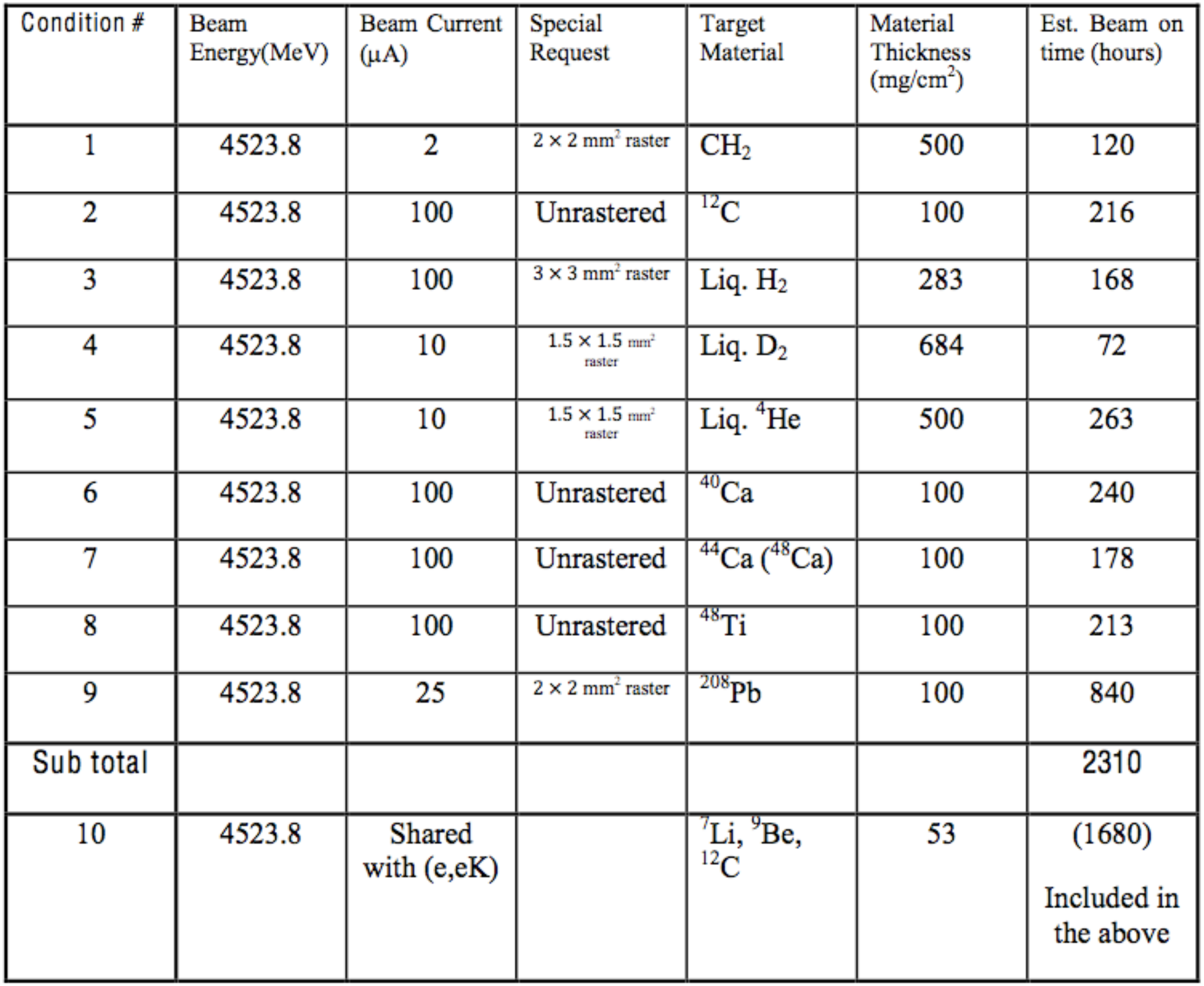
New physics ideas from the Hypernuclear Workshop

Joerg Reinhold
Florida International University

A study with high precision on the electro-production of the Λ and Λ-hypernuclei in the full mass range (PR12-13-002)



