Joint THEIA-STRONG2020
and JAEA/Mainz REIMEI Web-Seminar

Spectroscopy of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and other hypernuclei with electron beam at JLab

Graduate School of Science, Kyoto University, Japan

Toshiyuki Gogami

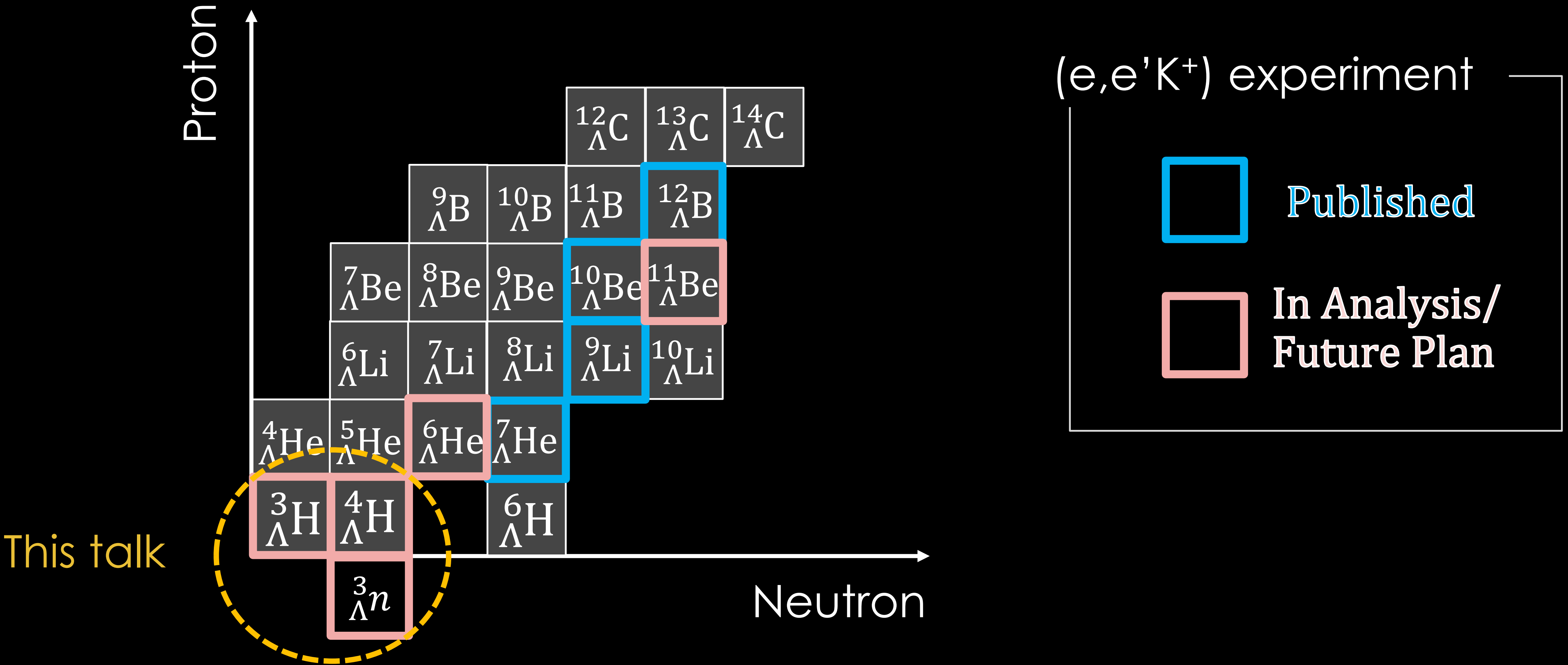
Oct 21, 2020

京都大学
KYOTO UNIVERSITY

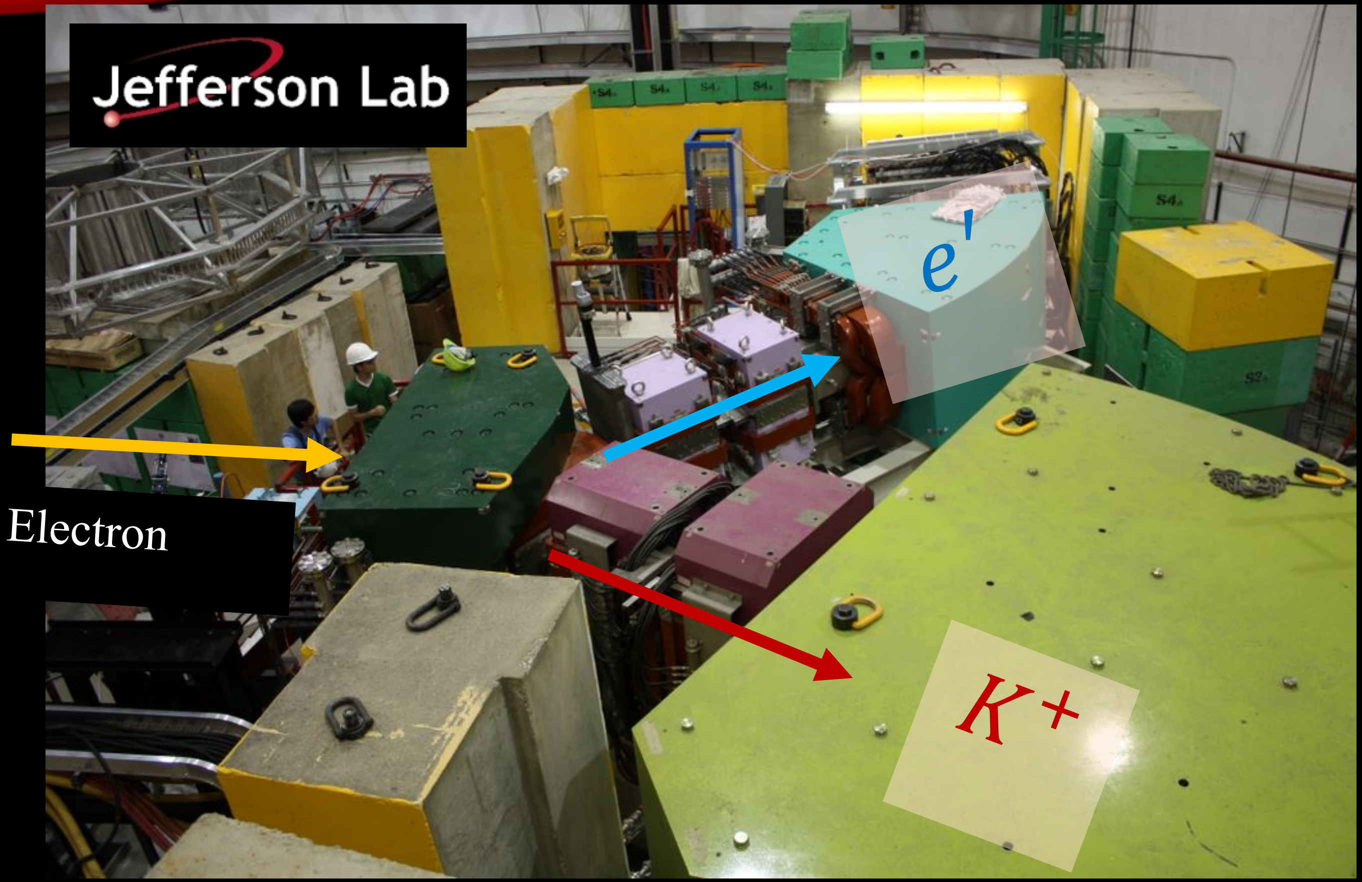
科研費 KAKENHI
SPIRITS
SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

CONTENTS

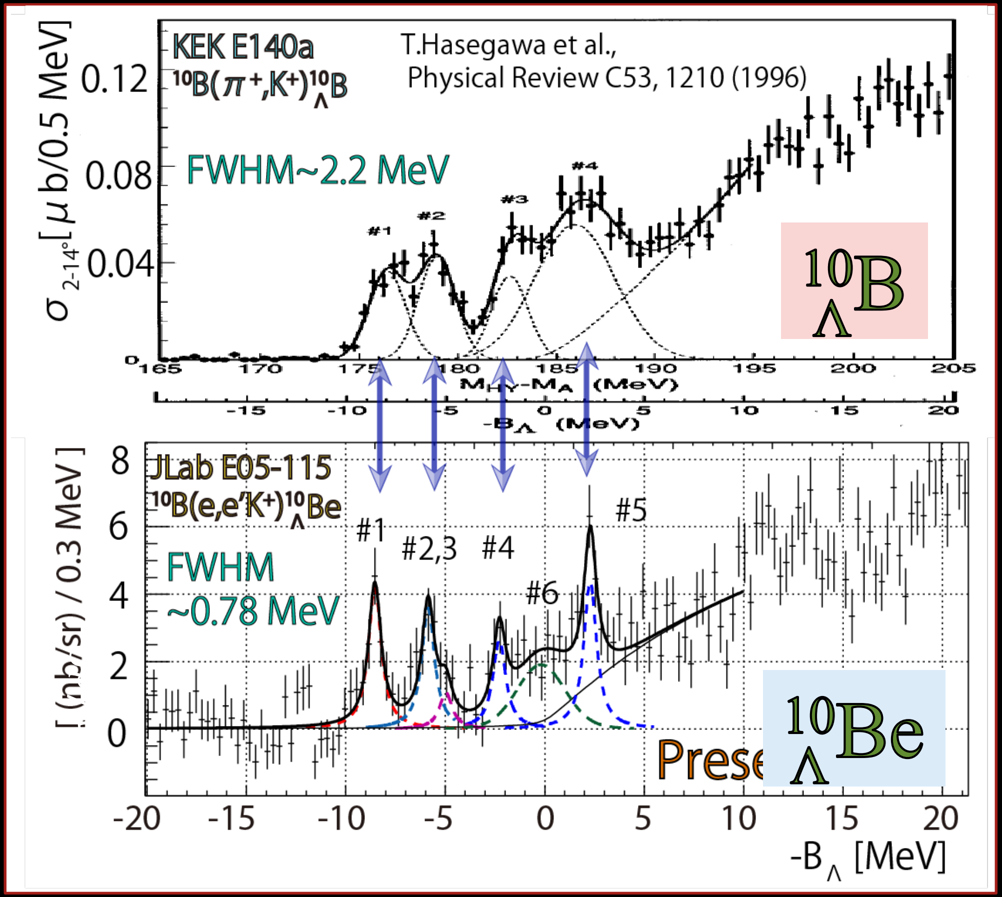
HYPERNUCLEAR CHART FOR LIGHT MASS REGION (Z<7)



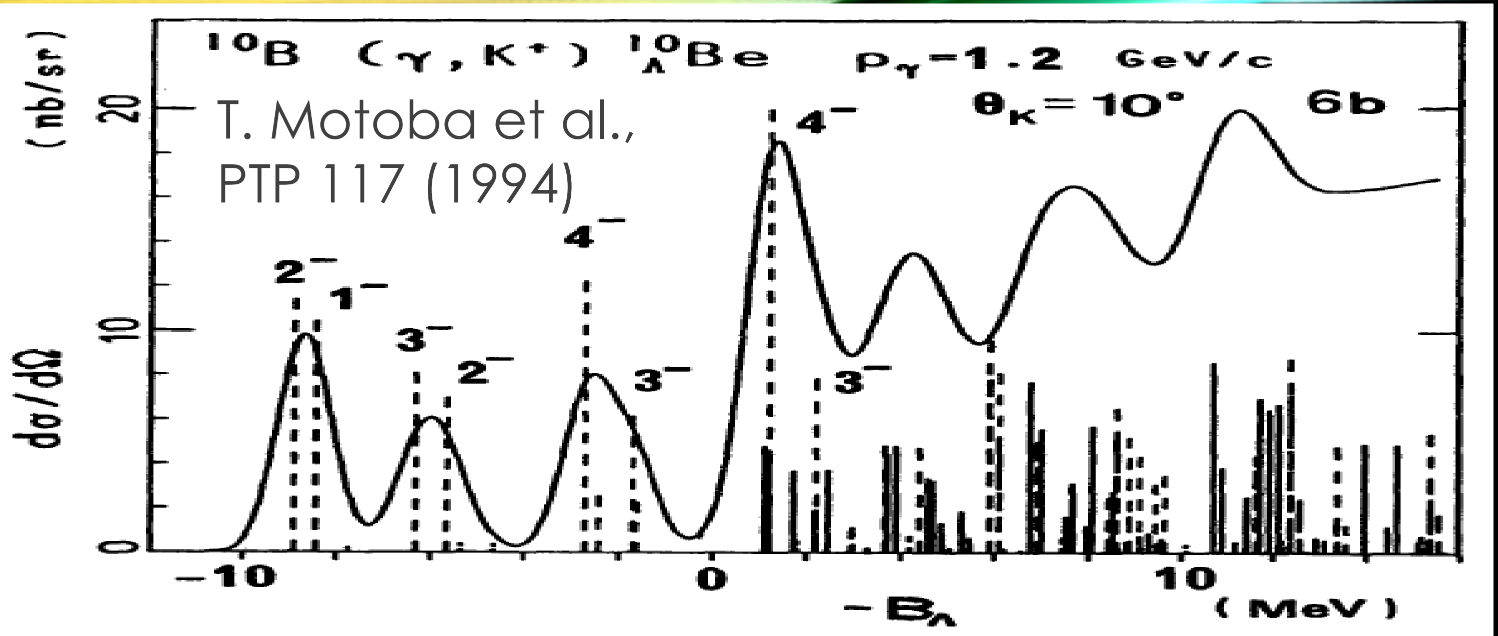
High precision measurement $^{10}_{\Lambda}$B and $^{10}_{\Lambda}$Be

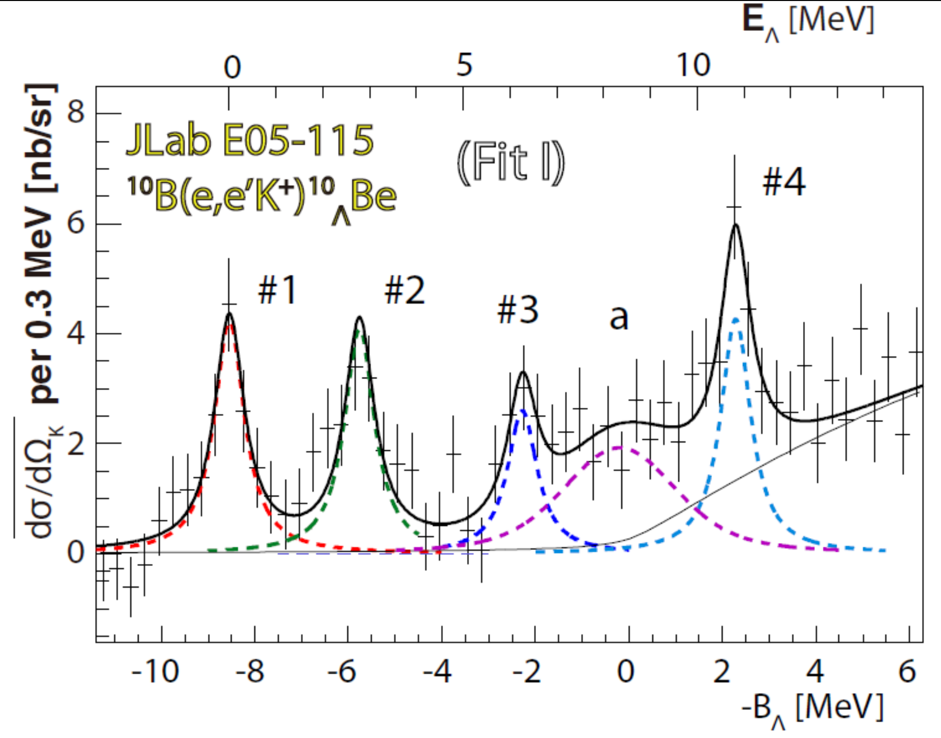


- ✓ High resolution
- ✓ High accuracy



RPC 93 (2016) 034314.





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

What's surplus, a ?

