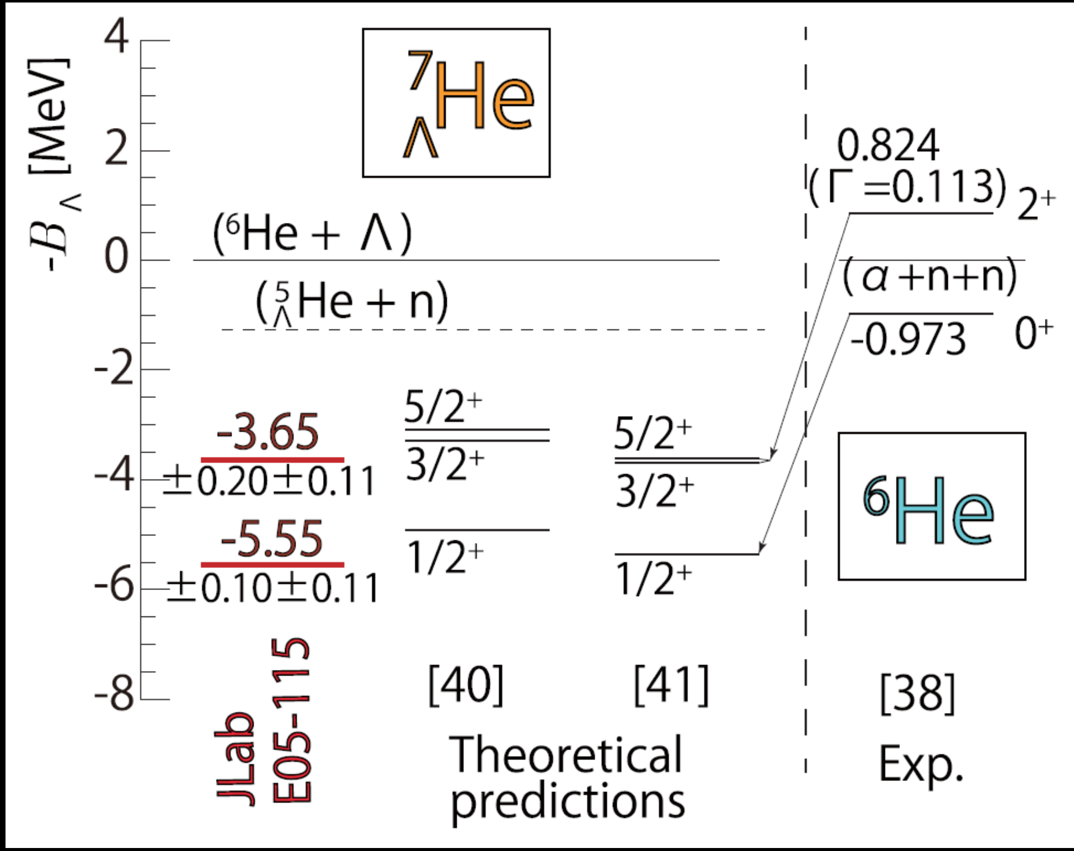


E. Hiyama et al., PRC91, 054316 (2015)

$^{6}He \otimes \Lambda = {}^{7}_{\Lambda}He$ (Hyperhelium)

HKS Collaboration, PRC 94, 021302(R) (2016)





Glue-like behavior can be a tool to investigate nuclear structures for neutron rich systems

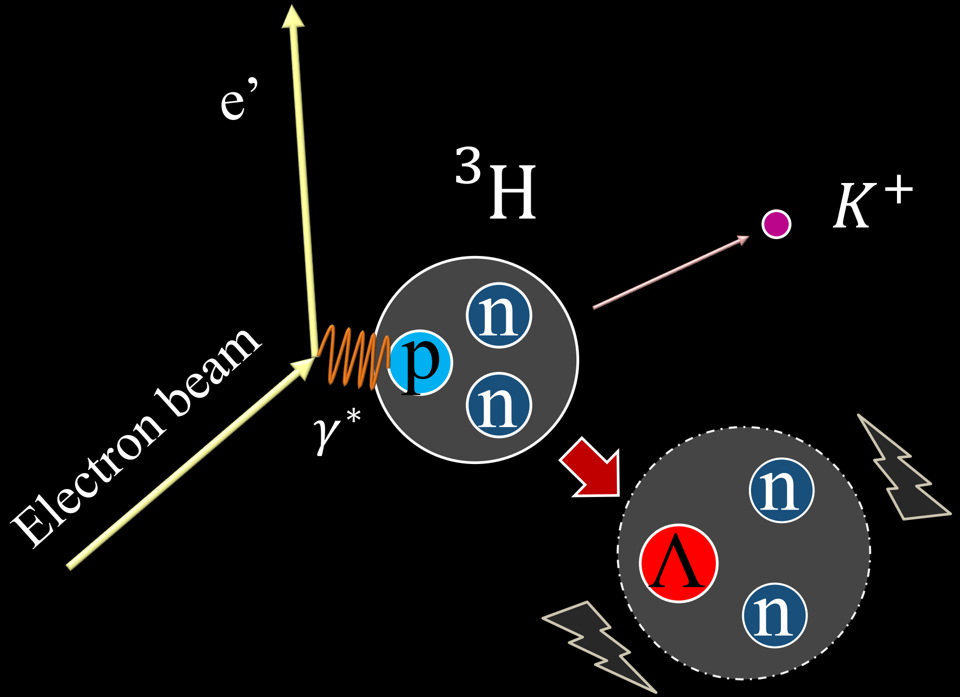
nnΛ search experiment at JLab (E12-17-003)

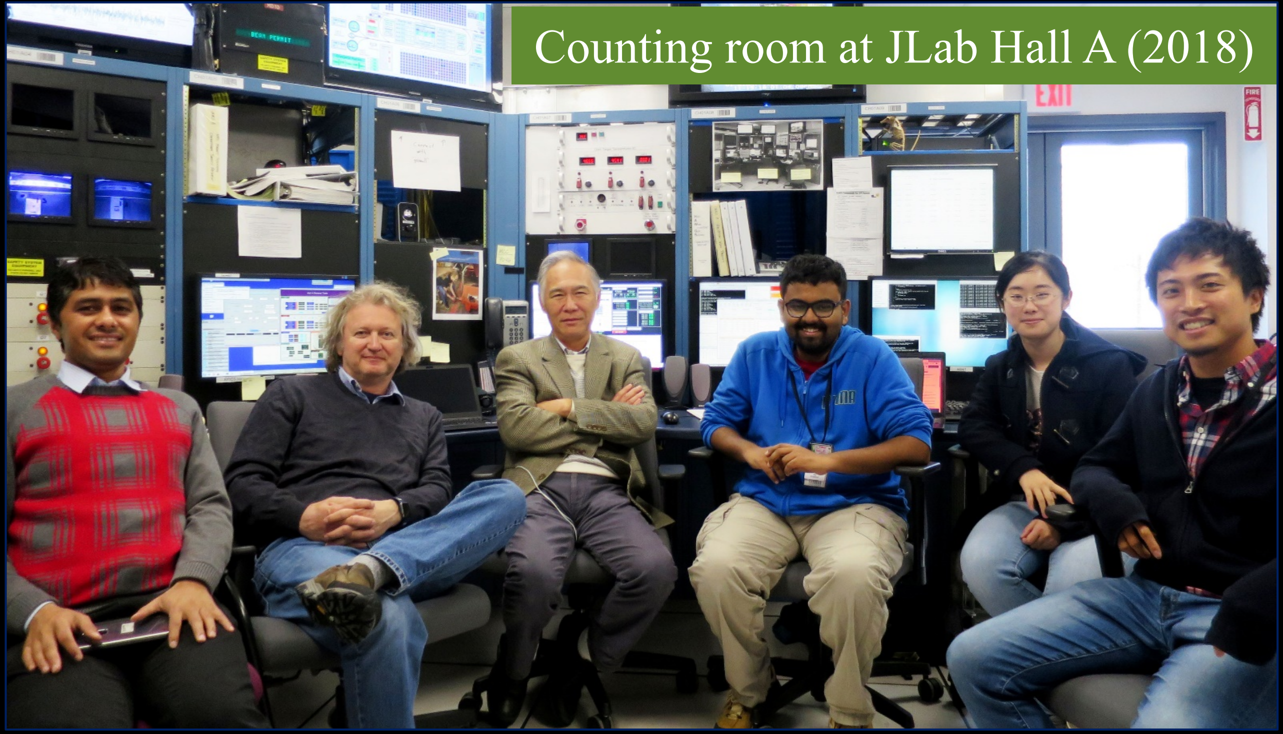
C. Rappold et al. (HypHI Collaboration), Phys. Rev. C 88, 041001(R) (2013).

bound nnΛ?

