Electro- and Photoproduction of Hypernuclei and Related Topics 2021

Hypertriton and nnΛ measurements at Jefferson Lab

Kyoto University, Japan

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Sep 9, 2021

GRADUATE SCHOOL OF SCIENCE
FACULTY OF SCIENCE
KYOTO UNIVERSITY

科研費 KAKENHI

SPIRITS
SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

CONTENTS

1. Physics motivation

2. Experiments
   - $^{3,4}_{\Lambda}\mathrm{H}$ (2024?～): E12-19-002
   - $nn\Lambda$ (2018): E12-17-003

3. Summary

PROPOSAL TO JLAB PAC49

C12-19-002

High accuracy measurement of nuclear masses of Λ hyperhydrogens

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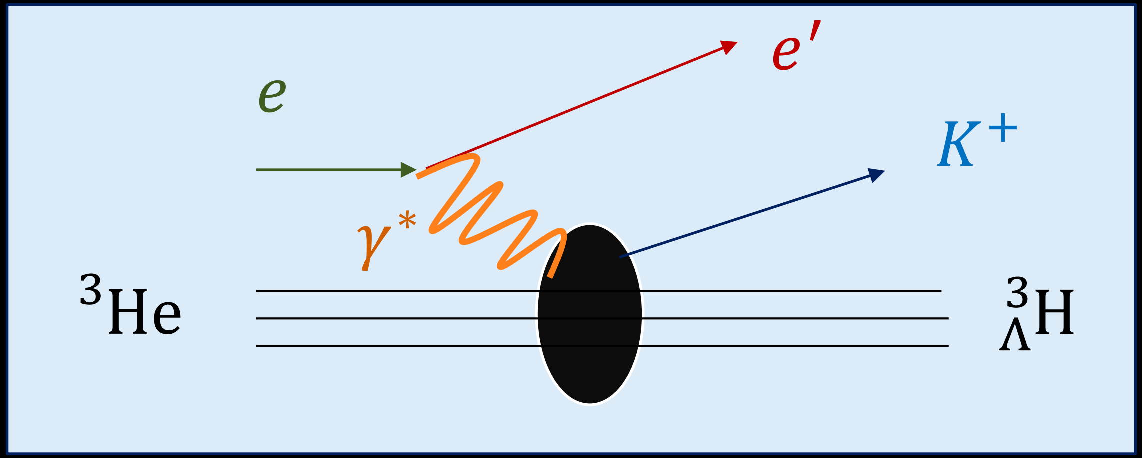
[7] *Thomas Jefferson National Accelerator Facility (JLab), Newport News, VA 23606, USA*

(Dated: May 23, 2021)

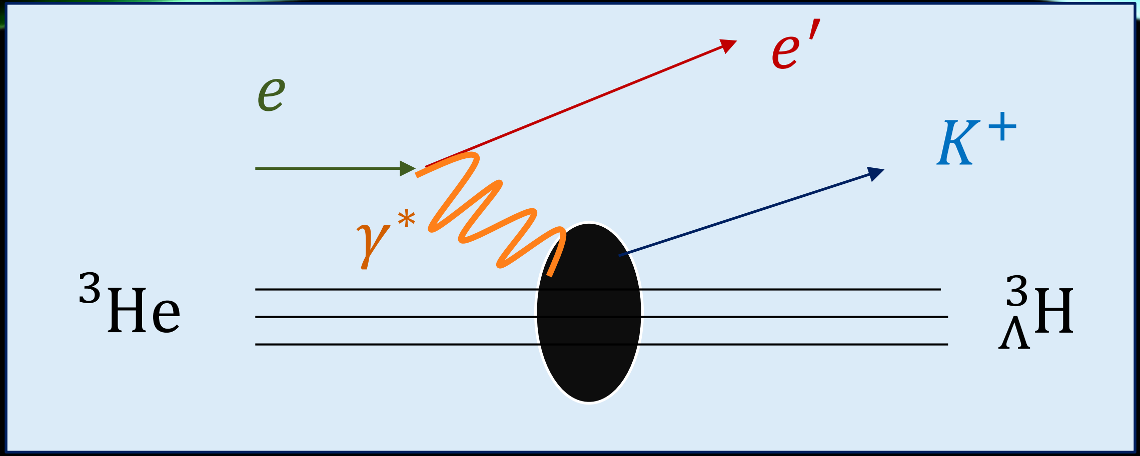
https://www-nh.scphys.kyoto-u.ac.jp/~gogami/e12-19-002/opensrc/Proposal-C12-19-002_PAC49_submitted.pdf

(e,e'K⁺) reaction



➔ Missing mass spectroscopy

Jefferson Lab
Thomas Jefferson National Accelerator Facility



Done (in analysis):

① E12-17-003 ($^{3}_{\Lambda}$n): nnΛ puzzle, ΛN interaction **(done in 2018)**

Future experiments:

① E12-19-002 ($^{3,4}_{\Lambda}$H): hypertriton puzzle, CSB issue = **14.5 days (approved)**

② E12-15-008 ($^{40,48}_{\Lambda}$K): ΛNN isospin interaction = **28 days (approved)**

③ E12-20-013 ($^{208}_{\Lambda}$Tl): ΛNN 3BF in uniform nuclear medium = **20 days (approved)**

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

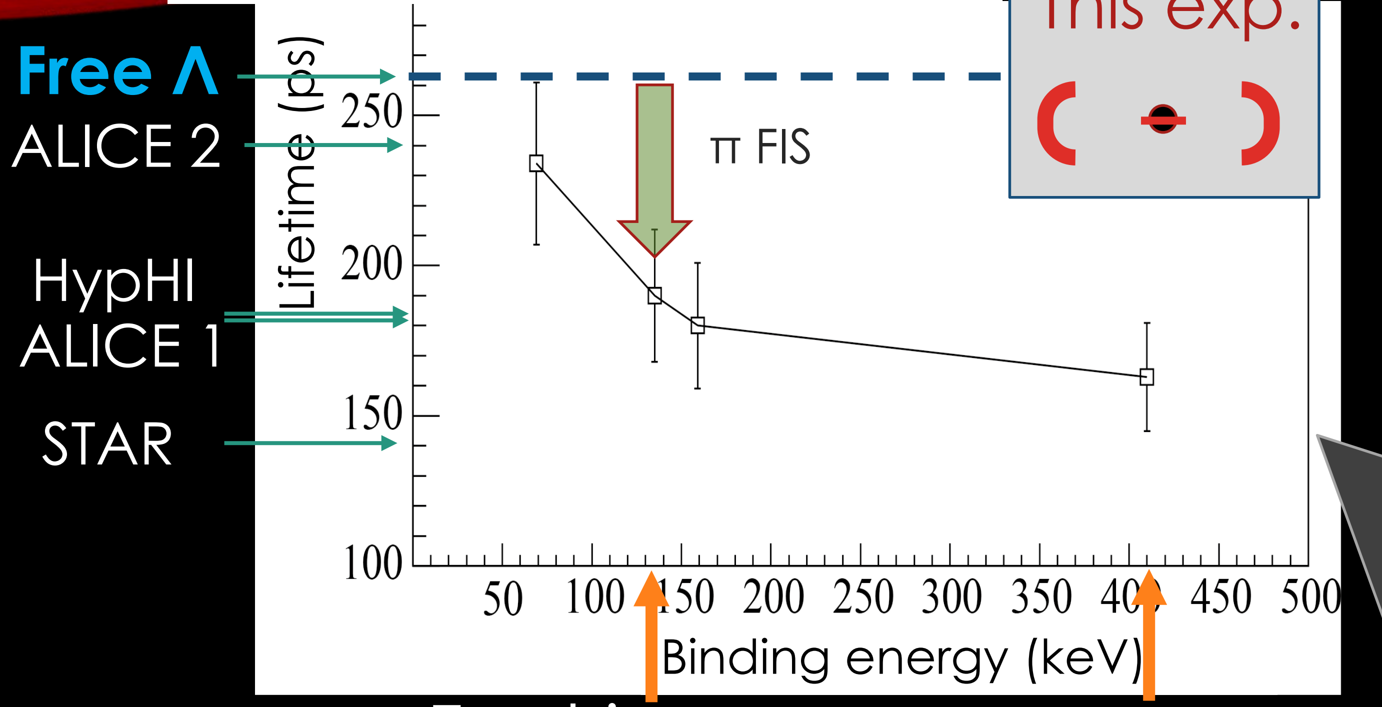
$\tau = (0.5 \sim 0.92)\, \tau_\Lambda$
(HypHI, STAR, ALICE)

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)

$\propto \sqrt{B_\Lambda}$

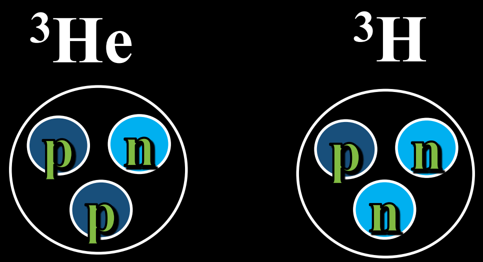
JLab E12-19-002 Experiment:
$|\Delta B^{\mathrm{stat.}}| = 20$ keV, $|\Delta B^{\mathrm{sys.}}| = 55$ keV

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

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).**



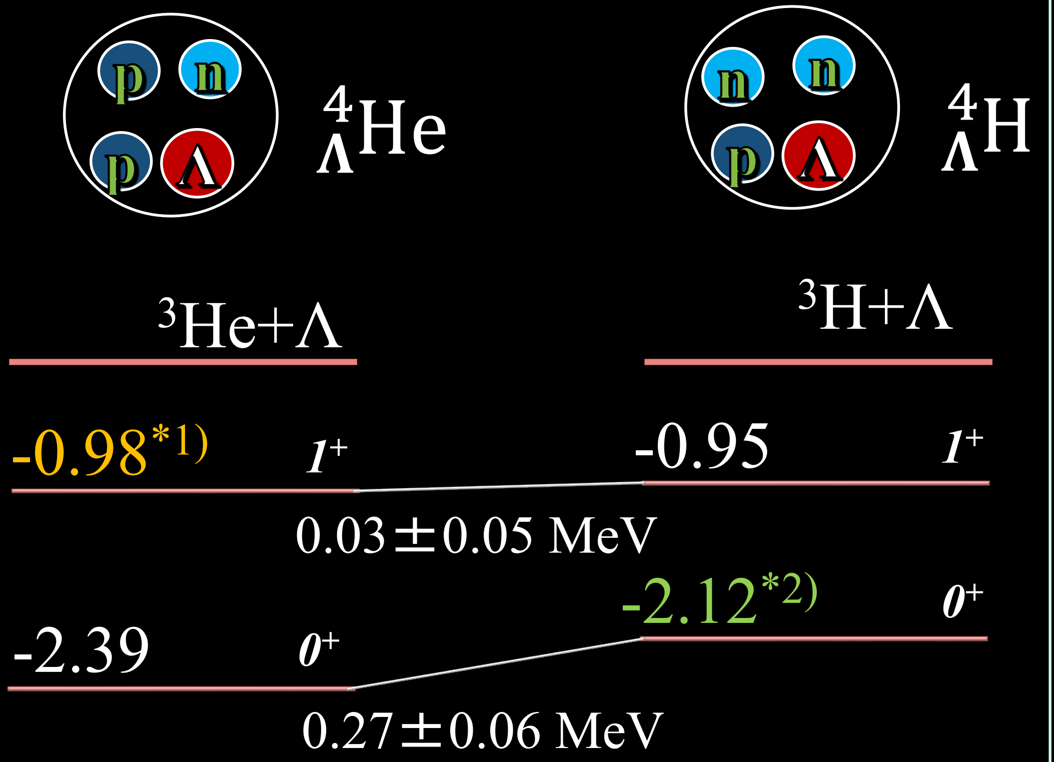
$\Delta B = 0.76384\,(26)^{*1)}$ MeV

$\Delta B_{\mathrm{Coulomb}} = 0.683^{*2)}$ MeV

→ ***0.081 MeV***

*1) J.H.E.Mattauch *et al., Nucl. Pys.* **67**, 1 (1965).

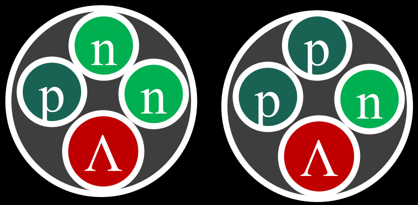
*2) R.A.Brandenburg, S.A.Coon *et al., NPA***294,** 305 (1978).



