APFB2020, Kanazawa, Japan, Mar 1—5, 2021

Lambda hypertriton binding energy measurement at Jefferson Lab

Graduate School of Science, Kyoto University, Japan

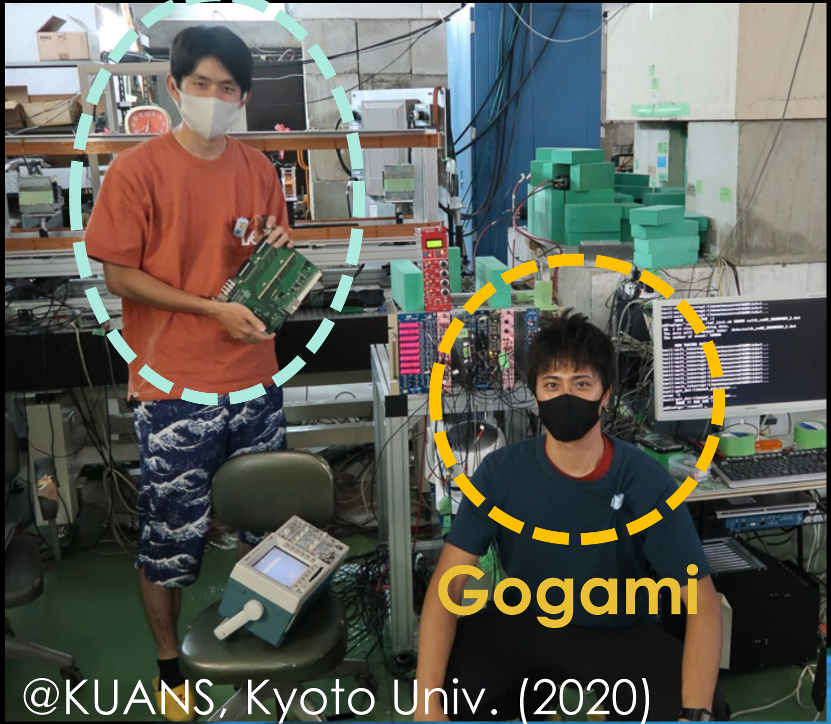
Toshiyuki Gogami

for the ***JLab Hypernuclear Collaboration***

Mar 2, 2021

京都大学
KYOTO UNIVERSITY

Talk about the trigger system by Katayama (Kyoto Univ.), Room C at 15:00 on Mar 2



科研費 KAKENHI
SPIRITS
SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

CONTENTS

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

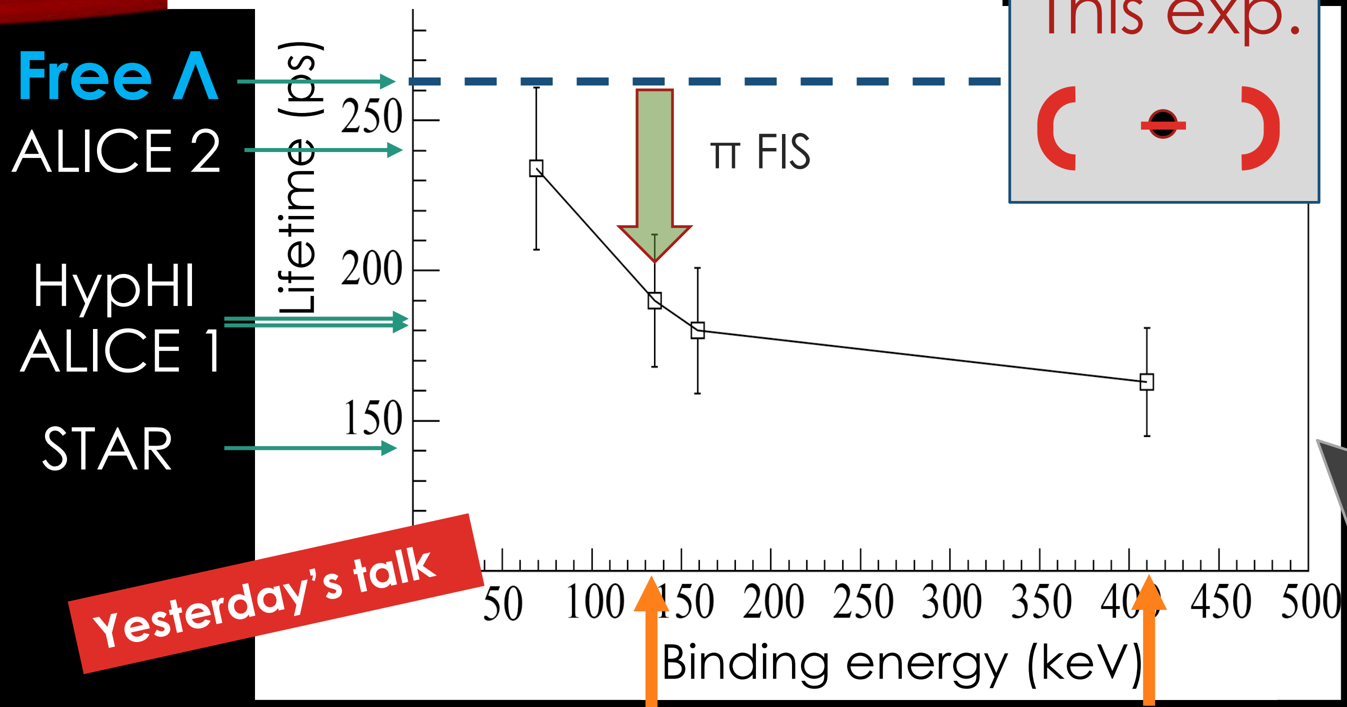
$\tau = (0.5\sim 0.92)\,\tau_\Lambda$
(HypHI, STAR, ALICE)

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)

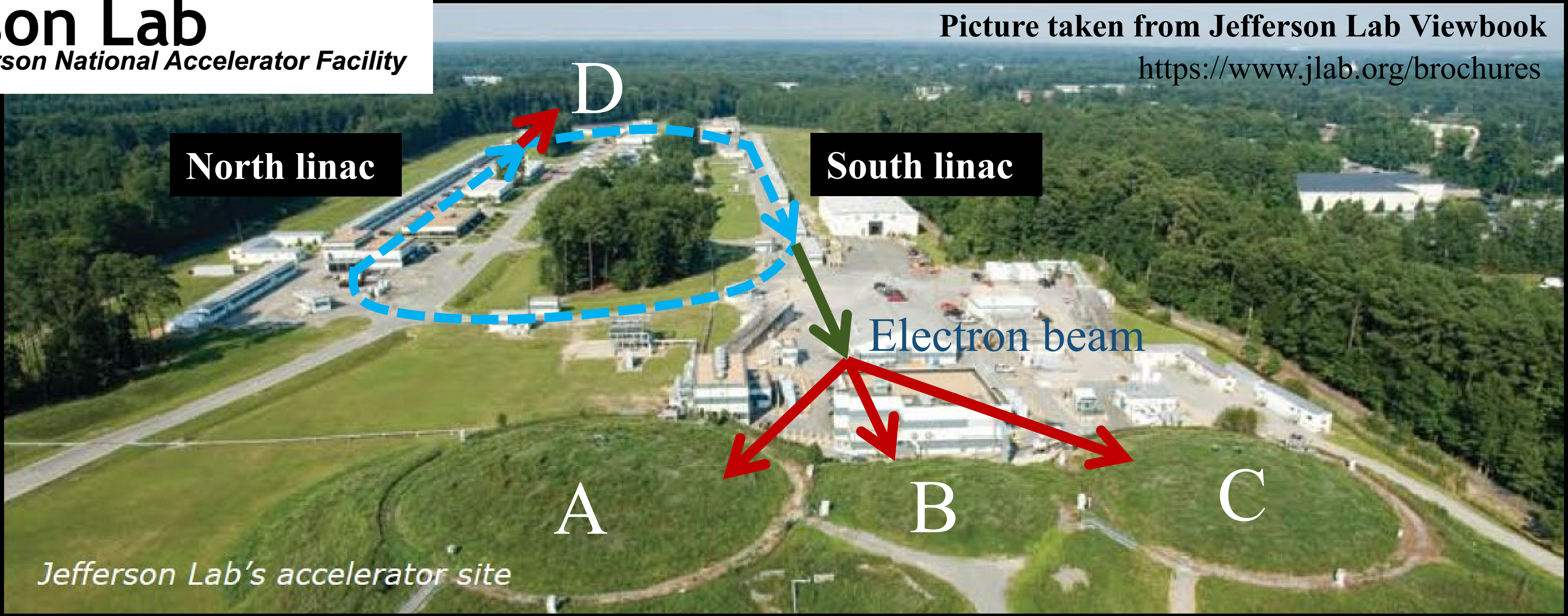
$\propto \sqrt{B_\Lambda}$

Proposed experiment (C12-19-002)
$|\Delta B^{\mathrm{stat.}}| = 20$ keV, $|\Delta B^{\mathrm{sys.}}| = 55$ keV

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

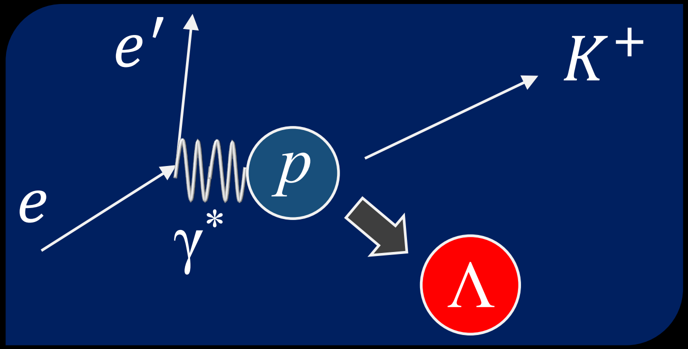
CEBAF AT JEFFERSON LAB

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

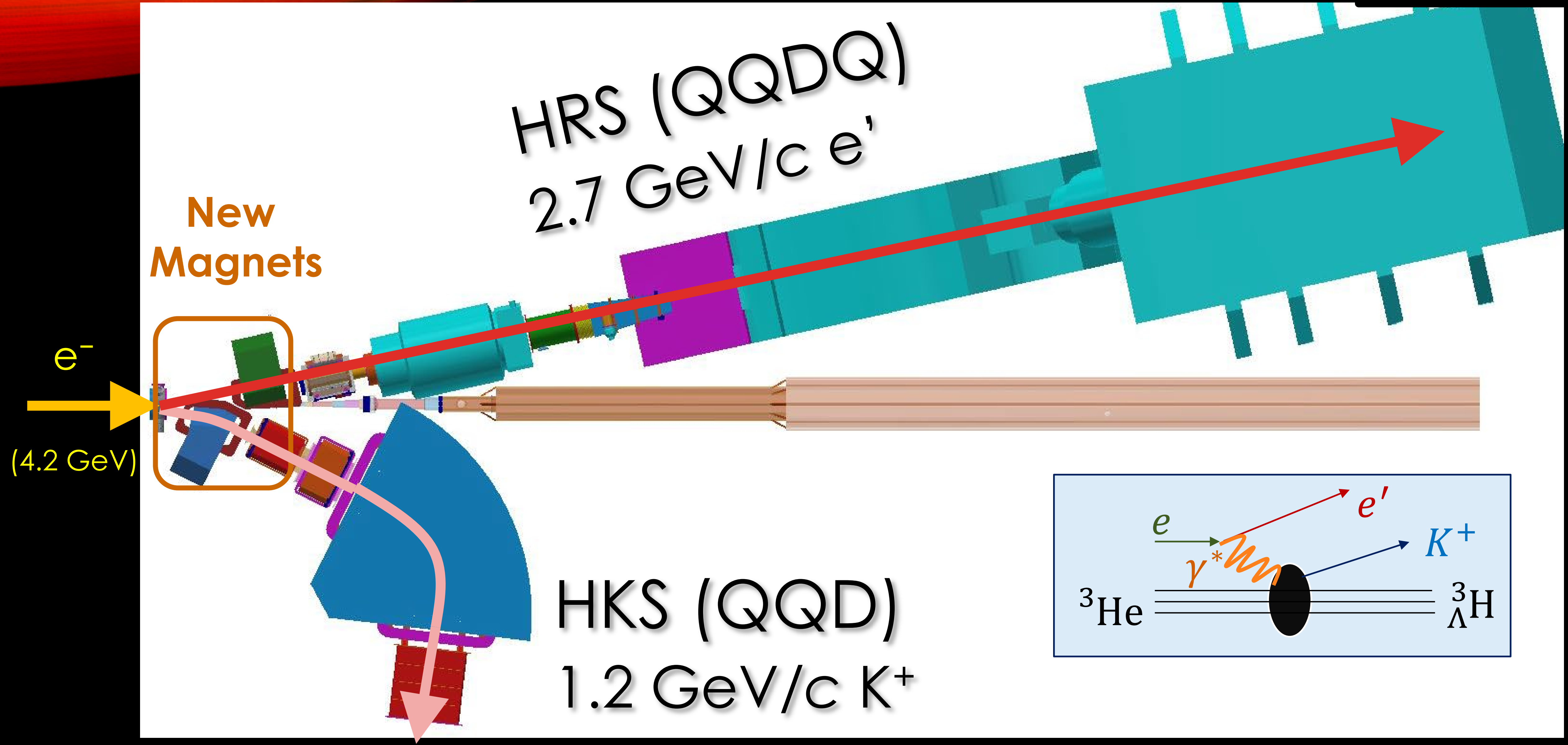
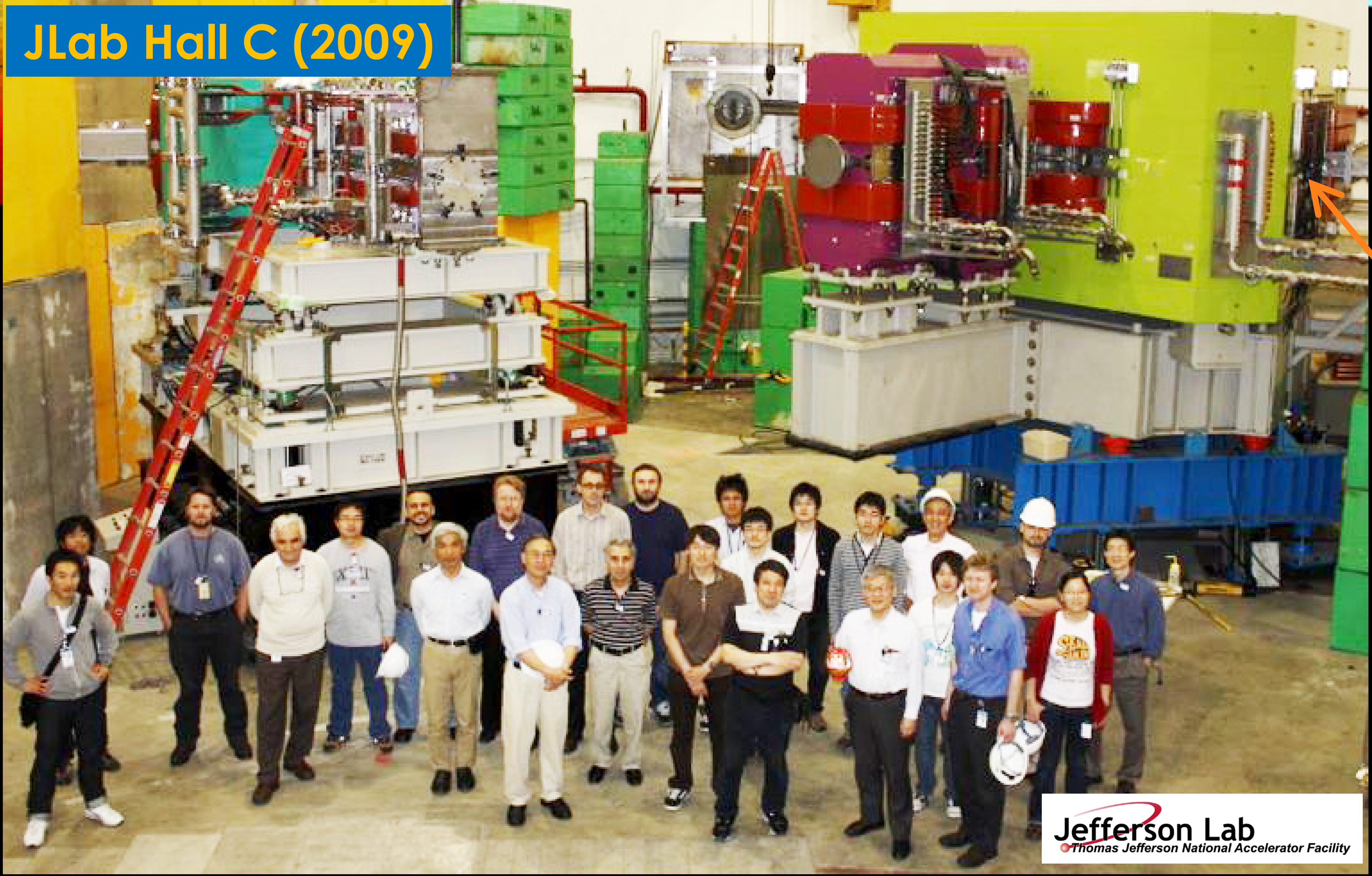


Figure taken from Sho's slides (Tohoku Univ.)