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

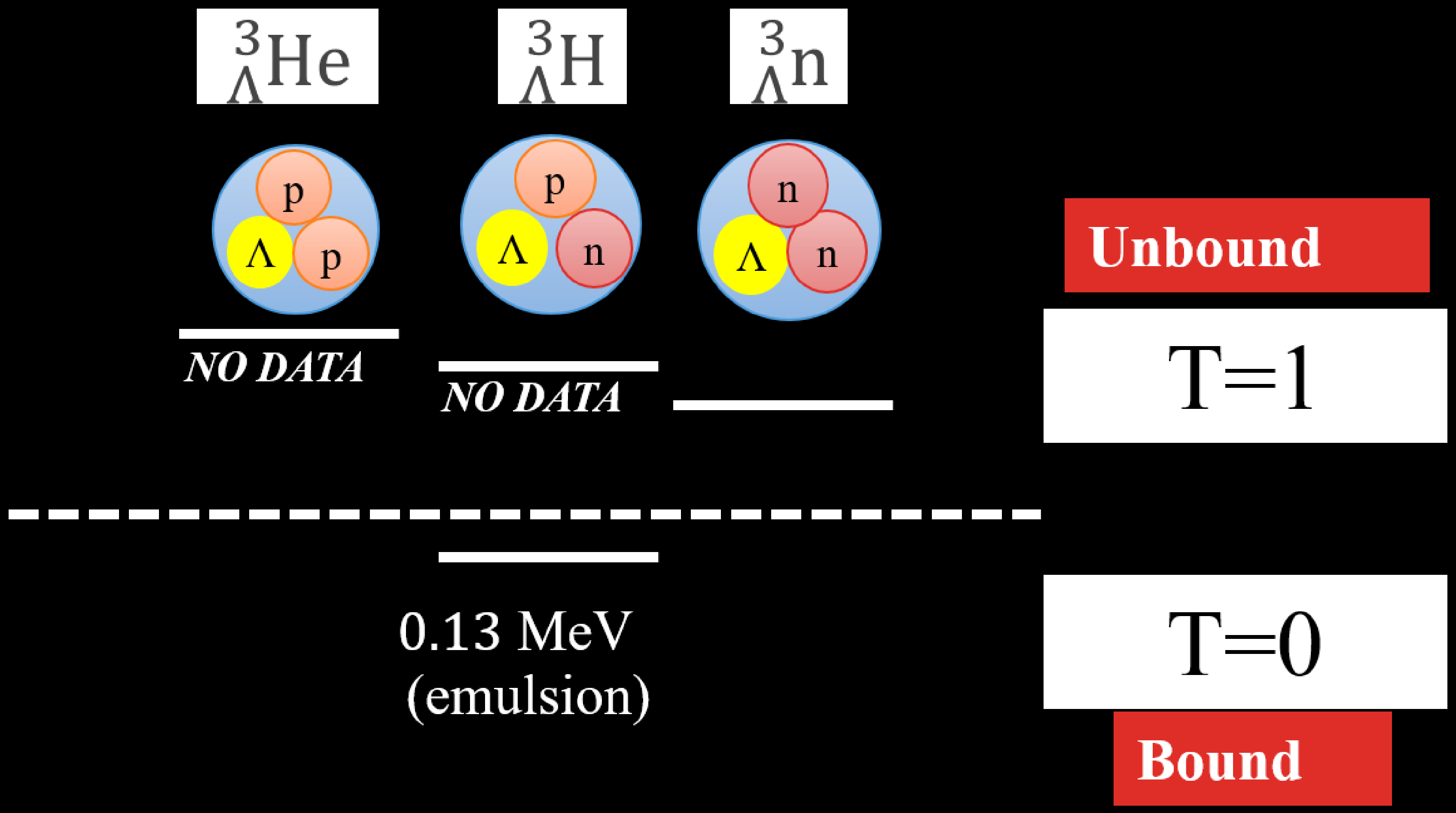
E12-17-003 (Oct 30—Nov 25, 2018)





Missing mass measurement has sensitivity to both bound and resonant states

What we believe for the three-body system with a Λ



STUDENTS WHO ANALYZE DATA

Independent analyses are in progress by students to doublecheck (triplecheck) results

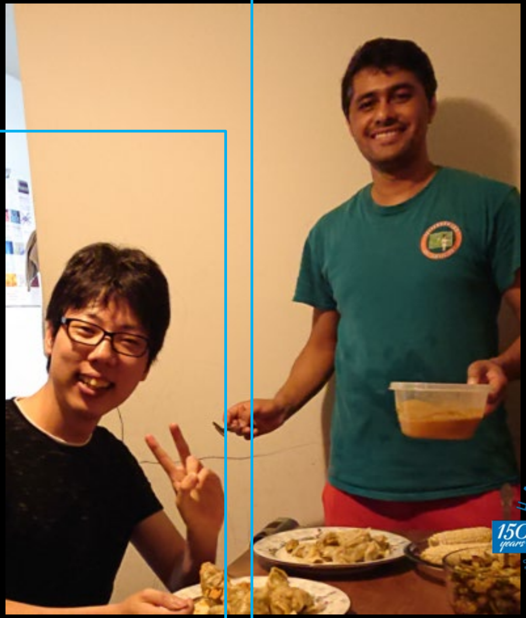
K. Itabashi

K. Okuyama

東北大学

Tohoku Univ., Japan

E. Umezaki



K.N. Suzuki

Kyoto Univ., Japan

B. Pandey

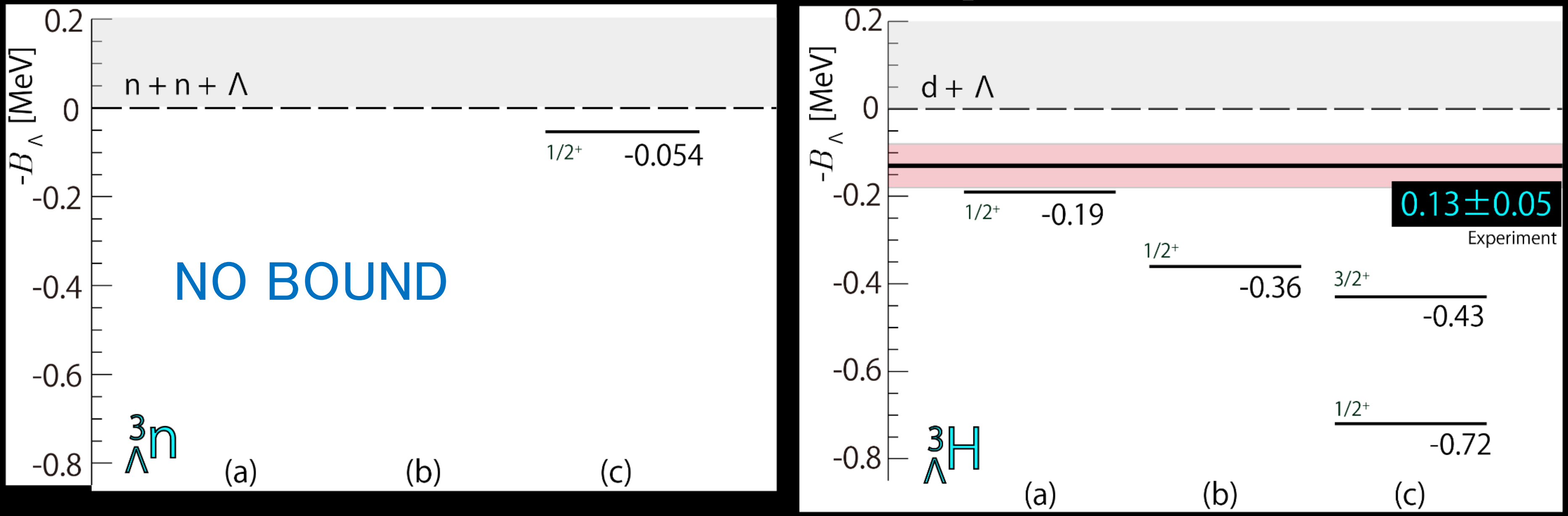
Hampton Univ., US

An FSI, elementary production, nnΛ search/CS, etc.

CAN THE *NNΛ* BE BOUND?

E. Hiyama, S. Ohnishi, B.F. Gibson, and Th. A. Rijken, Physical Review C 89, 061302(R) (2014).

AV8 ***NN*** + NSC97f ***YN*** potentials



(a) $^{3}V^{T}_{\Lambda N-\Sigma N} \times 1.0$

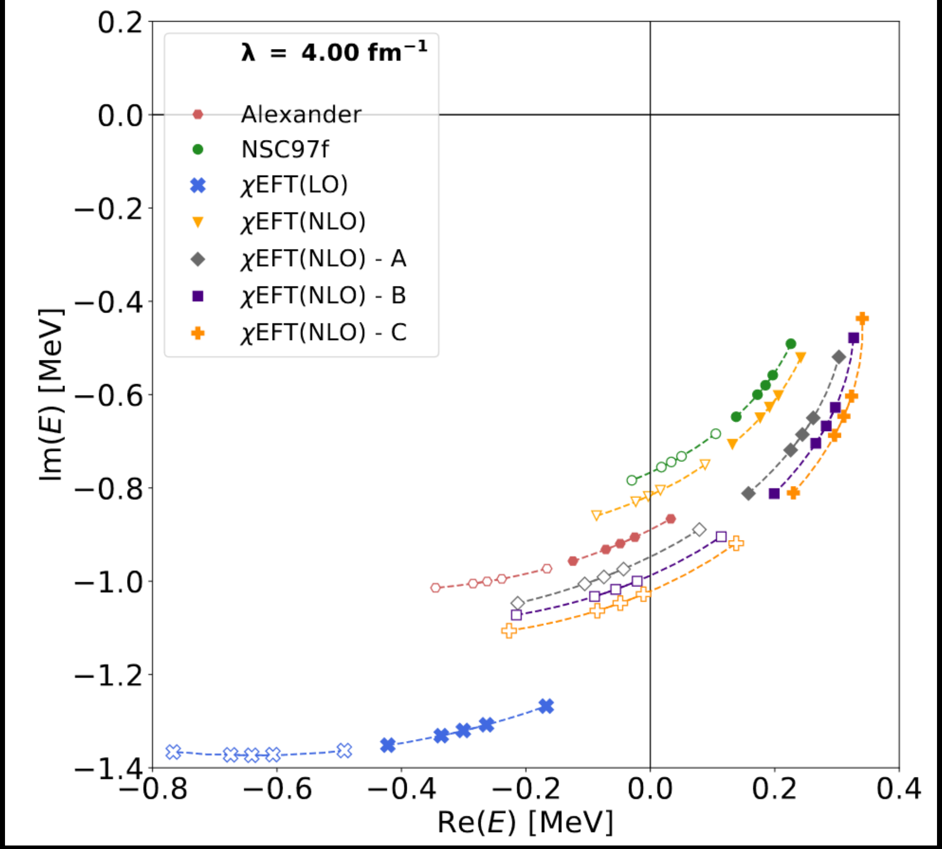
(b) $^{3}V^{T}_{\Lambda N-\Sigma N} \times 1.1$

(c) $^{3}V^{T}_{\Lambda N-\Sigma N} \times 1.2$

Tensor component of the ΛN-ΣN coupling was varied.
→ No solution was found to make the *nn*Λ bound maintaining the consistency with the $^{3}_{\Lambda}$H ($^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He) data.