→ ***≈0.4 MeV w/ correction***

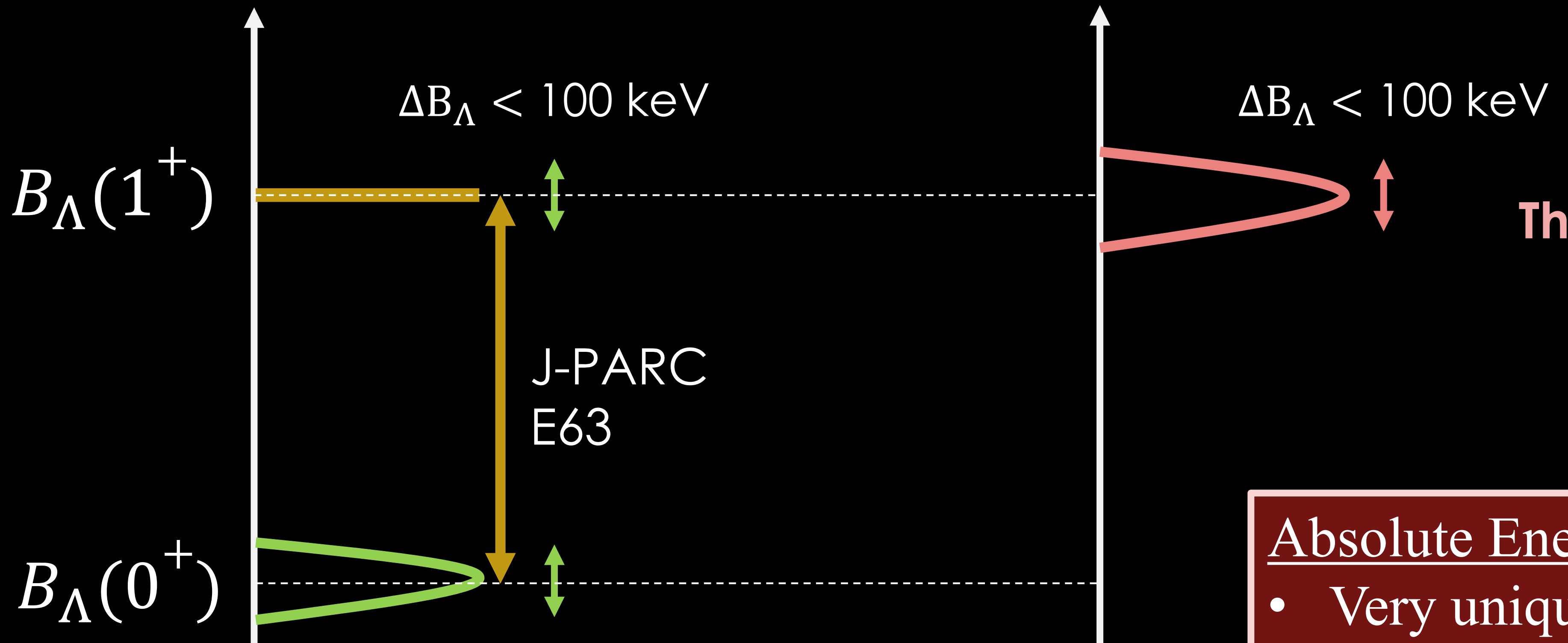
- Five times larger effect
- Spin dependent

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



Conventional way

JLab E12-19-002



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

This Experiment

<u>Absolute Energy Measurement:</u>

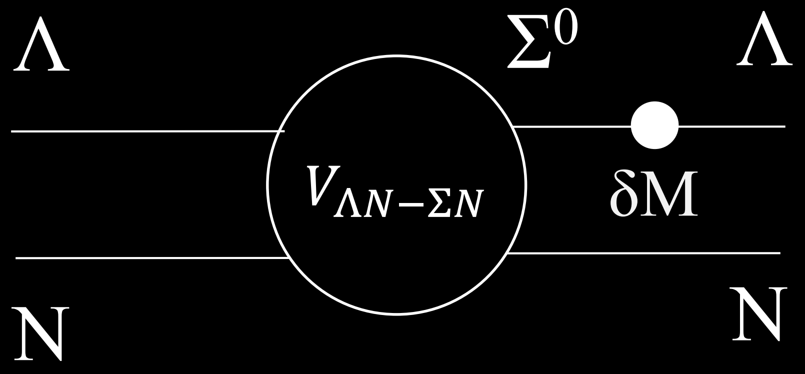
- Very unique (direct meas.)
- Complementary with other data

(1) NPB 52, 1-30 (1973)

(2) PRL 114, 232501 (2015)

ΛN-ΣN COUPLING

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



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

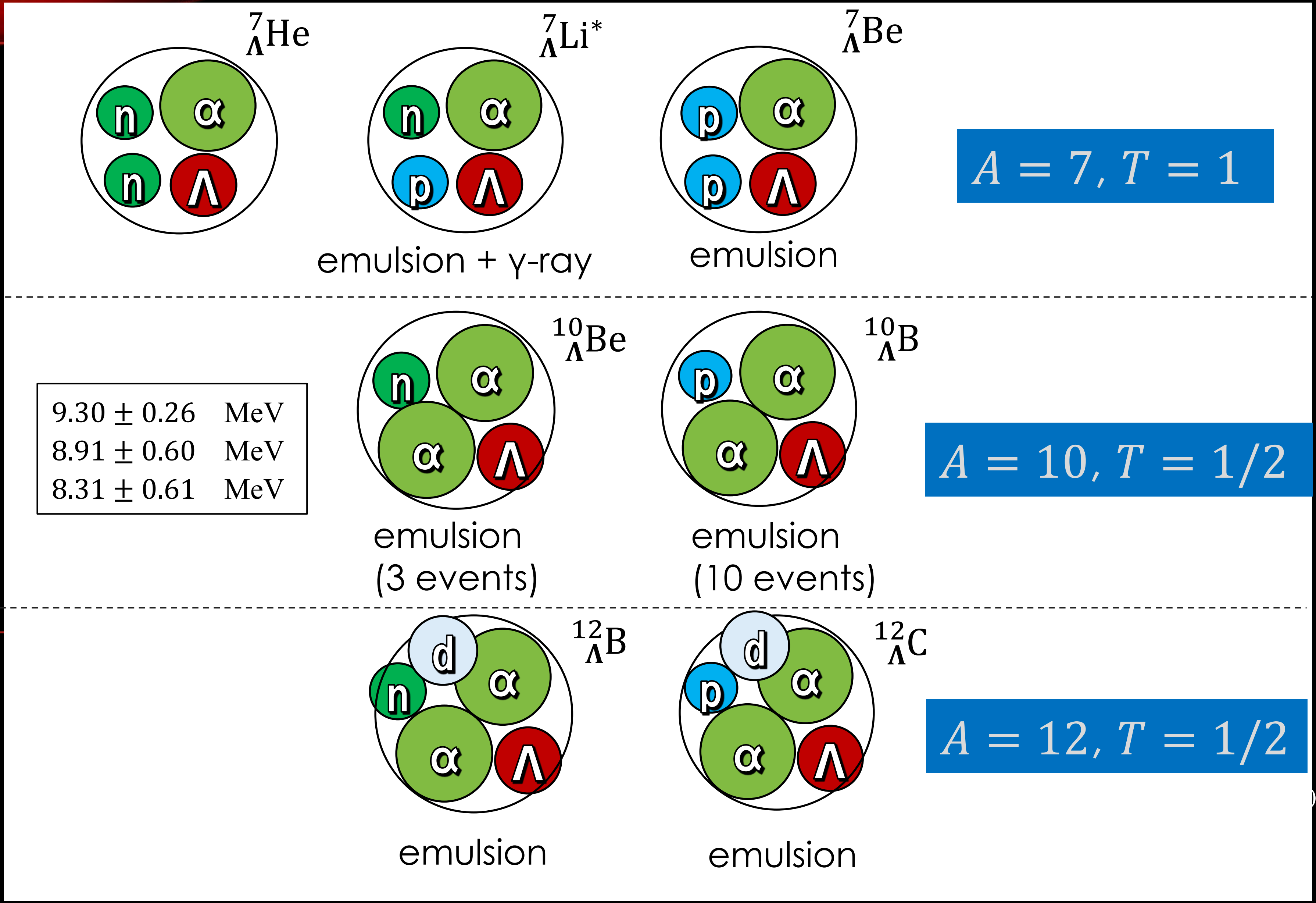
ΛN-ΣN COUPLING

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

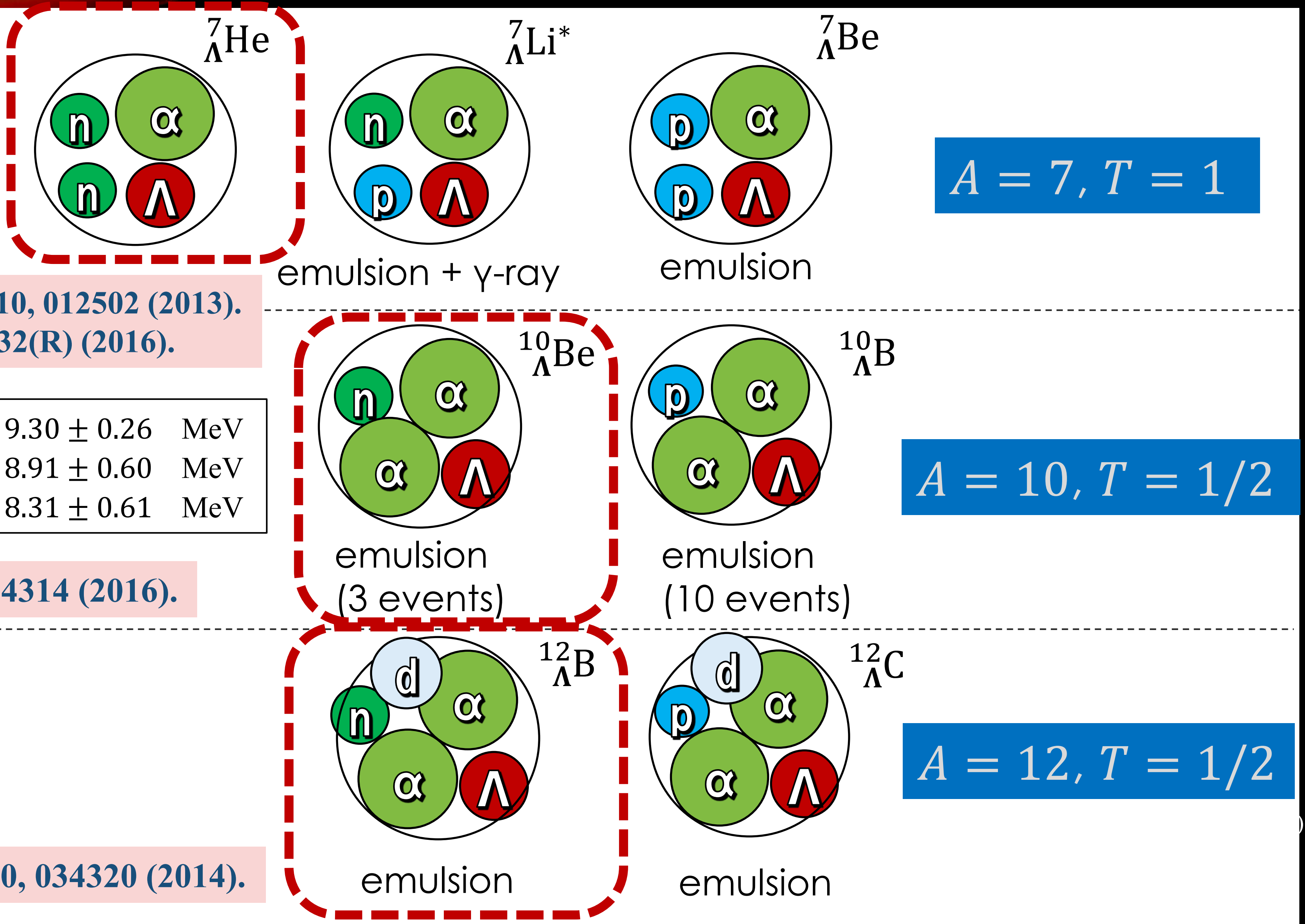
What about other systems such as the p-shell region? (theories predict small effect)

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

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



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



S.N.Nakamura, PRL 110, 012502 (2013).
TG et al., PRC 94, 02132(R) (2016).

