JLab PAC 49

Conditional Experiment: JLab C12-19-002

High accuracy measurement of nuclear masses of hyperhydrogens

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S.N. Nakamura, F. Garibaldi, P. Markowitz, J. Reinhold, L. Tang, G.M. Urciuoli

for the JLab Hypernuclear Collaboration

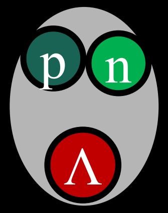
July 20, 2021

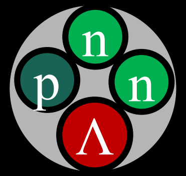
京都大学

KYOTO UNIVERSITY

REQUEST SUMMARY (C12-19-002)

- ☆ **HRS-HKS @ Hall A**
- ☆ **50-μA beam on ^{3}He and ^{4}He gas targets**
- ☆ **Beamtime = 14.5 days**
  - ✓ 12 days for Physics
  - ✓ 2.5 days for Calibrations





➔ World best accuracy in measuring $B_{\Lambda}({}^{3,4}_{\Lambda}\mathrm{H})$

➔ Hypertriton Puzzle / Charge Symmetry Breaking

CONTENTS

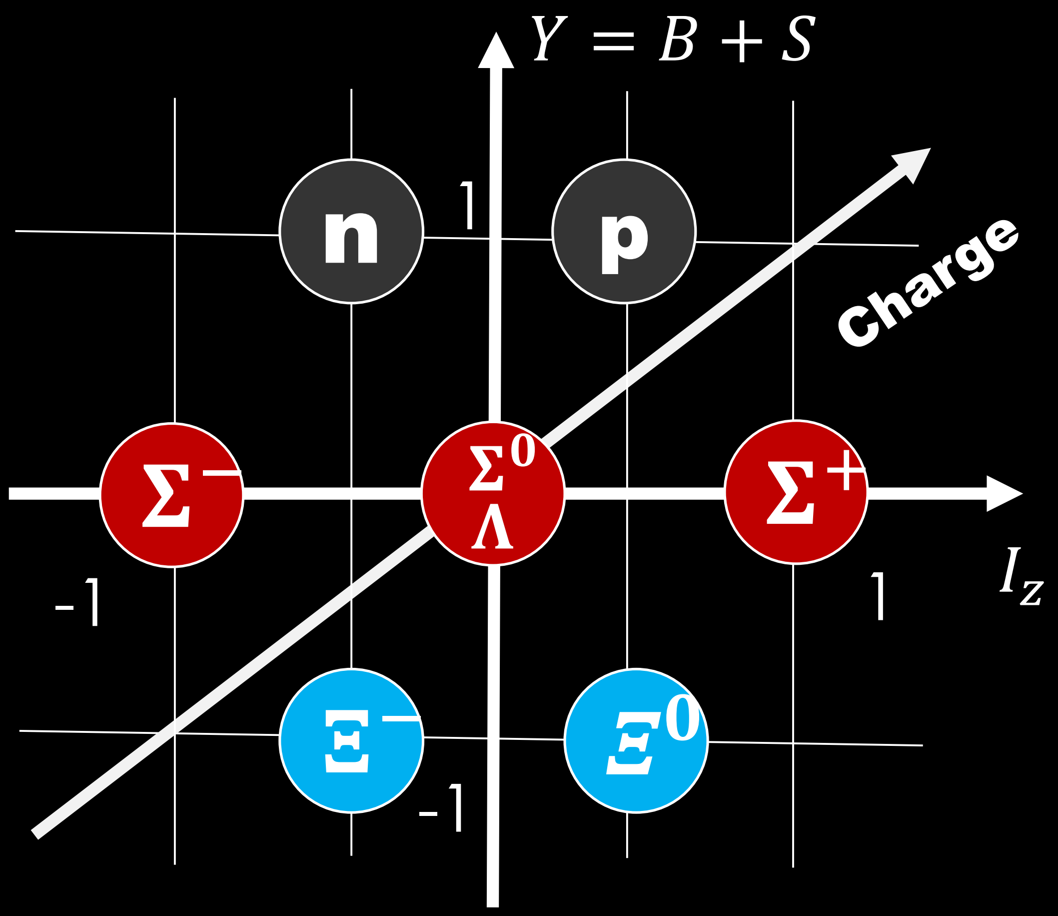
1. **Introduction**
   - Hypernuclear Study
   - Physics motivation for $^{3,4}_{\Lambda}\mathrm{H}$ measurement

2. **Experiment**

3. **Summary**

INTRODUCTION (HYPERNUCLEAR STUDY)

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

HOW TO INVESTIGAE THE BB INTERACTION

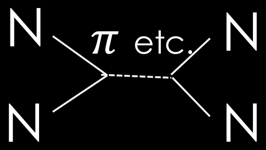
Method A

Data

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

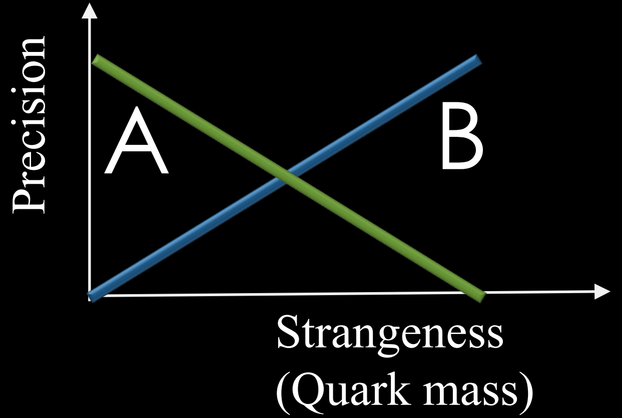
Phenomenological Theories

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



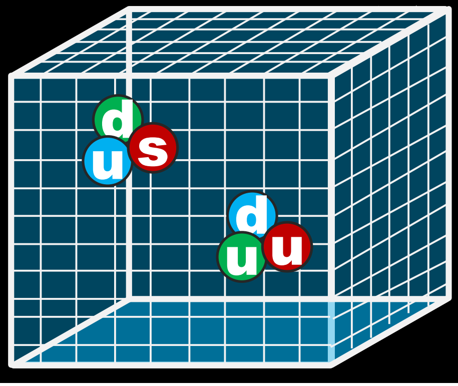
H. Yukawa (Kyoto Univ.)
Novel Prize 1949

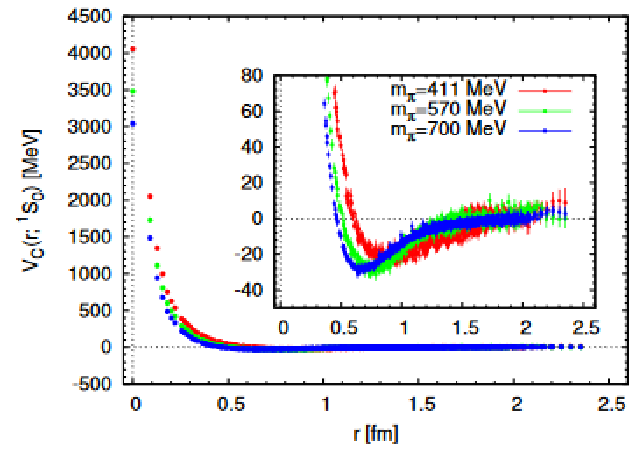
Complementary



Method B

Lattice QCD
(First principle calc.)

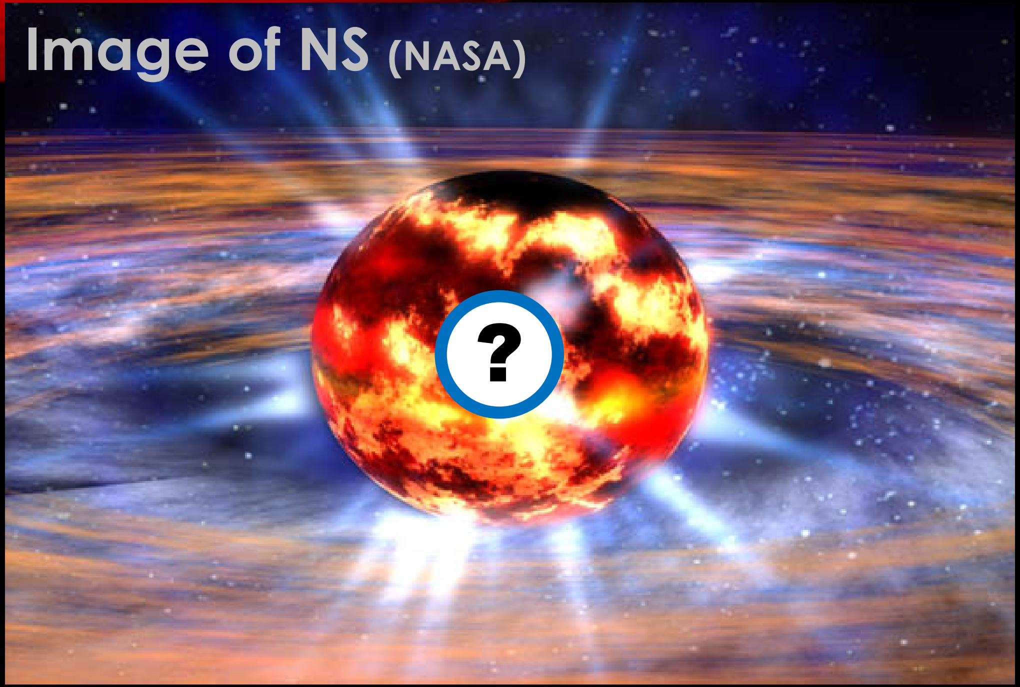




arXiv:2003.10730v2 [hep-lat] 12 Jul 2020

BB interaction (Strong force)

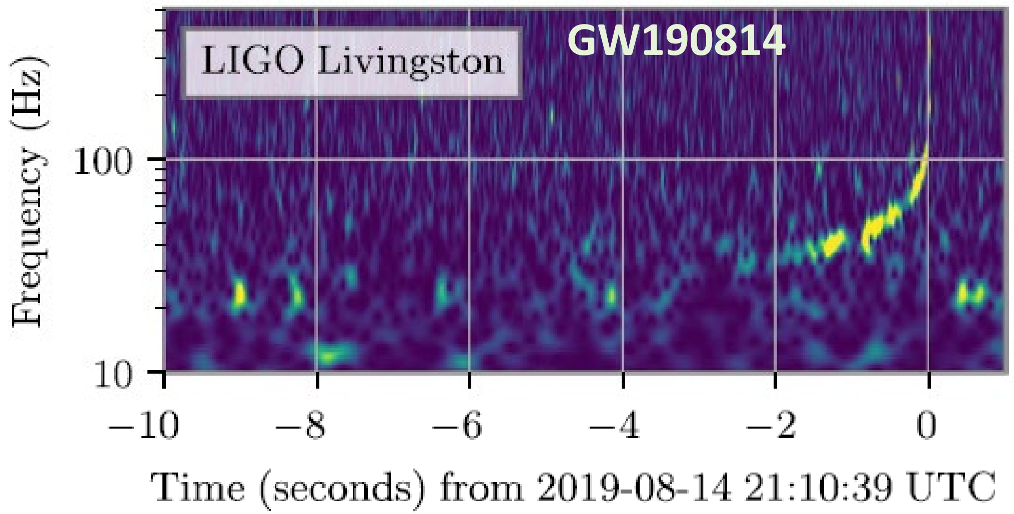
NEUTRON STARS AND HYPERONS



What's inside ?

