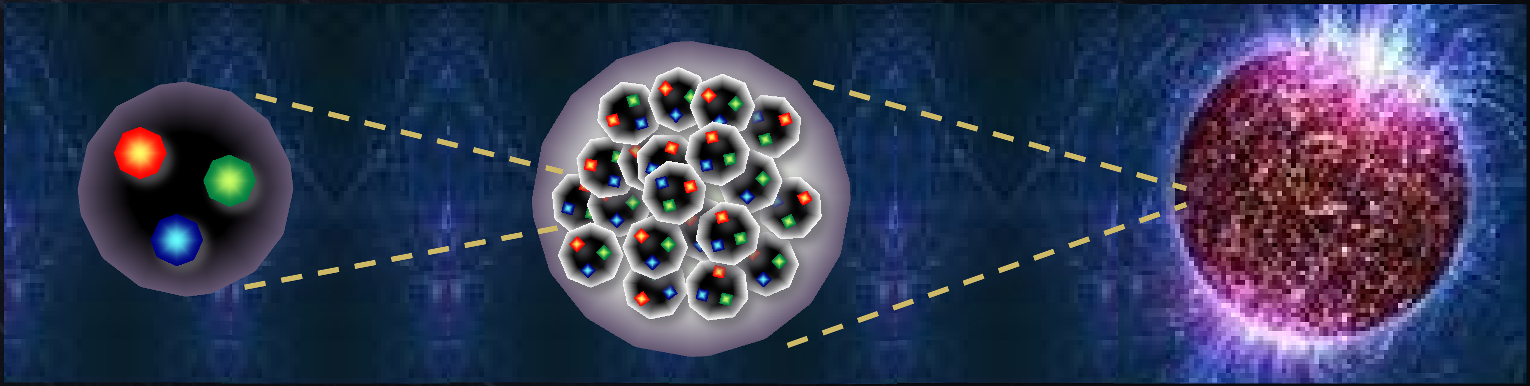
JLAB PAC43

8 July 2015

Satoshi N Nakamura, Tohoku University

on behalf of the JLab Hypernuclear Collaboration

A study of the ΛN interaction through the high precision spectroscopy of Λ-hypernuclei with electron beam

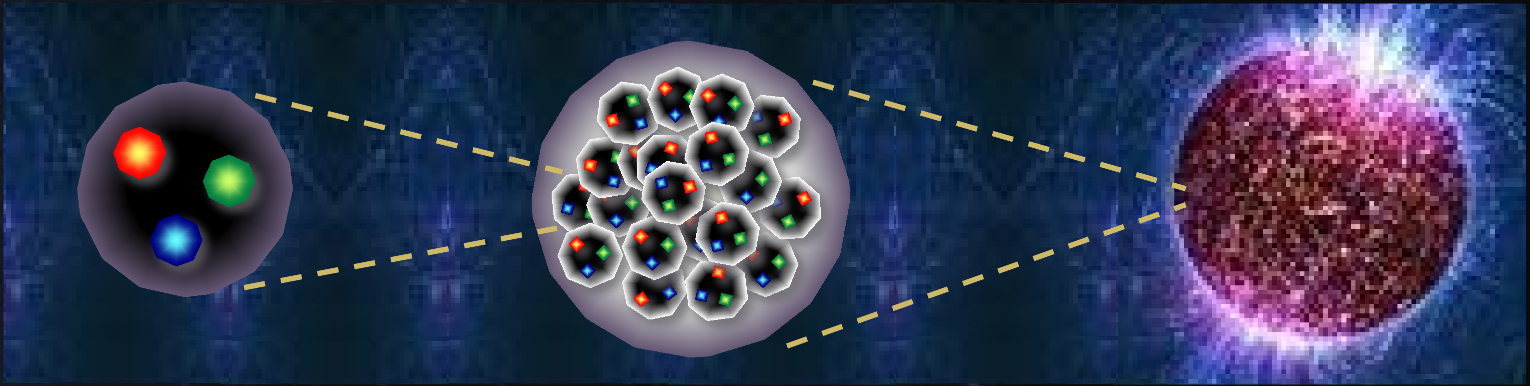


Quantum Many-body System Bound by the Strong Int.

Baryon

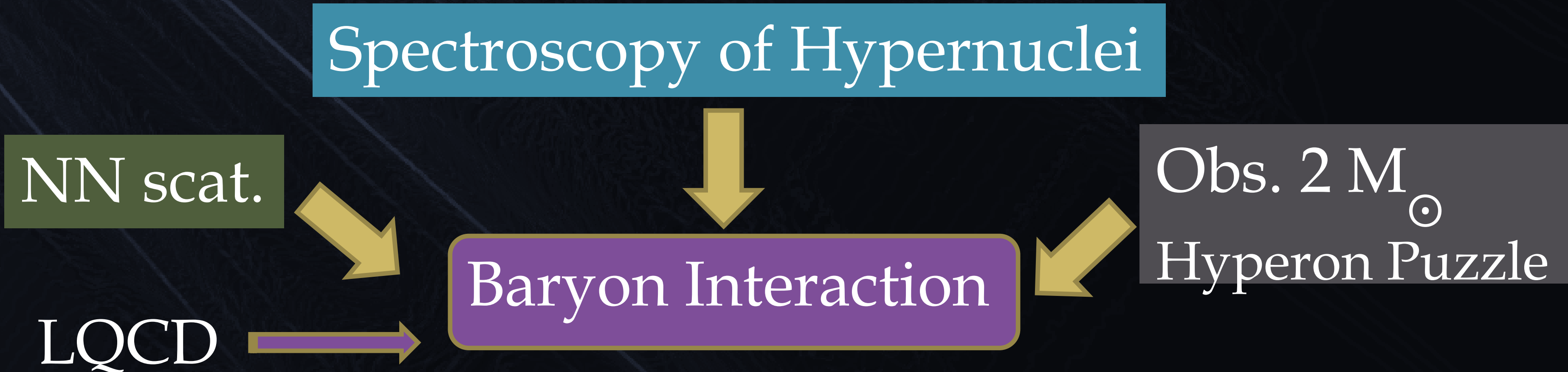
(Hyper)
Nucleus

Neutron Star



10^{-15} m

10^{4} m



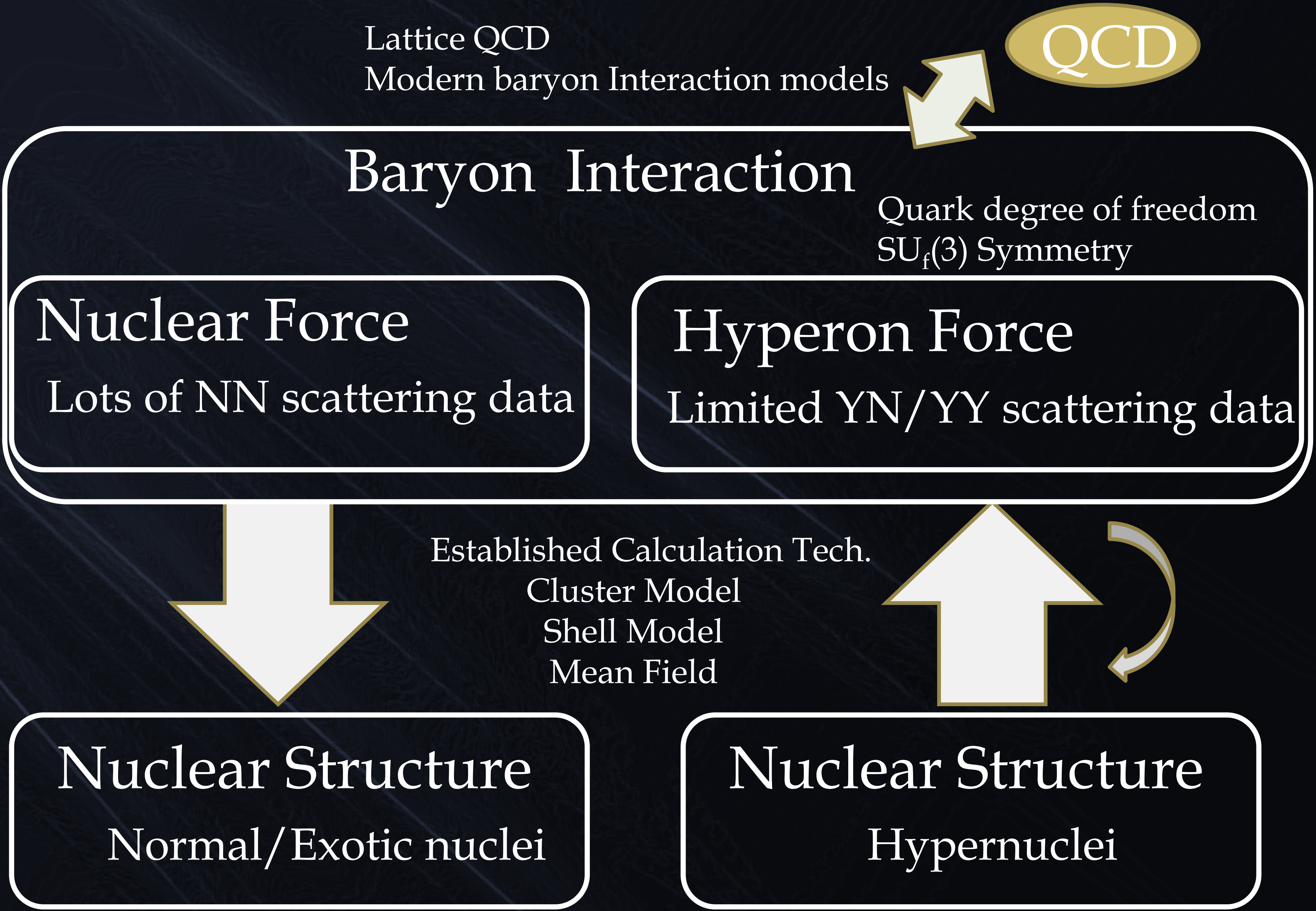
Spectroscopy of Hypernuclei

NN scat.

Obs. $2\ M_{\odot}$
Hyperon Puzzle

LQCD

Baryon Interaction



Lattice QCD
Modern baryon Interaction models

QCD

Baryon Interaction

Quark degree of freedom
$SU_f(3)$ Symmetry

Nuclear Force

Lots of NN scattering data

Hyperon Force

Limited YN/YY scattering data

Established Calculation Tech.
Cluster Model
Shell Model
Mean Field

Nuclear Structure

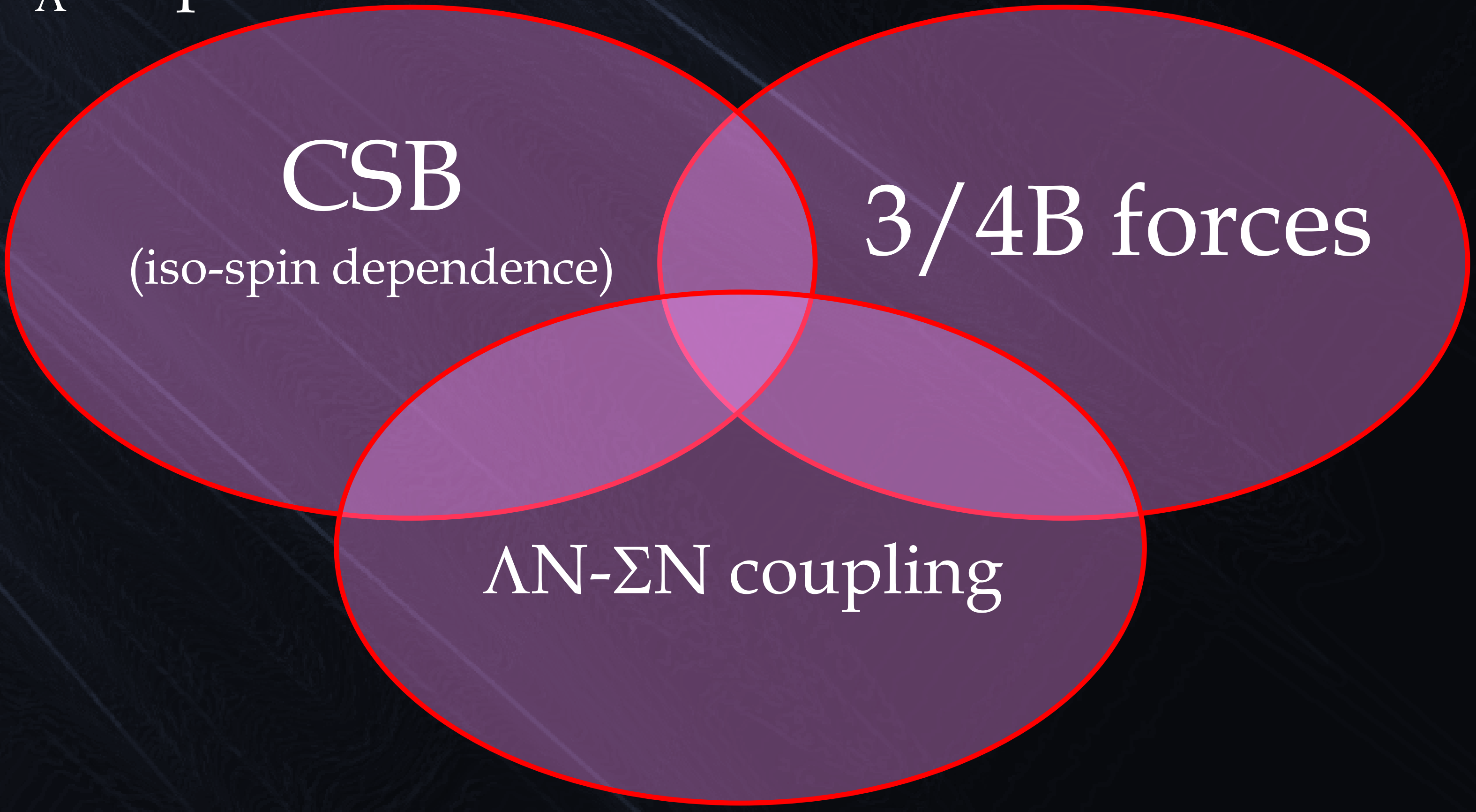
Normal/Exotic nuclei

Nuclear Structure

Hypernuclei

Proposed experiments

YN interaction



$^{4}_{\Lambda}$H-$^{4}_{\Lambda}$He problem

Hyperon puzzle

CSB

(iso-spin dependence)

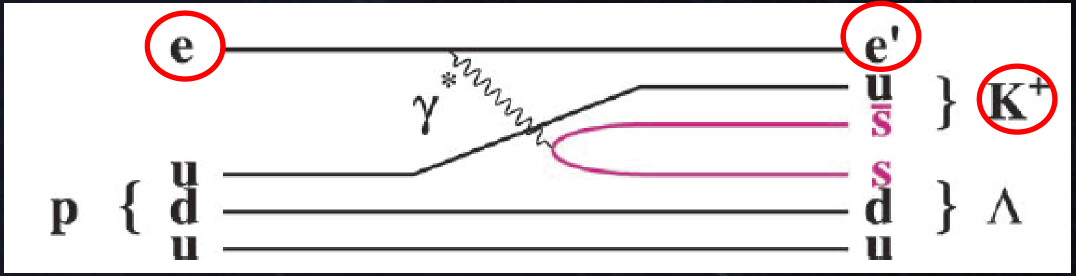
3/4B forces

ΛN-ΣN coupling

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

Initiated and established at **JLab**

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



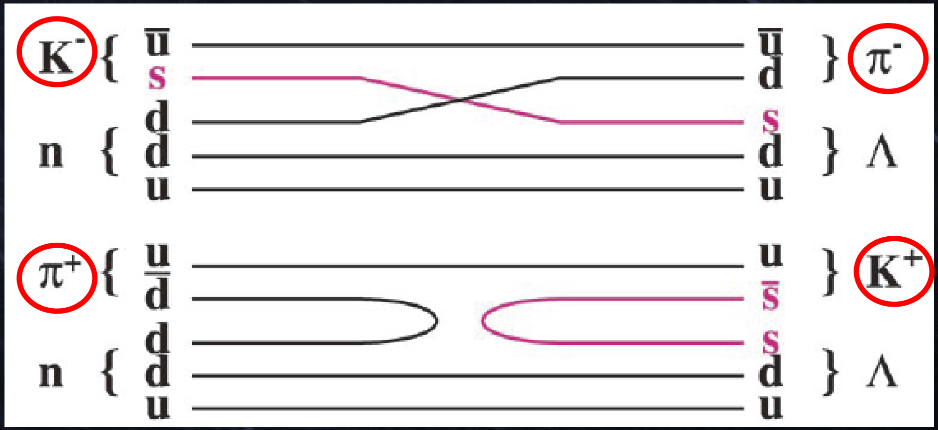
(e,e'K$^+$)

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)

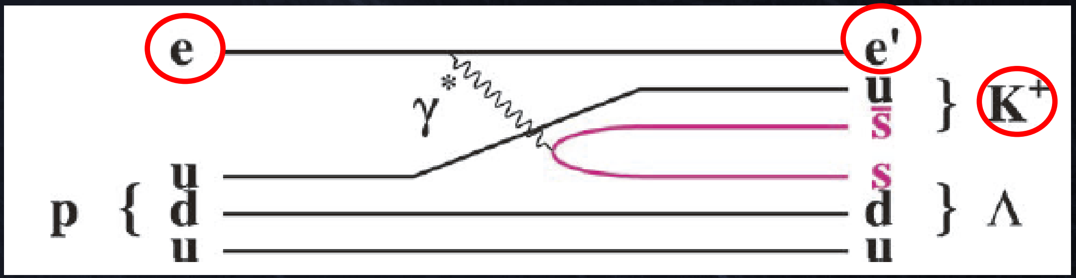
But **ONLY** **level spacing** measurable

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$^+$) Λ, Σ^0

Currently ONLY possible at JLab

E_e > 1.5 GeV high quality e beam

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

Proposed experiments

YN interaction

Charge Sym. Breaking

Hyperon puzzle
in neutron stars

Part I.

Light Hyp.Nucl.

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

p(e,e′K^{+})Λ, Σ^{0}

Exotic systems ([nΛ],[nnΛ])

Established lightest HY ($^{3}_{\Lambda}$H)

Part II.

Mid-Heavy Hyp.Nucl.

A dependence of B_{Λ}

(**$^{40}_{\Lambda}$K**, $^{89}_{\Lambda}$Sc, **$^{208}_{\Lambda}$Tl**)

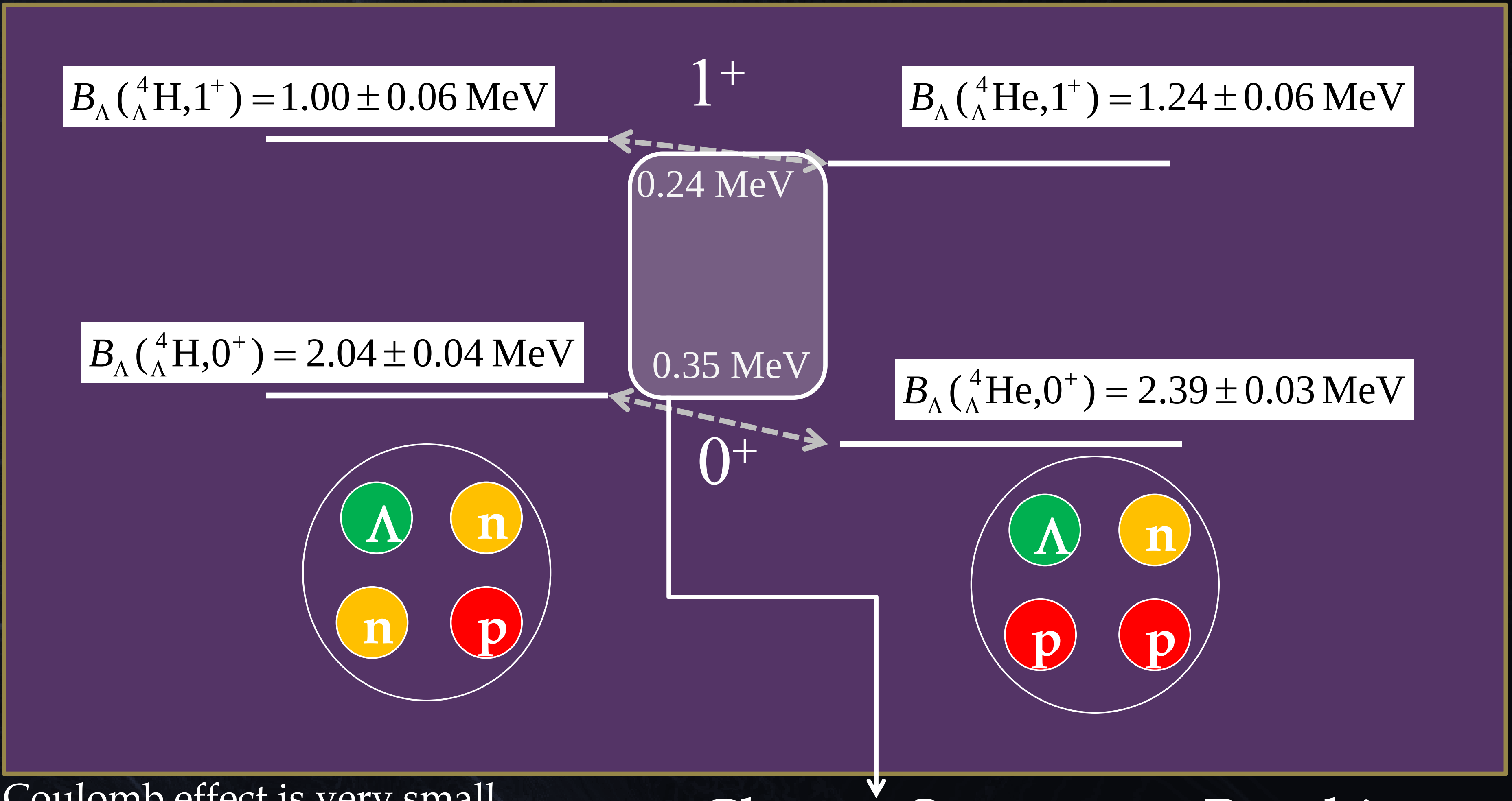
Isospin dependence (**$^{48}_{\Lambda}$K**)

Part I.

