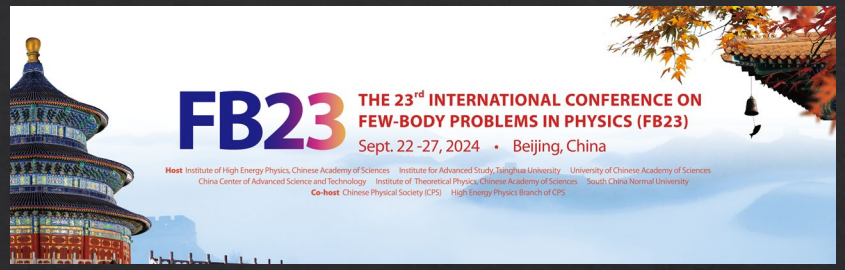
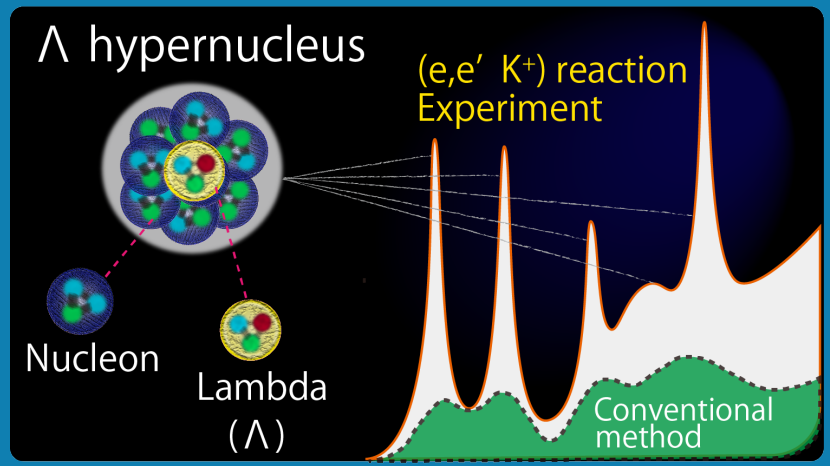


Next generation hypernuclear spectroscopy with the (e,e'K$^+$) reaction at Jefferson Lab



Graduate School of Science, Kyoto University

Toshiyuki Gogami

Sep 24, 2024

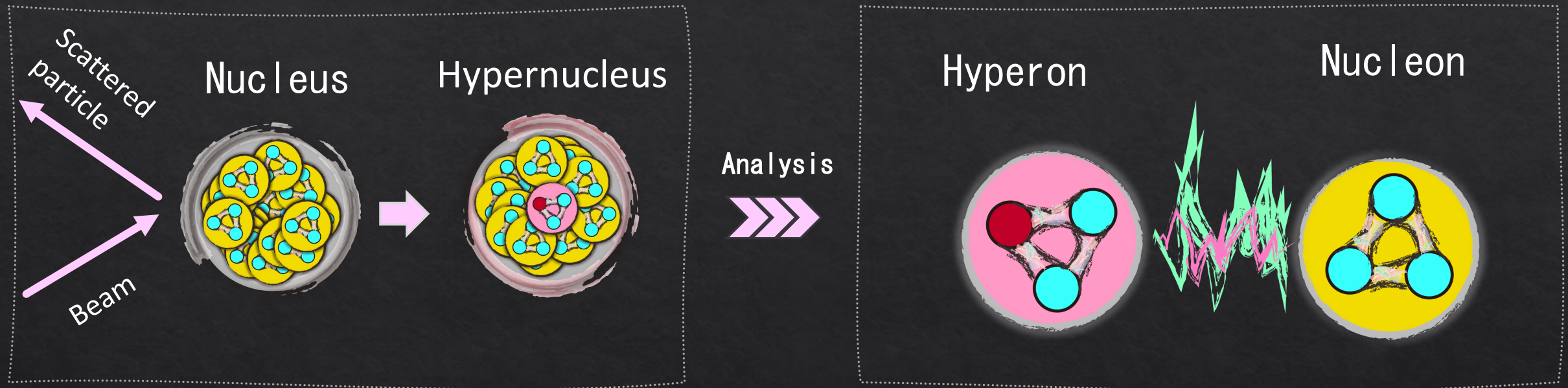
Hypernucleus

Nucleon
only up, down quarks

Hyperon
(u, d +) strange (s) quark

Hypernucleus

Baryon interaction study through hypernuclei

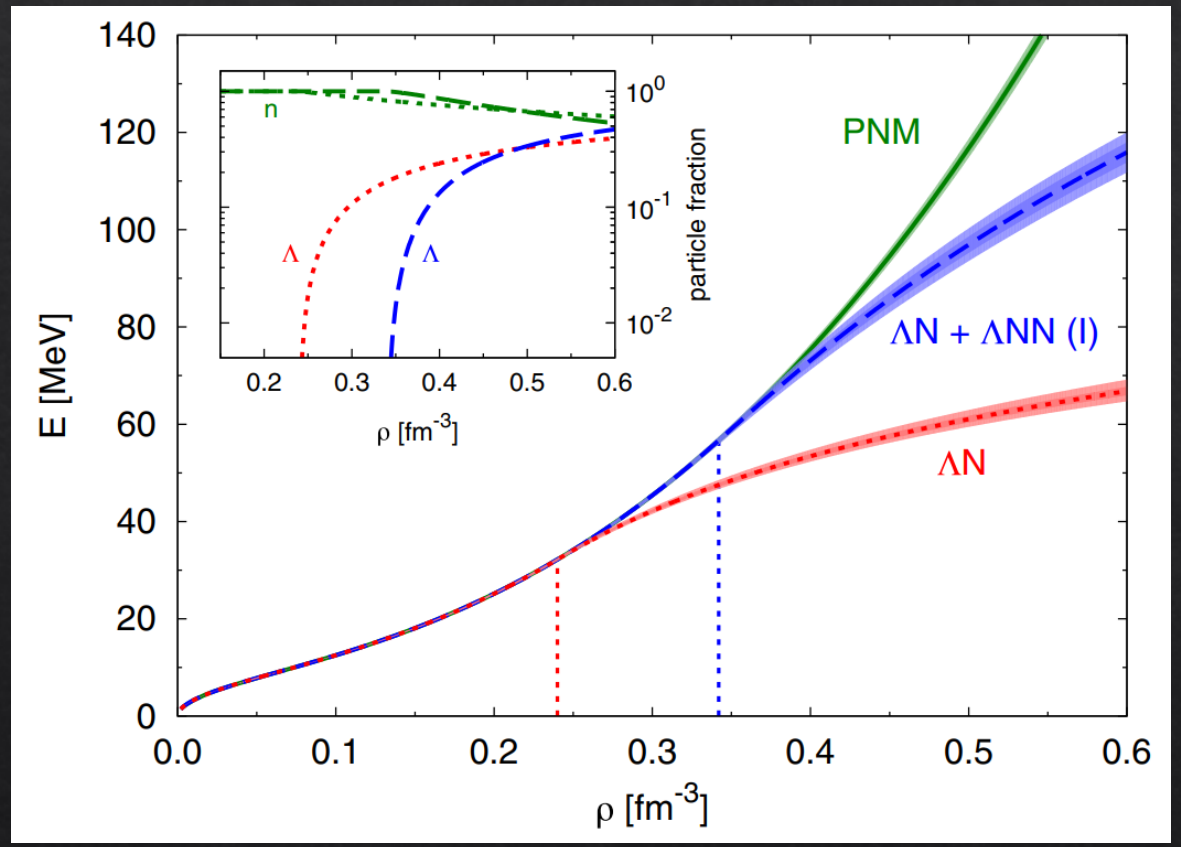


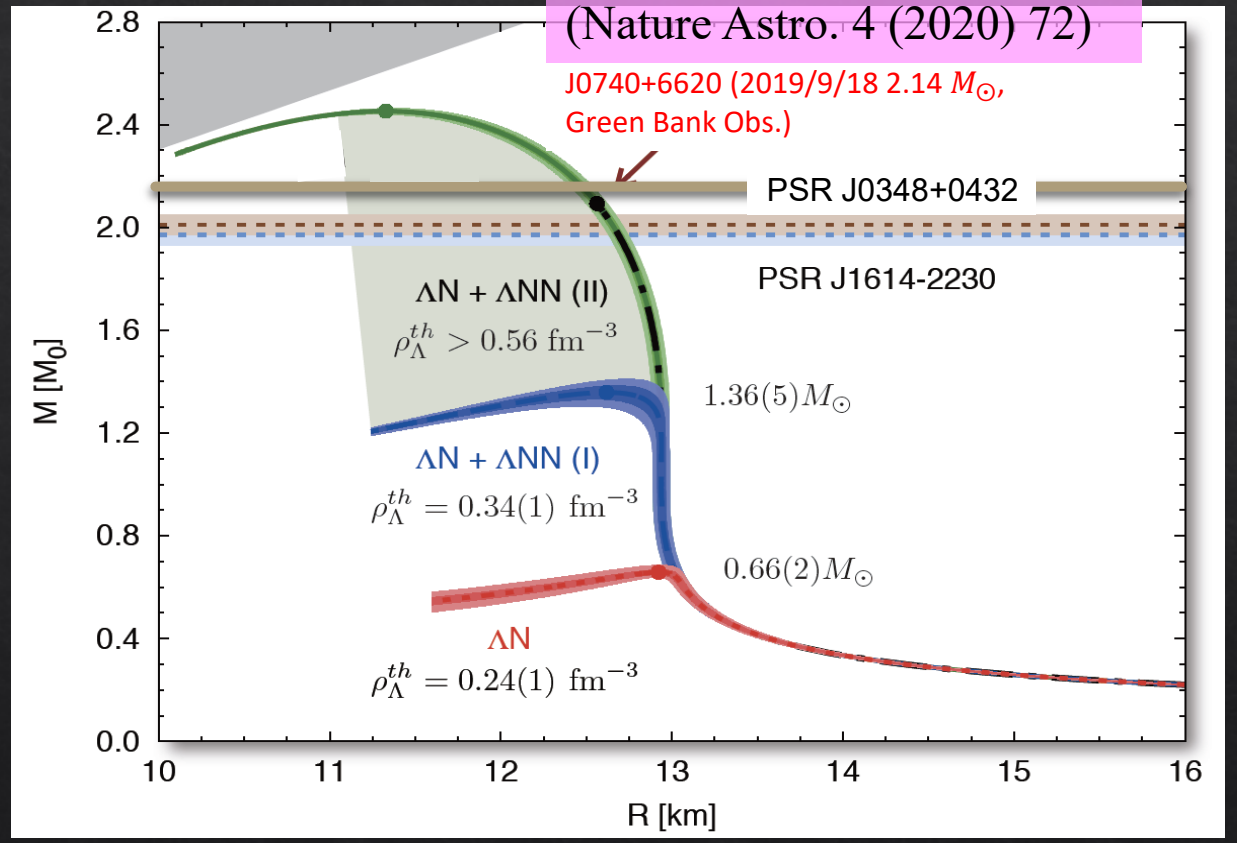
➔ Hyperon(Y)–nucleon(N) interaction

➔ More general baryon–baryon interaction

Hyperons in neutron stars

D. Lonardoni et al., Phys. Rev. Lett. 114, 092301 (2015)





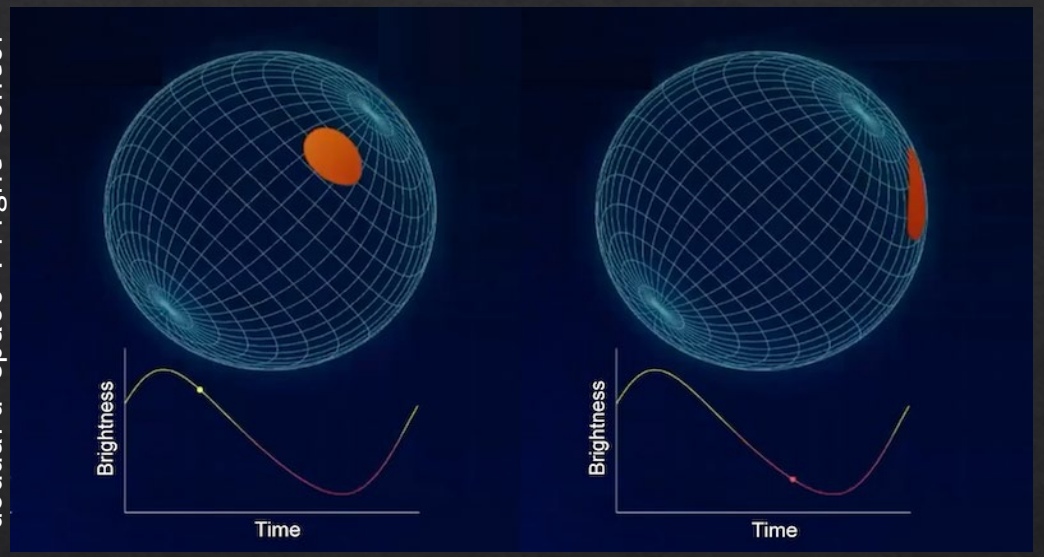
➔ Multi-body force may play an important role

New astronomical observations

CC4.0 ESO/L. Calçada/M. Kornmesser

Gravitation Wave from neutron star mergers
LIGO/Virgo PRL **119**, 161101 (2017)

Goddard Space Flight Center



NICER : NS x-ray hot spot measurement
Physics 14, 64 (Apr. 29, 2021)

Macroscopic features of NS : Tidal deformability, masses and radii

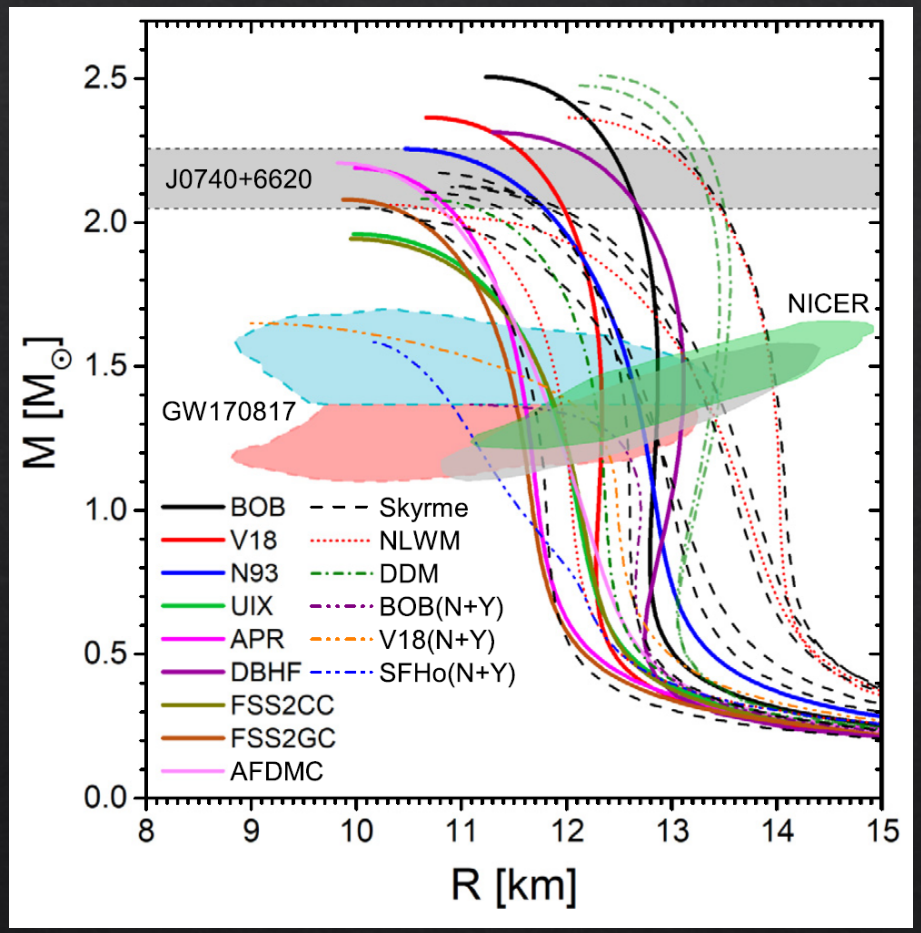
vs.

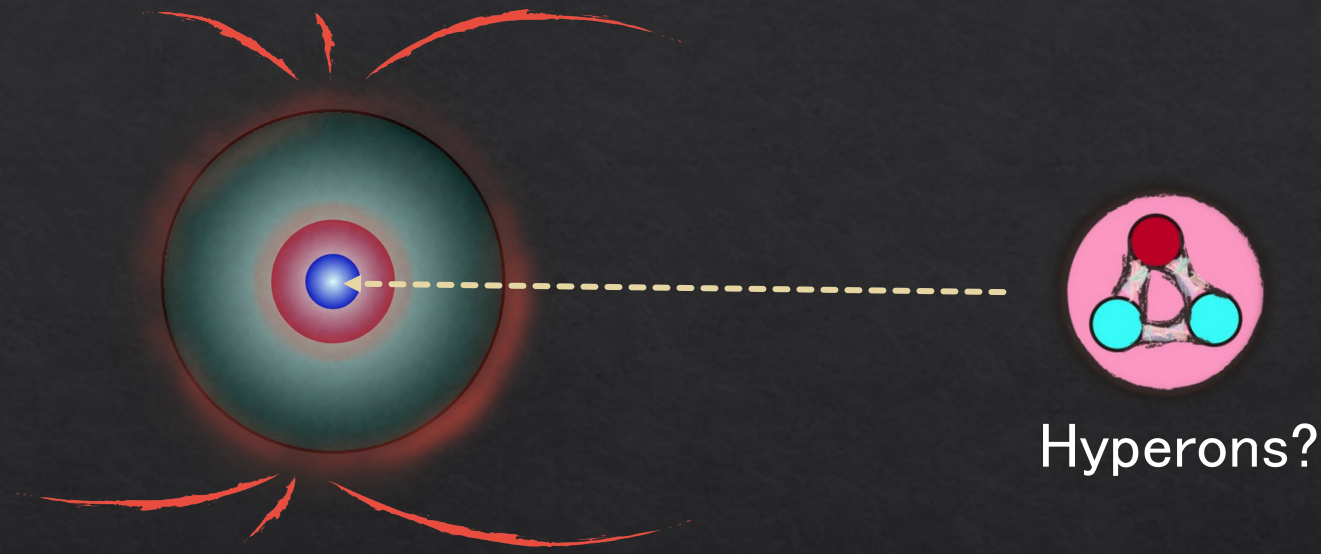
Microscopic investigation of NS: Inner composition

➡ HYPERNUCLEAR SPECTROSCOPY

New constrains from astronomical observations

C.F. Burgio et al. Prog. Part. Nucl. Phys 120 (2021) 103879.

