JLab Hall A/C meeting

High accuracy measurement of nuclear masses of hyperhydrogens

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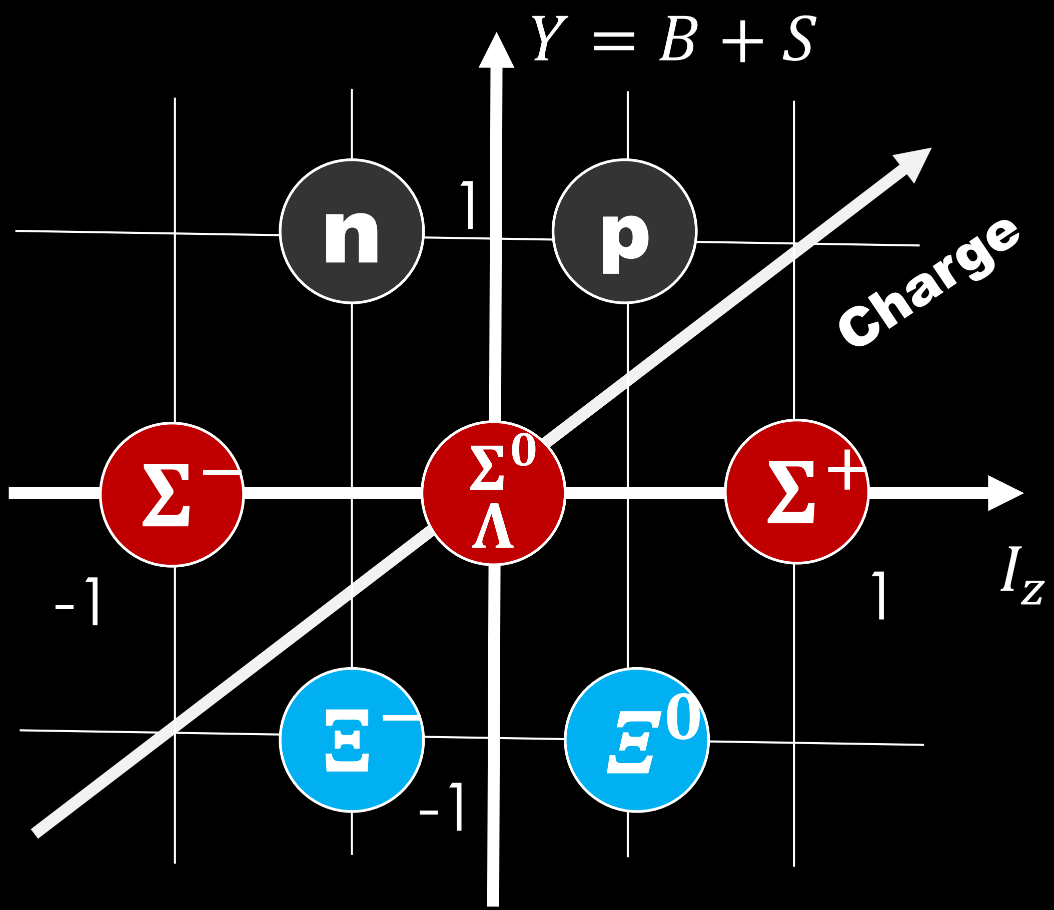
S.N. Nakamura, F. Garibaldi, P. Markowitz, J. Reinhold, L. Tang, G.M. Urciuoli

for the JLab Hypernuclear Collaboration

Jul 9, 2021

京都大学
KYOTO UNIVERSITY

STUDY ON BARYON INTERACTION (BB INT.)



Baryon Octet $J^\pi = \frac{1}{2}^+$

Nuclear Sector (NN)

- Rich data of scattering experiment
- Nuclear data > 3000

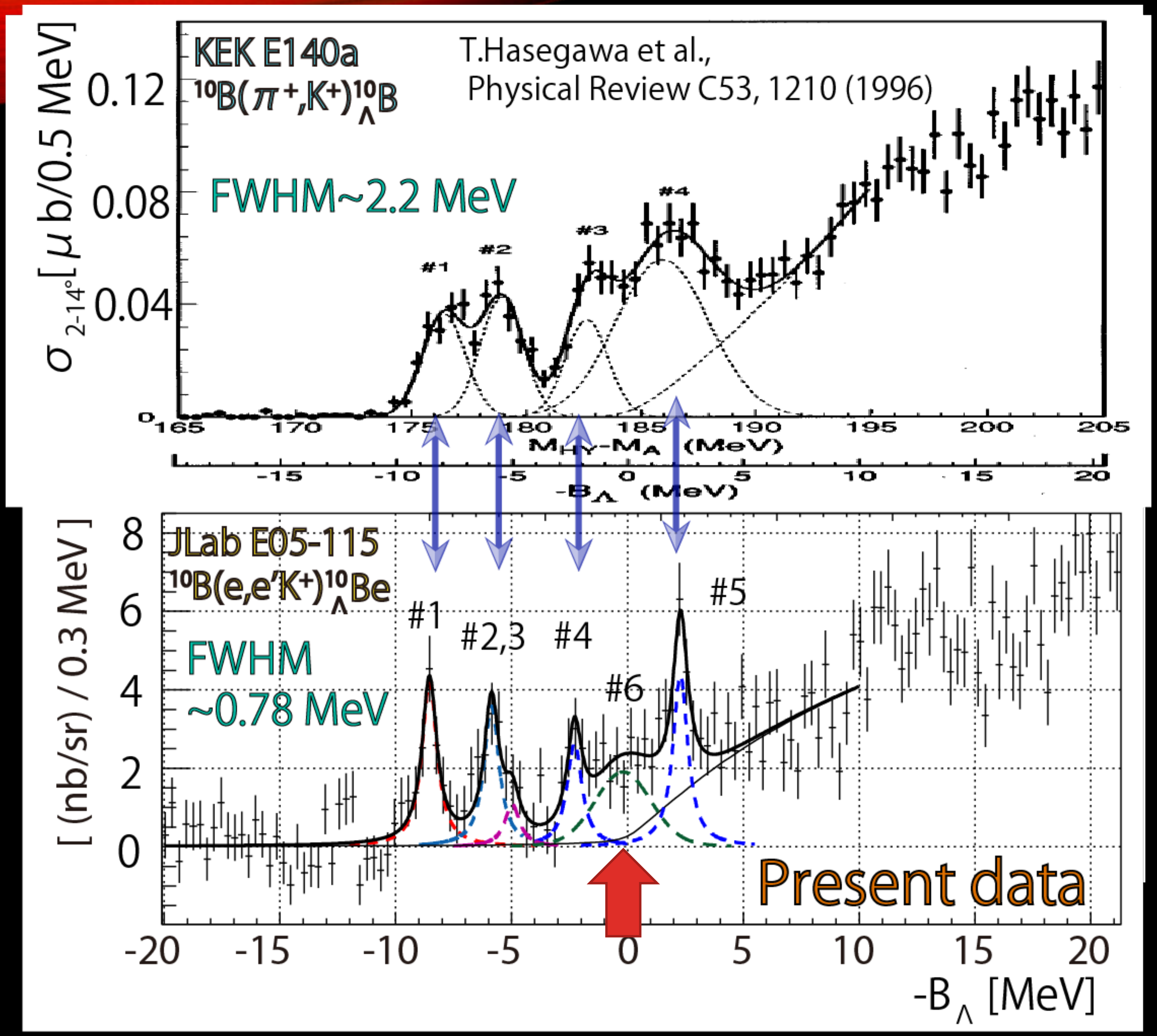
Strangeness Sector (ΛN, ΣN, ΞN etc.)

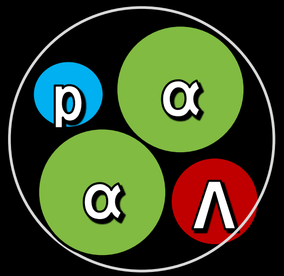
- Scarce data of scattering experiment
- Hypernuclear data ~ only 40 !!

Available facilities for HN experiments:

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

HIGH RESOLUTION SPECTROSCOPY (A=10)

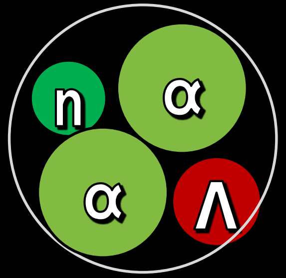




$^{10}B(\pi^+,K^+)\,^{10}_{\Lambda}B$ @KEK

$^{10}B(e,e'K^+)\,^{10}_{\Lambda}Be$ @JLab

HKS Collaboration, *PRC 93* (2016) 034314



A new structure was found !!

