Hypernucler experimental program

At Spiaggia La FENICIA
28 June 2016

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Tohoku University

30 June 2016

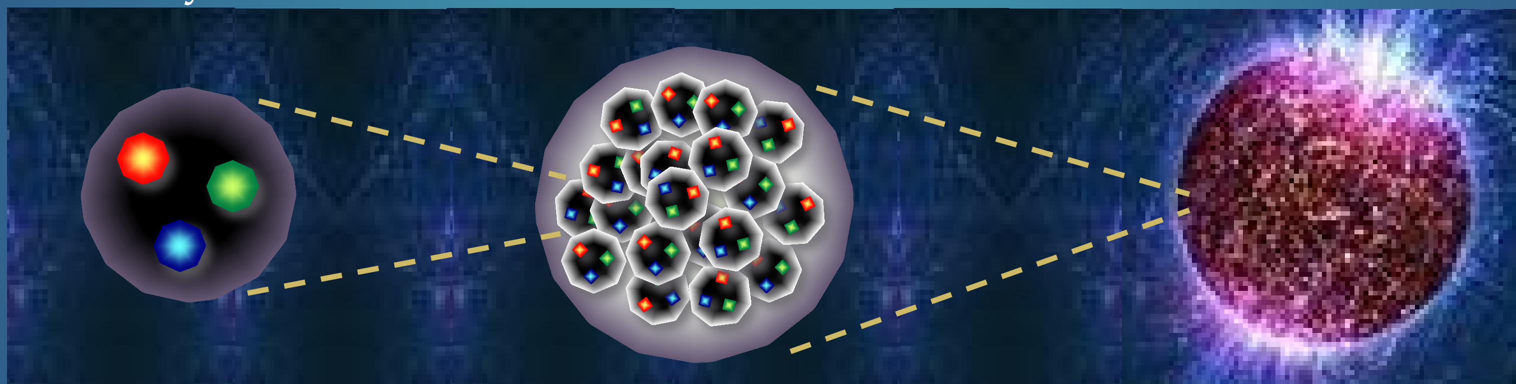
Marciana Marina, Isola d'Elba

Quantum Many-body System Bound by the Strong Int.

Baryon

(Hyper) Nucleus

Neutron Star



10^{-15} m

10^{4} m

Spectroscopy of Hypernuclei

NN scat.

Obs. NS 2 $M_{\odot}$

Hyperon Puzzle

Baryon Interaction

LQCD

History of Hypernuclear Study (experiment)

1953 discovery of hypernucleus (emulsion with cosmic-ray, by Danysz and Pniewski)

1970s CERN, BNL Counter experiments
with Kaon beam

1980s BNL-AGS, KEK-PS Counter experiments
with K/π beam

1998- γ-spectroscopy with Hyperball

FINUDA at DAΦNE
$\Phi \rightarrow K^{+}K^{-}$ (49%)

2000~
$(e,e'K^{+})$ spectroscopy @ JLab

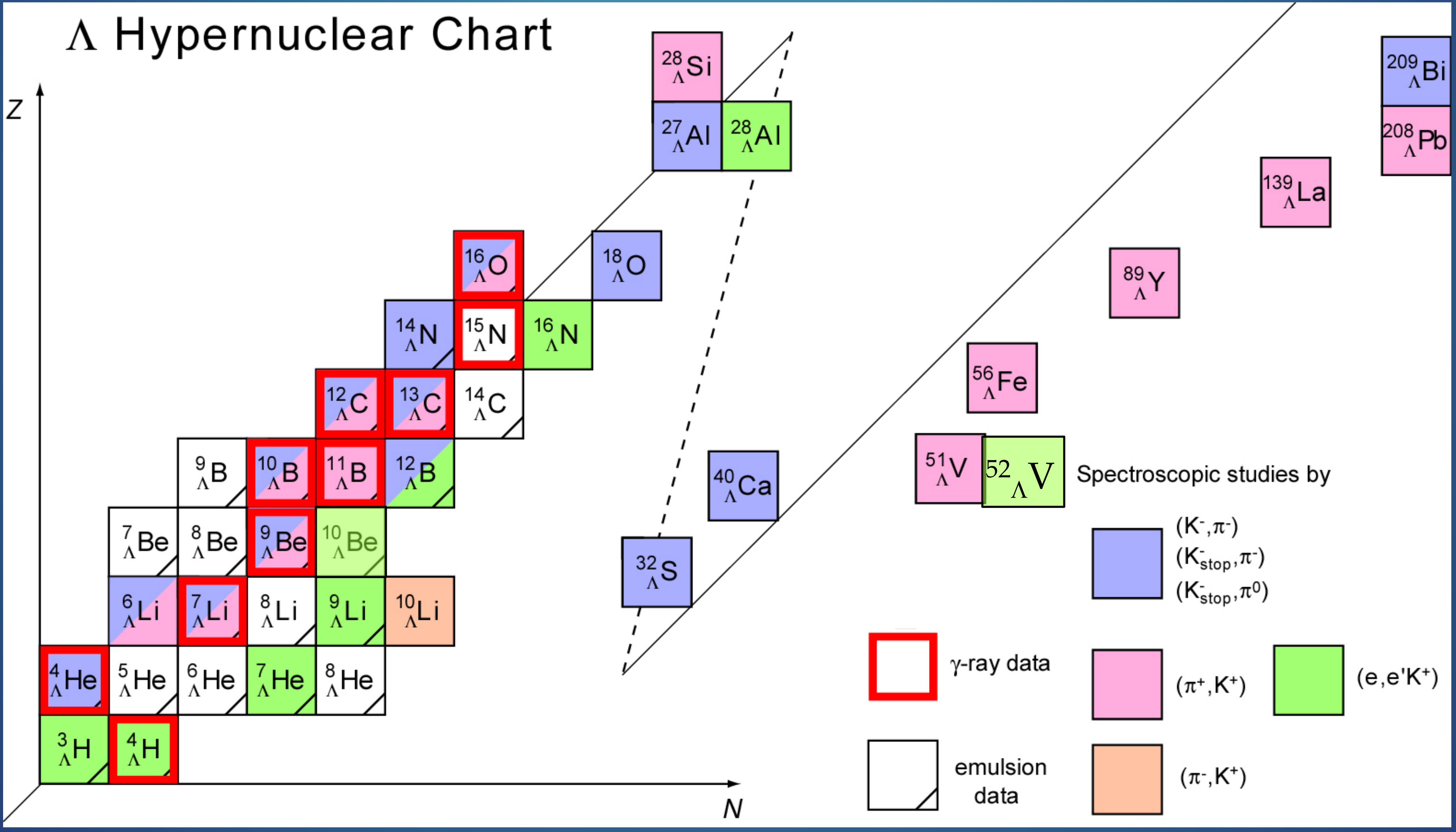
$Z(e^{-},e'K^{+})_{\Lambda}(Z-1)$ reaction

HI-Beams @ GSI, RHIC, LHC

Meson beam experiments at J-PARC

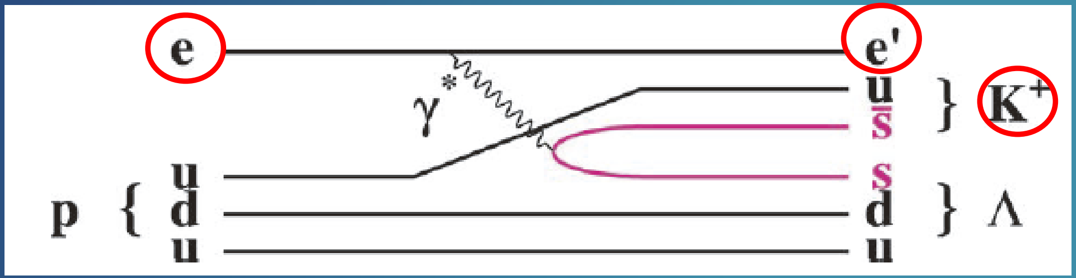
Decay π @ Mainz

Present Status of Λ Hypernuclear Spectroscopy



Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

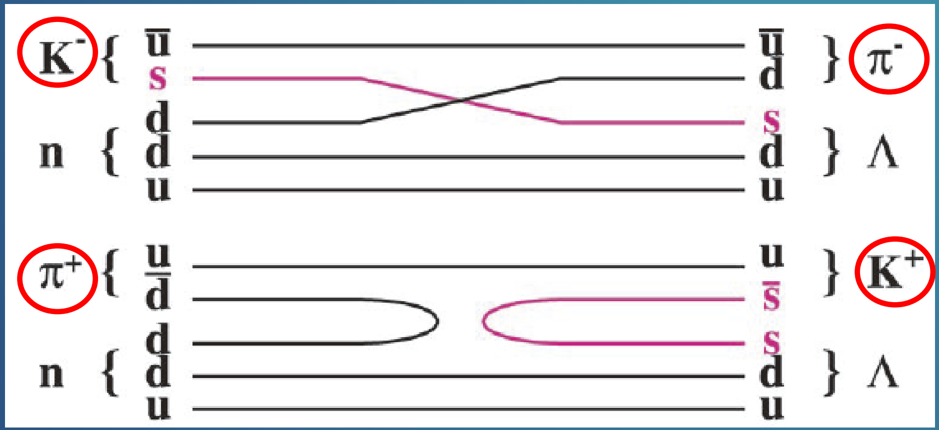
(e,e'K+) vs. others



(e,e'K+)

Excellent mass resolution
(~ 0.5 MeV)

Absolute energy calibration
p(e,e'K+) Λ, Σ^0



(K-, π-)

1-2 MeV resolution
Normalized to $^{12}{}_{\Lambda}C$ mass

(π+, K+)

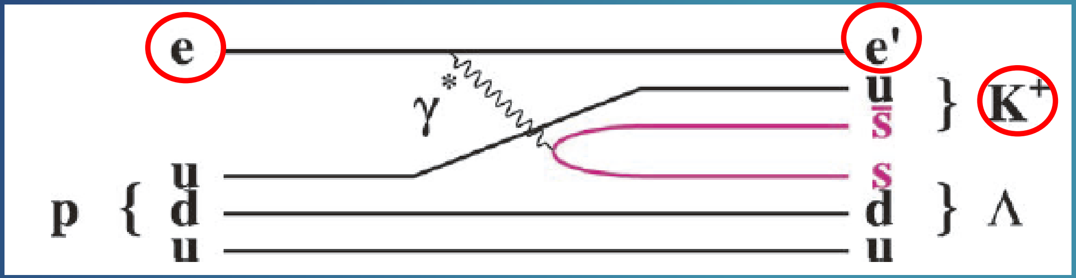
γ-ray spectroscopy

Super high resolution (a few keV)
But **ONLY** **level spacing** measurable

decay π

Excellent mass resolution (~0.1 MeV)
But **ONLY mass of** **ground state** **of light HY**

$(e,e'K^+)$ vs. others



$(e,e'K^+)$

Excellent mass resolution

(~ 0.5 MeV)

Absolute energy calibration

$p(e,e'K^+)\ \Lambda,\ \Sigma^0$

So far performed only at JLab

$E_e > 1.5$ GeV high quality e beam

$\Delta p/p \sim 10^{-4}$, >1GeV/c spectrometers

Techniques for Hypernuclear Spectroscopy

Method	Resolution	Absolute E	Yield	comments
$(e,e'K^+)$	0.5 MeV	◎	× 100nb/sr	$p \to \Lambda$
(π^+,K^+)	1.5 – 2 MeV	○ (norm $^{12}{}_{\Lambda}C$)	○ 10μb/sr	$n \to \Lambda$
(K^-, π^-)	~2 MeV	○ (norm $^{12}{}_{\Lambda}C$)	◎ 10mb/sr	$n \to \Lambda$
γ-ray	0.003 MeV	×	-	-
Decay π	0.1 MeV	◎ (only g.s.) w/elastic sc.	-	Fragments

All techniques are complementary.

Hypernuclear experiments at JLab

E89-009 (2000) : Existing spectrometers,
SOS + Enge

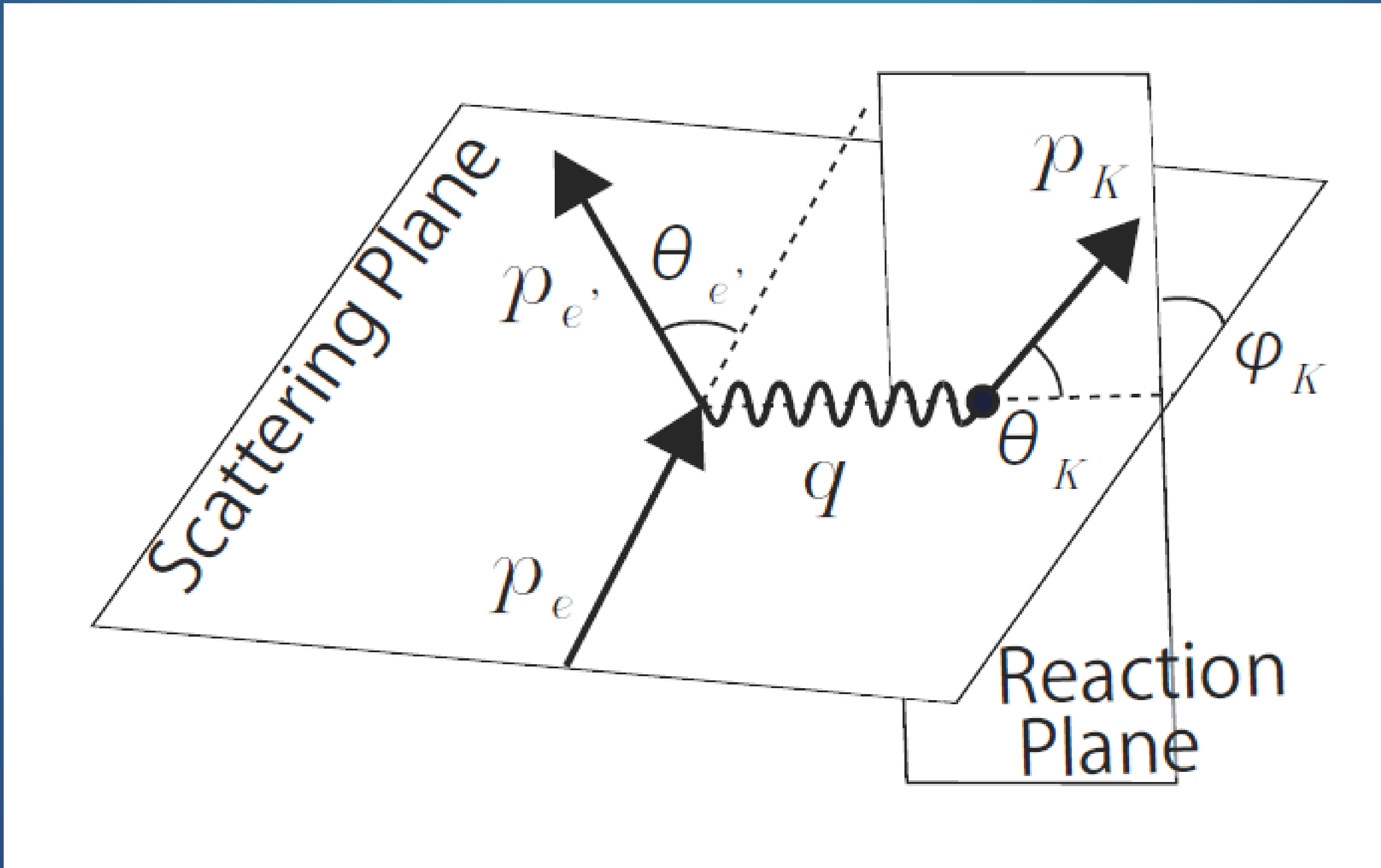
Proof of Principle

E01-011 (2005) :
Construction of HKS, Tilt Method
Λ, Σ^0, ${}^{7}_{\Lambda}$He, ${}^{12}_{\Lambda}$B, ${}^{28}_{\Lambda}$Al
Light Hypernuclei

