

A 3D CAD rendering of a complex particle detector or accelerator component, possibly a spectrometer. The structure is composed of various colored blocks (yellow, green, blue, red) and features a central cylindrical chamber, multiple levels of walkways with railings, and a long, narrow beamline extending from the bottom left towards the center. The background is a dark, textured surface, possibly a tunnel or a large hall.

Hypernuclear Spectroscopy I: Λ N Charge Symmetry in Light Hypernuclei

Quark Nuclear Science Institute (QNSI)

The University of Tokyo

Sho Nagao

on behalf of

JLab hypernuclear collaboration

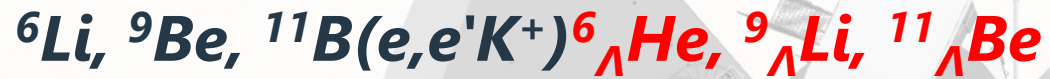
Hall A/C Summer Meeting 2026

Hypernuclear project at Jefferson Lab Hall-C

s-, p-shell hypernuclei with Decay Pion Spectroscopy

E12-15-008A / E12-20-013A

High-resolution spectroscopy of light hypernuclei with the decay pion spectroscopy



E12-24-004 (24 days)

Study of charge symmetry breaking in p-shell hypernuclei



E12-24-011 (28 days)

Study of a triaxially deformed nucleus using a Lambda particle as a probe



E12-24-013 (55 days)

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



E12-24-003 (42 days)

Studying Λ interactions in nuclear matter with the ${}^{208}\text{Pb}(e,e'K^+){}^{208}_{\Lambda}\text{Tl}$ reaction

Installation
2027-
Running
2029-

Contents

What is hypernucleus and Basic Question

Hypernuclear Electro-Photo Production Overview

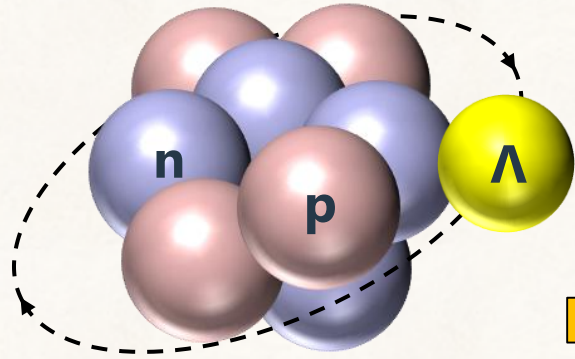
**Hypernuclear Spectroscopy I:
 Λ N Charge Symmetry in Light Hypernuclei**

**Hypernuclear Spectroscopy II:
 Λ N Interactions across a Wide Mass Range**

NEXT Talk

Apparatus, Preparation Work and Schedule

Hypernucleus



Lambda (Λ) #

Notation

"12" baryons



"5"

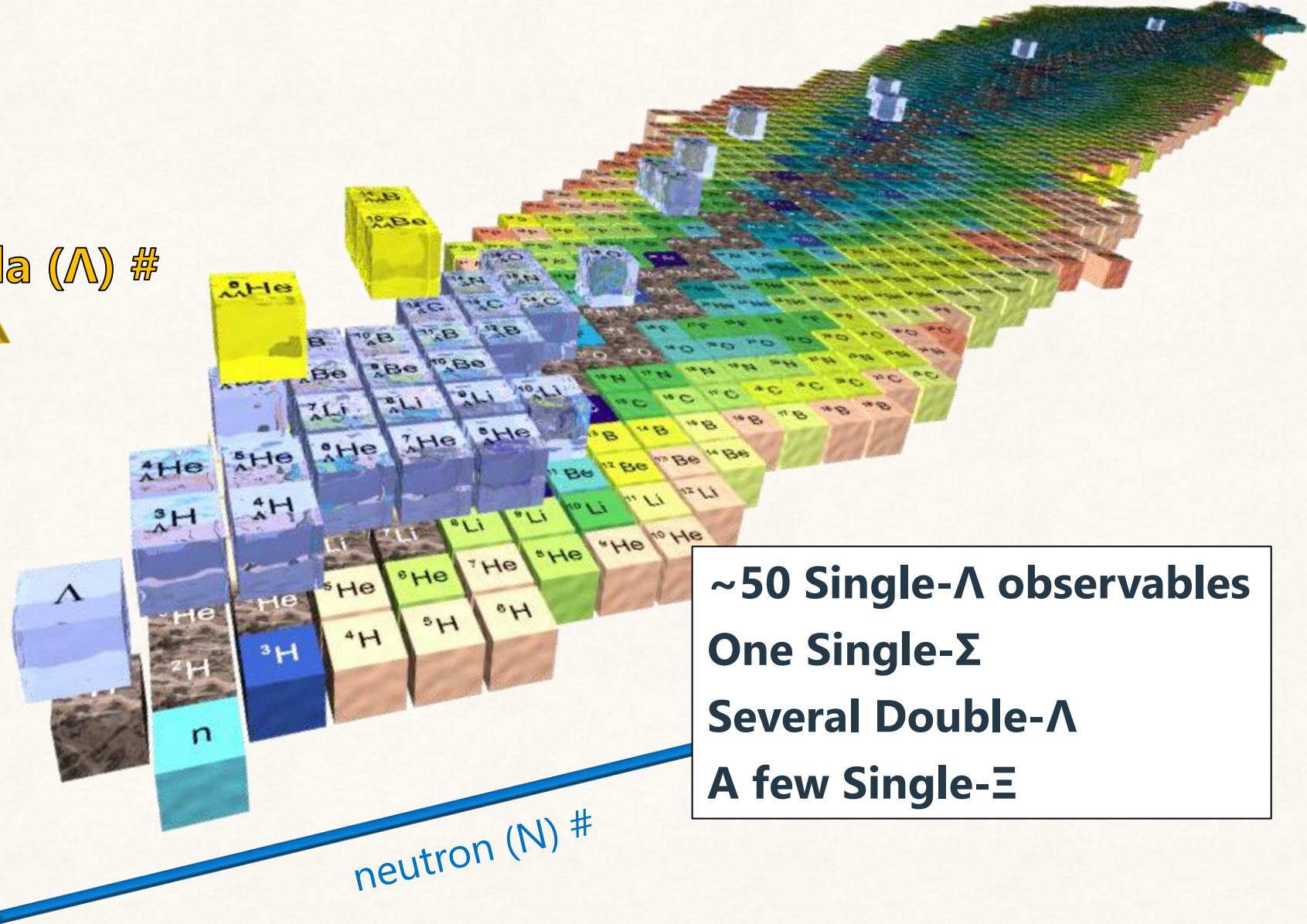
Protons

"1"

Lambda

proton (Z) #

neutron (N) #



~50 Single- Λ observables
 One Single- Σ
 Several Double- Λ
 A few Single- Ξ

Hypernuclear Properties

Precise Measurement of Λ Binding Energy

Study of NN and BB interaction

$$B_{\Lambda} = M_{\text{core}} + M_{\Lambda} - M_{\text{HYP}}$$

Core Λ Hypernucleus
Mass Mass Mass

$$U_{\Lambda N} \approx 2/3 U_{NN}$$

High-resolution spectroscopy available

No Pauli blocking from other nucleons

Weakly interacting Λ and N

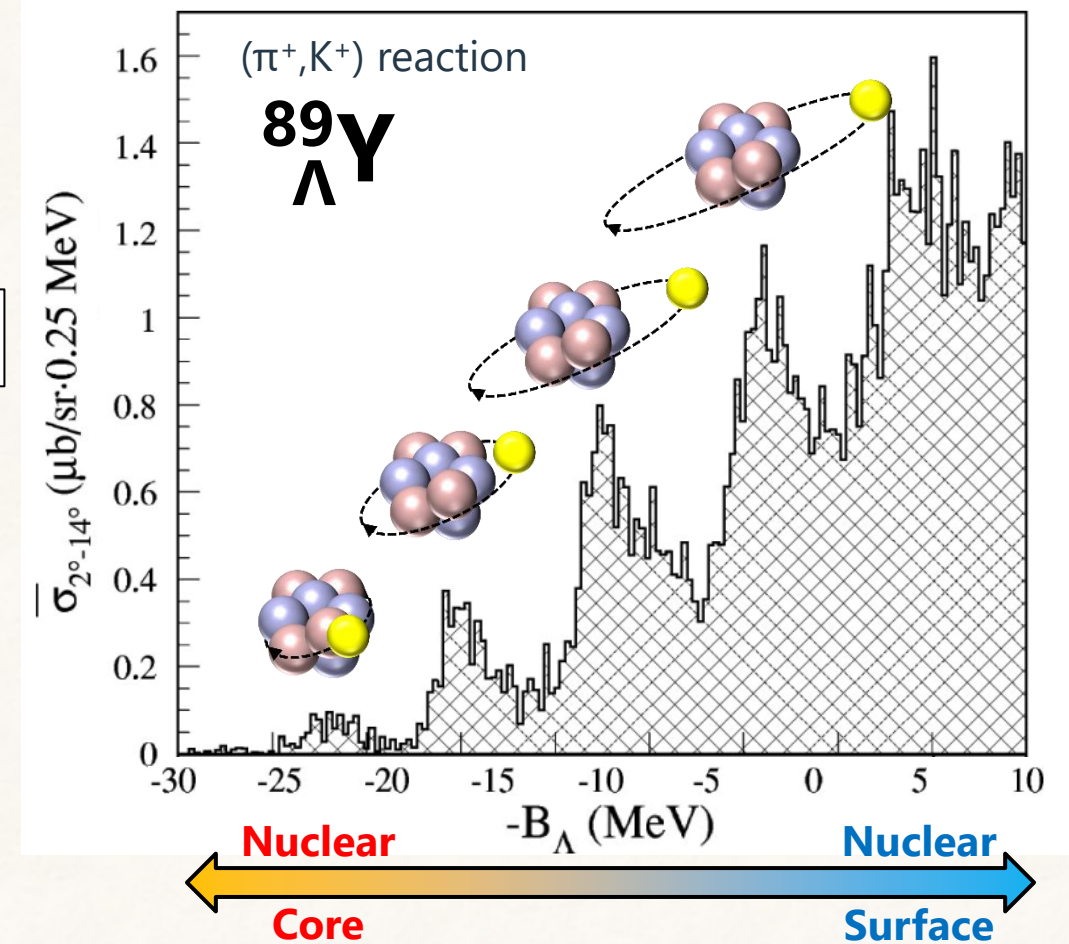
$\rightarrow \tau(\text{g.s.}) \sim 200 \text{ ps}, \Gamma(\text{e.x. above Sn}) < 100 \text{ keV}$