→ A. Umeya *et al* 2020 *J. Phys.: Conf. Ser.* **1643** 012110

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)

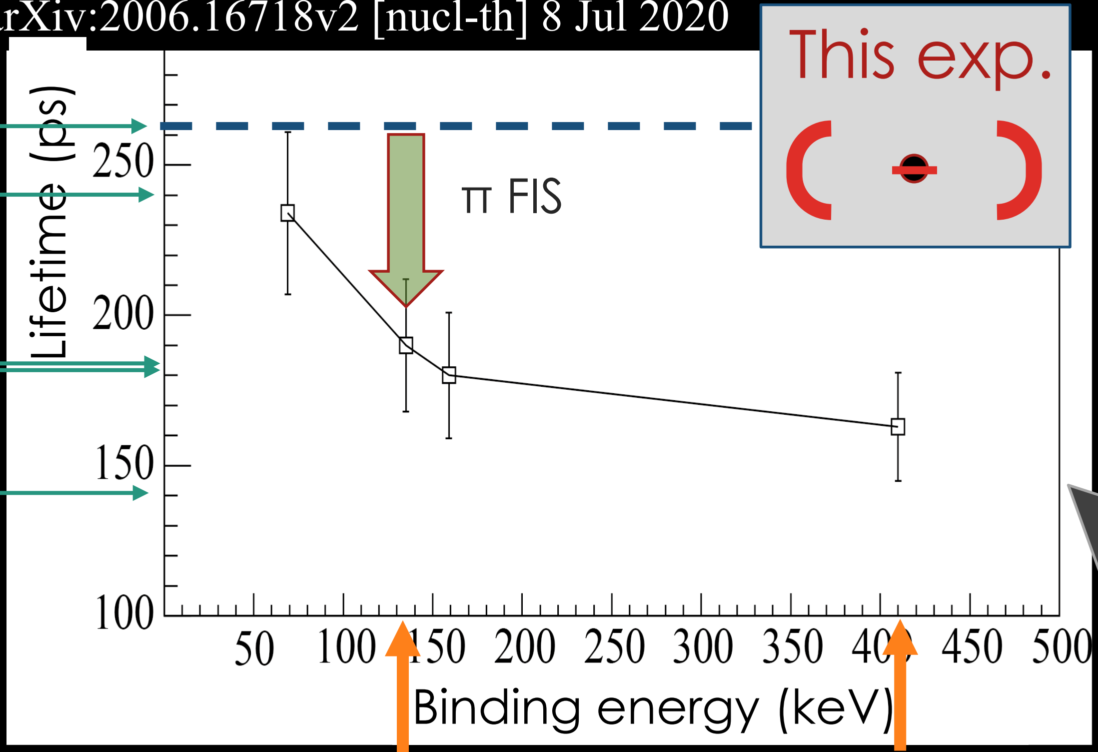
Fadeev calcuation with realistic NN/YN interactions
→ $\boldsymbol{\tau = 0.97\, \tau_\Lambda}$
(H. Kamada *et al.*, *Phys. Rev. C* **57**, 4 (1998))

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

arXiv:2006.16718v2 [nucl-th] 8 Jul 2020

Free Λ
ALICE 2
HypHI
ALICE 1
STAR



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)

$\propto \sqrt{B_\Lambda}$

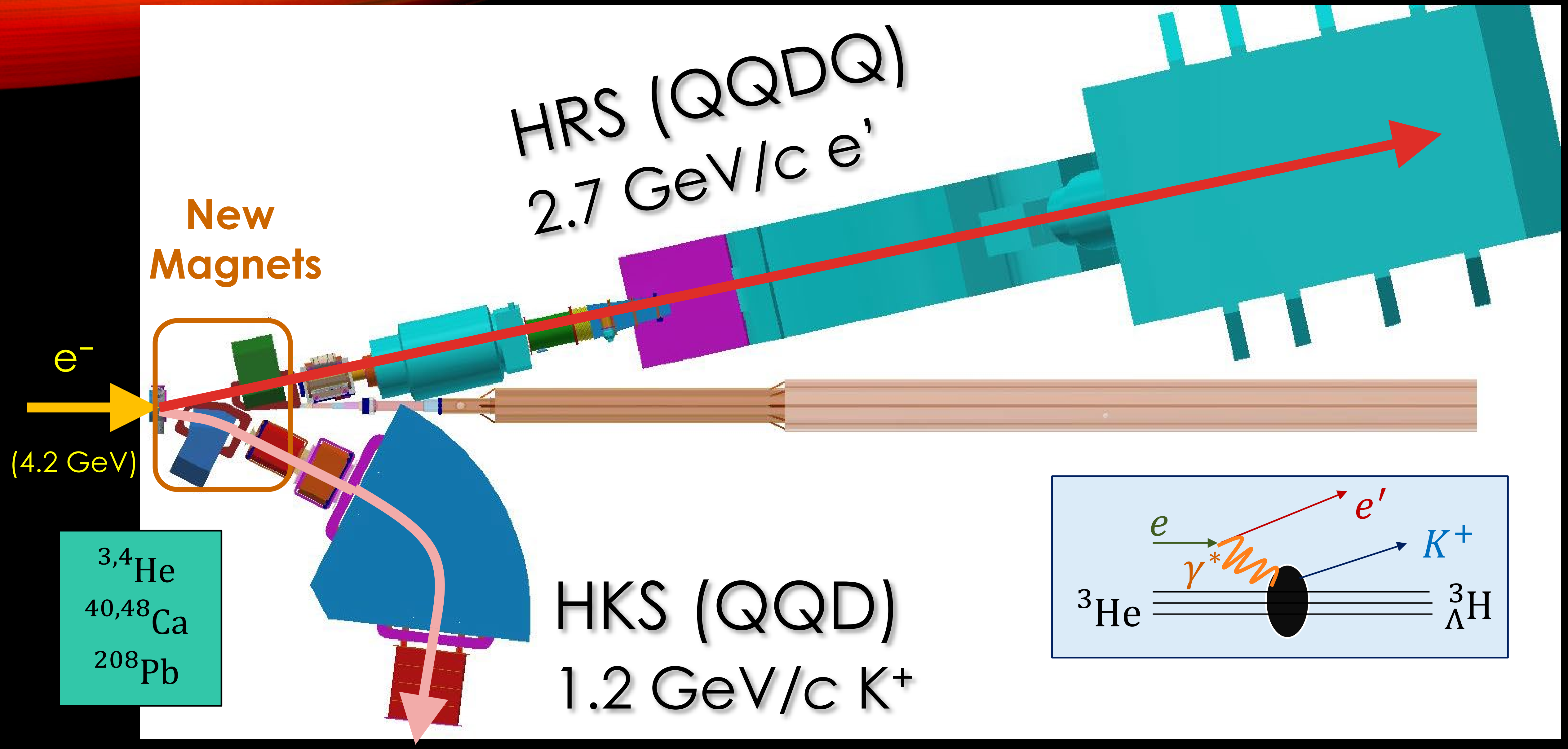
Proposed experiment (C12-19-002)

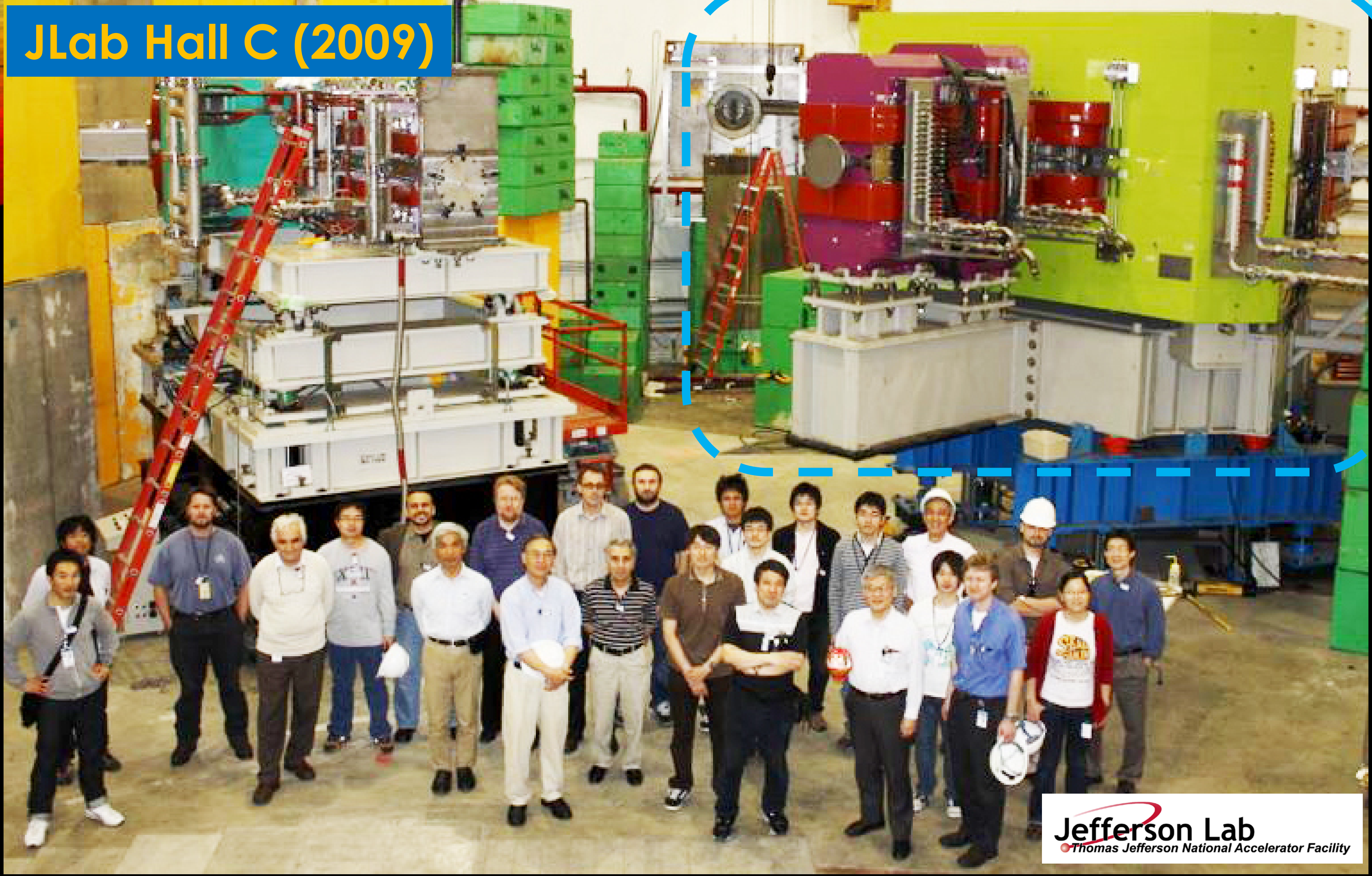
$|\Delta B^{\mathrm{stat.}}| = 20$ keV, $|\Delta B^{\mathrm{sys.}}| = 70$ keV

