July 24—28, 2023, Jefferson Lab PAC51, Newport News, VA, US

JLab E12-15-008

An isospin dependence study of the Λ-N interaction through the high precision spectroscopy of Λ hypernuclei with electron beam

Contact Person:

S.N. Nakamura (University of Tokyo, Japan)

Presented by:

T. Gogami (Kyoto University, Japan)

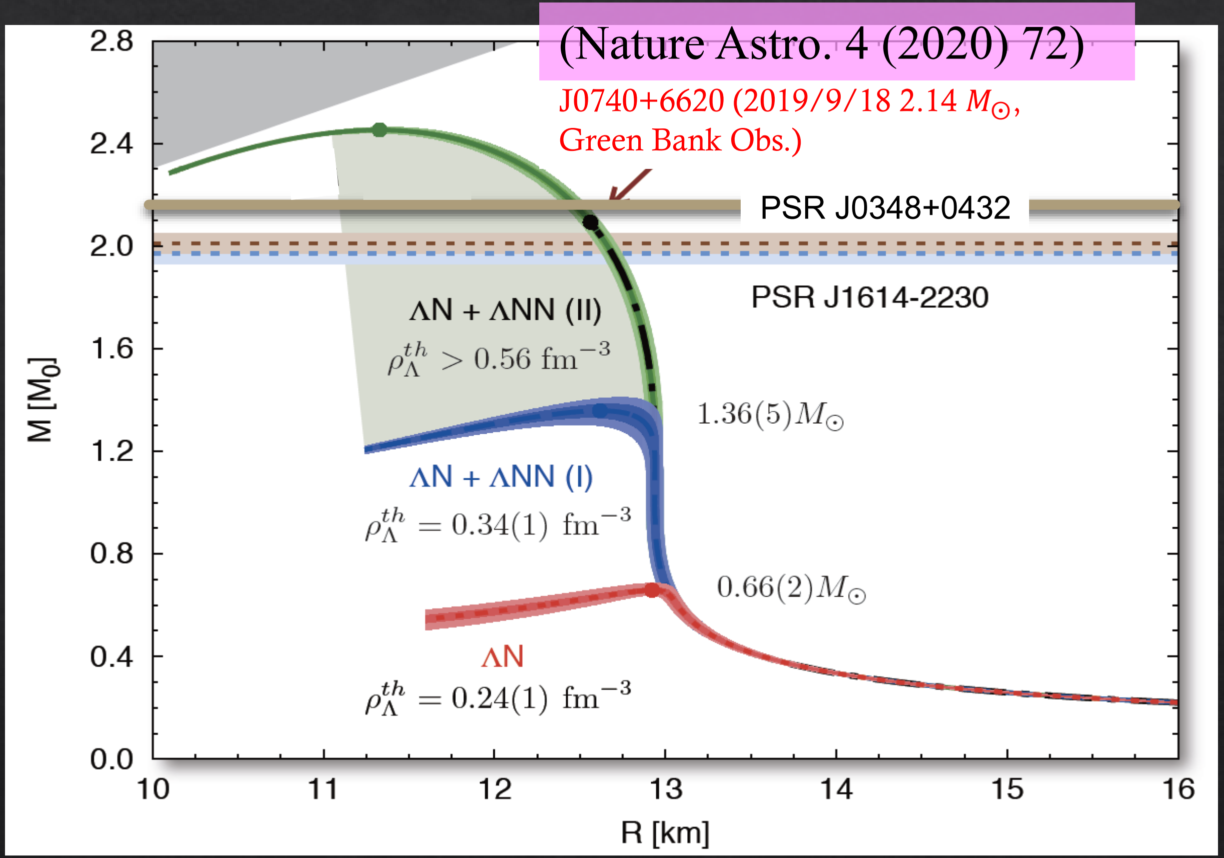
on behalf of **the JLab Hypernuclear Collaboration**

July 27, 2023

One page summary of physics motivation

- **EOSs with hyperons are too soft to sustain neutron stars with $\geq 2M_{\odot}$ (HYPERON PUZZLE)**
  - ➔ Repulsive forces by ΛNN?
  - ➔ E12-15-008 is the first attempt to investigate the ΛNN force ($|\Delta B_{\Lambda}| \lesssim 100$ keV)

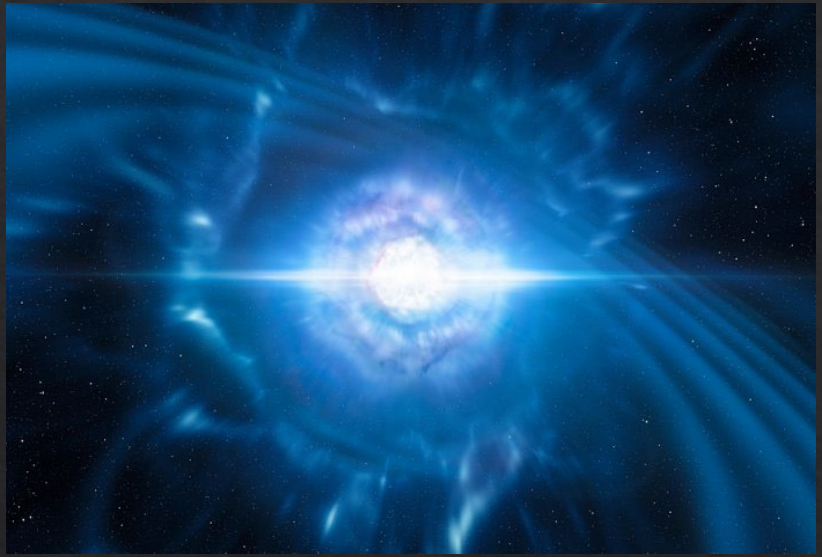
- **Isospin dependent ΛN interaction**
  - ◆ ΛN-ΣN coupling
  - ◆ Related to the ΛN charge symmetry breaking
  - ➔ There is no data at medium heavy mass region
  - ➔ E12-15-008 will provide the first data (Z = 19: A = 40 vs. 48)



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

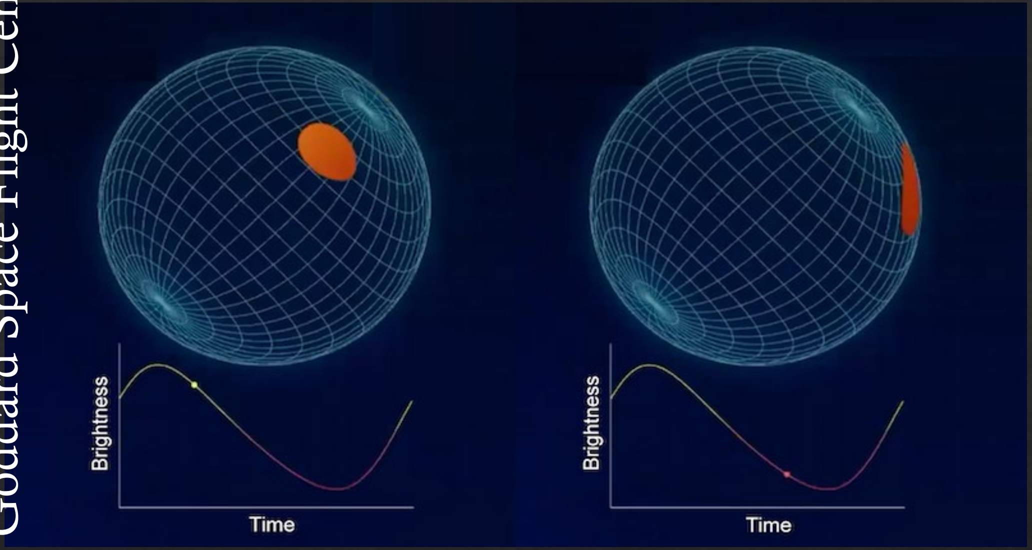
New astronomical observations

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)

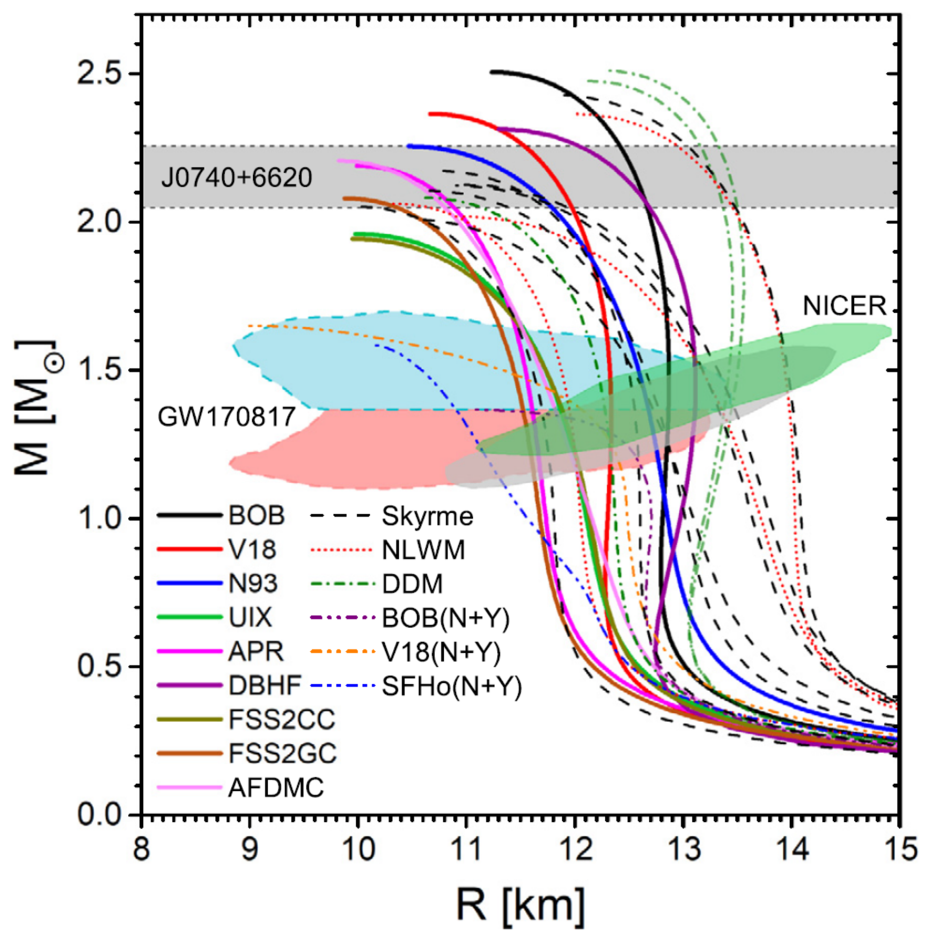
Macroscopic features of NS : Tidal deformabilities, masses and radii

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.