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

The Astrophysical Journal Letters, 896:L44 (20pp), 2020 June 20



→ $23.2^{+1.1}_{-1.0} M_\odot$ - $\mathbf{2.59}^{+0.08}_{-0.09} M_\odot$

Hyperons make a NS softer

→ $\geq 2M_\odot$ 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

INTRODUCTION
(PHYSICS MOTIVATION)

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

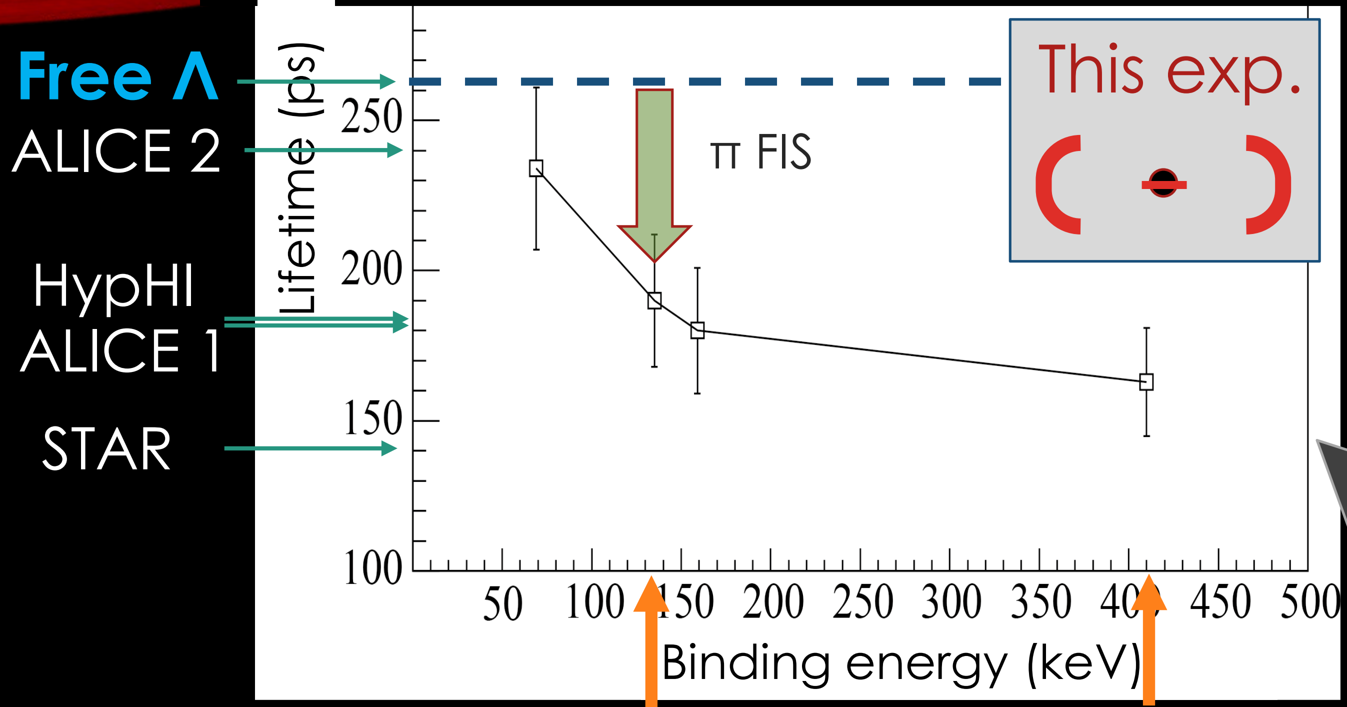
$\tau = (0.5\sim0.92)\,\tau_{\Lambda}$
(HypHI, STAR, ALICE)

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

A.Pérez-Obiol et al., Phys Lett. B 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)

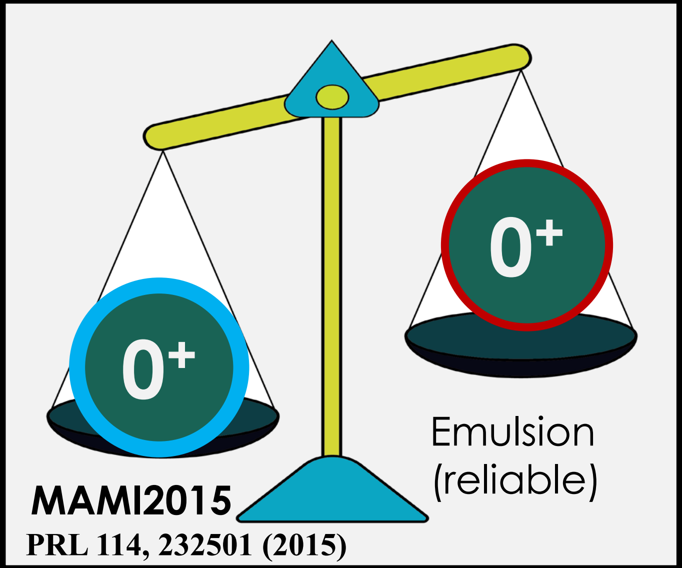
$\propto \sqrt{B_\Lambda}$

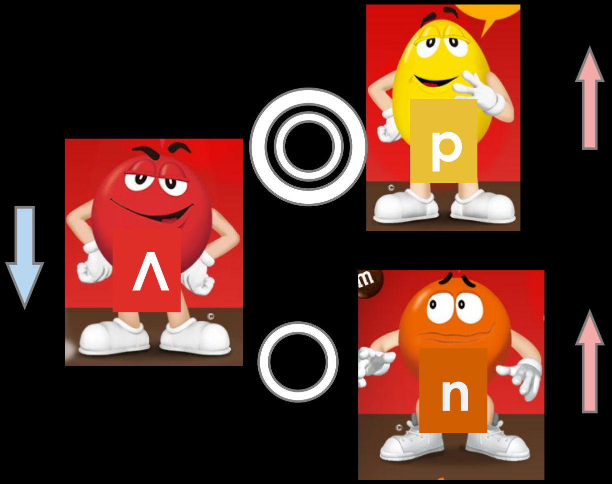
Proposed experiment (C12-19-002)
$|\Delta B^{stat.}| = 20$ keV, $|\Delta B^{sys.}| = 55$ keV

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

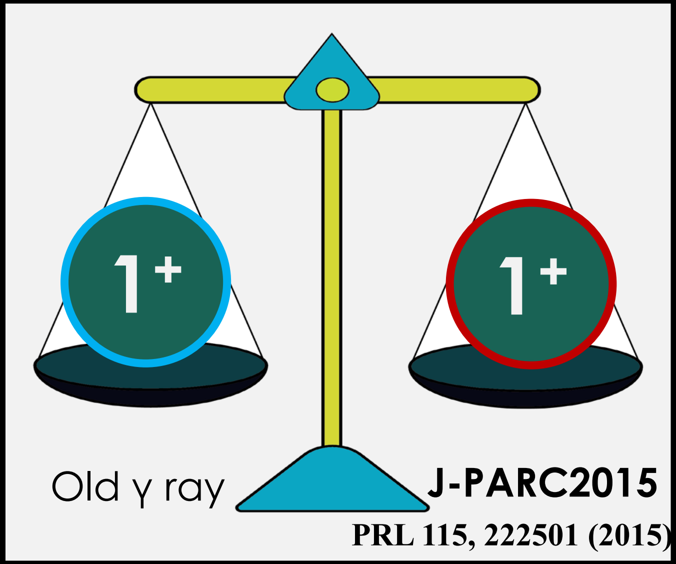
CHARGE SYMMETRY BREAKING (CSB) IN THE ΛN INTERACTION

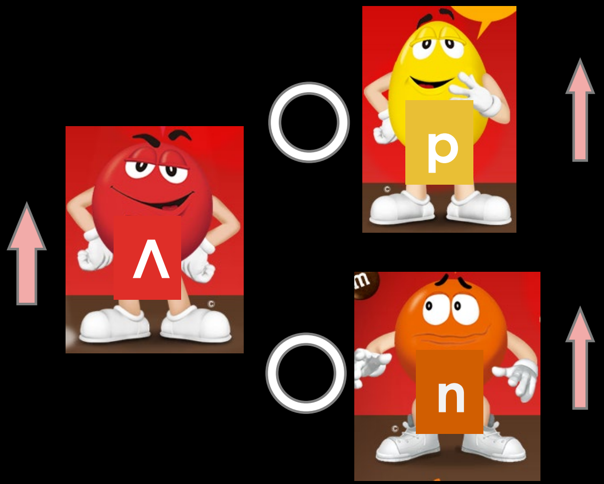
Unbalanced

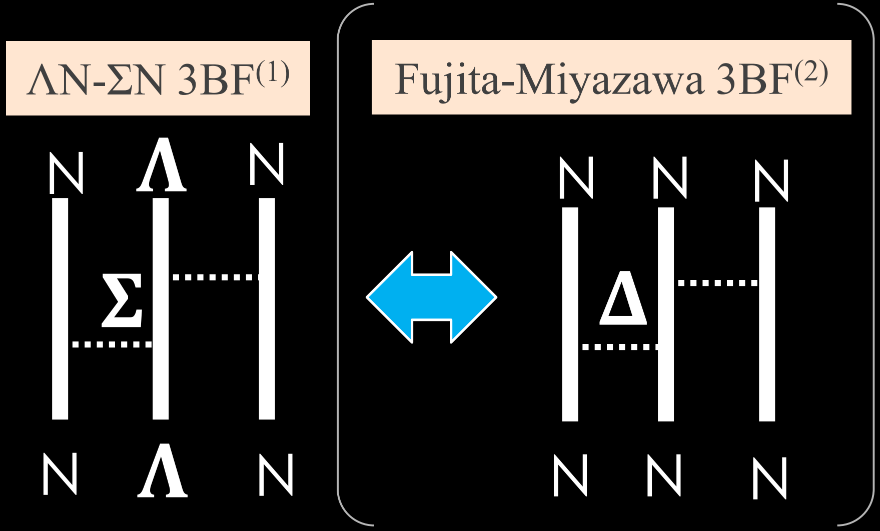




Balanced







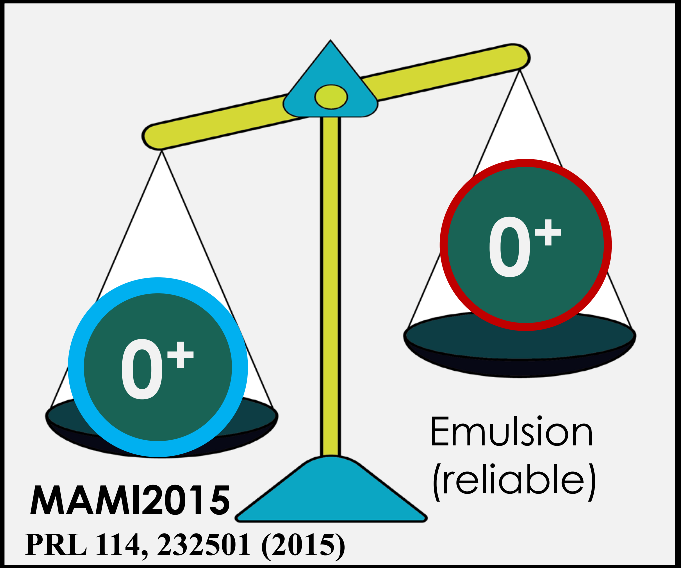
Σ may admix in the ΛN/ΛNN interaction

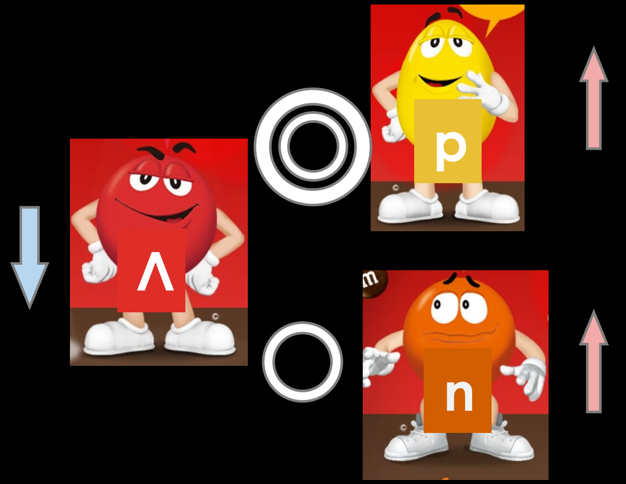
(1) Y. Akaishi et al., PRL 84, 3539 (2000)