Good probe for ΛN interaction / (Hyper)nuclear structure

Mass, Isospin dependence etc. provide important information about effective $\Lambda N/\Lambda NN$ interaction

Light hypernuclei that can be applied for precise calculations are useful probes thanks to the recent progress of theories

Possible to approach changes of nuclear structure and deformation using Λ as a probe

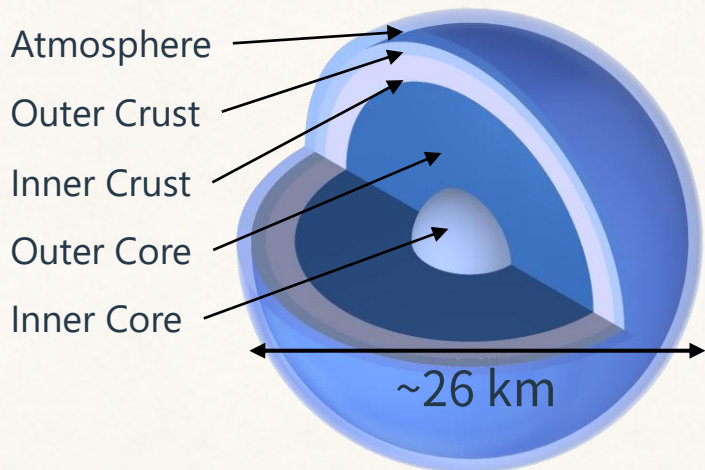


Textbook experiment at KEK

Beautiful shell-structure on med-heavy nucleus

Key Questions in Nuclear Physics

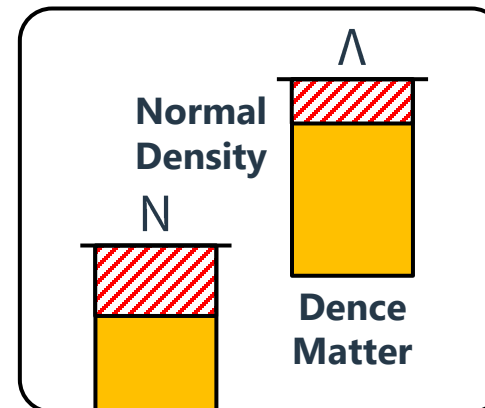
How Does Nuclear Matter Behave at Extreme Density ?
What is the Equation of State (EOS) of Dense Matter ?



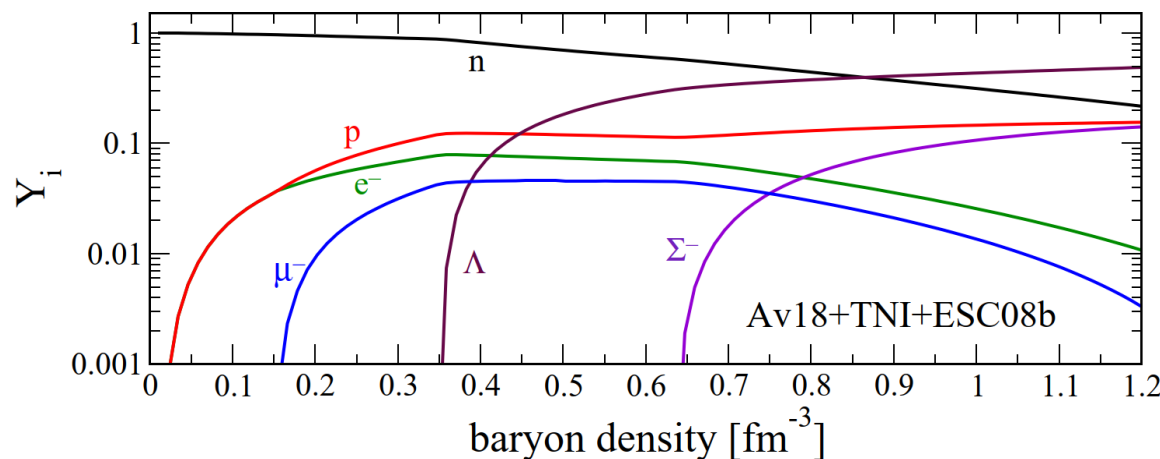
Nuclear Fermi Energy

$$E_F = \frac{p_F^2}{2m}$$

$$p_F = \hbar \left(\frac{3\pi^2 n}{V} \right)^{1/3}$$



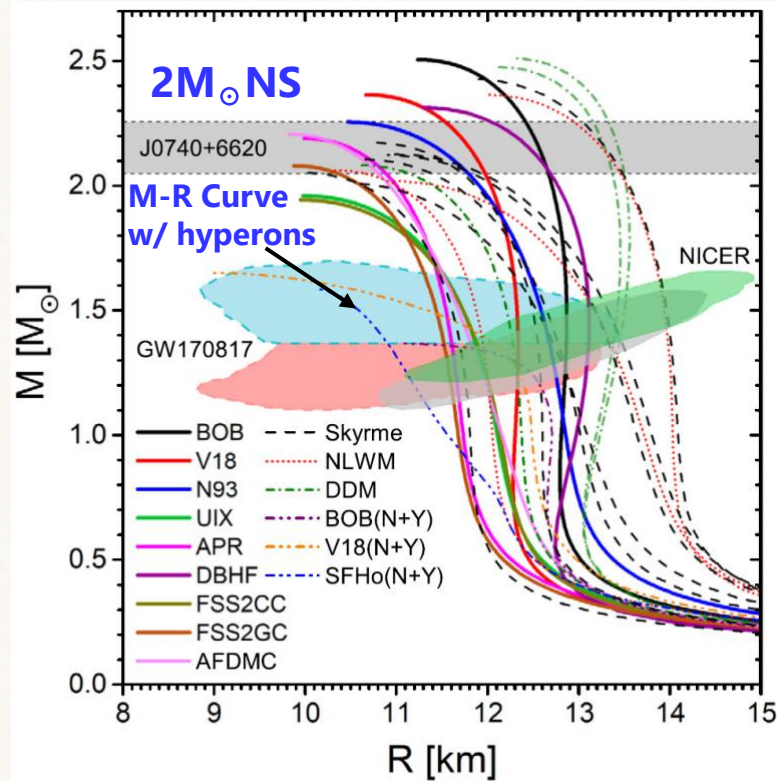
At high density, the nucleon Fermi energy increases, hyperons are expected to appear when the nucleon chemical potential becomes large enough



I. Bombaci, JPS Conf. Proc. 17, 101002 (2017)

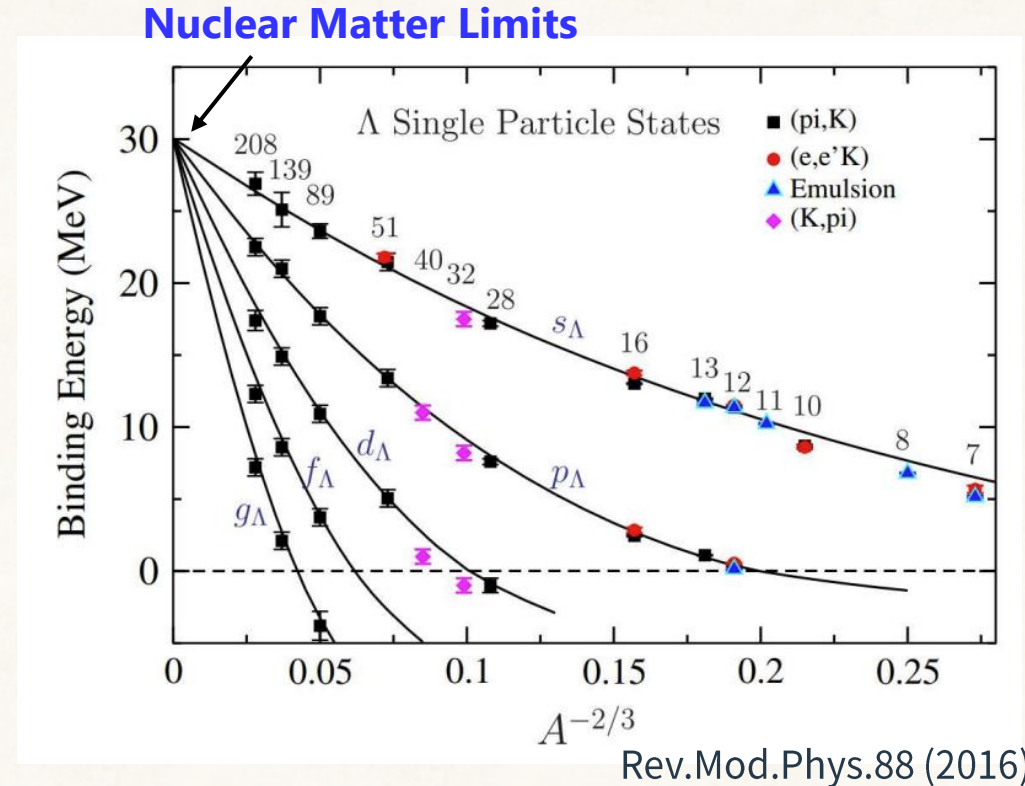
What is the EoS of Dense Nuclear Matter?

