JLab Hypernuclear Collaboration Meeting, Jefferson Lab, US, May 15—16, 2025

Research of Charge Symmetry Breaking in the Lambda-Nucleon Interaction by Electron Probe

Graduate School of Science, Kyoto University

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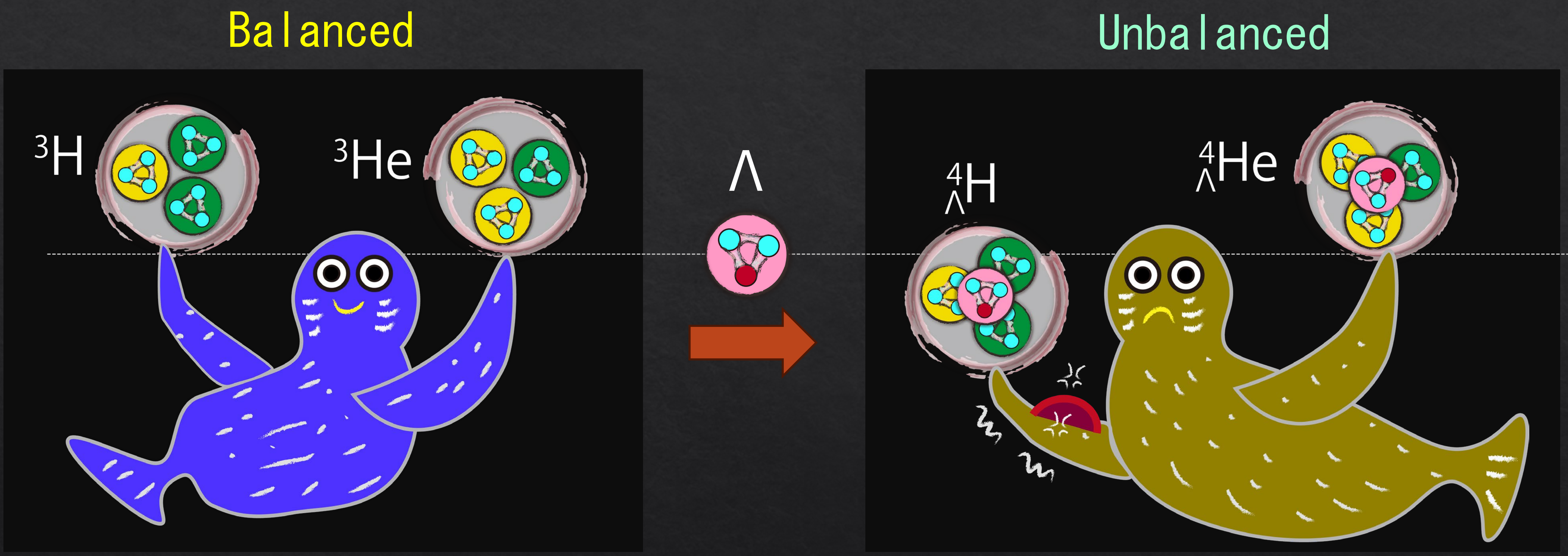
May 15, 2025

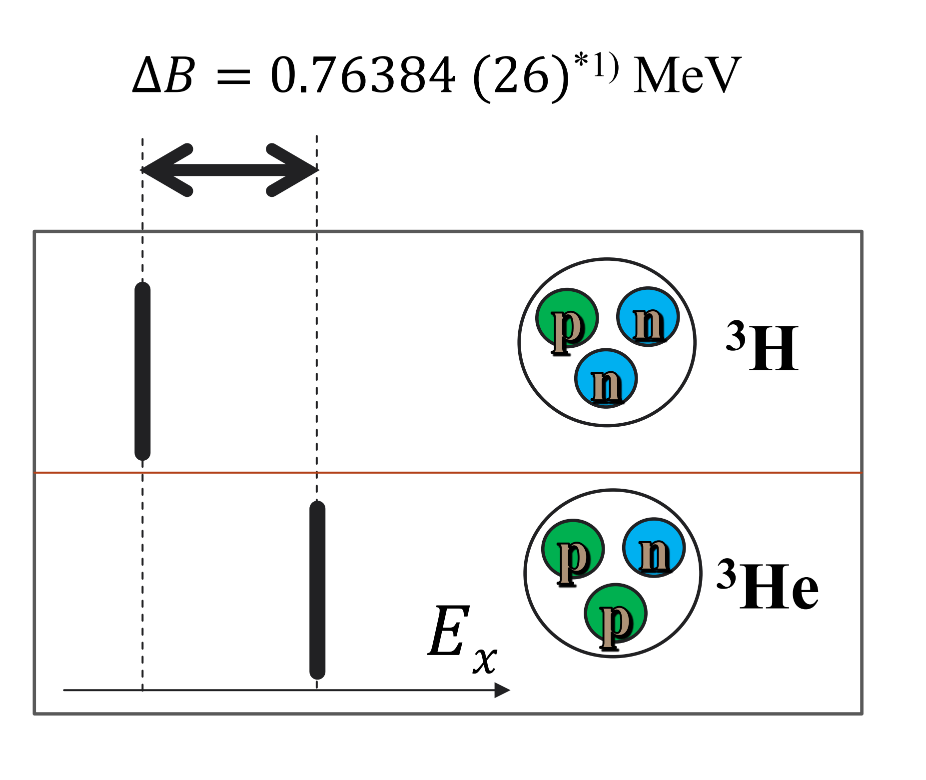
KYOTO UNIVERSITY

Charge Symmetry Breaking (CSB)



Charge Symmetry Breaking (CSB), the mystery

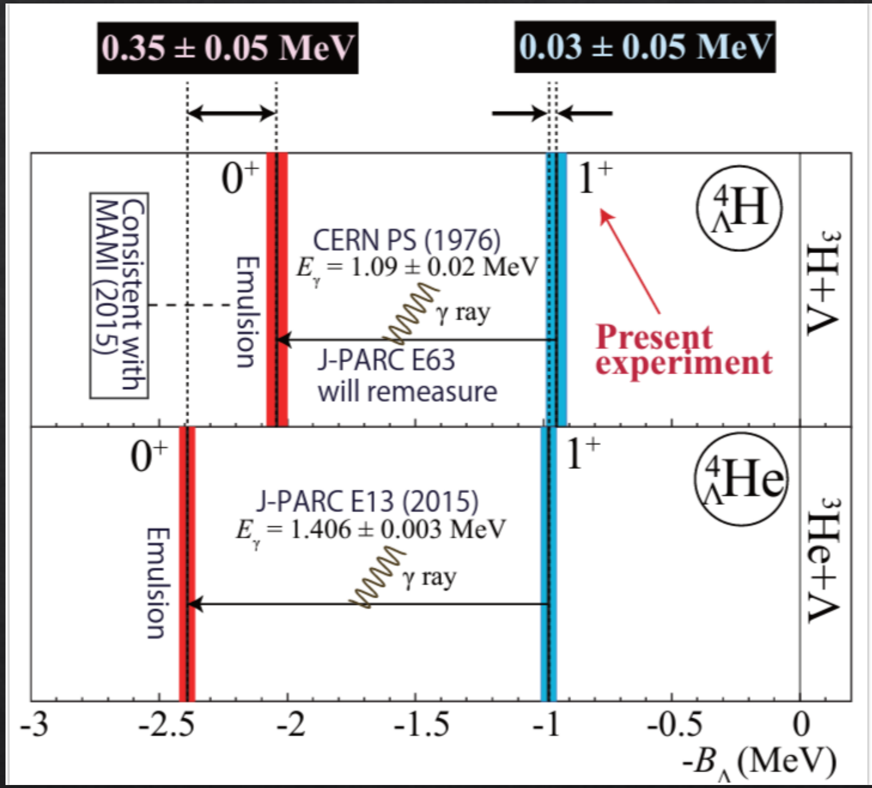
*1) J.H.E.Mattauch *et al.*, *Nucl. Pys.* **67**, 1 (1965).

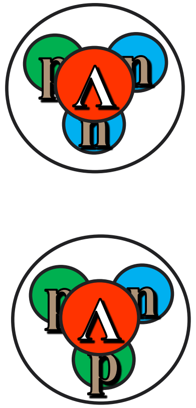


81 keV after Coulomb correction

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

Figure from proposal of JLab E12-19-002

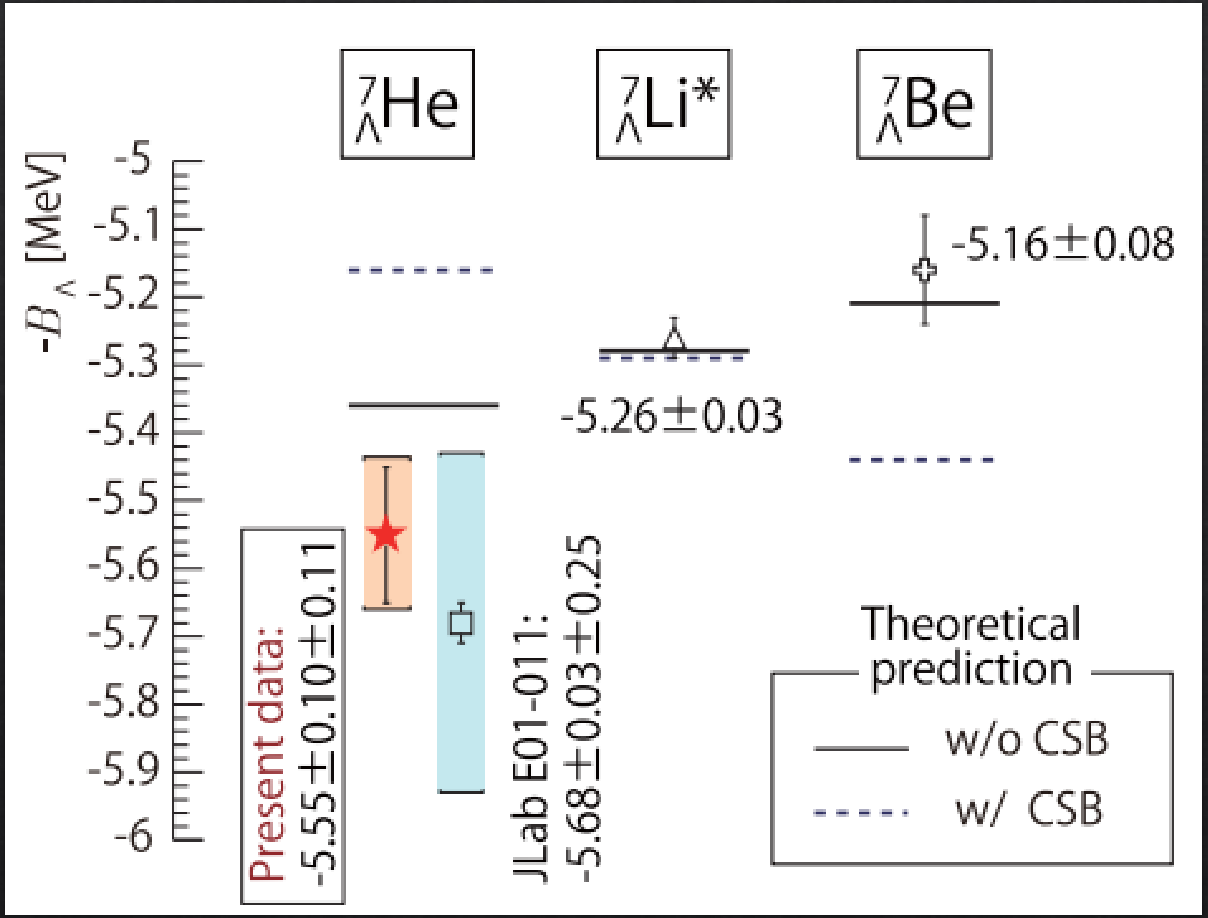




~400 KeV after Coulomb correction

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

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

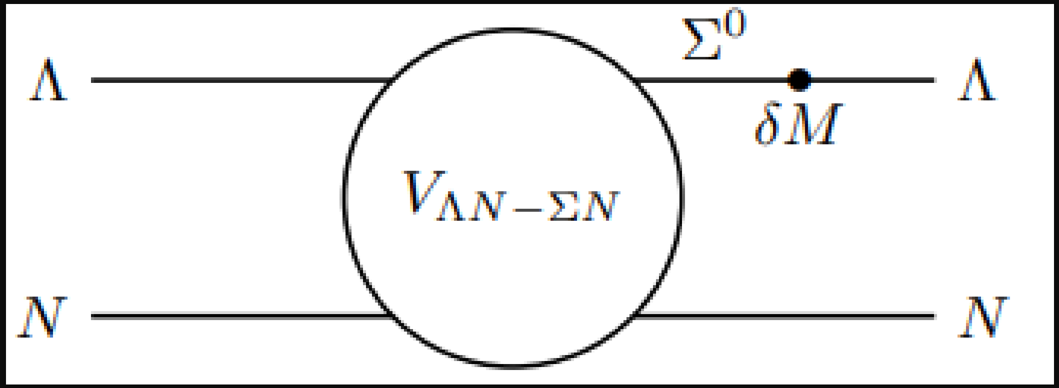
Parameters were adjusted to reproduce the binding energies of $^{4}_{\Lambda}$He, $^{4}_{\Lambda}$H, $^{8}_{\Lambda}$Li, $^{8}_{\Lambda}$Be hypernuclei

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

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

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

Energies in keV

Isomultiplet	${}^{4}_{\Lambda}$He–${}^{4}_{\Lambda}$H	${}^{7}_{\Lambda}$Be–${}^{7}_{\Lambda}$Li*	${}^{7}_{\Lambda}$Li*–${}^{7}_{\Lambda}$He	${}^{8}_{\Lambda}$Be–${}^{8}_{\Lambda}$Li	${}^{9}_{\Lambda}$B–${}^{9}_{\Lambda}$Li	${}^{10}_{\Lambda}$B–${}^{10}_{\Lambda}$Be*
Shell model (Gal *et al.*)	+226	−17	−28	+49	−54	−136
Cluster model (Hiyama *et al.*)		+150	+130			+20
No-core shell model (Le *et al.*)	+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)

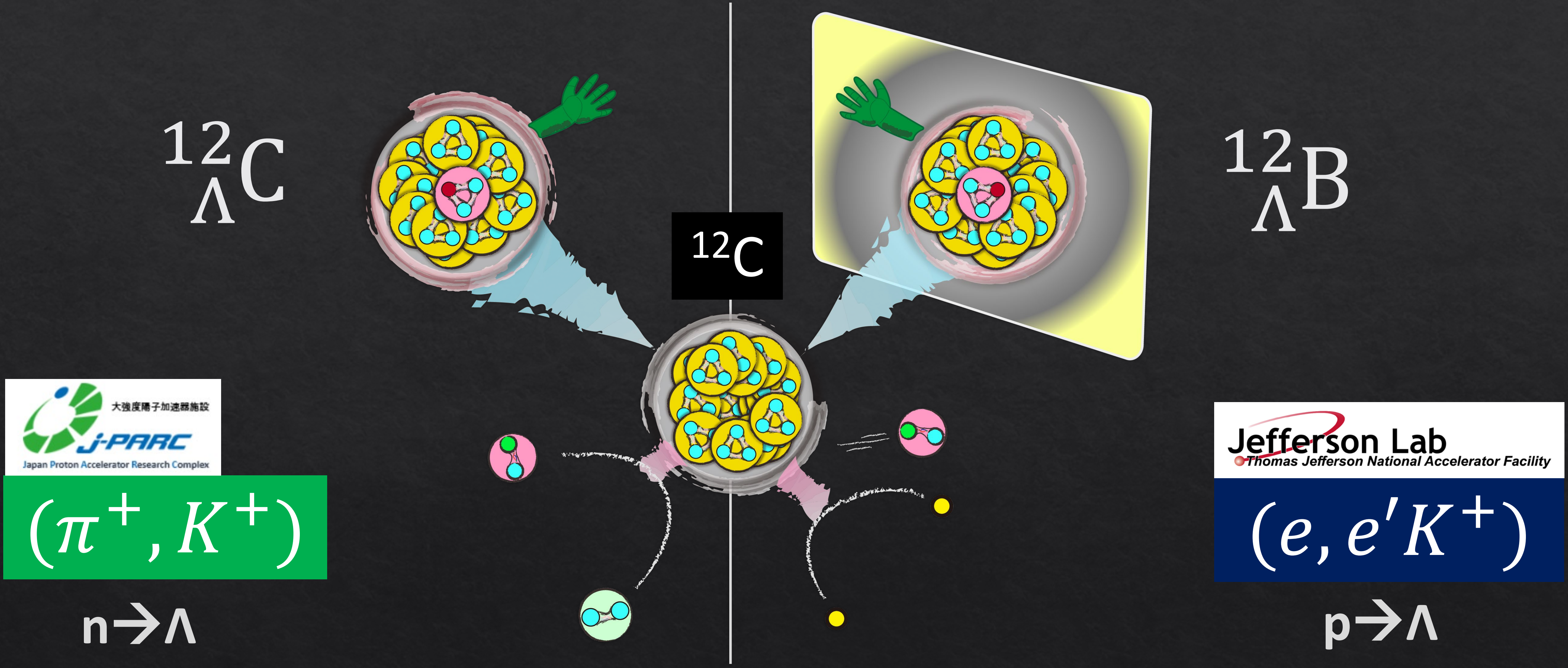
E. Hiyama et al., Prog. Theor. Phys. 128, 105 (2012).

H. Le et al., Phys. Rev. C 107, 24002 (2023)

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

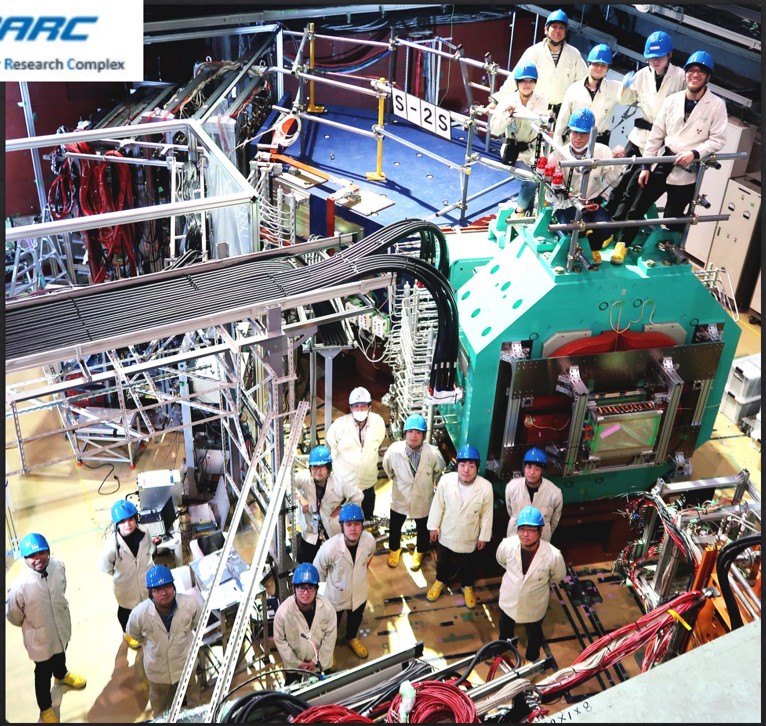
→ ΔB_{diff}∼100 keV for A = 6, 7, 9, 10, 11, 12

Mirror Hypernuclear Study



Missing mass spectroscopy for Λ hypernuclei

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



S-2S (2025～)

Λ: A = 7, 10, 12

Ξ: A = 12, 7

HES-HKS (2027～)

Λ: A = 6, 9, 11, 12, 27, 40, 48, 208

Limited data for the CSB study

○: Data w/ ≤100 keV accur. exists

Shell	A	Component	Isospin T<0	Isospin T=0	Isospin T>0	CSB study w/ 100 keV accur.
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 T<0	Isospin T=0	Isospin T>0	CSB study w/ 100 keV accur.
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**

Limited data for the CSB study

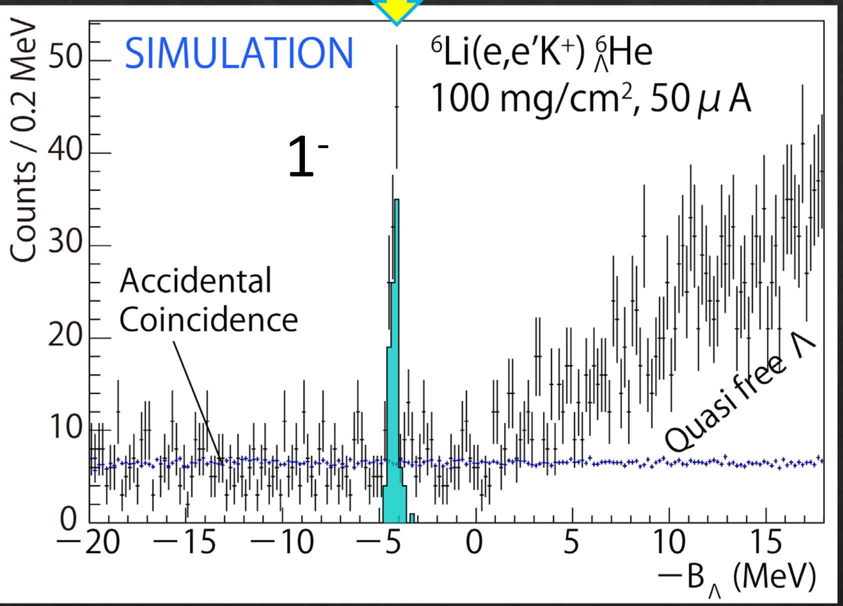
○: Data w/ ≤100 keV accur. exists

Data from JLab ($^{6}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{11}_{\Lambda}$Be) are unique and necessary to pin down the CSB origin

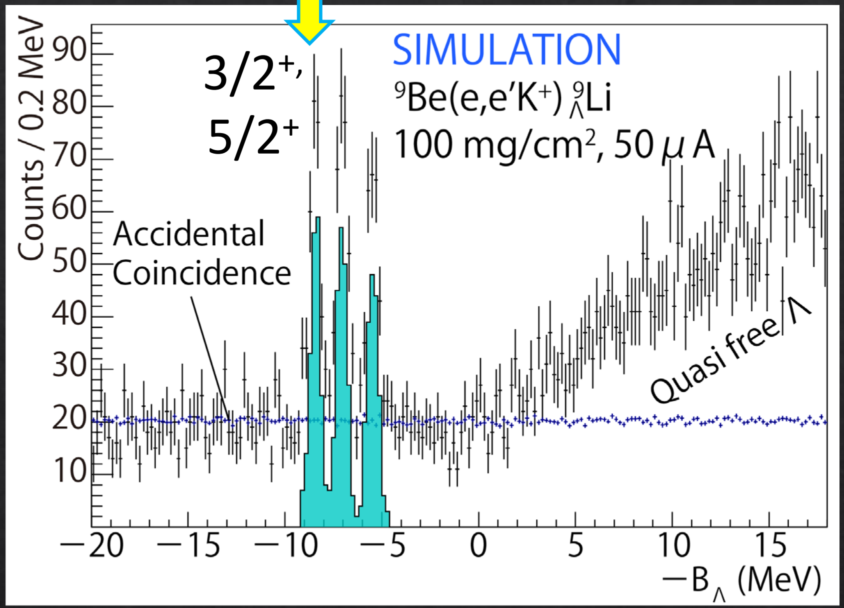
Shell	A	Component	Isospin T<0	Isospin T=0	Isospin T>0	CSB study w/ 100 keV accur.
						Yes / **Yes**
						Yes
						Yes
						Yes
						Yes
	10	α α N Λ	○ (JLab)	-	J-PARC E94	**Yes**
	11	α α N N Λ	This pro.	J-PARC		**Yes**
	12	α α d N Λ	○ (JLab)	-	J-PARC E94	**Yes**