Condition #	Beam Energy(MeV)	Beam Current (μA)	Special Request	Target Material	Material Thickness (mg/cm^2)	Est. Beam on time (hours)
1	4523.8	2	2×2 mm^2 raster	CH_2	500	120
2	4523.8	100	Unrastered	^{12}C	100	216
3	4523.8	100	3×3 mm^2 raster	Liq. H_2	283	168
4	4523.8	10	1.5×1.5 mm^2 raster	Liq. D_2	684	72
5	4523.8	10	1.5×1.5 mm^2 raster	Liq. ^4He	500	263
6	4523.8	100	Unrastered	^{40}Ca	100	240
7	4523.8	100	Unrastered	^{44}Ca (^{48}Ca)	100	178
8	4523.8	100	Unrastered	^{48}Ti	100	213
9	4523.8	25	2×2 mm^2 raster	^{208}Pb	100	840
Sub total						2310
10	4523.8	Shared with (e,eK)		^7Li, ^9Be, ^{12}C	53	(1680) Included in the above

PAC 41 deferred (June 2013):

Issues:

The beam time required for the full program constituted about 100 days. A significant setup time for this experiment requires both resources and significant planning. The PAC felt that the case had not yet been made for such a significant investment, and would encourage, as PAC39 had done, that the proponents work closely with the theory community to identify the most important cases for study. A future proposal should also clearly state the impact of measurements for our understanding of the Λ-N interactions. A careful analysis of how these sets of measurements and their uncertainties constrain nuclear theory would be of value. **A dedicated Workshop focused on these questions could be very helpful.** The PAC needs to see a sense of priority from the proponents. This was missing in the current proposal and in the talks given to the PAC.

Since the Mainz program has not yet produced final results, we are also not in a position to comment on the backgrounds for decay-pion spectroscopy experiments. We believe this is also an important hurdle, as discussed by PAC39, to enable a positive decision for the program at JLab.

Hypernuclear Workshop
May 27-29, 2014
Jefferson Lab
Newport News, VA

18 talks by theorists

Achenbach, Patrick	
Benhar, Omar	**INFN Roma**
Bressani , Tullio	INFN-Sezione di Torino
Bydzovsky , Petr	**Nuclear Physics Institute, Rez**
Cardman , Lawrence	Jefferson Lab
Carman , Daniel	JLab
Drago , Alessandro	**University of Ferrara**
Ent , Rolf	Jefferson Lab
Garibaldi , Franco	INFN Roma1
Gibson , Benjamin	**LANL**
Haidenbauer , Johann	**Forschungszentrum Juelich**
Hiyama , Emiko	**RIKEN**
Isaka , Masahiro	**RIKEN Nichina center**
Lonardoni , Diego	**Argonne National Laboratory**
Markowitz , Pete	Florida International University
McKeown , Robert	Jefferson Lab
Millener, John	**BNL**
Motoba , Toshio	**Osaka E-C University**
Nakamura , Satoshi	Thoku University
Nogga, Andreas	**Bochum**
Pederiva , Francesco	**University of Trento**
Pochodzalla, Joseph	MAMI
Reinhold , Joerg	Florida International University
Rijken , Thomas	**IMAPP, Radboud university Nijmegen**
Rodriguez , Victor	Universidad Metropolitana
Schulze , Hans-Josef	**INFN Catania**
Sherrill , Bradley	Michigan State University
Tang , Liguang	JLAB/Hampton Univ.
Urciuoli , Guido	INFN Sezione di roma
Vidana , Isaac	**University of Coimbra**
Wirth , Roland	**Technische Universität Darmstadt**

Charge to Panel Discussion

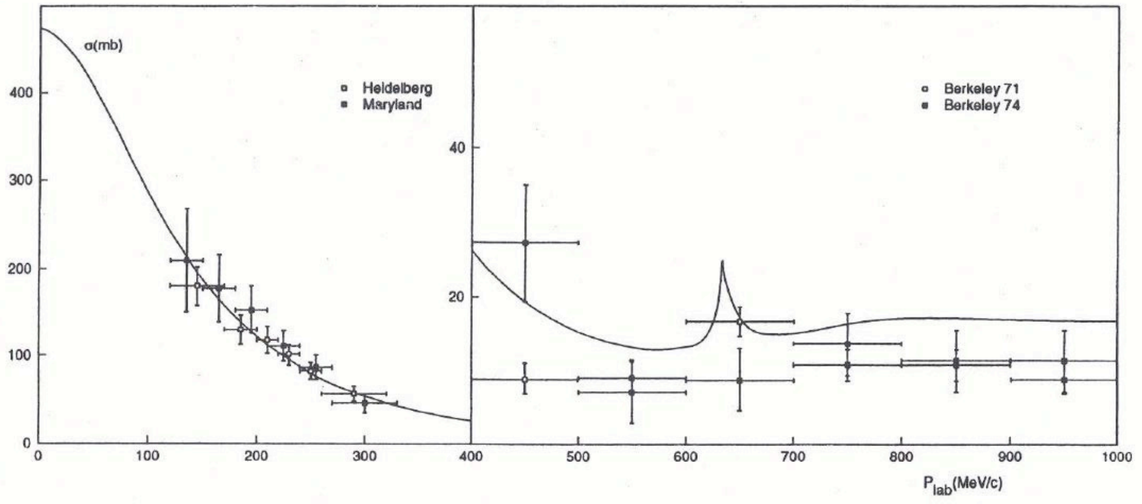
It would be helpful if the workshop could provide guidance to the proponents, specifically to