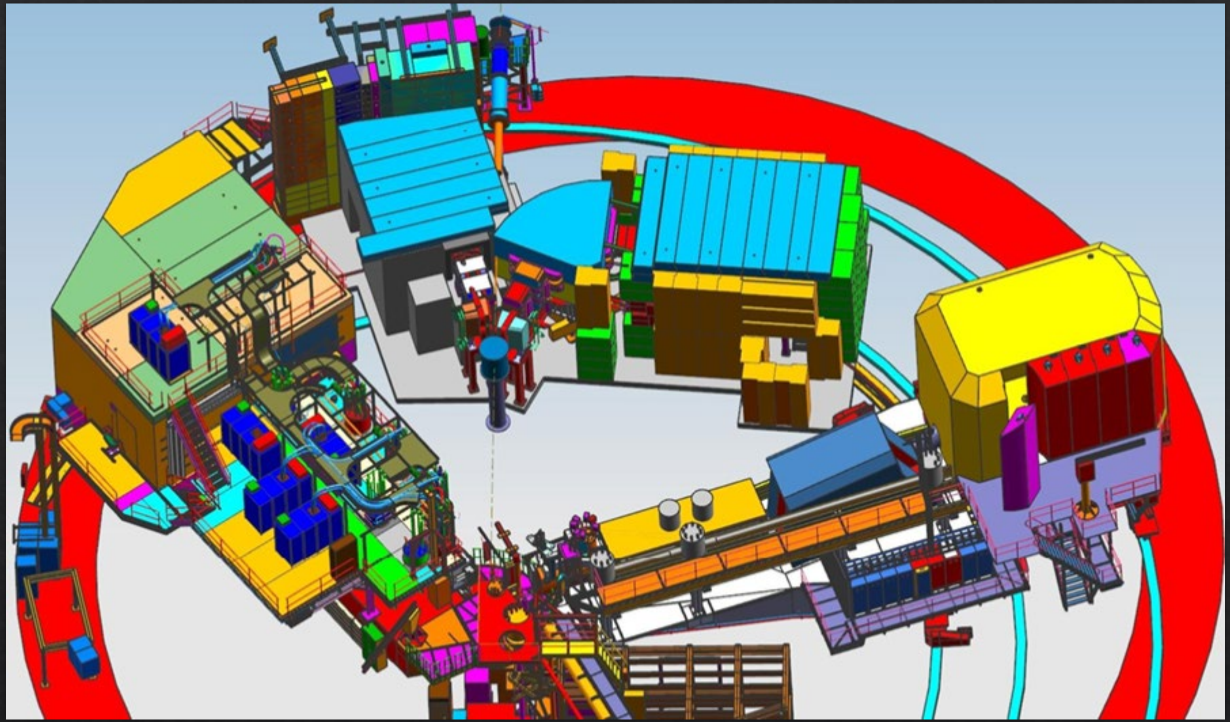


Macroscopic understanding of NS made great progress.

But, we need to know why NSs can be so heavy and large.
➔ Microscopic study (nuclear physics exp) has become more important than ever!

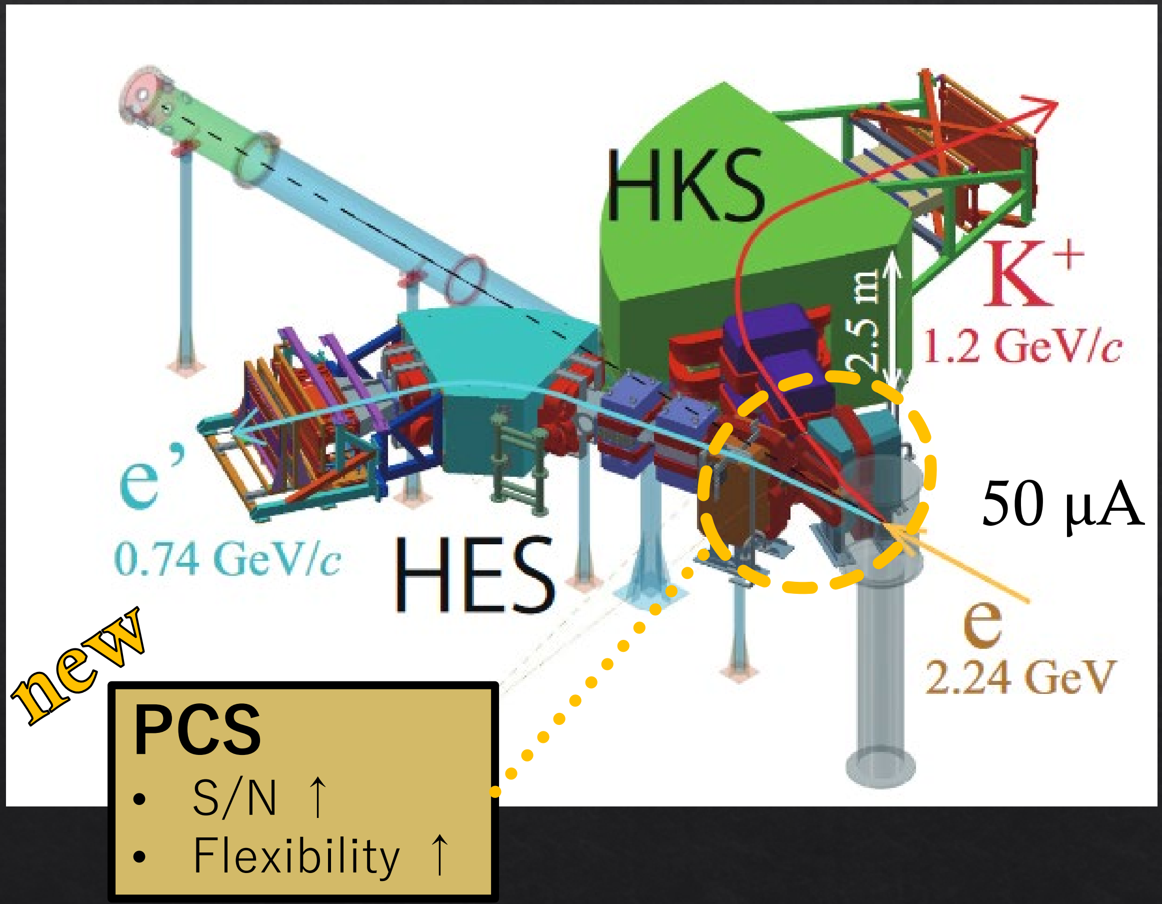
Next experiment at JLab Hall C (FY2026~)

Hall A (original proposal) → Hall C



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



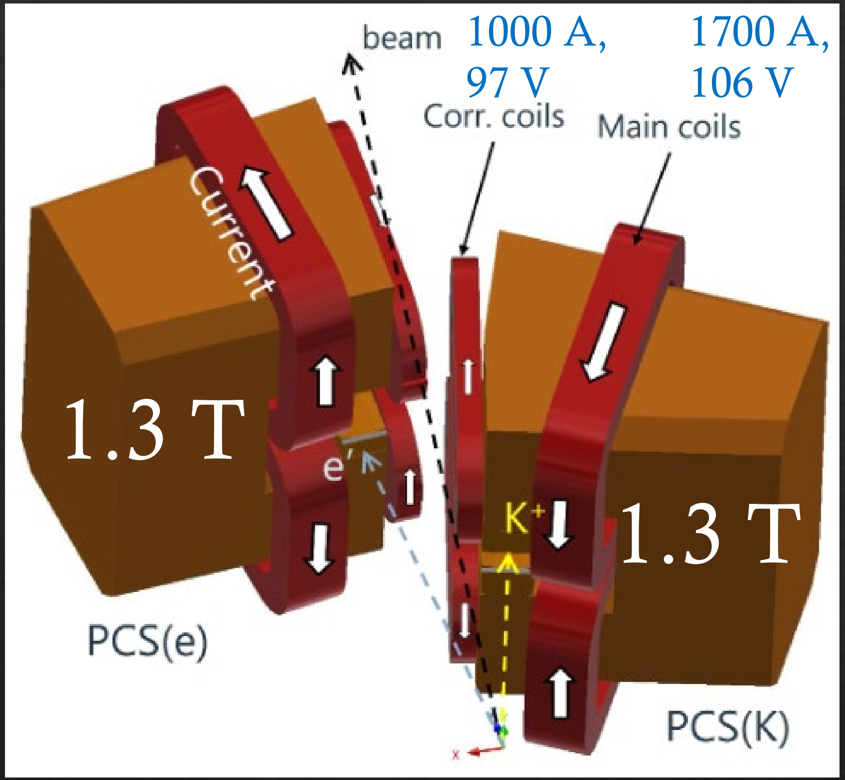
Existing spectrometers HES and HKS are going to be used


HES
HKS
Jefferson Lab
Thomas Jefferson National Accelerator Facility

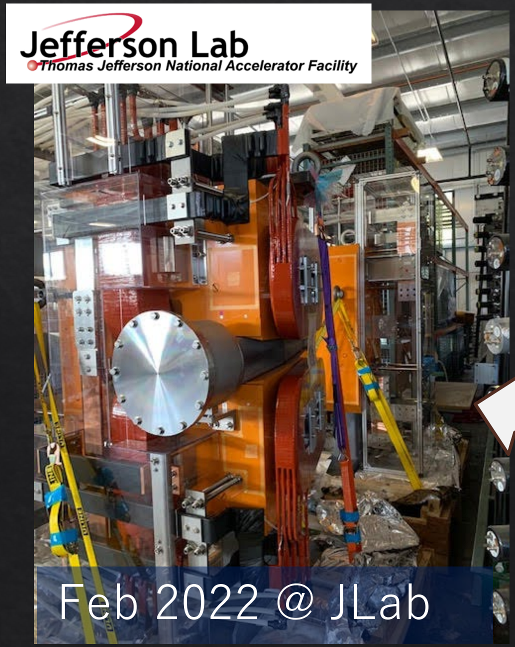
normal conduction

New magnet PCS

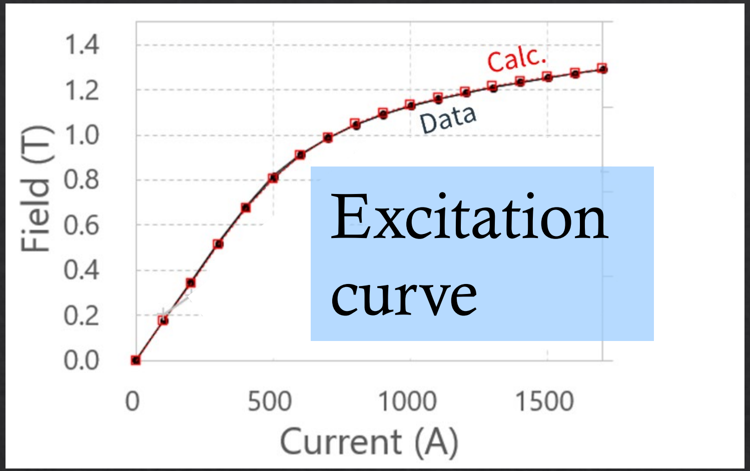
(Pair of charge separation dipole magnets)

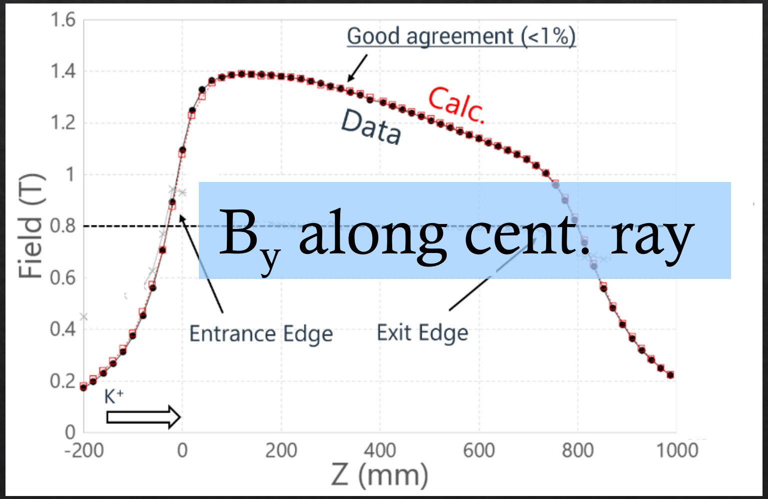


Shipping



Measurement vs. TOSCA calc.





Supported by KAKENHI:
No. 17H01121 (**33,500,000 JPY**)
No. 18H05459 (**144,100,000 JPY**)

> $ 1 M

It worked as expected !!

Beam time request (E12-15-008)

Table 6: Updated request of beamtime.