→ Conventional shell model did not predict the state

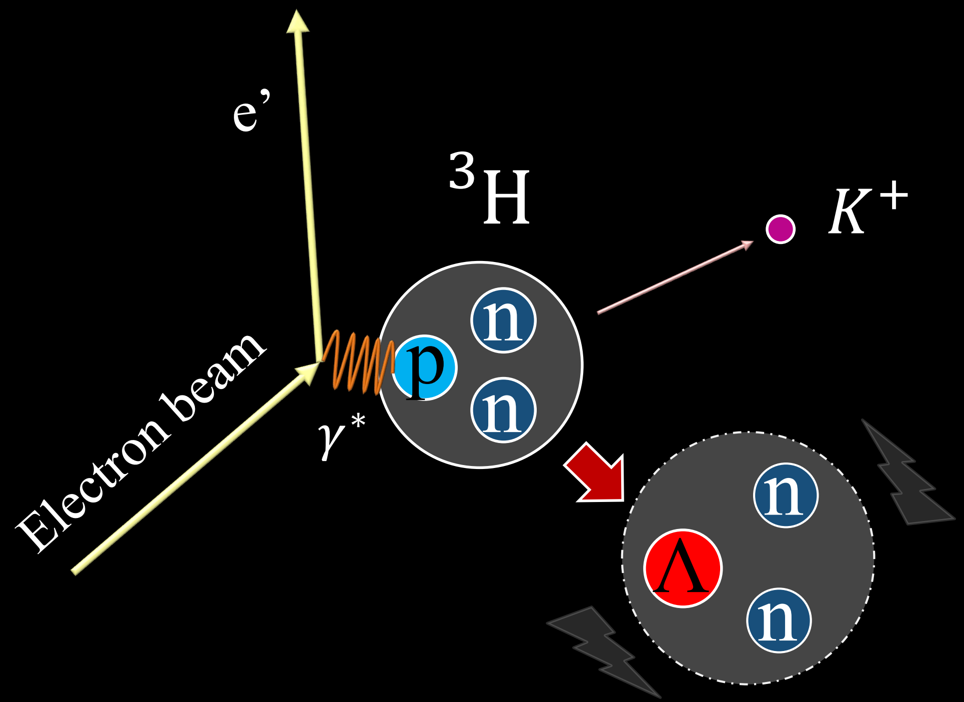
→ It was found that model space needs to be extended (A. Umeya et al., JPS Conf. Proc. 26, 023016 (2019)).

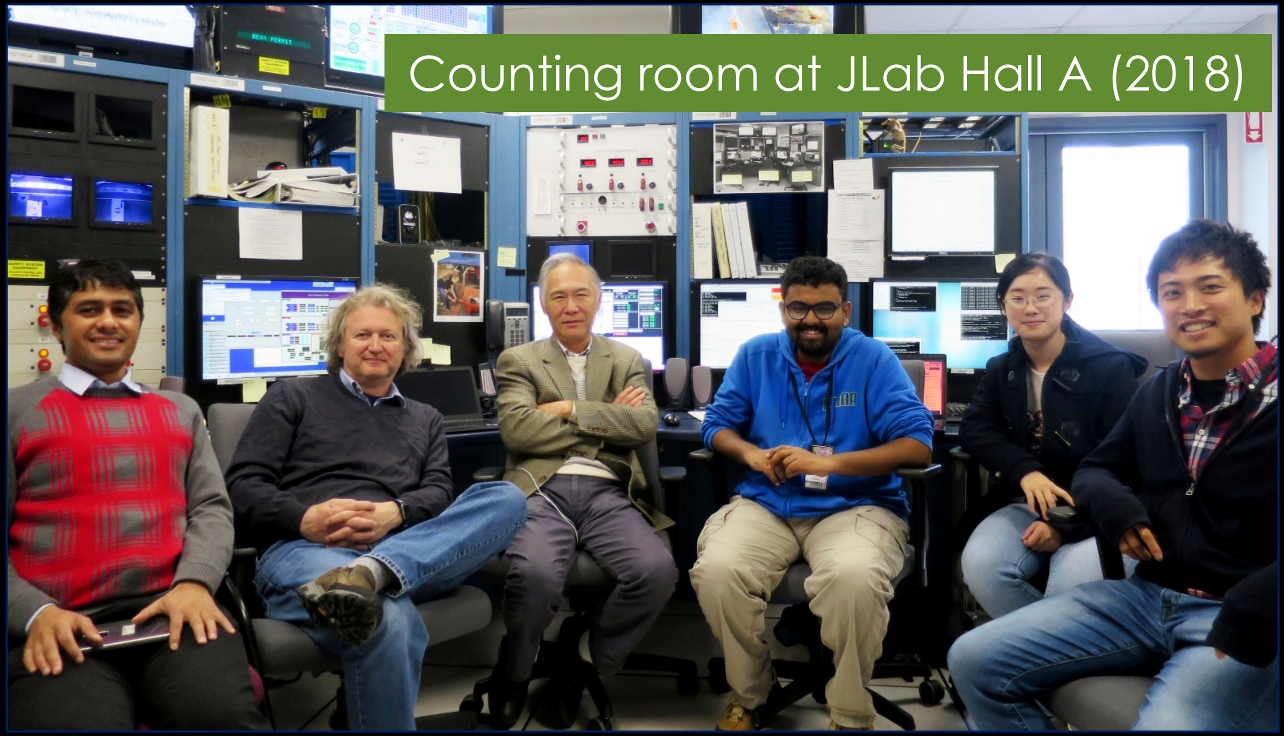
$nn\Lambda$

nnΛ search experiment at JLab

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

E12-17-003 (Oct 30—Nov 25, 2018)

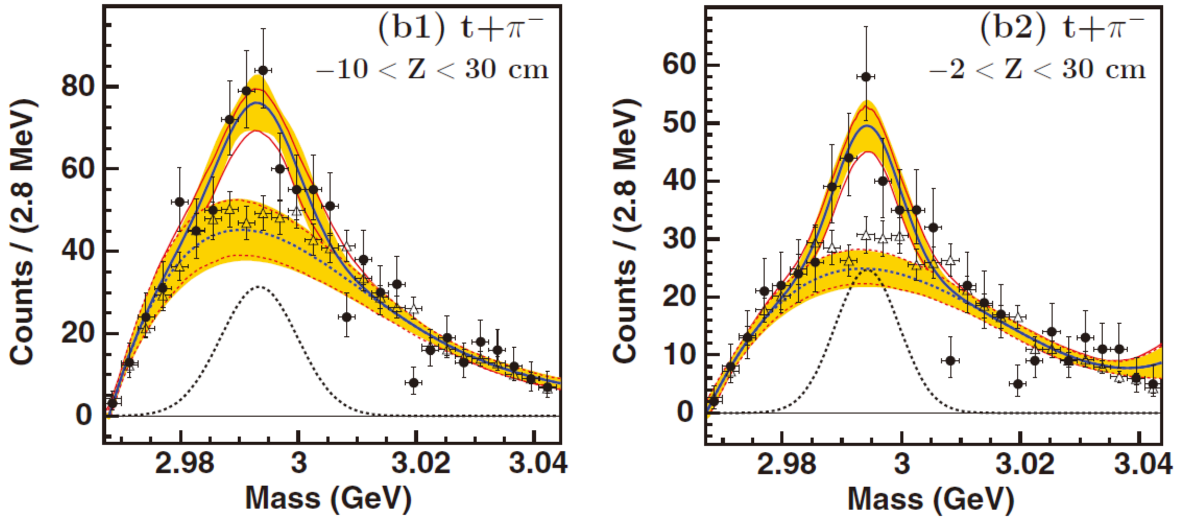


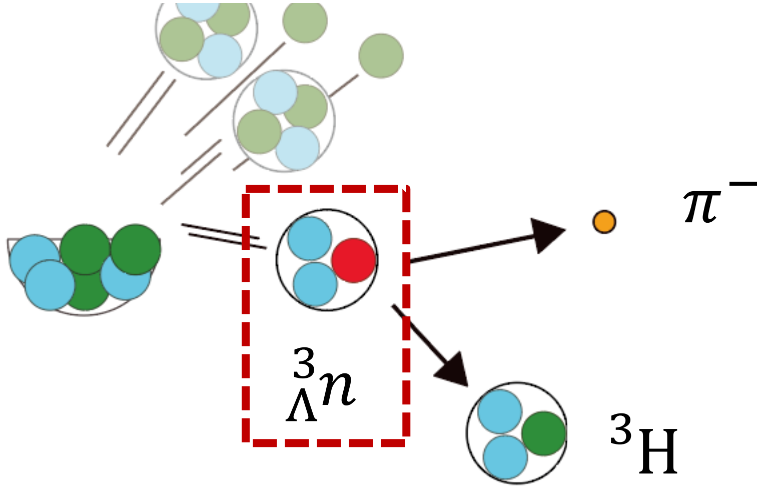


We have sensitivity to both bound and resonant states

NNΛ (T=1)

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





Dr. T.R. Saito presented last week

Bound state is hard to reproduce by current theoretical models

Theories support a resonant state of nnΛ:

- A. Gal et al., PLB 736, 93—97 (2014)
- I.R. Afnan et al. PRC92, 054608 (2015).
- E.Hiyama et al., PRC 89, 061302(R) (2014)
- H. Kamada et al., EPJ Web Conf. 113, 07004 (2016)
- M.Schäfer et al., PLB 88, 135614 (2020)

STUDENTS WHO ANALYZE DATA

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

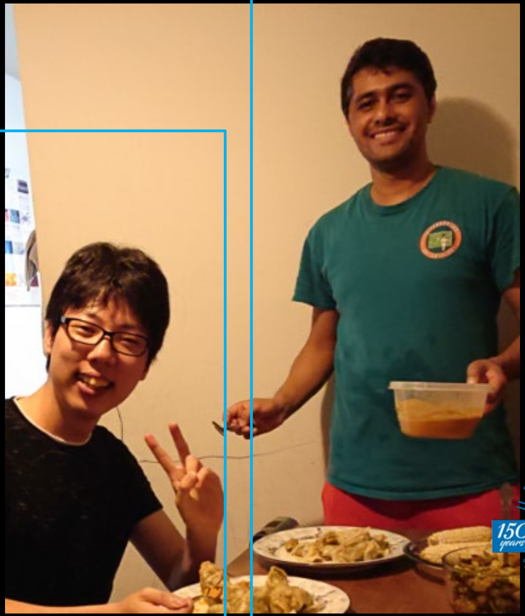
K. Itabashi

K. Okuyama

東北大学

Tohoku Univ., Japan

E. Umezaki



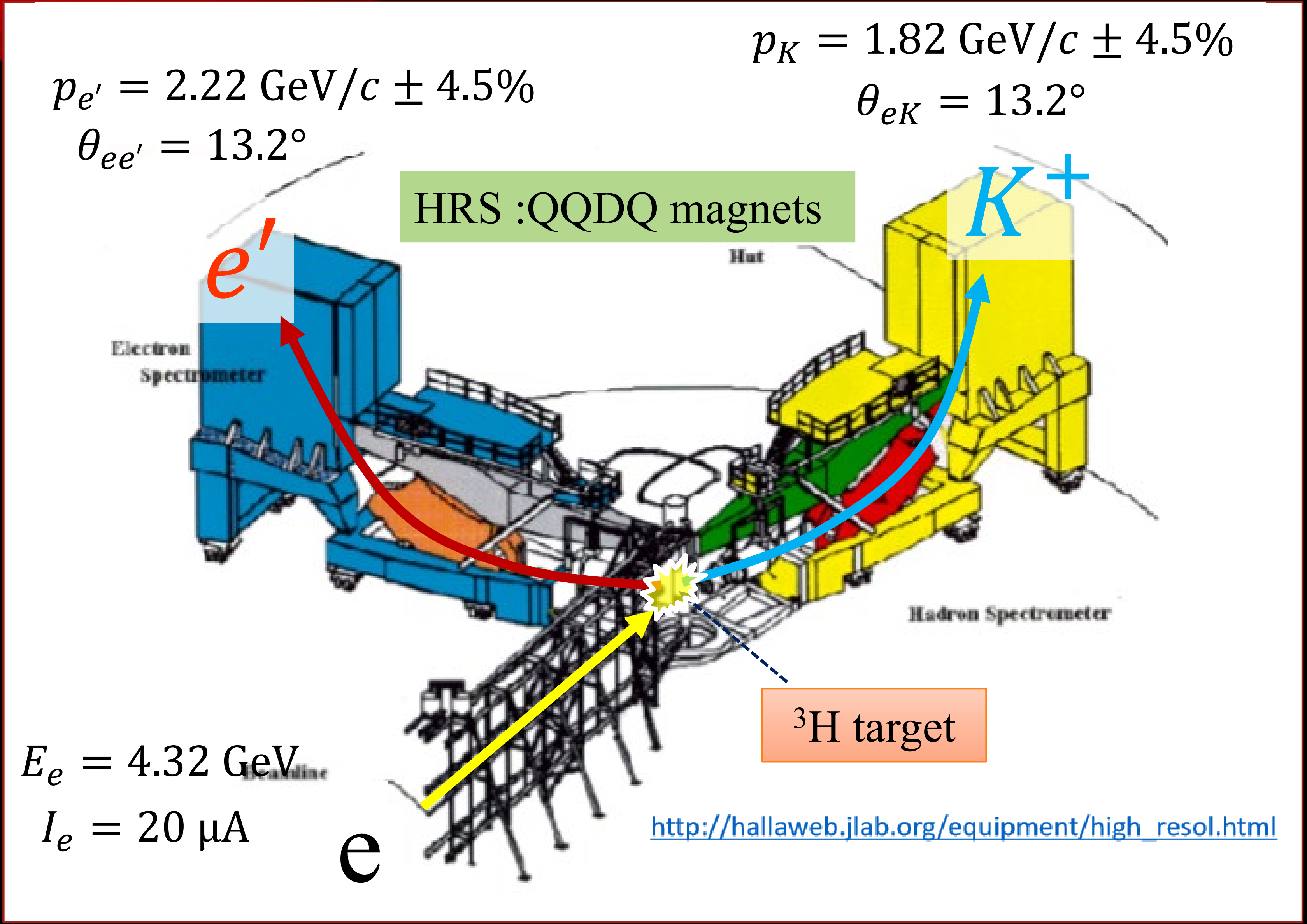
K.N. Suzuki

Kyoto Univ., Japan

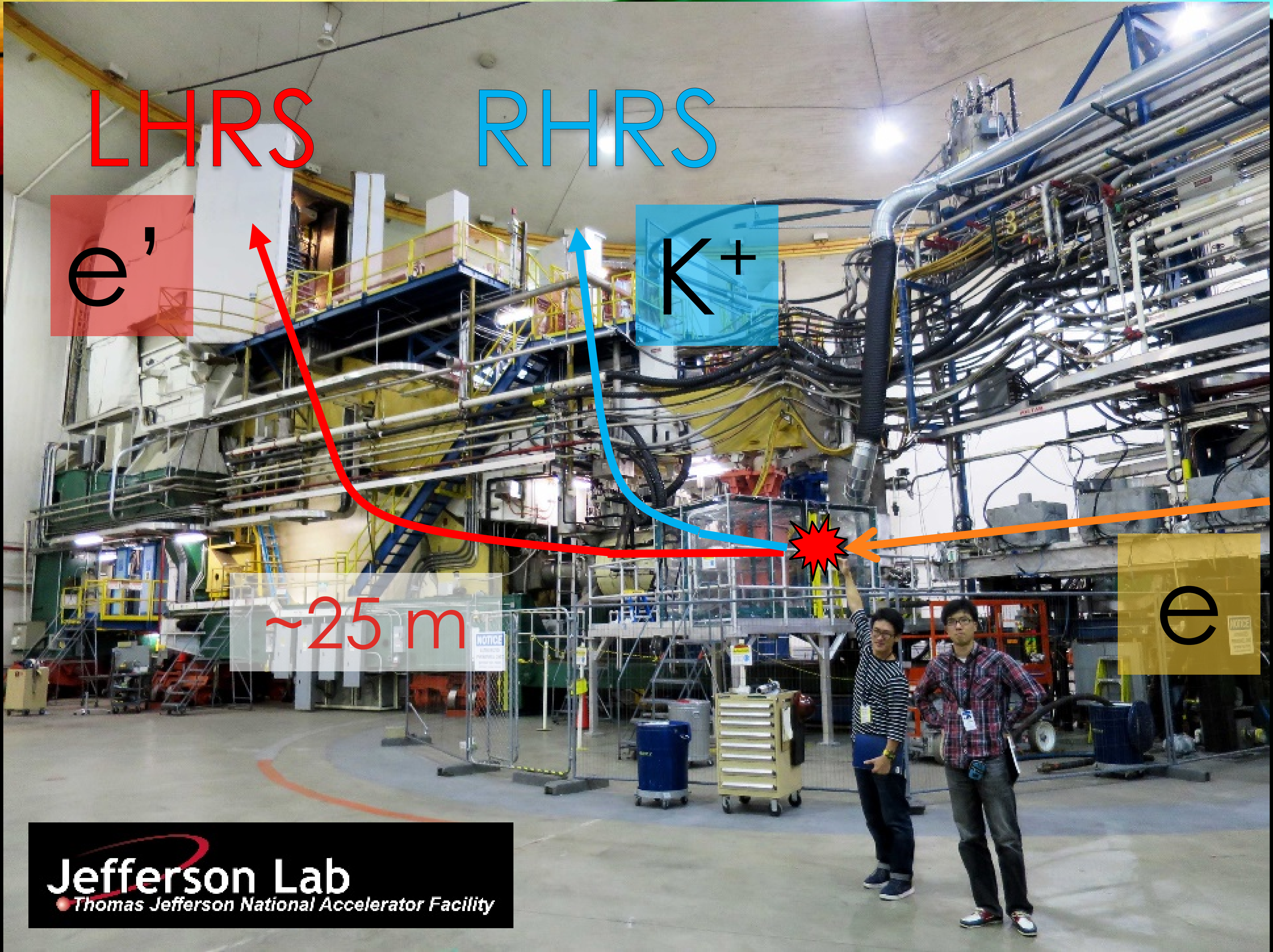
B. Pandey

Hampton Univ., US

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)