- **Identify the most important one or two key measurements to be pursued at JLab that would provide a substantial advance in our knowledge of hypernuclear physics. These measurements could form the initial program motivating the mounting of a more extensive hypernuclear physics program at JLab.**

McKeown

ΛN Data

B. Gibson



Λp total cross section data for $p_{\rm lab}$ in the range from 0 to 1000 MeV/c compared with predictions from the Nijmegen soft-core potential model.

From J. J. de Swart, P. M. M. Maessen, and Th. A. Rijken in "Properties and Interactions of Hyperons," edited by B. F. Gibson, P. D. Barnes, and H. Nakai (World Scientific, Singapore, 1994) p. 37.

The Λp data have not changed since the bubble chamber work from which these cross sections resulted. There are no Λn cross section data.

Where Can We Go From Here???

- $p + p \rightarrow K^+ + \Lambda + p$ to enhance the Λp data base
- Electronic chamber experiments to measure $K^- + d \rightarrow \Lambda + \pi^- + p$ to do the same
- JLab $\gamma + d \rightarrow K^0 + \Lambda + p$ to do the same
- Stopped $K^- + d \rightarrow n + \Lambda + \gamma$ to provide missing Λn data

In each of the first three one must deal with three strongly interacting hadrons in the final state to extract the relatively weak Λp interaction. This does not look promising, given our lack of success in extracting from the $n + d \rightarrow n + n + p$ reaction the large n-n scattering length.

2 JLab scientific mission ⋆ M.Battaglieri 2013

JLab Scientific Mission

⋆ Understand the quark-gluon structure hadrons

⋆ Understand the baryon-baryon force and its QCD basis [⋆]

⋆ Explore the limits of knowledge of nuclear structure: ● high precision, ● short distances [⋆], ● transition baryon-meson to the QCD description

⋆ Address critical issues in "strong QCD": ● mechanism of confinement, ● q-q interaction [⋆] and the transition in QCD from the confined to the perturbative QED-like regime?

⋆ Probe new physics through high precision tests of the "SM"

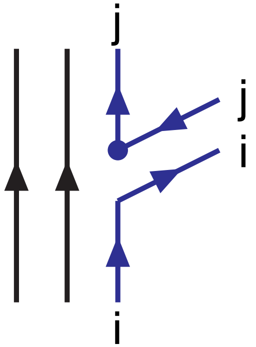
In this talk it will be shown/argued that the [⋆]-items are addressed in the combined experimental and theoretical study of baryon-baryon and hyper-nuclear systems.

⋆ Relevant topics discussed:

- Quark-antiquark pair creation (QPC) meson-baryon couplings
- Multi-gluon exchange for short-range BB-interactions and nuclear matter.
- Pauli-repulsion due to quark structure baryons.

19b QPC: ${}^3P_0$-model

Meson-Baryon Couplings from ${}^3P_0$-Mechanism



${}^3P_0$ Interaction Lagrangian:

$$\mathcal{L}_I^{(S)} = \gamma \left(\sum_j \bar{q}_j\ q_j\right) \cdot \left(\sum_i \bar{q}_i\ q_i\right)$$

Fierz Transformation

$$\begin{aligned}\mathcal{L}_I^{(S)} \quad &= \quad -\frac{\gamma}{4}\sum_{i,j}\Big[+\ \bar{q}_i\ q_j \cdot \bar{q}_j\ q_i + \ \bar{q}_i\gamma_\mu q_j \cdot \bar{q}_j\gamma^\mu q_i - \ \bar{q}_i\gamma_\mu\gamma_5 q_j \cdot \bar{q}_j\gamma^\mu\gamma^5 q_i \\ &\qquad + \bar{q}_i\gamma_5 q_j \cdot \bar{q}_j\gamma^5 q_i - \frac{1}{2}\ \bar{q}_i\sigma_{\mu\nu} q_j \cdot \bar{q}_j\sigma^{\mu\nu} q_i\Big]\end{aligned}$$