Expected Spectra (JLab E12-24-004)

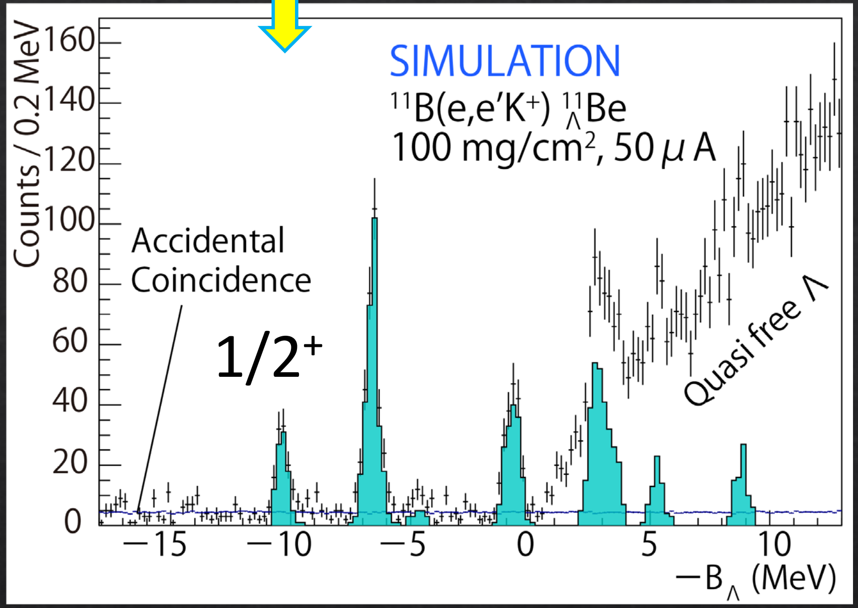
for CSB study 120 hours



for CSB study 384 hours



for CSB study 72 hours

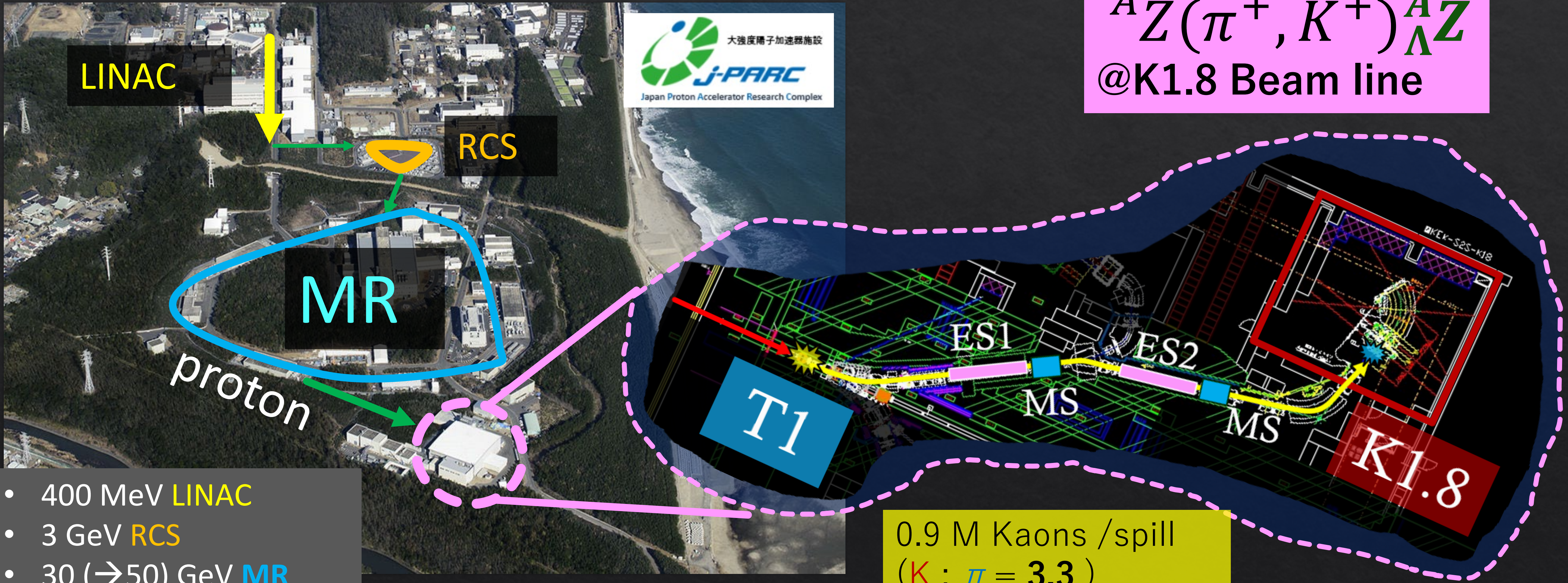


Total accuracy:

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

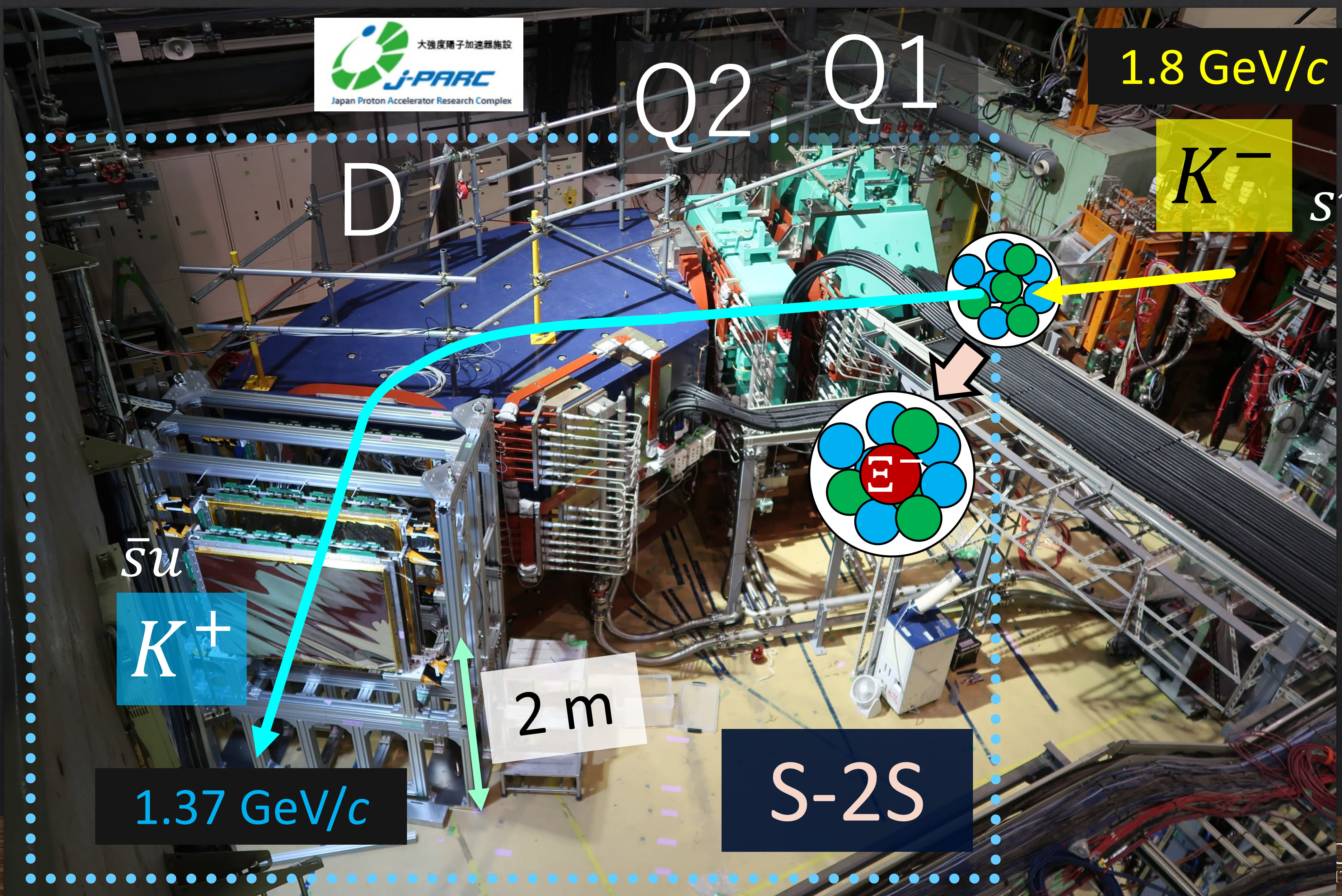
Japan Proton Accelerator Research Complex (J-PARC), Ibaraki, Japan

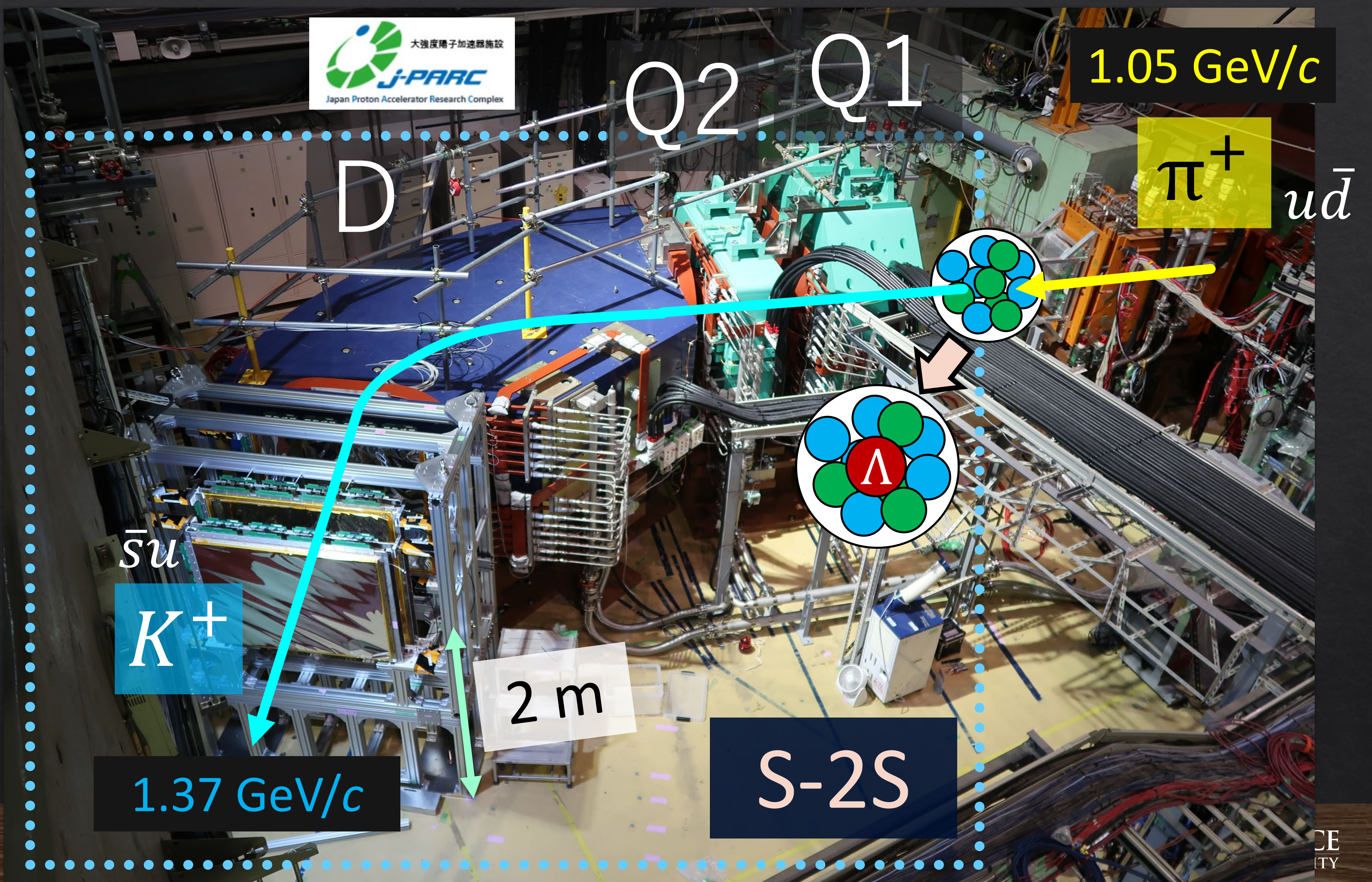
$^{A}Z(\pi^+, K^+)^{A}_{\Lambda}Z$
@K1.8 Beam line



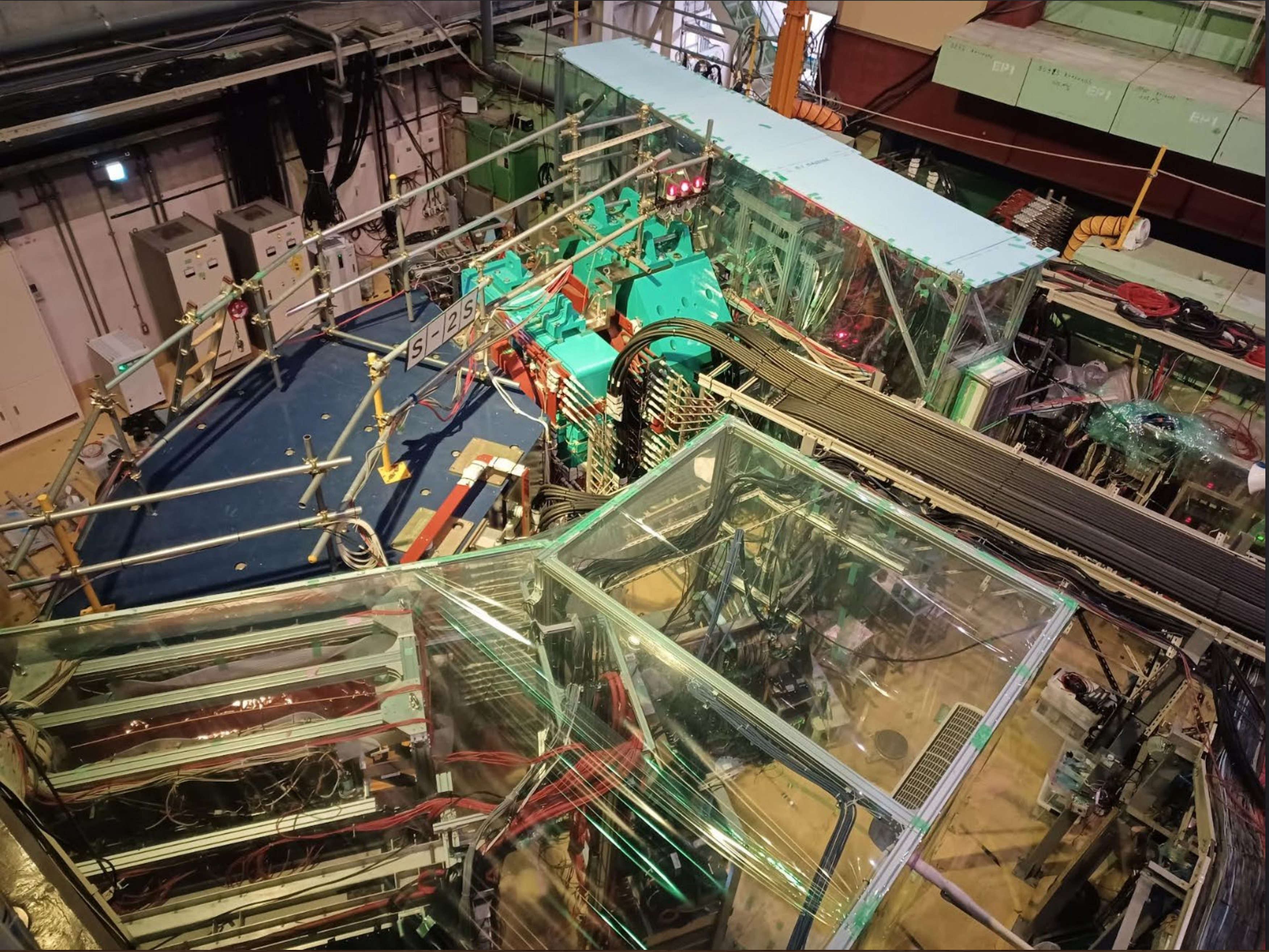
- 400 MeV LINAC
- 3 GeV RCS
- 30 (→50) GeV MR

0.9 M Kaons /spill
(K : π = **3.3**)


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^-
$s\bar{u}$
Ξ^-
$\bar{s}u$
K^+
2 m
1.37 GeV/c
S-2S



大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex
Q2
Q1
D
1.05 GeV/c
π^+
$u\bar{d}$
Λ
$\bar{s}u$
K^+
2 m
1.37 GeV/c
S-2S

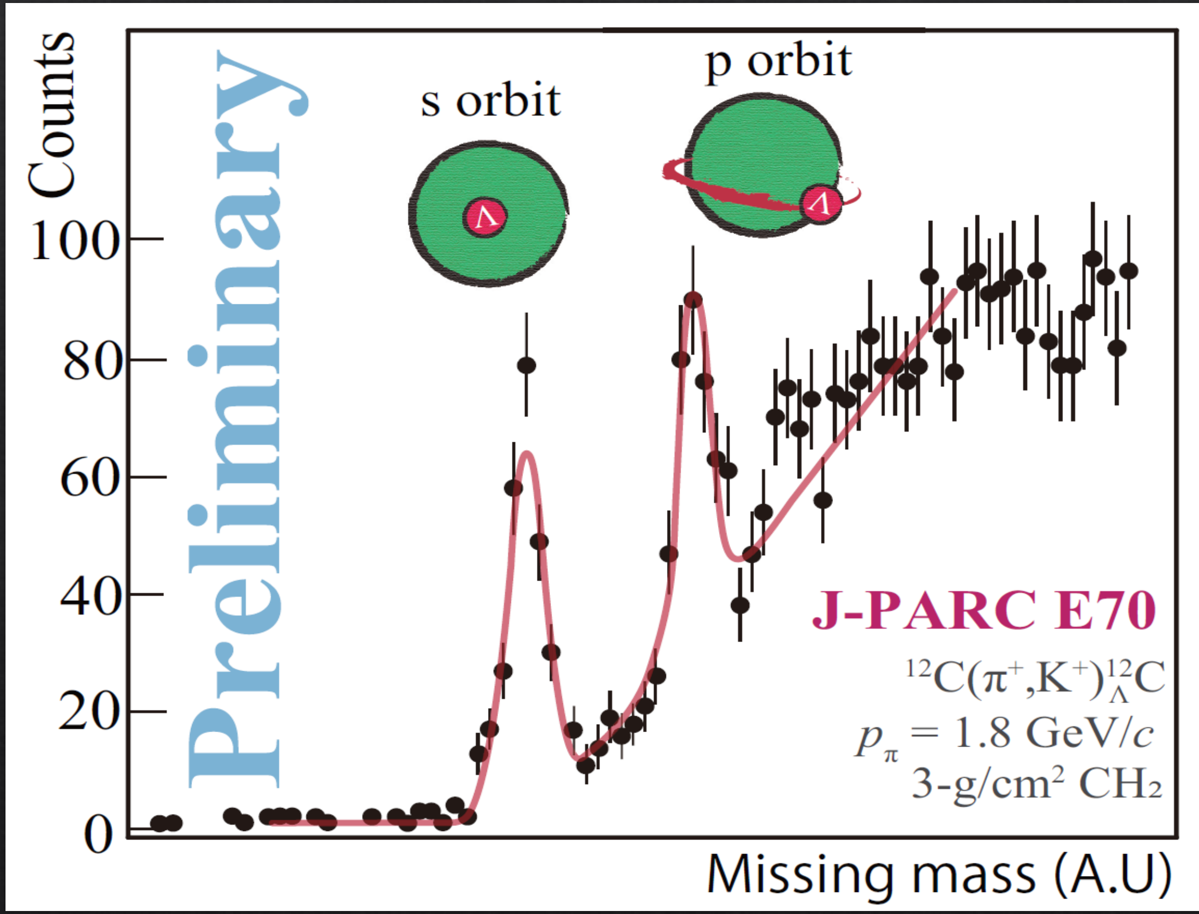


J-PARC E70 experiment
(Ξ hypernuclear spectroscopy)
is being carried out now!