Mass–Radius Curves for Neutron Stars



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

Λ Single-Particle Potential in Hypernuclei



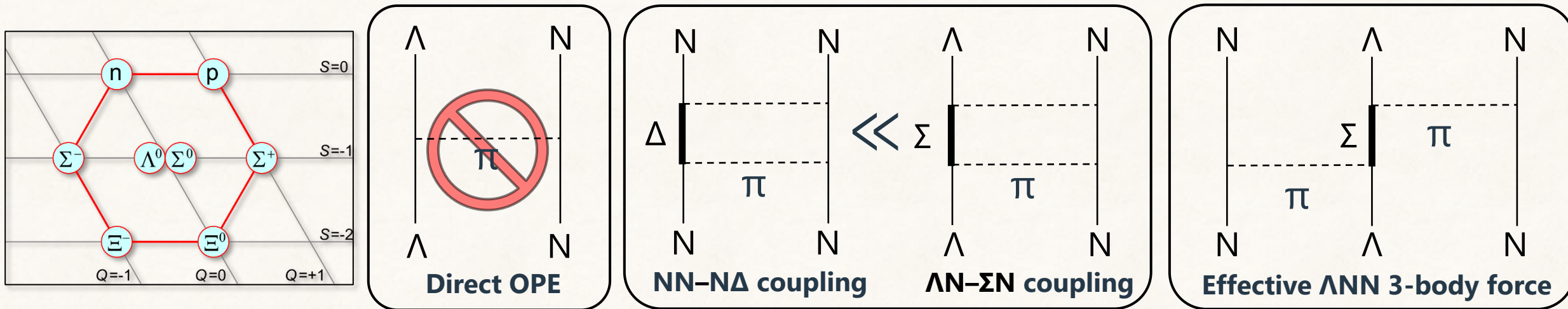
Rev.Mod.Phys.88 (2016) 035004.

- EOSs with hyperons are generally too soft to support $2M_{\odot}$ neutron stars.
- Unified understanding both astrophysical observations and terrestrial experiments is essential.
- **Repulsive Λ NN three-body** forces may be needed to support $2M_{\odot}$ neutron stars

Key Questions in Nuclear Physics

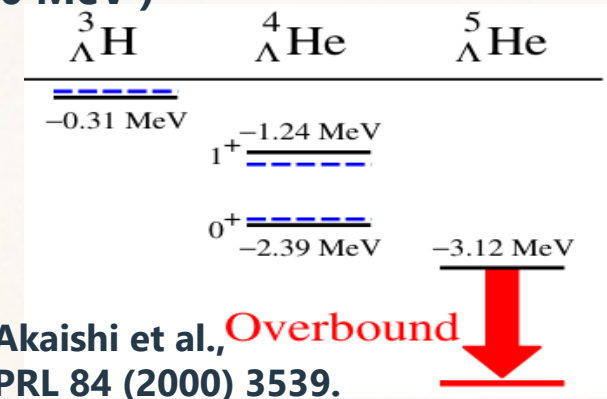
How do nuclear forces emerge from QCD ?

Hypernuclear physics extends nuclear forces from the N–N sector to the B–B sector, providing a unique window on coupled-channel dynamics and effective three-body forces.



($M_\Delta - M_N \approx 300 \text{ MeV} \gg M_\Sigma - M_\Lambda \approx 80 \text{ MeV}$)

- Direct OPE is forbidden in the ΛN channel.
- The small $\Sigma-\Lambda$ mass splitting enhances Σ -mixing effects.
- The resulting effective ΛNN three-body force is important, as suggested by the over-binding problem of ${}^5_\Lambda\text{He}$.



Charge (Isospin) Symmetry on $A=3$ nuclei



$$M(^3\text{H}) = 2808.9210045 (23) \text{ MeV}/c^2$$

$$M(^3\text{He}) = 2808.3914756 (24) \text{ MeV}/c^2$$

[Ann. Rev. Nucl. Part. Sci. 56 (2006) 253.]

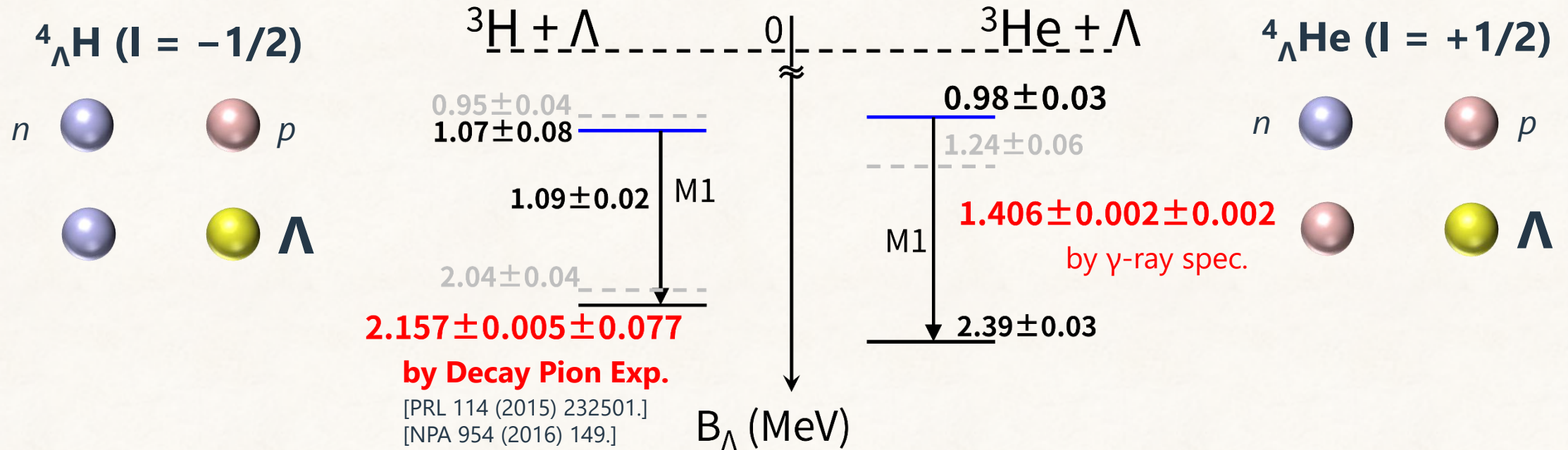
$$\Delta B(^3\text{He} - ^3\text{H}) = -0.763755 (1) \text{ MeV} \left\{ \begin{array}{l} \text{Ele.-Mag. Effect} = -0.693 \pm 0.019 \pm 0.005 \text{ MeV} \\ \Delta B^{\text{CSB}}(^3\text{He} - ^3\text{H}) = -0.07 \text{ MeV} \quad \text{only 0.0025\% difference !} \end{array} \right.$$

| | |
|------------------------------------|---------------------------------|
| Coulomb-modified Faddeev equation: | -0.072 MeV [PRL64 (1990) 1875.] |
| Isobaric Mass Multiplet equation: | -0.059 MeV [PRC37 (1988) 781.] |

Charge symmetry of NN sector is a good symmetry

Breaking term can be understood by mass difference of u and d quarks.

A=4 Hypernuclear Charge Symmetry Breaking



$$\Delta B^{\text{CSB}}({}^4_{\Lambda}\text{He}(1^+) - {}^4_{\Lambda}\text{H}(1^+)) = -0.09 \text{ MeV}$$

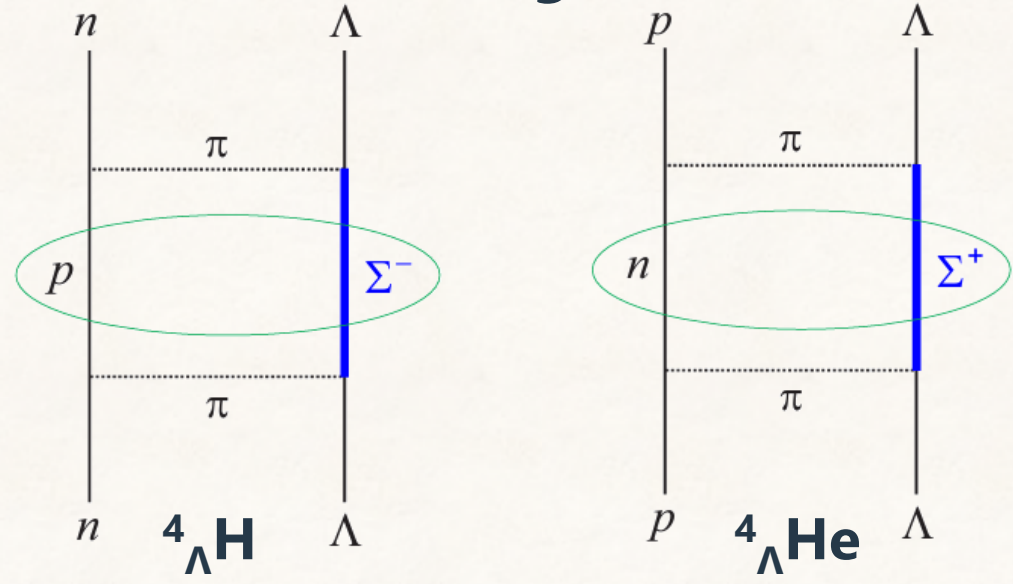
$$\Delta B^{\text{CSB}}({}^4_{\Lambda}\text{He}(0^+) - {}^4_{\Lambda}\text{H}(0^+)) = +0.23 \text{ MeV}$$

Larger B_{Λ} difference between the mirror hypernuclei (ΔB^{CSB}) exists for the ground state
 Λp interaction would be more attractive than Λn interaction (too naive discussion !!)