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

➔ Pin down the hyperon puzzle

Experimental Setup at JLab Hall A



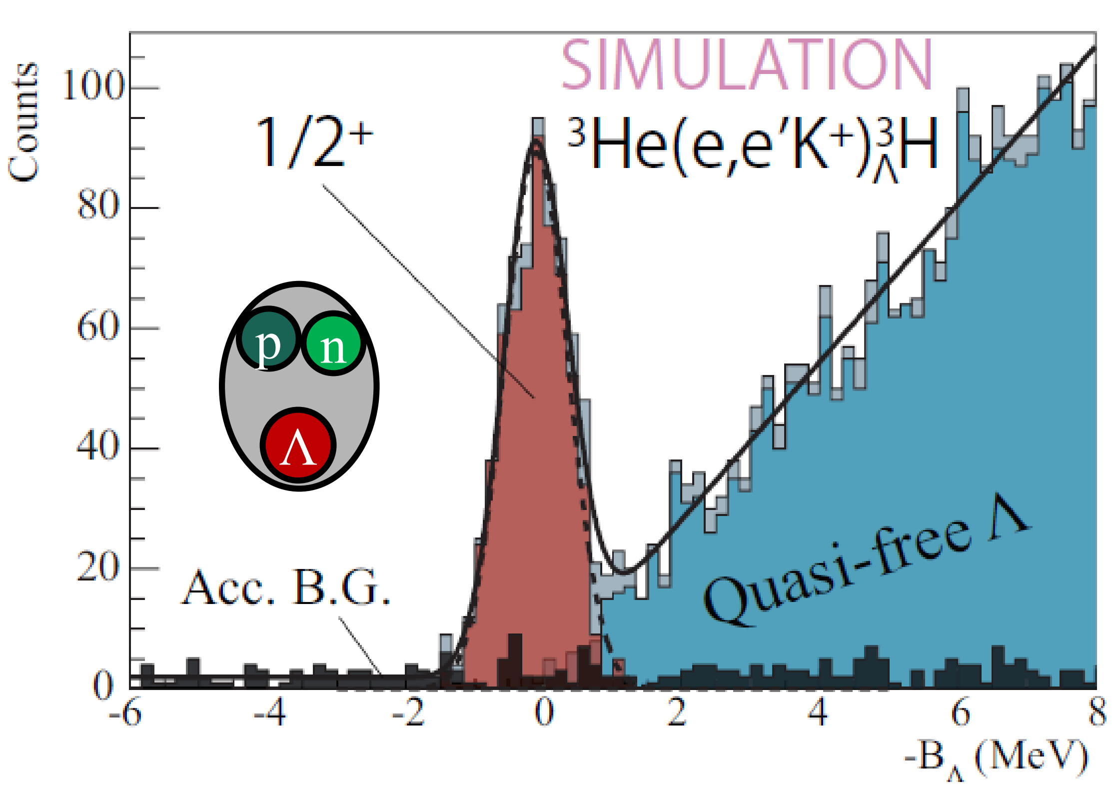


HKS

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

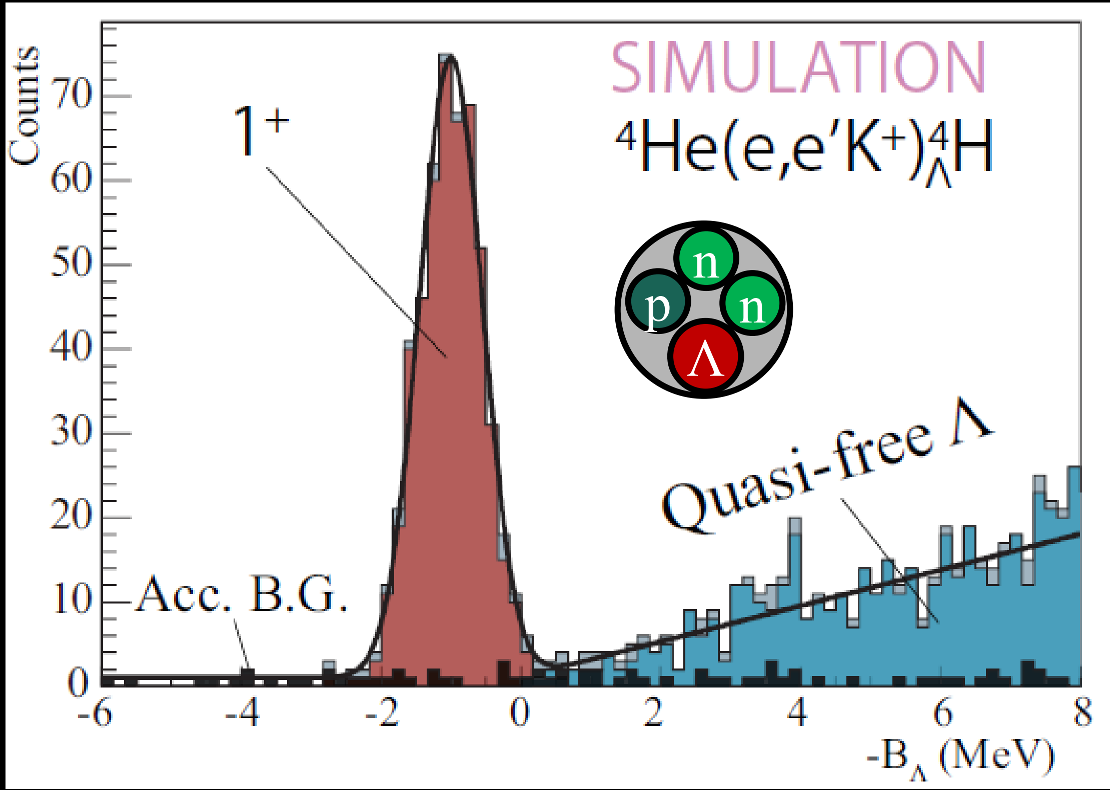
TG et al., PRC 103, L041301 (2021).
TG et al., NIMA 900, 69—83 (2018)
TG et al., PRC 94, 021302(R) (2016).
TG et al., PRC 93, 034314 (2016).
L. Tang et al., PRC 90, 034320 (2014).
TG et al., NIMA 729, 816—824 (2013).