Charge Symmetry Breaking of the ΛN interaction

A=4 system
CSB ΛN potential

Data from
Emulsion
NaI γ-ray



$B_\Lambda({}^4_\Lambda\mathrm{H},1^+) = 1.00 \pm 0.06\ \mathrm{MeV}$

1^+

$B_\Lambda({}^4_\Lambda\mathrm{He},1^+) = 1.24 \pm 0.06\ \mathrm{MeV}$

0.24 MeV

0.35 MeV

$B_\Lambda({}^4_\Lambda\mathrm{H},0^+) = 2.04 \pm 0.04\ \mathrm{MeV}$

$B_\Lambda({}^4_\Lambda\mathrm{He},0^+) = 2.39 \pm 0.03\ \mathrm{MeV}$

0^+

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

Three-body ΛNN force

Modern ChPT-NLO calculation predicts 3NF effect is < 100keV
NLO calculation cannot explain experimental results for A=4, T=1/2, hypernuclei.
(Nogga, HYP2012)

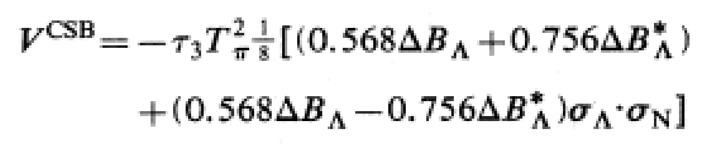
ΛΣ mass difference ~ 80 MeV < NΔ mass difference ~ 300MeV

$M(\Sigma^+) < M(\Sigma^0) < M(\Sigma^-)$, $\Delta M(\Sigma^- - \Sigma^+)$~8MeV

Consistent ~~understanding of 0^+, 1^+ of ${}^4_\Lambda$H, ${}^4_\Lambda$He~~

Phenomenological potential :

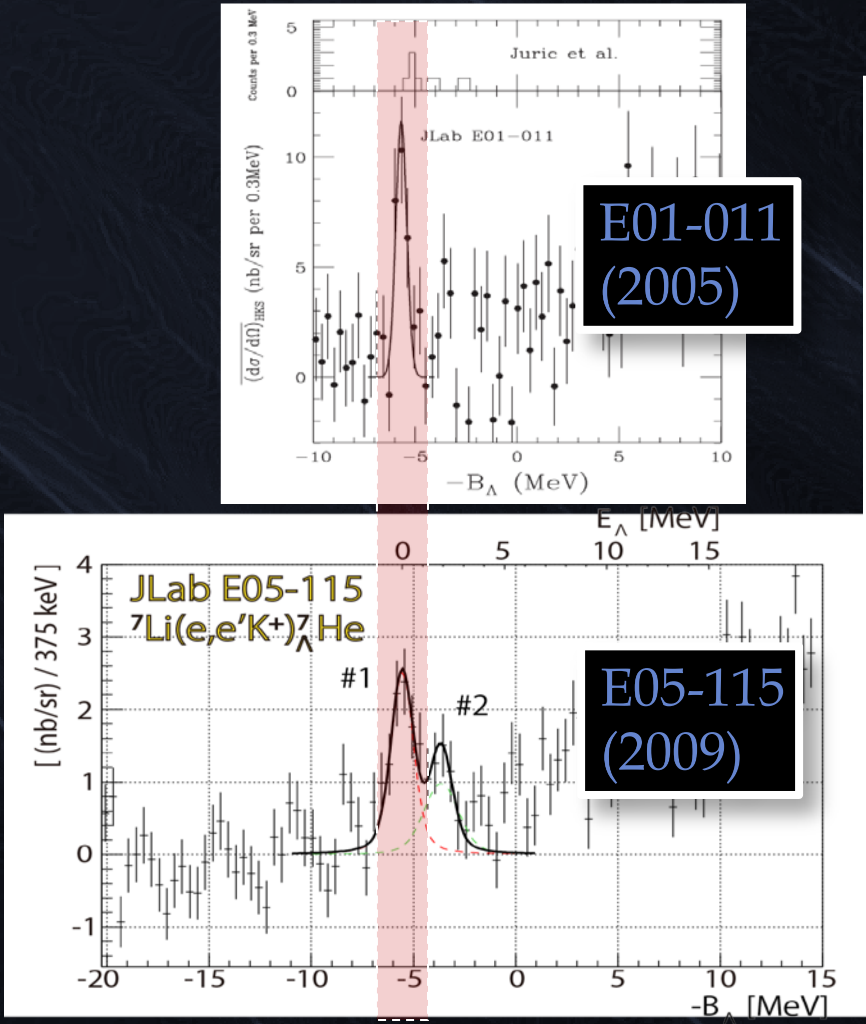
A.R.Bodmer&Q.N.Usmani, PRC 31(1985)1400.



$$V^{\mathrm{CSB}} = -\tau_3 T_\pi^2 \tfrac{1}{8}[(0.568\Delta B_\Lambda + 0.756\Delta B^*_\Lambda) + (0.568\Delta B_\Lambda - 0.756\Delta B^*_\Lambda)\sigma_\Lambda \cdot \sigma_N]$$

CSB interaction test in A=7 iso-triplet comparison

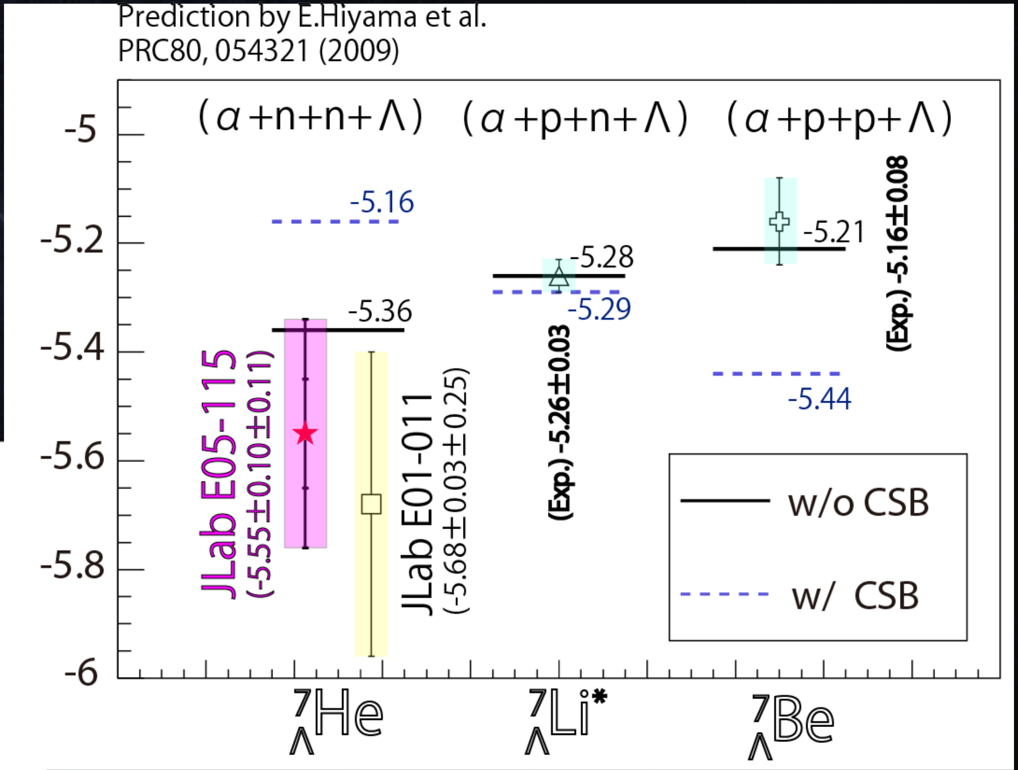
SNN et al., PRL 110, 012502 (2013)



E01-011 (2005)

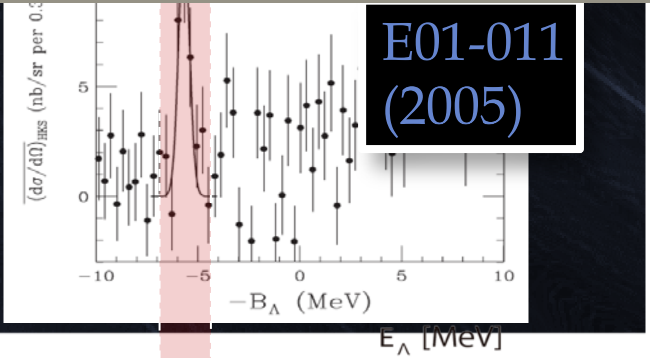
E05-115 (2009)

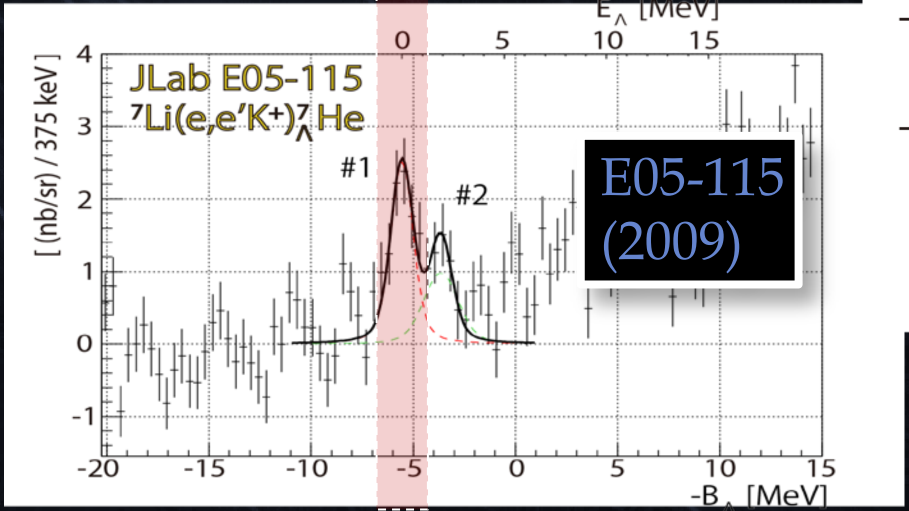
T.Gogami, Doctor Thesis (2014) Tohoku Univ.


Prediction by E.Hiyama et al.
PRC80, 054321 (2009)

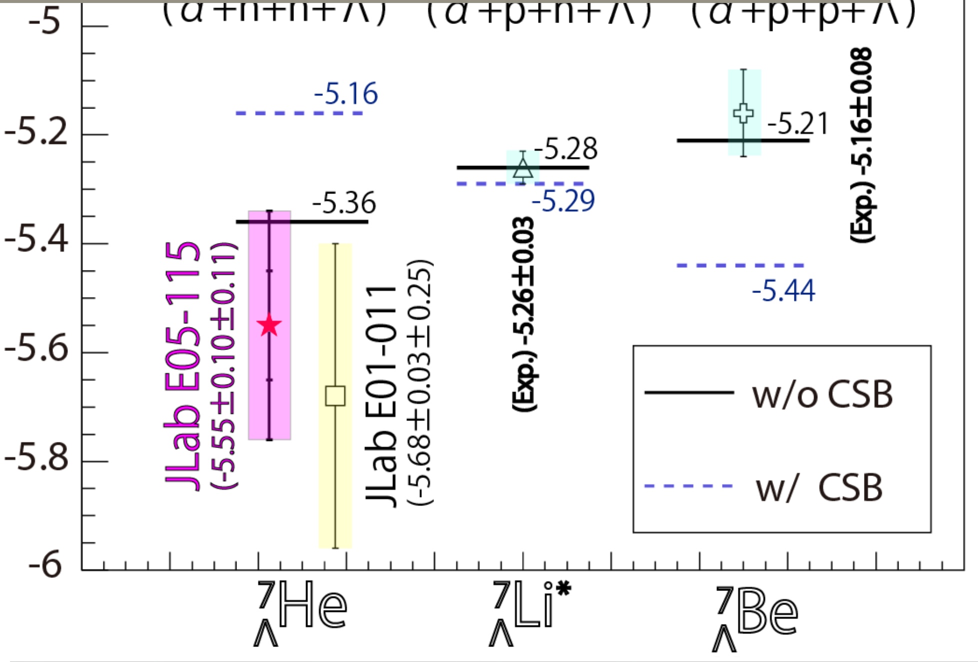
CSB interaction test in A=7

CSB potential is not necessary for A=7
Assumed CSB potential is too naïve or
problem for A=4 data





T.Gogami, Doctor Thesis (2014) Tohoku Univ.

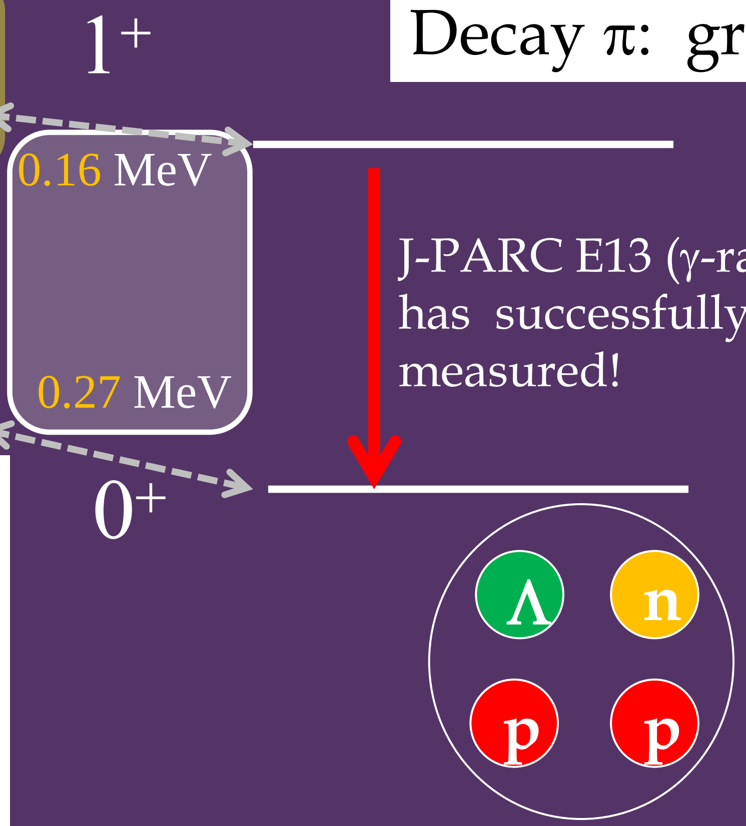


Study of A=4 system

Only accessible by the ^{4}He(e,e'K$^+$)$^4_\Lambda$H at JLab

γ-ray : level spacing
Decay π: ground state

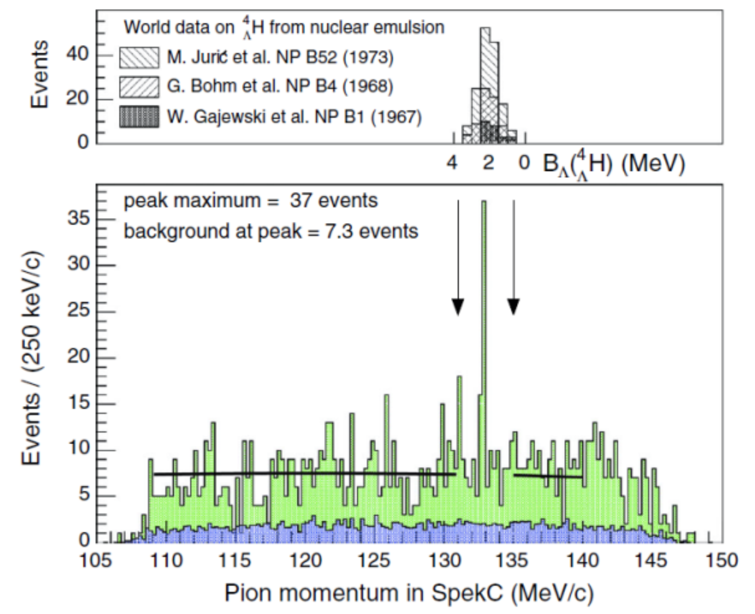
$B_\Lambda(^4_\Lambda\mathrm{H},1^+)$ = New data necessary



Mainz New data :
PRL **114**, 232501 (2015)

$B_\Lambda(^4_\Lambda\mathrm{H},0^+) = 2.12 \pm 0.09$ MeV

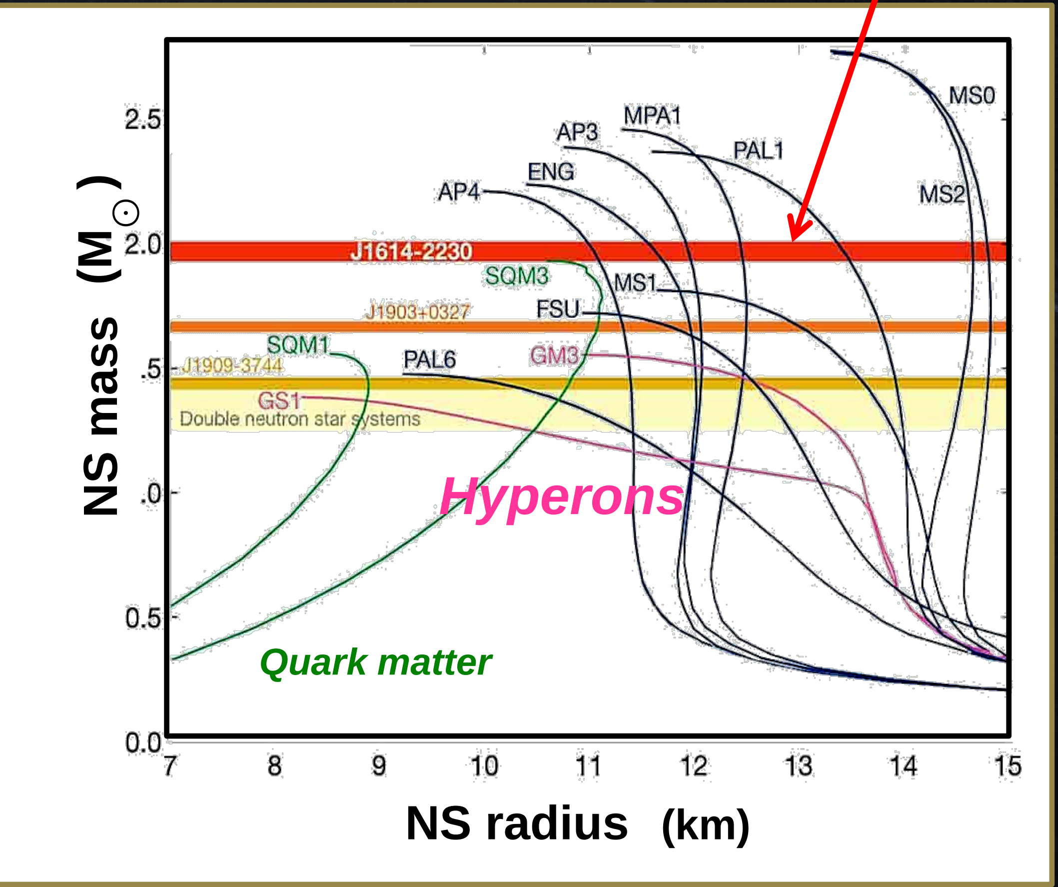
J-PARC E13 (γ-ray; hyperball) has successfully measured!



Part II.
3B/4B Repulsive Hyperon Interaction for EOS of neutron stars

Hyperon Puzzle

PSR J1614-2230 (2010) 1.97±0.04 M_{sun}
PSR J0348-0432 (2013) 2.01±0.04 M_{sun}



Hyperons <u>must appear</u> at

$\rho = 2\text{~}3\ \rho_0$

EOS w/hyperons is too soft for $2M_{sun}$

Contradicts observation!