LHRS
RHRS
e'
K+
~25 m
e
Jefferson Lab
Thomas Jefferson National Accelerator Facility

TARGET CELL OF TRITIUM GAS

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

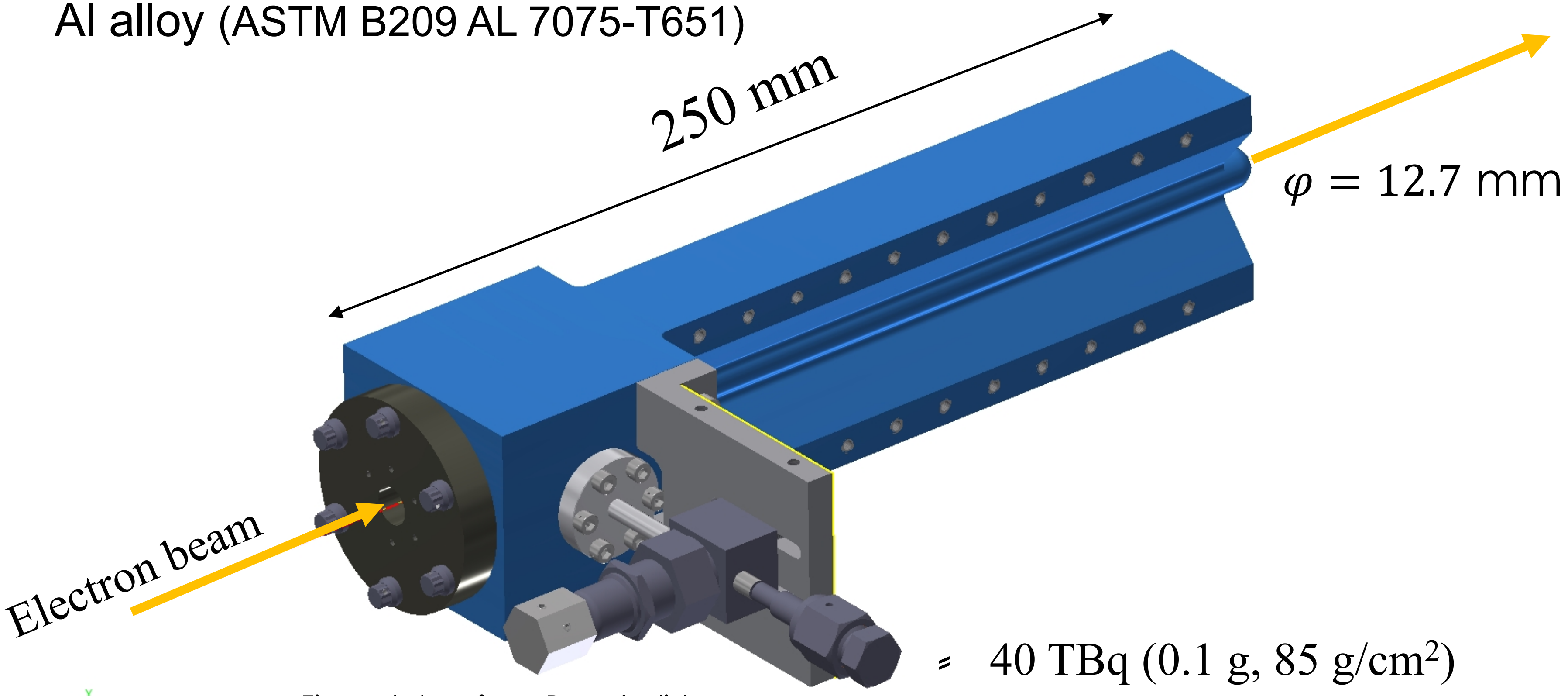
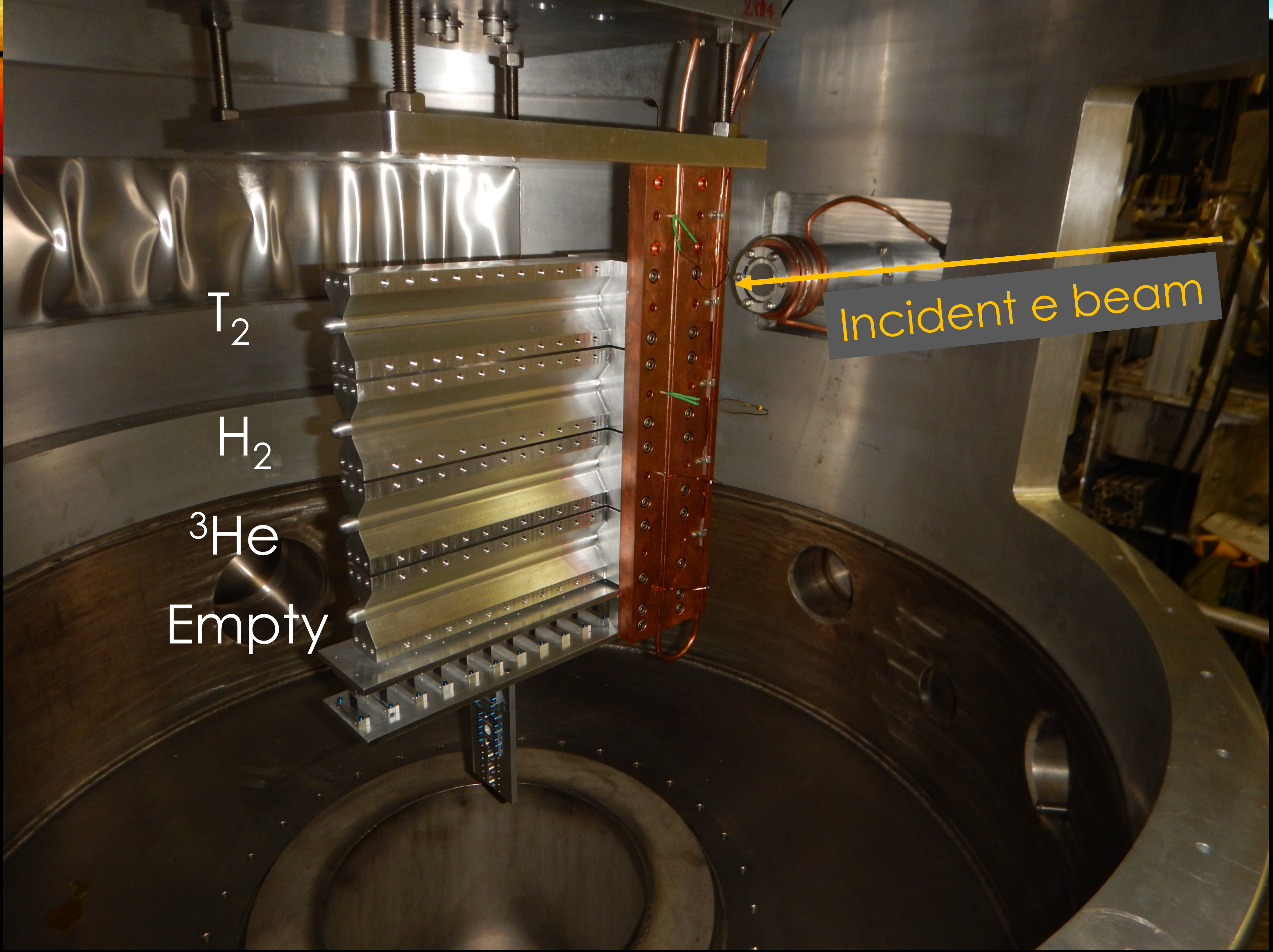


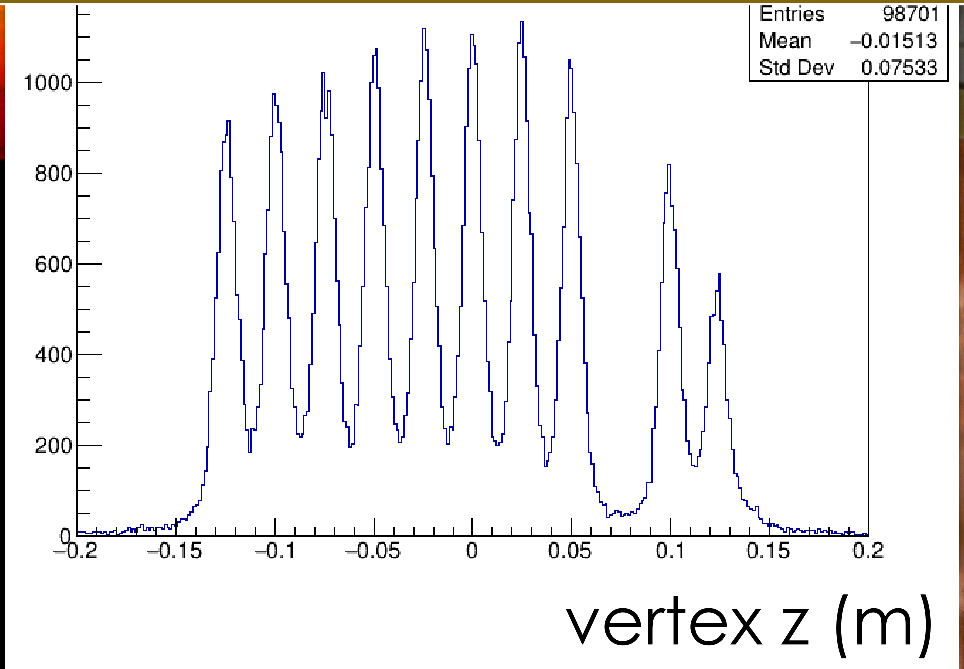
Figure taken from Dave's slide (2015).

- 40 TBq (0.1 g, 85 g/cm^2)
- 1.4 MPa at 295K (0.3 MPa at 40K)
- 34 cc



T_2
H_2
^3He
Empty
Incident e beam

Particle vertex z (Left HRS)



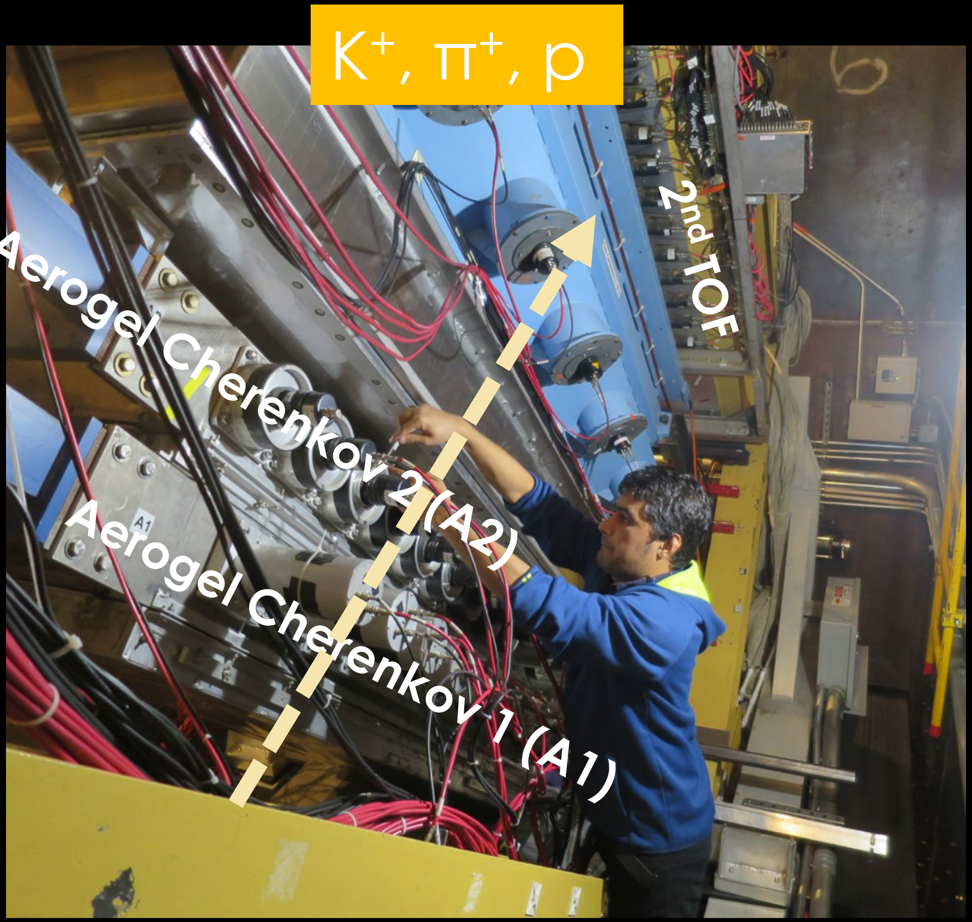
FWHM = 12 mm
(by single arm)

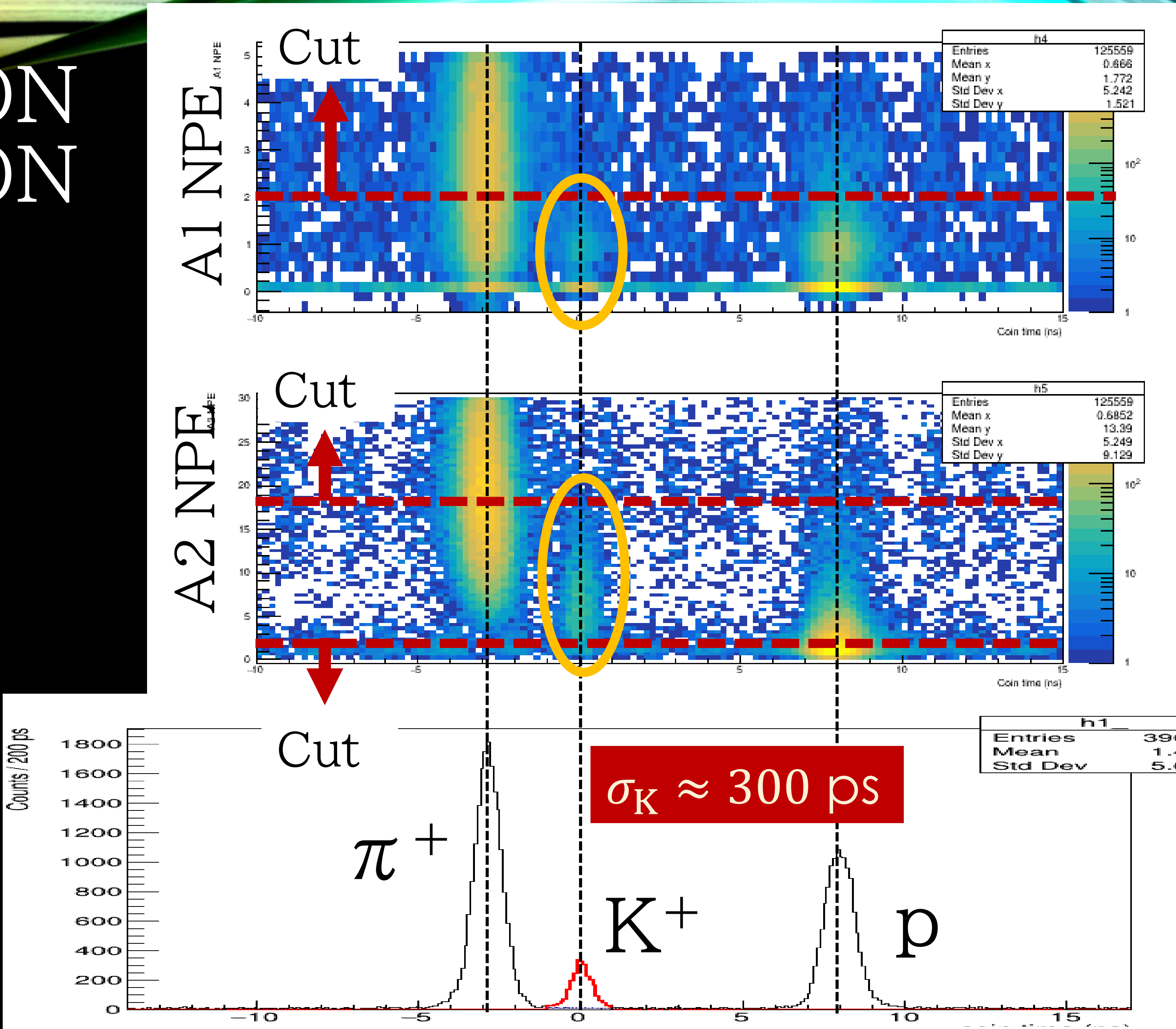
$$z_T^{L,R} = \begin{pmatrix} p_1^z & p_2^z & p_3^z & p_4^z & \cdots \end{pmatrix} \begin{pmatrix} x_{RP} \\ x'_{RP} \\ y_{RP} \\ y'_{RP} \\ x_{RP}^2 \\ \cdots \end{pmatrix}$$

