JLab Hypernuclear Collaboration Meeting 2021

Physics Overview
${}^{3,4}_{\Lambda}$H measurement (E12-19-002)

Kyoto University, Japan

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Dec 7, 2021

GRADUATE SCHOOL OF FACULTY OF SCIENCE KYOTO UNIVERSITY

科研費 KAKENHI

SPIRITS SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

PROPOSAL TO JLAB PAC49

C12-19-002

High accuracy measurement of nuclear masses of Λ hyperhydrogens

T. Gogami,[1,*] S. N. Nakamura,[2] F. Garibaldi,[3,4] P. Markowitz,[5] J. Reinhold,[5] L. Tang,[6,7] G. M. Urciuoli,[3] for the JLab Hypernuclear Collaboration, and the JLab Hall A Collaboration

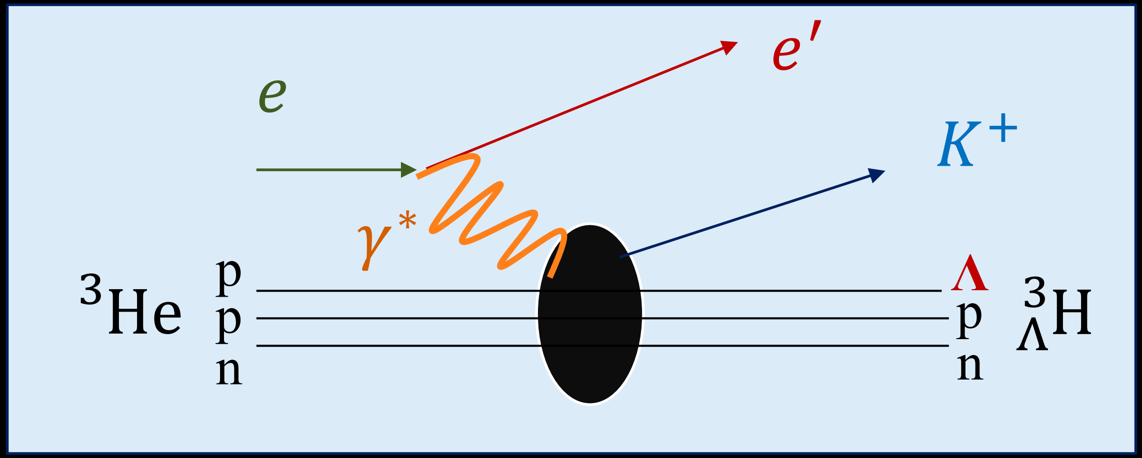
https://www-nh.scphys.kyoto-u.ac.jp/~gogami/e12-19-002/opensrc/Proposal-C12-19-002_PAC49_submitted.pdf

- 2018 LOI
- 2019 Proposal → Conditional Appr. (C2)
- 2020 Proposal → Conditional Appr. (C2)
- 2021 Proposal → **Approved** (SR = A)

(https://www.jlab.org/physics/PAC/PAC49)

Mode	Hypernucleus	Target (mg/cm^2)	Beam current (μA)	Beamtime (day)	Yield
Physics	$^{3}_{\Lambda}$H	^{3}He (165)	50	10	600 ($1/2^+$, $3/2^+$)
	$^{4}_{\Lambda}$H	^{4}He (228)	50	2	500 (1^+)
	Subtotal			**12**	-
Calibration	Λ Σ^0	H_2 (54)	50	1	3500 1150
	$^{12}_{\Lambda}B^{g.s.}$	Multi foil (100×5)	50	1	300×5
	-	Multi foil + Sieve slit	50	0.2	-
	-	Empty cell	50	0.1	-
	-	Empty cell + Sieve slit	50	0.2	-
	Subtotal			**2.5**	-
Total				**14.5**	-

(e,e'K⁺) reaction



→ Missing mass spectroscopy

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

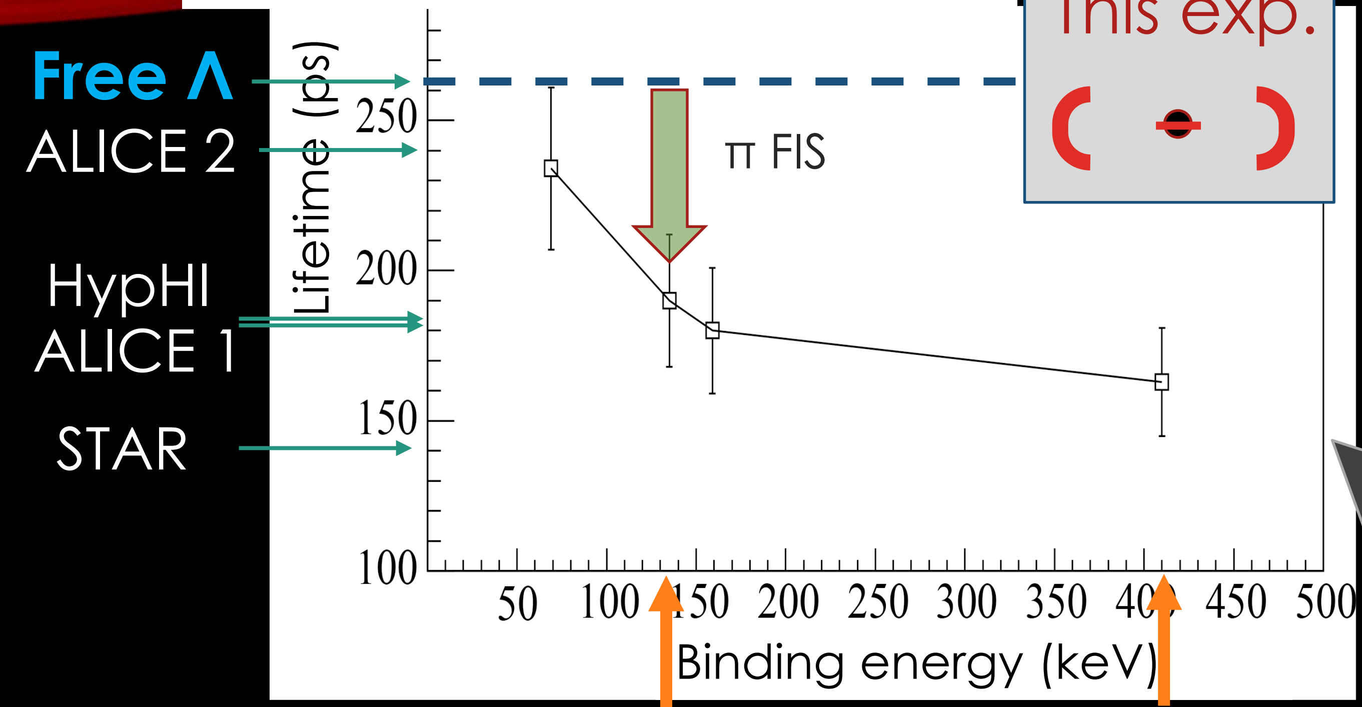
$\tau = (0.5 \sim 0.92)\,\tau_\Lambda$
(HypHI, STAR, ALICE)

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:
$|\Delta B^{stat.}| = 20$ keV, $|\Delta B^{sys.}| = 55$ 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).**

^{3}He **^{3}H**

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

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

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

^{3}He+Λ | ^{3}H+Λ

-0.98*1) *1*$^{+}$ | -0.95 *1*$^{+}$

0.03±0.05 MeV

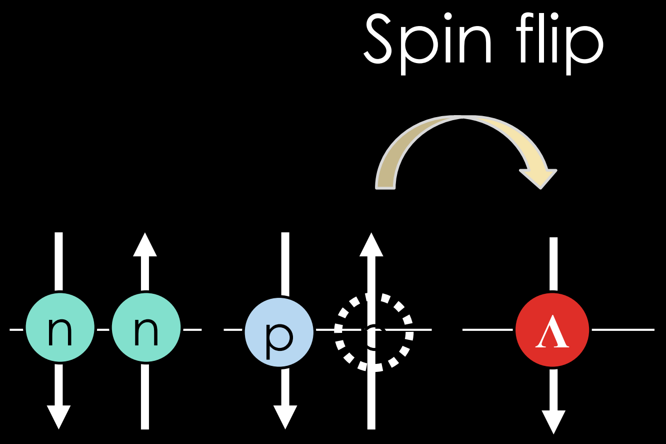
-2.39 *0*$^{+}$ | -2.12*2) *0*$^{+}$

0.27±0.06 MeV

➡ ***≈0.4 MeV w/ correction***

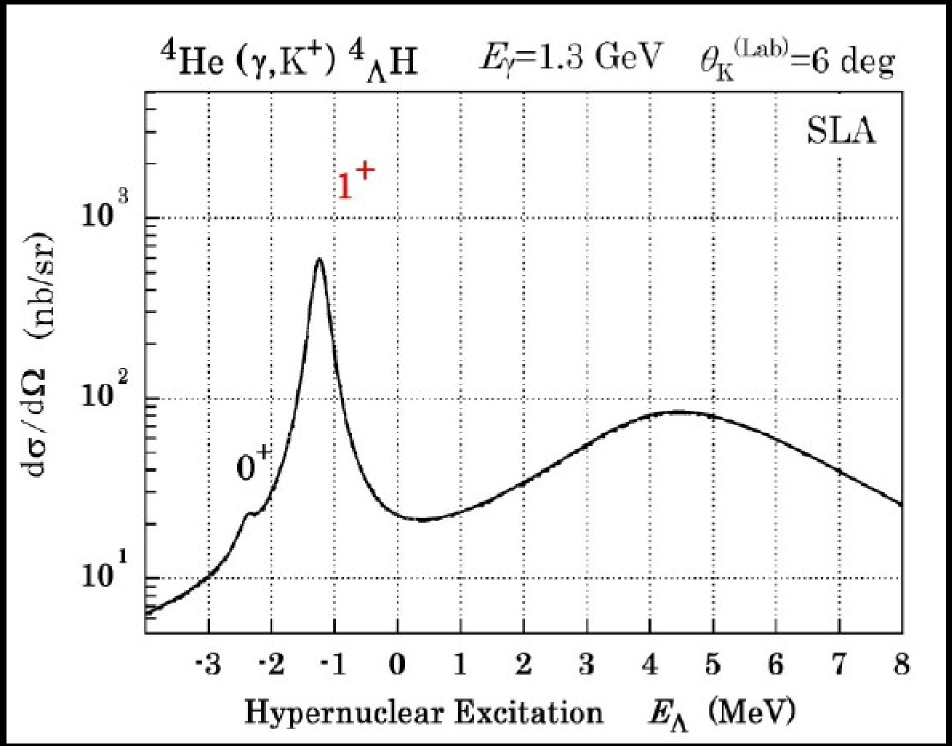
- ☐ Five times larger effect
- ☐ Spin dependent

Direct production of ${}^{4}_{\Lambda}\mathrm{H}\ (1^{+})$



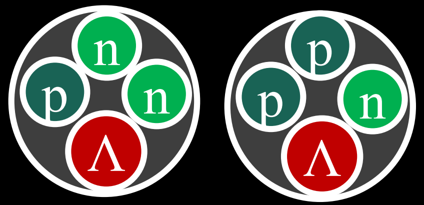
$$^{4}\mathrm{He}(\gamma, K^{+})^{4}_{\Lambda}\mathrm{H}$$