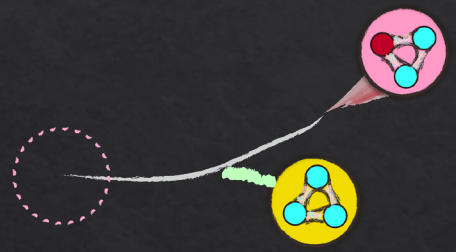


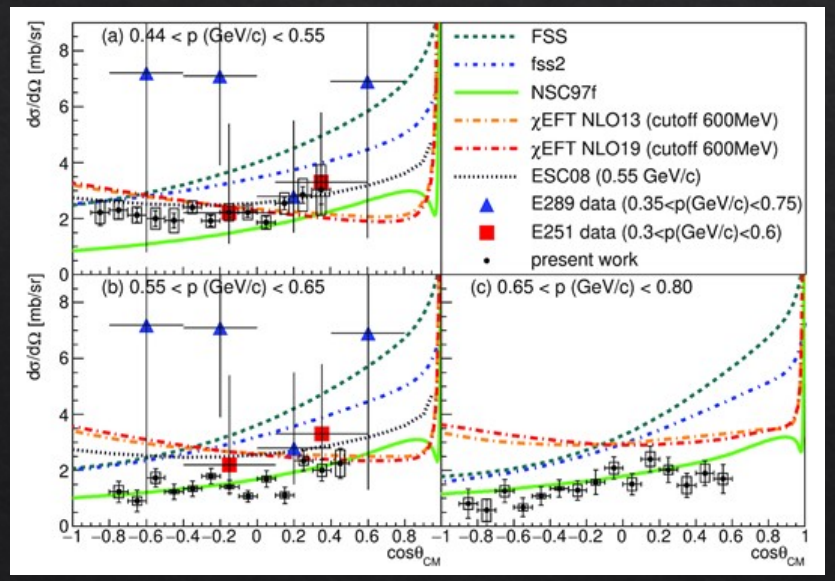


Microscopic study
(← nuclear/hypernuclear research) has become more important as the macroscopic study is in great progress

YN/YY interaction study

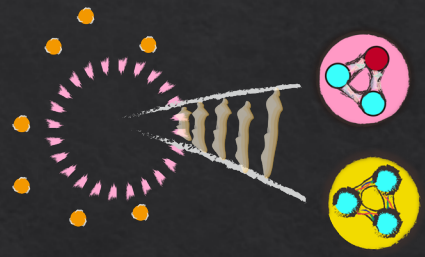
Scattering experiments

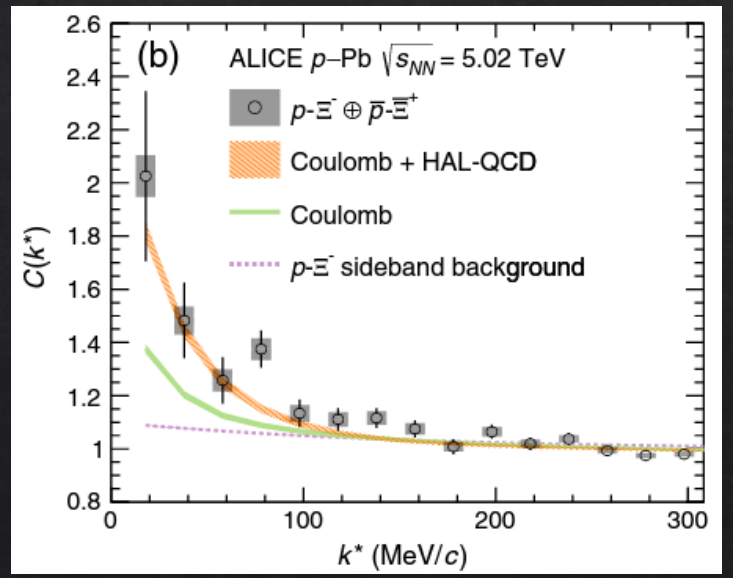




T. Nanamura et al., PTEP 2022, 9, 093D01 (2022)

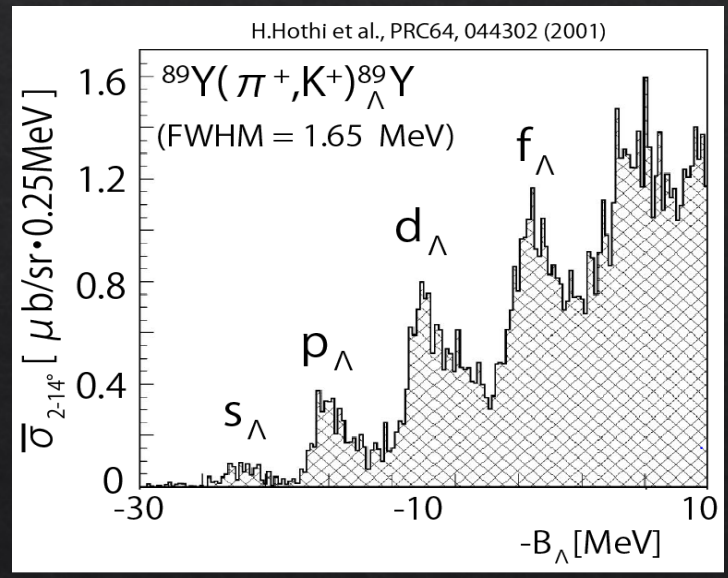
Femtoscopy





S. Acharya et al., Phys. Rev. Lett. 123, 112002 (2019)

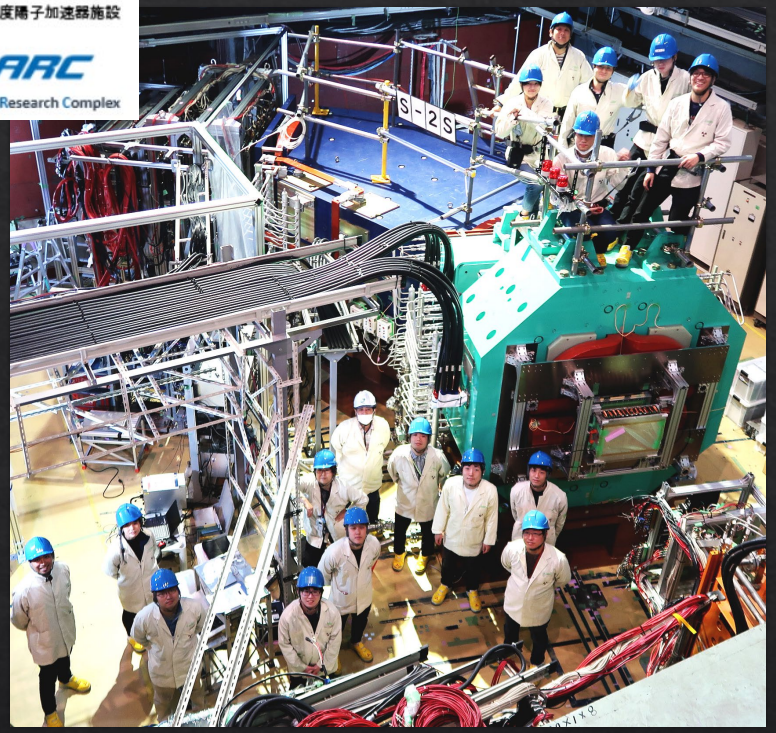
Hypernuclear spectroscopy



H. Hotchi et al., Phys. Rev. C 64, 044302 (2001)

Missing mass spectroscopy for Λ hypernuclei

大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex



S-2S (2025～)

A = 7, 10, 12

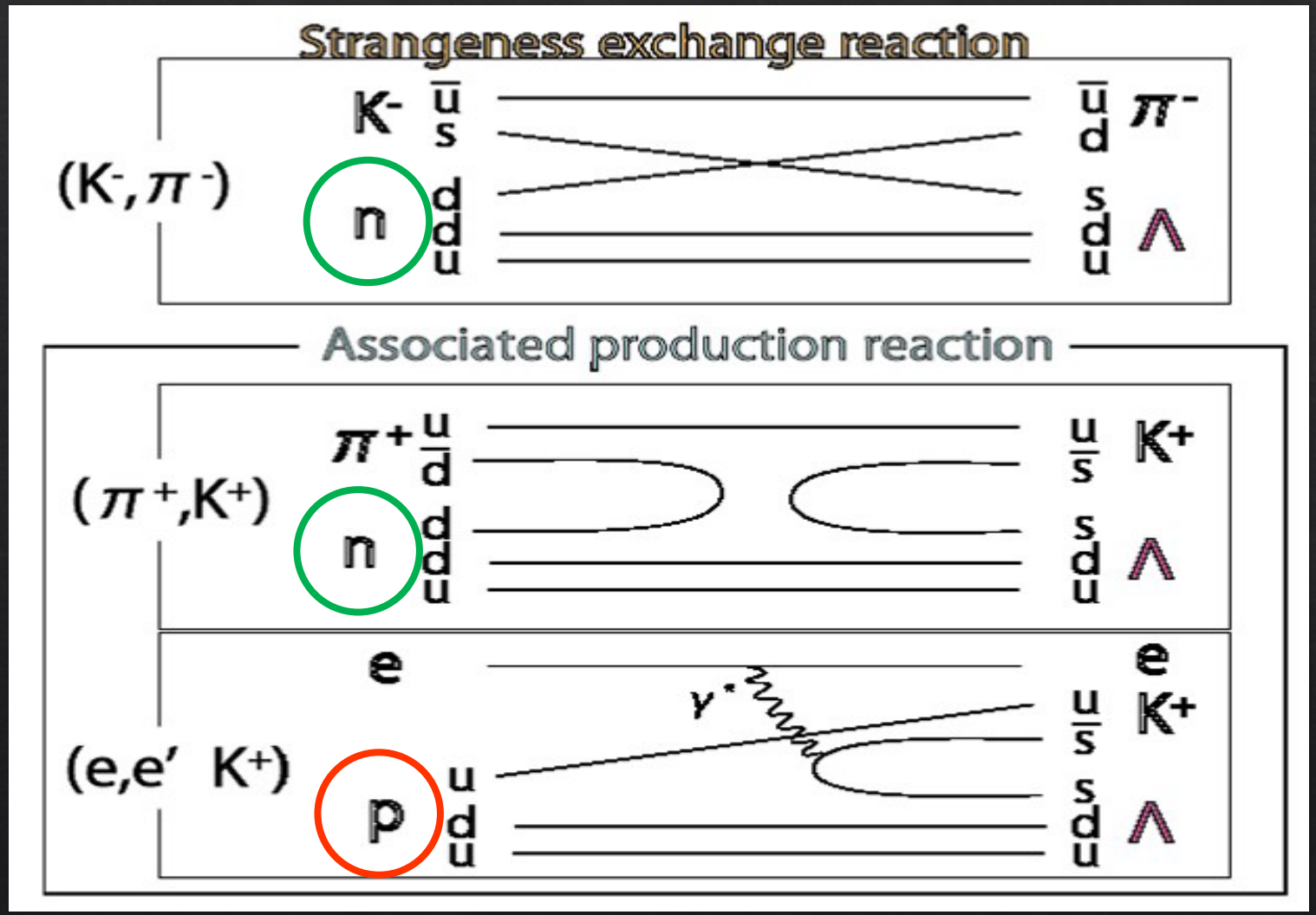
T. Gogami et al., EPJ Web Conf. 271, 11002 (2022).

Jefferson Lab
Thomas Jefferson National Accelerator Facility

HES-HKS (2027～)

A = 6, 9, 11, 12, 27, 40, 48, 208

Reactions used at J-PARC and JLab



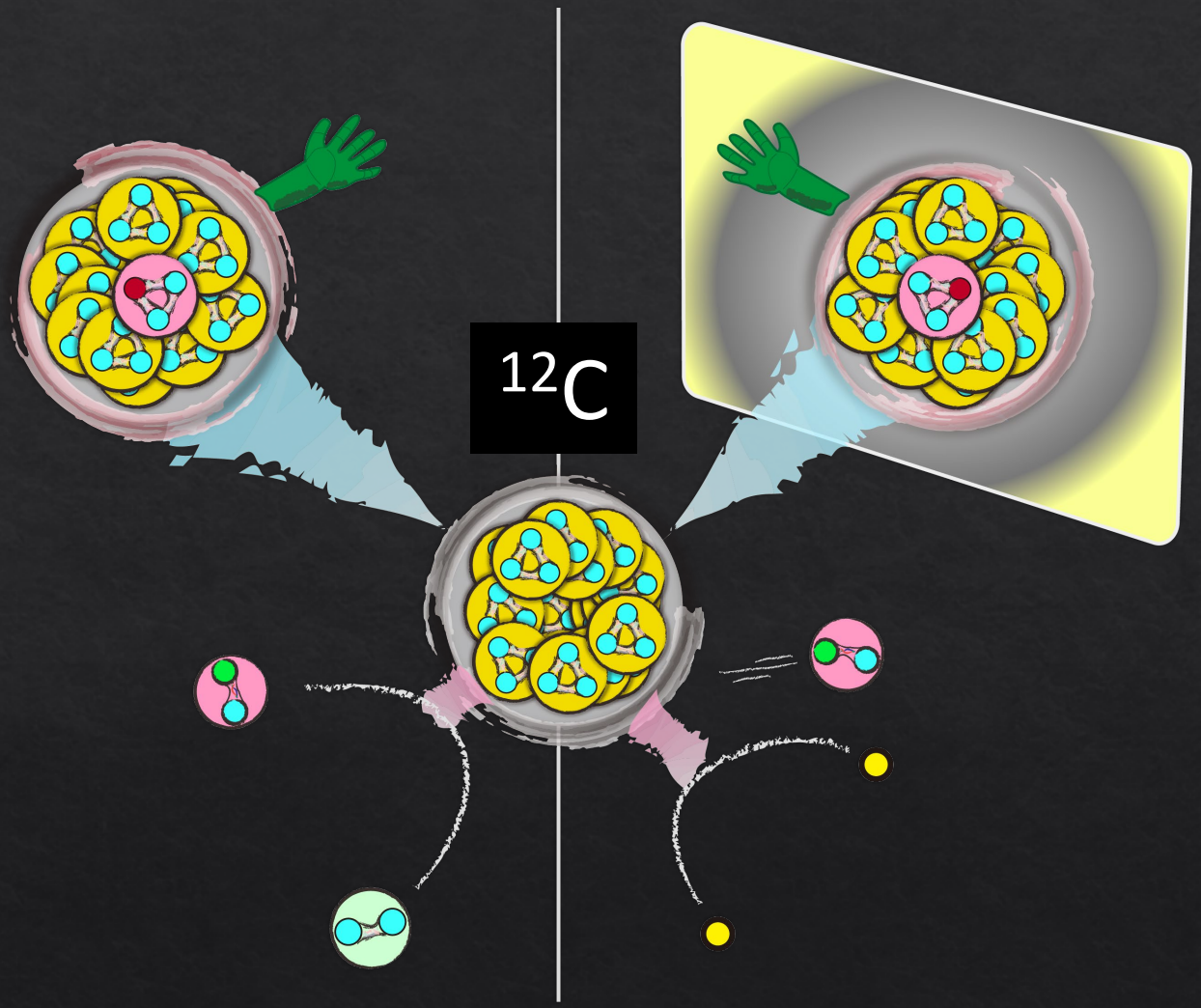
Hadron Beams
@J-PARC, Japan

Electron Beams
@JLab, US

Mirror Hypernuclear Study

$^{12}_{\Lambda}\mathrm{C}$

$^{12}_{\Lambda}\mathrm{B}$



大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex

(π^+, K^+)