3rd order:
35 parameters

Multi foil target (10 foils)
→ **z vertex calibration**

KAON IDENTIFICATION

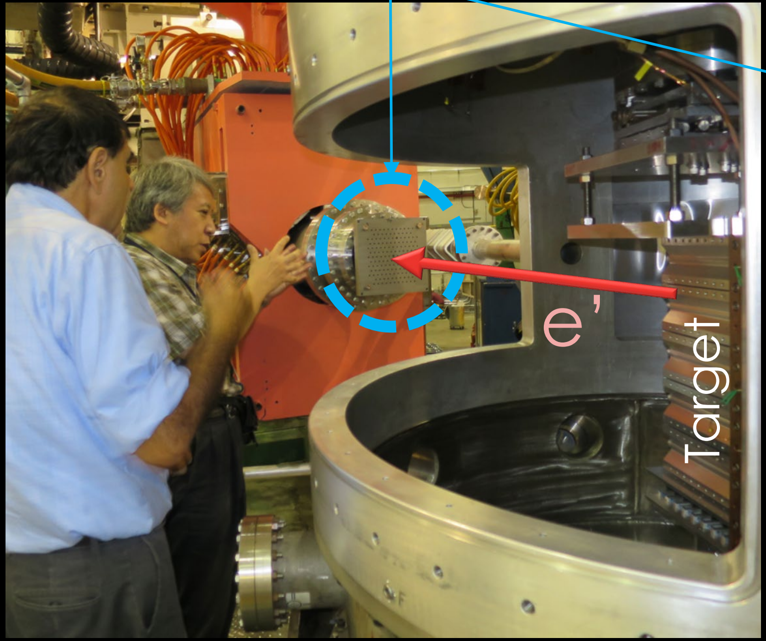




Timing consistency between L and R assuming m_K

CALIBRATION

Sieve Slit



5^{th} order matrix (z_t<2)

Angle calibration

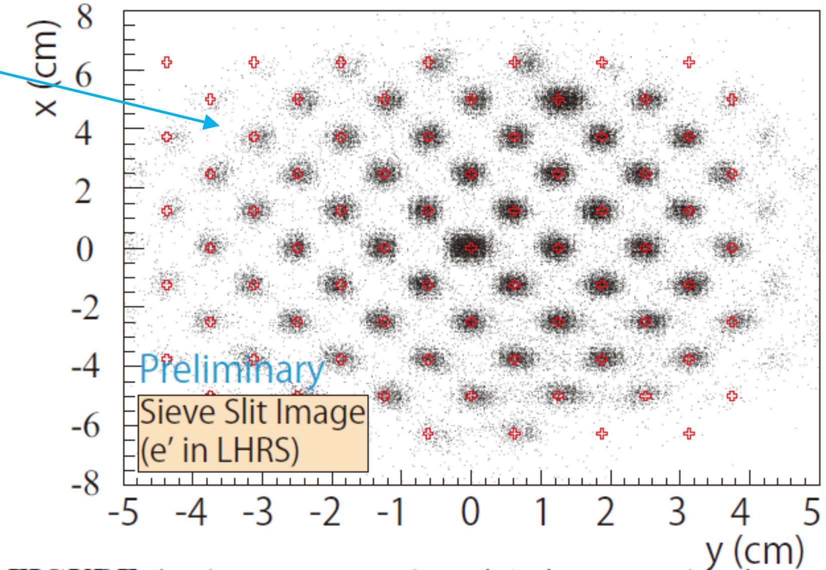


FIGURE 1. A reconstructed particle image at the sieve slit for the sieve slit data in LHRS (e'). Matrix parameters for reconstruction of angle at target were calibrated by using the sieve slit image. π^-s were eliminated by an event selection of light yield of a gas Cherenkov detector (CO_2) [41] installed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

5^{th} order matrix (z_t<2)

Momentum calibration

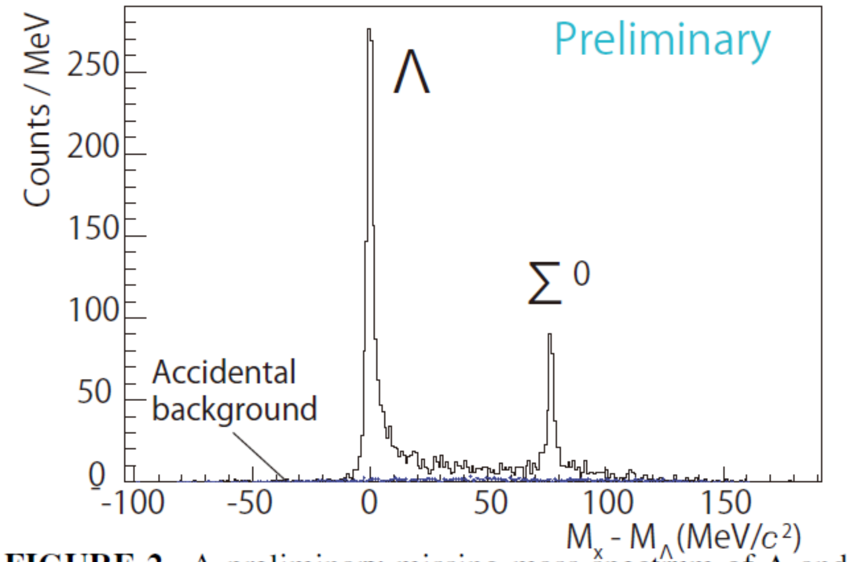


FIGURE 2. A preliminary missing mass spectrum of Λ and Σ^0 from a 71-mg/cm^2 H_2 gas target for a kinematics condition of M-kine in JLab E12-17-003. The beam charge on the H_2 target with M-Kine was about 2.5 C. The mass resolution is about 3.5 MeV/c^2 (FWHM).

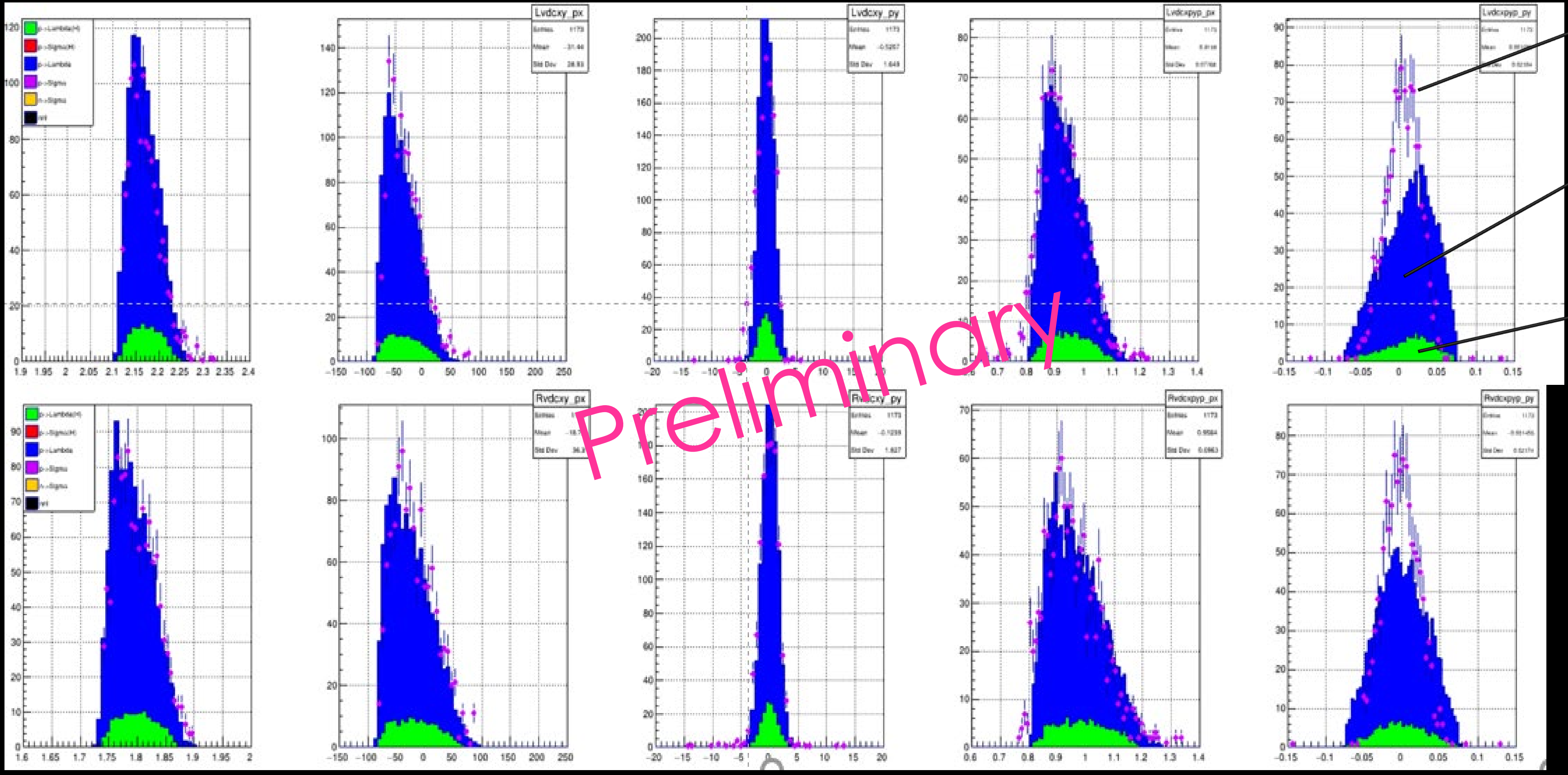
TG et al., APPC14, Proceedings (in Press)

Data vs. Geant4 (sim) for T_2 target

Momentum | x_{FP} (cm) | y_{FP} (cm) | x'_{FP} | y'_{FP}

L-HRS (e')

R-HRS (K^+)



DATA (Λ, Σ)

G4 SIM. (T2)

G4 SIM. (H)
H contamination
(~3%)

→ Acceptance evaluation
→ Cross section

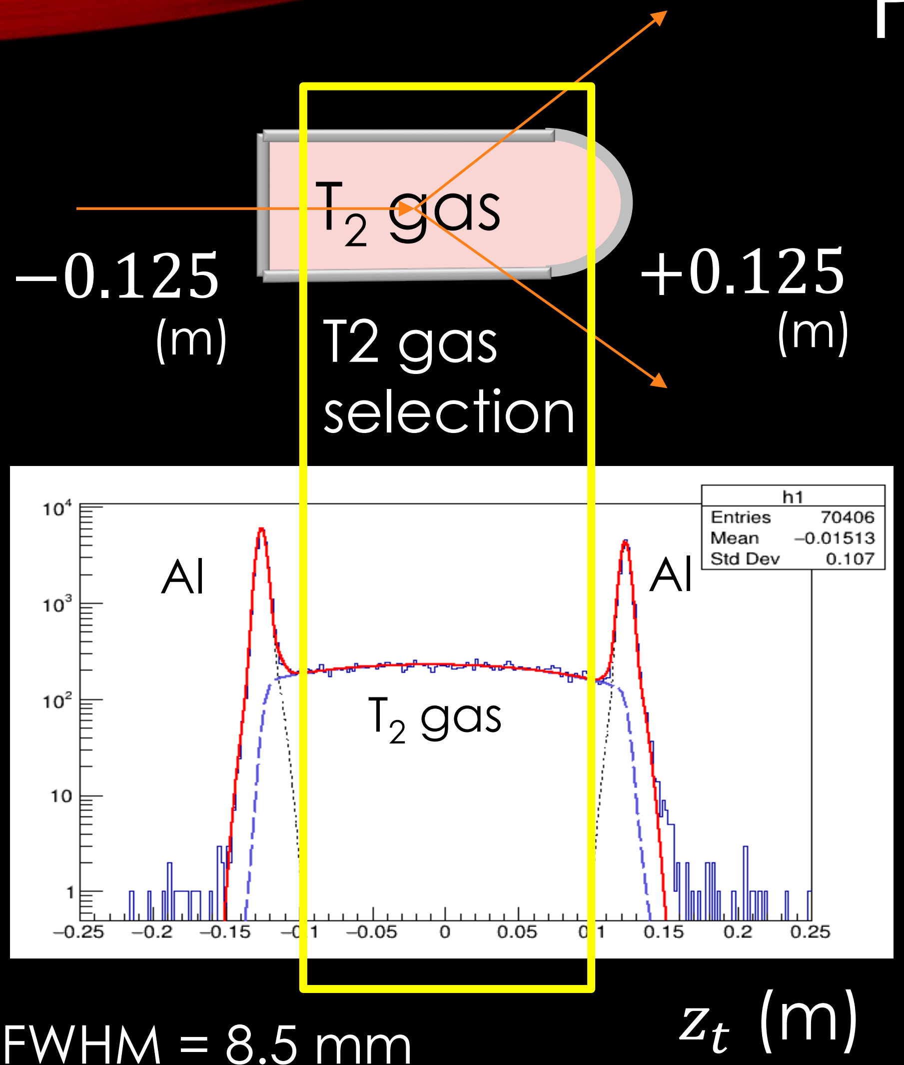
Simulation by K.N. Suzuki (Kyoto)

PRELIMINARY EFFICIENCIES EVALUATED

Item	Efficiency / factor etc.	Remark
Tracing		Data + MC simulation
DAQ		Data
Aerogel Cherenkov selection		Data
Coincidence time selection		Data
Vertex z selection		Data
Acceptance		MC sim. (that reproduces data)
K survival ratio		MC sim. (that reproduces data)
K absorption factor		MC sim. (that reproduces data)
Gas density reduction @22.5μA		Data (NIMA 940 (2019)351—358)
Virtual photon flux		MC sim. (that reproduces data)