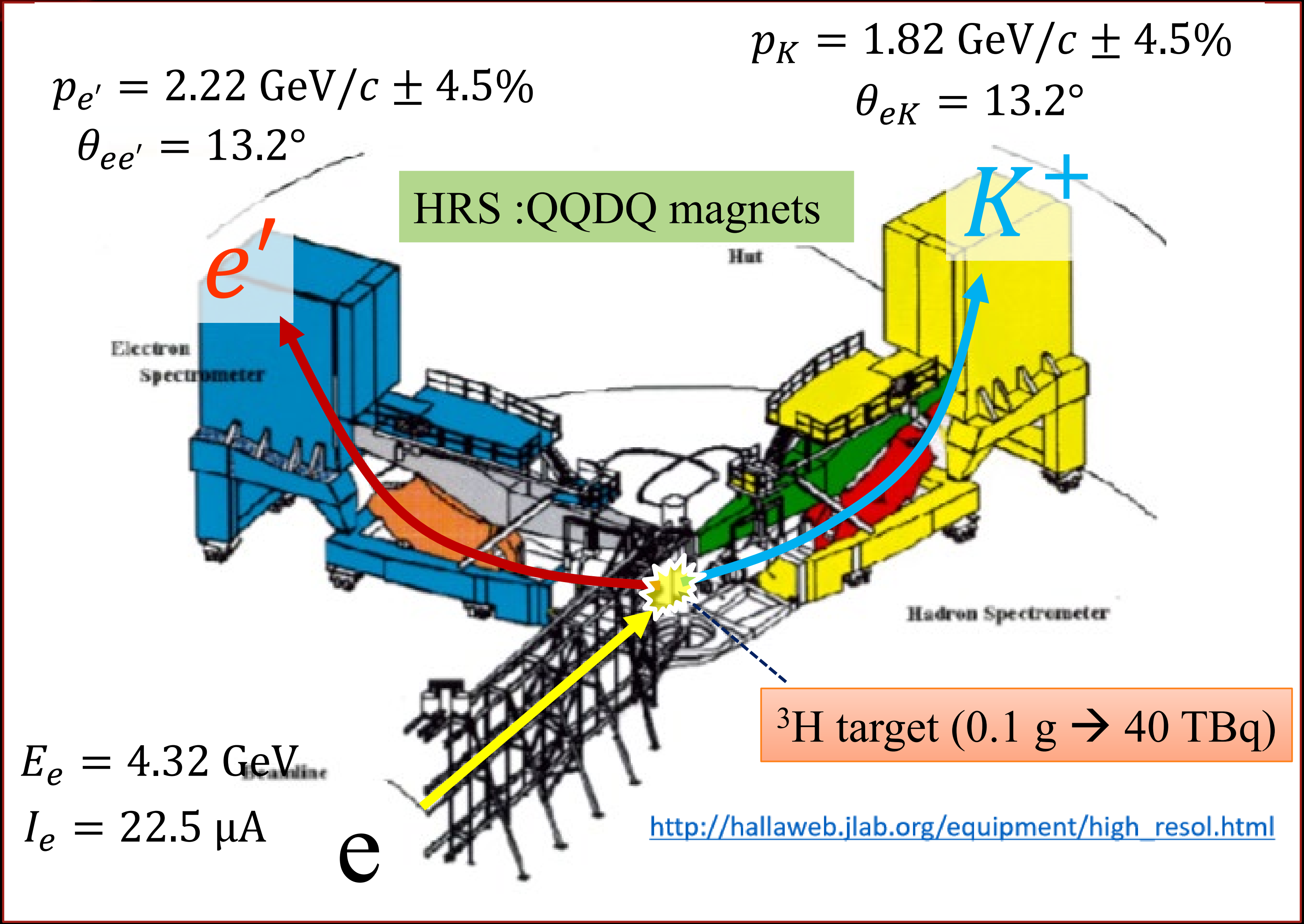
RESONANT STATE

M. Schafer et al., arXiv:2108.13900v1 [nucl-th] 31 Aug 2021



Resonant sate may exist

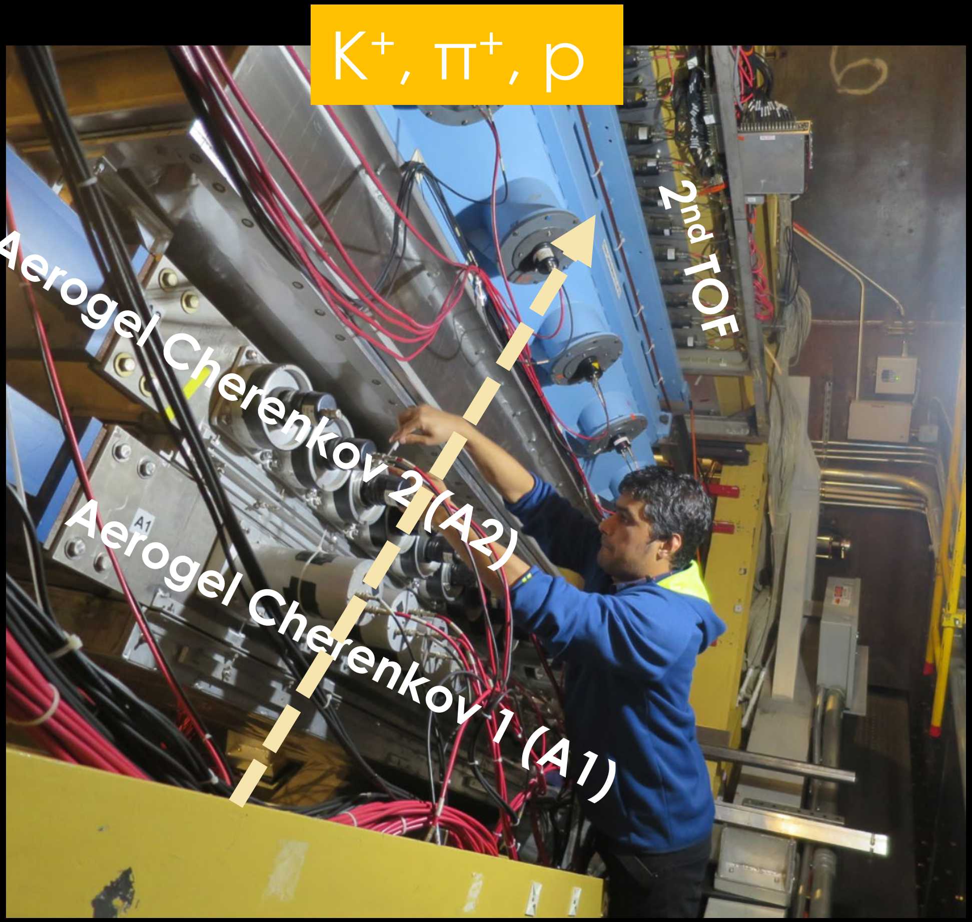
EXPERIMENTAL SETUP (JLAB E12-17-003)

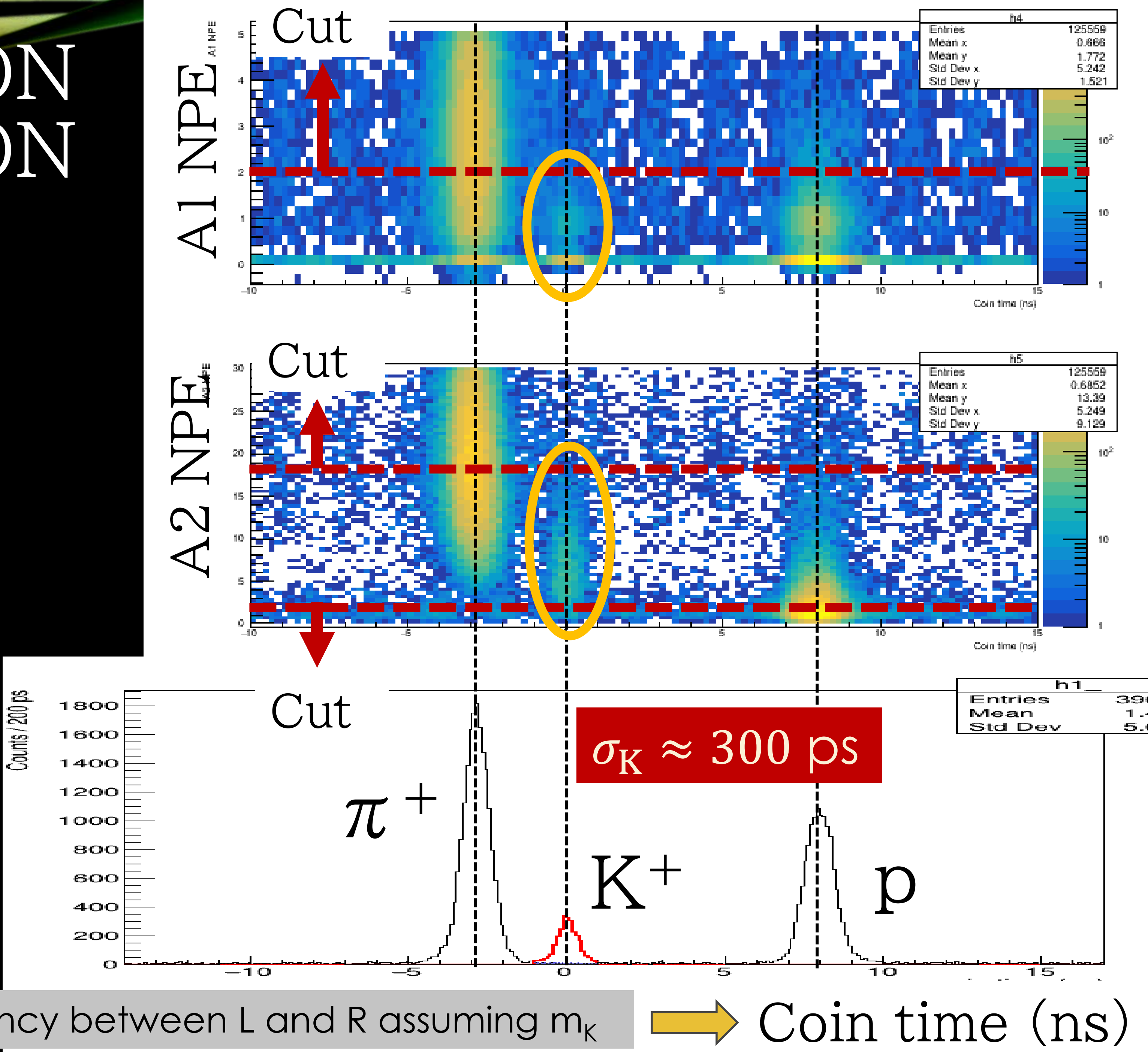


LHRS

RHRS
JLab Hall A (Apr 2019)
KYOTO UNIVERSITY
KYOTO JAPAN
FOUNDED 1897
HAMPTON UNIVERSITY
150 years
40 years
CELEBRATING A LEGACY AND A LEGEND OF EXCELLENCE
Jefferson Lab
Thomas Jefferson National Accelerator Facility