2023.6 commissioning
2024.4—6 commissioning
2025.1—2 comm. + calib.
2025.4—5 Physics data

0.9M K^-/spill
(K:π = 3.3)

Preliminary (π^+,K^+) data



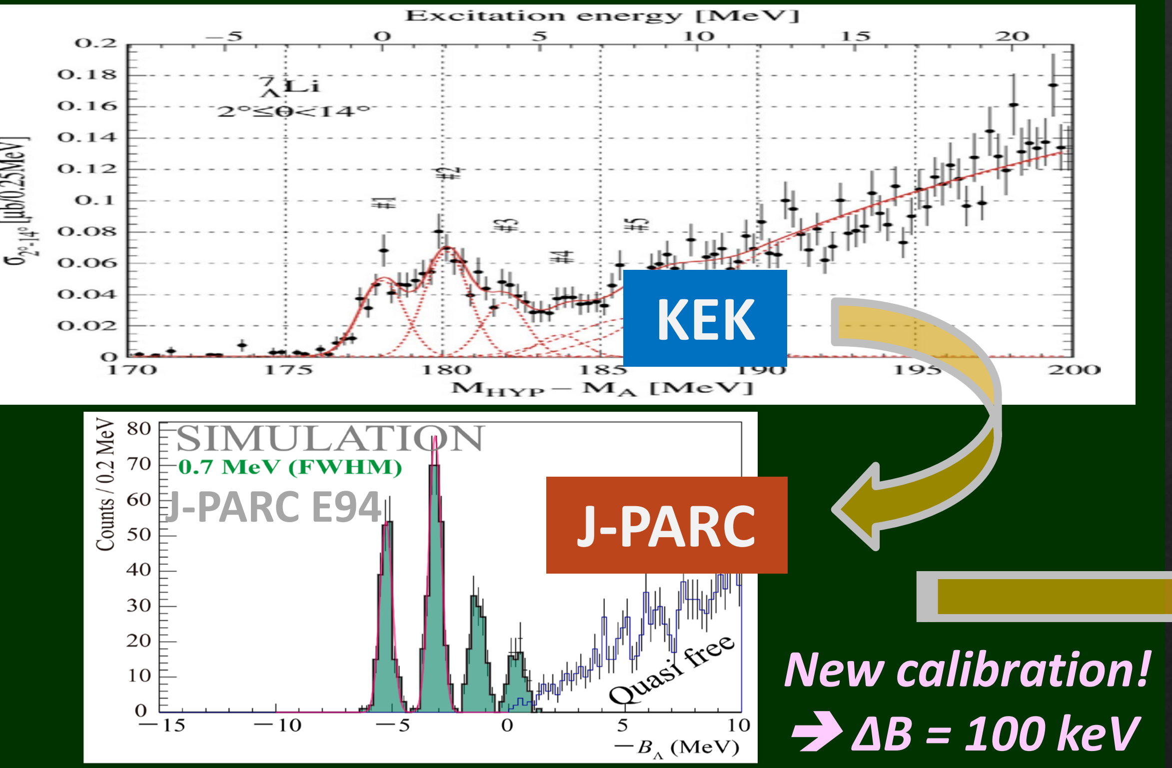
High resolution spectroscopy by π beam which is **complementary with JLab experiments** is promising

➔ Opened new era for studying CSB / isospin dependent interaction!

CSB study by J-PARC and JLab data

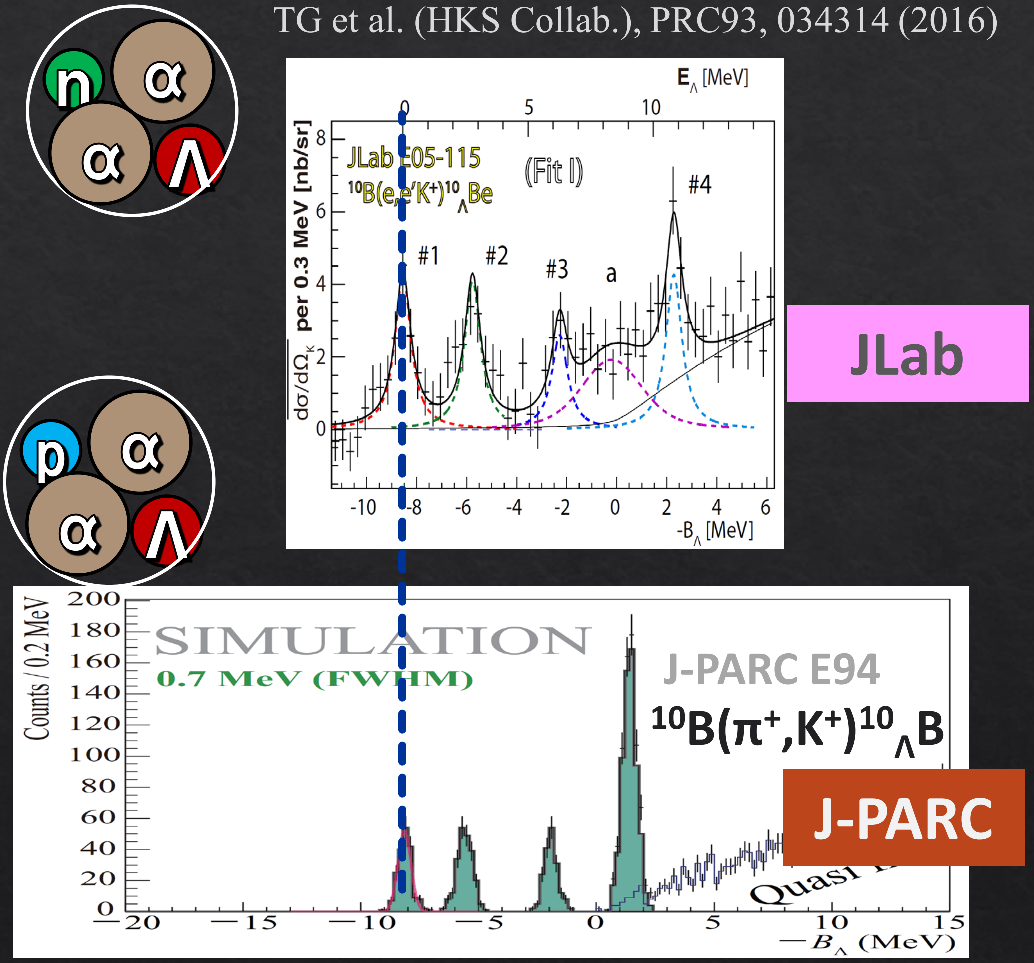
$^{7}Li(\pi^{+},K^{+})^{7}{}_{\Lambda}Li$

https://doi.org/10.1016/j.ppnp.2005.07.001



New calibration!
➔ ΔB = 100 keV

TG et al. (HKS Collab.), PRC93, 034314 (2016)



Summary

Hypernuclear research

- The most important tool to investigate strange baryonic interaction
- Various features (production, energy levels, decay) are investigated in the world
- Missing mass spectroscopy at JLab and J-PARC is unique
  - High resolution / High Accuracy / Wide mass range ➔ CSB, Multi-body force etc.

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

- $(e, e'K^+)$ reaction at $\omega = 1.5$ GeV
- ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{6}_{\Lambda}\mathrm{He}$, ${}^{9}_{\Lambda}\mathrm{Li}$, ${}^{11}_{\Lambda}\mathrm{Be}$, ${}^{27}_{\Lambda}\mathrm{Mg}$, ${}^{40}_{\Lambda}\mathrm{K}$, ${}^{48}_{\Lambda}\mathrm{K}$, ${}^{208}_{\Lambda}\mathrm{Tl}$ ➔ 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
- ${}^{6}_{\Lambda}\mathrm{Li}$, ${}^{10}_{\Lambda}\mathrm{B}$, ${}^{12}_{\Lambda}\mathrm{C}$, ${}^{7}_{\Xi}\mathrm{H}$, ${}^{12}_{\Xi}\mathrm{Be}$ ➔ ΛN CSB, ΞN interaction

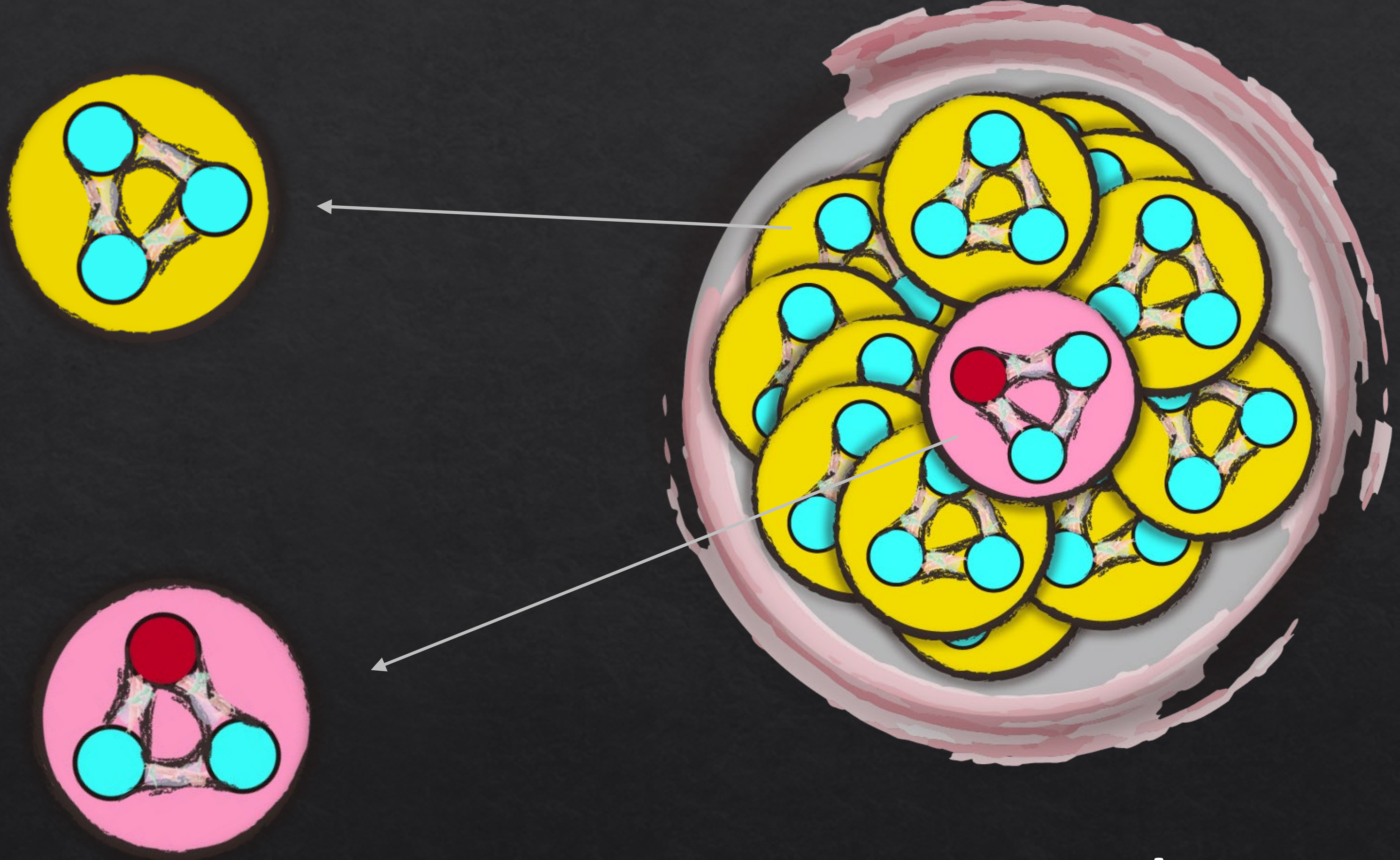
Thank you for your attention

Hitachi Seaside Park, Ibaraki, Japan

Hypernucleus

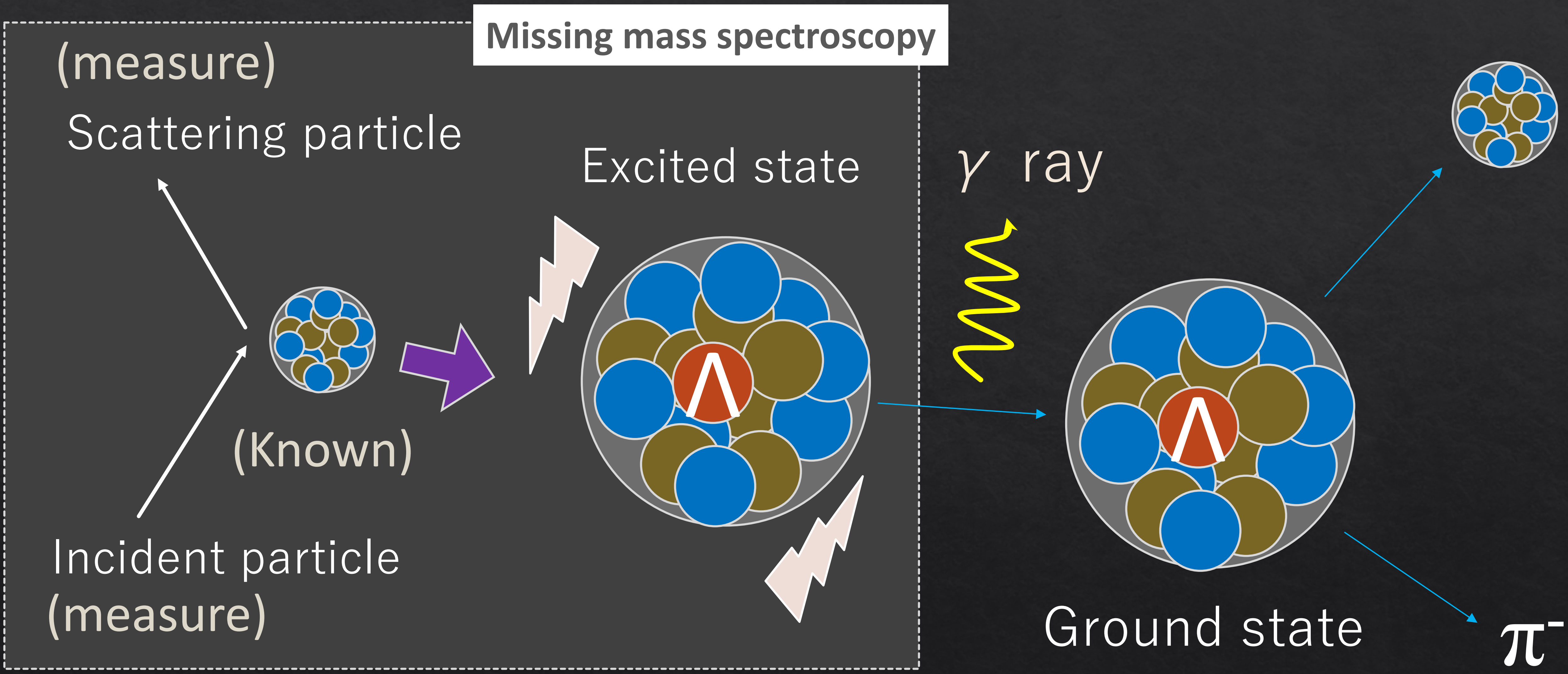
Nucleon
only up, down quarks

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

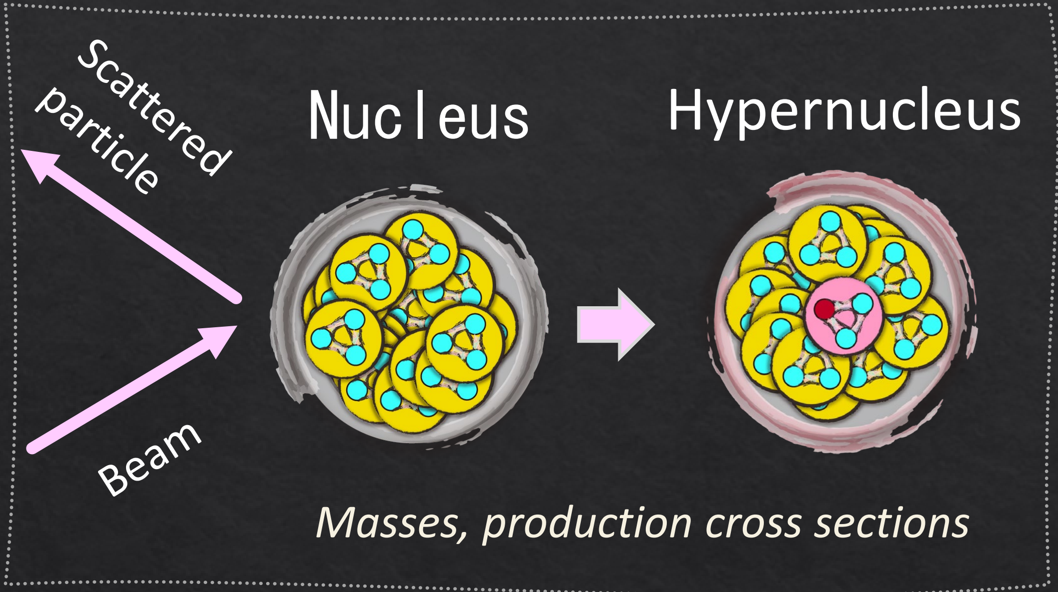


Hypernucleus

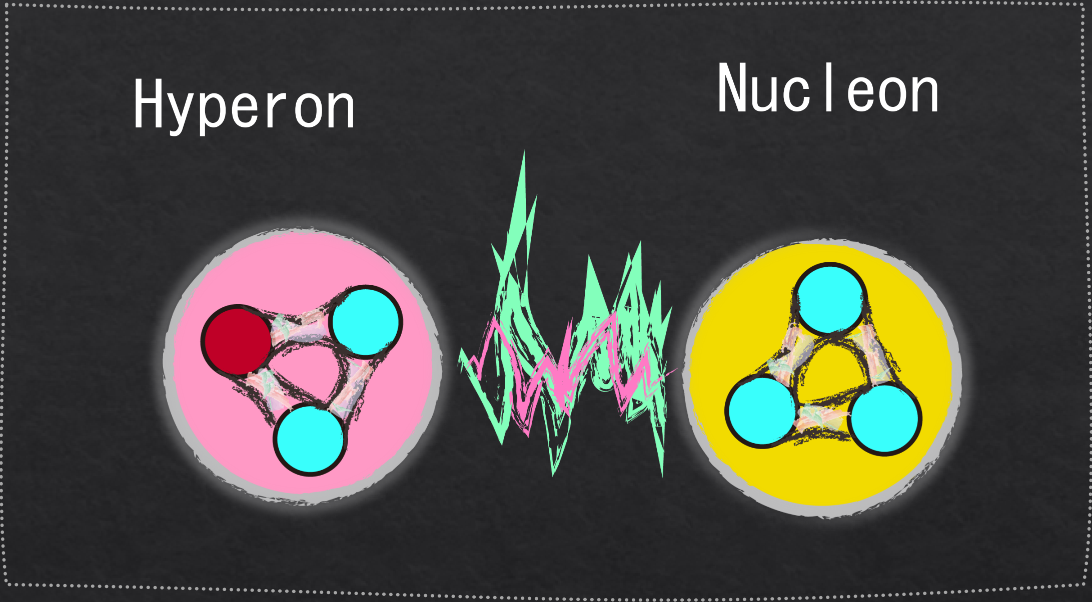
The mass at the moment of production



Baryon interaction study through hypernuclei



Analysis



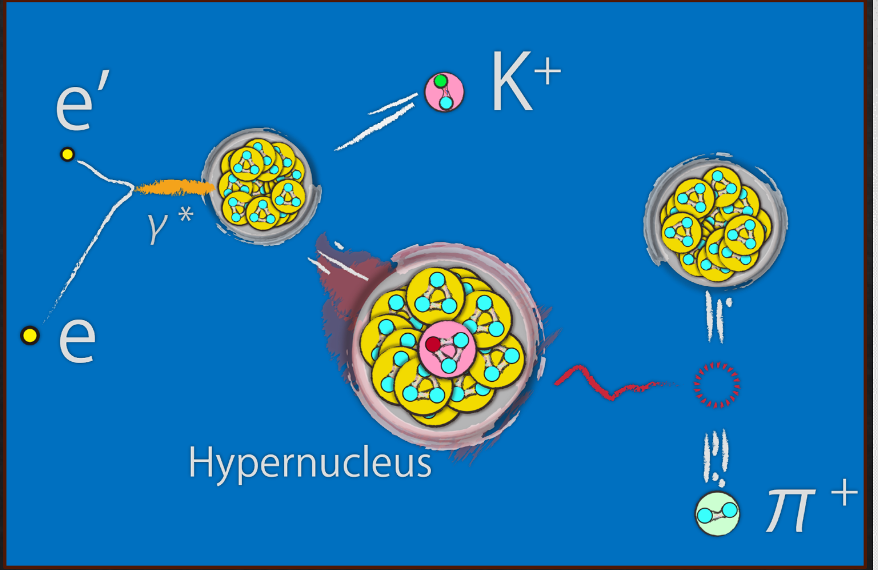
➔ Hyperon(Y)–nucleon(N) interaction

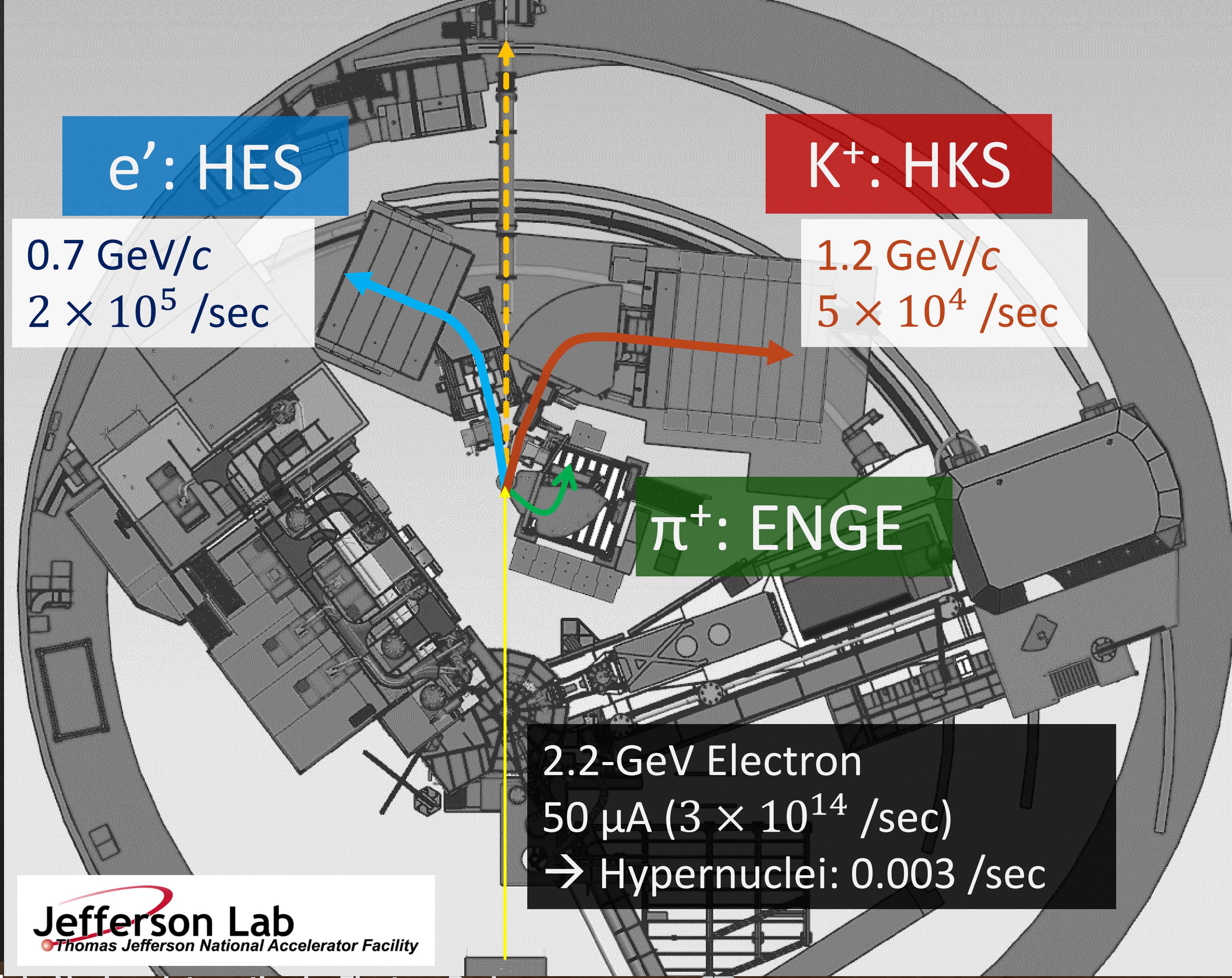
➔ More general baryon–baryon interaction