1^{+} is preferably produced



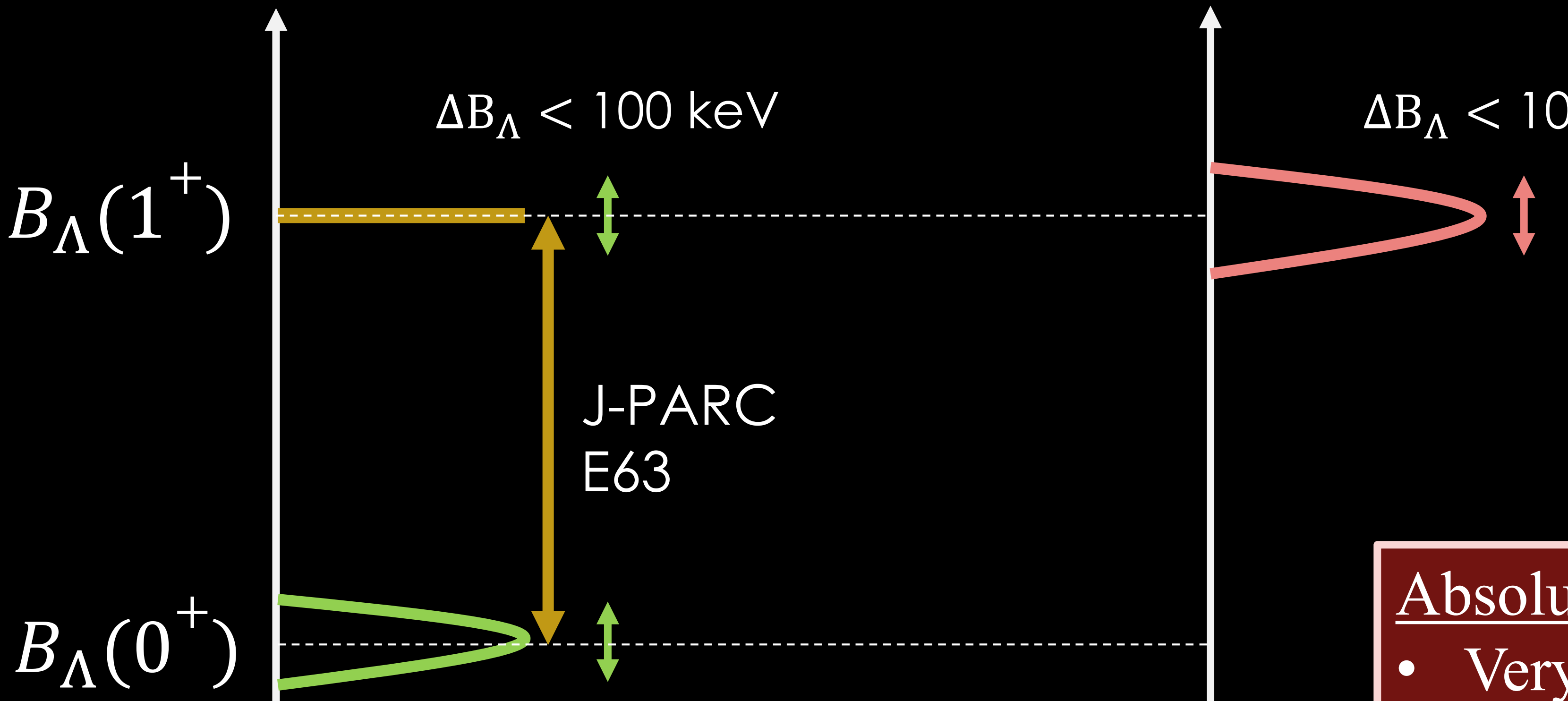
T. Motoba, JPS Conf. Proc. , 011003 (2017)

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



Conventional way

JLab E12-19-002

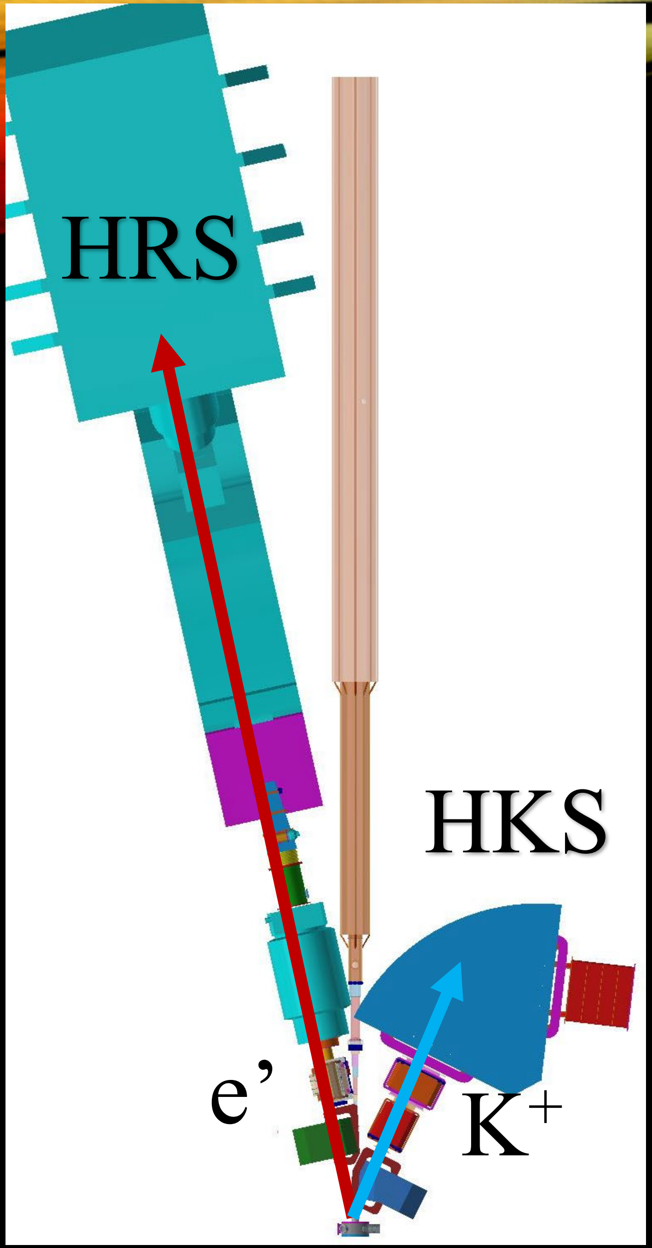


This Experiment

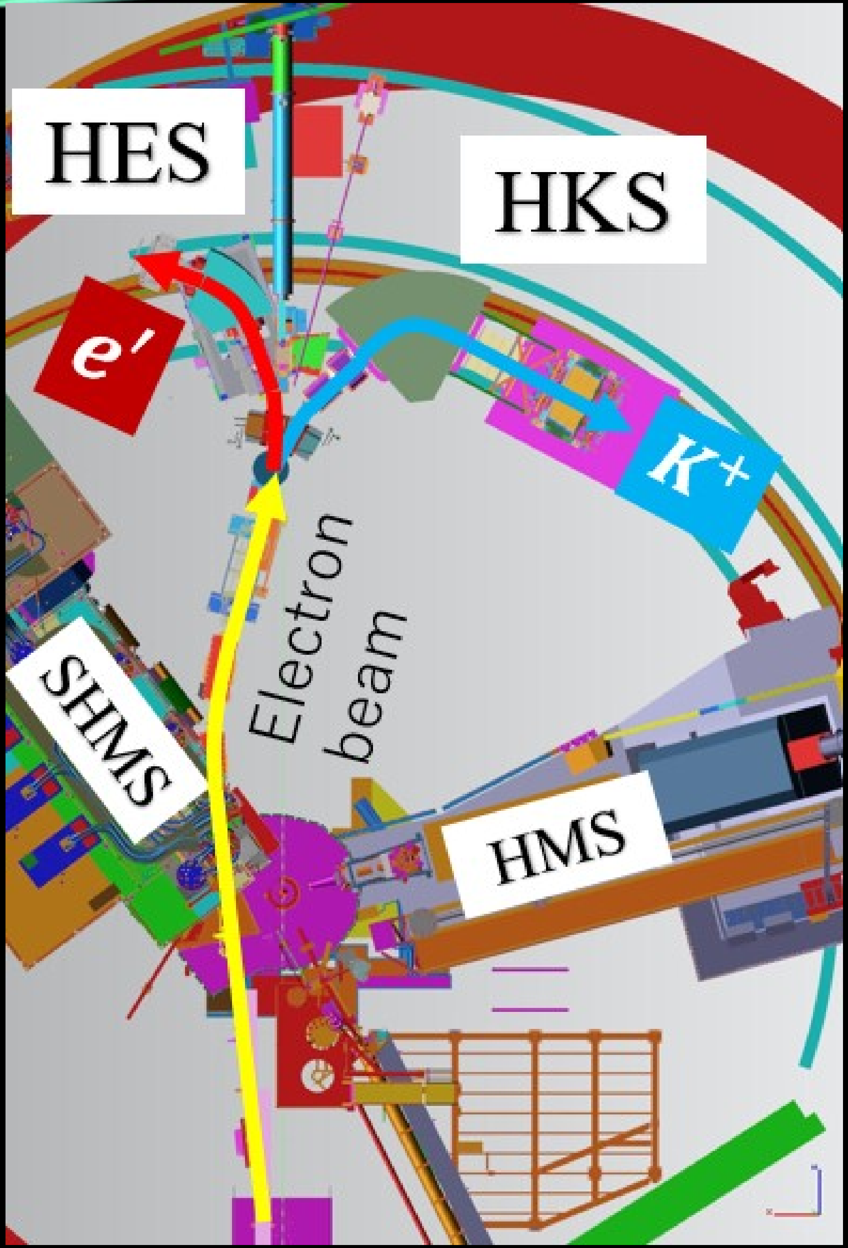
- Emulsion: $\mathbf{2.08 \pm 0.06 \pm\ 0.04}$ **MeV** [(1)]
- MAMI: $\mathbf{2.12 \pm 0.01 \pm\ 0.09}$ **MeV** [(2)]