KAON IDENTIFICATION

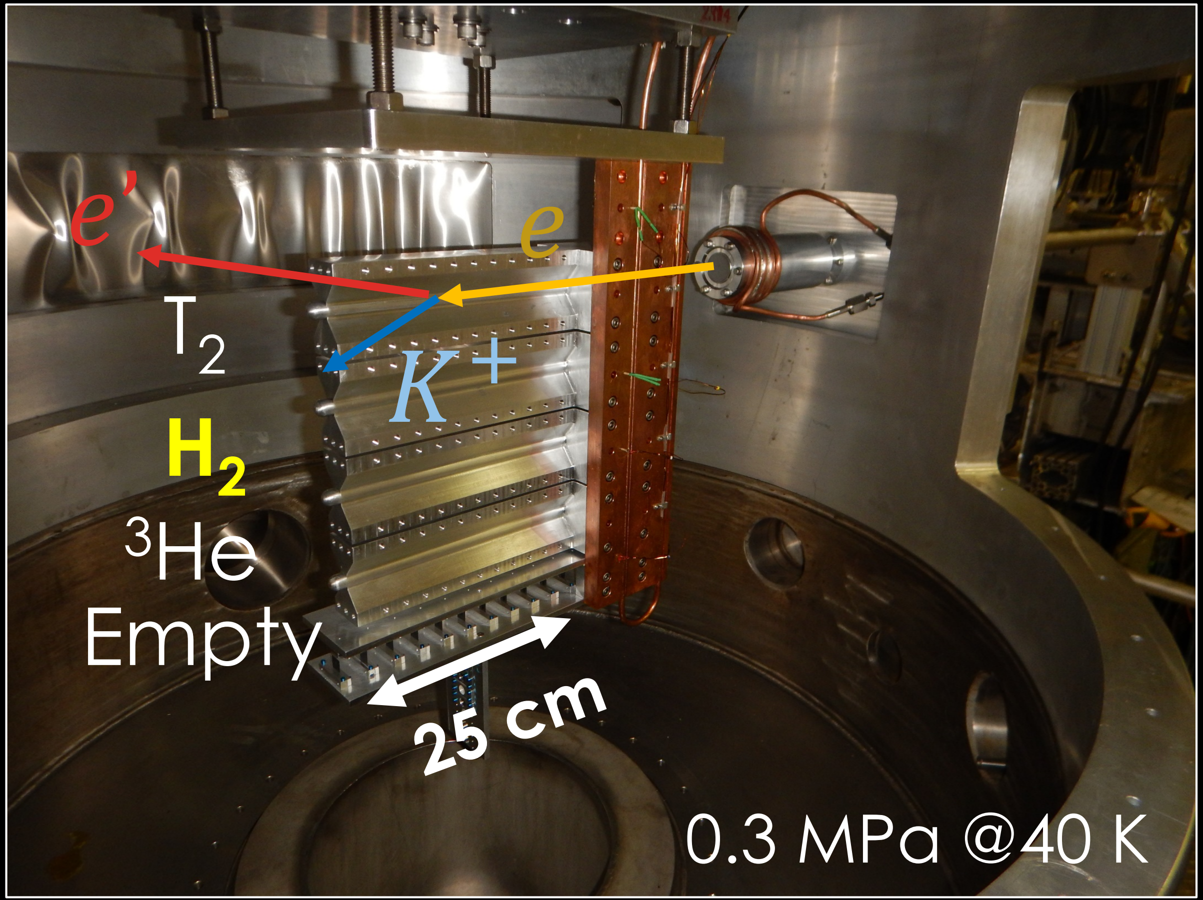




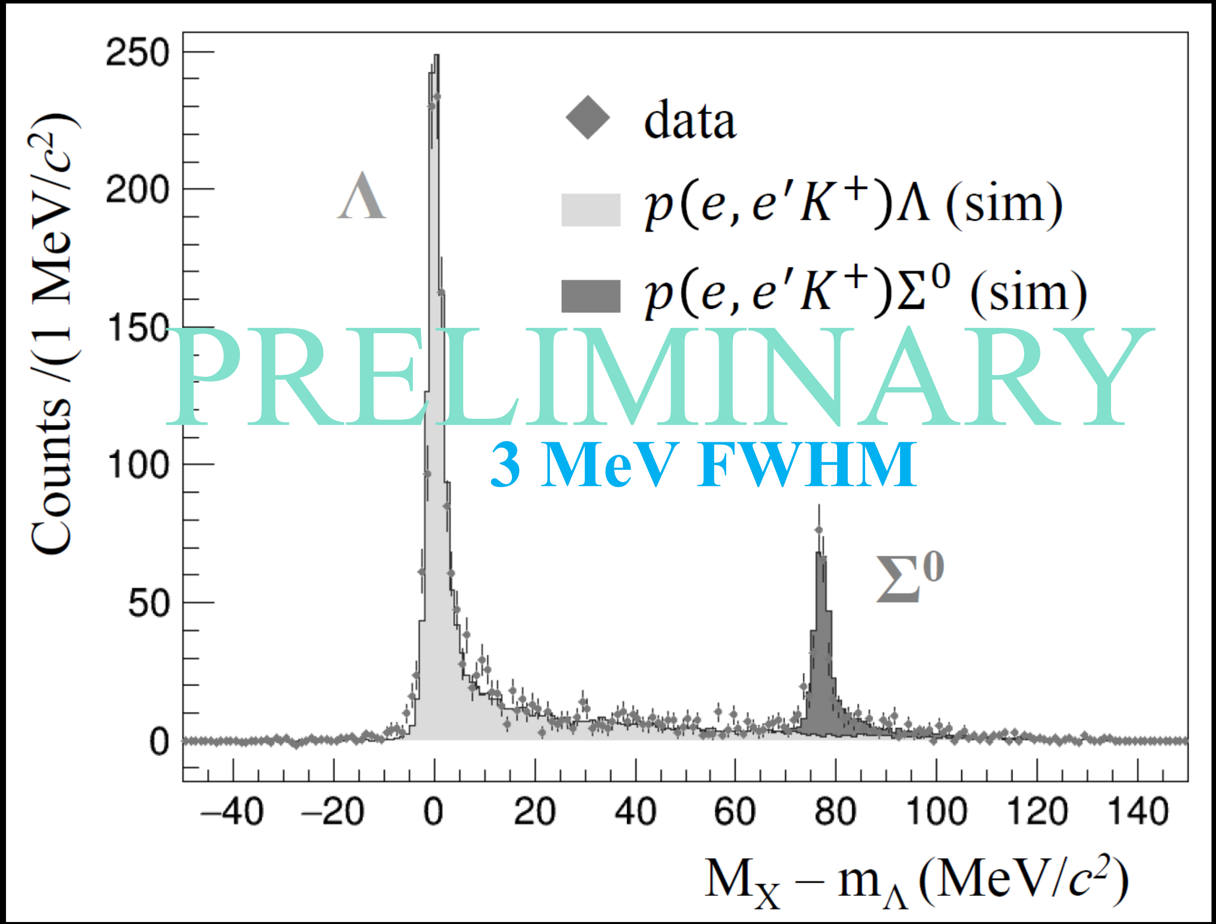
Timing consistency between L and R assuming m_K