(2) *J. Fujita and H. Miyazawa, Prog. Theor. Phys.,17, 3, 360–365 (1957)*

Charge Symmetry Breaking (CSB) in the ΛN Interaction

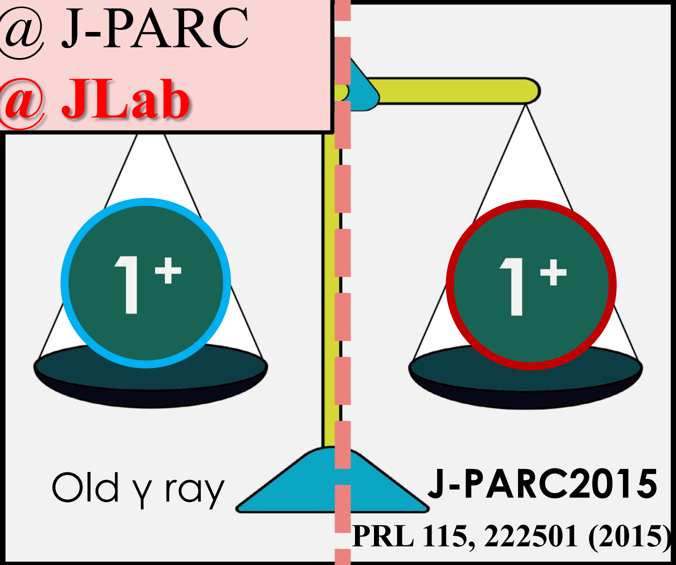
Unbalanced

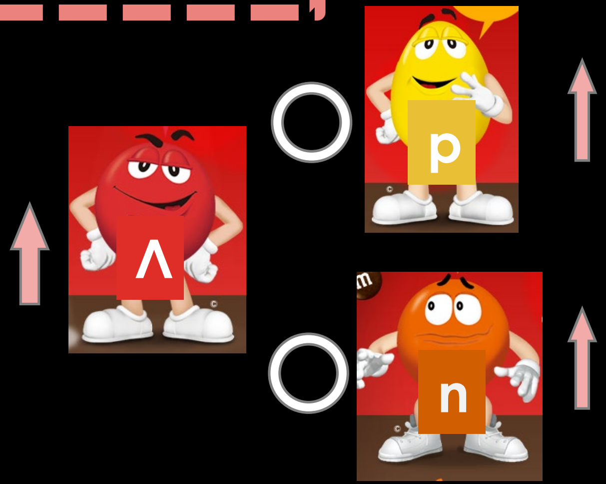


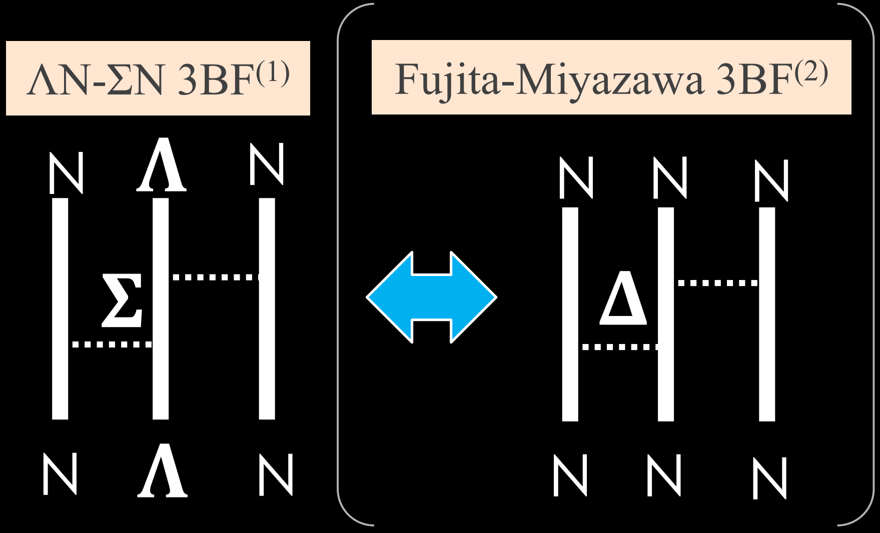


...ced

New exps.
@ J-PARC
@ JLab







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(1) Y. Akaishi et al., PRL 84, 3539 (2000)
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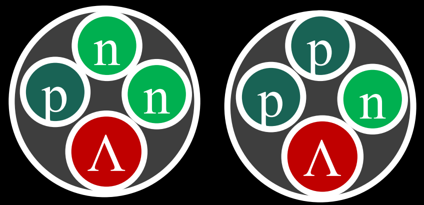
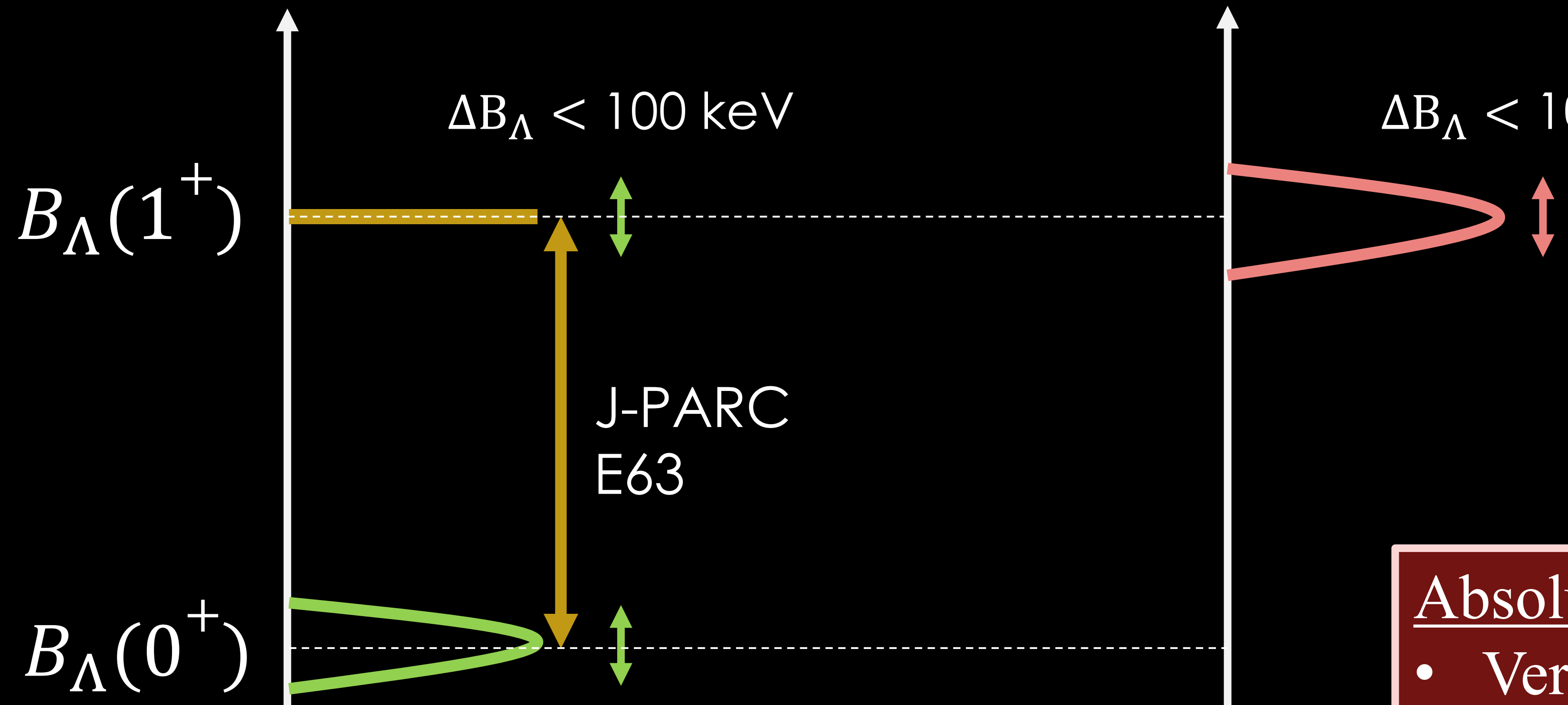
HOW WE CONFIRM THE $B_\Lambda({}^4_\Lambda\mathrm{H};\ 1^+)$



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)]

This proposal (2 PAC days)

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

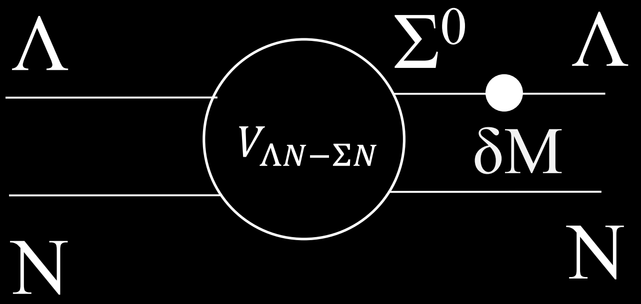
(1) NPB 52, 1-30 (1973)
(2) PRL 114, 232501 (2015)

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).

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

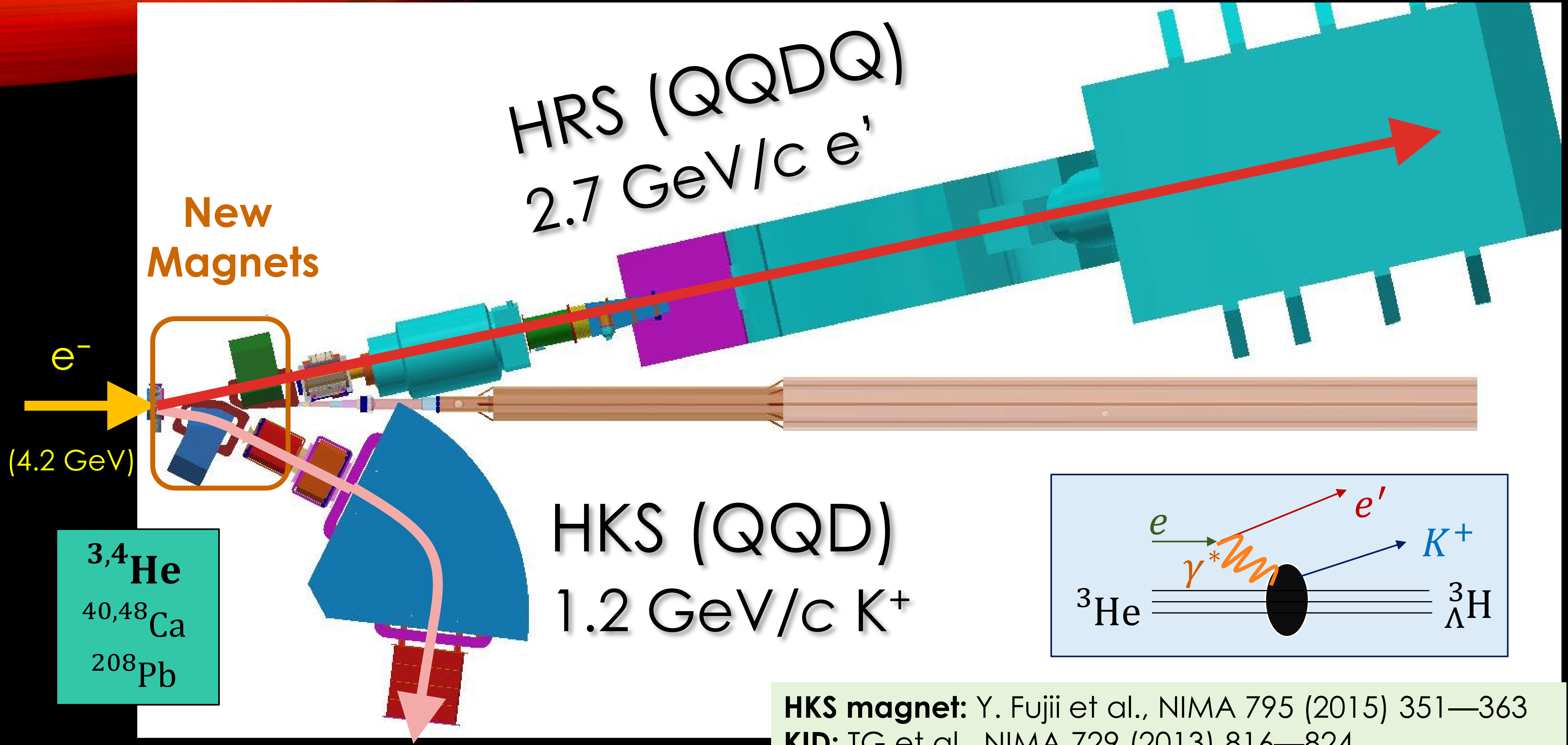
Basic Input (This proposal)

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) …

PROPOSED EXPERIMENT

Experimental Setup at JLab Hall A



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

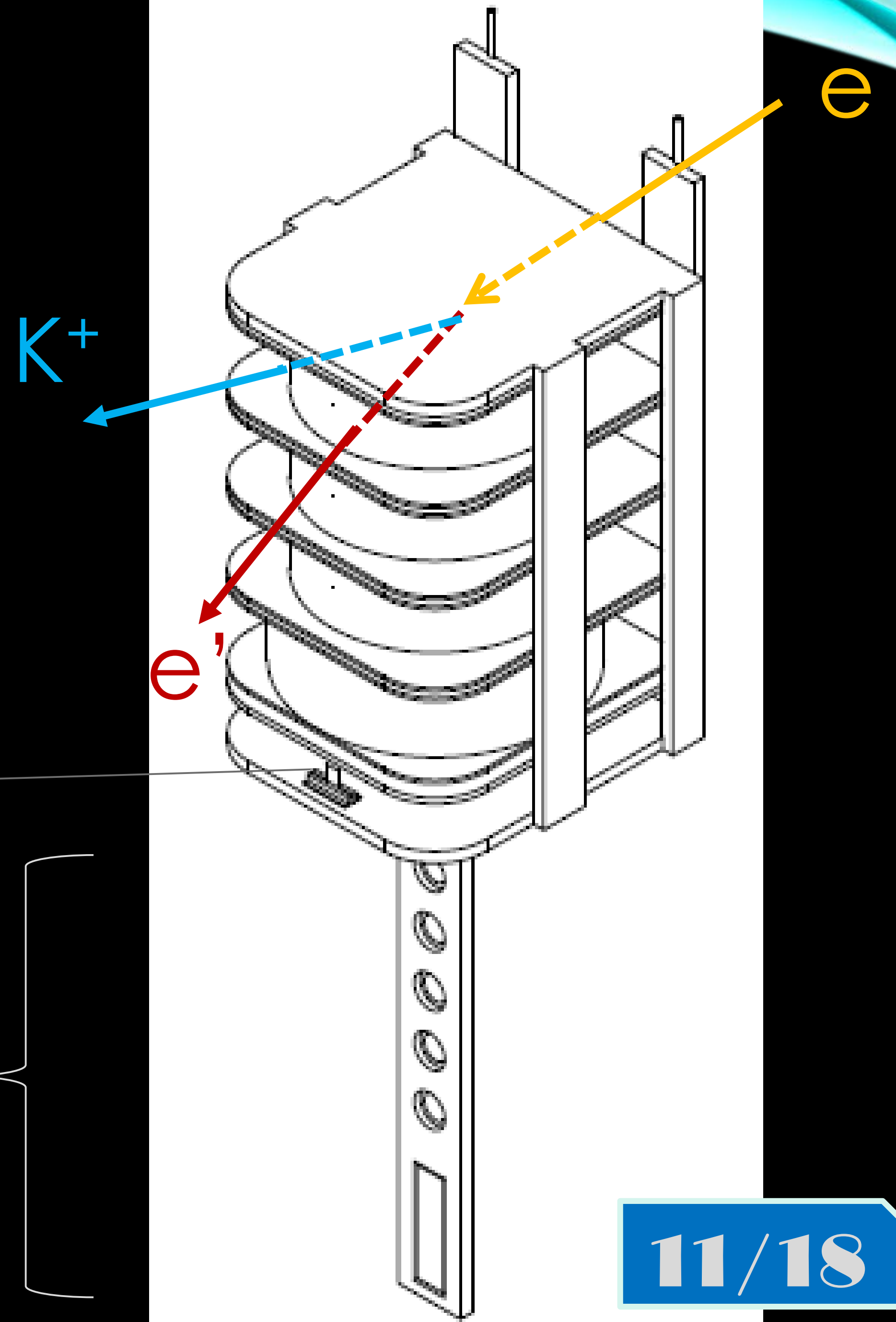
PCS IS READY TO BE TRANSPORTED TO JLAB

TARGET CELLS (TUNA CAN)