E94-107 (2004-5)
Two HRSs + SC Septum
Λ, Σ^0, ${}^{9}_{\Lambda}$Li, ${}^{12}_{\Lambda}$B, ${}^{16}_{\Lambda}$N
Light Hypernuclei

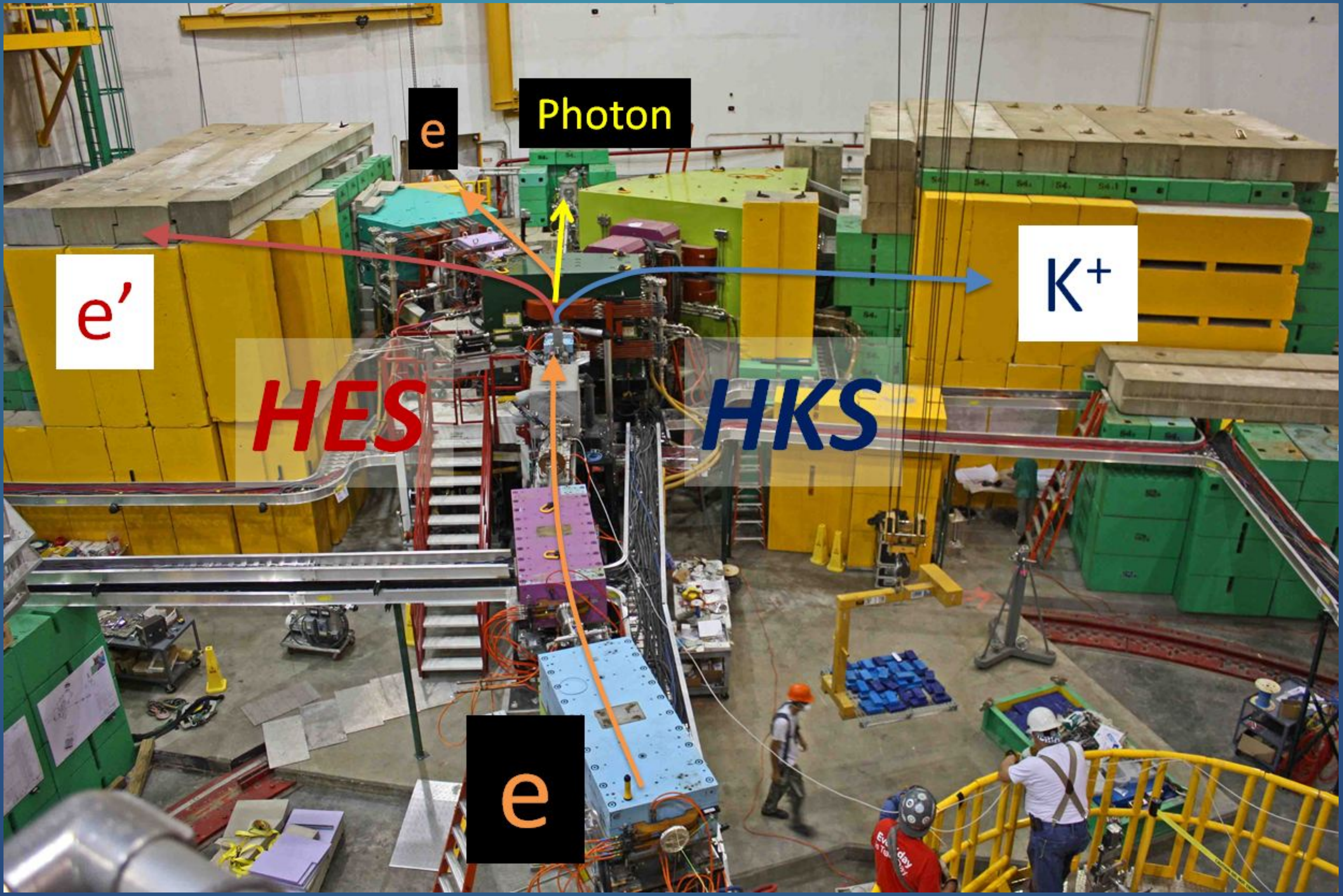
E05-115 (2009) :
HKS+HES, new Chicane beamline, Splitter
Λ, Σ^0, ${}^{7}_{\Lambda}$He , ${}^{12}_{\Lambda}$B, ${}^{52}_{\Lambda}$V
Light to medium-heavy Hypernuclei

(e,e'K+) reaction

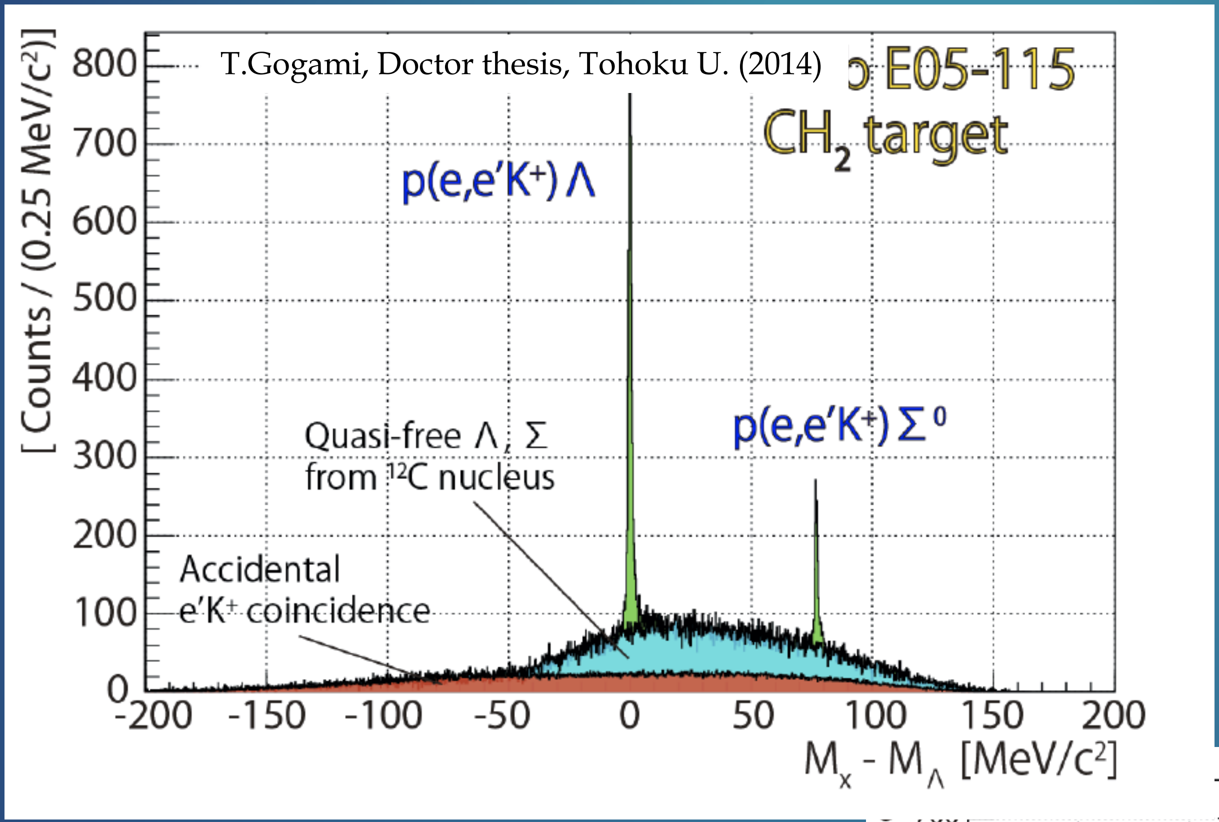


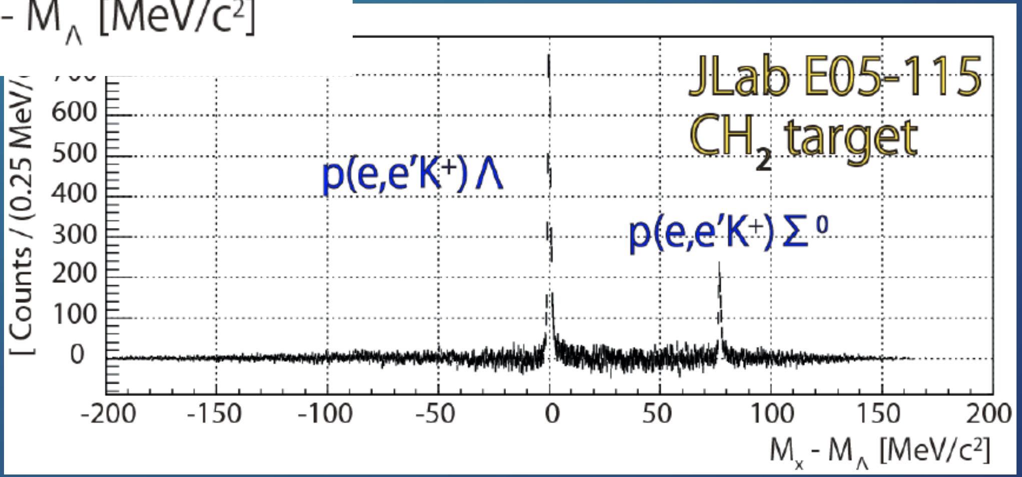
Hypernuclear study with the (e,e'K$^+$) reaction

Initiated and established at **JLab**



p(e,e'K⁺)Λ, Σ⁰: Elementary Process



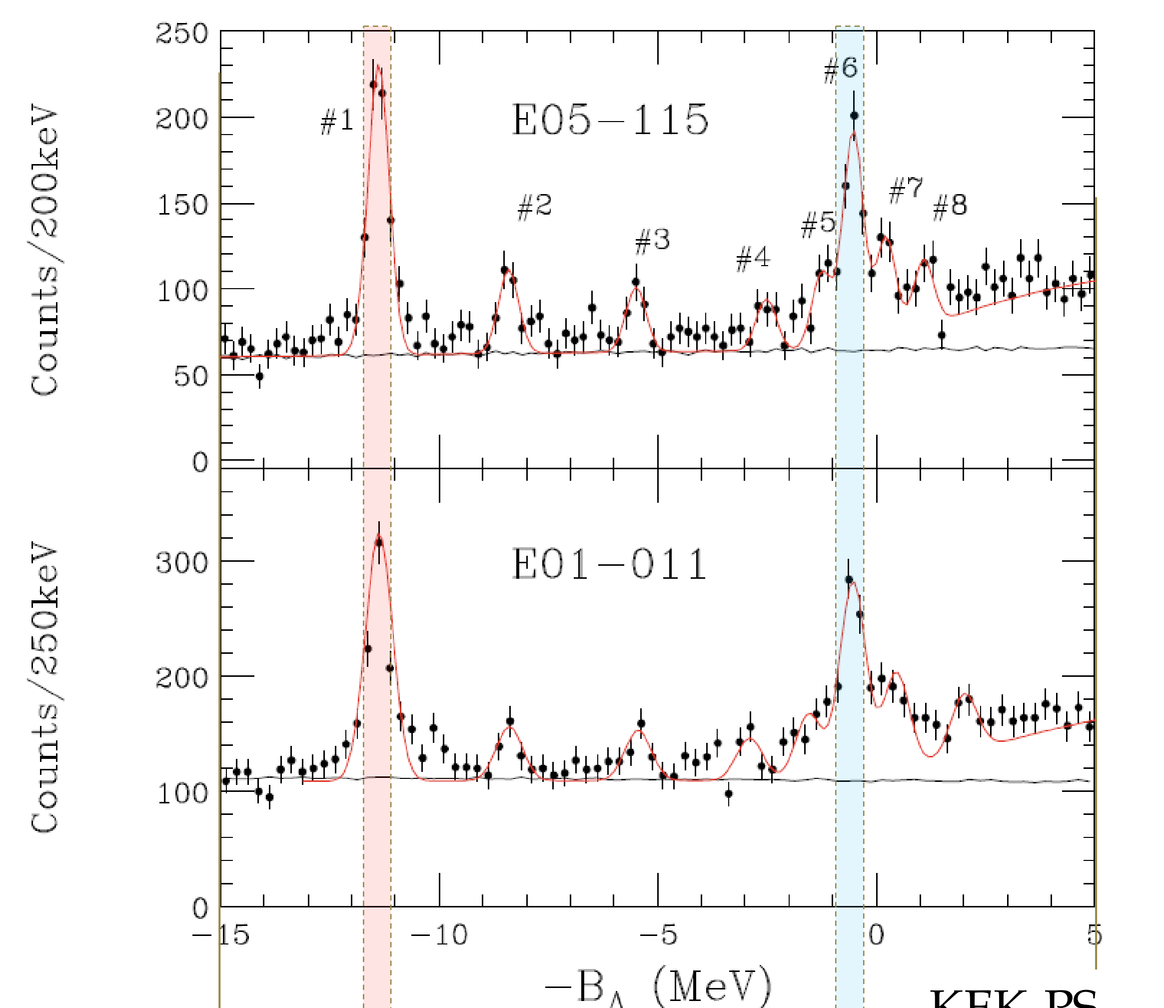


$^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$

0.5 MeV (FWHM)

Absolute MM calibration

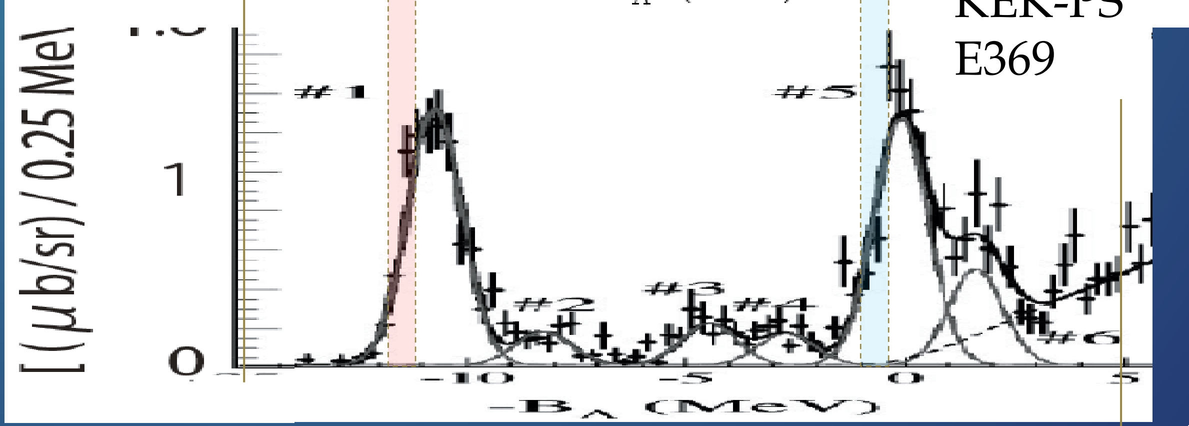
0.7 MeV (FWHM)



$^{12}C(\pi^+,K^+)^{12}{}_{\Lambda}C$

1.45 MeV (FWHM)

$^{12}{}_{\Lambda}C_{gs}$ energy from emulsion



$^{12}{}_{\Lambda}B$ emulsion data

Nuclear Physics B52 (1973) 1–30.

