JLab PAC 48

Conditional Experiment: JLab C12-19-002

High accuracy measurement of nuclear masses of hyperhydrogens

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for the JLab Hypernuclear Collaboration

and for the JLab Hall A Collaboration

Aug 11, 2020

京都大学
KYOTO UNIVERSITY

REQUEST SUMMARY (C12-19-002)

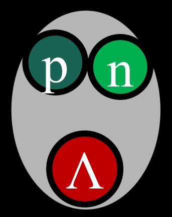
☆ **HRS-HKS @ Hall A**

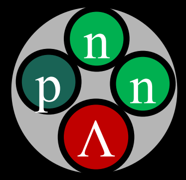
☆ **50-μA beam on ^{3}He and ^{4}He gas targets**

☆ **Beamtime = 13.5 days**

✓ 11 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

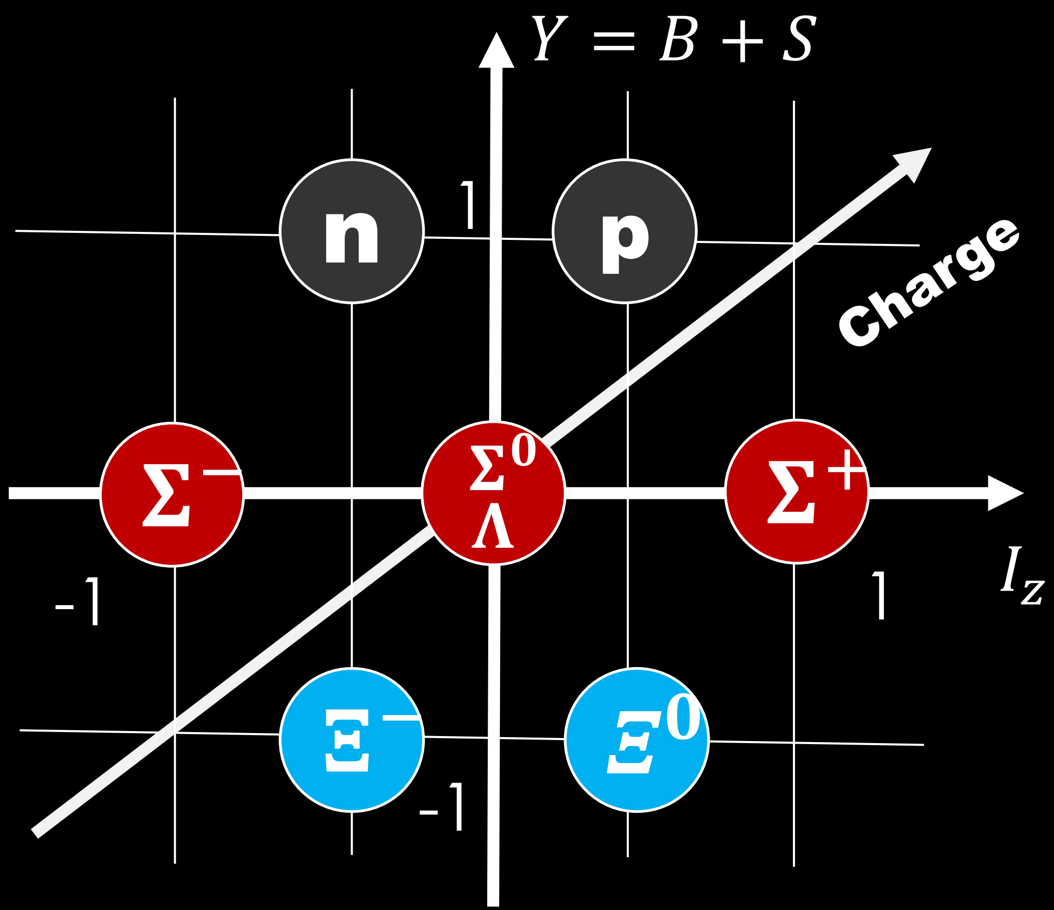
1. **Introduction**
   - Hypernuclear Study
   - Physics motivation for $^{3,4}_{\Lambda}\mathrm{H}$ measurement

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:

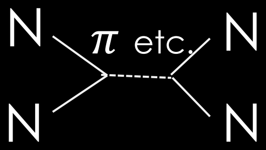
- ◆ $S = -1$: CERN, RHIC, GSI, J-PARC, MAMI, **JLab**
- ◆ $S = -2$: J-PARC

HOW TO INVESTIGAE THE BB INTERACTION

Method A

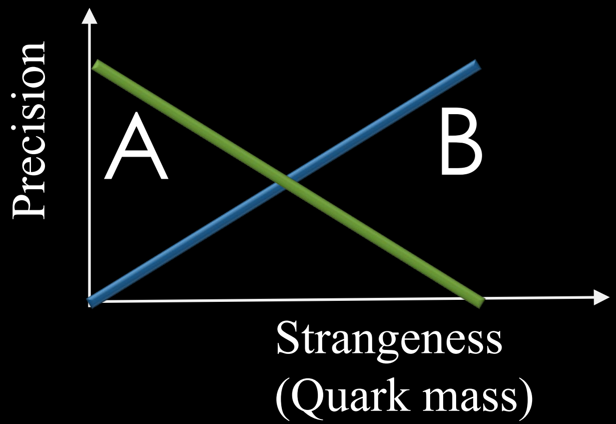
Data
- Scattering experiment
- (hyper)nuclear spectroscopy
- Phemtoscopy (ALICE, PRL123, 112002 (2019))

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



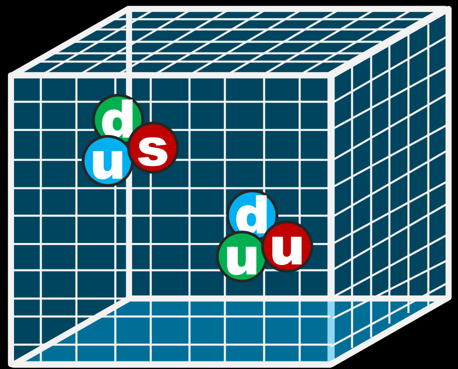
H. Yukawa (Kyoto Univ.)
Novel Prize 1949

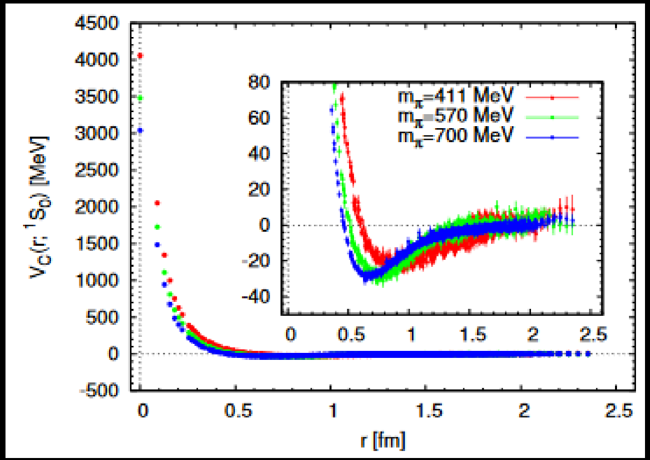
Complementary



Method B

Lattice QCD
(First principle calc.)

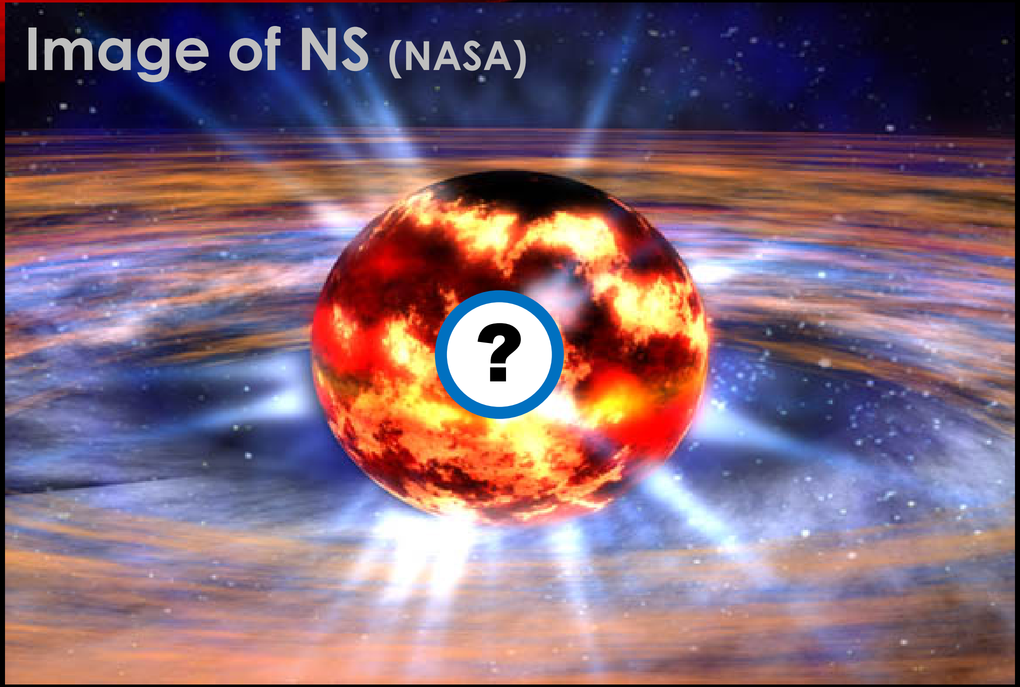




arXiv:2003.10730v2 [hep-lat] 12 Jul 2020

BB interaction (Strong force)

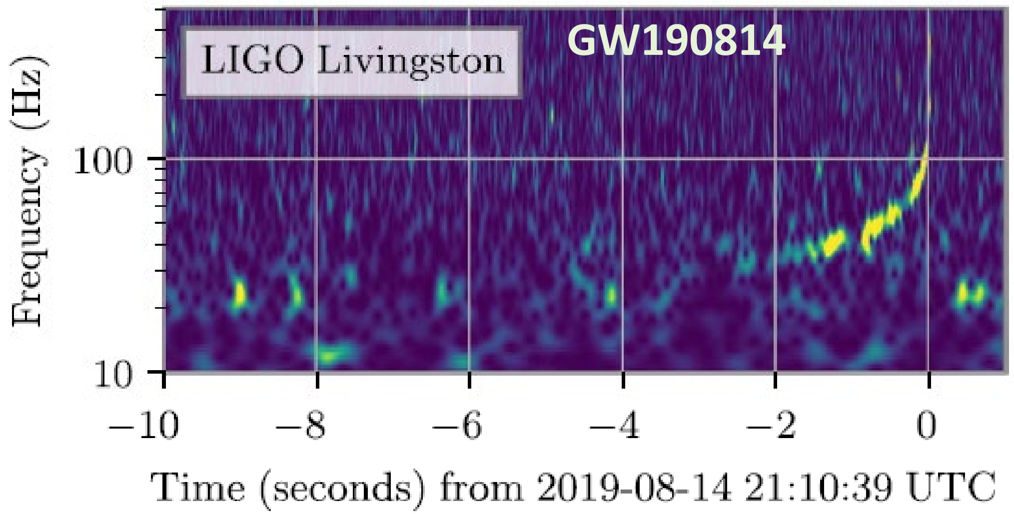
NEUTRON STARS AND HYPERONS



What's inside ?