One of most serious problems of nuclear physics

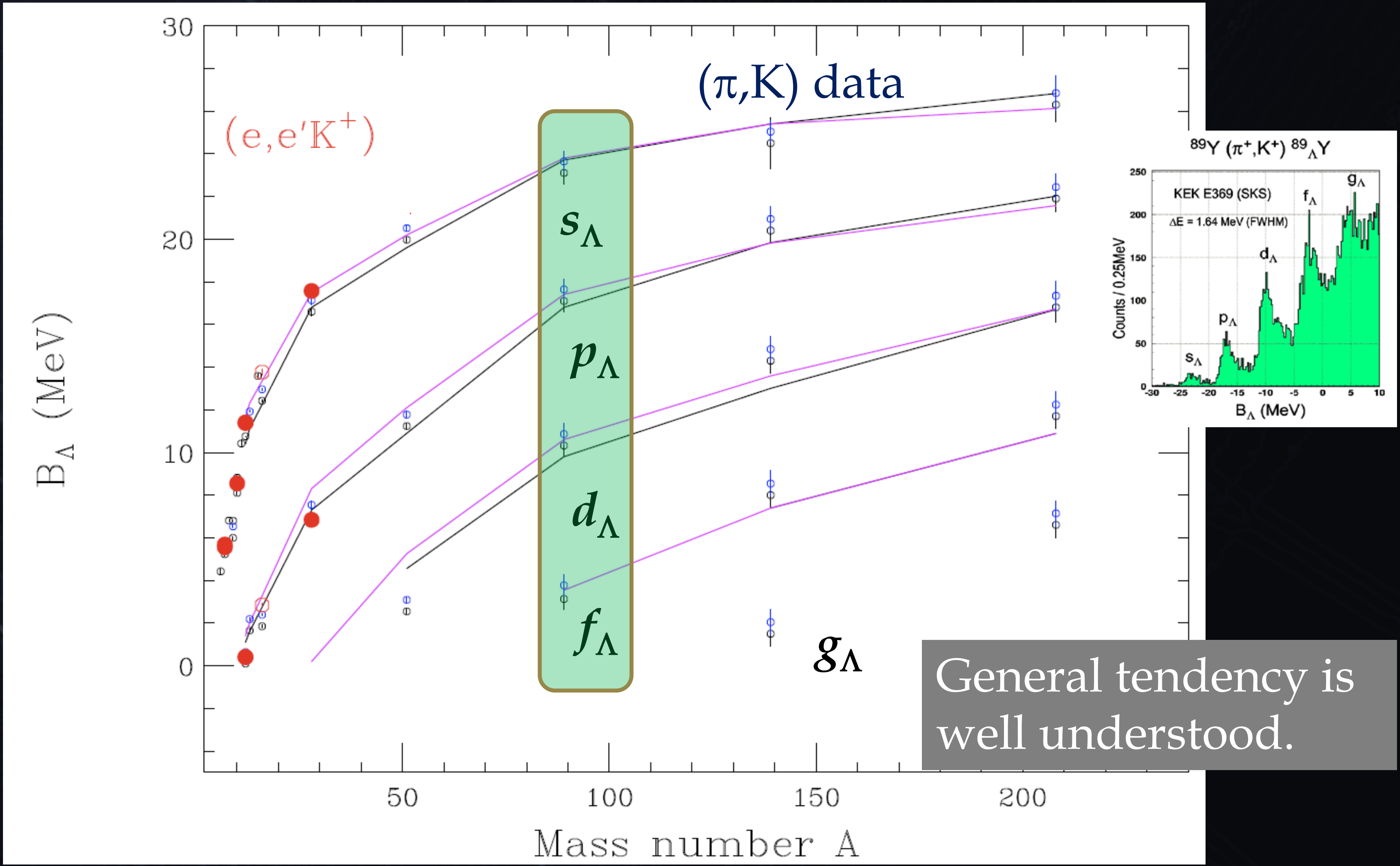
Key points to understand Neutron Stars

Nuclear (Hyperon) Force
under high ρ

3B repulsive force

Inclusion of Hyperon
Soften EOS

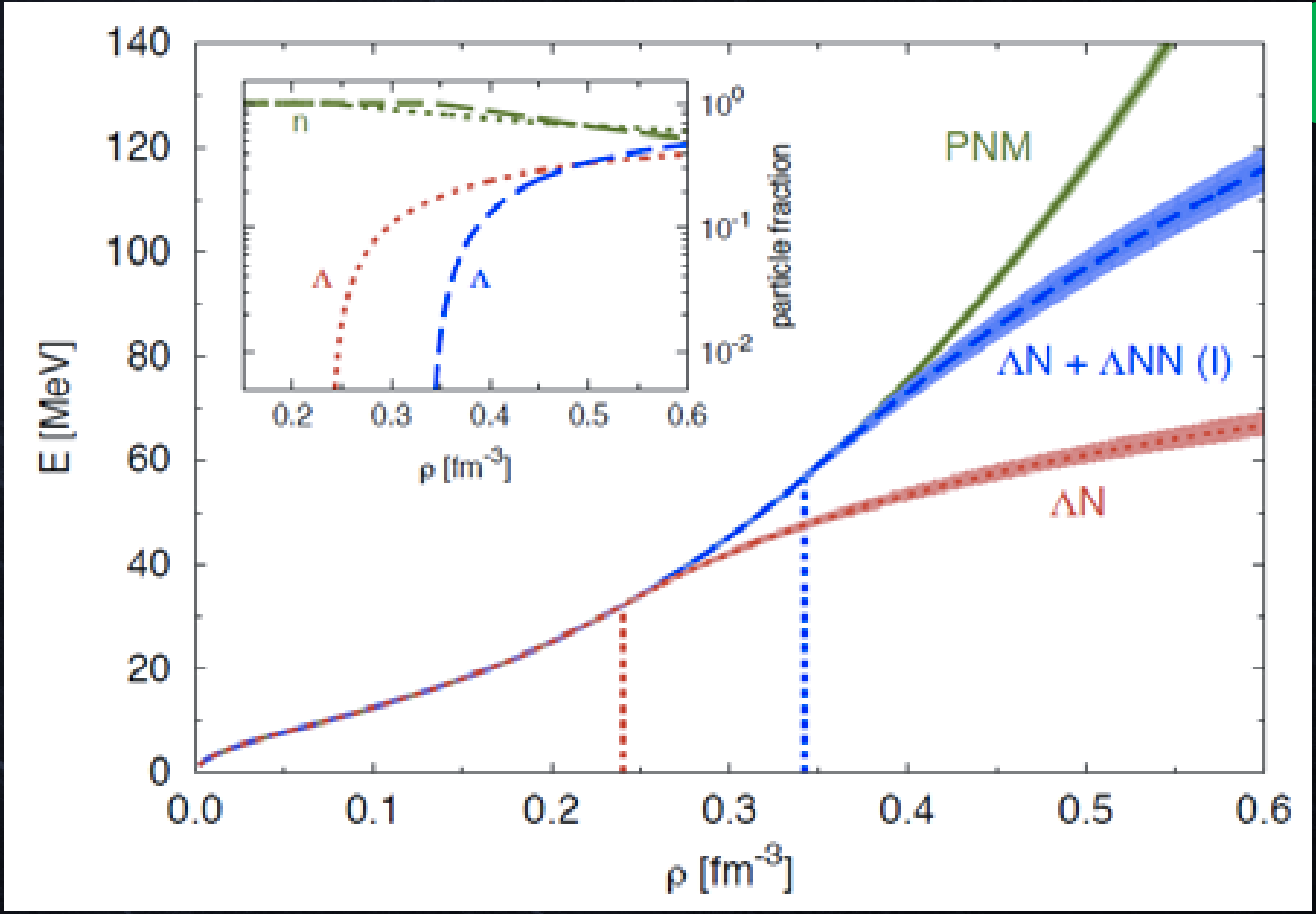
Mass dependence of B_Λ



General tendency is well understood.

Lines: Calc. by Yamamoto & Rijken

NS EOS with hyperon and 3BRF



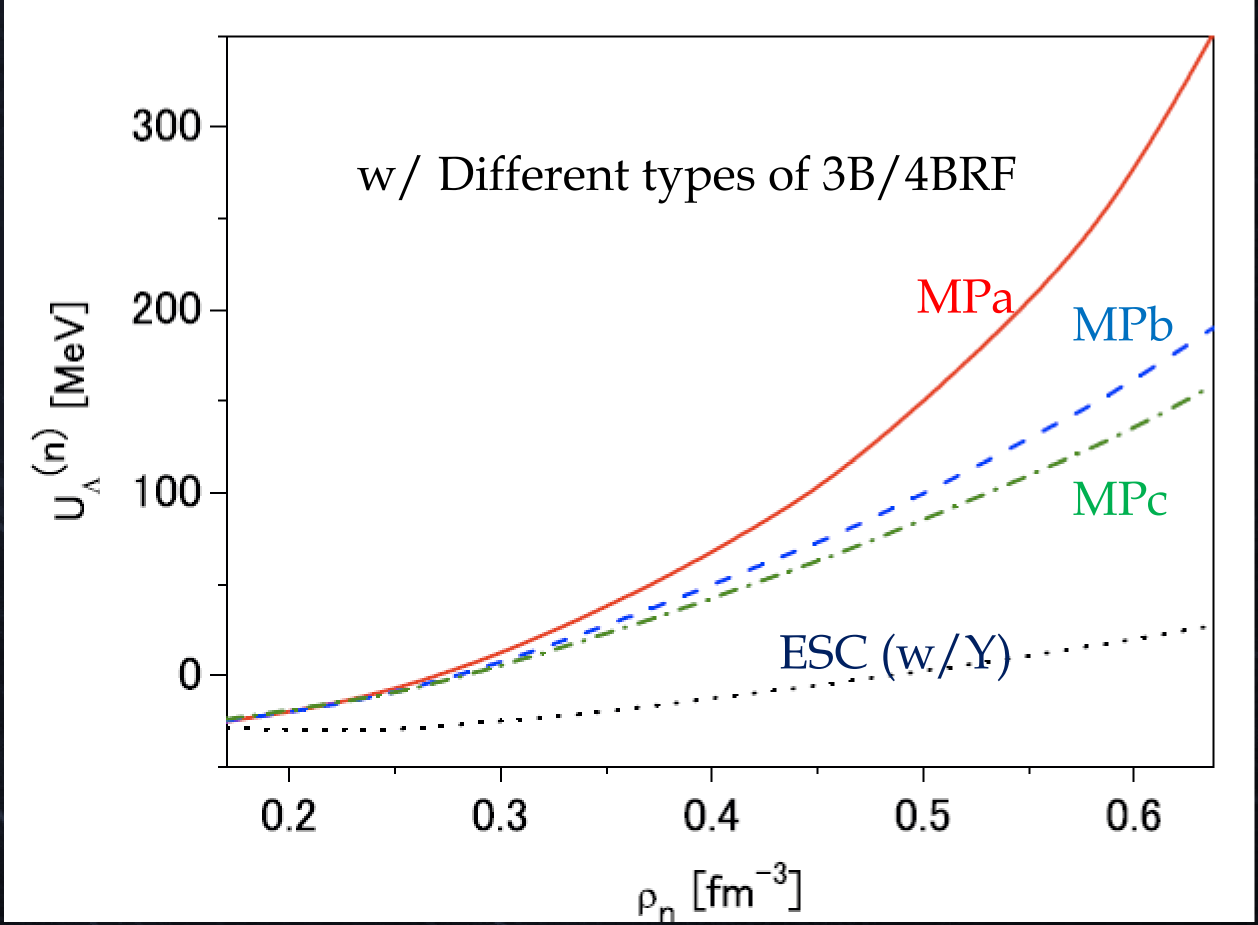
AFDMC by D.Lonardoni et al.

PNM

With Hyperon
too Soft

With 3BRF
recover hardness

NS EOS with hyperon and 3BRF



With 3BRF recover hardness

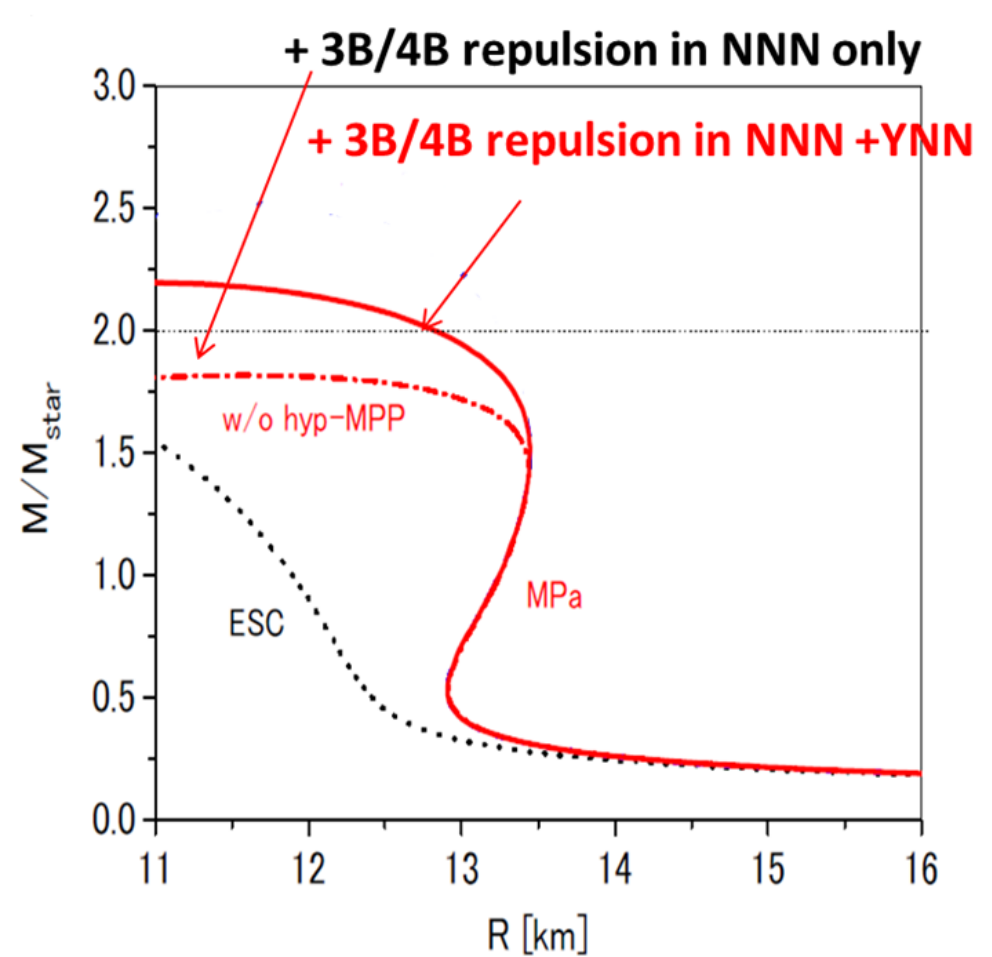
With Hyperon too Soft

Yamamoto et al., Brueckner theory + G-matrix YN

EOS of nuclear matter (with hyperons)

To solve hyperon puzzle

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



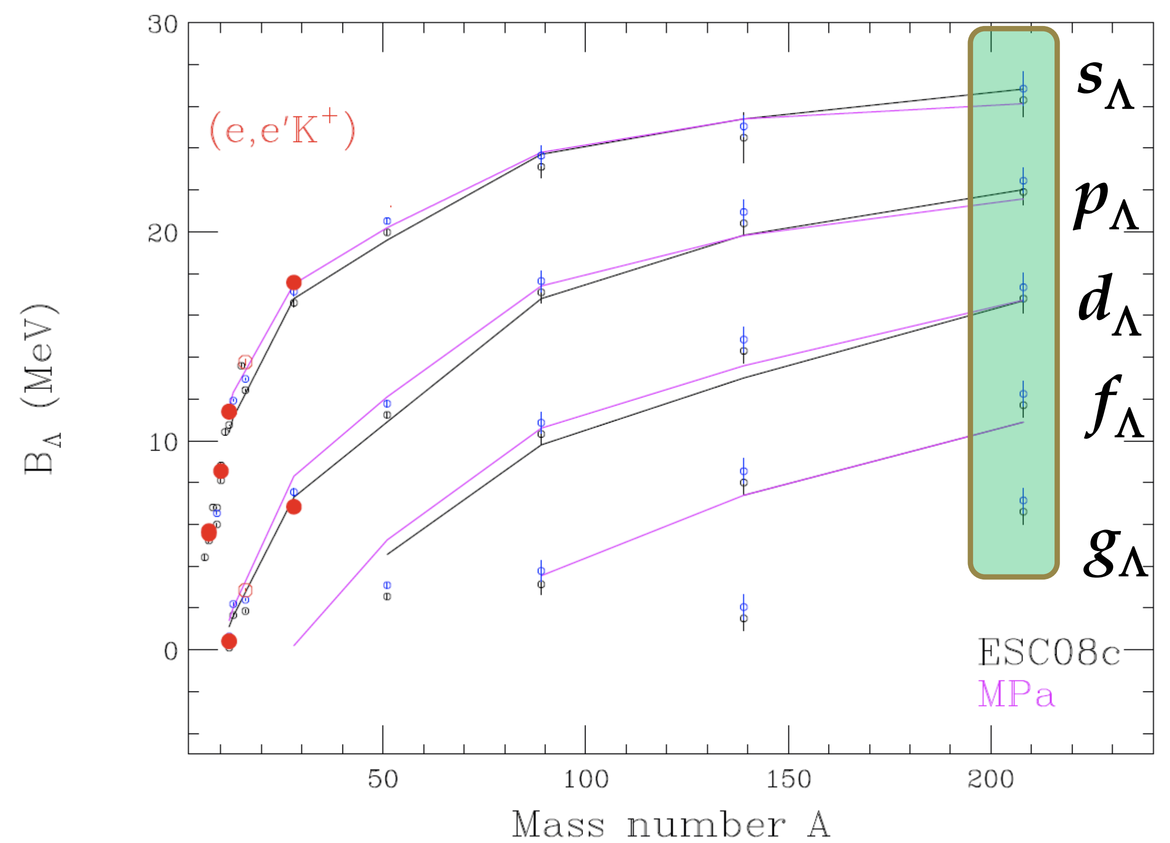
Density dependence with hyperons

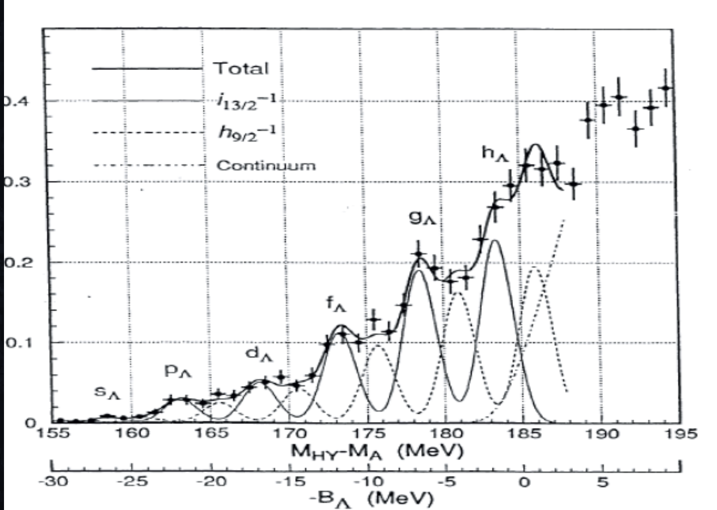
⇩

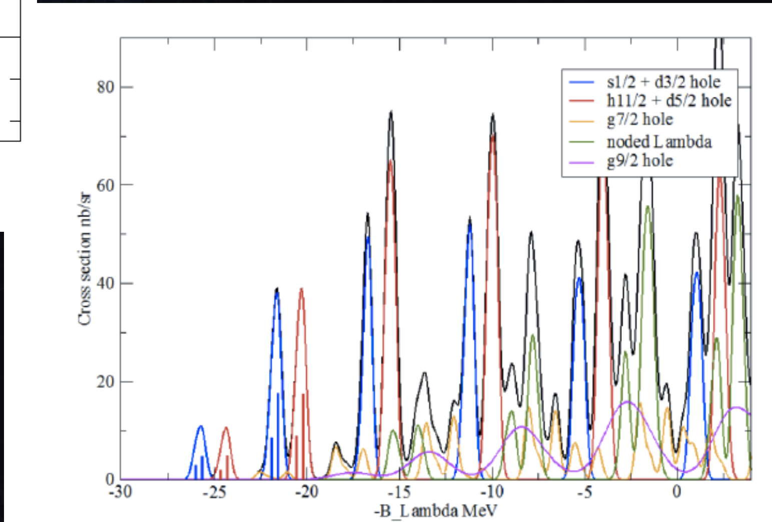
Importance of 3B/4BF

An approach to solve Hyperon Puzzle

Mass dependence of B_Λ





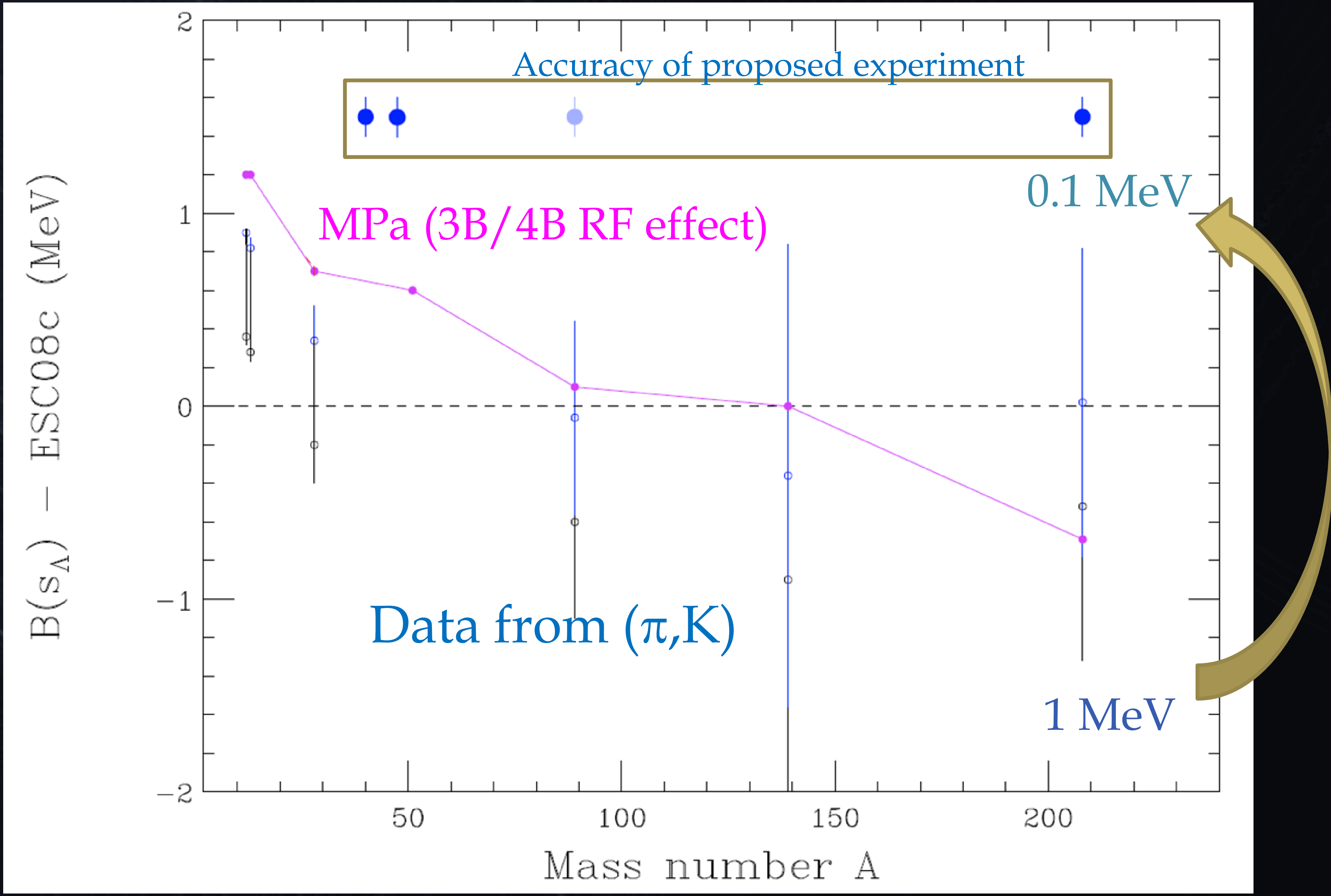


Lines: Calc. by Yamamoto & Rijken

Nijmegen ESC08c : Commonly used realistic YN

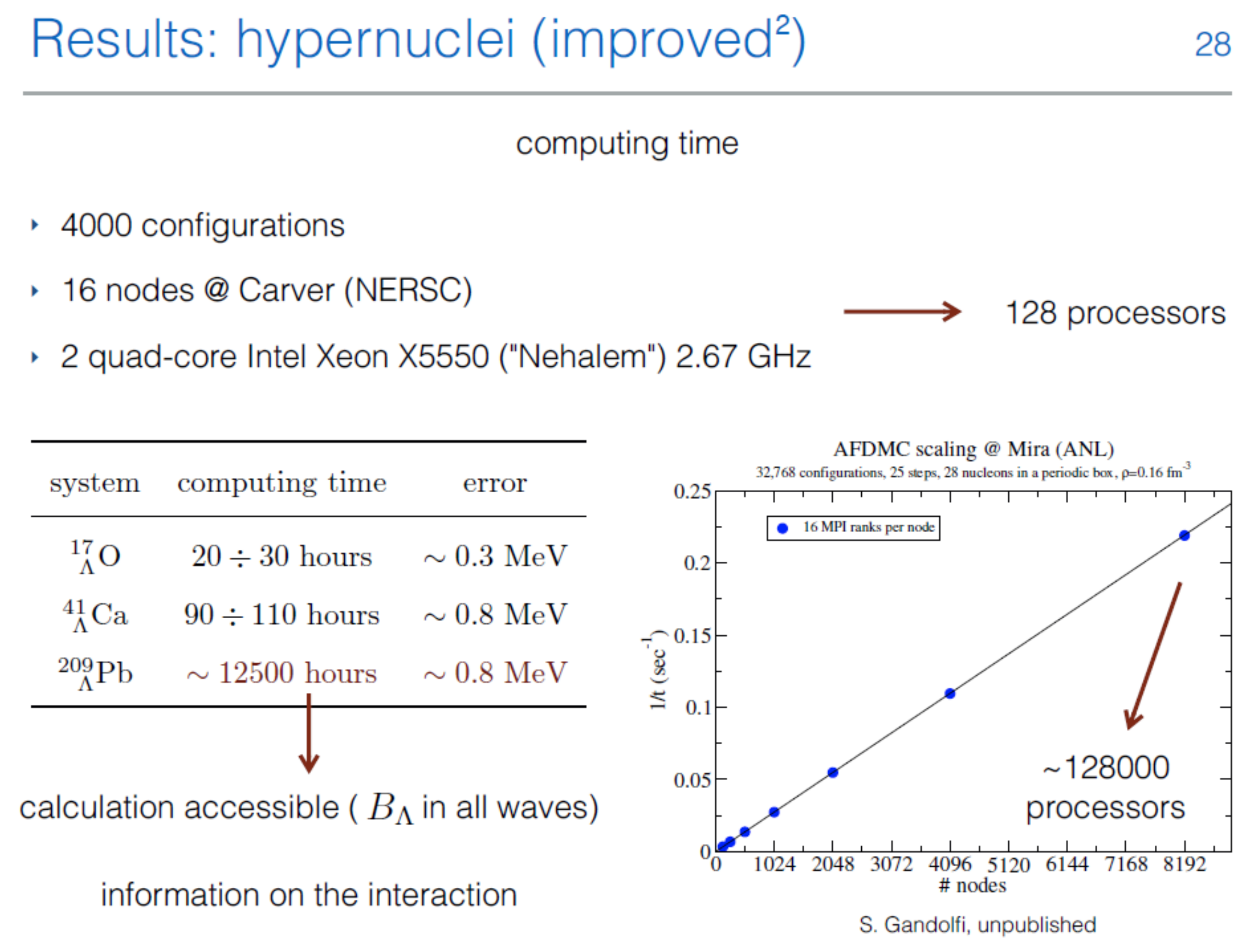
MPa : ESC08c + 3B/4B RF

Mass dependence of B_Λ



Theoretical cost for more sophisticated calculation

D.Lonardoni @ JLab Hypernuclear WS, May (2014)