JLab Hall C (2009)



HKS

Y. Fujii et al., NIMA 795, 351—363 (2015).

- L. Tang et al., PRC 90, 034320 (2014).
- TG et al., PRC 94, 02132(R) (2016).
- TG et al., PRC 93, 034314 (2016).
- TG et al., Submitted to PRC (2021); https://arxiv.org/abs/2102.04437

LHRS


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

TRIGGER RATE ESTIMATION

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

Talk about the trigger system by Katayama (Kyoto Univ.), Room C at 15:00 on Mar 2

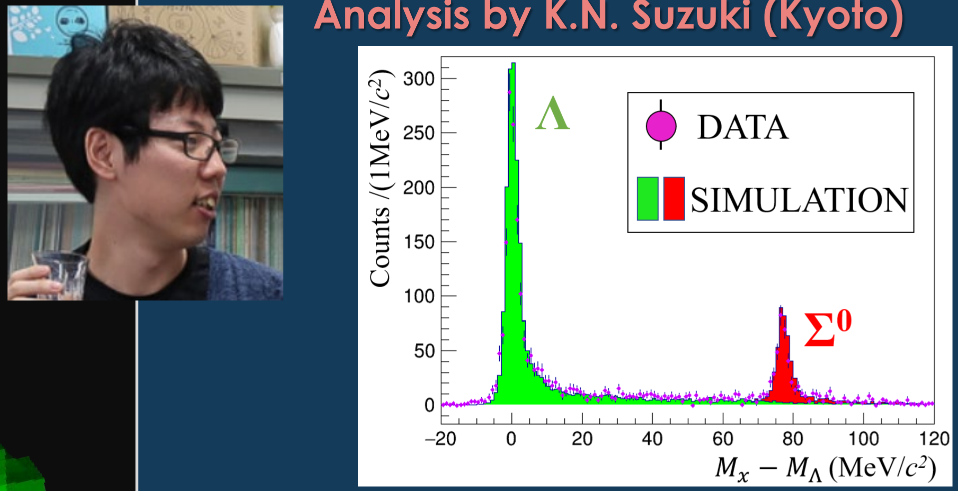
(K. Katayama, "Development of HRS-HKS coincidence trigger with FPGA - Precise Hypernuclear Spectroscopy at JLab -", Master's Thesis, Kyoto Univ. JFY2020)

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	37+160	50	71.8	95	170	2.8	**0.13**
^{4}He+^{27}Al	74+160	50	74.0	112	197	3.4	**0.16**

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

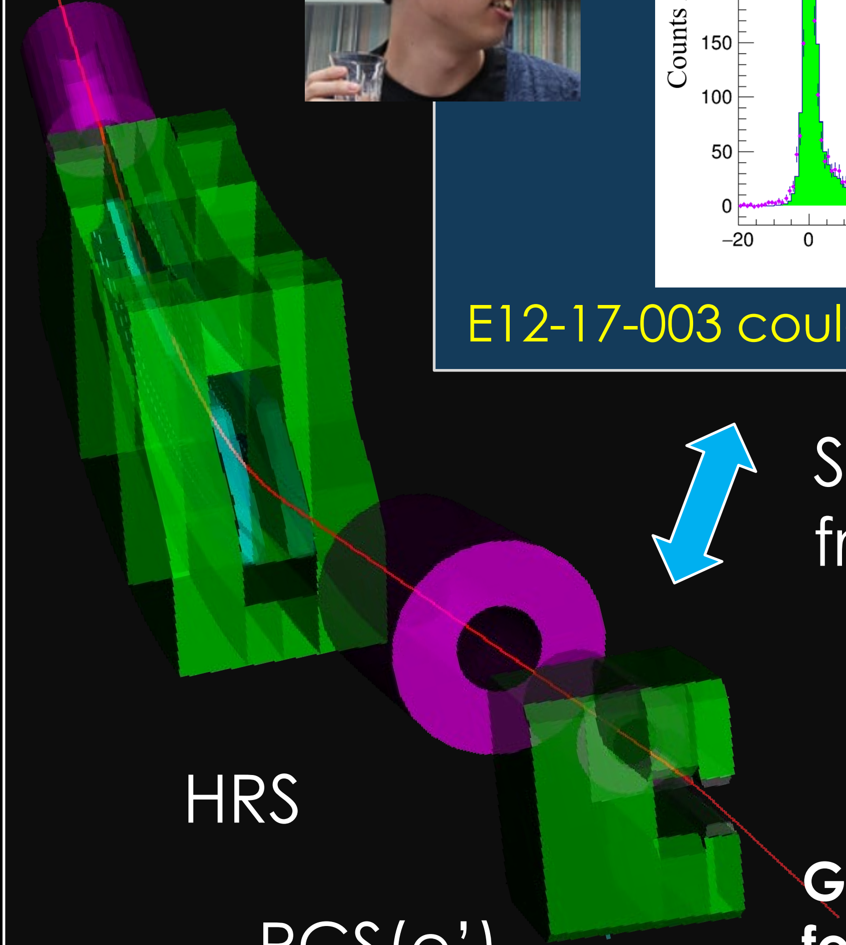
EXPECTED MISSING MASS RESOLUTION

Analysis by K.N. Suzuki (Kyoto)



E12-17-003 could be reproduced

Same framework



Geant4 simulation for C12-19-002

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

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

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

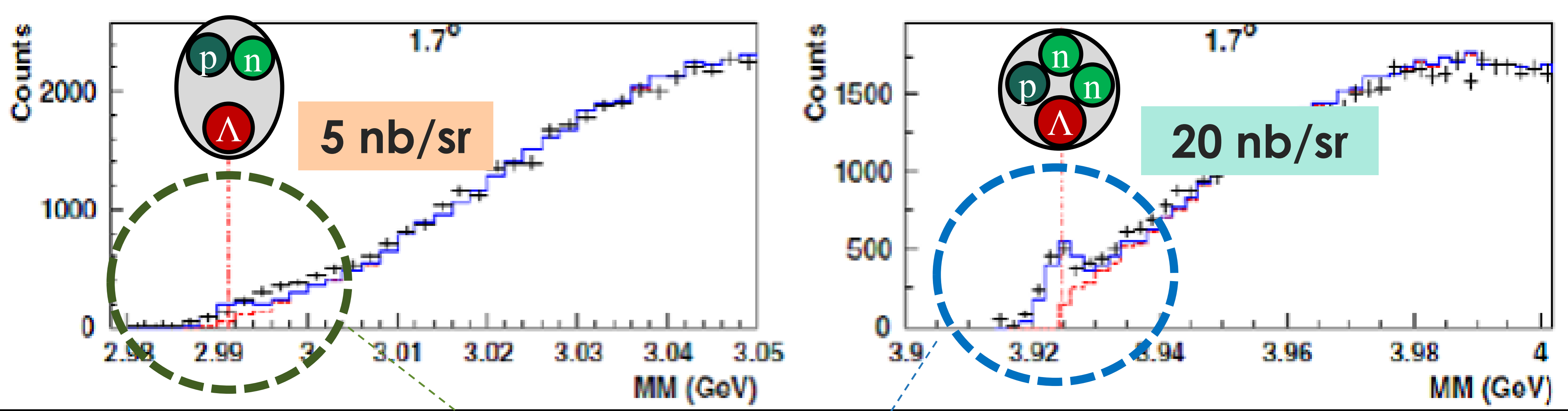
Spectrometer	$\Delta p/p$ (FWHM)
HRS (e')	3.2×10^{-4}
HKS (K+)	5.7×10^{-4}

↓

$\Delta M_{\mathrm{HYP}} = 1.1\ \mathrm{MeV}/c^2$ (FWHM)

YIELD ESTIMATION

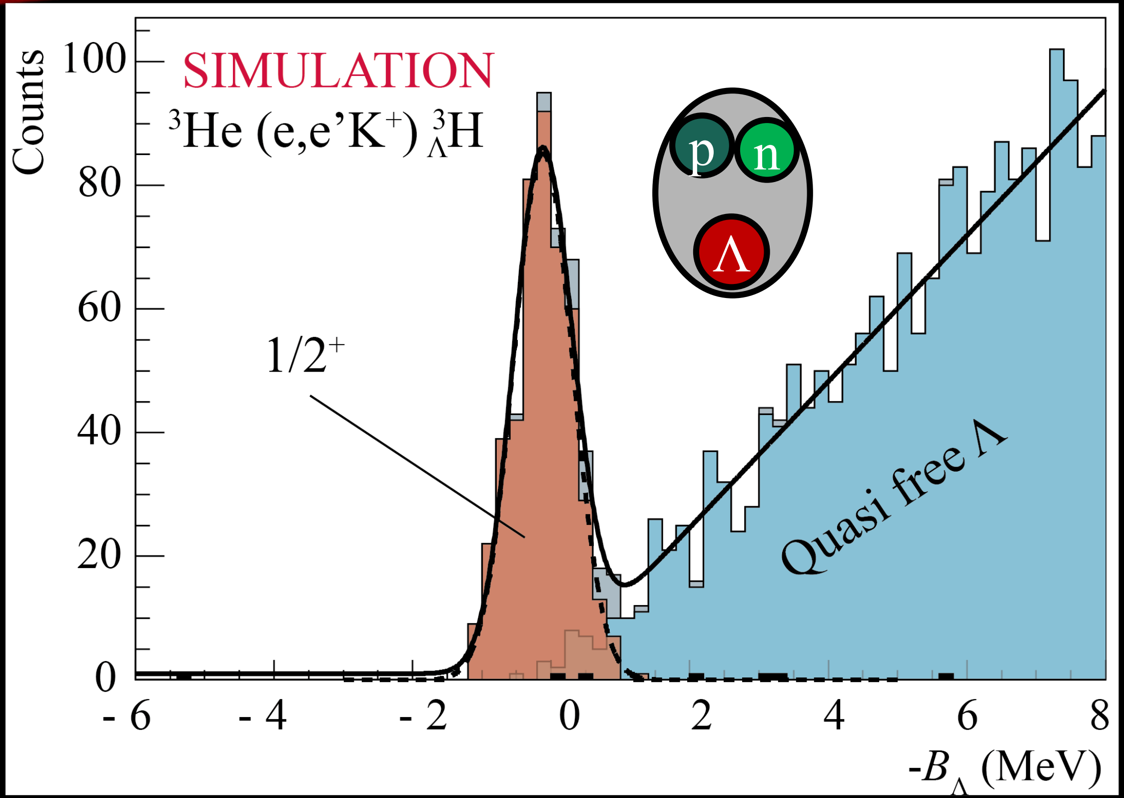
F. Dohrmann et al., *Phys. Rev. Lett.* **93**, 242501 (2004).

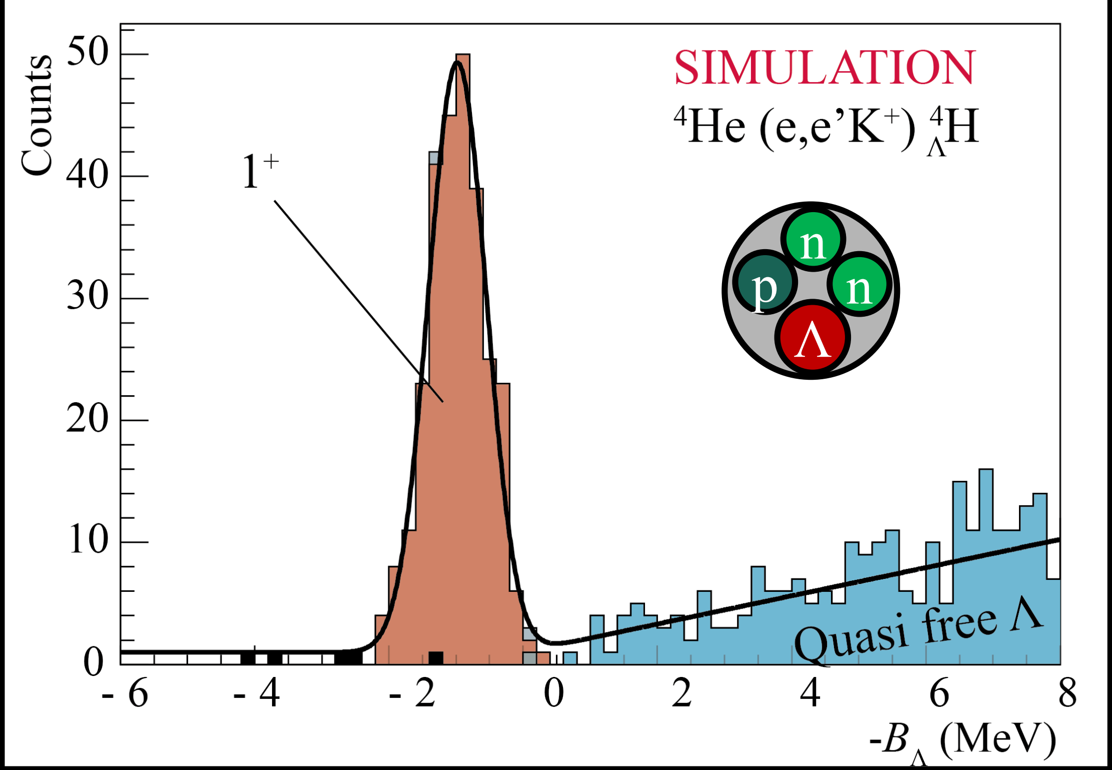


Product	Target (mg/cm^2)	I_{beam} (μA)	CS (nb/sr)	Yield / day	Beamtime (day)	**Total yield**
${}^{3}_{\Lambda}H$	${}^{3}He$ (37)	50	5	23	20	**464**
${}^{4}_{\Lambda}H$	${}^{4}He$ (74)		20	139	2	**278**

VP flux = 2×10^{-5} (/e), $\epsilon_{\text{det}} = 0.75, f_{\text{density}} = 0.85, f_{Kdecay} = 0.26, \Omega_K = 7$ msr

EXPECTED SPECTRA AND STATISTICAL ERRORS





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

$\left|\Delta B_{\Lambda}^{\text{stat.}}\right| = 30$ keV

➡ Hypertriton Puzzle + ΛN int.
(g.s. or excited states)

➡ ΛN CSB in A = 4

CALIBRATIONS AND A SYSTEMATIC ERROR ON B_Λ

Calibration	Target + Sieve Slit	Reaction	z_t range (mm)	Beamtime (day)	Remarks
Mom. + z_t	H	$p(e,e'K^+)\Lambda,\Sigma^0$	$-115 < z_t < 115$	1	Λ: 6100, Σ^0: 2030
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	$^{3,4}_{\Lambda}H$	$-100 < z_t < 100$	22	

Major contributions to a systematic error on B_Λ

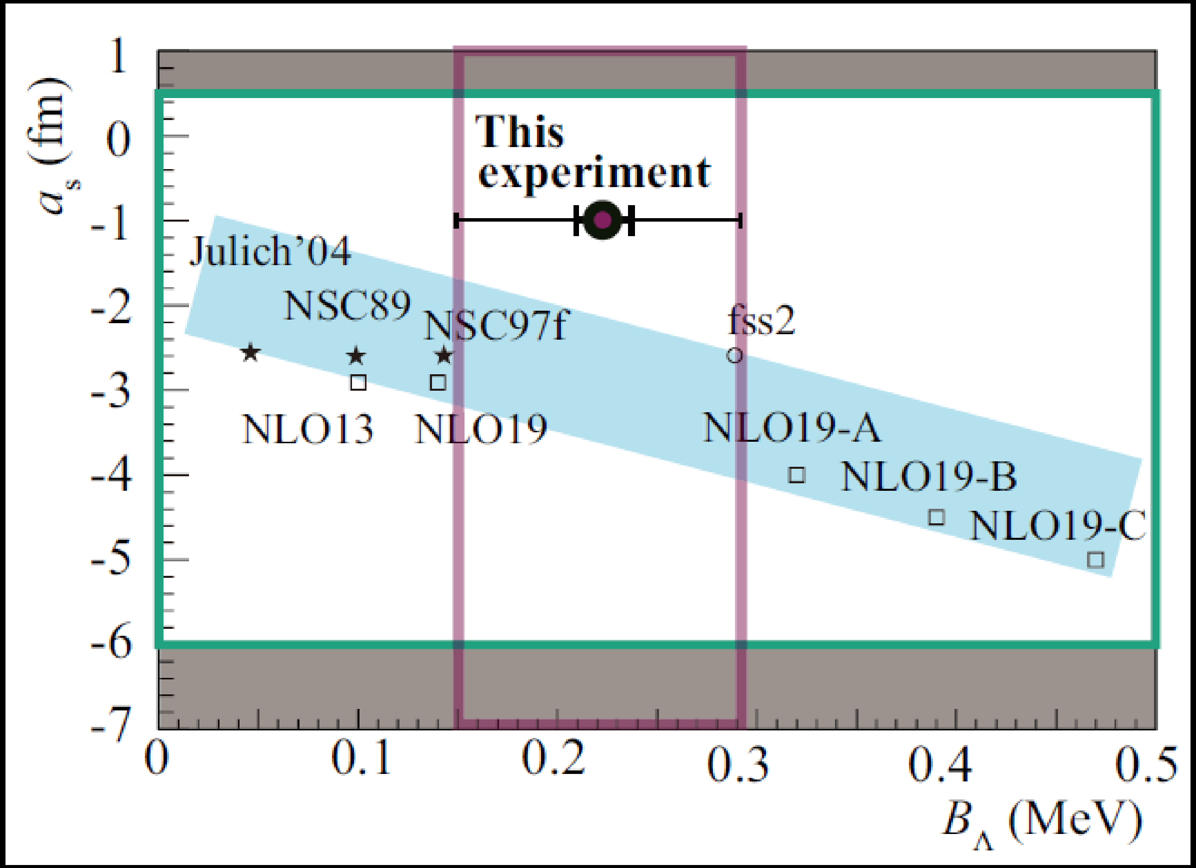
- Energy scale calibration(*) : ± 50 keV
- Energy loss correction: ± 23 keV
  - target density $|\Delta d| = 3\%$
  - cell thickness uniformity $|\Delta t| = 10\%$

→ $|\Delta B_\Lambda^{sys.}| = 55$ 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