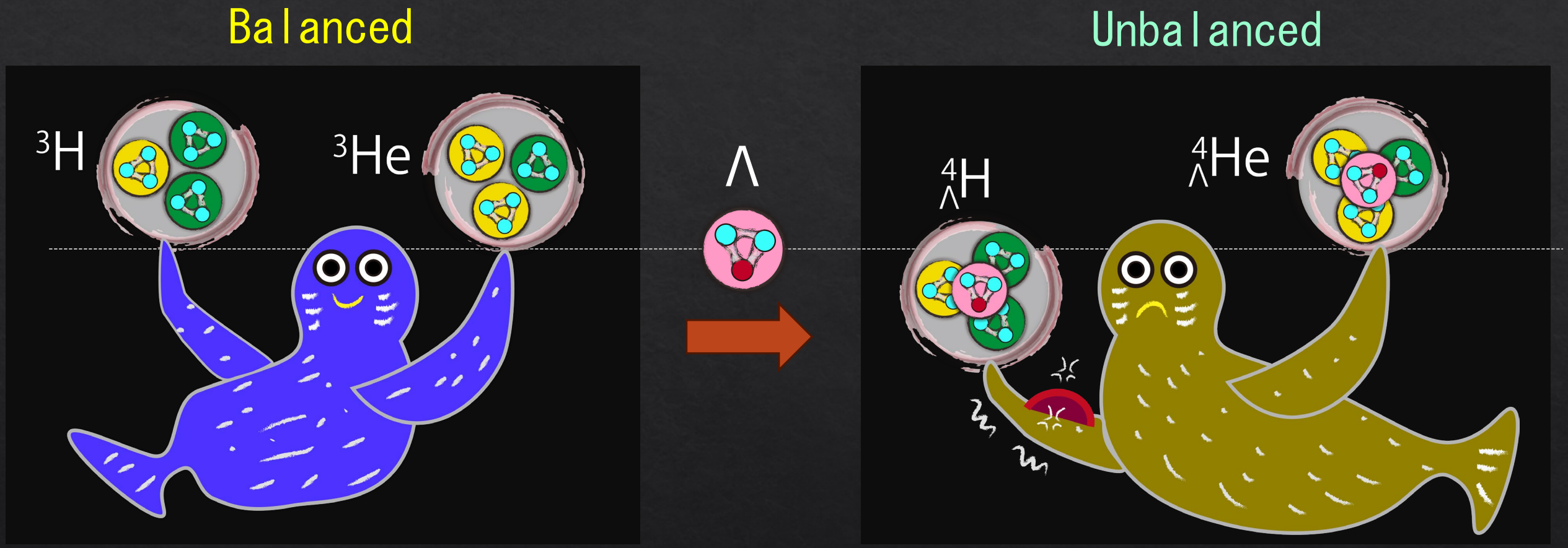
n→Λ

Jefferson Lab
Thomas Jefferson National Accelerator Facility

$(e, e'K^+)$

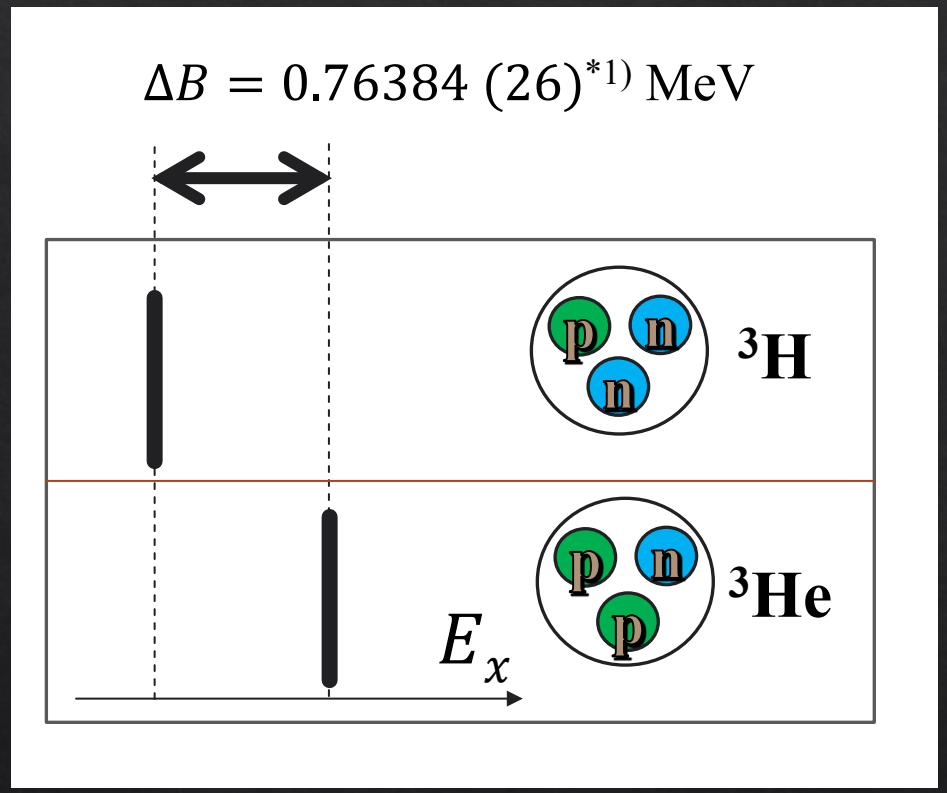
p→Λ

Charge Symmetry Breaking (CSB)



Charge Symmetry Breaking (CSB), the mystery

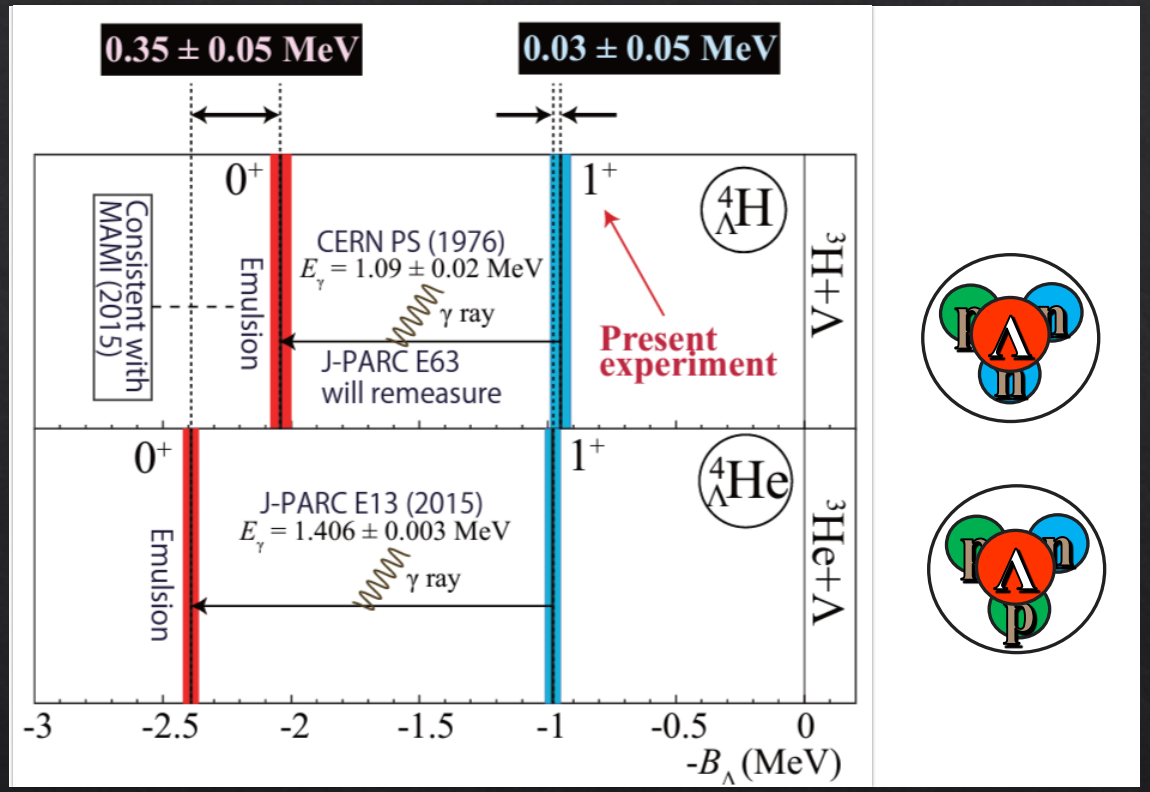
*1) J.H.E.Mattauch *et al., Nucl. Pys.* **67**, 1 (1965).



81 keV after Coulomb correction

[R.A.Brandenburg, S.A.Coon *et al.*, *NPA***294**, 305 (1978)]

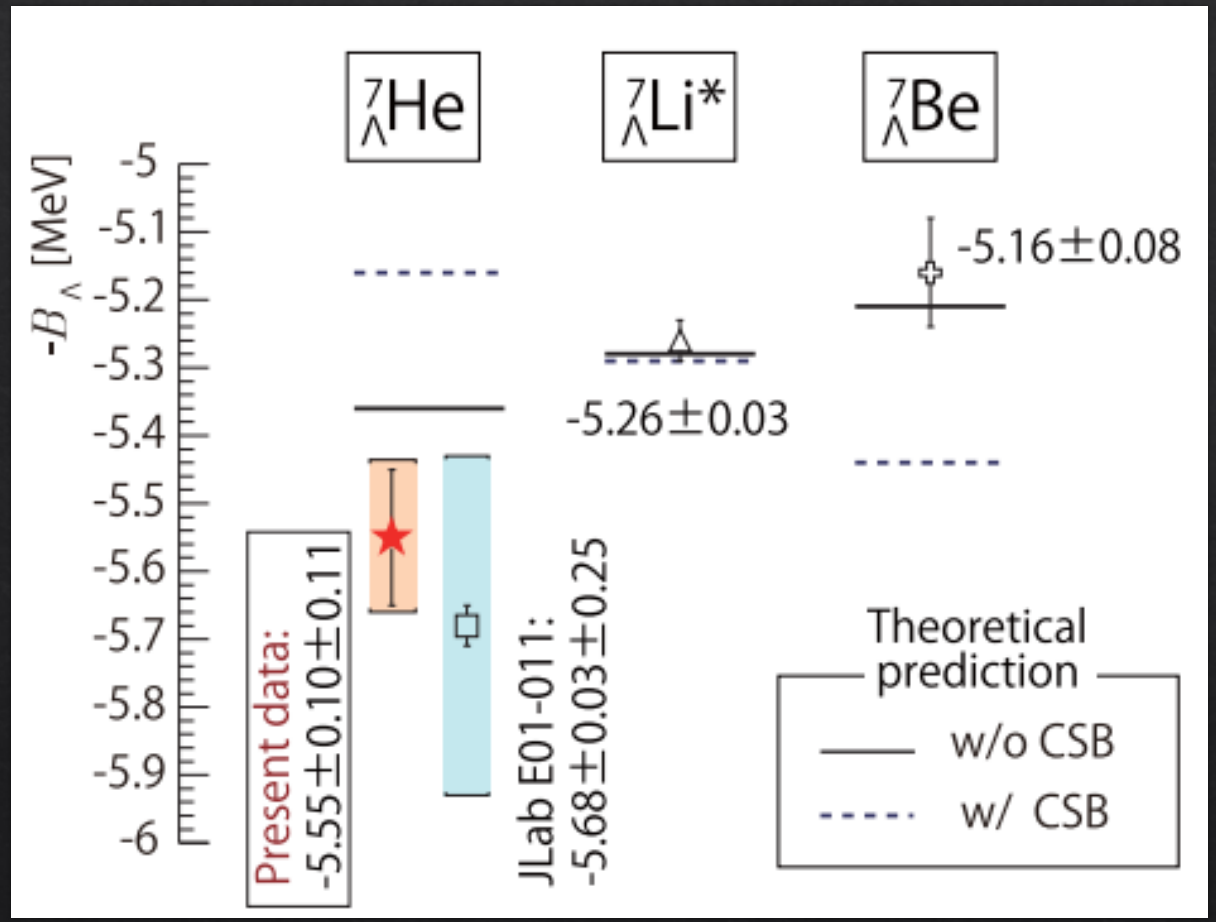
Figure from proposal of JLab E12-19-002



~400 KeV after Coulomb correction

➡ **5 times larger CSB than NN interaction!**

Previous study of CSB effect for A = 7 at JLab



TG et al., PRC 94, 021302(R) (2016)

E. Hiyama et al., PRC80, 054321 (2009)

Phenomenological CSB potential

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

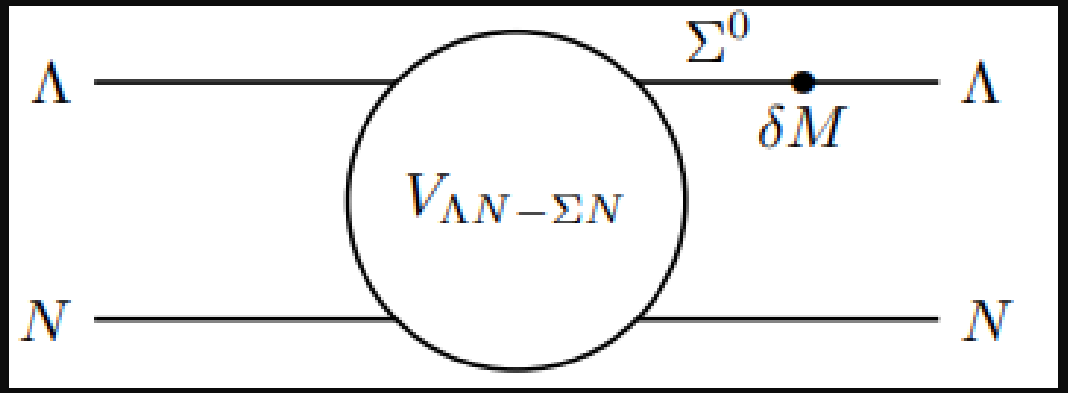
Parameters were adjusted to reproduce the binding energies $^{4}_{\Lambda}$He, $^{4}_{\Lambda}$H, $^{8}_{\Lambda}$Li, $^{8}_{\Lambda}$Be hypernuclei

The calc. w/o the CSB potential is more consistent with the data.

The origin of CSB is more complex?

ΛN-ΣN coupling effect

A. Gal and D. Gazda, J. Phys.: Conf. Ser. 966 012006 (2018)



Charge symmetric ΛN-ΣN

±1

$$\langle N\Lambda|V_{\rm CSB}|N\Lambda\rangle = -0.0297\,\tau_{Nz}\,\frac{1}{\sqrt{3}}\,\langle N\Sigma|V_{\rm CS}|N\Lambda\rangle$$

ΛΣ mixing matrix element

A = 4 CS average	LO	LO [22]	NLO [22]	Exp. (Fig. 1)
$B_\Lambda^{J=0}$	$2.37^{+0.20}_{-0.13}$	2.5 ± 0.1	$1.53^{+0.08}_{-0.06}$	2.27 ± 0.09
$B_\Lambda^{J=1}$	$1.08^{+0.58}_{-0.47}$	$1.4^{+0.5}_{-0.4}$	$0.83^{+0.07}_{-0.10}$	1.03 ± 0.09
$E_{\rm x}(0^+_{\rm g.s.}\to1^+_{\rm exc})$	1.29 ± 0.38	1.05 ± 0.25	0.71 ± 0.04	1.25 ± 0.02

w/o CSB

Mirror hypernuclear data for p-shell systems

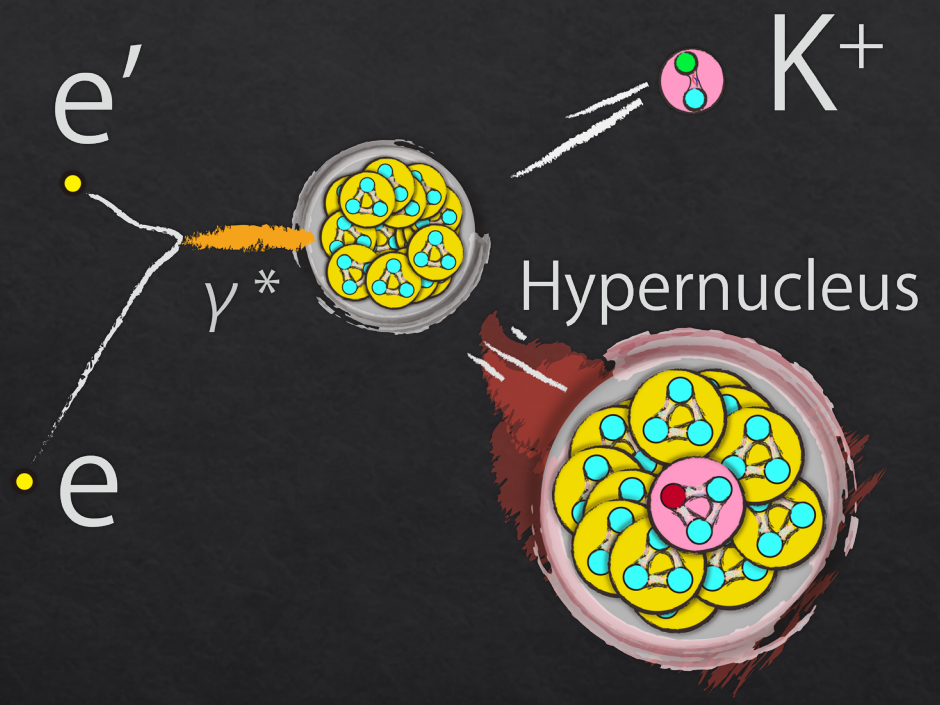
Isomultiplet	${}^{4}_{\Lambda}\mathrm{He}-{}^{4}_{\Lambda}\mathrm{H}$	${}^{7}_{\Lambda}\mathrm{Be}-{}^{7}_{\Lambda}\mathrm{Li}^{*}$	${}^{7}_{\Lambda}\mathrm{Li}^{*}-{}^{7}_{\Lambda}\mathrm{He}$	${}^{8}_{\Lambda}\mathrm{Be}-{}^{8}_{\Lambda}\mathrm{Li}$	${}^{9}_{\Lambda}\mathrm{B}-{}^{9}_{\Lambda}\mathrm{Li}$	${}^{10}_{\Lambda}\mathrm{B}-{}^{10}_{\Lambda}\mathrm{Be}^{*}$
Shell model (Gal *et al.*) [41]	+226	−17	−28	+49	−54	−136
Cluster model (Hiyama *et al.*) [39, 40]		+150	+130			+20
No-core shell model (Le *et al.*) [43]	+238	−35	−16	+143		
Experiment	$+233 \pm 92$	-100 ± 90	-20 ± 230	$+40 \pm 60$	-210 ± 220	-220 ± 250

A. Gal, and D. Gazda, Jour. Phys.: Conf. Ser. 966, 012006 (2018)
E. Hiyama et al., Prog. Theor. Phys. 128, 105 (2012).
H. Le et al., Phys. Rev. C 107, 24002 (2023)