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

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



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

<u>Hyperons make a NS softer</u>

→$\geq 2M_\odot$ 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**

$$\begin{cases} B_\Lambda = 0.13 \pm 0.05 \text{ MeV (emulsion[1])} \\ B_\Lambda = 0.41 \pm 0.12 \pm 0.10 \text{ MeV (STAR[2])} \end{cases}$$

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

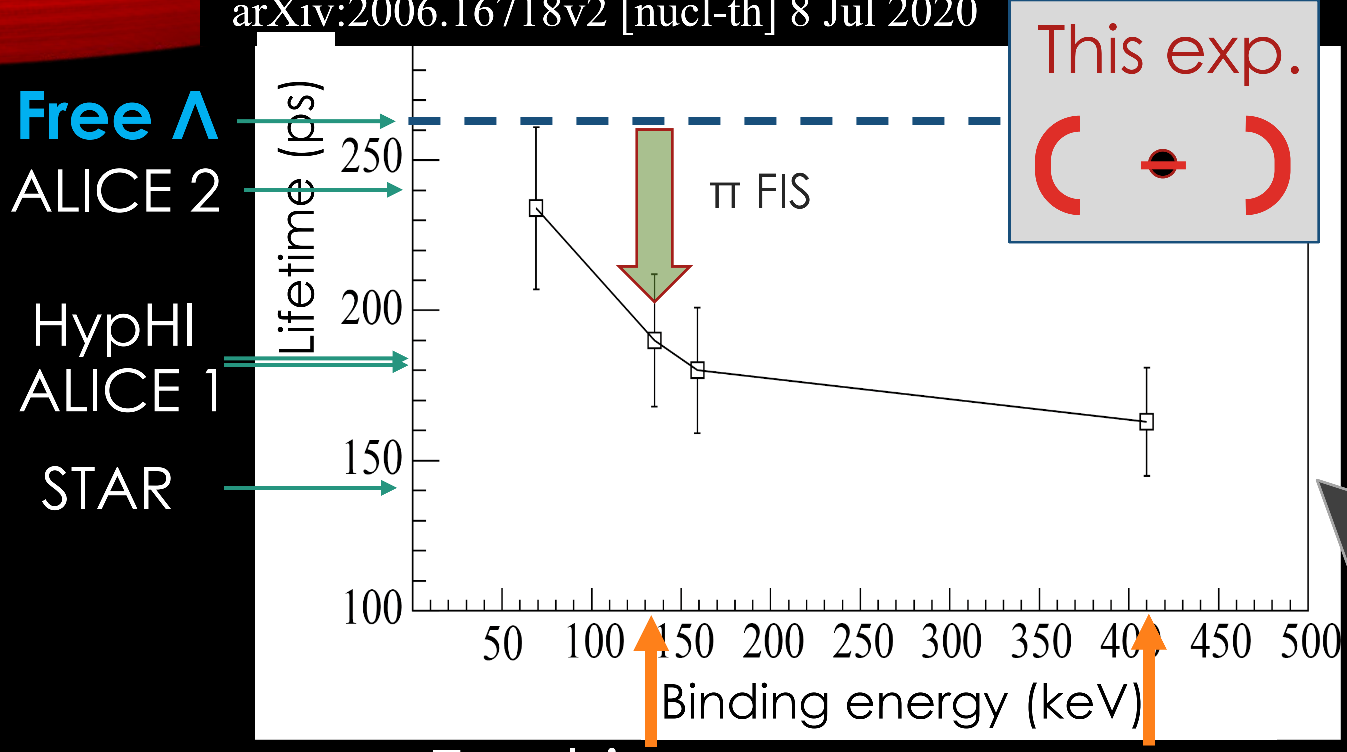
$\tau = (0.5 \sim 0.92)\,\tau_\Lambda$
(HypHI, STAR, ALICE)

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

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:

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

Spin indep. amp.

Spin dep. amp.

From factor (π FSI is included)

$\propto \sqrt{B_\Lambda}$

Proposed experiment (C12-19-002)

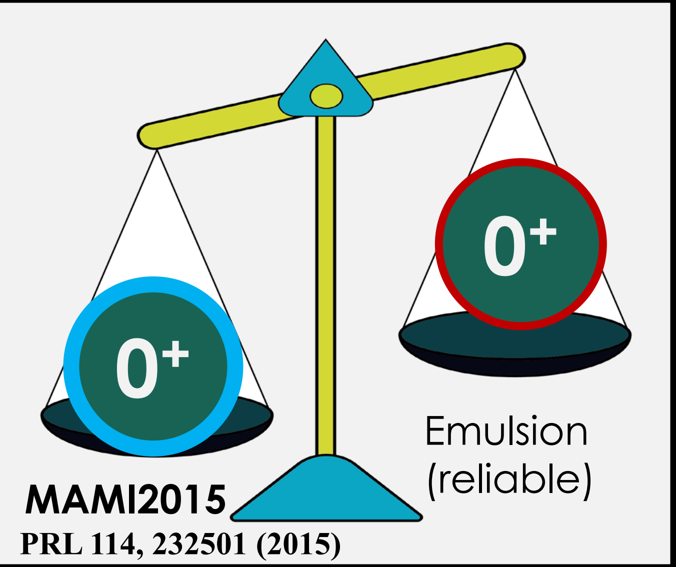
$|\Delta B^{\mathrm{stat.}}| = 20$ keV, $|\Delta B^{\mathrm{sys.}}| = 70$ keV

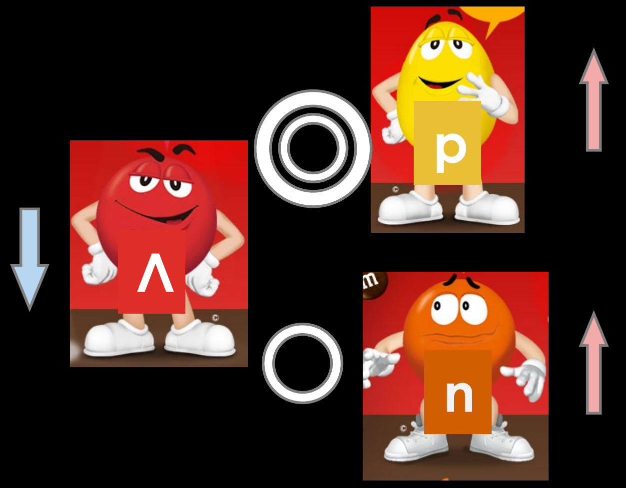
Best Accuracy on $B_\Lambda(^3_\Lambda\mathrm{H})$

➔ Pin down the hyperon puzzle

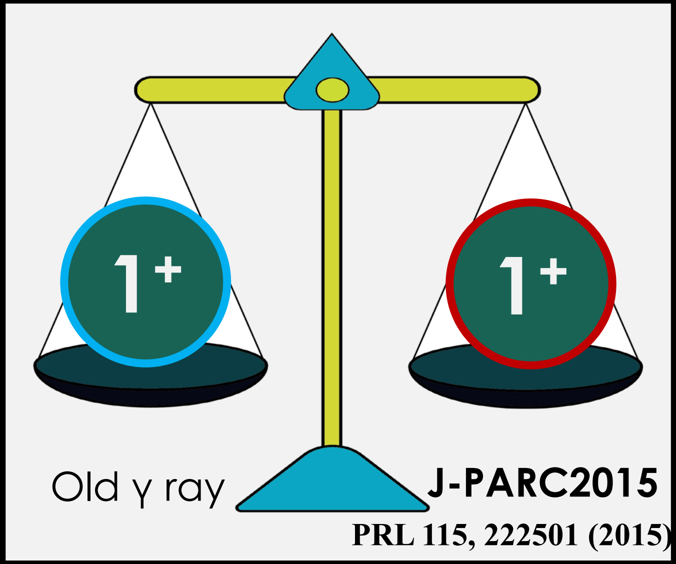
CHARGE SYMMETRY BREAKING IN THE ΛN INTERACTION