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



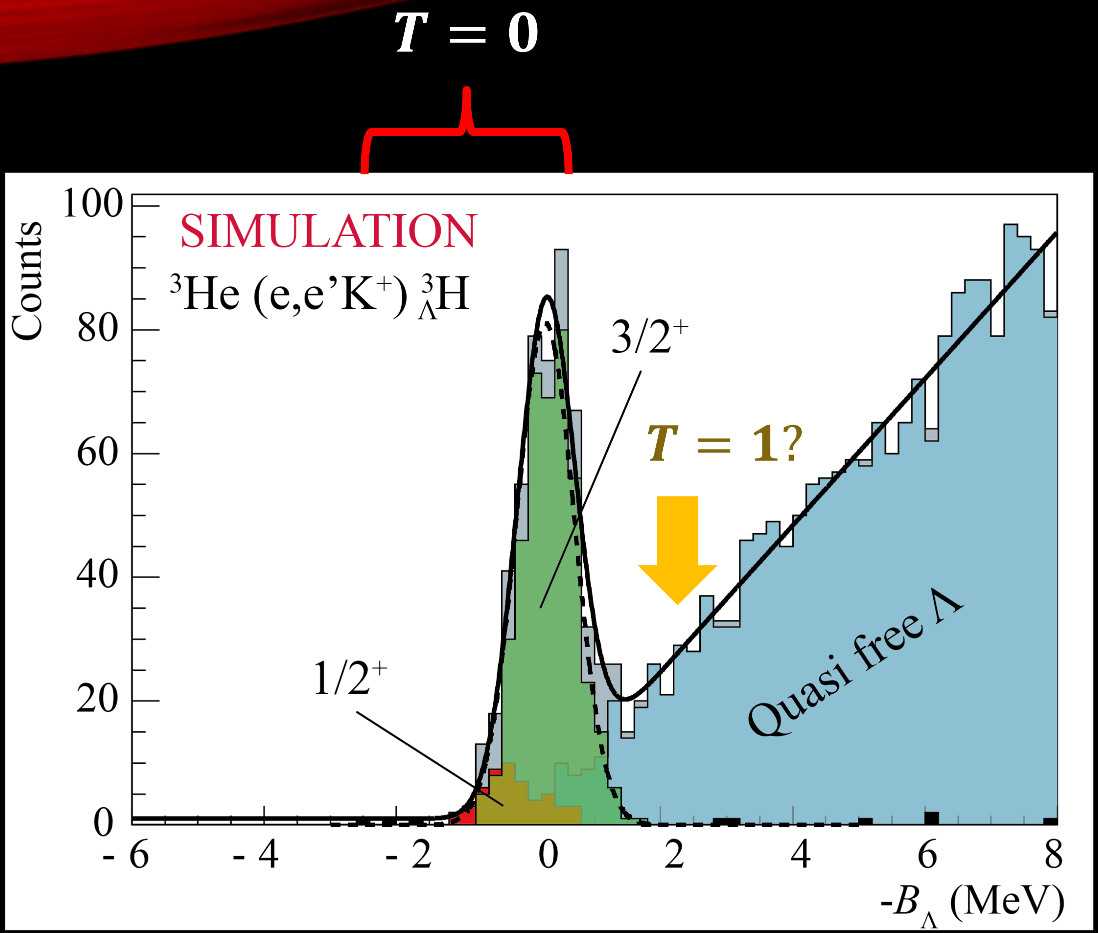
Hypertriton Puzzle

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

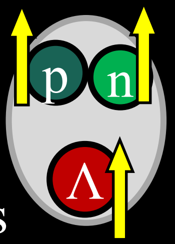
ΛN interaction

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

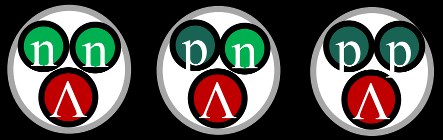


${}^{3}_{\Lambda}\mathrm{H}\left(T=0,\ J^{\pi}=3/2^{+}\right)$



- 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**

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



- 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 → $\left|\Delta B_{\Lambda}^{\mathrm{stat.}}\right| \sim 70$ 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

HRS-HKS @ Hall A (JLab C12-19-002, 2023~)

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

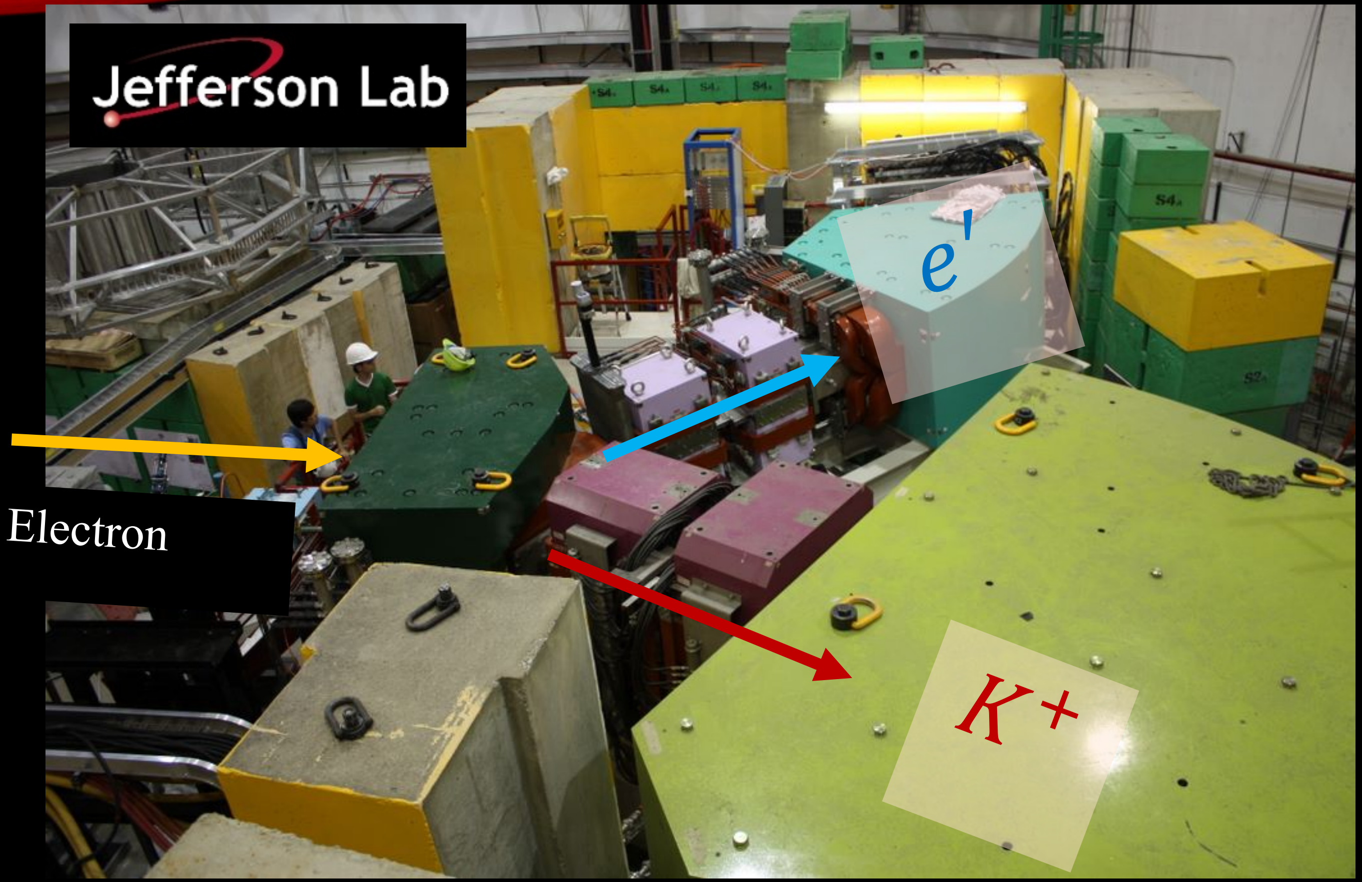
$$\Delta B_{\Lambda}^{\mathrm{tot.}} = \sqrt{\left|\Delta B_{\Lambda}^{\mathrm{sys.}}\right|^2 + \left|\Delta B_{\Lambda}^{\mathrm{stat.}}\right|^2} < 70\ \mathrm{keV}$$

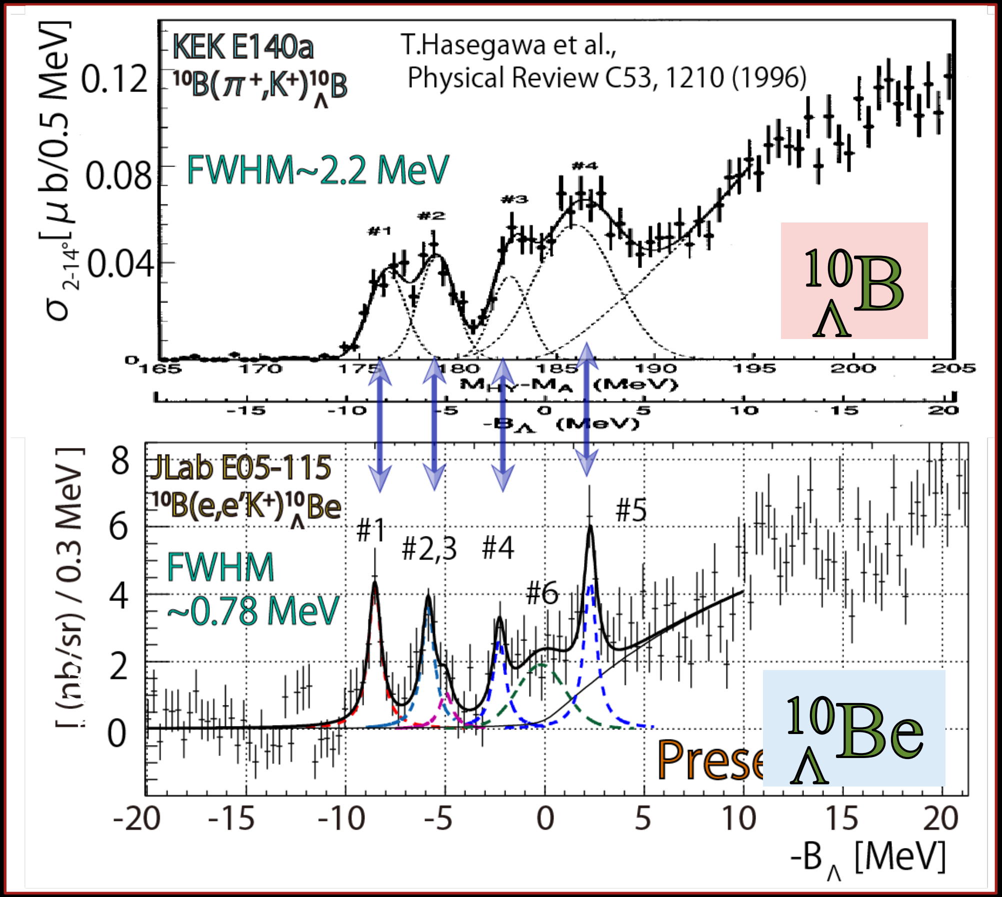
➔ Hypertriton Puzzle / Charge Symmetry Breaking

Reference:
TG et al., "Accurate Λ hypernuclear spectroscopy with electromagnetic probe at Jefferson Lab ", AIP Conf. Proc. **2319**, 080019 (2021); https://doi.org/10.1063/5.0037353

BACKUP

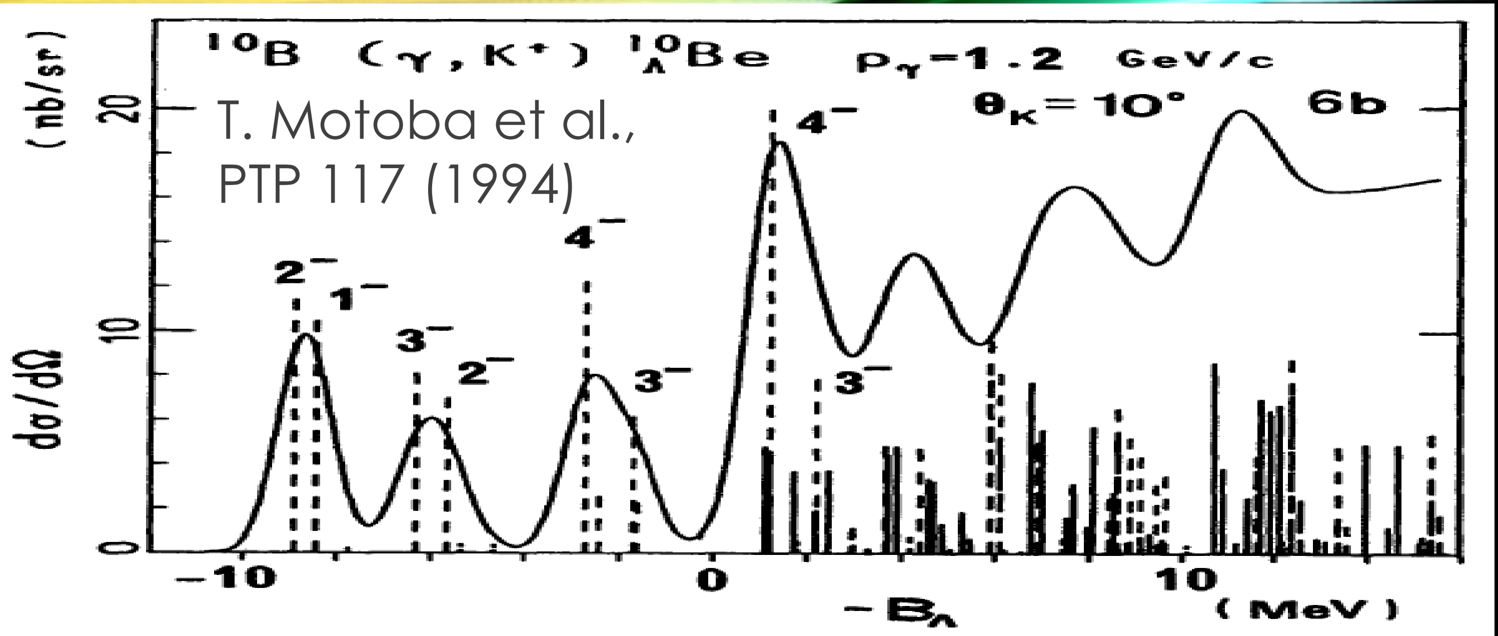
High precision measurement $^{10}_{\Lambda}B$ and $^{10}_{\Lambda}Be$

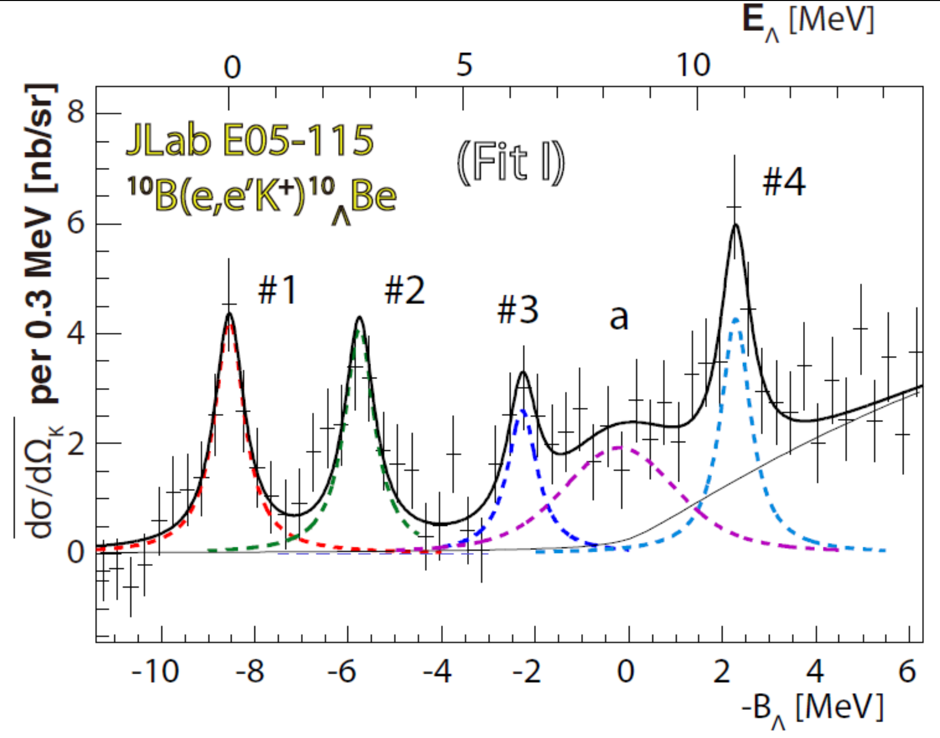




RPC 93 (2016) 034314.

- ✓ High resolution
- ✓ High accuracy





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

What's surplus, a ?

→ Conventional shell model did not predict the state

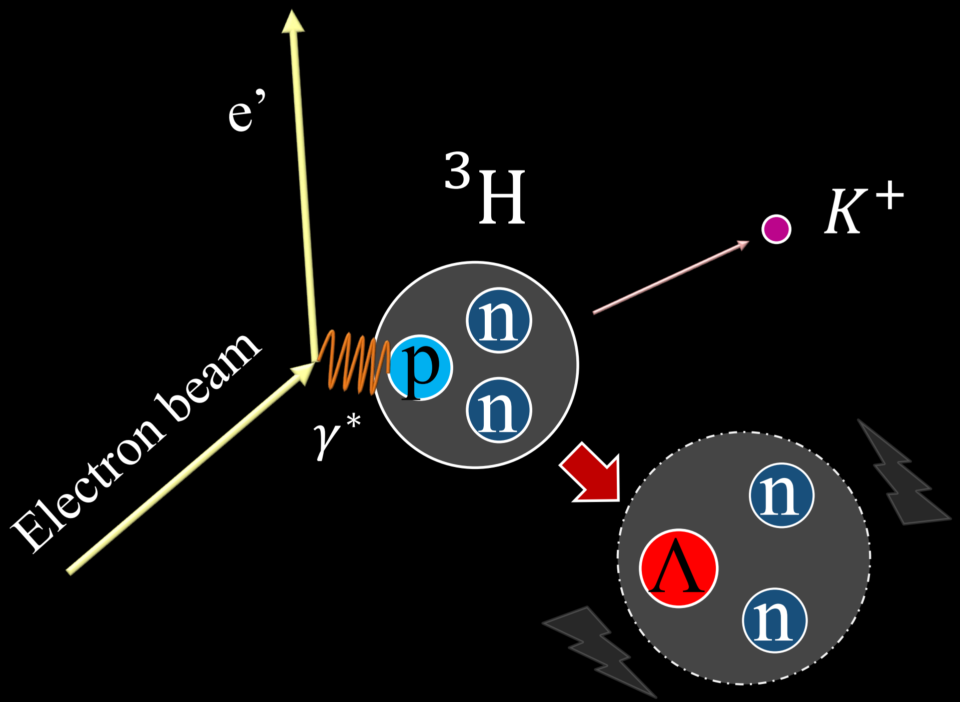
→ It was found that model space needs to be extended (A. Umeya et al., JPS Conf. Proc. 26, 023016 (2019)).