EXPECTED SPECTRA AND STATISTICAL ERRORS



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

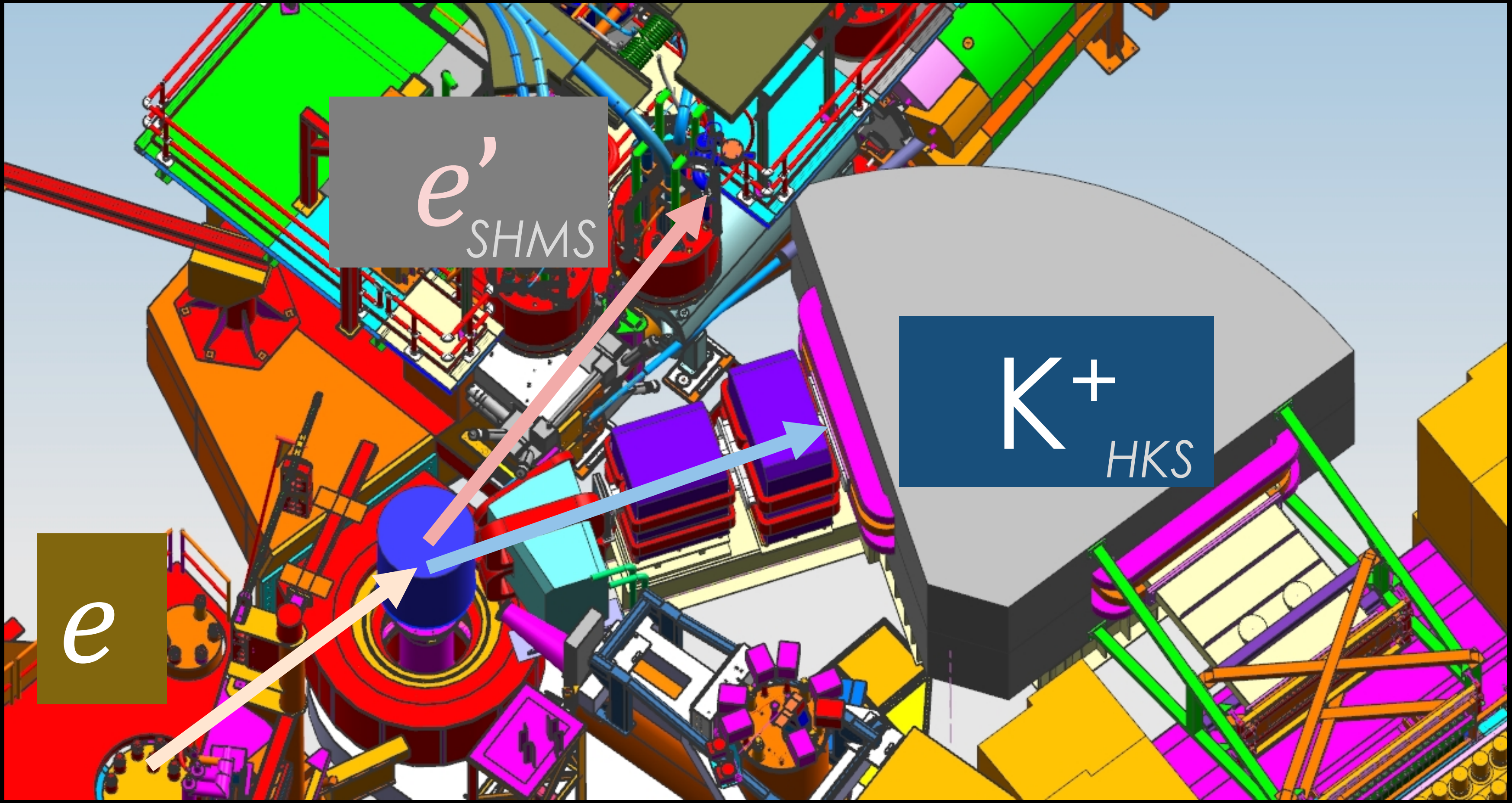
➡ Hypertriton Puzzle + ΛN int.
(g.s. or excited states)



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

➡ ΛN CSB in A = 4

Possibility in Hall C



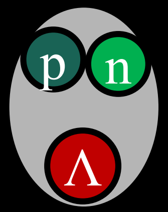
Thank you for the drawings + discussions → Bert, Paul, Steve

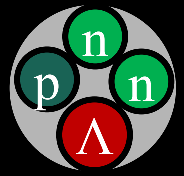
Evaluations are in progress

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

SUMMARY (C12-19-002)

☆ **HRS-HKS @ Hall A**
(It may be possible at Hall C)
☆ **50-μA beam on ^{3}He and ^{4}He gas targets**
☆ **Beamtime = 14.5 days**
(including calibration runs)

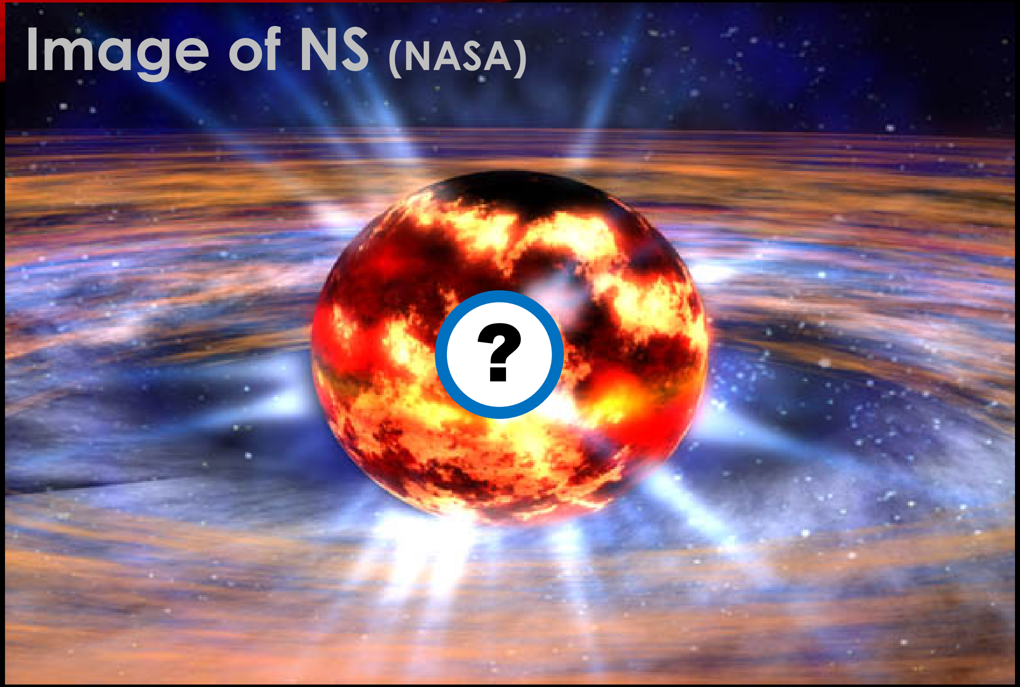




➔ World best accuracy in measuring $B_{\Lambda}({}^{3,4}_{\Lambda}\mathrm{H})$
➔ Hypertriton Puzzle / Charge Symmetry Breaking

BACKUP

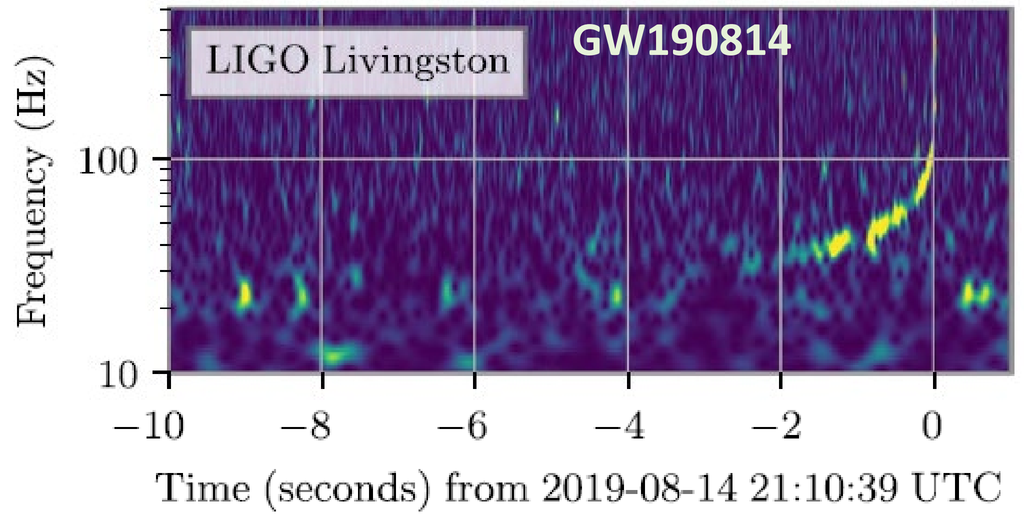
NEUTRON STARS AND HYPERONS



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>

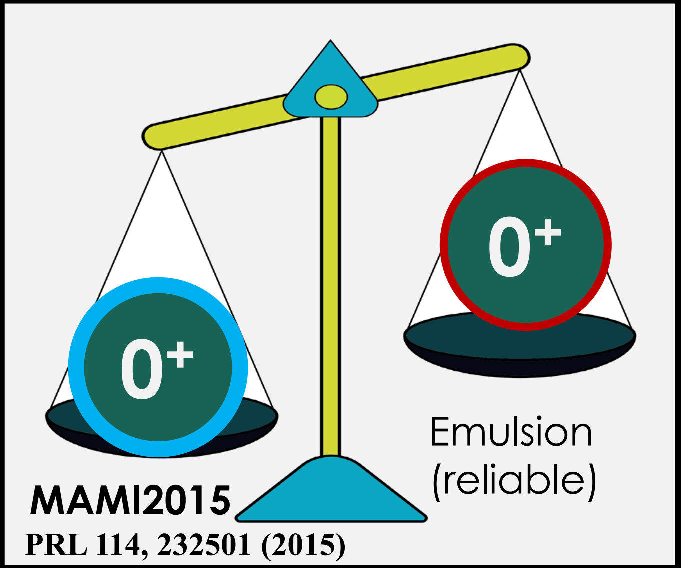
→$\geq 2M_\odot$ is hard to support by only 2BF