Results: hypernuclei (improved^2)

computing time

- 4000 configurations
- 16 nodes @ Carver (NERSC)
- 2 quad-core Intel Xeon X5550 ("Nehalem") 2.67 GHz

→ 128 processors

system	computing time	error
${}^{17}_{\Lambda}\mathrm{O}$	$20 \div 30$ hours	~ 0.3 MeV
${}^{41}_{\Lambda}\mathrm{Ca}$	$90 \div 110$ hours	~ 0.8 MeV
${}^{209}_{\Lambda}\mathrm{Pb}$	~ 12500 hours	~ 0.8 MeV

calculation accessible (B_Λ in all waves)

information on the interaction

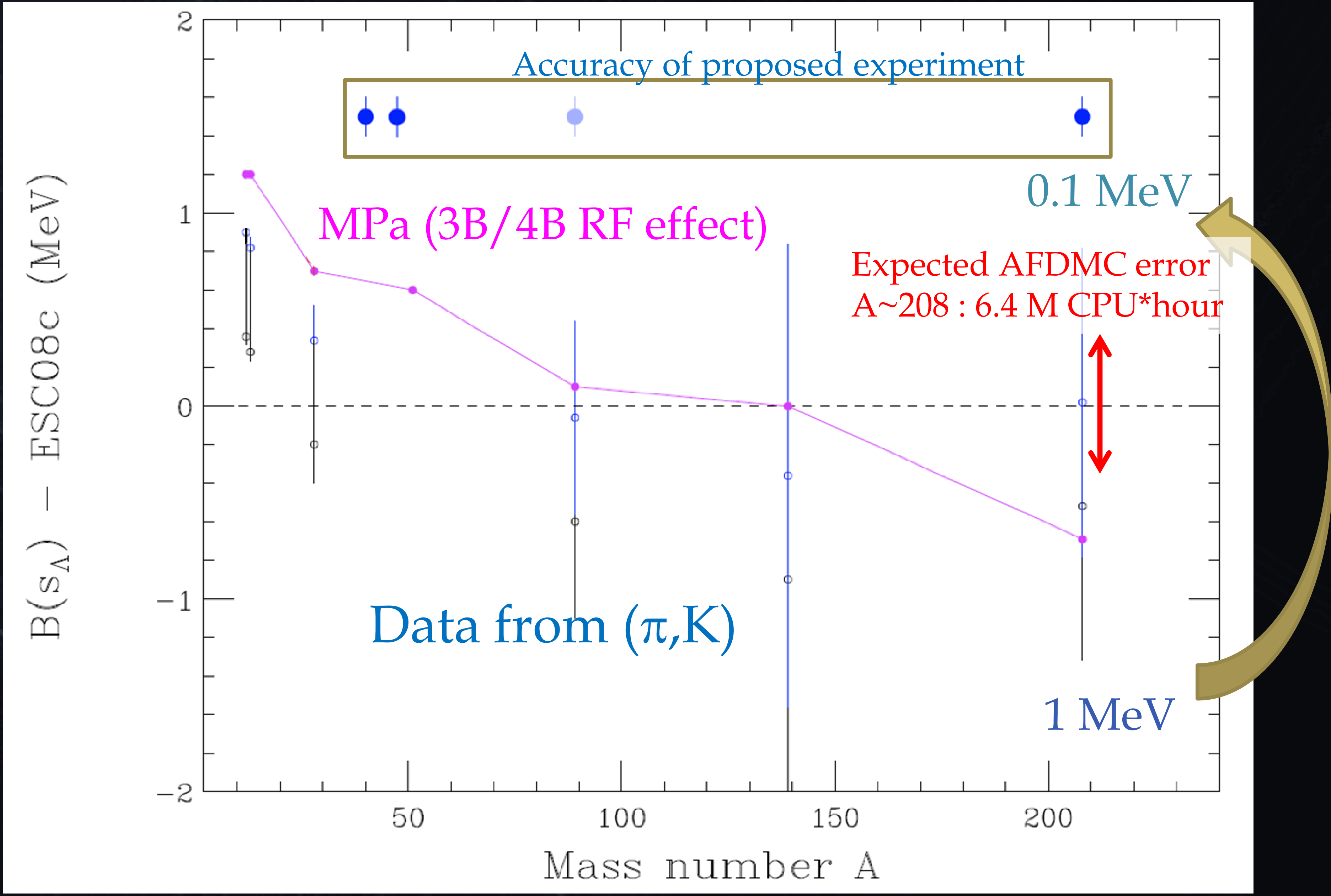
~128000 processors

S. Gandolfi, unpublished

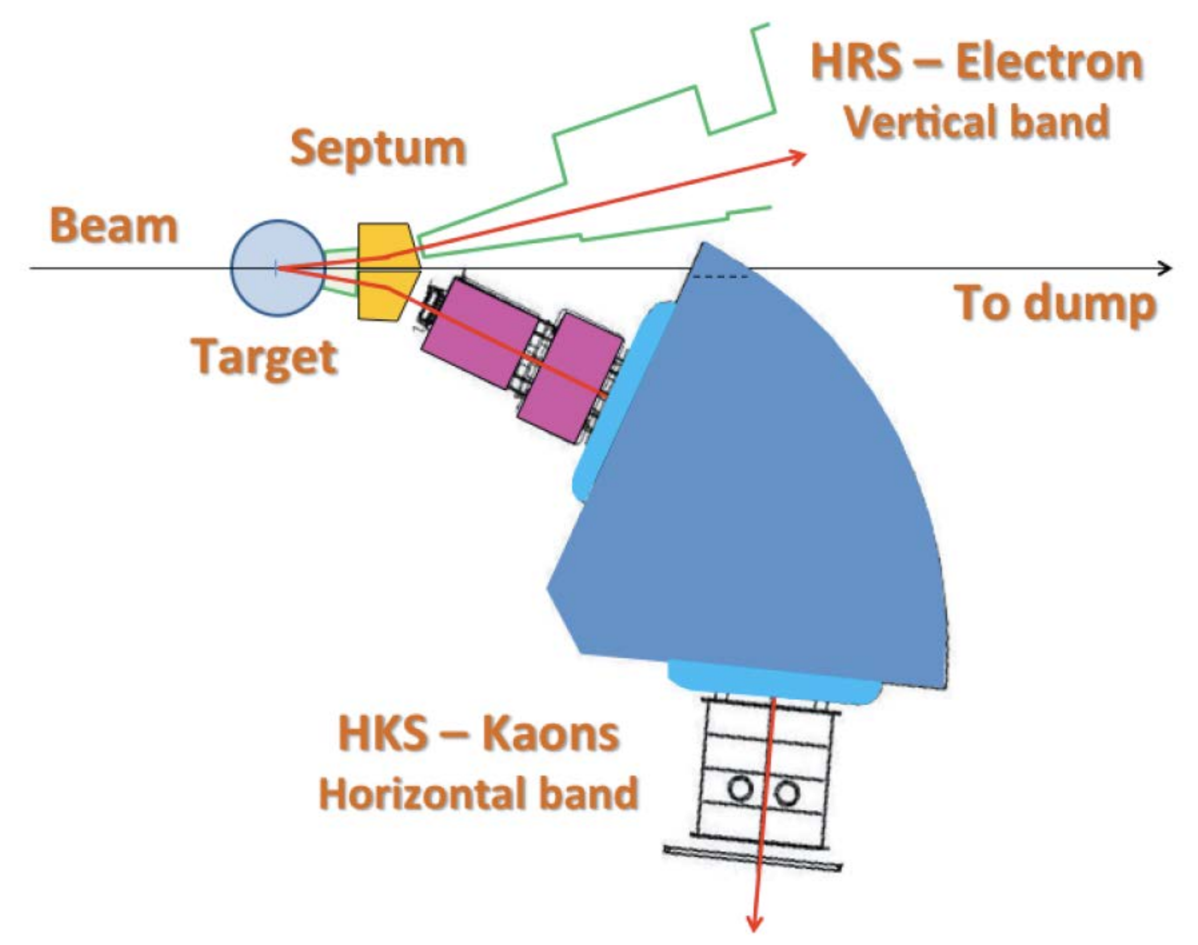
Calc. w/ 0.4 MeV error for A=208 requires 12500 x (0.8/0.4)^2 x 128 (CPU * hours)

= 6.4 M CPU hours = 130 days * 2048 CPU

Mass dependence of B_Λ



Proposed Setup



K(HKS) x HRS (e′)

Only **JLab** : Beam + Spectrometers for (e,e′K$^+$)

Advantage of the proposed setup over previous experiments.

Higher Pe' with HRS

Established in Hall-A

Excellent momentum resolution (2×10^{-4})

Orbit is long but no problem for e'

Allow to use higher (4.5 GeV) incoming electron beam.

Background from Bremsstrahlung will be boosted to forward.

Introduction of Septum magnet

Easier and more reliable calibration of HKS-HRS systems separately.

Good Signal to Noise ratio

Electron BG will be 1/40 of Hall-C exps.

HKS

Established in Hall-C

Excellent momentum resolution (2×10^{-4}) with short orbit to avoid decay loss of kaons with lower momentum (1.2 GeV/c).

Large solid angle as well as momentum acceptance.

High resolution

Large Yield (best virtual photon energy & HKS acceptance)

Keep resolution and 5.4 times larger yield than Hall-A exp.

Req. beamtime in proposal

Target	Purpose	Req. BT (hours)
Engineering	Beam, target, spectrometers, detectors and DAQ	1 calendar month
Calibrations Various targets	Optics, kinematics for energy resolution and absolute energy scale	167
Physics I : Few-body	Direct ΛN int. study (CSB,FSI)	
^{4}He ($^4_\Lambda$H)	CSB for A=4 system	266
H_2 (Λ, Σ^0)	Elementary, calibration	52
D_2 and ^{3}He ($^2_\Lambda$n, $^3_\Lambda$H)	ΛN int. study through FSI	210
^{3}T ($^3_\Lambda$n)	Exotic bound state search	130
Subtotal		658
Physics II : Mid-Heavy	3B force study – EoS w/ Y	
^{40}Ca ($^{40}_\Lambda$K)	High precision exp. Reliable Calc.	124
^{48}Ca ($^{48}_\Lambda$K)	Iso-spin dep.	148
^{208}Pb ($^{208}_\Lambda$Tl)	Heaviest HY	642
Subtotal		914
Total		1739

Possible 1 Year Plan

Installation	**1-June**	**15-Nov**	**5.5 months (assuming summer shutdown from 1-June to 31-Aug)**
Eng. Runs	16-Nov	14-Dec	4 weeks
Data Check	No Beam	Analysis of	Eng. runs
Physics Runs	19-Jan	1-May	102 days = 2448 hour (51 PAC days = *1224 hours*)
De-commission	2-May	31-May	4 weeks

Prioritize targets to fit physics runs in 1224 hours.

Avoid complicated targets.
To have realizable A dependence, avoid similar A targets.
Optimize beam current and target thickness.

51 days (1224h) option for high priority targets

Target	Purpose	High Priority (hours)
Engineering	Beam, target, spectrometers, detectors DAQ	1 calendar month
Calibrations Various targets	Optics, kinematics, absolute energy scale	**167**
Physics I : Few-body	**Direct ΛN int. study (CSB,FSI)**	
^{4}He ($^{4}_{\Lambda}$H)	CSB for A=4 system	**177**
H_2 (Λ, Σ^0)	Elementary, calibration	35
D_2 and ^{3}He ($^{2}_{\Lambda}$n, $^{3}_{\Lambda}$H)	ΛN int. study through FSI	140
~~^{3}T ($^{3}_{\Lambda}$n)~~	~~Exotic bound state search~~	
Subtotal		352
Physics II : Mid-Heavy	**3B force study – EoS w/ Y**	
^{40}Ca ($^{40}_{\Lambda}$K)	High prec. exp. Reliable Calc.	**103**
~~^{48}Ca ($^{48}_{\Lambda}$K)~~	~~Iso-spin dep.~~	
^{89}Y ($^{89}_{\Lambda}$Sr)	Heavy HY	**124**
^{208}Pb ($^{208}_{\Lambda}$Tl)	Heaviest HY	**478**
Subtotal		705
Total	Fit in 51 PAC days (1224h)	**1224**

Summary

- Developed large spectrometers and new techniques in the last decade **at JLab**

  (e,e′K^+) hypernuclear spectroscopy **is *now established*.**
- Excellent energy resolution and absolute MM calibration
- Measurement of ${}^{7}_{\Lambda}\mathrm{He}_{gs}$ at JLab triggered CSB discussion.

  ${}^{4}_{\Lambda}\mathrm{H}\ 1^{+}$ measurement : Clarify **CSB of ΛN interaction**
- 3B repulsive force, key to solve **hyperon puzzle**.

  Precise measurement of B_{Λ} for ${}^{40}_{\Lambda}\mathrm{K}$, ${}^{89}_{\Lambda}\mathrm{Sr}$ and ${}^{208}_{\Lambda}\mathrm{Tl}$

JLab is the only place with excellent beam and spectrometers to perform the (e,e′K^+) hypernuclear spectroscopy

Responses to PAC43 reviewers

Satoshi N Nakamura
Tohoku Univ.
On be half of JLab hypernuclear collaboration
(PR12-15-008)
7 July 2015

Questions from Dr. Renee Fatemi

1) The proposal states that the experiment plans to use the existing HKS spectrometer to detect Kaons. Please send a 1-2 page summary of the main components, and their specifications, that comprise this spectrometer. It is fine to point to an existing publications that describes this detector package as long as there are no significant changes planned.

Toshi Gogami's thesis (2014, Tohoku U.) describes it in detail (Chap2 and Chap3).
http://ir.library.tohoku.ac.jp/re/handle/10097/57651

It is Quad-Quad-Dipole normal conducting spectrometer to achieve $\frac{\Delta P}{P} = 2 \times 10^{-4}$.

We are preparing a NIM paper for HKS&HES spectrometers to be submitted soon.

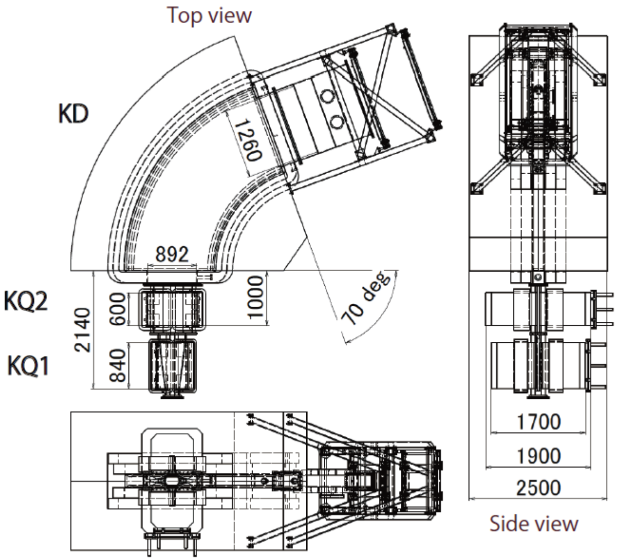


Figure 2.13: A schematic drawing of the HKS spectrometer. It consists of two quadrupole and one dipole magnets (KQ1, KQ2, KD). The unit is mm.

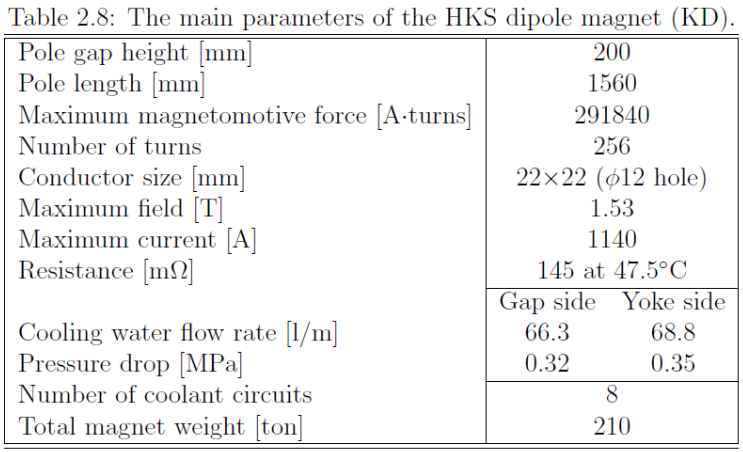
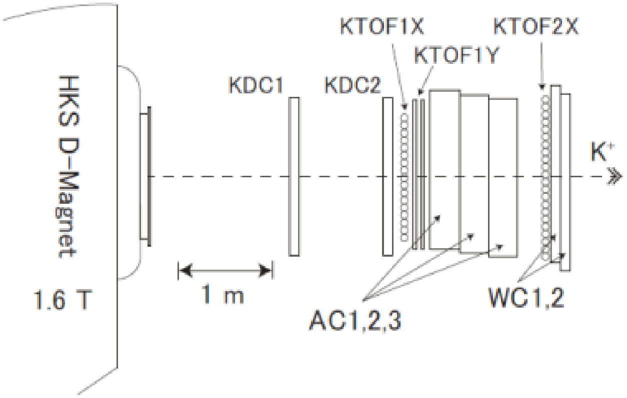


Table 2.8: The main parameters of the HKS dipole magnet (KD).

Pole gap height [mm]	200	
Pole length [mm]	1560	
Maximum magnetomotive force [A·turns]	291840	
Number of turns	256	
Conductor size [mm]	22×22 (ϕ12 hole)	
Maximum field [T]	1.53	
Maximum current [A]	1140	
Resistance [mΩ]	145 at 47.5°C	
	Gap side	Yoke side
Cooling water flow rate [l/m]	66.3	68.8
Pressure drop [MPa]	0.32	0.35
Number of coolant circuits	8	
Total magnet weight [ton]	210	

2) On page 14, in section 3.1, the proposal states "Its excellent detector system further cleanly identifies Kaons". Please send a 1-2 page summary describing how each of the components above are used to identify Kaons. Please show representative plots of Kaon distributions before and after cuts and discuss the remaining background distributions you see/expect. This discussion can be based on previous data and/or new simulations.



Gogami's thesis describes each component of HKS detector package. Drift Chambers for particle tracking to reconstruct momentum and TOF counters (plastic scintillator) for time of flight measurement and for DAQ trigger. Aerogel Cherenkov for pion veto and Water Cherenkov for proton rejection to select kaons.

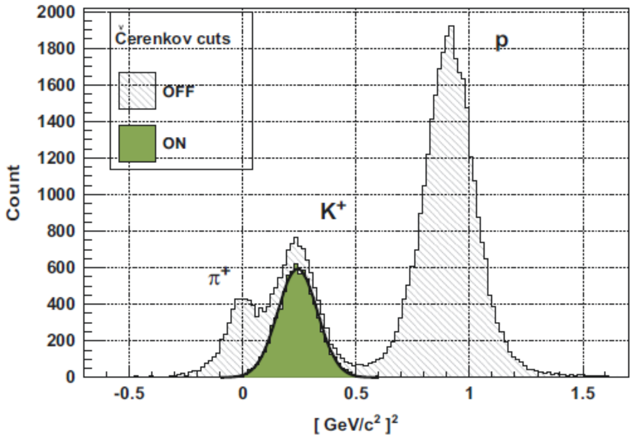


Fig. 25. Mass squared distribution before and after the cuts on the Čherenkov detectors. K^+ events are clearly selected after the cuts. The width of single gaussian fit to the kaon peak is $\sigma \sim$ (0.29 [GeV/c^2]) ^{2}.