Target (Hyper Nucleus)	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected yield (/h)	Num. of events	Req. beamtime (hours)	B.G. rate (/MeV/h)	S/N	Comments
CH_2 (Λ, Σ^0)	2	500	1000	8.62	1000	120	0.03	290	Calibration
^{6}Li ($^6_\Lambda$He)	50	100	10	—	—	—	—	—	Separate LoI
^{9}Be ($^9_\Lambda$Li)	50	100	10	—	—	—	—	—	Separate LoI
^{11}B ($^{11}_\Lambda$Be)	50	100	30	—	—	—	—	—	Separate LoI
^{12}C ($^{12}_\Lambda$B)	50	150	90	6.79	1100	168	1.20	5.67	Calibration
^{27}Al ($^{27}_\Lambda$Mg)	50	150	60 *	1.98	330	168	1.77	1.87	Calibration
Subtotal						456			Calibration
^{40}Ca ($^{40}_\Lambda$K)	50	150	50	1.13	520	456	2.41	0.47	Physics
^{48}Ca ($^{48}_\Lambda$K)	50	150	50	0.94	520	552	1.89	0.50	Physics
Subtotal						1008			Physics
Total						1464			

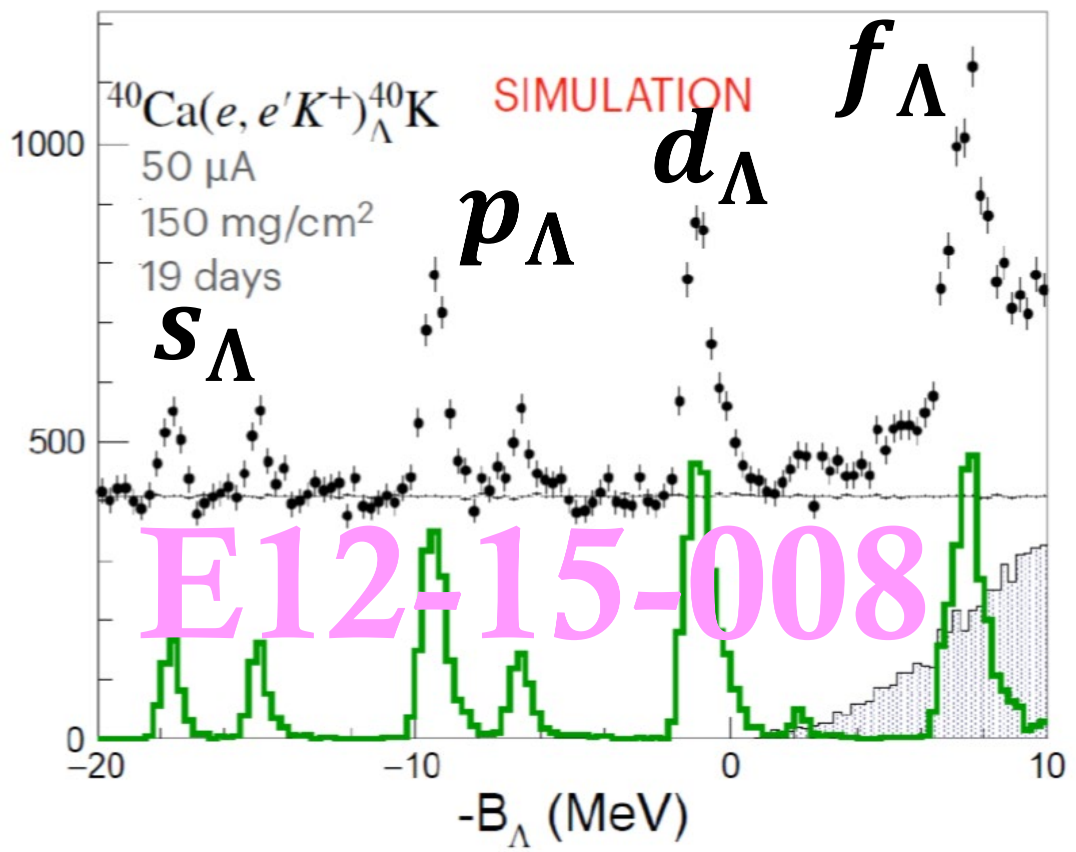
LoI12-23-013

* for $0s^\Lambda$ $9/2^+, 7/2^+$ doublet.

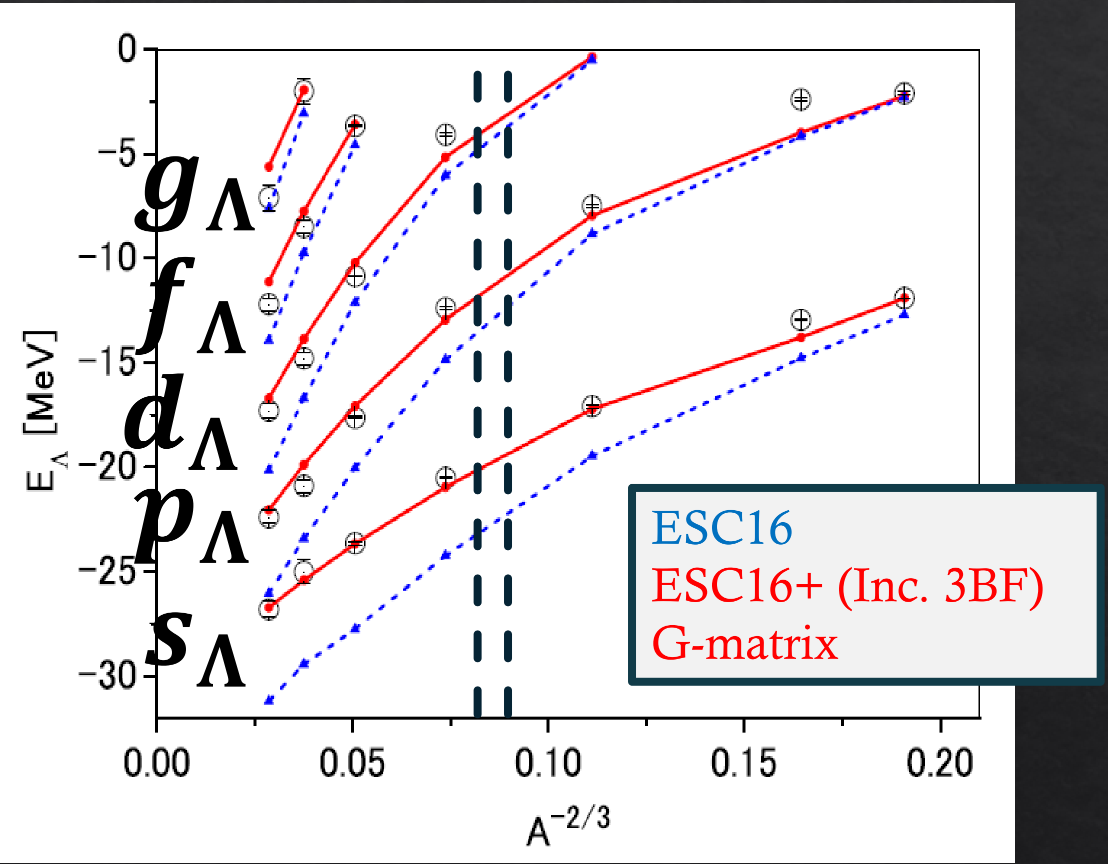
(=61 PAC days)

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

➡ Clearer understanding the 3BF

Summary (JLab E12-15-008)

Physics motivation ➔ **E12-15-008 is unique, and the importance has been more significant**

◆**EOSs with hyperons are too soft to sustain neutron stars with $\geq 2M_{\odot}$ (HYPERON PUZZLE)**

➔Repulsive forces by ΛNN?

➔**E12-15-008 is the first attempt to investigate the ΛNN force**

(Importance of the microscopic study of NS is more significant due to the recent progress of astronomical observations)

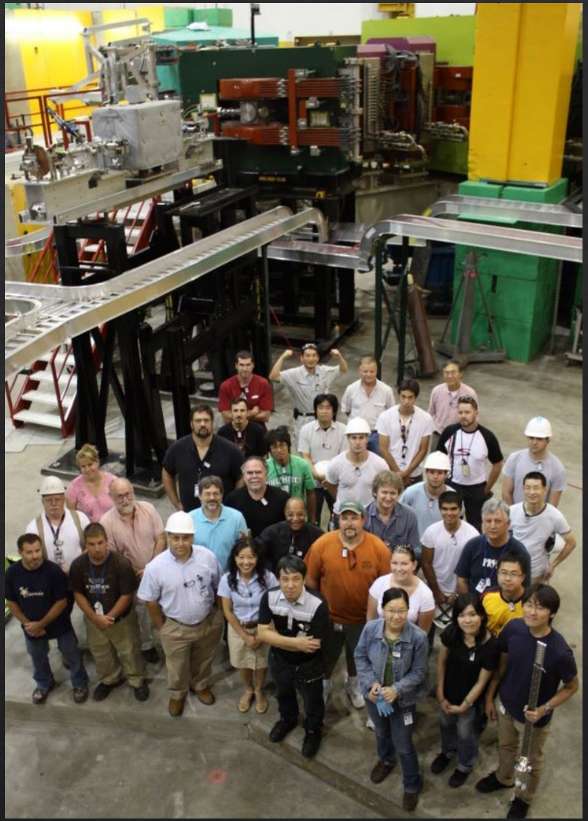
◆**Isospin dependent ΛN interaction**

◆ ΛN-ΣN coupling

◆ Related to the ΛN charge symmetry breaking

➔ There are no data at medium heavy mass region

➔ **E12-15-008 will provide the first data**



We thank the JLab staff for the great support

Preparation status and outlook

◆All spectrometer systems (HKS+HES+PCS) are ready

◆Detectors are being tested w/ cosmic rays

◆We plan ERR in the beginning of 2024

◆Long stay of Japanese members is planned to be from sometime in 2024

◆We aim to start the experiment in 2026

Q&A

Requested 4 points to be addressed by jeopardy presentation

1. Is there any new information that would affect the scientific importance or impact of the experiment since it was originally proposed?
   - **New Gravitational Waves from NS mergers and NICER : Macroscopic features of NS**
   - **Microscopic understanding of NS has become more important!**

2. If the experiment has already received a portion of its allocated beam time, the spokespersons should present the status of the analysis of the existing data and the projected result for the final complete data set. The goal is to show the physics impact of the beam time requested in the jeopardy update.
   - **Not applicable**

Requested 4 points to be addressed by jeopardy presentation

3. What is the status of the collaboration in terms of institutes, committed staff, and prospective students?

Currently, core members of JLab hypernuclear collaboration working on optimization of experiment design, commission/development of magnets, spectrometer.
Ten faculties of U Tokyo, Kyoto U., Tohoku U., Hampton U., Florida Int. U., INFN/Rome, Virginia M. Inst. Four Ph-D students and four master's students are working on the projects. One – two years before the beamtime, Japanese group members start to stay at JLab. More members of Hall A/C collaboration will participate in preparation works and taking shifts. (Hypernuclear workshop was organized at JLab in March, 2023 to share interests with potential collaborators at JLab.)

4. Should the remaining beam time allocation and experiment grade be reconsidered?

- Scientific significance is more than the original E12-15-008 (Grade A).
- Relocation of the experimental from Hall-A to Hall-C makes longer beamtime.

Answer to questions from Prof. Sawada (1)

Q1) Because several years have passed since the original proposal was approved and please show theoretical and experimental progress on the subject during the period.

A1) Hyperon puzzle was widely recognized and it is general consensus that some mechanism needs to make the EoS of massive neutron stars stiffer. In addition to AFDMC, various theoretical calculations based on different potential models with the three-body repulsive LNN force were performed for hypernuclei.

Theoretical studies made significant progresses.