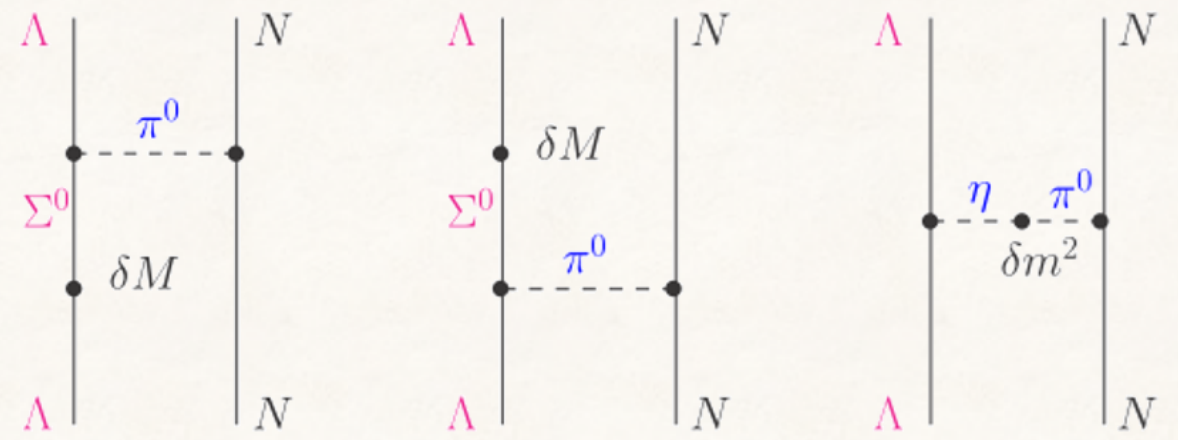
Different tendency between the $J^P=0^+$ ground-state and 1^+ excited-state (spin-dependent)

Possible Mechanisms of ΛN Charge-Symmetry Breaking

Σ mixing effect



Σ^0 mixing effect



Σ mixing effect allows a nonzero ΔB_Λ because of mass difference between of $M_{\Sigma^-} > M_{\Sigma^+}$

Σ^+ could appeared $\rightarrow +\Delta B_\Lambda$

Charge effect of $\Sigma^- p$ & $\Sigma^+ p \rightarrow -\Delta B_\Lambda$

Shrinkage effect $\rightarrow -\Delta B_\Lambda$

※ Similar discussion to 1^+ state

Difficult to reproduce large CSB.

Σ^0 mixing can be explained well ?

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

Additional Pion Exchange would be allowed

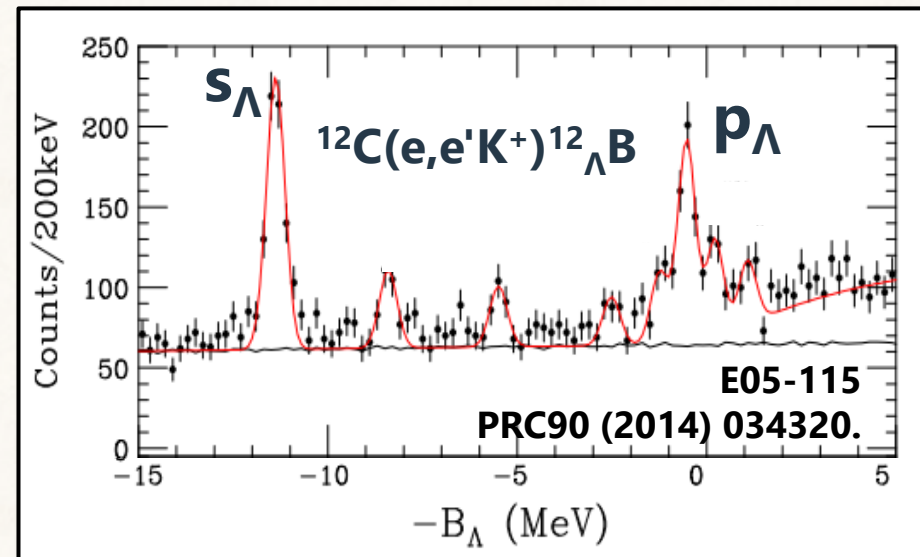
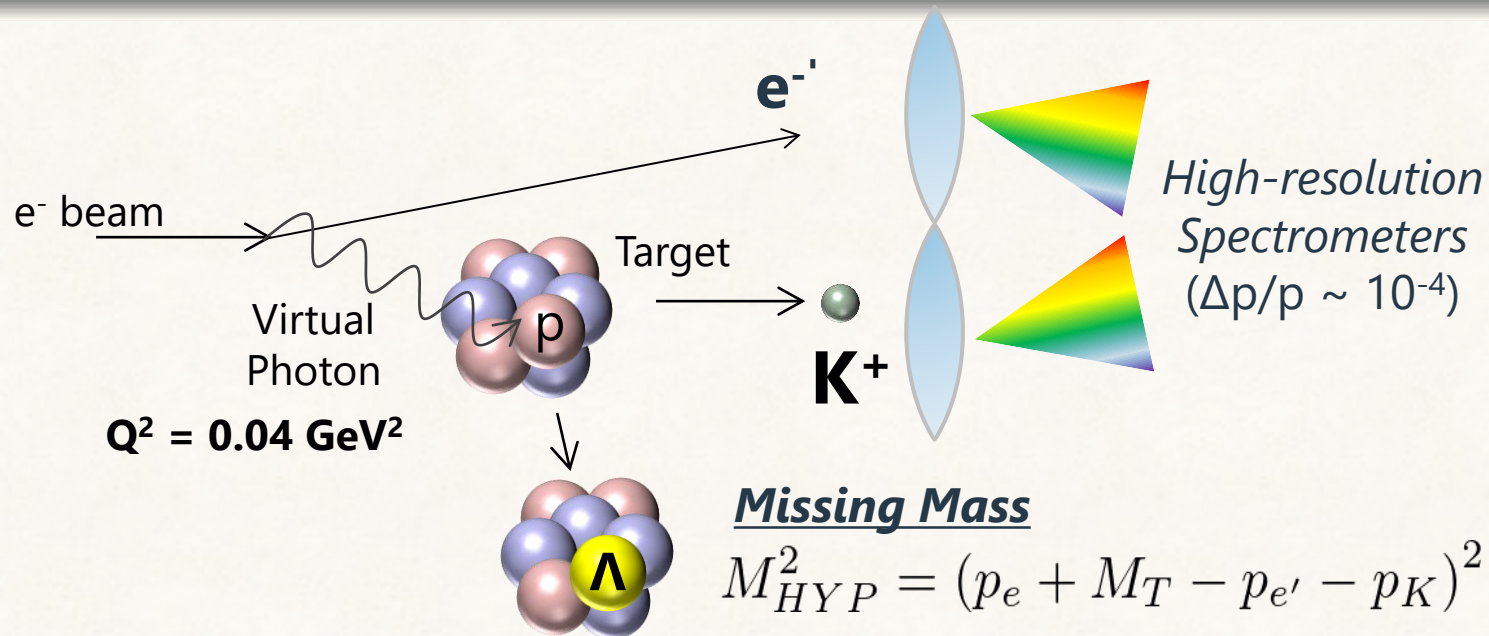
A. Gal, J. Phys. Conf. 966 (2018) 012006.
 J.Haidenbauer, Few-Body Syst. 62 (2021) 105.
 D. Gazda, PRC106 (2022) 054001.