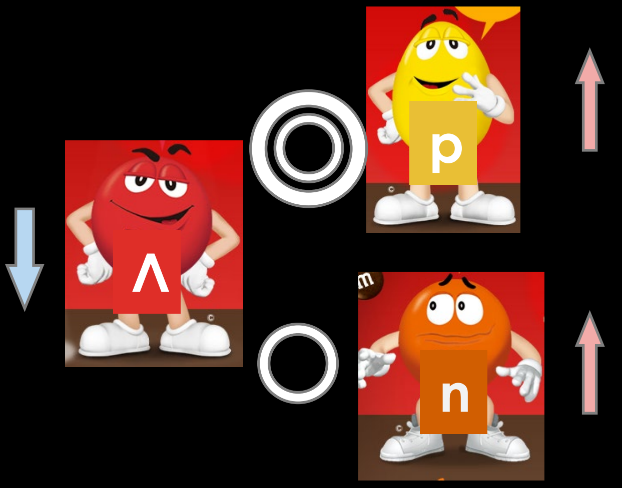
→Multi body repulsive forces may play a role

More precise studies on the strange BB/BBB interactions are needed

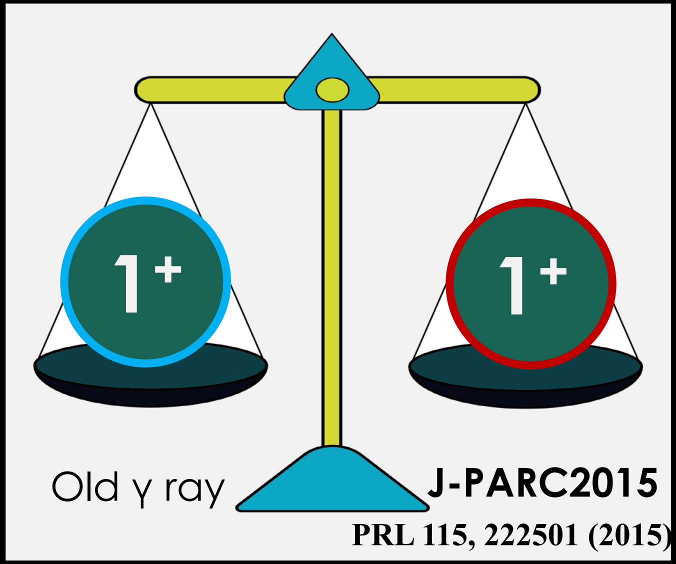
CHARGE SYMMETRY BREAKING IN THE ΛN INTERACTION

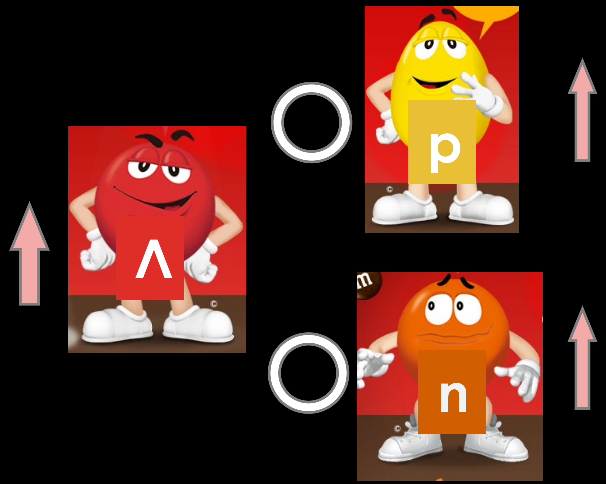
Unbalanced





Balanced

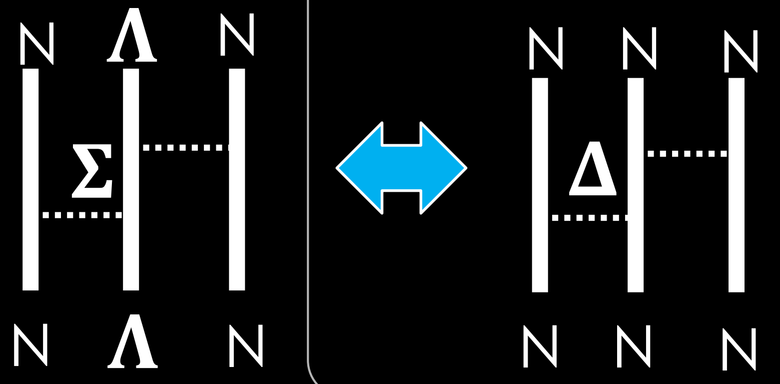




$^4_\Lambda H$ Mirror $^4_\Lambda He$

ΛN-ΣN 3BF[(1)]

Fujita-Miyazawa 3BF[(2)]

