Hypernuclear Physics Program at JLab; Results and Future Prospects

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GRADUATE SCHOOL OF FACULTY OF SCIENCE KYOTO UNIVERSITY

for the JLab Hypernuclear Collaboration

June 28, 2023

Hall A

- 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)

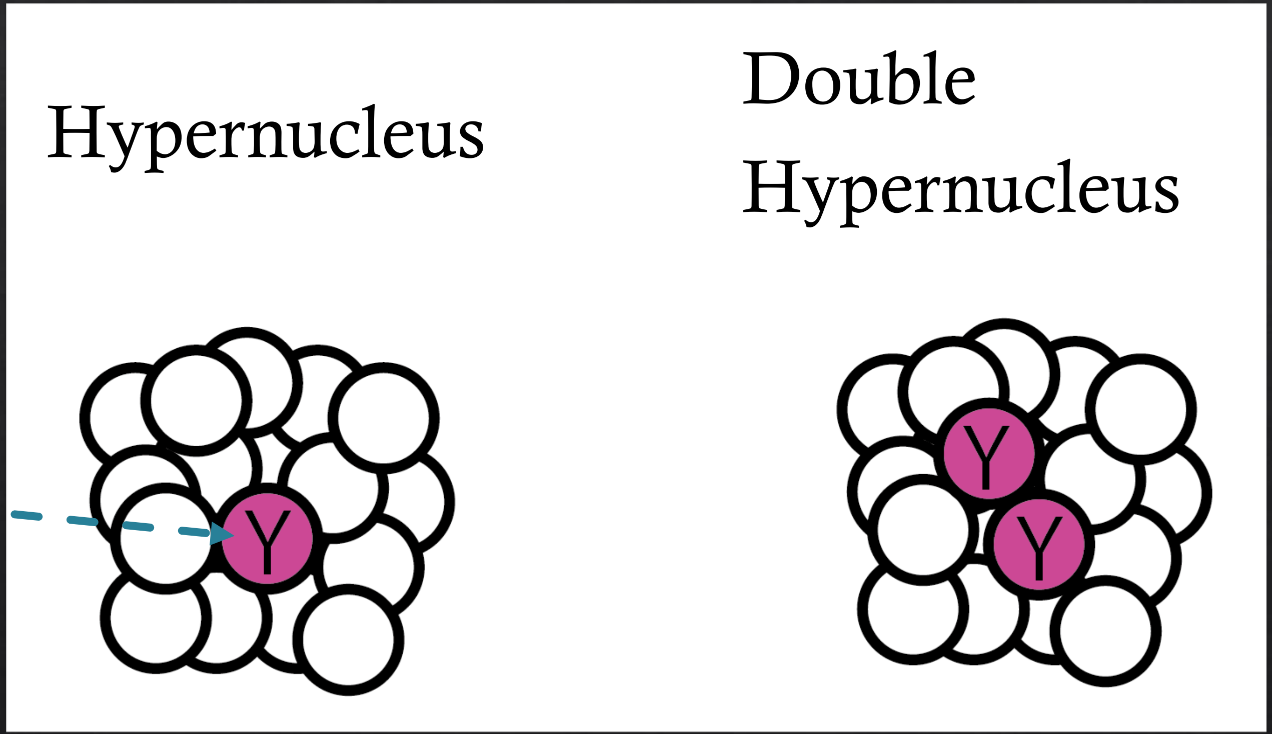
Hall C

- 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)

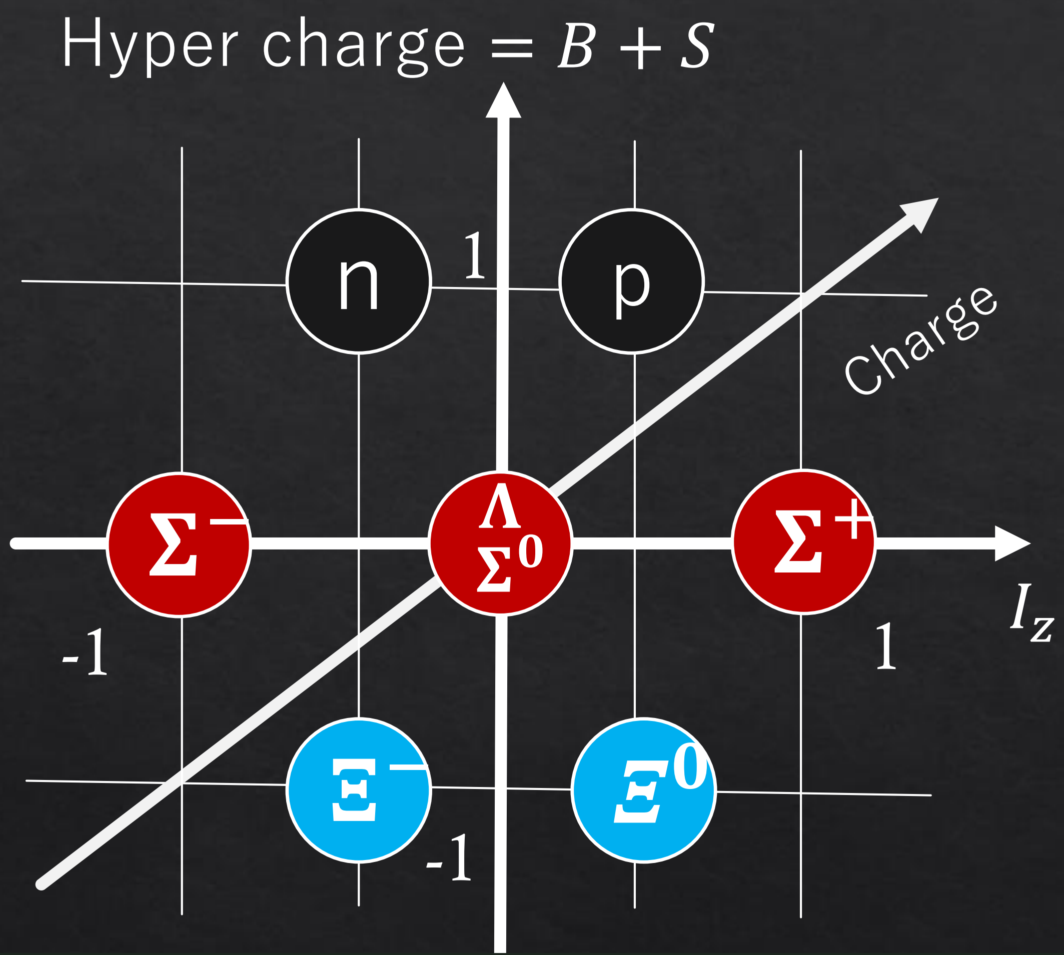
Hypernuclei

<u>Nucleon (N)</u>
up (u)、down (d) quark

<u>hyperon (Y)</u>
strange (s) quark is contained



Baryon-baryon (BB) interaction



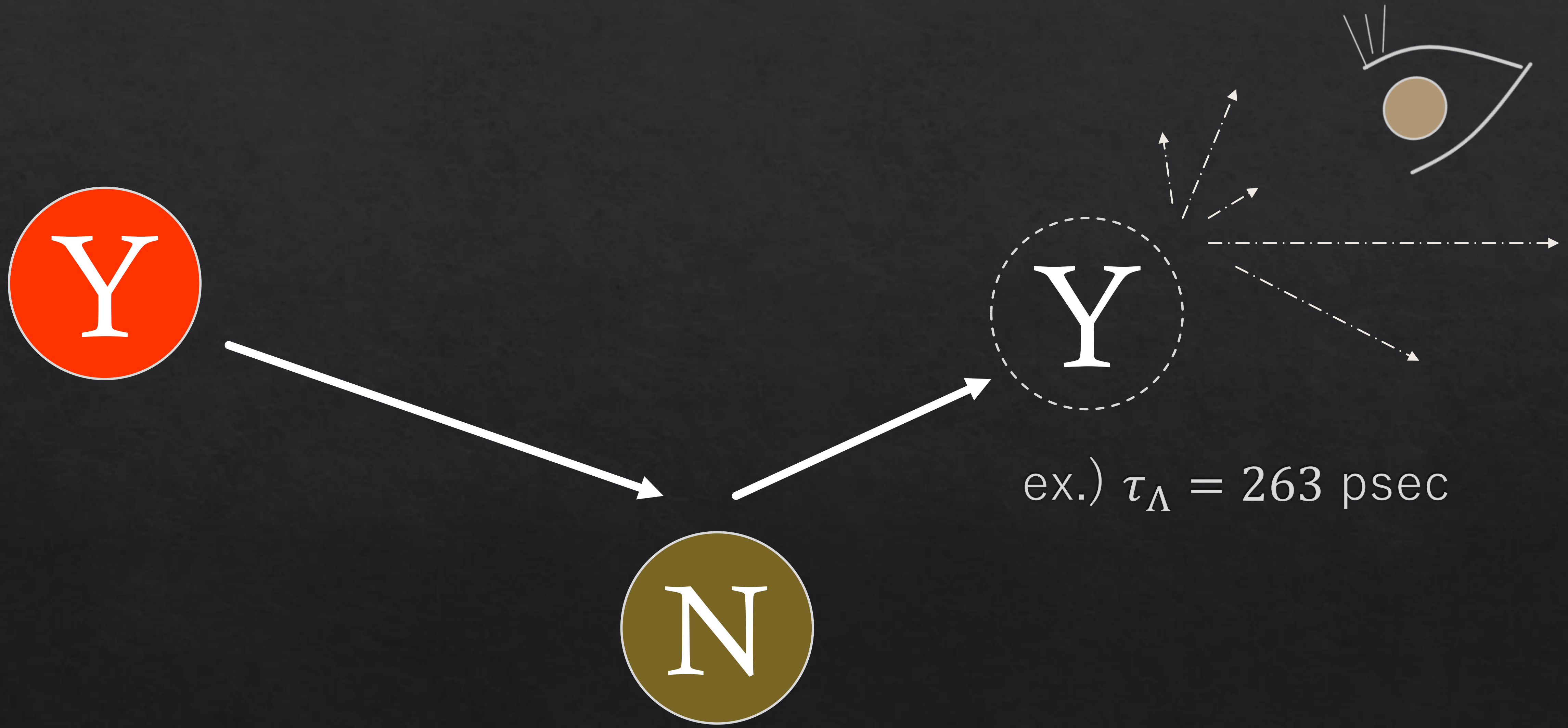
Baryon Octet $J^\pi = \frac{1}{2}^+$ (ground state)

Nuclear force
(= Strong force between Ns)

Strong force between **YN/YY**
← Hypernuclear spectroscopy

More general BB int.

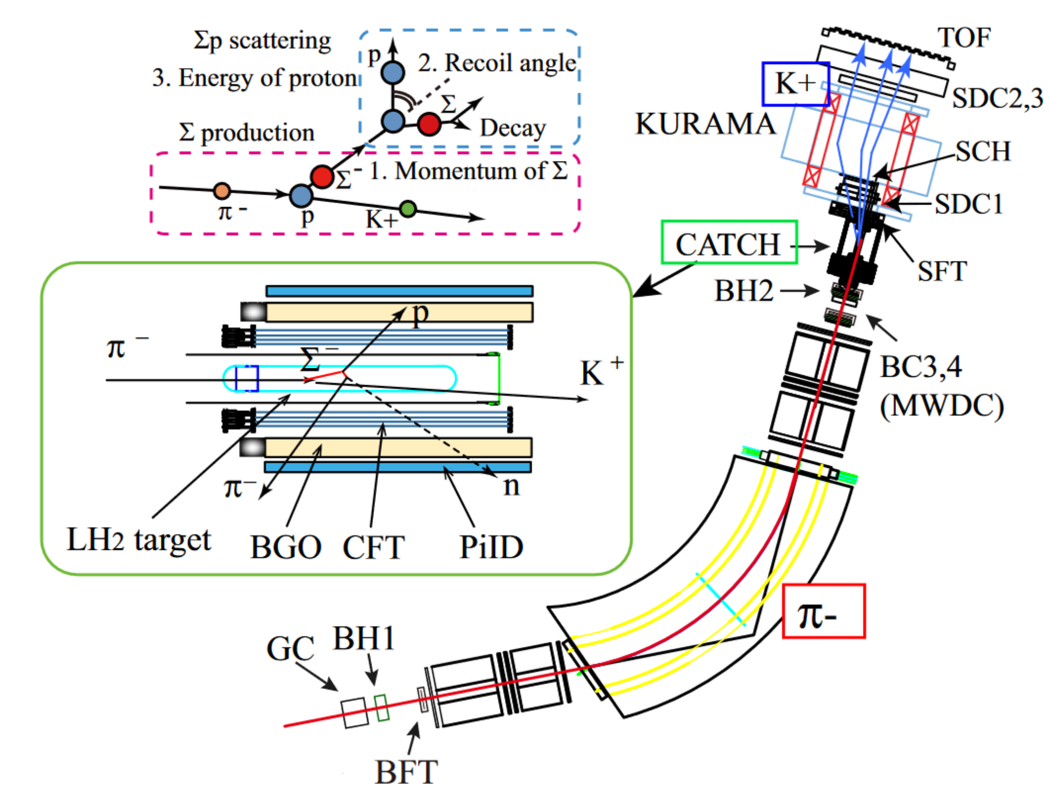
Hyperons' lifetime are too short…



ex.) $\tau_{\Lambda} = 263$ psec

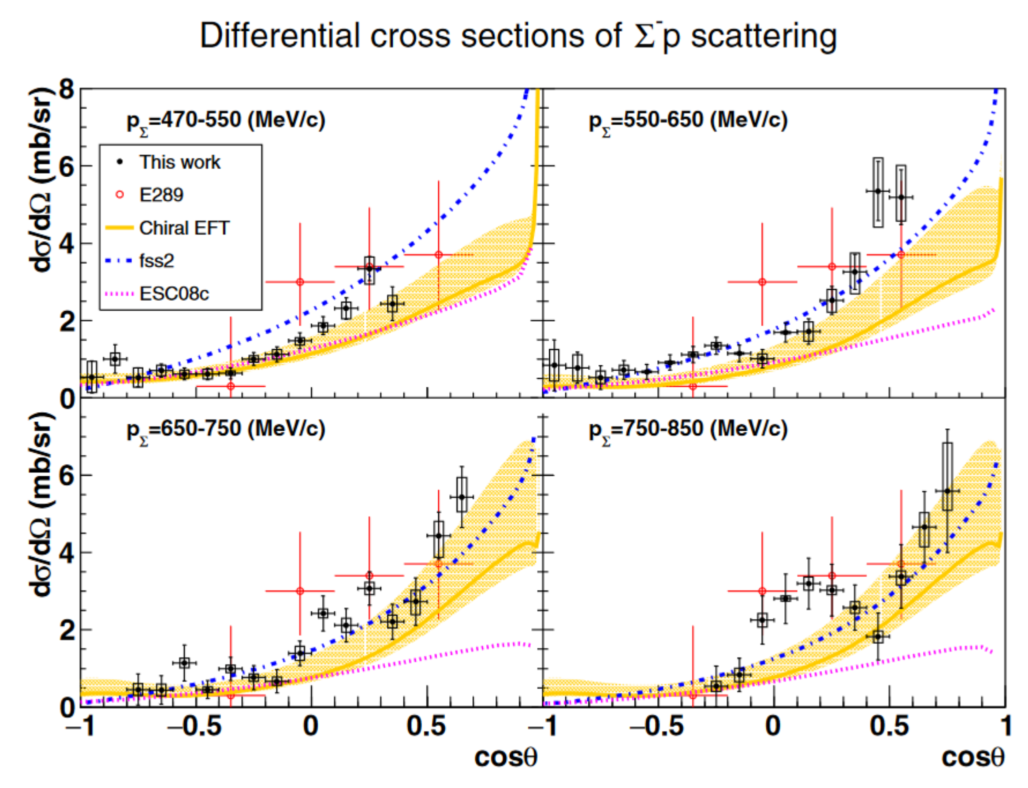
Recent progress in YN scattering experiment

K. Miwa et al., PRC 104, 045204 (2021)



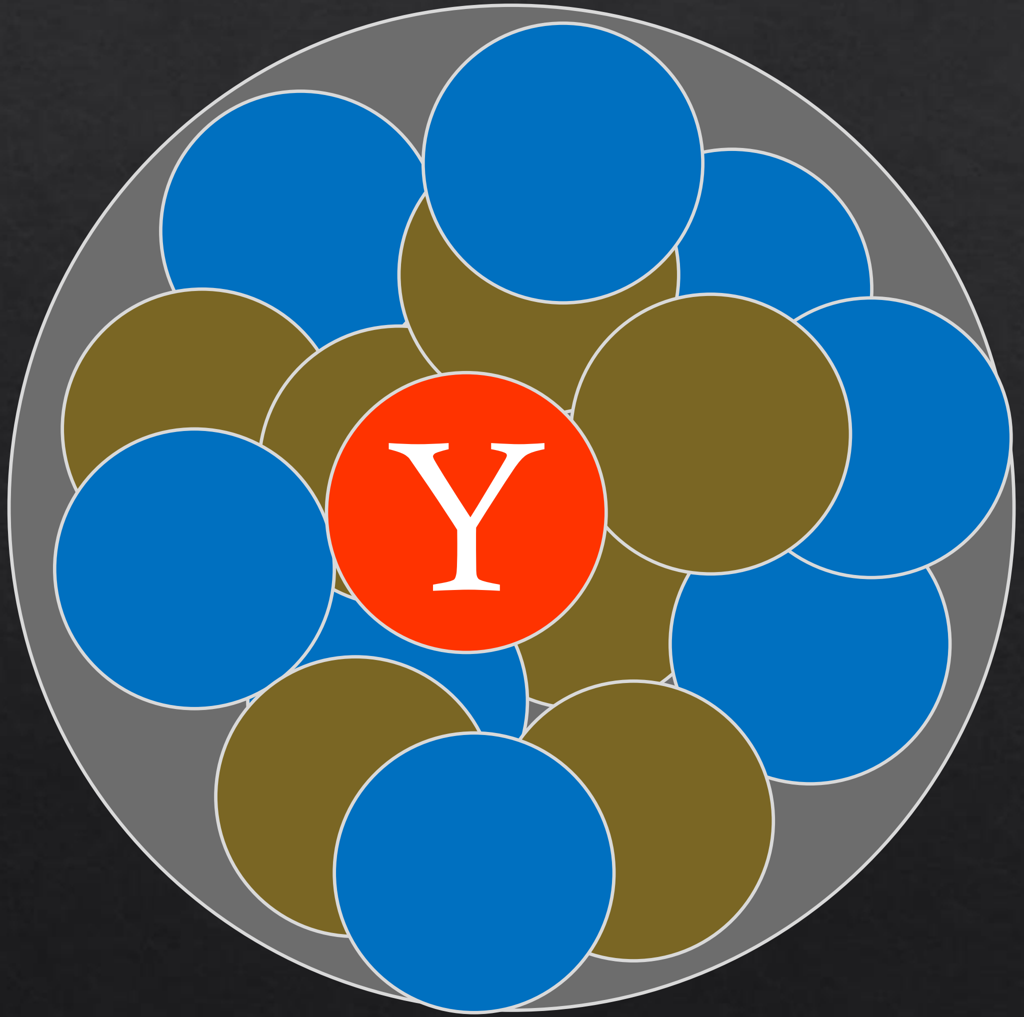
J-PARC E40 Experiment

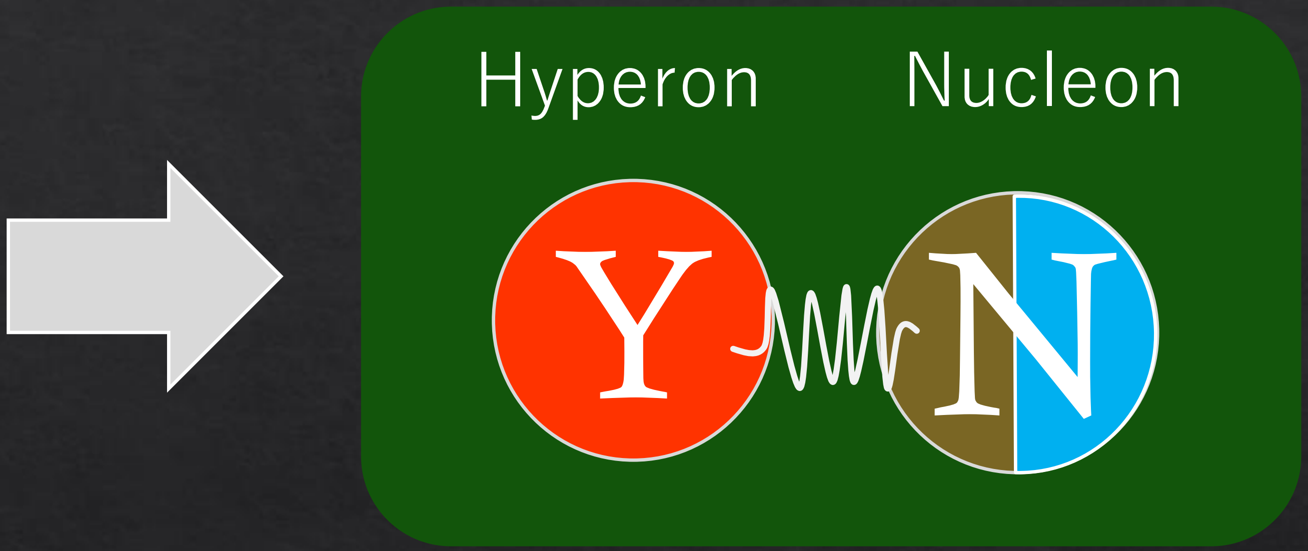
Σ^{-}p elastic



Σ^{-}p→ Λn：K. Miwa et al., Phys. Rev. Lett. 128, 072501 (2022)
Σ^{+}p: T. Nanamura et al., arXiv:2203.08393 [nucl-ex] (2022)
Λp : J. W. Price et al., AIP Conf. Proc. 2130, 020004 (2019)
Λp : K. Miwa et al., Proposal to J-PARC, P86 (2021)

Hypernuclei → YN/YY interactions



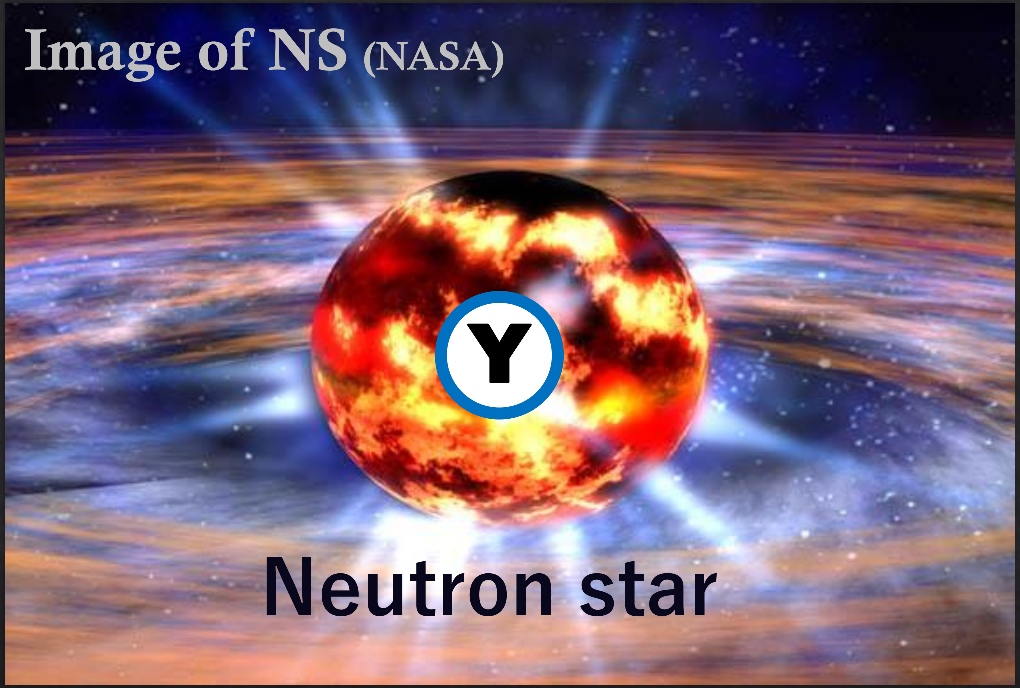


Hypernuclear spectroscopy has been playing the most important role for the YN/YY-interaction study

Hyperons in the nature

Hypernuclear research

- Internal structure



- Cosmological observation
- Gravitational wave measurement

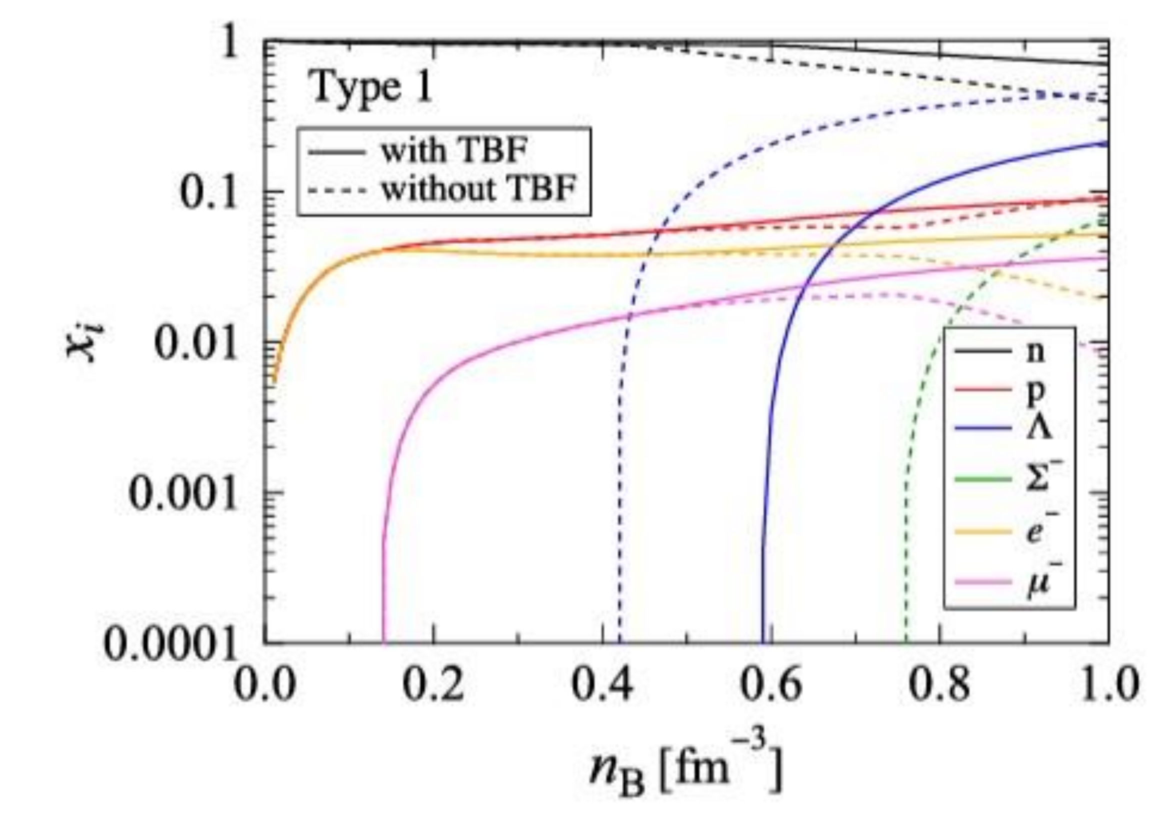
- Mass, radius etc.