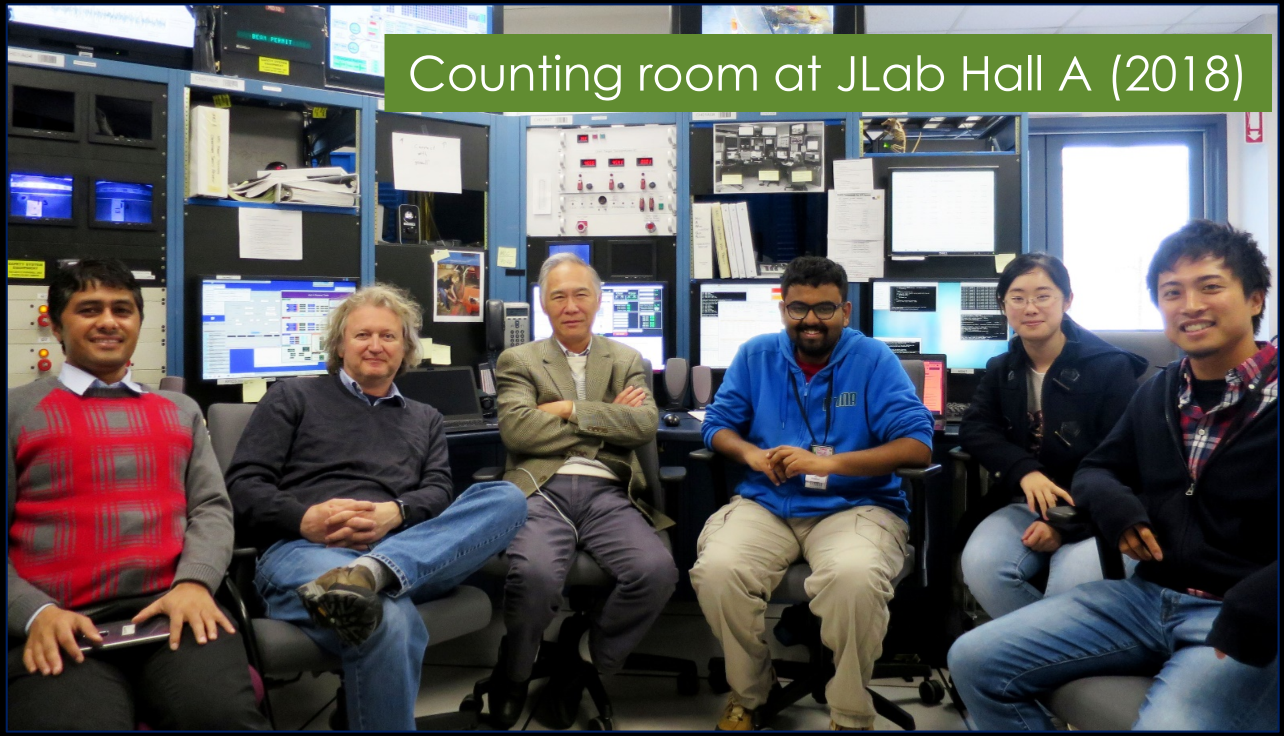
E12-17-003 (nnΛ)

nnΛ search experiment at JLab

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

E12-17-003 (Oct 30—Nov 25, 2018)





We have sensitivity to both bound and resonant states

STUDENTS WHO ANALYZE DATA

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

Talked Yesterday

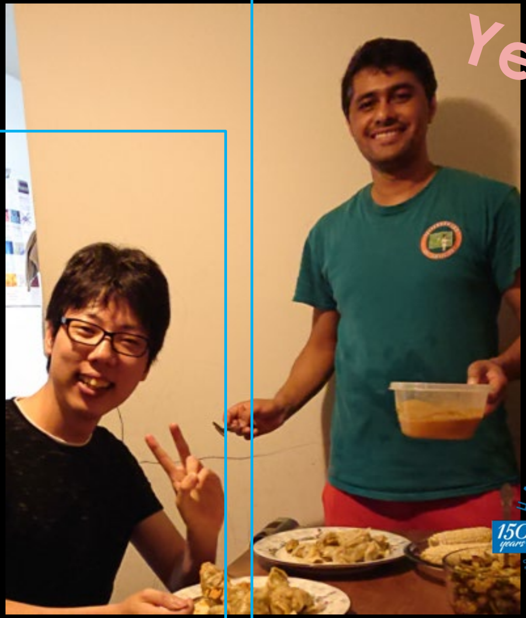
K. Itabashi

K. Okuyama

東北大学

Tohoku Univ., Japan

E. Umezaki



K.N. Suzuki

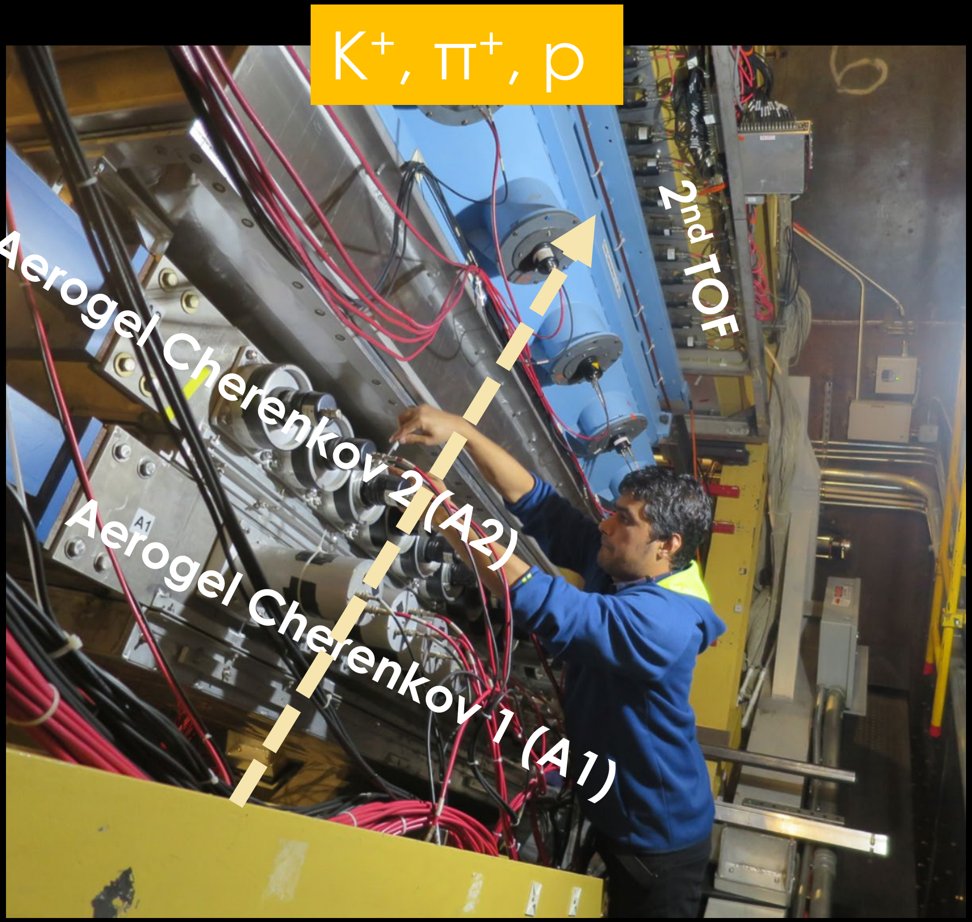
Kyoto Univ., Japan

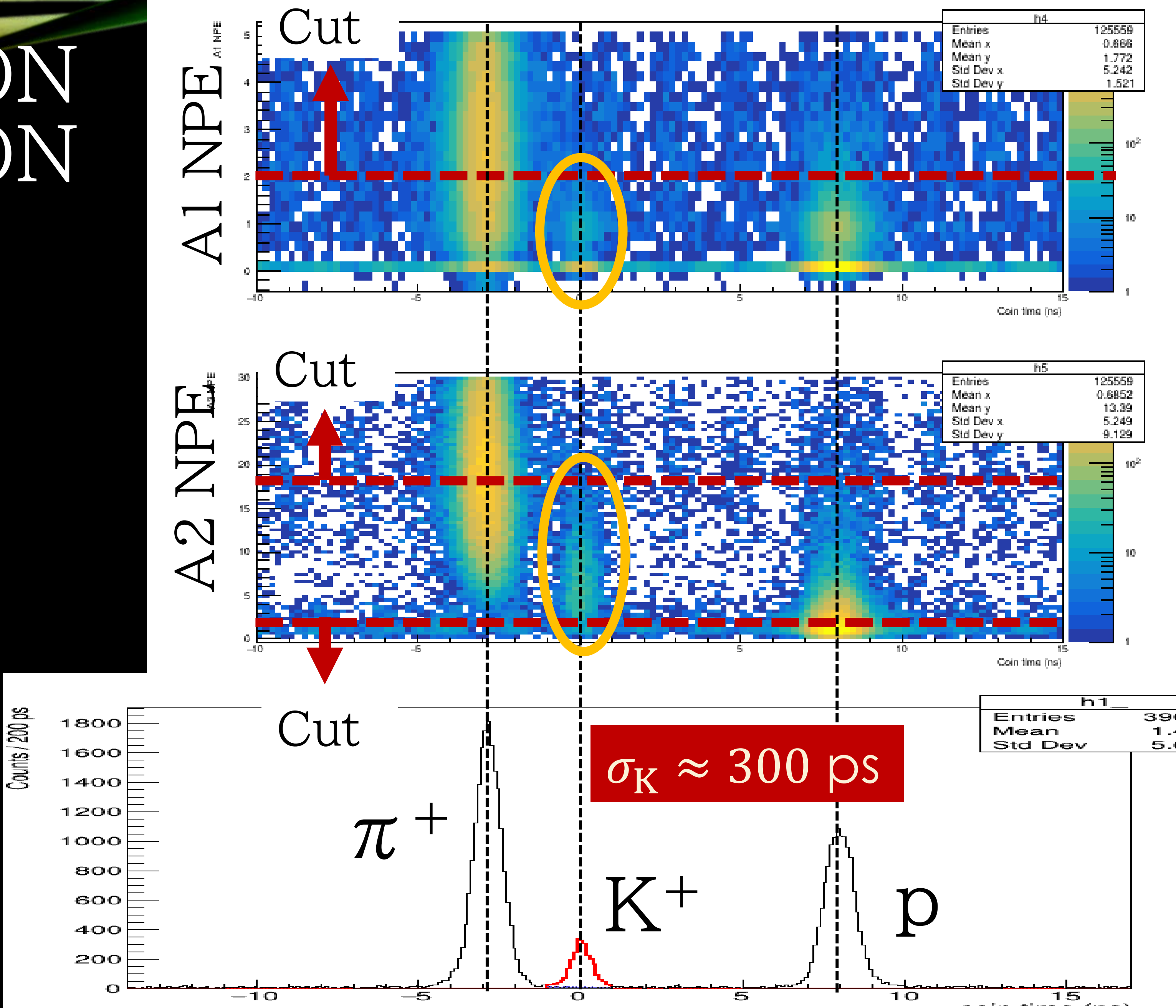
B. Pandey

Hampton Univ., US

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

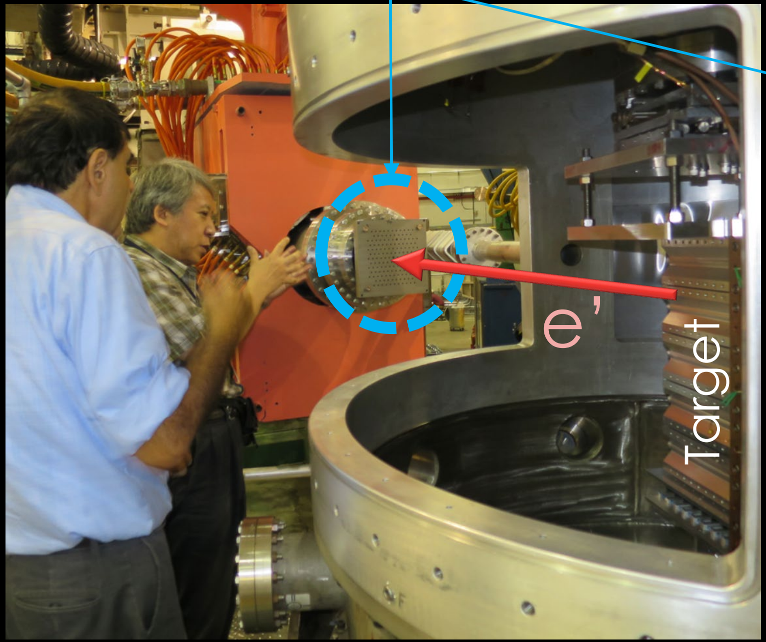
KAON IDENTIFICATION





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

CALIBRATION



5th order matrix (z_t<2)

Angle calibration

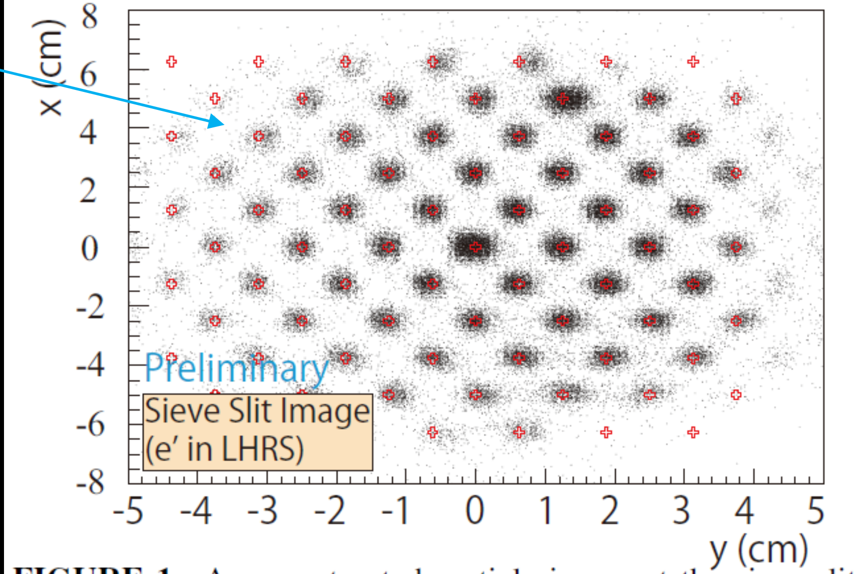


FIGURE 1. A reconstructed particle image at the sieve slit for the sieve slit data in LHRS (e'). Matrix parameters for reconstruction of angle at target were calibrated by using the sieve slit image. π^-s were eliminated by an event selection of light yield of a gas Cherenkov detector (CO_2) [41] installed in LHRS.

5th order matrix (z_t<2)

Momentum calibration

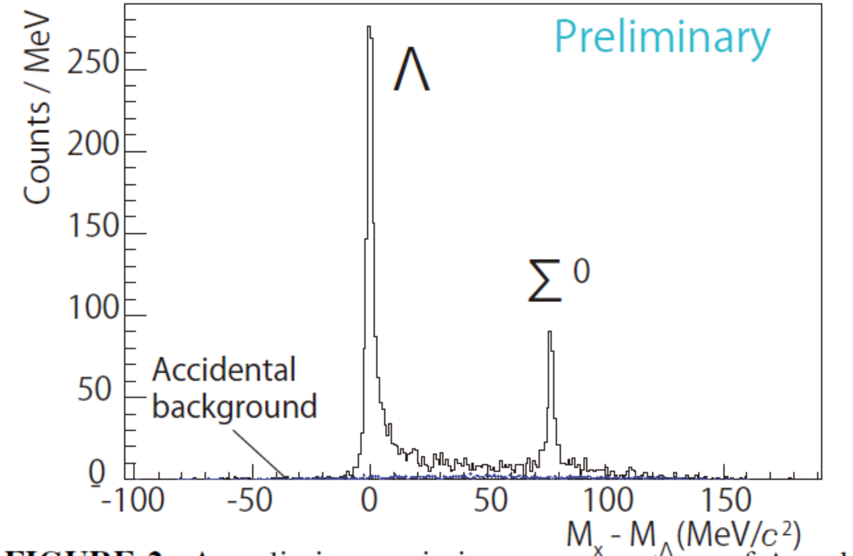
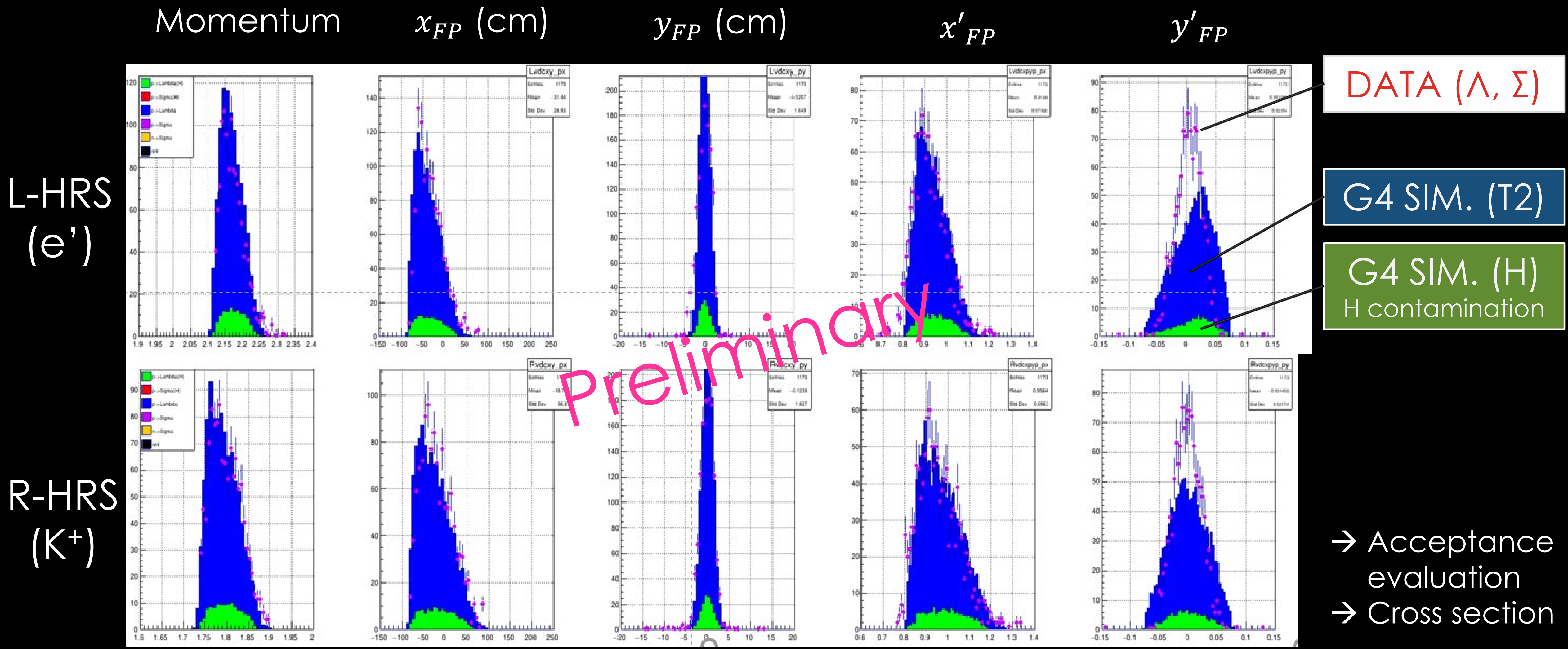


FIGURE 2. A preliminary missing mass spectrum of Λ and Σ^0 from a 71-mg/cm^2 H_2 gas target for a kinematics condition of M-kine in JLab E12-17-003. The beam charge on the H_2 target with M-Kine was about 2.5 C. The mass resolution is about 3.5 MeV/c^2 (FWHM).