A NEW DETERMINATION OF THE BINDING-ENERGY VALUES OF THE LIGHT HYPERNUCLEI ($A \leqslant 15$)

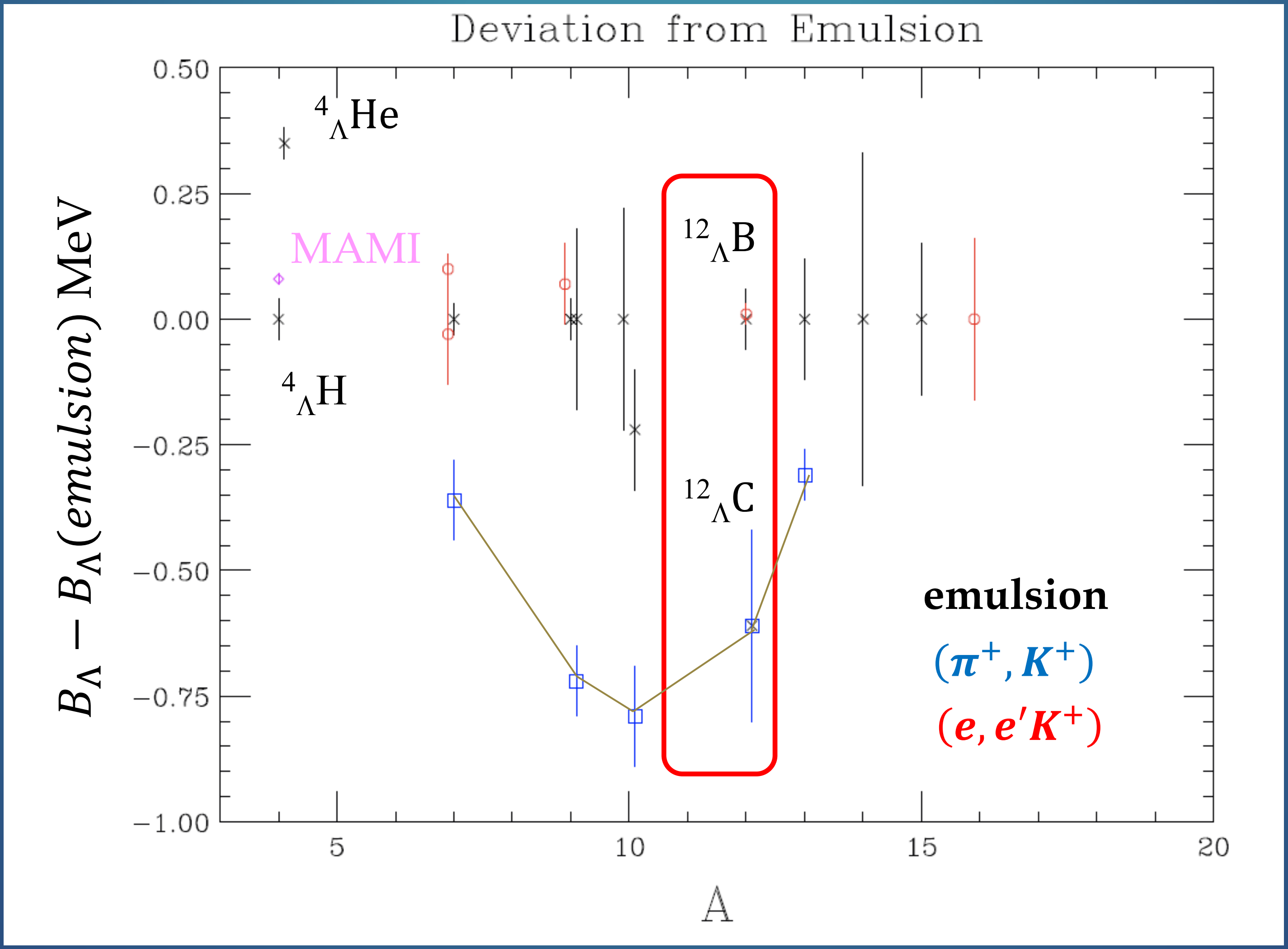
		(# of events)	
$^{12}_{\Lambda}B$	$\pi^- + {}^4He + {}^4He + {}^4He$	61	11.45 ± 0.07

B_{Λ} ($^{12}{}_{\Lambda}$Bg.s.) = 11.45 +-0.07 MeV   Emulsion Result (M.Juric et al.)

B_{Λ} ($^{12}{}_{\Lambda}$Bg.s.) = 11.38 +- 0.02 (stat) MeV (JLab E05-115)

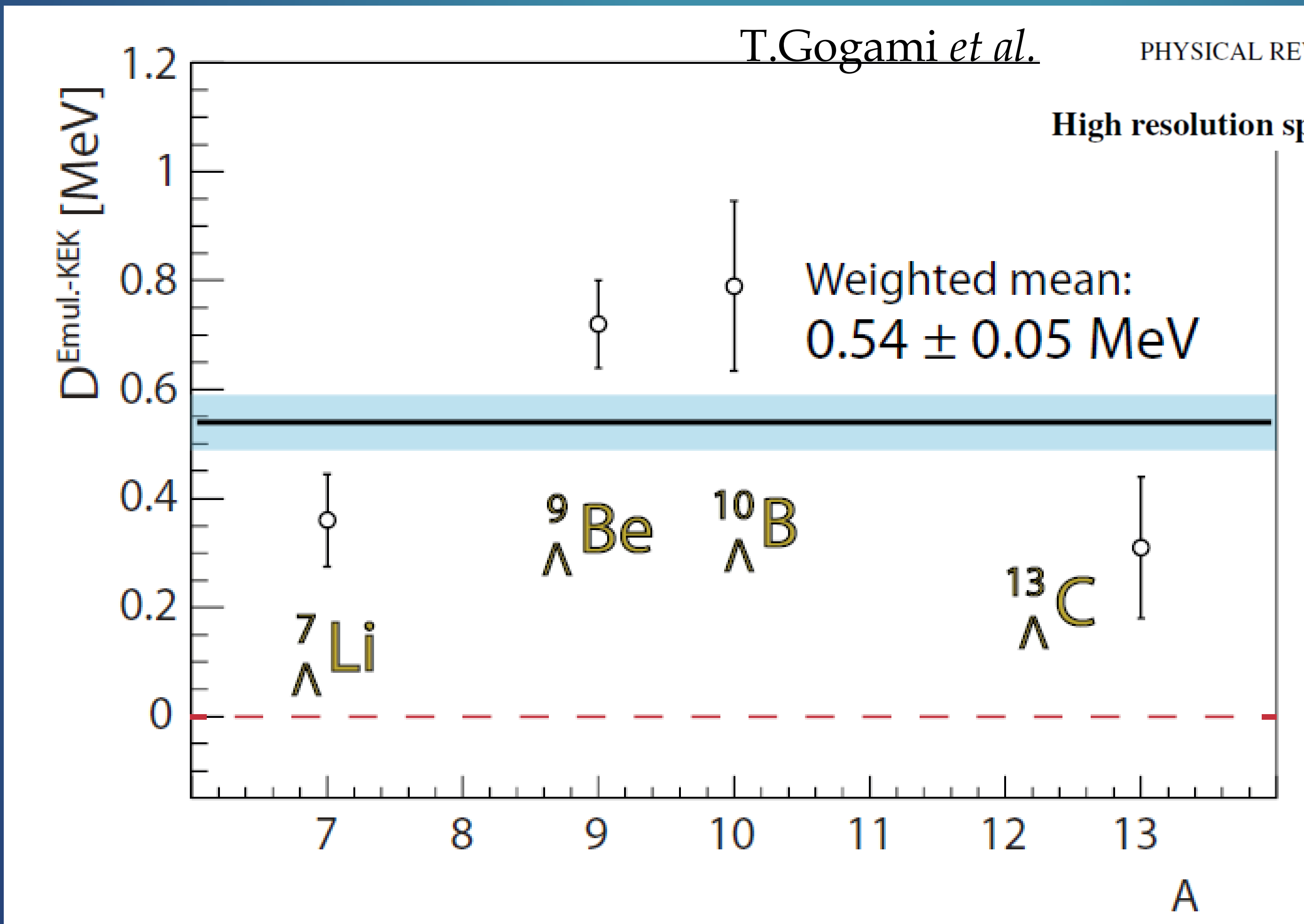
Totally independent measurement

Remove apparent A dependence



Possible shift of ${}^{12}_{\Lambda}C_{gs}$ B_{Λ}

${}^{12}_{\Lambda}\mathrm{C} - {}^{12}_{\Lambda}\mathrm{B}$	-0.57 ± 0.19 $-0.62 \pm 0.19 \pm 0.11$	${}^{12}_{\Lambda}\mathrm{C}$: 6 events, ${}^{12}_{\Lambda}\mathrm{B}$: 87 events present data for ${}^{12}_{\Lambda}\mathrm{B}$



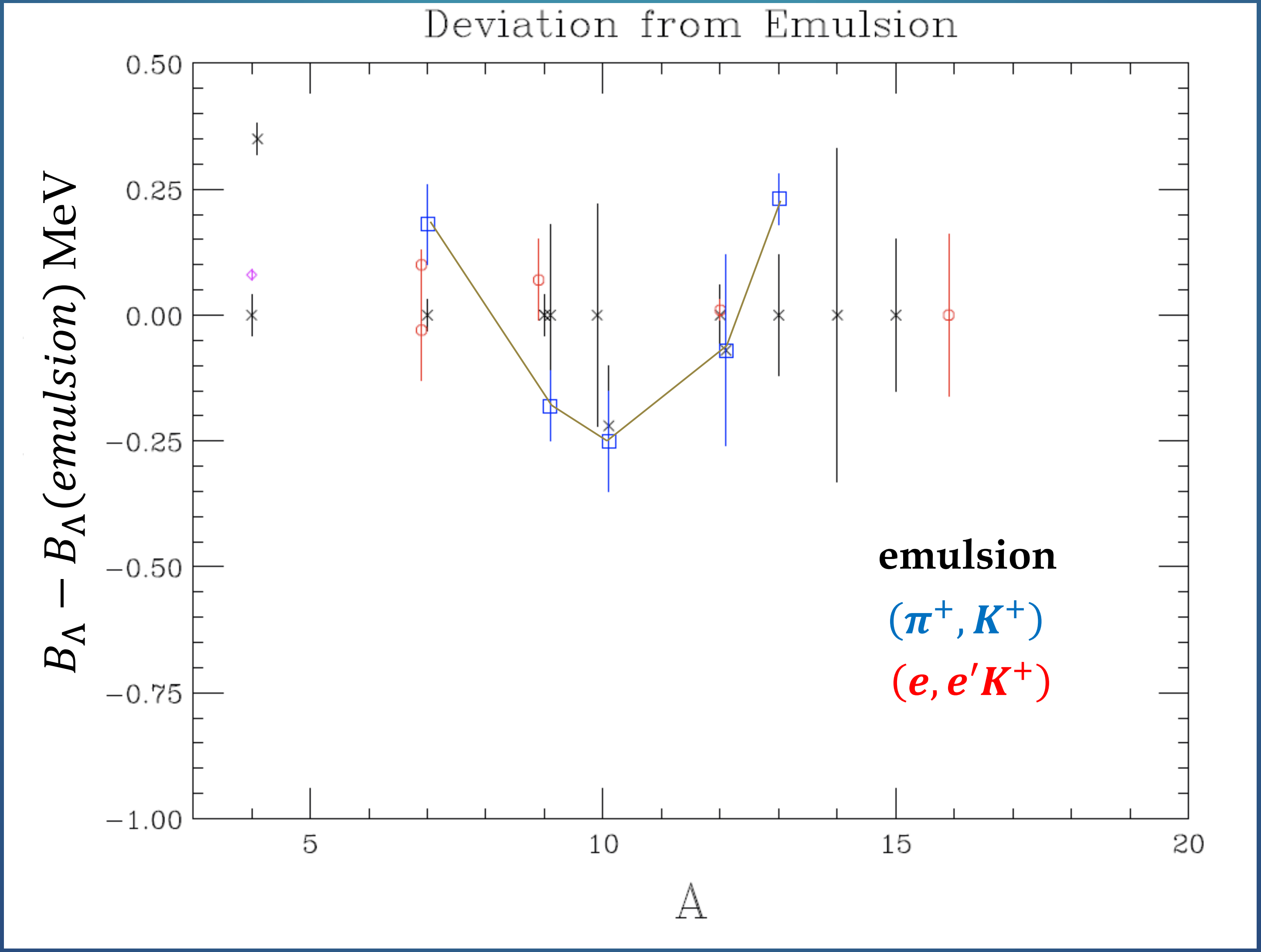
PHYSICAL REVIEW C **93**, 034314 (2016)