➔ Plenary talk by **A. Gal** on Mar 30

New experiment at JLab Hall-C (2027～)

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





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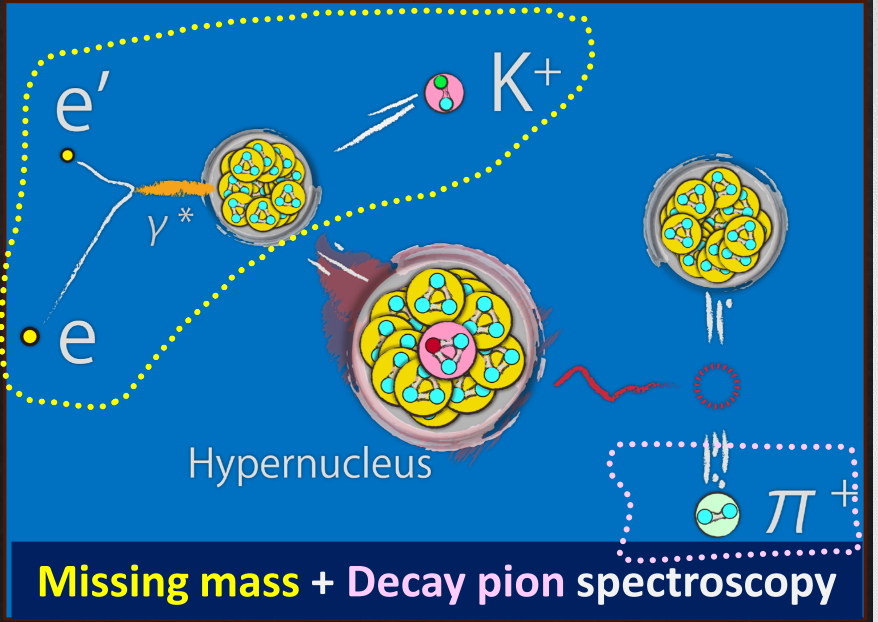
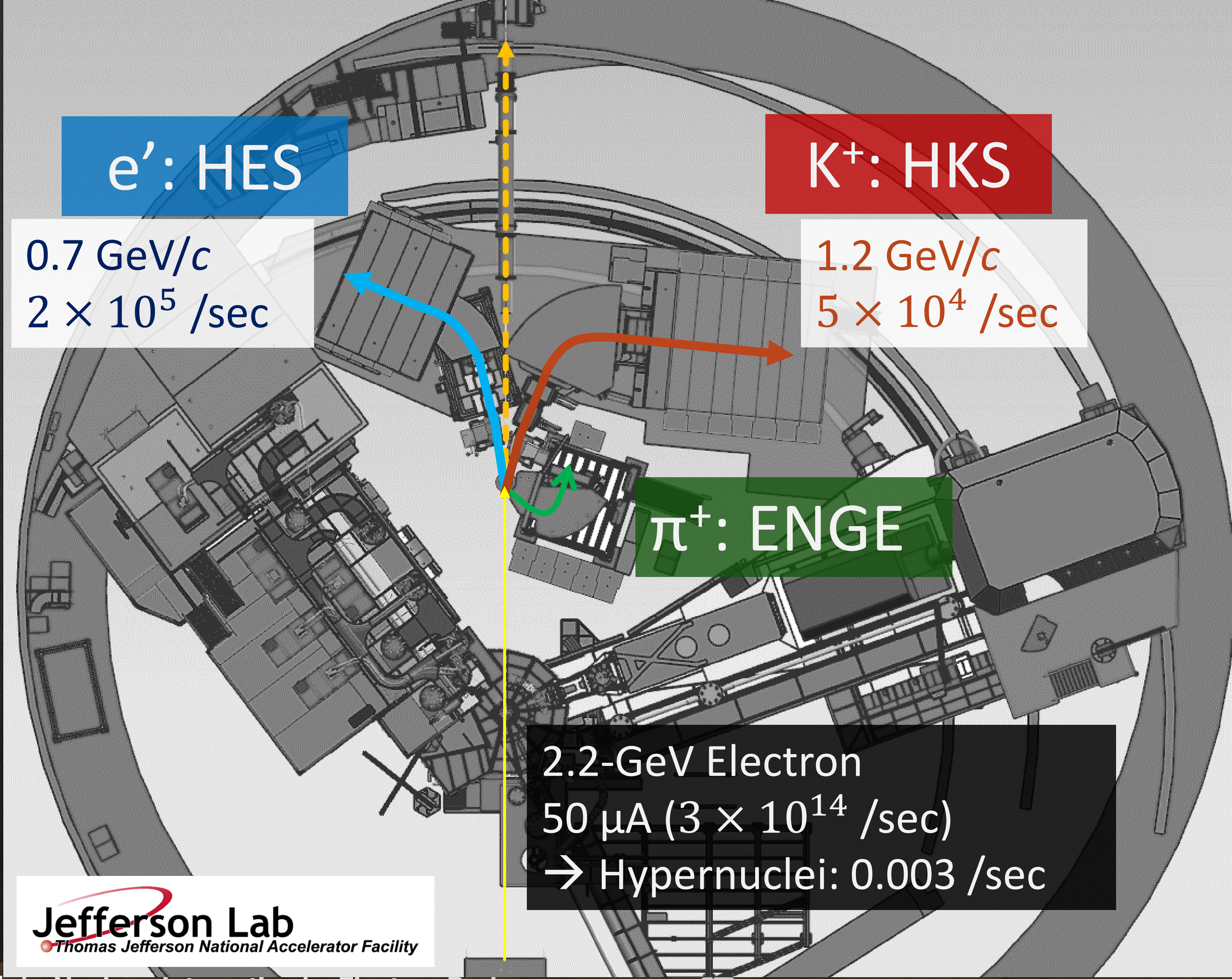
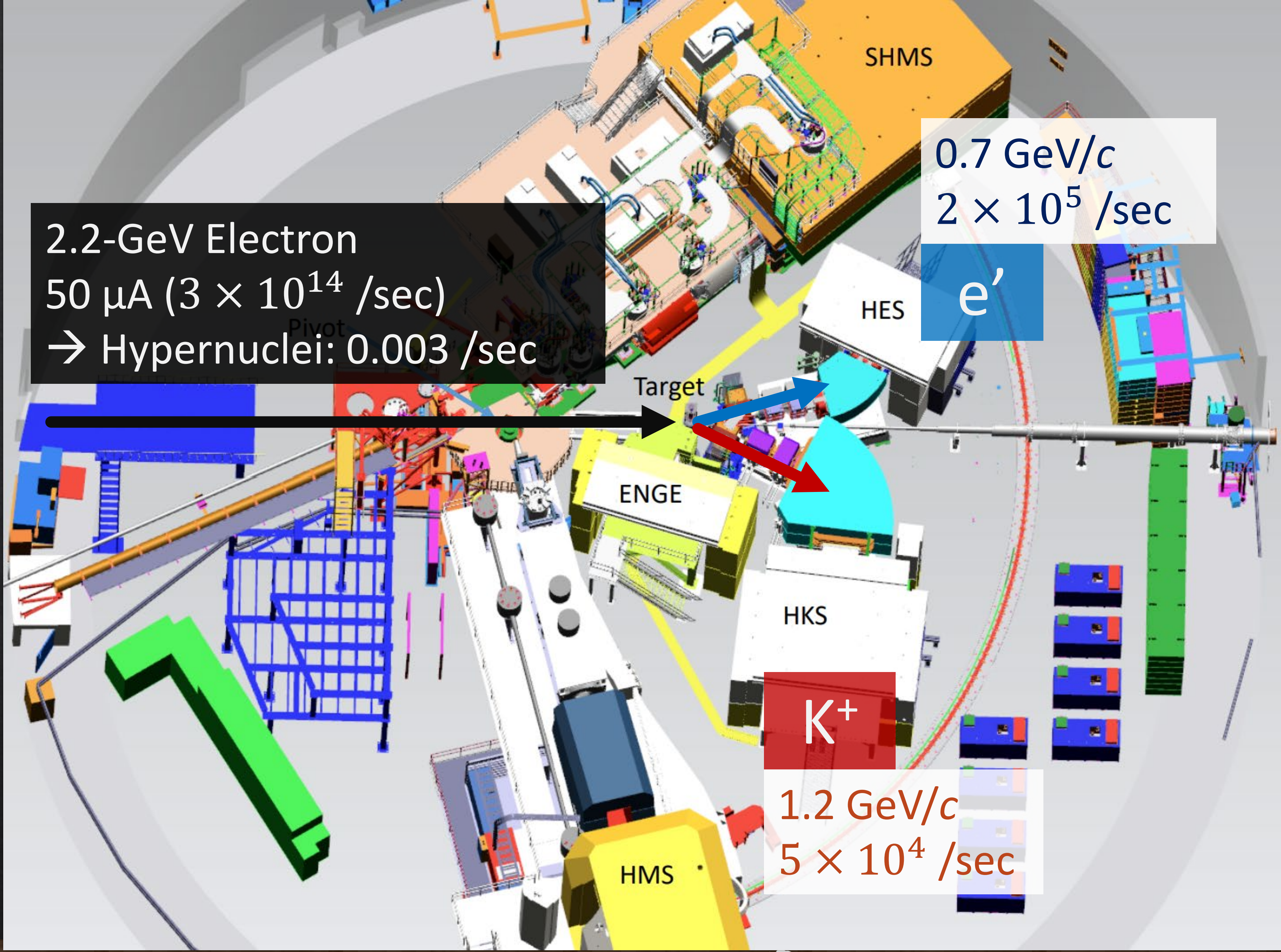


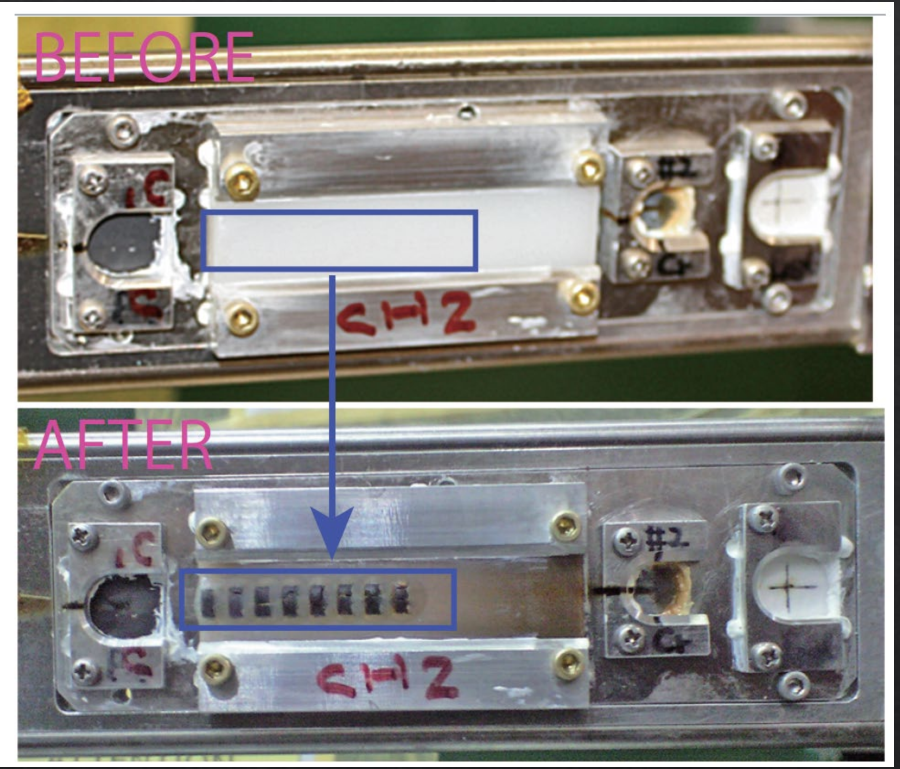


Experimental setup

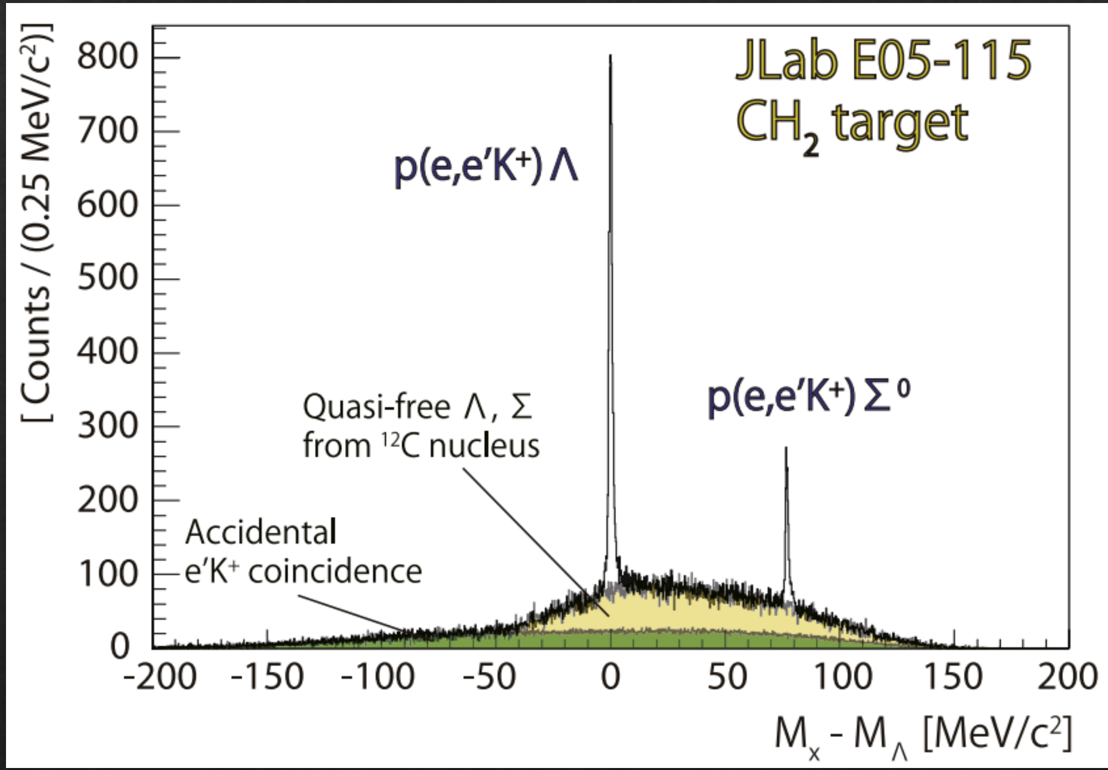
- High resolution: 0.6 MeV FWHM
- High accuracy: 0.07 MeV
- Wide mass number: A = 6—208



Energy Calibration (example from JLab E05-115)



TG et al., NIMA 900, 69—83 (2018)



➔ High accuracy spectroscopy is passible

Approved Hypernuclear Experiments (proposed by JLab Hypernuclear Collaboration)

① E12-15-008 → ${}^{40}_{\Lambda}$K、${}^{48}_{\Lambda}$K
"Isospin dependence of ΛN interaction"

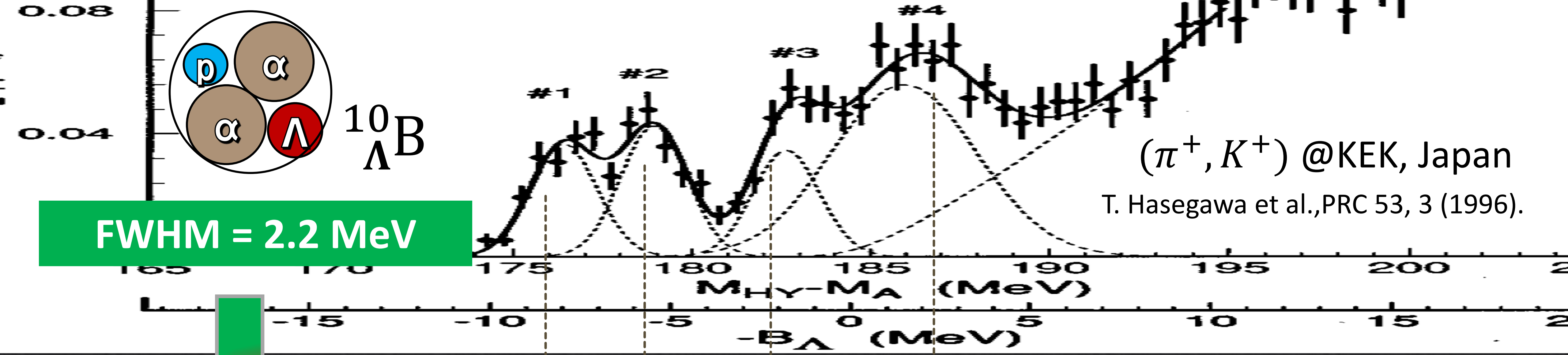
② E12-19-002 → ${}^{3}_{\Lambda}$H、${}^{4}_{\Lambda}$H
"Hypertriton puzzle, s-shell CSB"

③ E12-20-013 → ${}^{208}_{\Lambda}$Tl
"ΛNN three body force"

④ E12-24-004 → ${}^{6}_{\Lambda}$He、${}^{9}_{\Lambda}$Li、${}^{11}_{\Lambda}$Be
"p-shell CSB"

⑤ E12-24-011 → ${}^{27}_{\Lambda}$Mg
" Search for triaxially deformation states in ^{26}Mg"

⑥ Run group experiment (E12-15-008A):
Decay-pion spectroscopy

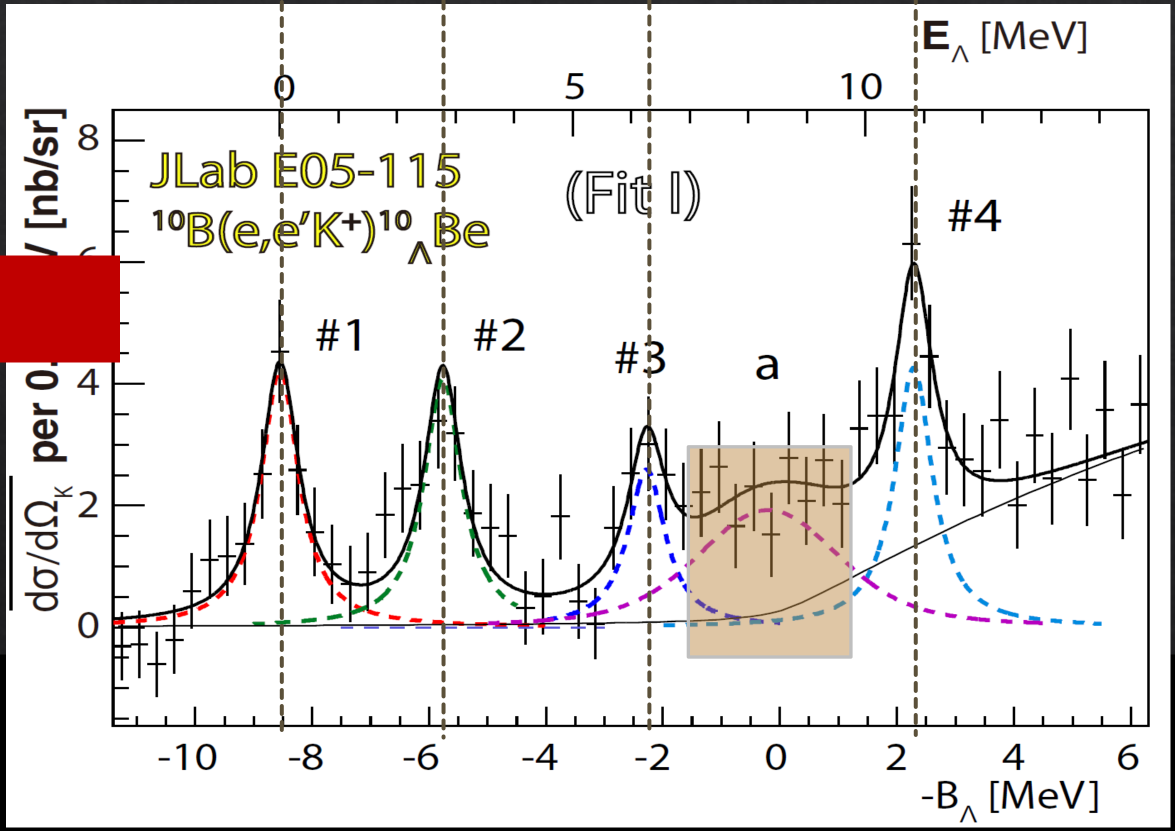


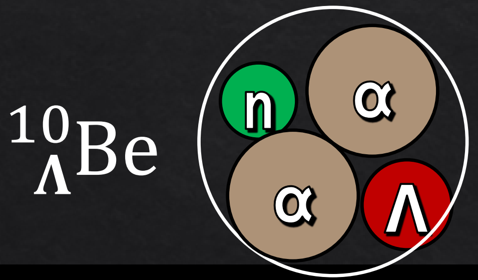
(π^+, K^+) @KEK, Japan

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

FWHM = 2.2 MeV

FWHM = 0.8 MeV

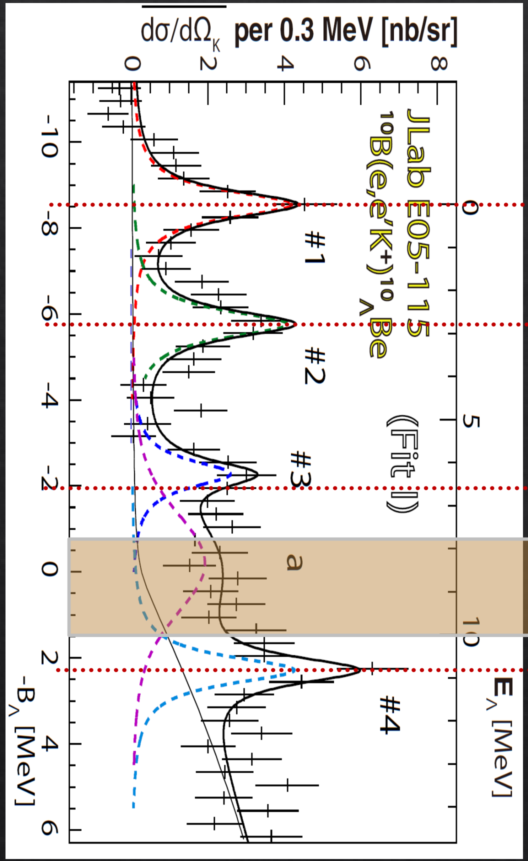




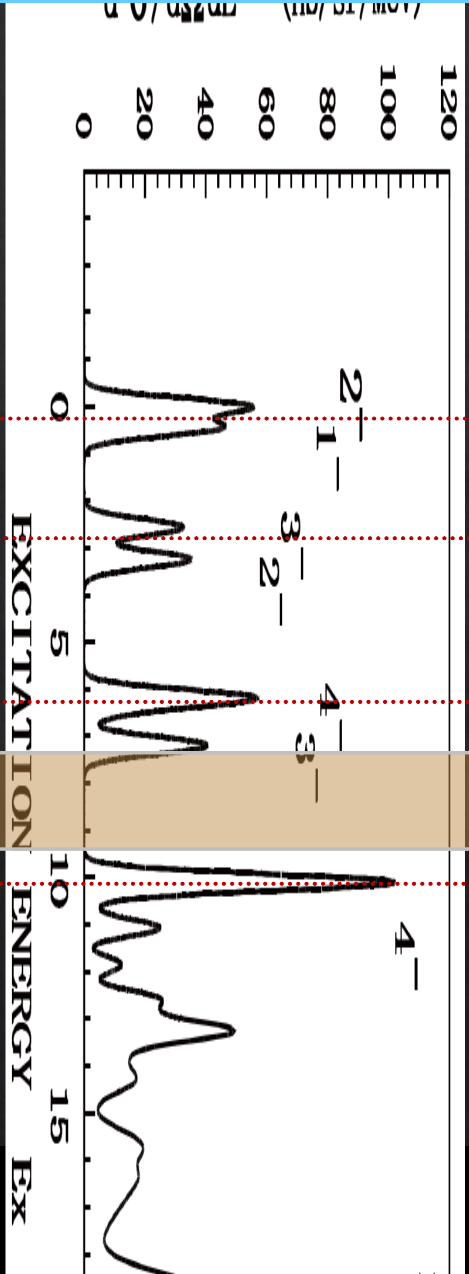
TG et al.,
PRC 93, 034314 (2016).