- Meson exch. Potential (Nijmegen) + G-matrix M.M. Nagels et al., PRC 99 (2019) 044003.
- Chiral EFT + G-matrix J.Haidenbauer, I.Vidana, EPJA (2020) 56:55.
- Hyper AMD M.Isaka et al., PRC94, 044310 (2016), PRC 95, 044308 (2017)

Experimentally, Charge Symmetry Breaking study made great progress for light (A=4) hypernuclei, and large CSB was observed for ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ at MAMI and J-PARC. But there is still **no CSB study or iso-spin dependence study for medium-heavy hypernuclei**. At J-PARC, ΣN scattering experiment was successfully performed and it becomes possible to obtain direct information about the hyperon-nucleon two-body force. Femtoscopy study also give important Information about two-body baryonic force. **A better understanding of the two-body baryon force is important to a more reliable analysis of the ΛNN three-body force. Therefore, these progresses will help our analysis.**

Answer to questions from Prof. Sawada (2)

Q2) You claim that from the viewpoint of international competition this experiment should be implemented early. Please explain the international situation.

A2) At **J-PARC**, hadron experimental facility extension project (HEF-ex) has been discussed seriously and KEK Project Implementation Plan (PIP 2022) awarded the first priority to the project. Hopefully the project will be budgeted soon. Precise spectroscopy of hypernuclei with the (π^+, K^+) reaction is one of flagship experiments at J-PARC HEF-ex. (π^+, K^+) and $(e, e'K^+)$ reactions produce iso-spin partner hypernuclei and thus these studies are complementary and both of them are quite important to study Charge Symmetry Breaking of hypernuclei with a sub-MeV resolution. It is important to establish high-precision spectroscopy techniques (<0.5 MeV, FWHM resolution) for medium-heavy hypernuclei under high counting rate at JLab before J-PARC HEF-ex. Experiences at JLab will significantly contribute to the hypernuclear study at J-PARC HEF-ex project.

At MAMI, high resolution spectroscopic study with decay p spectroscopy is on going. It is currently limited to A=3,4 hypernuclei, but it would be possible to extend the study at JLab as LoI12-23-011 proposes.

At GSI, WASA-FRS Hyp-HI is exploring study of light hypernuclei with heavy-ion beams and FAIR PANDA is aiming to study multi-L hypernuclei with anti-proton beams.

Answer to questions from Prof. Sawada (3)

Q3) With the move from Hall-A to Hall-C of the experiment, we got a new TAC report on the experiment. If you have comments on the TAC report, please let us know.

A3) We would like to add comments to the TAC report.

As TAC recognizes, a cryogenic gas target need a vertical bending spectrometer and modification of HES to be a vertical one is not simple task.
Considering heavy load of design of new cryogenic gas target to the JLab target group and potential difficulties of the HES modification, we are concentration only on the solid targets including lead as the first campaign of the next JLab hypernuclear program. Solid targets with a movable ladder system were already used in the previous Hall-C hypernuclear experiments and it is not very complicated. We have been working on design of cryogenic target with the JLab target expert and continue to ask his help for the solid target design.

Possibility of B_4C target instead of a thin foil of Boron will be considered carefully. We need isotopically enriched boron target and availability of $^{11}B_4C$. We will evaluate which is better option to use $^{11}B_4C$ or a ^{11}B foil, considering effect of carbon data contamination the boron calibration data.

Backup

Requested 4 points to be addressed by jeopardy presentation

1) Is there any new information that would affect the scientific importance or impact of the experiment since it was originally proposed?

New astronomical observations

PSR J1614 – 2230 ($M = 1.928 \pm 0.017\ \boldsymbol{M_\odot}$) (Nature 467 (2010) 1081, APJ 832 (2016) 167)

PSR J0348 + 0432 ($M = 2.01 \pm 0.04\ \boldsymbol{M_\odot}$) (Science 340 (2013) 1233232)

PSR J0740 + 6620 ($M = 2.14^{+0.10}_{-0.09} M_\odot$) (Nature Astro. 4 (2020) 72)

➔ New observation of heaviest neutron star ever observed.

Existence of massive neutron stars ($\geq 2\ M_\odot$) is more certain!

HYPERON Puzzle

Based on our knowledge of baryonic force,
Hyperon naturally appear at high density ($\rho\sim 2,3\rho_0$)

Too soft EOS. **NS cannot support mass of 2** $M_\odot$

Contradict to astronomical observations.
(One more massive NS after PAC44)

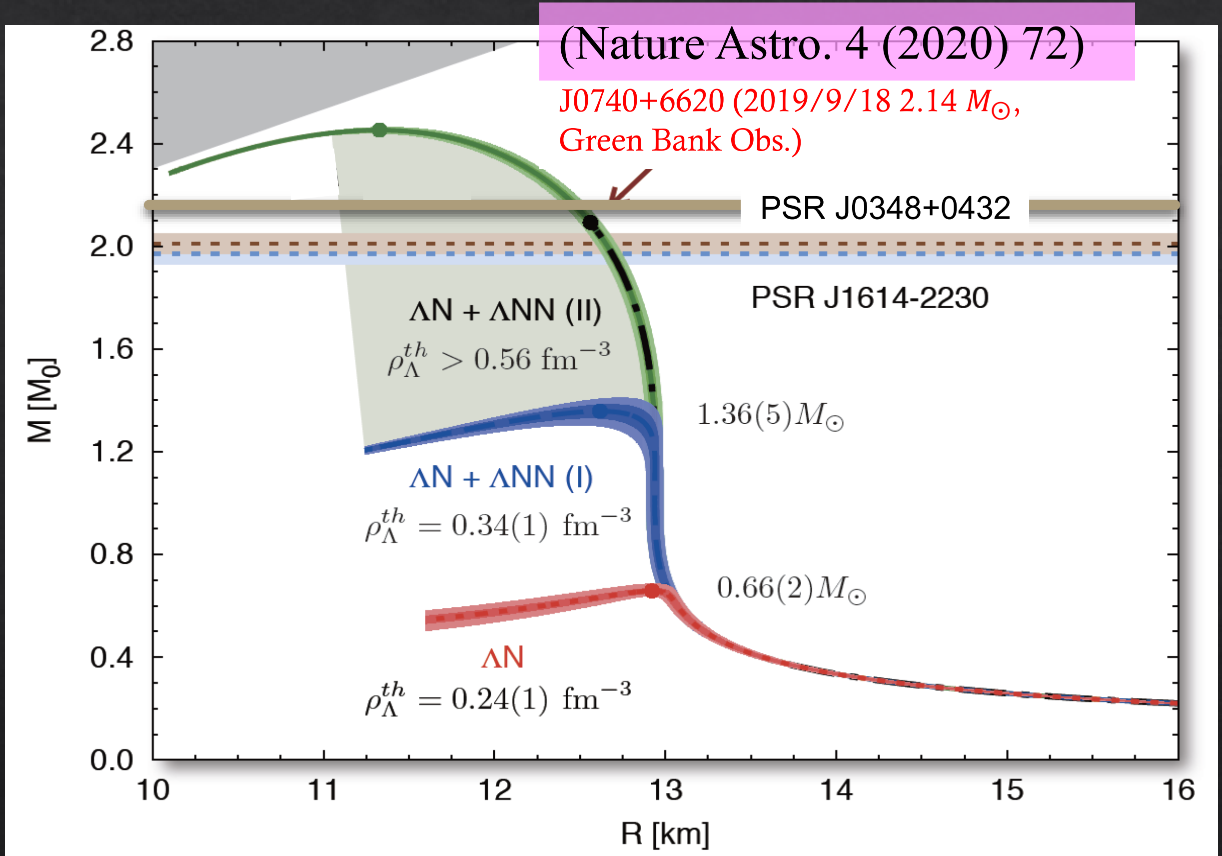
Need **additional repulsive force**
(ΛNN 3-body repulsive force)
Make stiffer EOS

Neutron star : **Large** $(N-Z)/A \geq$ **0.9 and Large A**

Iso-spin dependence
E12-15-008

A dependence
E12-20-013

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



PAC44 approval of E12-15-008 with grade-A

Charge Symmetry Breaking (CSB), the mystery

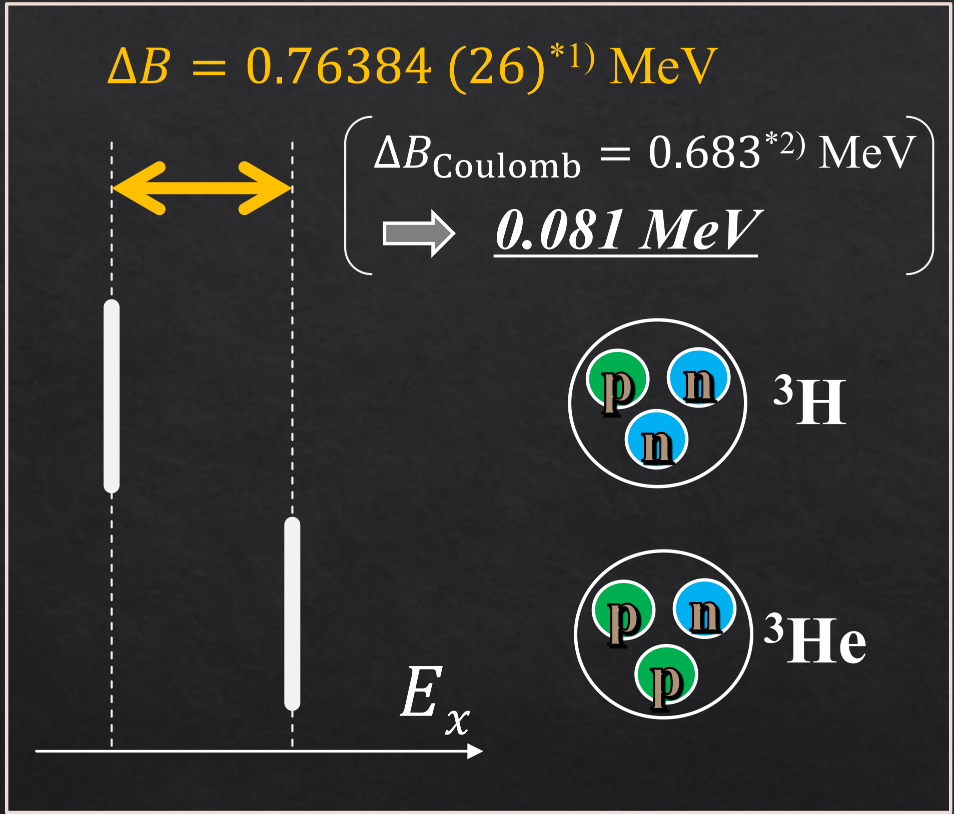
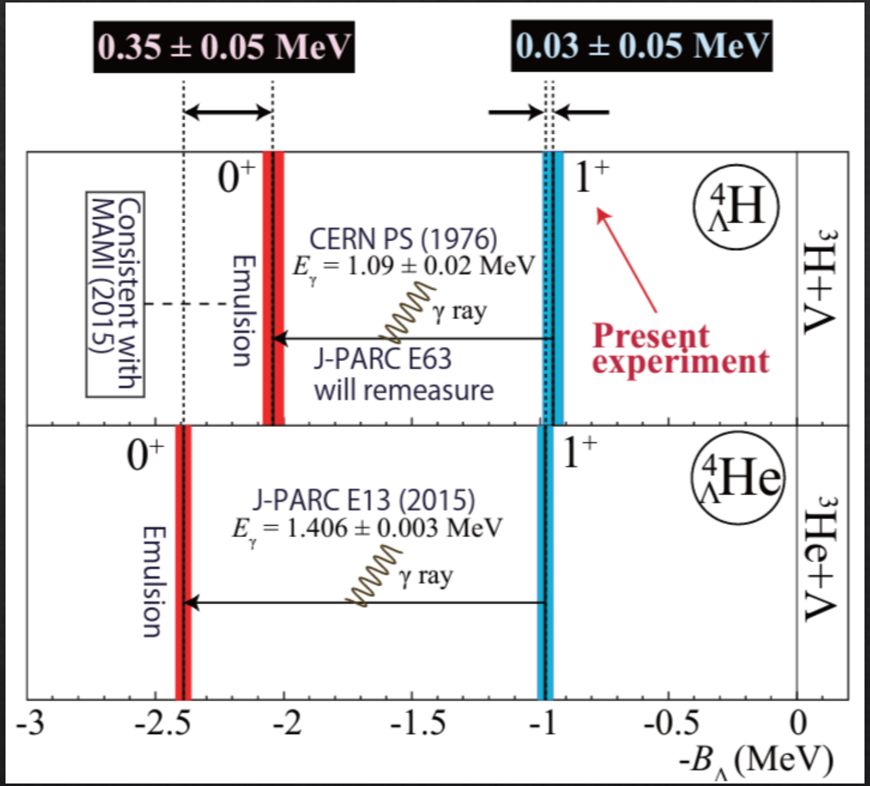
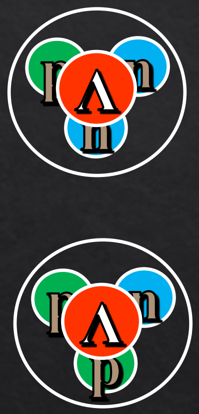