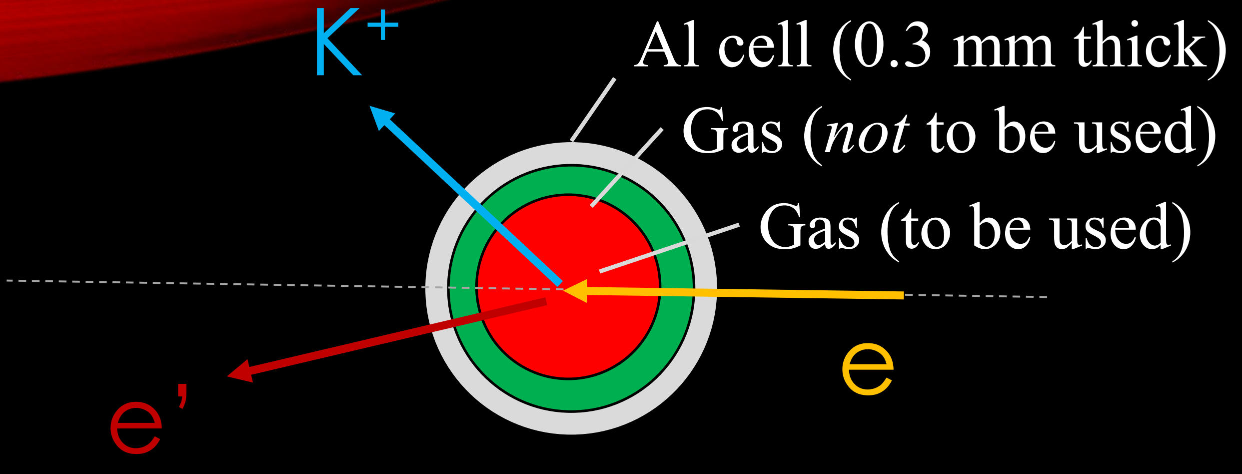
Gas targets (φ200 mm, height = 50 mm)

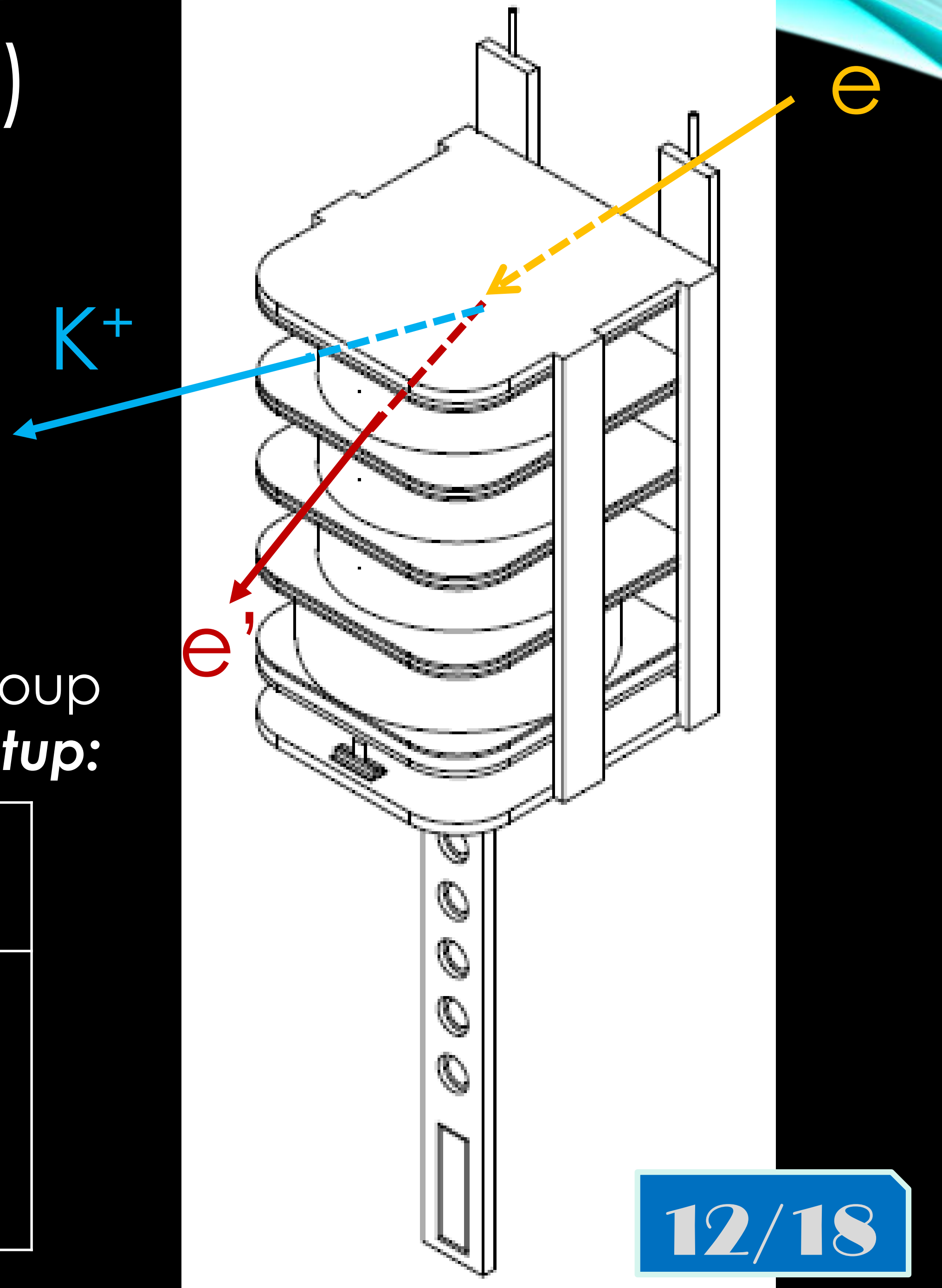
Multi carbon targets

Solid targets (E12-15-008, E12-20-013)



TARGET CELLS (TUNA CAN)

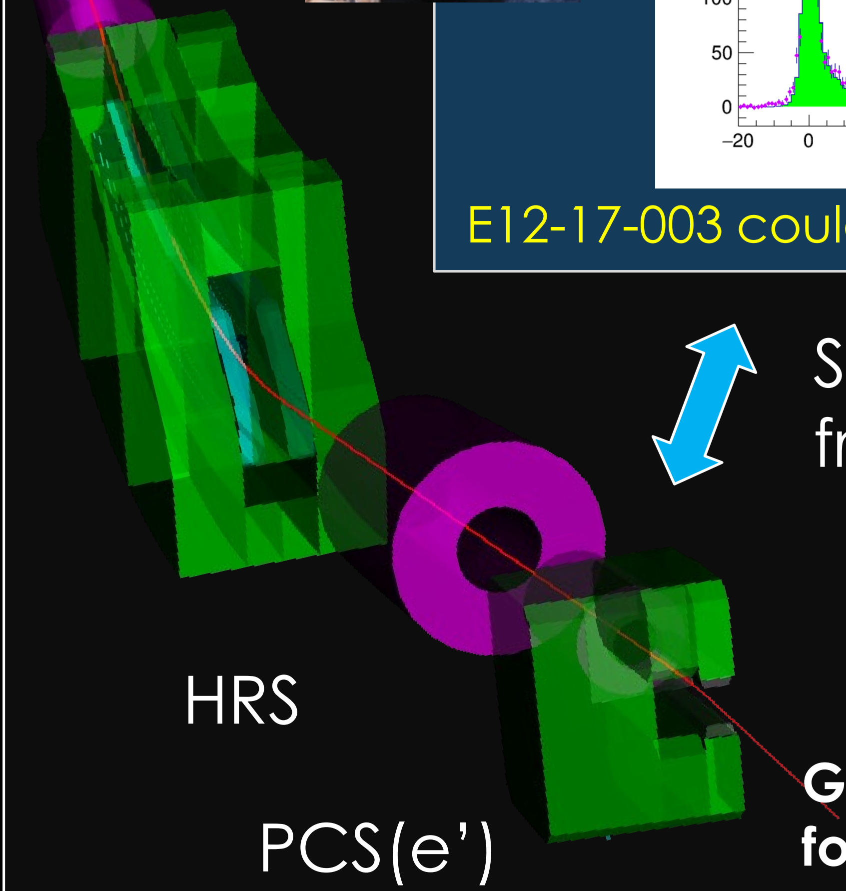




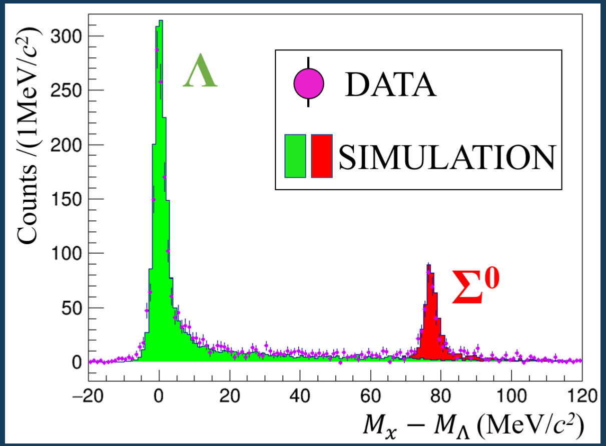
Available densities calculated by the JLab Target Group ***maintaining a compatibility with our experimental setup:***

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

EXPECTED MISSING MASS RESOLUTION



Analysis by K.N. Suzuki (Kyoto)



E12-17-003 could be reproduced

Same framework

Geant4 simulation for C12-19-002

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

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

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

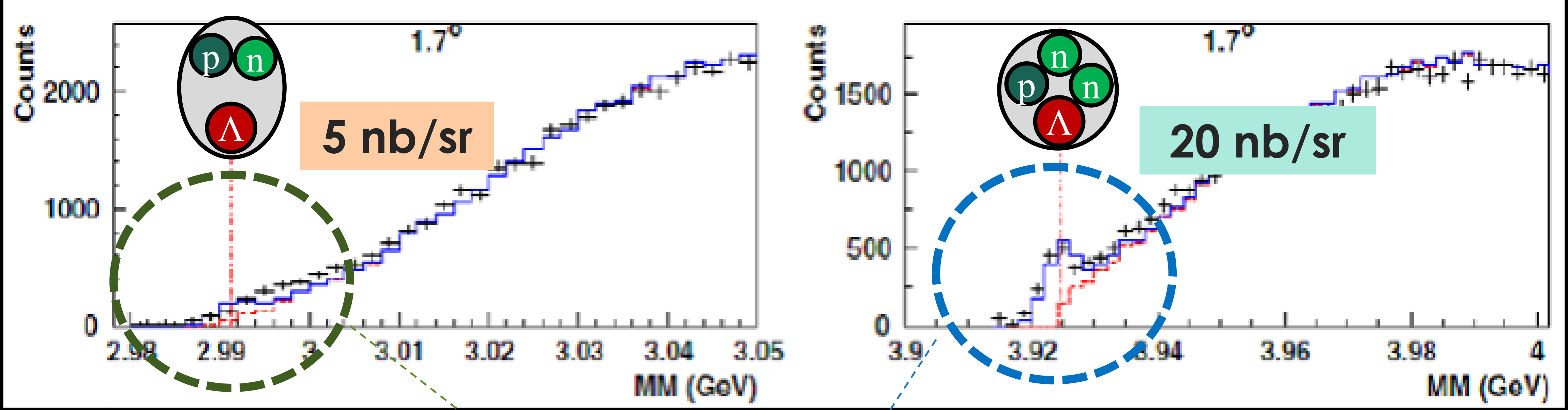
Spectrometer	$\Delta p/p$ (FWHM)
HRS (e')	3.2×10^{-4}
HKS (K^+)	5.7×10^{-4}