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

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

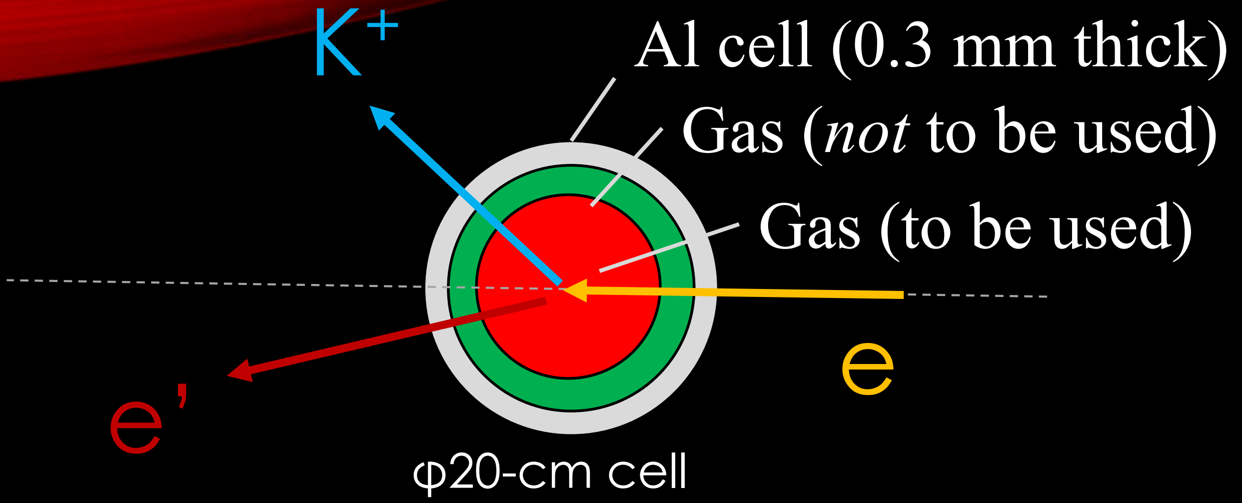


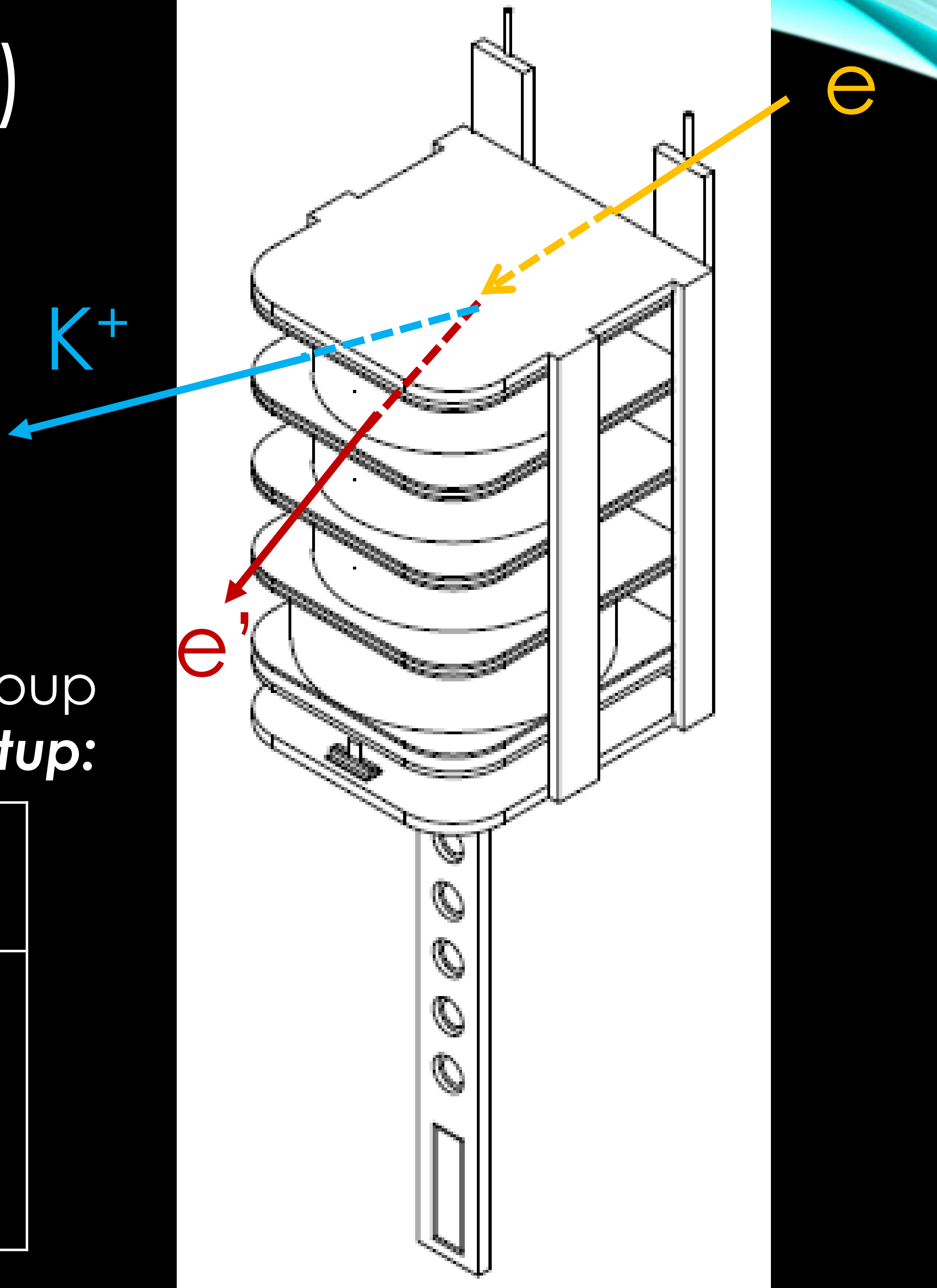
Hall A



Hall C

TARGET CELLS (TUNA CAN)

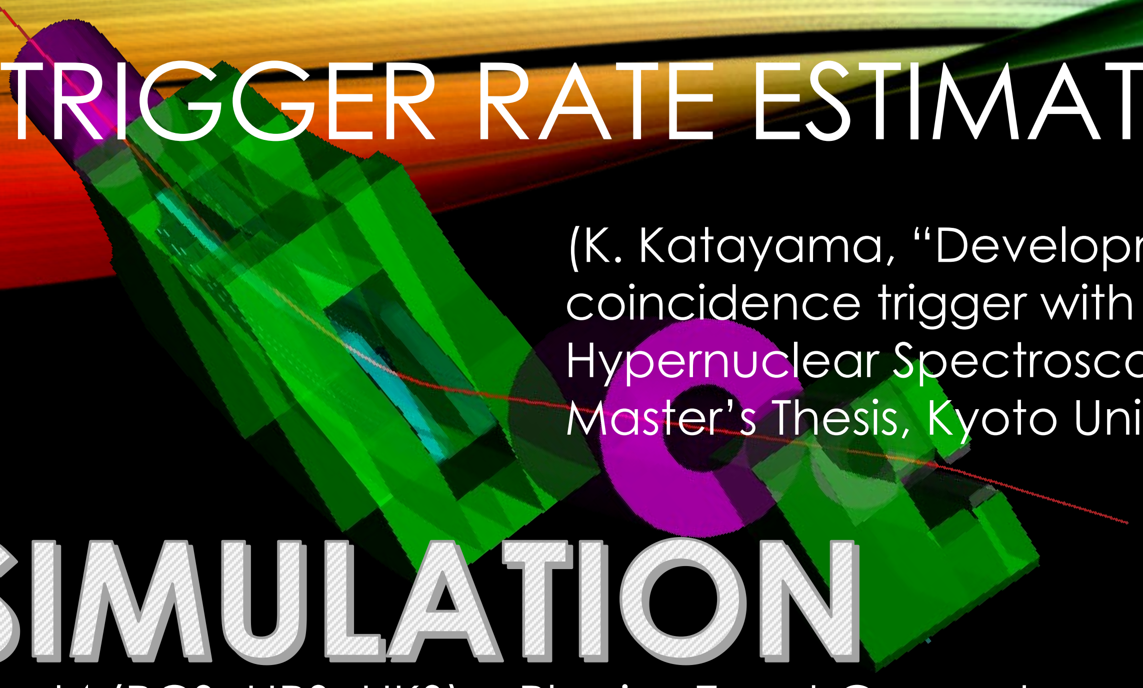




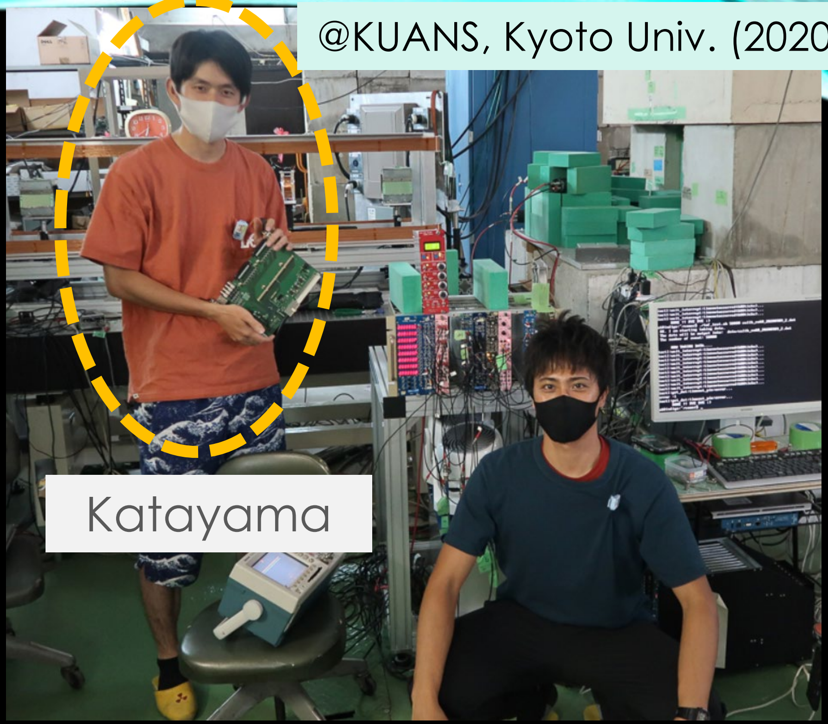
Available densities calculated by the JLab Target Group ***maintaining a compatibility with our experimental setup:***

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

TRIGGER RATE ESTIMATION



(K. Katayama, "Development of HRS-HKS coincidence trigger with FPGA - Precise Hypernuclear Spectroscopy at JLab -", Master's Thesis, Kyoto Univ. JFY2020)



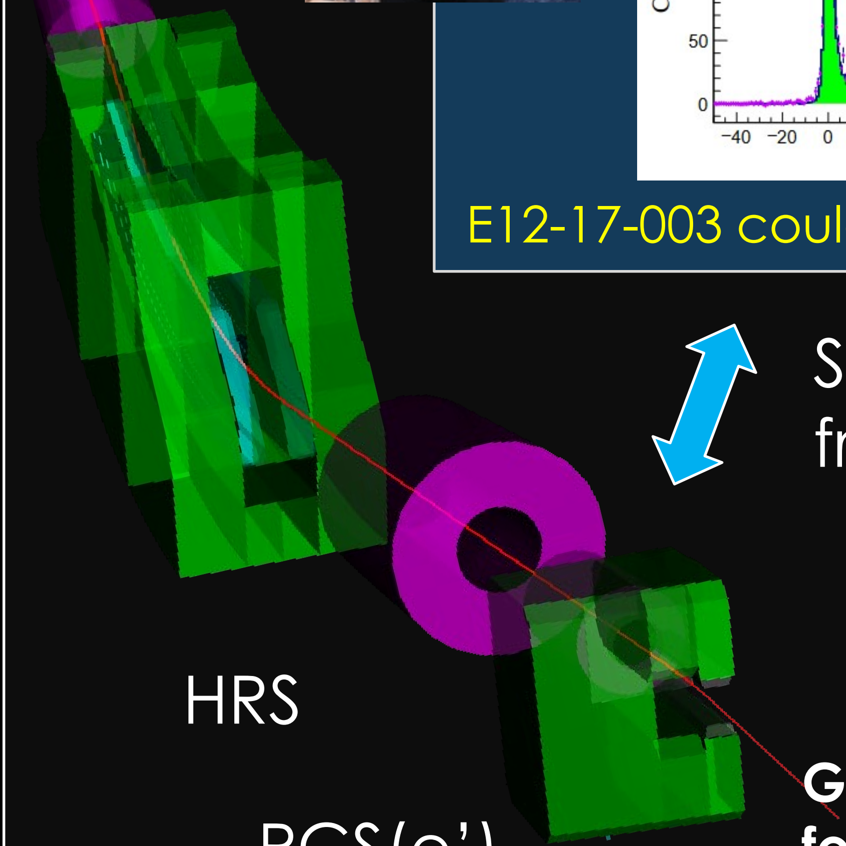
SIMULATION

Geant4 (PCS+HRS+HKS) + Physics Event Generators

Target	Thickness (mg/cm^2)	Beam Current (μA)	e' (kHz)	p (kHz)	π (kHz)	Acc. rate (kHz)	Acc. rate w/ Chernkovs (kHz)
^{12}C	100	100	21.5	56	71	**0.4**	0.023
^{40}Ca	100	50	64.5	48	71	**1.2**	0.060
^{208}Pb	100	25	97.0	22	33	**0.8**	0.041
$^{3}He+^{27}Al$	190+162	50	90.8	163.2	252.5	**3.2**	**0.15**
$^{4}He+^{27}Al$	262+162	50	91.2	201.6	355.9	**4.9**	**0.23**

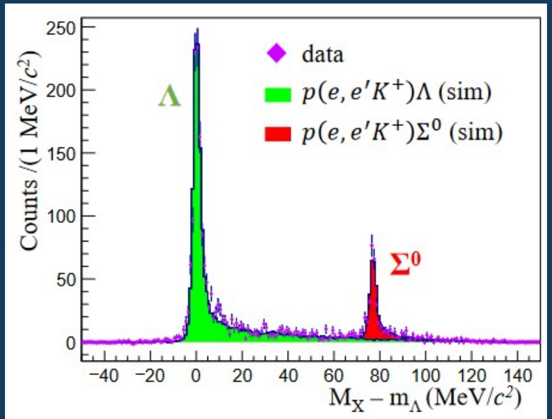
Particle identification by HKS: **TG et al., NIMA 729, 816—824 (2013).**

EXPECTED MISSING MASS RESOLUTION



K.N. Suzuki et al., PTEP in Press (2021)

https://academic.oup.com/ptep/advance-article/doi/10.1093/ptep/ptab158/6454035



E12-17-003 could be reproduced

Same framework

Geant4 simulation for C12-19-002

$$z_{T,\mathrm{HRS}} = \sum_{i+j+k+l=0}^{n_1} a_{ijklm} x_{\mathrm{FP}}^{i} x'^{j}_{\mathrm{FP}} y^{k}_{\mathrm{FP}} y'^{l}_{\mathrm{FP}}$$

$$\overrightarrow{p^{\mathrm{HRS,HKS}}} = \sum_{i+j+k+l+m=0}^{n_2} a_{ijklm} x_{\mathrm{FP}}^{i} x'^{j}_{\mathrm{FP}} y^{k}_{\mathrm{FP}} y'^{l}_{\mathrm{FP}} (z^{m}_{T,\mathrm{HRS}})$$