Energy calibration by Λ and Σ

Inside of scattering chamber



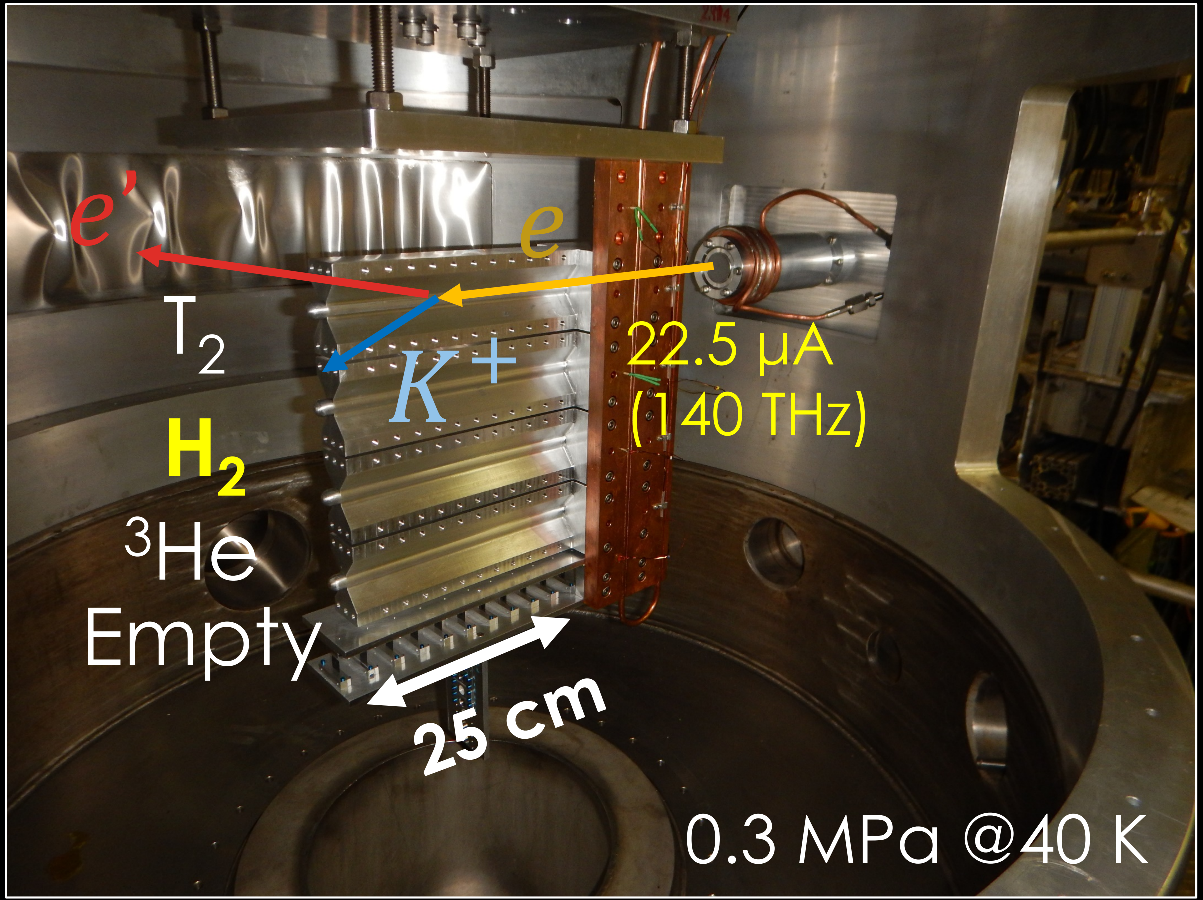
$H(e,e'K^+)\Lambda, \Sigma^0$



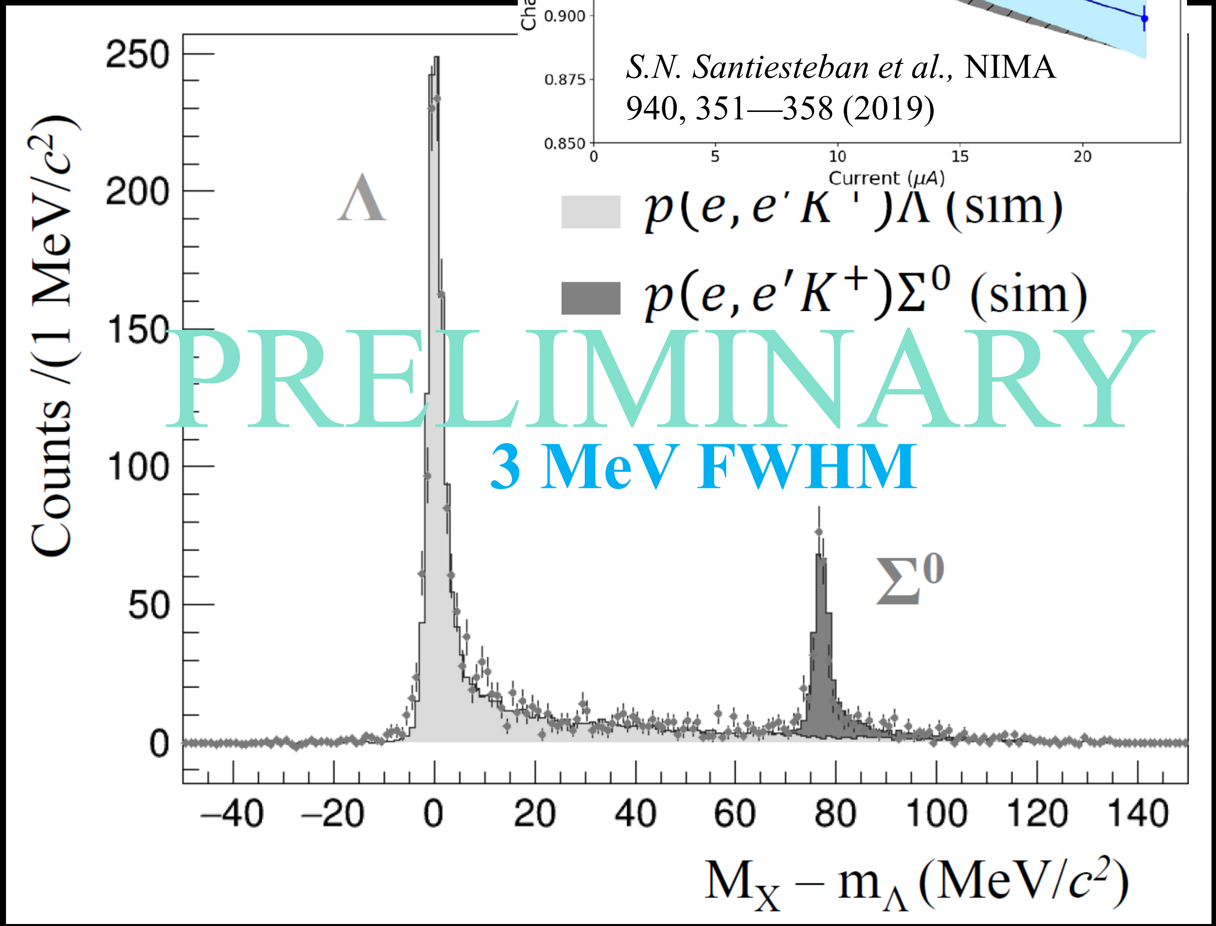
➡ System worked as we designed

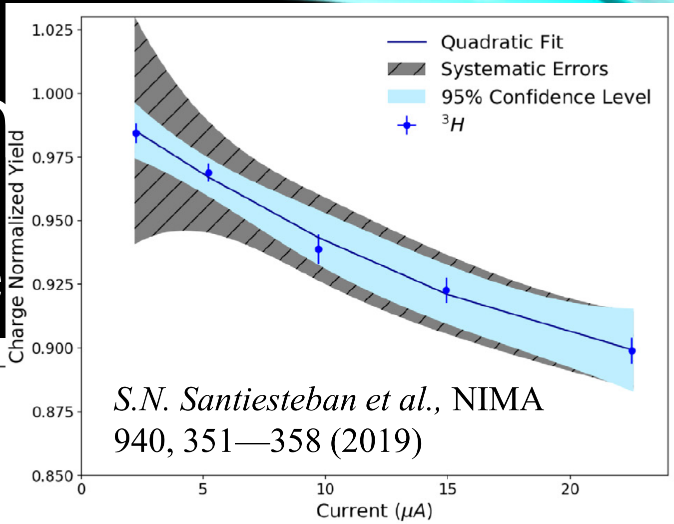
Energy calibration

Inside of scattering chamber



H(e,e





System worked as we designed

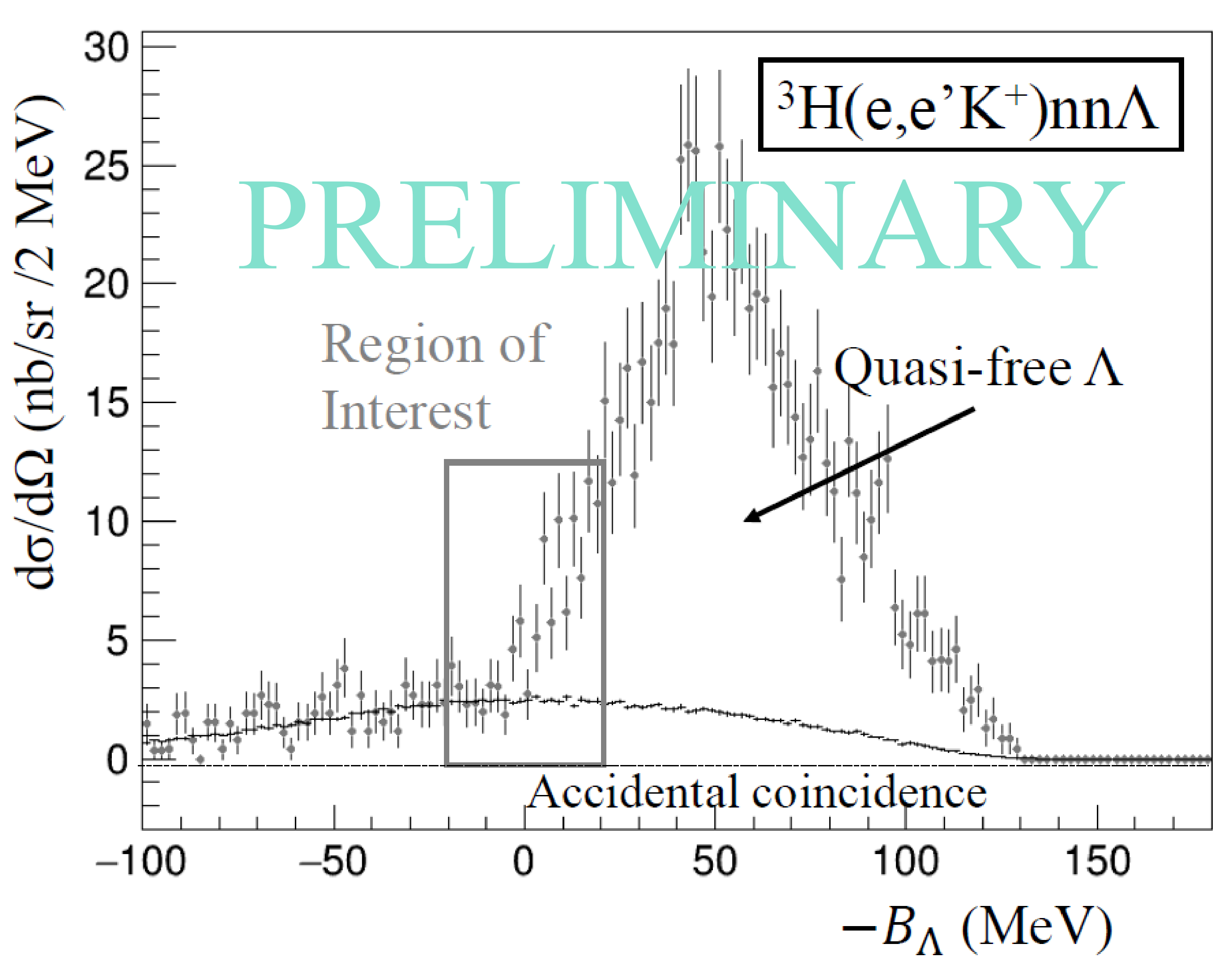
CROSS SECTION ANALYSIS

1. Acceptance cut
   → Lower statistics
2. Systematic error in addition to statistical error

Other ongoing analyses:

A) Peak search with higher statistics
B) Λn FSI fom QF shape

Theoretical calculations are needed !