Existing data accuracy is not sufficient for CSB study (ΔB_{diff} > 200 keV)

→ ΔB_{diff}～100 keV for A = 6, 7, 9, 10, 11, 12

Missing-mass spectroscopy at JLab



$$M_H = \sqrt{(E_e + M_T - E_{e'} - E_K)^2 - \left(\overrightarrow{P_e} - \overrightarrow{P_{e'}} - \overrightarrow{P_K}\right)^2}$$

To be measured

$$B_\Lambda = M_H - M_{core} - M_\Lambda$$

Electro-production

- Better understanding of reaction — GOOD
- Small cross section — Bad
- Larger noise as Z gets larger — Bad

Primary beam

- High precision / small emittance — GOOD
- High intensity → thin target — GOOD
  (→ High energy resolution)

Virtual photo production

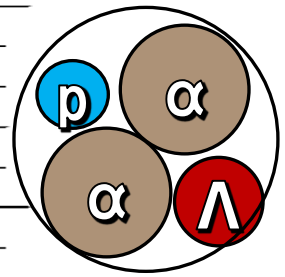
→ Large spin flip amplitude — GOOD / Bad

p → Λ

GOOD

→ Good calibration with proton target

→ Mirror Hypernuclear study — GOOD



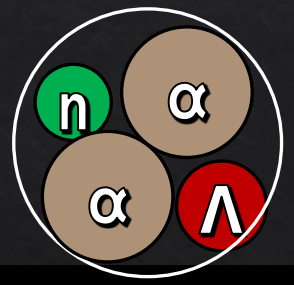
$^{10}_{\Lambda}\mathrm{B}$

FWHM = 2.2 MeV

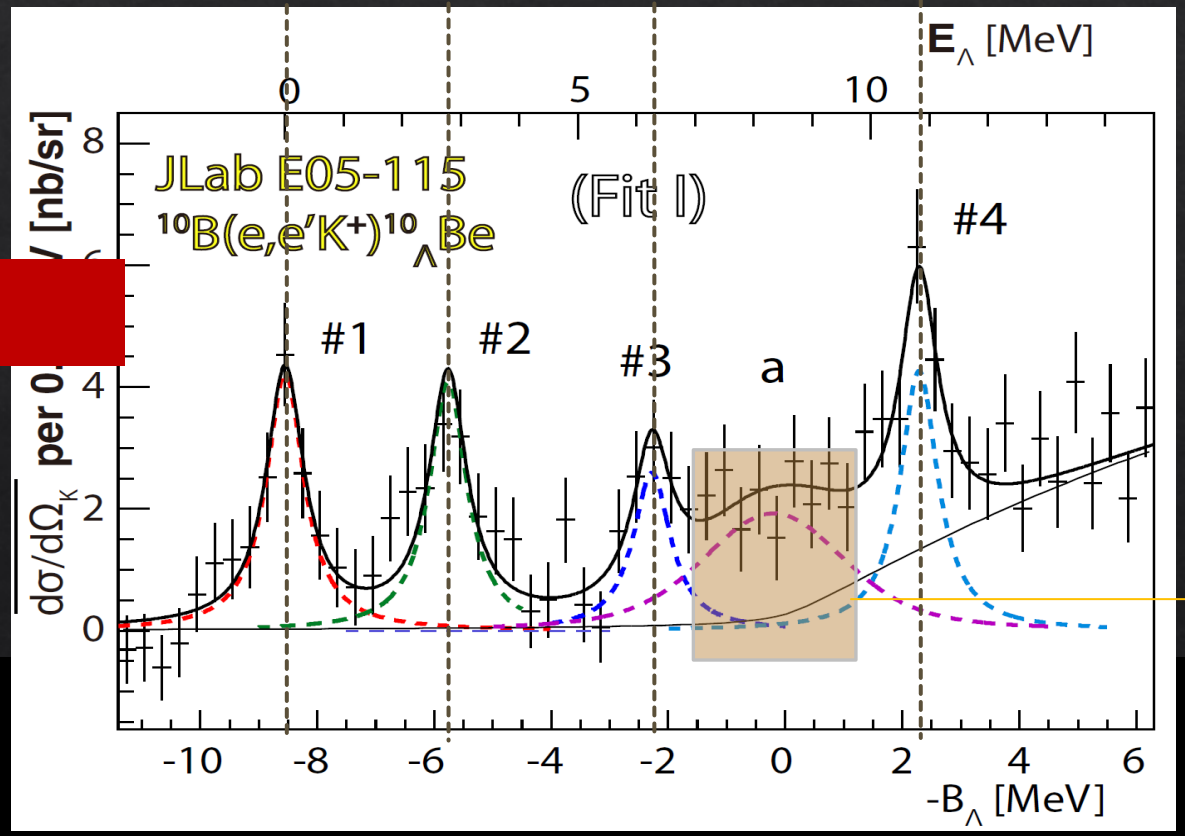
(π^+, K^+) @KEK, Japan

T. Hasegawa et al.,PRC 53, 3 (1996).

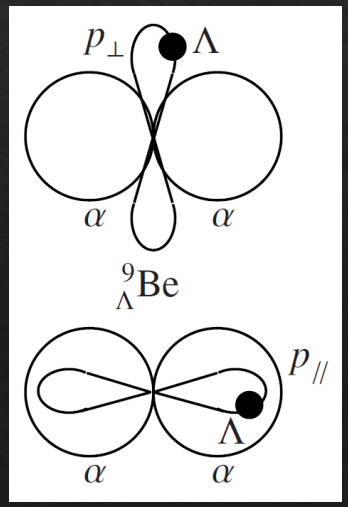
FWHM = 0.8 MeV



$^{10}_{\Lambda}\mathrm{Be}$



Cluster structure!!



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

A. Umeya *et al., J. Phys.: Conf. Ser.* **1643** 012110 (2020).

Approved Hypernuclear Experiments (proposed by JLab Hypernuclear Collaboration)

① E12-15-008 (Contact Person: S.N. Nakamura (Univ. Tokyo)) → $^{40}_{\Lambda}\mathrm{K}$、$^{48}_{\Lambda}\mathrm{K}$

"Isospin dependence of ΛN interaction"

② E12-19-002 (CP: TG) → $^{3}_{\Lambda}\mathrm{H}$、$^{4}_{\Lambda}\mathrm{H}$

"Hypertriton puzzle, s-shell CSB"

③ E12-20-013 (CP: F. Garibaldi (INFN)) → $^{208}_{\Lambda}\mathrm{Tl}$

"ΛNN three body force"

④ E12-24-004 (CP: TG) → $^{6}_{\Lambda}\mathrm{He}$、$^{9}_{\Lambda}\mathrm{Li}$、$^{11}_{\Lambda}\mathrm{Be}$

"p-shell CSB"

⑤ E12-24-011 (CP: S.N. Nakamura) → $^{27}_{\Lambda}\mathrm{Mg}$

" Search for triaxially deformation states in $^{26}\mathrm{Mg}$"

Approved Hypernuclear Experiments (proposed by JLab Hypernuclear Collaboration)

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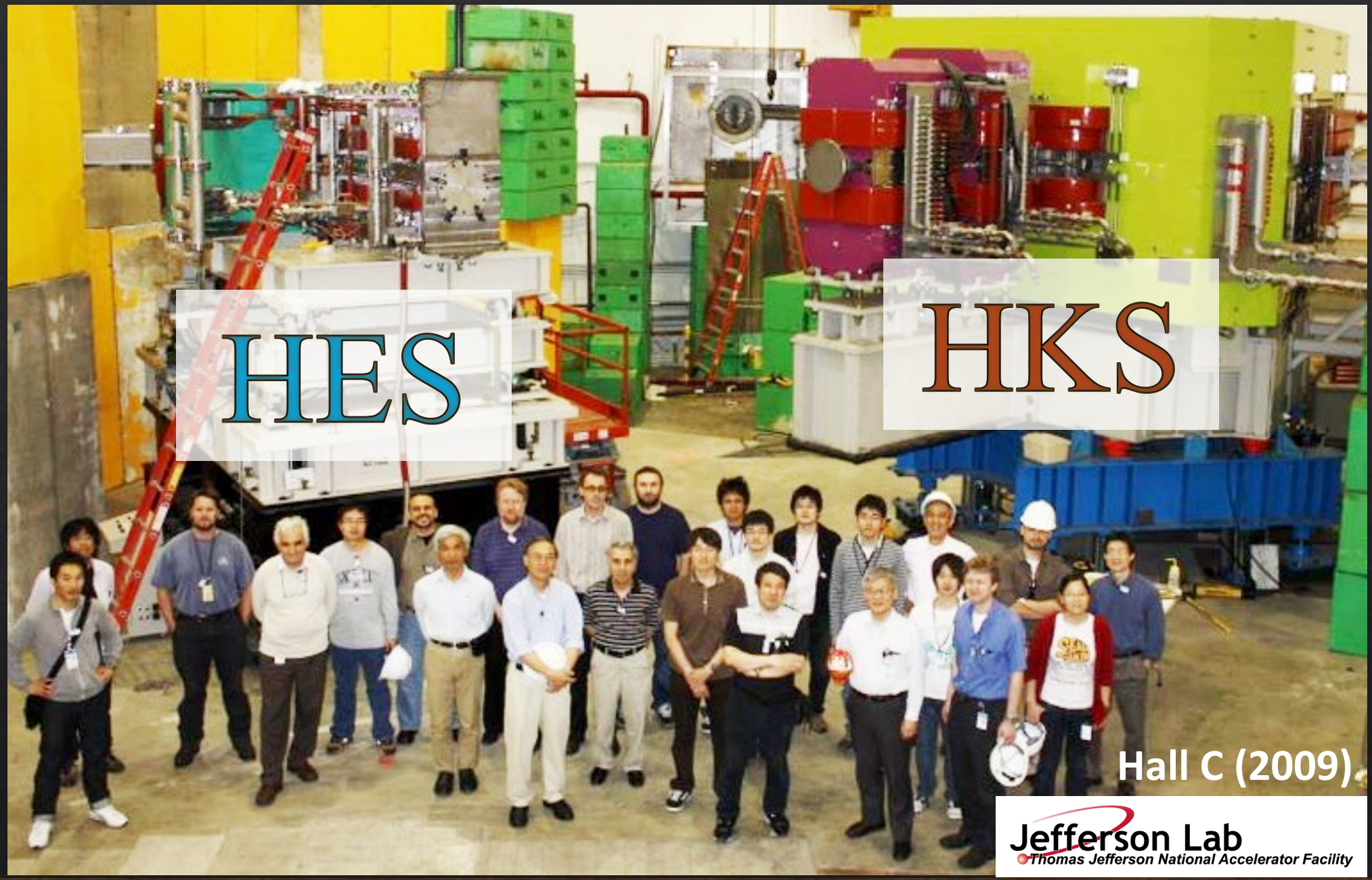
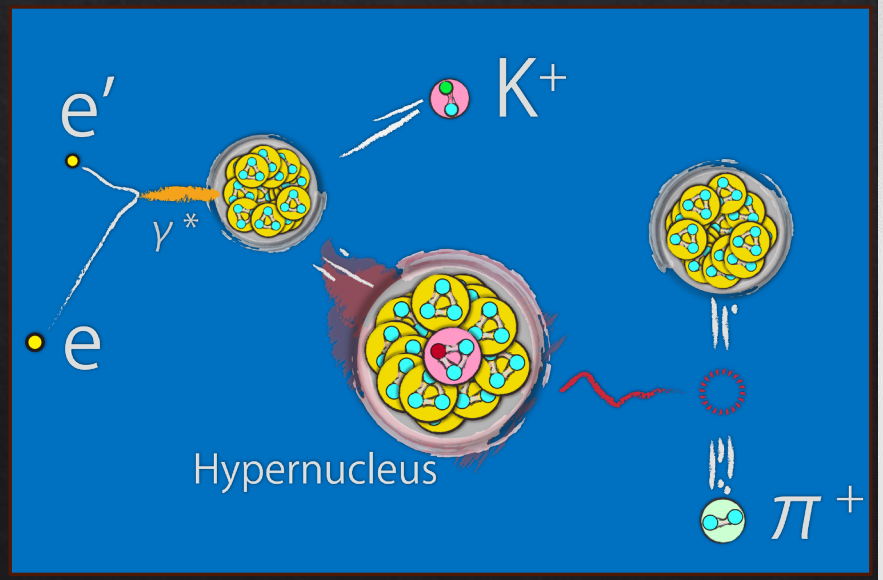
" Search for triaxially deformation states in ^{26}Mg"

Will be performed in 2027~


HES
HKS
Hall C (2009)
Jefferson Lab
Thomas Jefferson National Accelerator Facility

New experiment at JLab Hall-C (2027～)

- High resolution: 0.6 MeV FWHM
- High accuracy: 0.07 MeV
- Wide mass number: A = 6—208



e′: HES

0.7 GeV/c
2×10^5 /sec

K^+: HKS

1.2 GeV/c
5×10^4 /sec

π^+: ENGE

2.2-GeV Electron
50 μA (3×10^{14} /sec)
→ Hypernuclei: 0.003 /sec

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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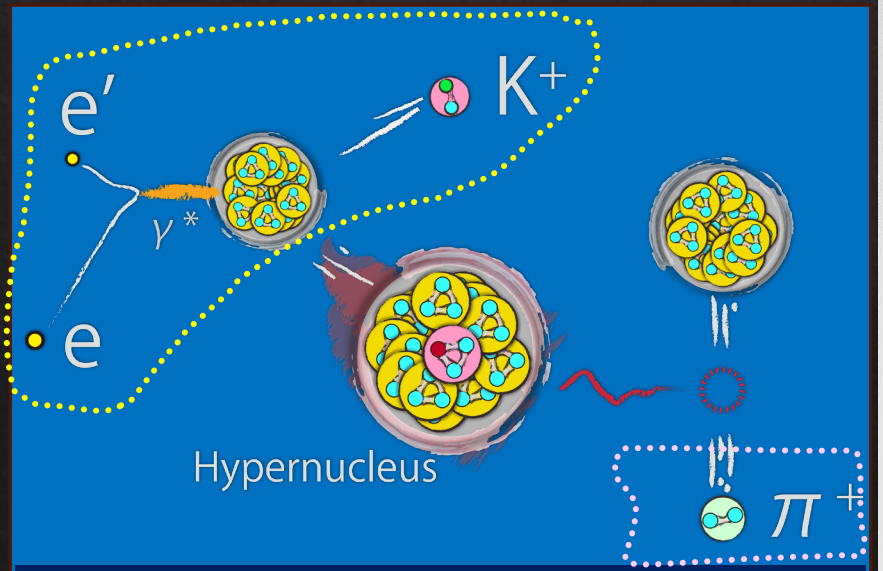


Missing mass + Decay pion spectroscopy

e': HES

0.7 GeV/c
2×10^5 /sec

K^+: HKS

1.2 GeV/c
5×10^4 /sec

π^+: ENGE

2.2-GeV Electron
50 μA (3×10^{14} /sec)
→ Hypernuclei: 0.003 /sec

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Particle Detectors

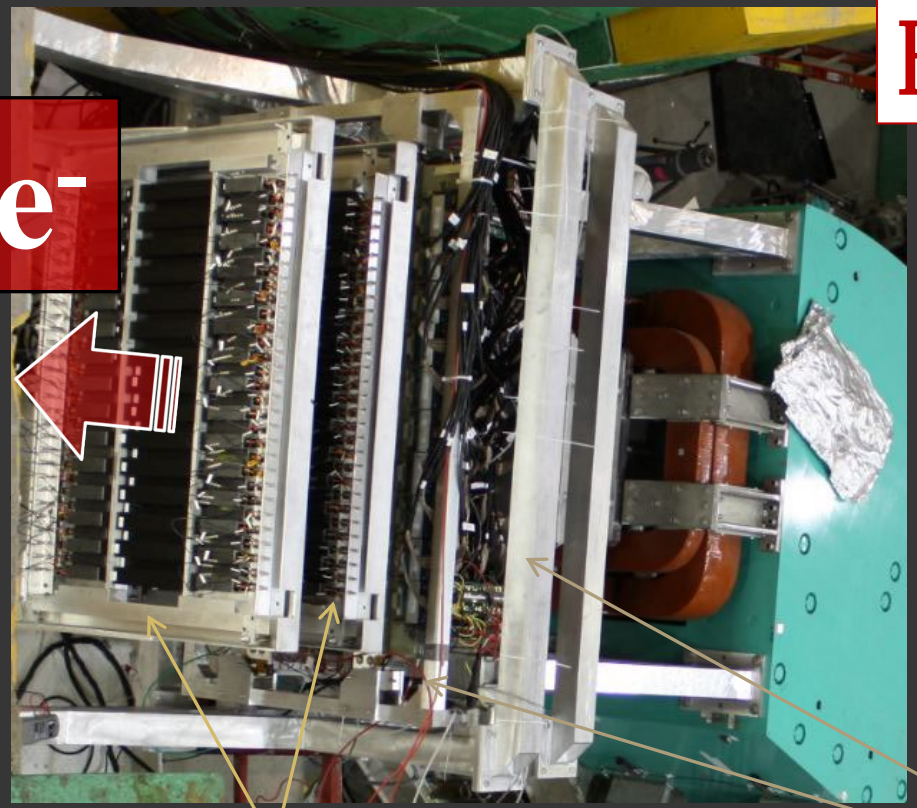
TG et al., NIMA 900, 69—83 (2018)
TG et al., NIMA 729, 816—824 (2013)