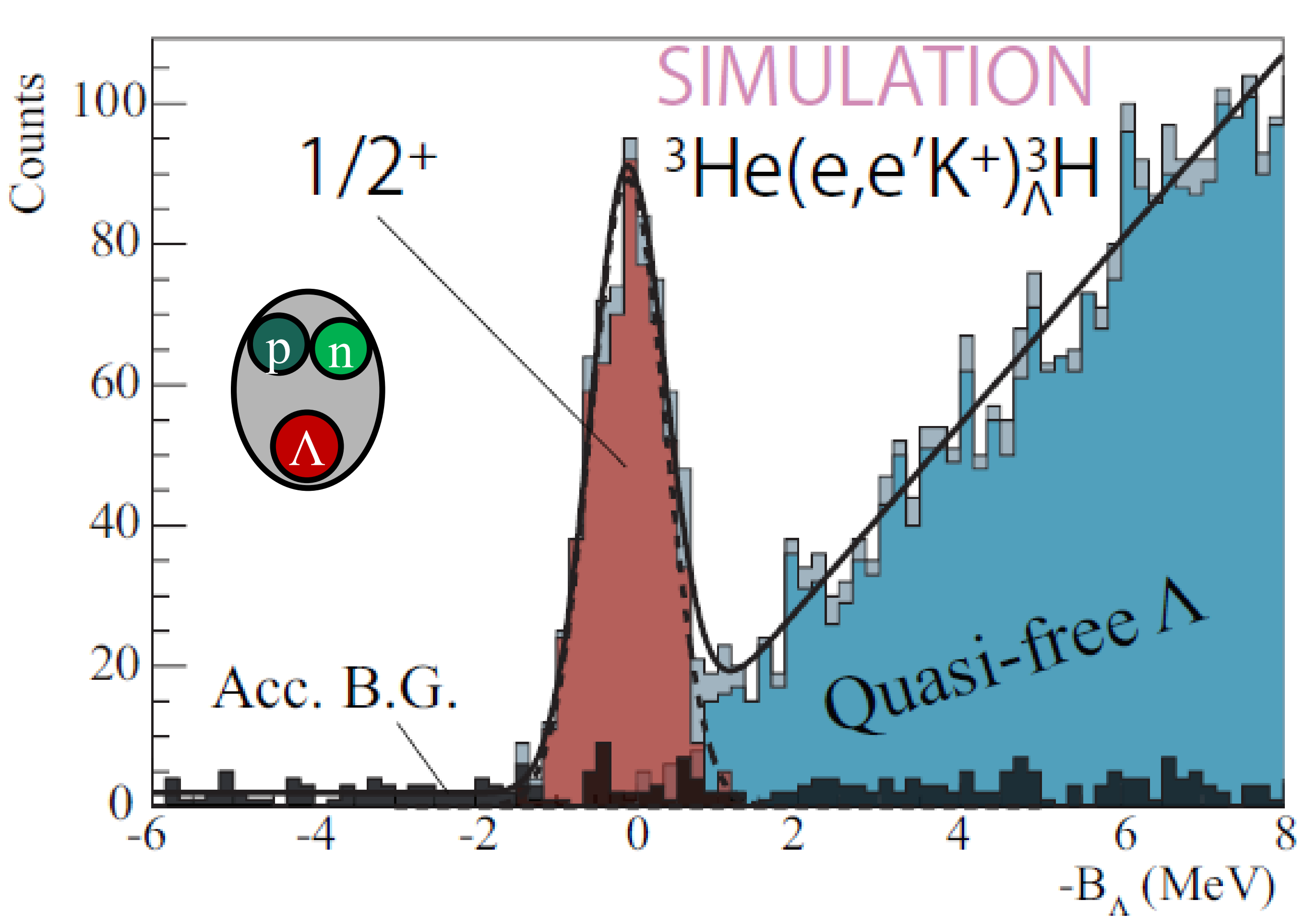
w/ materials (e.g. target cell):

Spectrometer	$\Delta p/p$ (FWHM)
HRS (e')	3.2×10^{-4}
HKS (K+)	5.7×10^{-4}

↓

$\Delta M_{\mathrm{HYP}} = 1.1$ **MeV/c² (FWHM)**

EXPECTED SPECTRA AND STATISTICAL ERRORS



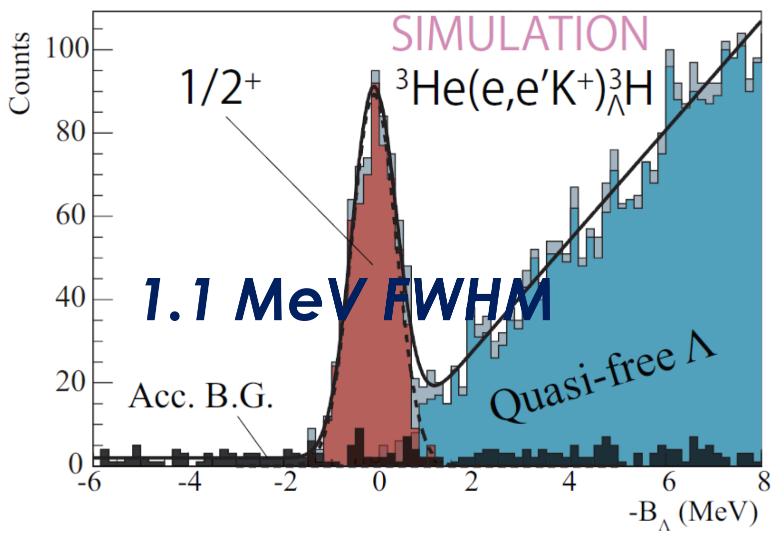
Hall A case

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

systematic error < ±60 keV

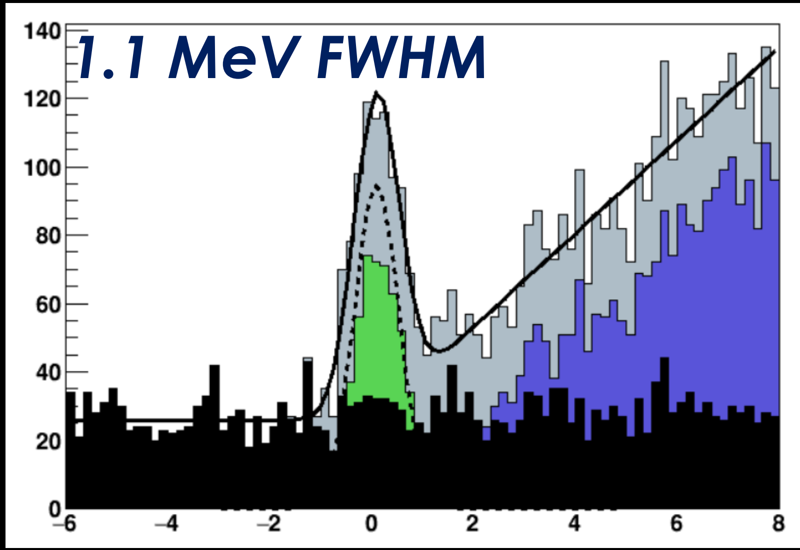
Comparison between Hall A and C

HRS-HKS @Hall A, 50 μA



Stat. err. = 20 keV

HES-HKS @Hall C, 20 μA

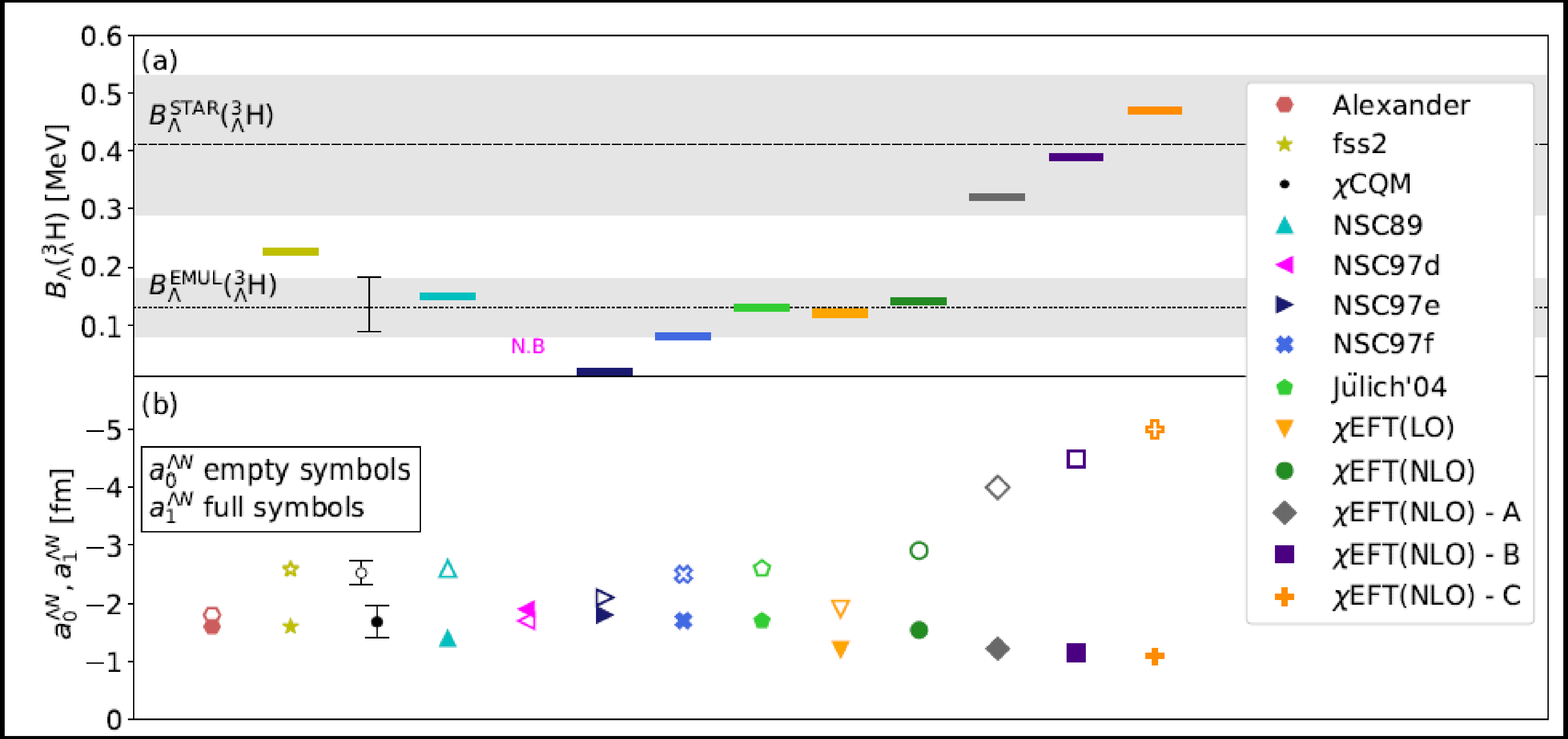


Stat. err. < 30 keV

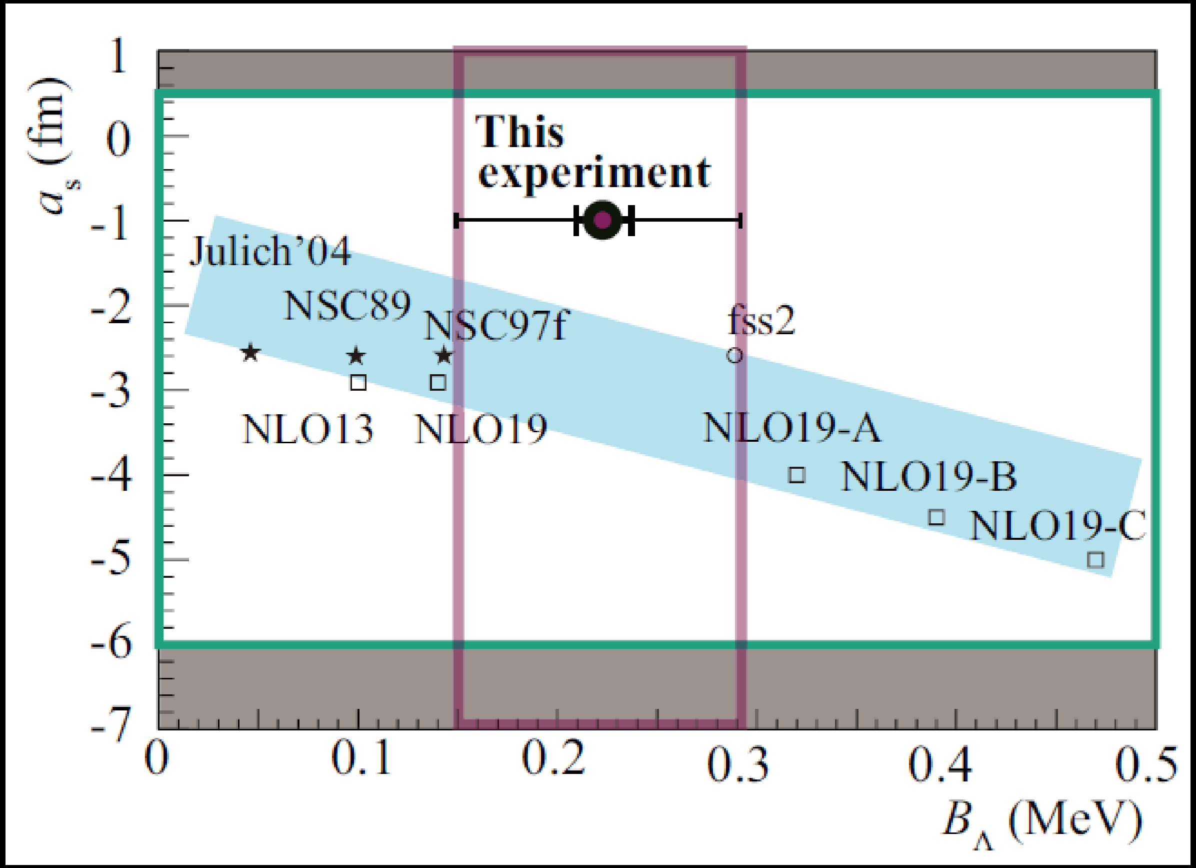
Feasibility at Hall C is carefully being studied (Resolution, S/N, Yield)