Figure from proposal of JLab E12-19-002





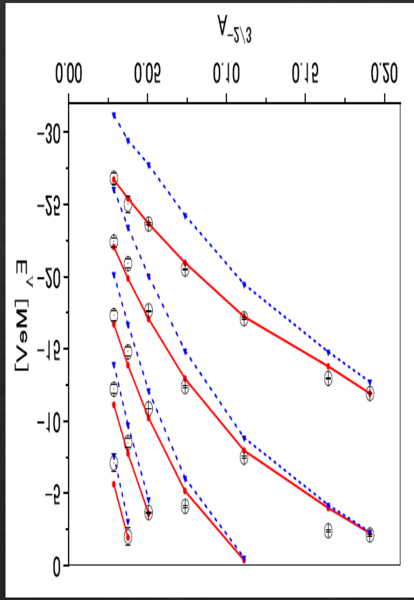
*1) J.H.E.Mattauch *et al.*, *Nucl. Pys.* **67**, 1 (1965).

*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

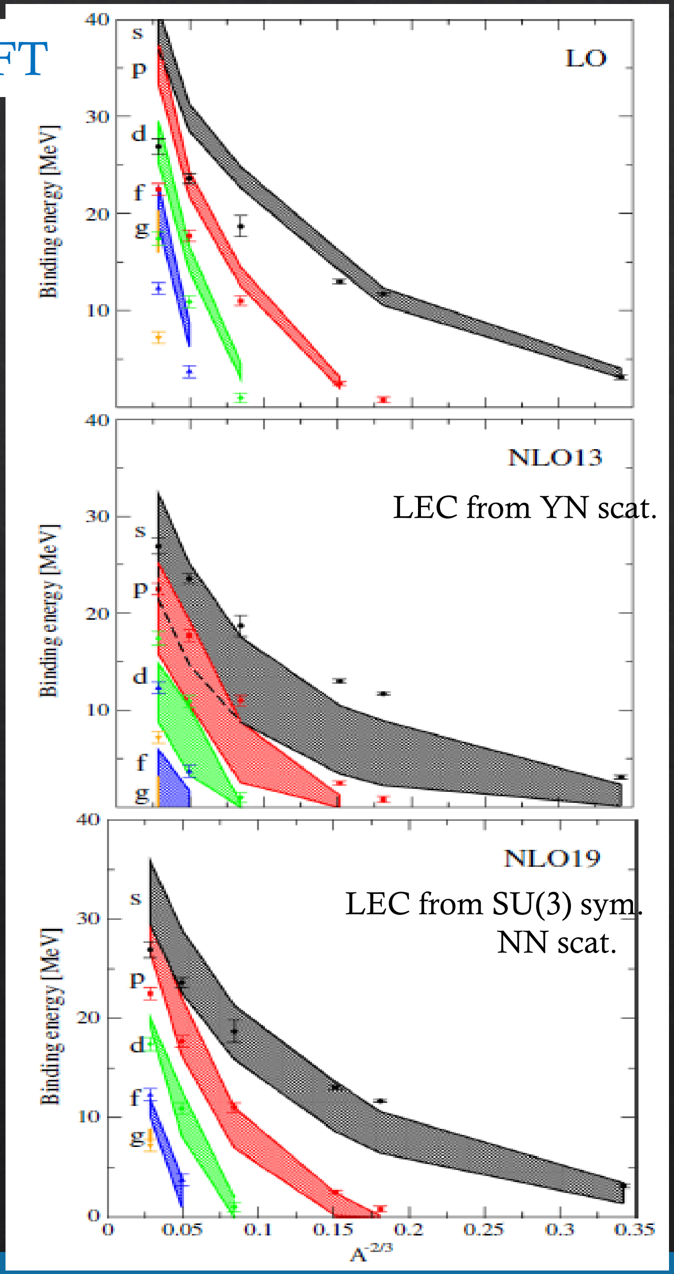
Λ Single Particle Energies of Λ Hypernuclei by Various Calculations

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

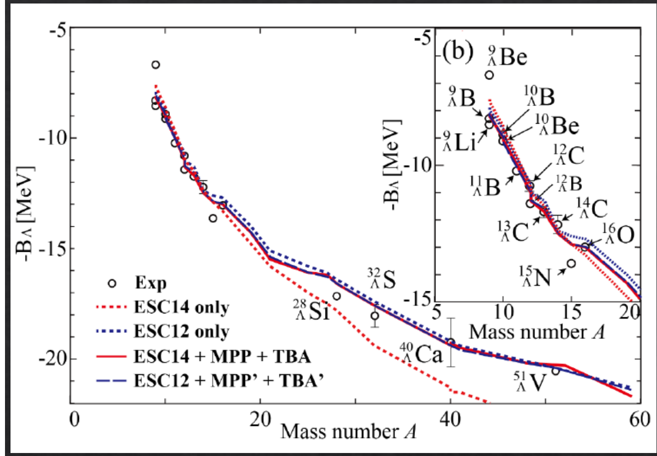


ESC16
ESC16+ (Inc. 3BF)
G-matrix

ChEFT



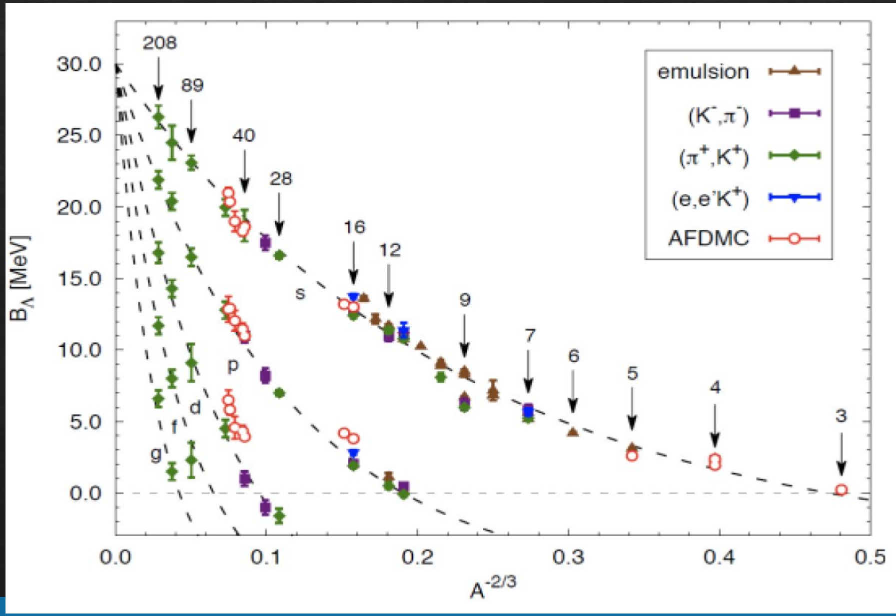
Hyper-AMD



M.Isaka et al.,
PRC94, 044310 (2016),
PRC 95, 044308 (2017)

D.Lonardoni and F. Pederiva, arXiv:1711.07521.

AFDMC



J.Haidenbauer, I.Vidana, EPJA (2020) 56:55.

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

Isospin multiplet for CSB study

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+)	${}^{4}_{\Lambda}$H		${}^{4}_{\Lambda}$He	○	○	○
		(1+)	new			△	●	●
p-shell	α N Λ		${}^{6}_{\Lambda}$He new		${}^{6}_{\Lambda}$Li new			●
	α N N Λ		${}^{7}_{\Lambda}$He	${}^{7}_{\Lambda}$Li*	${}^{7}_{\Lambda}$Be	○	○	○
	α d N Λ		${}^{8}_{\Lambda}$Li		${}^{8}_{\Lambda}$Be	○	○	○
	α d N N Λ		${}^{9}_{\Lambda}$Li new	${}^{9}_{\Lambda}$Be	${}^{9}_{\Lambda}$B		●	●
	α α N Λ		${}^{10}_{\Lambda}$Be		${}^{10}_{\Lambda}$B new			●
	α α N N Λ		${}^{11}_{\Lambda}$Be new	${}^{11}_{\Lambda}$B new	${}^{11}_{\Lambda}$C		●	●
	α α d N Λ		${}^{12}_{\Lambda}$B		${}^{12}_{\Lambda}$C new			●

Electron-beam experiment at JLab
Hadron-beam experiment
Emulsion experiment
γ-ray experiment