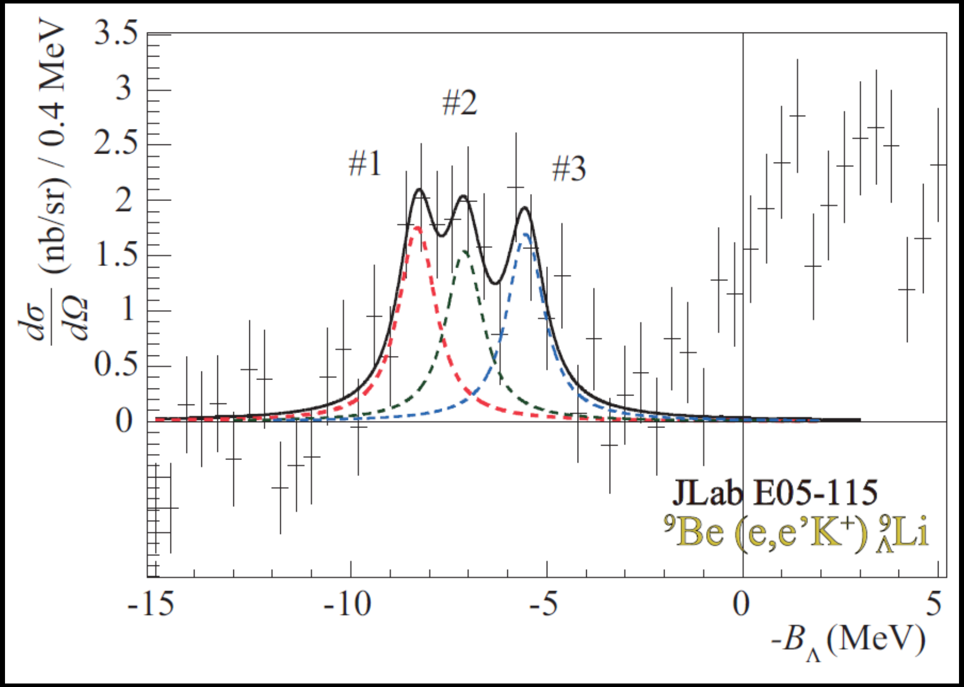
9.30 ± 0.26	MeV
8.91 ± 0.60	MeV
8.31 ± 0.61	MeV

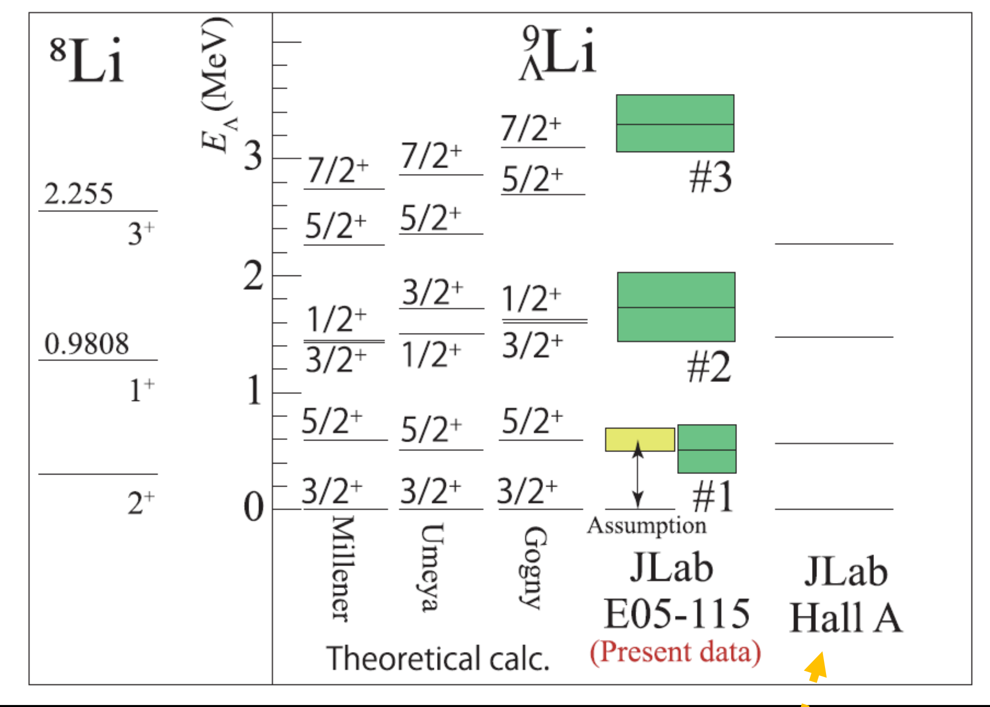
TG et al., PRC 93, 034314 (2016).

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

CSB in the p-Shell hypernuclei
→ A = 9 iso-doublet hypernuclei ($^{9}_{\Lambda}$Li vs. $^{9}_{\Lambda}$B)

TG et al., Phys. Rev. C 103, L041301 (2021)





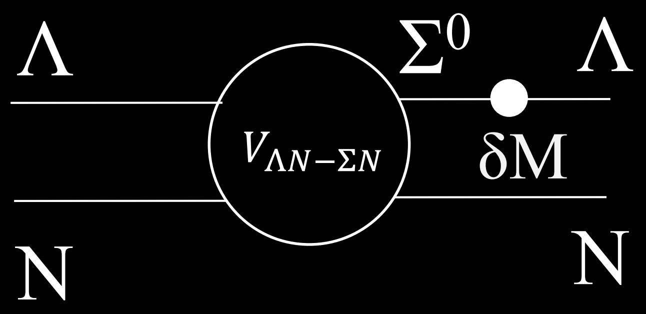
F. Garibaldi et al., Phys. Rev. C 99, 054309 (2019).

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)

A. Gal et al., IOP Conf. Series: Jour. Phys.: Conf. Ser. **966** (2018) 012006



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

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 (This Experiment)

A=4 → **CSB interaction** → A=5, A=7, A=9, A=10, …

HKS, PRL 110, 012502 (2013)

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

Hall A, PRC 91,034308 (2015)

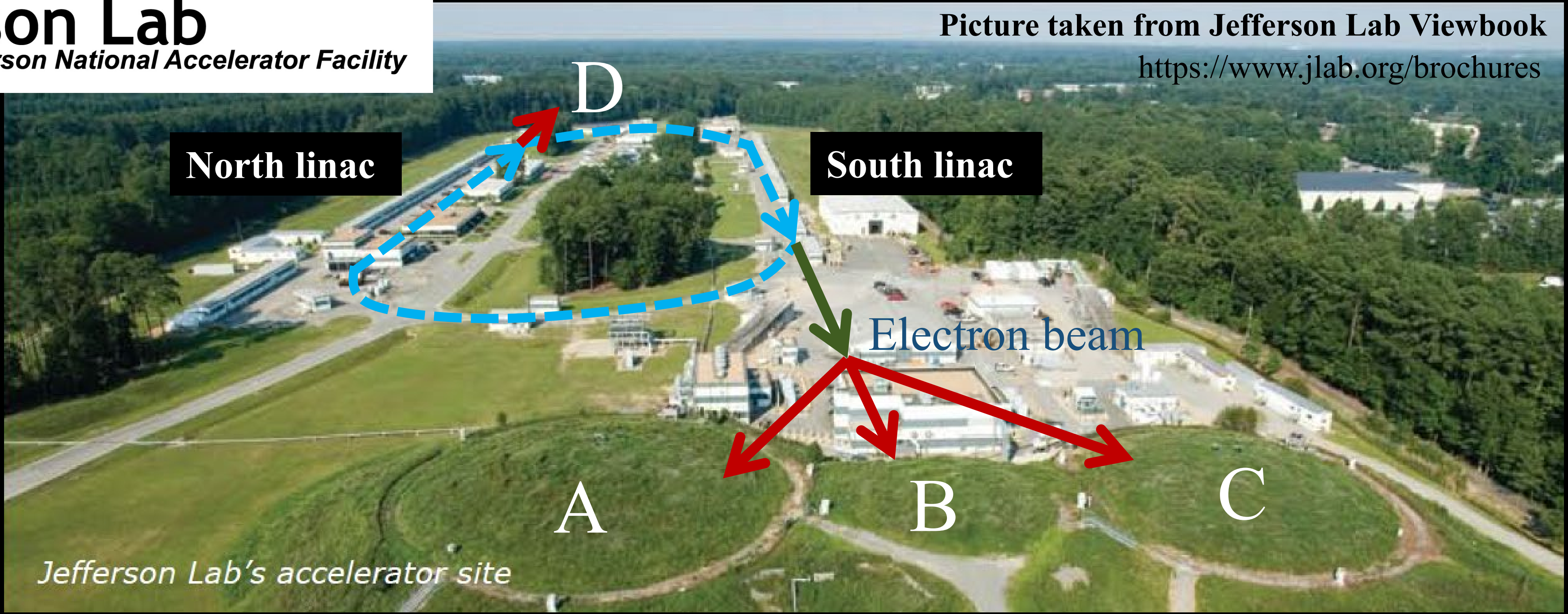
HKS, PRC103, L041301 (2021)

HKS, PRC 93, 034314 (2016)