NIM A729 (2013) 816.

T.Gogami et al. Nucl. Inst. Meth. A 729 (2013) 816. describes bucking coil of HKS Cherenkov counters' PMT. It shows almost perfect kaon selection result for real data (left figure)
(K eff. > 0.92; $\pi < 4.7 \times 10^{-4}$; $p < 1.9\times10^{-4}$).
If necessary, we can add RICH used for 2.5GeV/c in E94-107 to have stronger kaon selection.
From our experience in previous beams, expected background is mainly from accidental coincidence between real kaon and electron.

3) Where is the HKS spectrometer currently located? How much time and effort will it take to relocate it to Hall-A and reconstruct the spectrometer?

HKS is now disassembled and stored safely in storage building of JLab.

In 2009, installation of HKS, HES and chicane beamline including SPL magnet took 6 months of installation time at Hall C (original plan 4.5 months including decommission of SANE setup. But many unexpected troubles made the installation period longer.)
For proposed experiment, we will not change beamline and will not use HES.
Therefore 5.5 months of installation time is considered to be reasonable.
Here are a possible plan to fit 1224 hours (plus 100% contingency) of beamtime for high priority targets and installation/decomission in one year.

Installation	**1-June**	**15-Nov**	**5.5 months (assuming summer shutdown from 1-June to 31-Aug)**
Eng. Runs	16-Nov	14-Dec	4 weeks
Data Check	No Beam	Analysis of	Eng. runs
Physics Runs	19-Jan	1-May	102 days = 2448 hour (51 PAC days = 1224 hours)
De-commission	2-May	**31-May**	4 weeks

4) Please answer question #8 in the TAC document concerning targets. Please include a discussion about which of these targets already exist, their past performance and possible modifications that will be necessary. Please discuss the targets that do not currently exist and the necessary person-hours needed to design and construct these targets.

Replies to TAC review are given in different file. Here is a quick summary of target situation.

Target	Current Availability	comments
Cryo gas/liquid (H_2,D_2,^{3}He,^{4}He)	△ 1 man*year	Without T_2 target, straightforward based on existing target system.
Tritium Target	× Safety review 2 man*year (1 PD/staff + JLab expert)	New design referring Marathon exp's target. Without T_2 target, design of other cryo-targets can be much easier.
All solid targets for calib., ^{89}Y	○	Exist or can purchase easily
^{40}Ca	△ (1 special person * 1 year)	We have technique to make foil. 5g of ^{40}Ca costs $10K.
^{48}Ca	× (1 special person * 1 year)	5g of ^{48}Ca costs $1M. New budget is necessary to buy.
^{208}Pb	△ 1 man*year (1 PD/staff + JLab expert)	Conceptual design exists. Detailed mechanical design is necessary but D.Meekins (JLab target Gr.) thinks there is no serious problem.

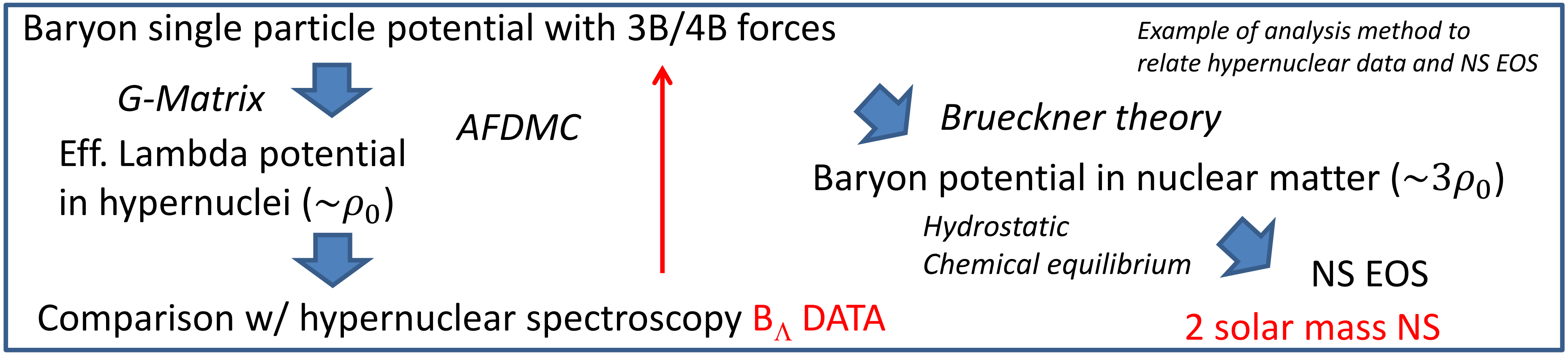
Questions from Dr. David Jarvis Dean

1) Let's suppose that one is able to produce the ^{208}Pb hyper nucleus. Why is it important in relation to a neutron star, where the relevant density is 3x larger than in a nucleus? The mass of a Lambda is just a bit more than a neutron. I don't see why there would be a significant change in local density within the nucleus.

Since current realistic baryon interactions such as Nijmegen models cannot explain the existence of two solar mass neutron stars, we already knew that the current interactions miss something important. One of candidates is 3B/4B repulsive forces which are known to be necessary in normal nucleon sector.

Densities of hypernuclei ($\sim\rho_0$)and neutron(hyperon) star ($\sim 3\rho_0$) are different as Dr. Dean pointed out but they should be understood on the same framework.

Hypernuclear data constraint baryon single particle potential which is used to calculate EOS of neutron stars. Maximum mass of 2 sol. Mass neutron star is another experimental constraint for the interaction. Hypernuclear data improve the baryon potentials and neutron star can select the right one.



Baryon single particle potential with 3B/4B forces

Example of analysis method to relate hypernuclear data and NS EOS

G-Matrix

Eff. Lambda potential in hypernuclei ($\sim\rho_0$)

AFDMC

Brueckner theory

Baryon potential in nuclear matter ($\sim 3\rho_0$)

Hydrostatic
Chemical equilibrium

NS EOS

Comparison w/ hypernuclear spectroscopy B_Λ DATA

2 solar mass NS

2) What is really needed to constrain an EFT approach to lambda-N interactions is scattering phase shift data. The effective field theory approach has been discussed in some detail at Next to Leading Order (NLO) by Haidenbaur et al (arXiv:1304.5339) and also a bit earlier at Leading Order by Parreno (NPA 754, 127 (2005)). In the Parreno paper, the LEC coefficients are determined with error bars, and clearly there is much room for experimental improvement of the phase shifts. How will your measurements help here?

In NN sector phase-shift analyses of scattering data exist, therefore low energy constants (LEC) can be determined from fit of partial waves.
However, in S=-1 sector, YN scattering data is basically only total cross section information with limited statistics (only 36 points from 1960s) and NO phase-shift analyses exist.
Thus direct scattering data fit is necessary to fix LECs. Data points are not enough so number of free LECs is reduced assuming SU(3)$_f$ symmetry; hypernuclear data are also used to select adequate set of parameters.

Ch EFT with various LECs and cut-off in LS eq. ⇨ Various interactions ⇨ Compare with light hypernuclei B$_\Lambda$ to choose adequate parameters

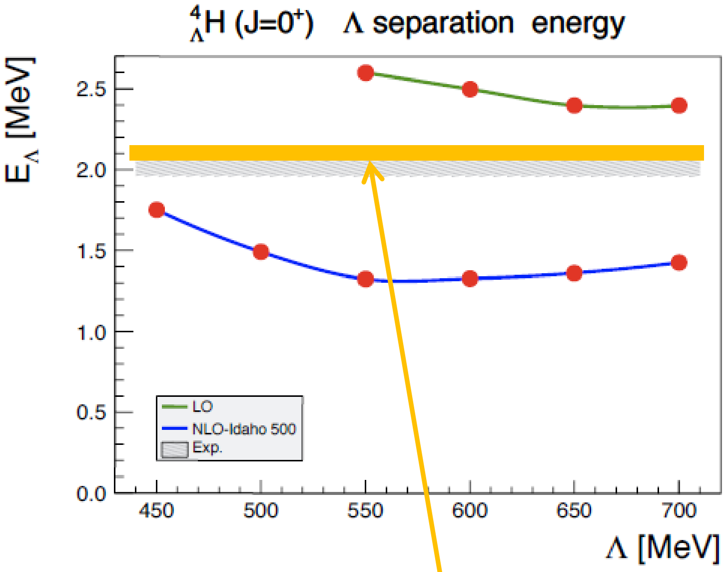
It should be quoted Nogga (Ch EFT expert) wrote:

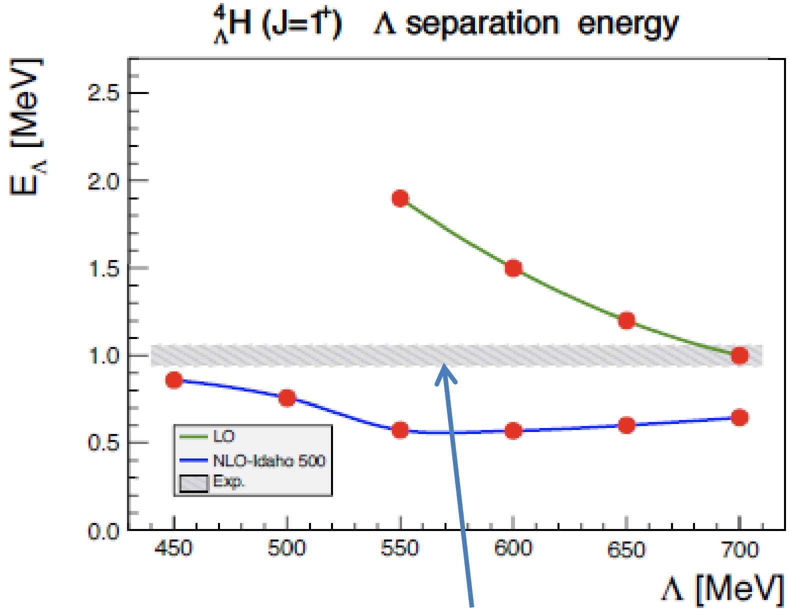
*"…**binding energies are especially sensitive to small contributions to the interactions (like 3NFs)** since strong cancelation of the kinetic and potential energy contributions enhances the effect. **Low energy scattering cross sections are therefore quite insensitive to 3N contributions** showing that the 3NF is only a small part of nuclear forces."*

(A.Nogga, *Light hypernuclei based on chiral and phenomenological interaction* NPA 914 (2013) 140.)

Cutoff of potential in coupled channel LS equation based on Ch EFT vs. $B_\Lambda({}^4_\Lambda\mathrm{H})$.

J. Haidenbauer, JLab Hypernuclear WS, May 2014





Recently re-measured at Mainz (PRL 114.232501, 2015)

$$2.12 \pm 0.02 \pm 0.09\ MeV$$

Proposed to re-measure with **(e,e'K) reaction at JLab**

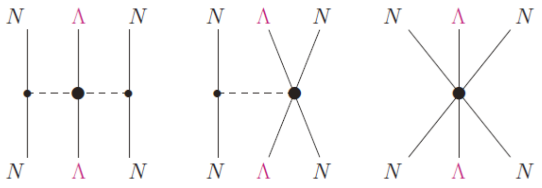
Existing experimental uncertainty may be larger. Since CSB term is not consistently understood for A=4 and A=7 hypernuclei. ⇒ CSB potential is too naïve or A=4 data have problem.

$^4_\Lambda$H data indicate : LO Ch EFT depends much on cut-off parameter (especially 1^+ excited state).

NLO looks underbind $^4_\Lambda$H

Long range 3BFs need to be estimated with reliable experimental inputs

N^{2}LO



2) What is really needed to constrain an EFT approach to lambda-N interactions is scattering phase shift data. The effective field theory approach has been discussed in some detail at Next to Leading Order (NLO) by Haidenbaur et al (arXiv:1304.5339) and also a bit earlier at Leading Order by Parreno (NPA 754, 127 (2005)). In the Parreno paper, the LEC coefficients are determined with error bars, and clearly there is much room for experimental improvement of the phase shifts. How will your measurements help here?

Parreno's calculation (NPA754,127) tries to analyze weak-decays of light hypernuclei with the EFT on the weak ΛN interaction. It uses a shell model with G-matrix effective ΛN strong interaction to obtain necessary wave-function.
The proposed experiment will improve the knowledge on the strong interaction part and thus more reliable wave-function can be obtained. However, no direct improvement is expected on the ΛN weak interaction.
Decay observables (weak decay width, n/p ratio, polarization) are sensitive to the weak ΛN interaction but they are out of scope in the proposed experiment.

3) Can you describe why the JLab experiments would be unique? Would they significantly reduce experimental errors? This needs to be clearly demonstrated for each of the proposed measurements. How will each measurement provide new, or improved, data that can be used to enable a better theoretical understanding?

The (e,e'K) measurement is unique since it can achieve much better mass resolution as well as perform absolute energy calibration. The method requires high quality >1.5 GeV electron beam which is available only at JLab and MAMI-C. High-resolution GeV spectrometers (HKS, HRS) exists only at JLab now.

New setup which combined advantages of previous Hall-A and Hall-C setups will reduce electron background to 1/40 from previous Hall-C experiment.
The new setup will keep resolution and increase the yield by a factor of 5.4 from previous Hall-A experiment. They are realized by combination of Septum + HRS (only exist in Hall-A) + HKS (move from Hall-C) with optimization of kinematics.

Another important feature is the (e,e'K) reaction converts a proton to a Λ while (π,K) and (K, π) convert a neutron to a Λ . Therefore using available targets, (e,e'K) can produce unique hypernuclei which (π,K) and (K, π) cannot create, such as ${}^{4}_{\Lambda}$H which is essential to measure for the CSB of ΛN interaction study.

Responses to
Technical Advisory Reviews

Satoshi N Nakamura
Tohoku Univ.
On be half of JLab hypernuclear collaboration
(PR12-15-008)
7 July 2015

C1. This experiment will be a major installation (>= 6 months) with
the HKS spectrometer in Hall A. If the proposal is approved, design and planning of
the installation should be started well in advance and
a review of the experiment should be scheduled early to address technical issues
and identify the source of (users vs. lab) of various resources.

A1. Yes. We will.

C2. The experiment would benefit from an engineering/commissioning run
separated in time from the production run.

A2. We totally agree. We thank TAC for suggesting the separated engineering/
commission run.

C3. New septa need to be designed. These will be in an asymmetrical setup, so beam steering due to the new septa magnets should be studied. The use of septa with HKS seems to have the advantage to sweep positron background before it could enter the HKS spectrometer. Some running will be done at high current. Radiation from beam halo hitting the septum poles should be considered.

A3. We will perform full simulation after mechanical design of new septa.
From previous experiences in Hall A (SC septa) and C (Splitter), we believe that radiation will not be very high since our targets are relatively thin (~100mg/cm^2).

C4. Use of a tritium target will require considerable planning, engineering and readiness/safety reviews.

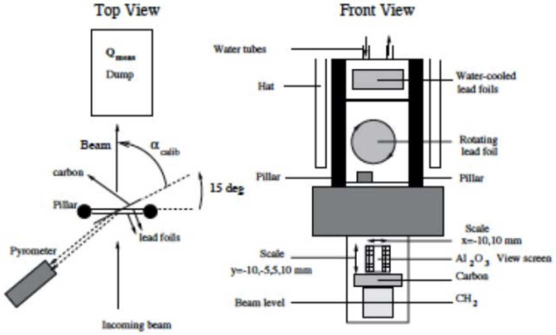
A4. Yes. Tritium target with handing system needs careful design in collaboration with JLab target group and safety reviews.

It should be noted that search of ${}^{3}_{\Lambda}n$ using tritium target is quite interesting subject as we proposed. However, **the priority of light hypernuclear study is given for the CSB study by precise measurement of ${}^{4}_{\Lambda}H$**. If usage of tritium target makes the system too complicated, we will concentrate on normal cryogenic gaseous targets. Without tritium, liquid targets are also possible options.

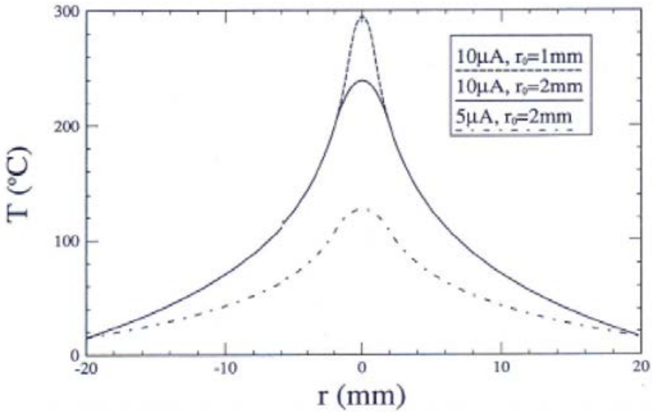
C5. This experiment includes a 27 day run on a lead target with a 25 uA beam. The effects of radiation should be assessed through simulation and the use of additional shielding should be considered to reduce the adverse effect of radiation. It could be checked if parts of the PREX shielding setup could be used for this experiment.

C6. Planning for larger raster sizes, if possible, could help with the lifetime of the lead target. Several lead targets should be planned, similar to the PREX experiment, since the targets tend to melt after a few weeks of beam. A few more details about the lead target would be useful. We assume that it would be similar to the PREX target which is a cryocooled lead diamond sandwich.

A5,6. Our target would be thinner (100mg/cm2) and much simpler without window than PREX one (570 mg/cm^2 Pb + 60mg/cm^2 C) and radiation should be much less. NIKHEF target which is water cooled and without window, would be a reference for our design. With cryogenic cooling with NIKHEF type target, a simple heat diffusion calculation tells that 25μA beam can be handled without problem.
Raster size will be optimized taking the achievable resolution based on full GEANT simulation and finite element heat calculation with the first priority of safe target operation.



The NIKHEF ^{208}Pb target layout

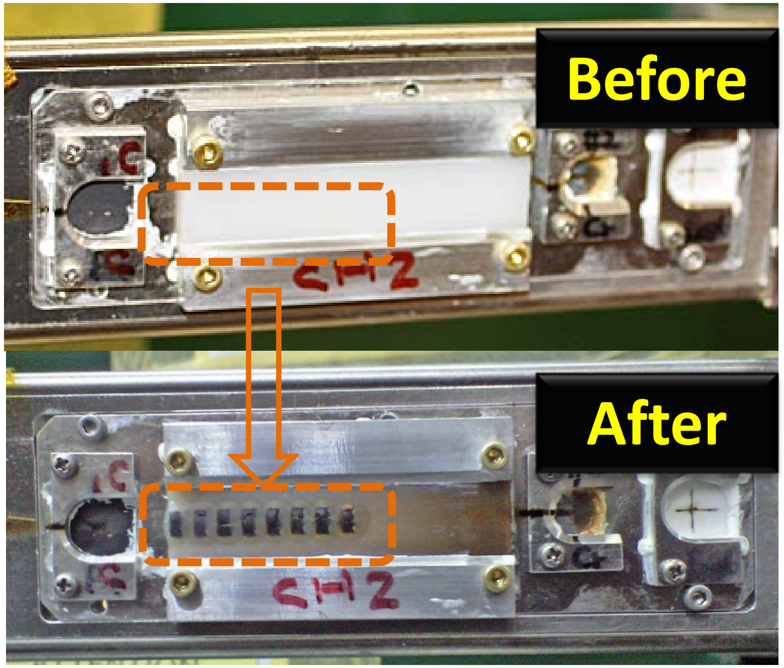


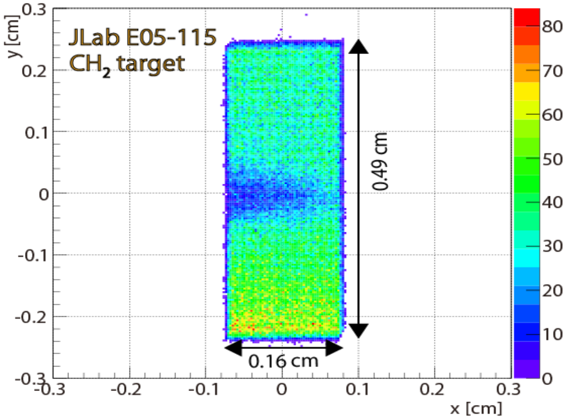
C7. Some more details about the other targets would be useful: The ^{48}Ca target availability and compatibility of the cell geometry with detector acceptances should be checked.
Li targets must be handled with care.
Cooling of the CH_2 target should be checked to make sure it will not melt.
Similar issues could be avoided if a boron-carbide target can be used instead of a boron targets.
It is not clear if natural or isotopically separated lithium and boron targets are planned.

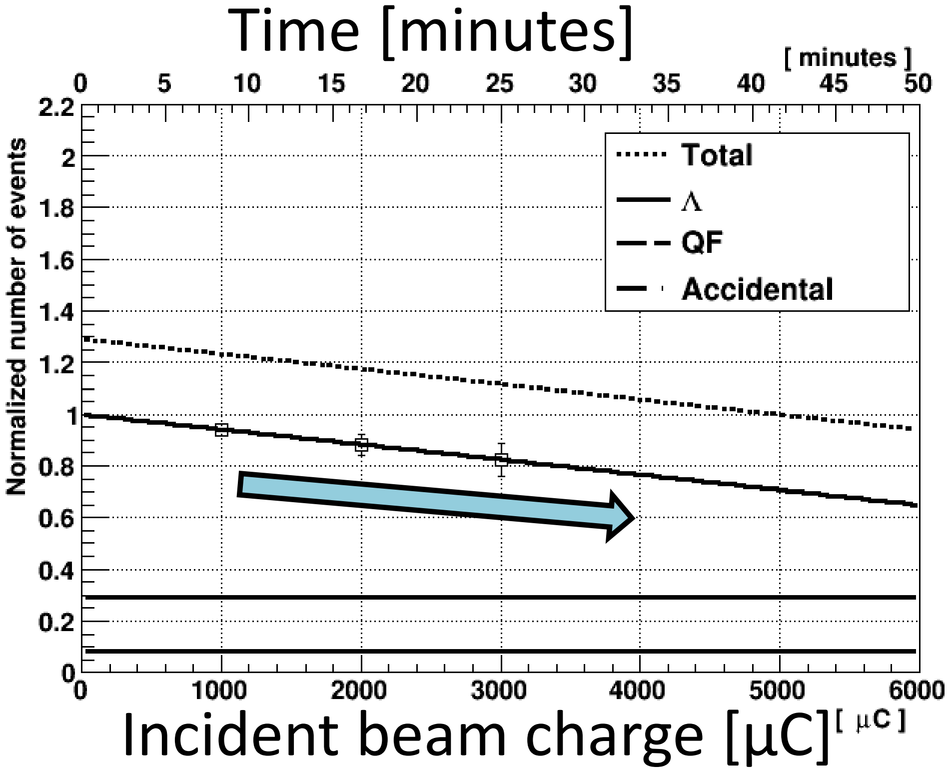
A7. For Ca target, we are considering to use HIVIPP (High energy Vibrational Powder Plating) method to make solid target from enriched powder. We successfully used this method for production of enriched ^{28}Si target in E01-011. For natural Ca, 50mg/cm^2 of target was successfully made. We believe that purchase of ^{40}Ca of enough quantity for 100mg/cm^2 target is affordable within our current budget, but we have no budgetary support to purchase ^{48}Ca for now.