ΛN scattering length vs. B_Λ

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



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



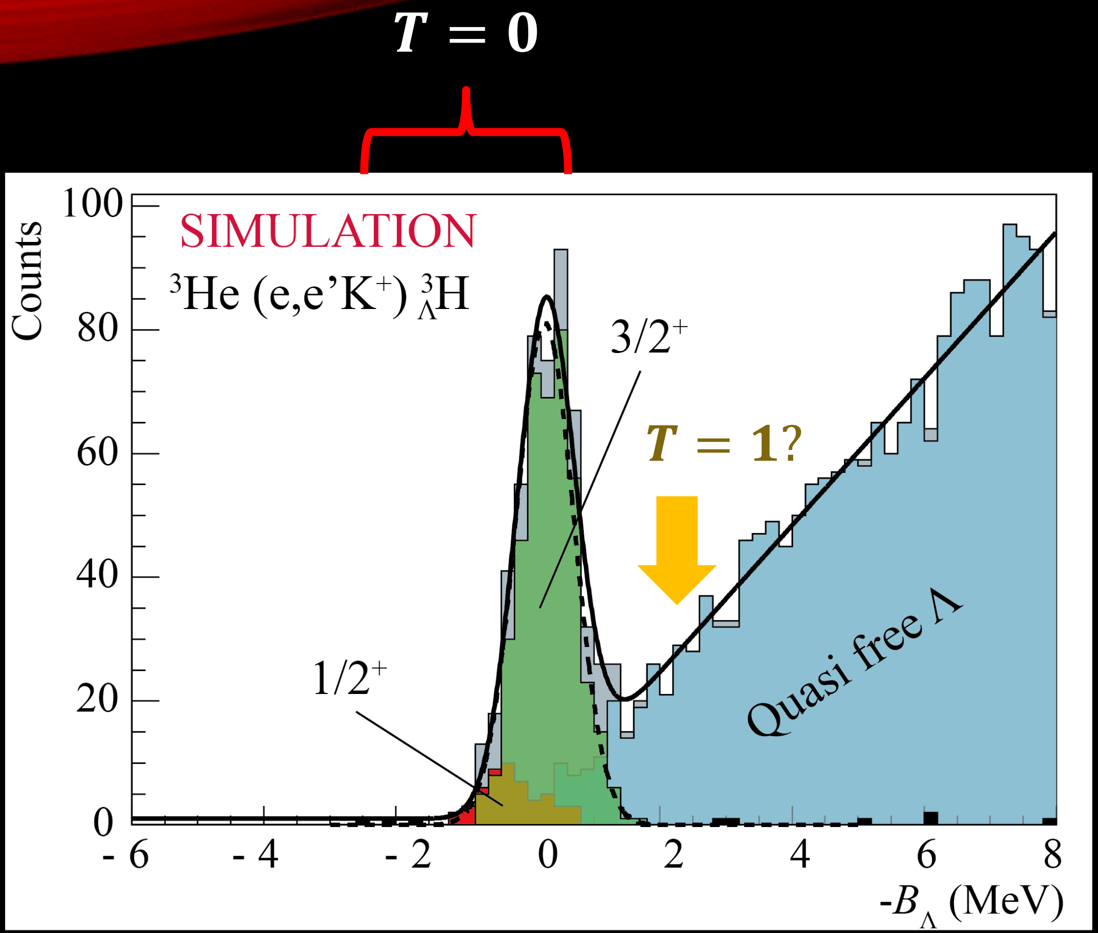
Hypertriton Puzzle

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

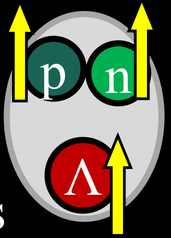
ΛN interaction

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

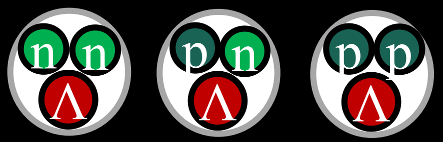


${}^{3}_{\Lambda}\mathrm{H}\,(T = 0,\ J^{\pi} = 3/2^{+})$



- 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 → $\left|\Delta B_{\Lambda}^{\mathrm{stat.}}\right| \sim 90$ keV

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

SUMMARY

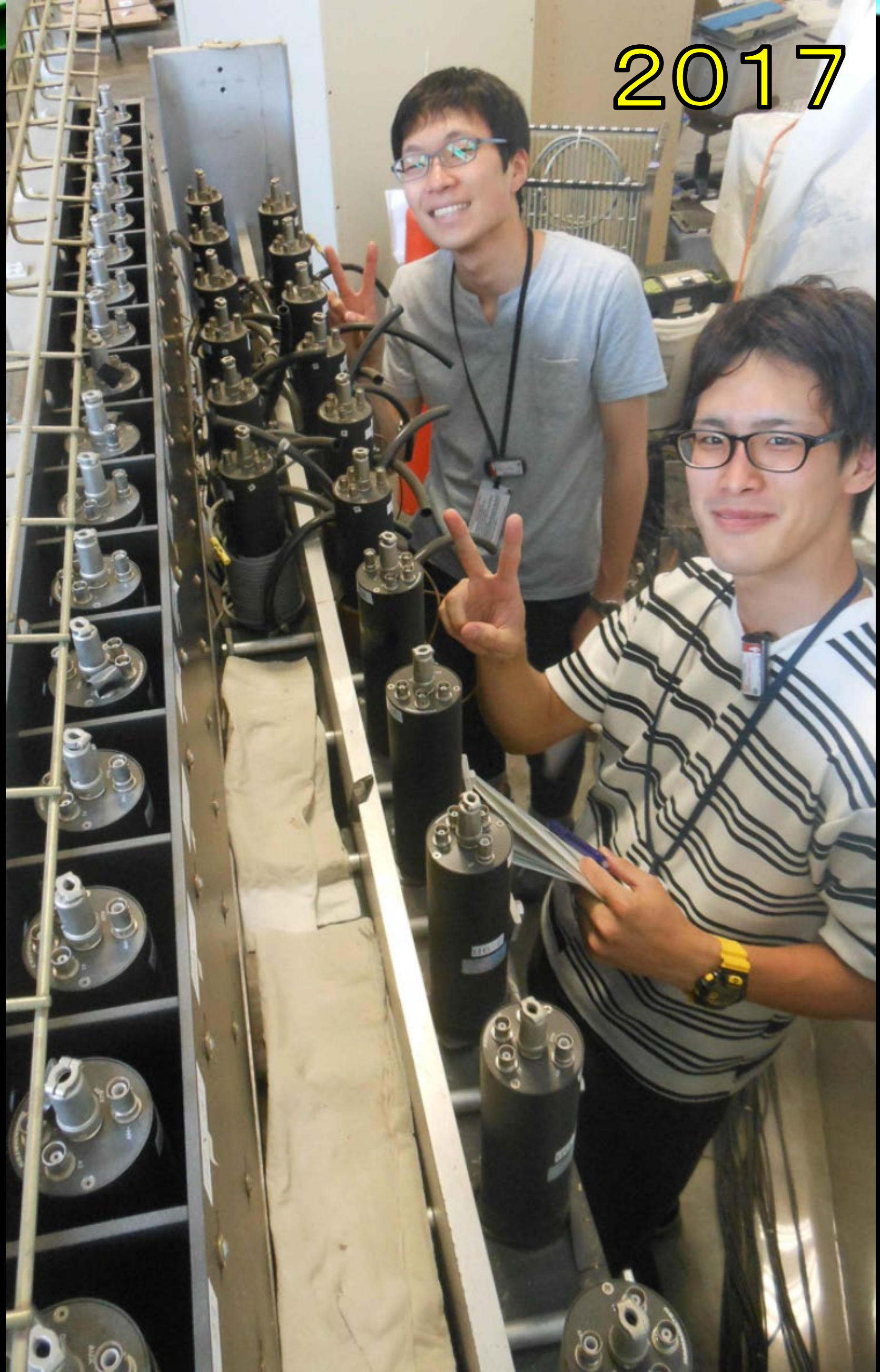
HKS experiment @ Hall A/C (JLab E12-19-002)

$B_\Lambda({}^{3,4}_{\Lambda}\mathrm{H})$ measurement with the 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 / CSB
(complementary with MAMI and J-PARC measurements)

C.F.) AIP Conf. Proc. **2319**, 080019 (2021); https://doi.org/10.1063/5.0037353



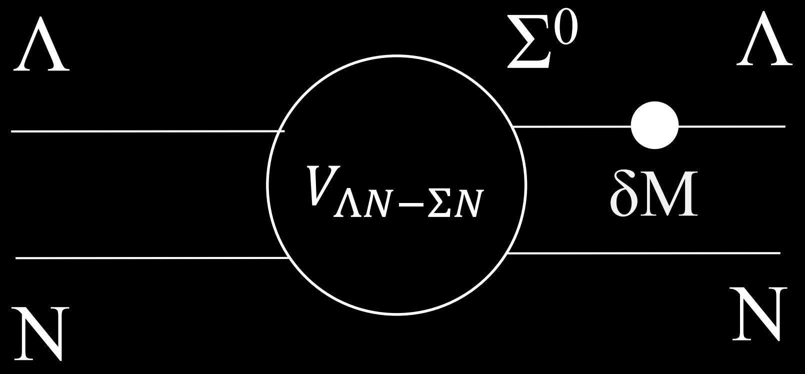
No chance in 2020, 2021…

We want to resume preparation in 2022!