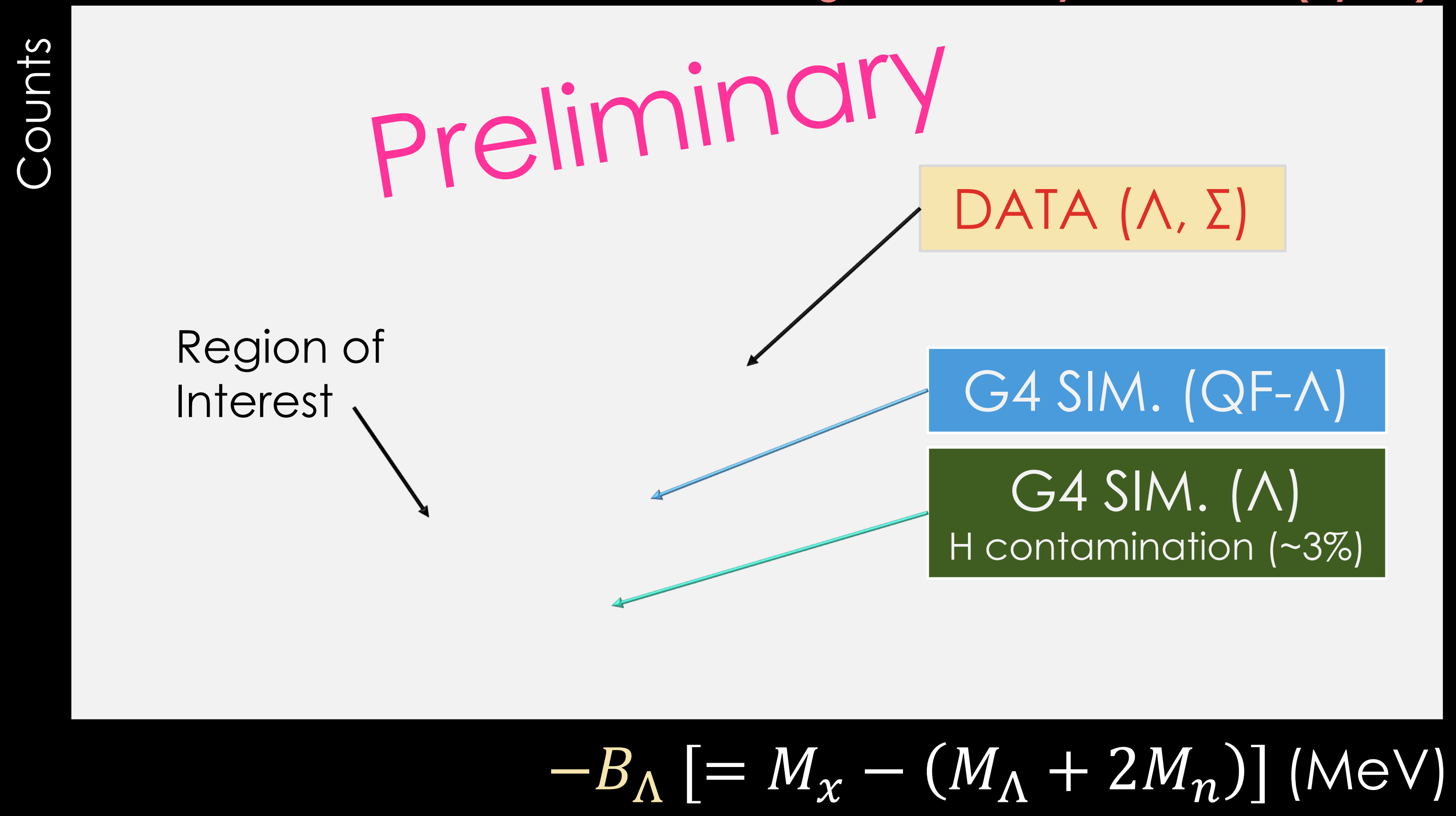
Preliminary

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



FWHM = 8.5 mm
(by two arms)

Figure made by K.N. Suzuki (Kyoto)



$^{3,4}_{\Lambda}H$

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

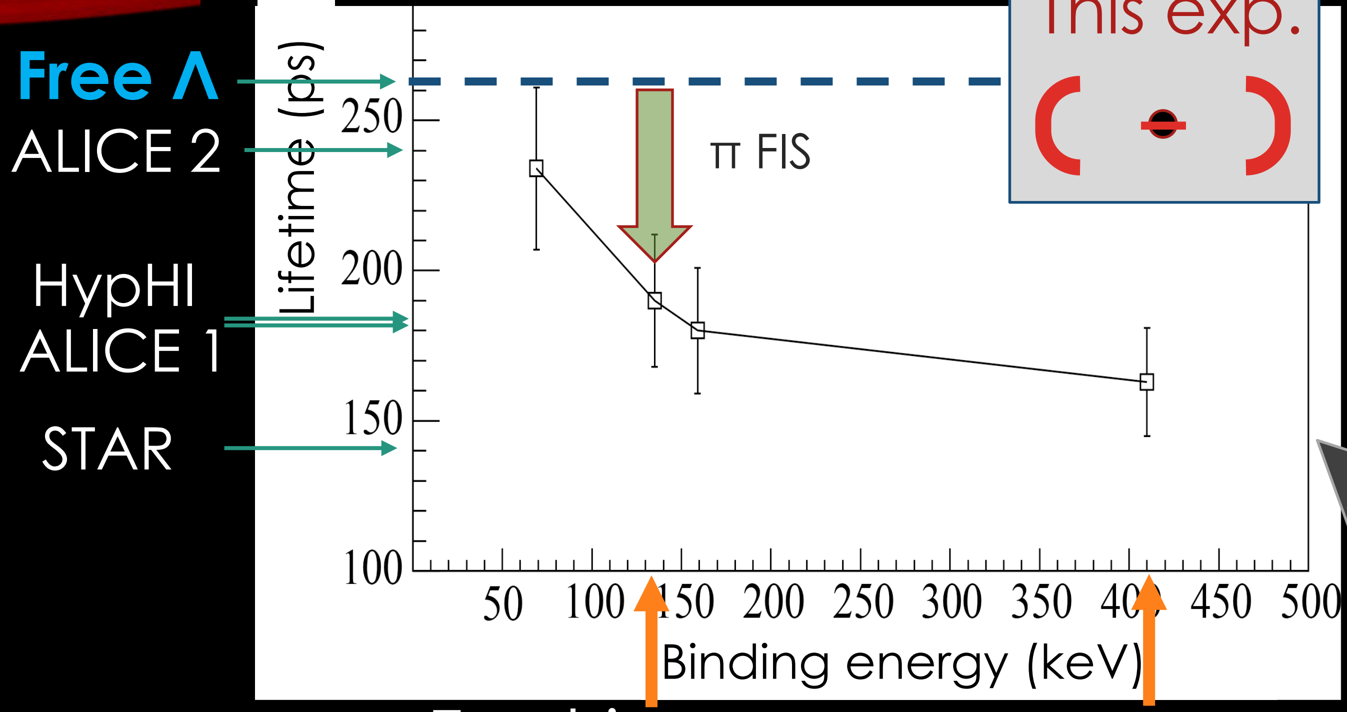
$\tau = (0.5 \sim 0.92)\, \tau_{\Lambda}$
(HypHI, STAR, ALICE)

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 $^3_\Lambda$H

arXiv:2006.16718v2 [nucl-th] 8 Jul 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:

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

Spin indep. amp.

Spin dep. amp.

Form factor
(π FSI is included)

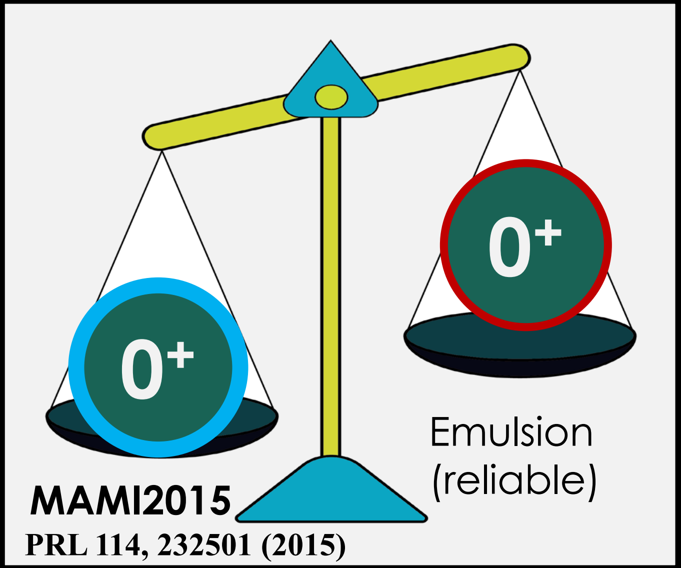
$\propto \sqrt{B_\Lambda}$

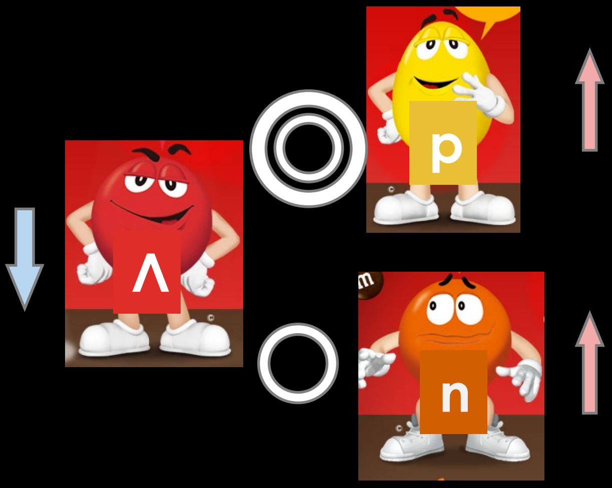
Proposed experiment (C12-19-002)
$|\Delta B^{stat.}| = 30$ keV, $|\Delta B^{sys.}| = 70$ keV

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

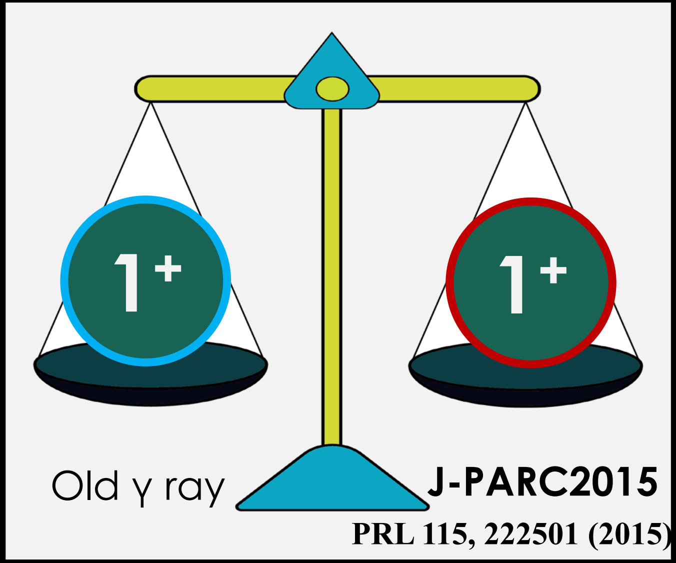
CHARGE SYMMETRY BREAKING IN THE ΛN INTERACTION