New finding from improved precision

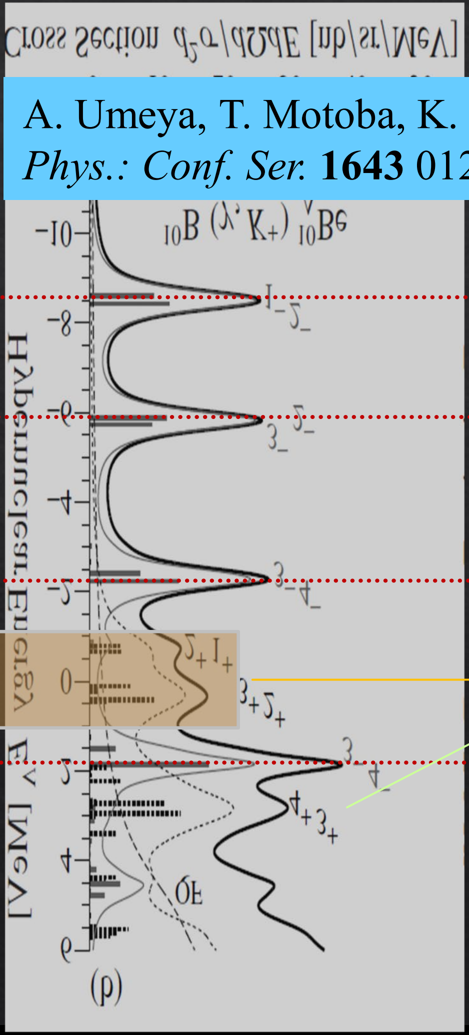
DATA
(TG et al., PRC93, 034314 (2016))



T. Motoba, P. Bydzovsky, M. Sotona, K. Itonaga, PTP Suppl. 185 (2010)



A. Umeya, T. Motoba, K. Itonaga, *J. Phys.: Conf. Ser.* **1643** 012110 (2020)



$J_C^- \otimes s_\Lambda$

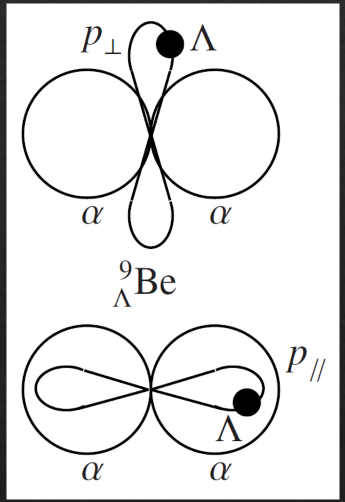
$J_C^- \otimes s_\Lambda$

$J_C^- \otimes s_\Lambda$

$J_C^- \otimes s_\Lambda$

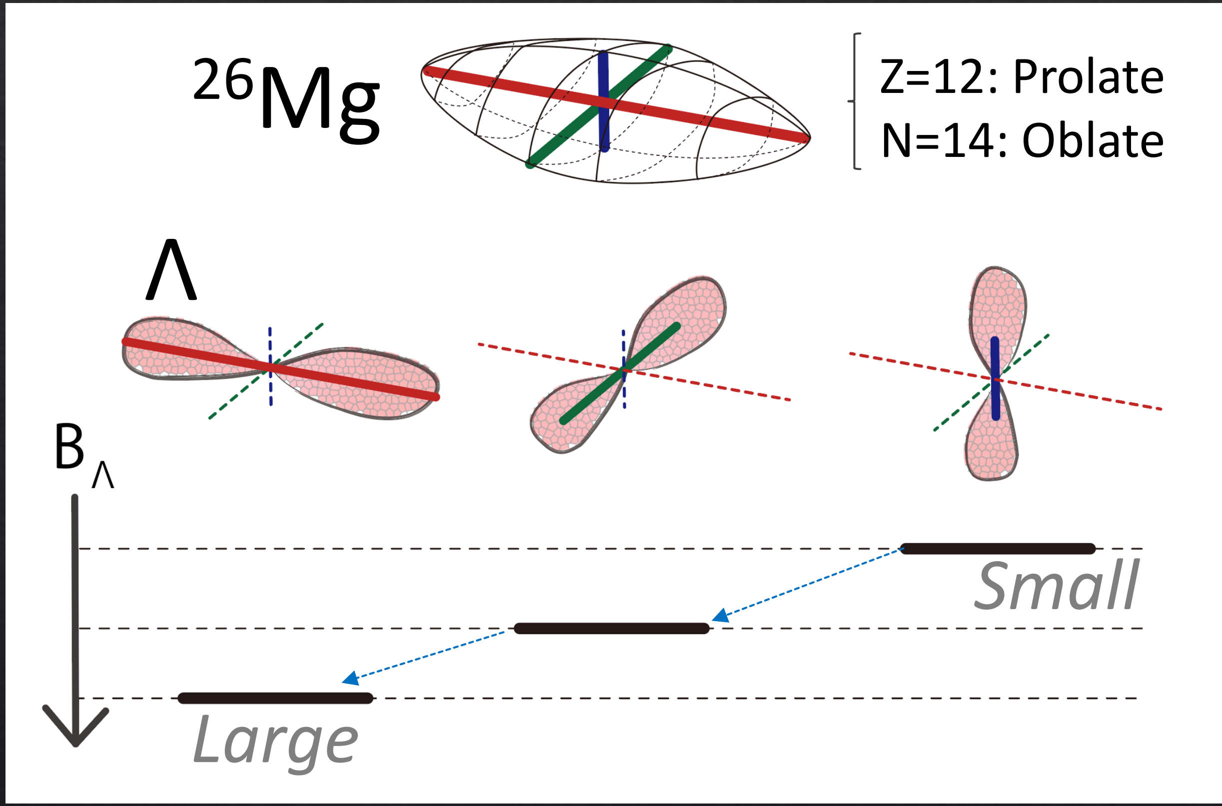
$J_C^- \otimes p_\Lambda$

α - α structure splits p_Λ state

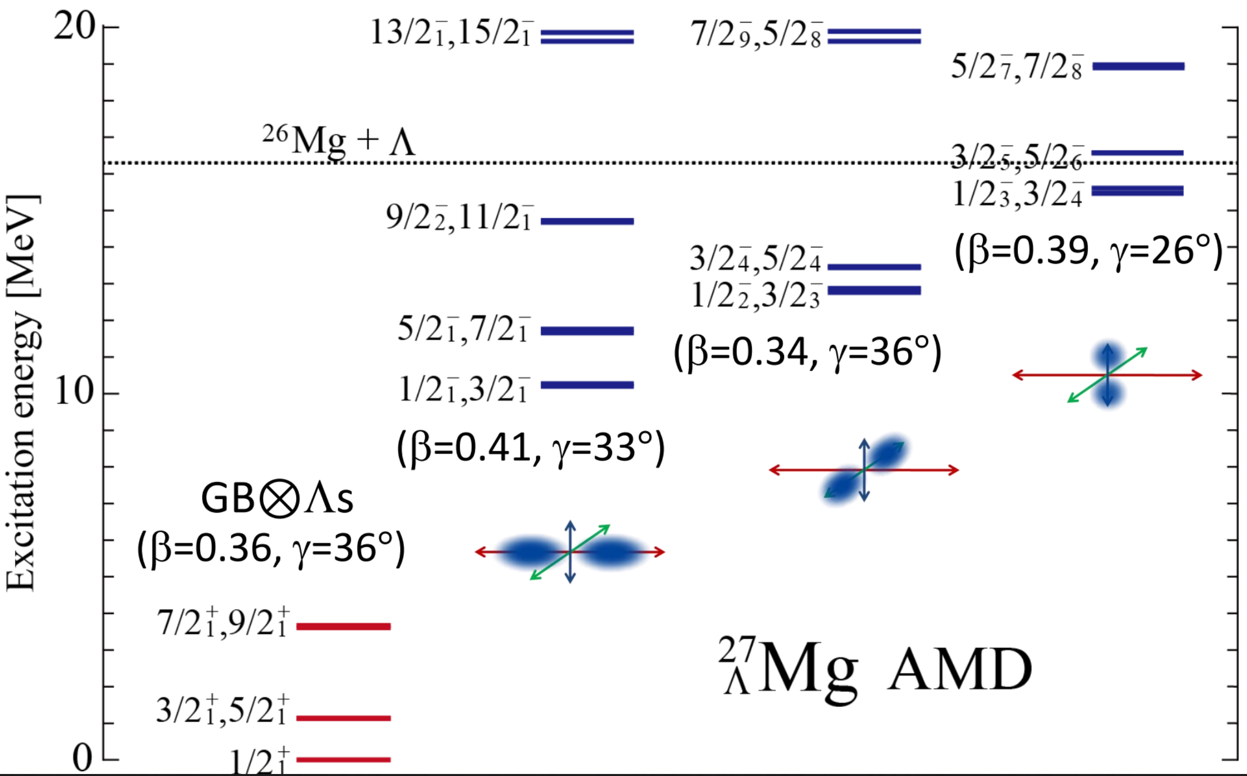


c.f.)
A. Umeya, T. Motoba, K. Itonaga, EPJ Web Conf. 271, 01010 (2022)

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



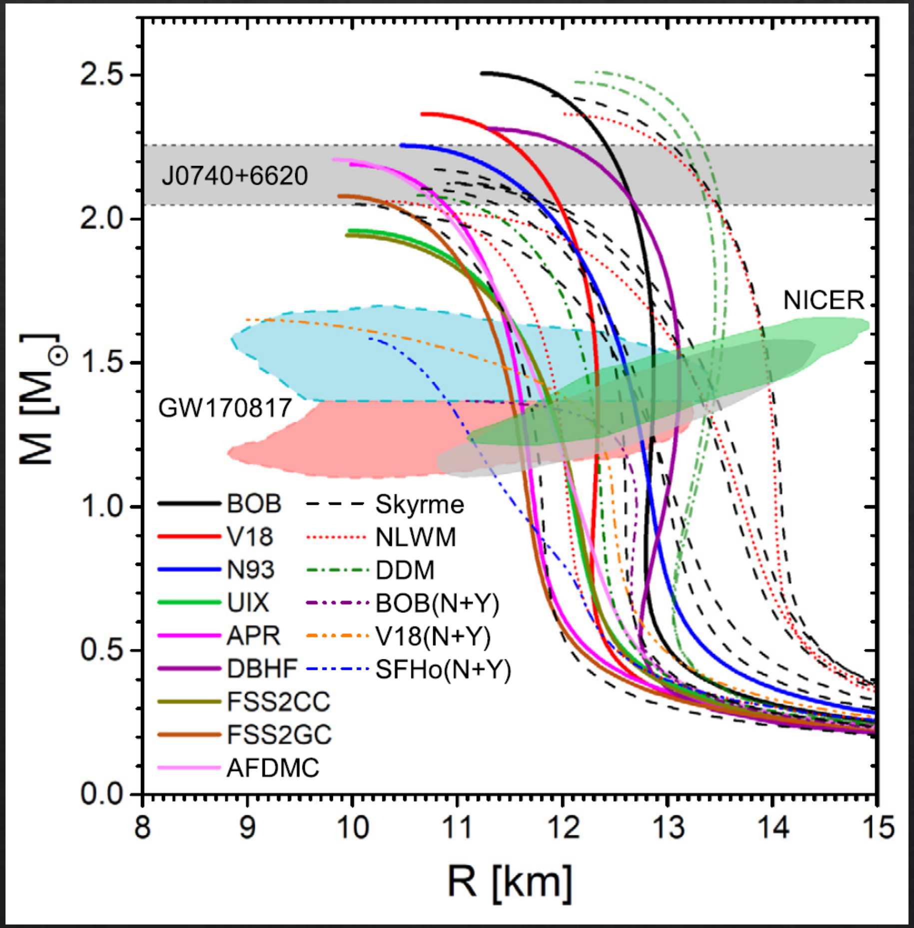
Anti-molecular dynamics (AMD) calculation
Presentation by M. Isaka (2023); https://indico.jlab.org/event/705/

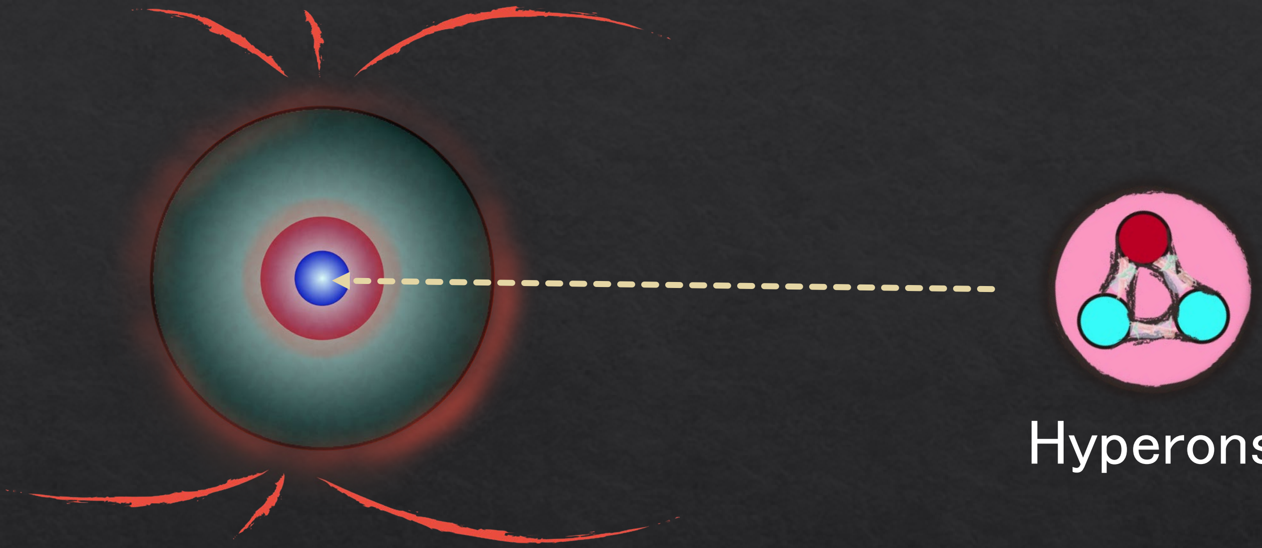


$^{26}\mathrm{Mg} \times p_\Lambda$ ➔ Probing triaxially deformation

New constrains from astronomical observations

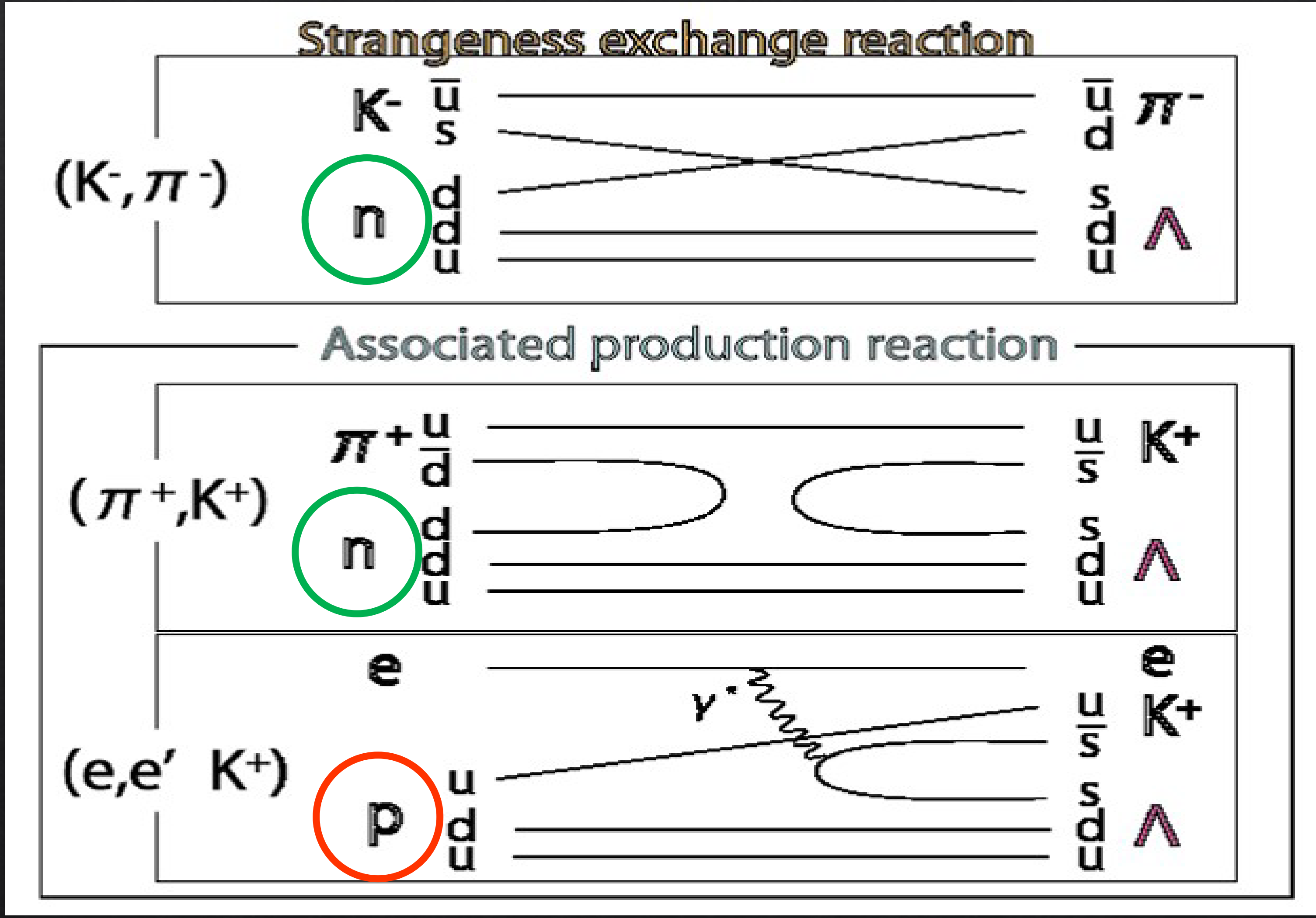
C.F. Burgio et al. Prog. Part. Nucl. Phys 120 (2021) 103879.