BACKUP

ΛN-ΣN COUPLING

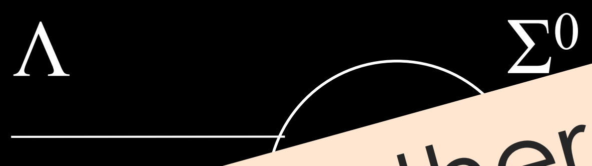
A. Gal, Phys. Lett. B 744, 352 (2015)



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

ΛN-ΣN COUPLING

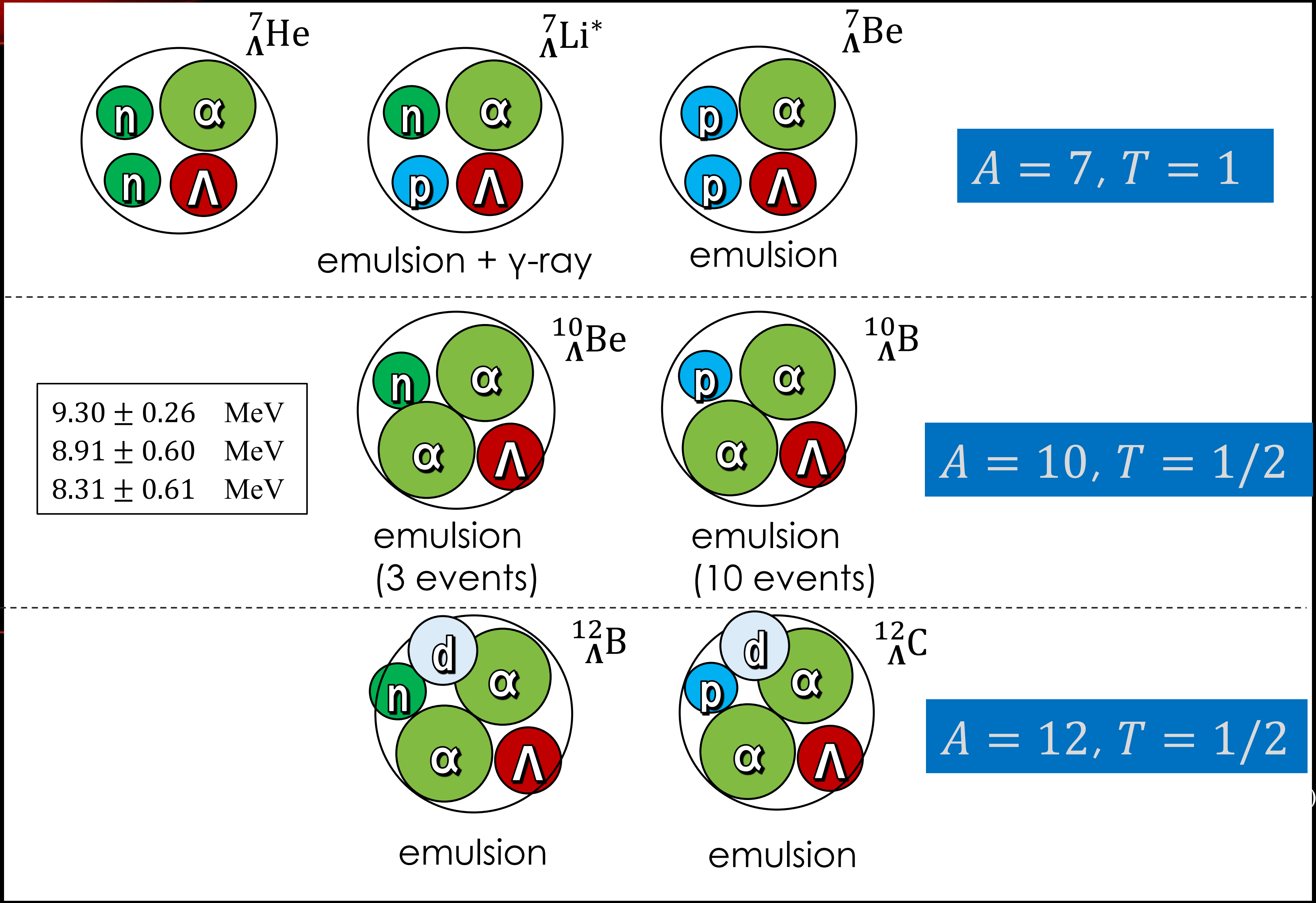
A. Gal, Phys. Lett. B 744, 352 (2015)



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



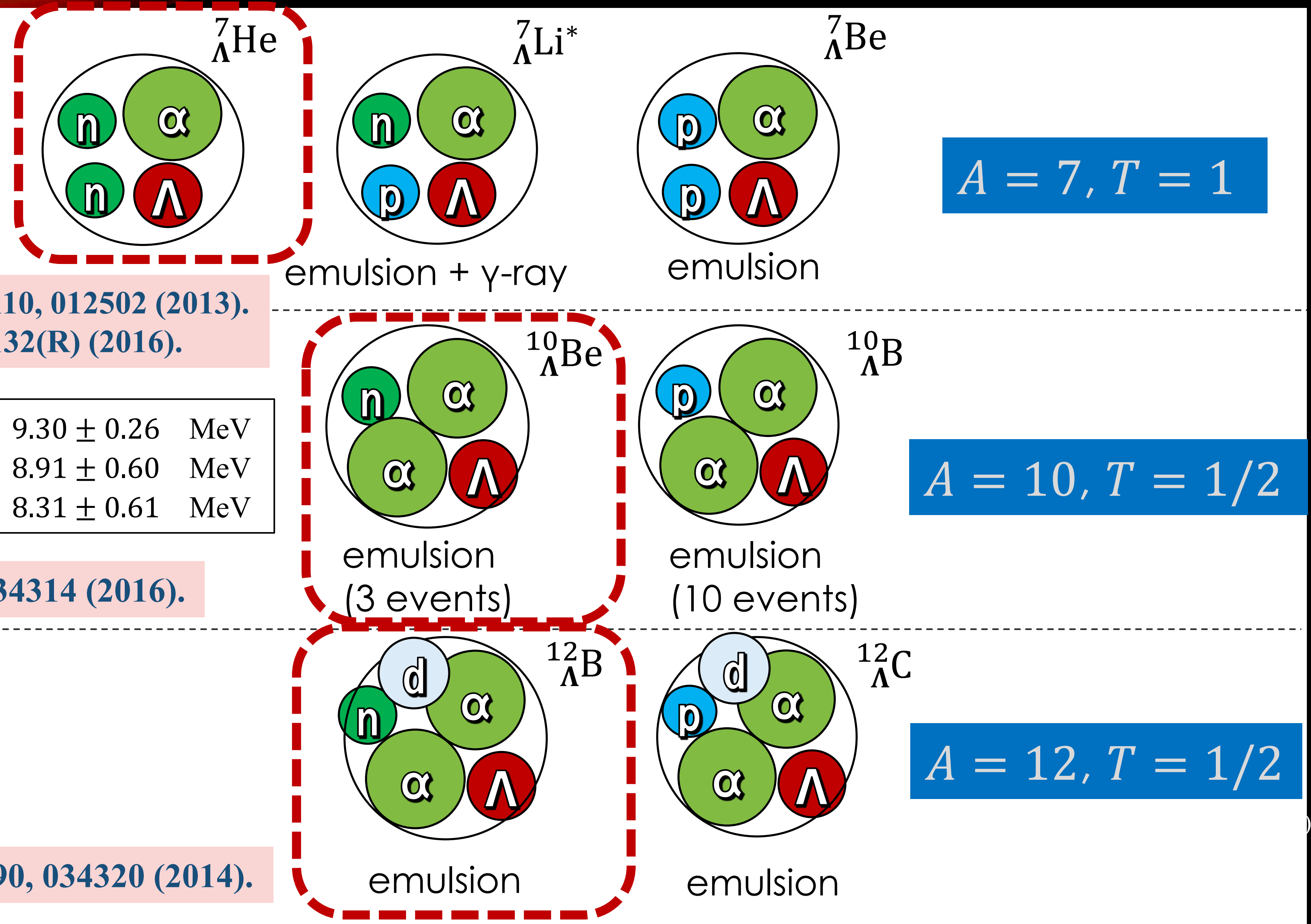
Charge symmetry breaking (CSB) in the p-Shell hypernuclei

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

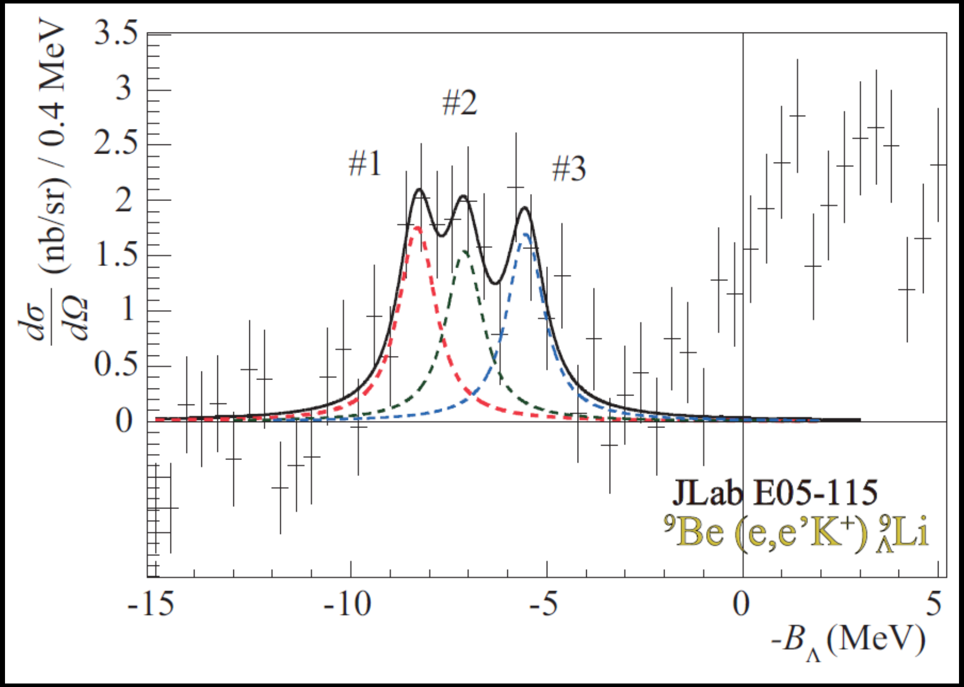
TG et al., PRC 93, 034314 (2016).

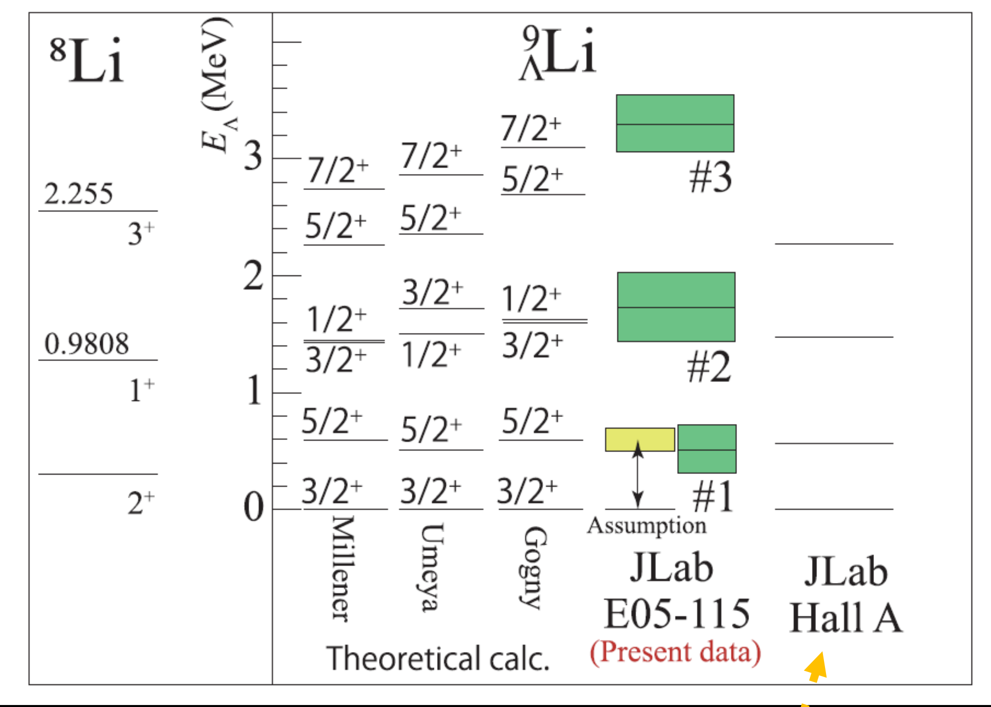
L. Tang et al., PRC 90, 034320 (2014).



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)





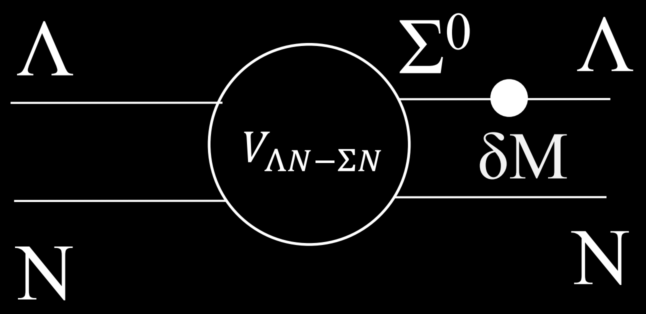
F. Garibaldi et al., Phys. Rev. C 99, 054309 (2019).

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).