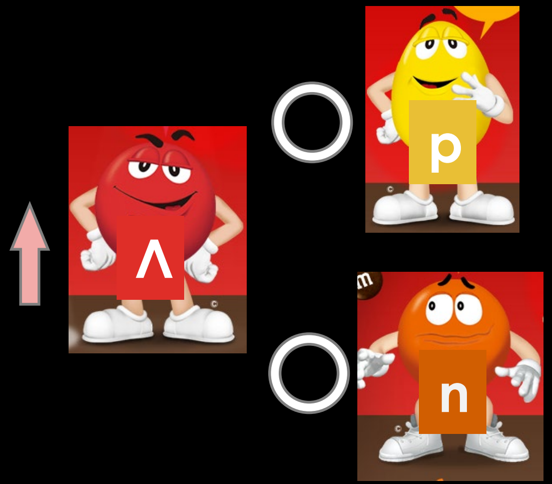
Unbalanced

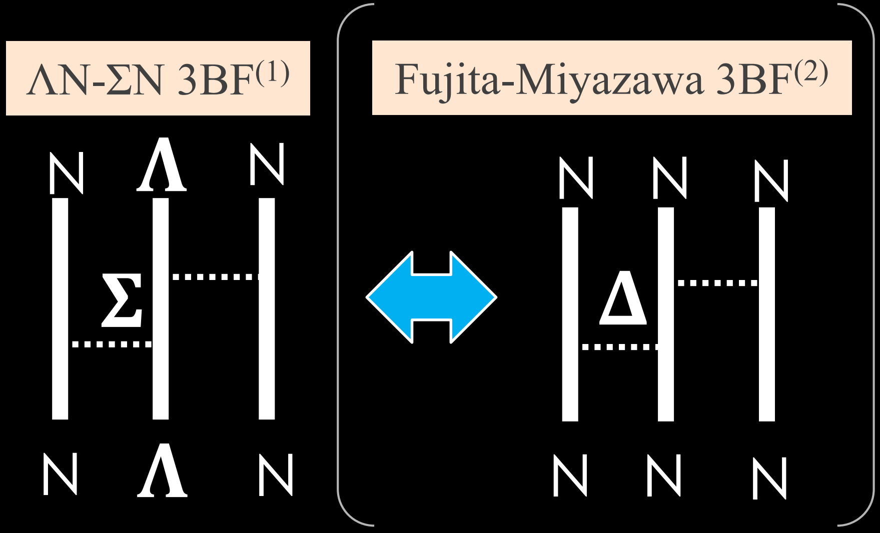




Balanced





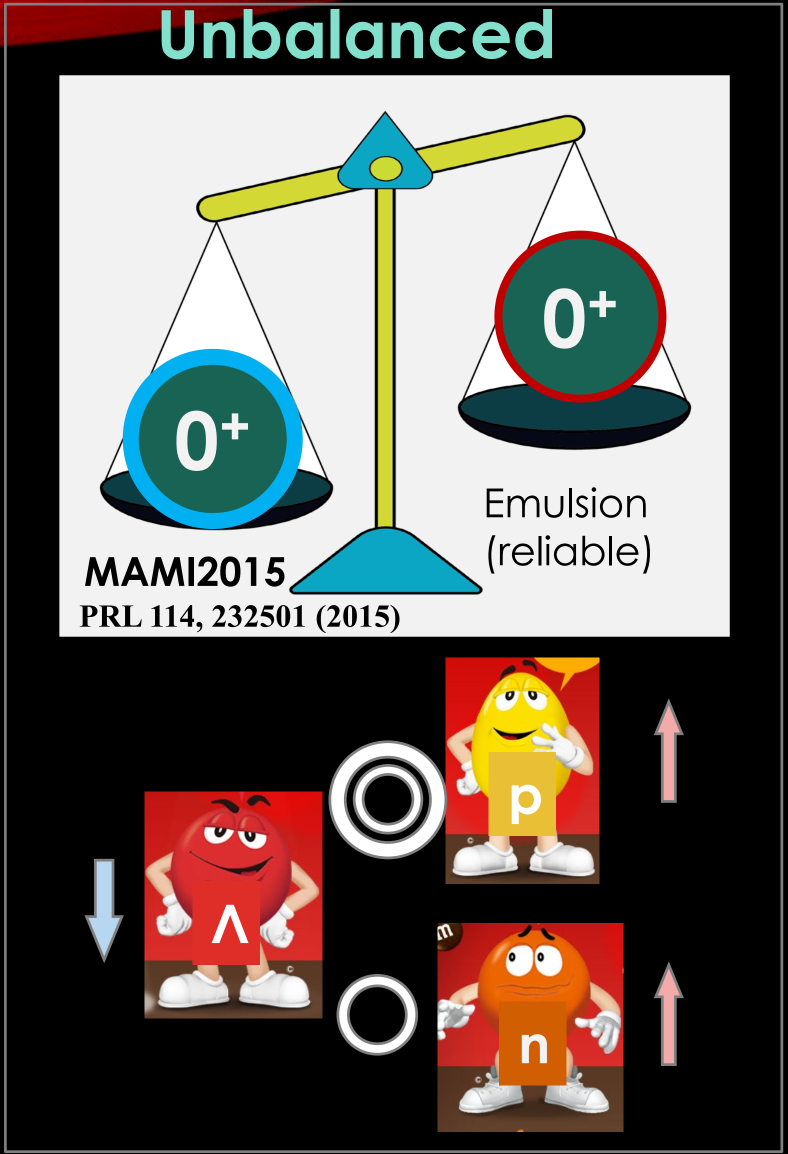


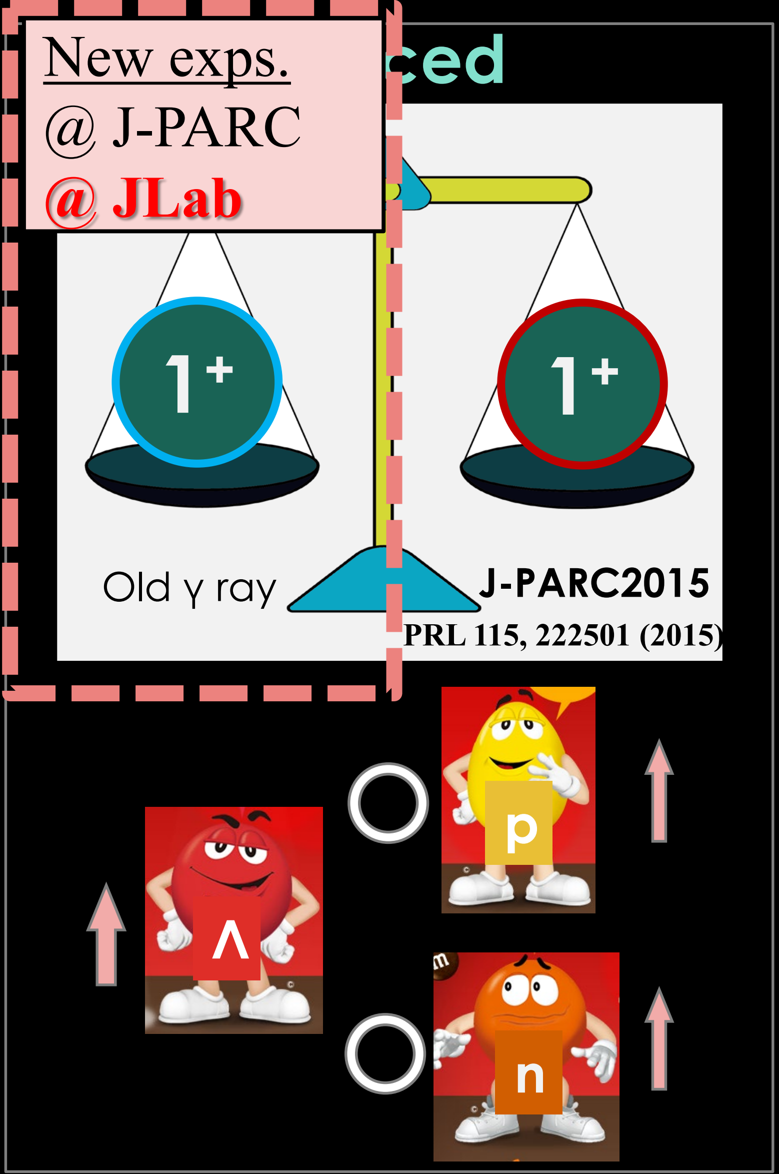
Σ may admix in the ΛN/ΛNN interaction

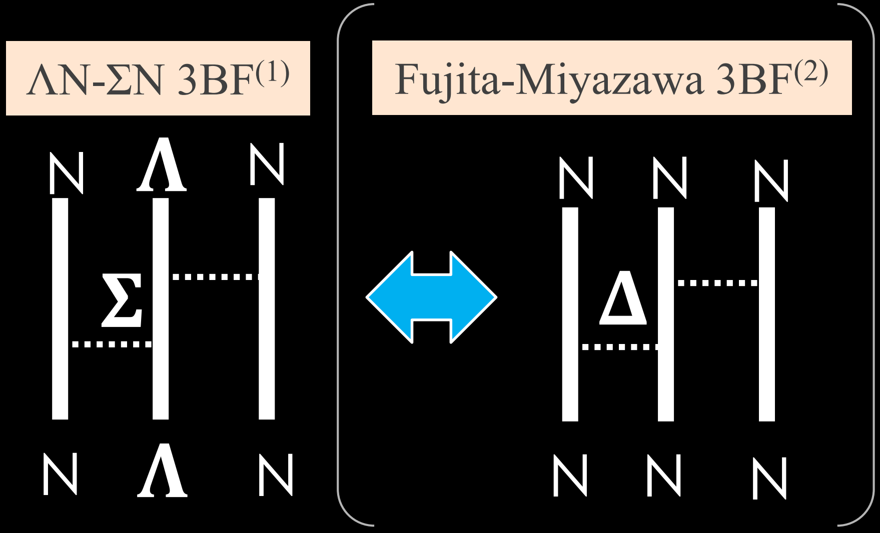
(1) Y. Akaishi et al., PRL 84, 3539 (2000)

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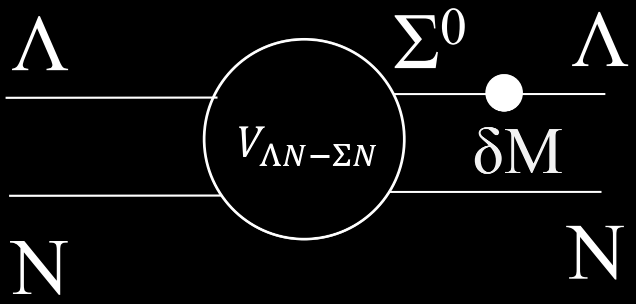
BASIC INFORMATION FOR THE ΛN CSB STUDY: ${}^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$

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).

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

Fundamental benchmark

A=4 → **CSB interaction**

→ A=5

→ A=7 HKS, PRL 110, 012502 (2013)

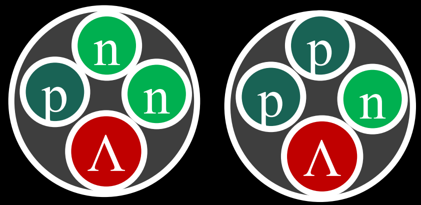
HKS, PRC 94, 021302(R) (2016)

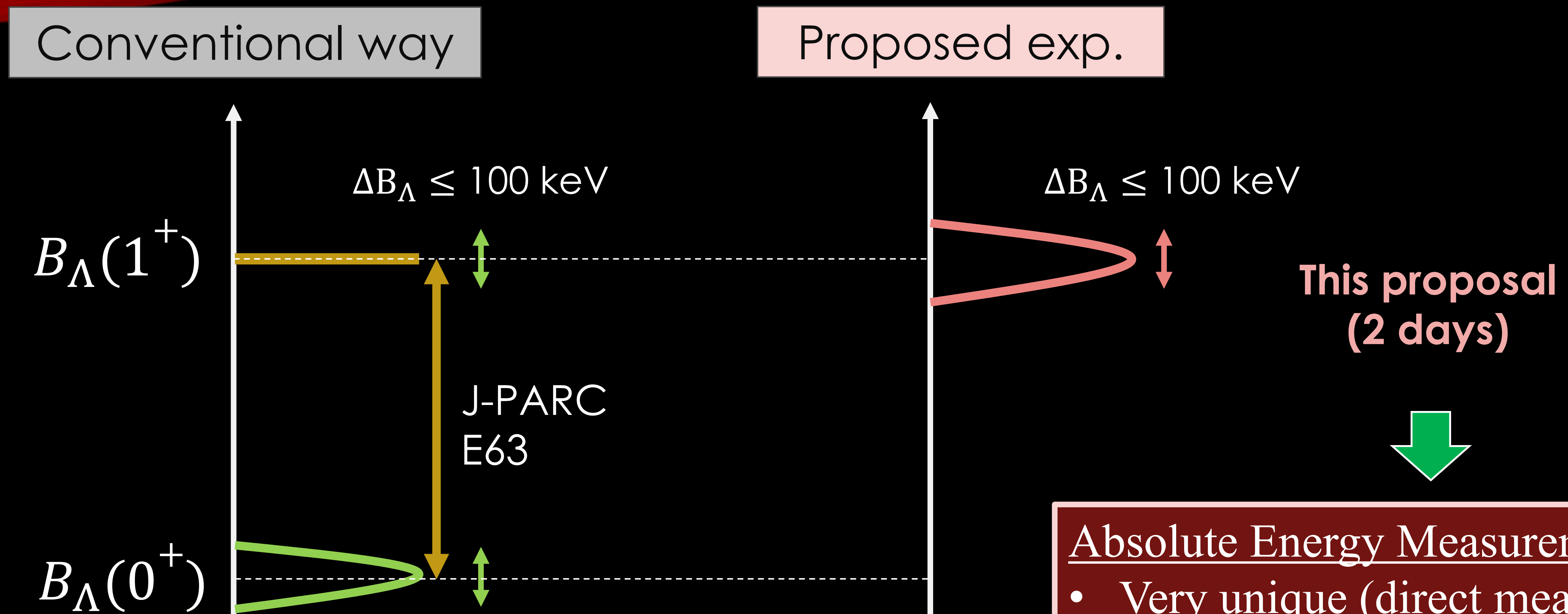
→ A=9 Hall A, PRC 91,034308 (2015)

→ A=10 HKS, PRC 93, 034314 (2016)

→ … HKS, PRC 90, 034320 (2014) …

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



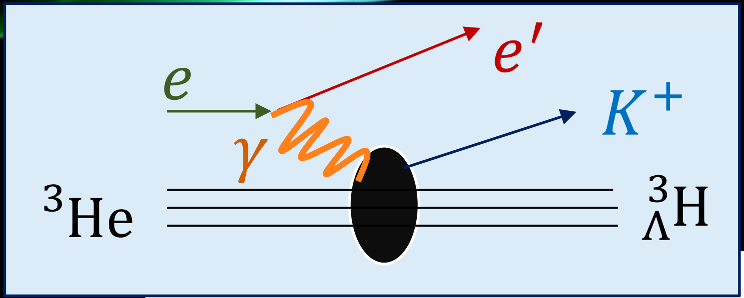


- Emulsion: **$2.08 \pm 0.06 \pm 0.04$ MeV** [(1)]
- MAMI: **$2.12 \pm 0.01 \pm 0.09$ MeV** [(2)]

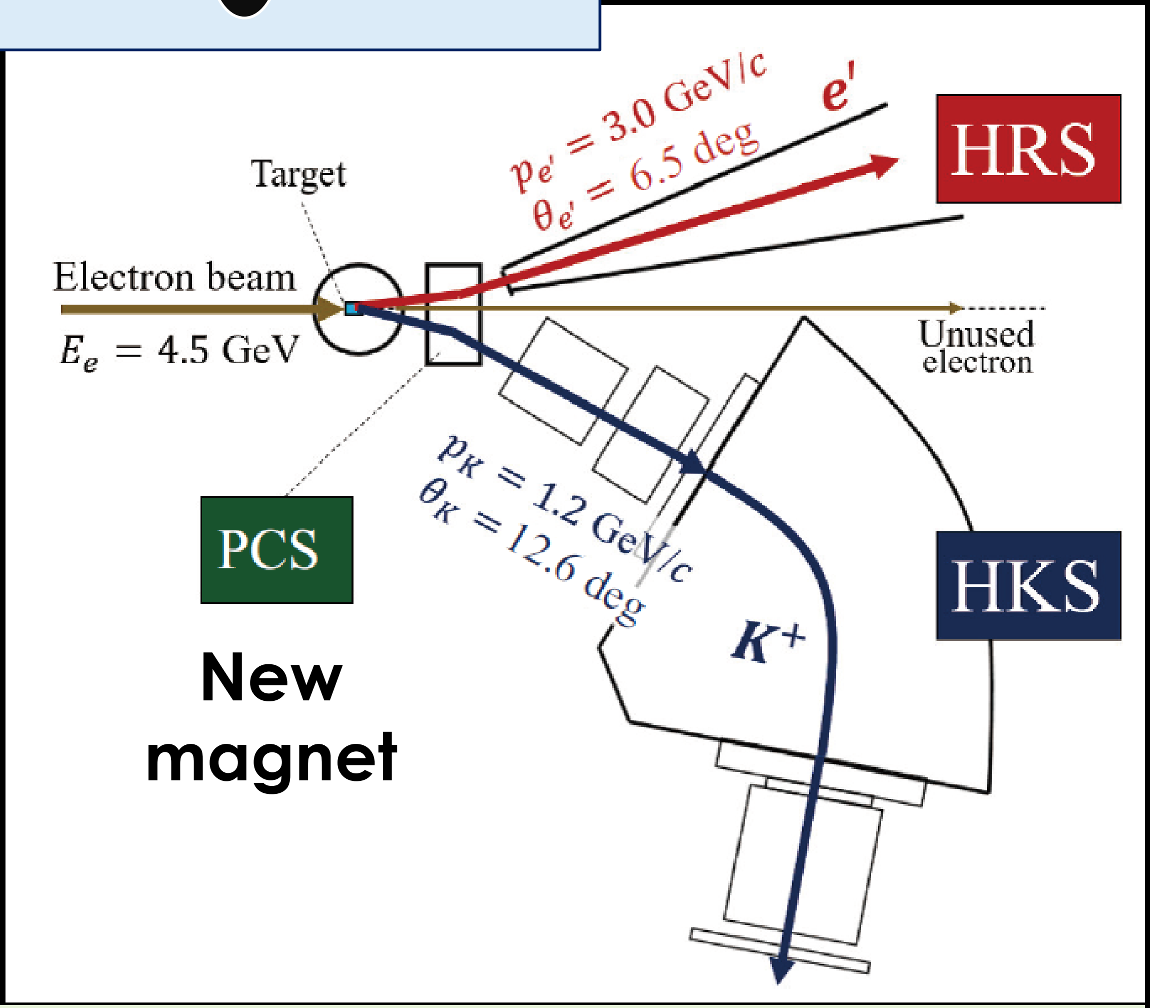
Absolute Energy Measurement:
- Very unique (direct meas.)
- Complementary with other data

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

EXPERIMENTAL SETUP



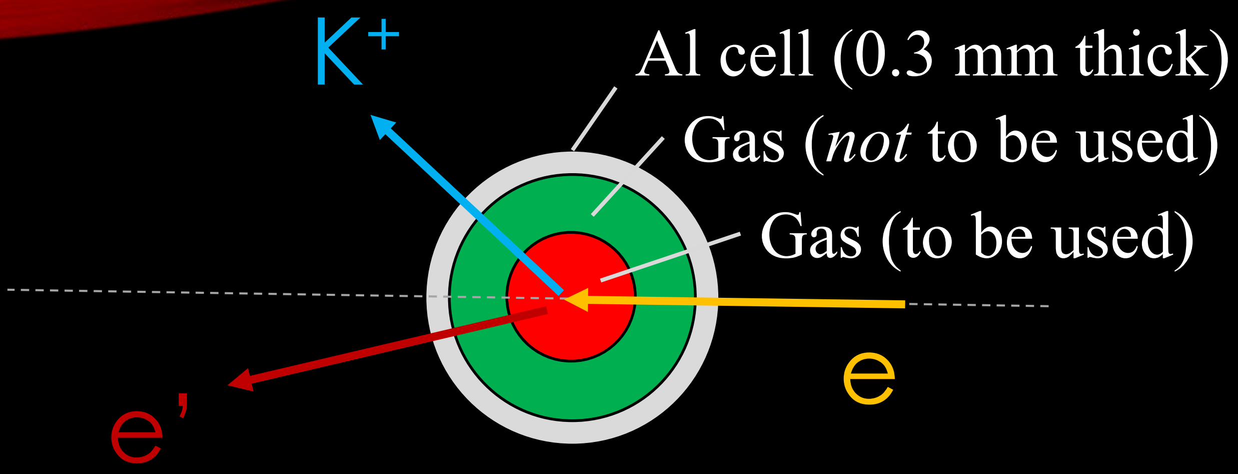
- Same as E12-15-008 ($^{40,48}_{\Lambda}$K)
- PCS → constructed in Japan
- Proposed targets
  - Physics: ^{3}He, ^{4}He gases
  - Calibration: ^{1}H gas, Multi-C, Empty
- Target ladder may be separated from others