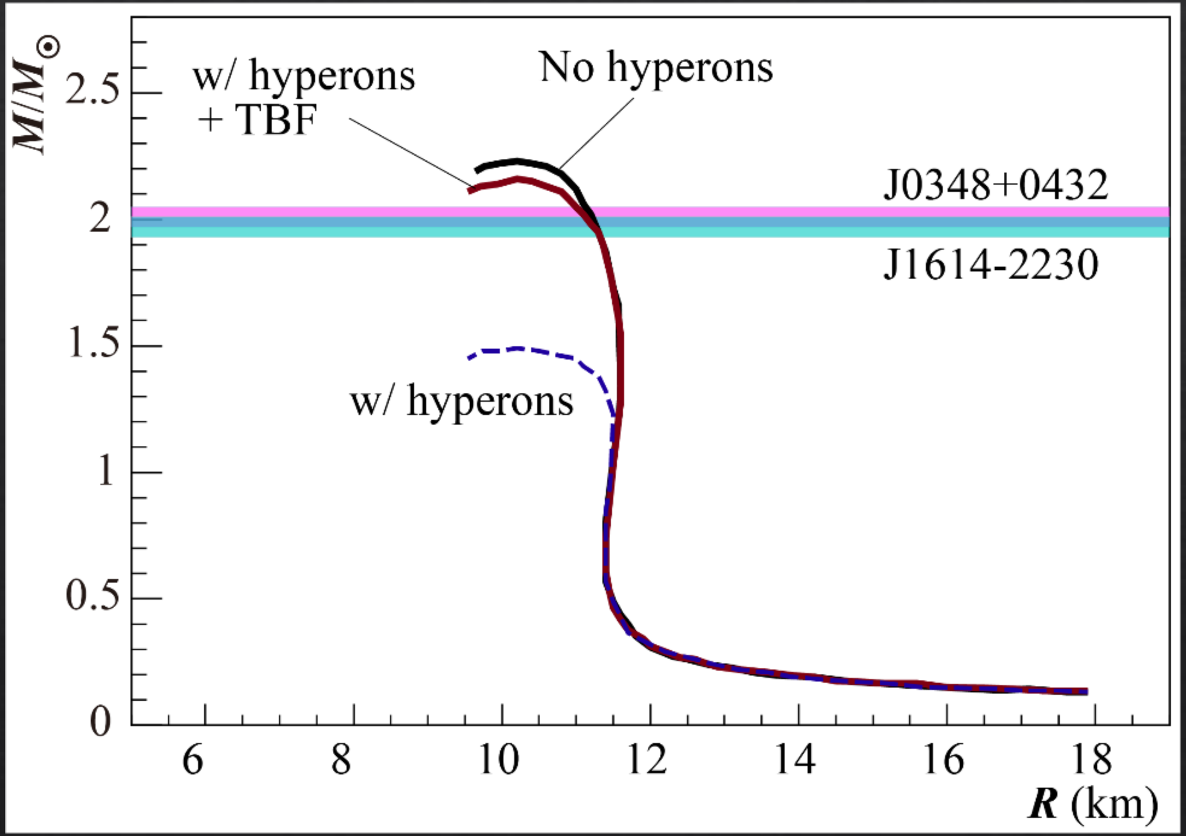
Microscopic

Macroscopic

Hyperon puzzle for neutron stars

H. Togashi *et al.*, Phys. Rev. C 93, 035808 (2016)





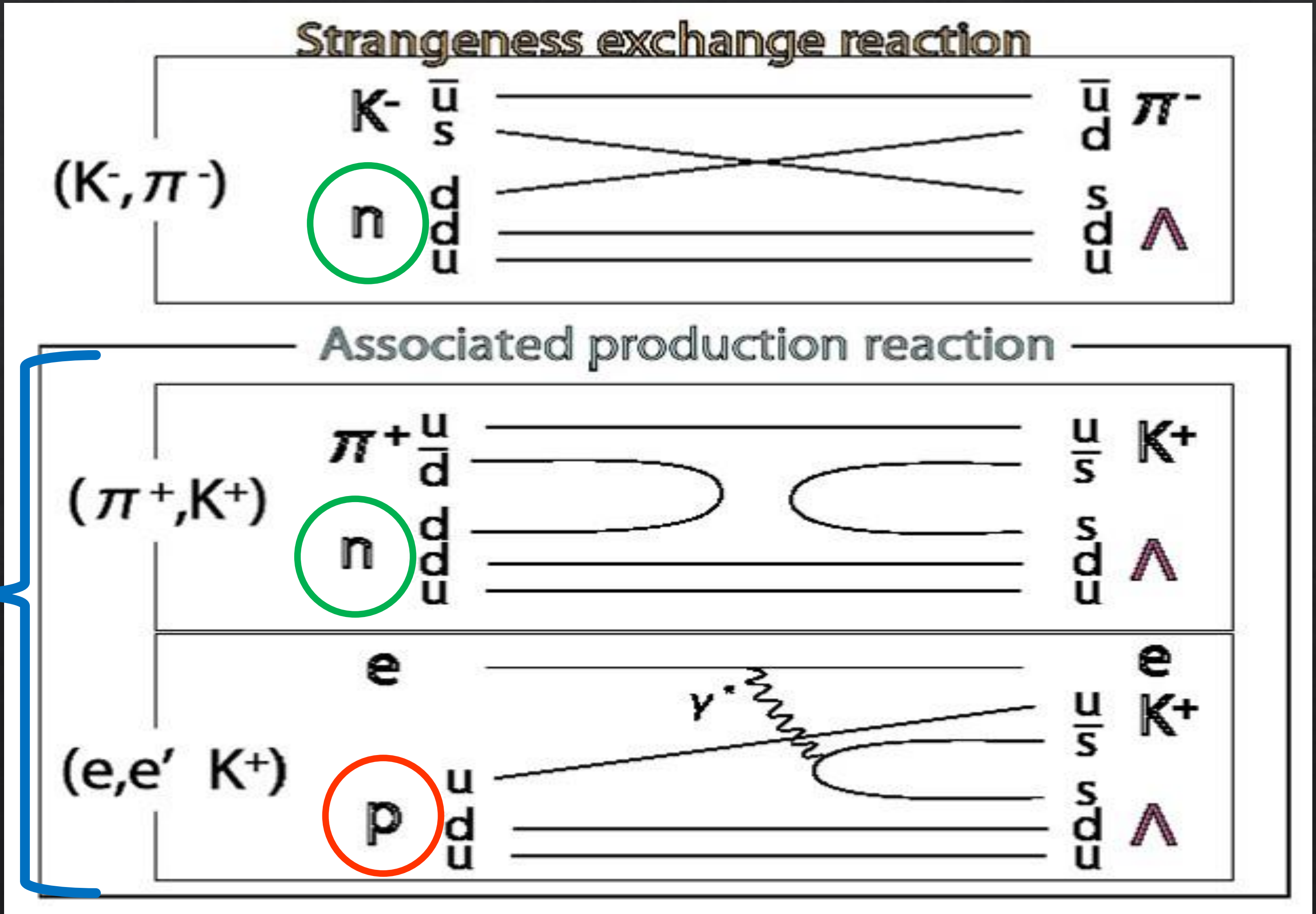
Multi-body force plays an important role

➔ JLab E12-15-008, E12-20-013

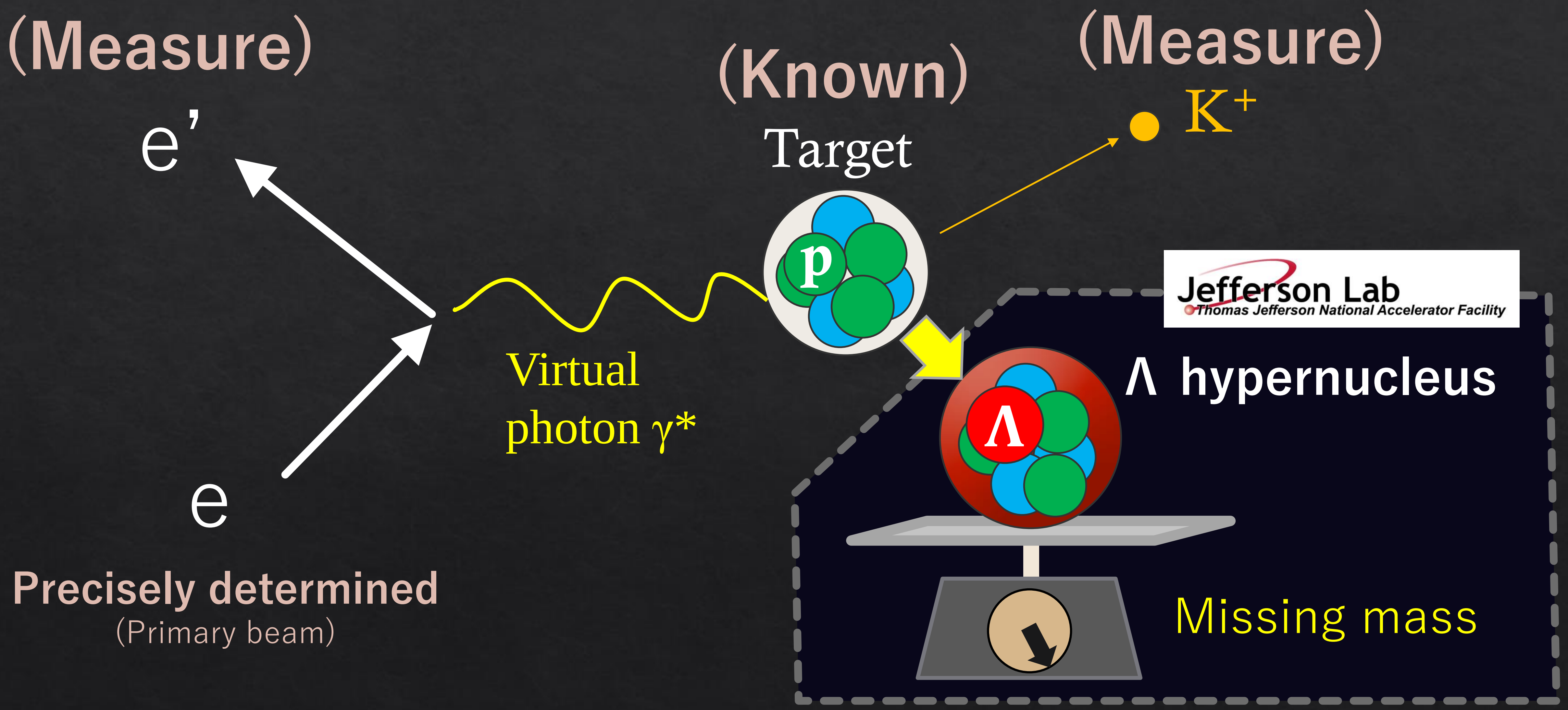
Typical production reaction

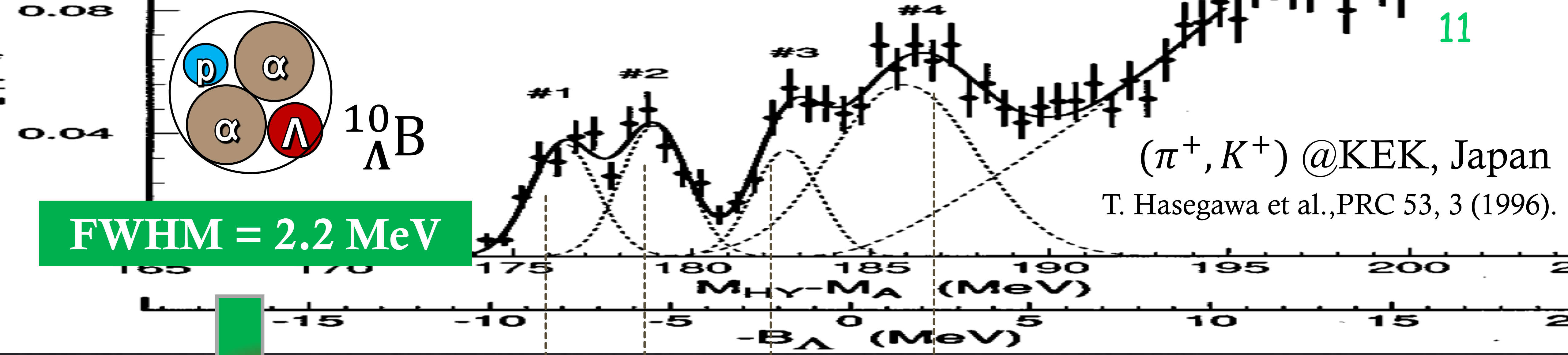
Implementation of
“**strangeness**” in baryon

Pair creation of
“**strangeness**” and
“**unti-strangeness**”



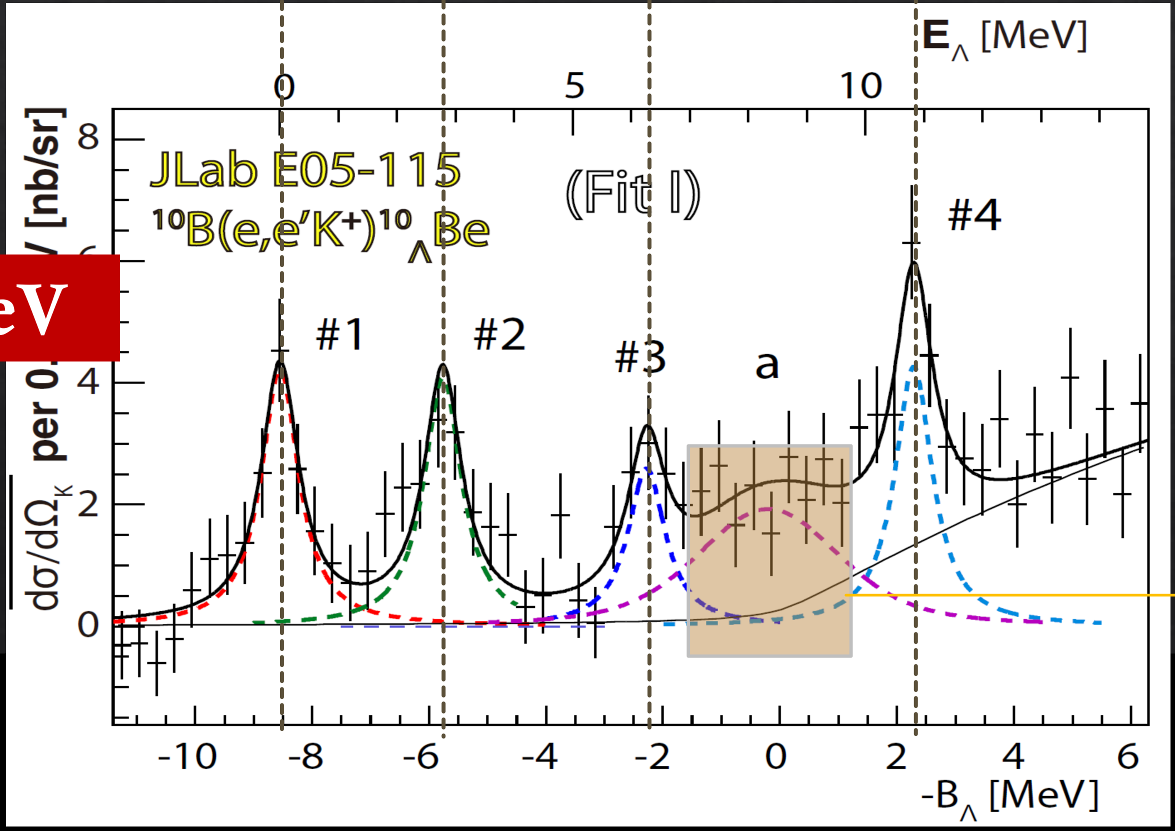
Hypernuclear production by electrons

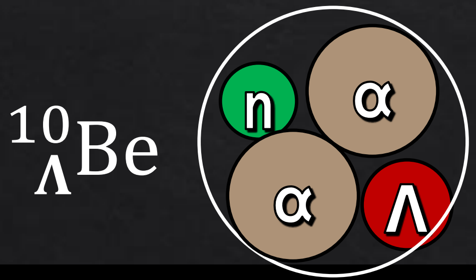




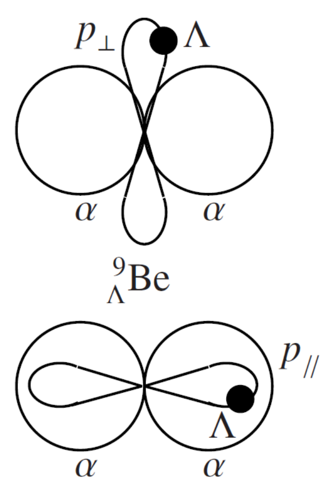
FWHM = 2.2 MeV

FWHM = 0.8 MeV





Cluster structure!!

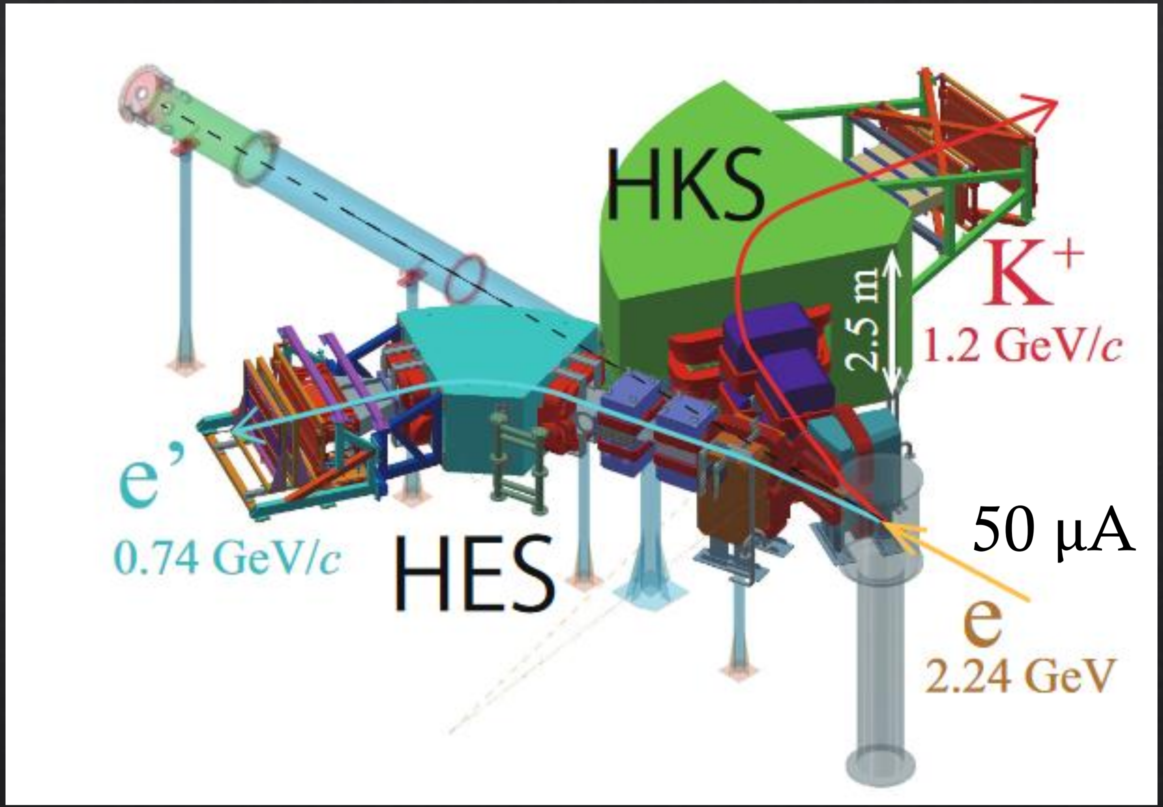


TG et al.,
PRC 93, 034314 (2016).

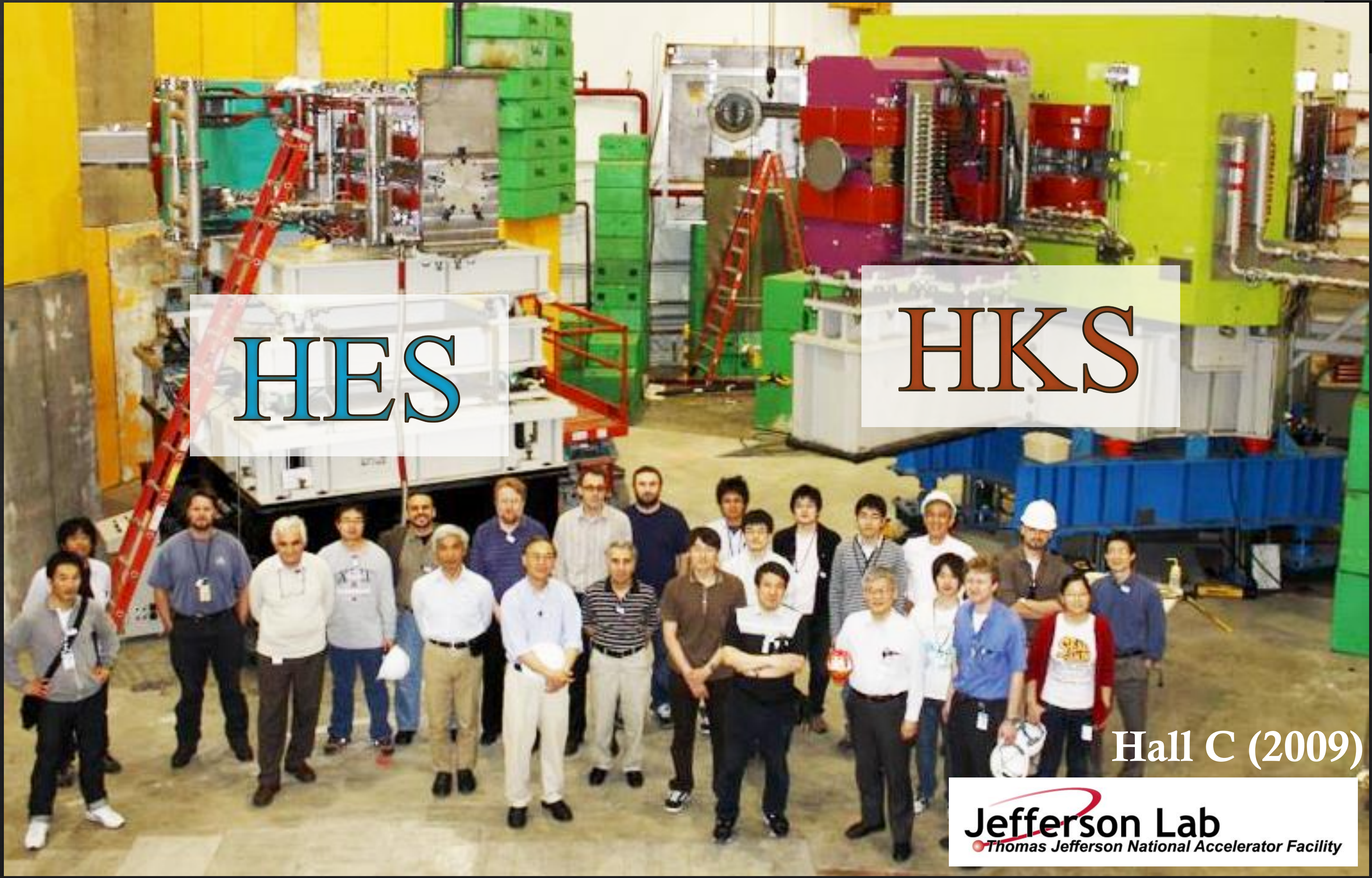
A. Umeya *et al.*, *J. Phys.: Conf. Ser.* **1643** 012110 (2020).