TG et al., "Accurate Λ hypernuclear spectroscopy with electromagnetic probe at Jefferson Lab ", AIP Conf. Proc. **2319**, 080019 (2021); https://doi.org/10.1063/5.0037353

Data vs. Geant4 (sim) for T_2 target

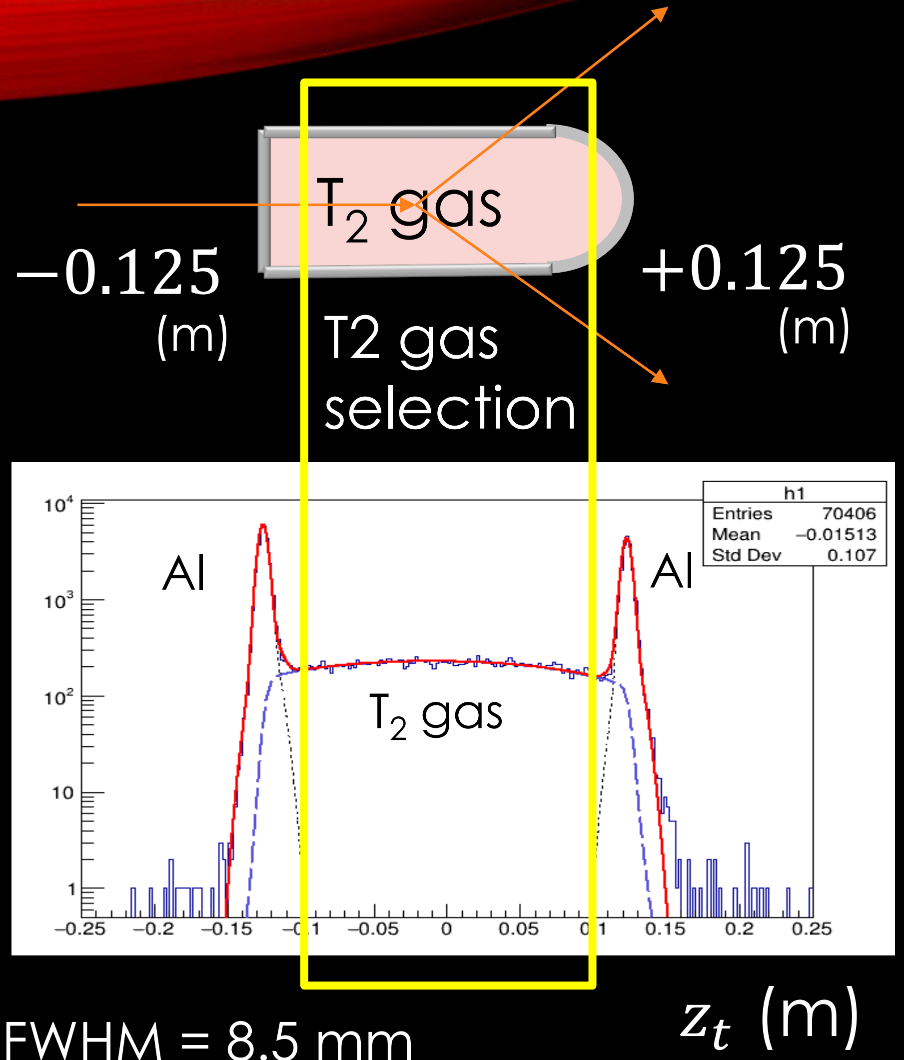


→ Acceptance evaluation

→ Cross section

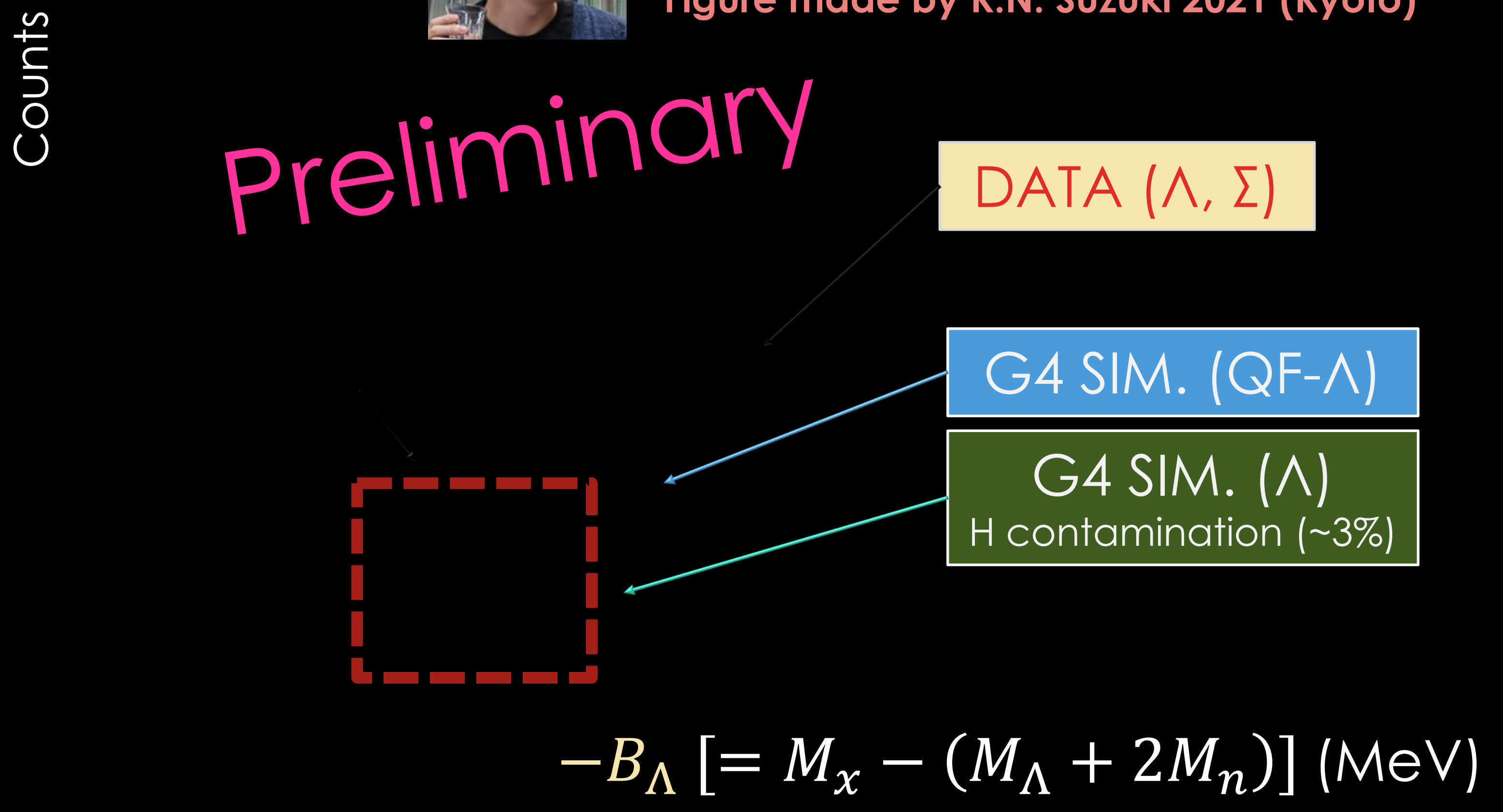
Simulation by K.N. Suzuki (Kyoto Univ., 2020)

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



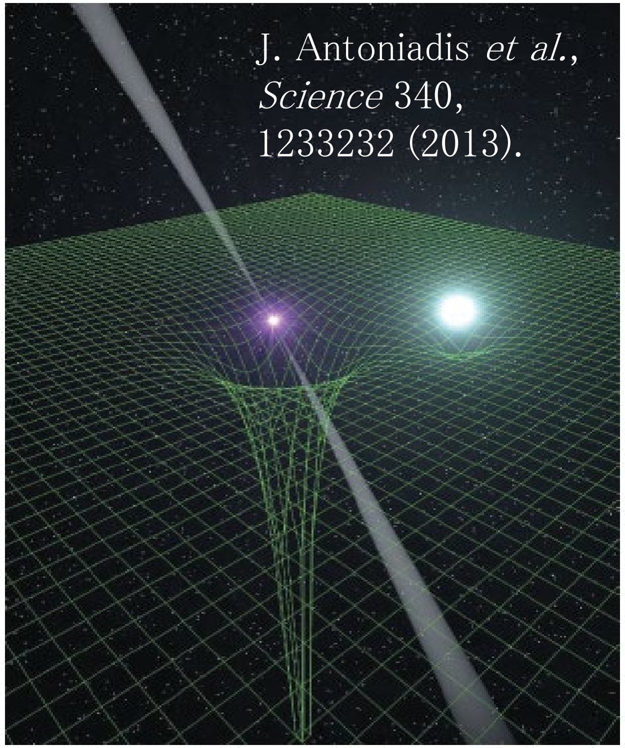
FWHM = 8.5 mm
(by two arms)

Figure made by K.N. Suzuki 2021 (Kyoto)

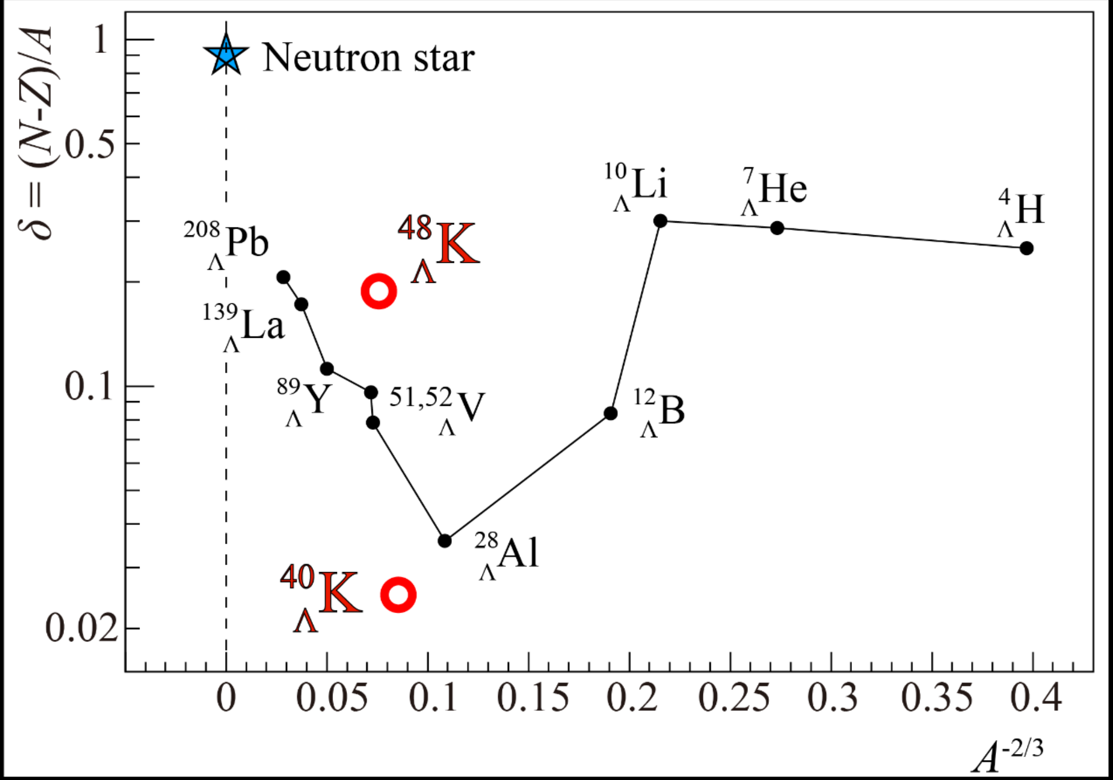


E12-15-008 ($^{40,48}_{\Lambda}$K)

Study of isospin dependence through precise measurement of $^{40,48}\mathrm{Ca}(e,e'K^+)^{40,48}_{\Lambda}\mathrm{K}$



Artist's impression of the PSR J0348+0432 system. The compact pulsar (with beams of radio emission) produces a strong distortion of spacetime (illustrated by the green mesh). Conversely, spacetime around its white dwarf com-



Neutron star:

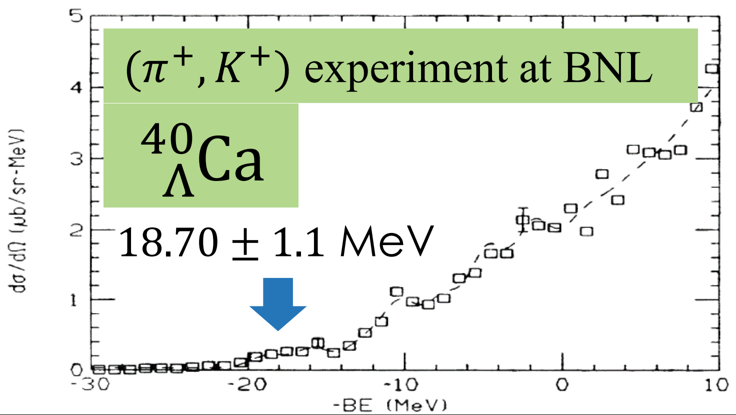
- ✓ Very dense nuclear matter ($\delta = \frac{N-Z}{A} \sim 0.9$)
- ✓ $\leq 2M_{\odot} \nLeftrightarrow \Lambda$ inclusion (hyperon puzzle)

$B_{\Lambda}(^{40,48}_{\Lambda}\mathrm{K})$ with high precision

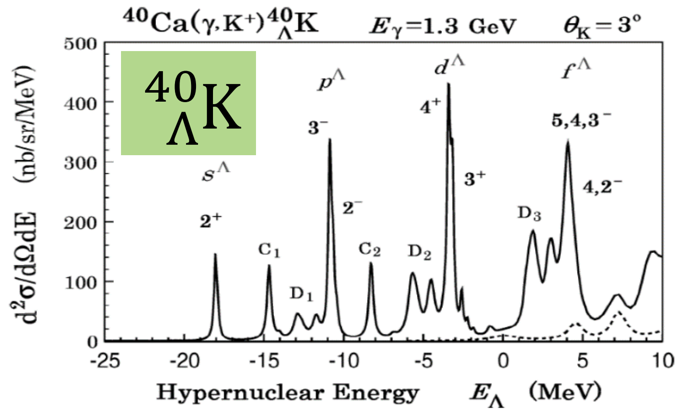
→ **Isospin dependence of the $NN\Lambda$ interaction**

ΛNN isospin dependence

P. H. Pile et al., Phys. Rev. Lett. 66, 20 (1991).

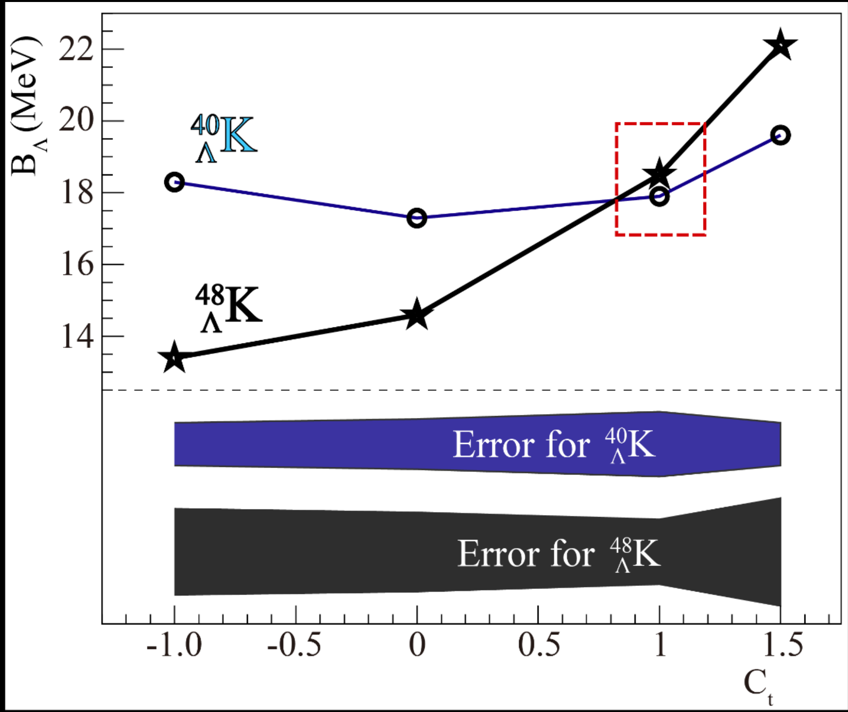


T. Motoba et al., Prog. Theor. Phys. Suppl., 185, 224 (2010).



AFDMC calculation

(F. Paderiva et al., arXiv:1506.04042v1 (2015))