Jefferson Lab
Thomas Jefferson National Accelerator Facility

J-PARC
Japan Proton Accelerator Research Complex

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

E12-19-002

LOI12-23-013

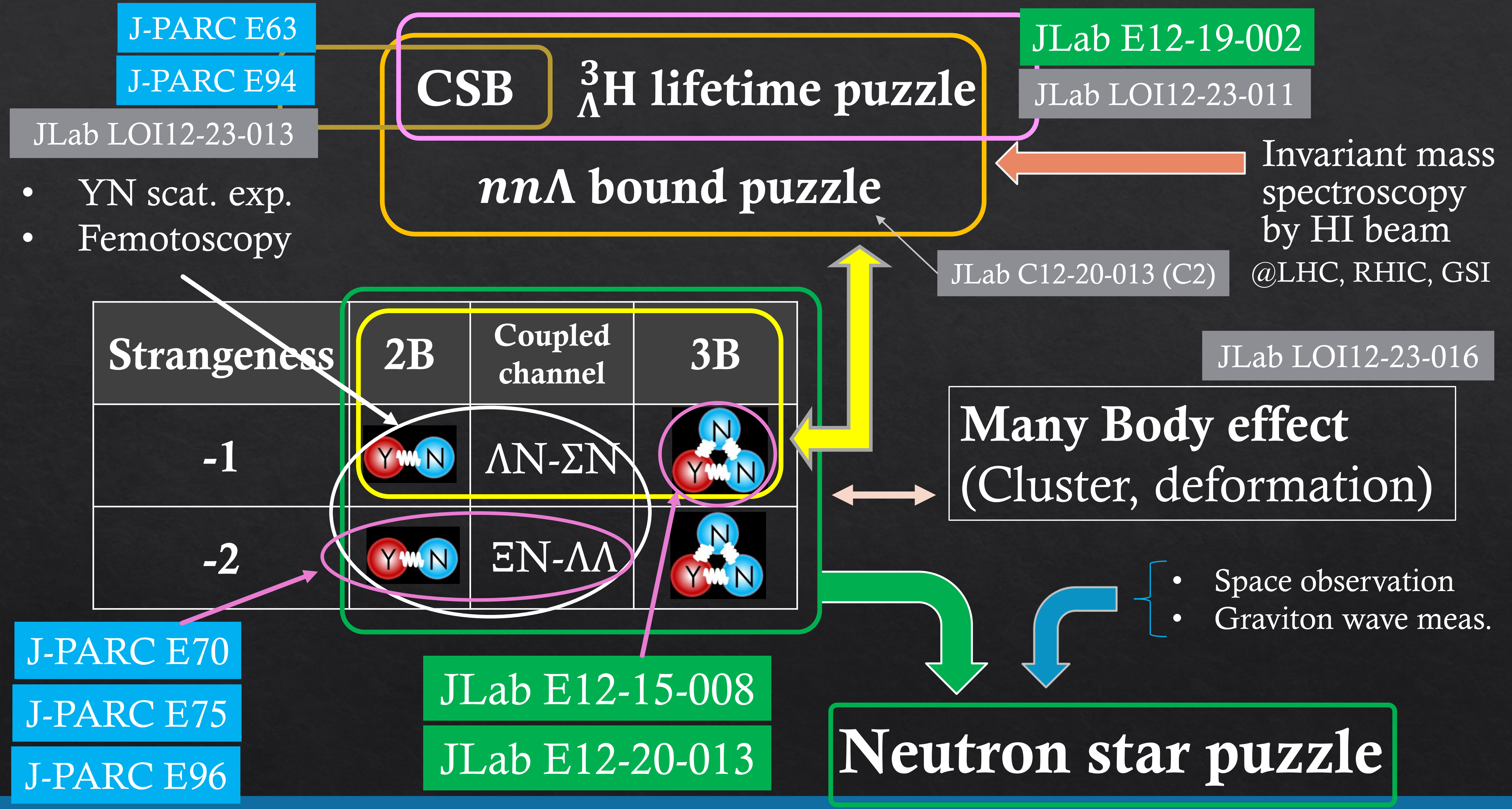
Proposing

Proposing

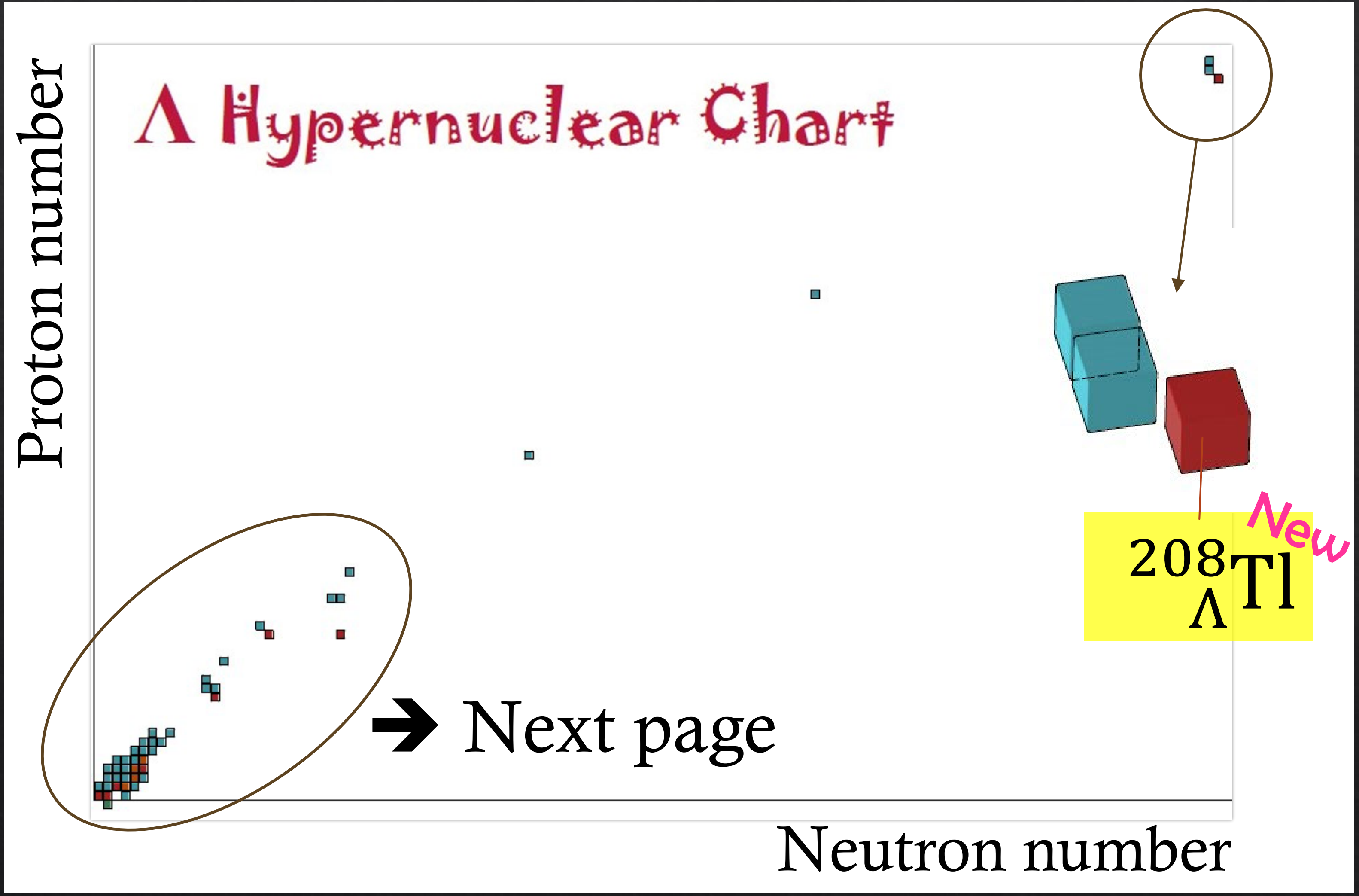
E94

E94

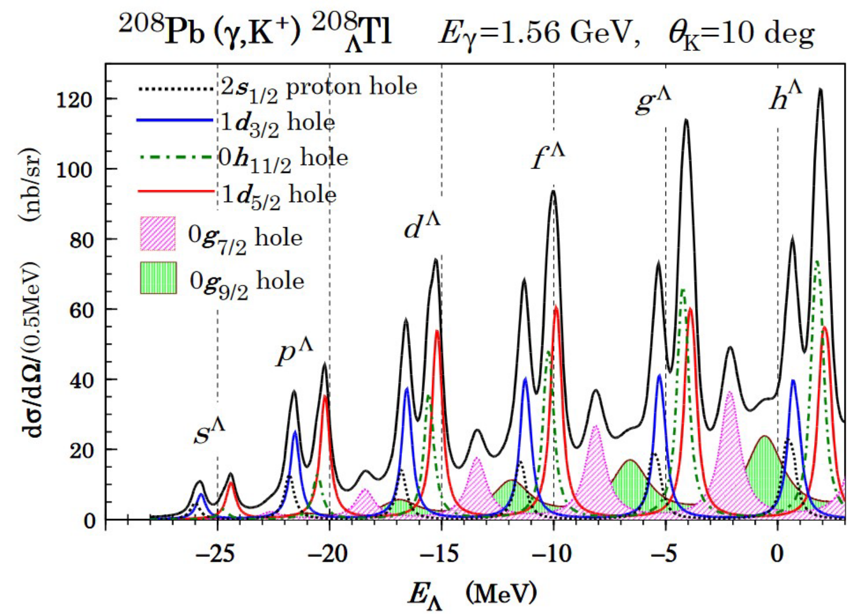
To "complete"
Isospin multiplet for **CSB** study


J-PARC E63
J-PARC E94
JLab LOI12-23-013
CSB
$^{3}_{\Lambda}$H lifetime puzzle
JLab E12-19-002
JLab LOI12-23-011
nnΛ bound puzzle
Invariant mass spectroscopy by HI beam
@LHC, RHIC, GSI
JLab C12-20-013 (C2)
• YN scat. exp.
• Femotoscopy
Strangeness
2B
Coupled channel
3B
-1
ΛN-ΣN
-2
ΞN-ΛΛ
Y
N
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

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

New

LOI12-23-013

→ Link

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

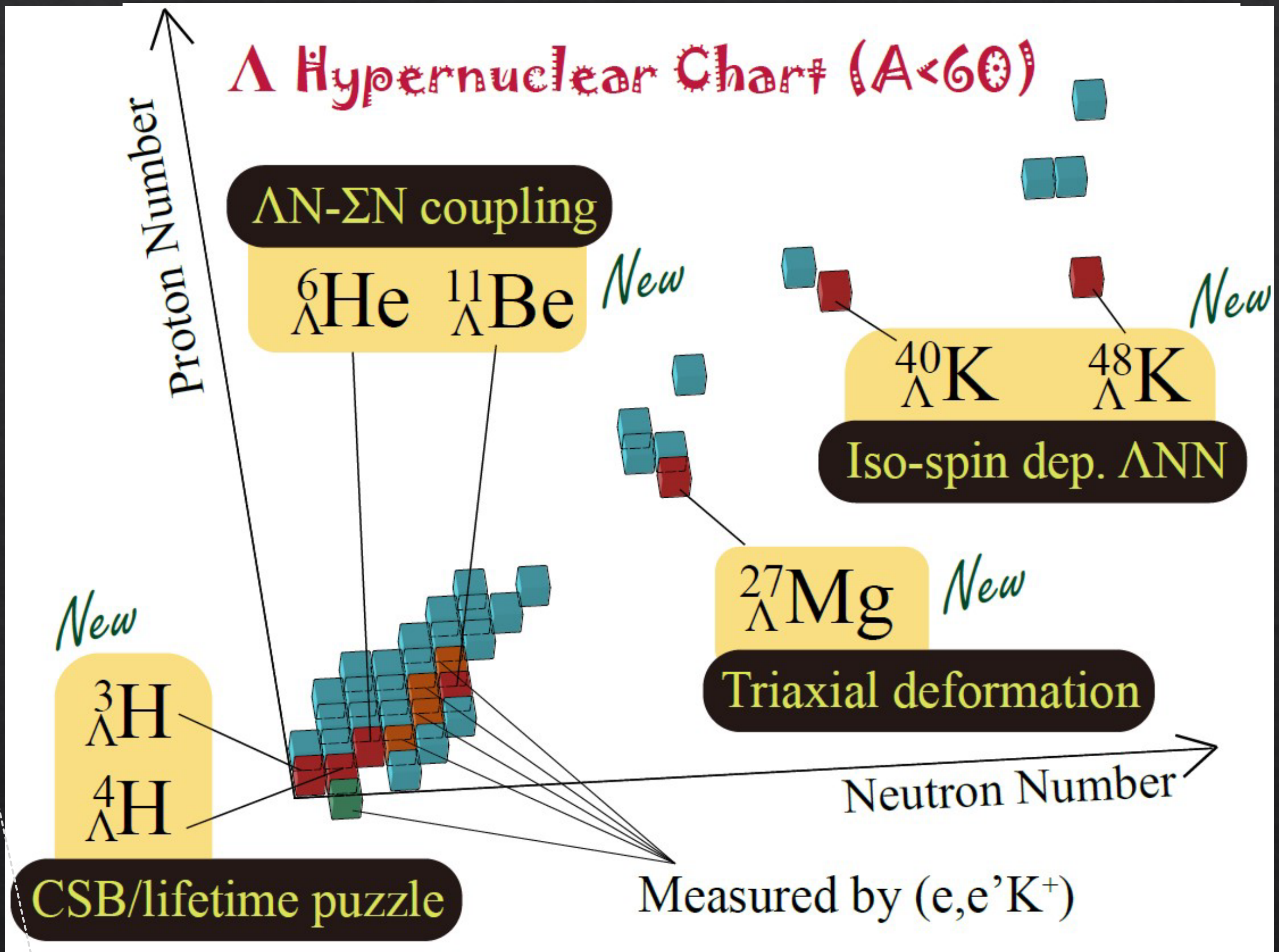
E12-19-002

- 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)