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

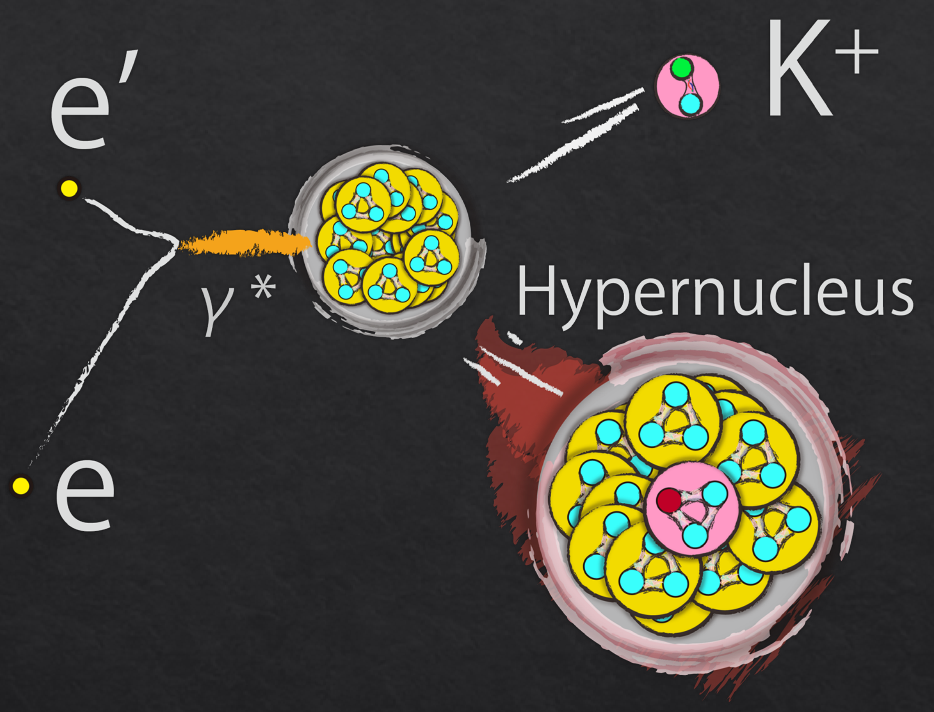
Reactions used at J-PARC and JLab



Hadron Beams
@J-PARC, Japan

Electron Beams
@JLab, US

Missing-mass spectroscopy at JLab



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

To be measured

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

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

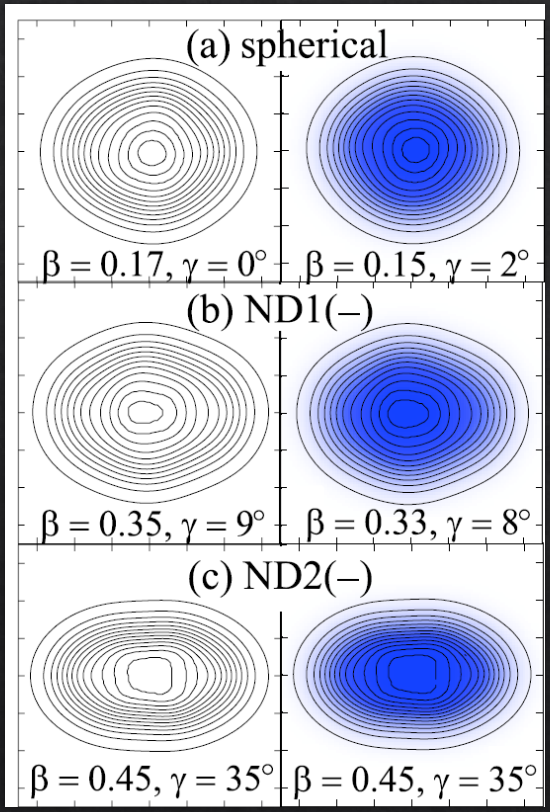
Primary beam
- High precision / small emittance GOOD
- High intensity → thin target GOOD
  (→ High energy resolution)

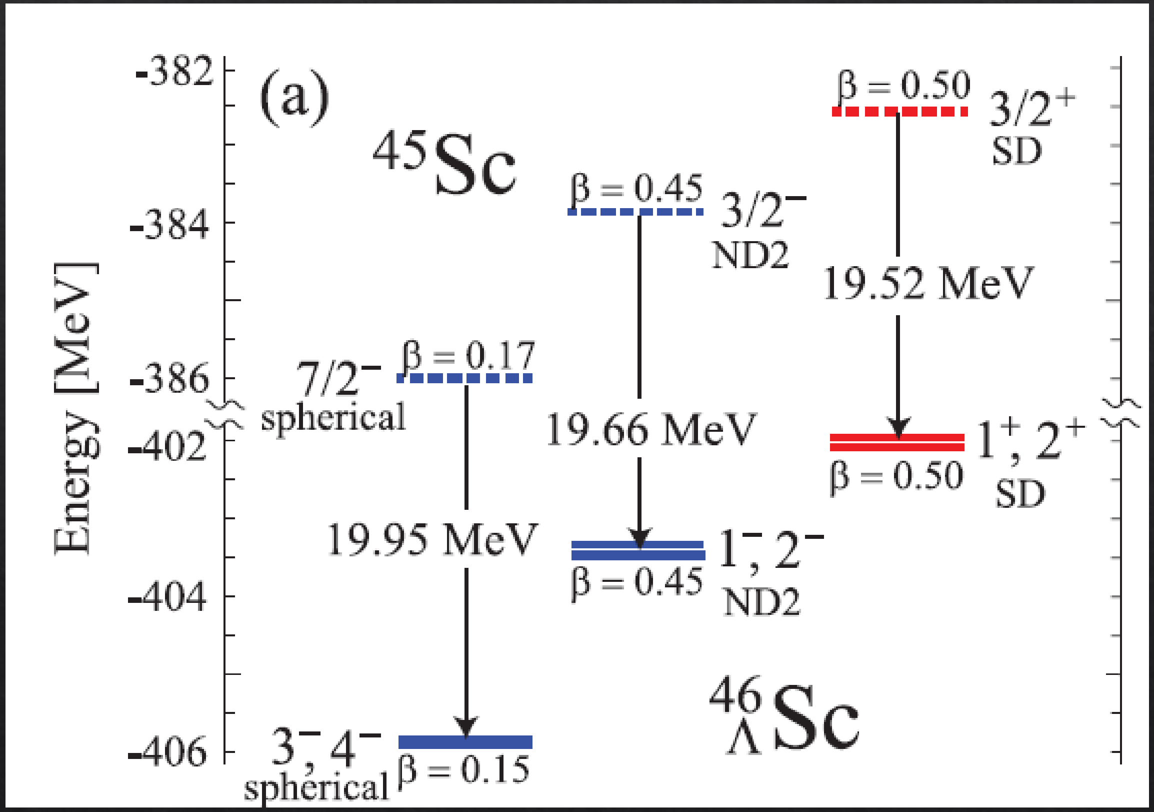
Virtual photo production
→ Large spin flip amplitude GOOD Bad

p → Λ
GOOD
→ Good calibration with proton target
→ Mirror Hypernuclear study GOOD

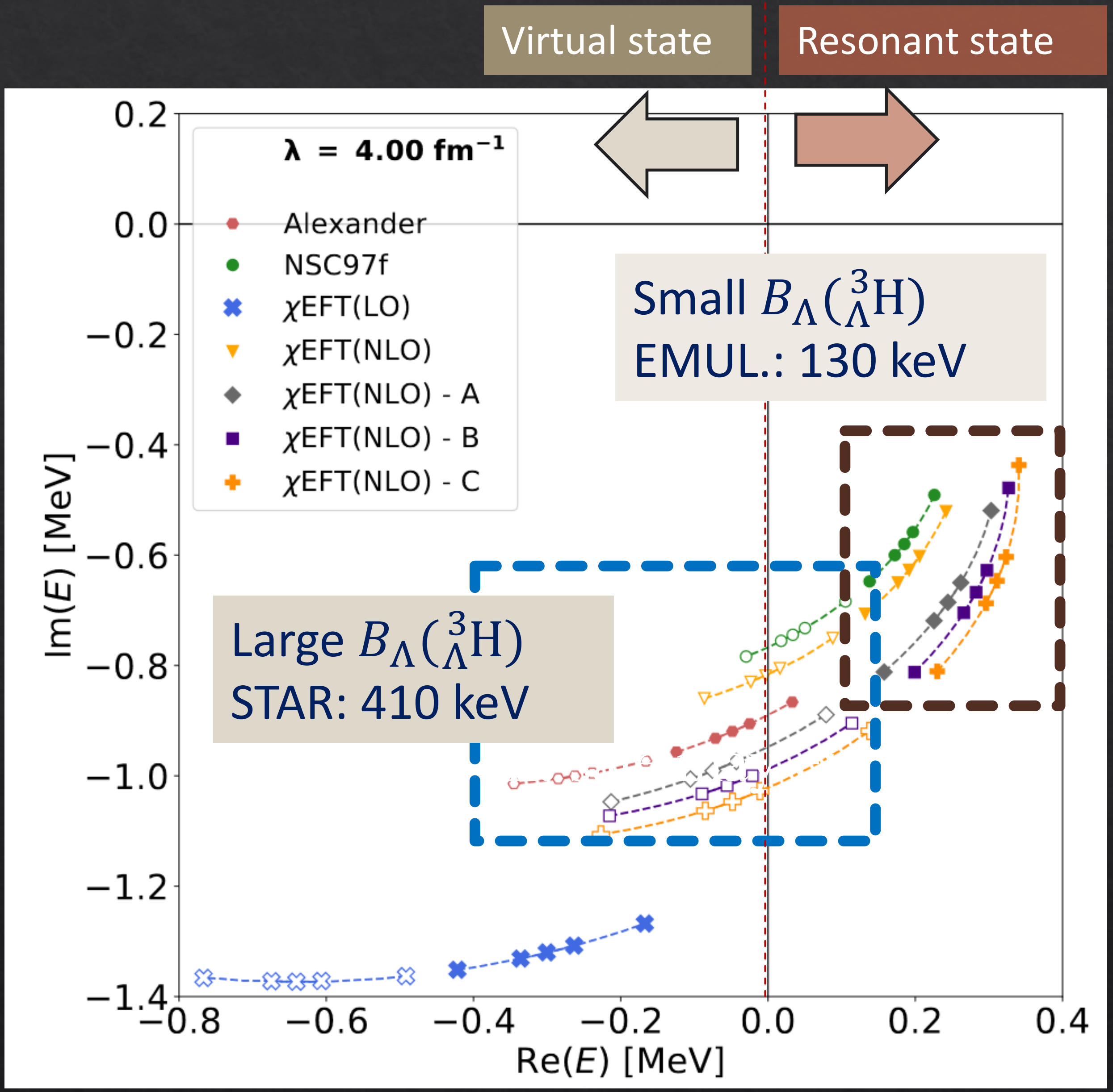
$^{46}\mathrm{Ti}(e,e'K^+)^{46}_{\Lambda}\mathrm{Sc}$

M. Isaka et al., PRC **89**, 024310 (2014)





Less bound as the core is more deformed due to smaller overlap between core and Λ



M. Schäfer et al., PRC 105, 015202 (2022)

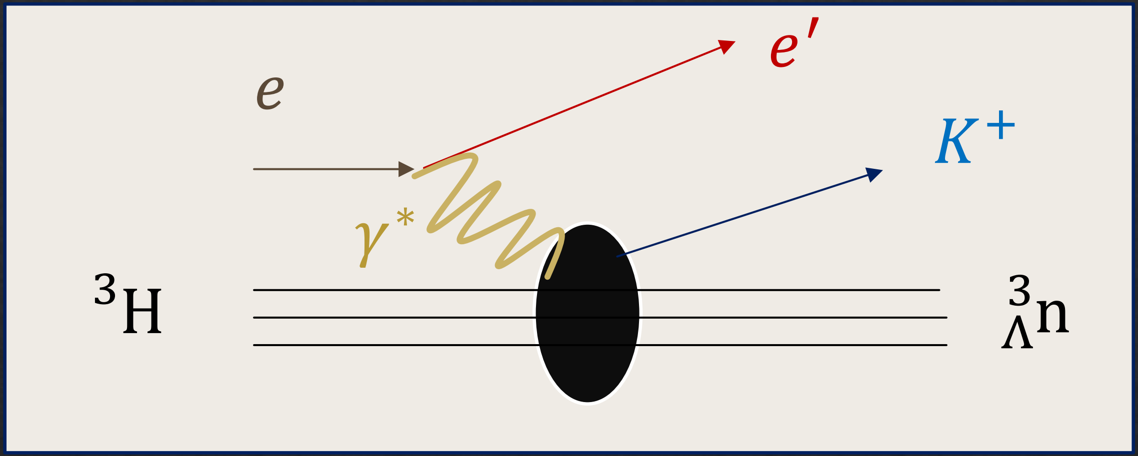
Resonant nnΛ state

nnΛ

- ✓ Resonant state may exist
- ✓ Energy + width → nΛ Interaction
- ✓ Strongly related to $B_\Lambda(^3_\Lambda\mathrm{H})$

  → E12-19-002 (HKS)

(e,e'K$^+$) reaction spectroscopy in 2018



Unti-strange quark

Strange quark

Missing-mass measurement at JLab

➔ **Sensitive to both bound and resonant states !!**

c.f.) Invariant mass spectroscopy is sensitive to only bound state

- ✓ HRS-HRS @ Hall A
- ✓ Tritium target
- ✓ (e,e'K$^+$)
- ✓ Oct—Nov 2018

Recent related paper
→ K. Okuyama et al., PRC 110, 025203 (2024)

PTEP Progress of Theoretical and Experimental Physics
JPS The Physical Society of Japan

The cross-section measurement for the ^{3}H(e, $e'K^+$)$nn\Lambda$ reaction

K N Suzuki ✉, T Gogami, B Pandey, K Itabashi, S Nagao, K Okuyama, S N Nakamura, L Tang, D Abrams, T Akiyama, D Androic, K Aniol, C Ayerbe Gayoso, J Bane, S Barcus, J Barrow, V Bellini, H Bhatt, D Bhetuwal, D Biswas, A Camsonne, J Castellanos, J-P Chen, J Chen, S Covrig, D Chrisman, R Cruz-Torres, R Das, E Fuchey, K Gnanvo, F Garibaldi, T Gautam, J Gomez, P Gueye, T J Hague, O Hansen, W Henry, F Hauenstein, D W Higinbotham, C E Hyde, M Kaneta, C Keppel, T Kutz, N Lashley-Colthirst, S Li, H Liu, J Mammei, P Markowitz, R E McClellan, F Meddi, D Meekins, R Michaels, M Mihovilovič, A Moyer, D Nguyen, M Nycz, V Owen, C Palatchi, S Park, T Petkovic, S Premathilake, P E Reimer, J Reinhold, S Riordan, V Rodriguez, C Samanta, S N Santiesteban, B Sawatzky, S Širca, K Slifer, T Su, Y Tian, Y Toyama, K Uehara, G M Urciuoli, D Votaw, J Williamson, B Wojtsekhowski, S A Wood, B Yale, Z Ye, J Zhang, X Zheng

Progress of Theoretical and Experimental Physics, Volume 2022, Issue 1, January 2022, 013D01, https://doi.org/10.1093/ptep/ptab158

Published: 06 December 2021 **Article history** ▾

https://doi.org/10.1093/ptep/ptab158 *(see also here)*

PHYSICAL REVIEW C
covering nuclear physics

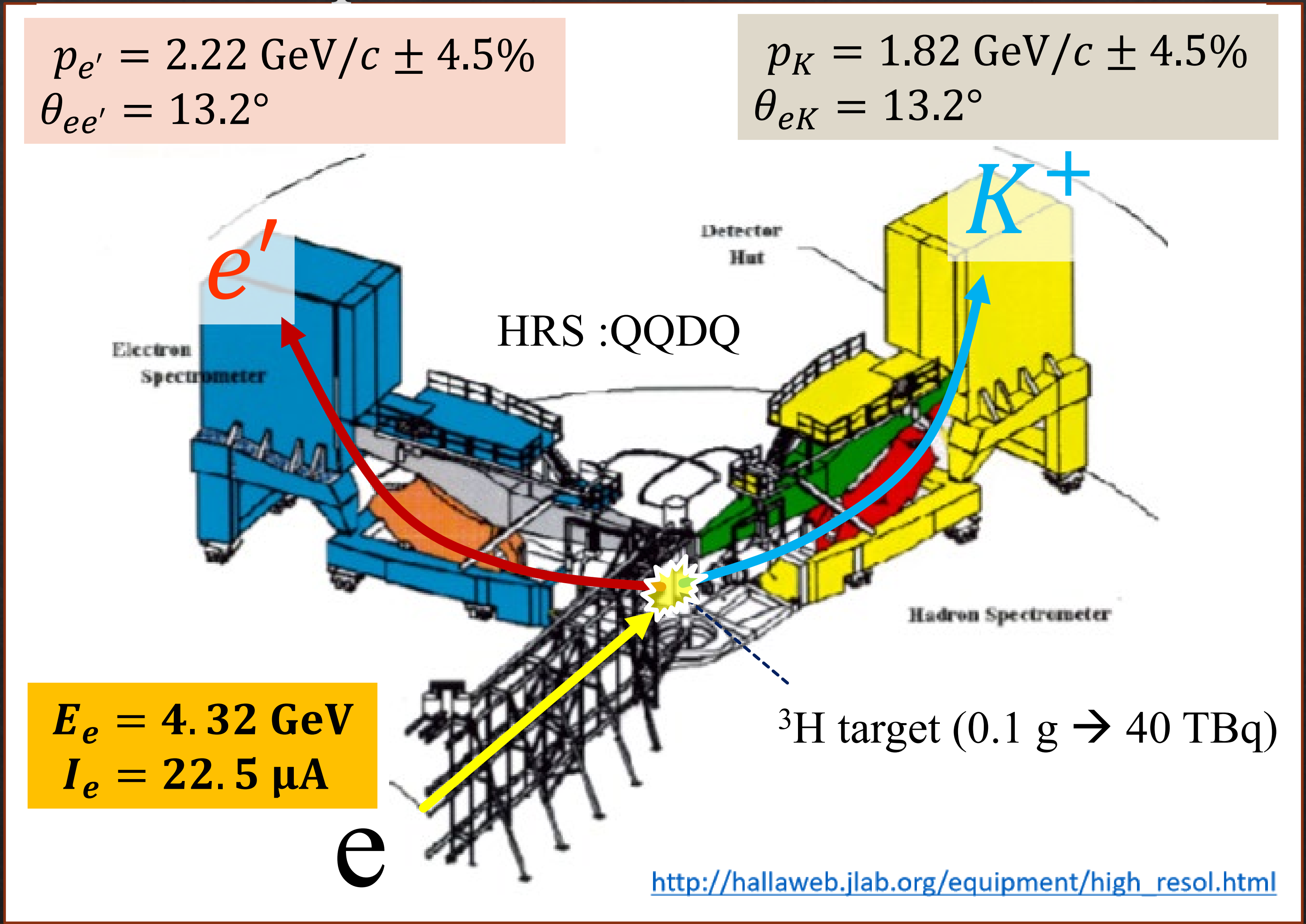
Letter

Spectroscopic study of a possible Λnn resonance and a pair of ΣNN states using the $(e, e'K^+)$ reaction with a tritium target

B. Pandey[1], L. Tang[1,2,*], T. Gogami[3,4], K. N. Suzuki[4], K. Itabashi[3], S. Nagao[3], K. Okuyama[3], S. N. Nakamura[3], D. Abrams[5], I. R. Afnan[6], T. Akiyama[3], D. Androic[7], K. Aniol[8], T. Averett[9], C. Ayerbe Gayoso[9], J. Bane[10], S. Barcus[9], J. Barrow[10], V. Bellini[11], H. Bhatt[12], D. Bhetuwal[12], D. Biswas[1], A. Camsonne[2], J. Castellanos[13], J-P. Chen[2], J. Chen[9], S. Covrig[2], D. Chrisman[14,15], R. Cruz-Torres[16], R. Das[17], E. Fuchey[18], C. Gal[5], B. F. Gibson[19], K. Gnanvo[5], F. Garibaldi[11,20], T. Gautam[1], J. Gomez[2], P. Gueye[1], T. J. Hague[21], O. Hansen[2], W. Henry[2], F. Hauenstein[22], D. W. Higinbotham[2], C. Hyde[22], M. Kaneta[3], C. Keppel[2], T. Kutz[17], N. Lashley-Colthirst[1], S. Li[23,24], H. Liu[25], J. Mammei[26], P. Markowitz[13], R. E. McClellan[2], F. Meddi[11], D. Meekins[2], R. Michaels[2], M. Mihovilovič[27,28,29], A. Moyer[30], D. Nguyen[16,31], M. Nycz[21], V. Owen[9], C. Palatchi[5], S. Park[17], T. Petkovic[7], S. Premathilake[5], P. E. Reimer[32], J. Reinhold[13], S. Riordan[32], V. Rodriguez[33], C. Samanta[34], S. N. Santiesteban[23], B. Sawatzky[2], S. Širca[27,28], K. Slifer[23], T. Su[21], Y. Tian[35], Y. Toyama[3], K. Uehara[3], G. M. Urciuoli[11], D. Votaw[14,15], J. Williamson[36], B. Wojtsekhowski[2], S. Wood[2], B. Yale[23], Z. Ye[32], J. Zhang[5], and X. Zheng[5] (Hall A Collaboration)

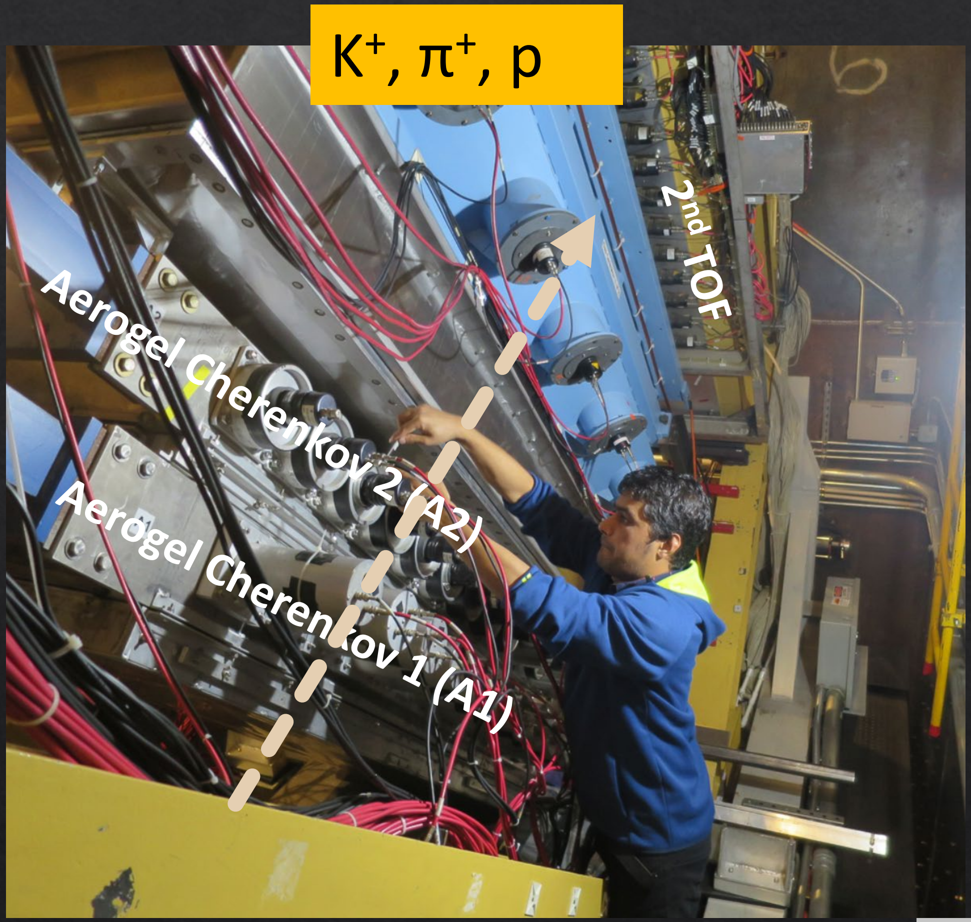
https://doi.org/10.1103/PhysRevC.105.L051001