HKS, PRC 90, 034320 (2014) …

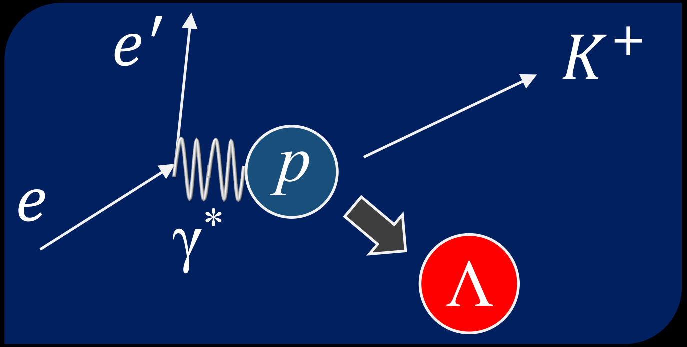
CEBAF AT JEFFERSON LAB

Jefferson Lab
Thomas Jefferson National Accelerator Facility

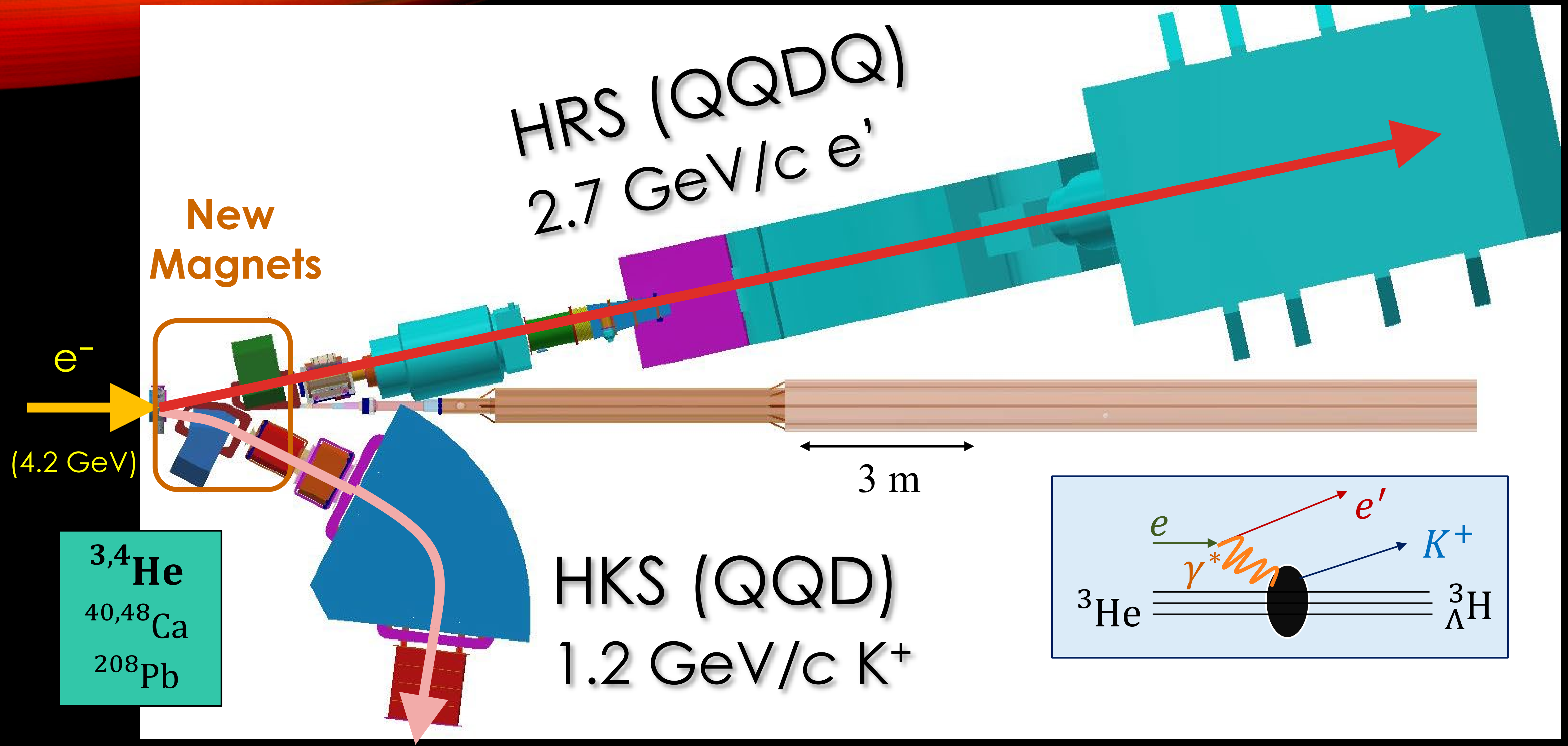


<u>Continuous electron beam facility (CEBAF)</u>

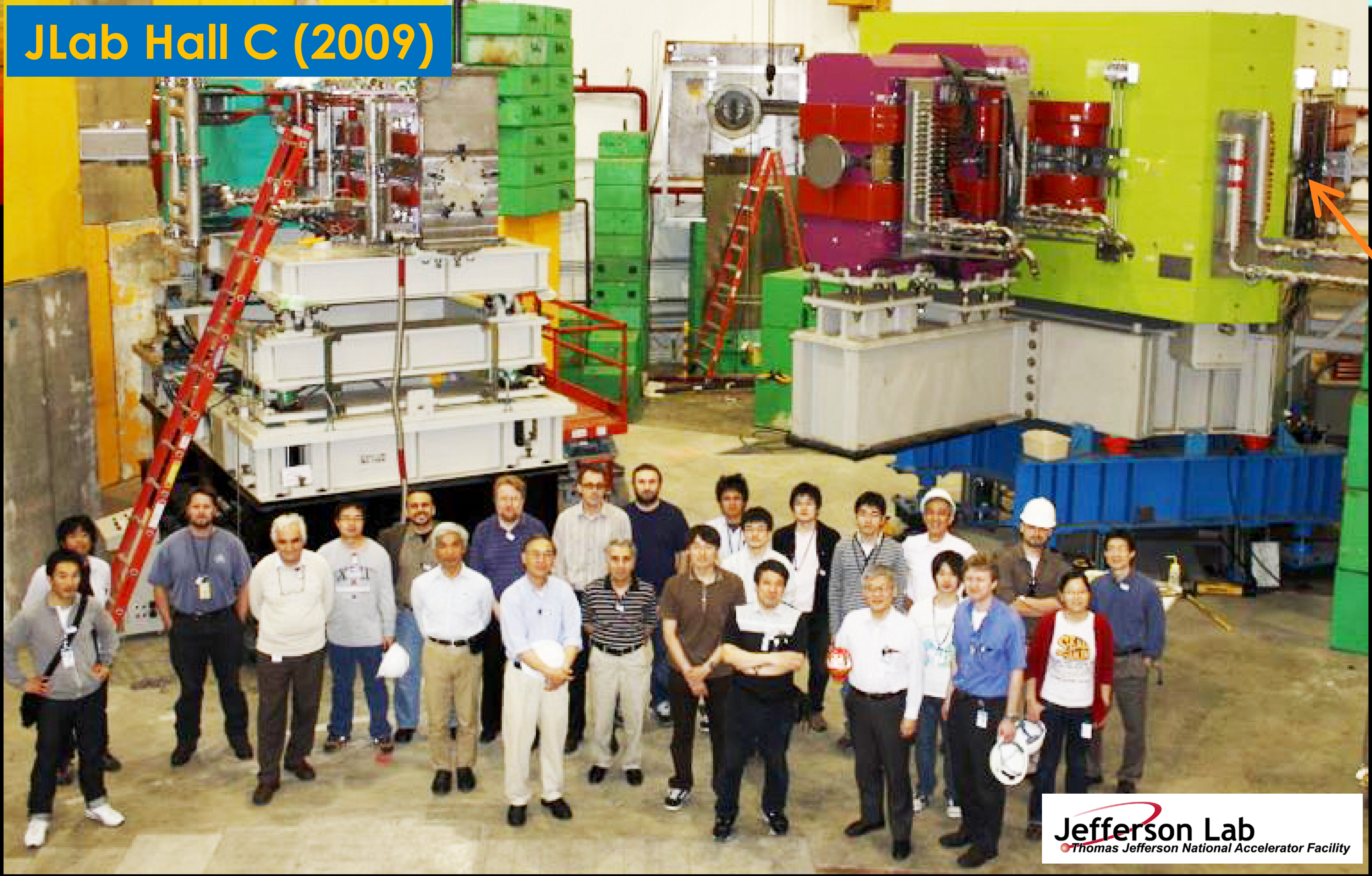
- ✓ 12 GeV at maximum
- ✓ 100 μA (> 600 THz)
- ✓ 2 or 4-ns interval bunches
- ✓ Emittance of 2 μm·mrad
- ✓ Energy spread ($^{\Delta E}/_{E} < 5 \times 10^{-5}$ rms)



Experimental Setup at JLab Hall A



JLab Hall C (2009)



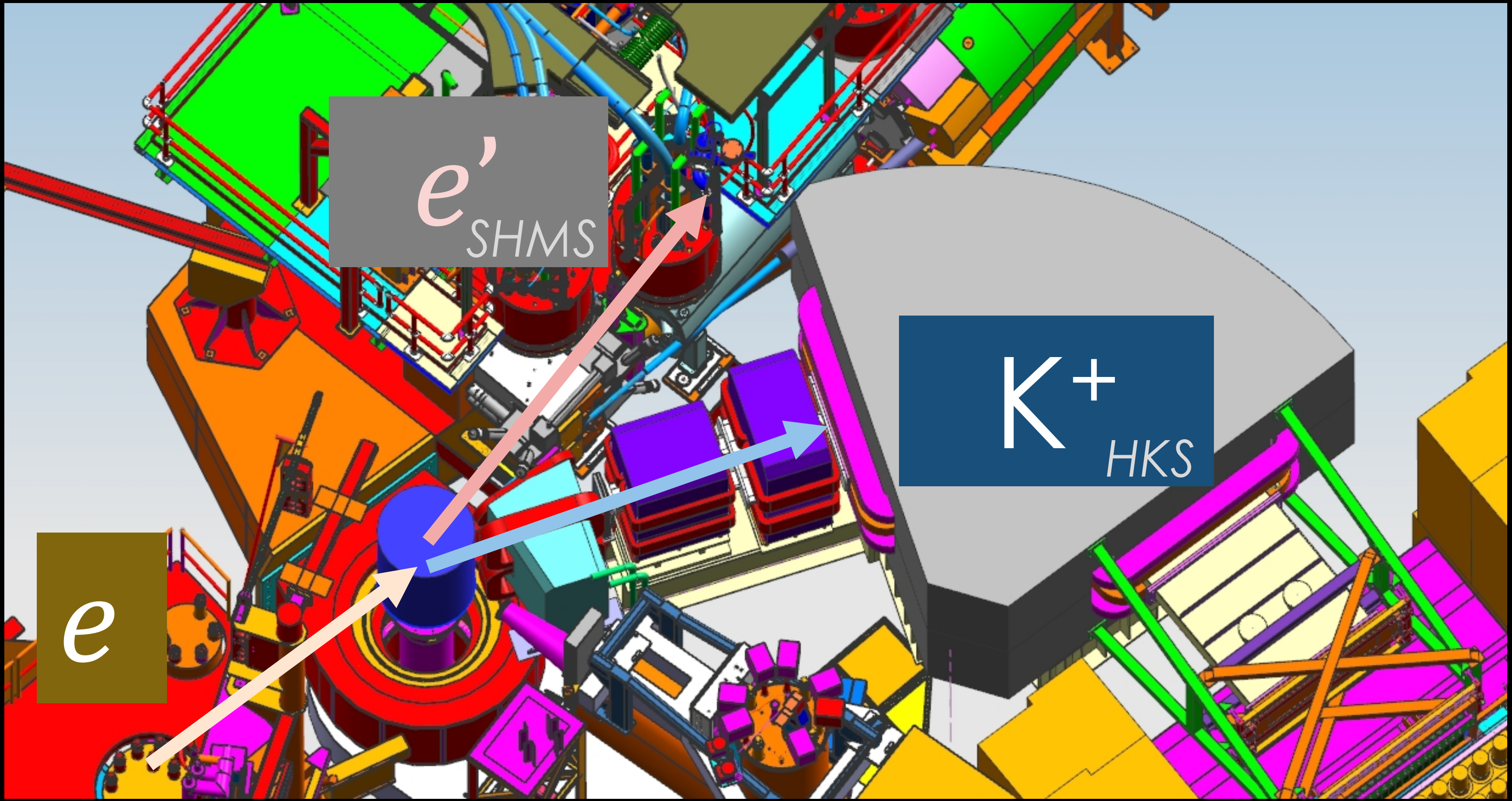
HKS

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

LHRS


RHRS
JLab Hall A (Apr 2019)
Jefferson Lab
Thomas Jefferson National Accelerator Facility

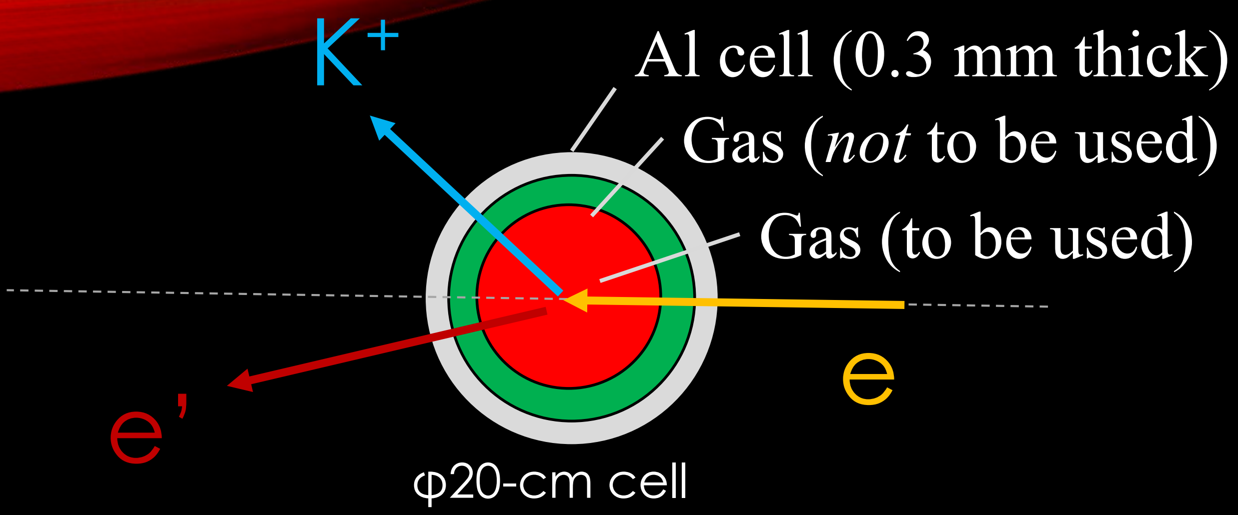
Possibility in Hall C

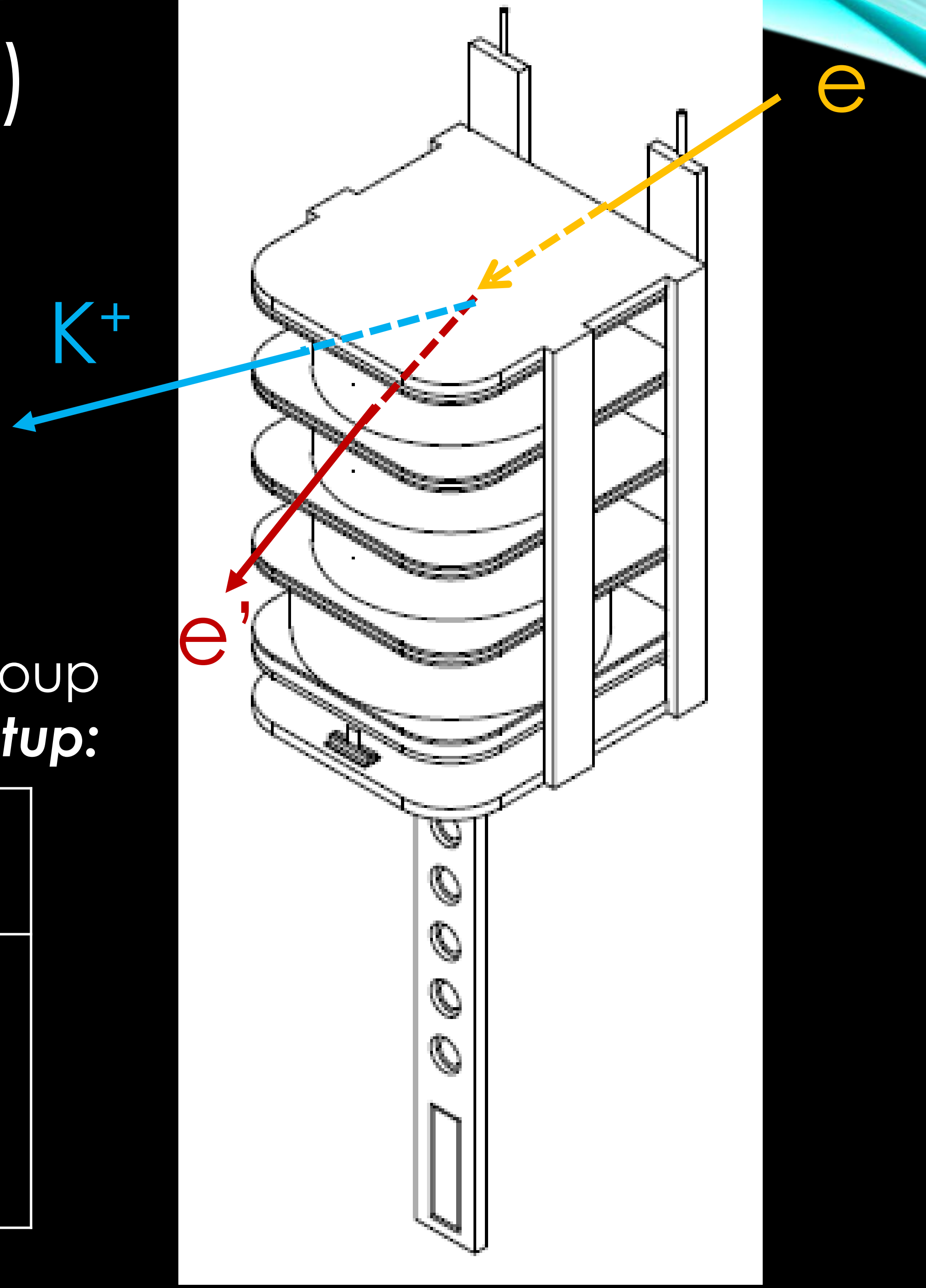


Evaluations are in progress

- SHMS + HKS
- Vertical HES + vertical HKS
- …

TARGET CELLS (TUNA CAN)