K.N. Suzuki, TG et al., arXiv:2110.09104 [nucl-ex]

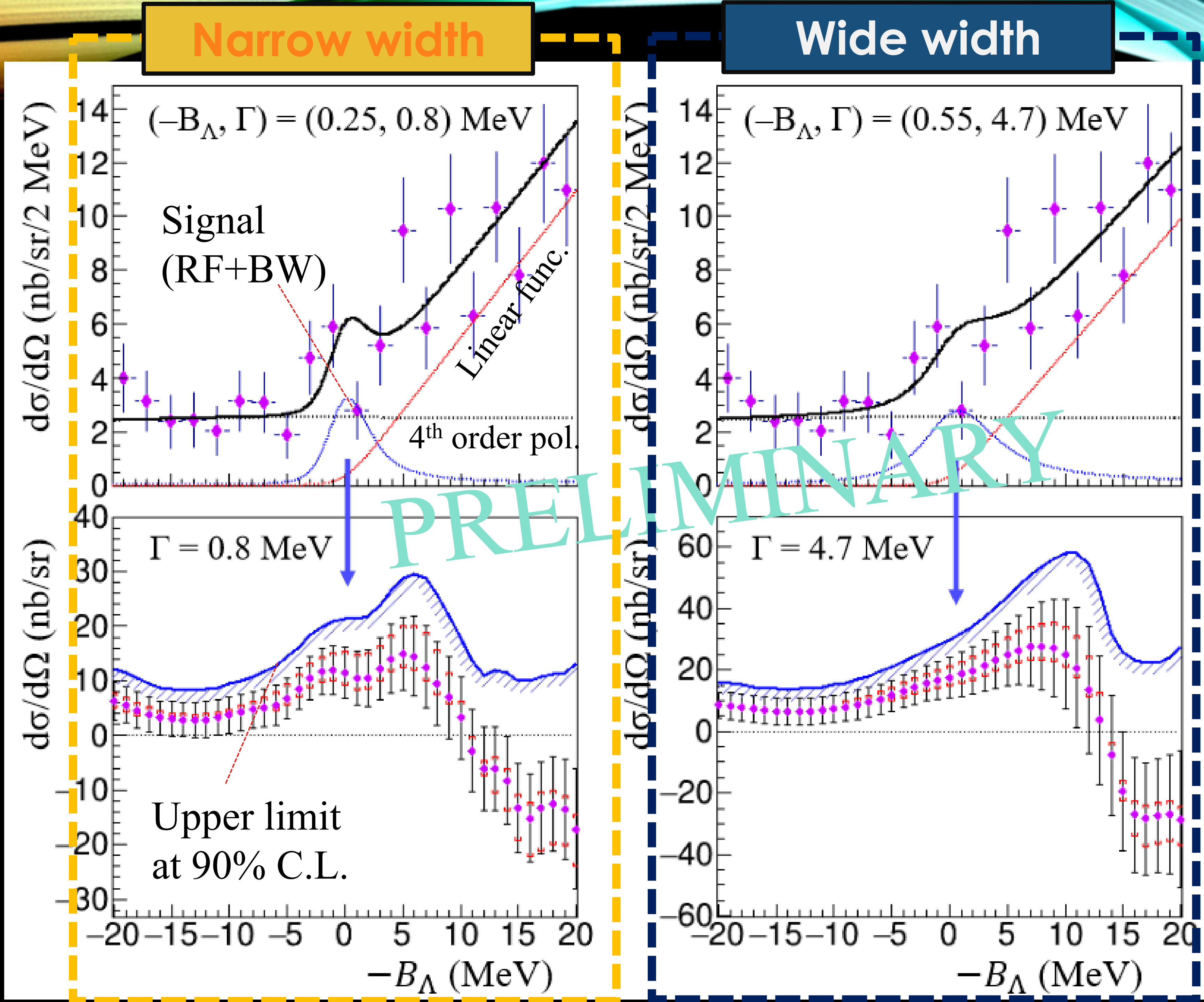
FIT RESULT (PRELIMINARY)

arXiv:2110.09104 [nucl-ex]

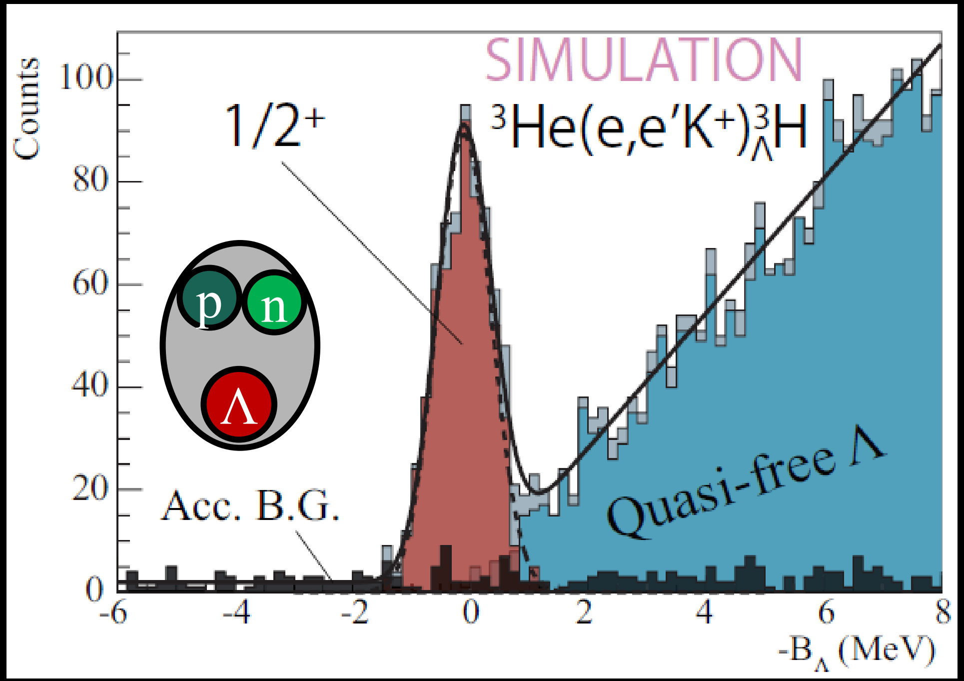
Test case1: narrow width Γ = 0.8 MeV
K.M.Kamada et al.,
EPJ Conf. 113, 07004 (2016)

Test case2: wide width Γ = 4.7 MeV
V.B. Belyaev et al., NPA 803, 210 (2008)

Unbinned maximum likelihood fitting
→ Cross section



Future programs being prepared



- $^{3,4}_{\Lambda}H$ (E12-19-002) → lifetime puzzle, CSB, $3/2^+$
- $^{40,48}_{\Lambda}K$ (E12-15-008) → Isospin dependence
- $^{208}_{\Lambda}Tl$ (E12-20-013) → NNΛ interaction

Very high accuracy

$$\Delta B^{total}_{\Lambda} = \pm 60 \text{ keV}$$

➡ Aim to carry out in 2023 or 2024

HYPERTRITON ($^{3}_{\Lambda}H$) PUZZLE

Small B_Λ **vs.** **Short Lifetime**

$B_\Lambda = 0.13 \pm 0.05$ MeV (emulsion[1])
$B_\Lambda = 0.41 \pm 0.12 \pm 0.11$ MeV (STAR[2])

➡ RMS radius, $\sqrt{< r^2 >} \cong \frac{\hbar}{\sqrt{4\mu B_\Lambda}}$

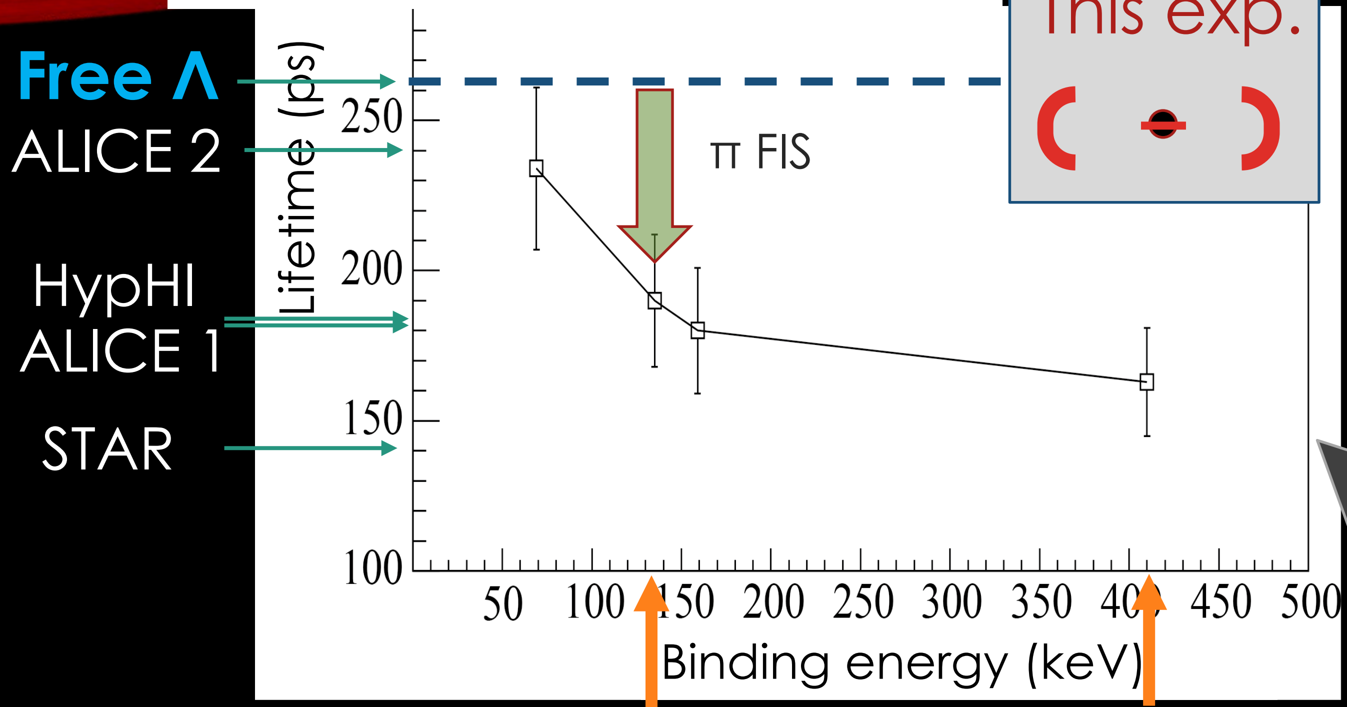
$\tau = (0.5 \sim 0.92)\, \tau_\Lambda$
(HypHI, STAR, ALICE)