↓

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

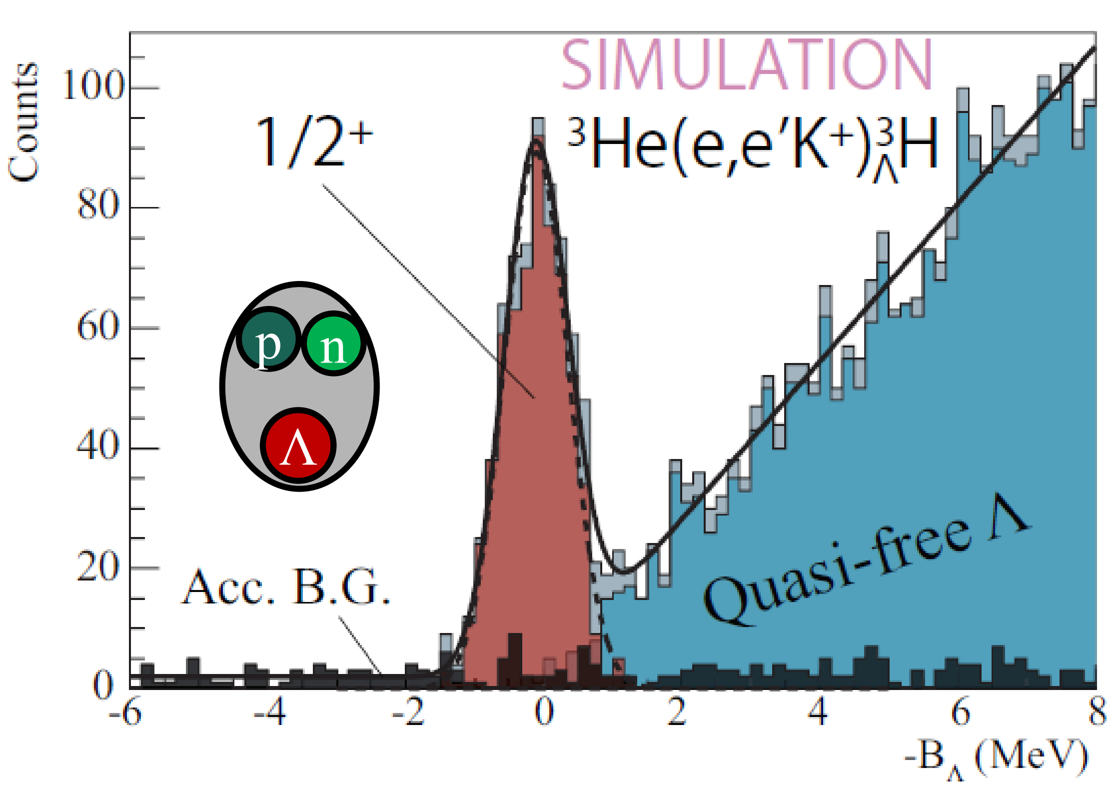
YIELD ESTIMATION

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



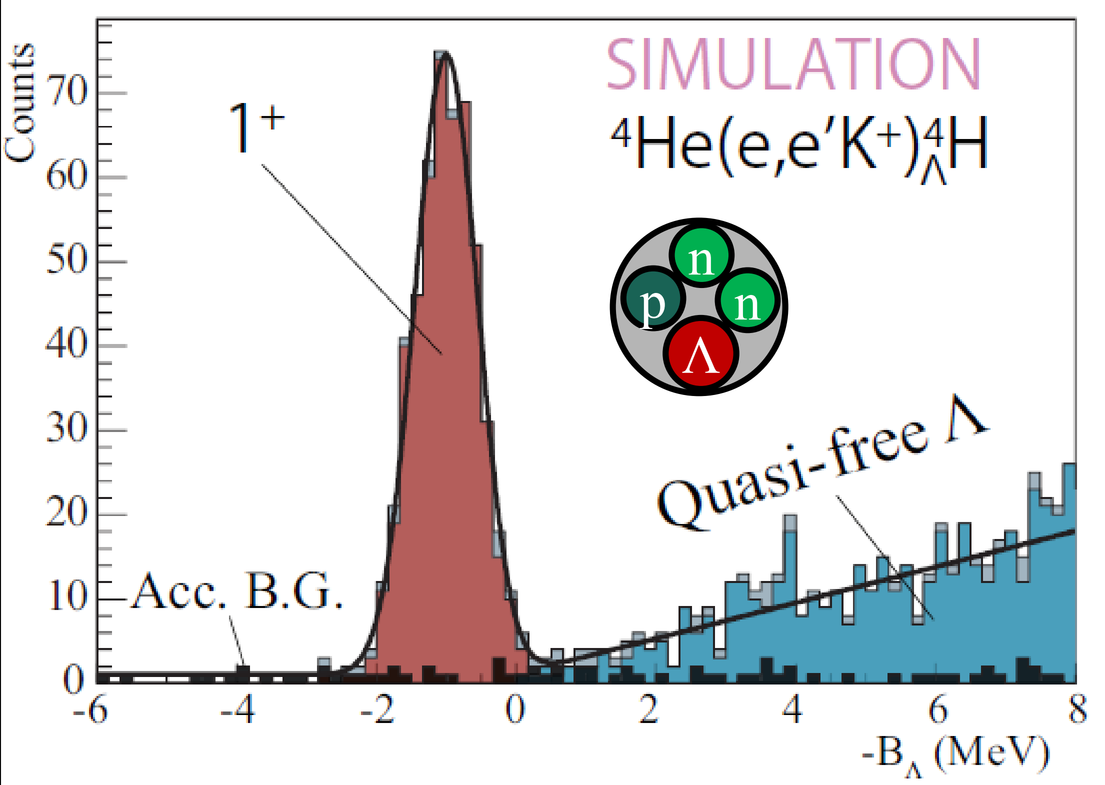
Product	Target [/(mg/cm²)]	I_{beam} (/μA)	CS [/(nb/sr)]	Yield / day	Beamtime (/day)	**Total yield**
${}^{3}_{\Lambda}H$	${}^{3}He$ (165)	50	5	60	10	**600**
${}^{4}_{\Lambda}H$	${}^{4}He$ (228)		20	250	2	**500**

EXPECTED SPECTRA AND STATISTICAL ERRORS



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

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



$\left|\Delta B_\Lambda^{stat.}\right| = 20$ 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	$p(e,e'K^+)\Lambda,\Sigma^0$	$-110 < z_t < 110$	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

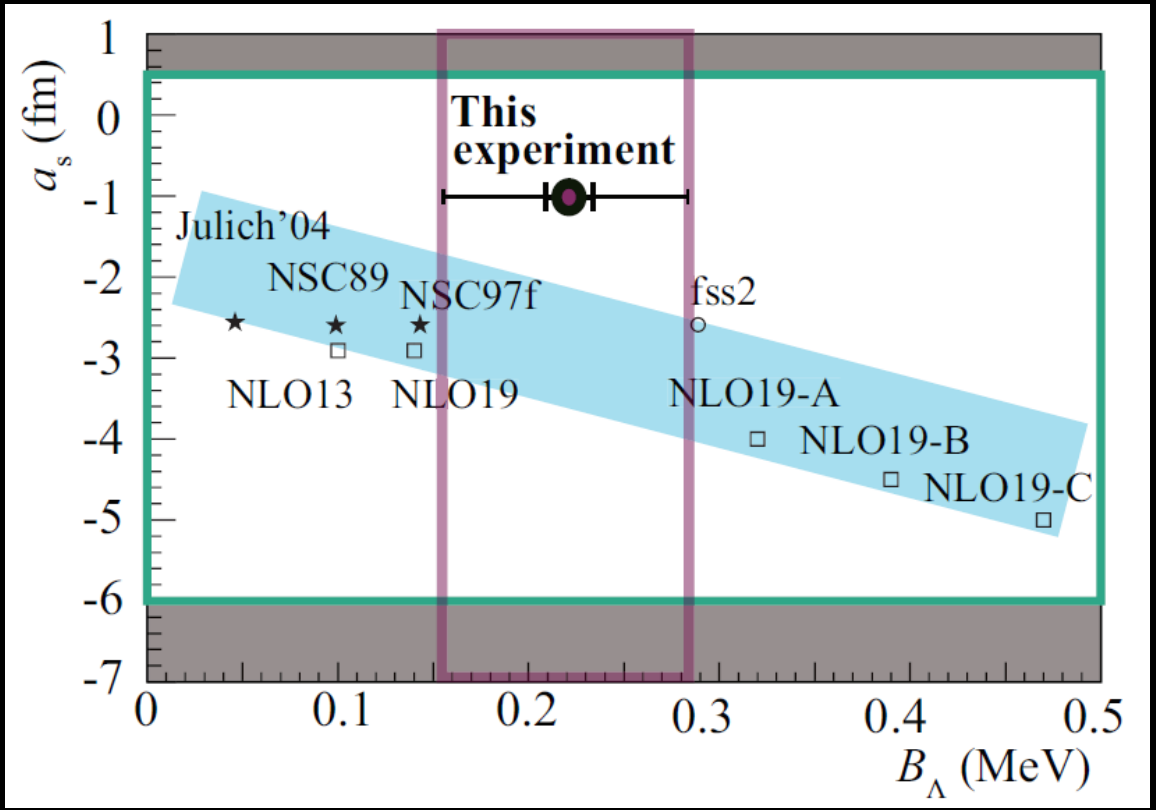
- Energy scale calibration(*) : ±50 keV
- Energy loss correction: ±23 keV
  - target density: ±3%
  - cell thickness uniformity: ±25μm

(*) TG et al., NIMA 900 (2018) 69—83

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

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

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



Hypertriton Puzzle

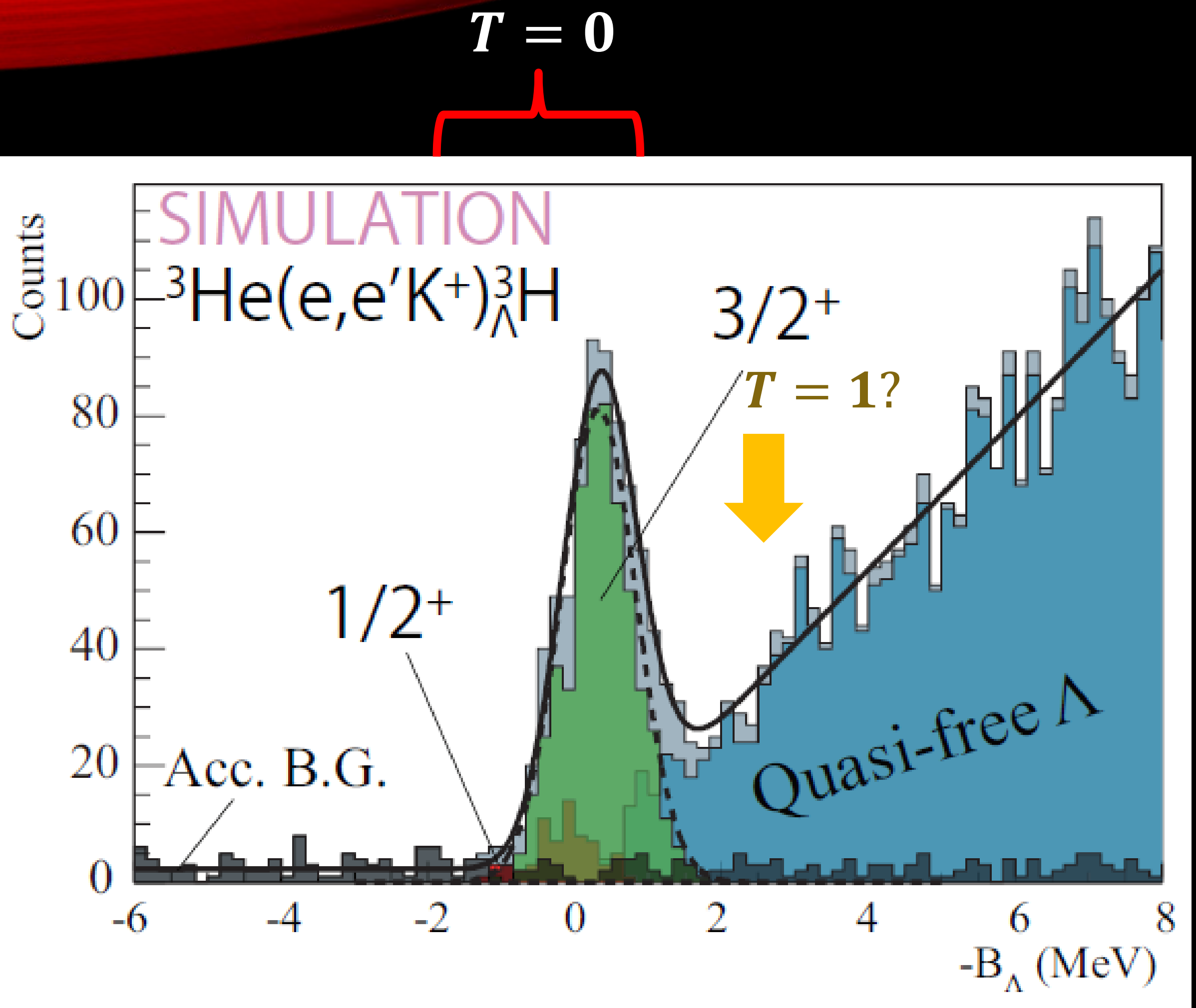
- Λd rm radius (**$|\Delta r| \lesssim 1$ fm**)

  ➔ Better estimation for the lifetime

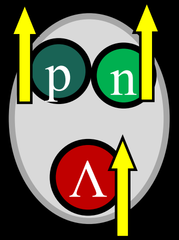
ΛN interaction

- 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 $(T = 0,\ J^{\pi} = 3/2^{+})$



- Has NOT been measured
- Emulsion / HI experiments cannot measure
- 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**

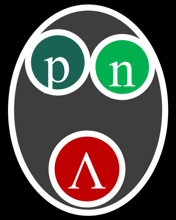
$^{3}_{\Lambda}$H $(T = 1,\ J^{\pi} = 1/2^{+})$

- 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 → $|\Delta B^{\mathrm{stat.}}_{\Lambda}| \sim 90$ 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 (JLAB C12-19-002)

- ☆ **HRS-HKS @ Hall A**
- ☆ **50-μA beam on ^{3}He and ^{4}He gas targets**
- ☆ **Beamtime = 14.5 days**
  - ✓ 12 days for Physics
  - ✓ 2.5 days for Calibrations



➔ World best accuracy in measuring $B_{\Lambda}({}^{3,4}_{\Lambda}\mathrm{H})$

➔ Hypertriton Puzzle / Charge Symmetry Breaking

RESPONSES TO TAC REPORT

1. TARGET

TAC COMMENT 1:
The authors indicate that a new target system design was developed i n collaboration with the JLab Target Group to accommodate the restricted space at the target pivot and for compatibility with the E12-15-008 experiment. Some existing cryogenic gas handling systems can be utilized with modified operating parameters specifi c to this application. It is noted a new ladder and motion system (which can be similar to that used for PREX) will need to be built. It was not clear the cost or how much time is needed for these developments. While the authors note a similar effort to that of PREX/CREX is likely, it would be useful to illustrate further details of the setup (e. anticipated power load, conceptual drawings, etc.) and required labor.