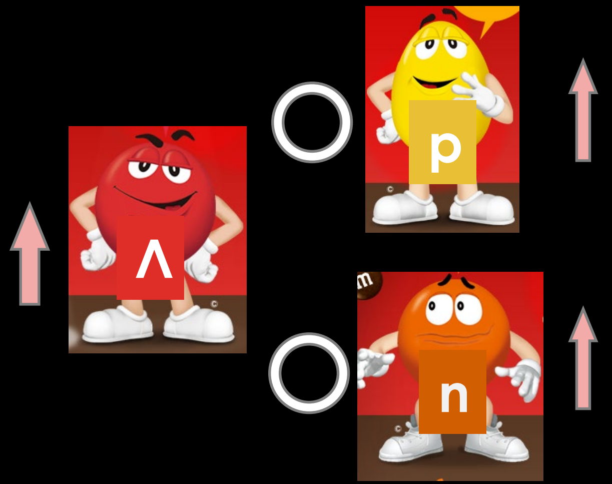
Unbalanced

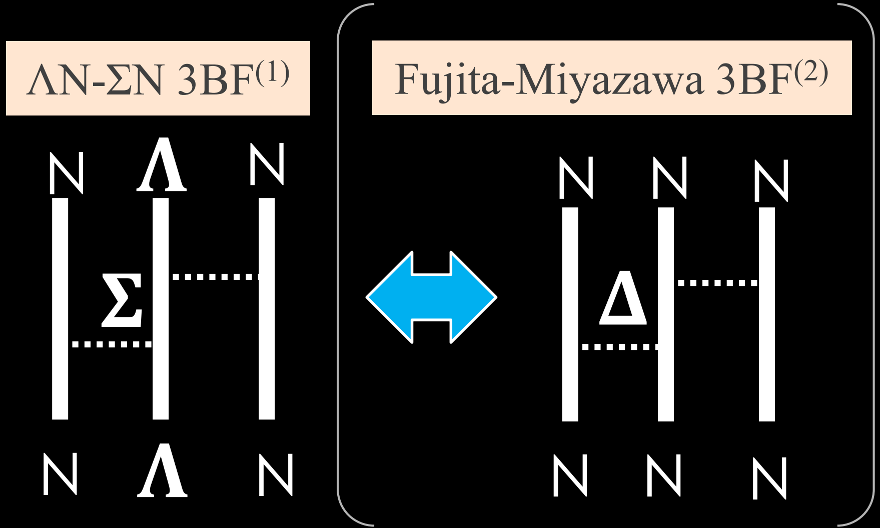




Balanced







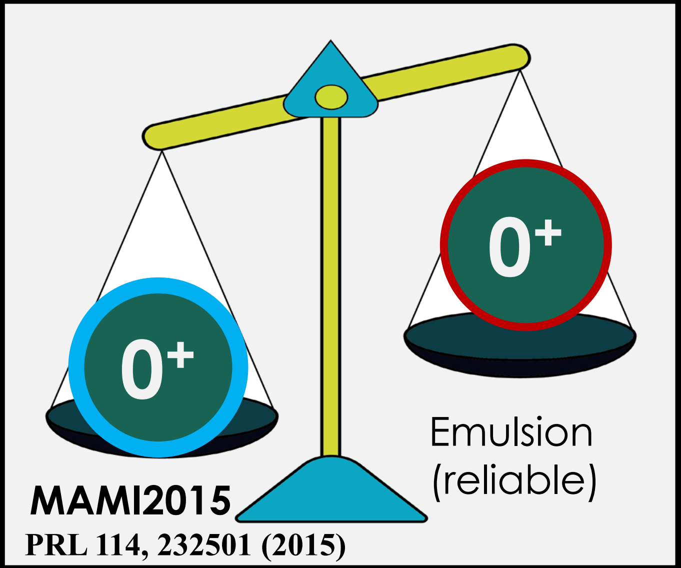
Σ may admix in the ΛN/ΛNN interaction

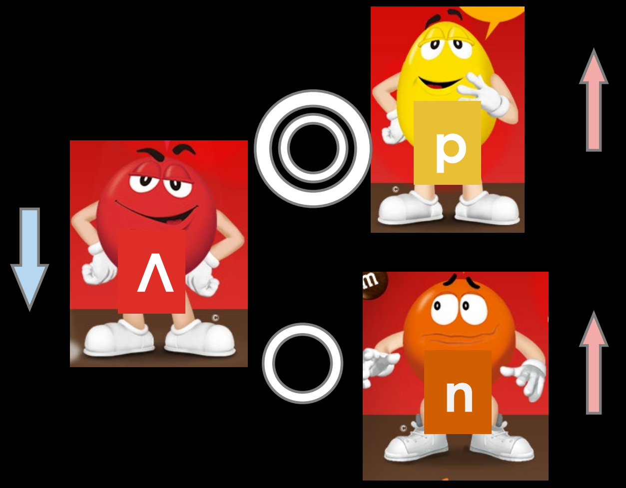
(1) Y. Akaishi et al., PRL 84, 3539 (2000)

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

CHARGE SYMMETRY BREAKING IN THE ΛN INTERACTION

Unbalanced





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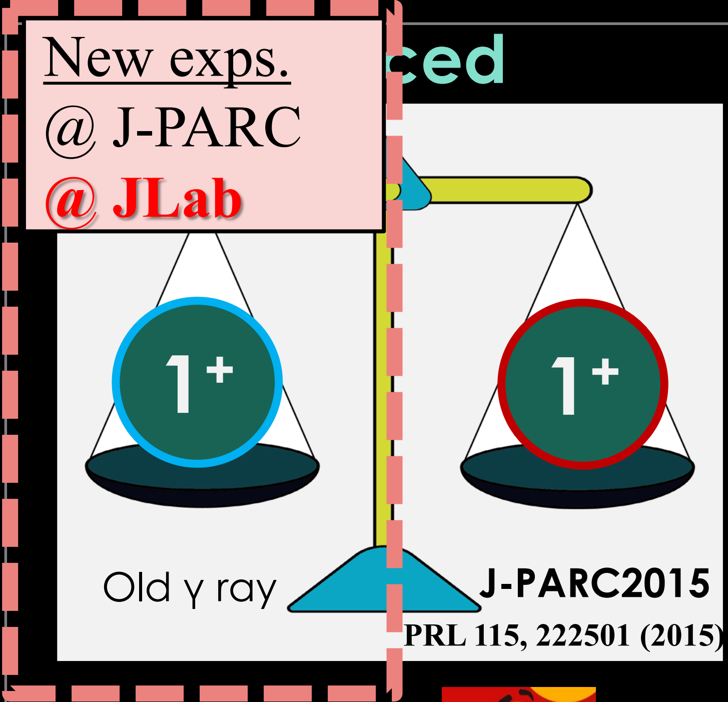

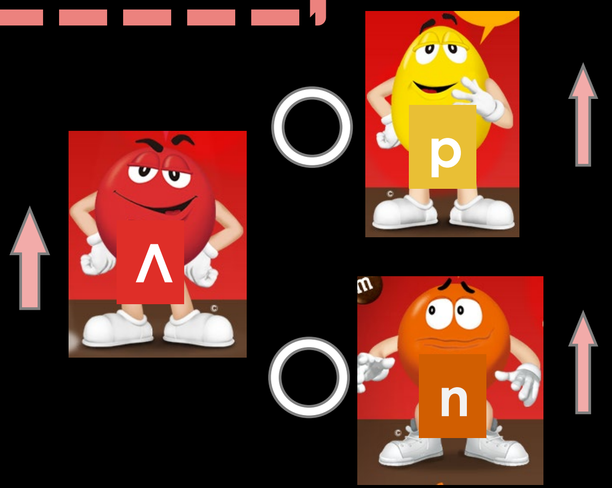

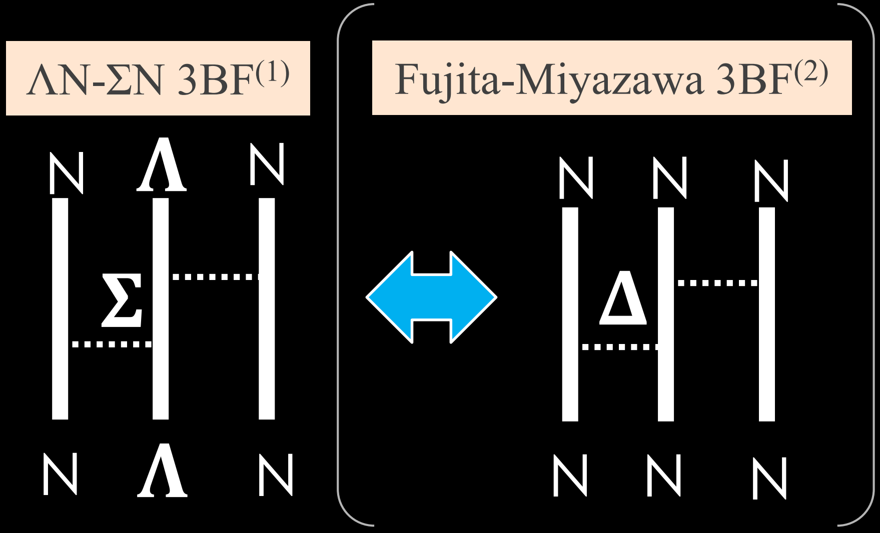

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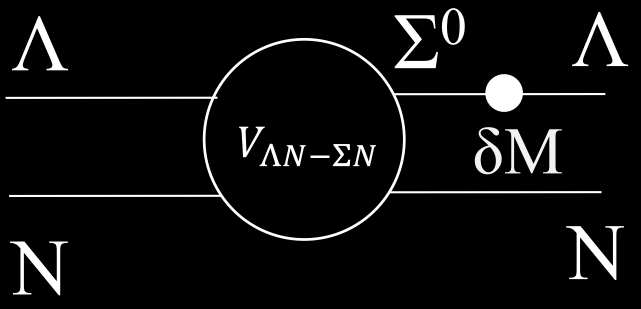
BASIC INFORMATION FOR THE ΛN CSB STUDY: $^4_\Lambda\mathrm{He} - ^4_\Lambda\mathrm{H}$

Explicit inclusion of Σ

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

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).