Next experiment at JLab Hall C (FY2026~)

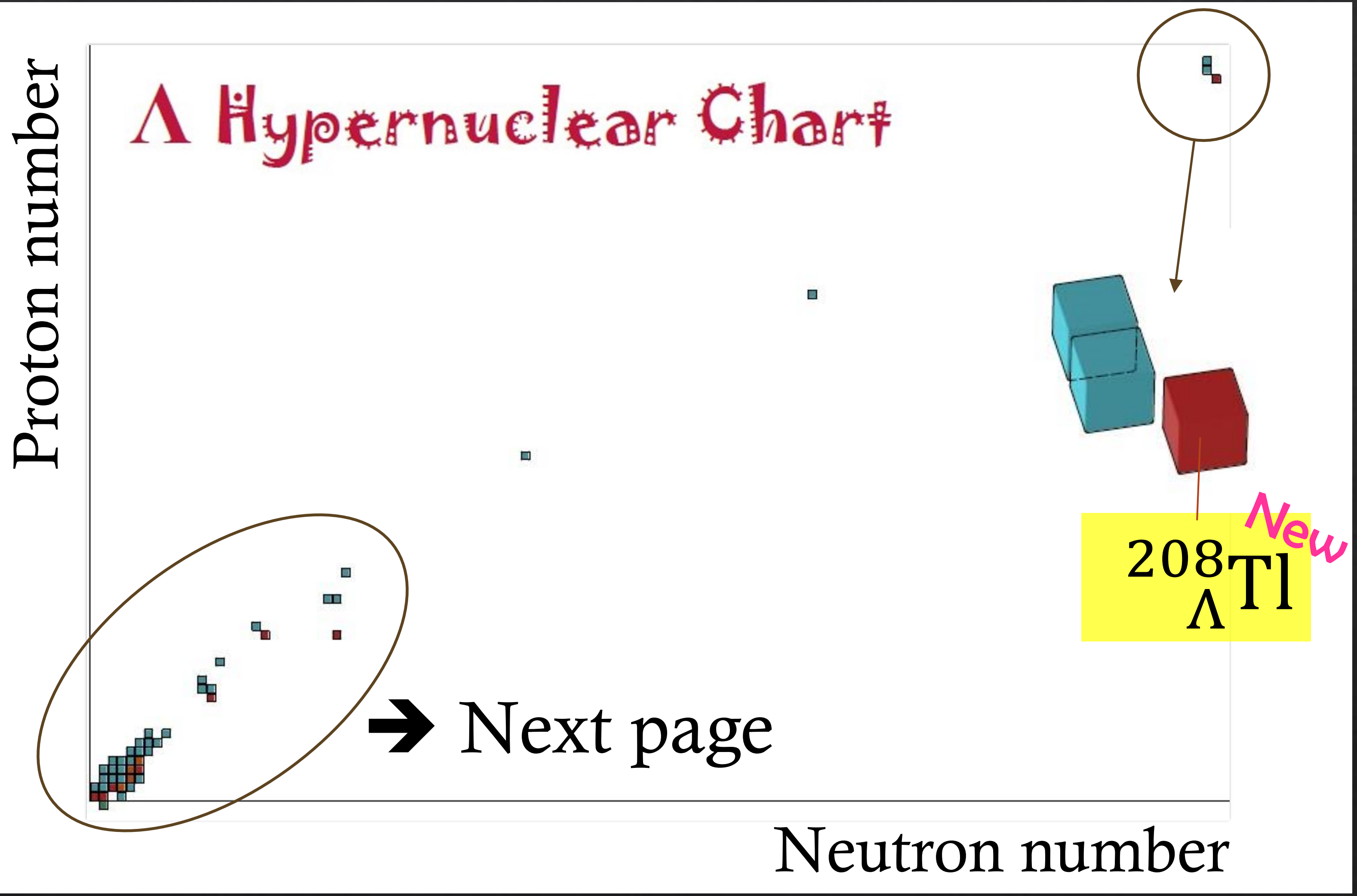
Steven Lassiter & Bert Metzger, JLab Hypernuclear Collaboration Meeting 2022, online, Dec 2022, https://wiki.jlab.org/tegwiki/index.php/Hypernuclear_CollaborationMeeting_2022Dec



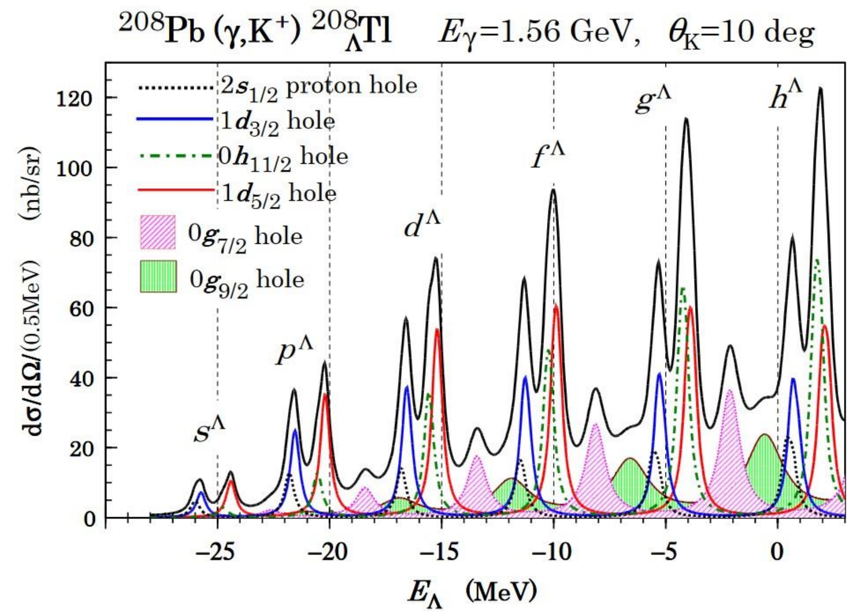
Schematic from LOI12-23-013 (TG et al., LoI to PAC51): https://researchmap.jp/gogami/published_papers/42361620/attachment_file.pdf


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

Next JLab experiments; light to heavy hypernuclei



T. Motoba, JPS Conf. Proc. 17, 011003 (2017)

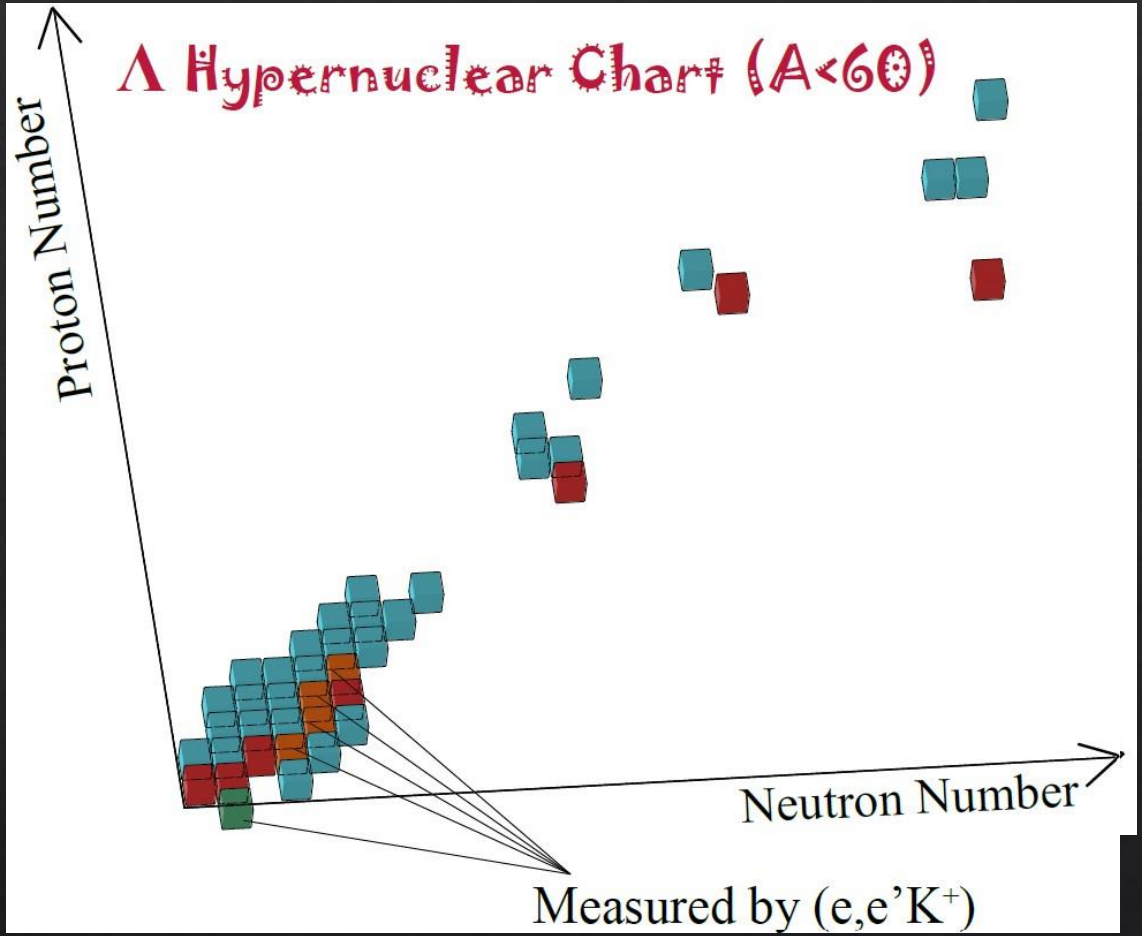


JLab E12-20-013

➔ ΛNN force

(F. Garibaldi et al., EPJ Web Conf. 271, 01007 (2022).)

Next JLab experiments; light to heavy hypernuclei

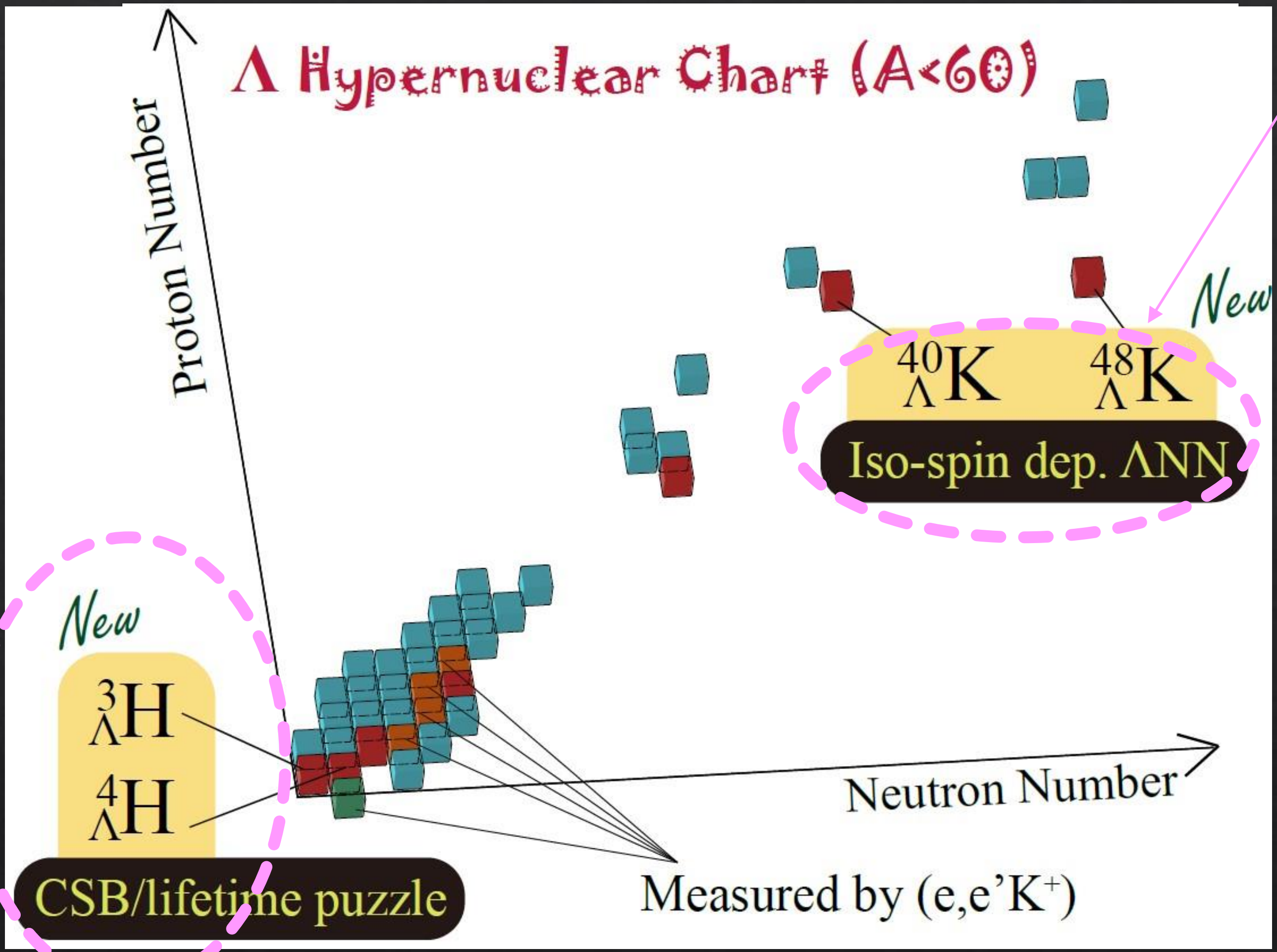


Next JLab experiments; light to heavy hypernuclei

Contact person
Prof. T. Gogami
(Kyoto Univ.)

E12-19-002

- Proposal → Link
- TG et al., EPJ Web Conf. 271, 01001 (2022).



E12-15-008

→ Link

Contact person
Prof. S. N. Nakamura
(U. Tokyo)

Next JLab experiments; light to heavy hypernuclei

New

LOI12-23-013

→ Link

Contact person
Prof. T. Gogami
(Kyoto Univ.)

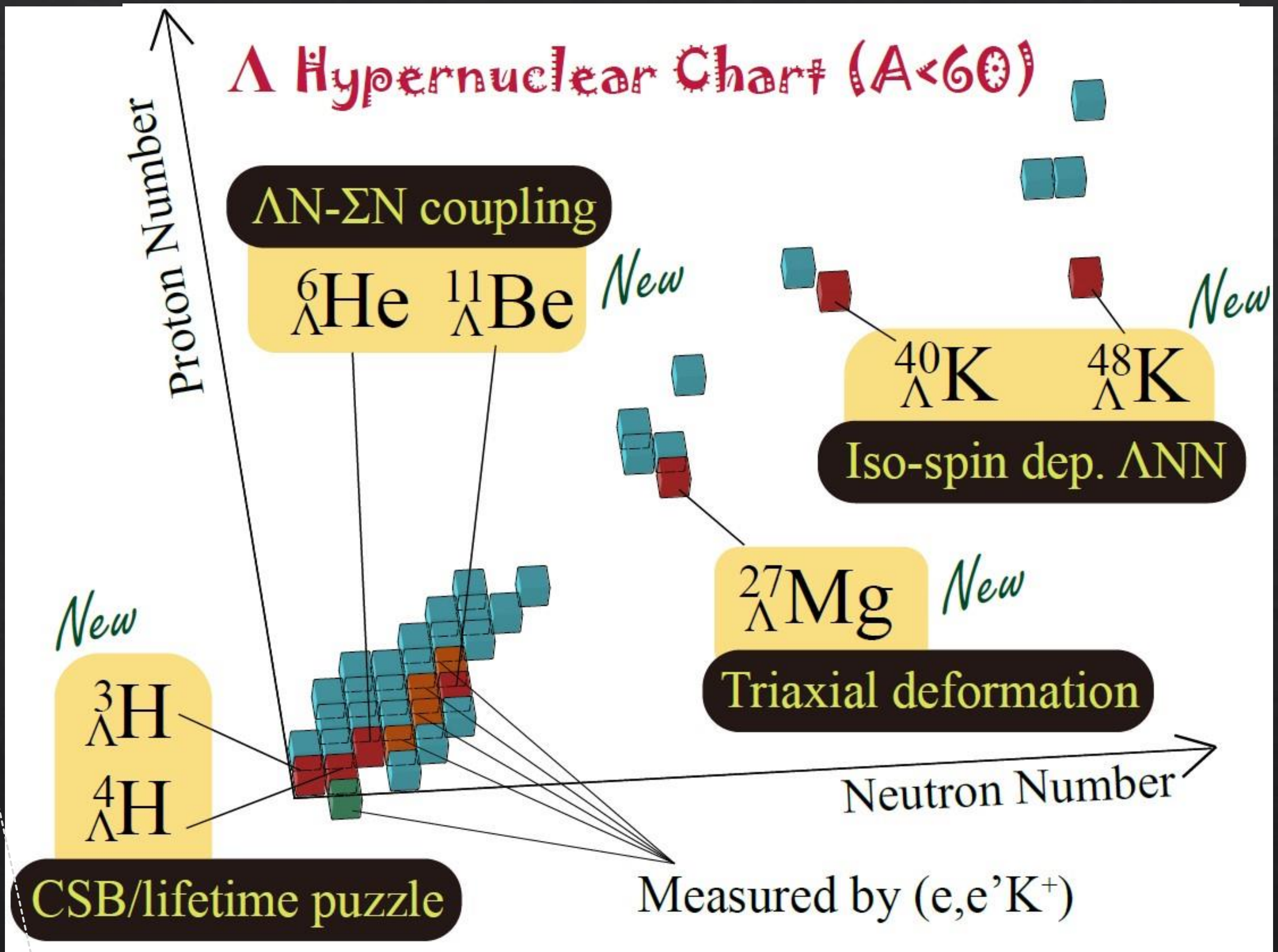
E12-19-002

- Proposal → Link
- TG et al., EPJ Web Conf. 271, 01001 (2022).

New

LOI12-23-011

Presentation by Prof. S. Nagao, "Mass Determination of Light Hypernuclei with the Decay Pion Spectroscopy: from MAMI to JLab", Hall A/C Summer meeting, June 30, 2023



Contact person
Prof. S. Nagao (U. Tokyo)

E12-15-008

→ Link

Contact person
Prof. S. N. Nakamura
(U. Tokyo)

New

LOI12-23-016

Presentation by Prof. M. Isaka, "Triaxial deformation of nuclei probed by Λ particle", Hall A/C Summer meeting, June 30, 2023

Charge Symmetry Breaking (CSB), the mystery

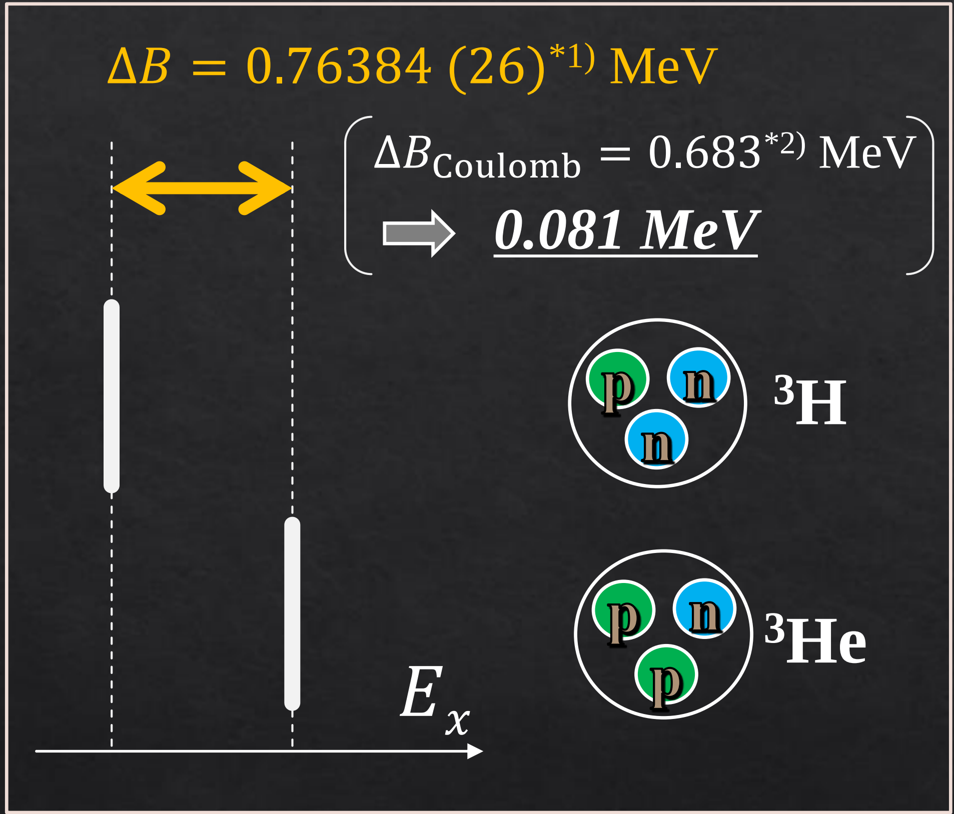
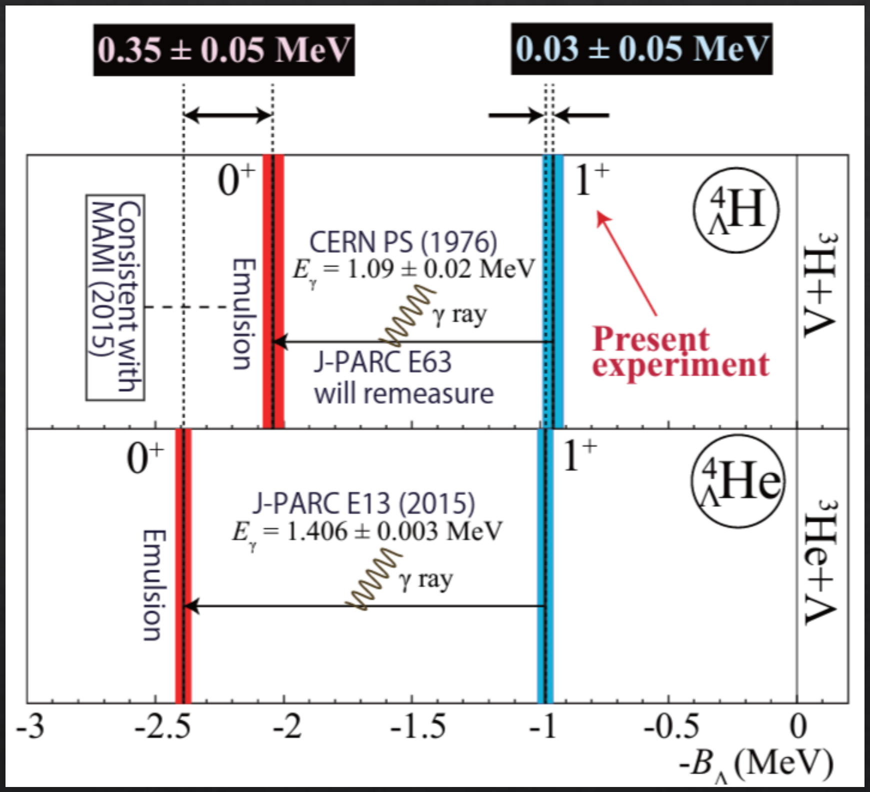


Figure from proposal of JLab E12-19-002



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

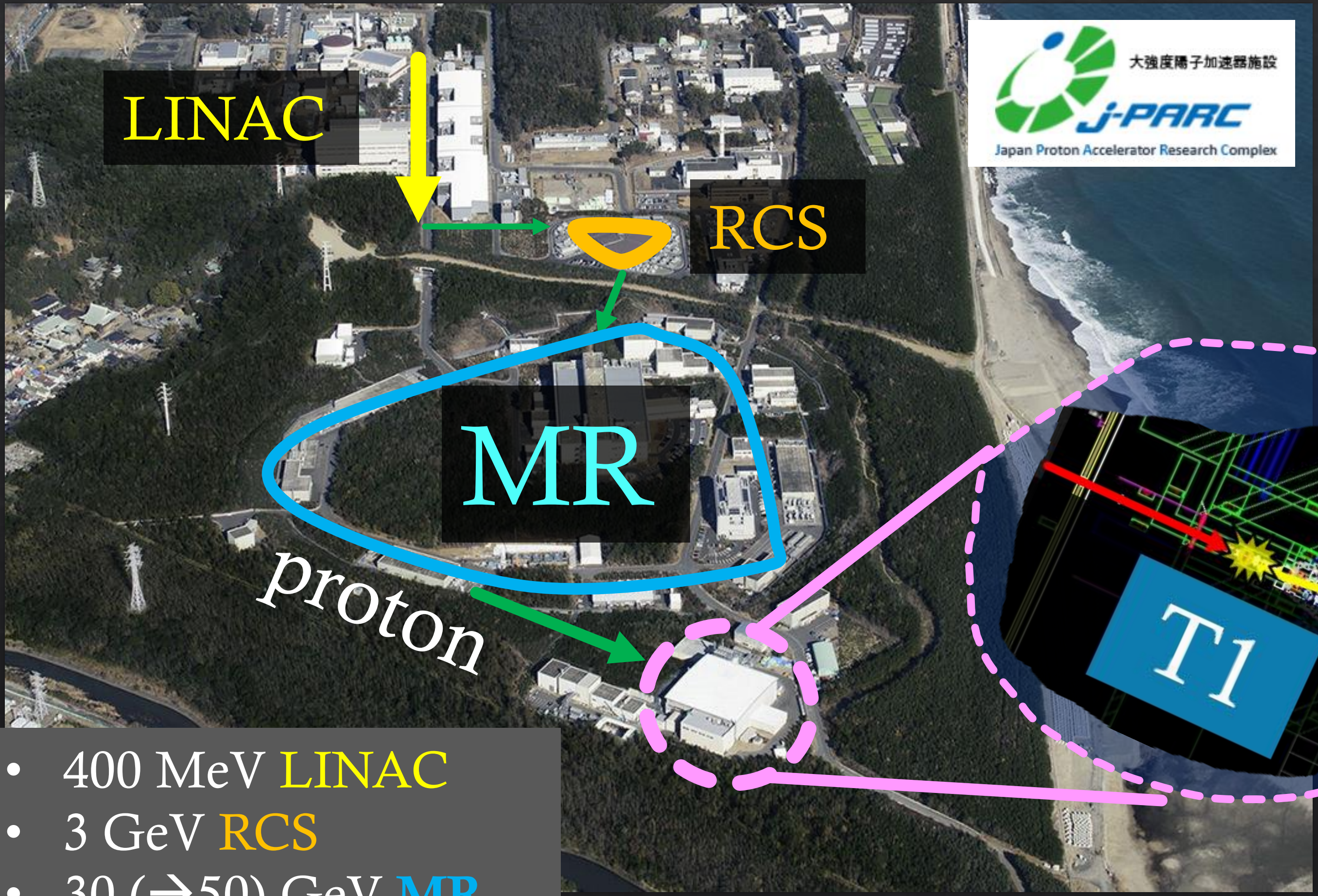
*2) R.A.Brandenburg, S.A.Coon *et al.*, *NPA***294,** 305 (1978).