High resolution spectroscopic study of ${}^{10}_{\Lambda}\mathrm{Be}$

${}^{10}_{\Lambda}\mathrm{B}$-${}^{10}_{\Lambda}\mathrm{Be}$ =-0.50MeV

Should be 0

Shift $^{12}{}_{\Lambda}C_{gs}$ B_{Λ} by 0.54 MeV



Hall A E94-107, Excellent S/N spectra

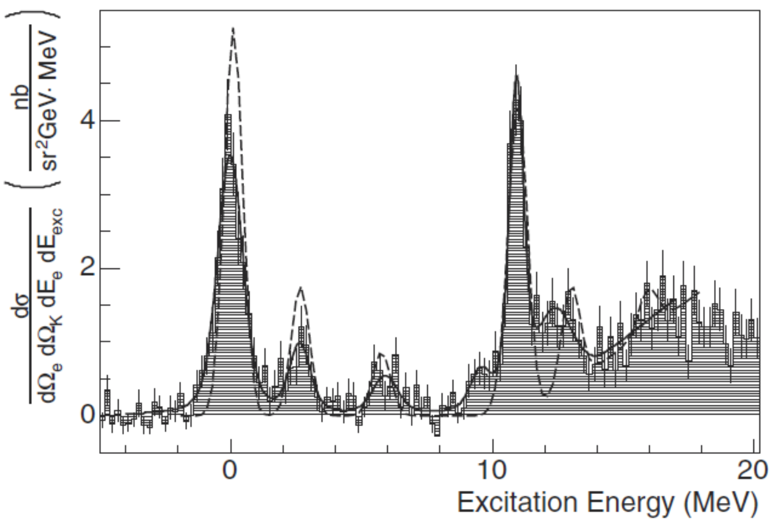


FIG. 3. The ${}^{12}_{\Lambda}$B excitation-energy
curve) and a theoretical prediction
imposed on the data. See text for de

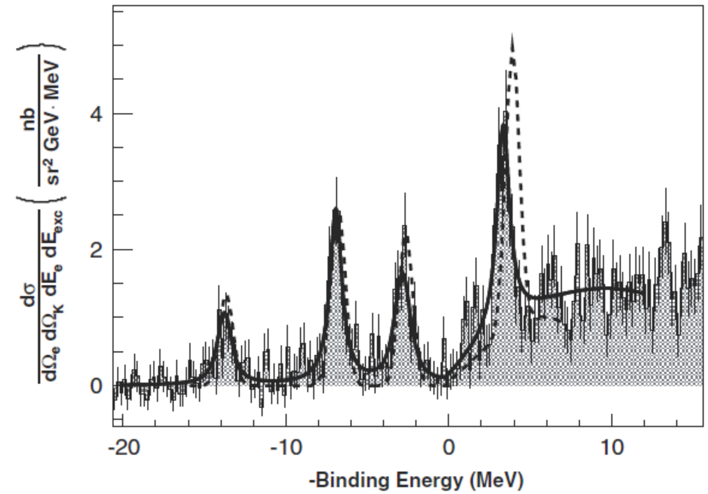


FIG. 3. The ${}^{16}_{\Lambda}$N binding-energy spectrum. The best fit using Voigt functions (solid curve) and a theoretical prediction (dashed
imposed on the data. See text for details.

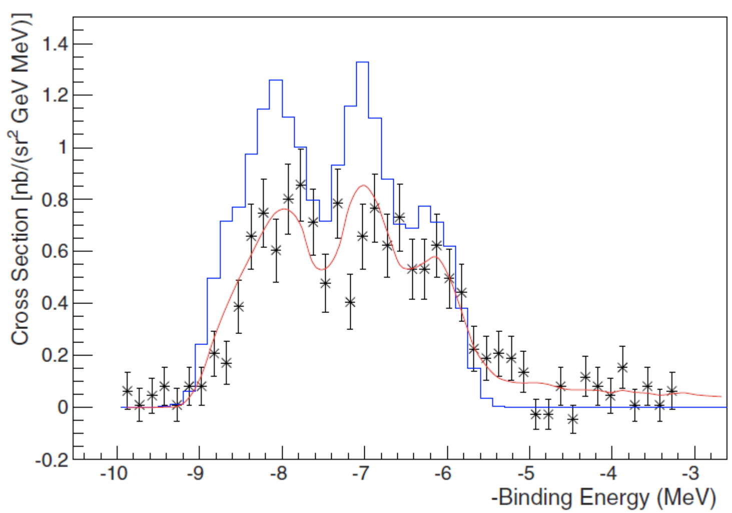
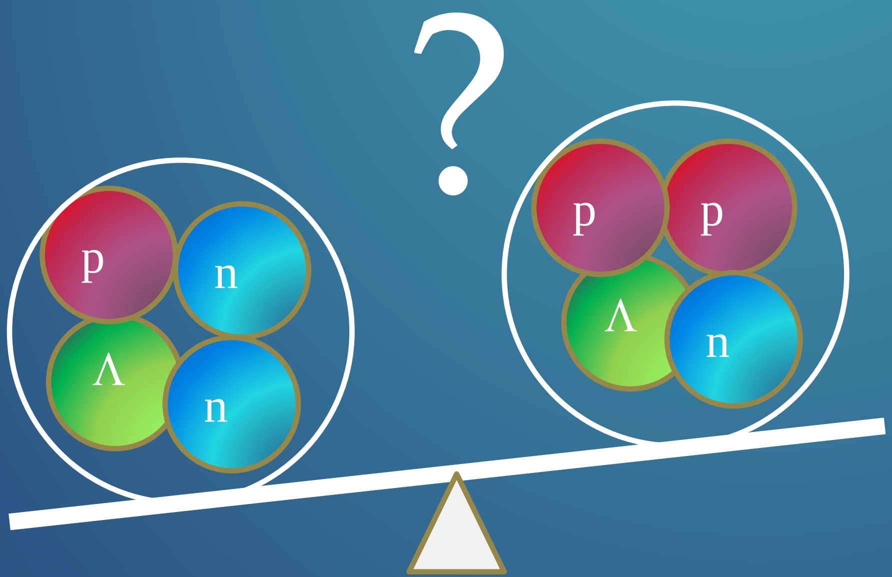


FIG. 3. (Color online) The ${}^{9}_{\Lambda}$Li differential cross section as a function of the binding energy. Experimental points vs Monte Carlo results (red curve) and vs Monte Carlo results with radiative effects turned off (blue histogram).

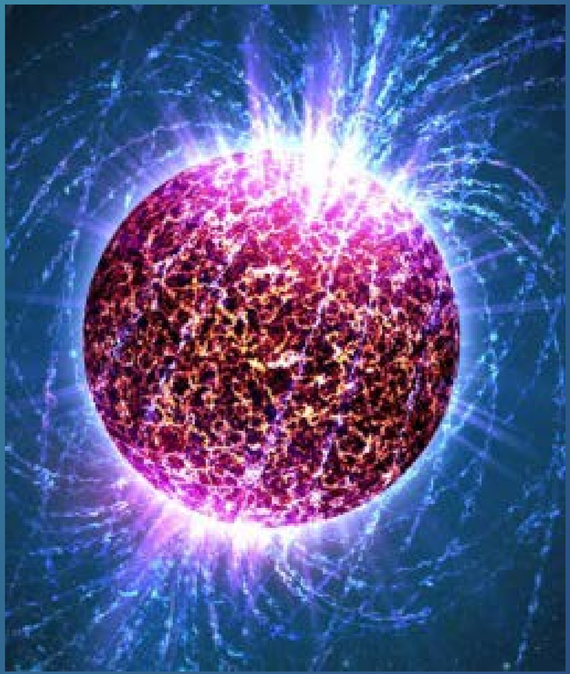
Recent

Mysteries in Hypernuclear Physics

Large CSB for A=4 hypernuclei



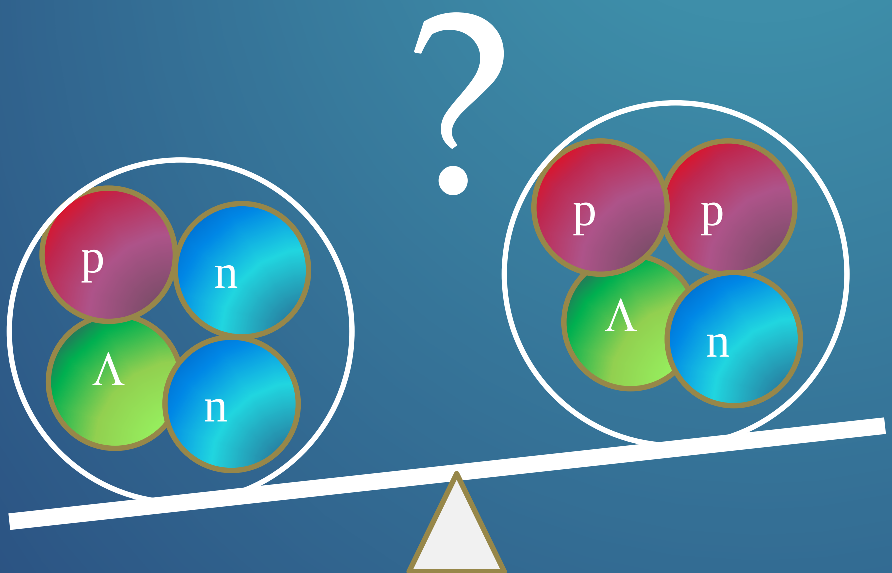
Hyperon Puzzle



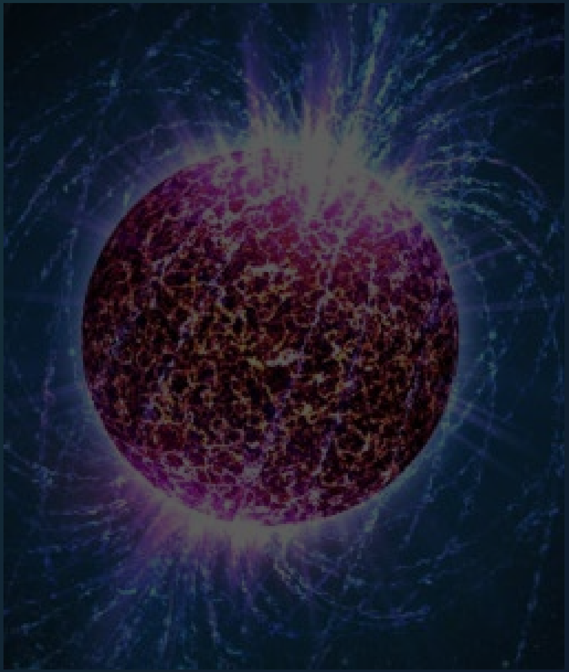
Two solar mass neutron stars

Mysteries in Hypernuclear Physics

Large CSB for A=4 hypernuclei



Hyperon Puzzle



Two solar mass neutron stars

Charge Symmetry Breaking of the ΛN interaction

Charge Symmetry Breaking for NN system

EM Corrections

$(a_{pp}) = -7.8 \text{ fm}$ → $[a_{pp}]_{SI} = -17.3 \pm 0.4 \text{ fm}$

$a_{nn} = -18.8 \pm 0.3 \text{ fm}$

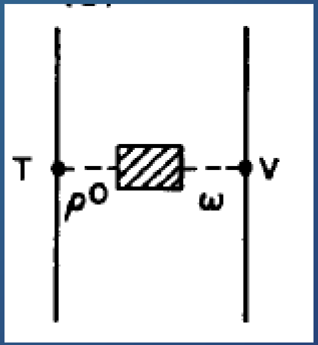
$\mathrm{B}(^3\mathrm{H}) - \mathrm{B}(^3\mathrm{He}) = 764 \text{ keV}$ → $[\mathrm{B}(^3\mathrm{H}) - \mathrm{B}(^3\mathrm{He})]_{SI} = 71 \text{ keV}$

$\Delta\mathrm{m} = \mathrm{m}(d) - \mathrm{m}(u) \cong 3\mathrm{MeV}$

$P_{CS}|u\rangle = |d\rangle$

$P_{CS}|d\rangle = -|u\rangle$

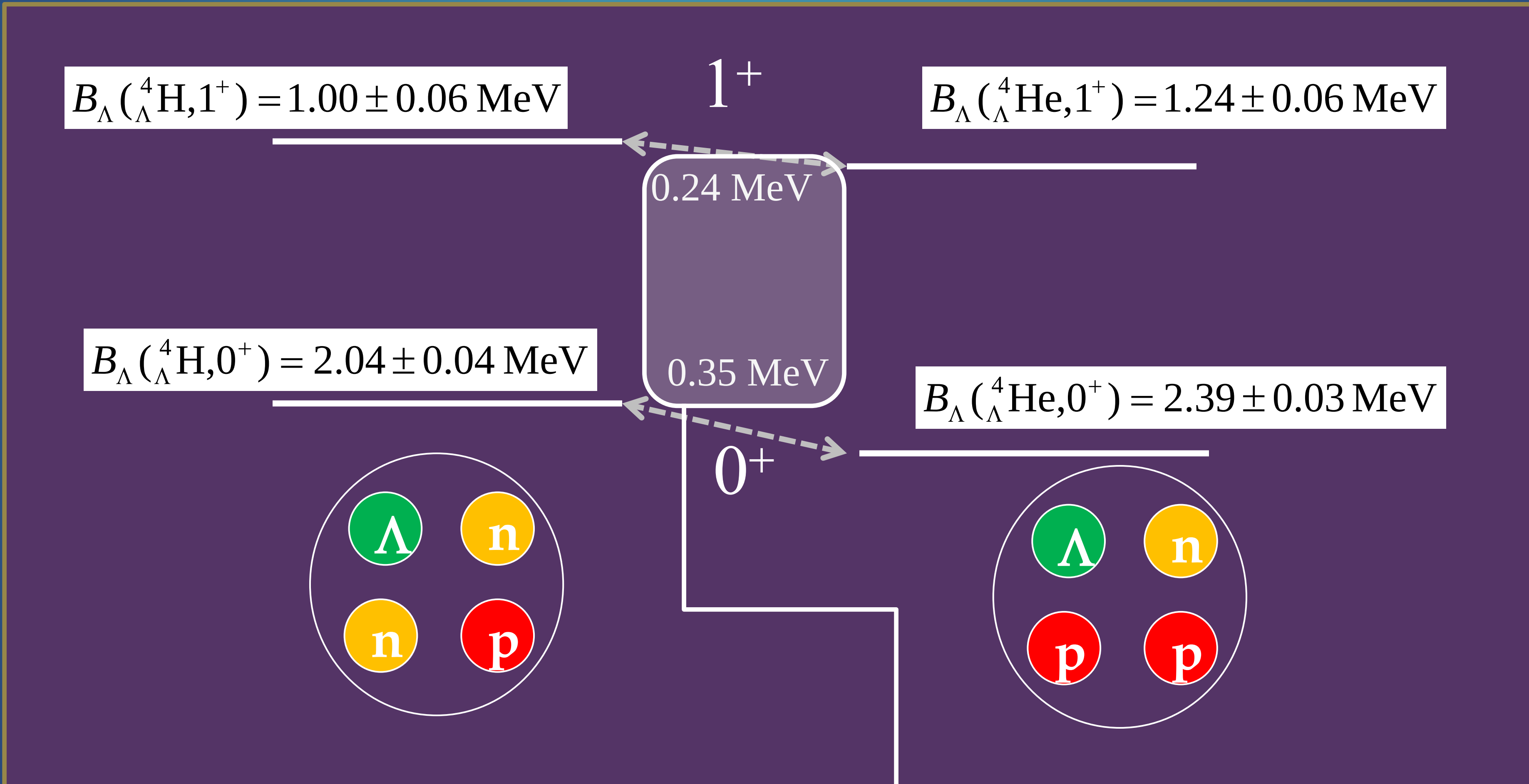
$\rho^0 - \omega$ mixing



A=4 system
CSB ΛN potential

Data from
Emulsion
NaI γ-ray

Before 2015



Coulomb effect is very small.