Λ N CSB on p-shell hypernuclei

| Hypernuclei | Exp. | [PTP128(2012)105] | | [PLB744(2015)352] | [PRC107(2023)024002] | |
|--|----------------|-------------------|------|----------------------|----------------------|---------------|
| | | Hiyama | Gal | Gazda-Gal | Le NLO13 | Le NLO19 |
| ${}^4_{\Lambda}\text{He} - {}^4_{\Lambda}\text{H} (0^+)$ | $+233 \pm 92$ | – | +226 | $+176^{+118}_{-146}$ | $+229 \pm 10$ | $+238 \pm 10$ |
| ${}^4_{\Lambda}\text{He} - {}^4_{\Lambda}\text{H} (1^+)$ | -83 ± 94 | – | +30 | -204^{+32}_{-24} | -94 ± 10 | -85 ± 10 |
| ${}^7_{\Lambda}\text{Be} - {}^7_{\Lambda}\text{Li}^*$ | -100 ± 90 | +150 | -17 | – | -40 ± 30 | -35 ± 30 |
| ${}^7_{\Lambda}\text{Li}^* - {}^7_{\Lambda}\text{He}$ | -20 ± 230 | +130 | -28 | – | -31 ± 30 | -16 ± 30 |
| ${}^8_{\Lambda}\text{Be} - {}^8_{\Lambda}\text{Li}$ | $+40 \pm 60$ | +160 | +49 | – | $+178 \pm 50$ | $+143 \pm 50$ |
| ${}^9_{\Lambda}\text{B} - {}^9_{\Lambda}\text{Li}$ | -210 ± 220 | – | -54 | – | – | – |
| ${}^{10}_{\Lambda}\text{B} - {}^{10}_{\Lambda}\text{Be}$ | -220 ± 250 | – | -136 | – | – | – |

- Recent χ EFT with Λ - Σ^0 coupling effect well reproduce A=4 system
- Recent calculations predict smaller and sometimes opposite-sign ΔB_{Λ} in p-shell hypernuclei.
- Existing data accuracy is not sufficient for CSB study ($\Delta B_{\Lambda} > 200$ keV)
- New <100 keV measurements for p-shell hypernuclei are essential

High Precision Hypernuclear Mass Spectroscopy



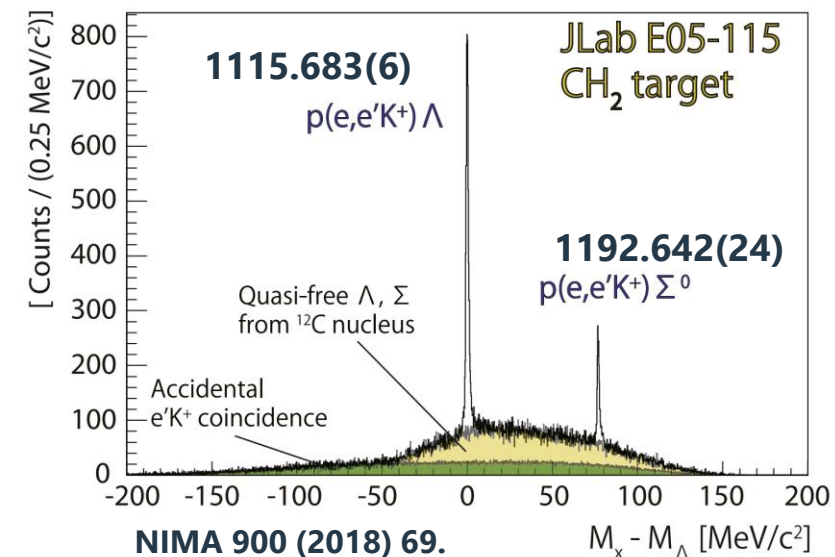
High-resolution ($e, e'K^+$) missing mass spectroscopy

Good peak separation on FWHM ~ 0.5 MeV

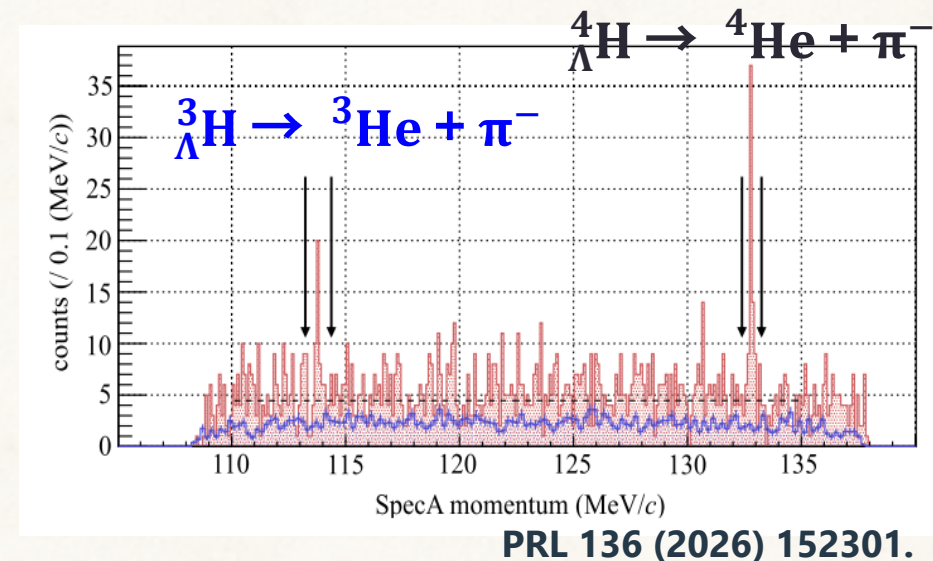
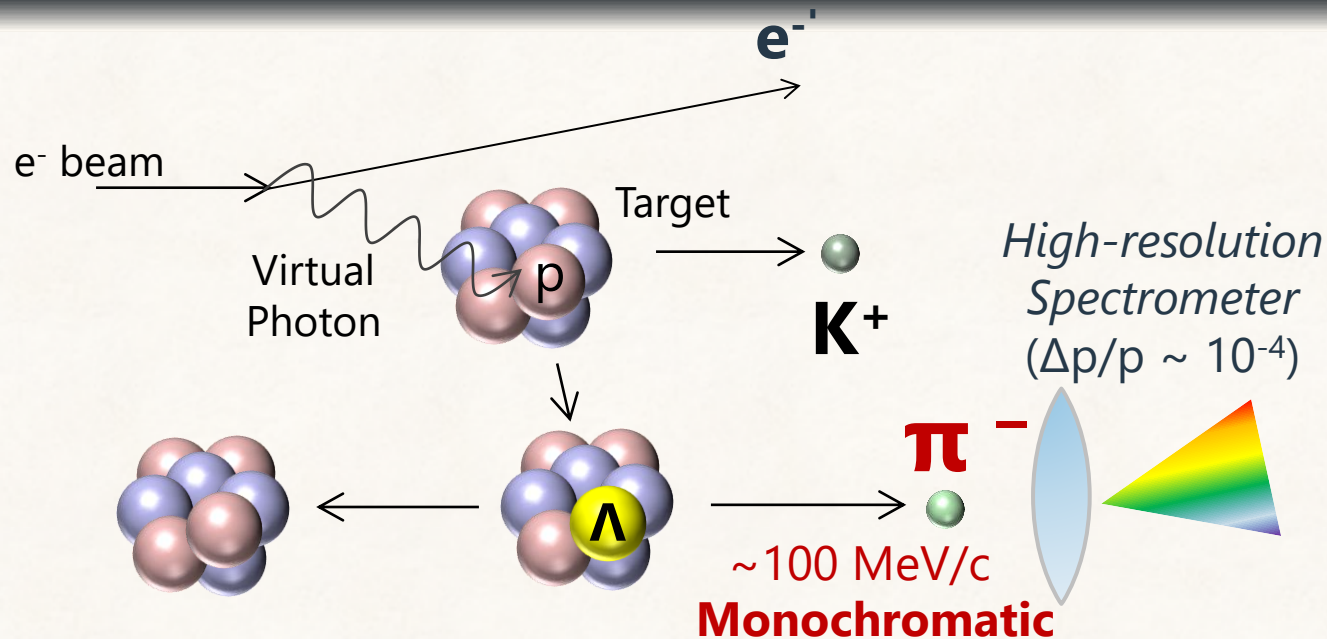
Hypernuclear masses, Level structure with $\delta E < 0.1$ MeV

Energy Calibration with $p(e, e'K^+)\Lambda$

Energy calibration with $p(e, e'K^+)\Lambda/\Sigma^0$ reaction



High Precision Hypernuclear Mass Spectroscopy



Invariant Mass (2-body decay from stopped hypernucleus)

$$M({}^A_{\Lambda}Z) = \sqrt{M({}^A(Z+1))^2 + p_{\pi}^2} + \sqrt{M_{\pi}^2 + p_{\pi}^2}$$