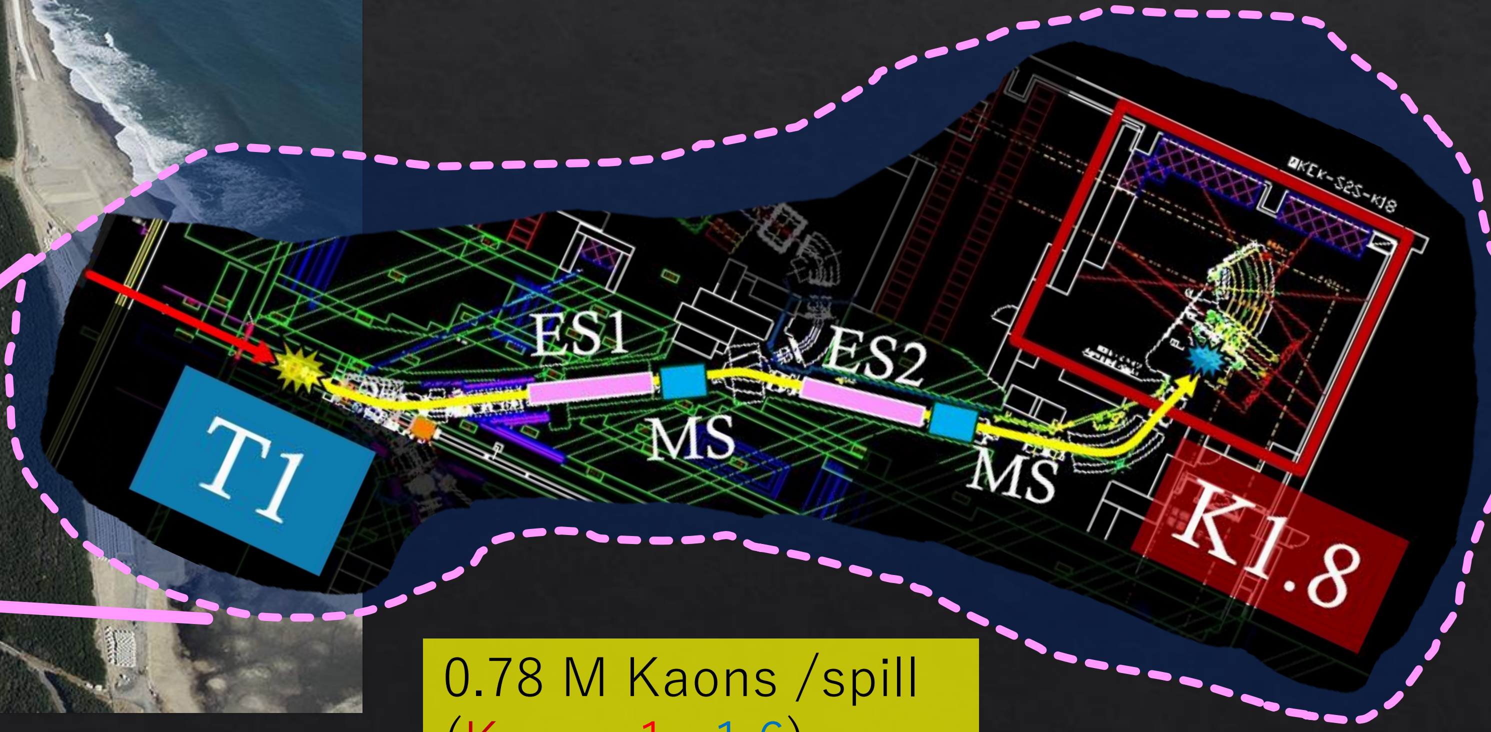
Data of other systems are necessary to pin down the origin of CSB

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

$^{A}Z(\pi^+, K^+)^{A}_{\Lambda}Z$

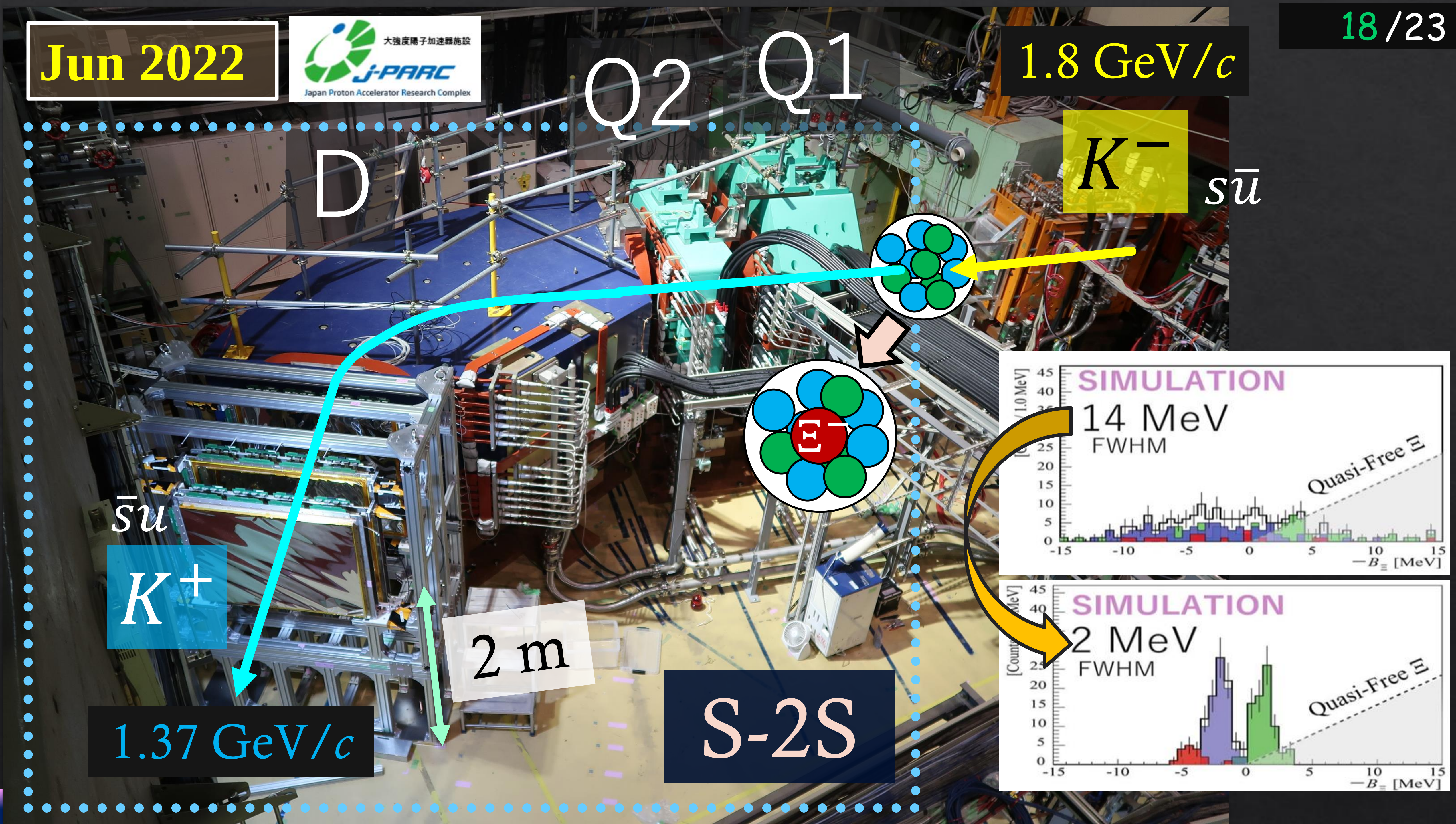
@K1.8 Beam line





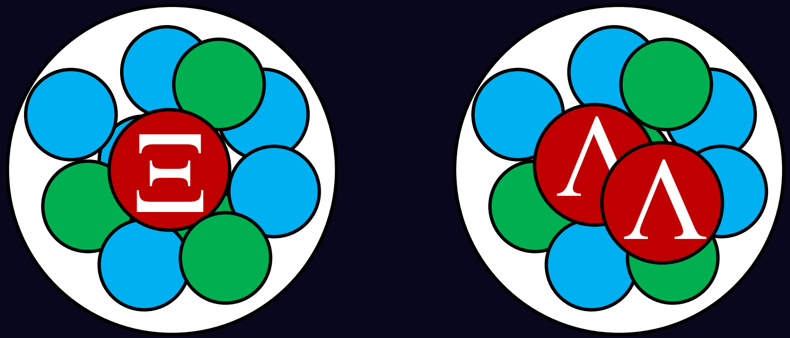
- 400 MeV LINAC
- 3 GeV RCS
- 30 (→50) GeV MR

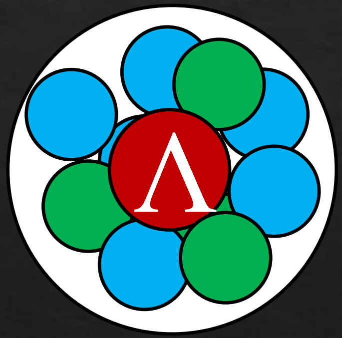
0.78 M Kaons /spill
(K : π =1 : 1.6)


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^-
$s\bar{u}$
Ξ^-
$\bar{s}u$
K^+
2 m
1.37 GeV/c
S-2S
SIMULATION
14 MeV
FWHM
Quasi-Free Ξ
$-B_\Xi$ [MeV]
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!





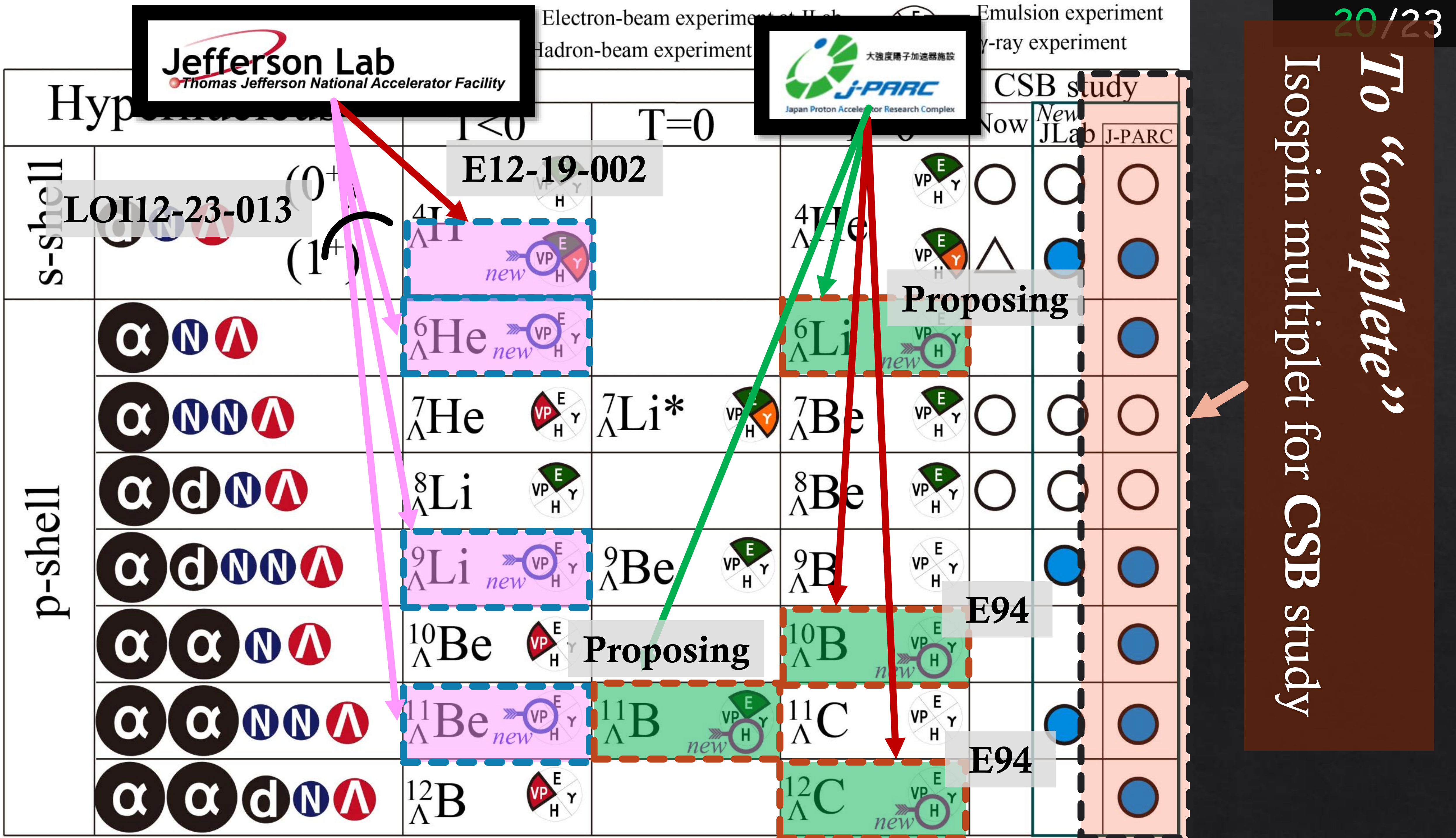
"S = −1" as well

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

Isospin multiplet for CSB study

Electron-beam experiment at JLab — VP
Hadron-beam experiment at J-PARC — H
Emulsion experiment — E
γ-ray experiment — γ

Hypernucleus			T<0	T=0	T>0	CSB study Now	CSB study New JLab	CSB study New J-PARC
s-shell	d N Λ	(0^+)	${}^{4}_{\Lambda}\mathrm{H}$		${}^{4}_{\Lambda}\mathrm{He}$	○	○	○
		(1^+)	new			△	●	●
p-shell	α N Λ		${}^{6}_{\Lambda}\mathrm{He}$ new		${}^{6}_{\Lambda}\mathrm{Li}$ new			●
	α N N Λ		${}^{7}_{\Lambda}\mathrm{He}$	${}^{7}_{\Lambda}\mathrm{Li}^*$	${}^{7}_{\Lambda}\mathrm{Be}$	○	○	○
	α d N Λ		${}^{8}_{\Lambda}\mathrm{Li}$		${}^{8}_{\Lambda}\mathrm{Be}$	○	○	○
	α d N N Λ		${}^{9}_{\Lambda}\mathrm{Li}$ new	${}^{9}_{\Lambda}\mathrm{Be}$	${}^{9}_{\Lambda}\mathrm{B}$		●	●
	α α N Λ		${}^{10}_{\Lambda}\mathrm{Be}$		${}^{10}_{\Lambda}\mathrm{B}$ new			●
	α α N N Λ		${}^{11}_{\Lambda}\mathrm{Be}$ new	${}^{11}_{\Lambda}\mathrm{B}$ new	${}^{11}_{\Lambda}\mathrm{C}$		●	●
	α α d N Λ		${}^{12}_{\Lambda}\mathrm{B}$		${}^{12}_{\Lambda}\mathrm{C}$ new			●

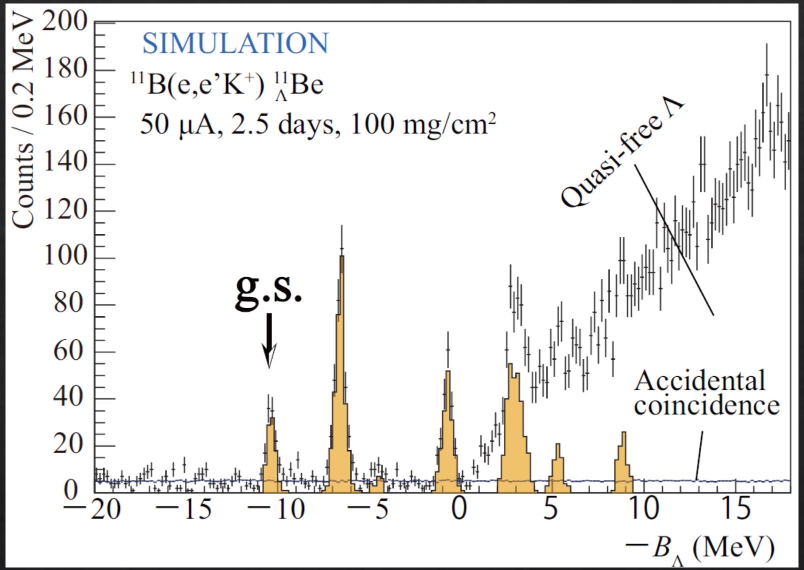

Jefferson Lab
Thomas Jefferson National Accelerator Facility
Electron-beam experiment at JLab
Hadron-beam experiment
Emulsion experiment
γ-ray experiment
大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex
Hypernucleus
T<0
T=0
T>0
CSB study
Now
New JLab
J-PARC
E12-19-002
LOI12-23-013
s-shell
p-shell
(0+)
(1+)
$^4_\Lambda$H
$^4_\Lambda$He
$^6_\Lambda$He
$^6_\Lambda$Li
$^7_\Lambda$He
$^7_\Lambda$Li*
$^7_\Lambda$Be
$^8_\Lambda$Li
$^8_\Lambda$Be
$^9_\Lambda$Li
$^9_\Lambda$Be
$^9_\Lambda$B
$^{10}_\Lambda$Be
$^{10}_\Lambda$B
$^{11}_\Lambda$Be
$^{11}_\Lambda$B
$^{11}_\Lambda$C
$^{12}_\Lambda$B
$^{12}_\Lambda$C
new
Proposing
Proposing
E94
E94
To "complete"
Isospin multiplet for CSB study

High resolution spectroscopy at J-PARC and JLab

$^{11}_{\Lambda}$Be

Jefferson Lab — Thomas Jefferson National Accelerator Facility

LOI12-23-013



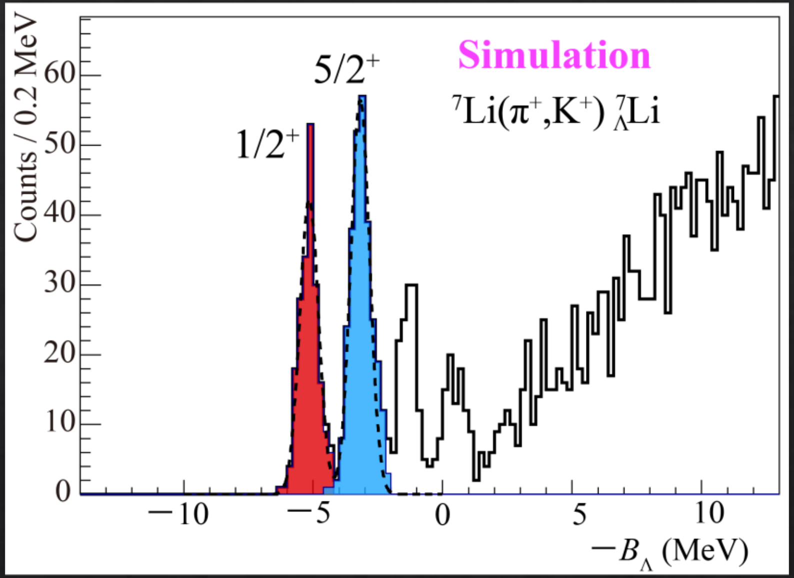
60 hours

0.6 MeV (FWHM)

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

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

E94

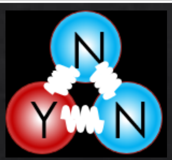


80 hours

1 MeV (FWHM)

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

***nn*Λ bound puzzle**

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

Many Body effect
(Cluster, deformation)

Neutron star puzzle

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

***nn*Λ bound puzzle**

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

- YN scat. exp.
- Femotoscopy

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

Many Body effect
(Cluster, deformation)

- Space observation
- Graviton wave meas.

Neutron star puzzle

J-PARC E63

J-PARC E94

JLab LOI12-23-013

- YN scat. exp.
- Femotoscopy

CSB

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

***nnΛ* 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		ΛN-ΣN	
-2		ΞN-ΛΛ	

JLab LOI12-23-016

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

J-PARC E63

J-PARC E94

JLab LOI12-23-013

CSB

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

JLab E12-19-002

JLab LOI12-23-011

*nn*Λ bound puzzle

Invariant mass spectroscopy

- YN scat. exp.

Hypernuclear scpectroscopy at JLab is the most important research activity in studying the Baryon-Baryon interaction, solving various "strange" puzzles.

- Space observation
- Graviton wave meas.

J-PARC E70

J-PARC E75

J-PARC E96

→ Good topics for students' theses

Feel free to contact me (us)

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 ($^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{6}_{\Lambda}$He, $^{11}_{\Lambda}$Be, $^{27}_{\Lambda}$Mg, $^{40}_{\Lambda}$K, $^{48}_{\Lambda}$K, $^{208}_{\Lambda}$Tl)
  - hypertriton puzzle (biding energy vs. lifetime)
  - Charge symmetry breaking
  - Deformation
  - ΛN-ΣN coupling
  - iso-spin dependence of ΛNN force

Mar 3, 2023

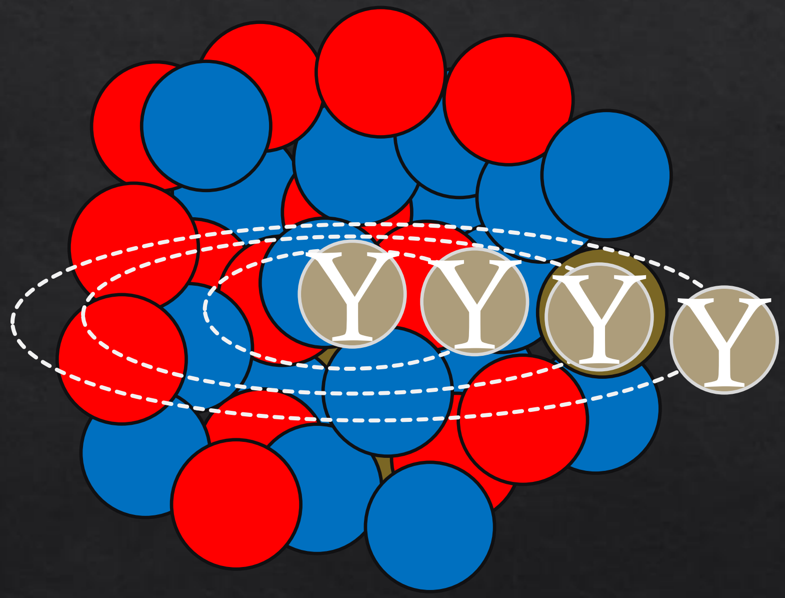
Hypernuclear Physics Workshop:

https://indico.jlab.org/event/685/

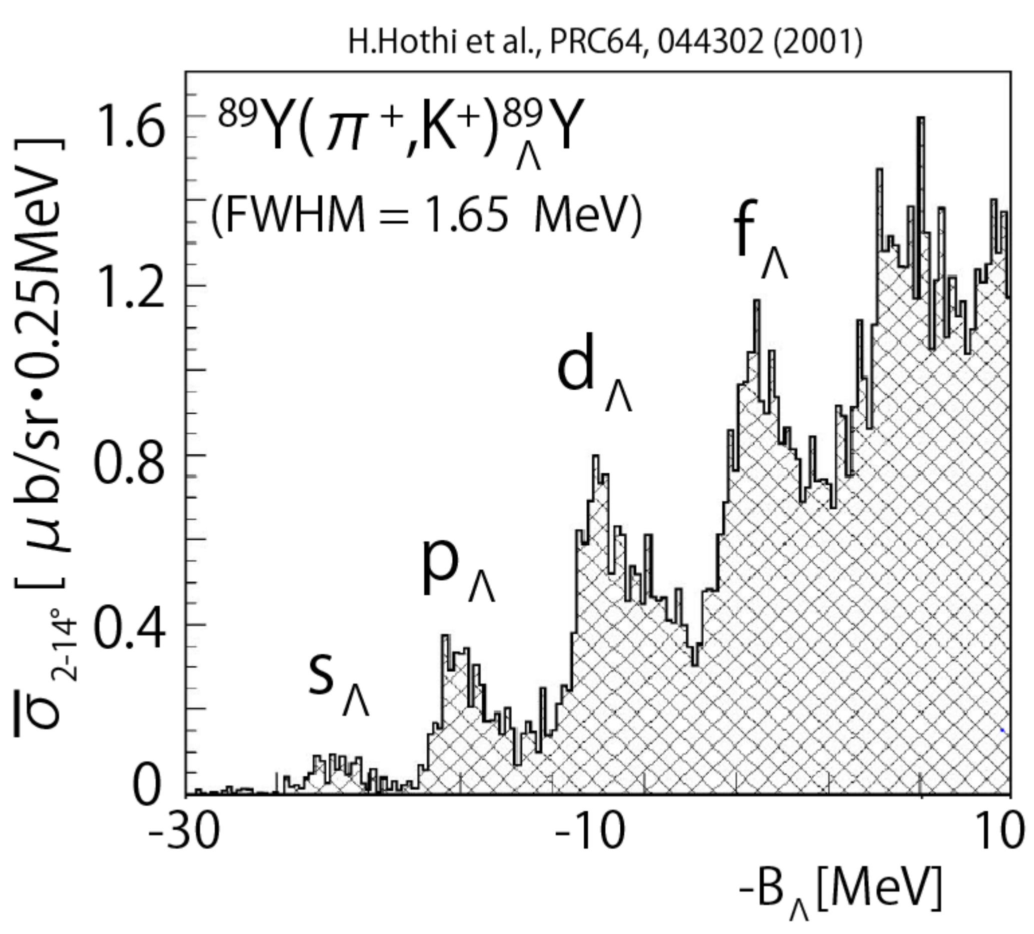
Thank you for your attention!