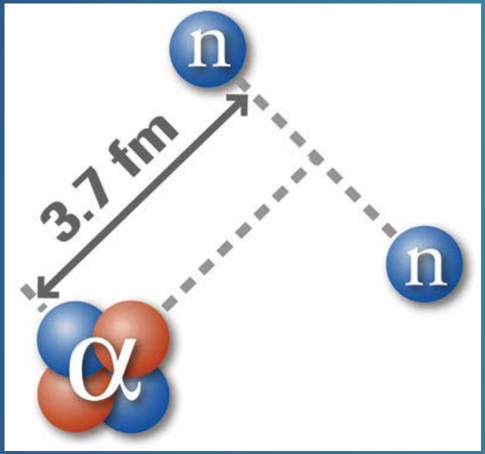
$$-\Delta B_c = 0.050 \pm 0.02\ \mathrm{MeV}\ ,$$

$$-\Delta B_c^* = 0.025 \pm 0.015\ \mathrm{MeV}$$

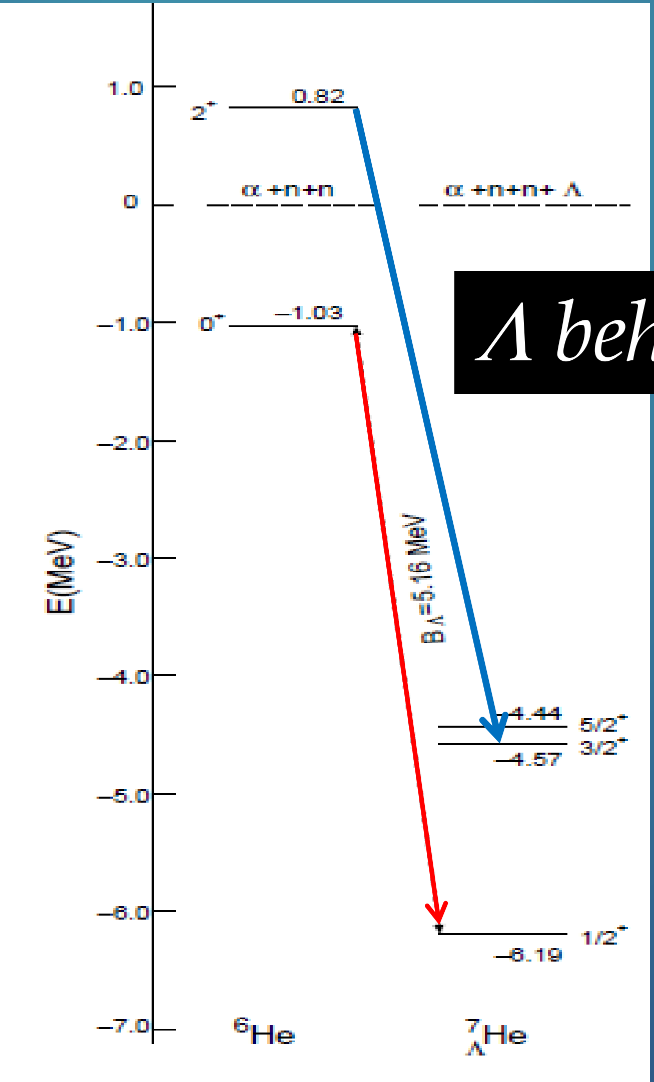
Charge Symmetry Breaking

cf) $B({}^3\mathrm{H})-B({}^3\mathrm{He})-\Delta B_c \sim 70$ keV

${}^{7}_{\Lambda}He = {}^{6}He + \Lambda$



${}^{6}He$: 2n halo

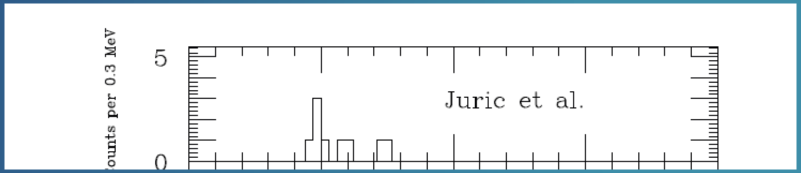


Λ behaves like glue

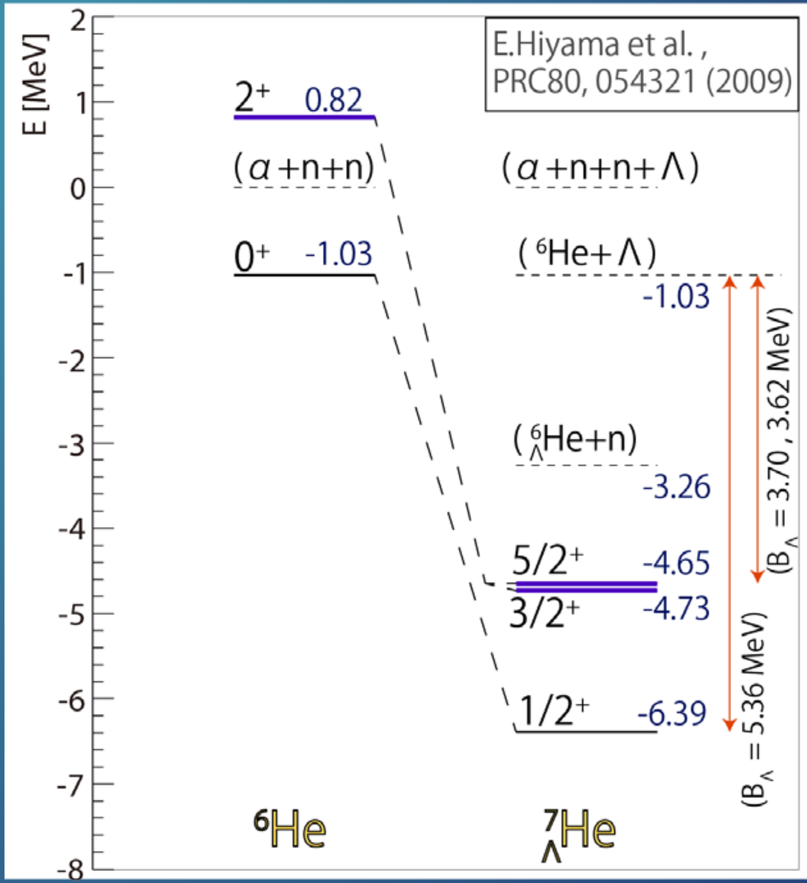
E.Hiyama et al. PRC 80, 054321 (2009)

$^{7}_{\Lambda}$He spectrum

Juric et al., Nucl. Phys. A484 (1988) 520

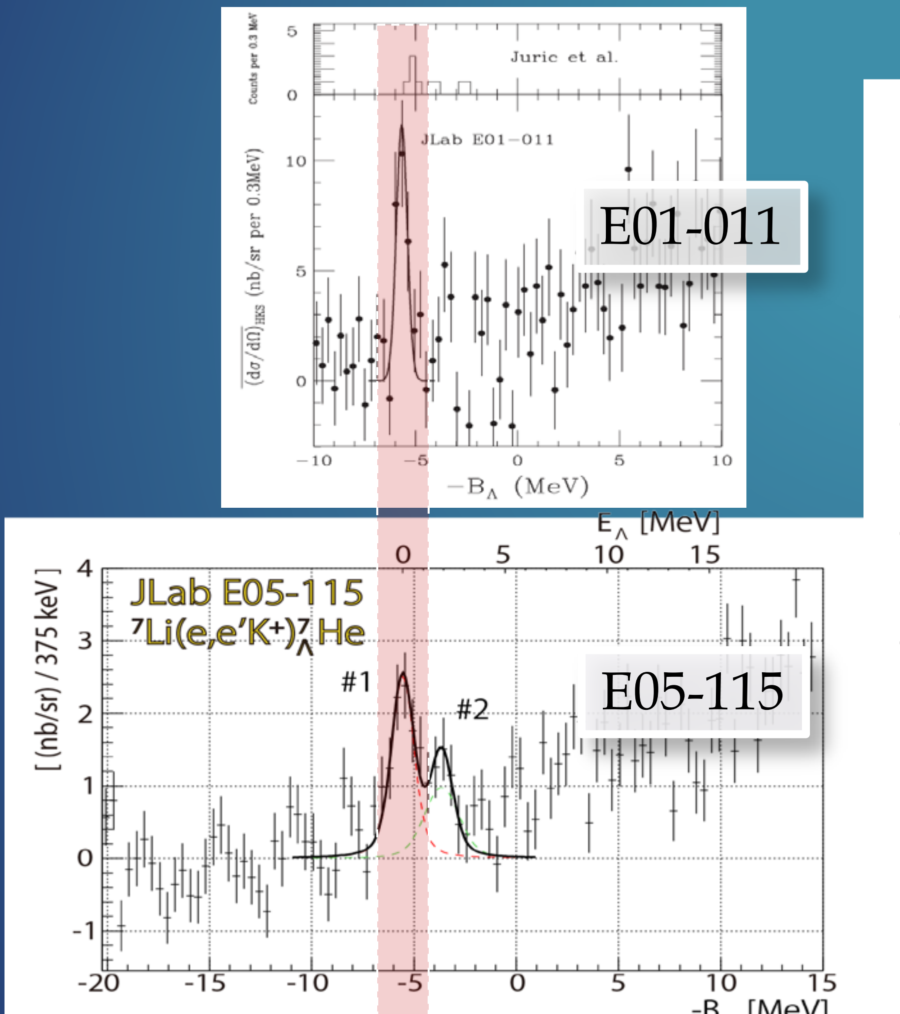


No B_Λ was obtained.

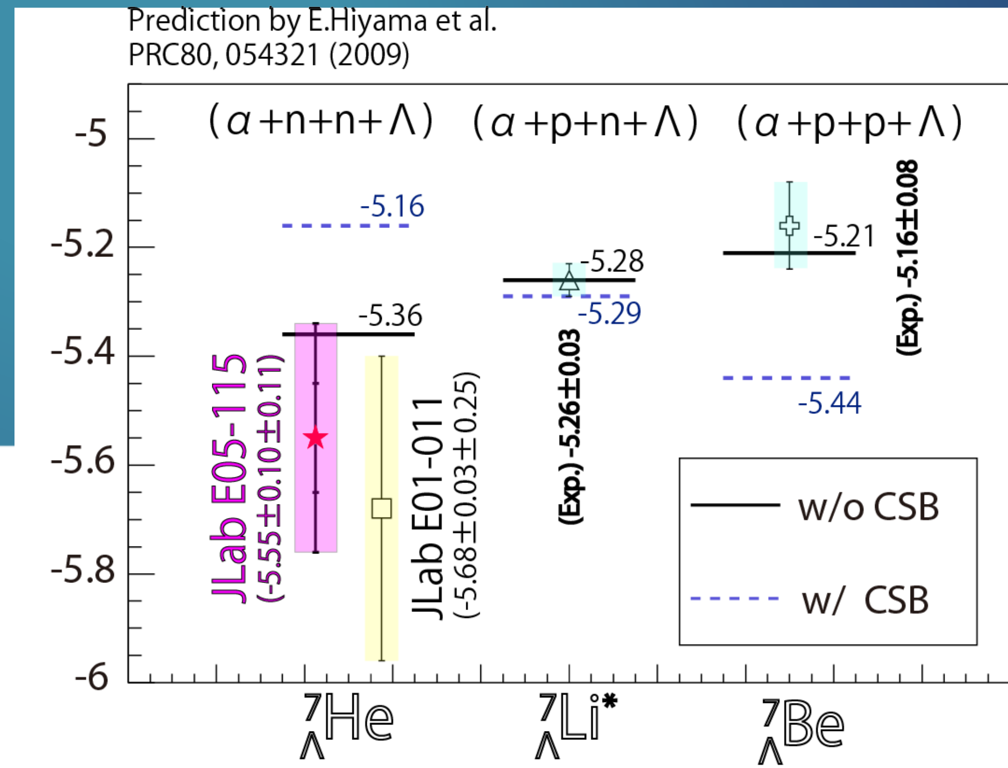


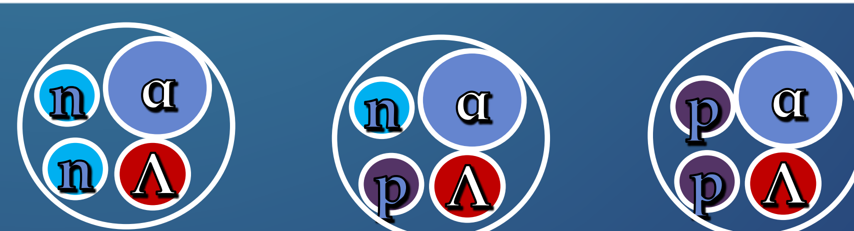
CSB interaction test in A=7 iso-triplet comparison

SNN et al., PRL 110, 012502 (2013)



T.Gogami et al. Submitted to PRC, yesterday!