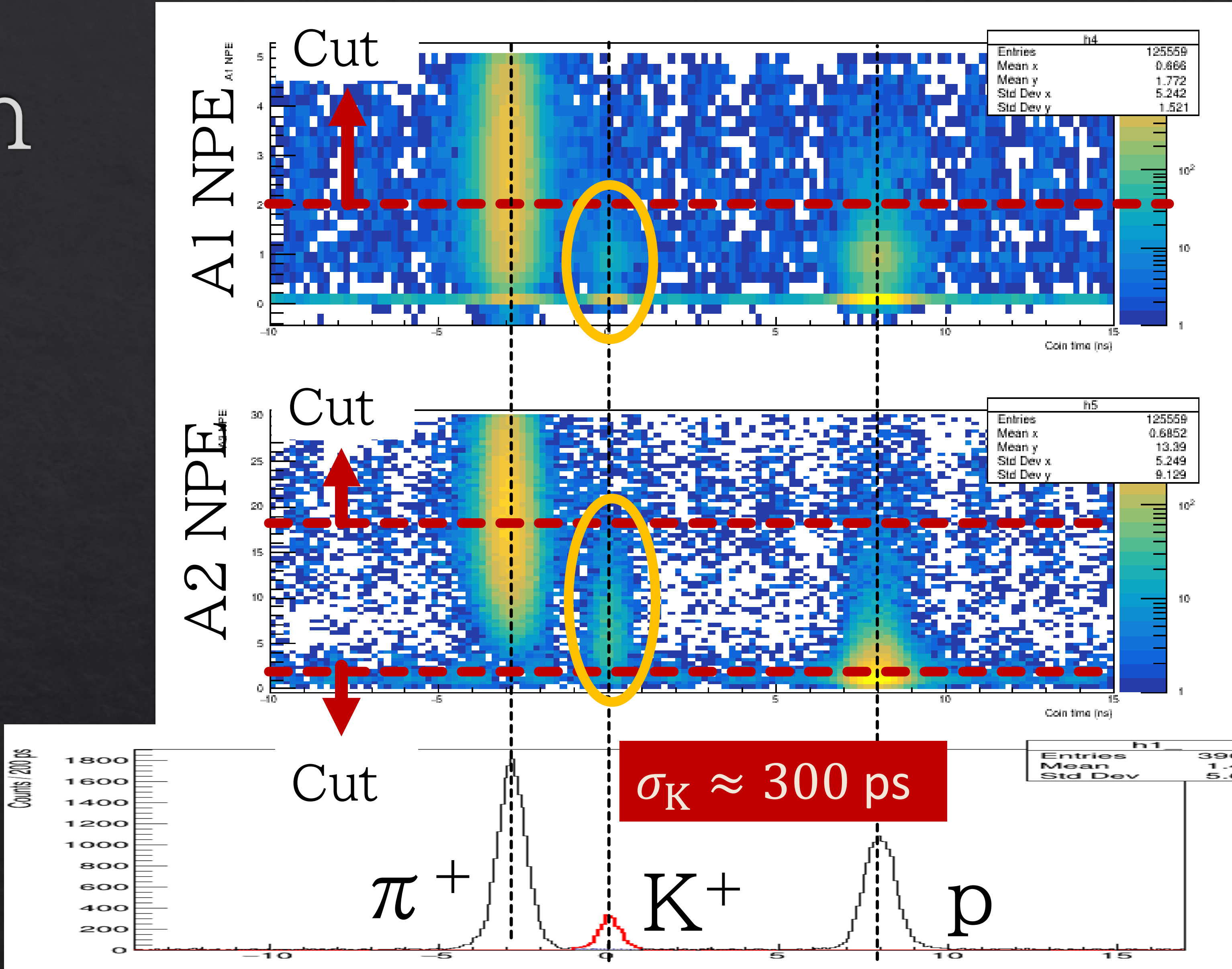
Experimental setup at Hall A




Right HRS
e’
Left HRS
K^+
e
JLab Hall A (Apr 2019)
Jefferson Lab
Thomas Jefferson National Accelerator Facility

K$^+$ identification

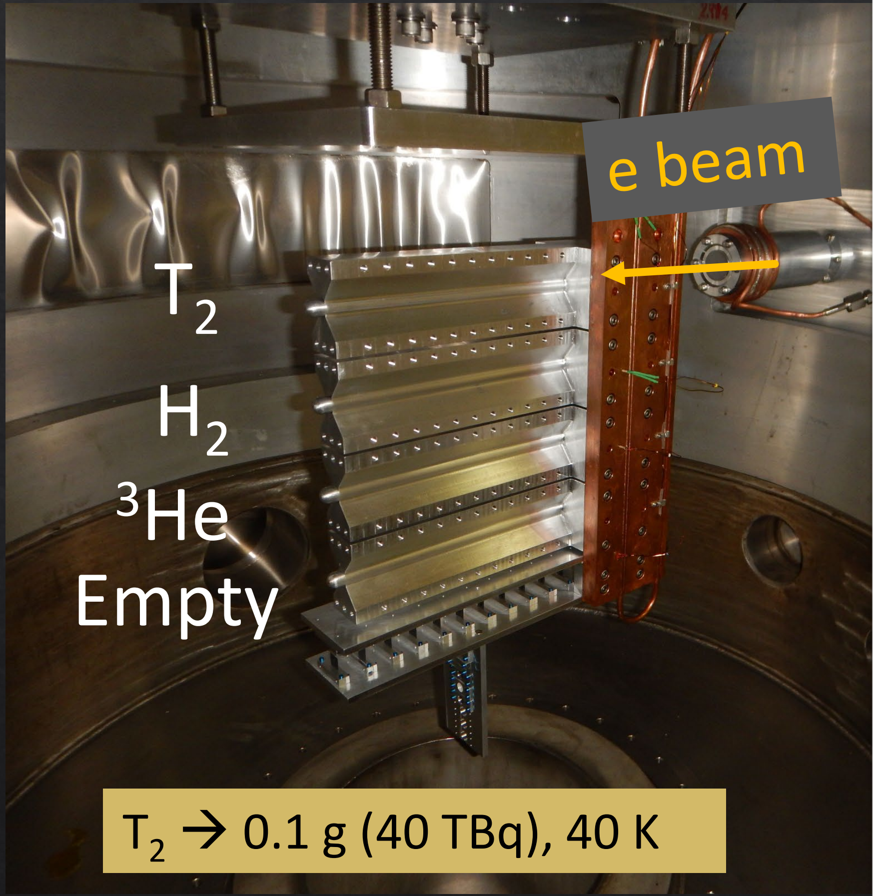


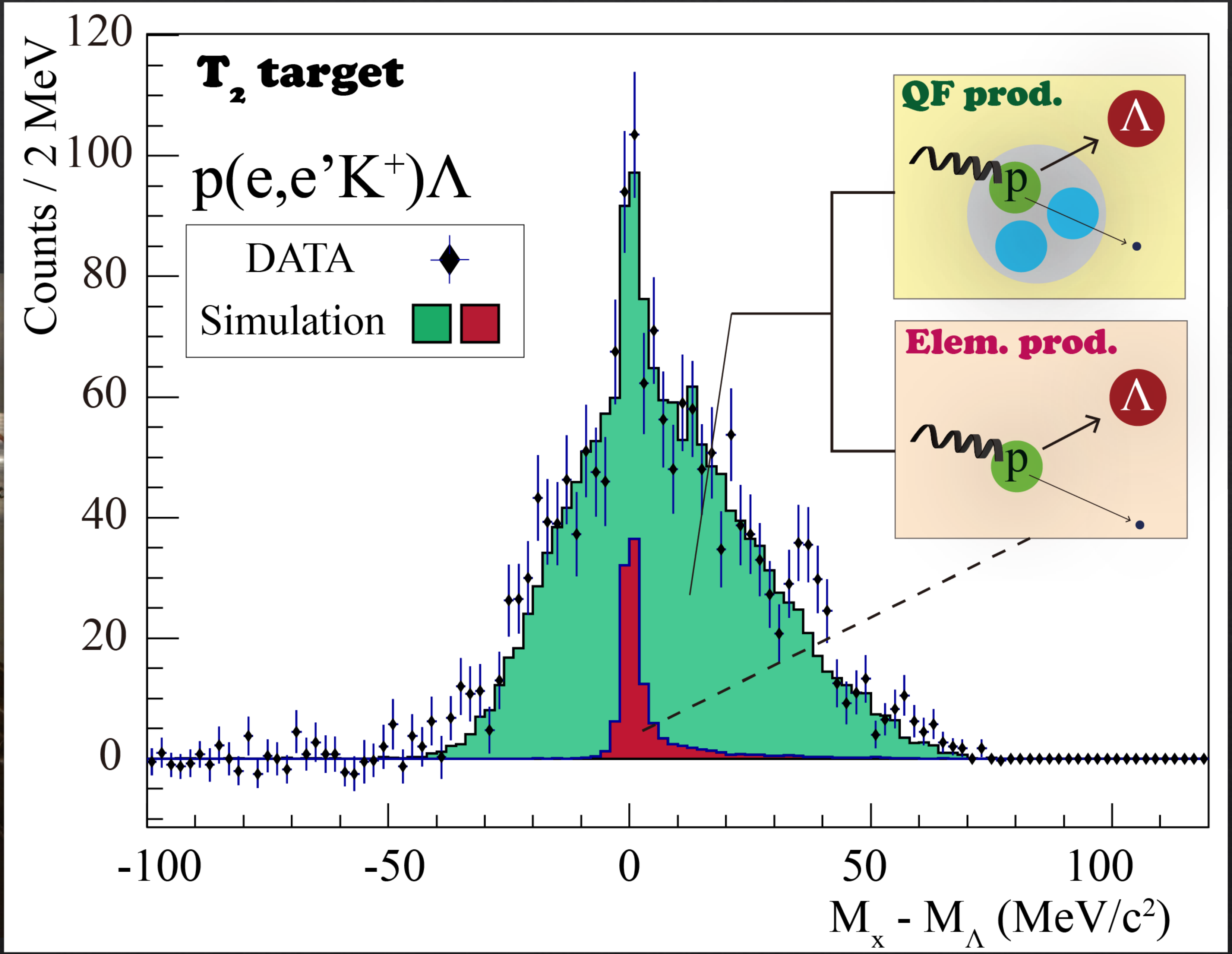


Timing consistency between L and R assuming m_K → Coin. time (ns)

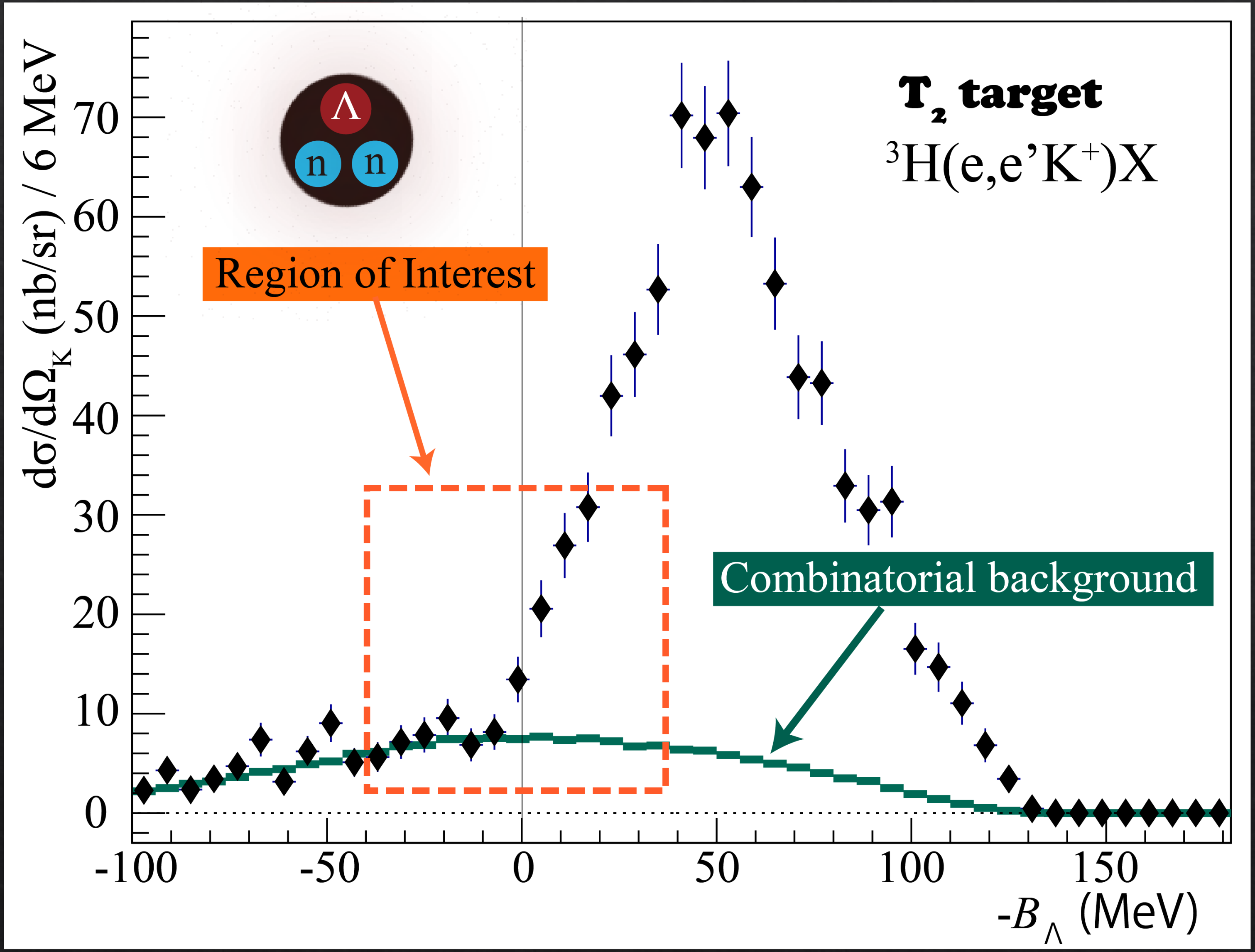
H_2 in T_2 target

A few % of H_2 compared to T_2





Cross section spectrum for Λnn



Unbinned maximum likelihood fit

($-20 < B_\Lambda < 20$ MeV)

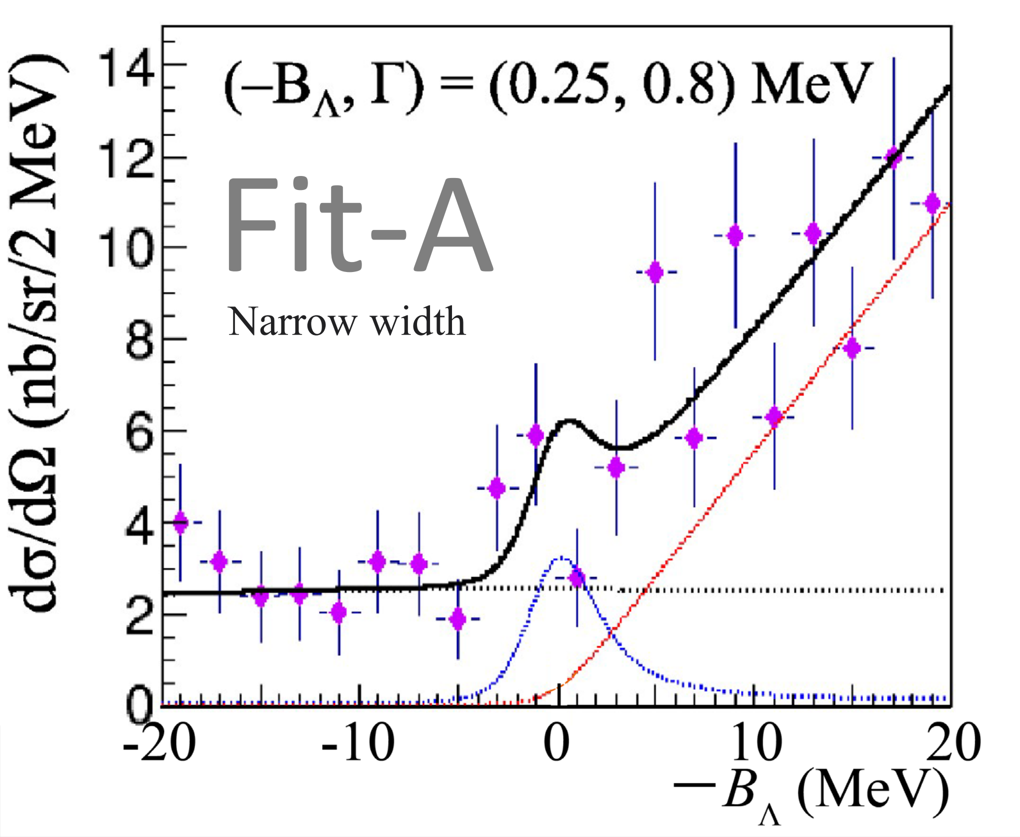
Probability density function (PDF):

1. Response function (RF)
   - Geant4 simulation
2. Decay width
   - Breit Wigner
3. QF shape ($-B_\Lambda > 0$)
   - Unknown
     → Linear function ⊗ RF
4. Combinatorial background
   - Data → the 4th order polynomial

Cross section analysis

- K.N. Suzuki et al., PTEP **2022**, 1, 013D01 (2022)
- TG et al., WPJ Web Conf. **271**, 02002 (2022)

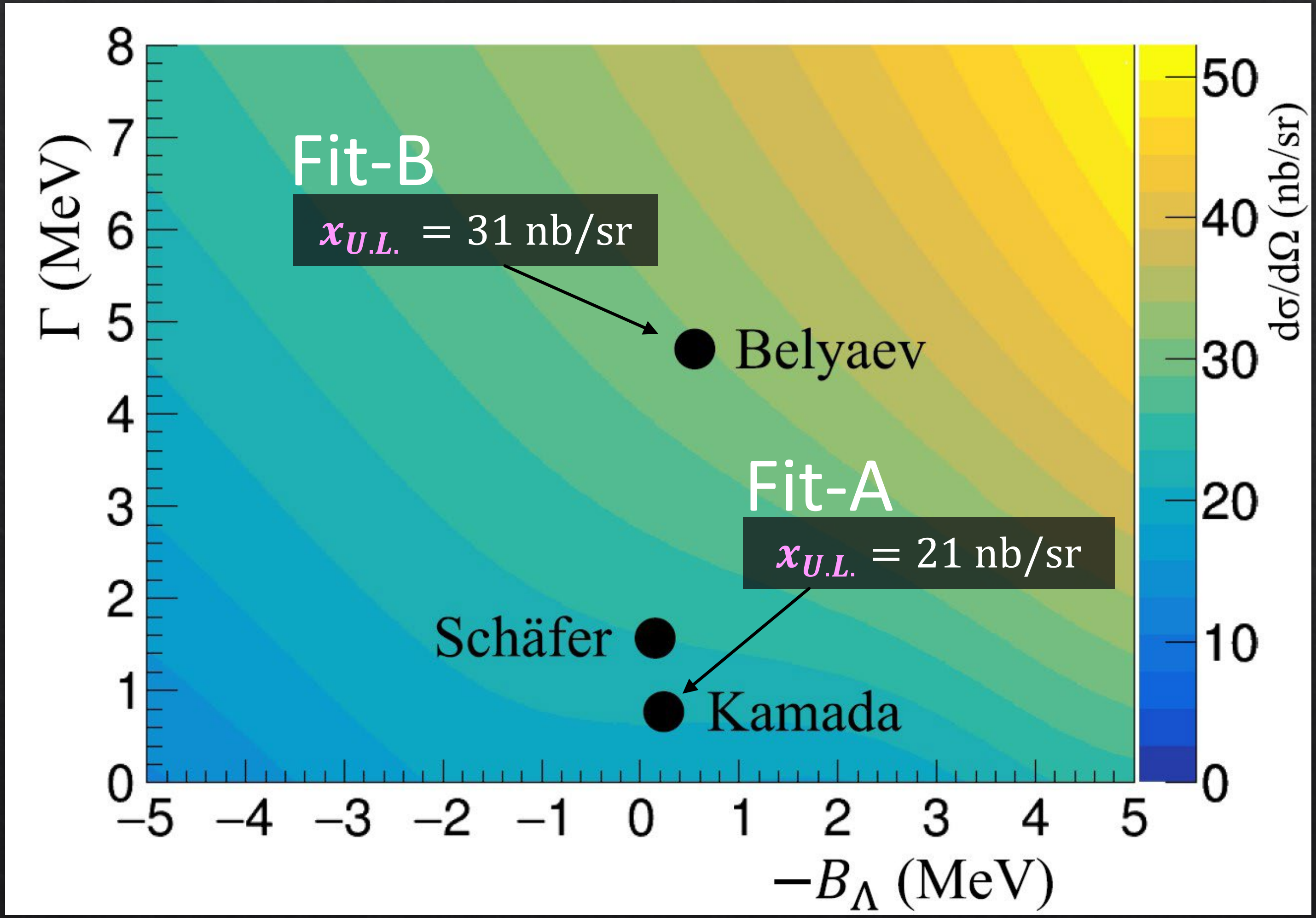
Fit by unbinned max. likelihood



Fit	A	B
YN Int.	Nijmegen89[(*1)]	Minesota[(*2)]
$-\mathbf{B}_\Lambda, \mathbf{\Gamma}$ (/ MeV)	0.25, 0.8	0.55, 4.7
$\left(\frac{d\sigma}{d\Omega_K}\right)$ [/(nb/sr)]	**11.2** $\pm 4.8\ (\text{stat.})^{+4.1}_{-2.1}\ (\text{sys.})$	**18.1** $\pm\ 6.8\ (\text{stat.})^{+4.2}_{-2.9}\ (\text{sys.})$
Significance (stat. only)	2.3	2.7

(*1) H. Kamada, K. Miyagawa, and M. Yamaguchi, EPJ Web Conf. 113, 07004 (2016).
(*2) V. B. Belyaev, S. A. Rakityansky, and W. Sandhas, Nucl. Phys. A 803, 210–226 (2008).

Upper limit at 90% C.L. (2-D scan)



Upper limit $x_{U.L.}$:

$$\frac{\int_0^{x_{U.L.}^{\text{stat.}}} g(x)dx}{\int_0^{\infty} g(x)dx} = 90\%$$

where, $g(x)$ is a Gaus.

⇩

$$x_{U.L.} = x_{U.L.}^{\text{stat.}} + sys.err.$$

Theoretical calculations to be compared with the results are awaited !!