Backup

Text book like example; shell structure

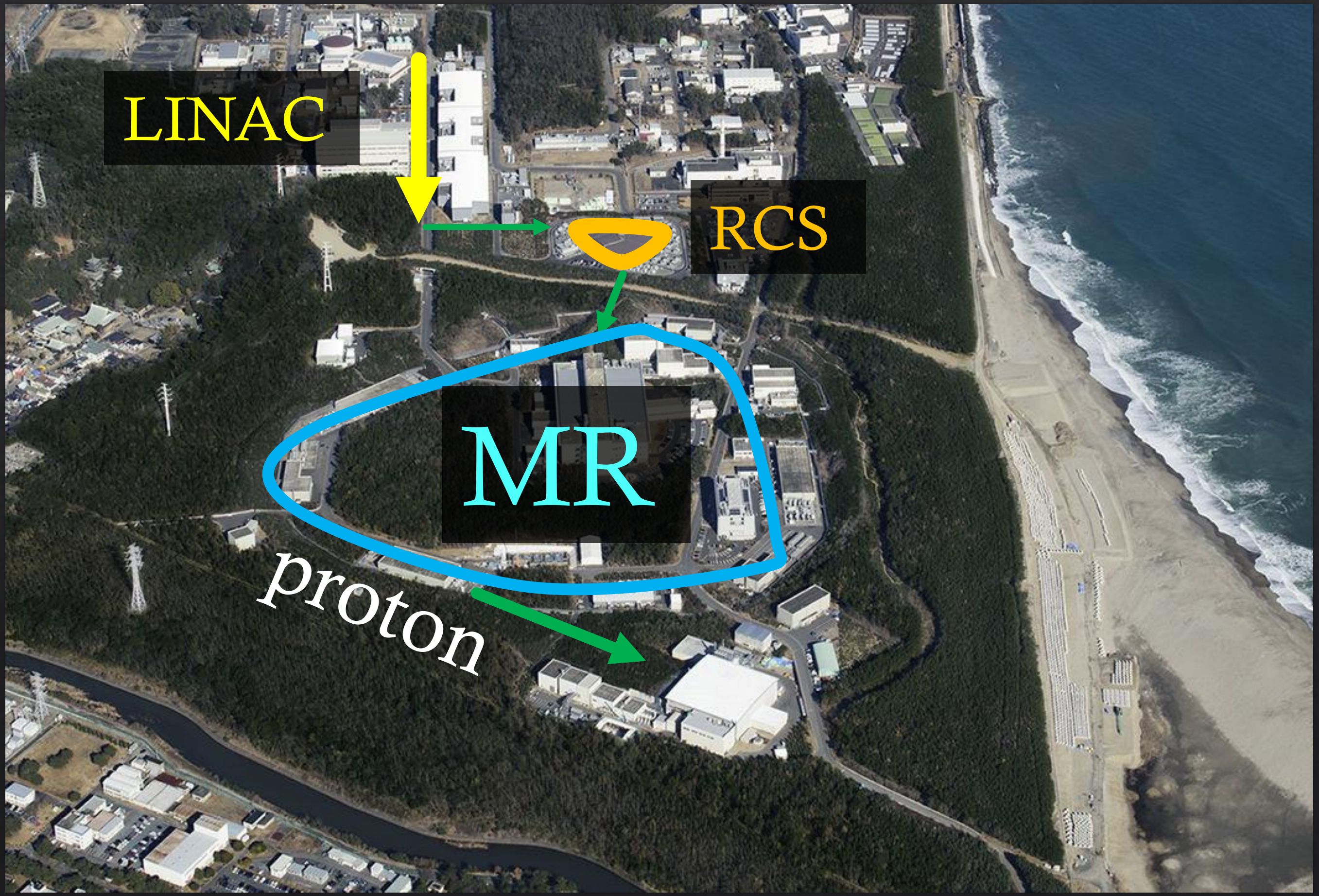


$$\Delta t \times \Delta E \geq \hbar$$



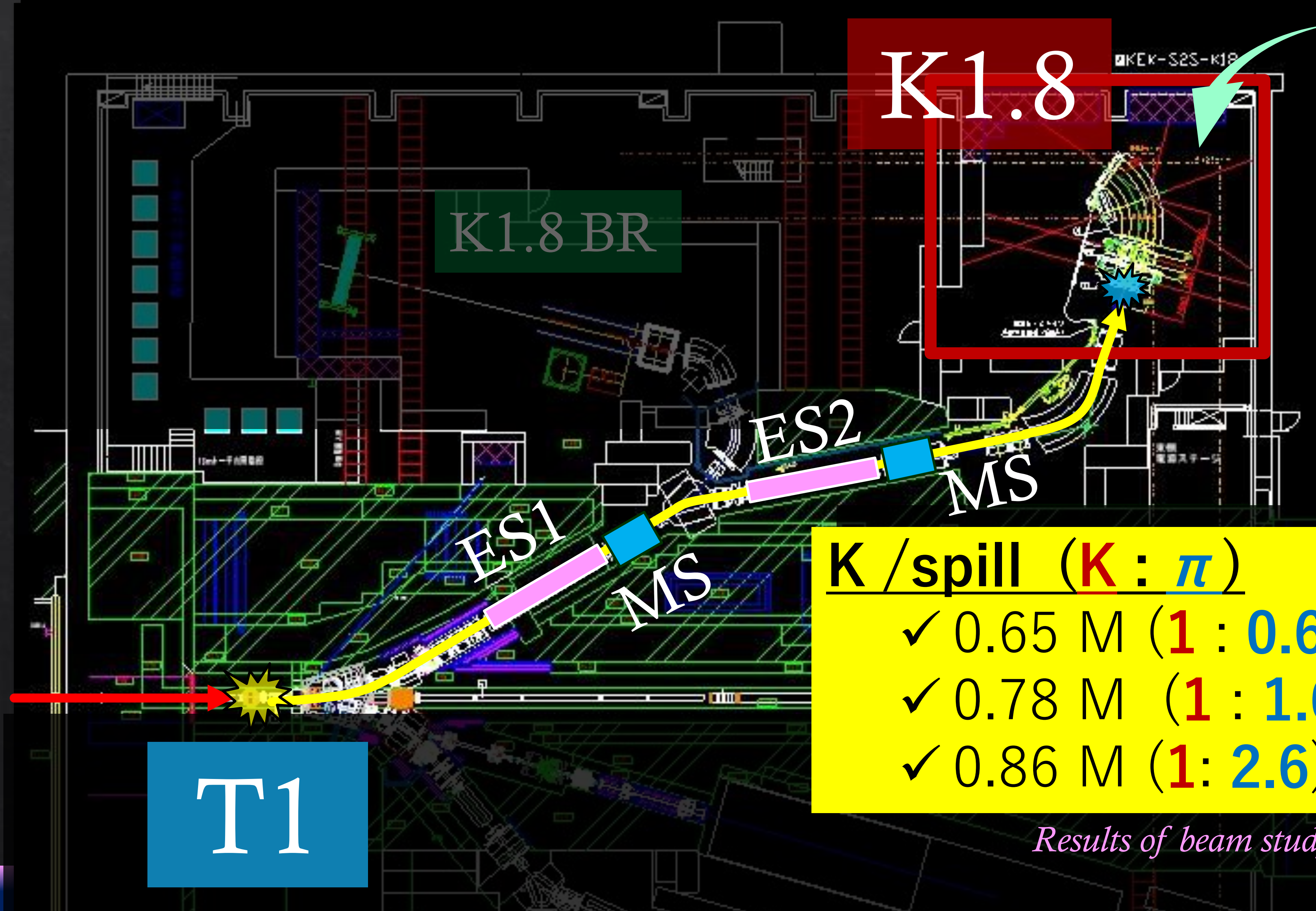
Deep inside nucleus

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



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

Strangeness −2 Spectrometer (S-2S) at K1.8

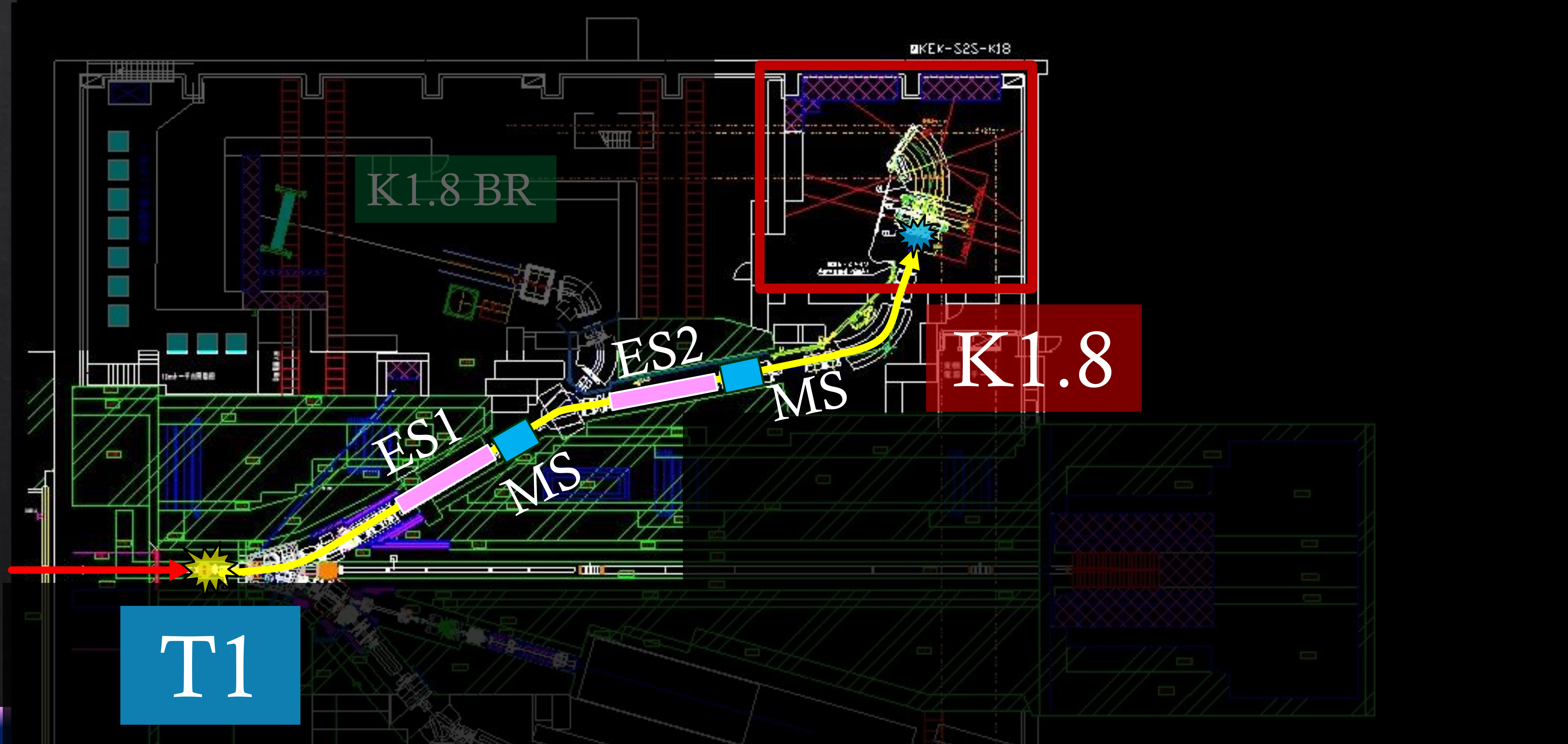


K /spill (K : π)

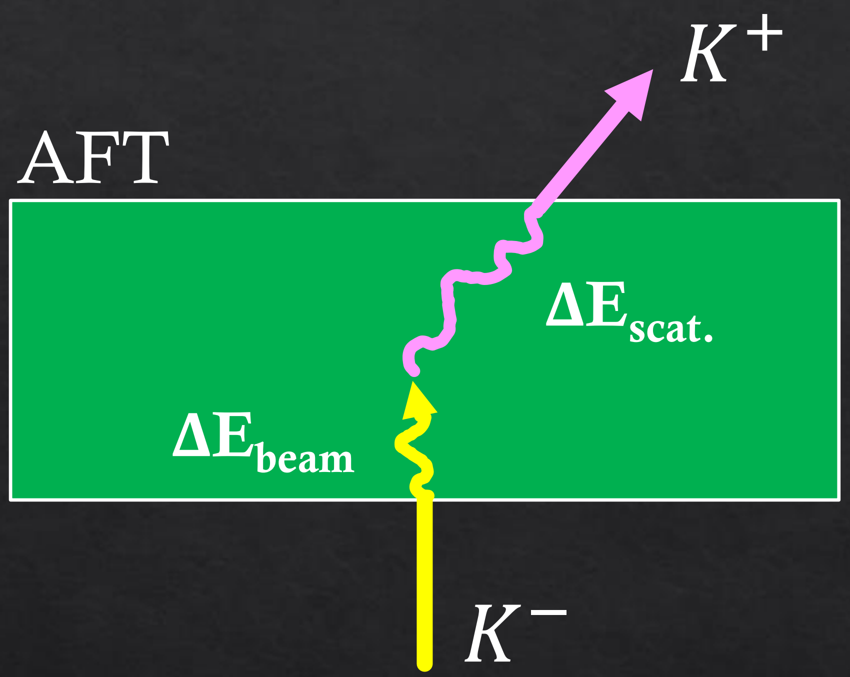
- ✓ 0.65 M (1 : 0.6)
- ✓ 0.78 M (1 : 1.6)
- ✓ 0.86 M (1: 2.6)

Results of beam study (2021)

Strangeness −2 Spectrometer (S-2S) at K1.8

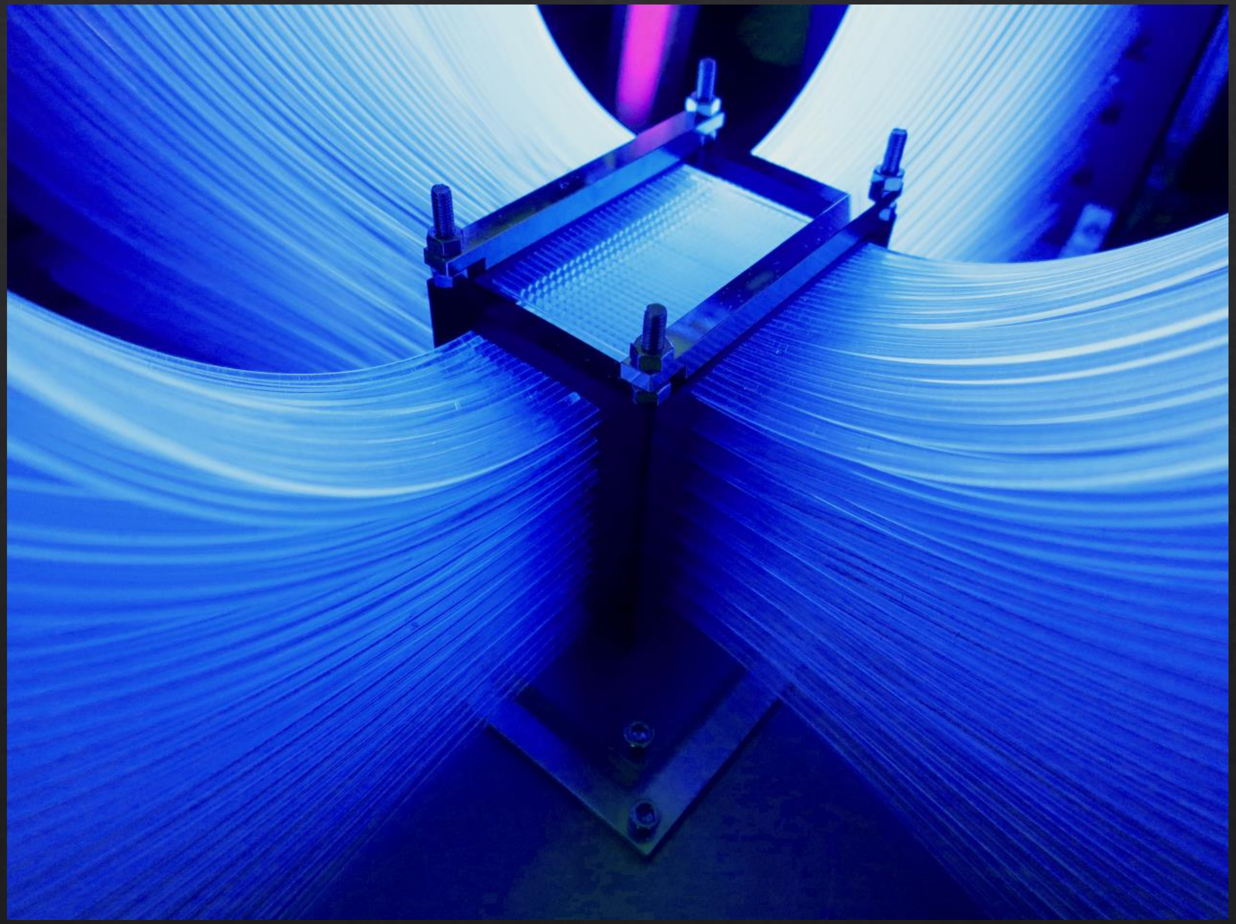


Direct measurement of energy loss in target



Thick target …
→ But, high resolution!!

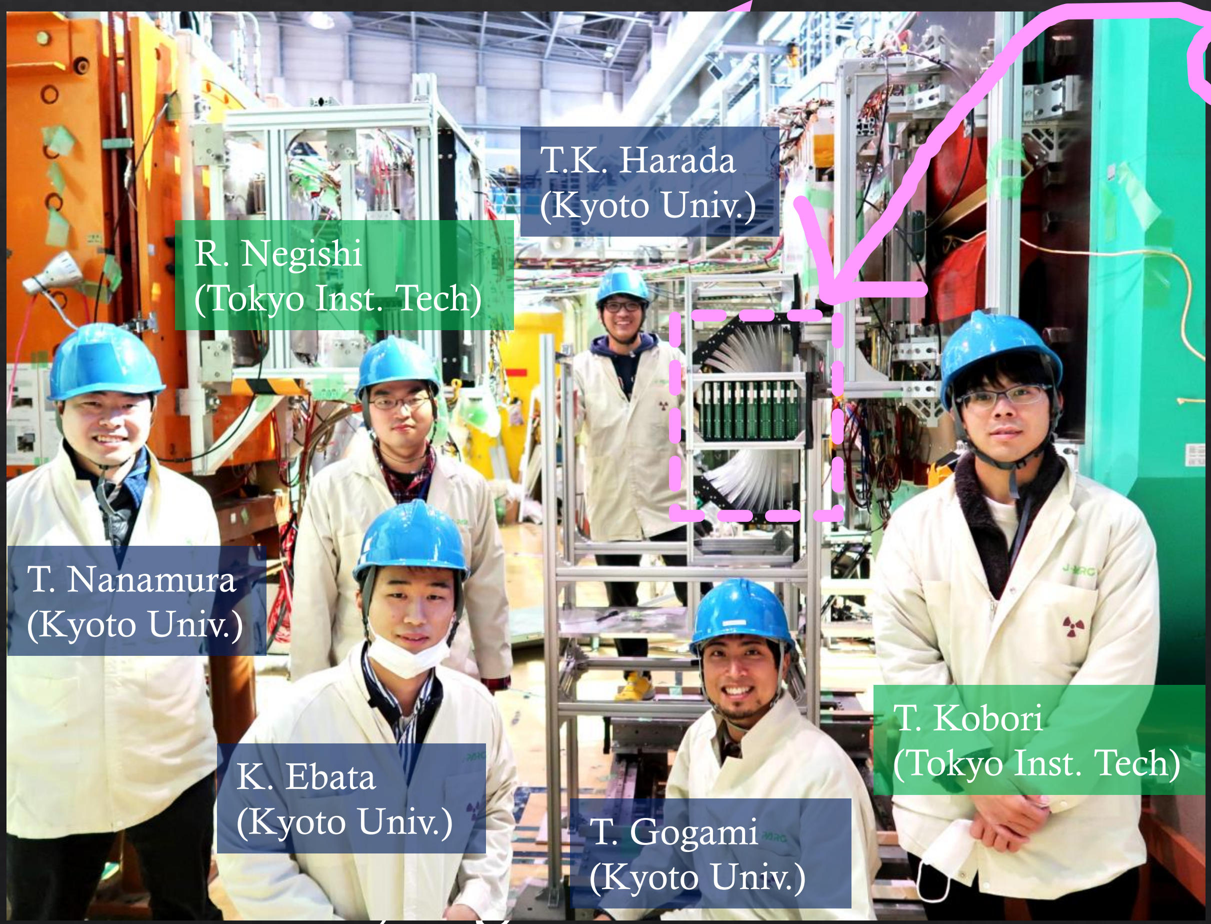
T. K. Harada, EPJ Web Conf. 271 (2022) 03006

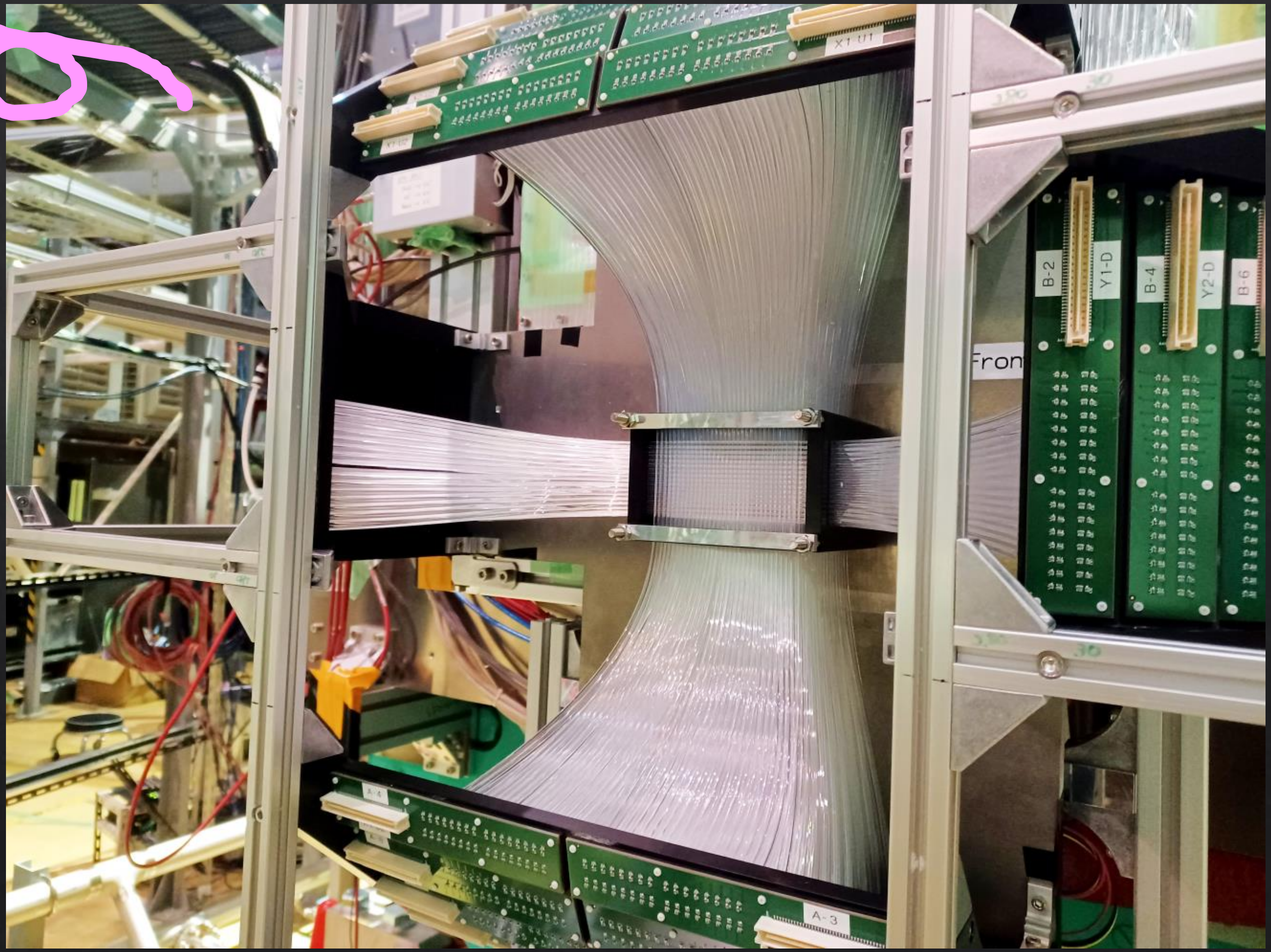


~900-ch of scintillation fibers (CH)