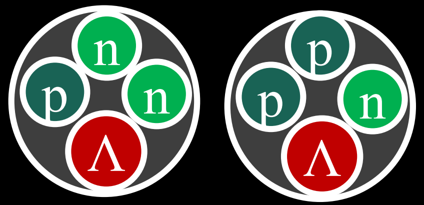
$$V_{\Lambda N}^{\mathrm{CSB}}(r) = -\frac{\tau_z}{2}\left[\frac{1+P_r}{2}\left(v_0^{\mathrm{even,CSB}} + \sigma_\Lambda\cdot\sigma_N v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{even,CSB}}\right)e^{-\beta_{\mathrm{even}}r^2} + \frac{1-P_r}{2}\left(v_0^{\mathrm{odd,CSB}} + \sigma_\Lambda\cdot\sigma_N v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{odd,CSB}}\right)e^{-\beta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

Basic Input (This proposal)

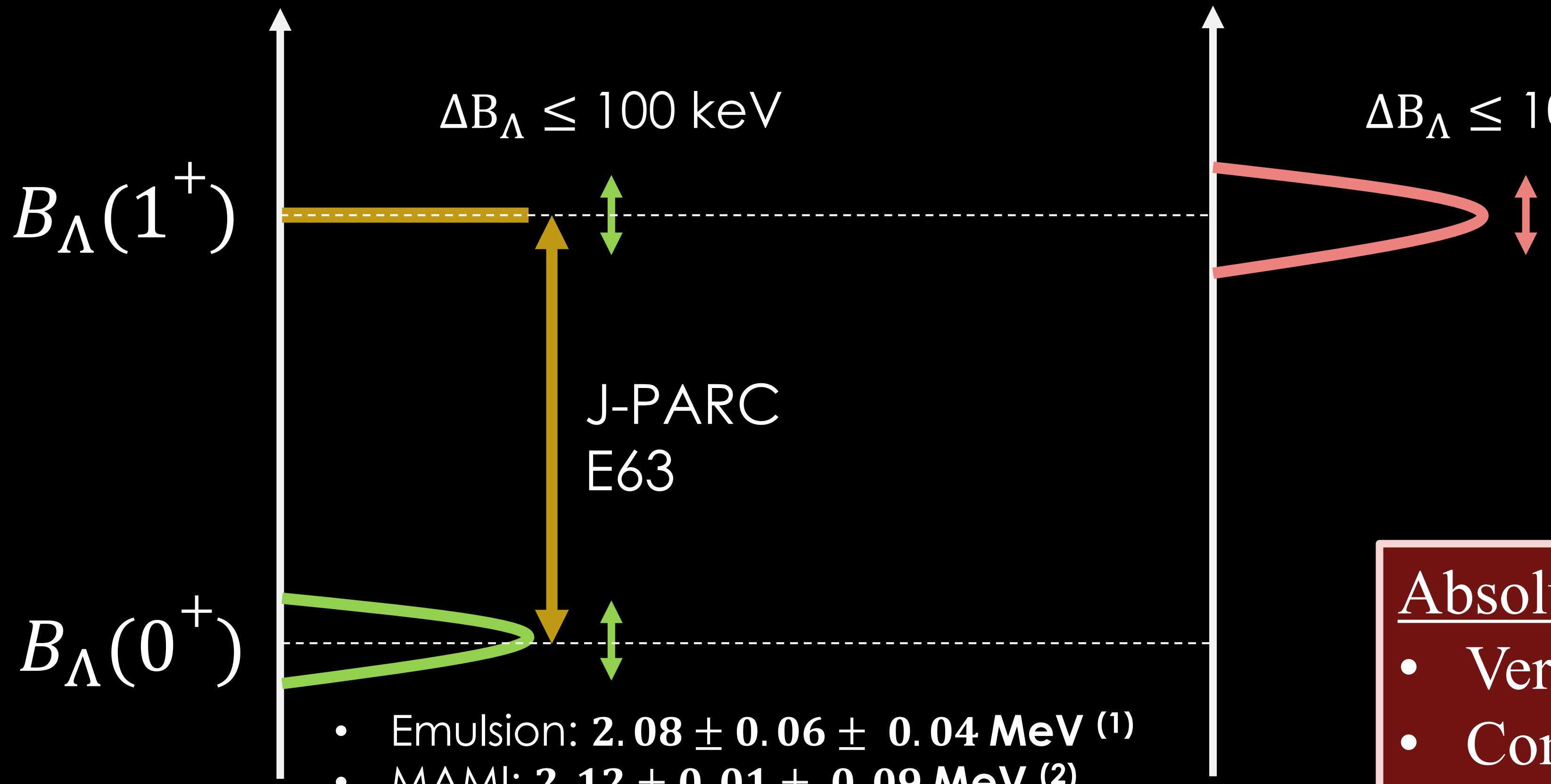
A=4 → **CSB interaction** →

- A=5
- 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 $B_\Lambda({}^4_\Lambda\mathrm{H};\ 1^+)$



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)]

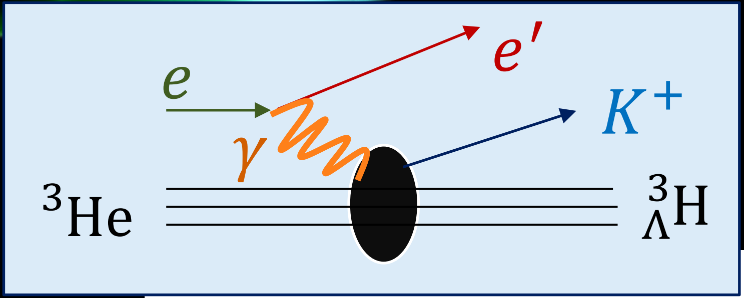
This proposal
(1 day)

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

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

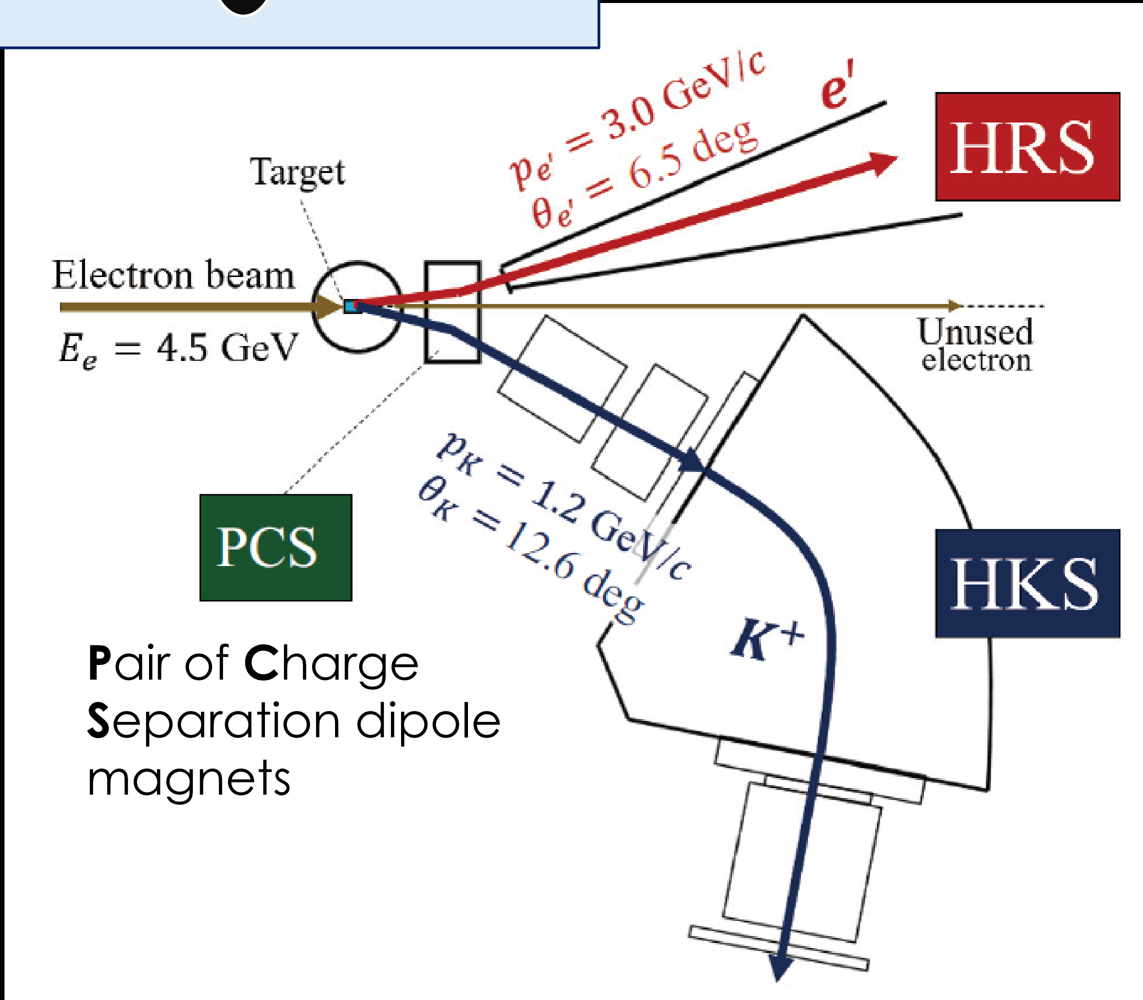
PROPOSED EXPERIMENT

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

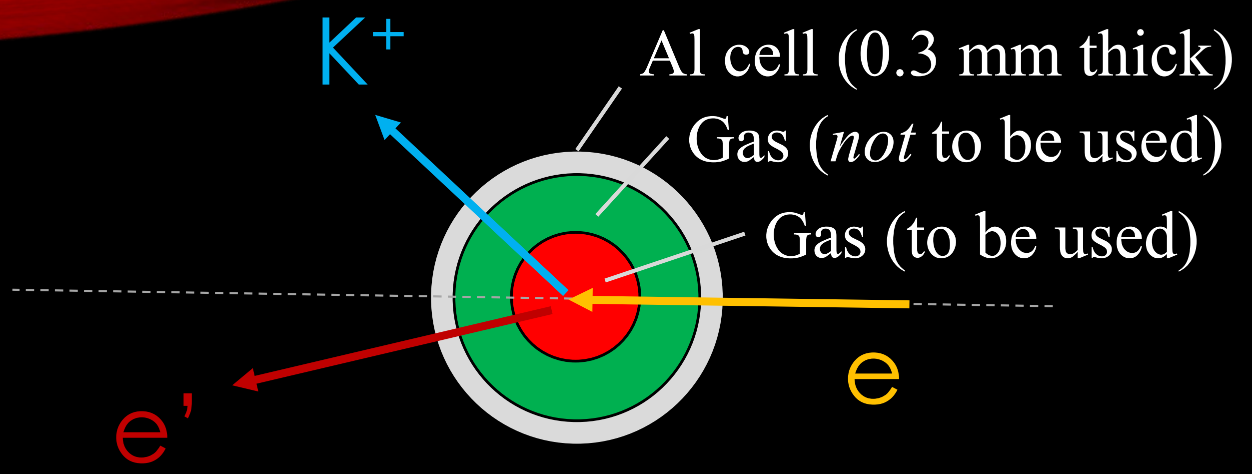
PCS @ TOKIN, Sendai, Japan (March 2020)