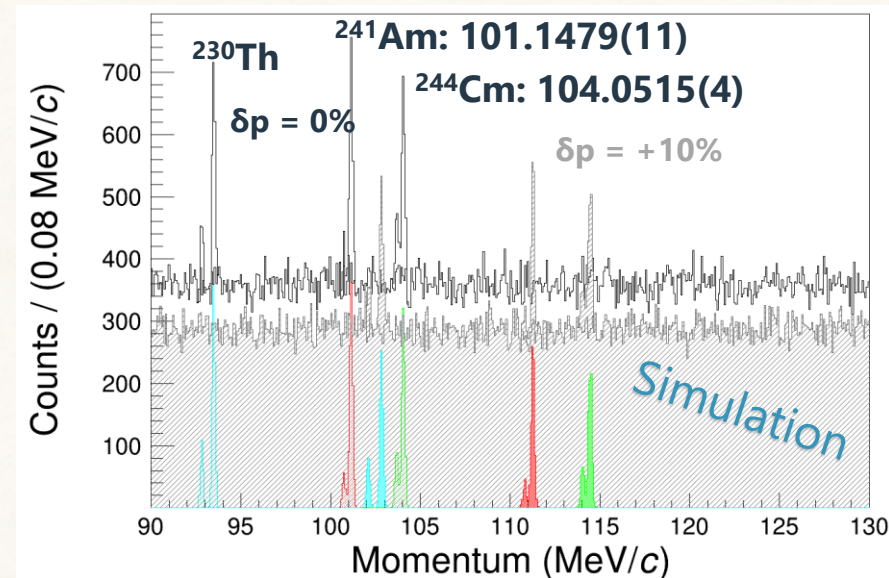
High-resolution decay pion spectroscopy

FWHM ~ 0.2 MeV

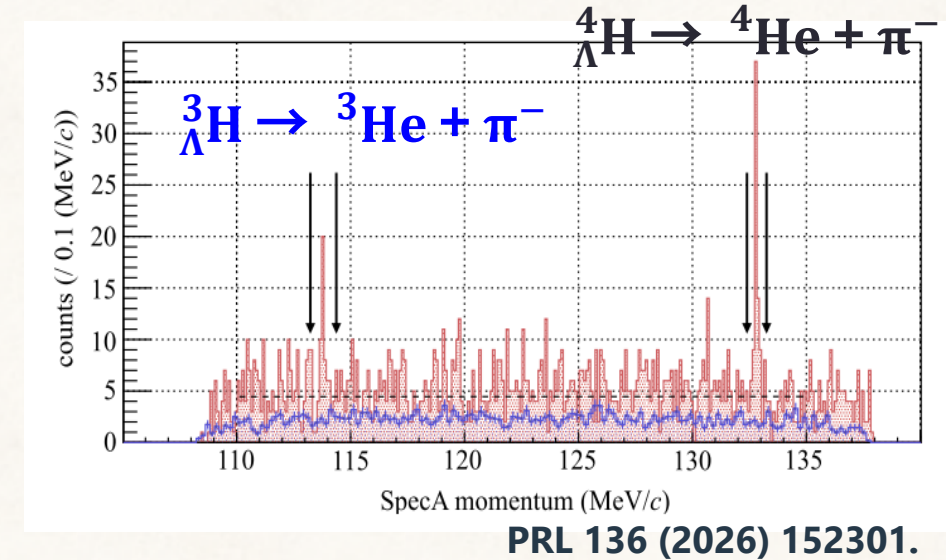
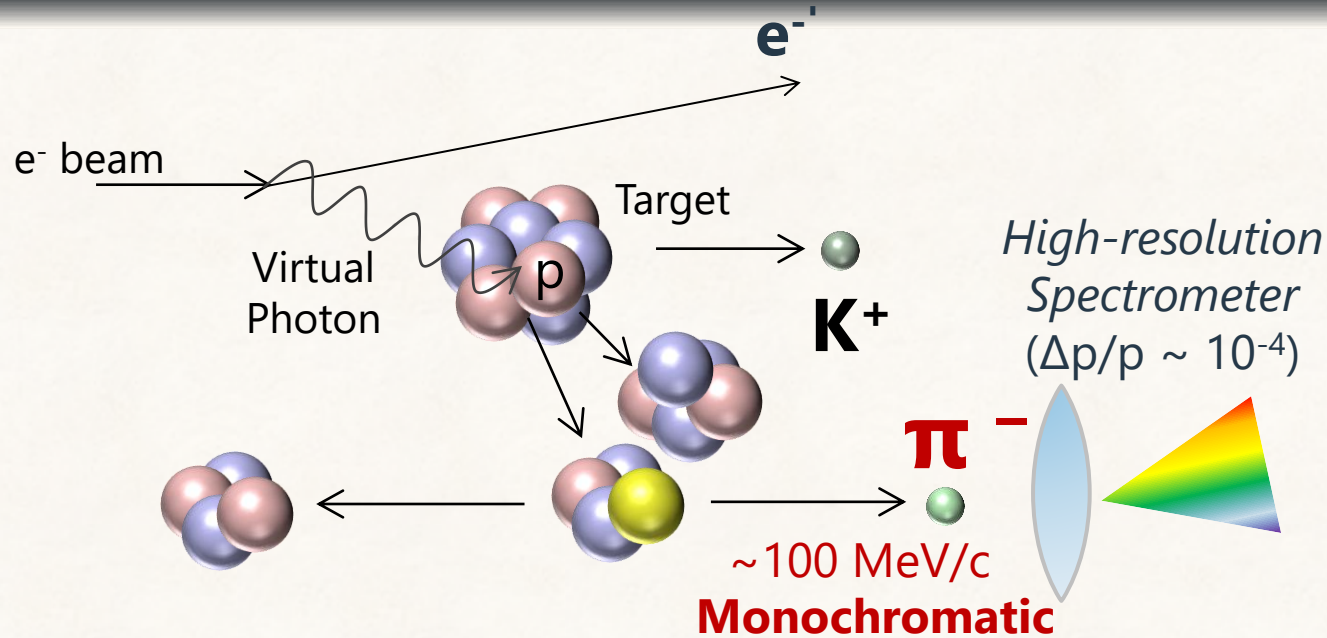
Hypernuclear ground-state masses with $\delta E \sim 0.01$ MeV

Various hypernuclei from fragmentation

Energy Calibration with well-known α sources



High Precision Hypernuclear Mass Spectroscopy



Invariant Mass (2-body decay from stopped hypernucleus)

$$M({}^A_{\Lambda}Z) = \sqrt{M({}^A(Z+1))^2 + p_{\pi}^2} + \sqrt{M_{\pi}^2 + p_{\pi}^2}$$

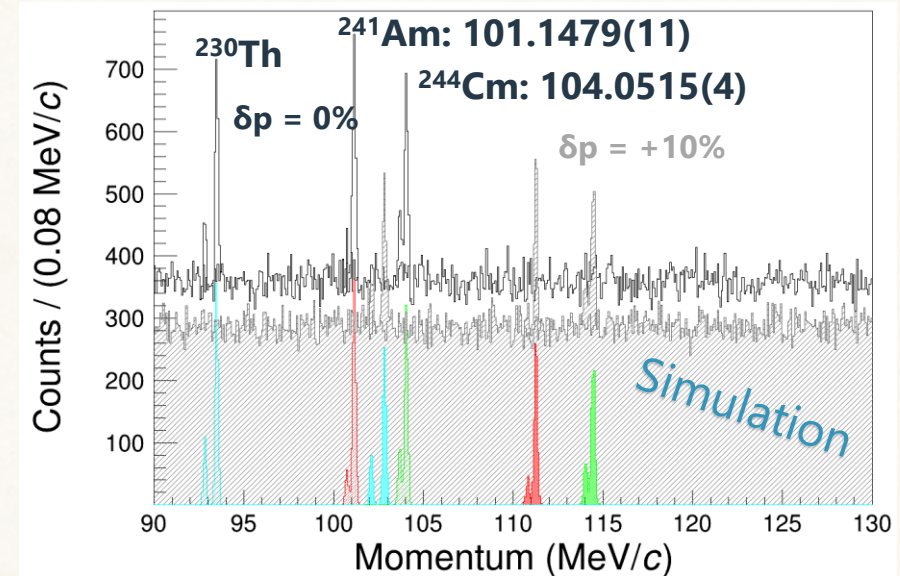
High-resolution decay pion spectroscopy

FWHM $\sim 0.2 \text{ MeV}$

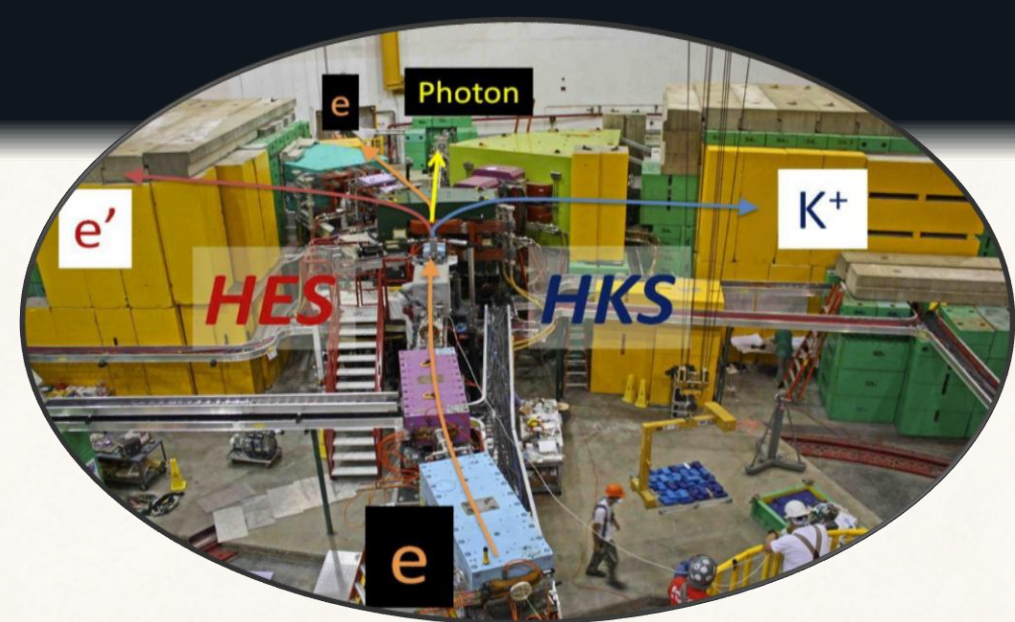
Hypernuclear ground-state masses with $\delta E \sim 0.01 \text{ MeV}$

Various hypernuclei from fragmentation

Energy Calibration with well-known α sources



History



**JLab
2000**

$^{12}_{\Lambda}\text{B}$ PRL90 (2000) 232502.

HKS Const.
Tilt Method

PRL110 (2013) 012502.
JPS Conf. Proc. 17, (2017) 011002.