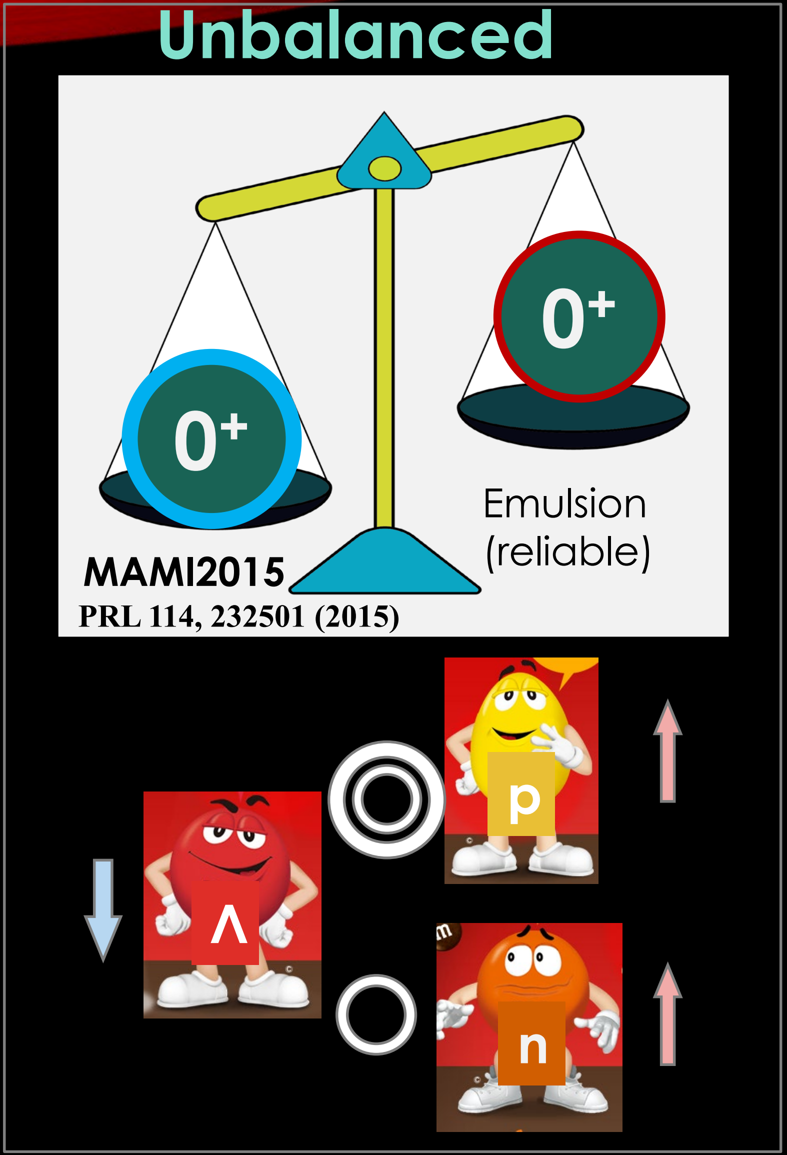


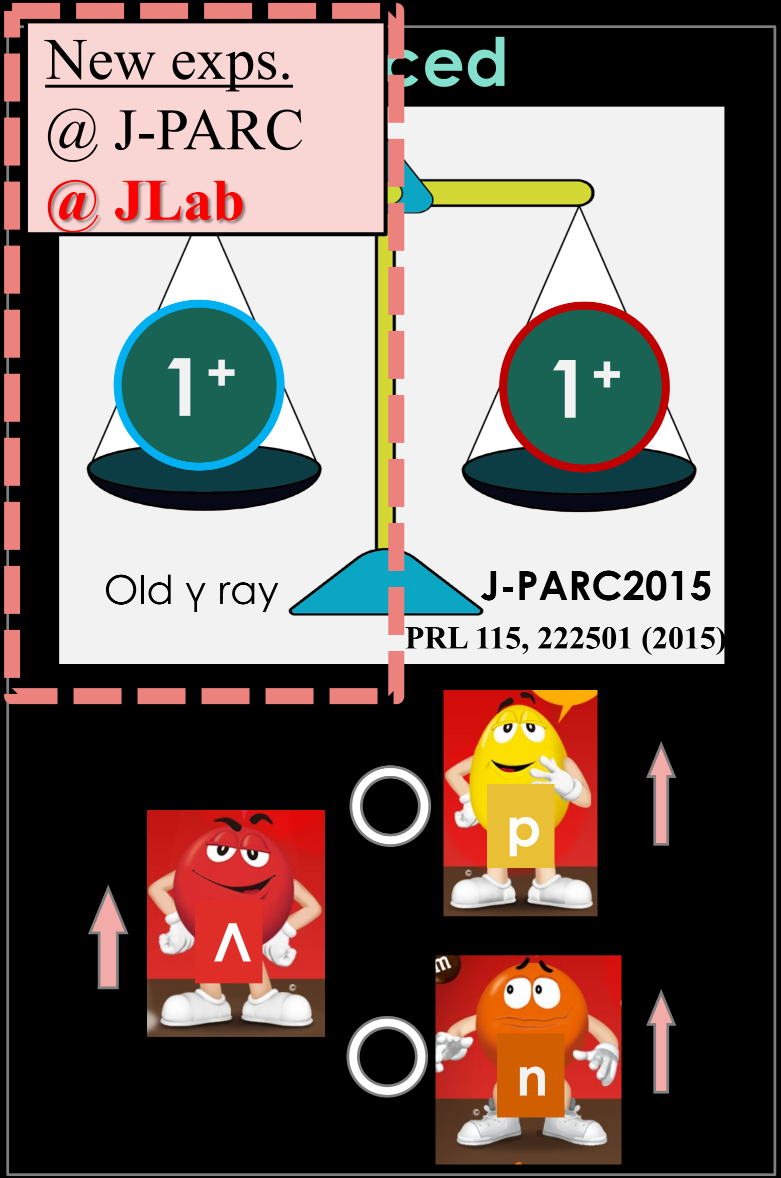
Σ may admix in the ΛN/ΛNN interaction

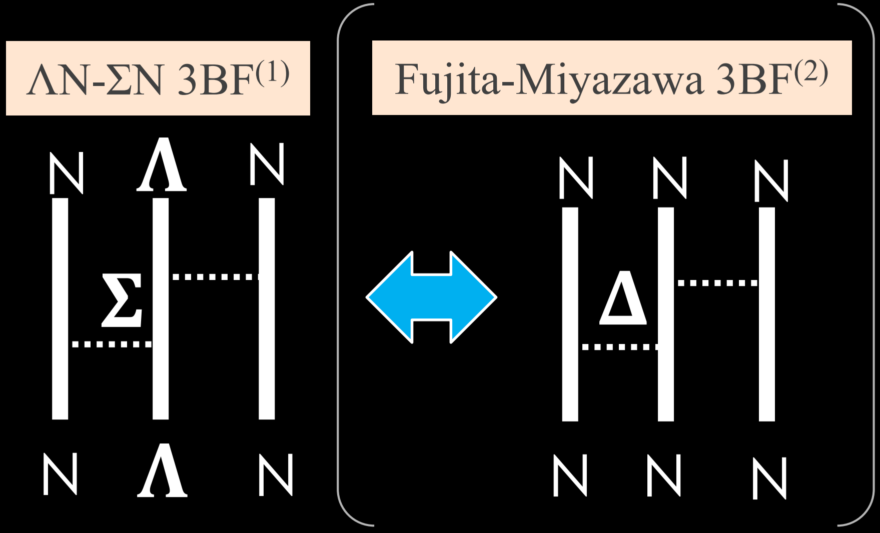
(1) Y. Akaishi et al., PRL 84, 3539 (2000)

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

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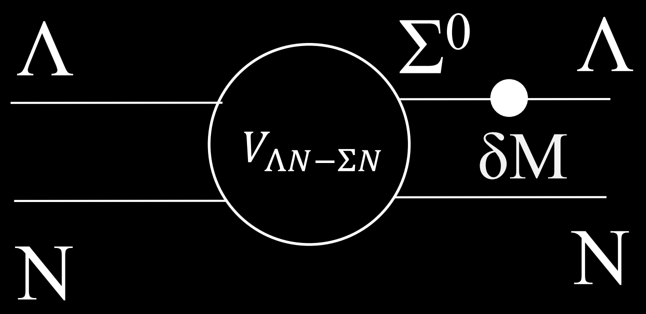
BASIC INFORMATION FOR THE ΛN CSB STUDY: ${}^{4}_{\Lambda}\mathrm{He} - {}^{4}_{\Lambda}\mathrm{H}$

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).

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

Basic Input (This proposal)

A=4 → **CSB interaction** →

A=5

A=7 HKS, PRL 110, 012502 (2013)

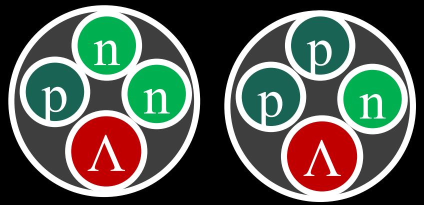
HKS, PRC 94, 021302(R) (2016)

A=9 Hall A, PRC 91,034308 (2015)

A=10 HKS, PRC 93, 034314 (2016)

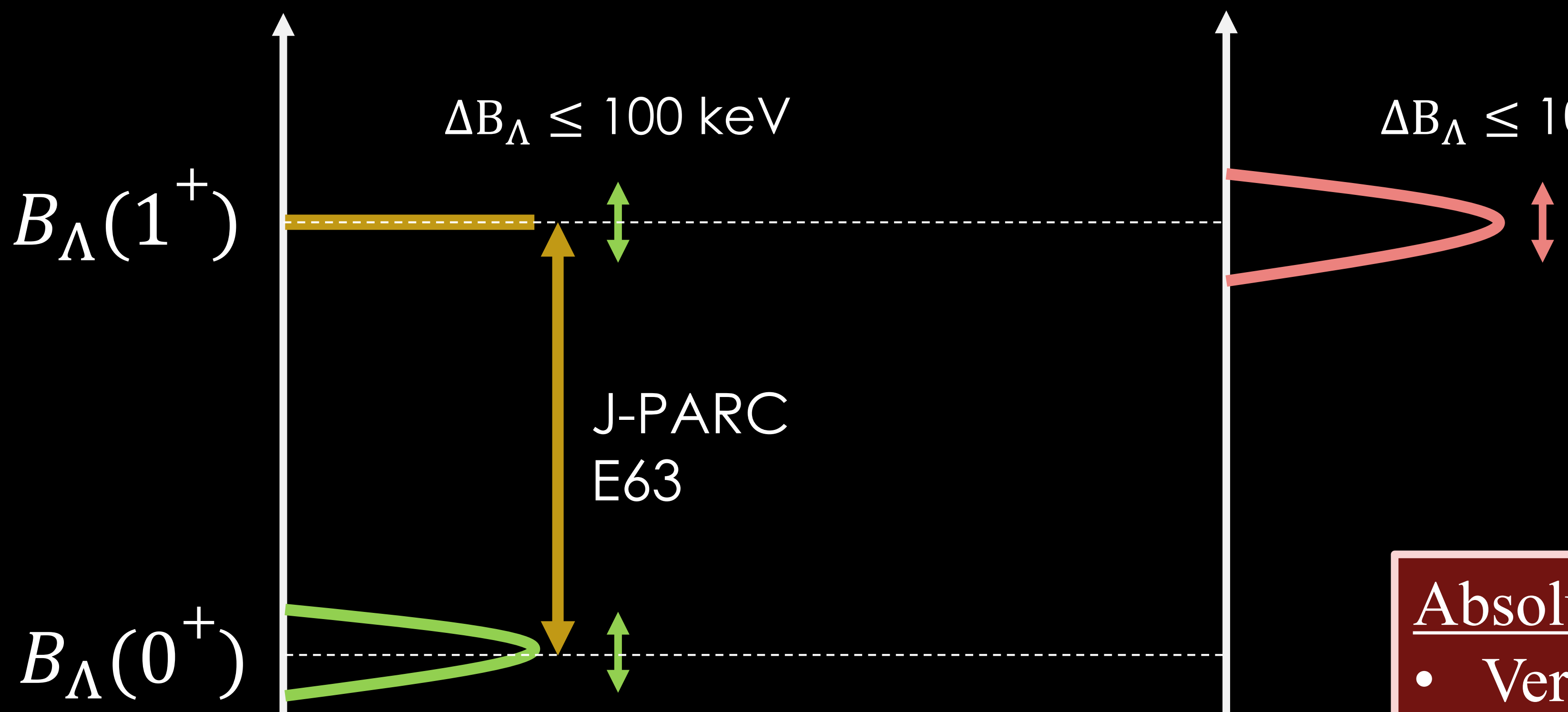
… HKS, PRC 90, 034320 (2014) …

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



Conventional way

Proposed exp.