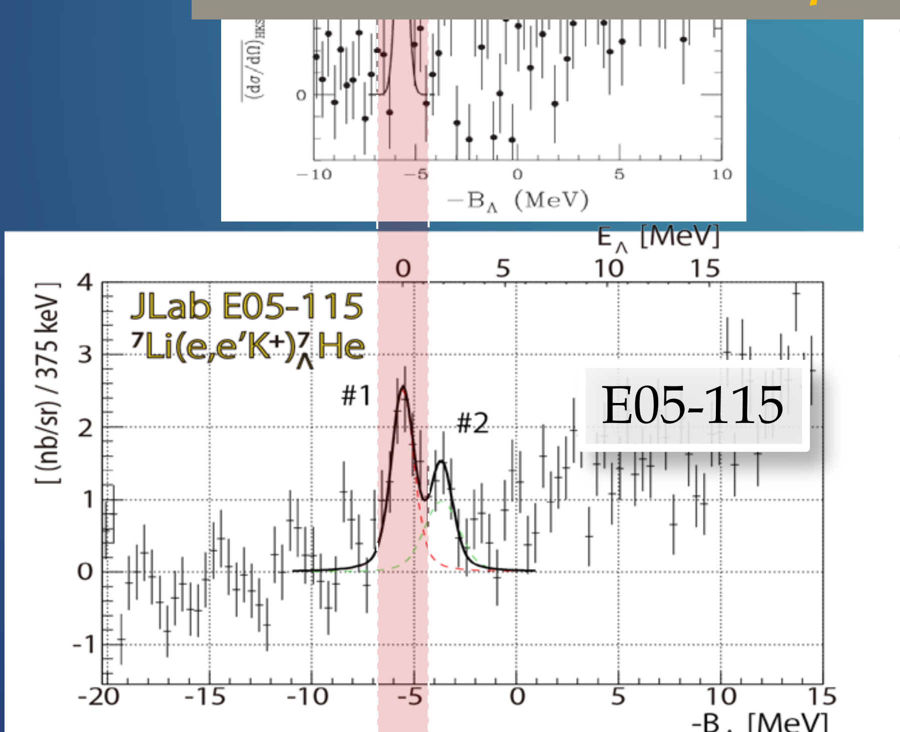


CSB interaction test in A=7

CSB potential is not necessary for A=7

Assumed CSB potential is too naïve or problem for A=4 data

→*New exps. at MAMI and J-PARC*



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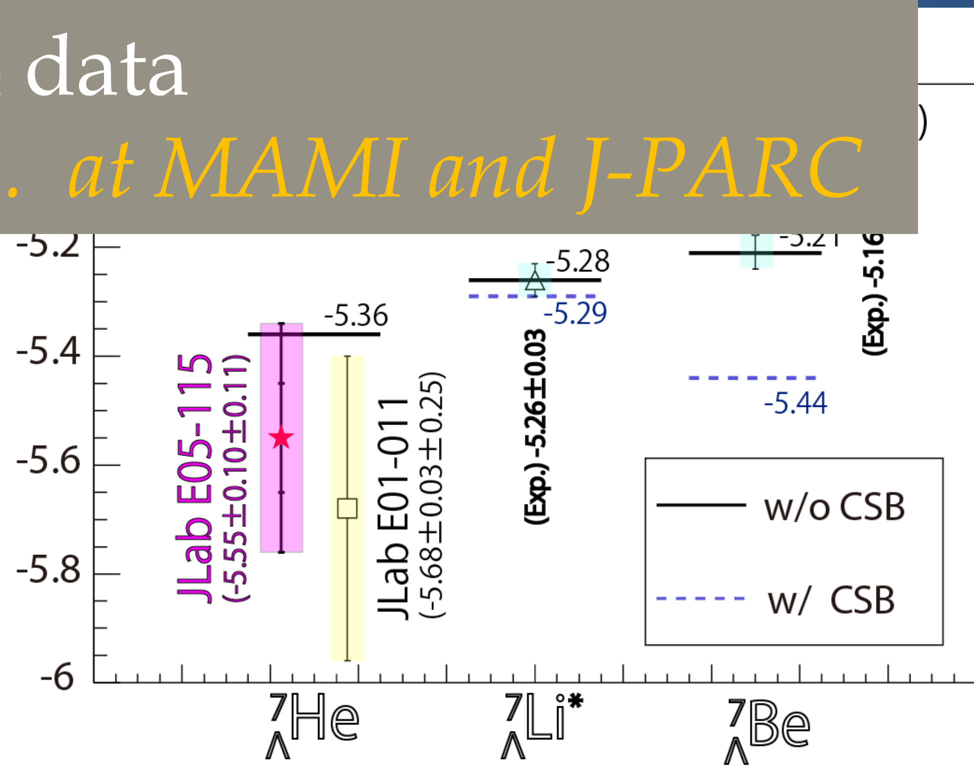
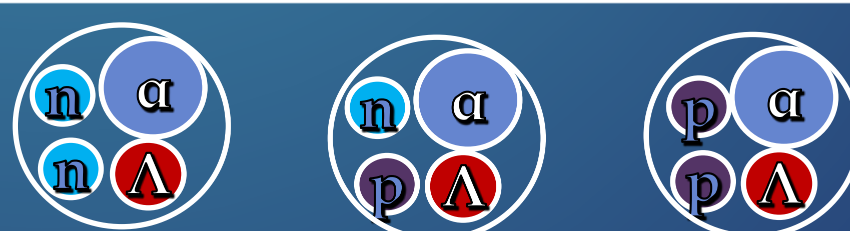
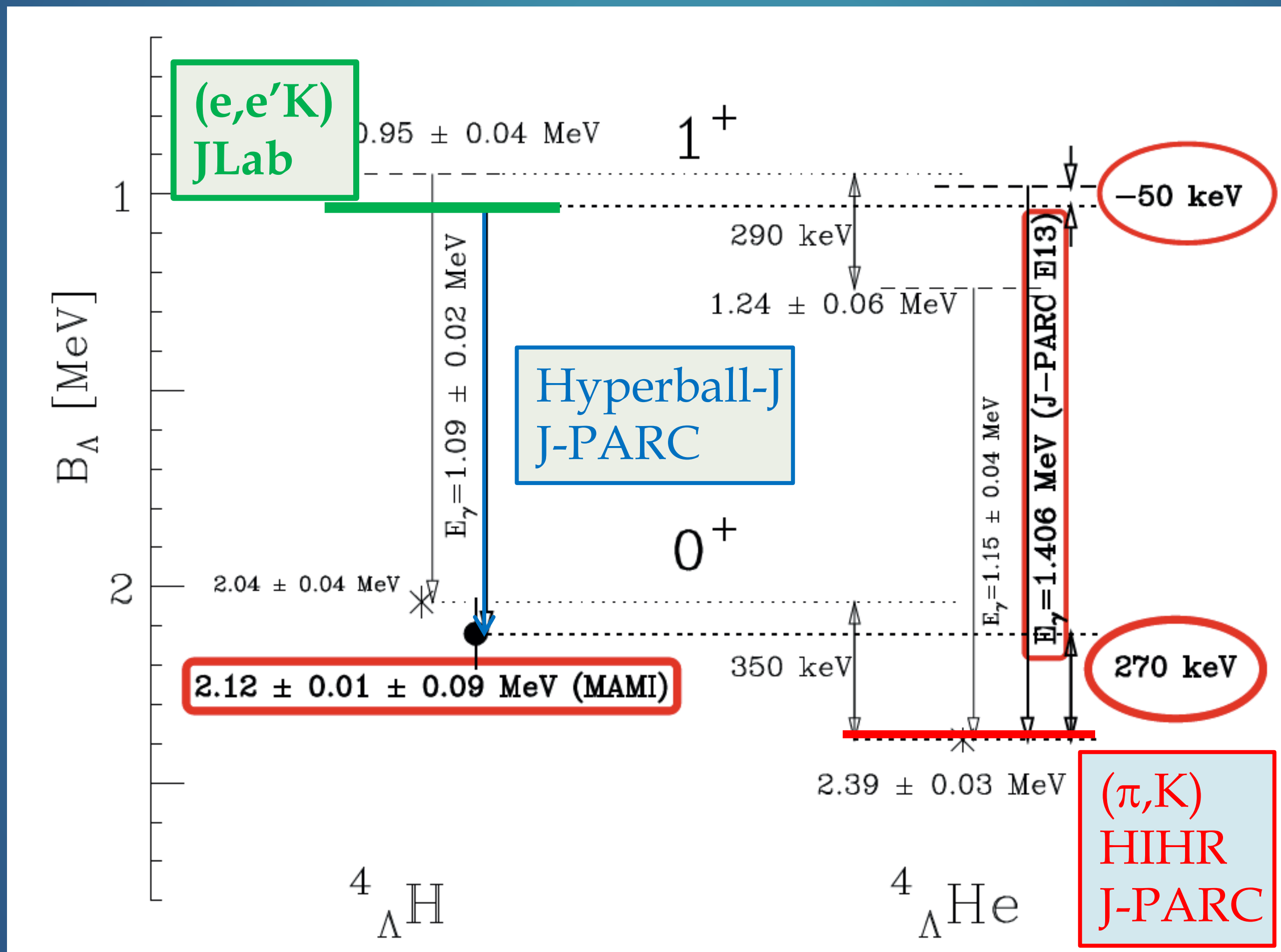


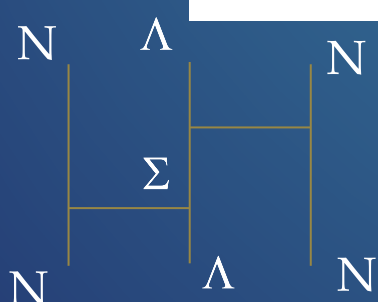


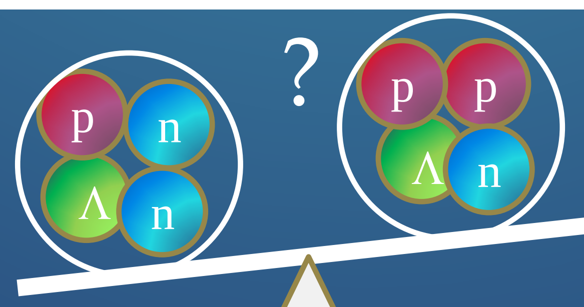
CSB for A=4 hypernuclei : *Future* Measurements



Small CSB

Large CSB





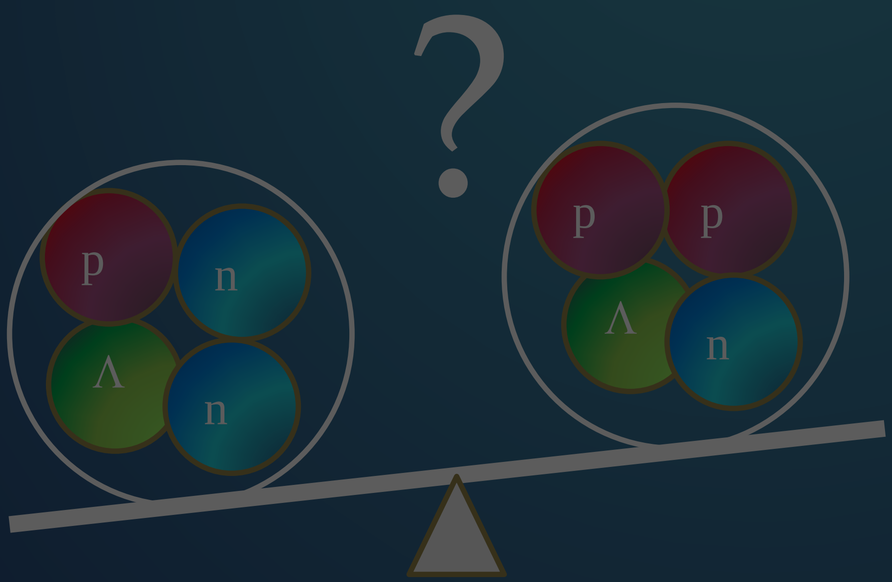
ΛN-ΣN coupling is a key

Isospin dependence of the ΛNN interaction and Hyperon Puzzle

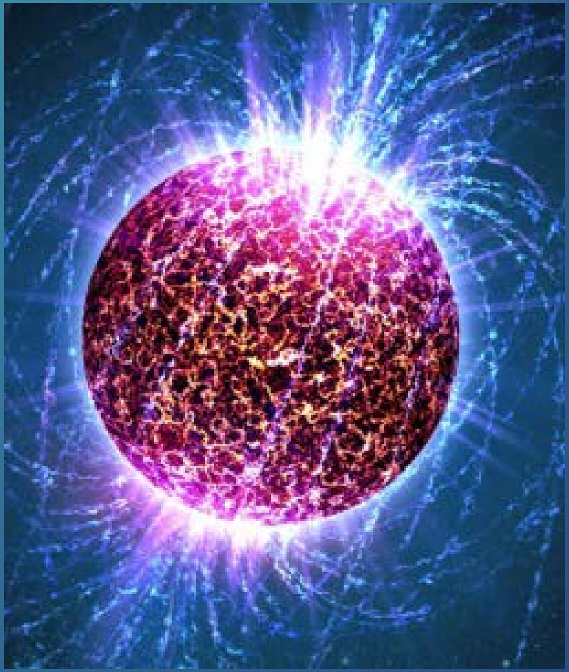
Recent

Mysteries in Hypernuclear Physics

Large CSB for A=4 hypernuclei



Hyperon Puzzle

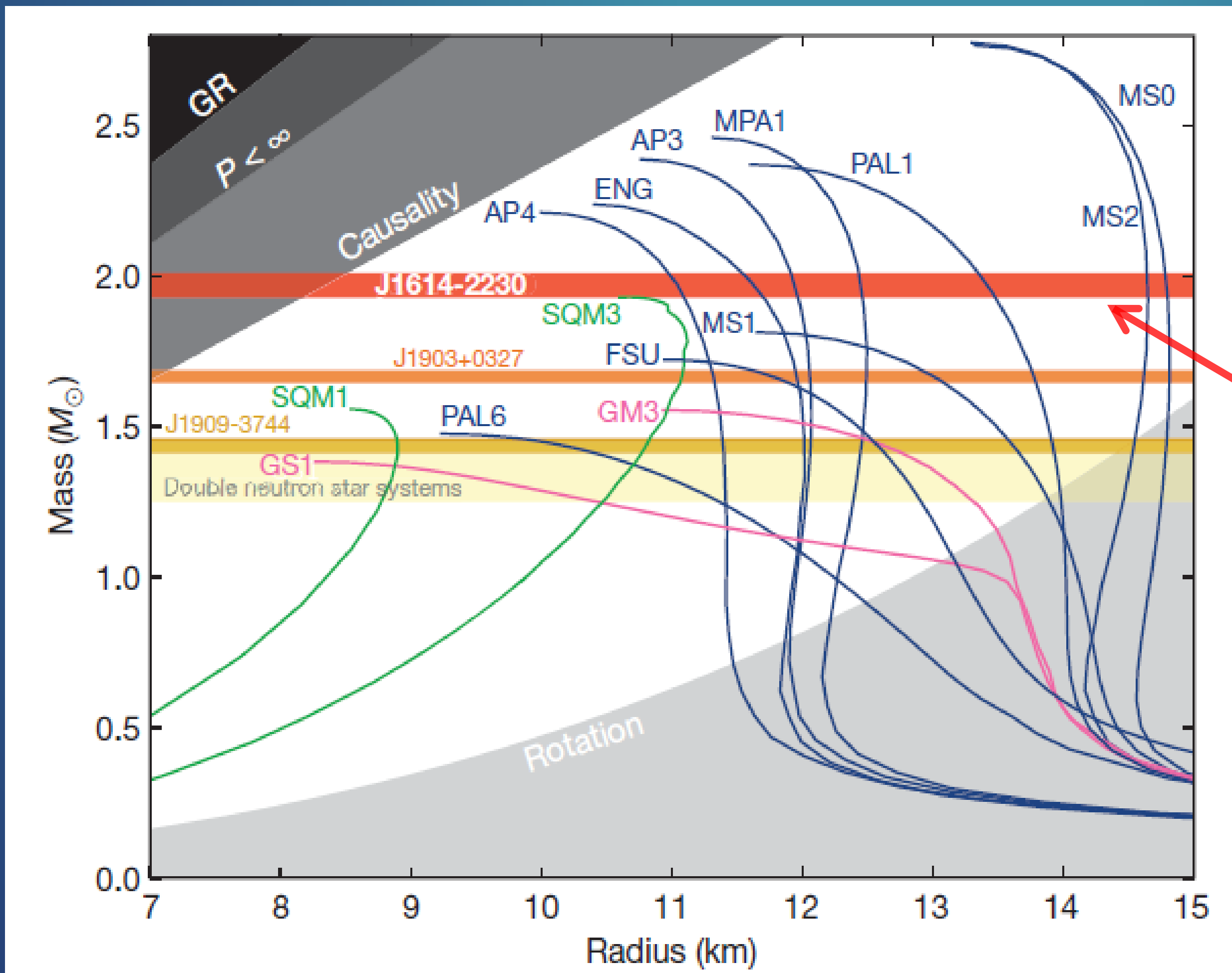


Two solar mass neutron stars

Hyperon Puzzle

Based on our knowledge on Baryonic Force:

Hyperon should appear at high density ($\rho=2\sim3\rho_0$)



Too Soft EOS

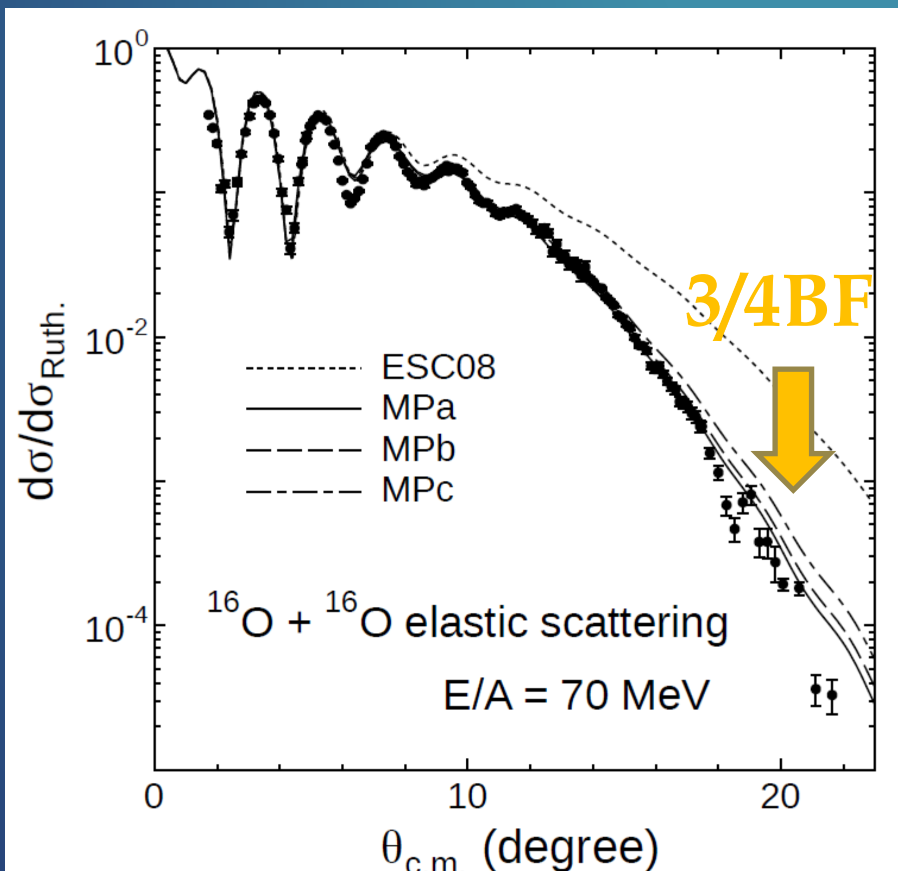
Contradict to observation

2 M_{solar} Neutron Stars

Hyperon Puzzle :
One of most important issues to be solved in nuclear physics

EOS of nuclear matter

Microscopic nuclear force model @ $\rho_0 \rightarrow 2\,\rho_0$



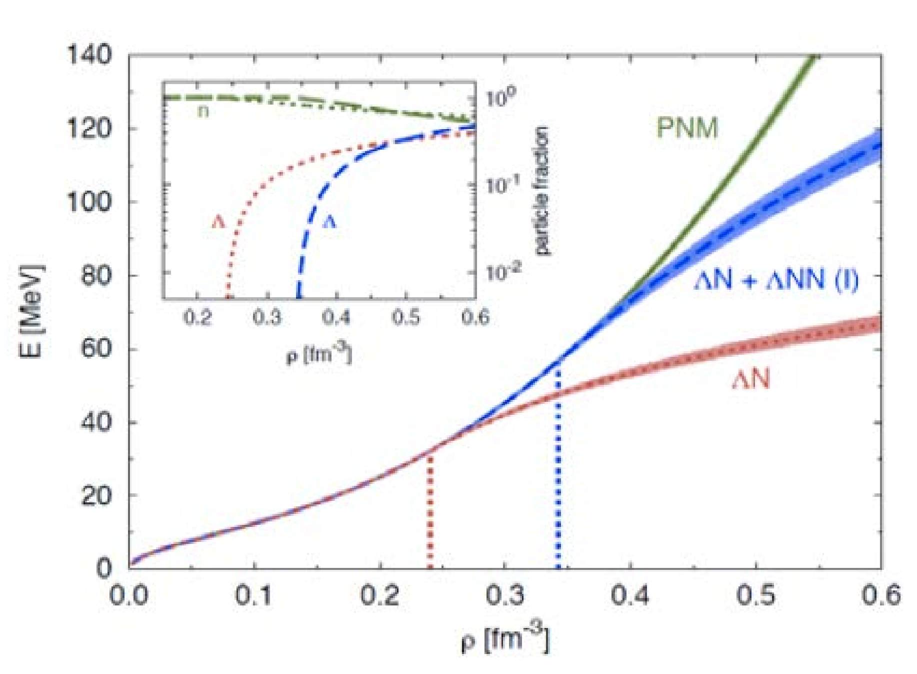
Higher density

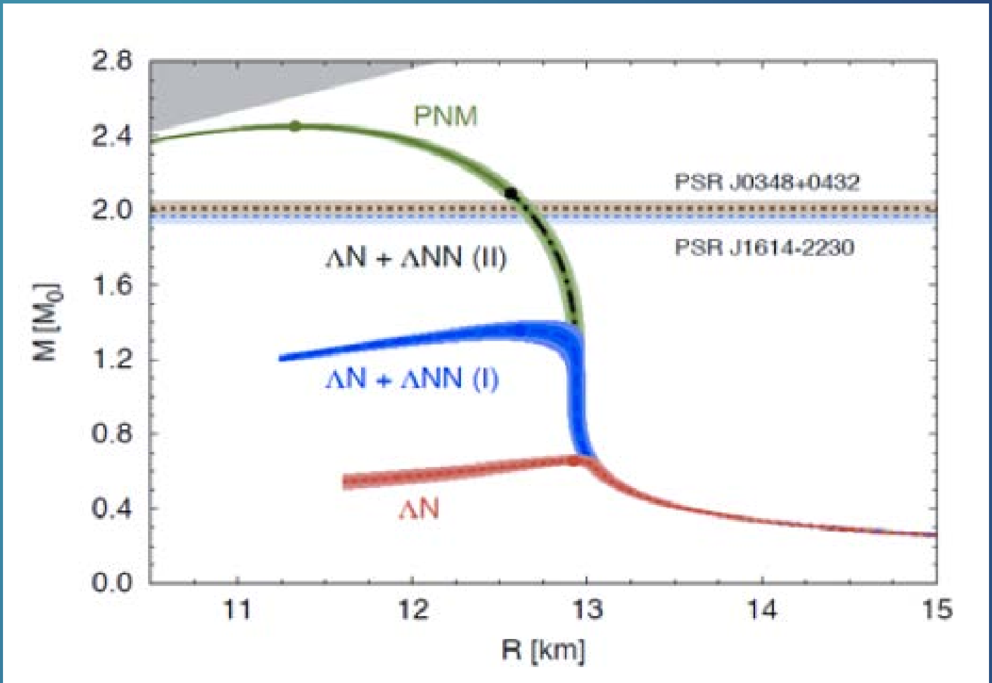
3B/4BF play key roles

Promising scenario to solve Hyp. Puzzle
Repulsive 3B/4B force in YN sector

Furumoto, Sakuragi, Yamamoto, PRC 79 (2009) 0011601(R)

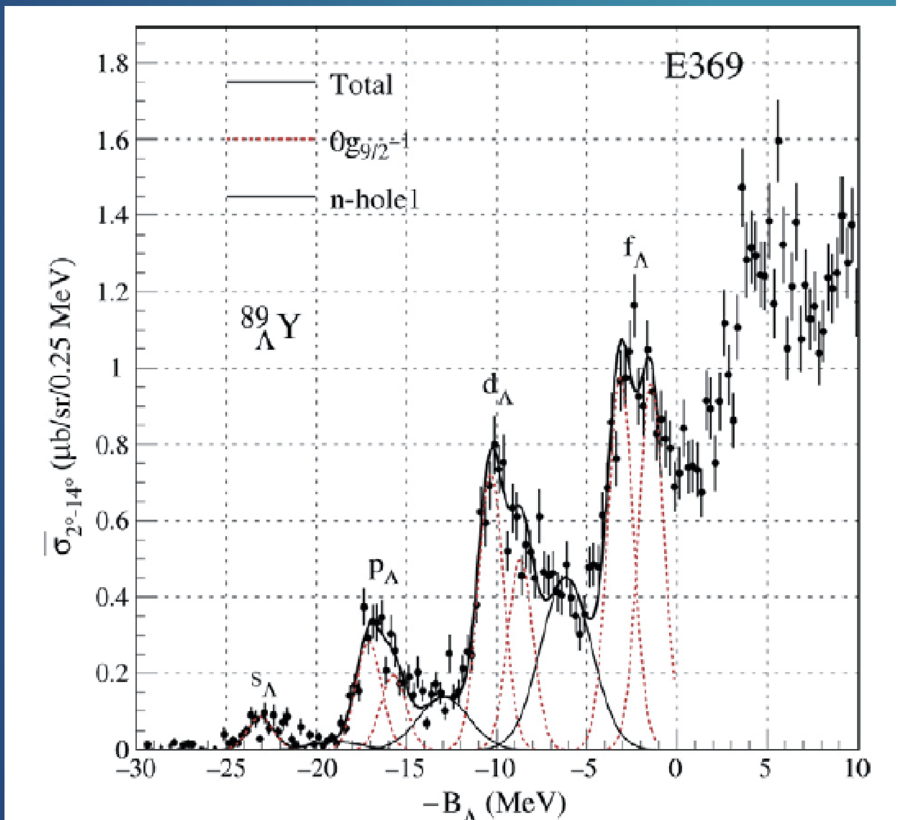
AFDMC by Lonardoni et al.





3BRF in hyperon sector is a key to solve ***Hyperon Puzzle!***

Mid-heavy data from (π,K) exp.