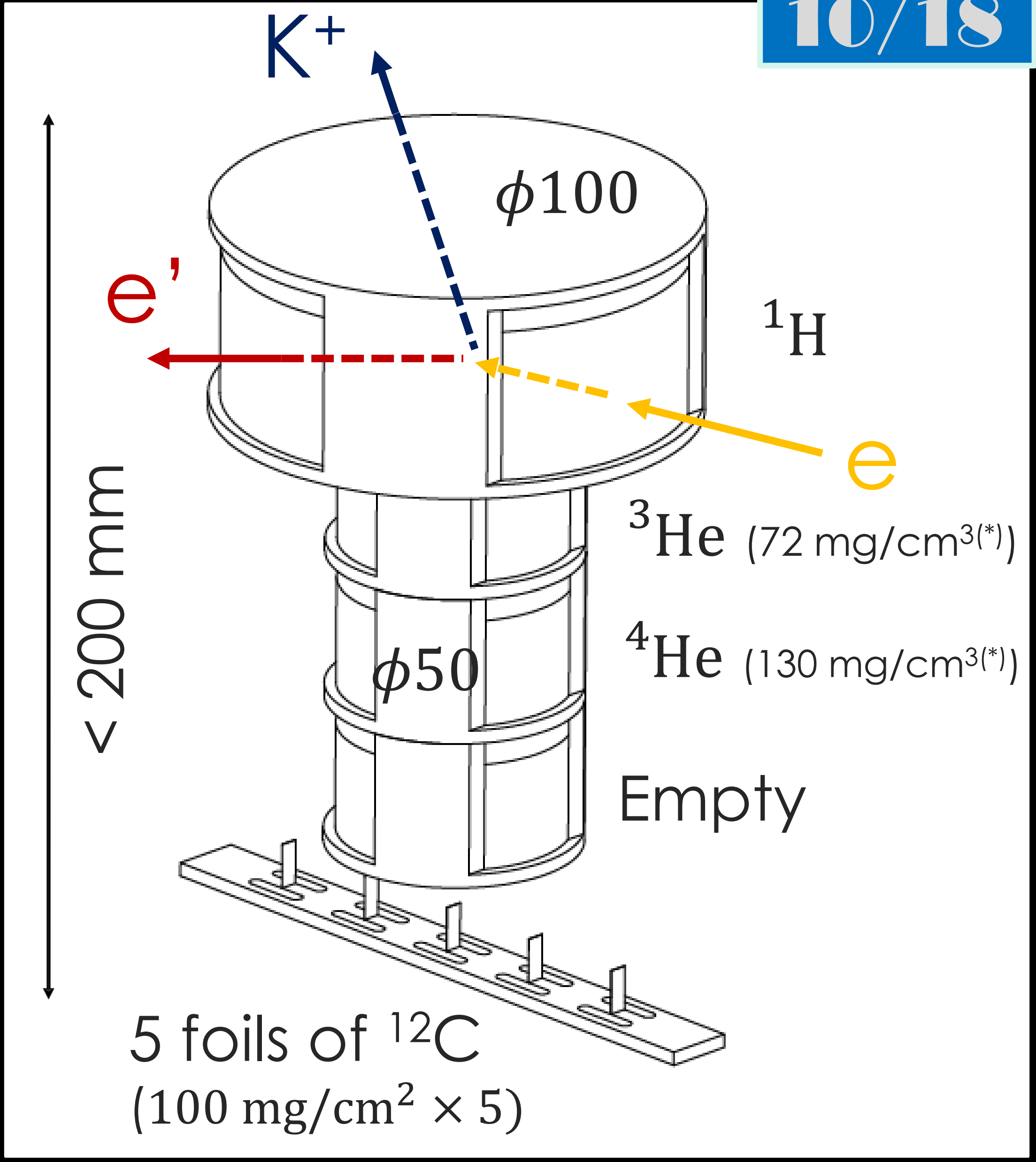


Pair of **C**harge **S**eparation dipole magnets

HKS magnet: Y. Fujii et al., NIMA 795 (2015) 351—363
KID: 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 ⇘; $\frac{x}{X_0} \simeq 3.4 \times 10^{-3}$)

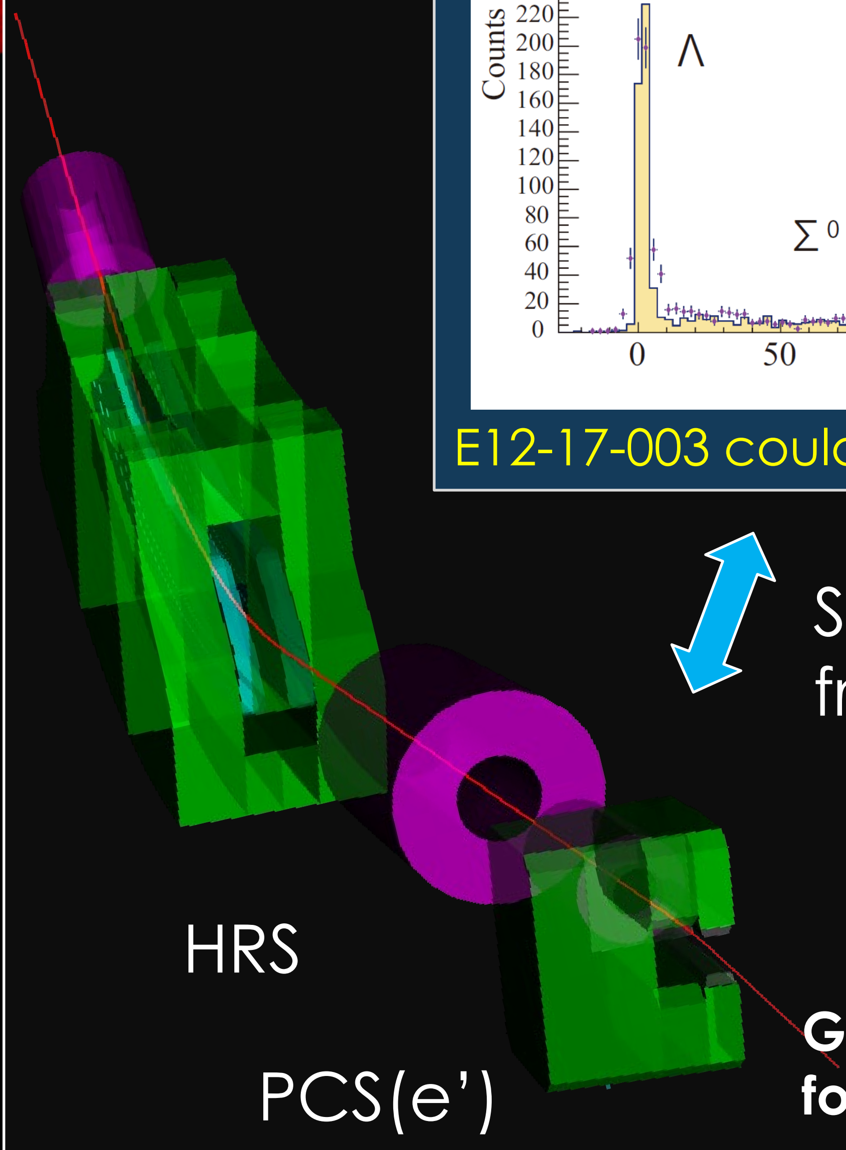
<u>To achieve better S/N</u>

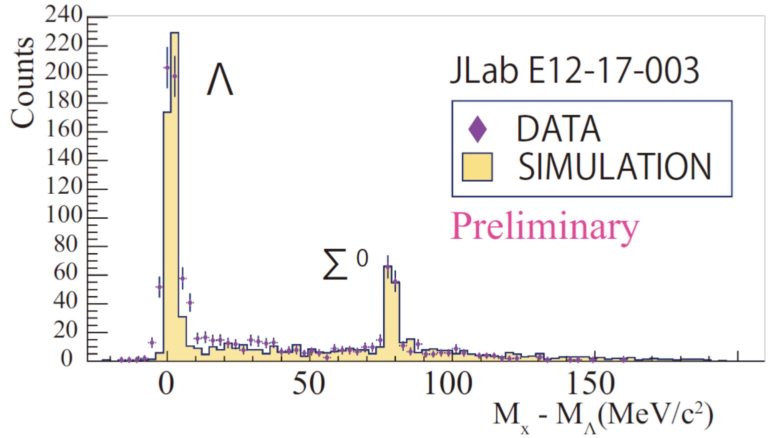
- Center part will be used for analysis

($\Delta z_t = 15$ mm FWHM is expected)