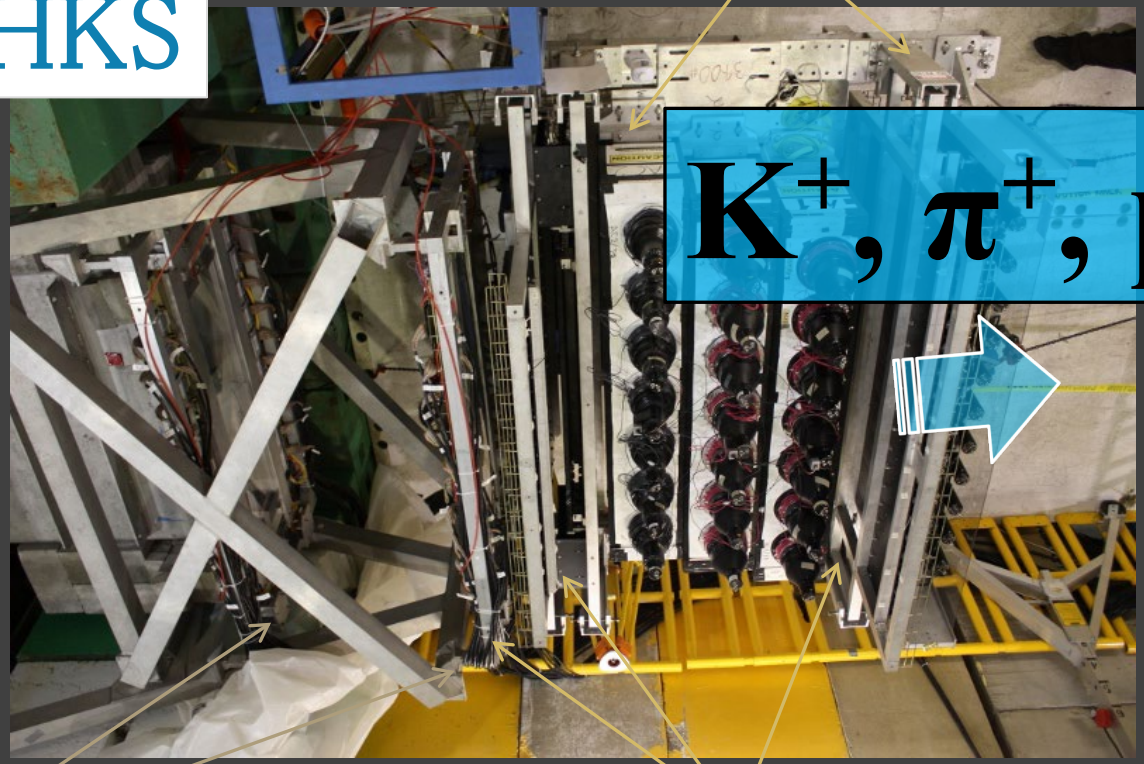
Cherenkov detectors
- **Aerogel (n=1.05)**
- **Water (n=1.33)**

HES

HKS

e^-





K^+, π^+, p

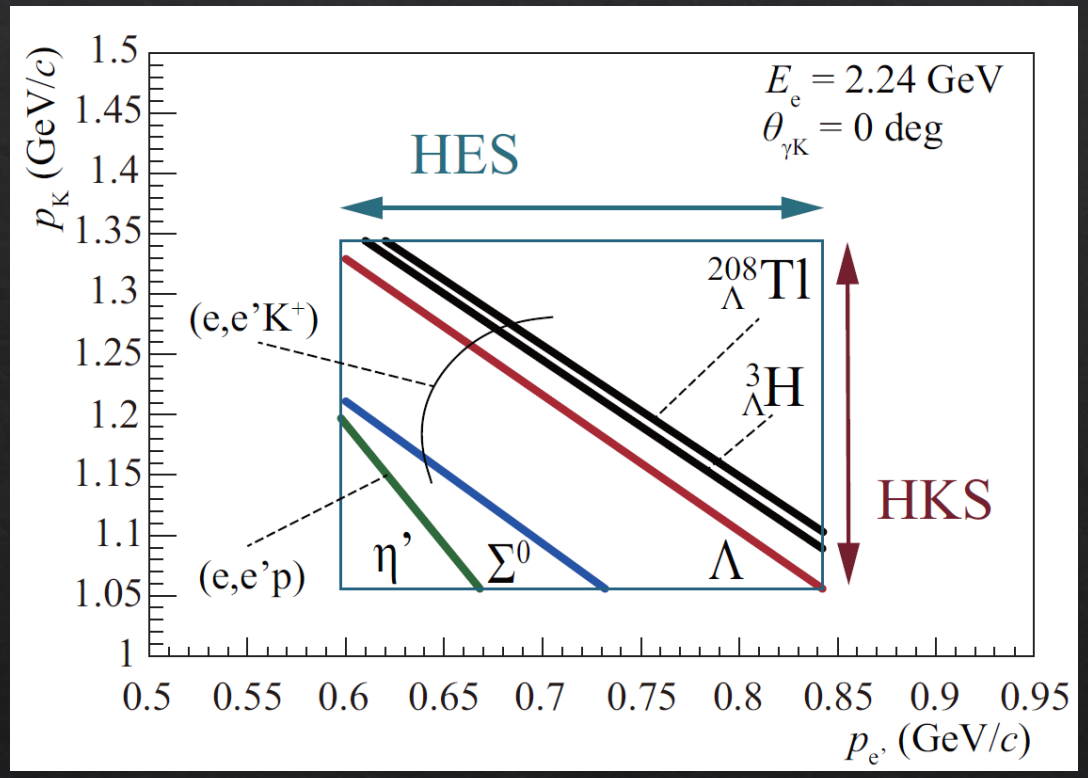
TOF walls (Plastic scintillators)

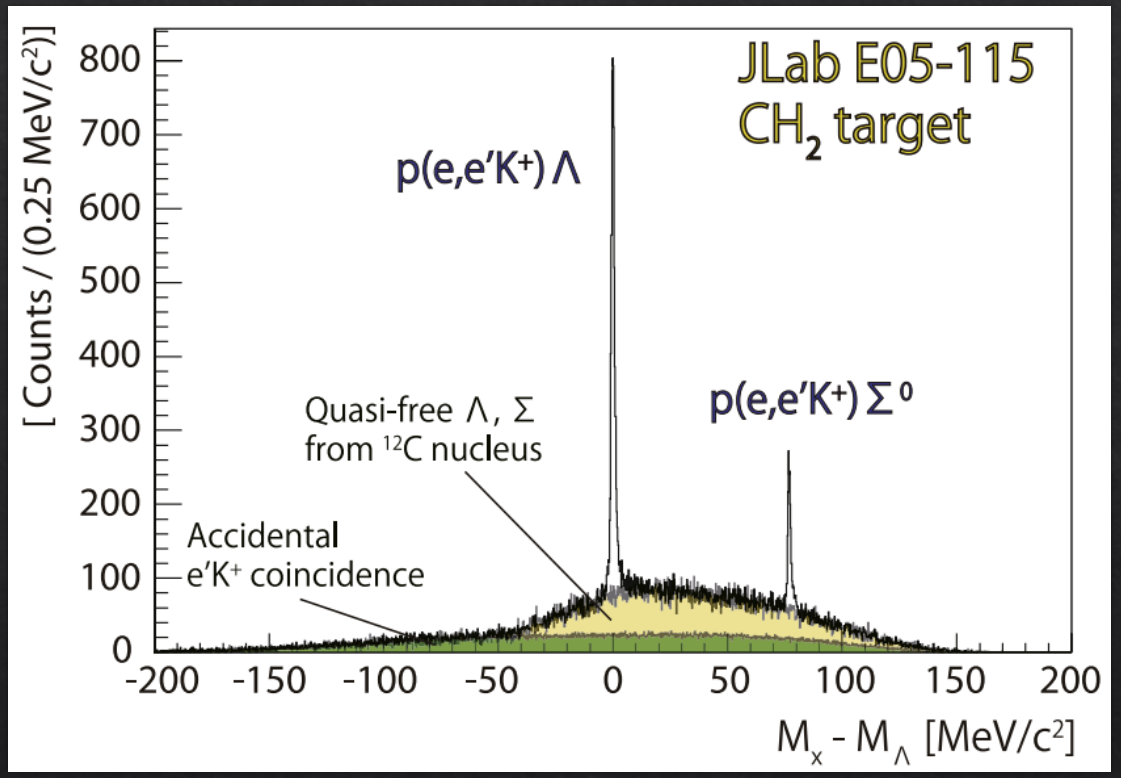
Drift chambers

TOF walls (Plastic scintillators)

Energy Calibration

TG et al., NIMA 900, 69—83 (2018)



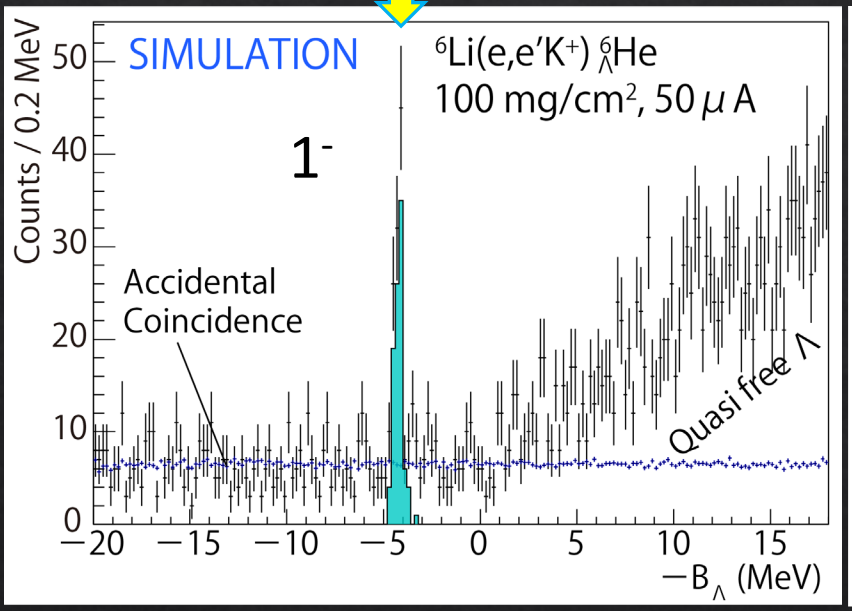


➔ Systematic error $|\Delta B_\Lambda^{\text{sys.}}| \simeq$ **60 keV**

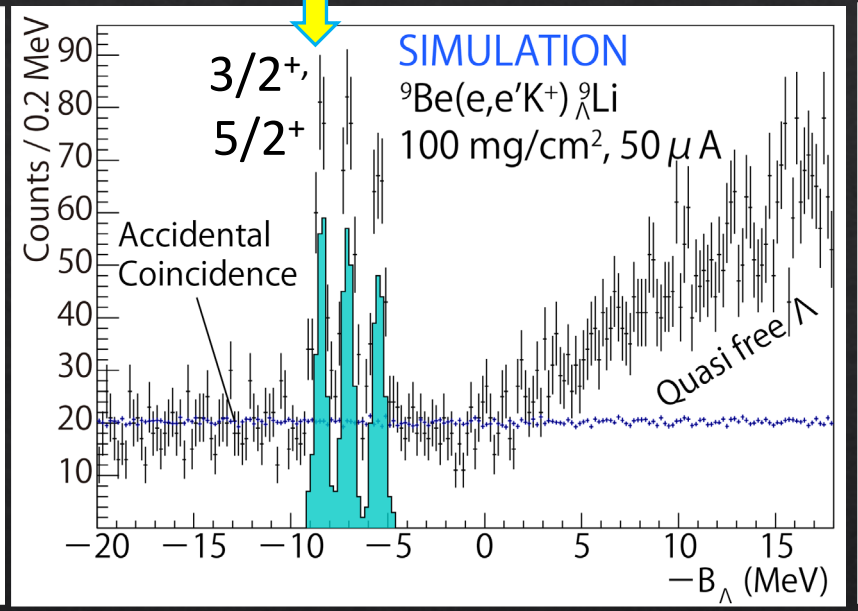
c.f.) T. Toyoda, Master's Thesis, *Kyoto University*, Kyoto, Japan, 2021 (in Japanese)

Expected Spectra (JLab E12-24-004)

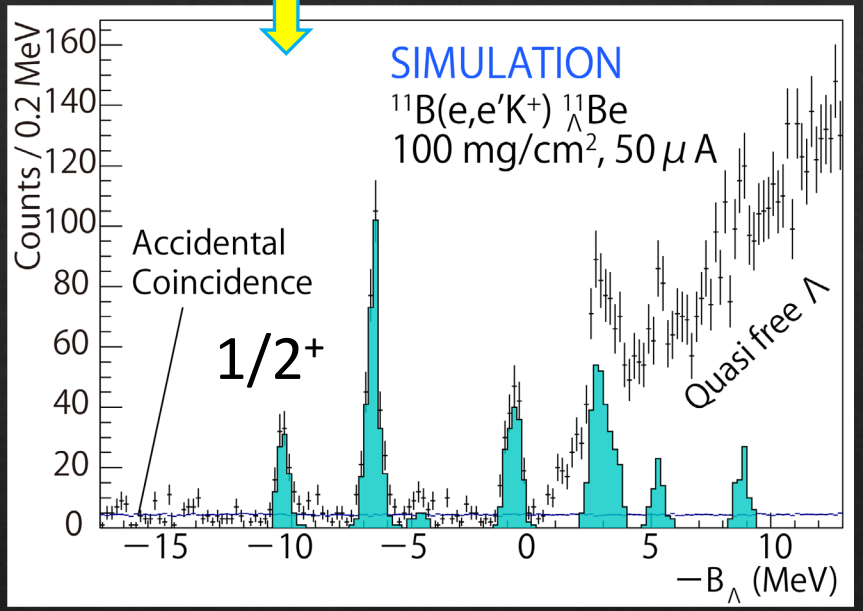
for CSB study 120 hours



for CSB study 384 hours



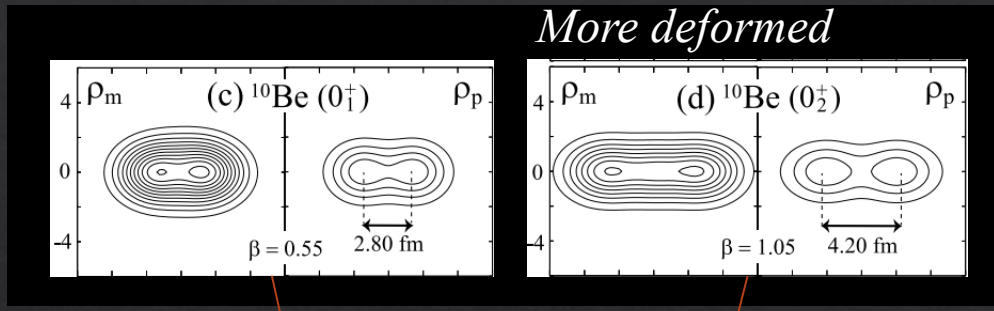
for CSB study 72 hours



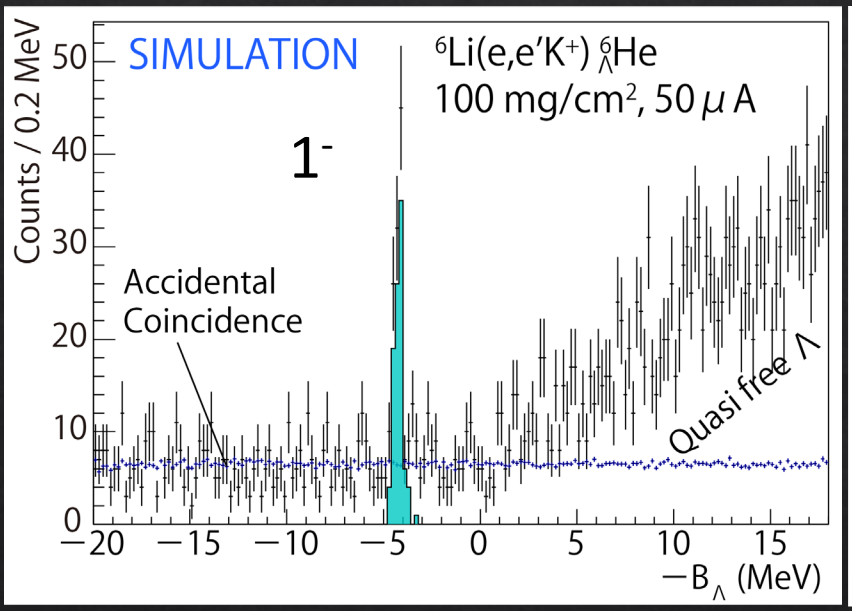
Total accuracy:

$$\left|\Delta B_{\Lambda}^{\text{total}}\right| = \sqrt{\left(\Delta B_{\Lambda}^{\text{stat.}}\right)^2 + \left(\Delta B_{\Lambda}^{\text{sys.}}\right)^2} \leq \mathbf{70\ keV}$$