Particle Detectors

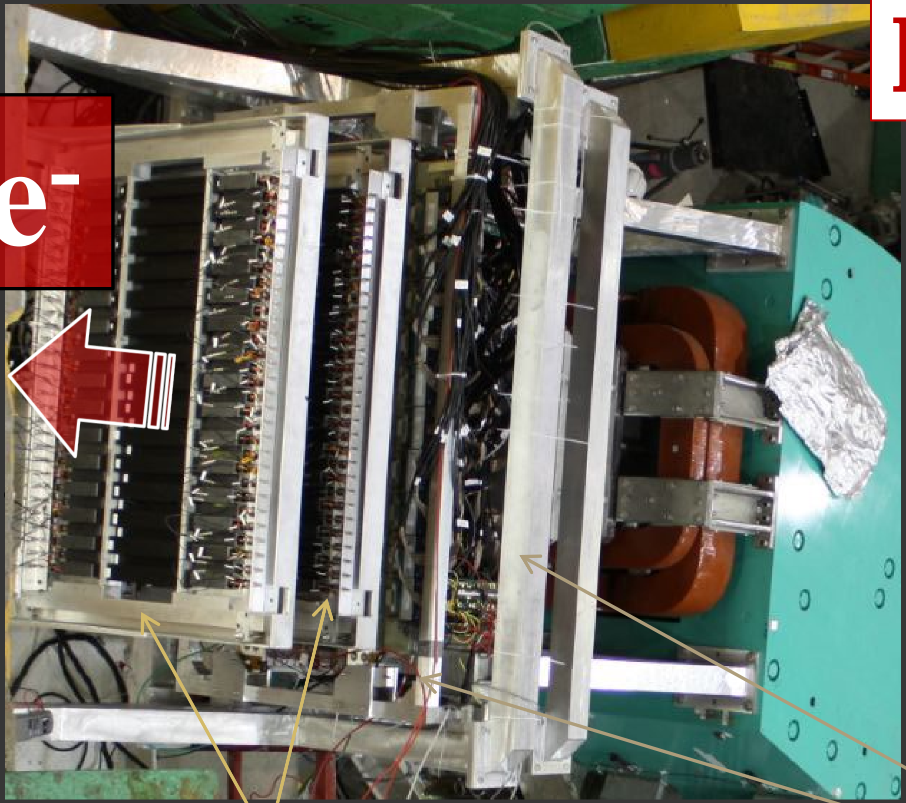
TG et al., NIMA 900, 69—83 (2018)
TG et al., NIMA 729, 816—824 (2013)

Cherenkov detectors

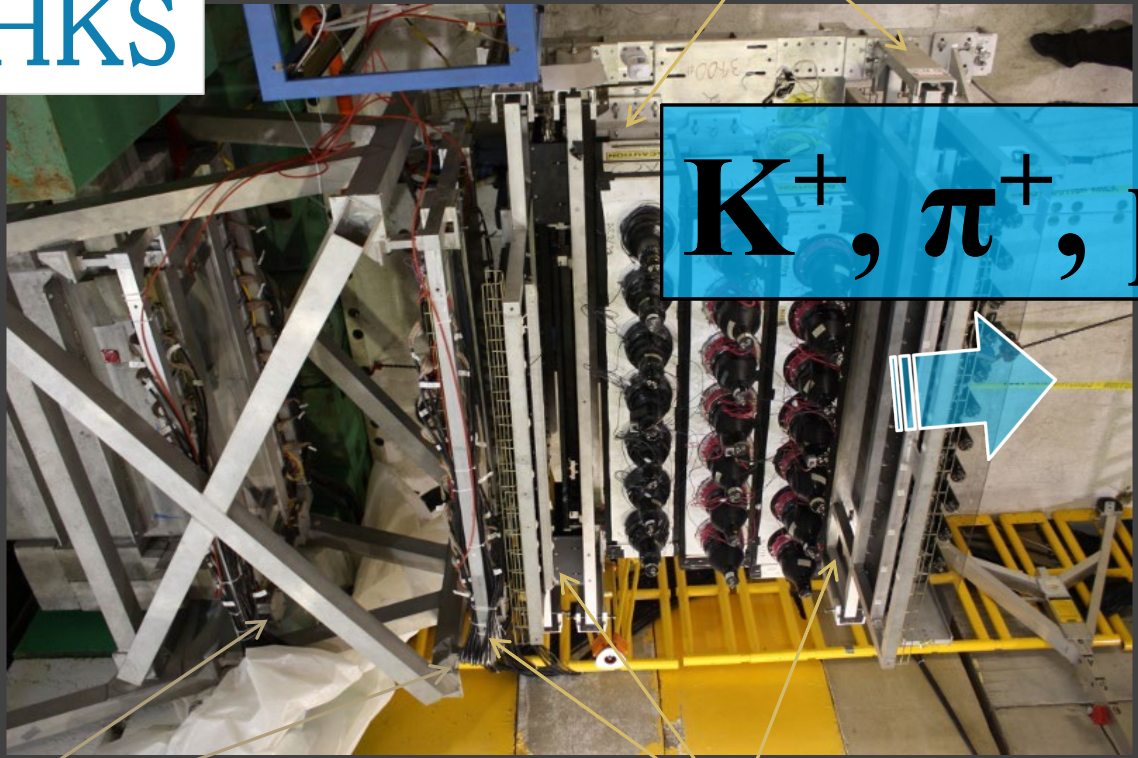
- **Aerogel (n=1.05)**
- **Water (n=1.33)**

HES

e^-



HKS

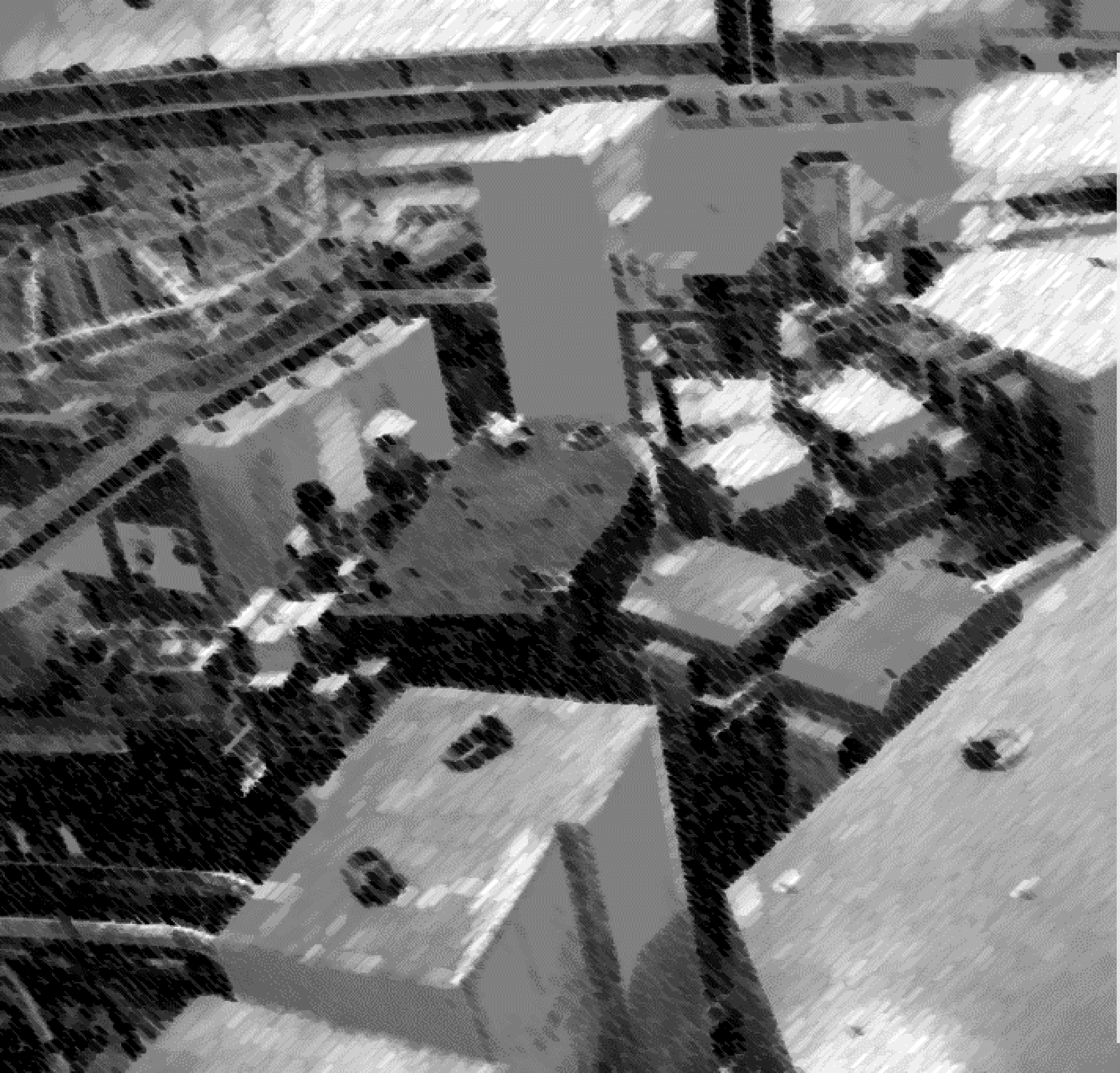


K^+, π^+, p

TOF walls
(Plastic scintillators)

Drift chambers

TOF walls
(Plastic scintillators)



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

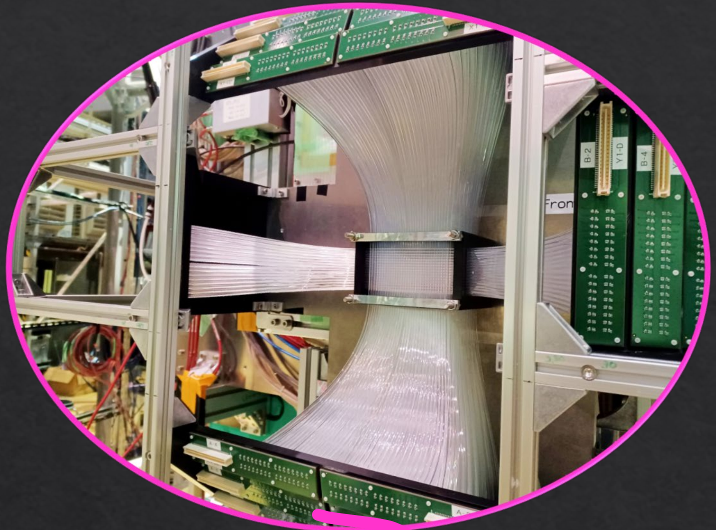
- TG et al., PRC 103, L041301 (2021)
- TG et al., NIMA 900, 69—83 (2018)
- TG et al., PRC 94, 021302(R) (2016)
- TG et al., PRC 93, 034314 (2016)
- Y. Fujii et al., NIMA795, 351—363 (2015)
- L. Tang et al., PRC 90, 034320 (2014)
- S.N. Nakamura et al., PRL 110, 012502 (2013)
- TG et al., NIMA 729, 816—824 (2013)
- L. Yuan et al., PRC 73, 044607 (2006)
- T. Miyoshi et al., PRL 90, 232502 (2003)

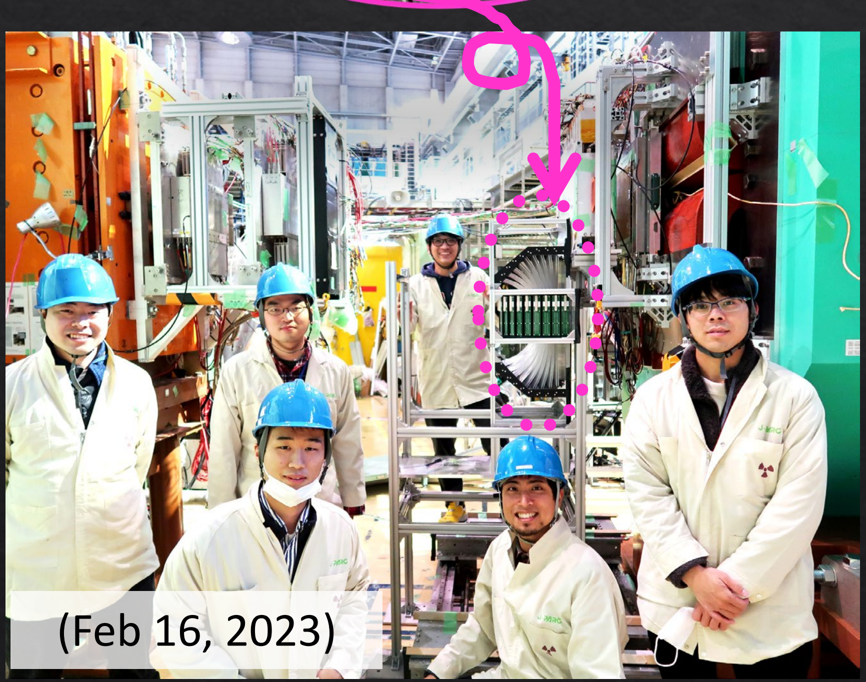
Experimental parameters for the next JLab Experiment (2027-)

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

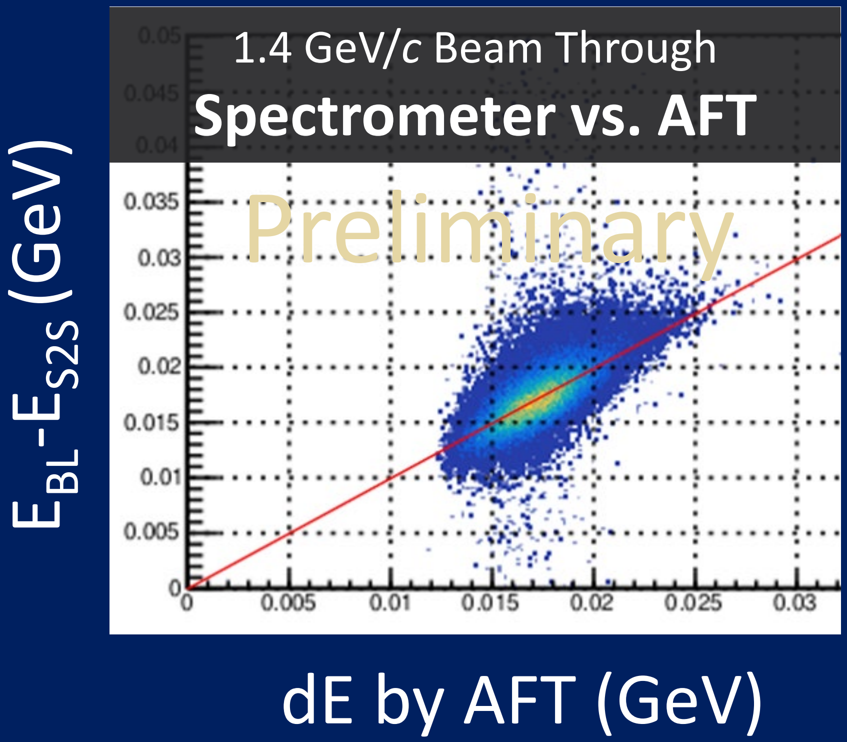
Item		Value
Beam (e)	Energy (/GeV)	2.24
	(Required) energy spread and drift	1×10^{-4} (FWHM)
PCS + HES (e')	Central momentum $p_{e'}^{\mathrm{cent.}}$ [/(GeV/c)]	0.74
	Central angle $\theta_{ee'}^{\mathrm{cent.}}$	8.5°
	Solid angle acceptance $\Omega_{e'}$ (/msr) (at $p_{e'}^{\mathrm{cent.}}$)	3.4
	Momentum resolution $\Delta p_{e'}/p_{e'}$	4.4×10^{-4} (FWHM)
PCS + HKS (K^+)	Central momentum $p_{K^+}^{\mathrm{cent.}}$ [/(GeV/c)]	1.20
	Central angle $\theta_{eK^+}^{\mathrm{cent.}}$	11.5°
	Solid angle acceptance Ω_{K^+} (/msr) (at $p_{K^+}^{\mathrm{cent.}}$)	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

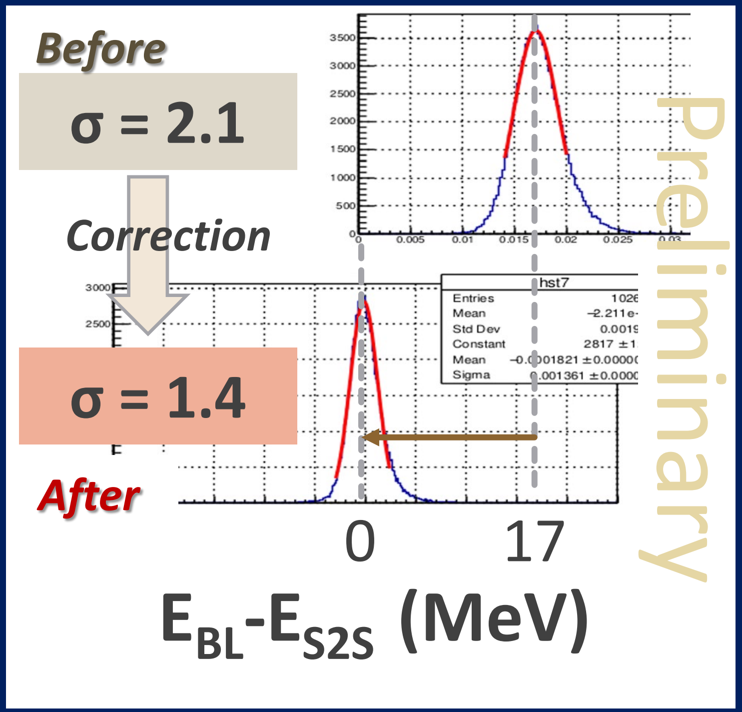
Active fiber target (AFT)




(Feb 16, 2023)

Energy loss & straggling correction

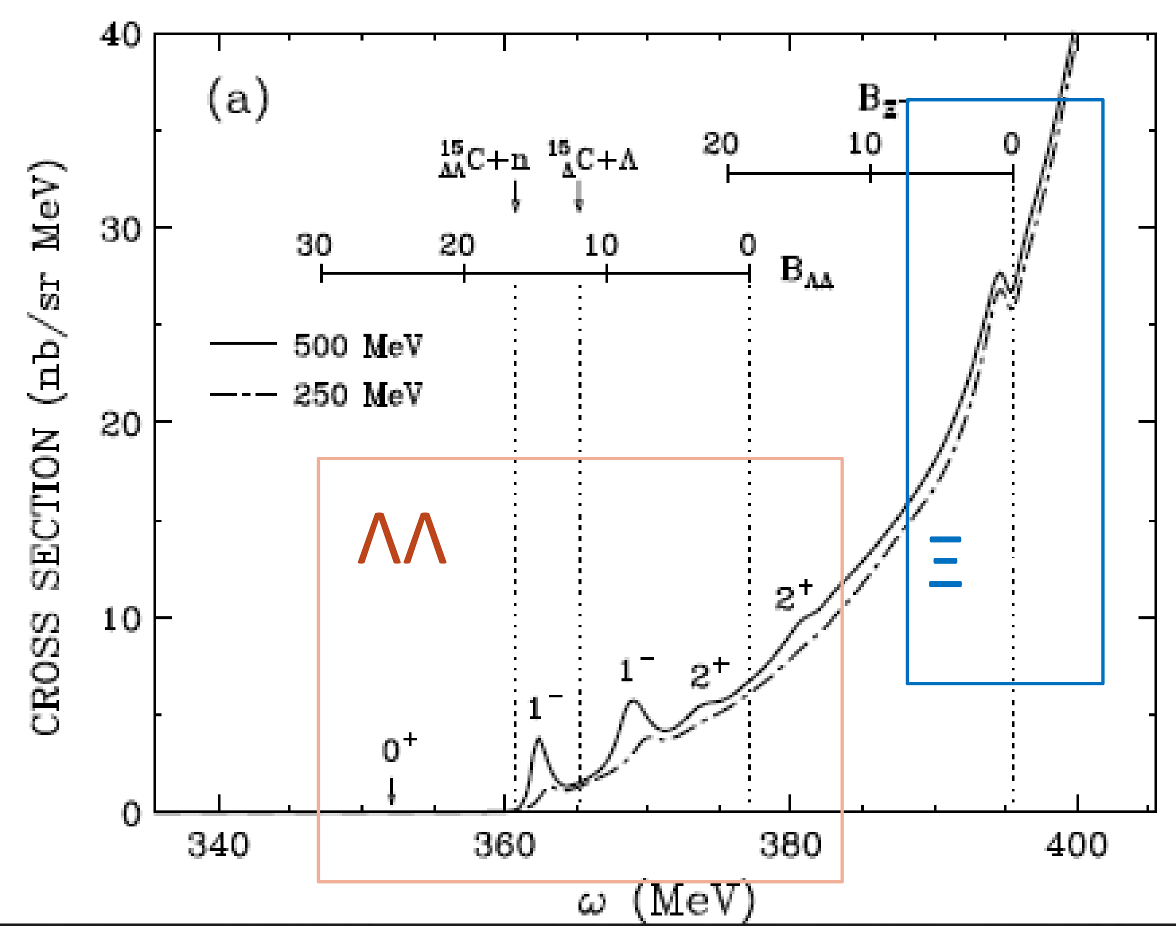


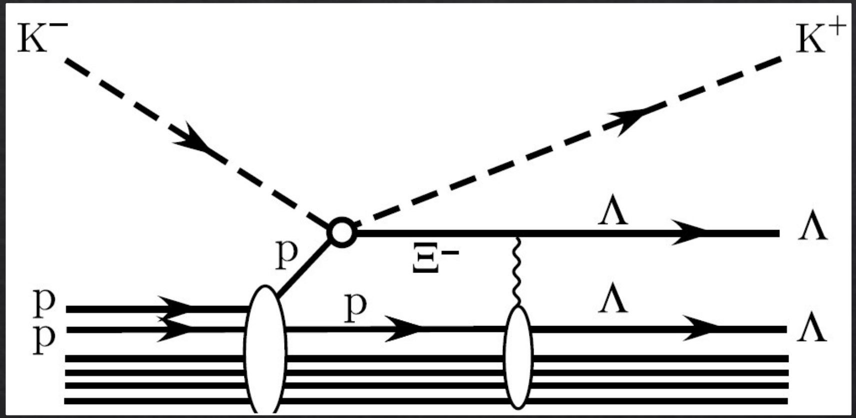


Event-by-event correction by AFT worked

Energy spectrum with the (K^-, K^+) reaction

T. Harada, Y. Hirabayashi, A. Umeya, NPA 914, 85—90 (2013)

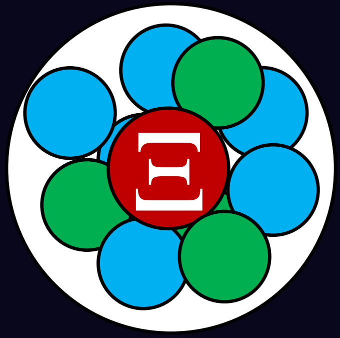


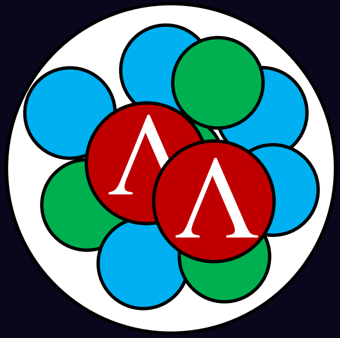


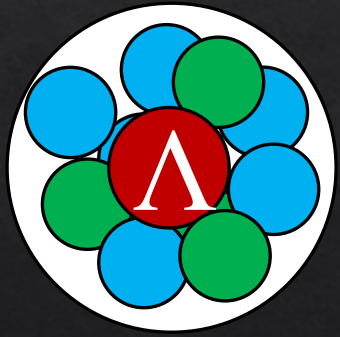
ΛΛ hypernuclei may be observed

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)](https://doi.org/10.1051/epjconf/202327111002).