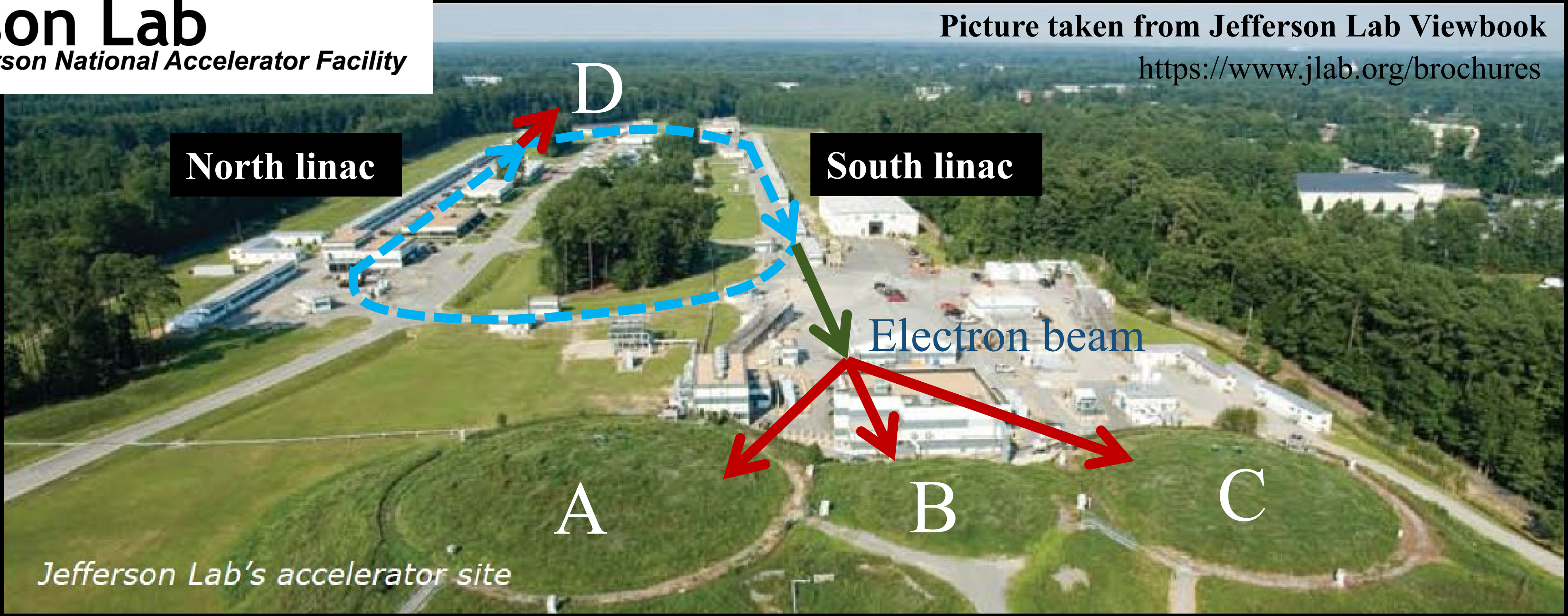
$$V_{\Lambda N}^{\mathrm{CSB}}(r) = -\frac{\tau_z}{2}\left[\frac{1+P_r}{2}\left(v_0^{\mathrm{even,CSB}} + \sigma_\Lambda \cdot \sigma_N v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{even,CSB}}\right)e^{-\beta_{\mathrm{even}}r^2} + \frac{1-P_r}{2}\left(v_0^{\mathrm{odd,CSB}} + \sigma_\Lambda \cdot \sigma_N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

Basic Input (This Experiment) — A=4 → **CSB interaction** →

- A=5 — 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) …

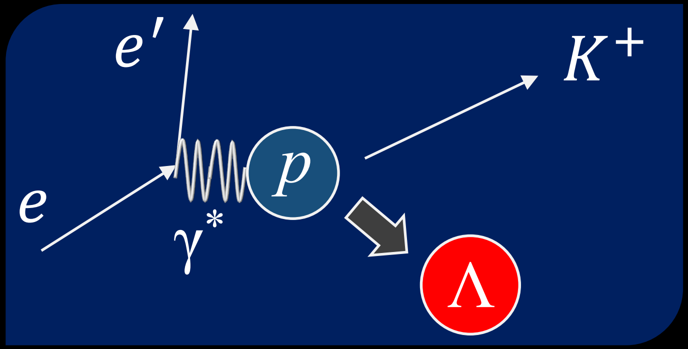
CEBAF AT JEFFERSON LAB

Jefferson Lab
Thomas Jefferson National Accelerator Facility

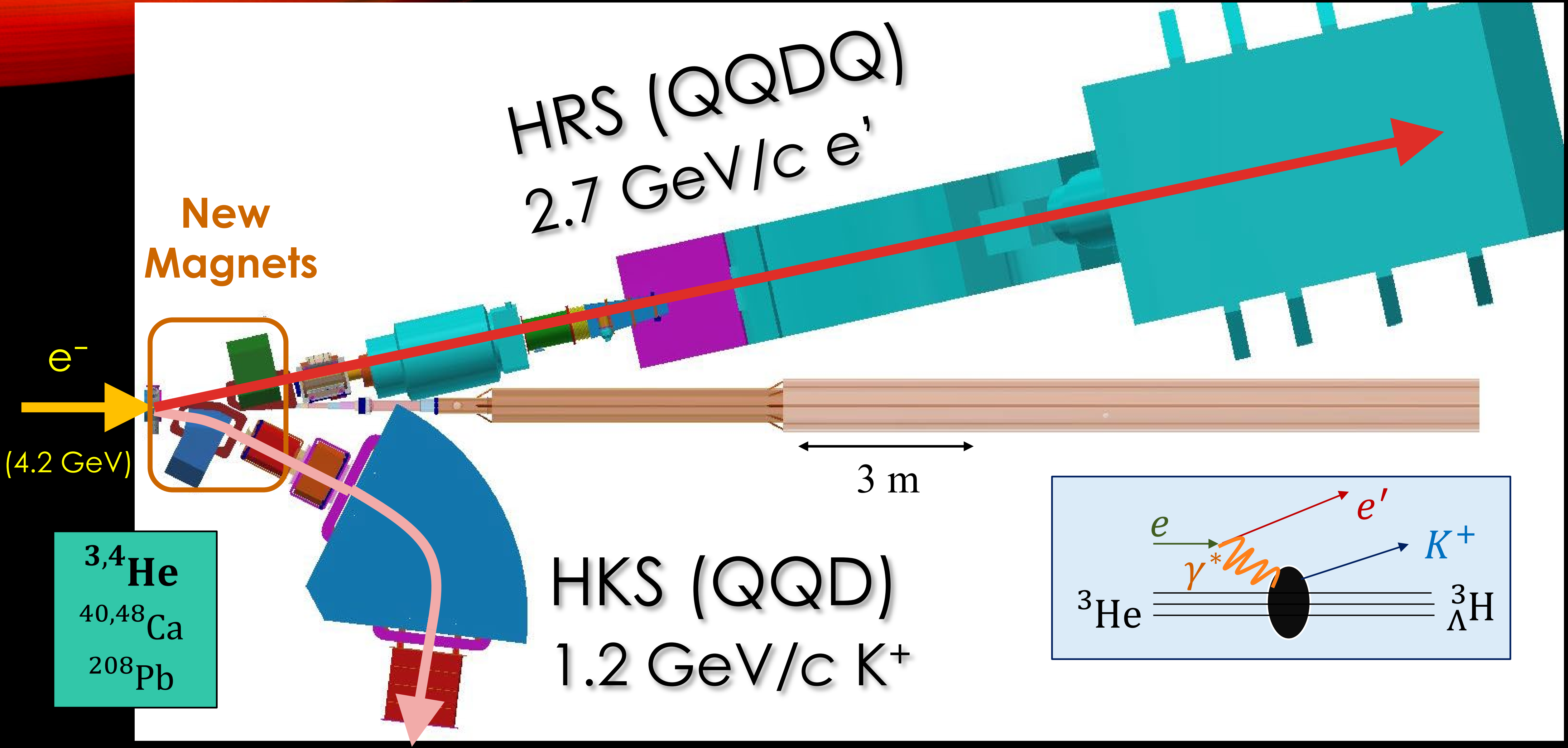


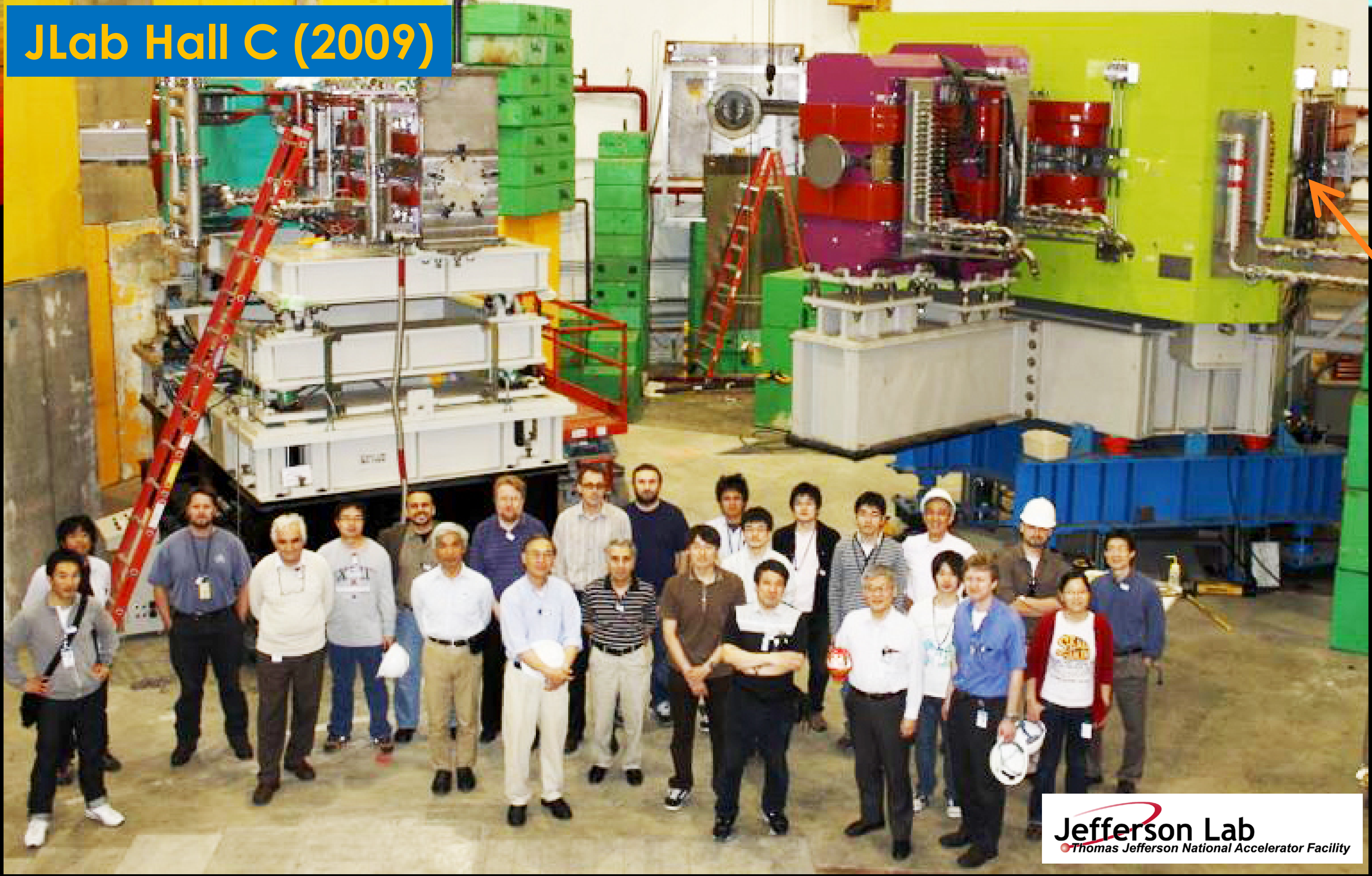
Continuous electron beam facility (CEBAF)