2005

$^7_{\Lambda}\text{He}$, $^{12}_{\Lambda}\text{B}$, $^{28}_{\Lambda}\text{Al}$

$^9_{\Lambda}\text{Li}$, $^{12}_{\Lambda}\text{B}$, $^{16}_{\Lambda}\text{N}$

PRL103 (2009) 202501.
NPA835 (2010) 129.

HES Const.

$^7_{\Lambda}\text{He}$, $^9_{\Lambda}\text{Li}$, $^{10}_{\Lambda}\text{Be}$, $^{12}_{\Lambda}\text{B}$, $^{52}_{\Lambda}\text{V}$

PRC73 (2006) 044607.
PRC90 (2014) 034320.
PRC93 (2016) 034314.
PRC94 (2016) 021302.
PRC103 (2021) L041301.

2009

MAMI

12 GeV Upgrade

$^3_{\Lambda}n$

PTEP, Vol2022, (2022) 013D01.
PRC105 (2022) L051001.

2012

$^4_{\Lambda}\text{H}$

2014

2018

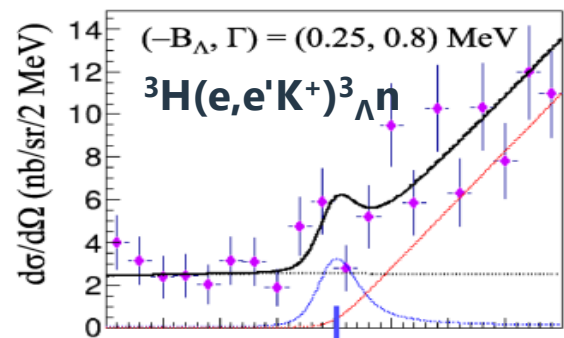
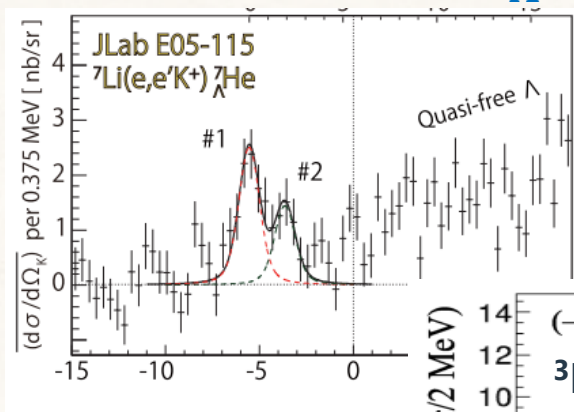
PCS Const.

PRL114 (2015) 232501.
NPA 954 (2016) 149.

$^3_{\Lambda}\text{H}$, $^4_{\Lambda}\text{H}$

PRL 136 (2026) 152301. **2022**

$^3_{\Lambda}\text{H}$ - $^{208}_{\Lambda}\text{Tl}$



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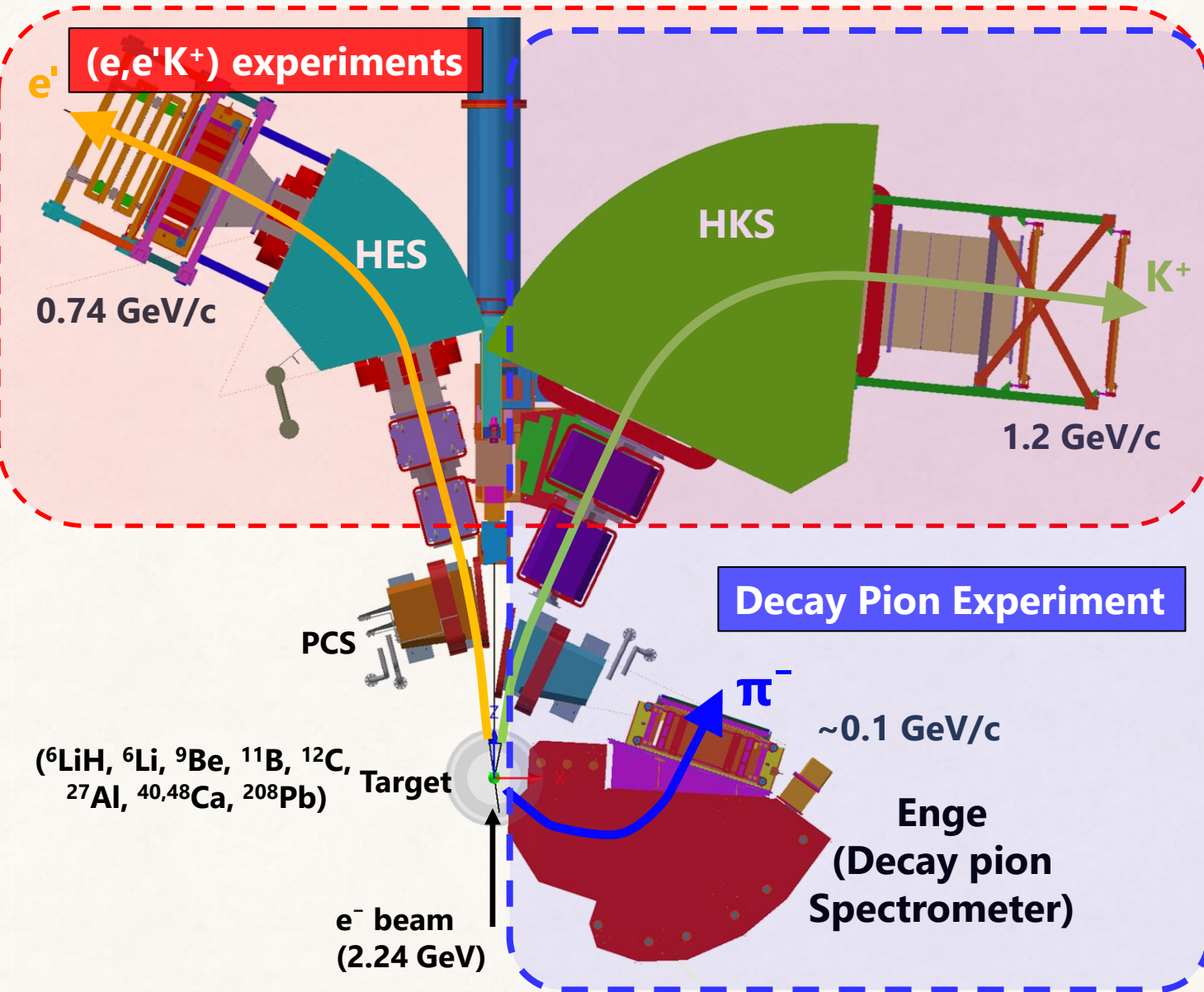


E12-24-003 (42 days)

Studying Λ interactions in nuclear matter with the ${}^{208}\text{Pb}(e,e'K^+){}^{208}_{\Lambda}\text{Tl}$ reaction



Experimental Setup



Production with a one-pass CEBAF beam
Beam current up to 50 μA .