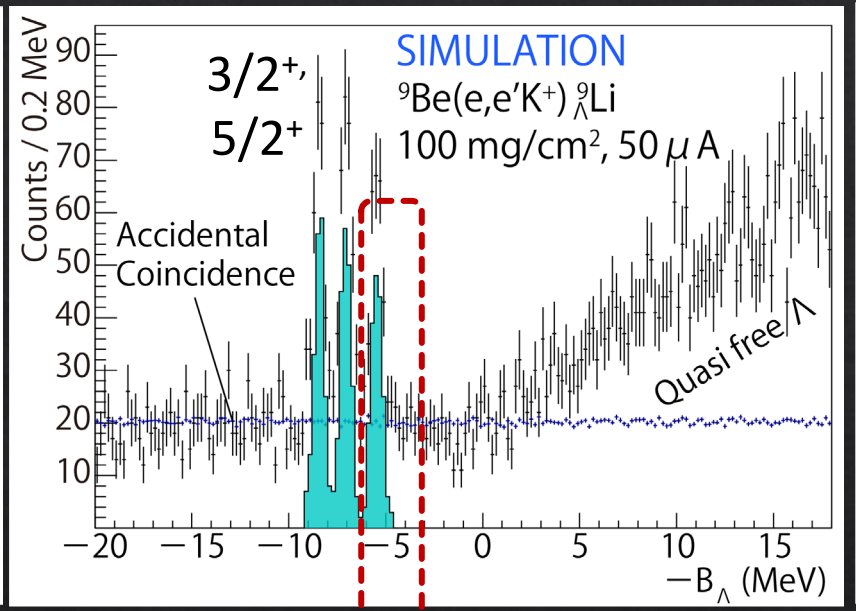
Expected Spectra



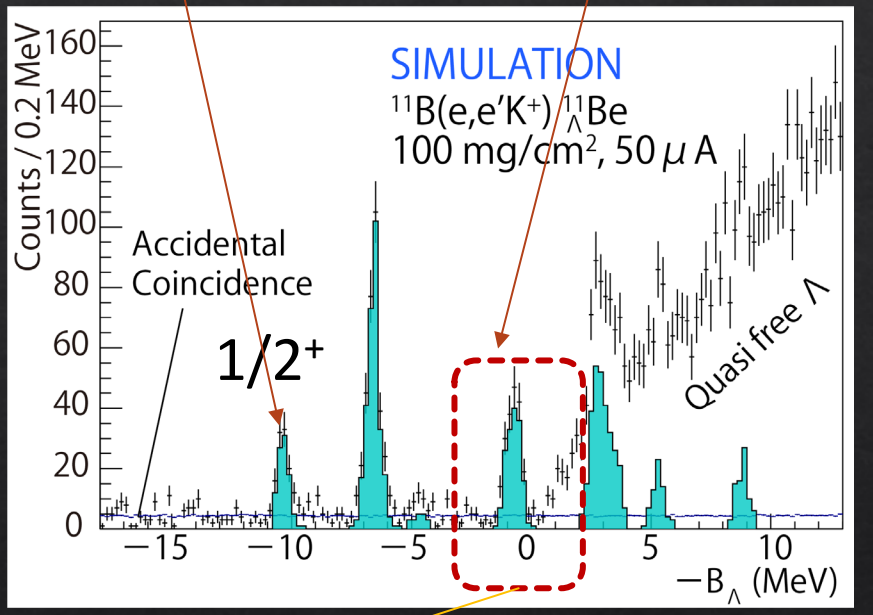
120 hours



384 hours



72 hours



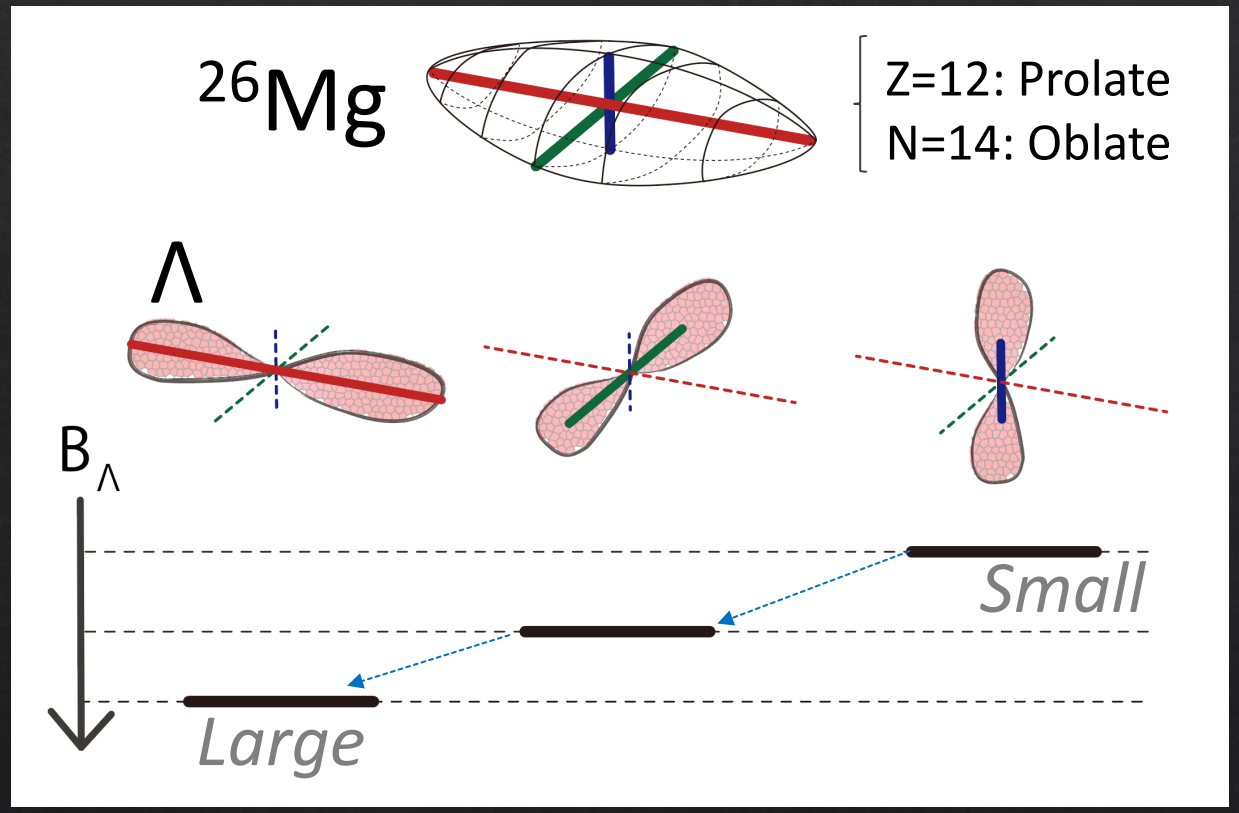
Total accuracy:
$|\Delta B_\Lambda^{\text{total}}| \leq$ **70 keV**

c.f.) TG et al., PRC 103, L041301 (2021)

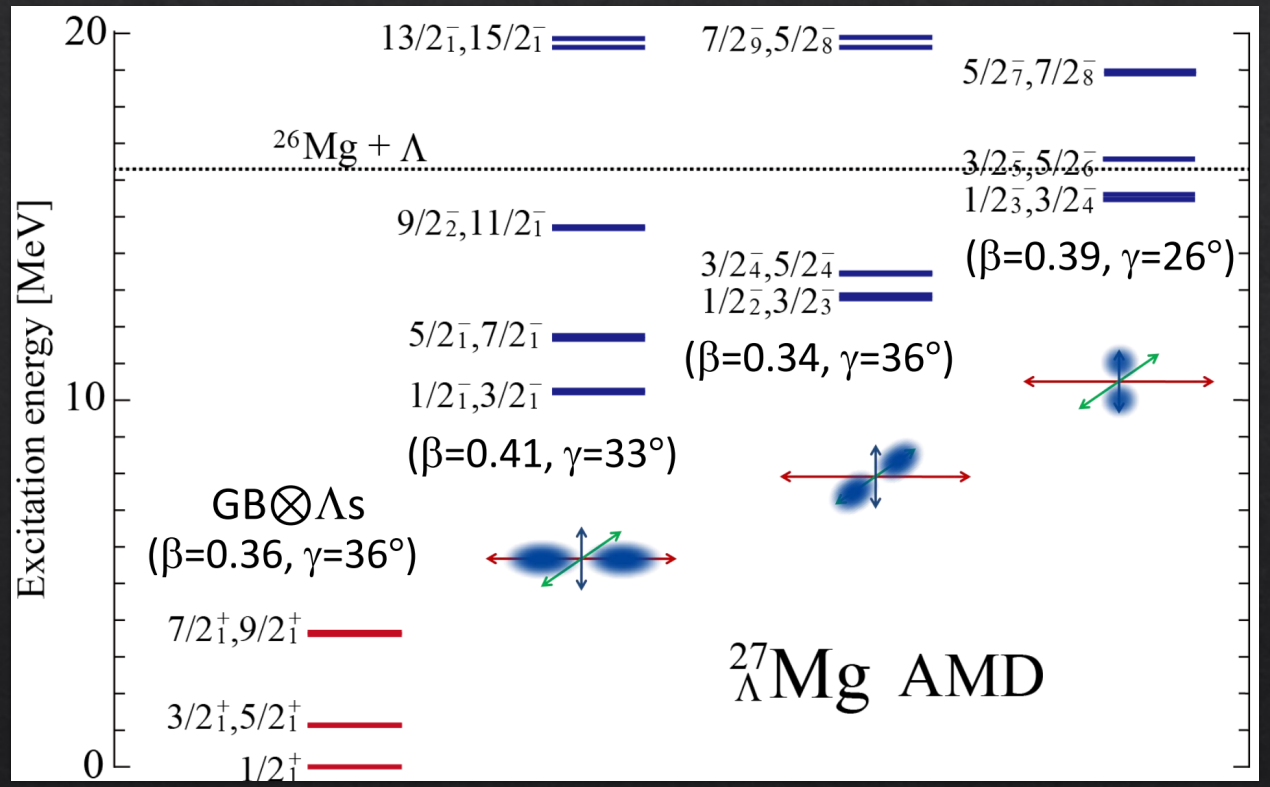
Cluster / deformation structures

M. Isaka et al., PRC 92, 044326 (2015)

$^{27}\mathrm{Al}(e,e'K^+)^{27}_{\Lambda}\mathrm{Mg}$ (JLab E12-24-011)



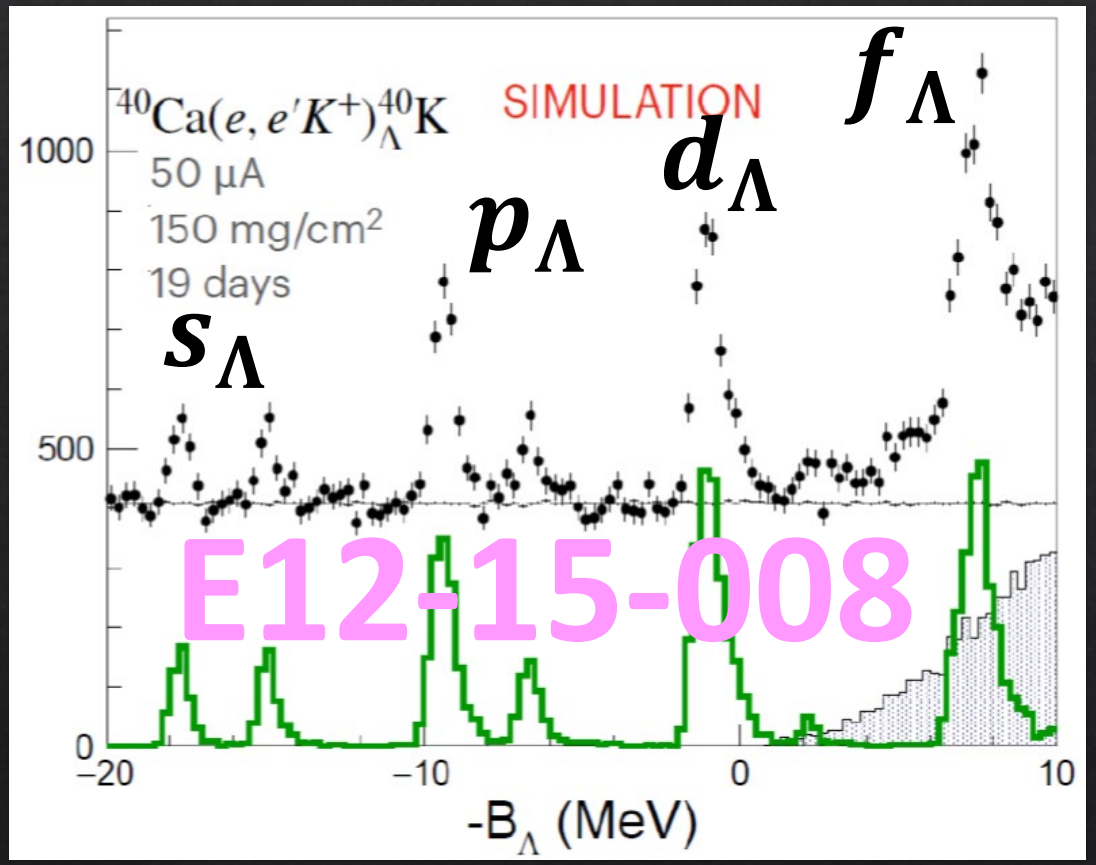
Anti-molecular dynamics (AMD) calculation
Presentation by M. Isaka (2023); https://indico.jlab.org/event/705/



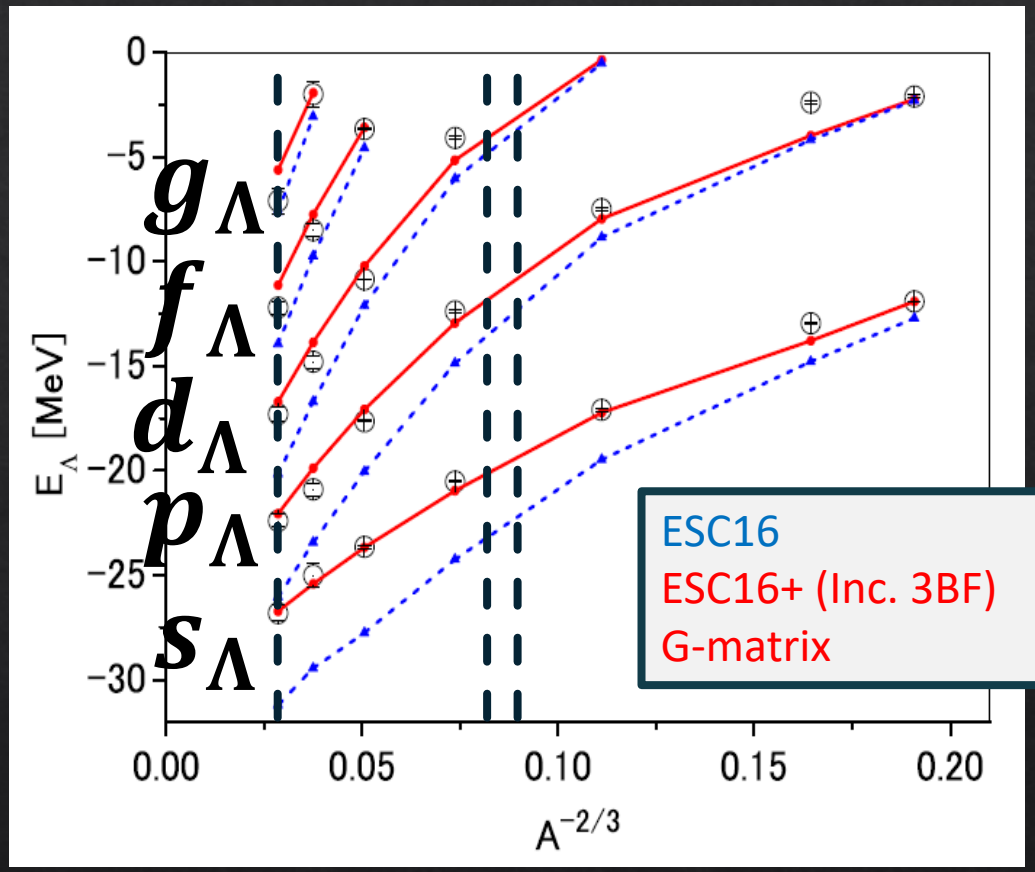
^{26}Mg × p_Λ ➔ Probing triaxially deformation

High accuracy experiment → 3-body force study

Expected spectrum based on Geant4 simulation



M.M. Nagels et al., PRC 99 (2019) 044003.