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

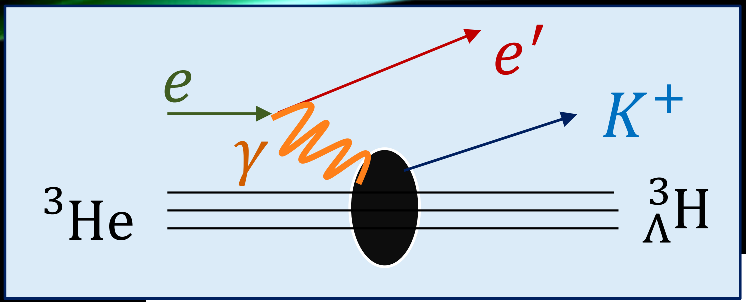
This proposal
(1 day)

<u>Absolute Energy Measurement:</u>

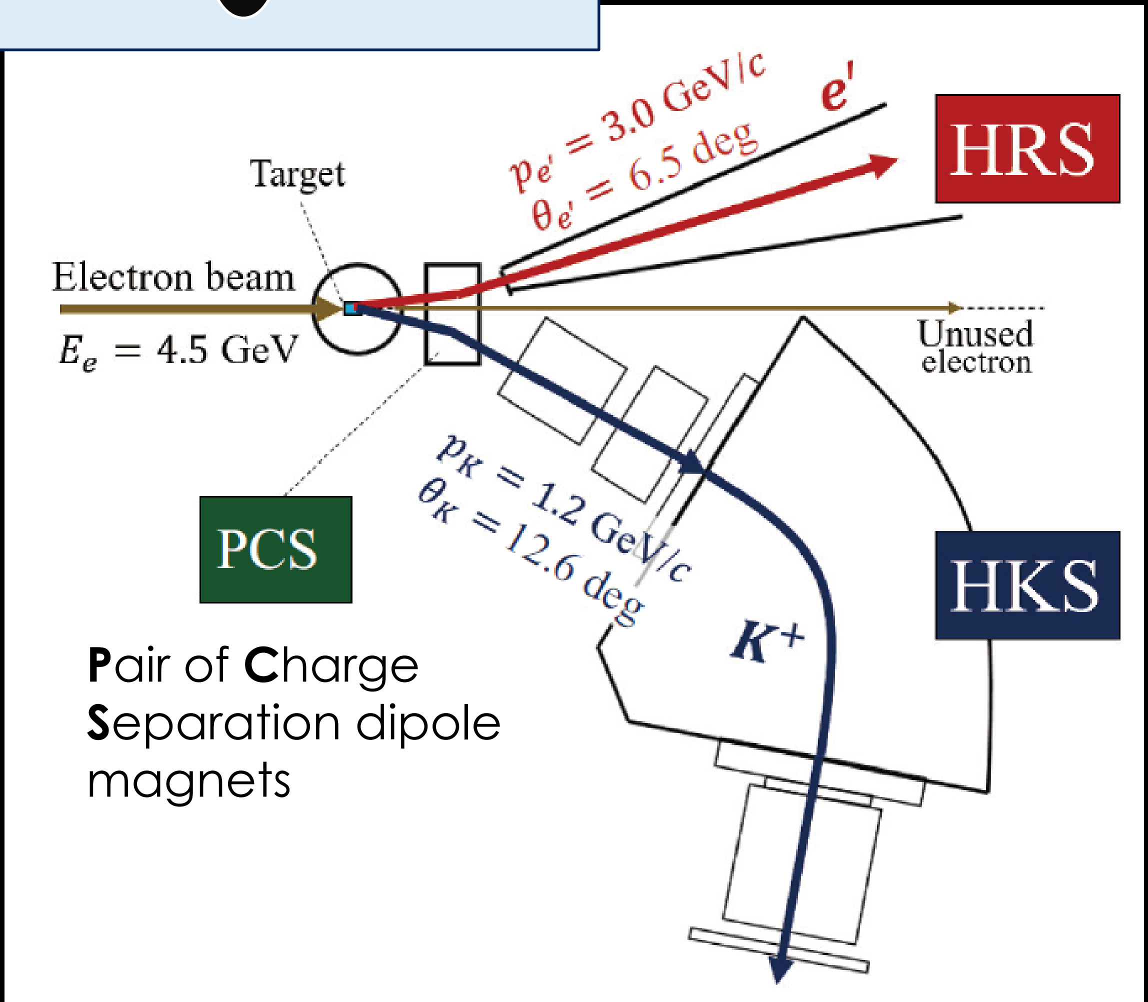
- Very unique (direct meas.)
- Complementary with other data

(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
KID: TG et al., NIMA 729 (2013) 816—824

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

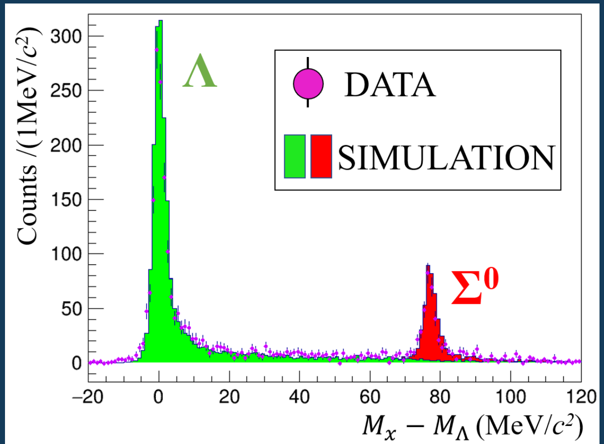
(K. Katayama, "Development of HRS-HKS coincidence trigger with FPGA - Precise Hypernuclear Spectroscopy at JLab -", Master's Thesis, Kyoto Univ. JFY2020)

Target	Thickness (mg/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
$^{3}He+^{27}Al$	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**

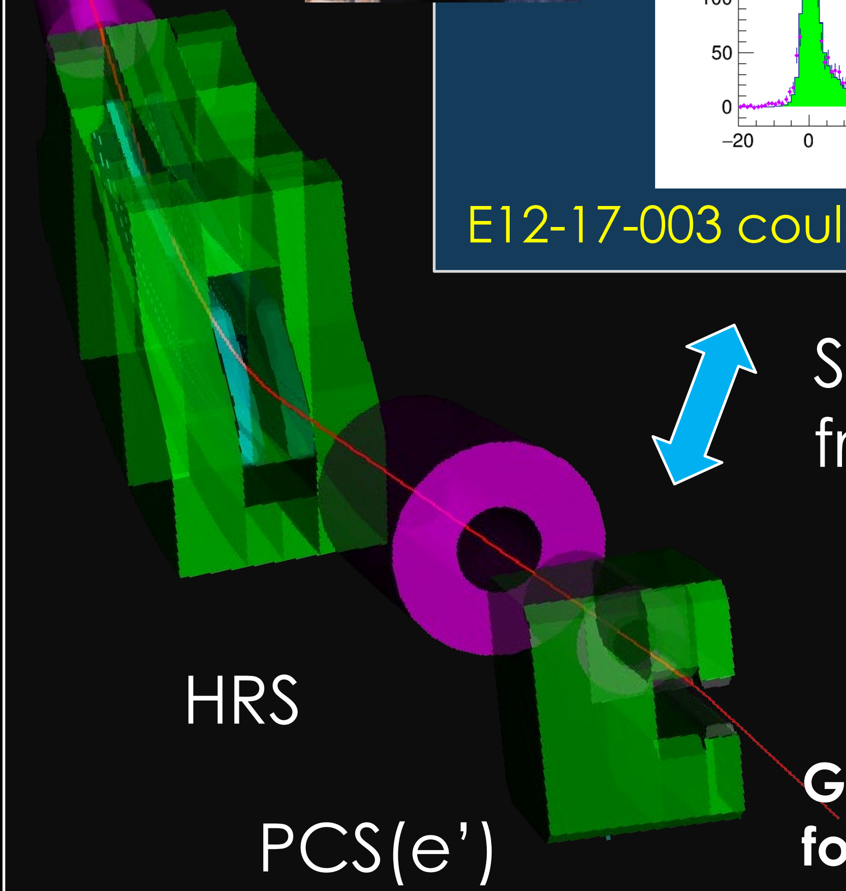
Particle identification by HKS: **TG et al., NIMA 729, 816—824 (2013).**

EXPECTED MISSING MASS RESOLUTION

Analysis by K.N. Suzuki (Kyoto)



E12-17-003 could be reproduced



Same framework

Geant4 simulation for C12-19-002

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

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

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

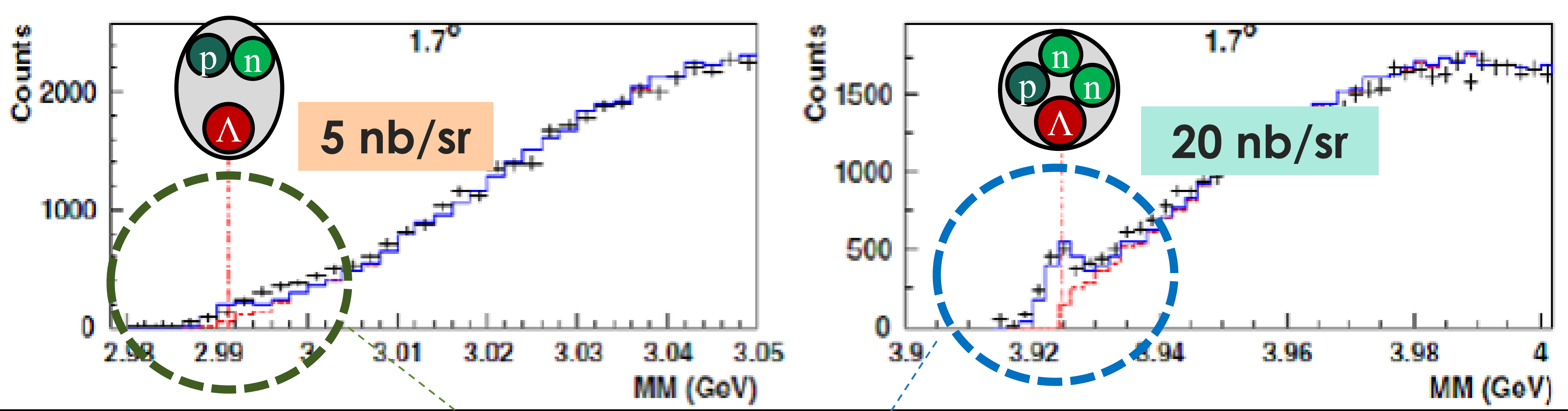
Spectrometer	$\Delta p/p$ (FWHM)
HRS (e')	3.2×10^{-4}
HKS (K^+)	5.7×10^{-4}