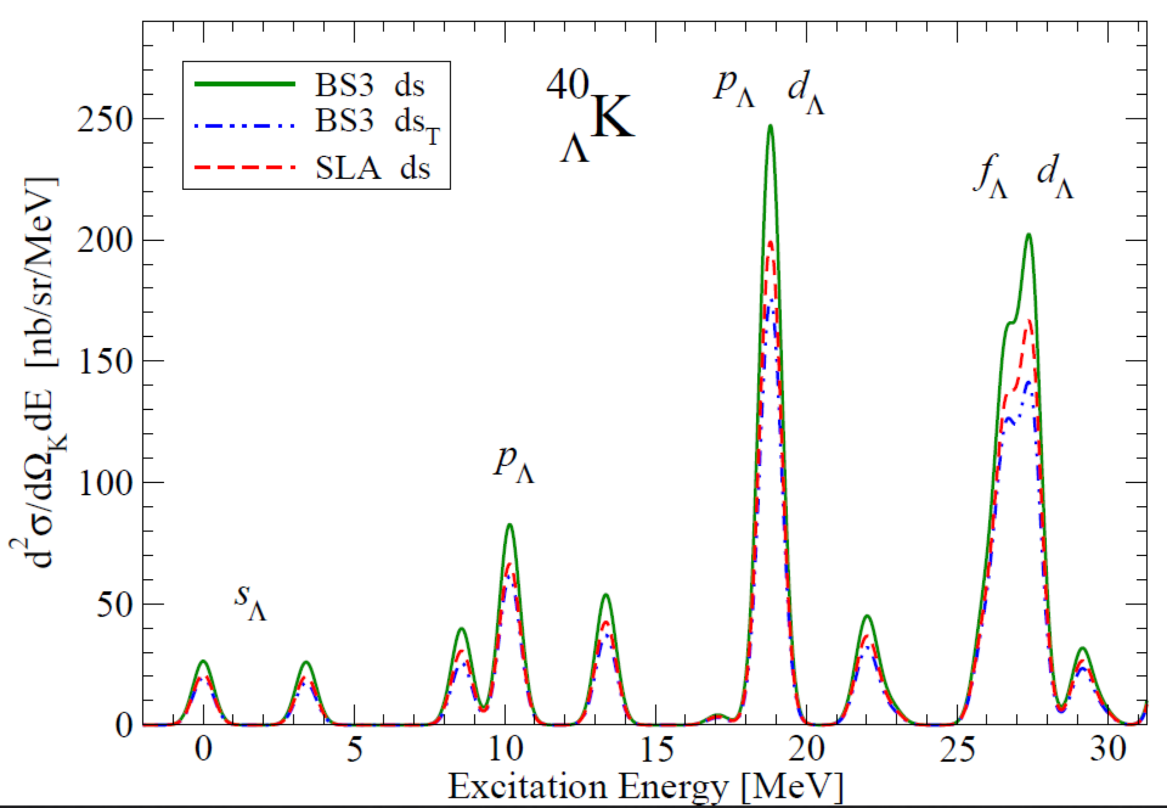
New

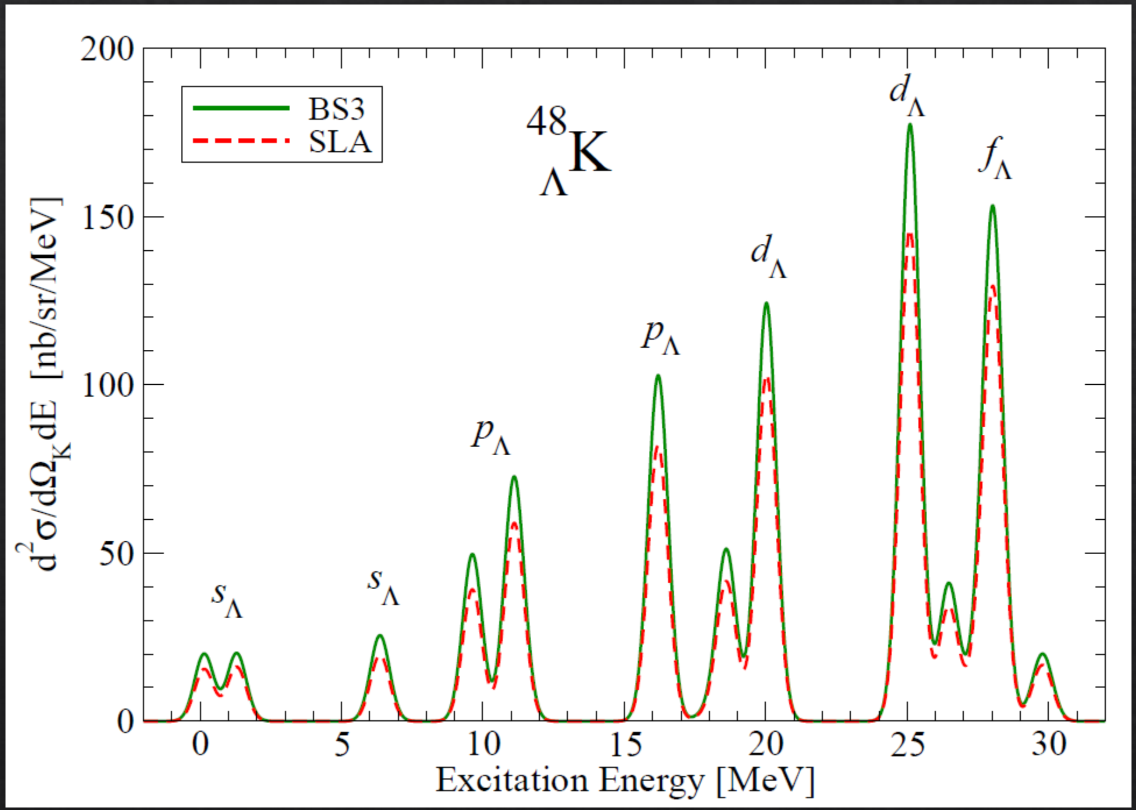
LOI12-23-016

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

Theoretical calculation, A = 40 and 48

P. Bydžovský, D. Denisova, D. Petrellis, D. Skoupil, P. Veselý,
G. De Gregorio, F. Knapp, N. Lo Iudice, arXiv:2306.01308 [nucl-th] (2023)





The CSB in p-shell Λ hypernuclei

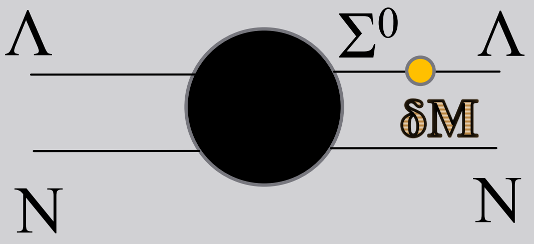
Phenomenological CSB:
E. Hiyama *et al.*, *Phys. Rev. C* **80**, 054321 (2009).

ΛN-ΣN coupling:
A. Gal, Phys. Lett. B 744, 352 (2015).

Phenomenological ΛN CSB interaction

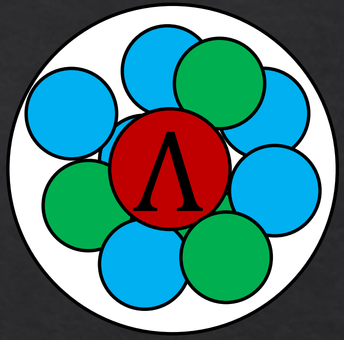
$$V_{\Lambda N}^{\mathrm{CSB}}(r) = -\frac{\tau_z}{2}\Big[\frac{1+P_r}{2}\Big(v_0^{\mathrm{even,CSB}} + \sigma_{\boldsymbol{\Lambda}}\cdot\sigma_{\mathbf{N}} v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{even,CSB}}\Big)e^{-\beta_{\mathrm{even}}r^2} + \frac{1-P_r}{2}\Big(v_0^{\mathrm{odd,CSB}} + \sigma_{\boldsymbol{\Lambda}}\cdot\sigma_{\mathbf{N}}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

Explicit inclusion of the ΛN-ΣN coupling



- ✓ Little effect on p-shell Λ hypernuclear system
- ✓ Large CSB in the A = 12 system ($^{12}_{\Lambda}$B and $^{12}_{\Lambda}$C) ??

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



$$B_{\Lambda}^{\mathrm{emul.}}({}^{12}_{\Lambda}\mathrm{C}) = 10.37\ \mathrm{MeV}$$

(The mean of 6 events)

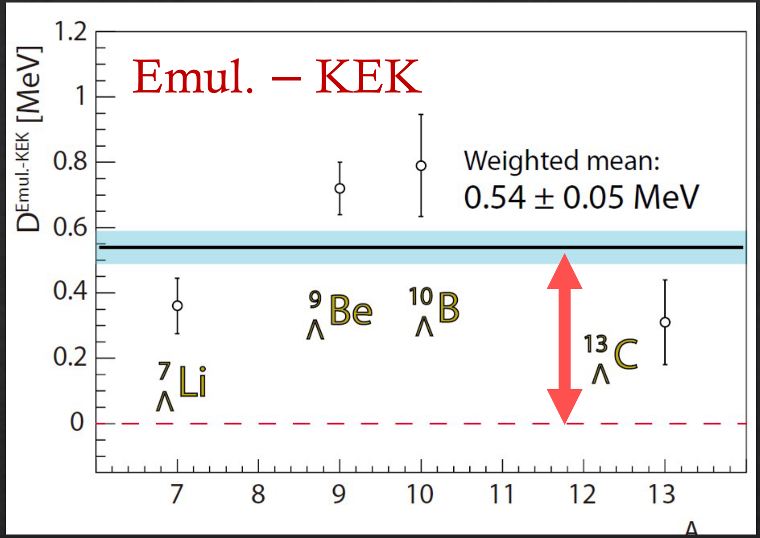
0.5—0.6 MeV correction is necessary

Direct measurement (J-PARC94)