Our response is shown in the next slide

1. TARGET

Our response 1:

- We gave up the high density targets (roughly 10 times larger density than that proposed this year was assumed last year) because of the space limitation.
- To compensate the density reduction, a larger cell is assumed in this proposal;

  50 mm → 200 mm for He gas targets (4 times thicker target).

  In addition, 2 times longer beamtime is requested for ^{4}He.
- Manpower and cost
  - Designer and scientist 6 months working at about 60% to complete the design of the target.
  - Fabrication of the target will take about 6 months and about $500K in material and fabrication labor.
  - The installation will be about 6 weeks and require 80% of the target group technical staff, 1 engineer and 2 scientists.
- Heat load $\leq$ 25 W (gas + cell)

2. PERFORMANCE CHECK IN E12-17-003

TAC comment 2:

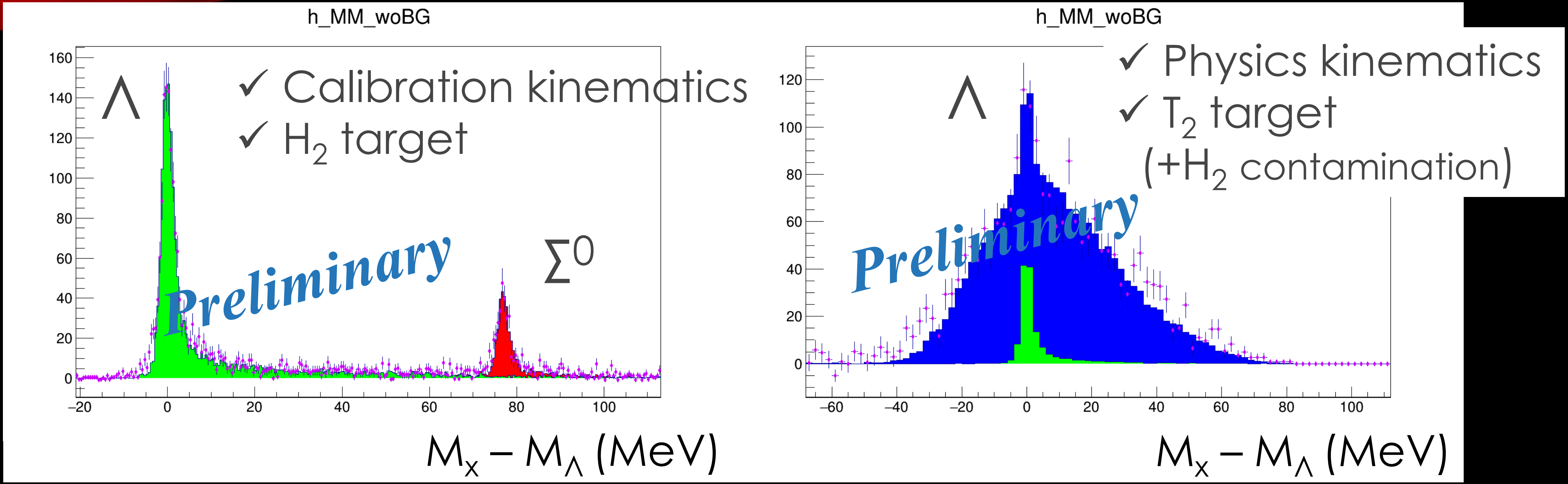
Regarding the feasibility of the nnΛ measurement/search, it would be very helpful and interesting to see at least preliminary results from the previous experiment E12 17 003 that performed this measurement. This can show what is already achievable and items for improvement that can be applied to this proposal.

Our response 2:

- Preliminary results are shown in the next page to show the analysis worked as expected. The similar analysis will be applied to the proposed experiment. The performance of the proposed experiment in terms of resolution was evaluated by the full modeled Geant4 MC simulation.

2. PERFORMANCE CHECK IN E12-17-003

(Figures made by K.N. Suzuki (Kyoto Univ.))



- **Geant4 MC data** + real data analysis = histograms
- **Real Data** + real data analysis = markers with error bars

Consistent

→ *System worked as expected*

The same Geant4 framework was used for estimations of the present proposal

3. The $3/2^+$ state on QF background

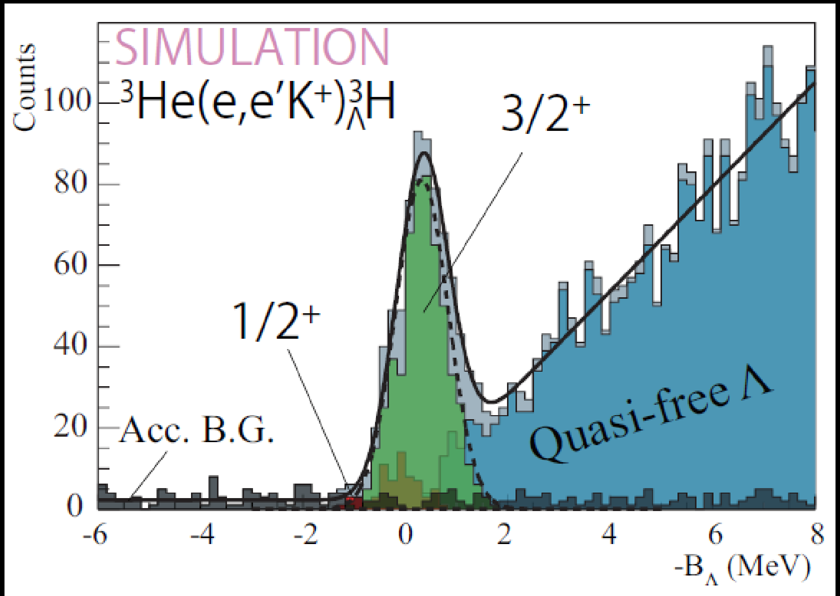
TAC comment 3:

The authors show how a cut on the z vertex can suppress the quasi free Λ background by a factor of 10 (p. 27). This significant reduction appears to be sufficient for the analysis. Figure 15 shows a simulated binding energy spectrum from the 3 He(e,e'K) 3 H Λ reaction. It appears that the quasi free Λ background falls off relatively quickly, though is roughly 25% of the peak amplitude of the 3/2+ excited state under investigation (if found). It is not clear if this represents the expectation before or after the vertex z cut is applied to the data. Given the narrow width of the $3/2^+$ peak, it would be interesting to see how sensitive the binding energy is to this background (if this plot represents what is seen after the vertex z cut).

Our response is shown in the next slide

3. The $3/2^+$ state on QF background

After z vertex cut



Our response 3:

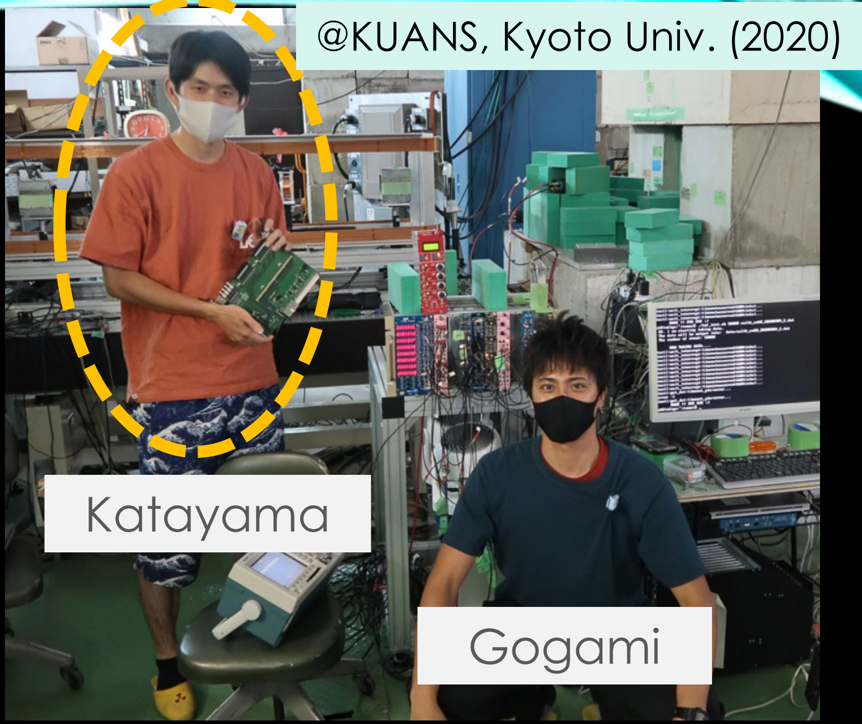
- The QF background increases the statistical error on the $3/2^+$ state by about a few ~ 5 keV
- MC simulation was done changing assumed peak position in order to estimate a systematic error. It was found that the systematic shift would be 10—30 keV due to the QF background. → This corresponds to a few keV deterioration of the total error (there are about 60 and 20 keV uncertainties for other systematic errors and the statistical error, respectively)

The effect of the QF background is negligible small

BACKUP

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

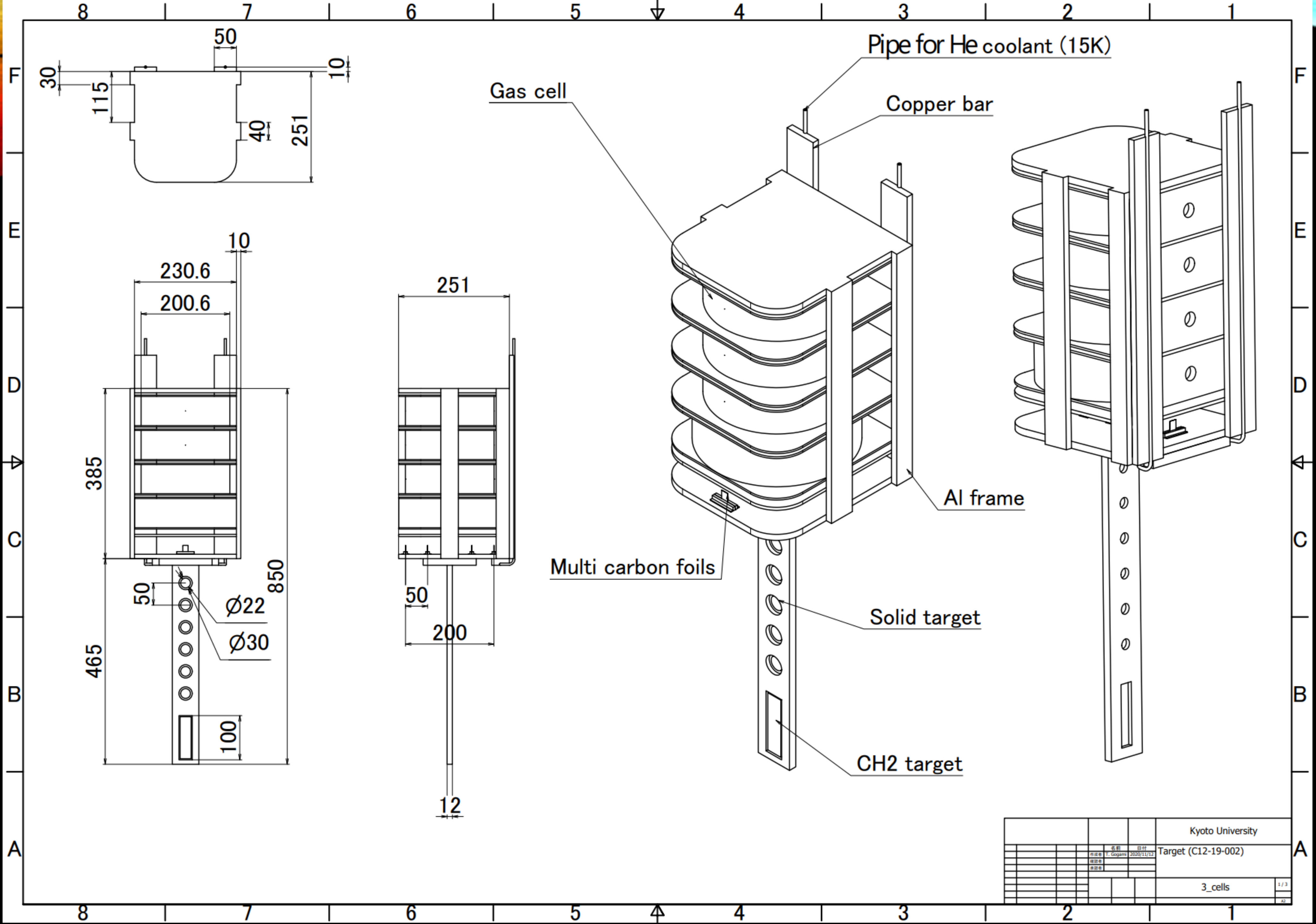
Target	Thickness (mg/cm²)	Beam Current (μA)	e' (kHz)	p (kHz)	π (kHz)	Acc. rate (kHz)	Acc. rate w/ Chernkovs (kHz)
^{12}C	100	100	21.5	56	71	**0.4**	0.023
^{40}Ca	100	50	64.5	48	71	**1.2**	0.060
^{208}Pb	100	25	97.0	22	33	**0.8**	0.041
^{3}He+^{27}Al	190+162	50	90.8	163.2	252.5	**3.2**	**0.15**
^{4}He+^{27}Al	262+162	50	91.2	201.6	355.9	**4.9**	**0.23**