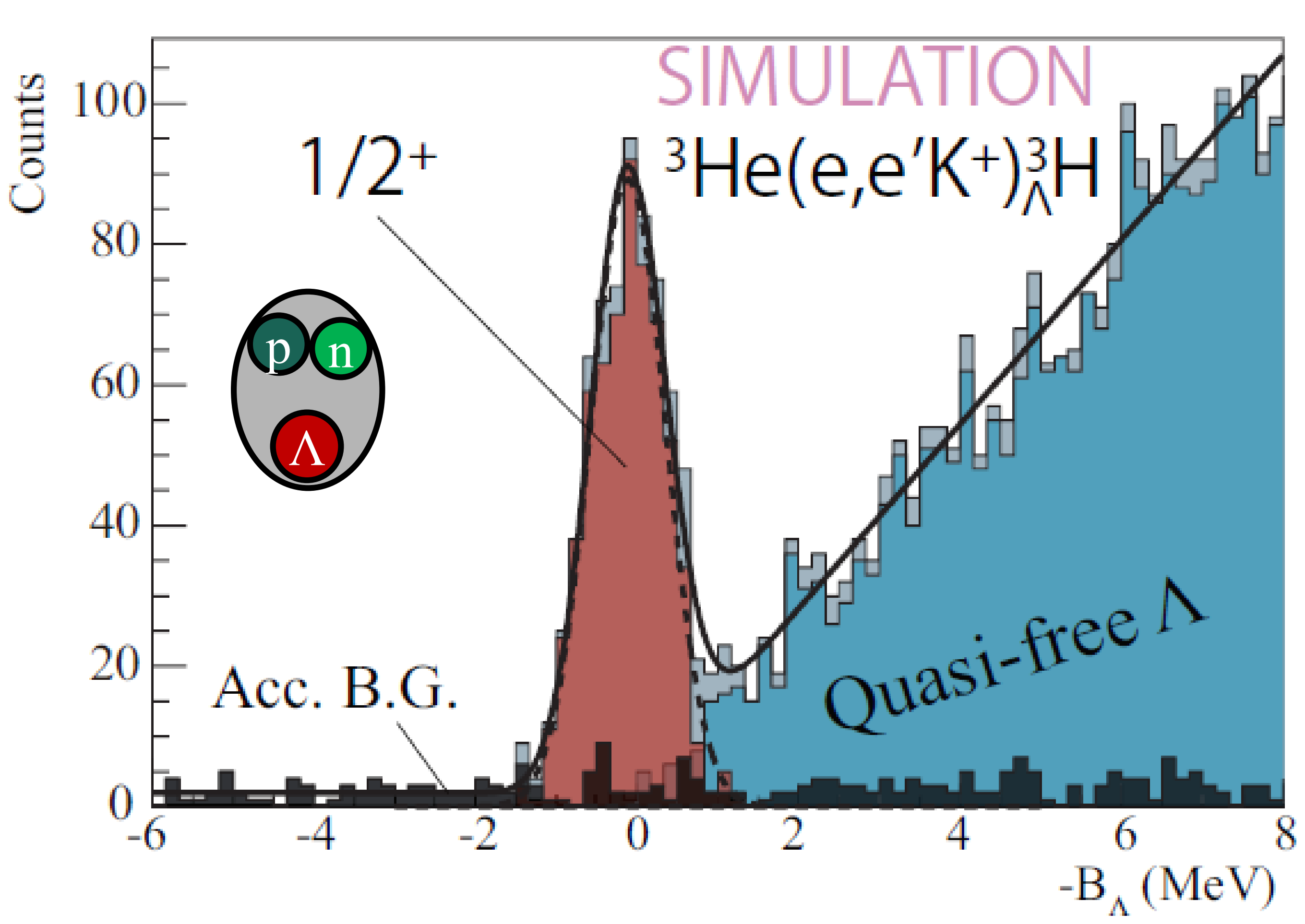




Available densities calculated by the JLab Target Group ***maintaining a compatibility with our experimental setup:***

Target	Density [/(g/cm³)]	Temperature [/K]	Pressure [/atm]
^{3}He	9.5	12	3
^{4}He	13.1		
$^{1}H_2$	2.8	30	