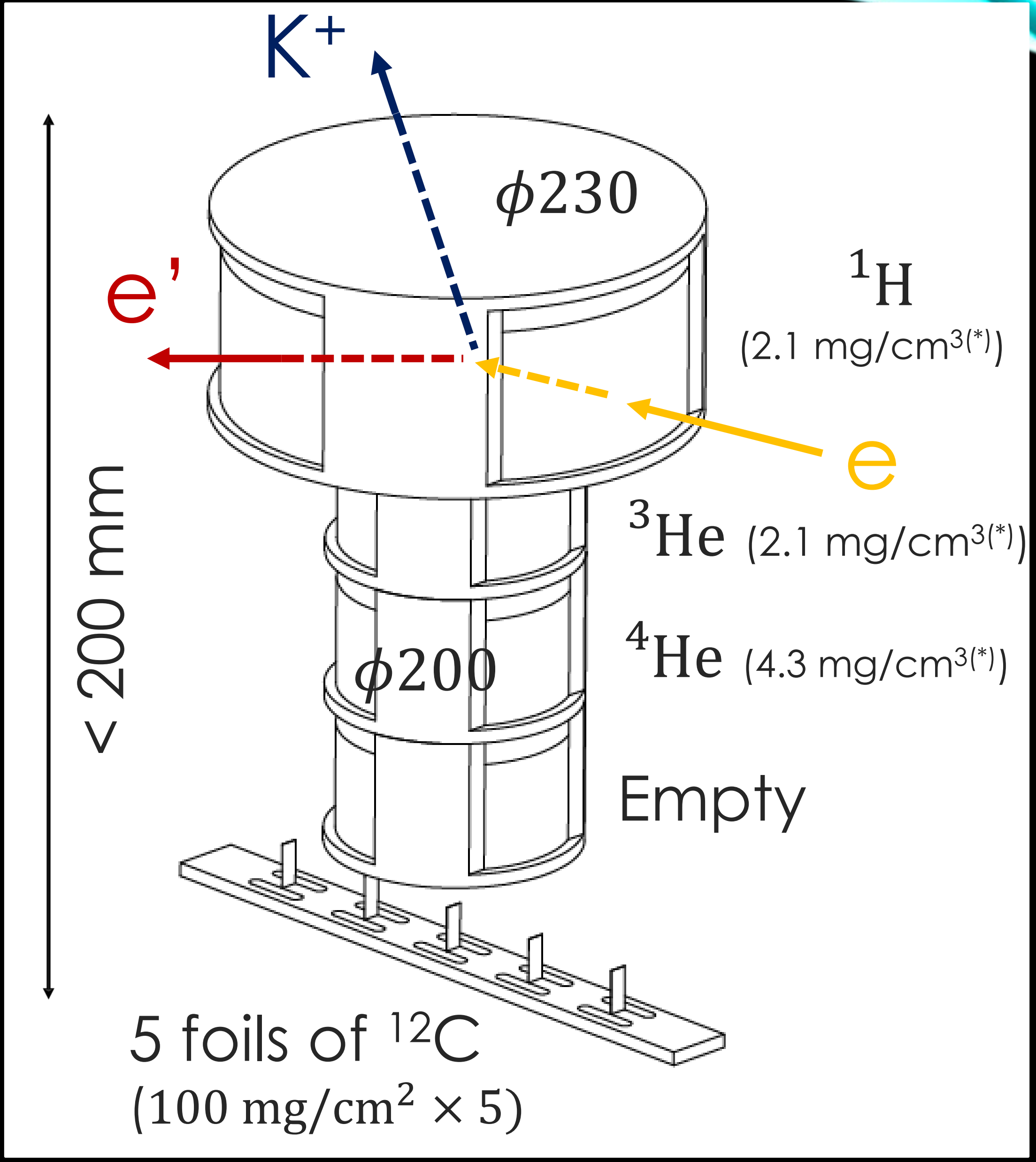


PCS @ TOKIN, Sendai, Japan (March 2020)

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

TARGET





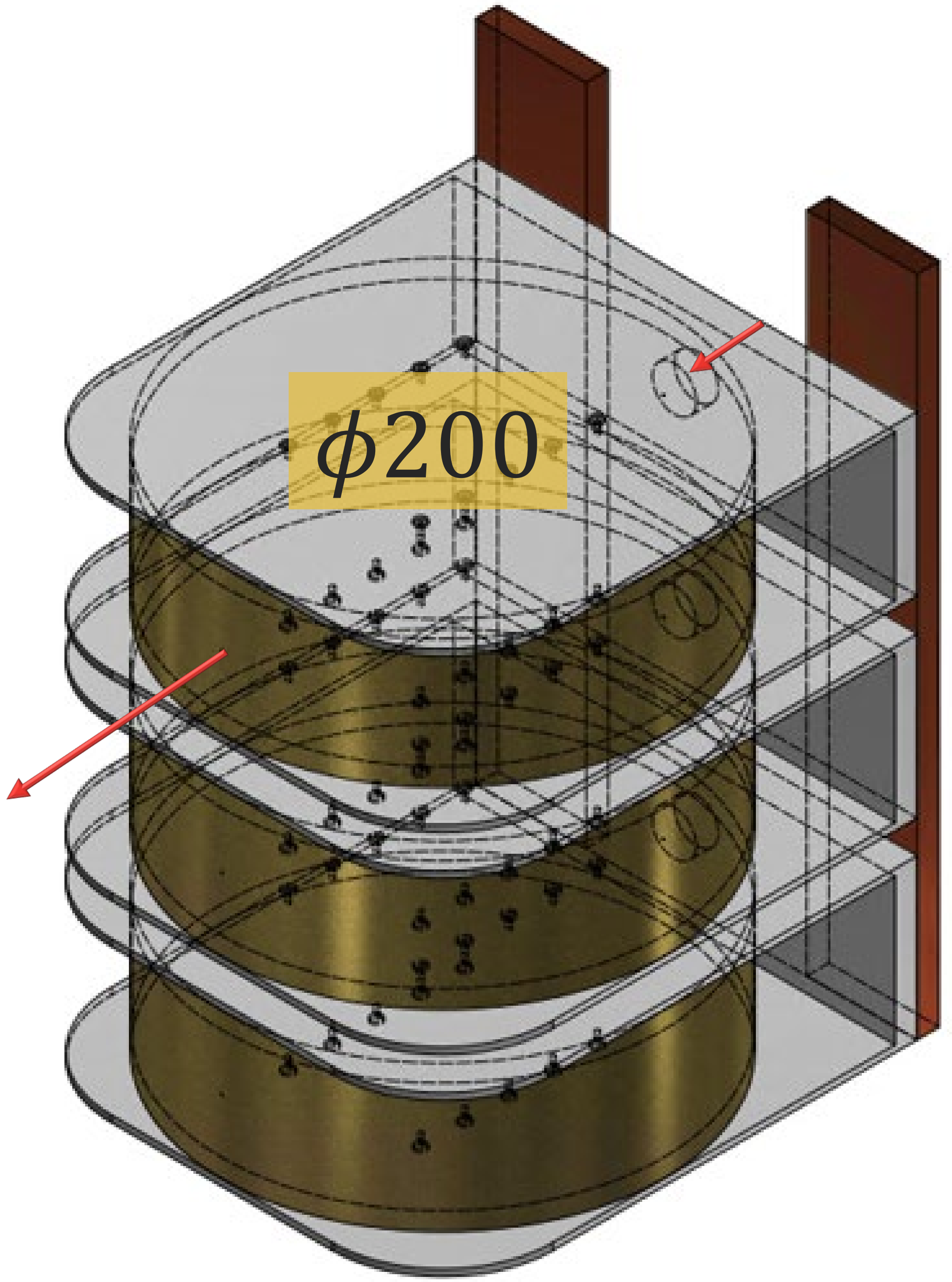
<u>To minimize systematic error on B_Λ</u>

- Tuna-can type of cell
  → Path length in Al cell wall ↘
  (Multiple scattering effect ↘; $\frac{x}{X_0} \simeq 3.4 \times 10^{-3}$)

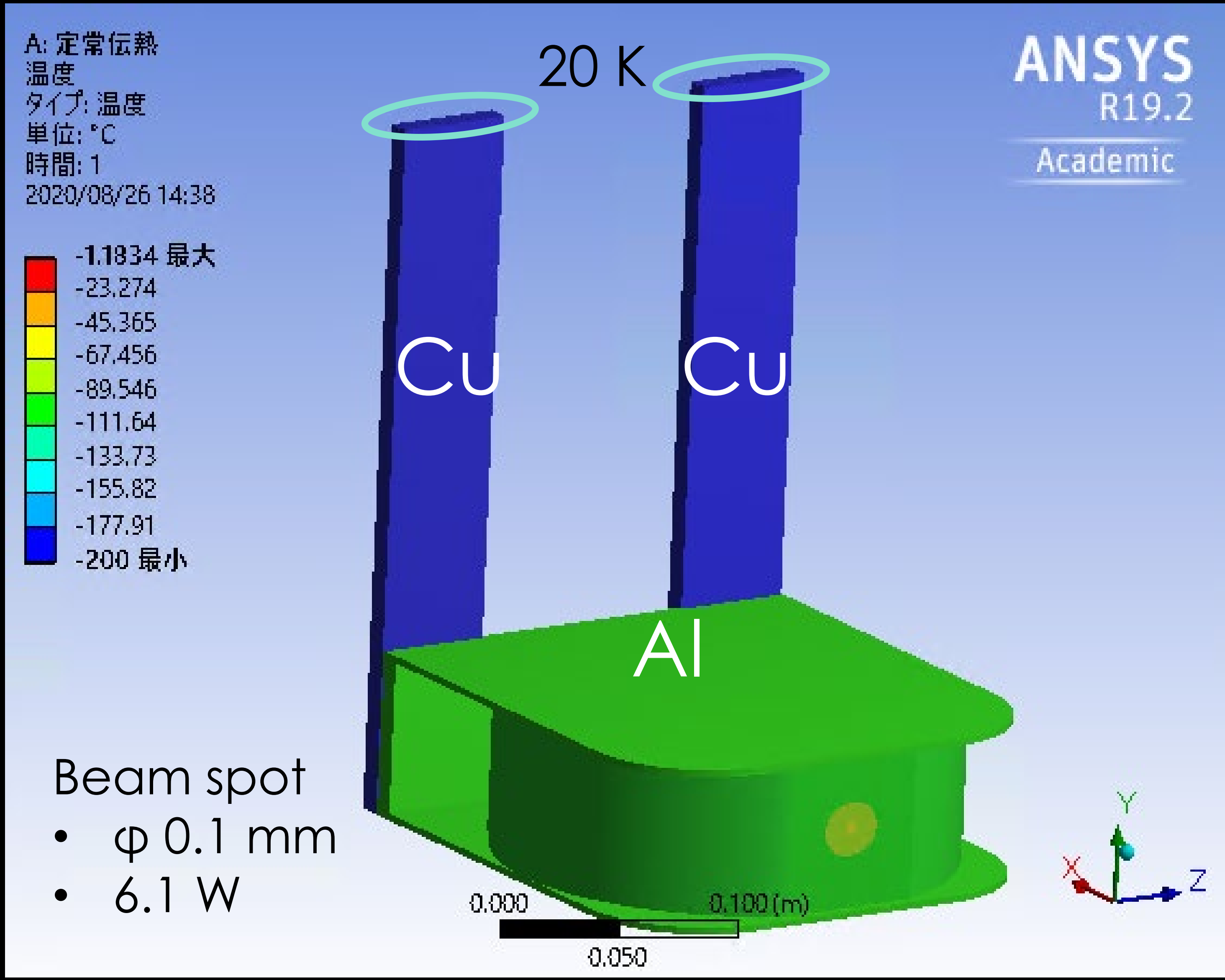
<u>To achieve better S/N</u>

- Center part will be used for analysis
  ($\Delta z_t = 15$ mm FWHM is expected)

(*) S.N. Santiesteban et al., NIMA 940 (2019)351—358

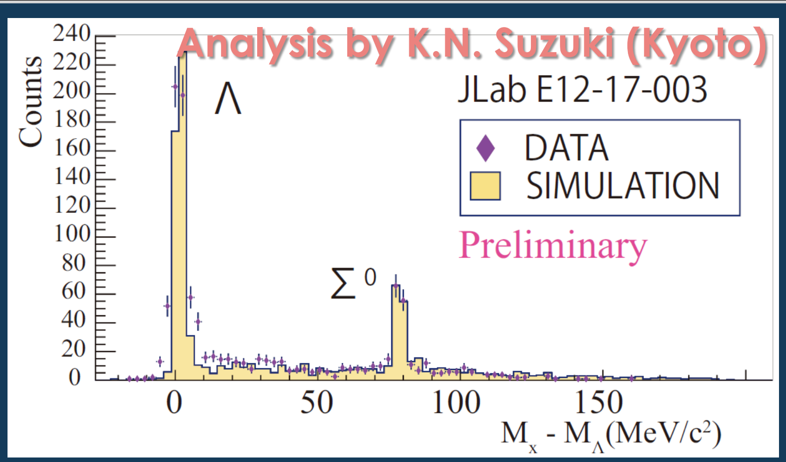


ϕ200



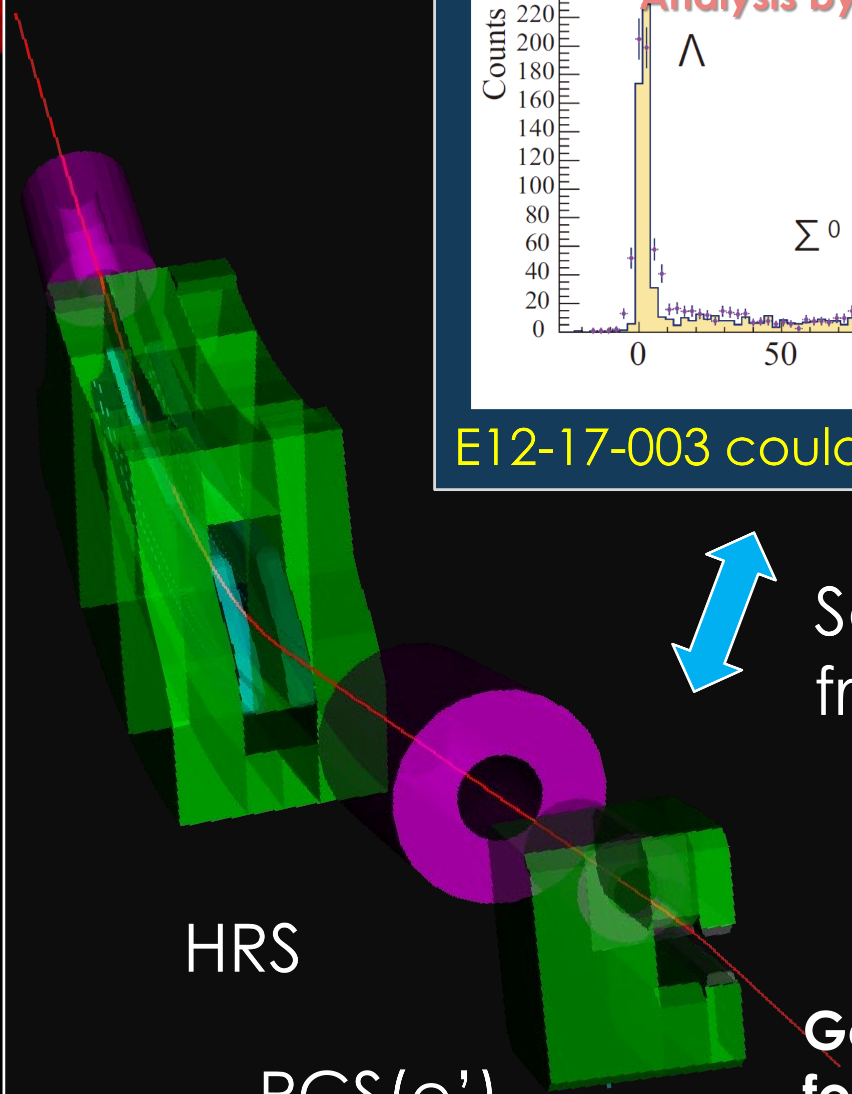
A: 定常伝熱
温度
タイプ: 温度
単位: °C
時間: 1
2020/08/26 14:38
-1.1834 最大
-23.274
-45.365
-67.456
-89.546
-111.64
-133.73
-155.82
-177.91
-200 最小
20 K
Cu
Cu
Al
ANSYS
R19.2
Academic
0.000
0.100 (m)
0.050
Beam spot
• φ 0.1 mm
• 6.1 W

EXPECTED MISSING MASS RESOLUTION



E12-17-003 could be reproduced

Same framework



Geant4 simulation for C12-19-002

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

$$\overrightarrow{p^{\mathrm{HRS,HKS}}} = \sum_{i+j+k+l+m=0}^{n_2} a_{ijklm} x^i_{\mathrm{FP}} x'^j_{\mathrm{FP}} y^k_{\mathrm{FP}} y'^l_{\mathrm{FP}} z^m_{T,\mathrm{HRS}}$$

	$\Delta p/p$	$\boldsymbol{\Delta\theta}$ (mrad)
HRS	2.6×10^{-4}	0.6
HKS	4.2×10^{-4}	1.5