E01-011 has experience for safe target operation of enriched ^{6,7}Li, ^{10,11}B. We monitor crack of the CH_2 target with raster image technique and yield of Lambda tells us real-time escape ratio of hydrogen. We are familiar with safe operation of the CH_2 target from E01-011 and E05-115 experiences.

Hydrogen escape from the polyethylene target (E05-115)







Hydrogen escaped due to the heat but we know when it should be changed.

C8. (Target group comments:) This proposal intends to use a very long list of targets, some of which are decidedly non-standard and have significant EHS&Q implications:
^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{9}Be, Li, B, ^{12}C, CH_2, ^{40}Ca, ^{48}Ca, Ta and ^{208}Pb.
While it is not implicitly stated, the first five on the list are probably cryogenically cooled gas targets, modeled after those for the upcoming Marathon experiments in Hall A.
Note that a ^{4}He cell is not currently planned for Marathon. Furthermore, the proposal indicates a new 60-90 cm diameter vacuum chamber for the target (Sec. 3.3) with a sieve slit device mounted internally. It also seems to imply a common vacuum between the new chamber and the two Hall A spectrometers. Considering the additional radioactive hazards associated with tritium, this design should be reviewed in considerable detail.

A8. For cryogenically cooled targets, we will draw Marathon experiment's experience in collaboration with the target group. However, discussion with experts and JLab management, use of tritium target makes cryo-target preparation too complicated. Physics of $^{3}_{\Lambda}$n is quite Interesting as we proposed, but our primary goal of light hypernuclear study is CSB and thus priority of tritium target is set lower than others.
Similarly ^{48}Ca target is quite interesting to see isospin dependence of the ΛN interaction, but our priority is set to understand 3B/4B repulsive force from A dependence. In addition, ^{48}Ca is really expensive (5g ~ $1M), so priority is lower than other medium- heavy targets.
For the Pb target, NIKIEF target will be used as a reference. It should be mentioned that use of ^{89}Y target whose handling is very easy is possible option as a heavier target though ^{208}Pb is better to see A dependence in wide range.
We will ask future TAC to review design of targets including vacuum chamber when they are ready.

C9. This experiment uses custom electronics which should be tested in advance to insure that it well integrated in the Hall A DAQ.

A9. In E01-011, we have experience to integrate our trigger modules in Hall-C DAQ. We will try to integrate them to Hall-A DAQ well before the beamtime.

C10. The beam energy was chosen to be 2 pass of beam so it would be compatible with Hall D running. Equipment to monitor the energy spread SLI and 1C12 OTR should be available and operational for the experiment. Energy feedback should be operational too. It might take a bit of time to achieve the $5\text{x}10^{-5}$ energy spread required after the 12 GeV upgrade when Hall D is running at 12 GeV so this should be demonstrated by accelerator before experiment is scheduled. Also, the 250 MHz repetition rate versus 499 MHz repetition will increase the accidental rate compared to 6 GeV running. It is not clear if this was taken into account when evaluating the signal to noise ratio.

A10. We need JLab expert's help to make SLI and OTR operational. Our estimation of background rate was carried out based on 499 MHz repetition. For 250 MHz repetition, accidental rate will be doubled ; it will not be four times higher since average K production rate in one bunch is less than 1.

C11. Obtaining good missing mass resolution with extended targets relies on the ability of the HRS with a septum magnet to determine the z position of the interaction. The Z resolution was simulated with GEANT. While the septum magnet for this experiment will be new, previous experience using other septa with HRS spectrometers could help to validate this simulation.

A11. When we fixed mechanical design of septa, full simulation and previous septa data will be compared to check validity of the simulation.

C12. Significant accelerator setup time is likely to be needed for the non-standard calibration energies. (1.2 and 3.0 GeV)

A12. We will communicate accelerator group well before the beam time.

C13. Power supplies for the two septum magnets and the 3 HKS magnets will need to be identified.

A13. Tohoku group owns HKS-D (1250A) and HES-D (1100A) power supplies.
For septa and one of HKS-Quads need power supplies from JLab.

Backup slides

Accurate measurement of B_Λ

L.Tang, C.Chen, T.Gogami *et al.*
Phys. Rev. C **90** (2014) 034320.

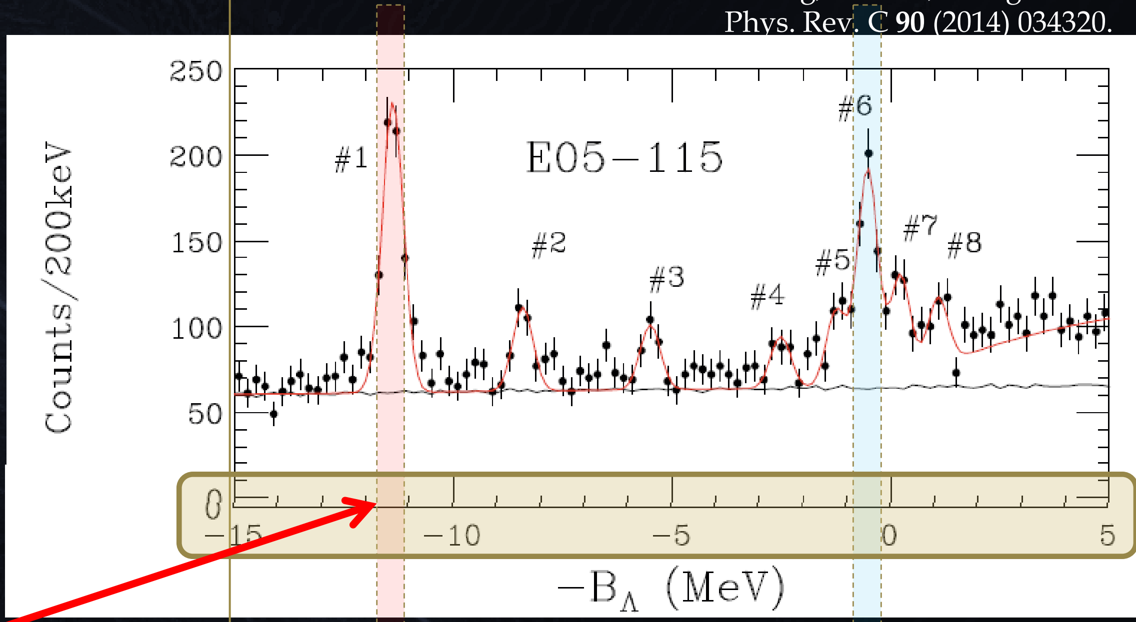
- Energy resolution

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

  0.5 MeV (FWHM)

- Absolute energy calibration

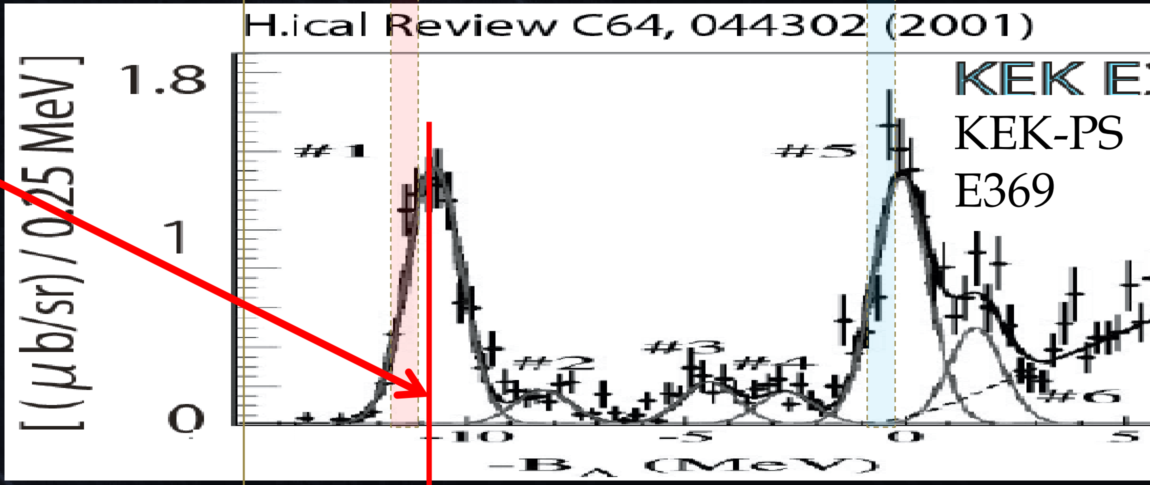
Calibrated by $p(e,e'K)\Lambda, \Sigma^0$



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

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

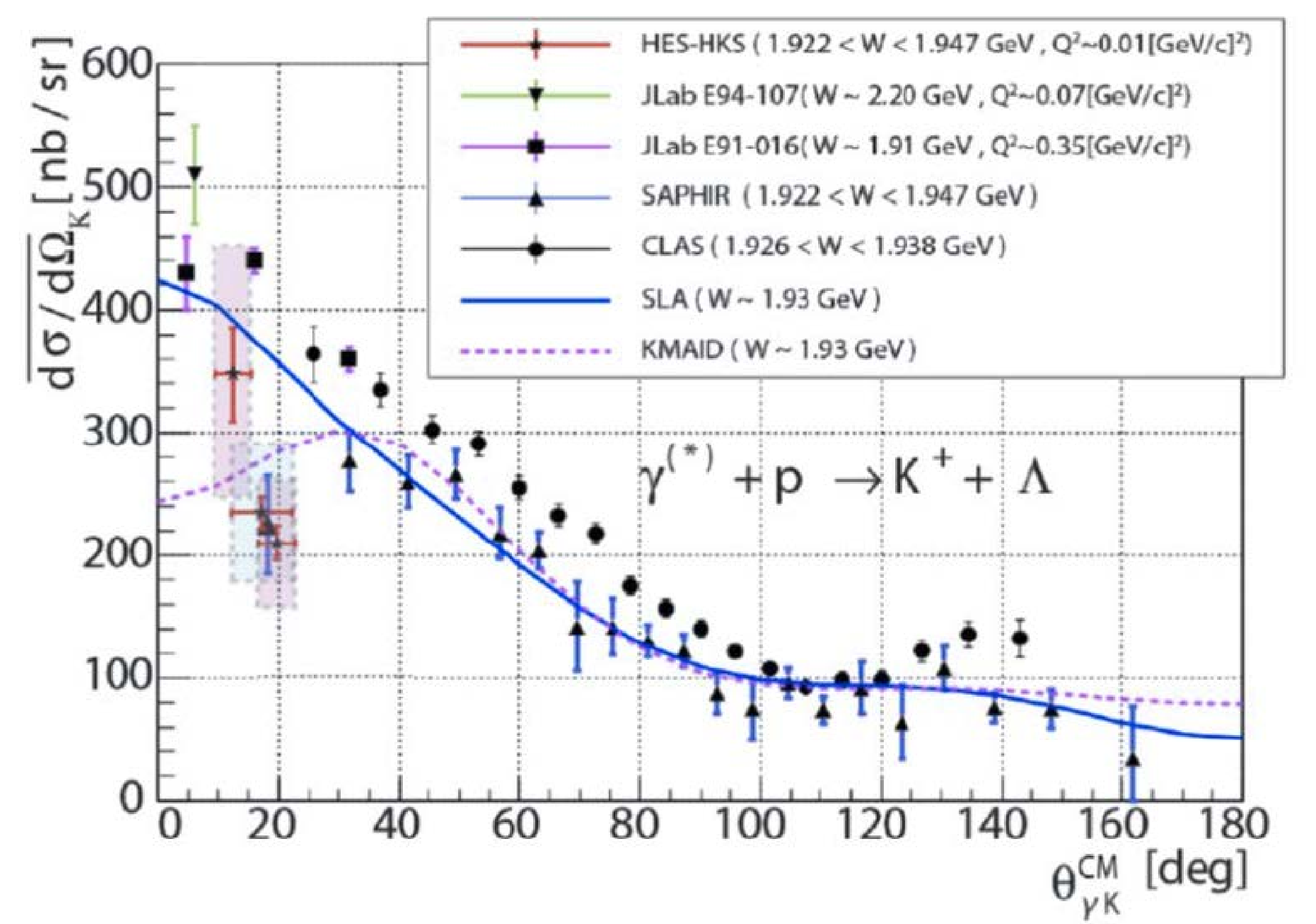
1.45 MeV (FWHM)



KEK-PS
E369

10.76 ± 0.19 ± (?) MeV

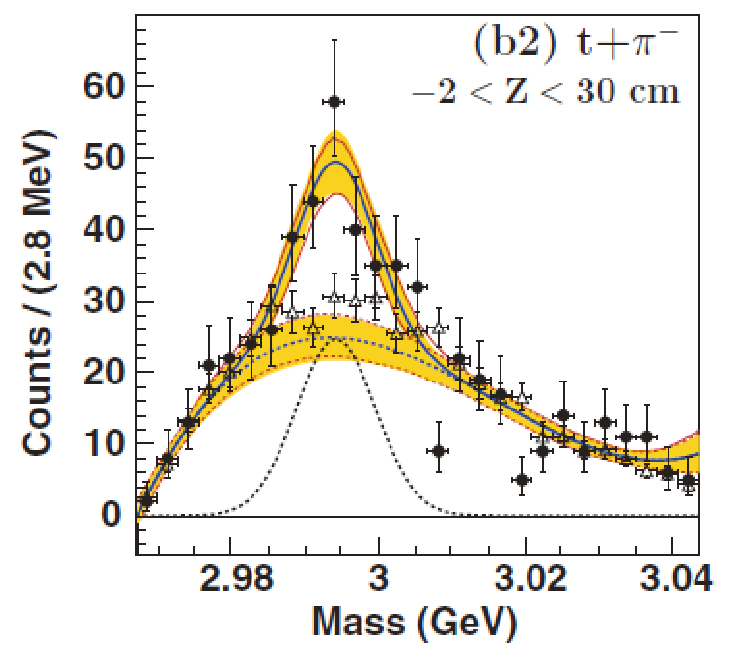
Elementary



P(e,e′K+)Λ, Σ^0 : Absolute Energy Calibration

Forward data is important for analysis of HY data.

Charge-zero hypernucleus



C.Rappold et al., PRC 88 041001(R) (2013)

Indication of $^{3}_{\Lambda}$n by HypHI at GSI.

So far established the ΛN potential models with few-body calculations predict **no bound states**.

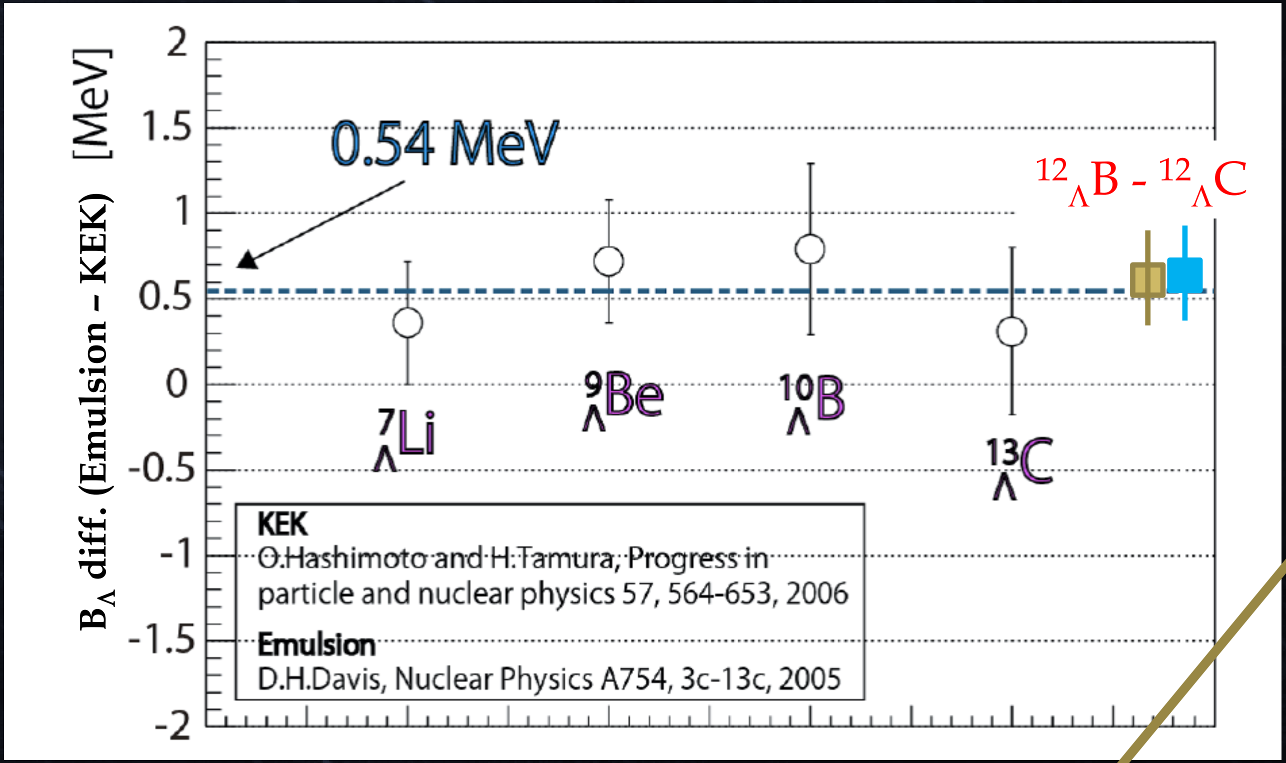
Not yet established.

$$^{3}T(\mathrm{e},\mathrm{e}'\mathrm{K}^{+})^{3}_{\Lambda}n$$

Direct and only method which is sensitive to resonant states as well as bound states.

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

$^{12}{}_{\Lambda}B$ - $^{12}{}_{\Lambda}C$: 0.57 ± 0.19 MeV (emulsion)
0.62 ± 0.19 MeV (E05-115 – emulsion)

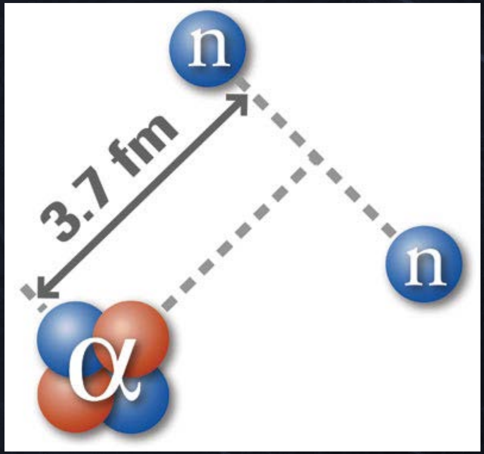


T. Gogami, Doctor thesis, (2014) Tohoku U.

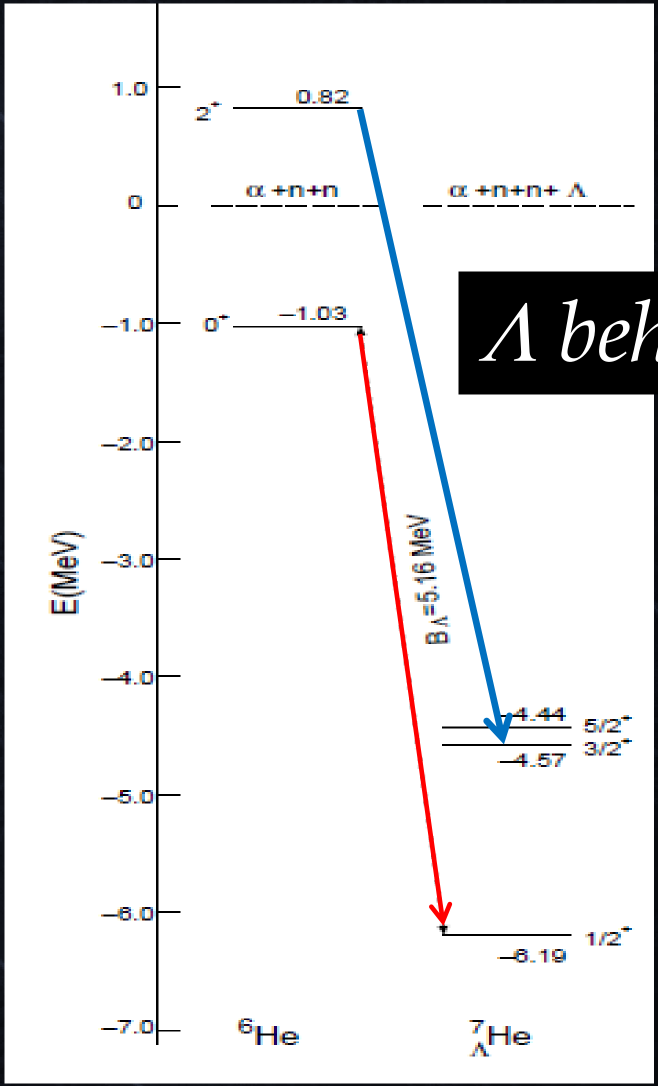
Large CSB
or
CSB ~ 0 with

$^{12}{}_{\Lambda}C$ is very special or B_{Λ} ($^{12}{}_{\Lambda}C_{gs}$) is shifted by ~0.5 MeV.