Direct measurement of energy loss in target

T. K. Harada, EPJ Web Conf. 271 (2022) 03006

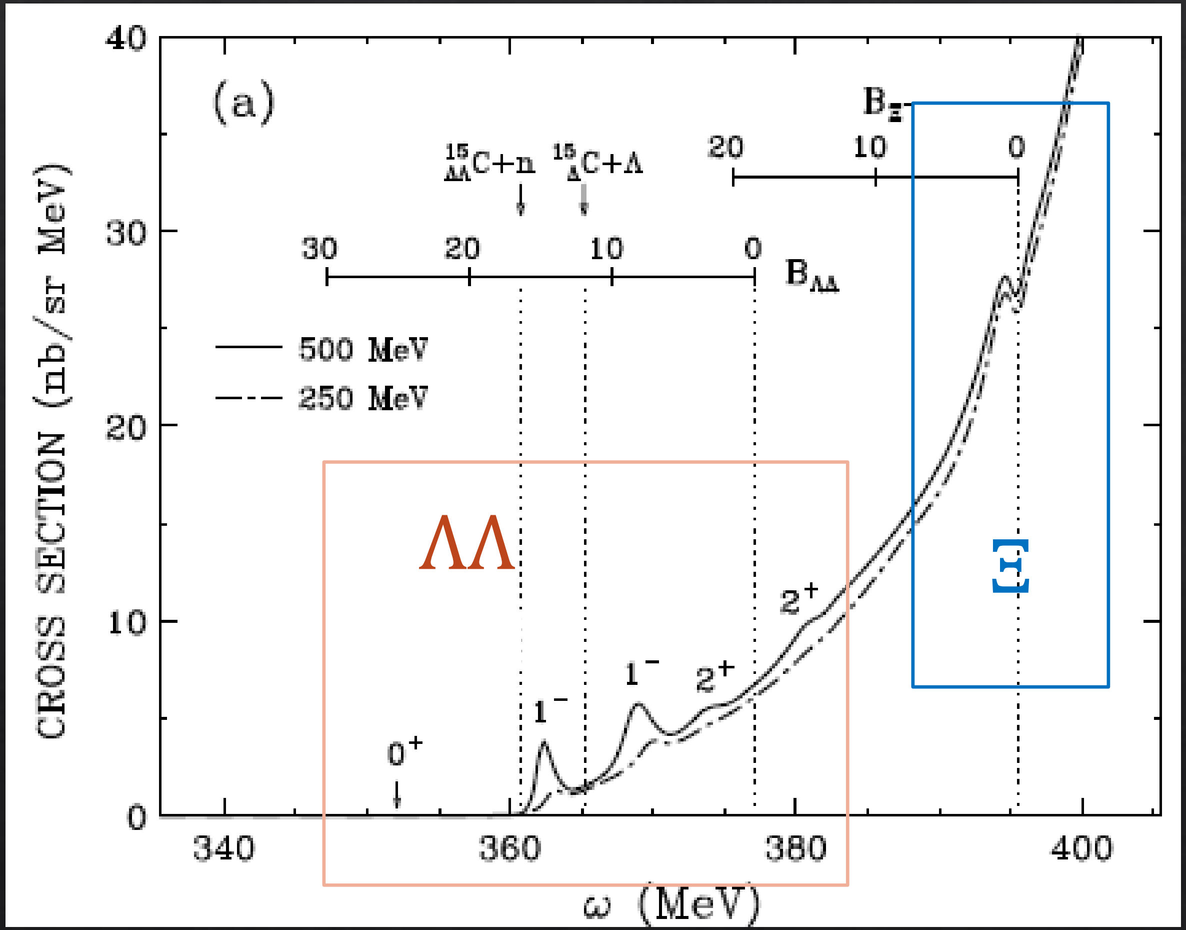


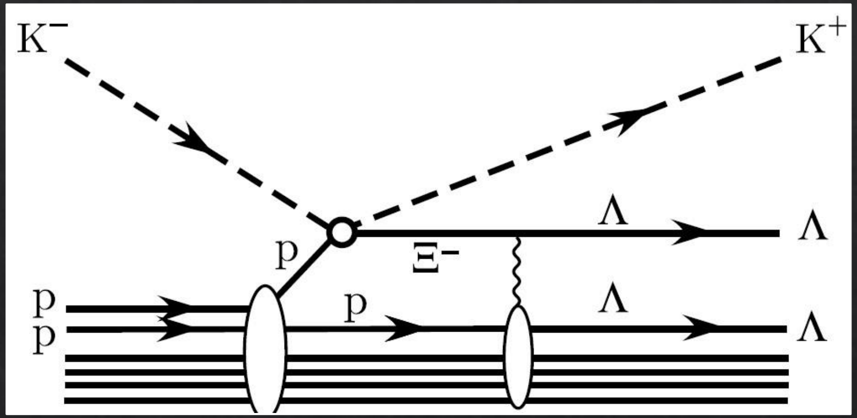


(Feb 16, 2023)

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

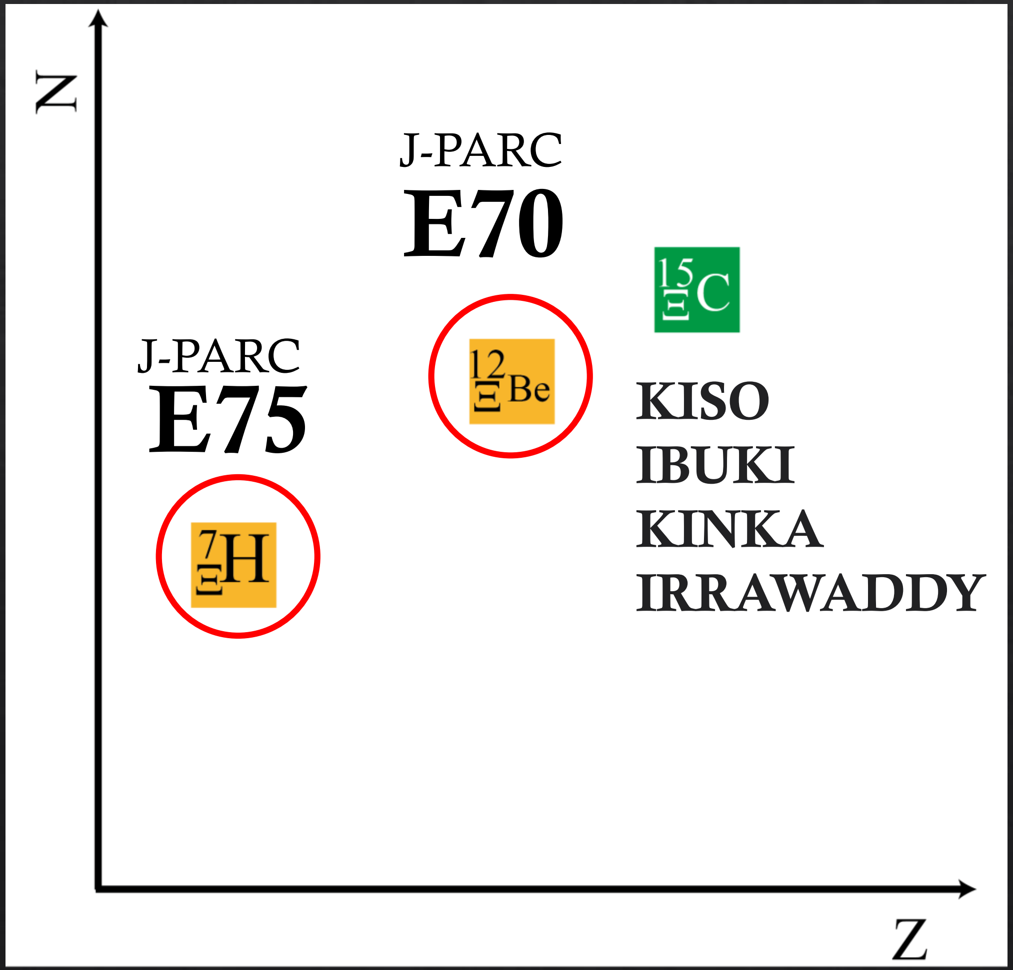
T. Harada, Y. Hirabayashi, A. Umeya, NPA 914, 85—90 (2013)

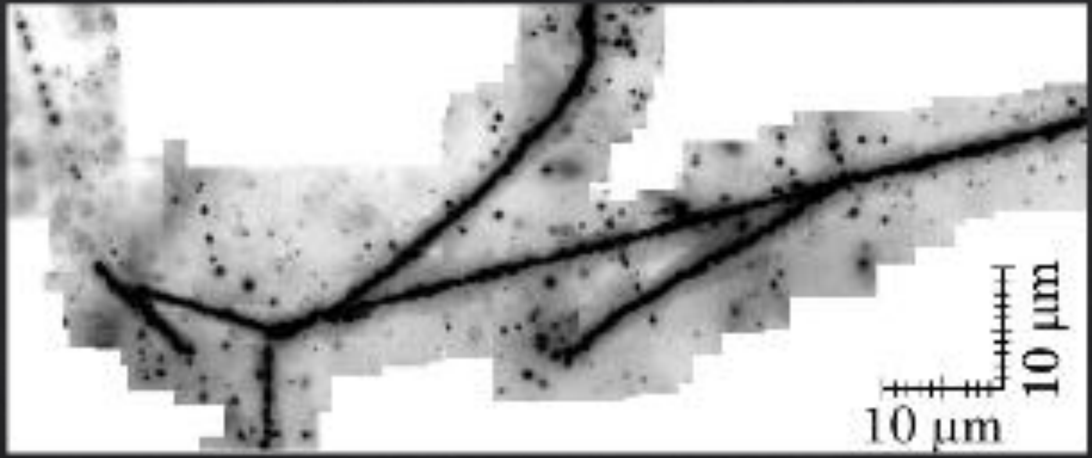




ΛΛ hypernuclei may be observed

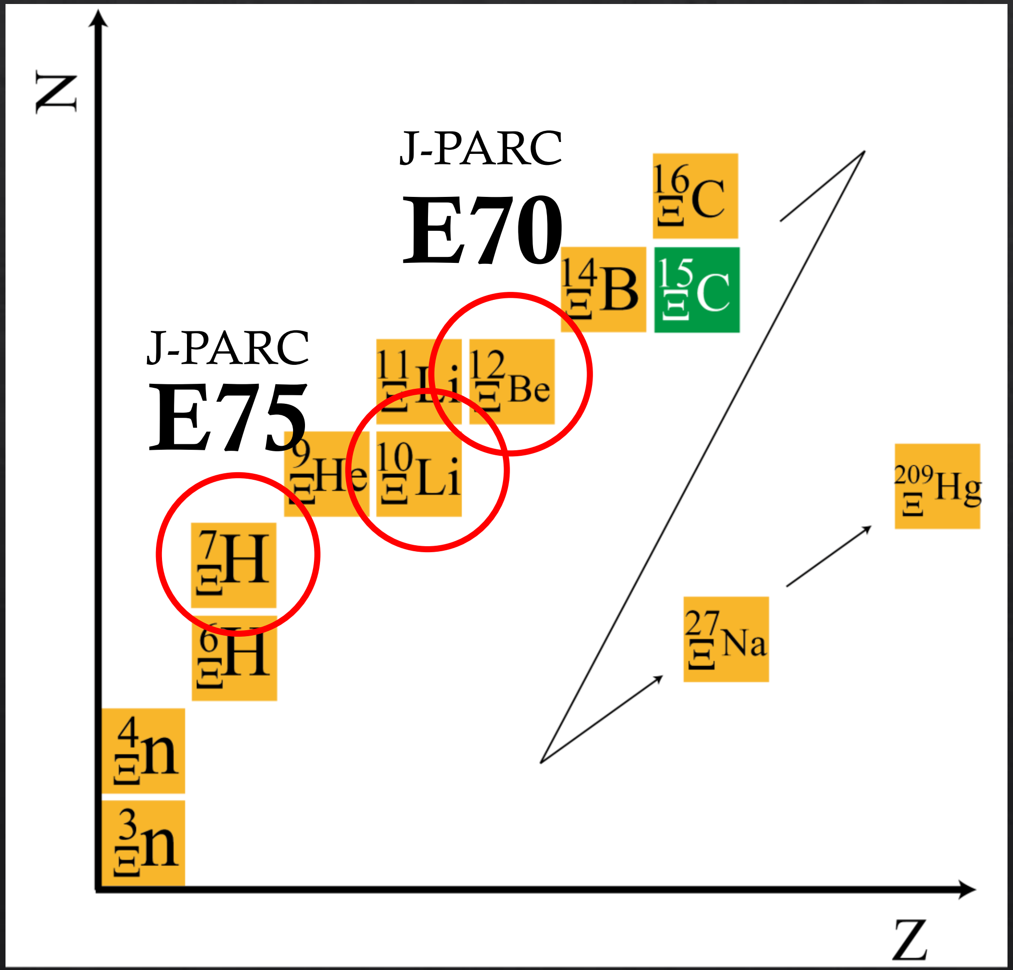
Hypernuclear chart ($S = -2$ floor)

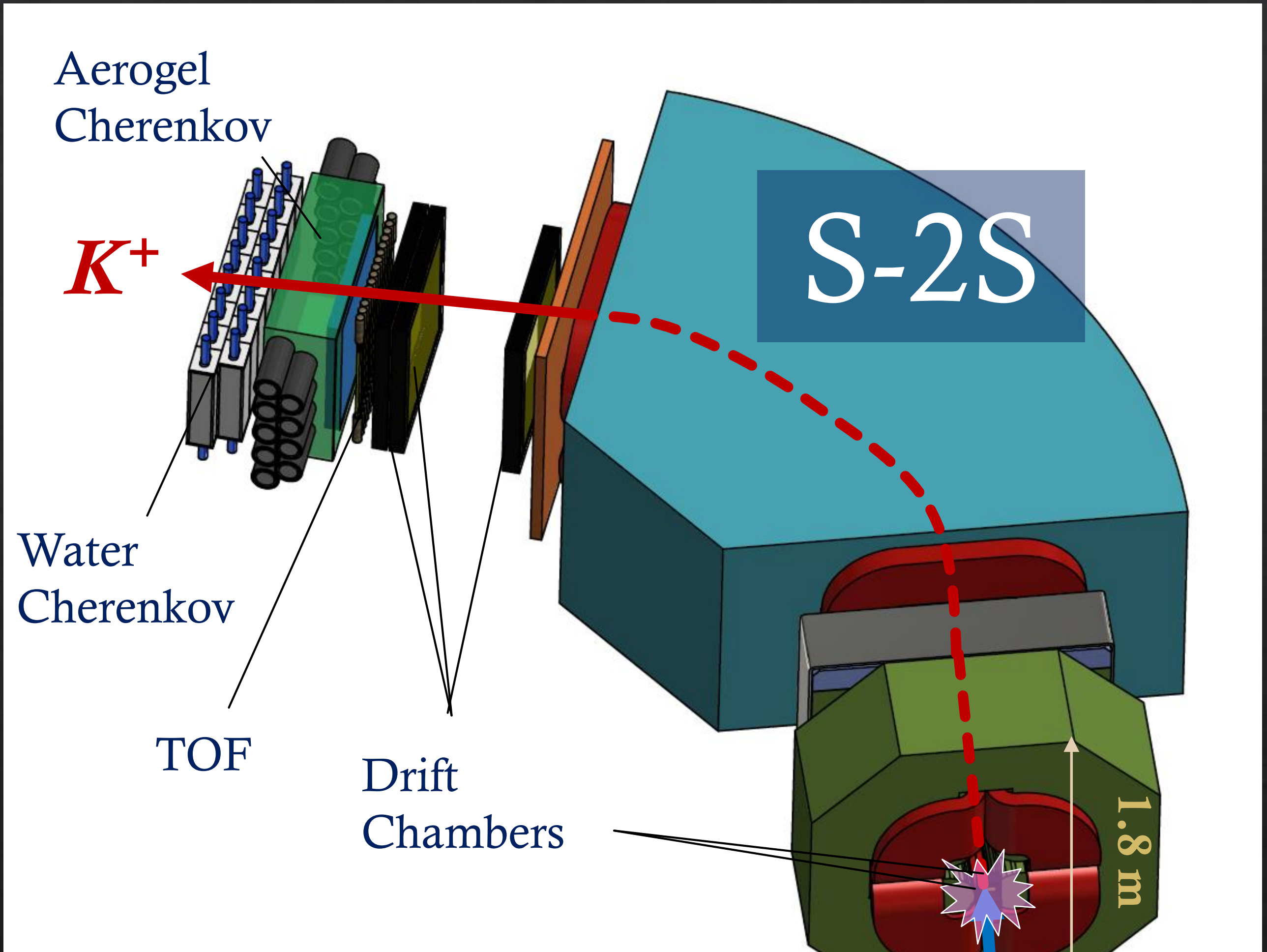




- K. Nakazawa et al., PTEP 2015, 033D02 (2015)
- M. Yoshimoto et al., PTEP 2021, 073D02 (2021)
- S. Hayakawa et al., PRL 126, 062501 (2021)

Hypernuclear chart ($S = -2$ floor)



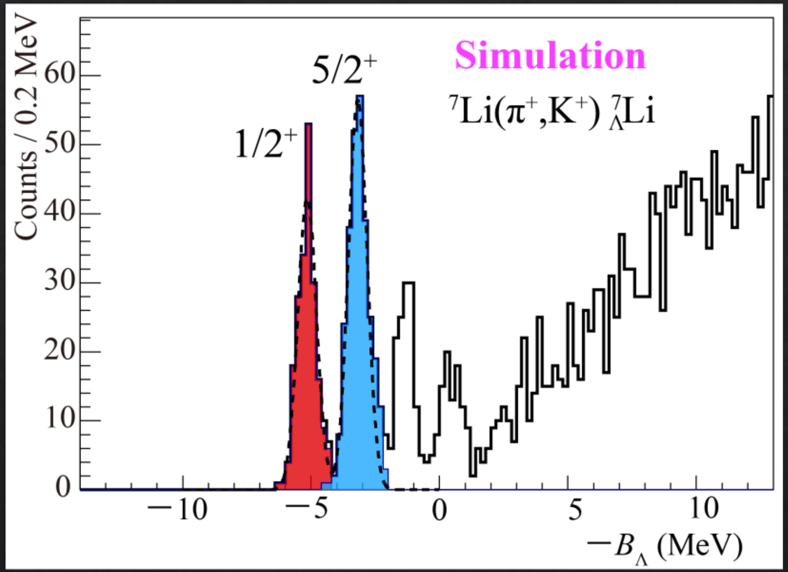


- Water-Cherenkov detector + PID: NIMA 817, 70-84 (2016).
- Recent preparation status: *J. Phys.: Conf. Ser.* **1643** 012133 (2020).

J-PARC E94

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

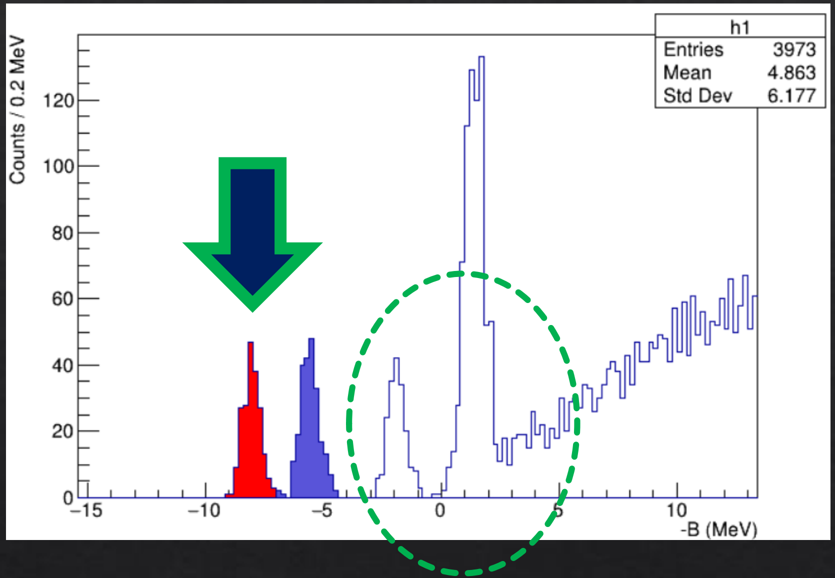
80 hours



Calibration

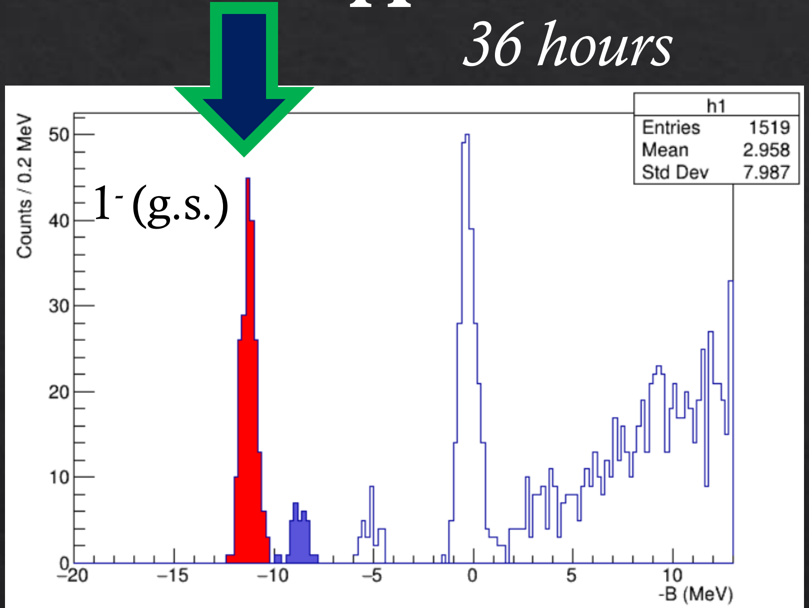
$^{10}_{\Lambda}\mathrm{B}$

112 hours



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

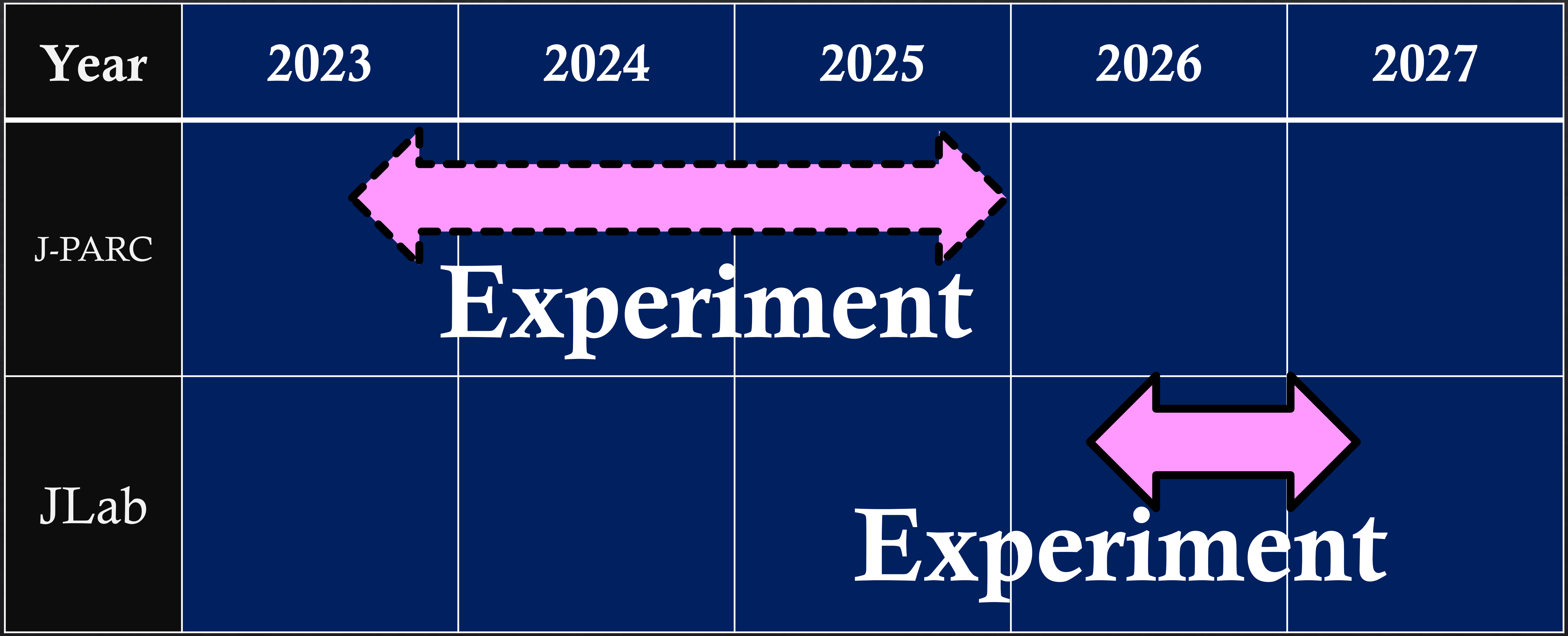
36 hours



Statistical error for the first peak:

$$\left|\Delta B_{\Lambda}^{stat.}\right| < 0.04\ \mathrm{MeV}$$

Schedule of the next experiments



Short summary

JLab (HES-HKS, 0.6 MeV FWHM, 70 keV accuracy, 2026)

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

J-PARC (S-2S, 1.0 MeV FWHM, 100 keV accuracy, 2023—25)

- (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: ${}^{6}_{\Lambda}\mathrm{Li}$, ${}^{11}_{\Lambda}\mathrm{B}$

Some References

J-PARC

- Resent results：https://j-parc.jp/c/press-release/2022/09/05001005.html
- Future projects：https://doi.org/10.1051/epjconf/202227111002