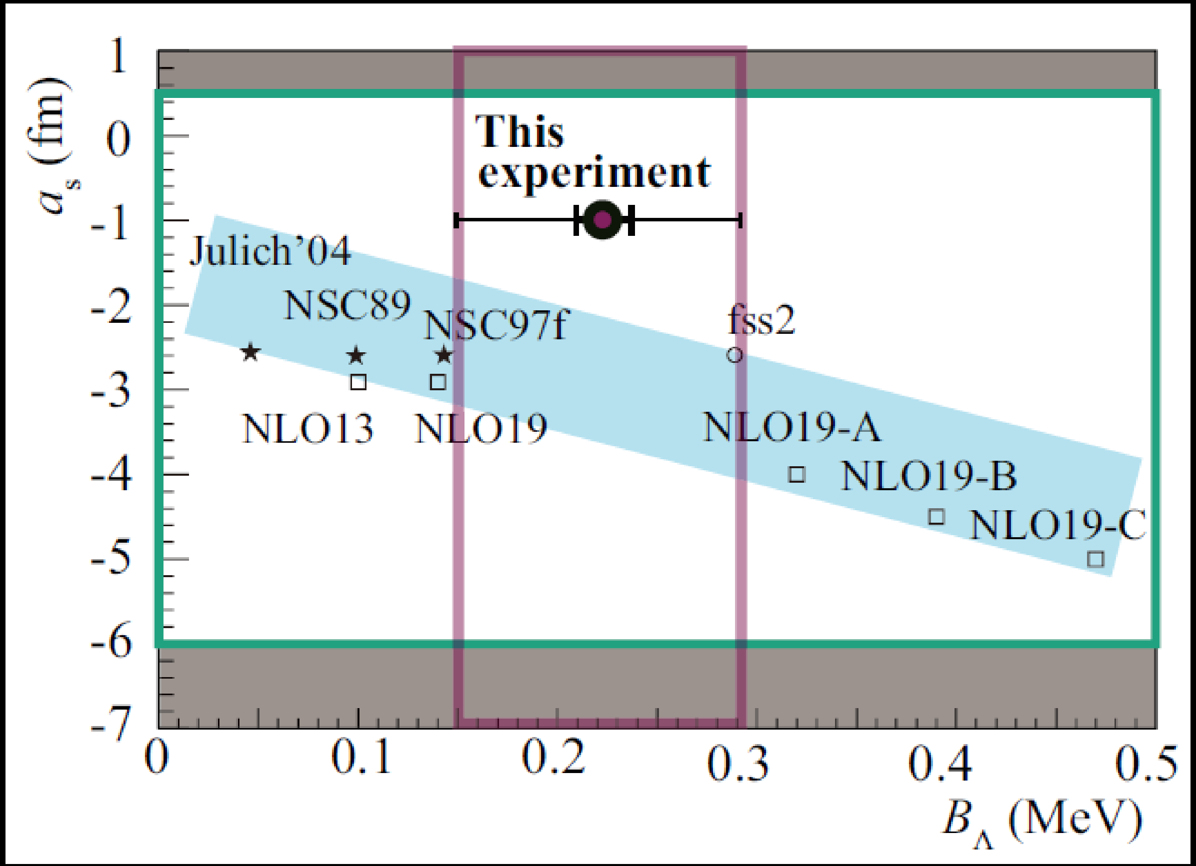
EXPECTED SPECTRA AND STATISTICAL ERRORS



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

systematic error < ±60 keV

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



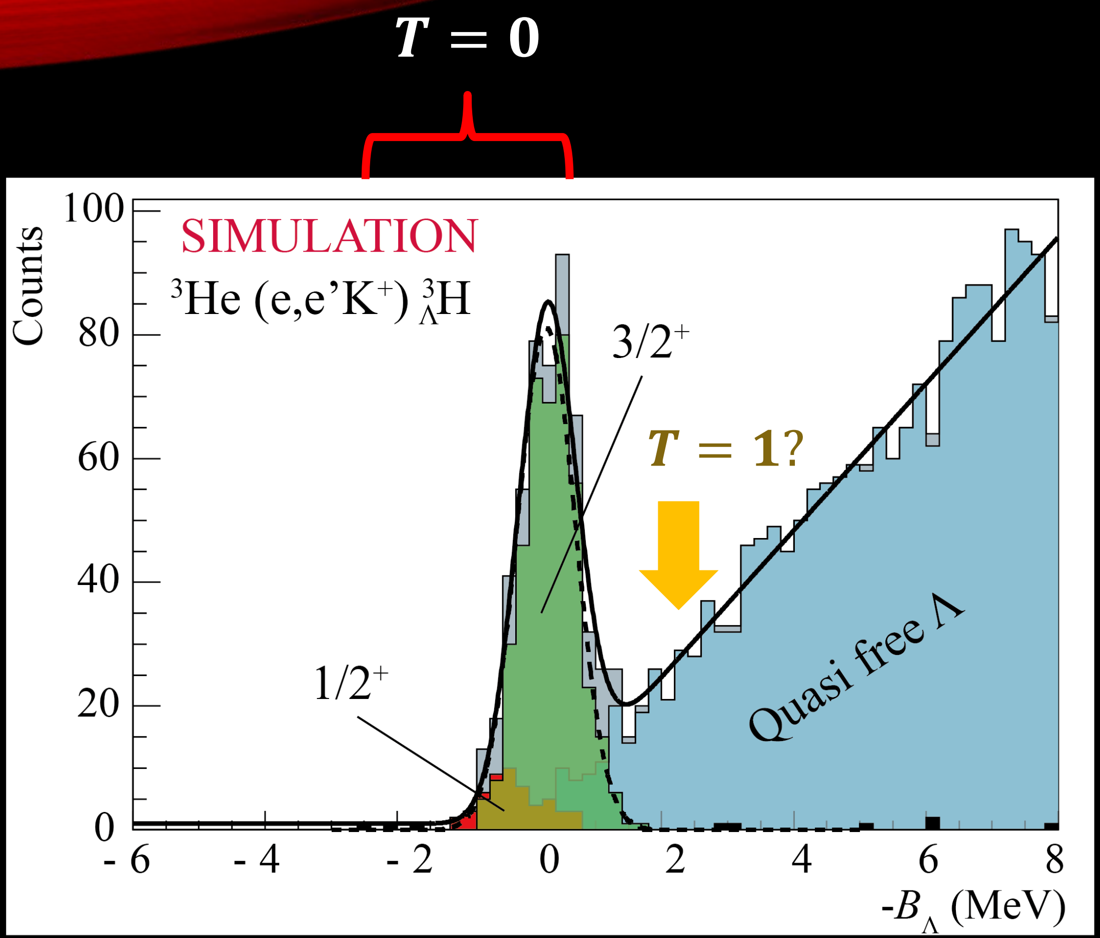
Hypertriton Puzzle

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

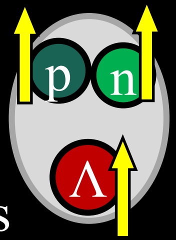
ΛN interaction

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

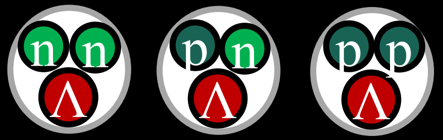


$^{3}_{\Lambda}H\left(T = 0,\ J^{\pi} = 3/2^{+}\right)$



- 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**

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



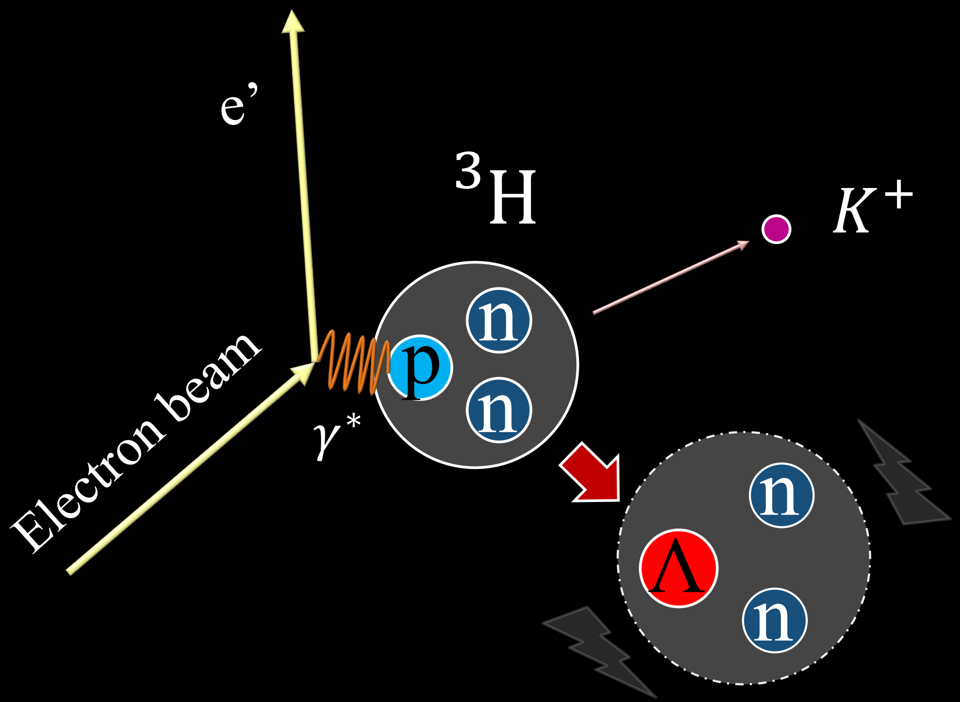
- Isospin partner of $nn\Lambda$ (and $pp\Lambda$)
  → significant information on the existence of $nn\Lambda$
- CSB study in the A = 3 hypernuclear system
- If the CS is 0.5 nb/sr → $\left|\Delta B_{\Lambda}^{\text{stat.}}\right| \sim 90$ keV

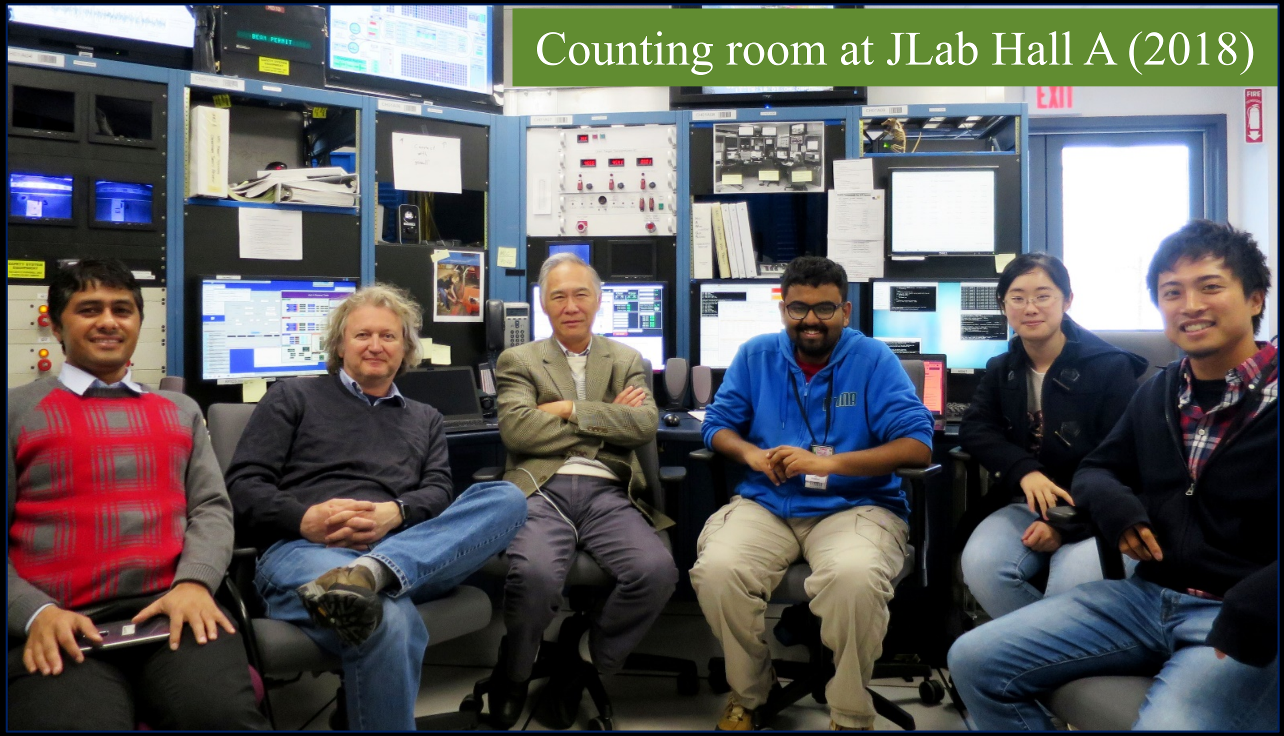
(1) T. Mart *et al*, *Nucl. Phys. A* **640**, 235-258 (1998)
(2) M. Schäfer et al., Phys. Lett. B 808, 135614 (2020)

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

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

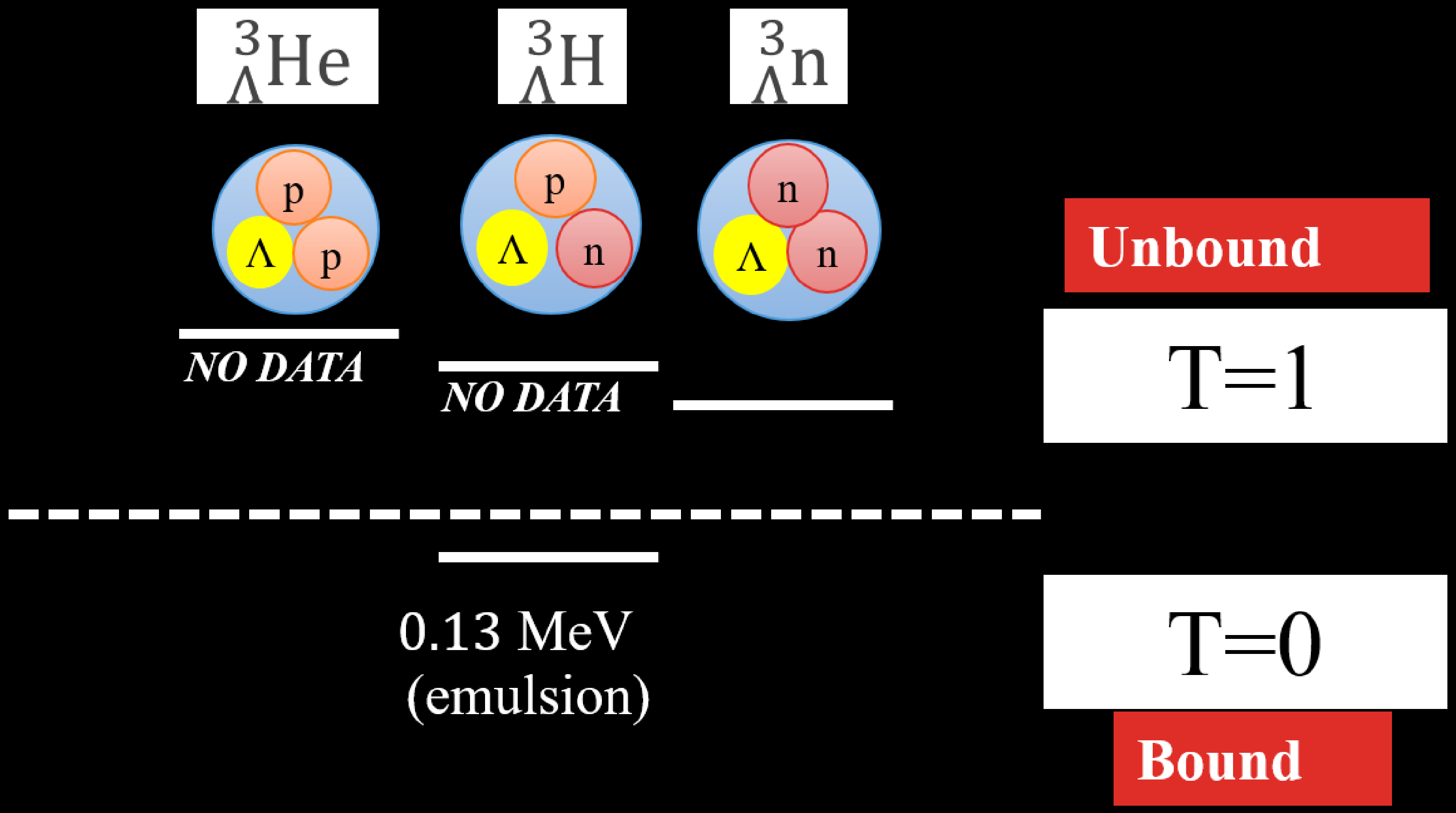
E12-17-003 (Oct 30—Nov 25, 2018)



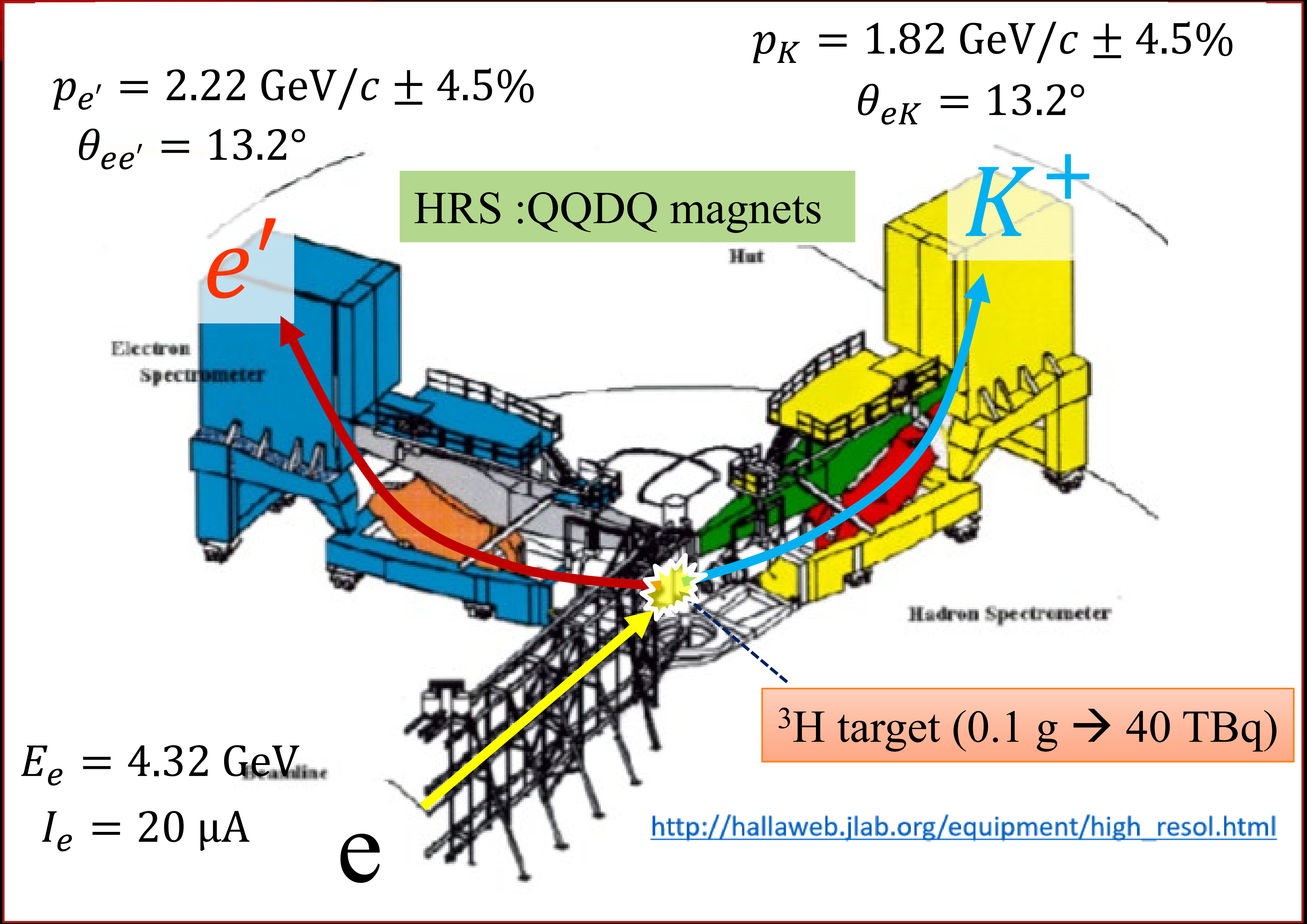


We have sensitivity to both bound and resonant states

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



EXPERIMENTAL SETUP (JLAB E12-17-003)