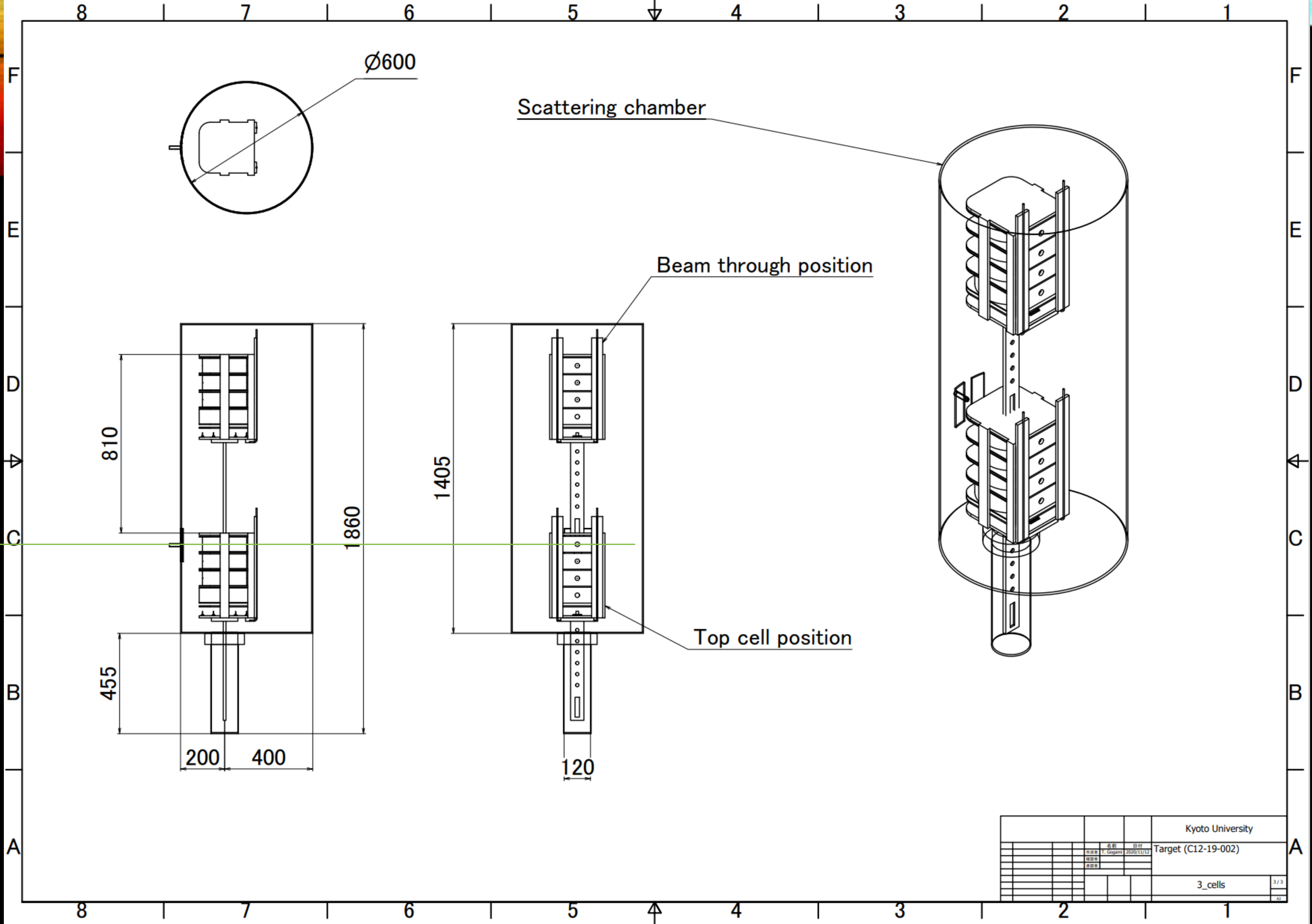
Particle identification by HKS: **TG et al., NIMA 729, 816—824 (2013).**

BEAMTIME REQUEST (C12-19-002)

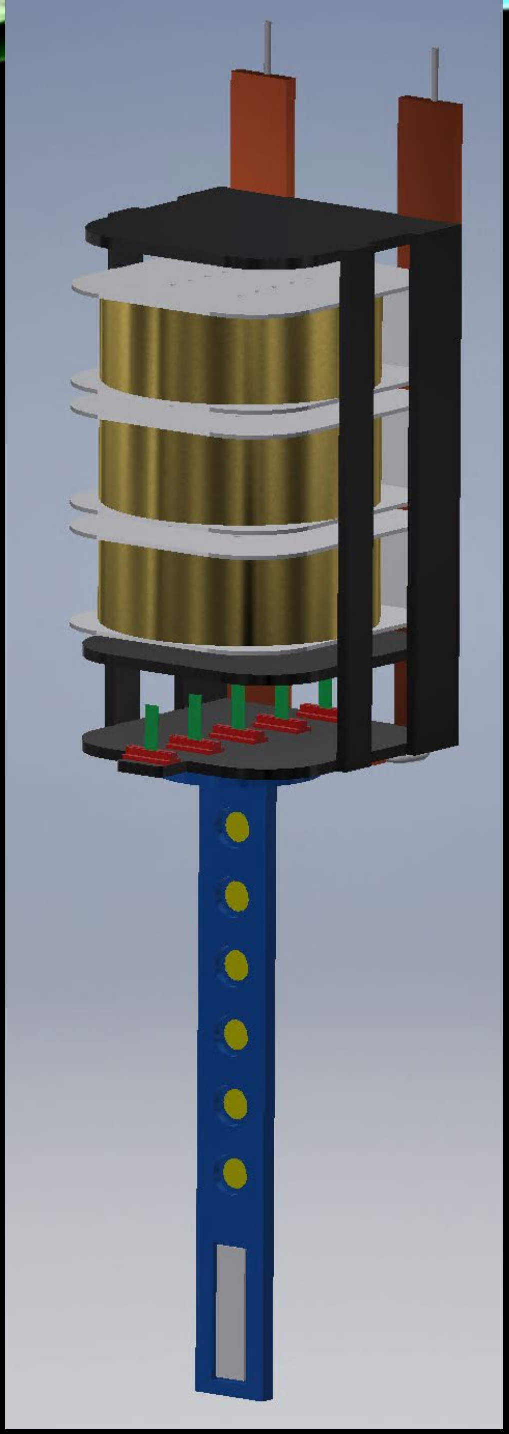
Physics				
Target (mg/cm^2)	I_e (μA)	Product	Beamtime (day)	Yield
^{3}He (165)	**50**	**${}^{3}_{\Lambda}\mathrm{H}$**	**10**	**600**
^{4}He (228)	**50**	**${}^{4}_{\Lambda}\mathrm{H}$**	**2**	**500**
Subtotal			**12**	

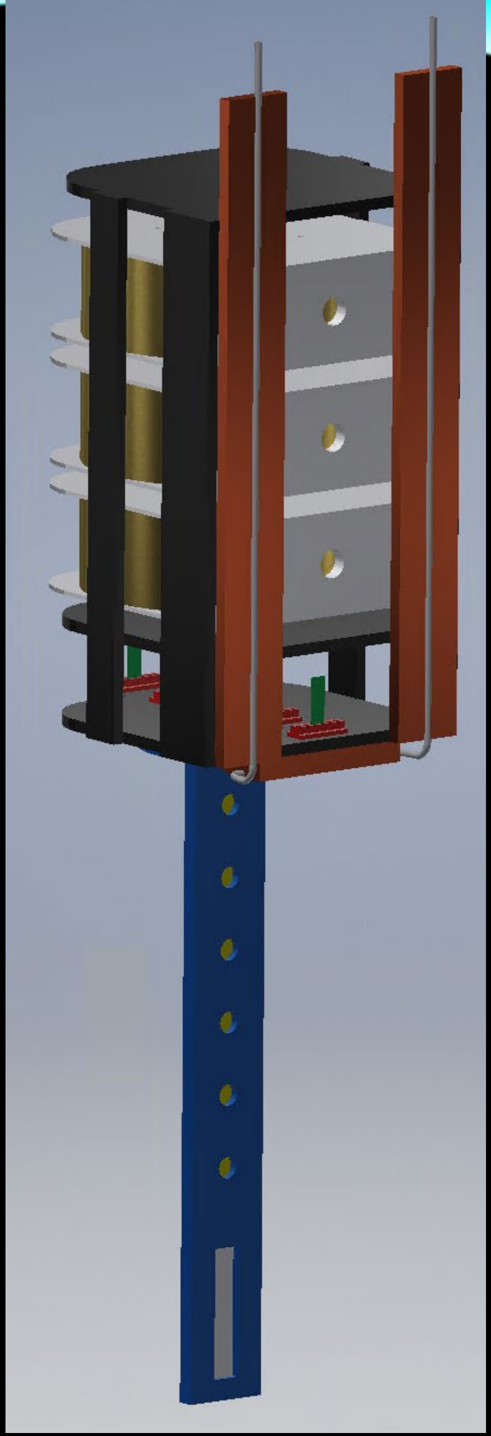
Calibration				
Target	I_e (μA)	Reaction	Beamtime (day)	Remarks
H (30)	**50**	**$\mathrm{p(e,e'K^+)\Lambda,\Sigma^0}$**	**1**	**Λ: 3500, Σ^0: 1150**
Multi foils (100 × 5)	**50**	**$\mathrm{{}^{12}C(e,e'K^+){}^{12}_{\Lambda}B}$**	**1**	**${}^{12}_{\Lambda}\mathrm{B}^{g.s.}$: 300 × 5**
Multi Foils + SS	**50**	**-**	**0.2**	
Empty	**50**	**-**	**0.1**	**+ Background study**
Empty (or gas) + SS	**50**	**-**	**0.2**	**+ Angle resolution check**
Subtotal			**2.5**	
Total			**14.5**	


Pipe for He coolant (15K)
Copper bar
Gas cell
Al frame
Multi carbon foils
Solid target
CH2 target
50
10
30
115
40
251
230.6
200.6
385
850
465
50
Ø22
Ø30
100
251
50
200
12
Kyoto University
Target (C12-19-002)
3_cells

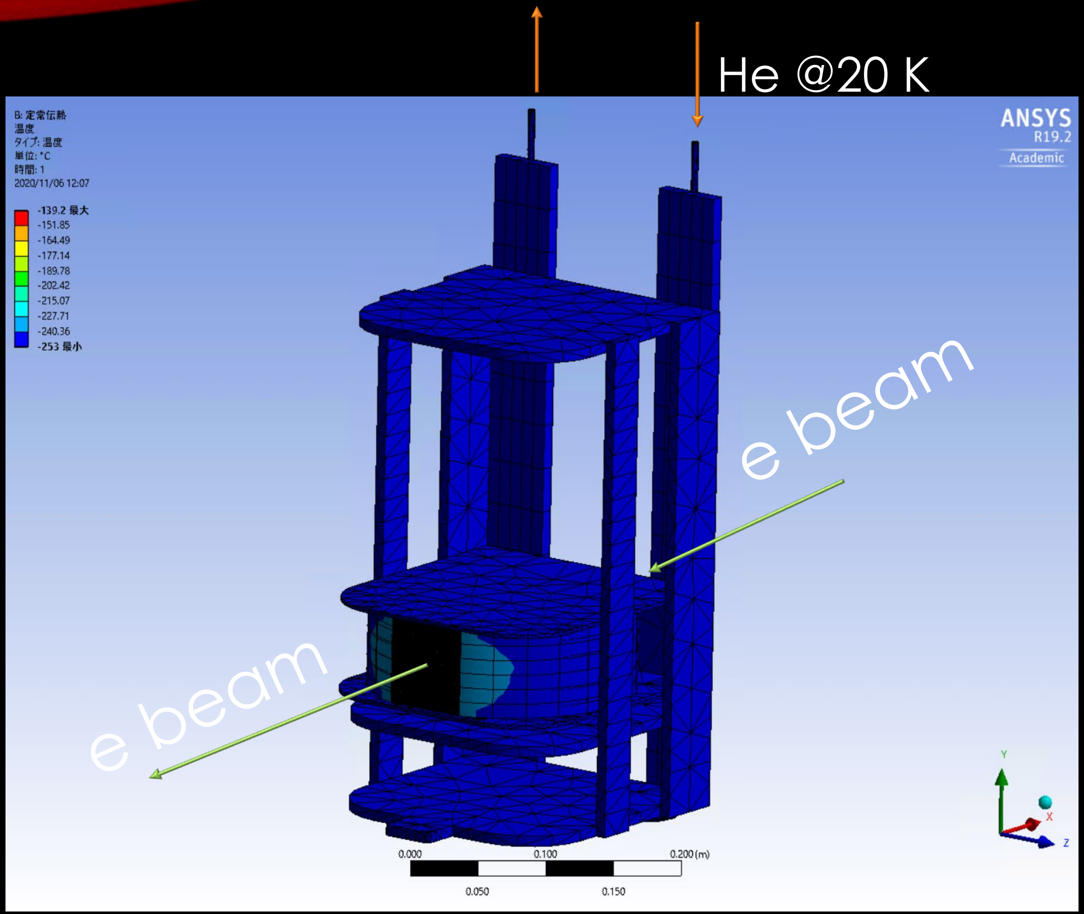

Ø600
Scattering chamber
Beam through position
Top cell position
810
1405
1860
455
200
400
120
Kyoto University
名前
日付
T. Gogami
2020/11/12
Target (C12-19-002)
3_cells
3 / 3
A2