Missing mass spectroscopy with the world best accuracy $|\Delta B_\Lambda| \leq 100$ keV

➡ New information for 3-body force

Summary

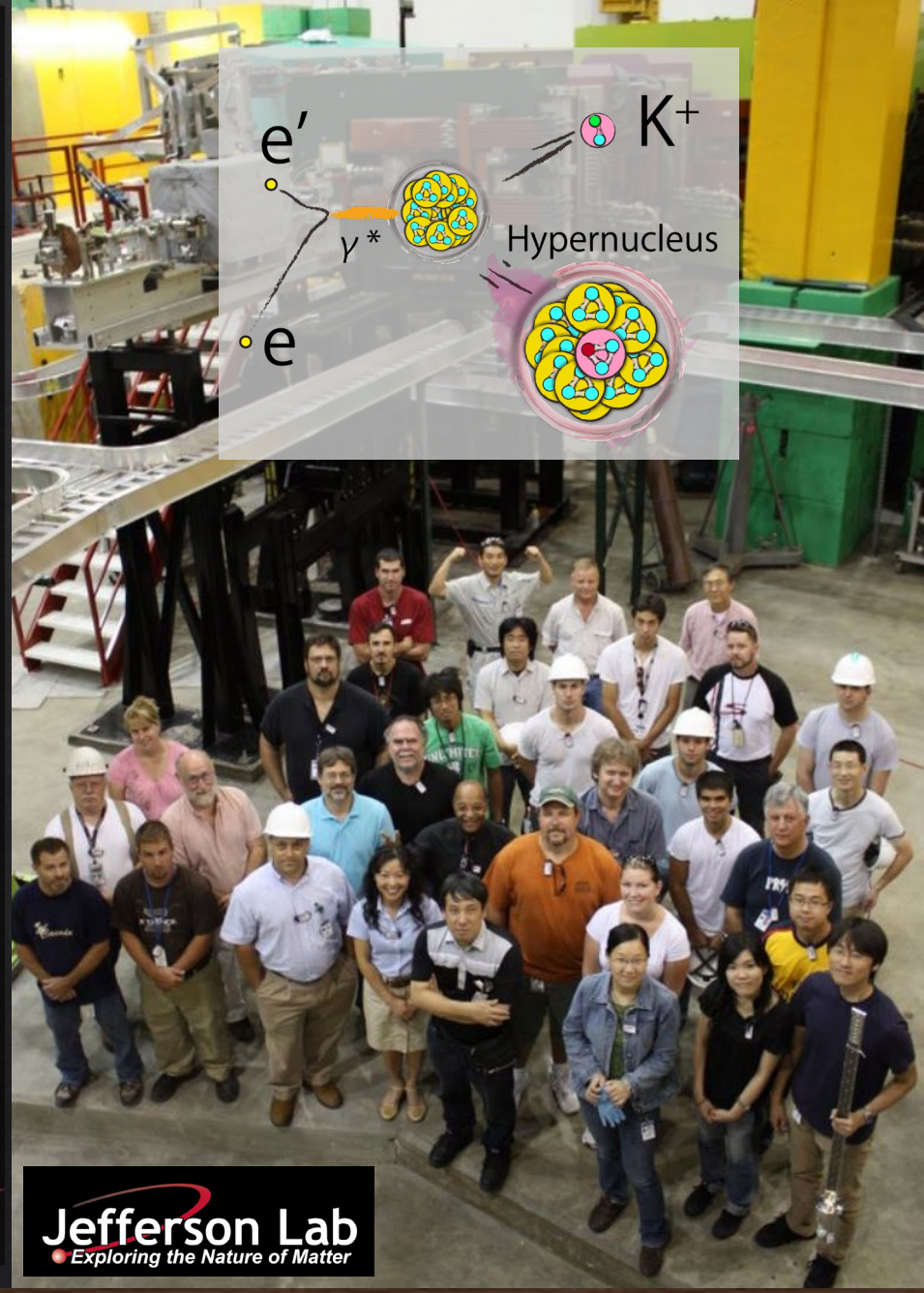
Λ hypernuclear spectroscopy

- Baryon interaction (YN, YNN)

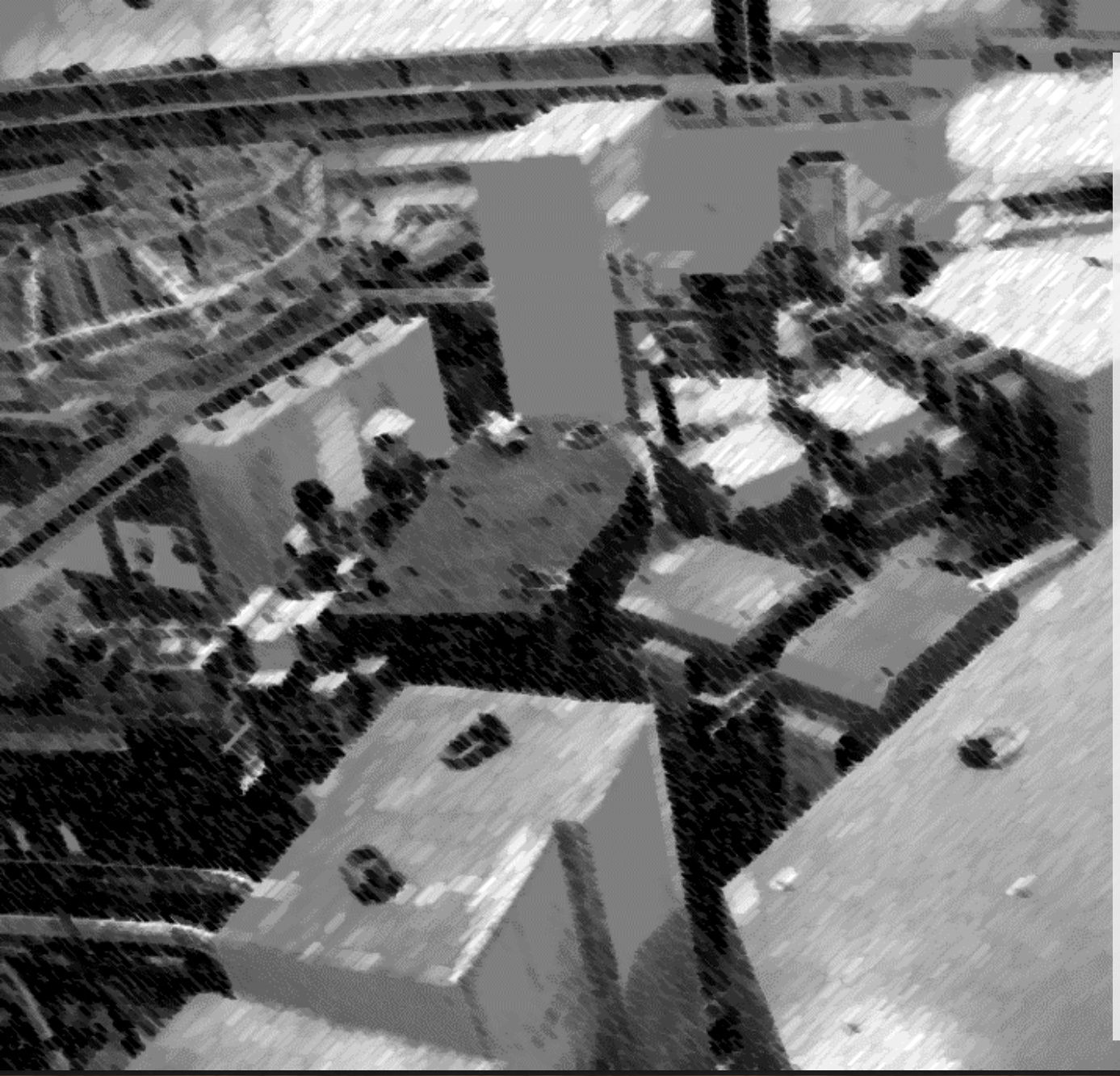
JLab Hypernuclear Collaboration

- (e,e' K^+) reaction → High resolution/accuracy spectroscopy
- The method was established at JLab
- Future experiment ($^{3}_{\Lambda}\mathrm{H}$, $^{4}_{\Lambda}\mathrm{H}$, $^{6}_{\Lambda}\mathrm{He}$, $^{11}_{\Lambda}\mathrm{Be}$, $^{27}_{\Lambda}\mathrm{Mg}$, $^{40}_{\Lambda}\mathrm{K}$, $^{48}_{\Lambda}\mathrm{K}$, $^{208}_{\Lambda}\mathrm{Tl}$)
  - hypertriton puzzle (biding energy vs. lifetime)
  - Charge symmetry breaking
  - (Triaxially) deformation
  - ΛN−ΣN coupling
  - iso-spin dependence of ΛNN force

2027～



Backup



Hall A

- K. Okuyama et al., PRC 110, 025203 (2024)
- B. Pandey et al., PRC 105, L051001 (2022)
- K.N. Suzuki et al., PTEP 2022, 1, 013D01 (2022)
- F. Garibaldi et al., PRC 99, 054309 (2019)
- G. M. Urciuoli et al., PRC 91, 034308 (2015)
- F. Cusanno et al., PRL 103, 202501 (2009)
- G. M. Urciuoli et al., NIMA612, 56—68 (2009)
- M. Iodice et al., PRL 99, 052501 (2007)

Hall C

- 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)
- Y. Fujii et al., NIMA795, 351—363 (2015)
- L. Tang et al., PRC 90, 034320 (2014)
- S.N. Nakamura et al., PRL 110, 012502 (2013)
- TG et al., NIMA 729, 816—824 (2013)
- L. Yuan et al., PRC 73, 044607 (2006)
- T. Miyoshi et al., PRL 90, 232502 (2003)

Experimental parameters for the next JLab Experiment

TABLE II. Summary of the kinematics parameters in the proposed experiment.

Item		Value
Beam (e)	Energy (/GeV)	2.24
	(Required) energy spread and drift	1×10^{-4} (FWHM)
PCS + HES (e')	Central momentum $p_{e'}^{\text{cent.}}$ [/(GeV/c)]	0.74
	Central angle $\theta_{ee'}^{\text{cent.}}$	8.5°
	Solid angle acceptance $\Omega_{e'}$ (/msr) (at $p_{e'}^{\text{cent.}}$)	3.4
	Momentum resolution $\Delta p_{e'}/p_{e'}$	4.4×10^{-4} (FWHM)
PCS + HKS (K^+)	Central momentum $p_{K^+}^{\text{cent.}}$ [/(GeV/c)]	1.20
	Central angle $\theta_{eK^+}^{\text{cent.}}$	11.5°
	Solid angle acceptance Ω_{K^+} (/msr) (at $p_{K^+}^{\text{cent.}}$)	7.0
	Momentum resolution $\Delta p_{K^+}/p_{K^+}$	2.9×10^{-4} (FWHM)
$p(e, e'K^+)\Lambda$	$\sqrt{s} = W$ (/GeV)	1.912
	Q^2 [/(GeV/c)^2]	0.036
	K^+ scattering angle wrt virtual photon, $\theta_{\gamma^* K^+}$	7.35°
	ϵ	0.59
	ϵ_L	0.0096

Limited data for the CSB study

○: Data w/ ≤100 keV accur. exists

Shell	A	Component	Isospin			CSB study w/ 100 keV accur.
			T<0	T=0	T>0	
s	4	d N Λ (0^+ / 1^+)	○	-	○ ○	Yes
p	6	α N Λ		-		
	7	α N N Λ	○ (JLab)	○	○	Yes
	8	α d N Λ	○	-	○	Yes
	9	α d N N Λ		○		
	10	α α N Λ	○ (JLab)	-		
	11	α α N N Λ				
	12	α α d N Λ	○ (JLab)	-		

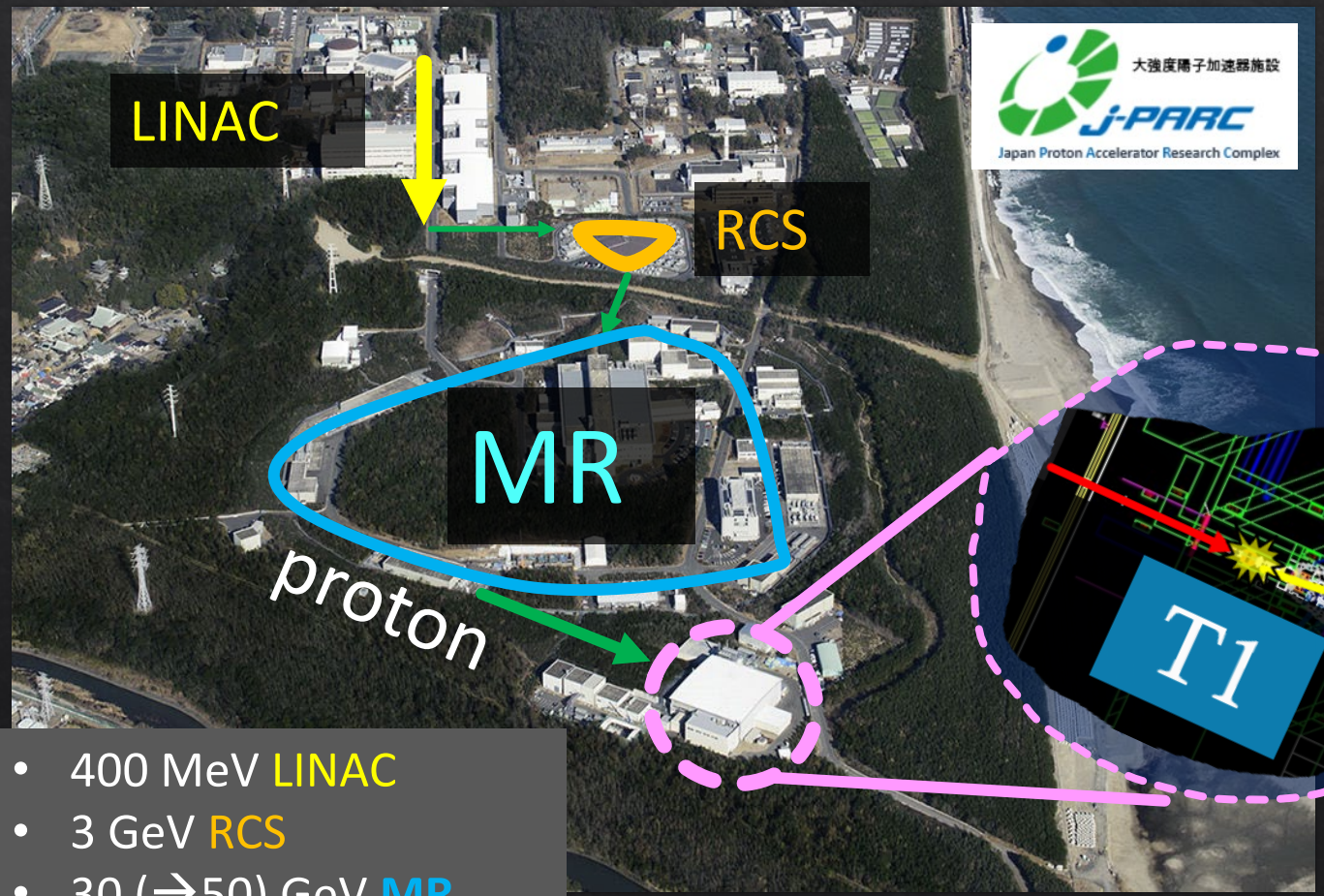
Limited data for the CSB study

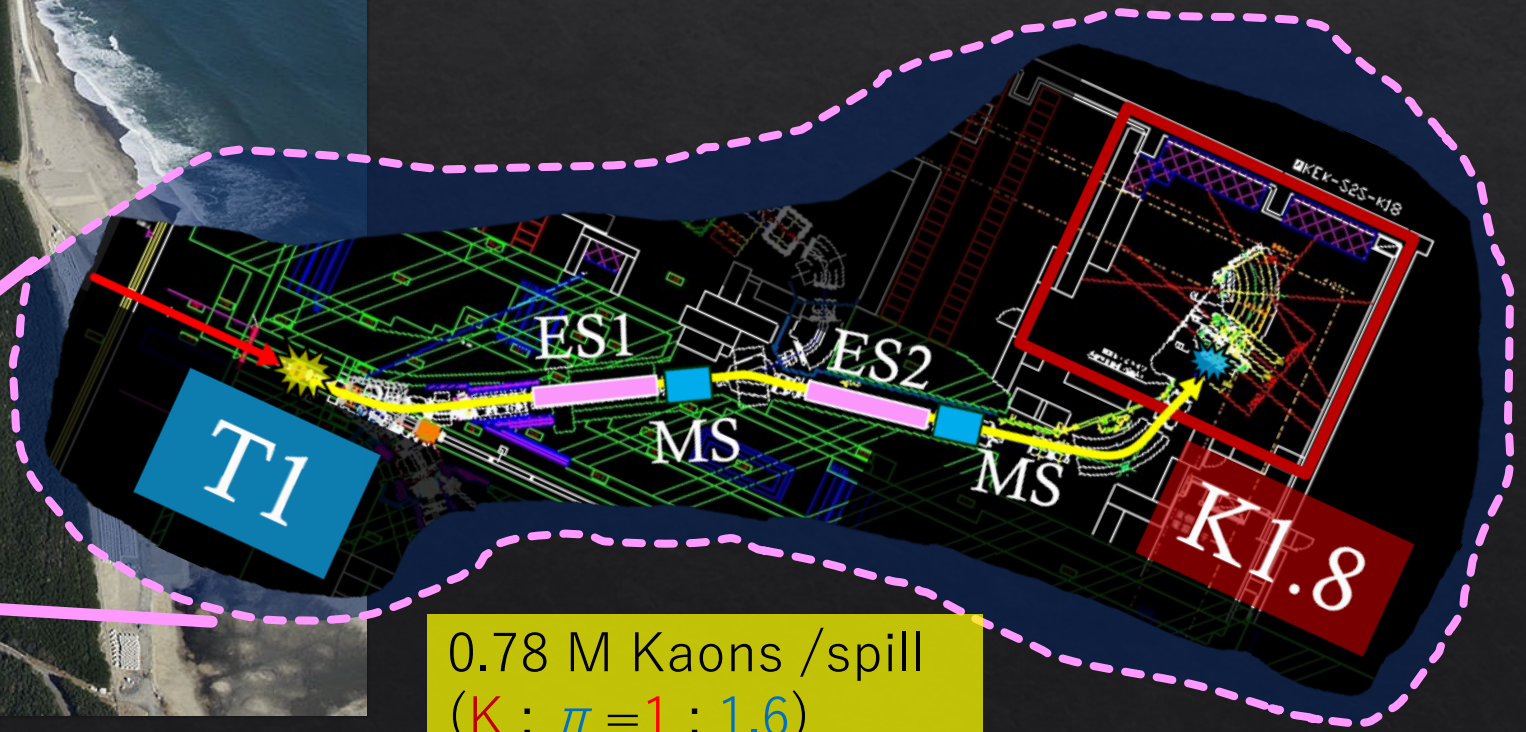
○: Data w/ ≤100 keV accur. exists

Shell	A	Component	Isospin			CSB study w/ 100 keV accur.	
			T<0	T=0	T>0		
s	4	d N Λ (0^+ / 1^+)	○ E12-19-002	-	○ ○	Yes	**Yes**
p	6	α N Λ	This prop.	-	J-PARC	**Yes**	
	7	α N N Λ	○ (JLab)	○	○	Yes	
	8	α d N Λ	○	-	○	Yes	
	9	α d N N Λ	This prop.	○		**Yes**	
	10	α α N Λ	○ (JLab)	-	J-PARC E94	**Yes**	
	11	α α N N Λ	This pro.	J-PARC		**Yes**	
	12	α α d N Λ	○ (JLab)	-	J-PARC E94	**Yes**	