(*) T. Alcorn et al., NIMA 522 (2004)294—346

EXPECTED MISSING MASS RESOLUTION





E12-17-003 could be reproduced

Same framework

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

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

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

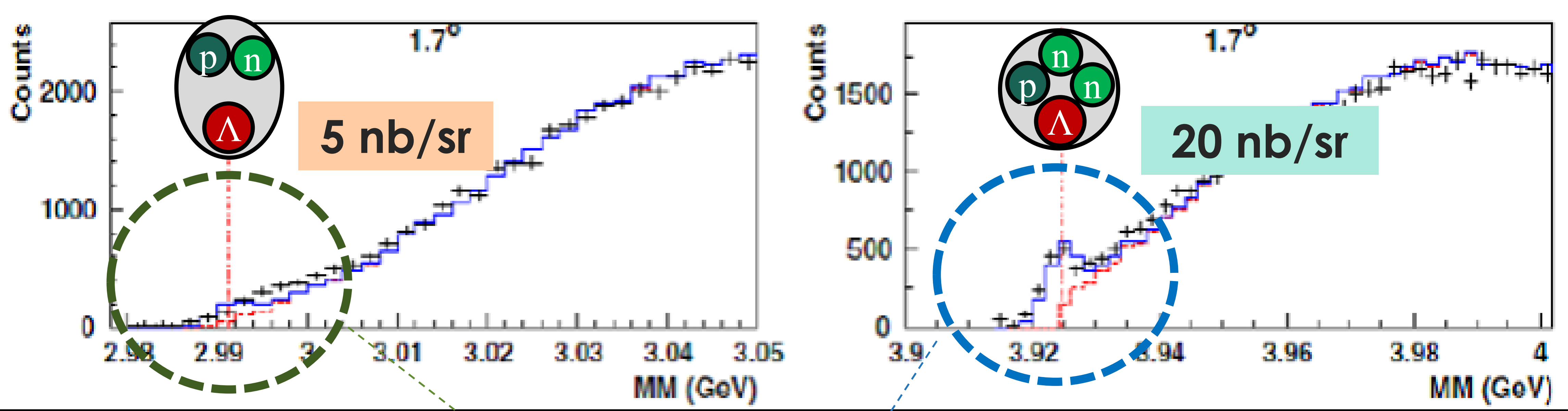
w/ materials (e.g. target):

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

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

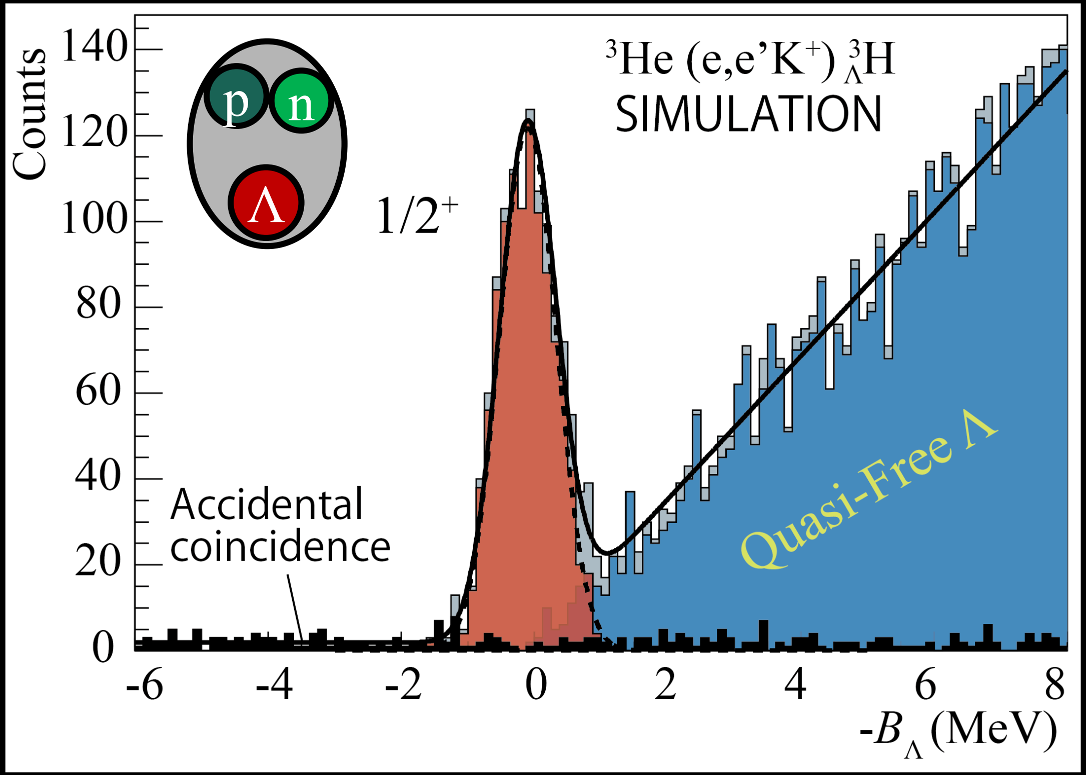
YIELD ESTIMATION

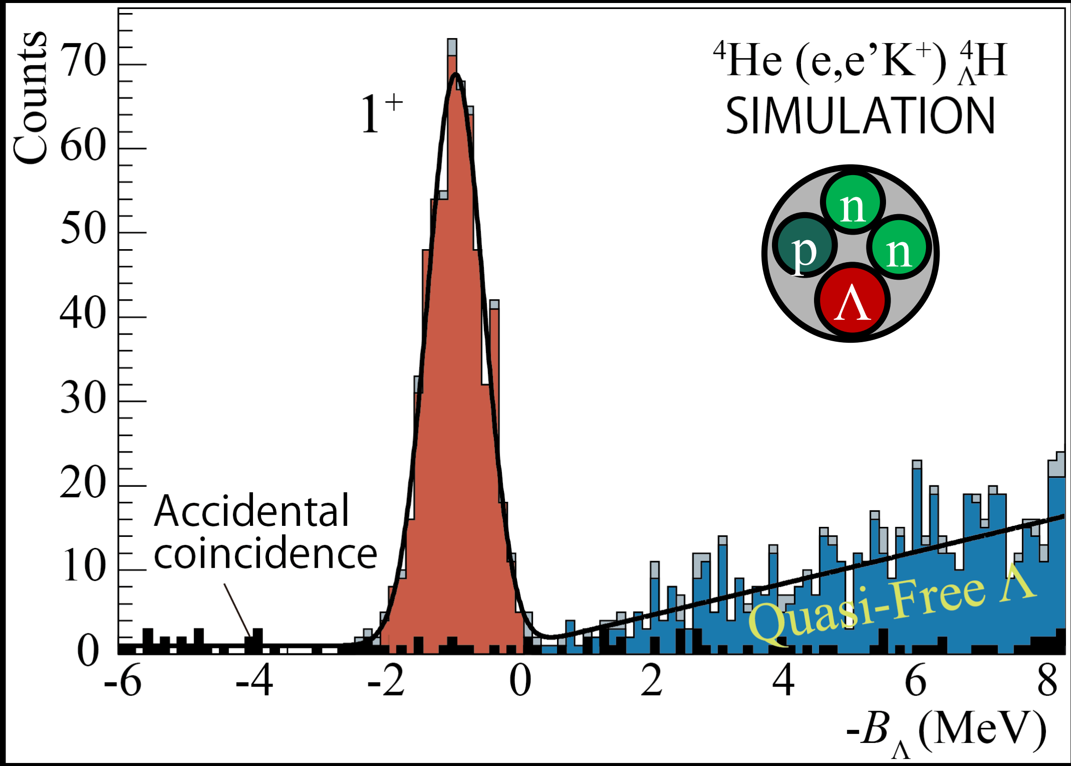
F. Dohrmann et al., *Phys. Rev. Lett.* **93**, 242501 (2004).



Product	Target (mg/cm^2)	I_{beam} (μA)	CS (nb/sr)	Yield / day	Beamtime (day)	**Total yield**
$^{3}_{\Lambda}H$	^{3}He (168)	50	5	105	10	**1050**
$^{4}_{\Lambda}H$	^{4}He (312)		20	587	1	**587**

EXPECTED SPECTRA AND STATISTICAL ERRORS





$|\Delta B_\Lambda^{stat.}| < 20$ keV

$|\Delta B_\Lambda^{stat.}| < 20$ keV

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

➡ ΛN CSB in A = 4

CALIBRATIONS AND A SYSTEMATIC ERROR ON B_Λ

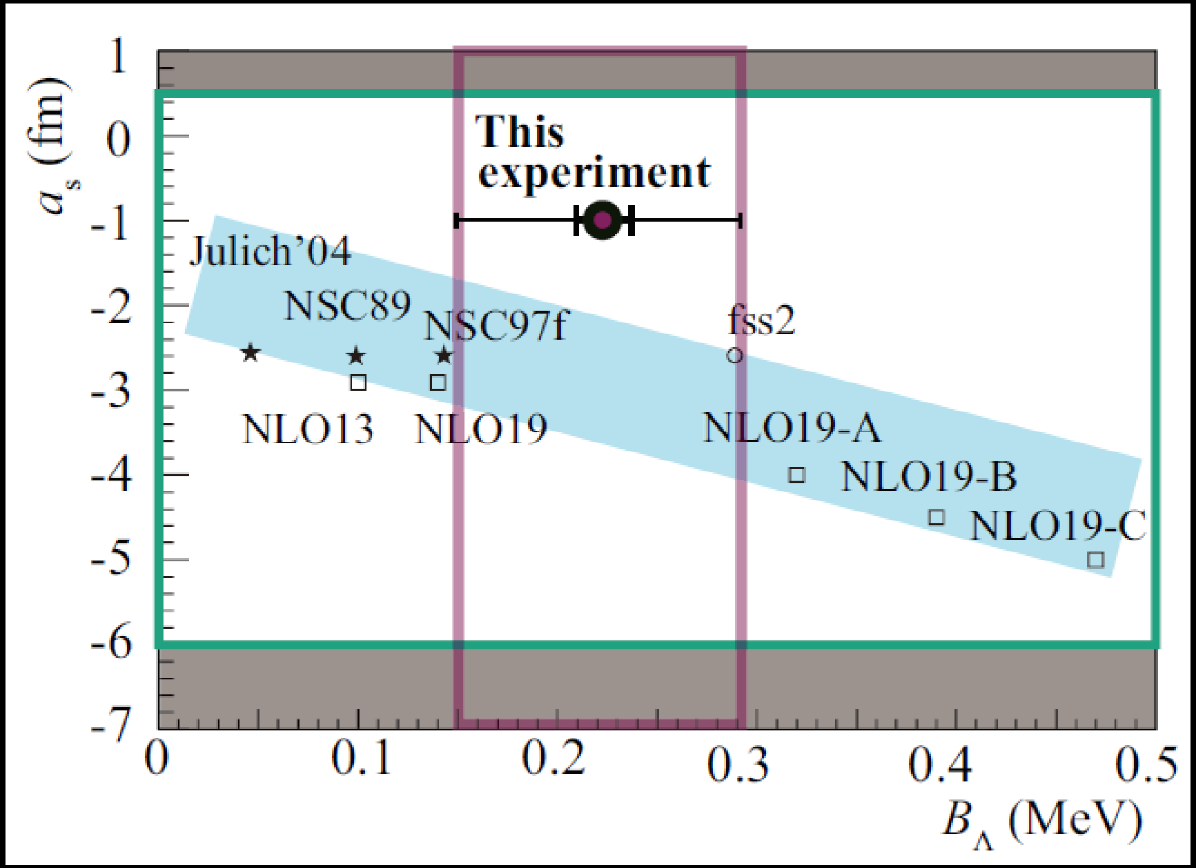
Calibration	Target + Sieve Slit	Reaction	z_t range (mm)	Beamtime (day)	Remarks
Mom. + z_t	H	$p(e,e'K^+)\Lambda,\Sigma^0$	$-50 < z_t < 50$	1	Λ: 3300, Σ^0: 1100
Mom. + z_t	^{12}C (multi foils)	$^{12}C(e,e'K^+)^{12}_{\Lambda}B$		1	$^{12}_{\Lambda}B^{g.s.}$: 300 × 5
Angle + z_t	^{12}C (multi foils) + SS	-		0.2	
z_t	Empty	-	$-25 < z_t < 25$	0.1	+ Background study
	Empty (or gas) + SS	-		0.2	+ Angle resolution check
Physics	^{3,4}He	$^{3,4}_{\Lambda}$H	$-25 < z_t < 25$	11	