Fadeev calcuation with realistic NN/YN interactions
→ $\boldsymbol{\tau = 0.97\, \tau_\Lambda}$
(H. Kamada *et al.*, *Phys. Rev. C* **57**, 4 (1998))

[1] M. Juric *et al.*, *Nucl. Phys. B* **52**, 1-30 (1973).
[2] The STAR Collaboration, *Nature Physics* (2020); https://doi.org/10.1038/s41567-020-0799-7

LIFETIME VS. BINDING ENERGY OF $^{3}_{\Lambda}\mathrm{H}$

A.Pérez-Obiol et al., PLB 811 135916 (2020)



Emulsion
NPB52 (1973)1—30
2BD: 60±110 keV
3BD: 230±110 keV

STAR
PRA982 (2019)811—814
2BD: 176±150 keV
3BD: 586±160 keV

ex.) Decay width of 2BD channel:

$$\frac{\Gamma_{^3_\Lambda\mathrm{H}\to{}^3\mathrm{He}+\pi^-}}{(G_F m_\pi^2)^2} \approx \frac{q}{\pi}\frac{M_{^3\mathrm{He}}}{M_{^3\mathrm{He}}+\omega_{\pi^-}(q)} \times \left[\mathcal{A}_\Lambda^2 + \frac{1}{9}\mathcal{B}_\Lambda^2\left(\frac{k_{\pi^-}}{2\bar{M}}\right)^2\right] 3|F^{\mathrm{PV}}(q)|^2$$

Spin indep. amp.

Spin dep. amp.

Form factor
(π FSI is included)

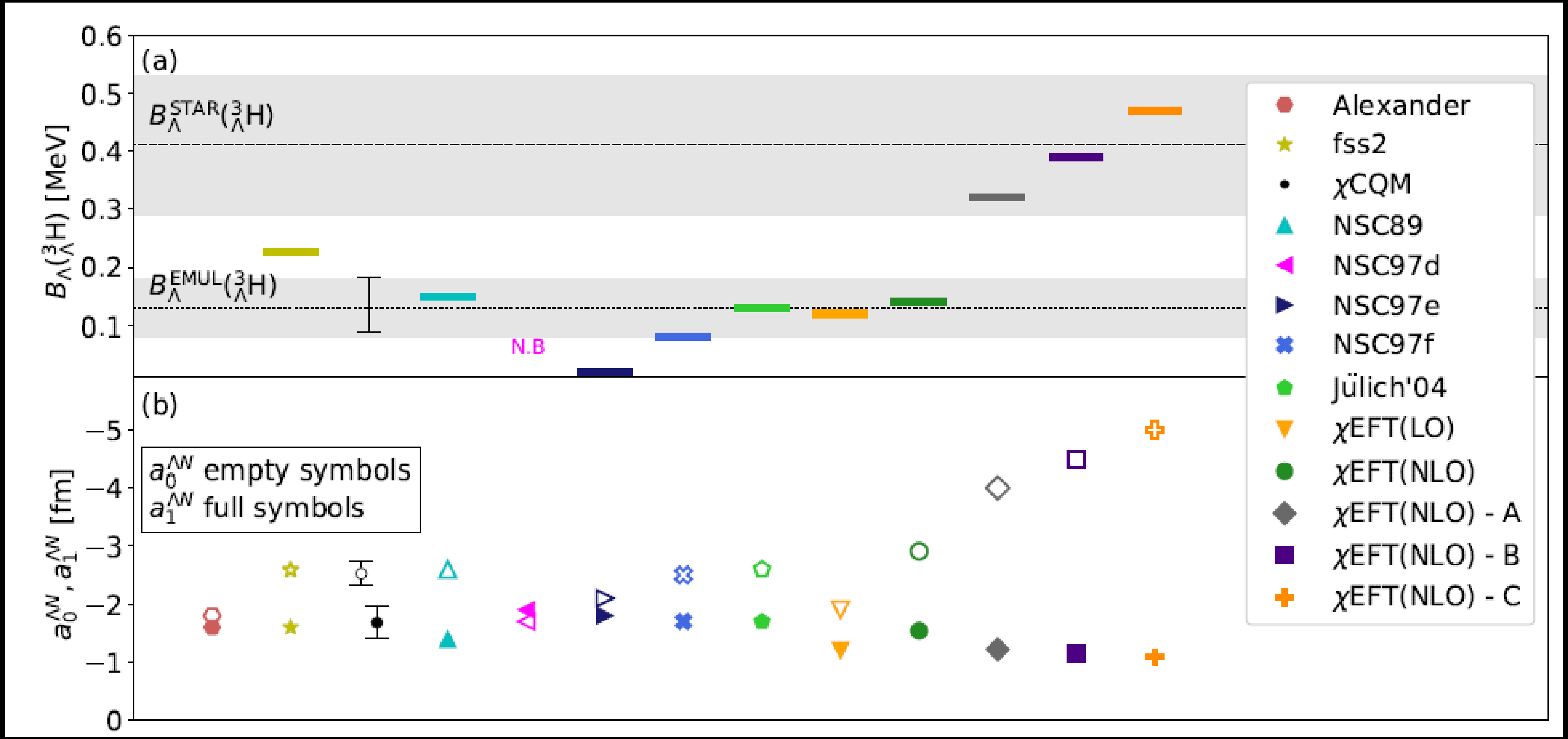
$\propto \sqrt{B_\Lambda}$

JLab E12-19-002 Experiment:
$|\Delta B^{\mathrm{stat.}}| = 20$ keV, $|\Delta B^{\mathrm{sys.}}| = 55$ keV

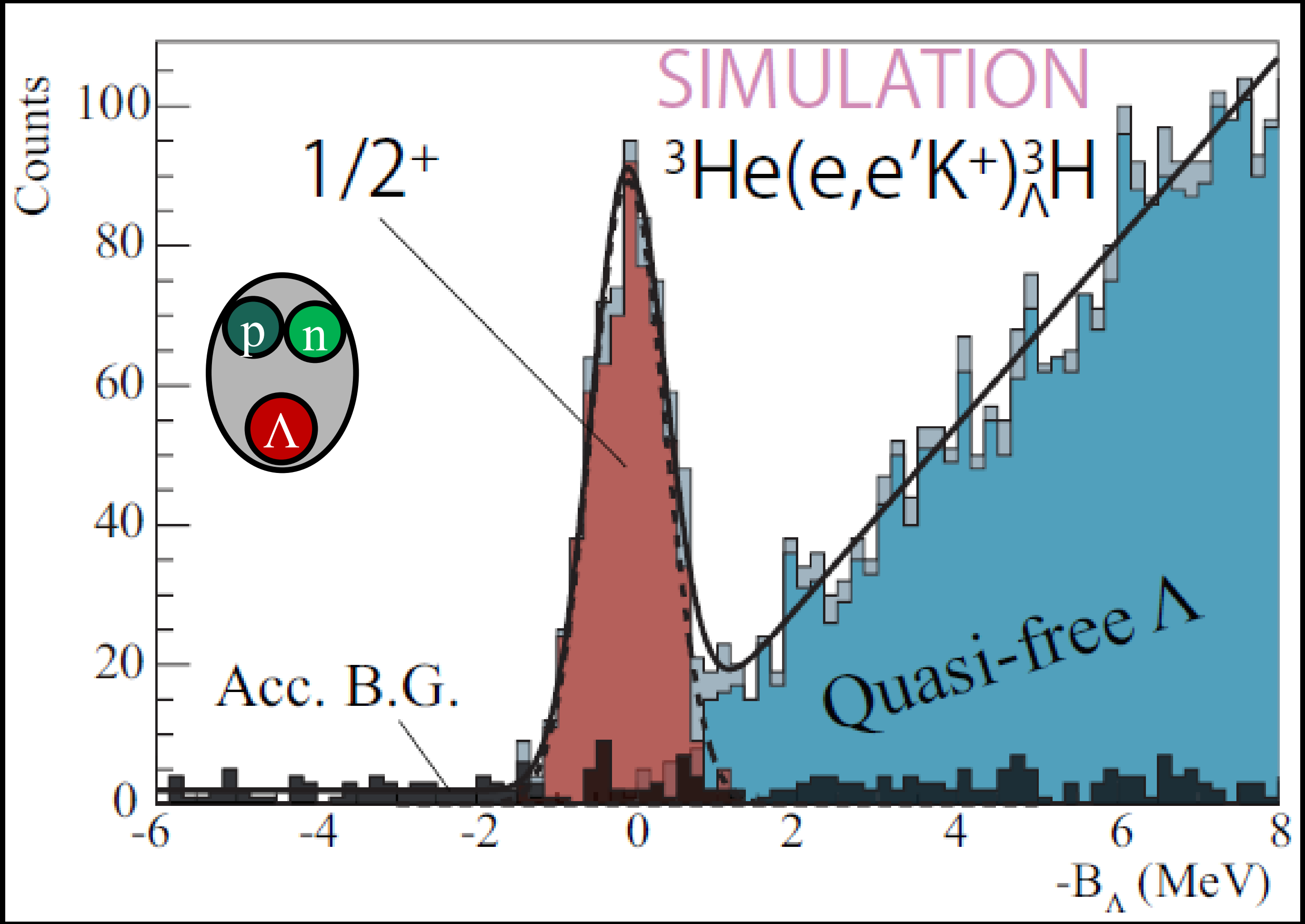
Great Accuracy on $B_\Lambda(^{3}_{\Lambda}\mathrm{H})$
➔ Pin down the hyperon puzzle