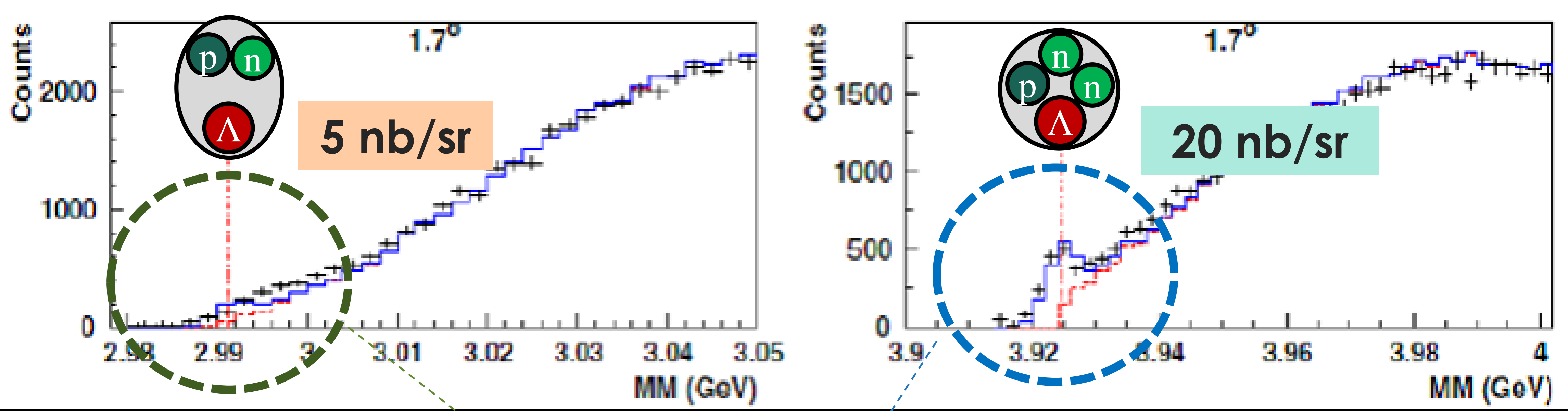
w/ materials (e.g. target):

$$\frac{\Delta p}{p} \Rightarrow \frac{\boldsymbol{\Delta p}}{\boldsymbol{p}} \times \mathbf{1.1},\ \Delta\theta \Rightarrow \boldsymbol{\Delta\theta} \times \mathbf{1.4}$$

$$\boldsymbol{\Delta M_{\mathrm{HYP}} = 1\ \mathrm{MeV\ (FWHM)}}$$

YIELD ESTIMATION

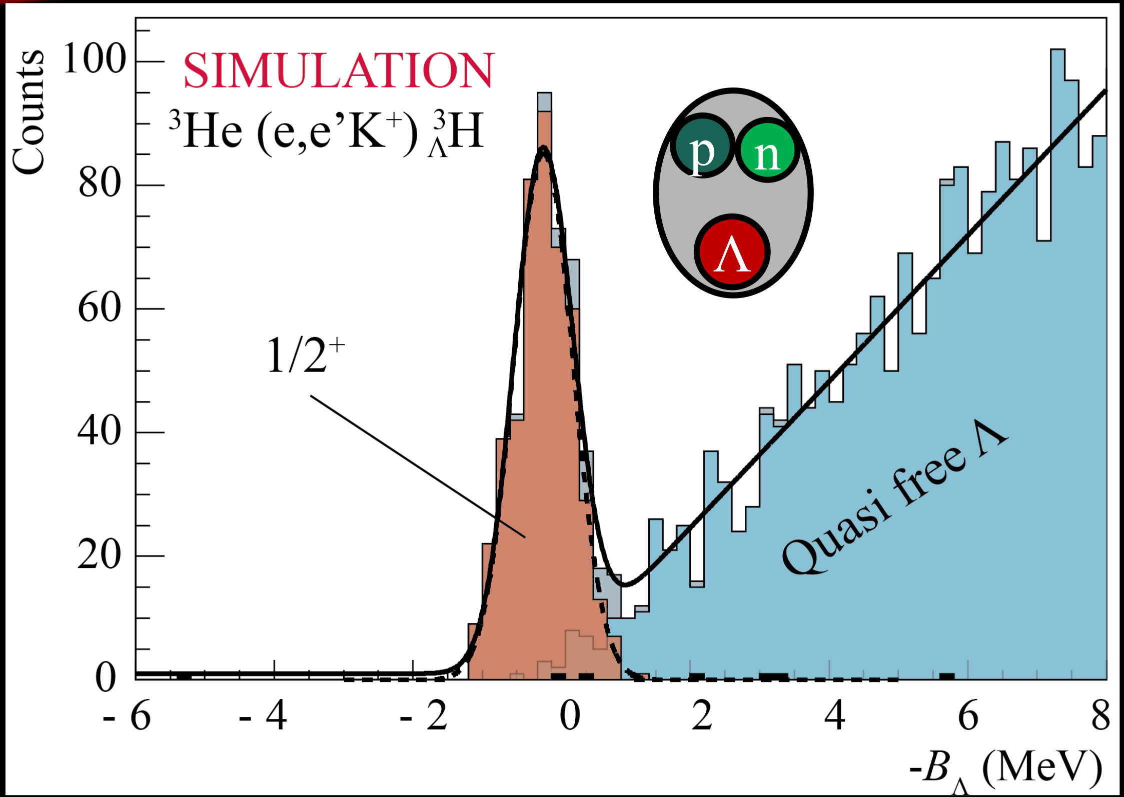
F. Dohrmann et al., *Phys. Rev. Lett.* **93**, 242501 (2004).



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**

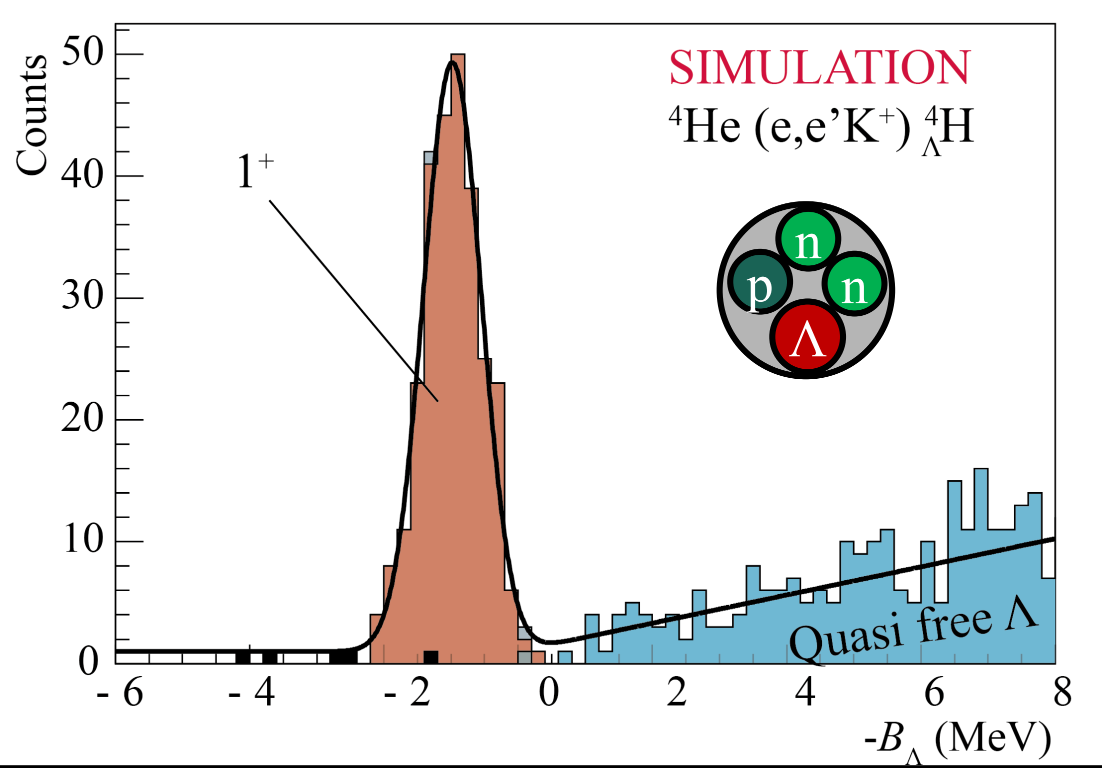
VP flux = 2 × 10^{-5} (/e), $\epsilon_{\text{det}} = 0.75, f_{\text{density}} = 0.85, f_{Kdecay} = 0.26, \Omega_K = 7$ msr

EXPECTED SPECTRA AND STATISTICAL ERRORS



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

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



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

➡ 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	

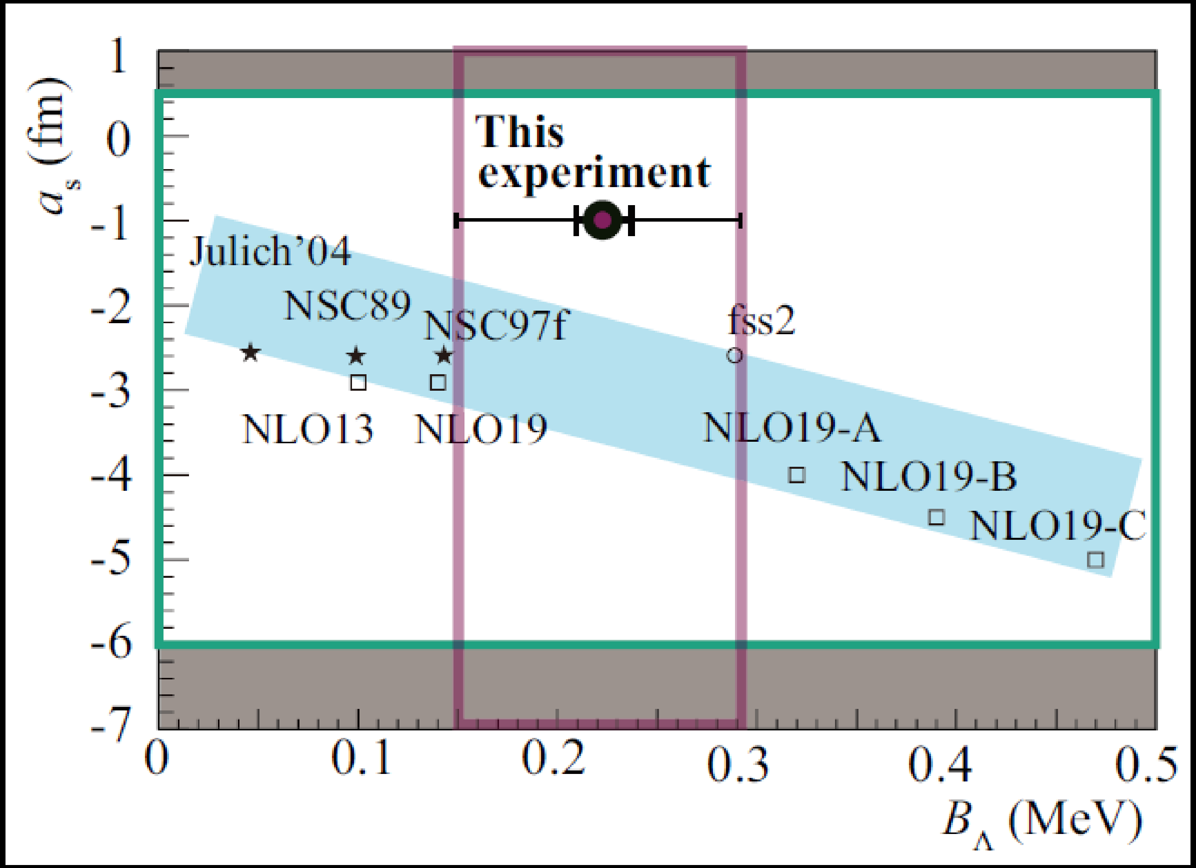
Major contributions to a systematic error on B_Λ

- Energy scale calibration(*) : ± 50 keV
- Energy loss correction: ± 40 keV
  - target density $|\Delta d| = 3\%$
  - cell thickness uniformity $|\Delta t| = 10\%$

$$|\Delta B_\Lambda^{sys.}| = 70 \text{ keV}$$

(*) TG et al., NIMA 900 (2018) 69—83

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



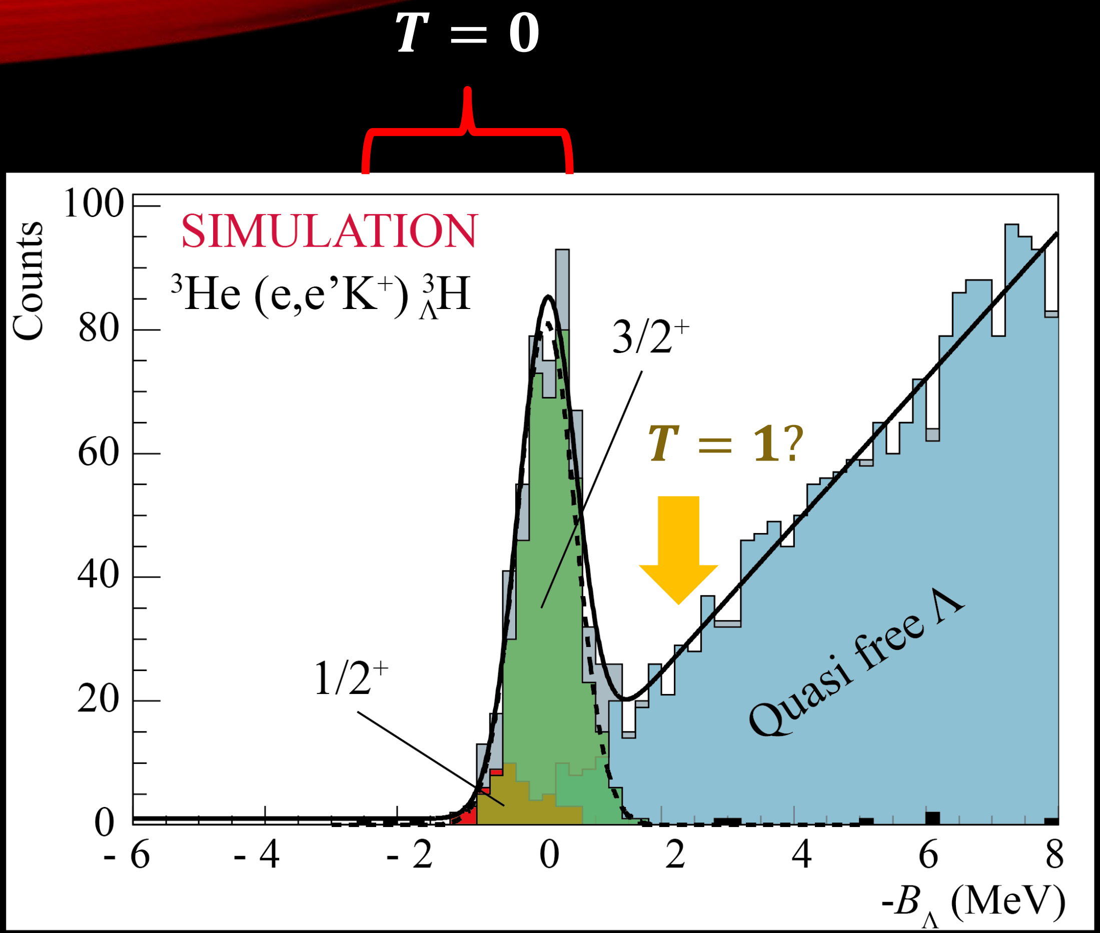
Hypertriton Puzzle

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

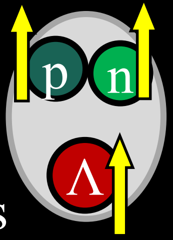
ΛN interaction

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



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



- 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
    - 🡐 $\not\pi$EFT 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 → $\left|\Delta B_{\Lambda}^{\mathrm{stat.}}\right| \sim 70$ 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-HRS @ Hall A (JLab E12-17-003, 2018)

- $^{3}\mathrm{H}(e, e'K^{+})nn\Lambda$
- Analysis in progress (by 3 independent teams)

  ➔ Peak search, n(n)-Λ FSI, reaction cross section

HRS-HKS @ Hall A (JLab C12-19-002, 2022/2023)

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

$$\Delta B_{\Lambda}^{\mathrm{tot.}} = \sqrt{\left|\Delta B_{\Lambda}^{\mathrm{sys.}}\right|^{2} + \left|\Delta B_{\Lambda}^{\mathrm{stat.}}\right|^{2}} < 80\ \mathrm{keV}$$

➔ Hypertriton Puzzle / Charge Symmetry Breaking