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



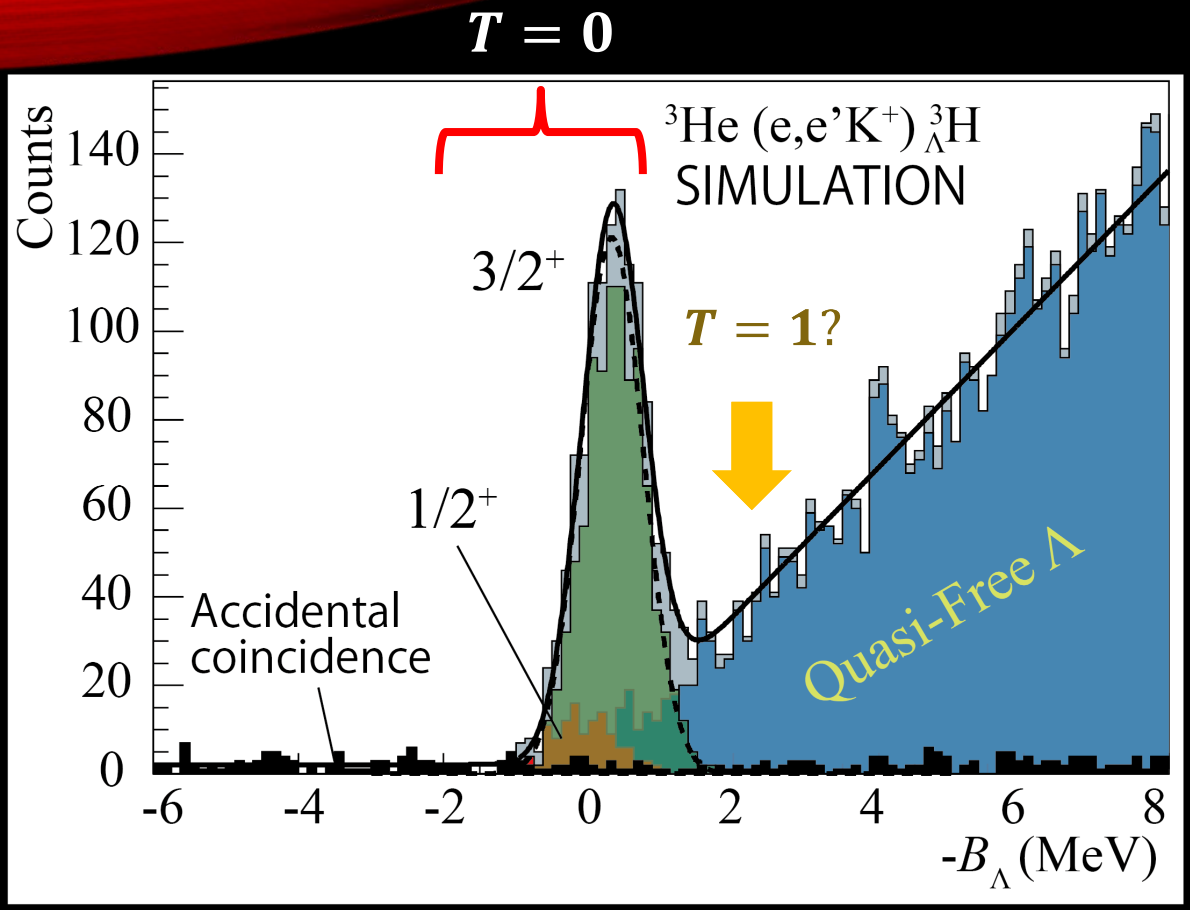
Hypertriton Puzzle

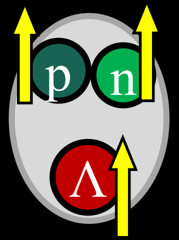
- Λd rm radius (**$|\Delta r| \lesssim 1$ fm**)
  ➔ Better estimation for the lifetime

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)

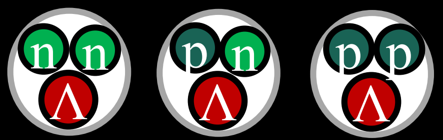
EXCITED STATES OF $^{3}_{\Lambda}$H





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

- 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
    - ← 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*Λ (and *pp*Λ)
  → significant information on the existence of *nn*Λ
- CSB study in the A = 3 hypernuclear system
- If the CS is 0.5 nb/sr → $|\Delta B_{\Lambda}^{\mathrm{stat.}}| < 50$ keV

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

BEAMTIME REQUEST (C12-19-002)

Physics				
Target (mg/cm^2)	I_e (μA)	Product	Beamtime (day)	Yield
^{3}He (168)	50	$^3_\Lambda$H	10	1050
^{4}He (312)	50	$^4_\Lambda$H	1	587
Subtotal			11	
Calibration				
Target	I_e (μA)	Reaction	Beamtime (day)	Remarks
H (30)	50	$p(e, e'K^+)\Lambda, \Sigma^0$	1	Λ: 3300, Σ^0: 1100
Multi foils (100 × 5)	50	$^{12}C(e, e'K^+)^{12}_{\Lambda}B$	1	$^{12}_{\Lambda}B^{g.s.}$: 300 × 5
Multi Foils + SS	20	-	0.2	
Empty	20	-	0.1	+ Background study
Empty (or gas) + SS	20	-	0.2	+ Angle resolution check
Subtotal			2.5	
Total			**13.5**	

SUMMARY (JLAB C12-19-002)

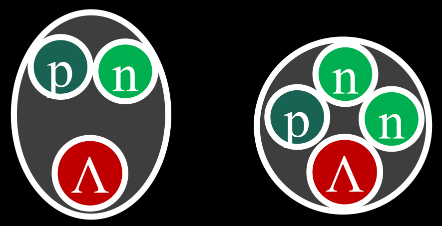
☆ **HRS-HKS @ Hall A**

☆ **50-μA beam on ^{3}He and ^{4}He gas targets**

☆ **Beamtime = 13.5 days**

✓ 11 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

BACKUP

RESPONSES FOR TAC REPORT

Responses for Technical Comments (C12-19-002)

C1. This experiment will be a major installation (>= 6 months) with the HKS spectrometer in Hall A. If the proposal is approved, design and planning of the installation should be started well in advance and a review of the experiment should be scheduled early to address technical issues and identify the source of (users vs. lab) of various resources.

A1. Yes, we agree that.

C2. A target system that can accommodate the calcium targets from E12-15-008, and cryogenic and optics targets from this experiment will need to be designed and could be costly. It is not clear if all desired targets will fit on a single ladder assembly. There may have to be a targets assembly swap and resurvey to accommodate all desired targets. Several days, not included in the beam time request, are needed to change the cryogenic cooling from the LH2 target to the helium targets. If it is not feasible to construct a target system that can accommodate all the targets simultaneously, time will be needed to change the physical configuration between E12-15-008 and this experiment.

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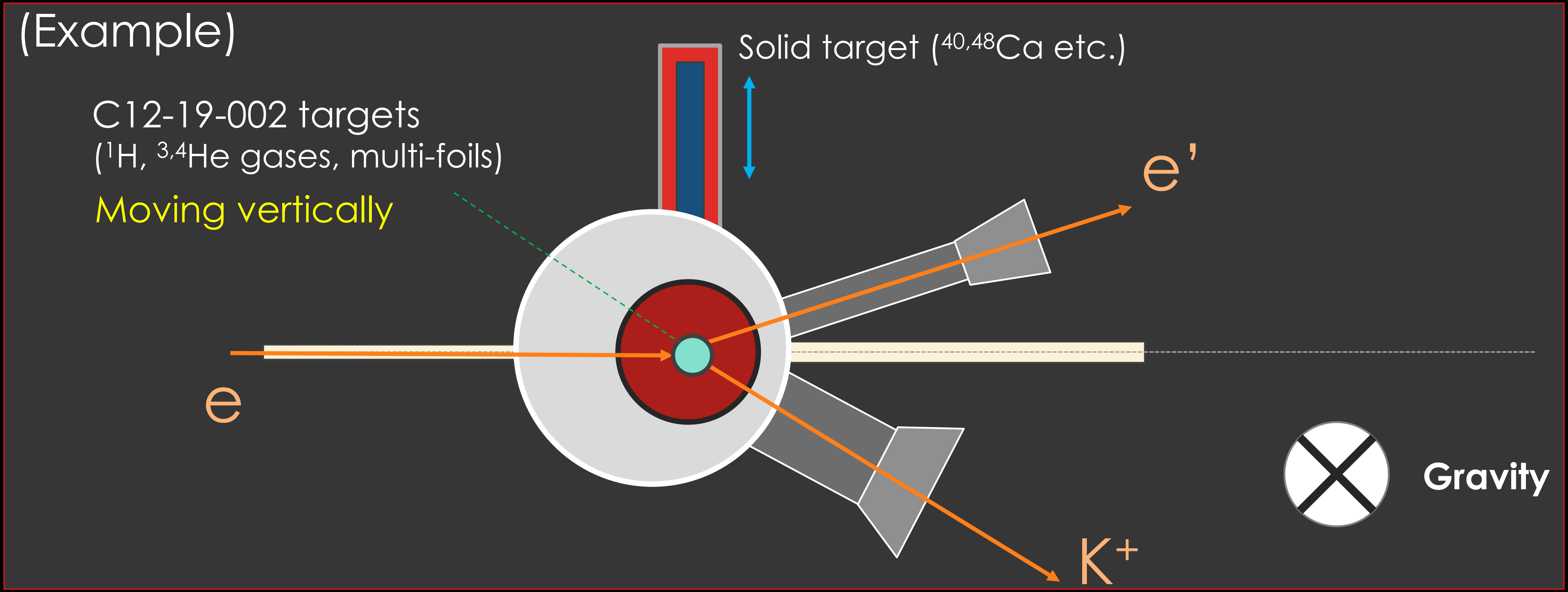
A2. A ladder that hold C12-19-002 targets could be separated from that for other targets (calcium targets etc. used for E12-15-008) as shown in a figure below. A detail design needs to be done with JLab target group taking into account physical space and a size of cryogenic system.