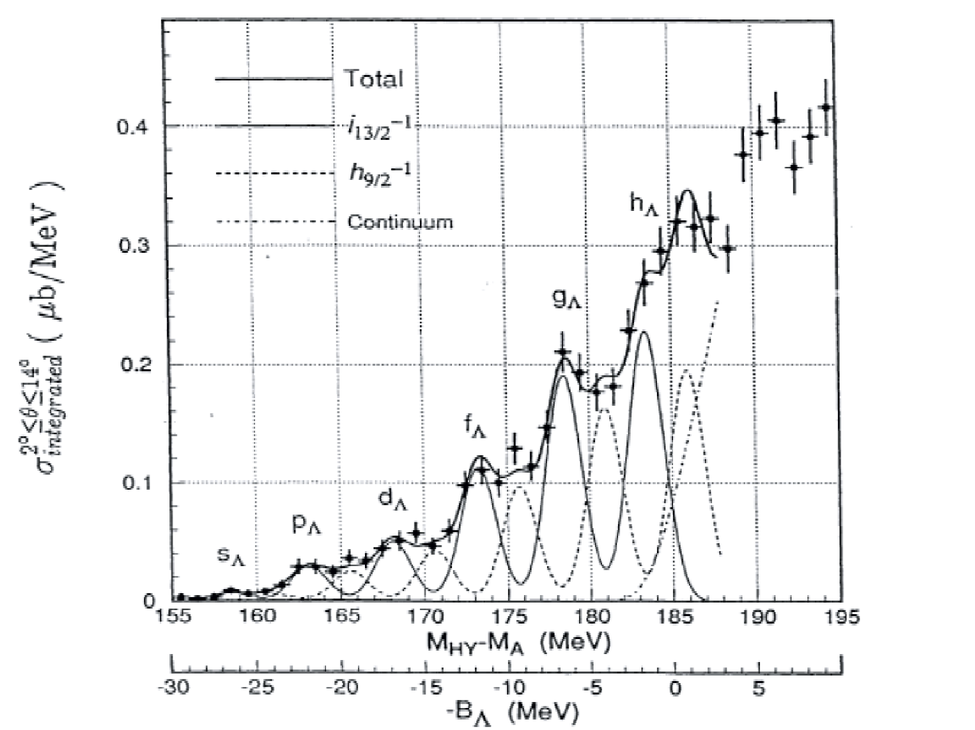
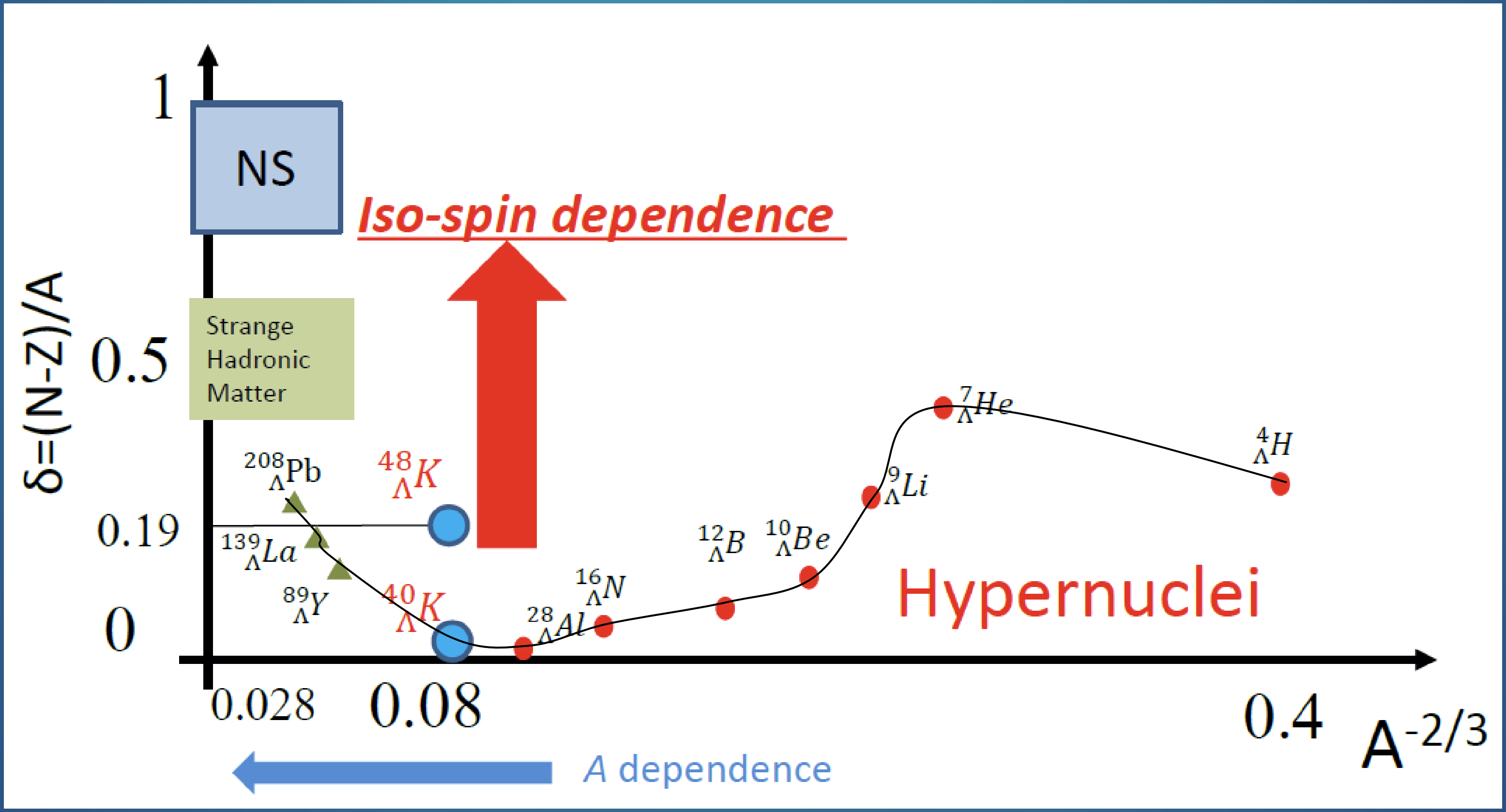
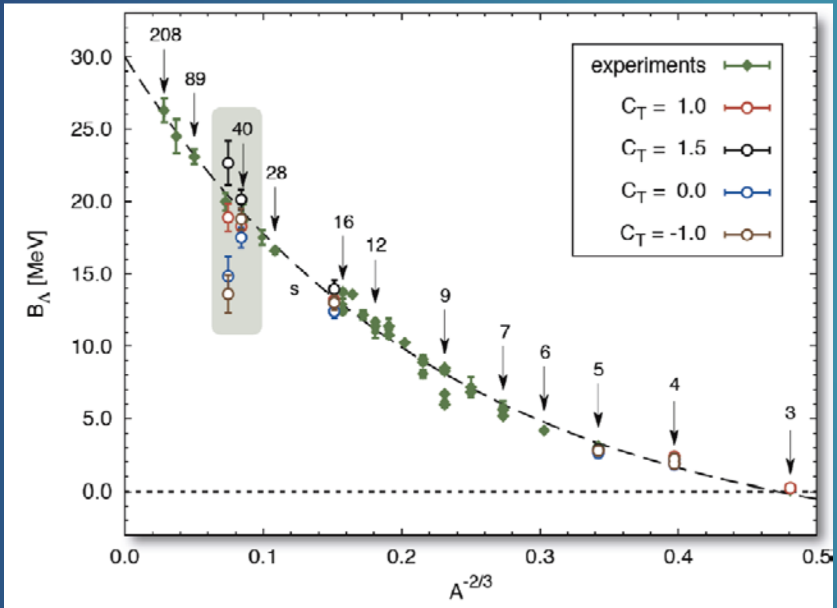


Figure B-5: Experimental $^{208}Pb(\pi^+,K^+)^{208}_{\Lambda}Pb$ excitation energy plot [HAS96].

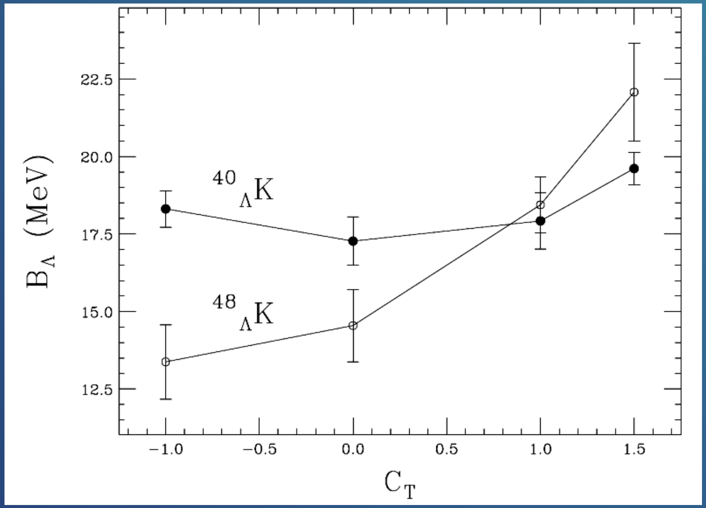
From HY to SHM and NS



Phenomenological 3 BRF+AFDMC



$$\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j = -3P^{\mathrm{T}=0} + \mathrm{C_T}\, P^{\mathrm{T}=1}$$



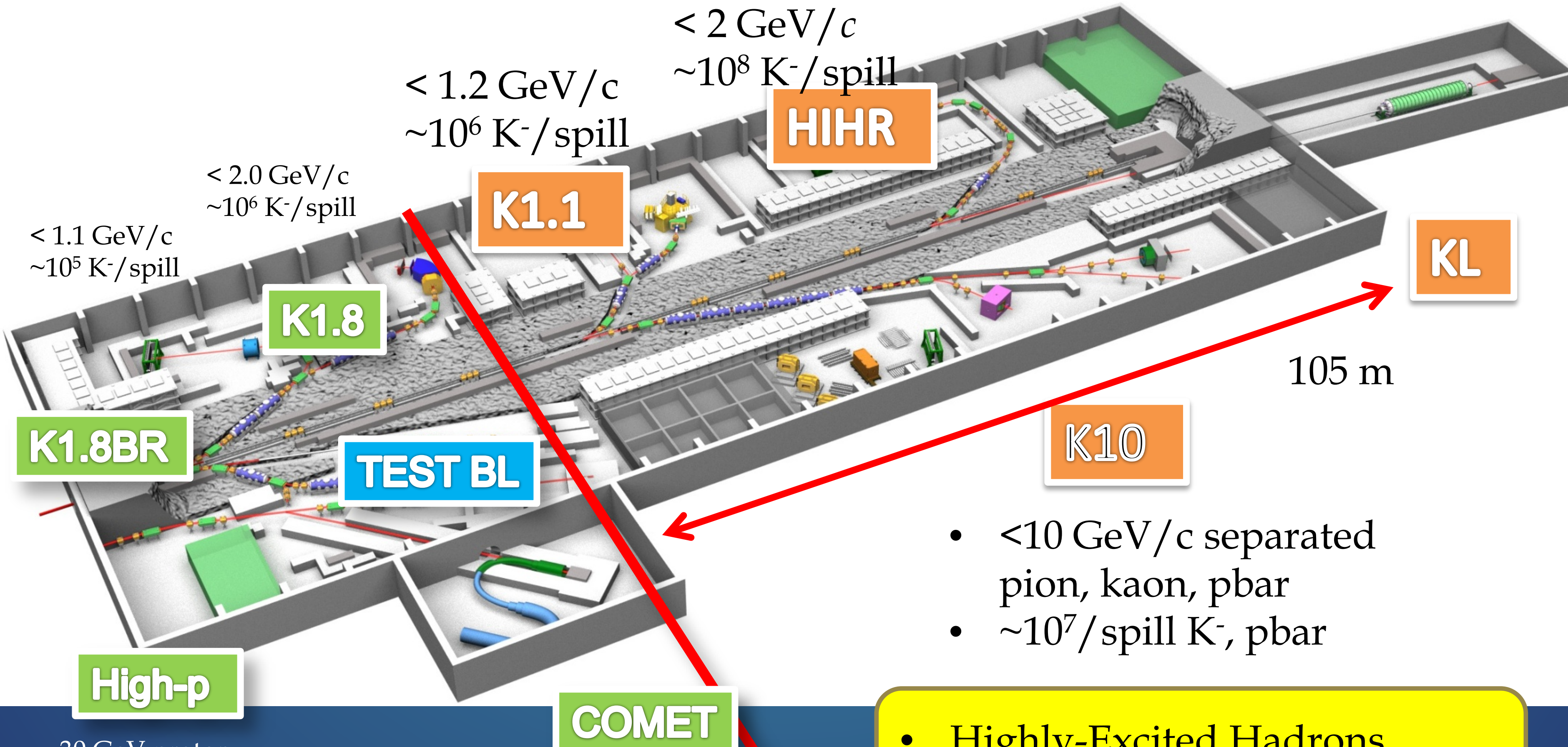
^{40}Ca(e ,e′K$^+$)$^{40}{}_\Lambda$K and , ^{48}Ca(e, e′K$^+$)$^{48}{}_\Lambda$K

New experiment (C2 update) submitted to JLab PAC44

New Project@J-PARC
Hadron Experimental hall Extension

Selected as one of 4 high-priority projects at KEK Program Implementation Plan Committee (May 2016)

- Baryon-Baryon Interaction at Short Distances
  - 3 body & 2 body BB interaction



30 GeV proton
<31 GeV/c unseparated 2ndary beams (mostly pions), ~10^7/spill

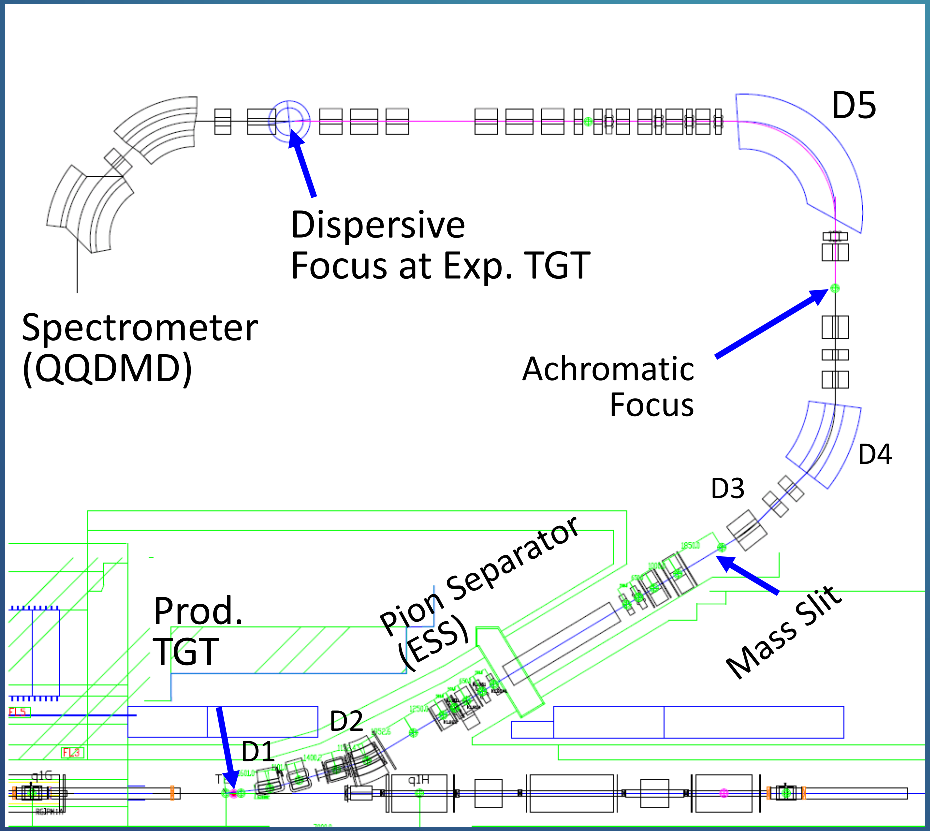
Muon

- Highly-Excited Hadrons
- Mesons in Nuclear Medium

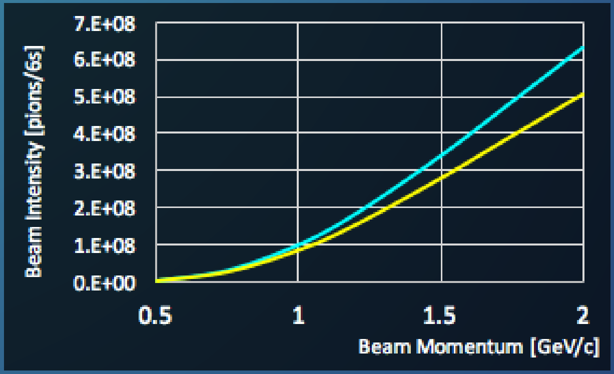
Future Plan at J-PARC : HIHR

Present beam lines:
~10^6 pions/pulse, $\Delta p/p \sim 1/1000$

- High-Intensity High-Resolution Beam line
for High Precision (π, K^+) Spectroscopy with ΔE=0.1 MeV
  - Dispersion matching + no beam tracking



Intensity: ~ 1.8×10^8 pion/pulse
(1.2 GeV/c, 58 m, 1.4msr*%,
100kW, 6s spill, Pt 60mm)
$\Delta p/p \sim 1/10000$



Complementary Program
to the JLab program

Summary

Spectroscopy of Lambda hypernuclei with electron beams

⇨ Established at JLab ⇨ Decay π at MAMI

$^{9}_{\Lambda}$Li $^{10}_{\Lambda}$Be $^{12}_{\Lambda}$B $^{16}_{\Lambda}$N ⇨

Abs. B_Λ determination sugg.
0.54MeV shift for all (π,K)

Observation of $^{7}_{\Lambda}$He excited state :
New possibility to bridge physics of hypernuclei and unstable nuclei.

Determination of $B_\Lambda(^{7}_{\Lambda}He_{gs})$ triggered intensive study for A=4 iso-doublet hypernuclei ($^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He)

⇨ Mainz : Decay π spectroscopy
J-PARC E13 : γ–ray spectroscopy

New experiment for ($^{40}_{\Lambda}$K and $^{48}_{\Lambda}$K) is planned to clarify the isospin dependence of 3BRF which is necessary to solve Hyperon puzzle.
New HIHR beamline @ J-PARC HExH for hypernuclear study