JLab

- Resent results (nnΛ search experiment)：
  - https://doi.org/10.1051/epjconf/202227102002
  - https://www.kyoto-u.ac.jp/ja/research-news/2022-03-08
- Future projects：https://doi.org/10.1051/epjconf/202227101001

Physics on a dish of S-2S

Strangeness $S = -2$ nuclear physics

Hypernuclei
Λ, Ξ, $\Lambda\Lambda$
(E70, E75, E94, E96)

- Missing mass
- Decay pion
- Gamma / X rays
- …

Mesic nuclei
η'

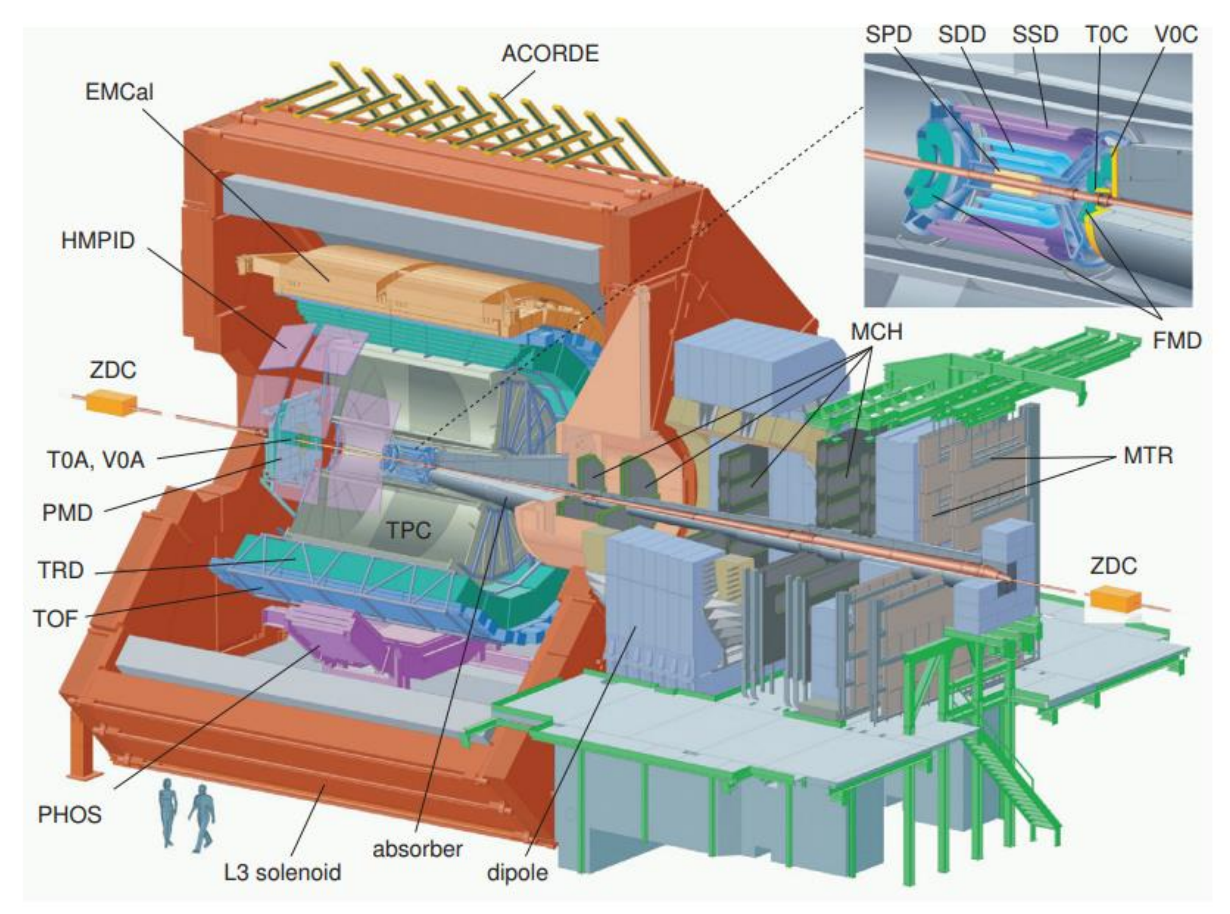
Ξ^* spectroscopy

ΣN cusp (E90)

etc.

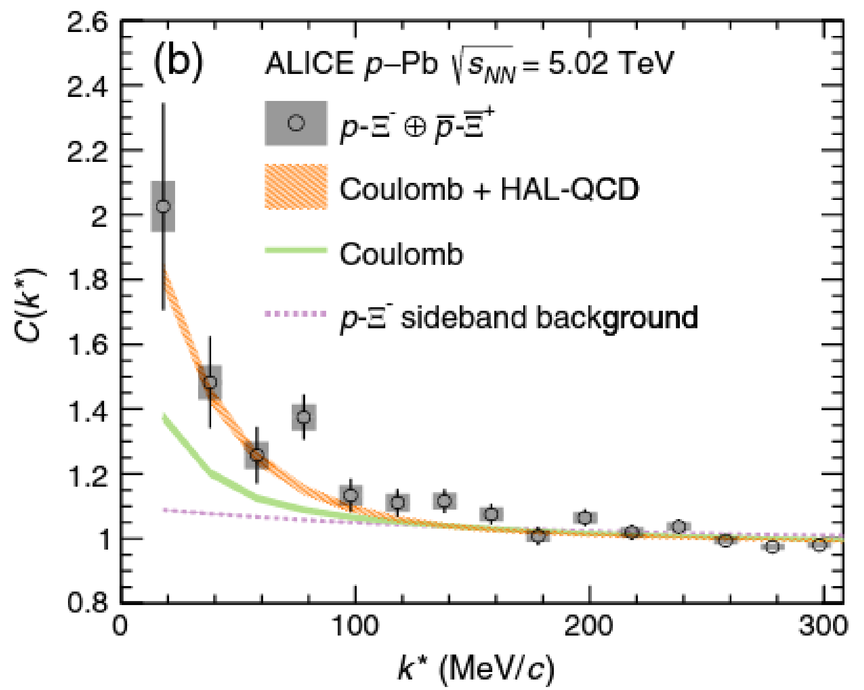
TG et al., EPJ Web Conf. 271, 11002 (2022)

Femtoscopy for p-Ξ⁻ by ALICE at LHC



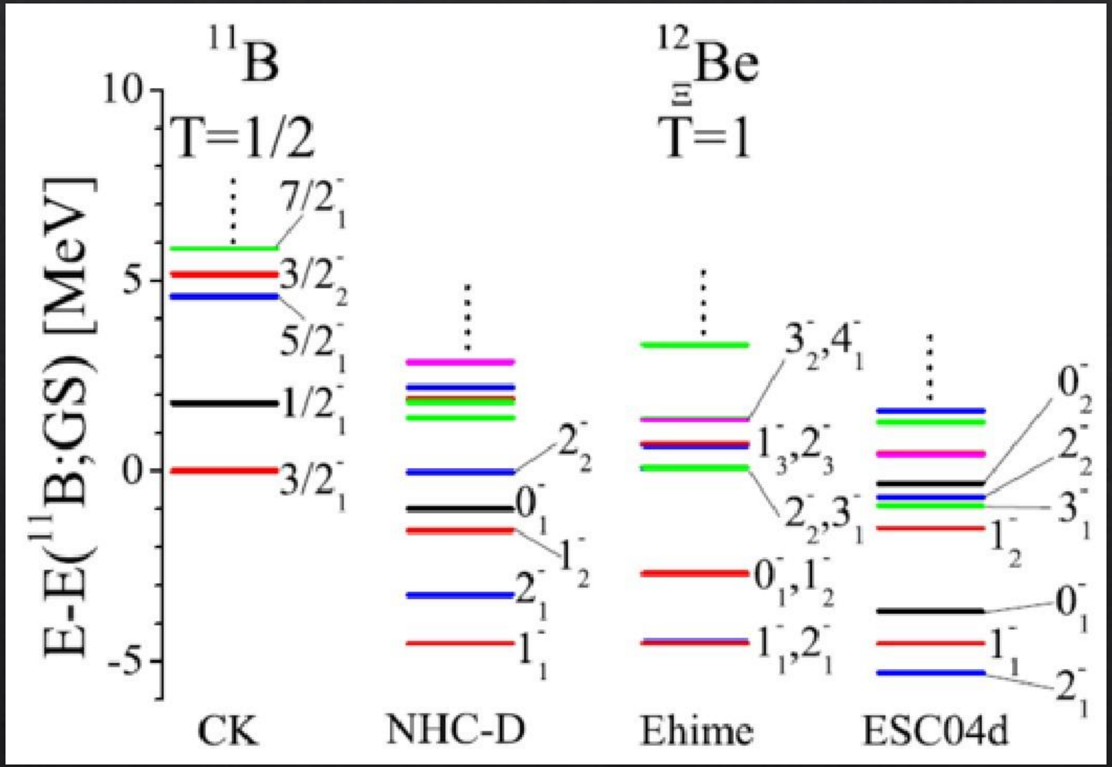
The ALICE Collaboration, Inter. Jour. Mod. Phys. A 29, 24, 1430044 (2014)

$$C_{\rm model}(k^*) = 1 + \lambda_{\rm genuine}[C_{\rm genuine}(k^*) - 1] + \sum_{\rm ij} \lambda_{\rm ij}[C_{\rm ij}(k^*) - 1],$$



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

Complication of structures



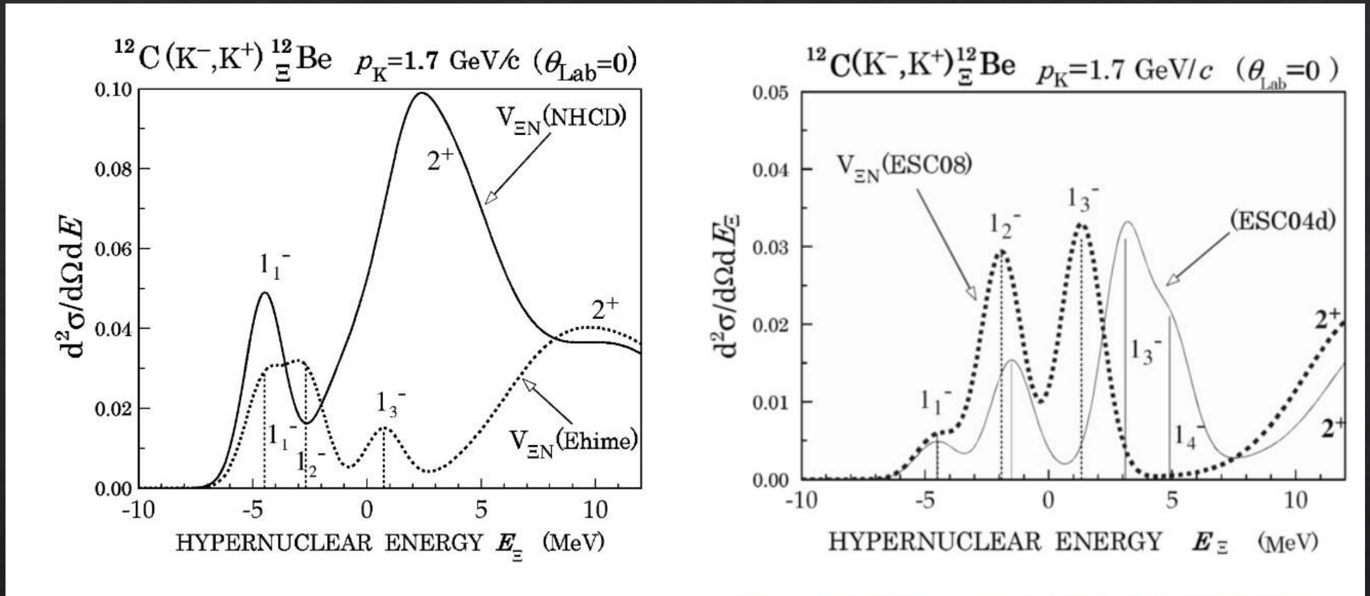
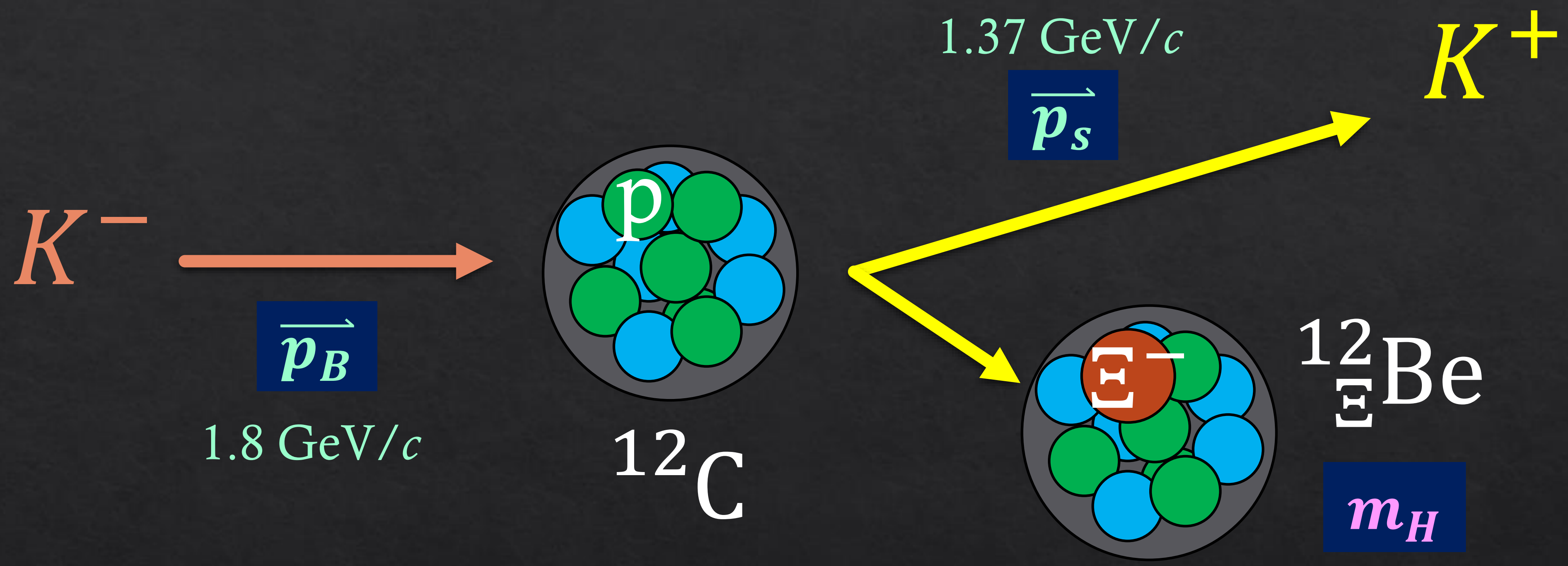


Figure 6: DWIA spectra with NHC-D and Ehime.

Figure 7: DWIA spectra with ESC04d and ESC08a.

T. Motoba and S. Sugimoto, *NPA* **835** (2010) 223-230

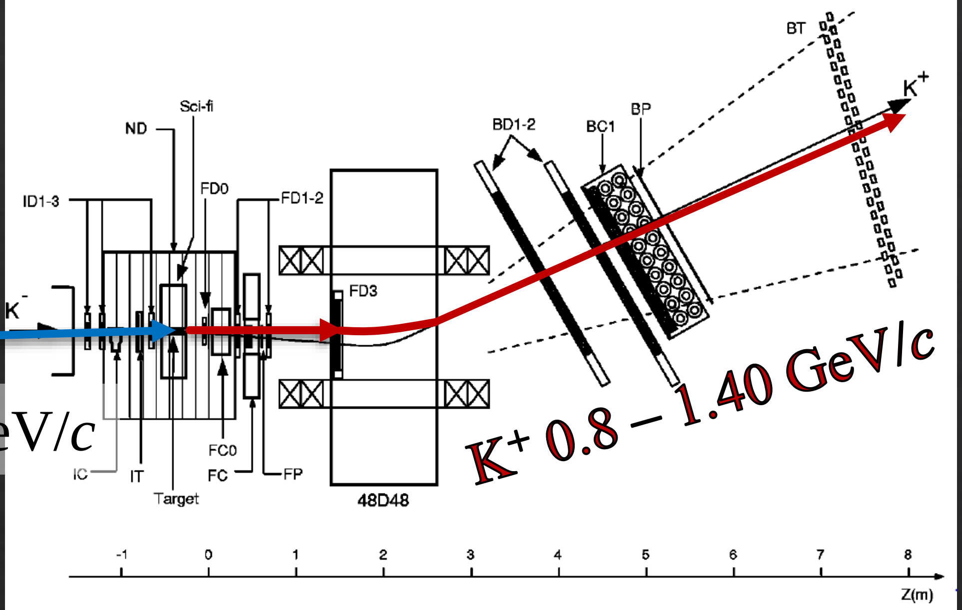
Missing mass spectroscopy



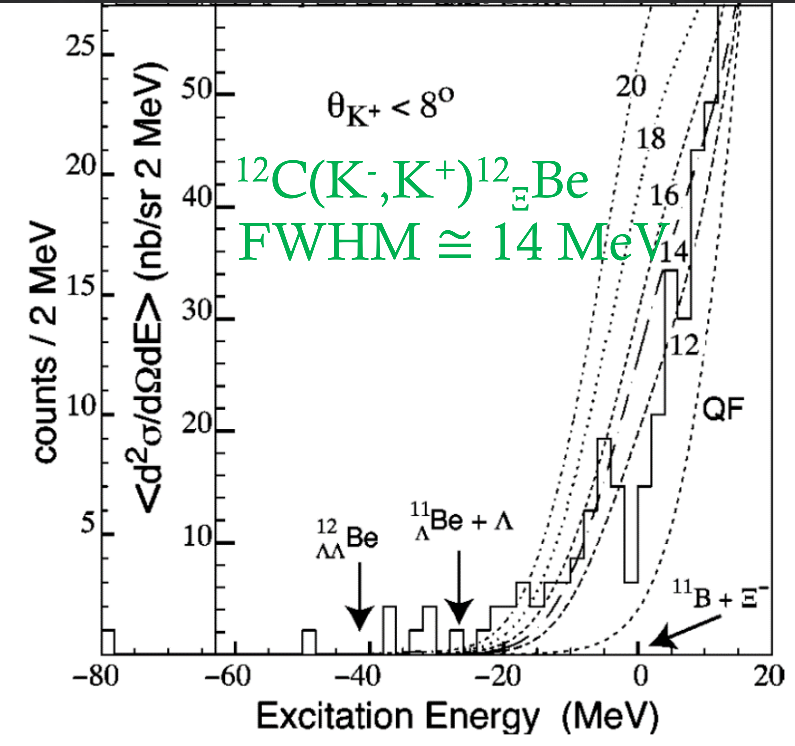
$$m_H = \sqrt{E_H^2 - \overrightarrow{p_H}^2} = \sqrt{(\boldsymbol{E}_{\mathbf{beam}} + M_t - \boldsymbol{E}_s)^2 - (\overrightarrow{p_B} - \overrightarrow{p_s})^2}$$

$$\rightarrow B_\Xi = (m_{core} + m_\Xi) - m_H$$

$^{12}C(K^-,K^+)^{12}_{\Xi}Be$ ← Missing-mass measurement



P. Khaustov et al., PRC **61** (2000) 054603



Experiment	KEK E224	BNL E885	J-PARC E05
Resolution in FWHM (MeV)	22	14	8

→ $V_{0\Xi} \lesssim 14$ MeV

→ 2 MeV in J-PARC E70

c.f.)
M. Kohno et al., PTP123, 1 (2010)
M. Kohno, PRC 100, 024313 (2019)

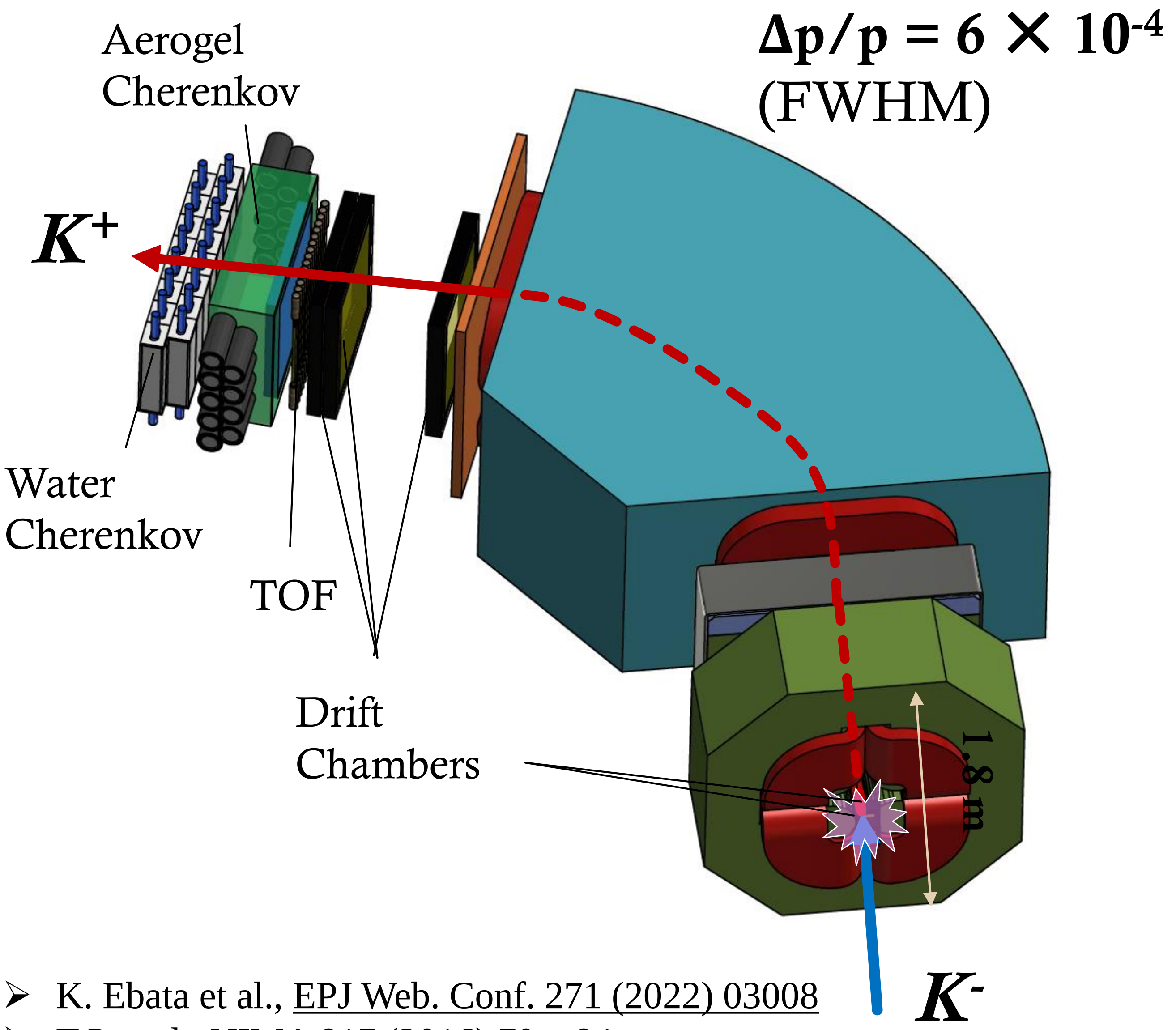
For high resolution spectroscopy → S-2S


Aerogel Cherenkov


Detector frame


Drift chamber


Water Cherenkov

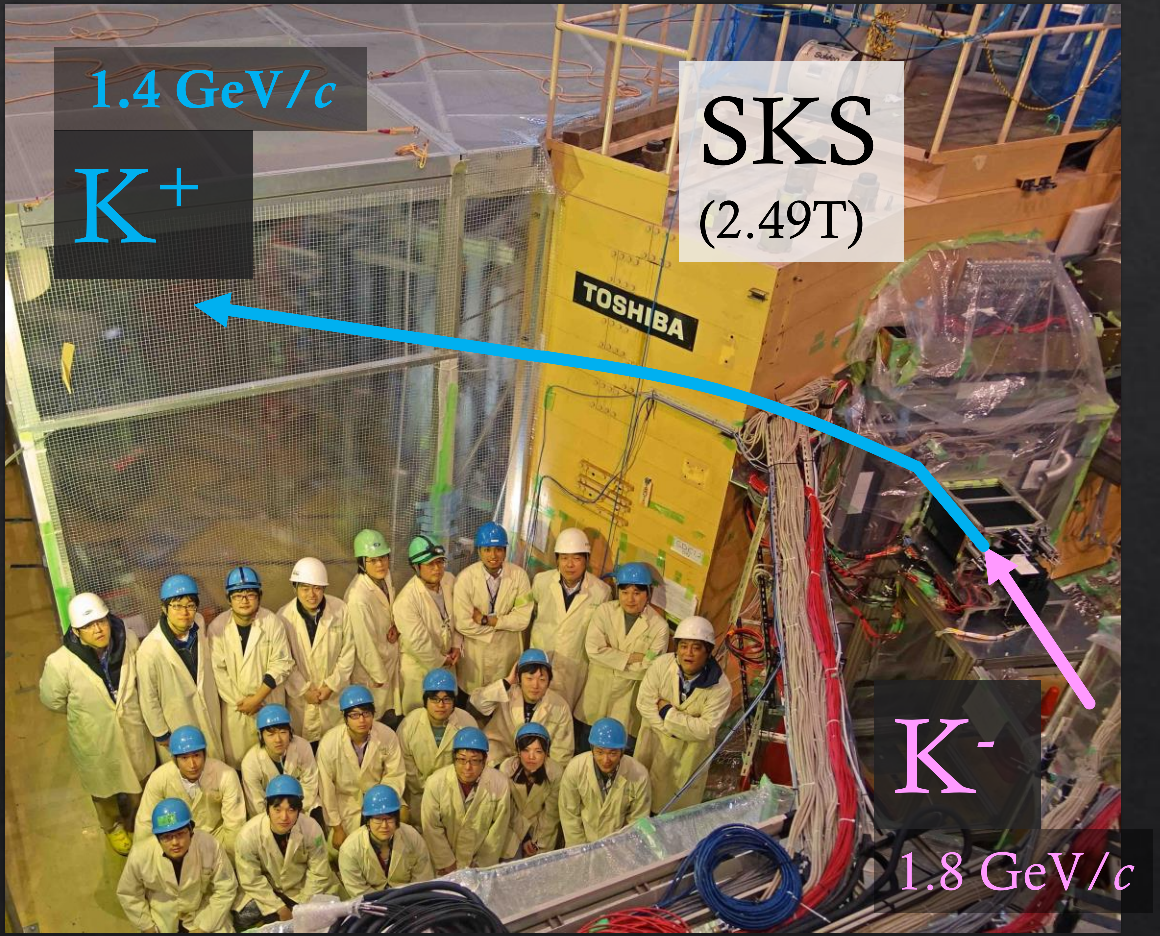


- K. Ebata et al., EPJ Web. Conf. 271 (2022) 03008
- TG et al., NIMA 817 (2016) 70—84