C3. Obtaining good missing mass resolution with extended targets relies on the ability of the HRS with a septum magnet to determine the z position of the interaction. The Z resolution was simulated with GEANT. While the septum magnet for this experiment will be new, previous experience using other septa with HRS spectrometers could help to validate this simulation.

A3. We built a Geant4 simulation that can reproduce experimental widths of a vertex z and a missing mass for E12-17-003 (nnΛ search experiment at Hall A with HRS-HRS). We coded a Geant4 simulation for C12-19-002 by adding new magnets (PCS) to the setup of E12-17-003 simulator. The new Genat4 simulation shows that the z vertex resolution is $|\Delta v_{zt}| = 15$ mm FWHM and the missing mass resolution is 1 MeV/c^2 FWHM. If the vertex resolution is $|\Delta v_{zt}| = 30$ mm FWHM which is about a resolution that the HRS+Septum system for hypernuclear spectroscopy was achieved at $\theta_{\mathrm{HRS}} = 6$ deg, the expected missing mass resolution is worse by 15% being about 1.15 MeV/c^2 FWHM. The worse resolution of 1.15 MeV/c^2 has a negligible effect on B_Λ accuracy (σ^{stat}: 13 keV → 15 keV).

It is worth noting that missing mass resolutions in E05-115 (HES-HKS at Hall C) in which we introduced a new e' magnet (HES) were also consistent with our Geant4 simulation results for all targets (TG et al., NIMA 900 (2018) 69—83).

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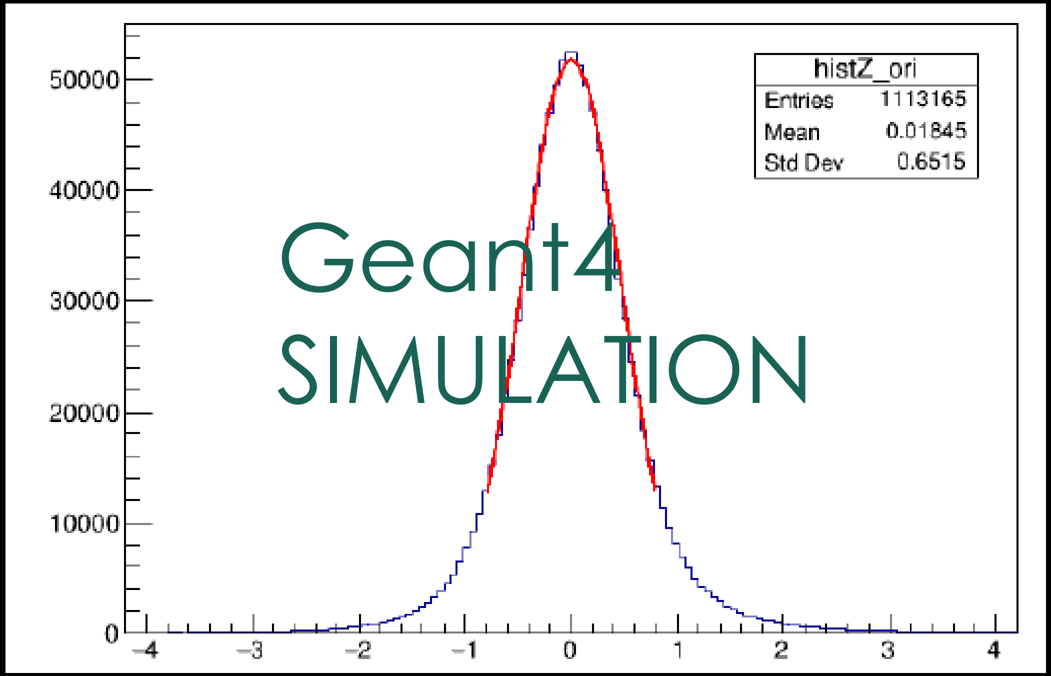
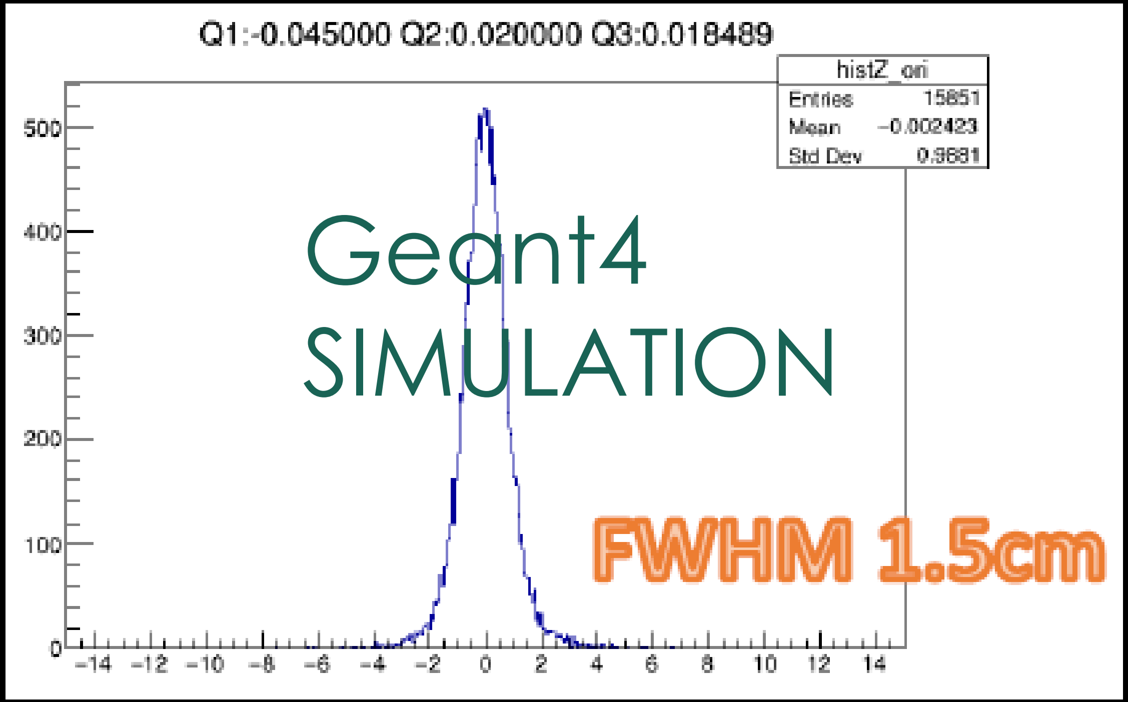
E12-17-003
HRS (single arm) @13.2 deg



Vertex z (cm)

Simulation: FWHM = 11 mm
Data (E12-17-003): FWHM = 12 mm

Proposed experiment
HRS+PCS @6.5 deg



Vertex z (cm)

Simulation: FWHM = 15 mm

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C4. This experiment and E12-15-008 would benefit from an engineering/commissioning run separated in time from the production run.

A4. We totally agree it. It would be great to have such runs.

C5. The PAC evaluating a proposal which ultimately became E12-15-008 decided that there were too many nuclei in the original proposal and recommended that only the K isotopes (calcium targets) be examined. (See PAC43 report -https://www.jlab.org/exp_prog/PACpage/PAC43/PAC43_FINAL%20_Report.pdf) This conditional proposal, PR12-20-003 and PR12-20-013 add back most of originally proposed targets. If the June 22 LIGO-Virgo announcement https://arxiv.org/abs/2006.12611 GW190814: Gravitational Waves from the Coalescence of a 23 $M_\odot$ Black Hole with a 2.6 $M_\odot$ Compact Object makes this physics more compelling, all three proposals should probably be mounted as a single campaign given installation and de-installation time of HKS.

A5. We thank the comments. we agree it.

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- **C6.** A binding energy with a statistical "accuracy < 20 keV" and overall systematic accuracy of 100 keV is specified (Bottom of page 13 and top of page 15). This will require a stable beam energy and small energy spread. The synchrotron light interferometer used to measure beam energy spread for previous hypernuclear experiments was decommissioned during the 12 GeV upgrade and the performance of a replacement has not been reported. Achieving the required 5×10^{-5} energy spread, particularly when Hall D is running at 12 GeV should be possible, but should be demonstrated by accelerator before experiment is scheduled.

A6. In E12-17-003 (nnΛ, 2018) experiment, the SLI was used and worked well to monitor the energy spread of $< 5 \times 10^{-5}$ in RMS which is good enough for the proposed experiment.

- **C7.** When HKS was used in Hall C the beam line to the dump passed close to the corner of the HKS (similar to shown in Figure 10). The field leaking from saturated steel required the use of relatively large-bore correctors after that point. These correctors should be still available.

A7. It is good to hear that and we would like to use it if it meets our condition of the experiment. Further study and discussions with JLab staff are needed.