Japan Proton Accelerator Research Complex (J-PARC), Ibaraki, Japan

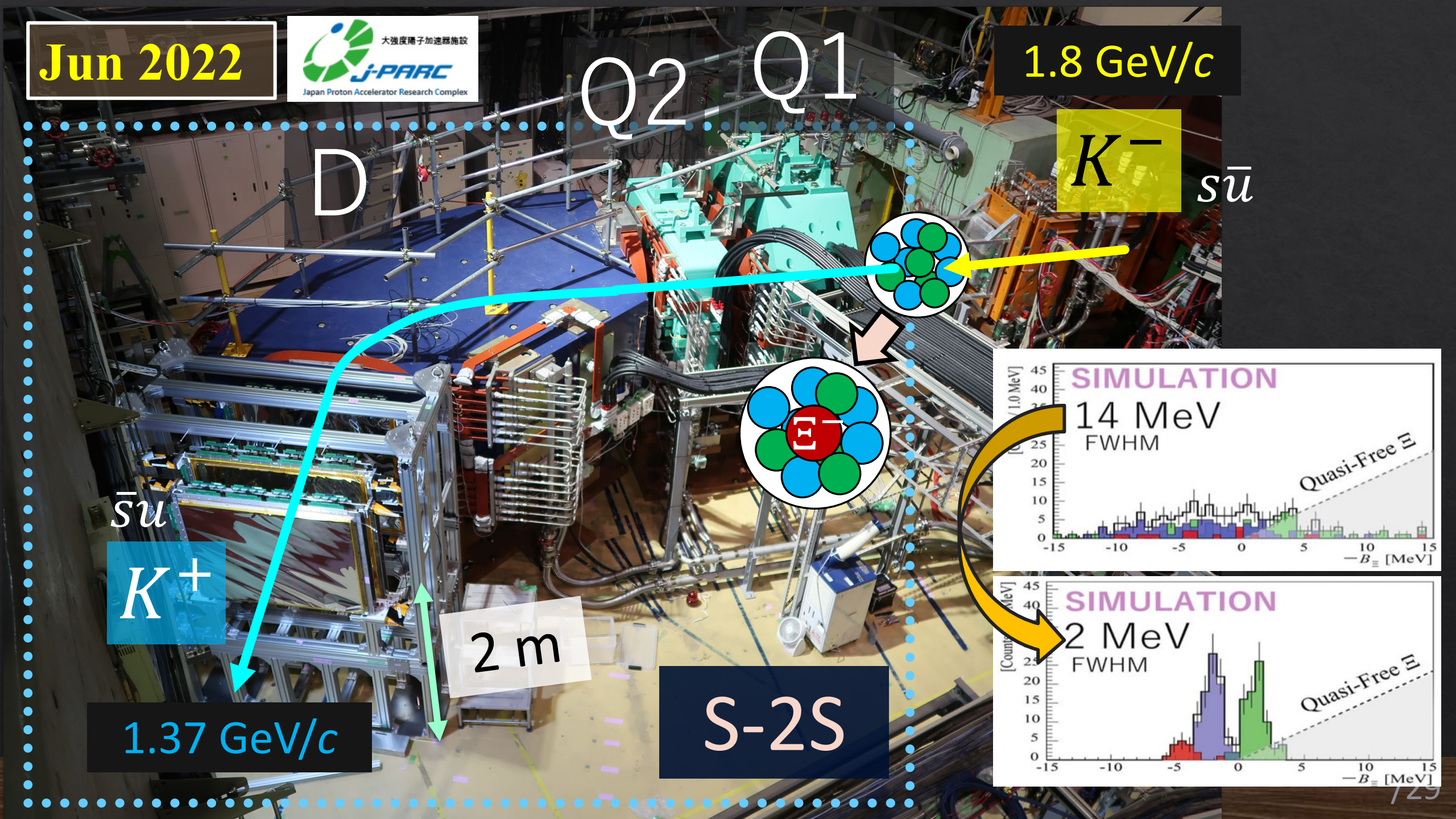
$^{A}Z(\pi^+, K^+)^{A}_{\Lambda}Z$
@K1.8 Beam line

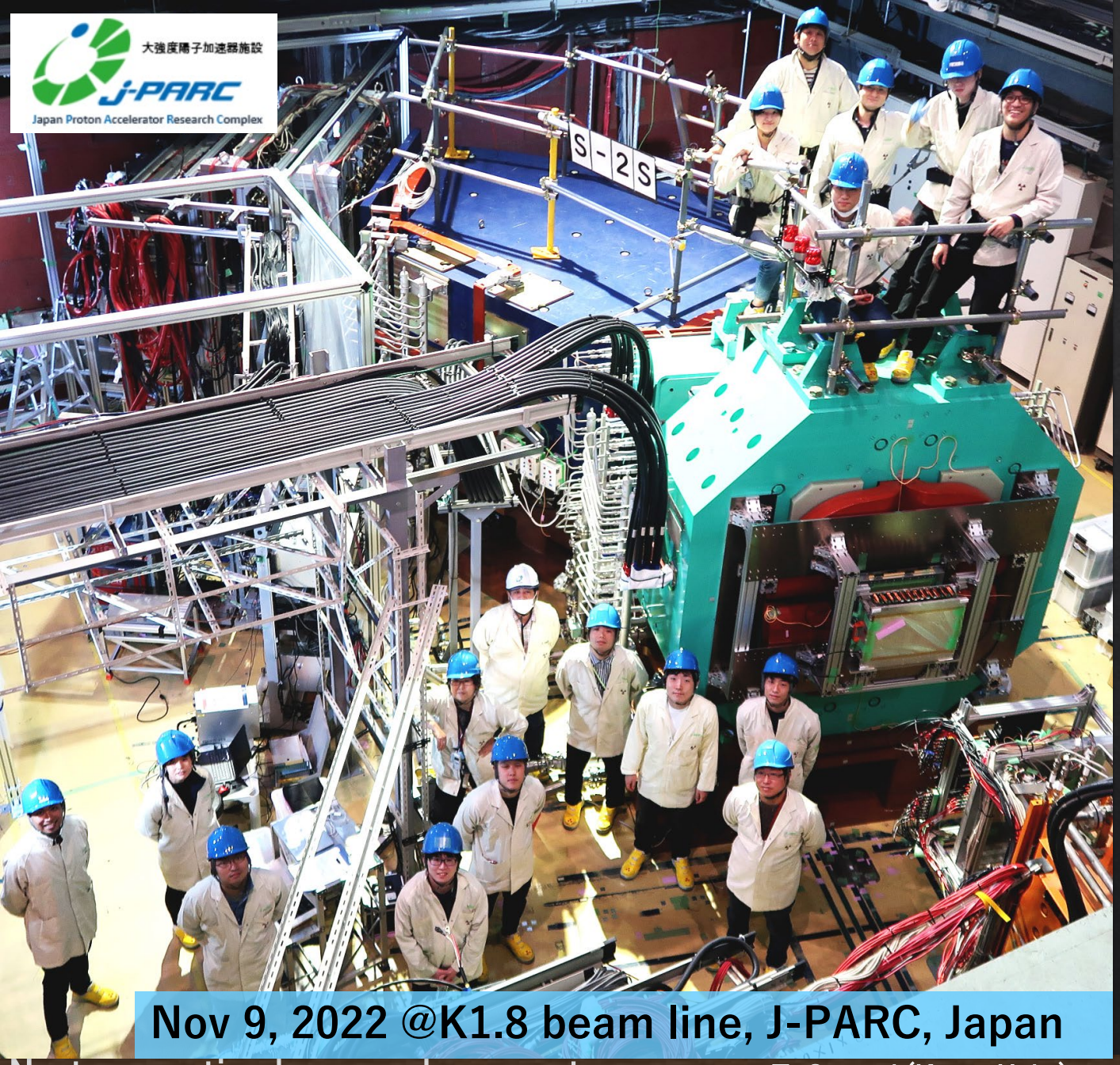




- 400 MeV LINAC
- 3 GeV RCS
- 30 (→50) GeV MR

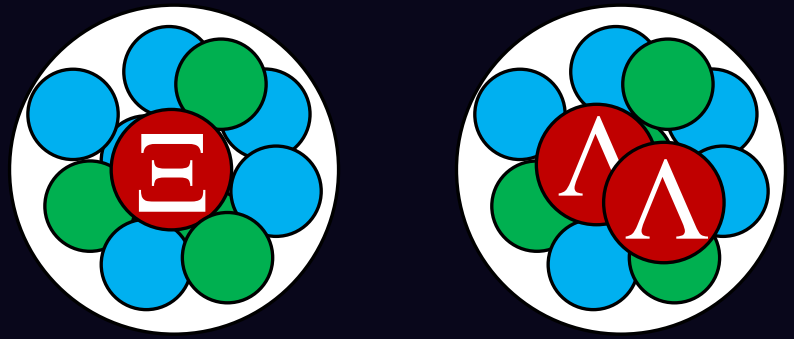
0.78 M Kaons /spill
(K : π =1 : 1.6)

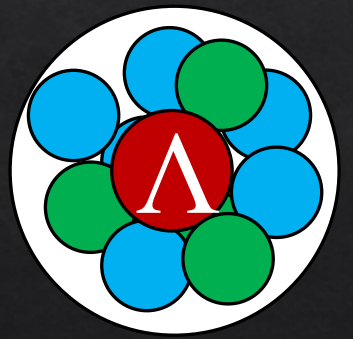

Jun 2022
大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex
Q2
Q1
D
1.8 GeV/c
K^-
$s\bar{u}$
$\bar{s}u$
K^+
2 m
1.37 GeV/c
S-2S
SIMULATION
14 MeV
FWHM
Quasi-Free Ξ
SIMULATION
2 MeV
FWHM
Quasi-Free Ξ
$-B_\Xi$ [MeV]



Nov 9, 2022 @K1.8 beam line, J-PARC, Japan

"S = −2" study will start!





"S = −1"

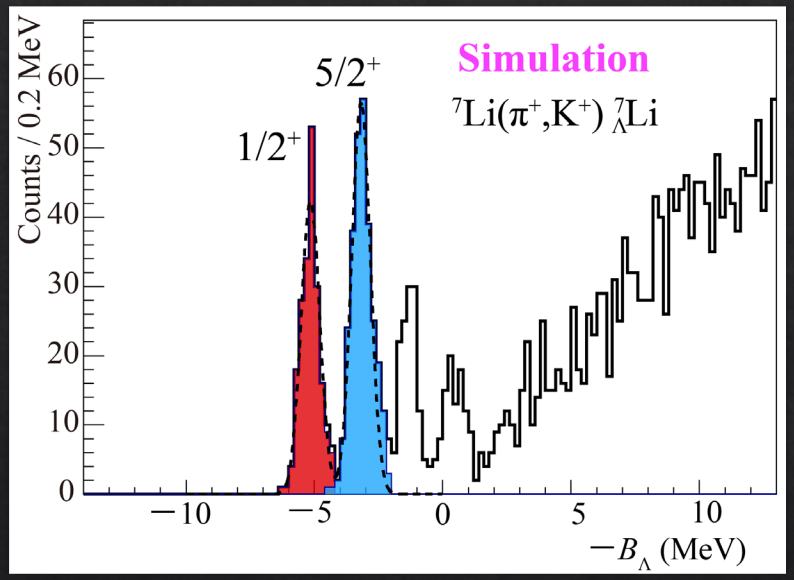
as well

T. Gogami et al., EPJ Web Conf. 271, 11002 (2022).

Expected spectra (J-PARC E94)

$^{7}_{\Lambda}$Li

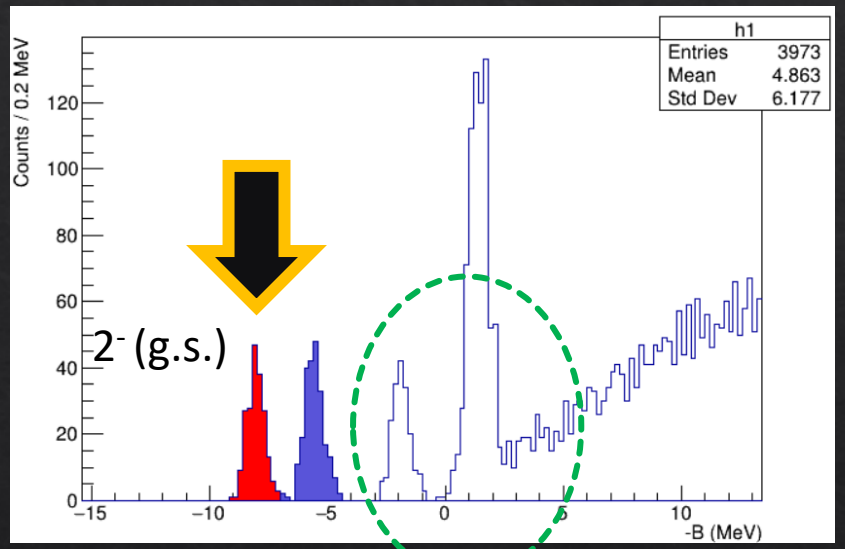
80 hours



Calibration source

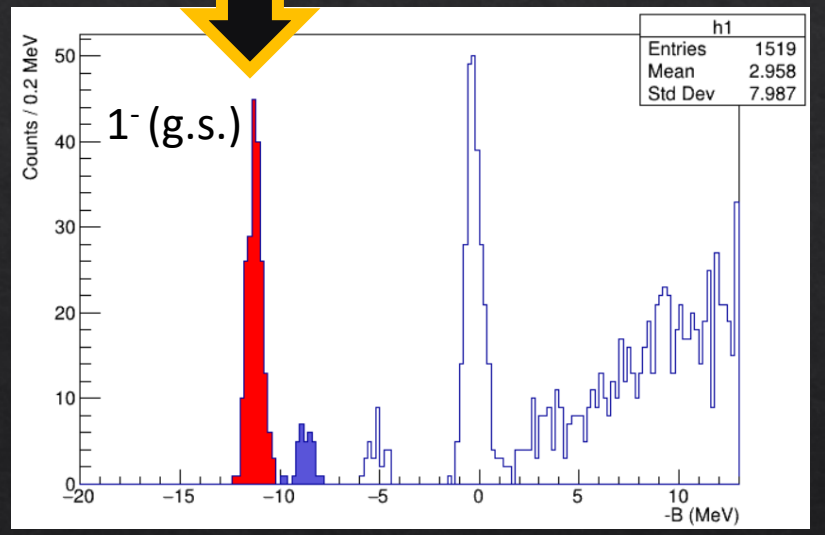
$^{10}_{\Lambda}$B

112 hours



$^{12}_{\Lambda}$C

36 hours



$$\left|\Delta B_{\Lambda}^{total\ (stat. \oplus sys.)}\right| < 0.1\ \text{MeV}$$

CSB $^{3}_{\Lambda}\mathrm{H}$ lifetime puzzle

$nn\Lambda$ bound puzzle

Strangeness	2B	Coupled channel	3B
-1		ΛN-ΣN	
-2		ΞN-ΛΛ	

Many Body effect
(Cluster, deformation)

Neutron star puzzle

CSB $^{3}_{\Lambda}\mathrm{H}$ **lifetime puzzle**

$nn\Lambda$ **bound puzzle**

Invariant mass spectroscopy by HI beam
@LHC, RHIC, GSI

- YN scat. exp.
- Femotoscopy

Strangeness	2B	Coupled channel	3B
-1		ΛN-ΣN	
-2		ΞN-ΛΛ	

Many Body effect
(Cluster, deformation)

- Space observation
- Graviton wave meas.

Neutron star puzzle

J-PARC E63

J-PARC E94

JLab E12-24-004

- YN scat. exp.
- Femotoscopy

CSB $^{3}_{\Lambda}\mathrm{H}$ **lifetime puzzle**

$nn\Lambda$ **bound puzzle**

JLab E12-19-002

JLab LOI12-23-011

Invariant mass spectroscopy by HI beam @LHC, RHIC, GSI

JLab C12-20-013 (C2)

Strangeness	2B	Coupled channel	3B
-1	Y N	ΛN-ΣN	N Y N
-2	Y N	ΞN-ΛΛ	N Y N

JLab E12-24-011

Many Body effect
(Cluster, deformation)

- Space observation
- Graviton wave meas.

J-PARC E70

J-PARC E75

J-PARC E96

JLab E12-15-008

JLab E12-20-013

Neutron star puzzle

Missing mass spectroscopy of hypernuclei at JLab and J-PARC

JLab (HES-HKS, 0.6 MeV FWHM, 0.07 MeV accuracy, 2027—)

- $(e, e'K^+)$ reaction at $\omega = 1.5$ GeV
- Approved: ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{6}_{\Lambda}\mathrm{He}$, ${}^{9}_{\Lambda}\mathrm{Li}$, ${}^{11}_{\Lambda}\mathrm{Be}$, ${}^{27}_{\Lambda}\mathrm{Mg}$, ${}^{40}_{\Lambda}\mathrm{K}$, ${}^{48}_{\Lambda}\mathrm{K}$, ${}^{208}_{\Lambda}\mathrm{Tl}$

➔ **ΛN CSB, ΛNN, tri-axial deformation**

J-PARC (S-2S, 1.0 MeV FWHM, 0.1 MeV accuracy, 2025—)

- (π^+, K^+) and (K^-, K^+) reactions at $p = 1.05$ and 1.8 GeV/c
- Approved: ${}^{6}_{\Lambda}\mathrm{Li}$, ${}^{10}_{\Lambda}\mathrm{B}$, ${}^{12}_{\Lambda}\mathrm{C}$, ${}^{7}_{\Xi}\mathrm{H}$, ${}^{12}_{\Xi}\mathrm{Be}$
- New additional plan: ${}^{6}_{\Lambda}\mathrm{Li}$, ${}^{11}_{\Lambda}\mathrm{B}$ *etc.*

➔ **ΛN CSB, ΞN interaction**