- High resolution
  - $\frac{\Delta p}{p} = 2 \times 10^{-4}$
- Long path length
  - ➔ $R_K \simeq 17$ %
  - (c.f. $R_K \simeq 30$ % at p = 1.2 GeV/c by HKS)

STUDENTS WHO ANALYZE DATA

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

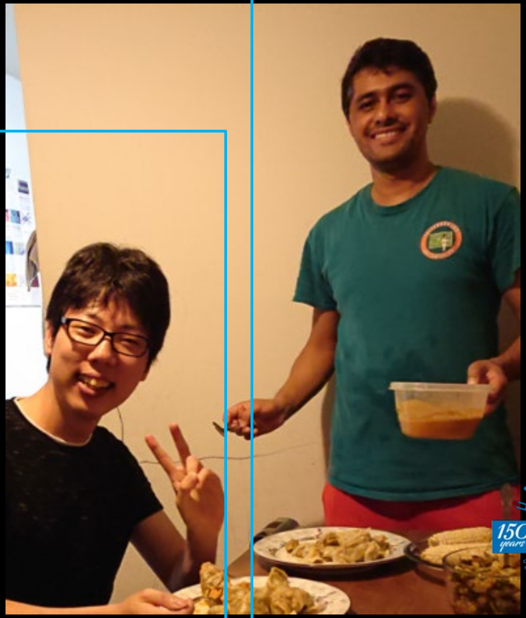
K. Itabashi

K. Okuyama

東北大学

Tohoku Univ., Japan

E. Umezaki



K.N. Suzuki

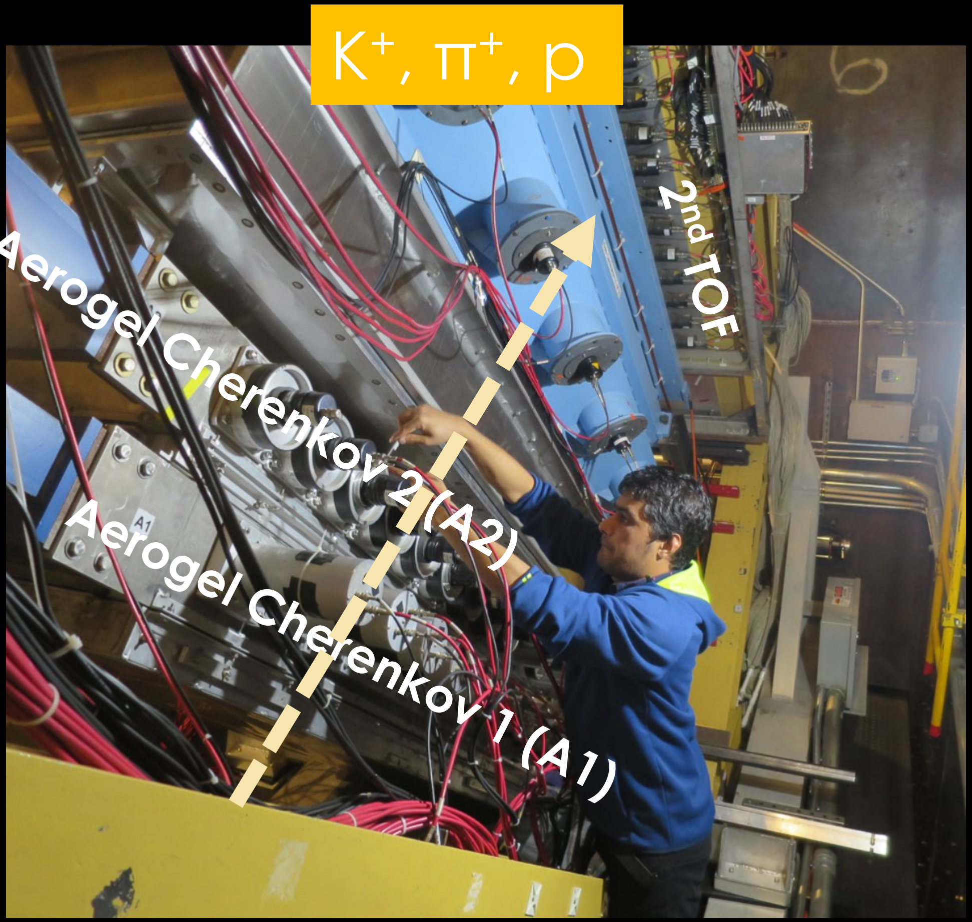
B. Pandey

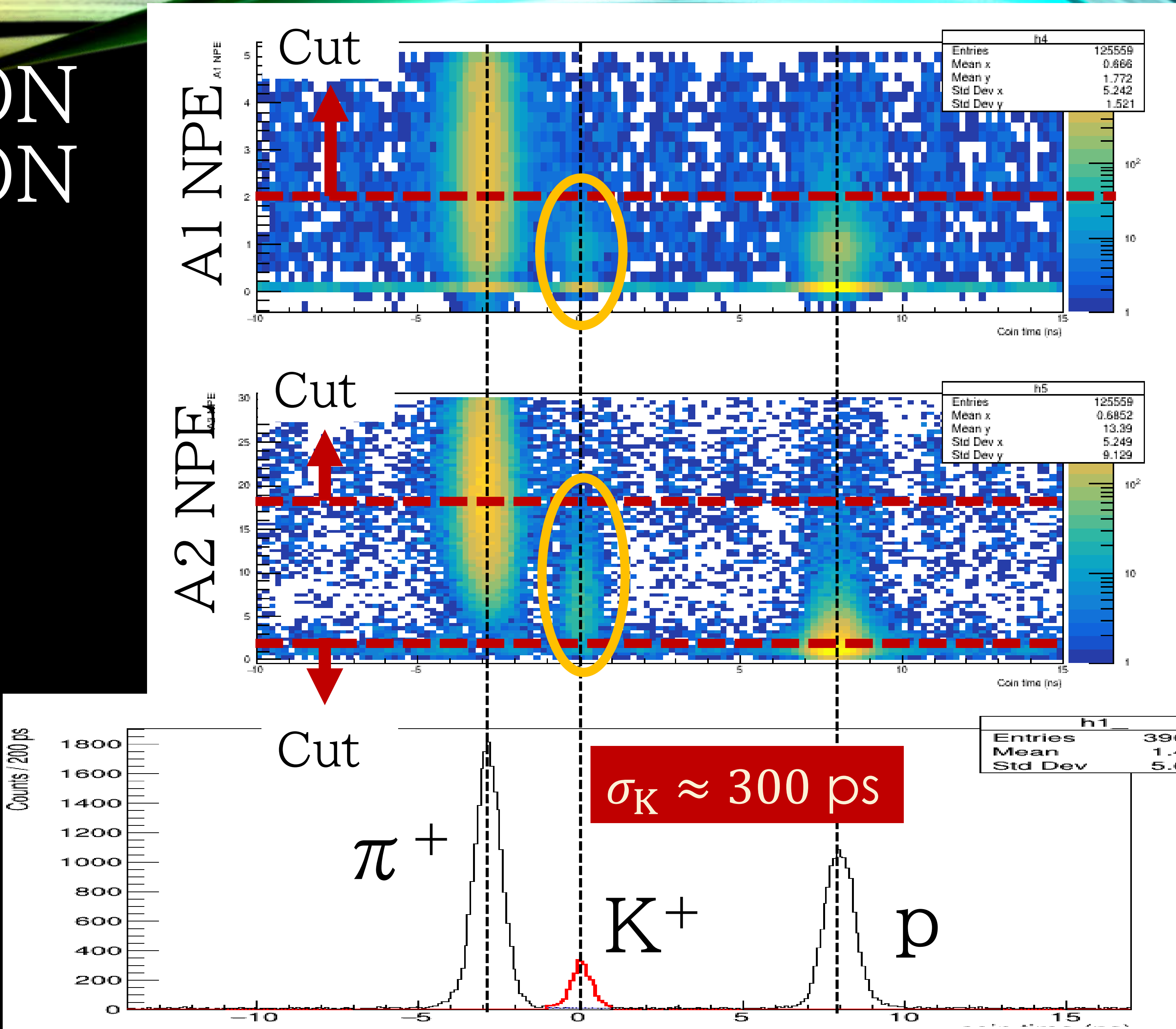
Kyoto Univ., Japan

Hampton Univ., US

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

KAON IDENTIFICATION

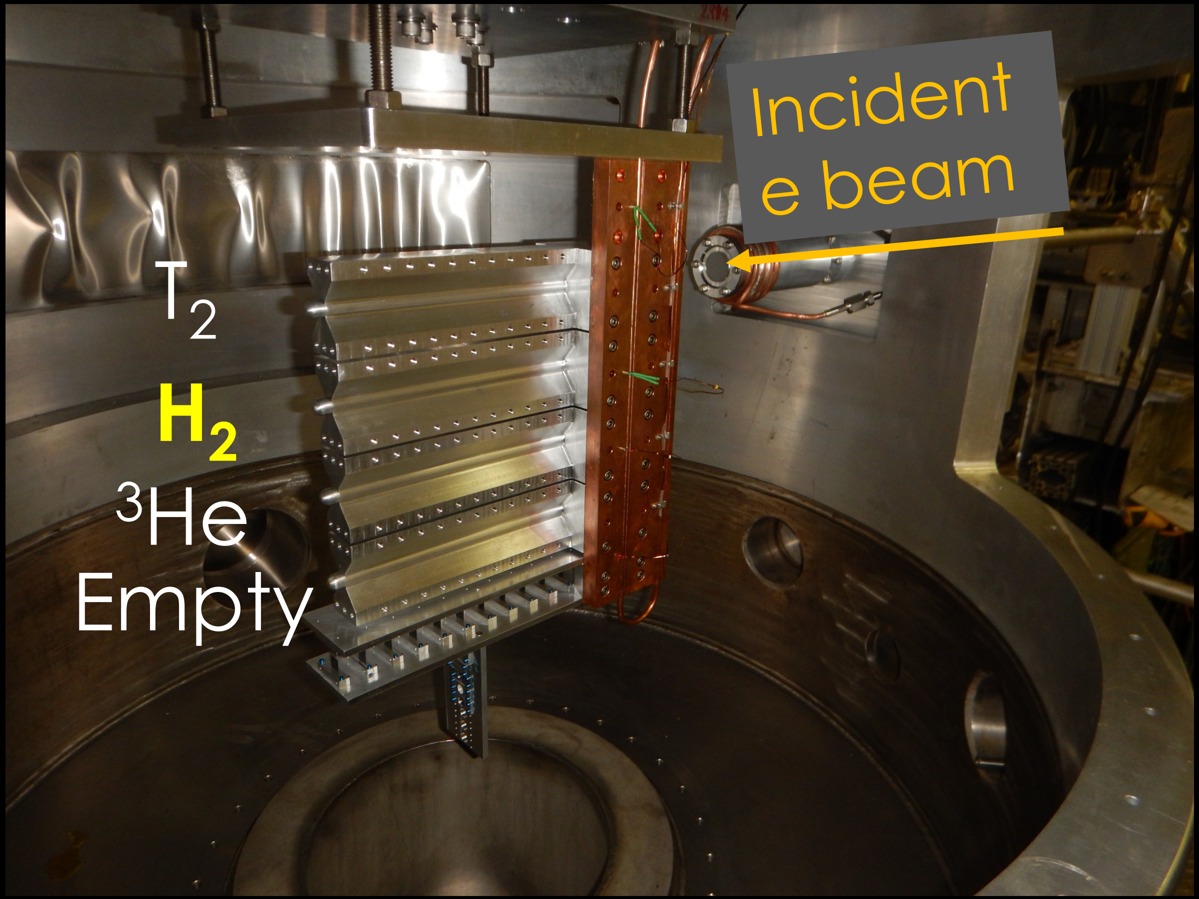


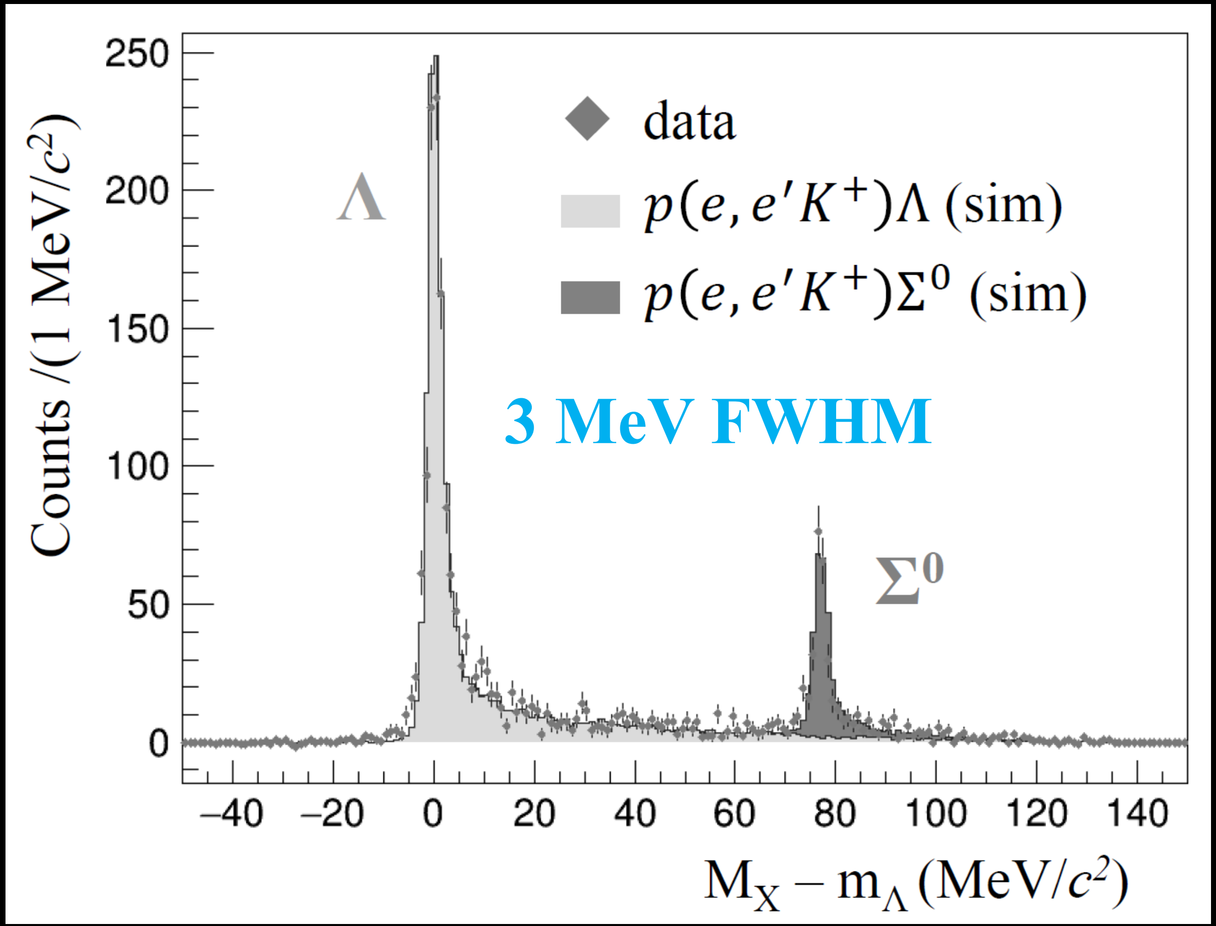


Timing consistency between L and R assuming m_K → Coin time (ns)

Energy calibration by Λ and Σ

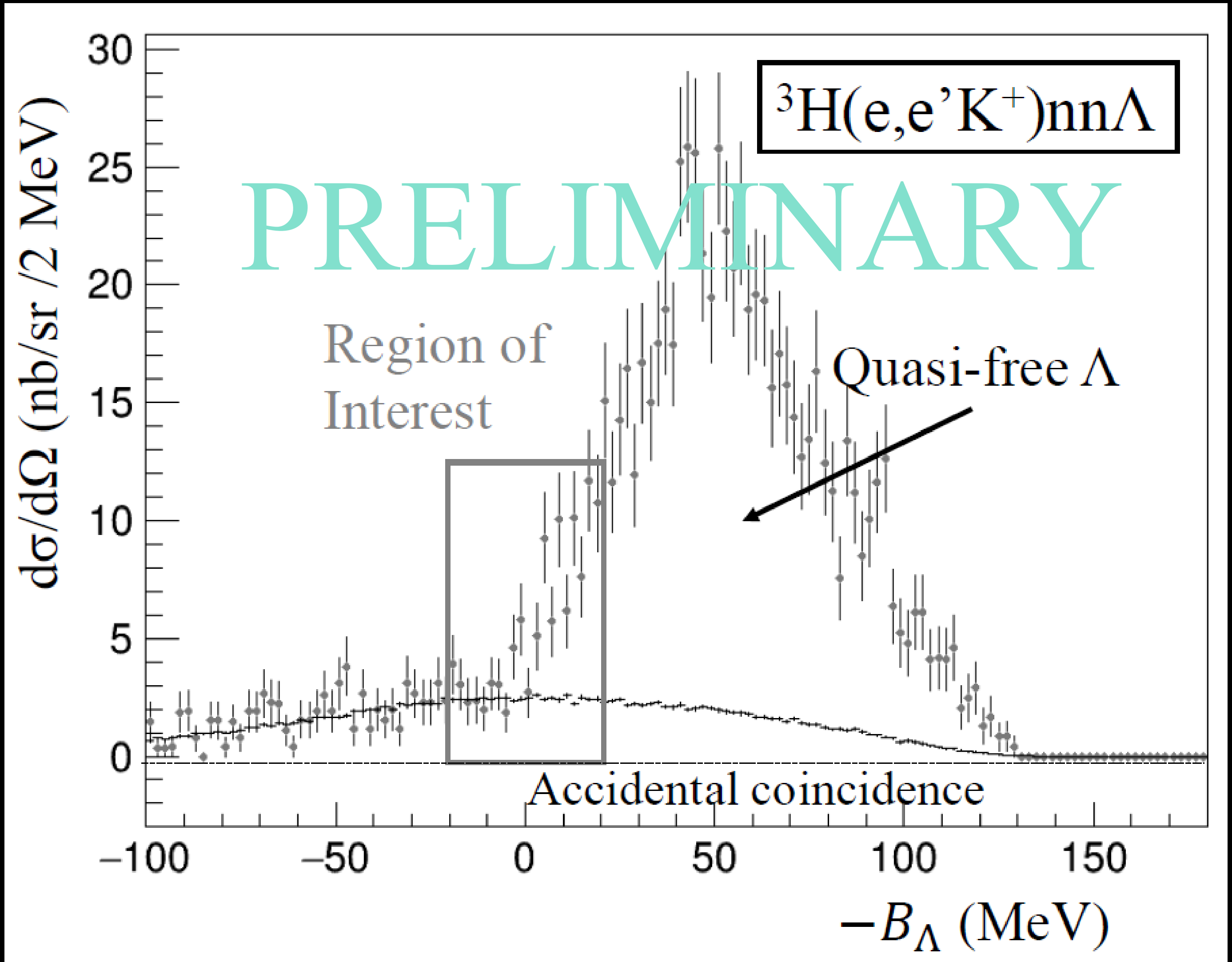
$H(e,e'K^+)\Lambda, \Sigma^0$





CROSS SECTION ANALYSIS

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



Other ongoing analyses:

A) Peak search with higher stat.
B) Λn FSI → Need theoretical supports

FIT RESULT (PRELIMINARY)

Narrow width

Wide width