- ✓ 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 at JLab Hall A





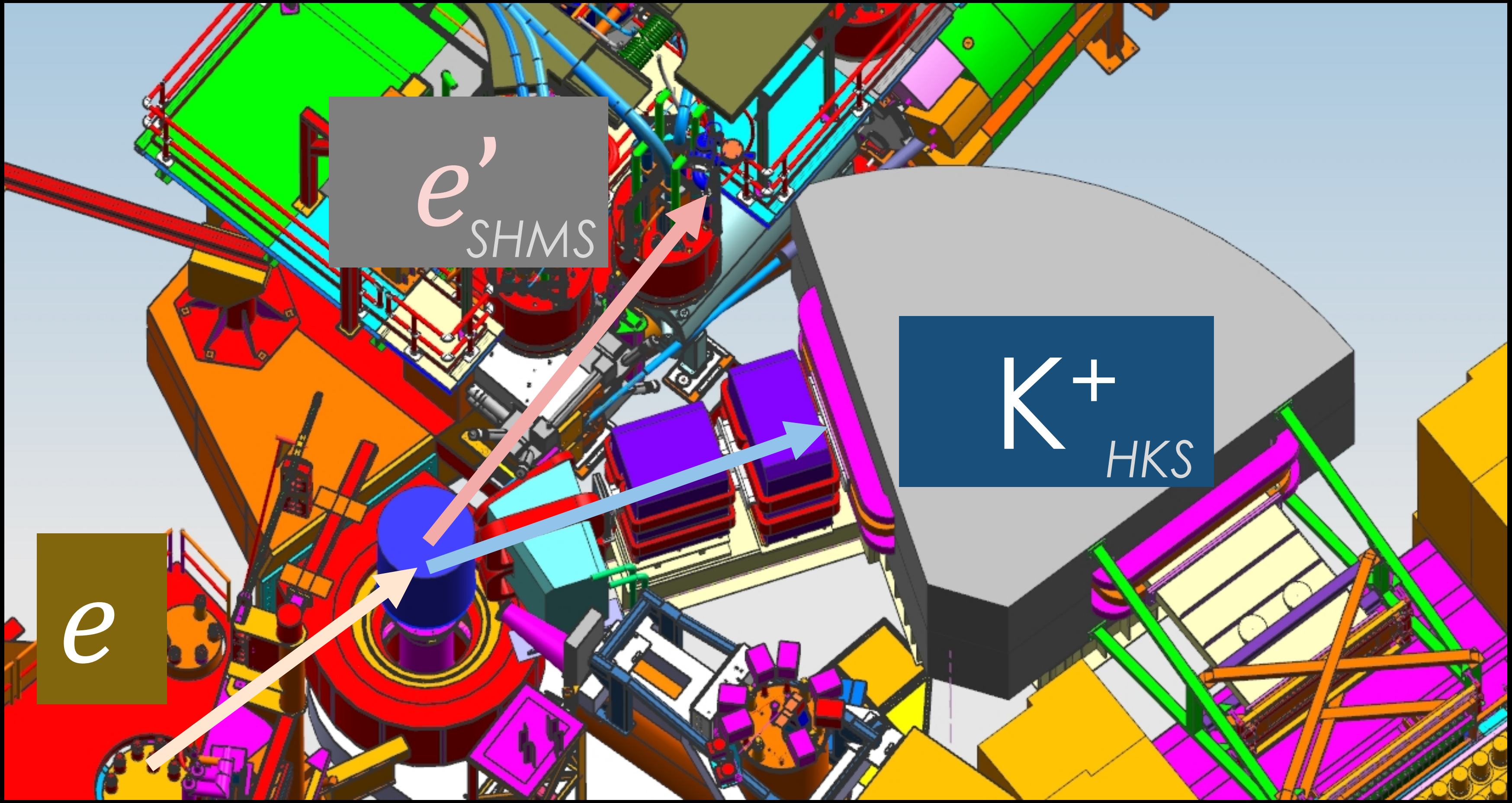
HKS

- 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)
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

Possibility in Hall C

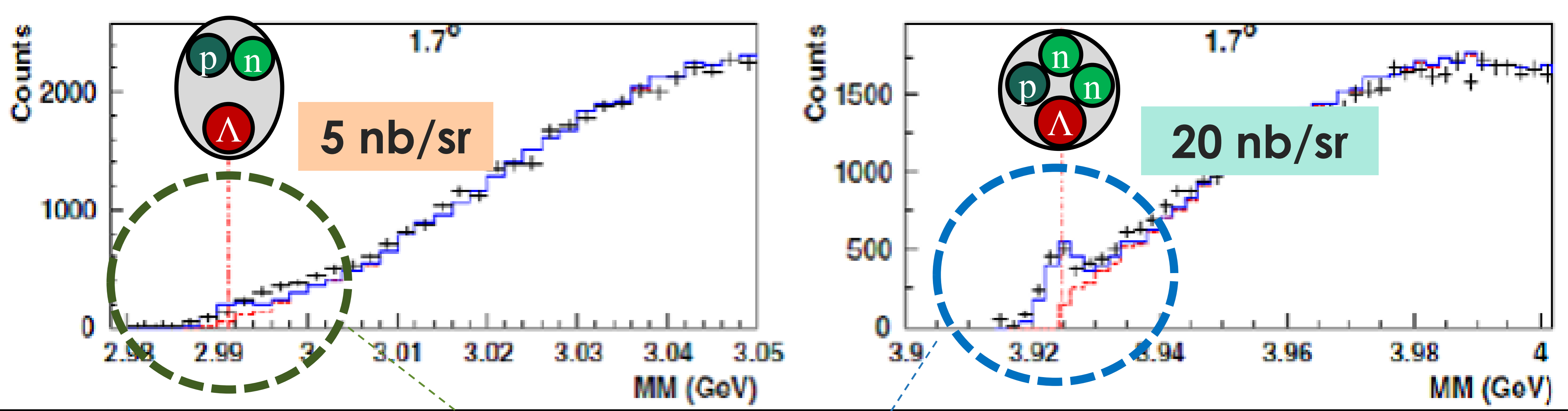


Evaluations are in progress

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

YIELD ESTIMATION

F. Dohrmann et al., *Phys. Rev. Lett.* **93**, 242501 (2004).



Product	Target [/(mg/cm^2)]	I_{beam} (/μA)	CS [/(nb/sr)]	Yield / day	Beamtime (/day)	**Total yield**
${}^{3}_{\Lambda}H$	^{3}He (165)	50	5	60	10	**600**
${}^{4}_{\Lambda}H$	^{4}He (228)		20	250	2	**500**

CALIBRATION AND SYSTEMATIC ERROR ON B_Λ

Calibration	Target + Sieve Slit	Reaction	z_t range (mm)	Beamtime (day)	Remarks
Mom. + z_t	H	$p(e,e'K^+)\Lambda,\Sigma^0$	$-110 < z_t < 110$	1	Λ: 3500, Σ^0: 1150
Mom. + z_t	^{12}C (multi foils)	$^{12}C(e,e'K^+)^{12}_{\Lambda}B$		1	$^{12}_{\Lambda}B^{g.s.}$: 300×5
Angle + z_t	^{12}C (multi foils) + SS	-		0.2	
z_t	Empty	-	$-100 < z_t < 100$	0.1	+ Background study
	Empty (or gas) + SS	-		0.2	+ Angle resolution check
Physics	^{3,4}He	$^{3,4}_{\Lambda}$H	$-100 < z_t < 100$	12	

Major contributions to a systematic error on B_Λ

- Energy scale calibration(*) : ±50 keV
- Energy loss correction: ±23 keV
  - target density: ±3%
  - cell thickness uniformity: ±25μm

$|\Delta B_{\Lambda}^{sys.}| = 55$ keV

(T. Toyoda, "Basic design of gas targets for precise hypertriton mass measurement at JLab", Master's Thesis, Kyoto Univ. JFY2020)

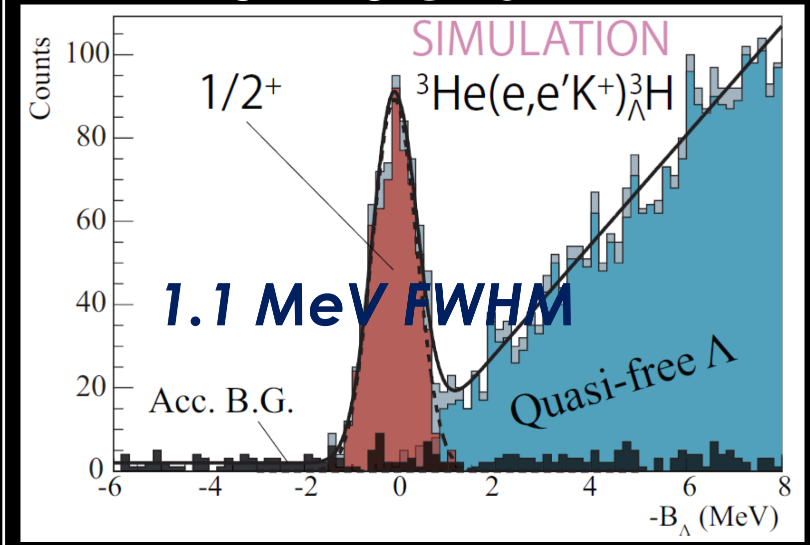
(*) **TG et al., NIMA 900 (2018) 69—83**

S/N comparison between Hall A and C

- Assumed that the e^+e^- backgrounds are perfectly rejected
- Expected rate (HES-HKS) @20uA (2.5 MHz @8uA, 52Cr in E05-115):
  - 2.2 MHz (^{3}He, 190+162 mg/cm^2) → coin = 1.5 kHz
  - 3.6 MHz (^{40}Ca, 100 mg/cm^2) → coin = 1.3 kHz
  - 55.7 MHz (^{208}Pb, 100 mg/cm^2) → **coin = 18.4 kHz**

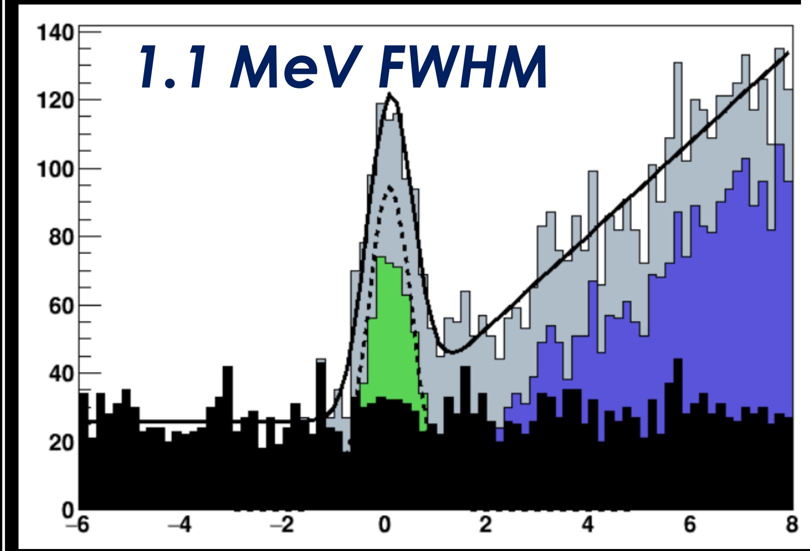
50 uA

HRS-HKS @Hall A

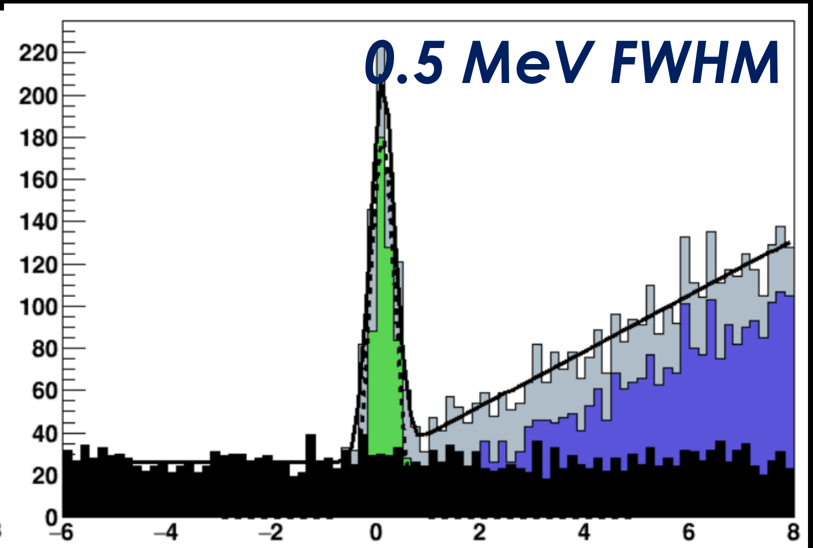


Stat. err. = 20 keV

S/N: HES-HKS @Hall C, 20 uA



Stat. err. < 30 keV



Stat. err. < 20 keV