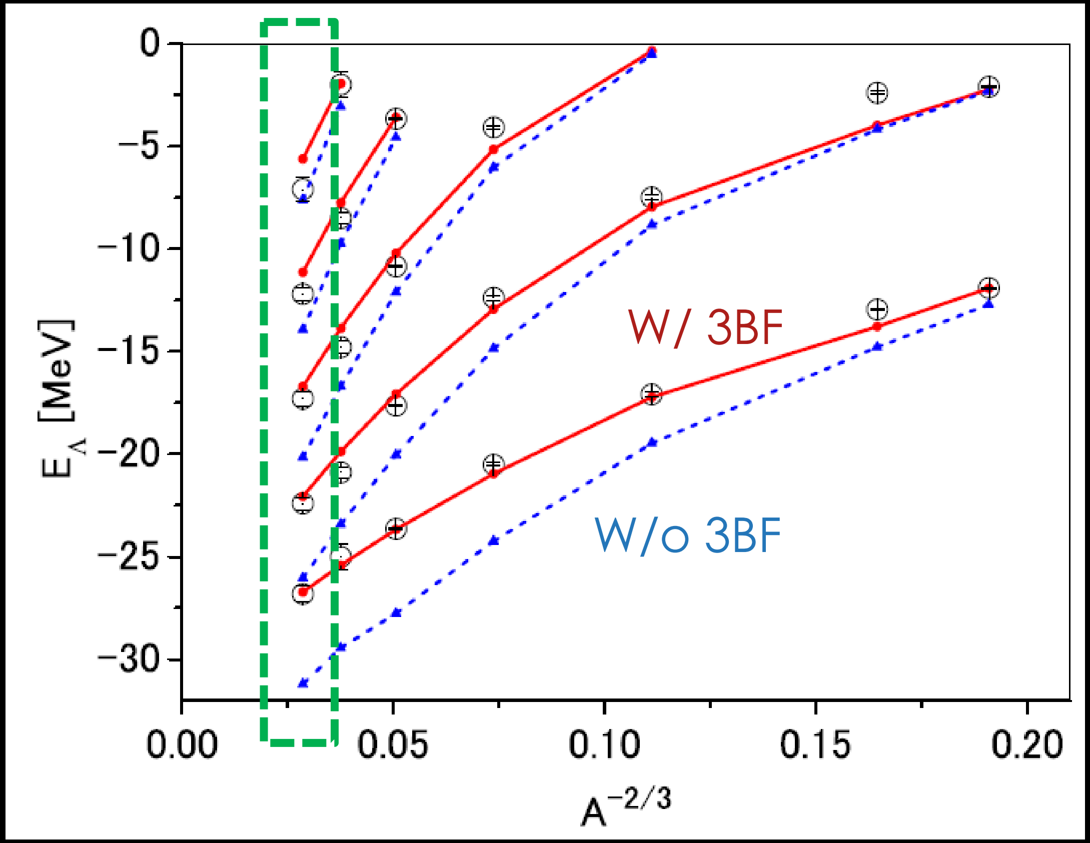
C_t: Strength factor for the isospin triplet term

$B_\Lambda(^{40}_{\Lambda}\mathrm{K}) - B_\Lambda(^{48}_{\Lambda}\mathrm{K})$
with < **100 keV accuracy**
→ Insights for the isospin dependence of ΛNN force

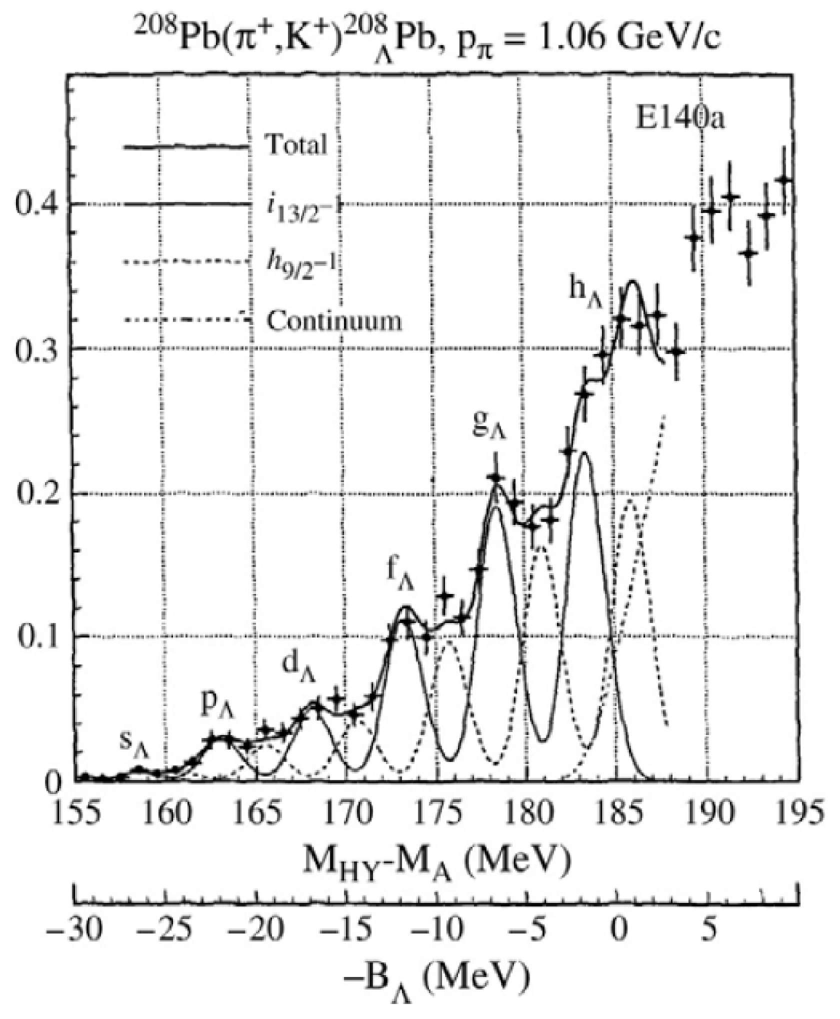
E12-20-013 ($^{208}_{\Lambda}\mathrm{Tl}$)

THREE BODY FORCE

ESC16+ / ESC16



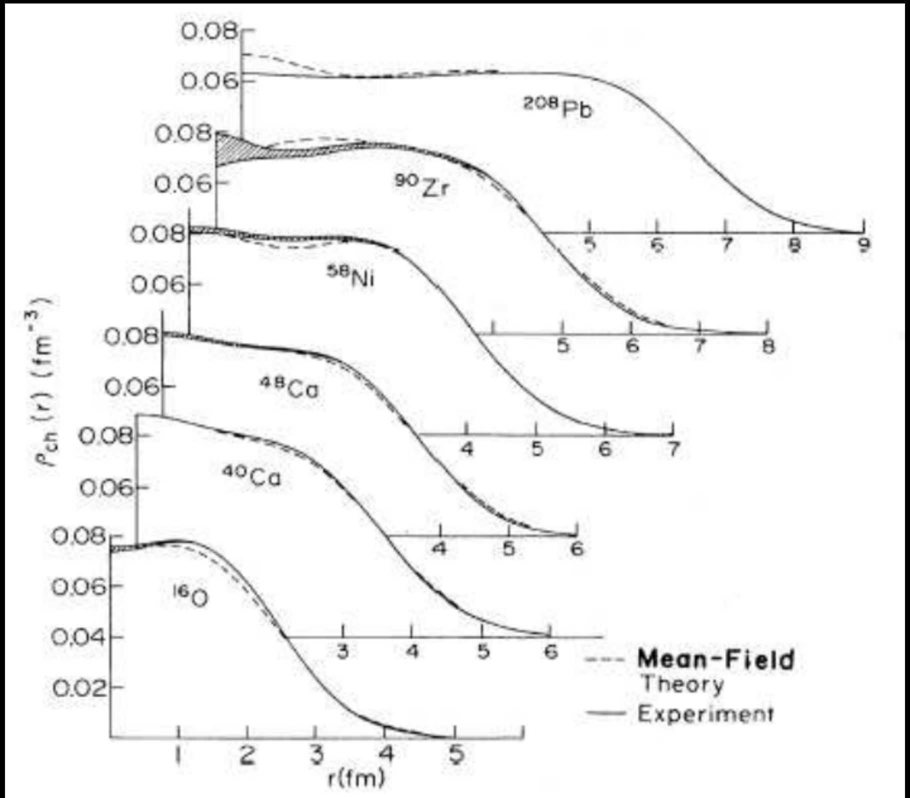
M. M. Nagels et al., Phys. Rev. C **99**, 044003 (2019)



T. Hasegawa et al., Phys. Rev. C 53 (1996) 1210.

Λ in (almost) nuclear matter

B. Frois and C.N. Papanicolas, Ann. Rev. Nucl. Part. Sci. 37, 133 (1987)

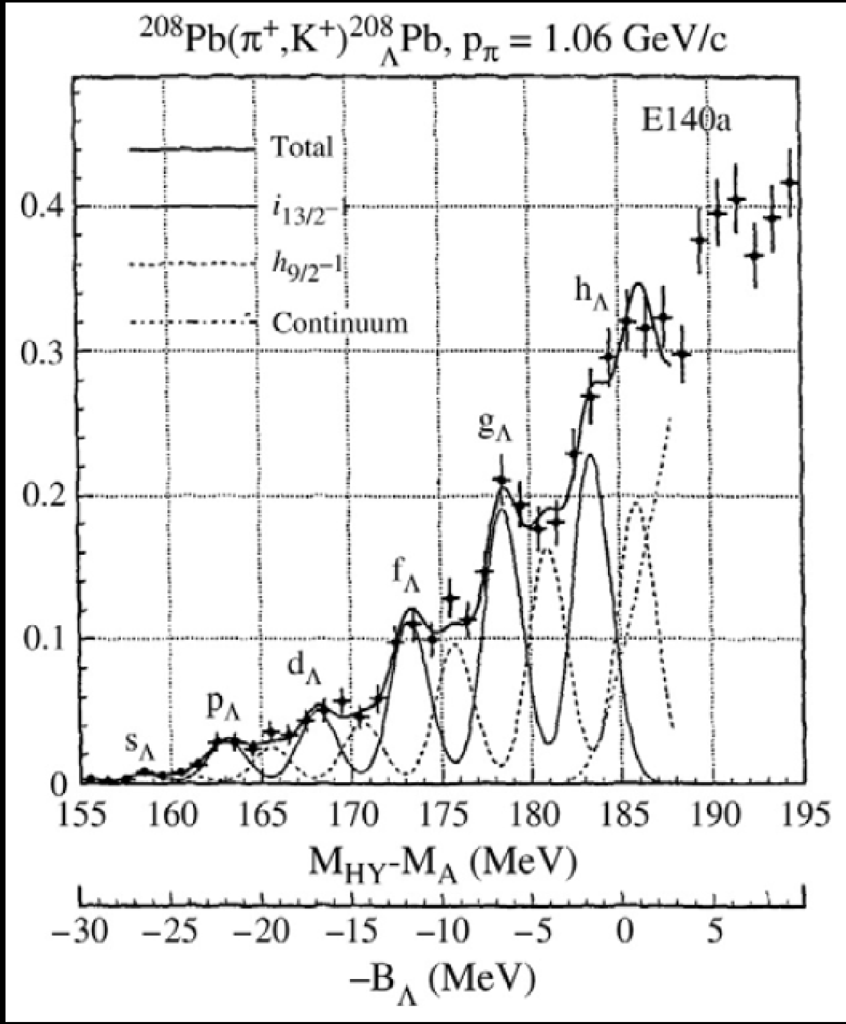


Deeply bound protons in the ^{208}Pb ground state largely unaffected by finite size and shell effect

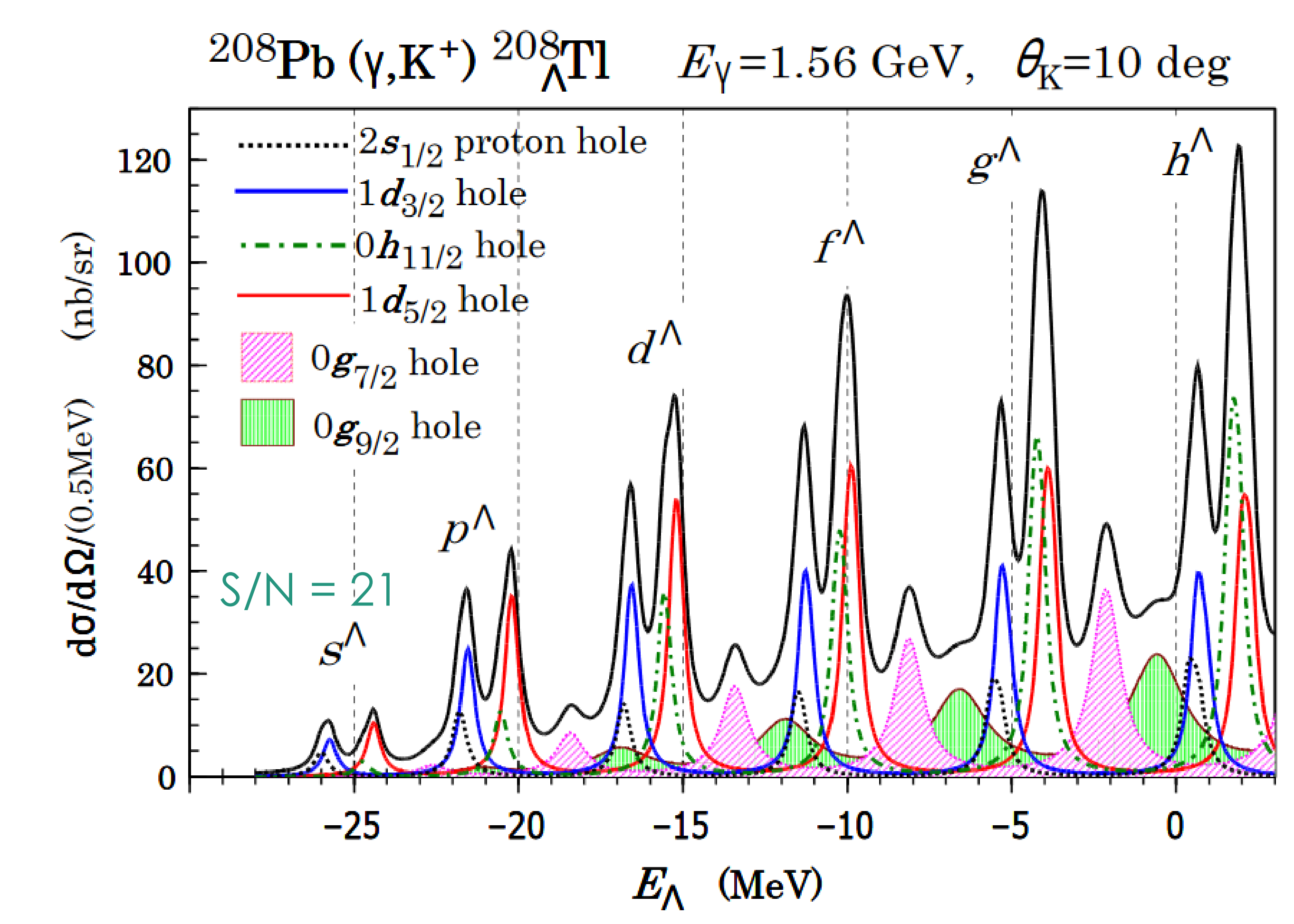
→ It behave as if they were in **nuclear matter**

→ The use of a ^{208}Pb target appears to be uniquely suited to study Λ interactions in a uniform nuclear medium with **large neutron excess**