↓

$\Delta M_{\mathrm{HYP}} = 1.1$ MeV/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**
${}^{3}_{\Lambda}H$	${}^{3}He$ (165)	50	5	60	10	**600**
${}^{4}_{\Lambda}H$	${}^{4}He$ (228)		20	250	2	**500**

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: 3500, Σ^0: 1150
Mom. + z_t	^{12}C (multi foils)	$^{12}\mathrm{C}(e,e'K^+)^{12}_{\Lambda}\mathrm{B}$		1	$^{12}_{\Lambda}\mathrm{B}^{\mathrm{g.s.}}$: 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}

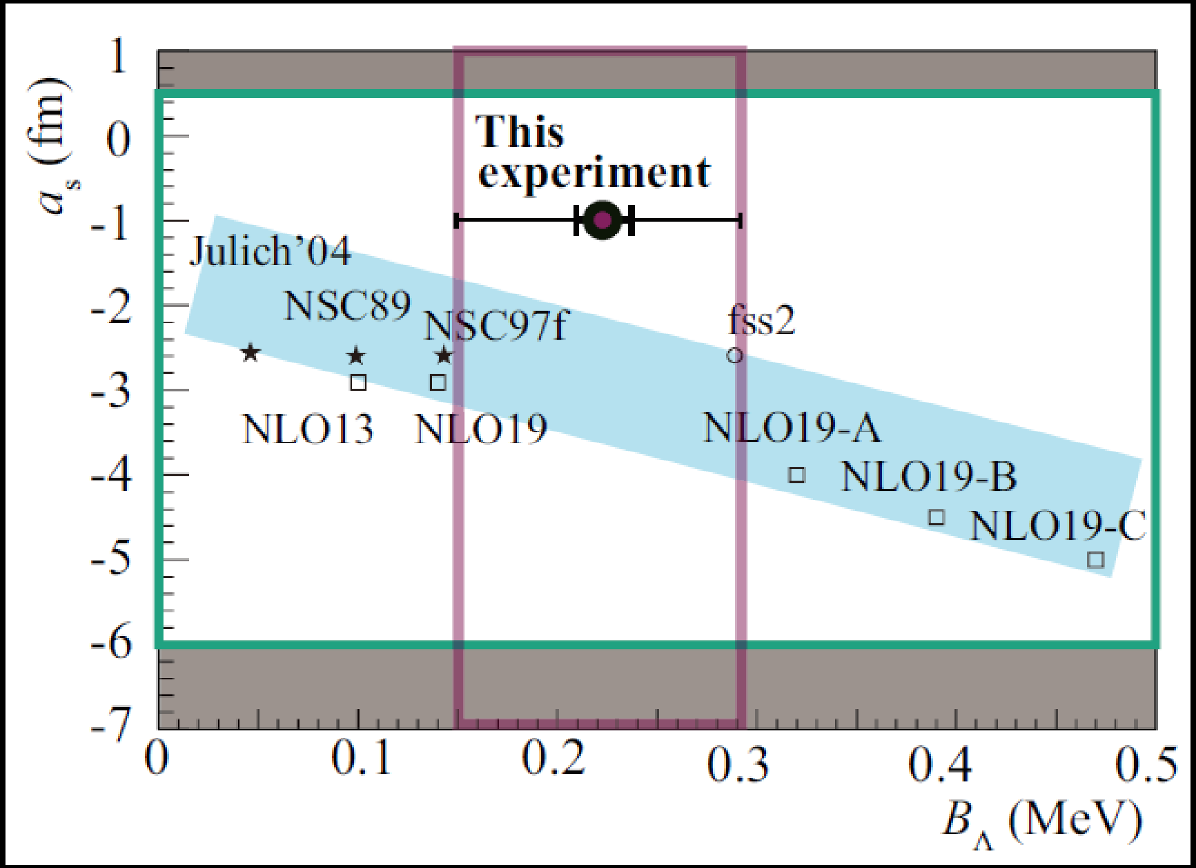
- Energy scale calibration(*) : ±50 keV
- Energy loss correction: ±23 keV
  - target density $|\Delta d| = 3\%$
  - cell thickness uniformity $|\Delta t| = 10\%$

→ $|\Delta B_{\Lambda}^{sys.}| = 55$ 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 ${}^{3}_{\Lambda}\mathrm{H}\ (T = 0, J^{\pi} = 1/2^{+})$



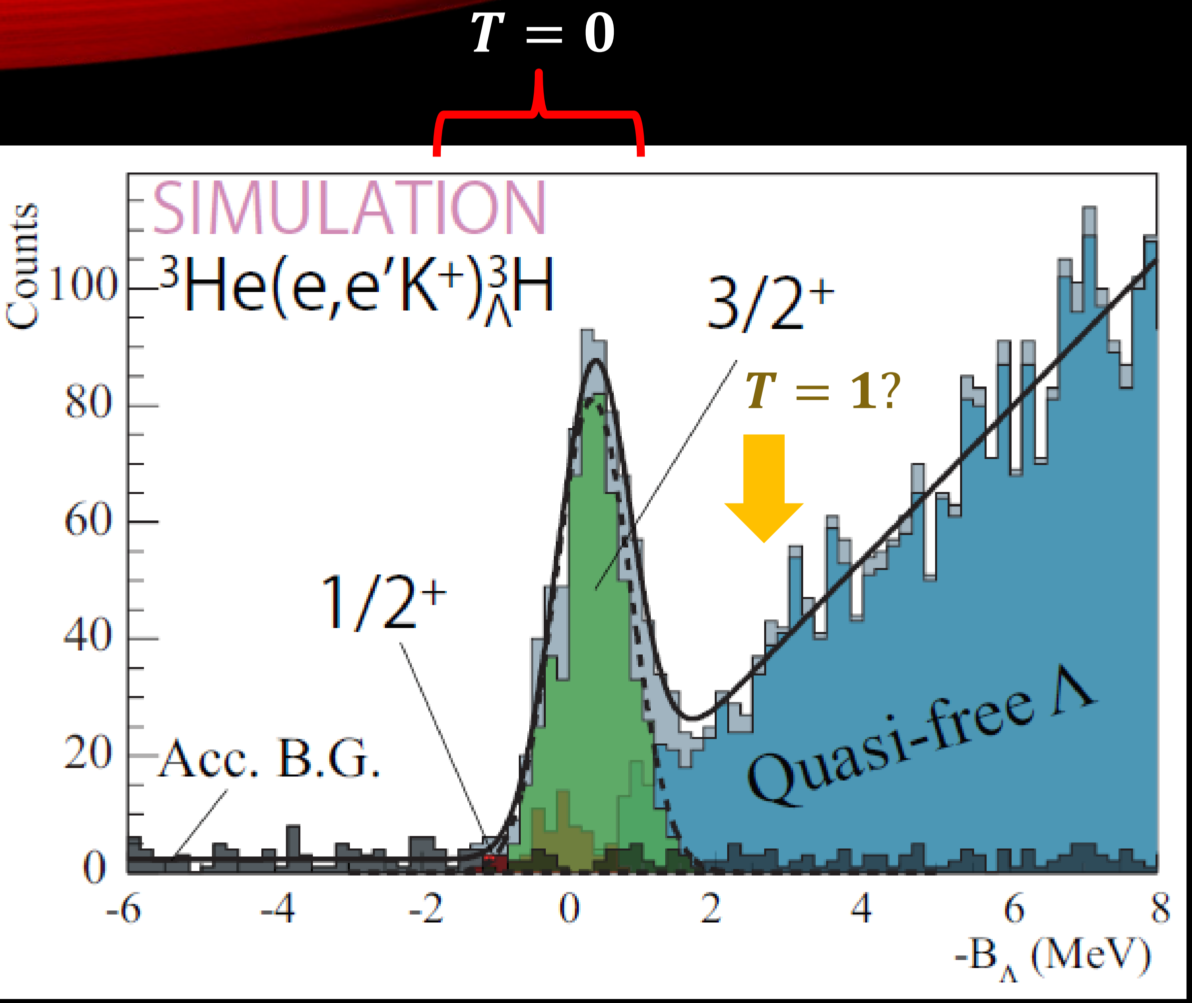
Hypertriton Puzzle

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

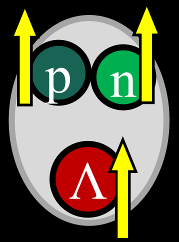
ΛN interaction

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

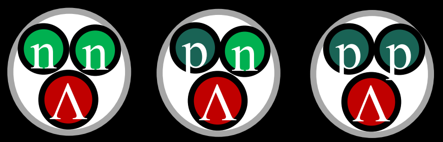


$^{3}_{\Lambda}$H $\left(T = 0,\ J^{\pi} = 3/2^{+}\right)$



- 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**

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



- 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 → $\left|\Delta B_{\Lambda}^{\mathrm{stat.}}\right| < 50$ keV

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