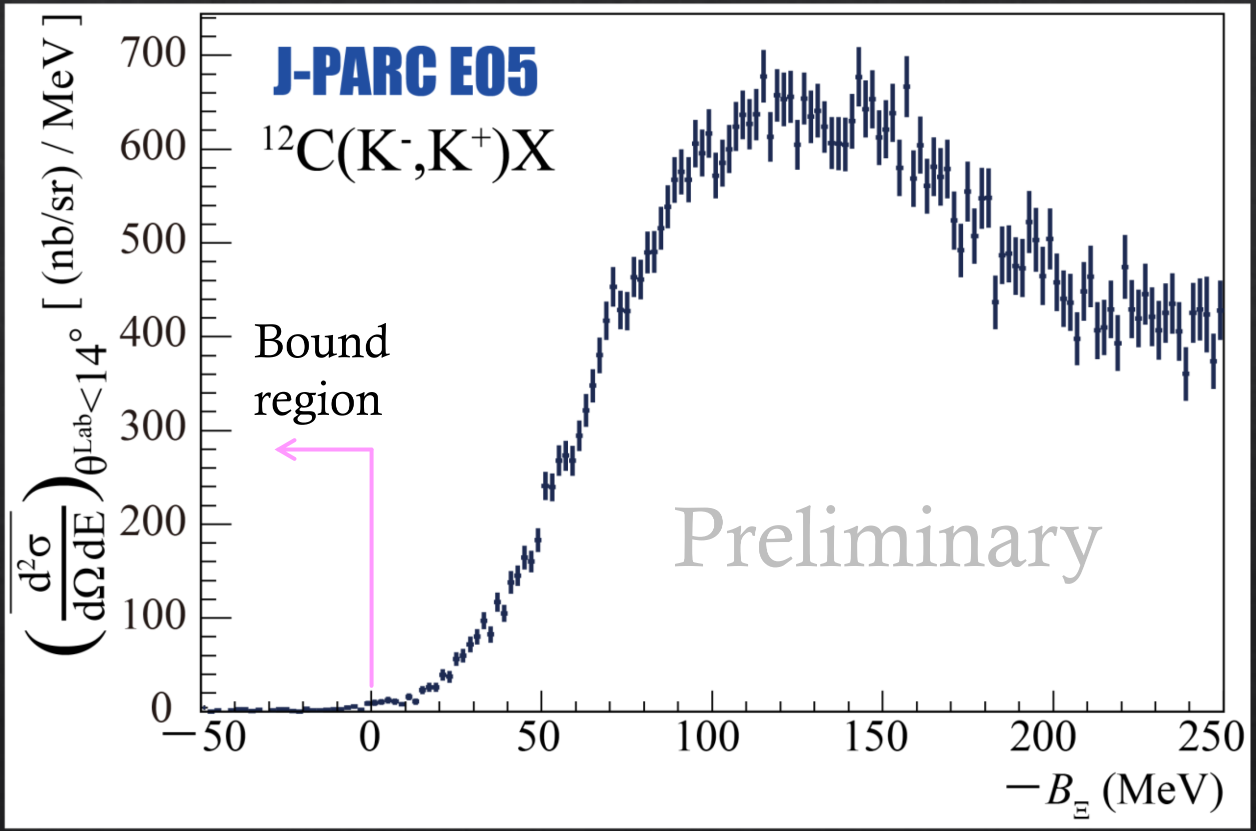
J-PARC E05 experiment at K1.8 beam line

TG et al., J. Phys.: Conf. Ser. 1643 (2020) 012133

Analysis by Y. Ichikawa



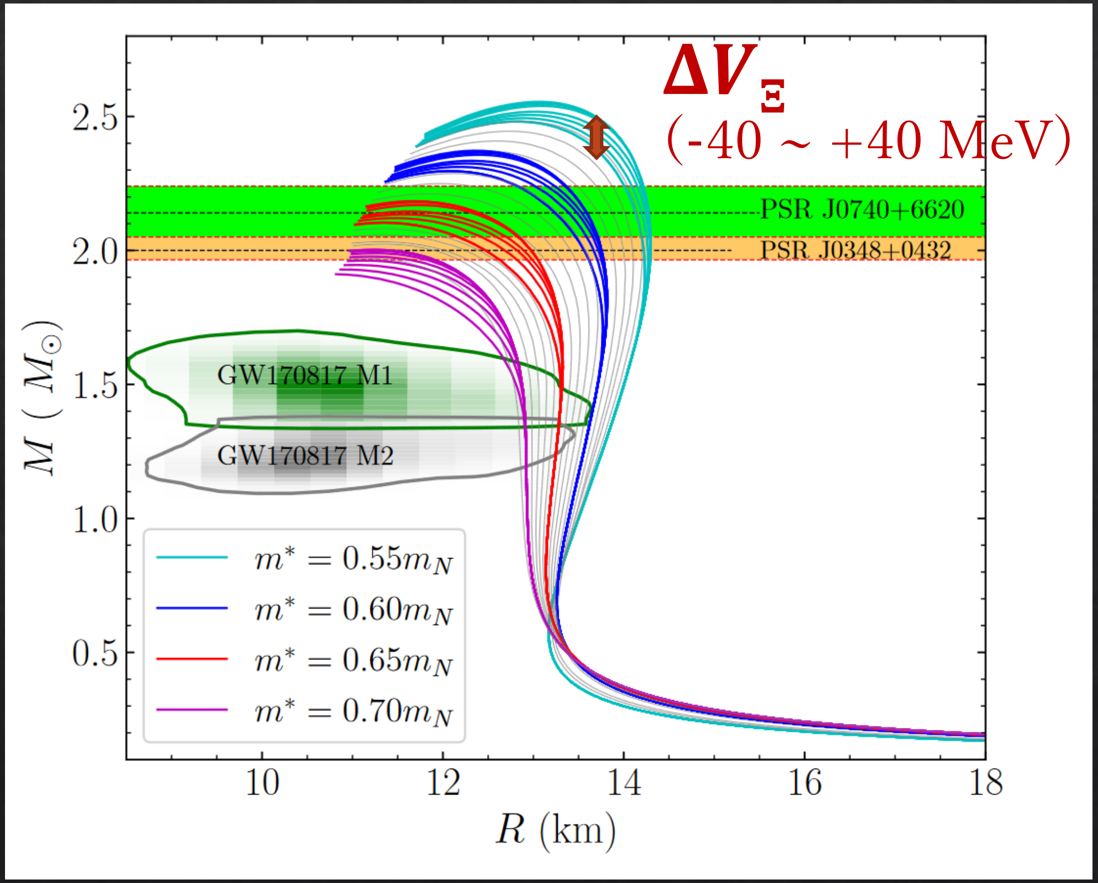
Nov 2015 @K1.8 beam line, J-PARC



c.f.) Result for the **^{12}C(K^{-},p)** reaction →
Y. Ichikawa et al., PTEP 2020, 123D01 (2020)

Ξ ($S = -2$ baryon) in neutron stars

RMF model



B. K. Pradhan and D. Chatterjee, PRC 103, 035810 (2021)

Tolman-Oppenheimer-Volkoff eqs.

$p = p(\epsilon)$ ← EOS

$$\frac{dm}{dr} = 4\pi r^2 \epsilon(r)$$

$$\frac{dp}{dr} = -[p(r) + \epsilon(r)] \times \frac{m(r)+4\pi r^3 p(r)}{r[r-2m(r)]}$$

V_Ξ is one of ingredients to tackle the hyperon puzzle of NS

Assumption for $^{12}_{\Lambda}$C production

$^{12}\mathrm{C}(\pi^+, K^+)^{12}_{\Lambda}\mathrm{C}$ @ $p_\pi = 1.64$ GeV/c

- Total efficiency = 0.5
- K survival ratio = 0.46
- Cross section = 1 μb/sr
- Solid angle = 55 msr
- Target thickness = 2 g/cm^2
- Beam = 3 M pion per spill (spill cycle of 4.2 sec)
- 5 days
- S-2S momentum setting is the same as that for the Ξ production

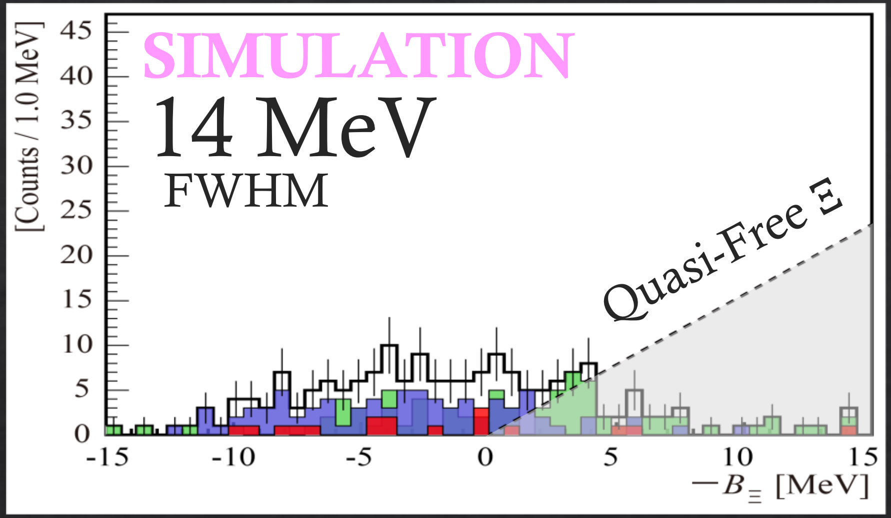
→ **391 counts**

Expected spectrum for the $^{12}_{\Xi}\mathrm{Be}$ production

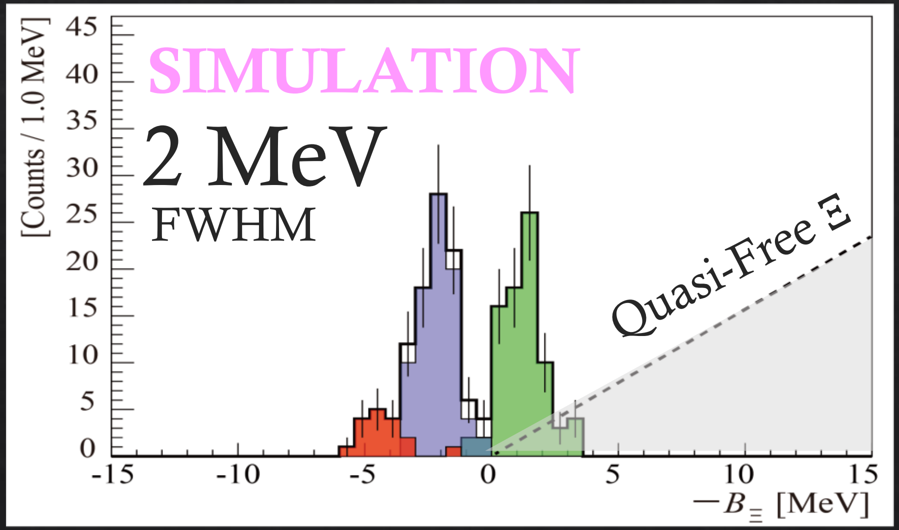
$^{12}\mathrm{C}(K^-, K^+)^{12}_{\Xi}\mathrm{Be}$ @ $p_\pi = 1.8$ GeV/c

- Total efficiency = 0.5
- K survival ratio = 0.46 (8 m optical length)
- Solid angle = 60 msr
- Cross section = 60 nb/sr (0—10 deg)
- Target thickness = 9 g/cm^2 (AFT made of CH)
- Beam = 0.8 M kaon per spill (spill cycle of 4.2 sec)
- 20 days

➡ **~100 counts**



S-2S



Theory (Interaction) LQCD etc.

M.M. Nagels, Th. A. Rijken, Y. Yamamoto, PRC 102, 054003 (2020)

	ESC16	A1	A2	B1	B2	HAL-QCD
X_2	0.0	2.85	2.55	1.65	1.07	
X_3	0.0	0.0	1.6	0.0	3.0	
X_s	0.0	0.0	0.0	10.	10.	
$^{11}S_0$	2.1	1.4	1.4	−4.0	−4.0	−4.9
$^{13}S_1$	−0.4	−2.2	−2.2	−2.8	−2.8	−2.2
$^{11}P_1$	−0.2	−0.3	−0.3	−0.3	−0.3	
$^{13}P_0$	−5.3	−3.5	−3.5	−2.0	−2.0	
$^{13}P_1$	1.5	1.3	1.3	1.7	1.7	
$^{13}P_2$	−1.2	−1.2	−1.2	−2.3	−2.3	
$^{31}S_0$	9.2	9.9	9.9	6.8	6.8	1.8
$^{33}S_1$	7.6	−13.5	−13.9	−4.7	−4.9	−5.4
$^{31}P_1$	1.0	1.3	1.3	1.0	1.0	
$^{33}P_0$	0.8	1.0	1.0	0.8	0.7	
$^{33}P_1$	−2.0	−2.8	−2.8	−3.0	−3.0	
$^{33}P_2$	0.5	0.1	0.1	−1.0	−1.0	
U_Ξ	+13.7	−8.5	−9.0	−10.1	−10.4	−10.6
Γ^c_Ξ	5.1	5.7	5.7	0.5	0.5	0.2

K. Sasaki et al., NPA 998, 121737 (2020)

Calc.	$^{12}C+\Xi^-$	$^{14}N+\Xi^-$	$^{27}Al+\Xi^-$
	B_Ξ (Γ) [/MeV]		
ESC16 (A1)	4.8 (2.8)	5.1 (3.3)	9.0 (2.9)
ESC16 (B1)	4.9 (0.2)	5.2 (0.24)	9.2 (0.22)
HAL-QCD	4.4 (0.13)	5.5 (0.16)	9.6 (0.12)

→ The **width** is important to be measured as well as the **energy**

X-ray spectroscopy of Ξ^--atom

Proton number

C (Z=6)-atom : J-PARC E07 (-2017) & Together with S-2S (2023-)

(also N-atom, O-atom…)

Fe (Z=26)-atom : J-PARC E03 (-2021)

Br (Z=35)-atom :

Ag (Z=47)-atom :

J-PARC E07 (-2017)

Pb (Z=82)-atom : PANDA (2027+)

The lightest Ξ hypernuclei

E. Hiyama et al., PRL 124, 092501 (2020)

Hypernuclei	chEFT (NLO)	HAL QCD	ESC08c
	B_Ξ (Γ) [/MeV]		
${}^{4}_{\Xi}\mathrm{H}$ (1^+)	0.48 (0.74)	0.36 (0.03—0.06)	10.2 (0.89)
${}^{4}_{\Xi}n$ (1^+)	0.64 (0.11)	Not bound 😥	10.1 (0.03)

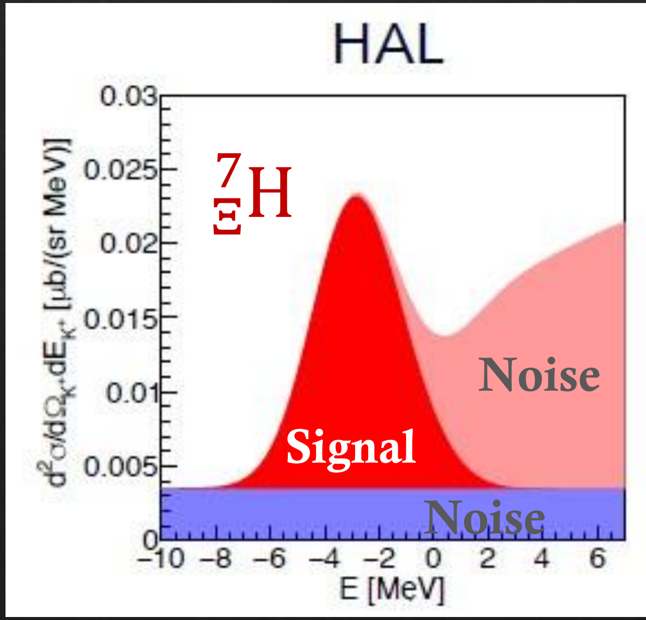
S-2S

H. Le, J. Haidenbauer, Ulf-G. Meiβner,
A. Nogga, Eur. Phys. J. A (2021) 57:339

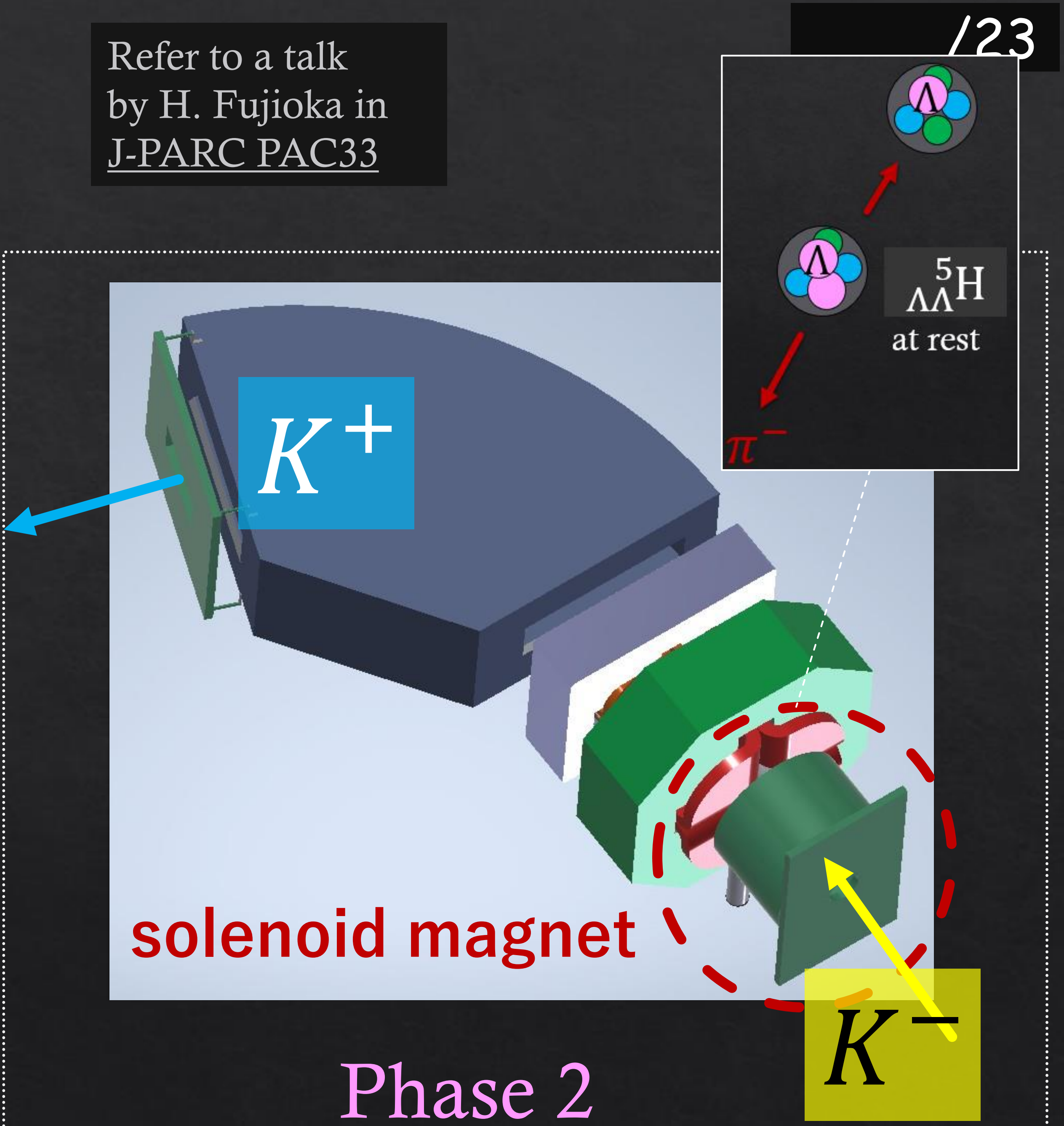
${}_{\Lambda\Lambda}^{5}\mathrm{H}$ measurement (E75)

Refer to a talk by H. Fujioka in J-PARC PAC33

Reaction cross section of ${}^{7}\mathrm{Li}(K^-, K^+){}_{\Xi}^{7}\mathrm{H}$ (w/o solenoid magnet)



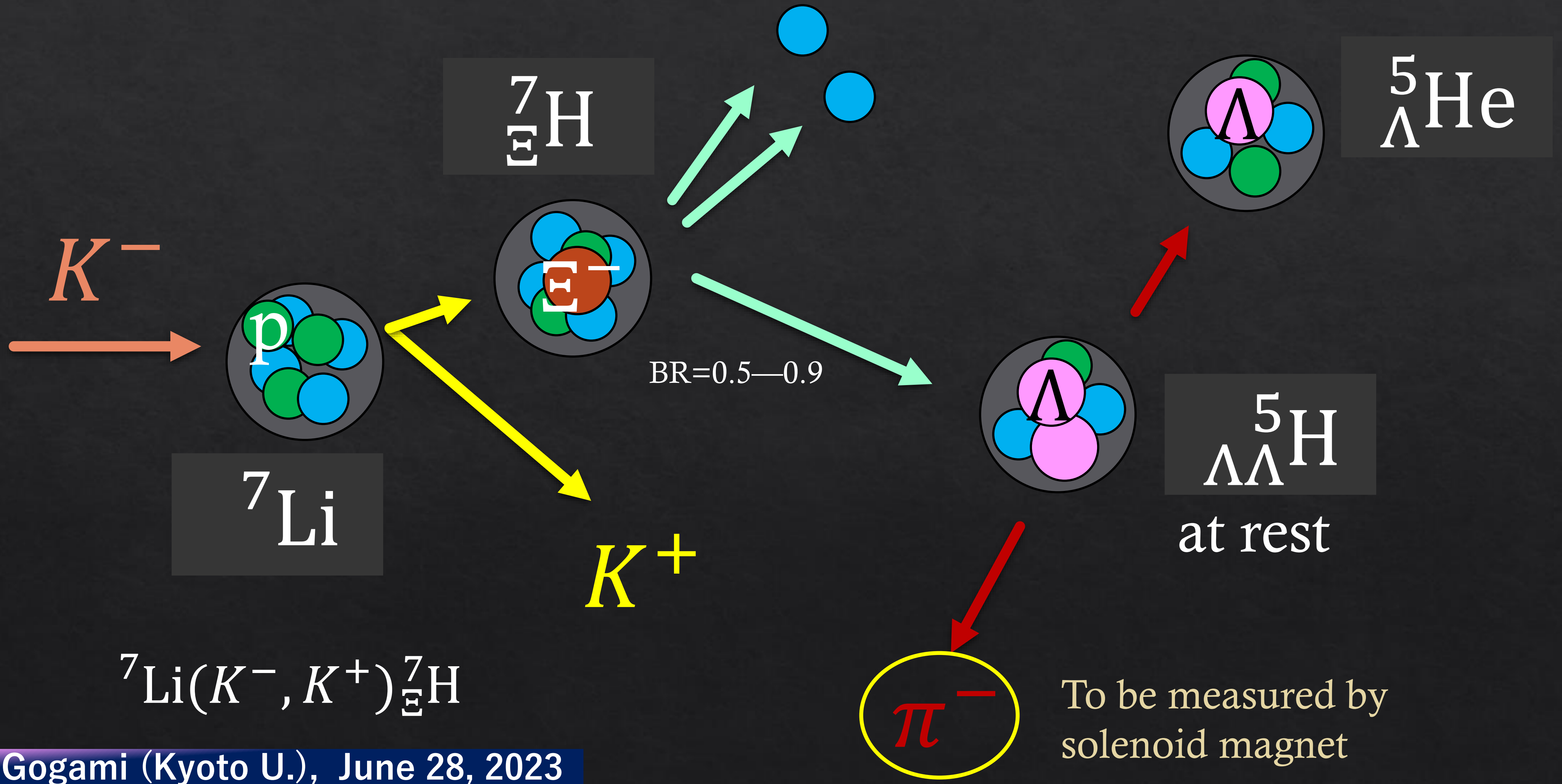
Phase 1



Phase 2

${}^{5}_{\Lambda\Lambda}\mathrm{H}$ measurement (E75)

I. K. Fuse et al., PRC ***54****, R24–R27 (1996)*
A. Ohnishi, et al., PTEP ***2020****, 063D01 (2020)*



$$^{7}\mathrm{Li}(K^-, K^+){}^{7}_{\Xi}\mathrm{H}$$