TOWARD PRECISE SPECTROSCOPY

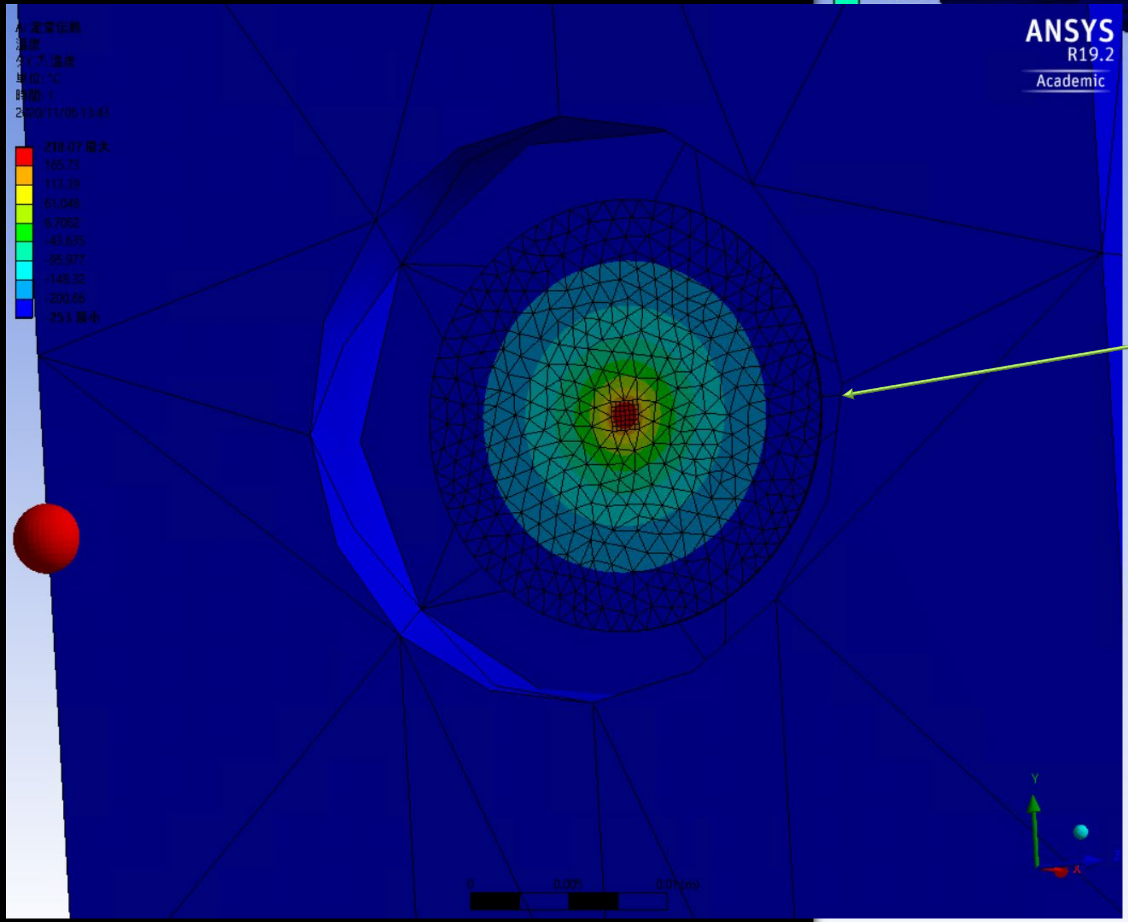


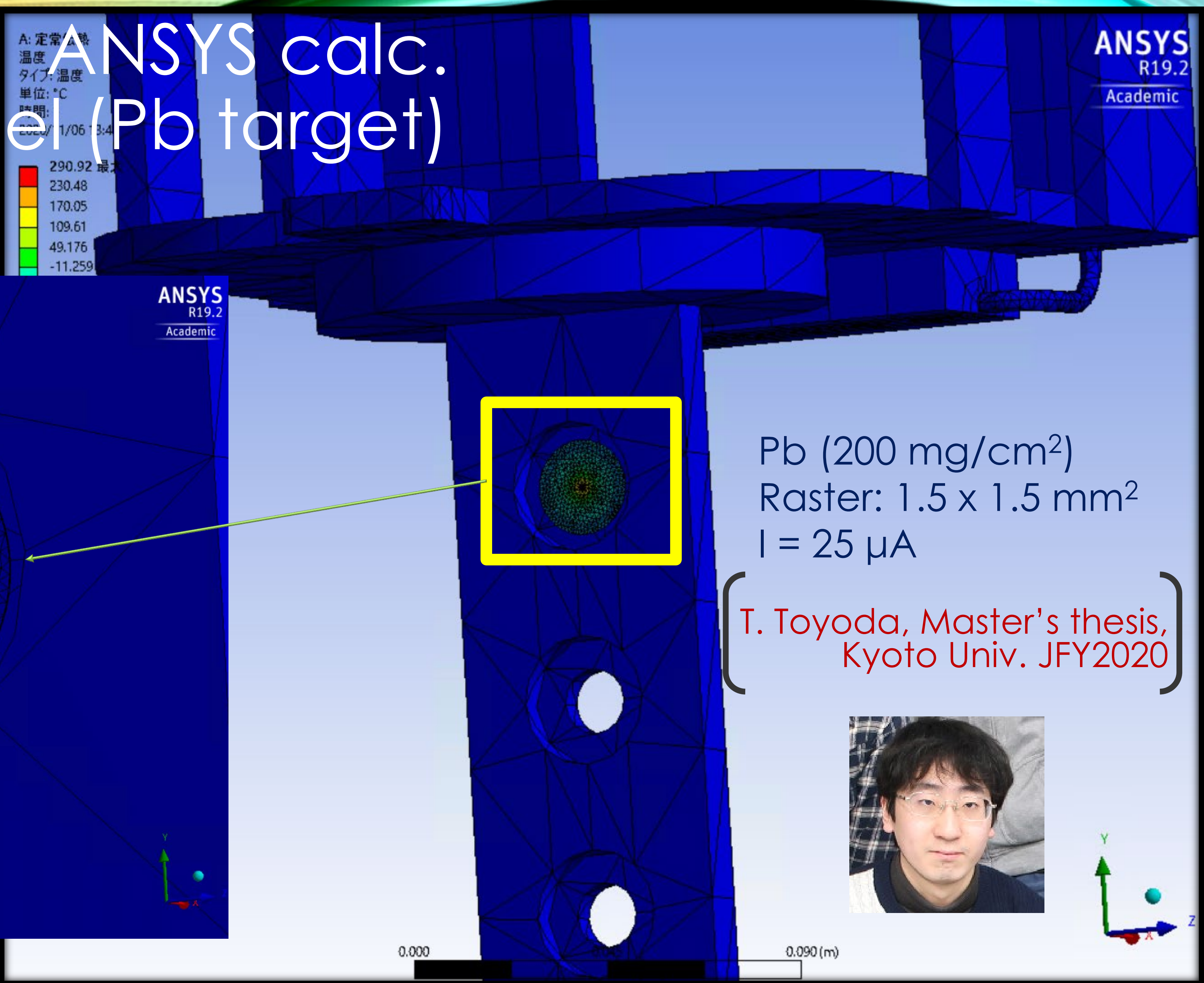
T. Hasegawa et al., Phys. Rev. C 53 (1996) 1210.



T. Motoba, JPS Conf. Proc. 17, 011003 (2017)

ANSYS calc. w/ simple model (Pb target)





Pb (200 mg/cm^2)
Raster: 1.5 x 1.5 mm^2
I = 25 μA

(T. Toyoda, Master's thesis, Kyoto Univ. JFY2020)

SUMMARY

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

② C12-19-002 ($^{3,4}_{\Lambda}\mathrm{H}$): hypertriton puzzle, CSB issue = **25 days (requesting)**

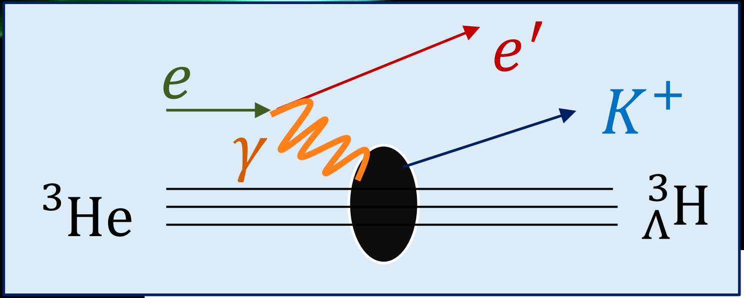
③ E12-15-008 ($^{40,48}_{\Lambda}\mathrm{K}$): ΛNN isospin interaction = **28 days (approved)**

④ E12-20-013 ($^{208}_{\Lambda}\mathrm{Tl}$): ΛNN 3BF in uniform nuclear medium = **20 days (approved)**

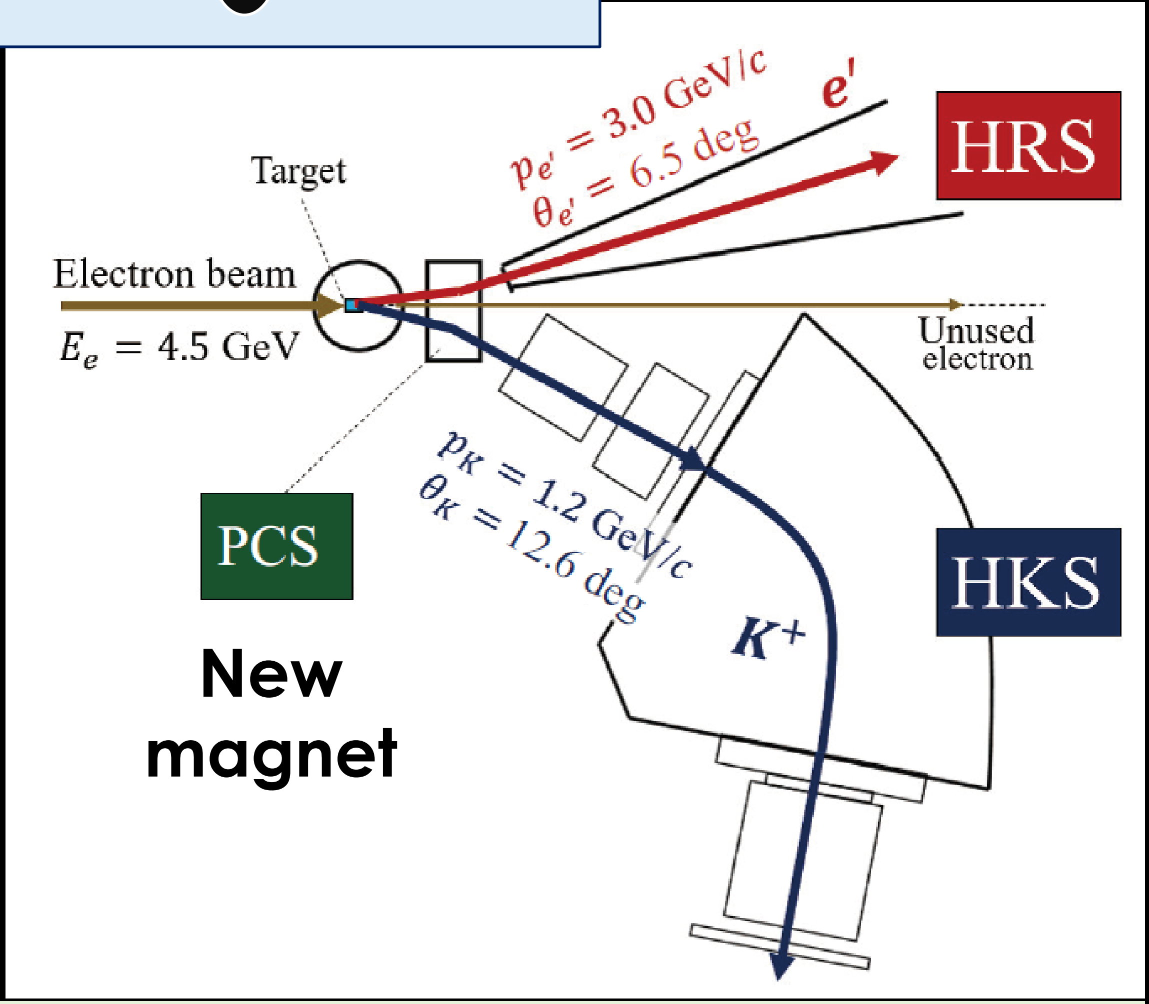
- Spectrometer system
  - PCS was constructed → needs to be transported to JLab
  - HKS base design/construction
- Detectors
  - New WC → Design was done (Master's thesis, Tohoku Univ. JFY2020)
  - Need detectors' commissioning
- Target
  - Basic concept to integrate solids and He targets was agreed
  → Detailed design with JLab target group will be done
- Software
  - Geant4 → Trigger rate / yield / resolutions were estimated
  - FPGA → Being developed (Master's thesis, Kyoto Univ. JFY2020)
  - Analyzer needs to be developed

→ Ready by 2022

EXPERIMENTAL SETUP



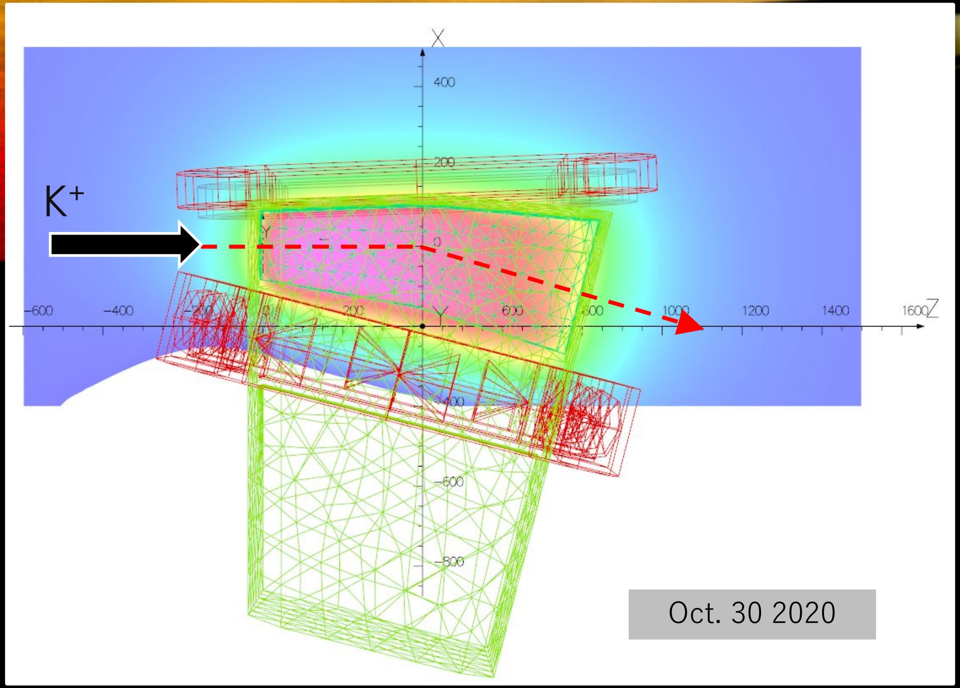
- Same as E12-15-008 ($^{40,48}_{\Lambda}$K)
- PCS → constructed in Japan
- Proposed targets
  - Physics: ^{3}He, ^{4}He gases
  - Calibration: ^{1}H gas, Multi-C, Empty
- Target ladder may be separated from others

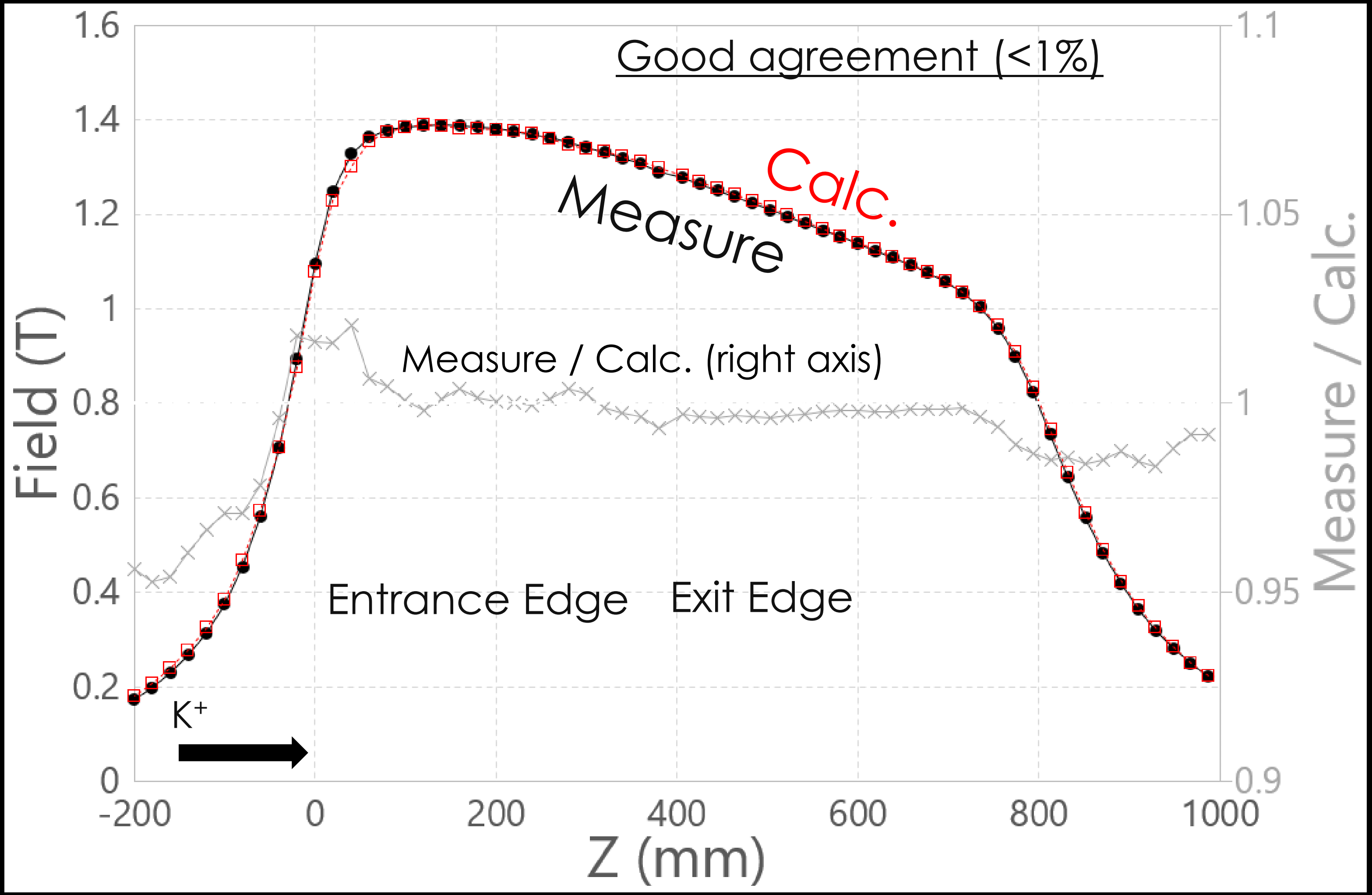


PCS @ TOKIN, Sendai, Japan (March 2020)

HKS magnet: Y. Fujii et al., NIMA 795 (2015) 351—363
Kaon ID: TG et al., NIMA 729 (2013) 816—824

MAGNETIC FIELD MEASUREMENT

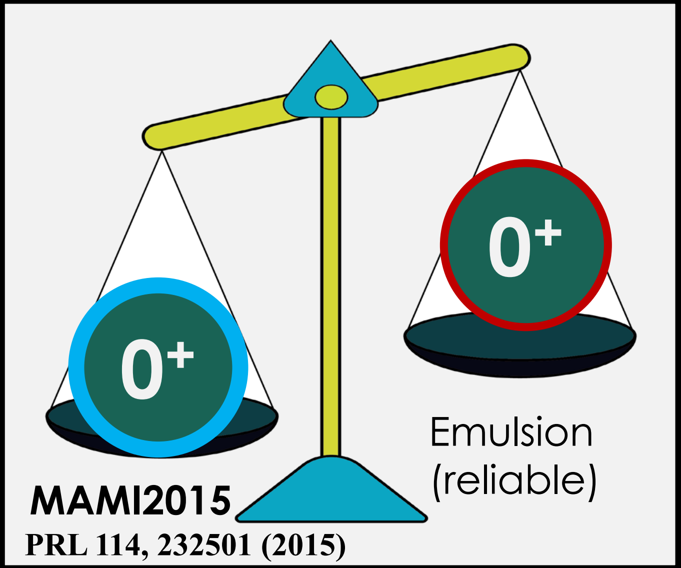


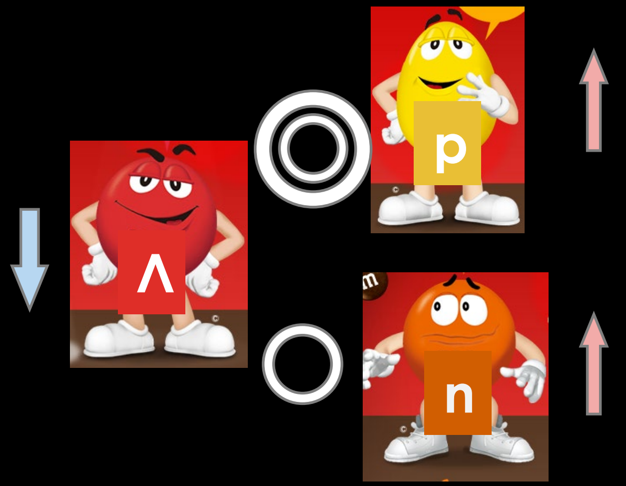


Taken from Sho's slides (Tohoku Univ.)