ΛN scattering length vs. B_Λ

M. Schafer et al., arXiv:2108.13900v1 [nucl-th] 31 Aug 2021



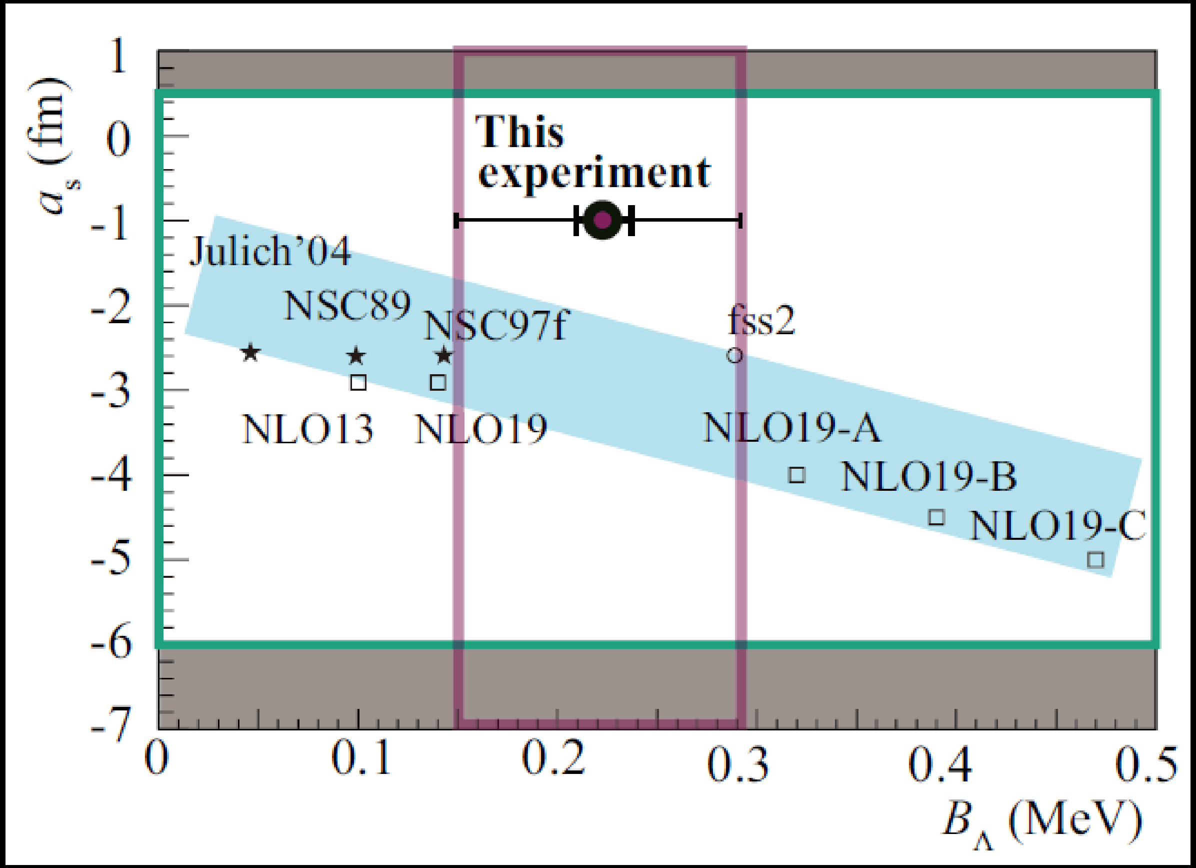
Expected Spectra and errors



$\left|\Delta B_\Lambda^{stat.}\right| = 20$ keV

systematic error < ±60 keV

GROUND STATE OF ${}^{3}_{\Lambda}\mathrm{H}\ (T = 0, J^{\pi} = 1/2^{+})$



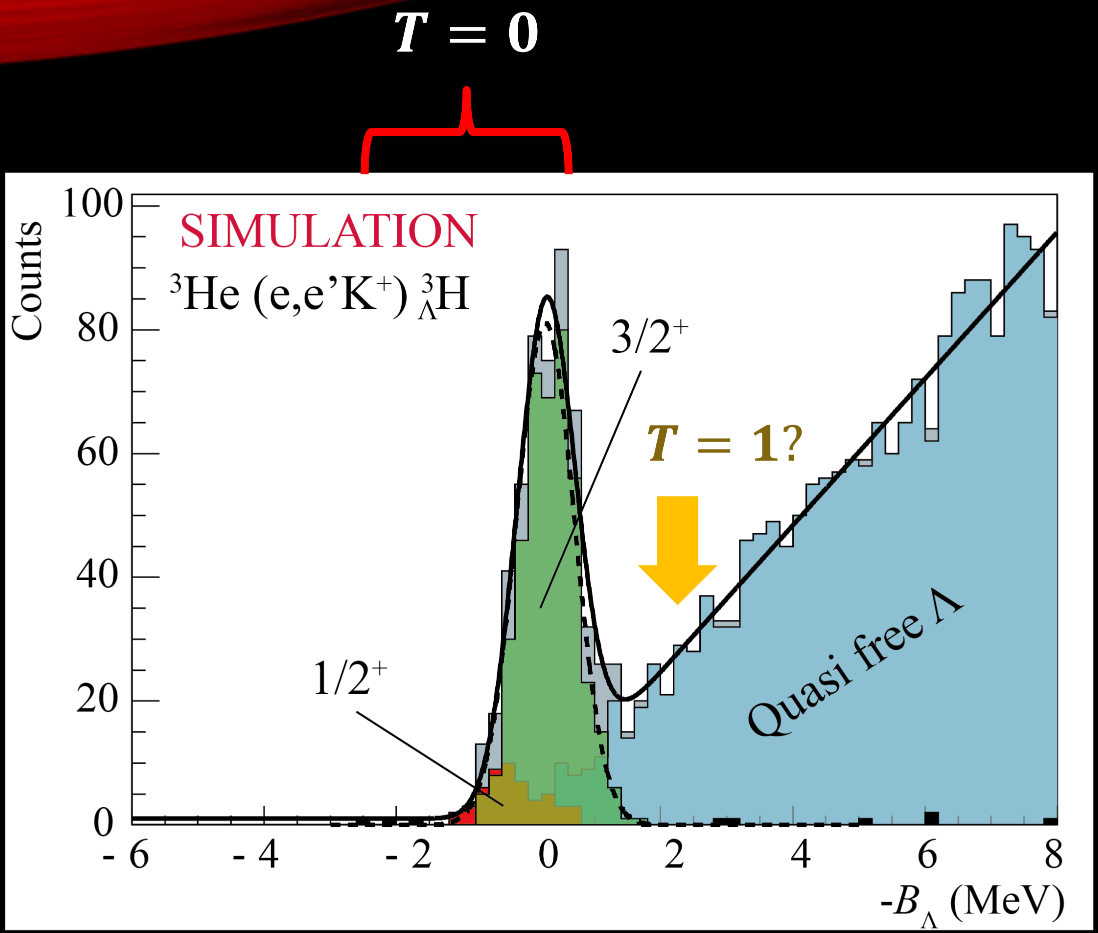
Hypertriton Puzzle

- Λd rm radius (**$|\Delta r| \lesssim 1$ fm**)
  ➔ Better estimation for the lifetime

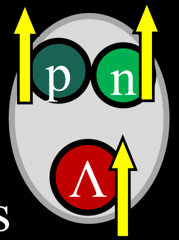
ΛN interaction

- Constraint for
  - Interaction models
  - The ΛN spin singlet scattering length (**$|\Delta a_s| \sim 1$ fm**; cf. $a_s = 1.8^{+2.3}_{-4.2}$ fm)

EXCITED STATES OF ${}^{3}_{\Lambda}\mathrm{H}$

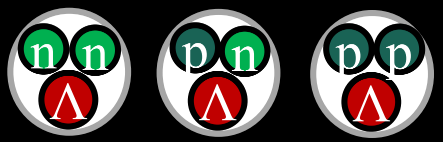


${}^{3}_{\Lambda}\mathrm{H}\ (T = 0,\ J^{\pi} = 3/2^{+})$



- Has NOT been measured
- Hard to measure by emulsion / HI experiments
- Does it exist?
  - If yes, the CS is larger than ½ by a factor of 8 (1)
  - If no, only the $1/2^{+}$ state will be observed
    - ← πEFT predicts $3/2^{+}$ as a virtual state (2)
- Strong constraint for **the ΛN spin triplet interaction**

${}^{3}_{\Lambda}\mathrm{H}\ (T = 1,\ J^{\pi} = 1/2^{+})$



- Isospin partner of $nn\Lambda$ (and $pp\Lambda$)
  → significant information on the existence of $nn\Lambda$
- CSB study in the A = 3 hypernuclear system
- If the CS is 0.5 nb/sr → $|\Delta B_{\Lambda}^{\mathrm{stat.}}| \sim 90$ keV

(1) T. Mart *et al*, *Nucl. Phys. A* **640**, 235-258 (1998)
(2) M. Schäfer et al., Phys. Lett. B 808, 135614 (2020)

SUMMARY

1. **Hypernuclear study by (e,e'K$^+$)**
   - **High resolution (0.5—1 MeV FWHM) / High accuracy**
2. **Project introduced**
   - Light hypernuclear measurements (CSB, probing a core nucleus)
     - ${}^{7}_{\Lambda}\mathrm{He}$, ${}^{9}_{\Lambda}\mathrm{Li}$
   - $nn\Lambda$ **search** (2018)
   - Future projects (2023, 24～)
     - ${}^{3,4}_{\Lambda}\mathrm{H}$ (E12-19-002) → lifetime puzzle / 3/2$^+$ existence for hypertriton, CSB
     - ${}^{40,48}_{\Lambda}\mathrm{K}$ (E12-15-008) → Isospin dependence
     - ${}^{208}_{\Lambda}\mathrm{Tl}$ (E12-20-013) → NNΛ interaction

THANK YOU FOR YOUR ATTENTION