$^{7}_{\Lambda}$He = ^{6}He + Λ



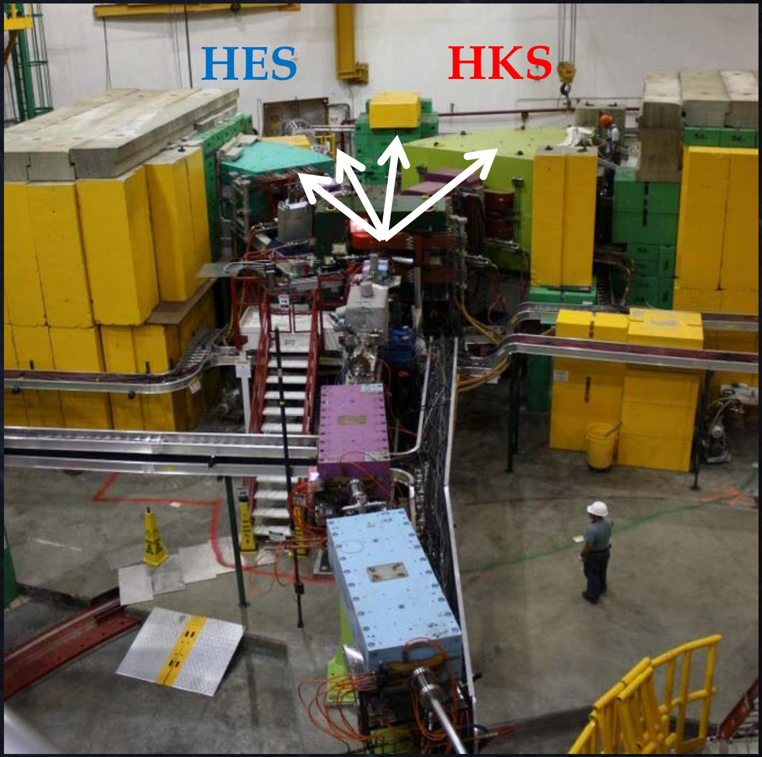
^{6}He : 2n halo



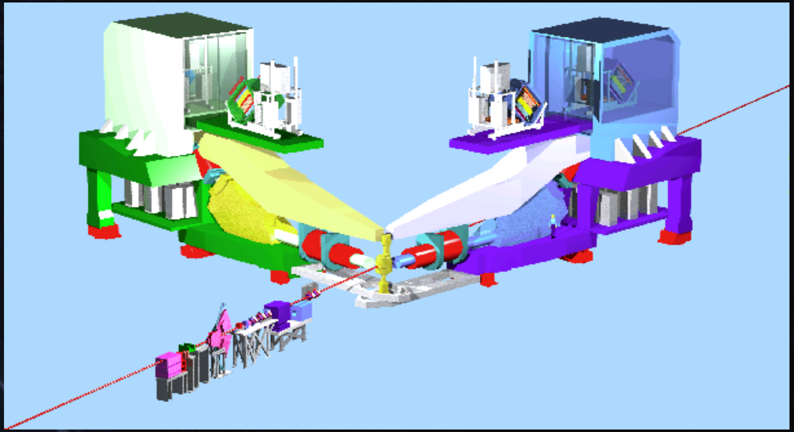
Λ behaves like glue

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

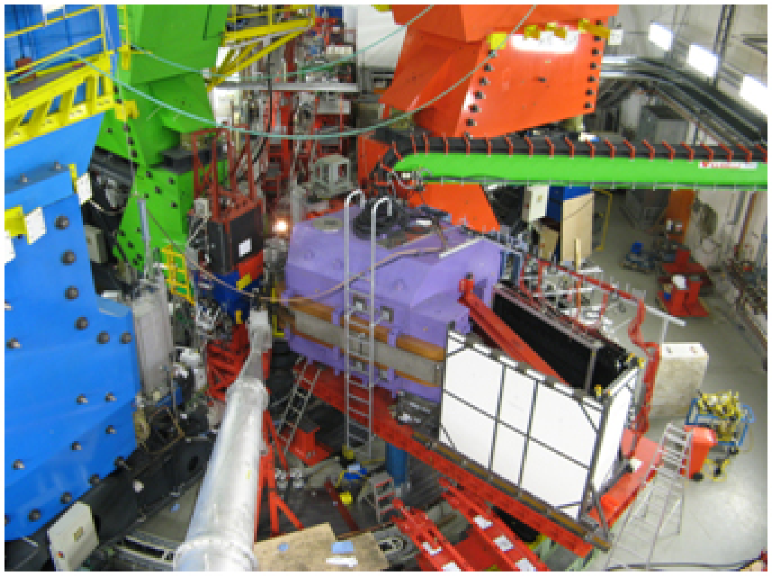
Facilities for (e,e'K$^+$) HY study



JLab Hall-C
HNSS (2000)
HKS (2005)
HKS+HES (2009)

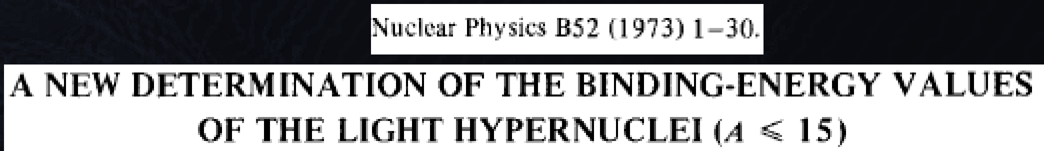


JLab Hall-A HRS+HRS (2004)



Mainz MAMI-C A1 KaoS (2008-)

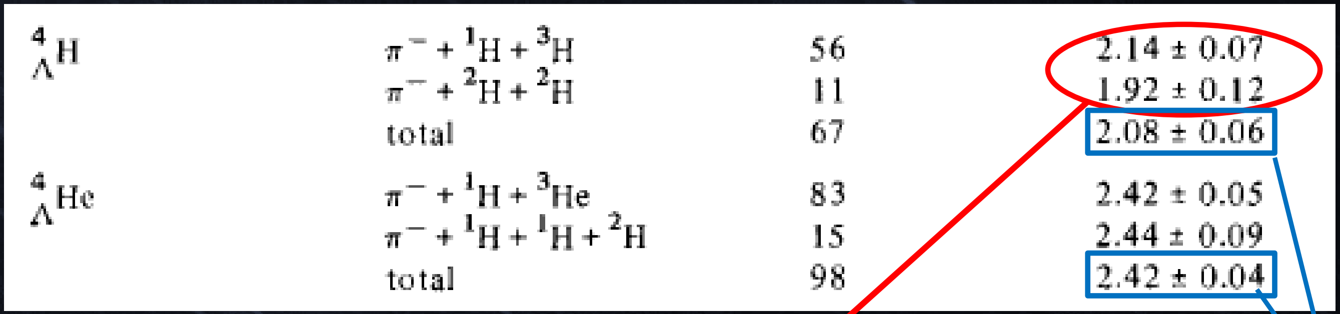
${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He emulsion data



Nuclear Physics B52 (1973) 1–30.

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

Emulsion Result (M.Juric et al.)



		(# of events)	B_{Λ} (MeV)
${}^{4}_{\Lambda}$H	$\pi^- + {}^{1}H + {}^{3}H$	56	2.14 ± 0.07
	$\pi^- + {}^{2}H + {}^{2}H$	11	1.92 ± 0.12
	total	67	2.08 ± 0.06
${}^{4}_{\Lambda}$He	$\pi^- + {}^{1}H + {}^{3}He$	83	2.42 ± 0.05
	$\pi^- + {}^{1}H + {}^{1}H + {}^{2}H$	15	2.44 ± 0.09
	total	98	2.42 ± 0.04

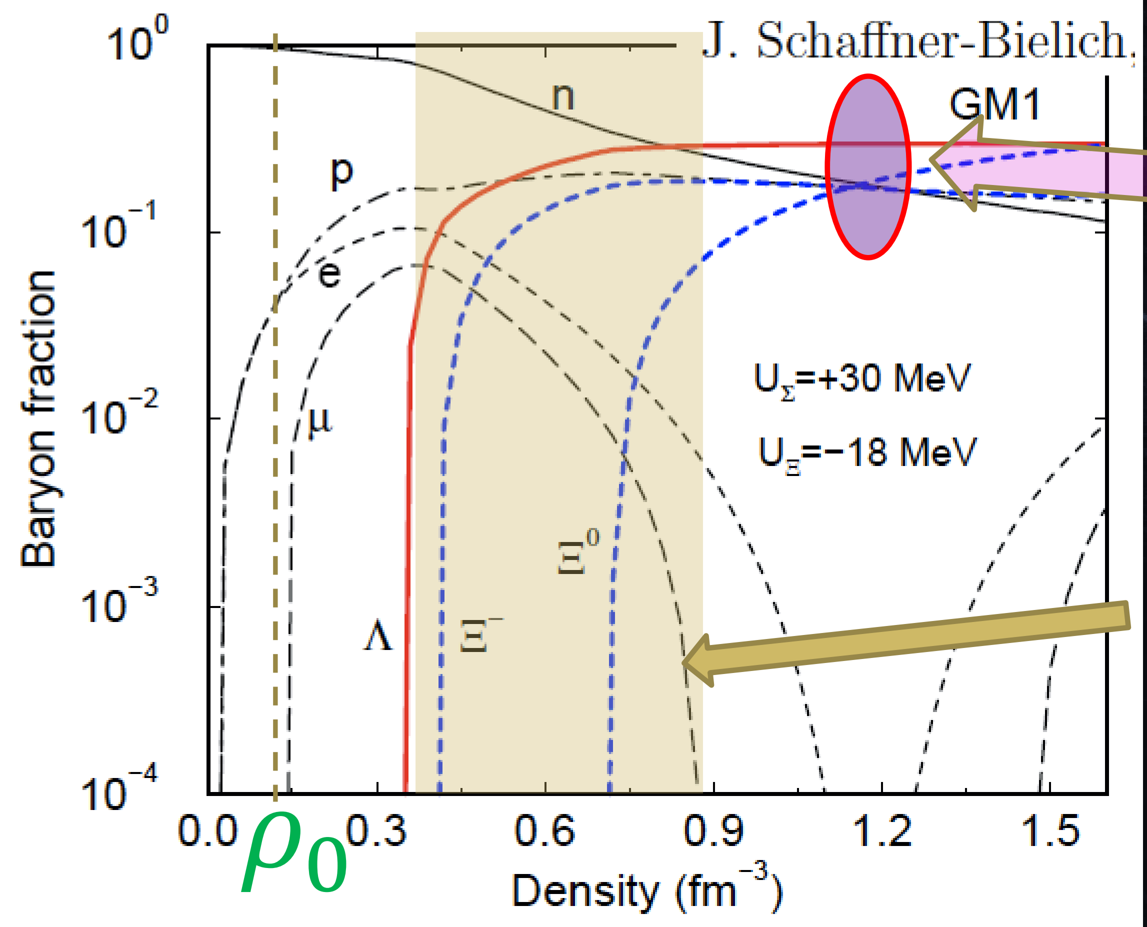
$$CSB = 0.35\ MeV$$

$$\begin{matrix} 2.14 \pm 0.07 \\ 1.92 \pm 0.12 \end{matrix} \longrightarrow \Delta = 0.22\ MeV$$

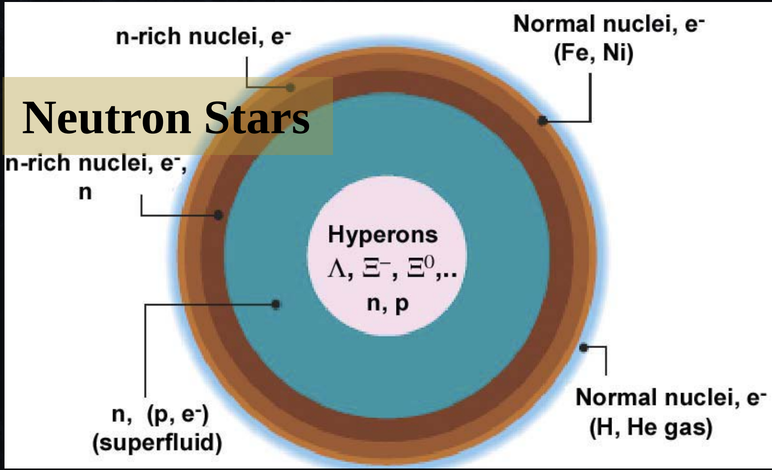
Neutron star and Strange hadronic matter

Sym. Nucl. Matter : Limit for size (due to Coulomb force)

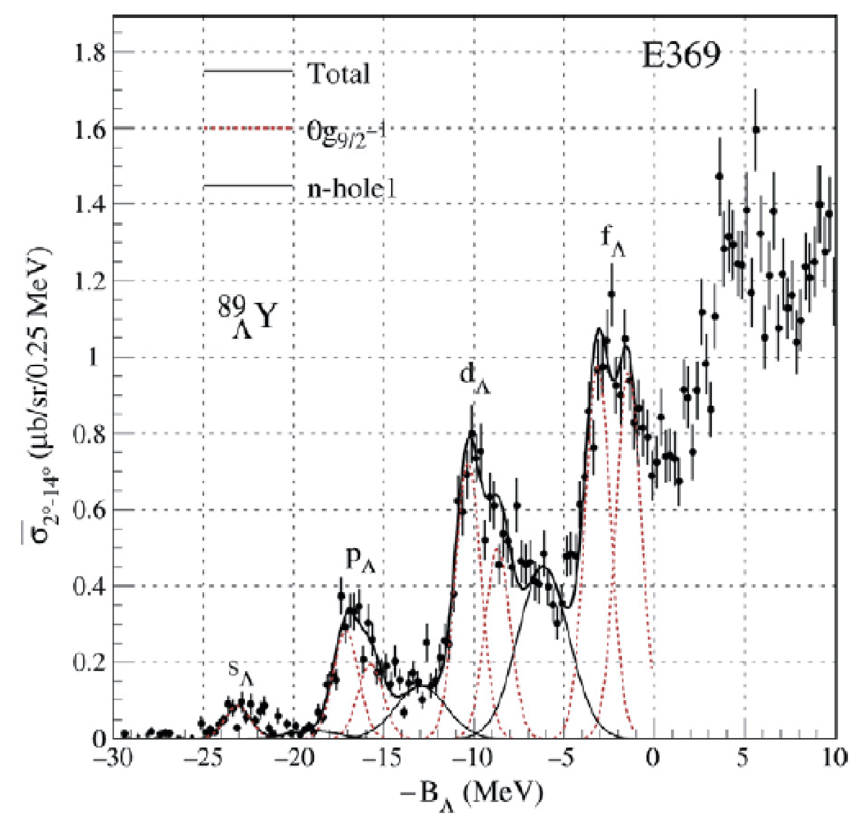
Asym. Nucl. Matter : Neutron Stars, Strange Hadronic Matter



Nu ~ Nd ~ Ns



Mid-heavy data from (π,K) exp.



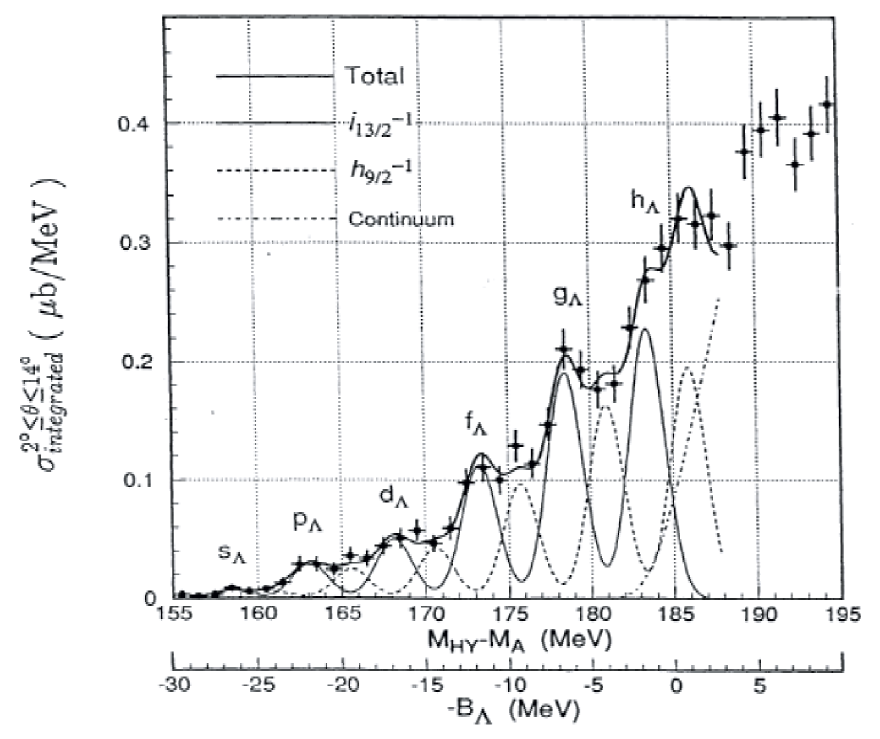
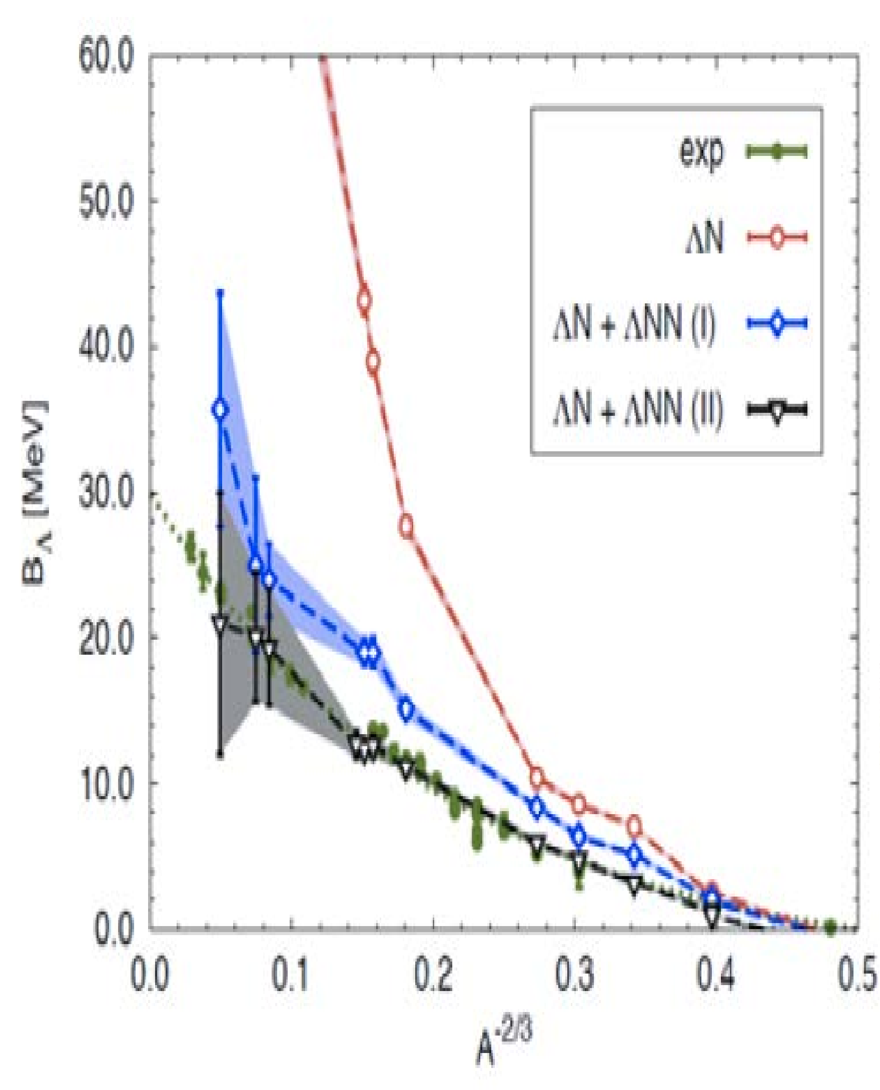
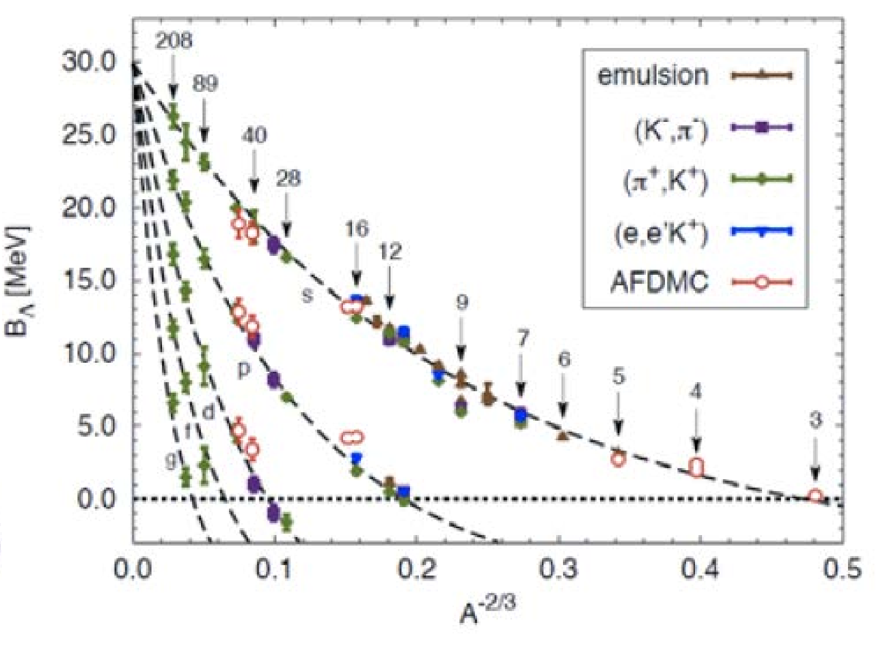


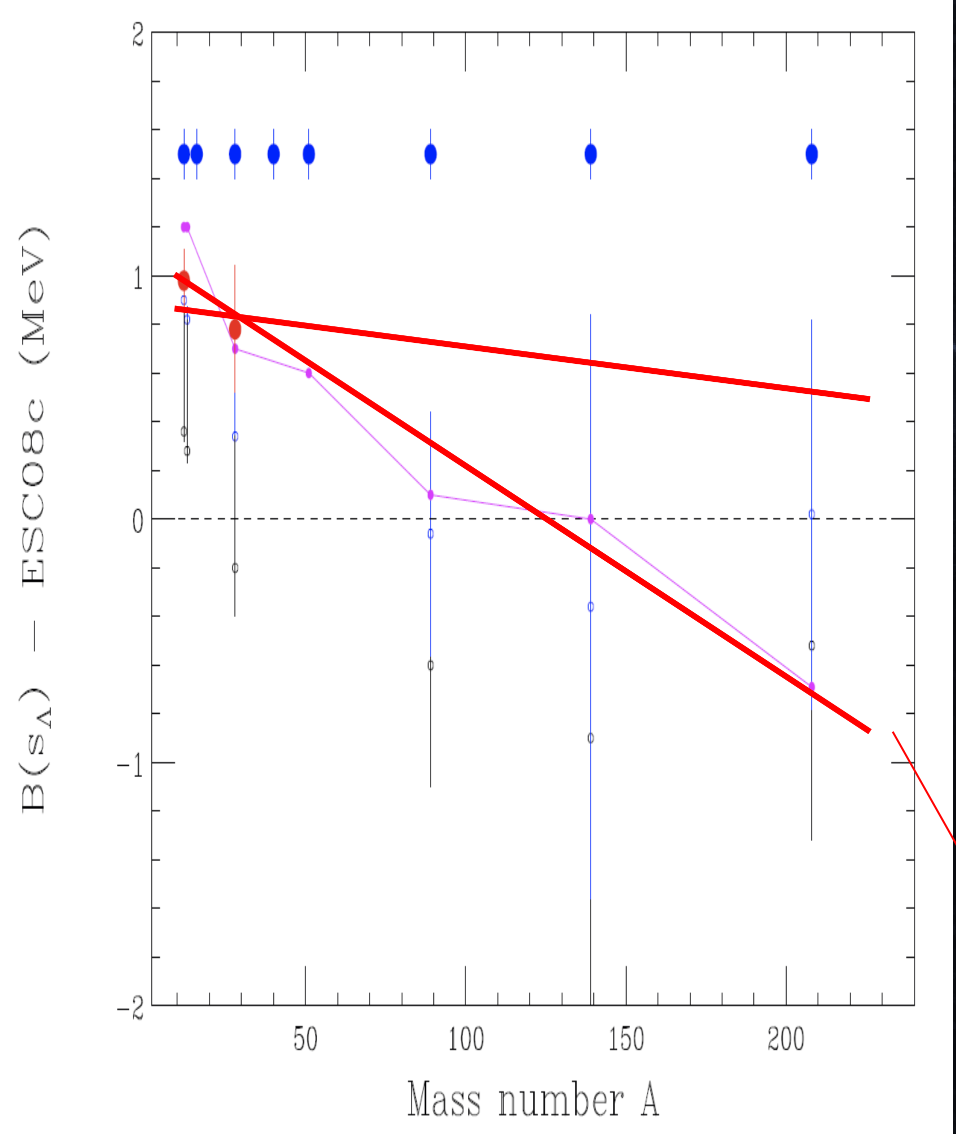
Figure B-5: Experimental $^{208}\text{Pb}(\pi^+,K^+)^{208}_{\Lambda}\text{Pb}$ excitation energy plot [HAS96].