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

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

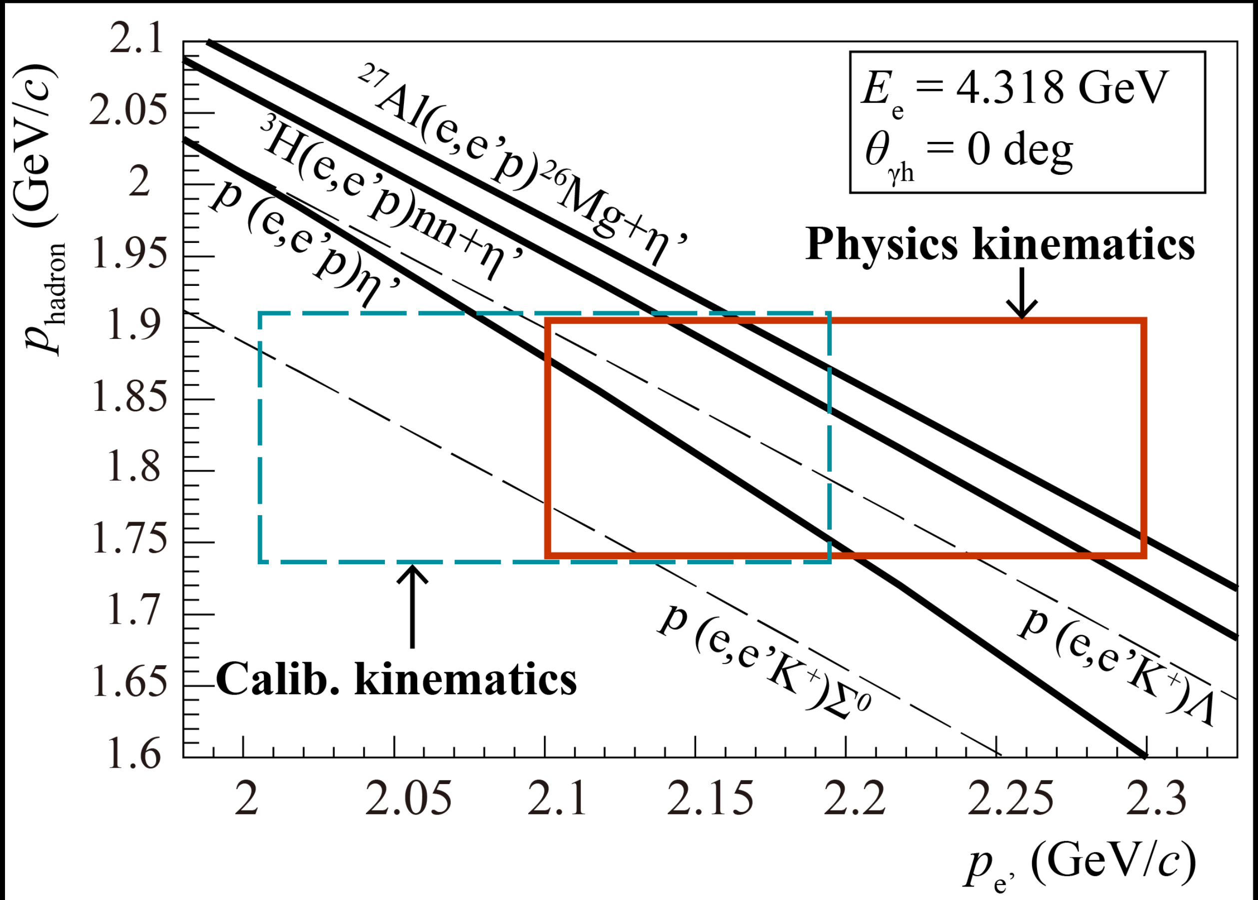
dσ/dΩ (nb/sr)

dσ/dΩ (nb/sr)

PRELIMINARY

Unbinned maximum likelihood fitting
→ Cross section

η' MESIC NUCLEI



We need theoretical calculations!

$p(e, e'p)\eta'$

PRELIMINARY

→ (virtual)photoproduction of **nnη' mesic nuclei**

→ **Nη' interaction**

Conf.) https://iopscience.iop.org/article/10.1088/1742-6596/1643/1/012181

SUMMARY

HRS-HKS @ Hall A (JLab E12-19-002, 2023〜)

- $B_\Lambda({}^{3,4}_{\Lambda}\mathrm{H})$ with an accuracy of

$$\Delta B_\Lambda^{\mathrm{tot.}} = \sqrt{\left|\Delta B_\Lambda^{\mathrm{sys.}}\right|^2 + \left|\Delta B_\Lambda^{\mathrm{stat.}}\right|^2} \simeq 60\ \mathrm{keV}$$

➔Hypertriton Puzzle / Charge Symmetry Breaking

nnΛ search experiment (E12-17-003, 2018)

1. Cross section analysis
2. Peak search with the count-base spectrum
3. nΛ FSI from the QF shape

Recent reference:
TG et al., AIP Conf. Proc. **2319**, 080019 (2021); https://doi.org/10.1063/5.0037353

THANK YOU FOR YOUR ATTENTION