ANSYS



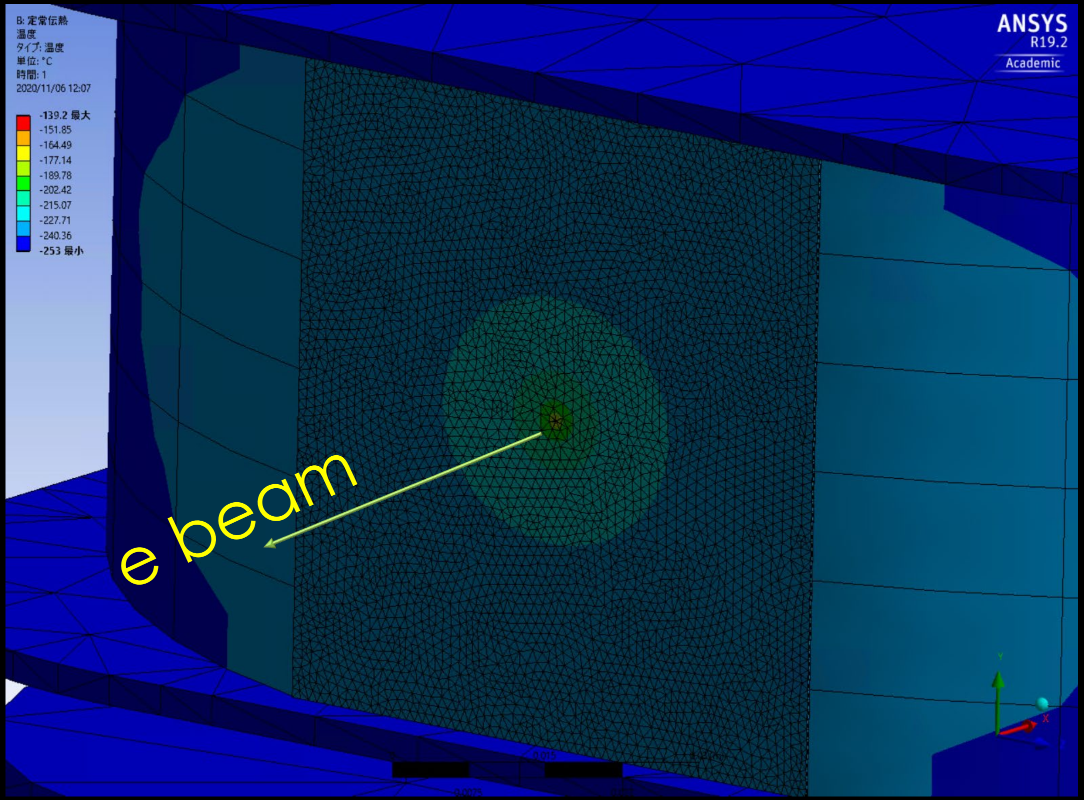


HEAT SIMULATION BY ANSYS (0.3 MM THICK AL)



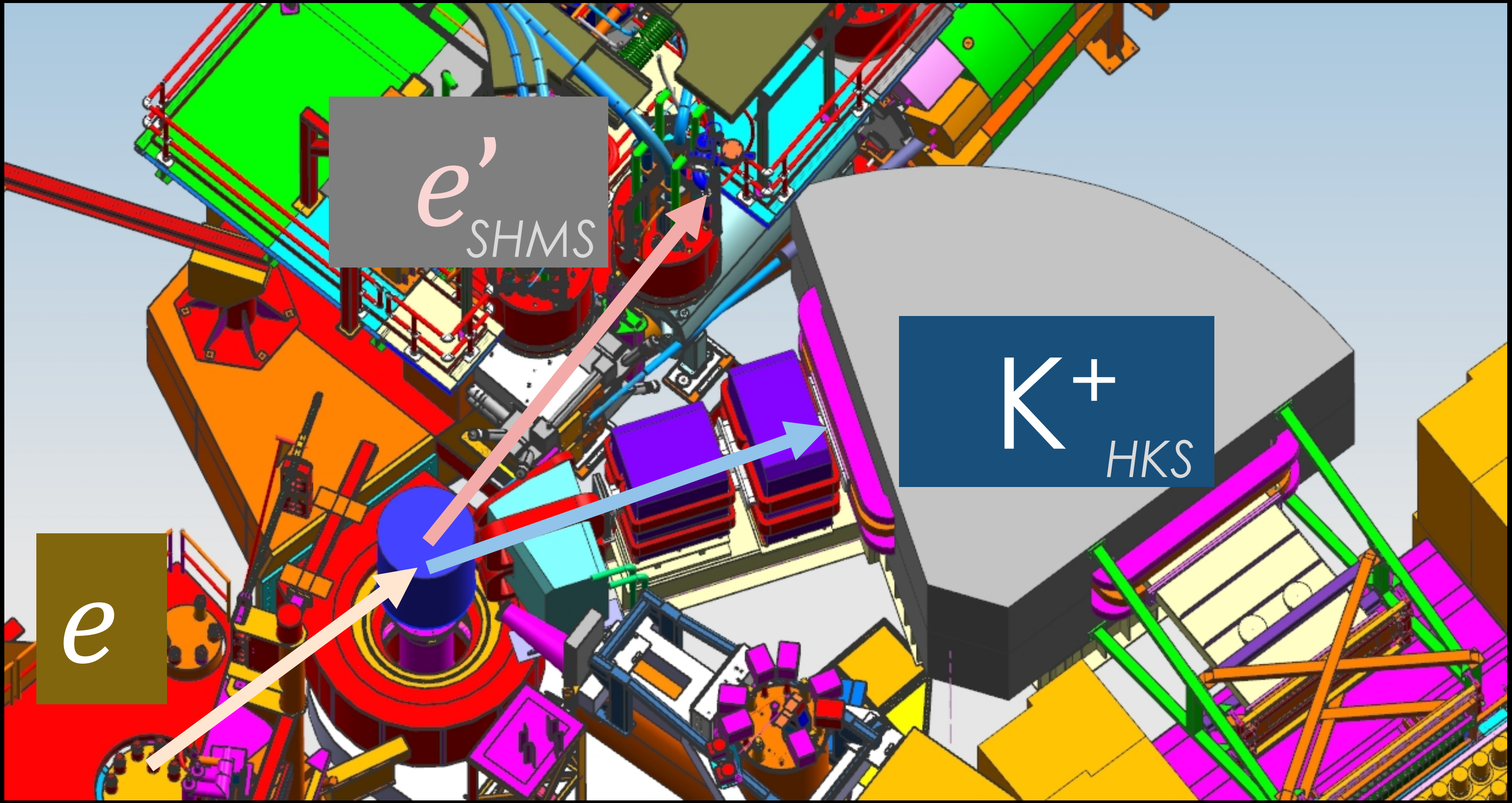
- 50μA electron beam
- 0.3 mm Al

➔ 6 W



Thermal contact coefficient h = 300 W/m^{2}K
→ Max temp. = 130 K

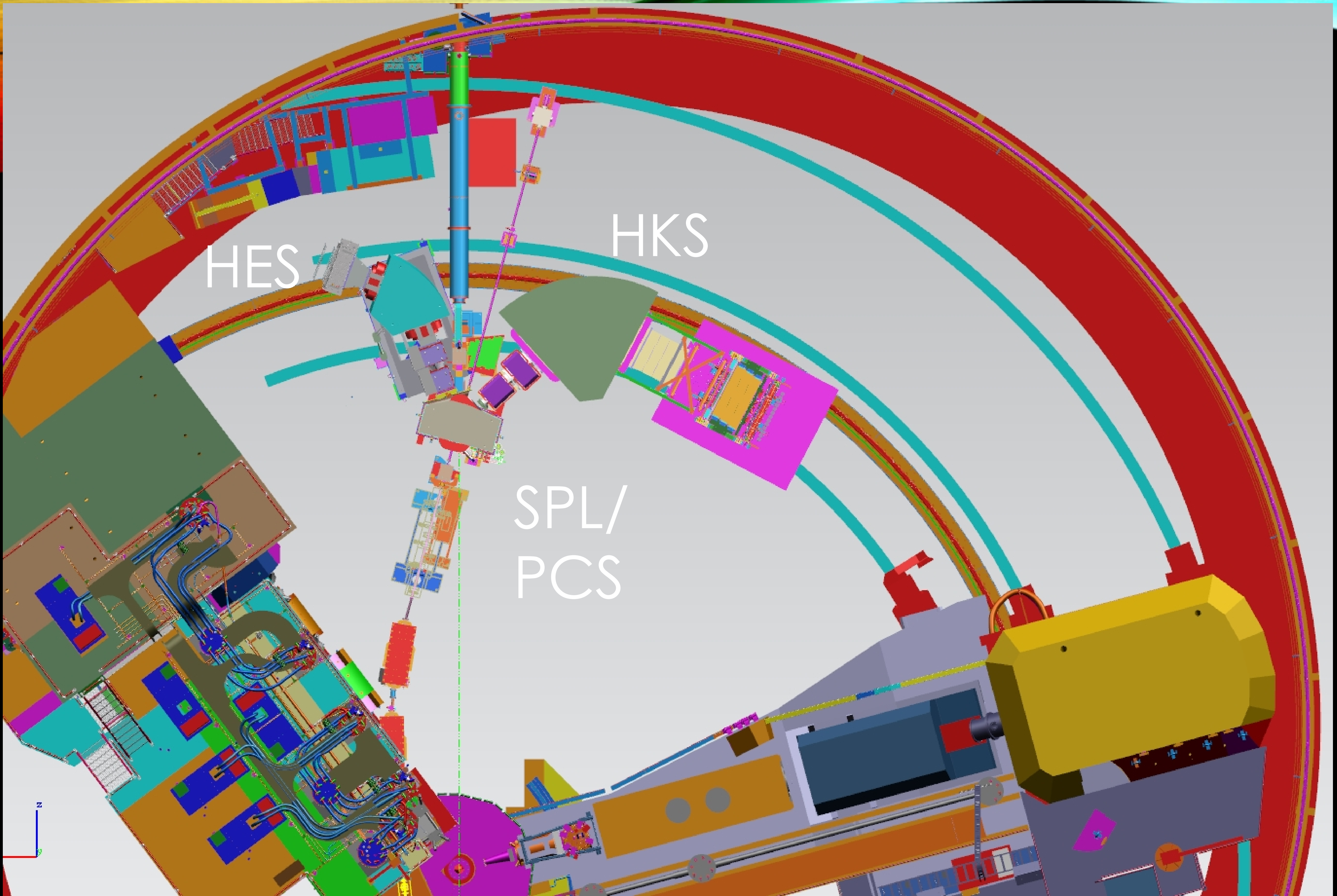
Possibility in Hall C



Evaluations are in progress

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

Thank you for the drawings + discussions → Bert, Paul, Steve


HES
HKS
SPL/
PCS

Yield per day (Hall C) @ 20μA

Areal density of target = 100 mg/cm^2

Configuration	ΔE_Λ (# of events needed for $\Delta B_\Lambda^{\text{stat.}} = 20$ keV)	$^{3}\text{He} \rightarrow {}^{3}_{\Lambda}\text{H}$ 5 nb/sr	$^{12}\text{C} \rightarrow {}^{12}_{\Lambda}\text{B}$ 100 nb/sr	$^{40}\text{Ca} \rightarrow {}^{40}_{\Lambda}\text{K}$ 10 nb/sr	$^{208}\text{Pb} \rightarrow {}^{208}_{\Lambda}\text{Tl}$ 10 nb/sr
SPL+(HES+HKS)	**0.5 (113)**	109 (1 day)	547	16 (7 days)	3.2 (35 days)
PCS+(HES+HKS)		40 (3 days)	203	6.1 (19 days)	1.2 (94 days)
SHMS+(PCS+HKS)	**1.0 (451)**	37 (12 days)	186	5.6 (81 days)	1.1 (410 days)

In case of $\Delta B_\Lambda^{\text{stat.}} = 50$ keV:
0.5 MeV FWHM → 18 counts
1.0 MeV FWHM → 72 counts

Not only yield and resolution, but also S/N needs to be studied
← S/N would be reasonable if the HKS-vacuum extension is modified

ISSUE TO SOLVE IN SPL+HKS

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

e^+/e^- backgrounds generated at HKS-D exit

- High accidental coincidence rate
  - Beam intensity was limited particularly for a large Z target
  - S/N was bad in resulting spectra

Possible solutions:

1. Introduction of a septum-type magnet
2. Changing to a lighter material for the lower momentum side of the HKS-D vacuum extension (or VE → He bag)
3. Changing to the vertical bending
   ← The need of massive modification (Base for HKS magnets, frames for detectors etc.)