Target set

${}^6\text{Li}$, ${}^9\text{Be}$, ${}^{11}\text{B}$: CSB study

${}^{27}\text{Al}$: triaxial deformed study

${}^{40,48}\text{Ca}$, ${}^{208}\text{Pb}$: ANN study

Spectrometers

HES: scattered electron

HKS: associated K^+

PCS instead of Splitter magnet

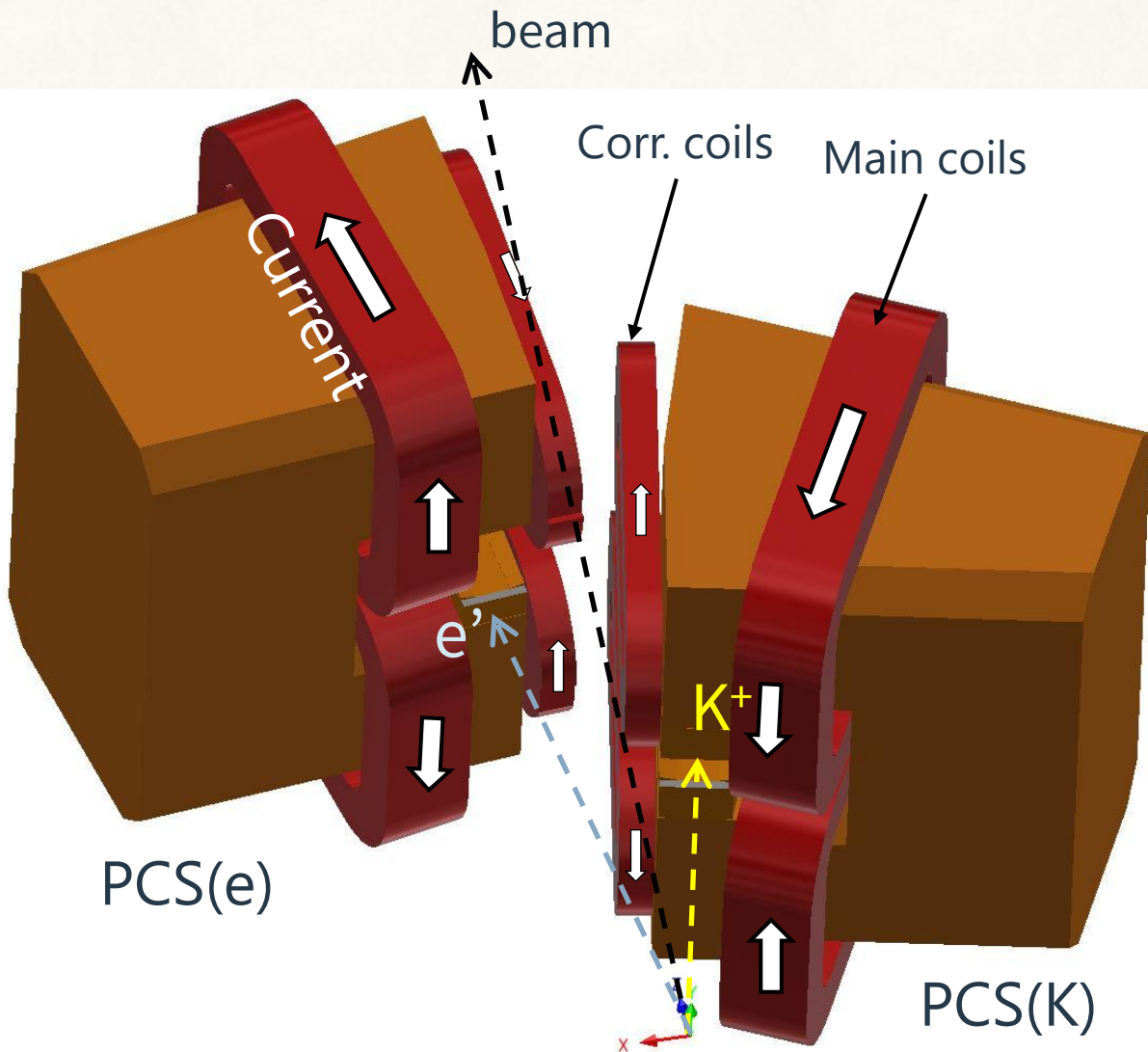
Enge: decay π^-

Calibration

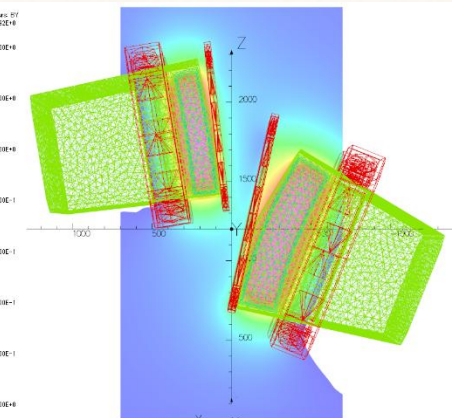
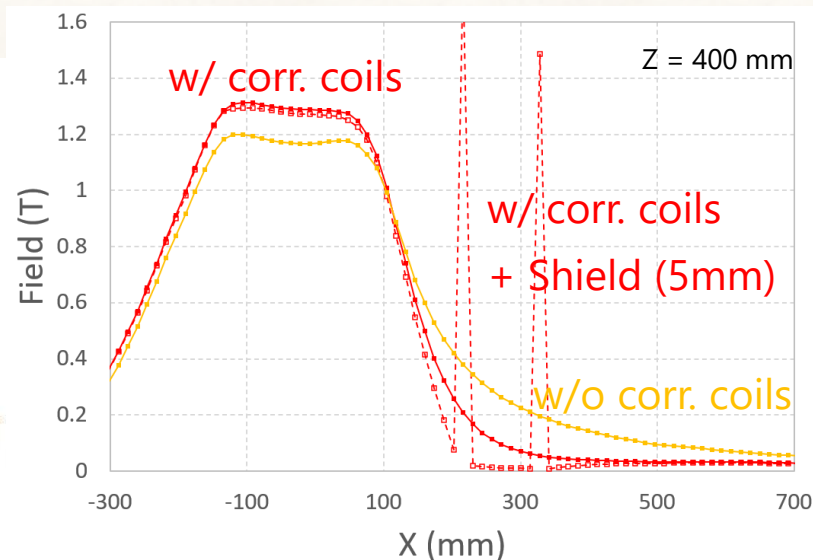
${}^6\text{LiH}$ and ${}^{12}\text{C}$ for HES-HKS

α -source pocket for Enge

Pair of Charge Separation (PCS) Magnet



Field dist. along X-axis (TOSCA Calc.)



PCS magnet guides very-forward scattered electrons and kaons into HES/HKS while preserving the electron beam tracking.

PCS improves the hypernuclear spectral S/N ratio by suppressing background and possible data taking to the heavy target.

PCS consists of main excitation coils and correction coils.

Summary

Hypernuclear physics

Λ hypernuclei are precision laboratories for studying baryon interactions with strangeness.

Λ binding energies constrain effective ΛN and ΛNN interactions in nuclei.

ΛN charge-symmetry breaking

$A = 4$ mirror hypernuclei show sizable, spin-dependent CSB.

Recent theories reproduce the $A = 4$ system, but existing data accuracy is not sufficient for p-shell.

Electromagnetic production of hypernuclei

The $(e, e'K^+)$ exp. provides a clean, high-resolution level structures with 500 keV width and 100 keV accuracy.

The decay pion exp. gives absolute mass for several s-, p-shell hypernuclear ground-state with 10 keV accuracy.

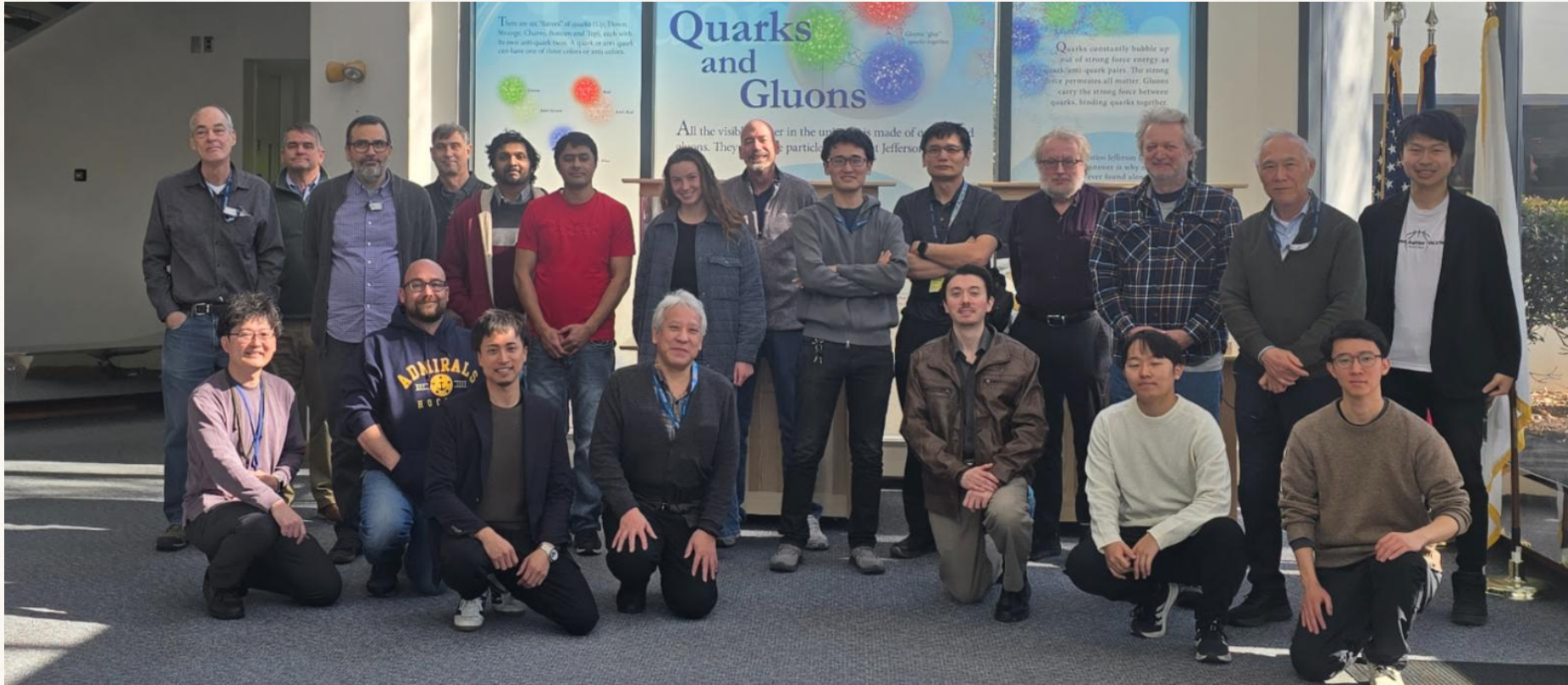
Hall-C experiment and expected outcomes

The JLab Hall-C program will measure light and p-shell Λ hypernuclei (${}^6_{\Lambda}\text{He}$, ${}^9_{\Lambda}\text{Li}$, ${}^{11}_{\Lambda}\text{Be}$, ${}^{12}_{\Lambda}\text{B}$ with $(e, e'K^+)$) and others for the decay pion experiment.

The experiment successfully passed the ERR, and installation is planned to start in 2027.

Detector preparation at ESB, as well as checks and preparation of required materials, are currently in progress.

Join the JLab Hypernuclear (HKS) Collaboration



We welcome new collaborators interested in hypernuclear physics, spectroscopy, detector development, simulations, and data analysis. If you are interested, please join us.

We hold collaboration meetings (about twice a year), as well as occasional workshops.

More information is available at [\[https://hallcweb.jlab.org/wiki/index.php?title=Hypernuclear Experiment in Hall C\]](https://hallcweb.jlab.org/wiki/index.php?title=Hypernuclear_Experiment_in_Hall_C).