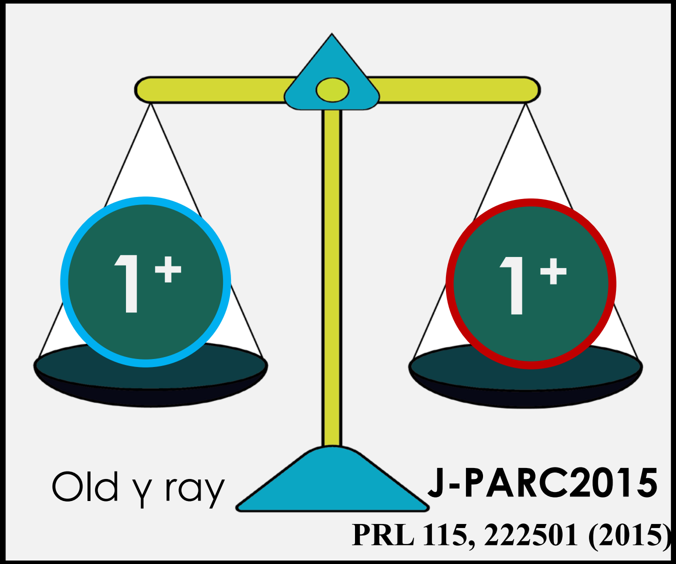
CHARGE SYMMETRY BREAKING IN THE ΛN INTERACTION

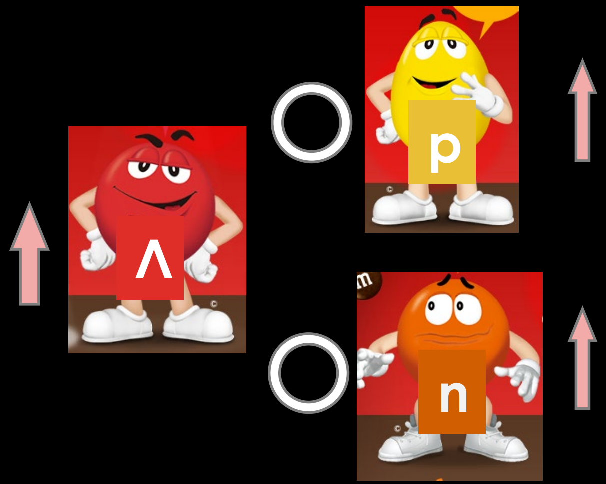
Unbalanced

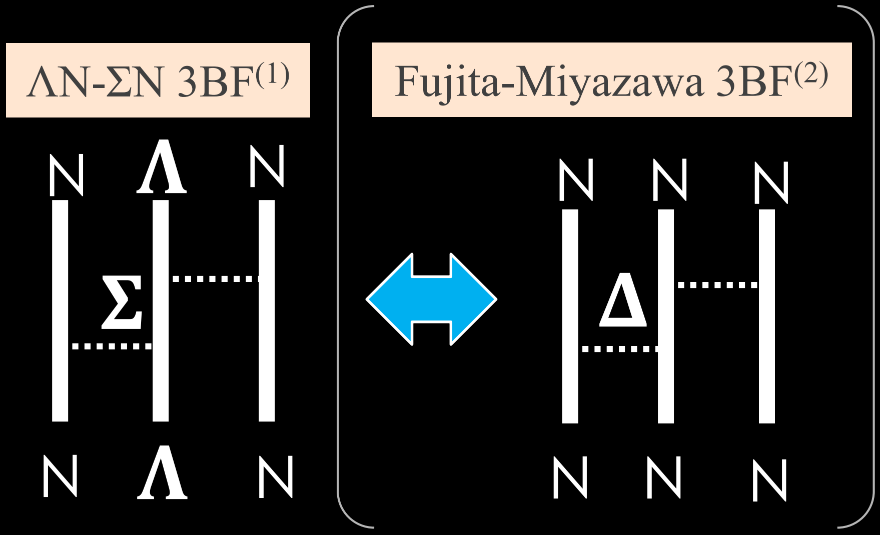




Balanced



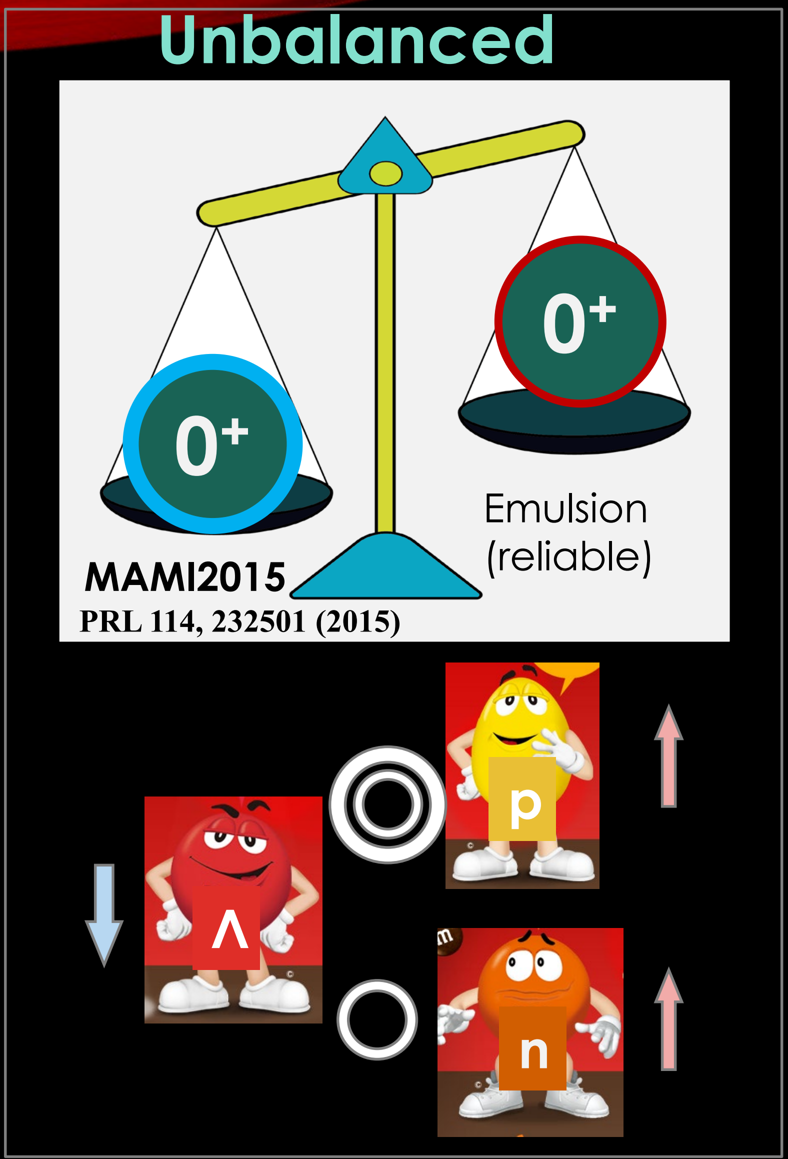


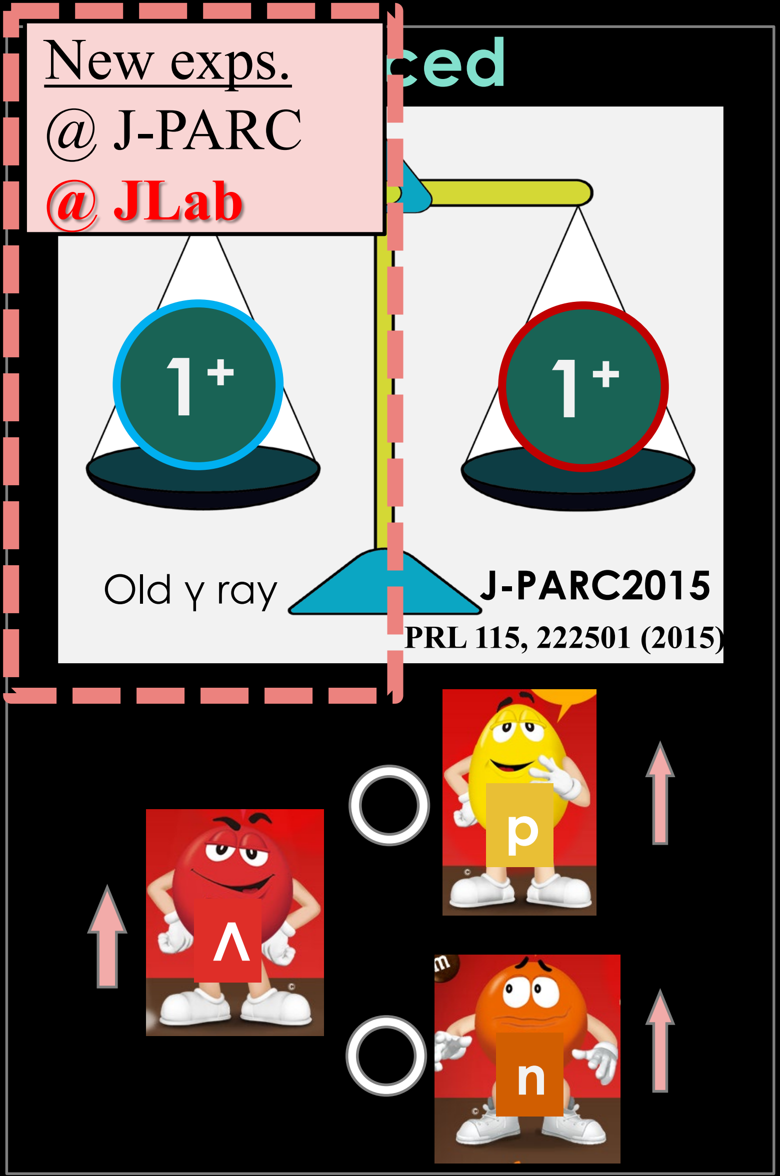


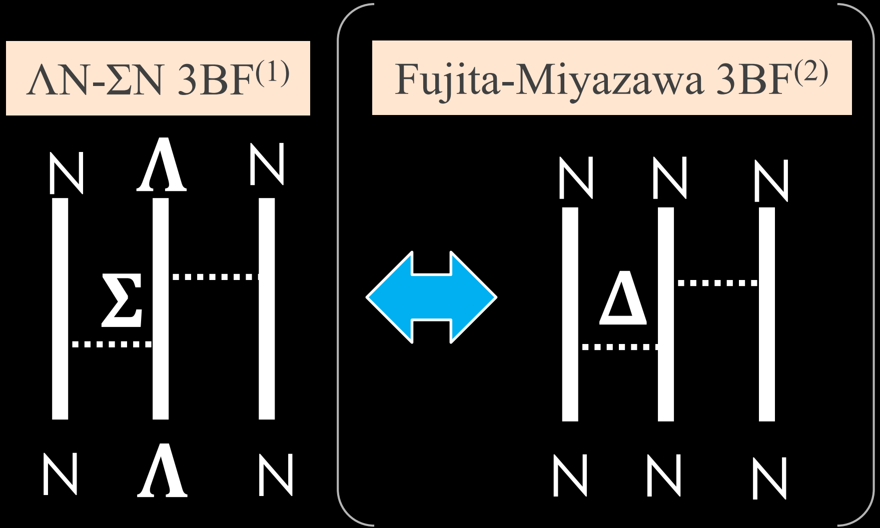
Σ may admix in the ΛN/ΛNN interaction

(1) Y. Akaishi et al., PRL 84, 3539 (2000)
(2) *J. Fujita and H. Miyazawa, Prog. Theor. Phys.,17, 3, 360–365 (1957)*

CHARGE SYMMETRY BREAKING IN THE ΛN INTERACTION







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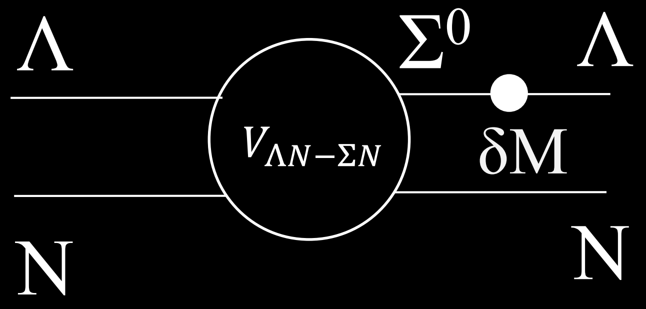
BASIC INFORMATION FOR THE ΛN CSB STUDY: ${}^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$

Explicit inclusion of Σ

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

D. Gazda and A. Gal, Phys. Rev. Lett. 116, 122501 (2016)

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).

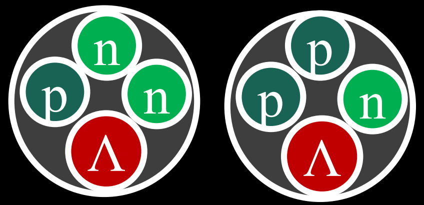
M. Isaka et al., Phys. Rev. C 101, 024301 (2020).

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

Fundamental benchmark — A=4 → **CSB interaction** →

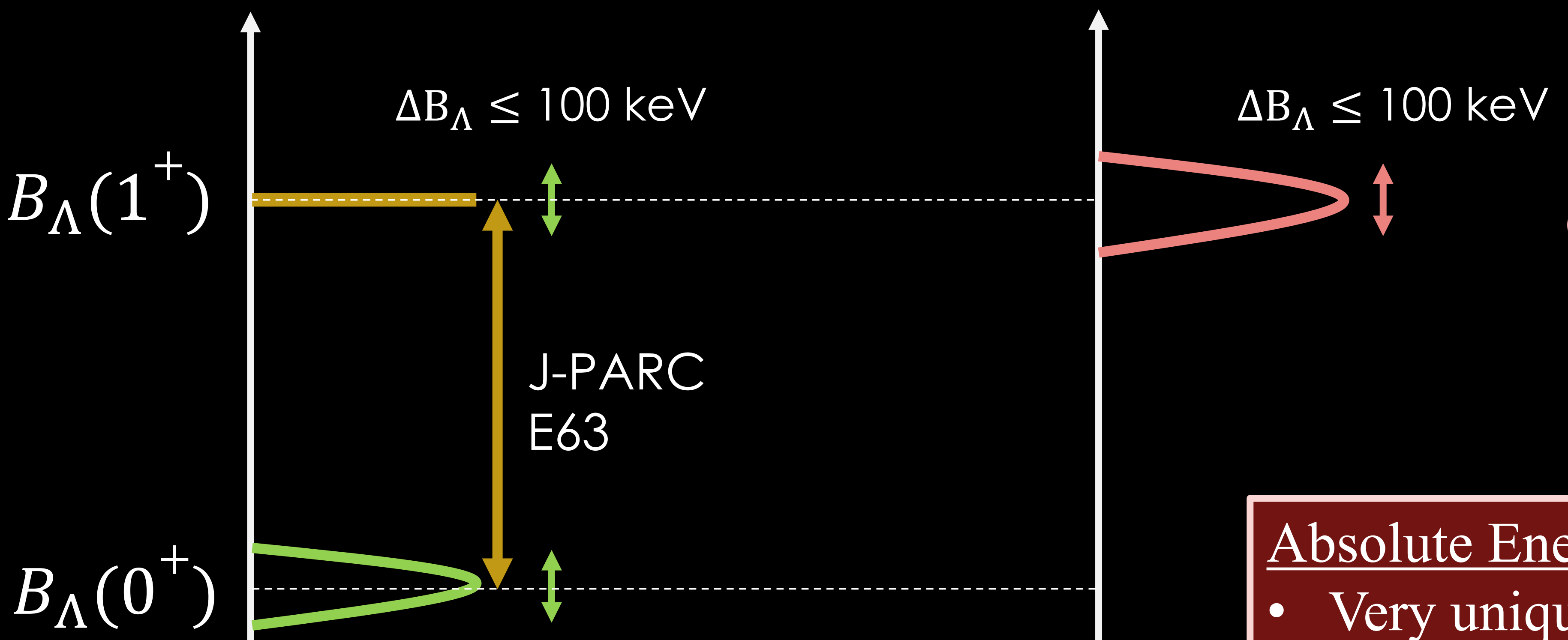
- A=5
- A=7 — HKS, PRL 110, 012502 (2013); HKS, PRC 94, 021302(R) (2016)
- A=9 — Hall A, PRC 91,034308 (2015)
- A=10 — HKS, PRC 93, 034314 (2016); HKS, PRC 90, 034320 (2014) …
- …

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



Conventional way

Proposed exp.



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

C12-19-002
(2 days)

<u>Absolute Energy Measurement:</u>

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

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