Mass dependence of B_Λ





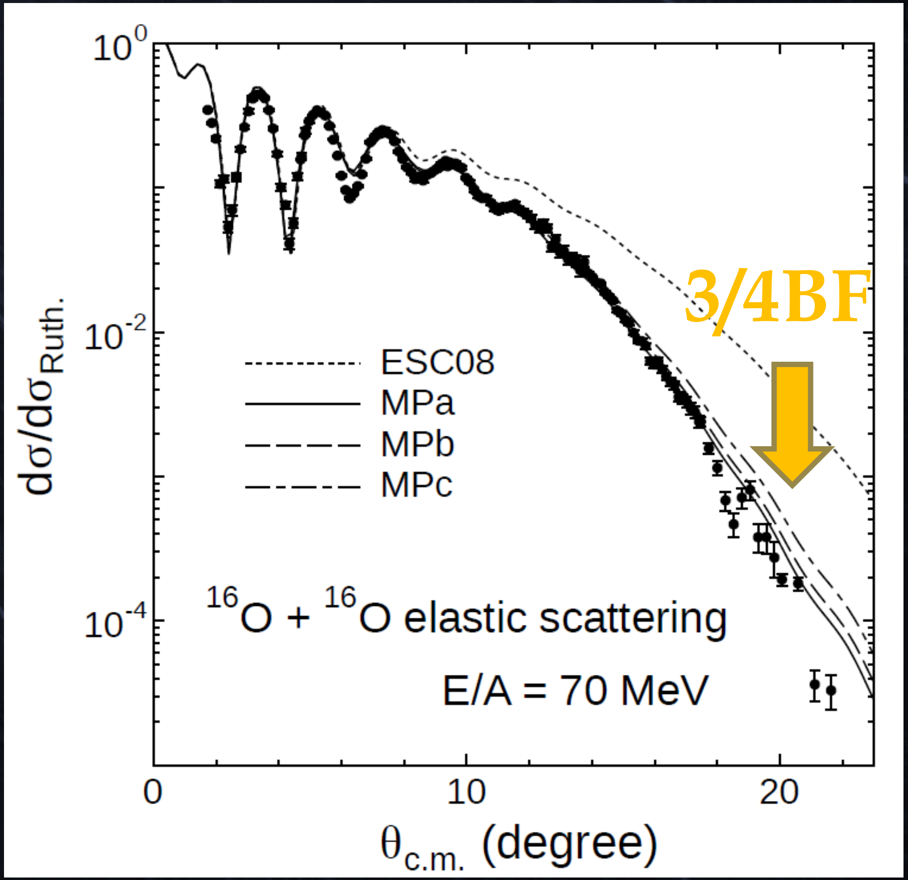
Possibility of a model-independent correlation between $B_\Lambda(A)$ and the maximum mass of NS.



Slope: $\partial[B_\Lambda - \mathrm{f}(\mathrm{A})]/\partial A$

EOS of nuclear matter

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

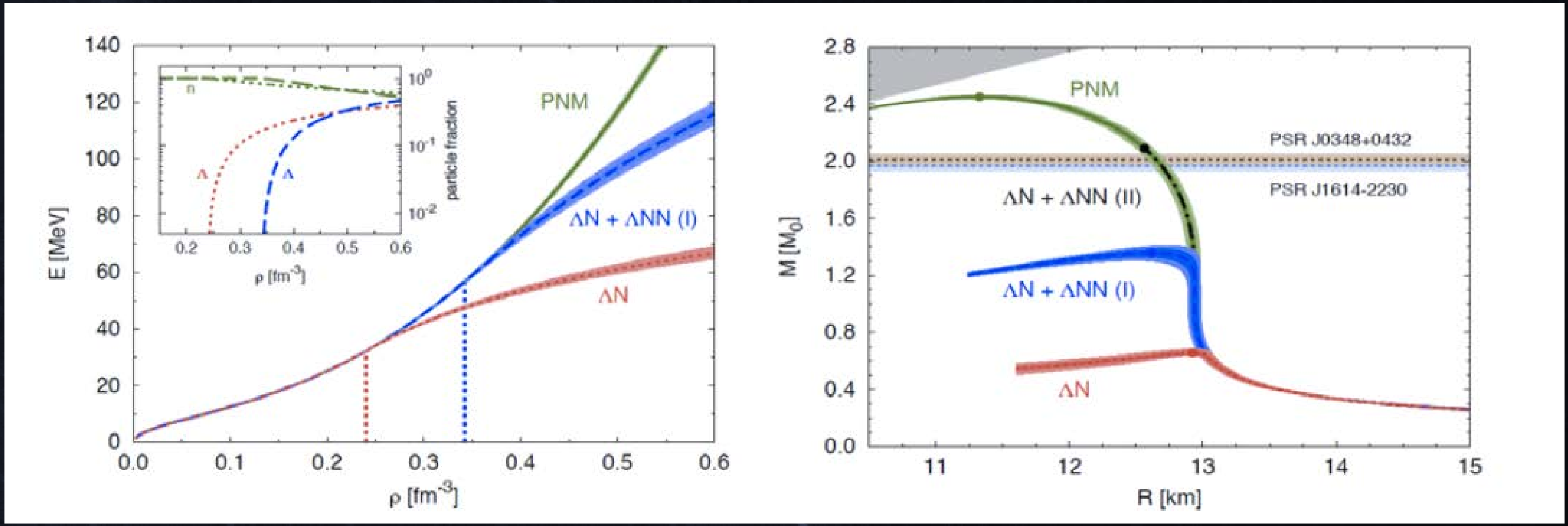


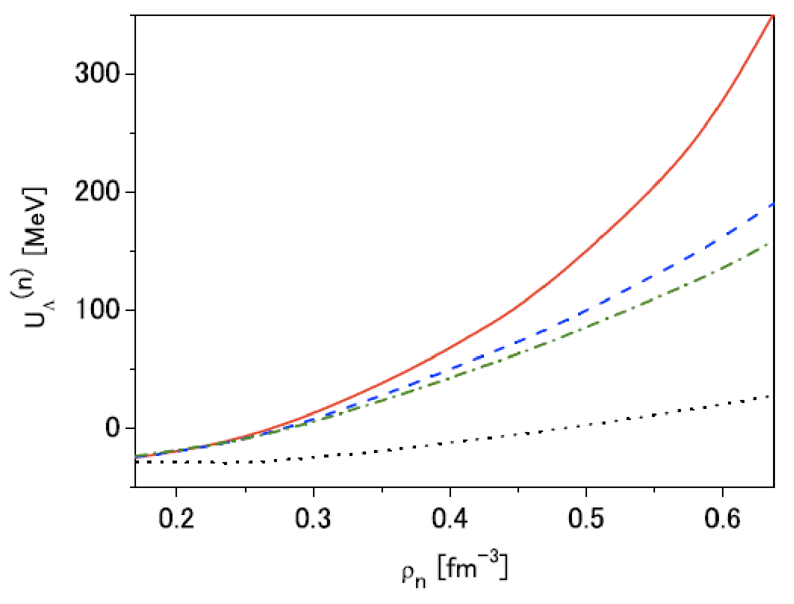
Higher density

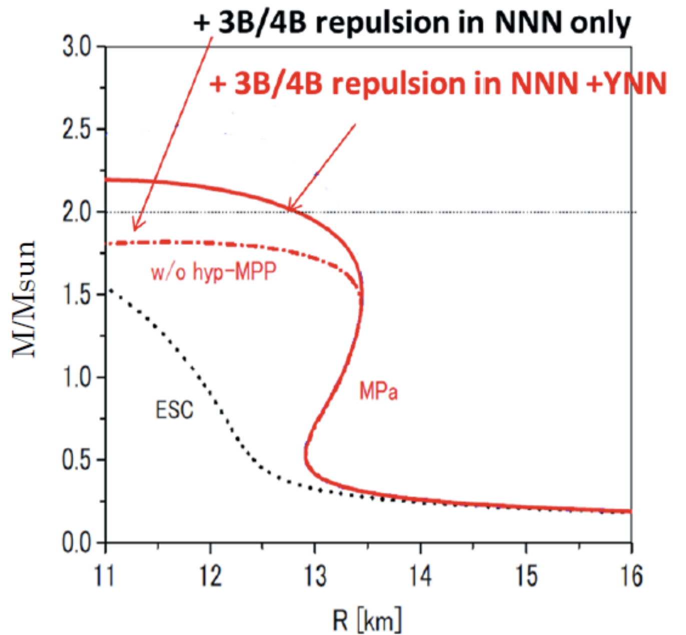
Importance of 3B/4BF

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

AFDMC by Lonardoni et al.







ESC08c + 3B/4B RF : G-Matrix Calc. by Yamamoto et al.

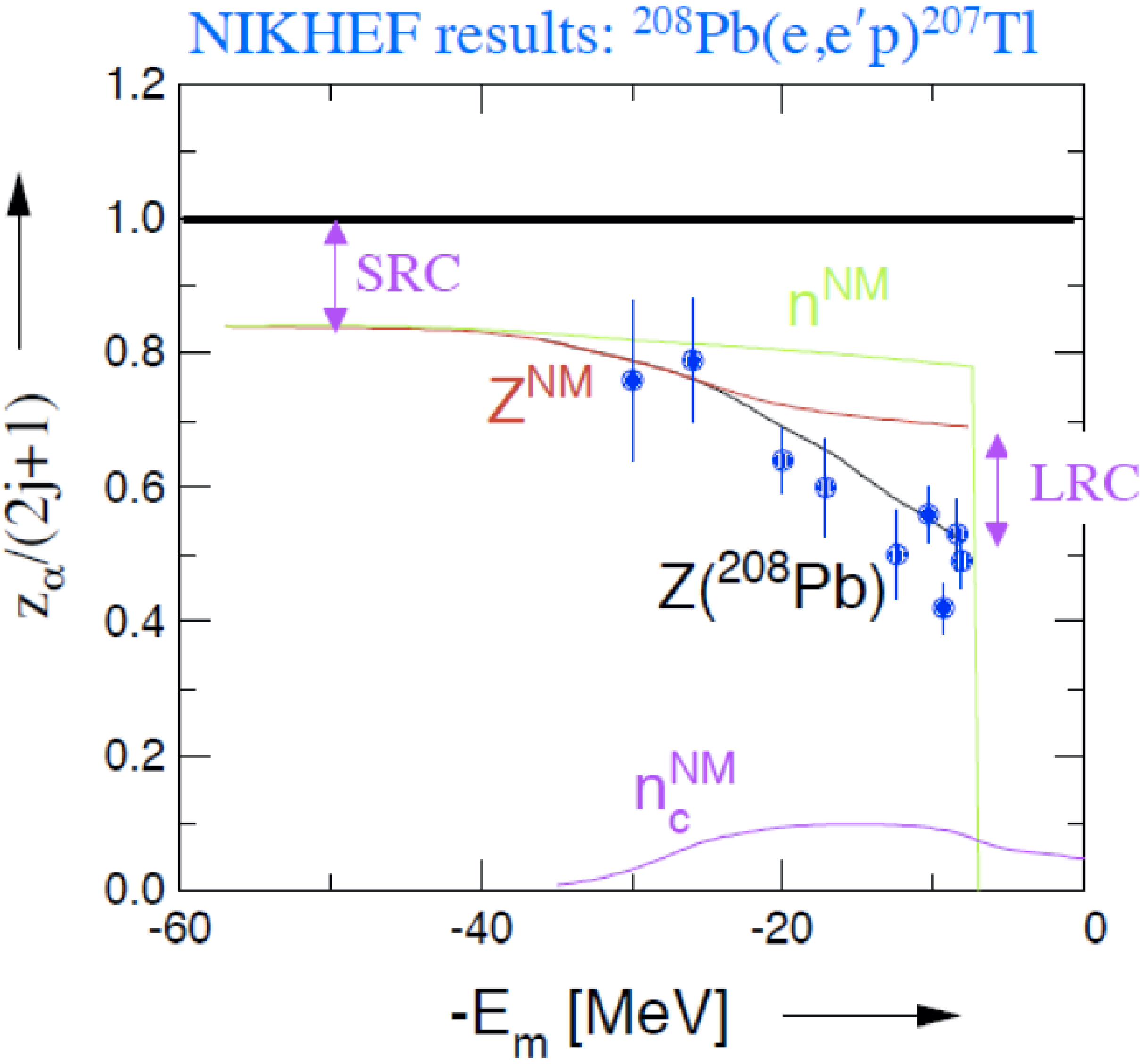
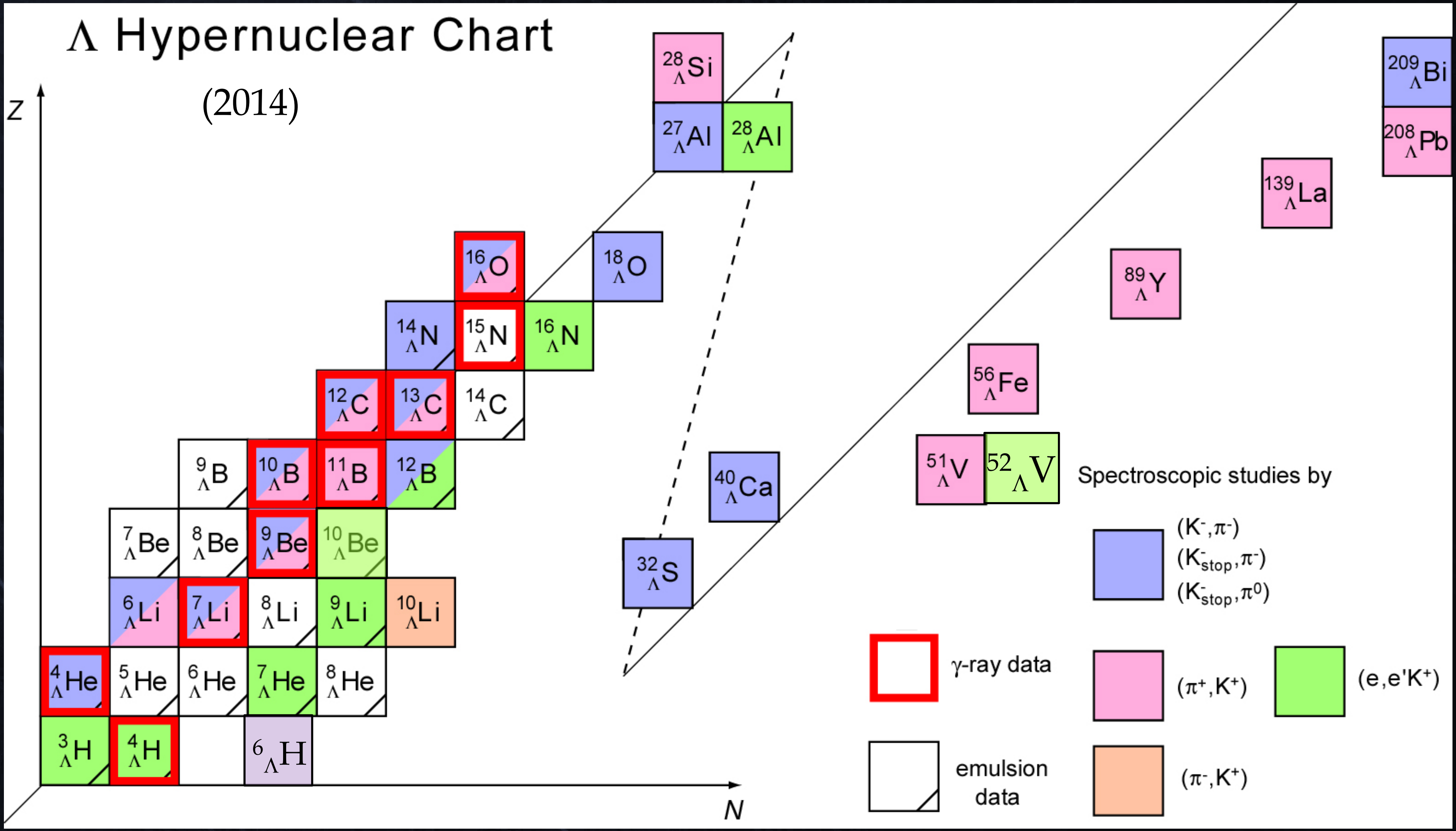


Figure 2-11: Energy dependence of the spectroscopic factors extracted from the measured ^{208}Pb(e, e′p)^{208}Tl cross sections [QUI86], compared to the theoretical resuls [BEN90]. The black and red solid lines, labelled Z(^{208}Pb) and Z^{NM}, correspond to uniform nuclear matter and ^{208}Pb, respectively. The effects of short- (SRC) and long-range-correlations (LRC), the latter arising from surface effects, are indicated.

Present Status of Λ Hypernuclear Spectroscopy



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

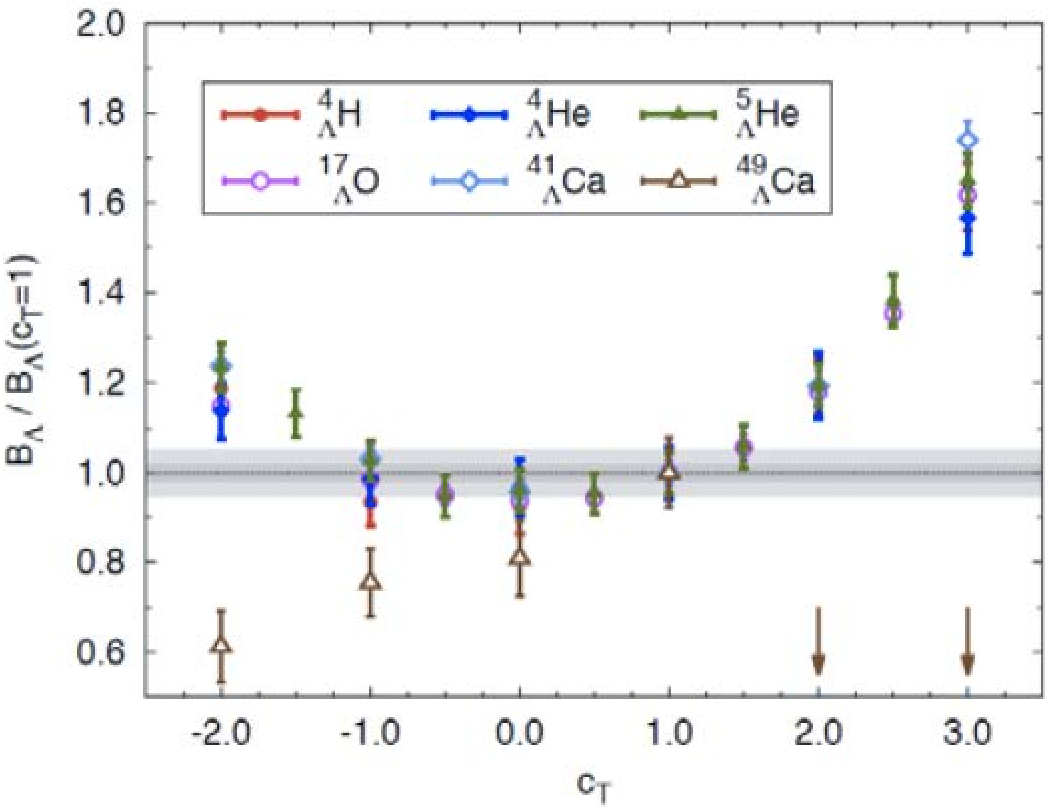


Figure 2-10: Λ separation energies normalized with respect to the $C_T = 1$ case as a function of C_T. Grey bands represent the 2% and 5% variations of the ratio B_Λ/B_Λ ($C_T = 1$). Brown vertical arrows indicate the results for ^{49}Ca in the case of $C_T = 2$ and $C_T = 3$, outside the scale of the plot.