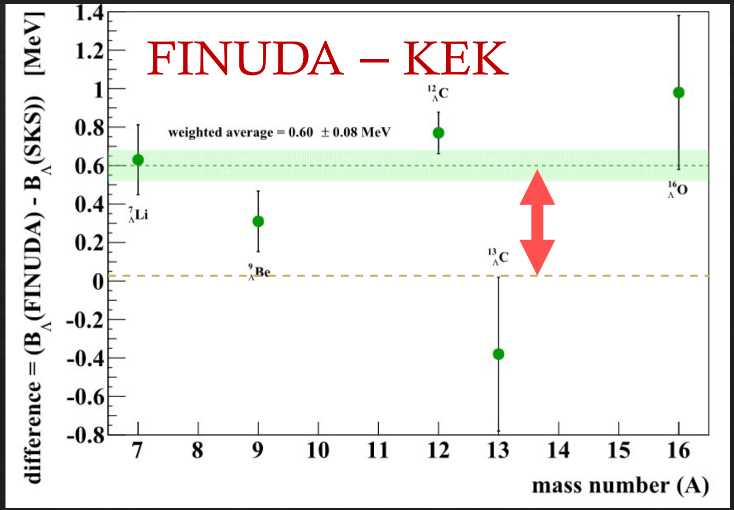
Indirect measurement

KEK: calibrated by $B_{\Lambda}^{\mathrm{emul.}}({}^{12}_{\Lambda}\mathrm{C})$

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

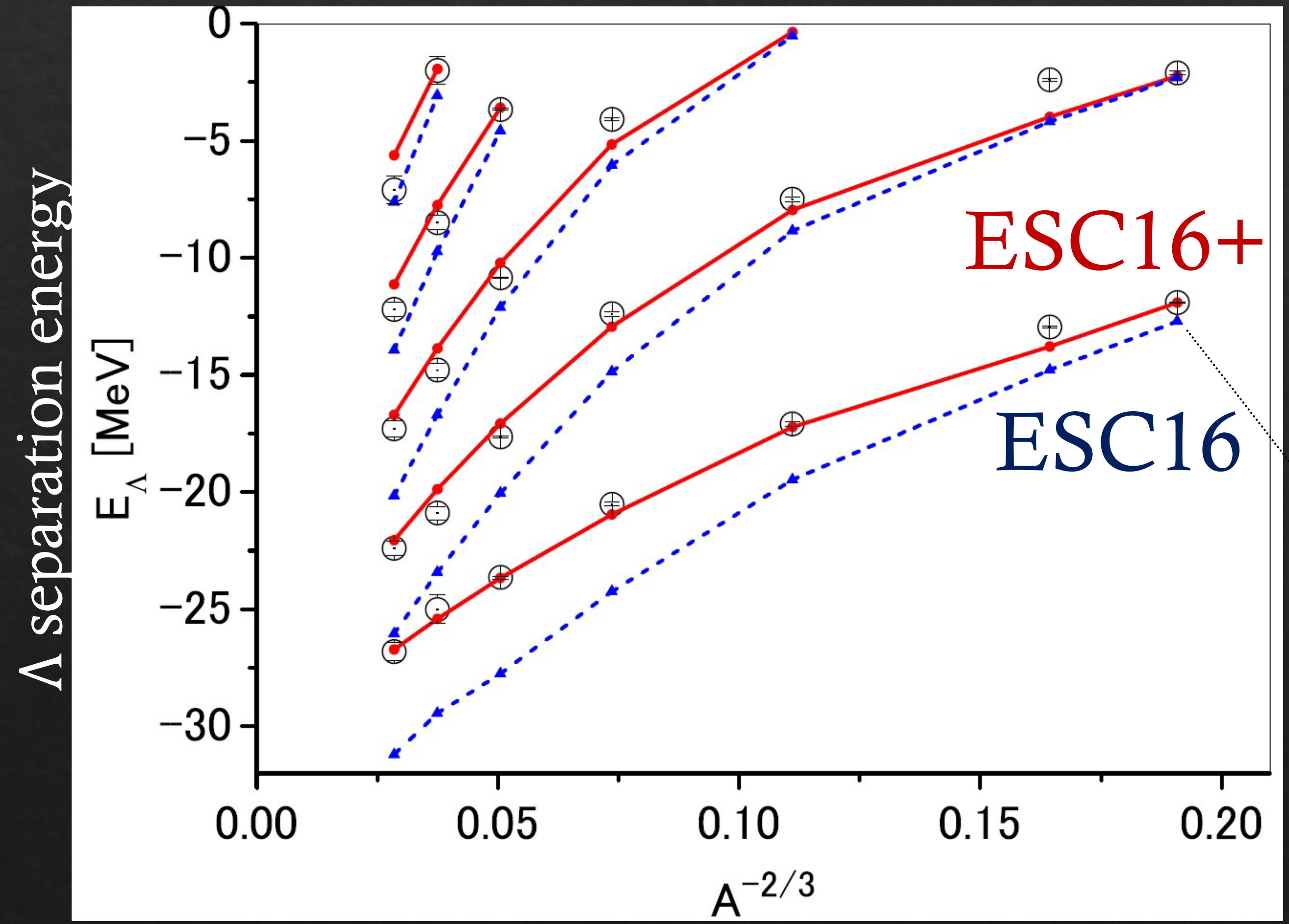


E. Botta et al., NPA 960, 165—179 (2017)



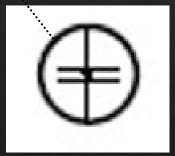
0.5 MeV shift became standard

M. M. Nagels et al., Phys. Rev. C **99**, 044003 (2019)



(A: Mass number of core nucleus)

$B_\Lambda^{\text{emul.}}({}^{12}_{\Lambda}\text{C})$ was used for the energy calibration of the (π^+, K^+) experiments

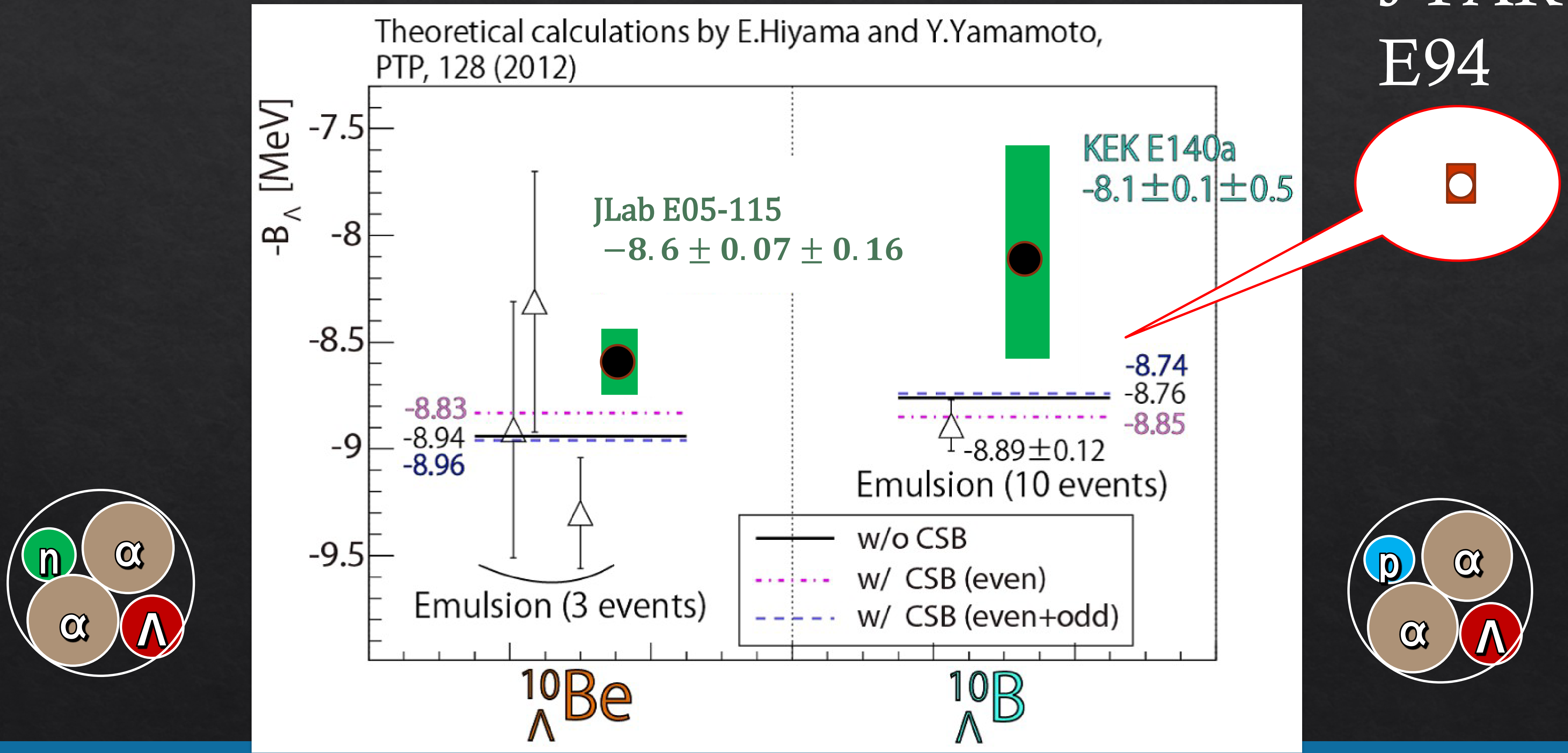


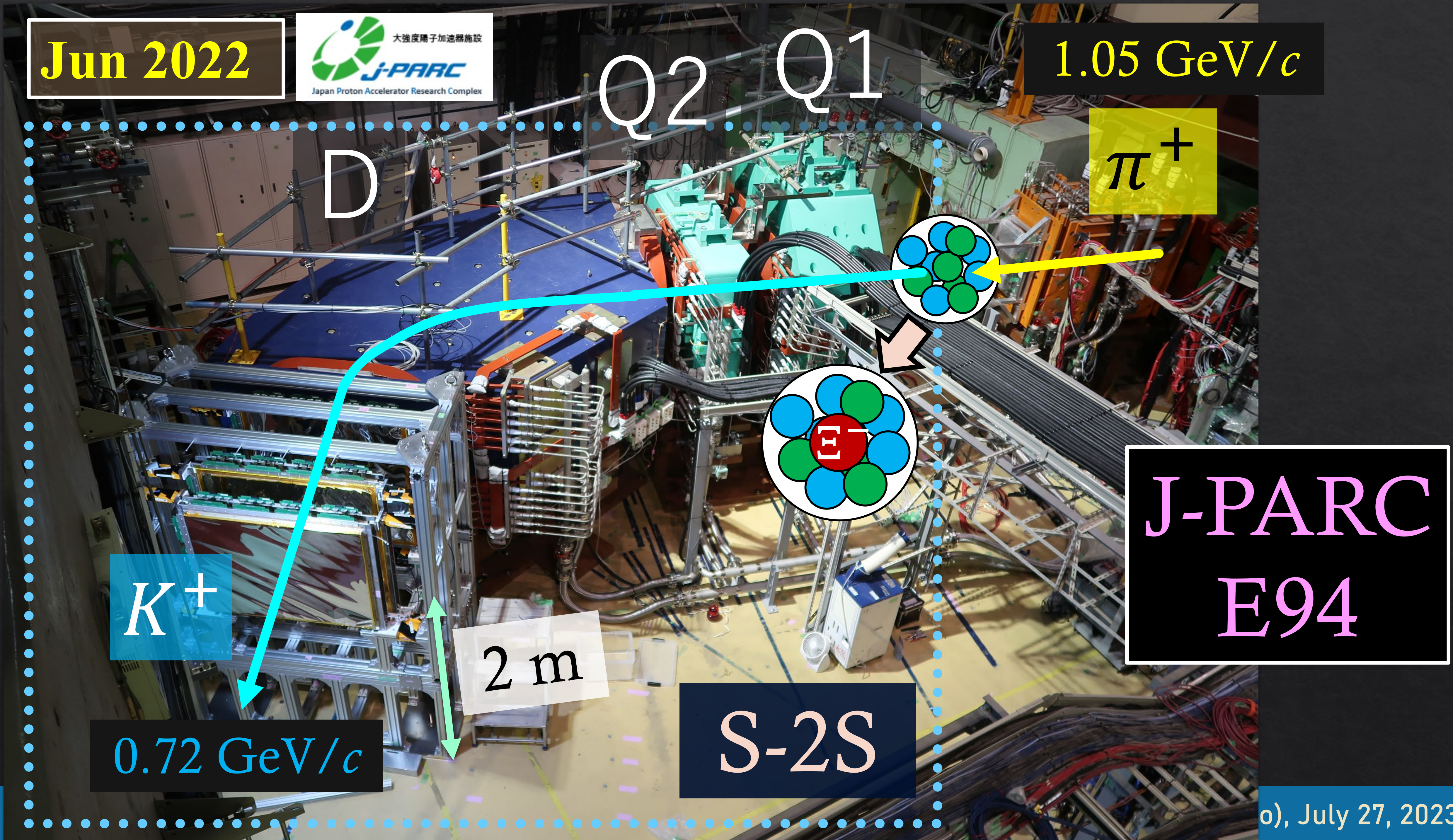
Data with 0.5 MeV correction

to be compared with theoretical calculations

CSB in the A = 10 iso-doublet HN

J-PARC
E94




Jun 2022
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^+
Ξ^-
J-PARC
E94
K^+
2 m
0.72 GeV/c
S-2S