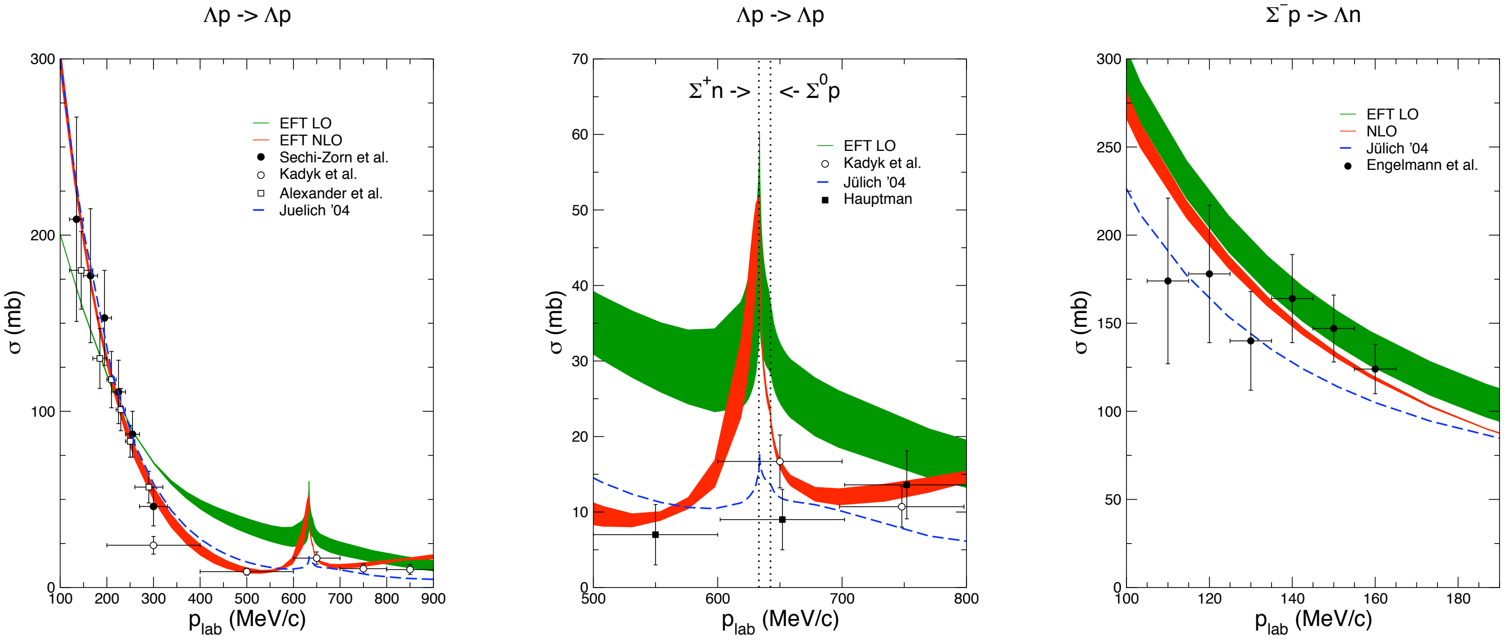
$$\chi_{ij}^S \quad \sim \quad \bar{q}_j\ q_i\ ,\ \chi_{\mu,ij}^V \sim \bar{q}_j\gamma_\mu q_i\ ,\ \chi_{\mu,ij}^A \sim \bar{q}_j\gamma_5\gamma_\mu q_i$$

1. $g_\epsilon = g_\omega$, and $g_{a_0} = g_\rho$!?
2. What about f_π , g_{a_1}, etc. ?
3. $g_{q,ij}^V = g_{q,ij}^S = -g_{q,ij}^A = g_{q,ij}^P$

$$CF = \left\{\begin{array}{ccc} 3 & 3 & 3^* \\ 1 & 1 & 1 \\ 3 & 3 & 3^* \end{array}\right\}$$

YN integrated cross sections

Juelich: Chiral EFT



Hypernuclear interactions

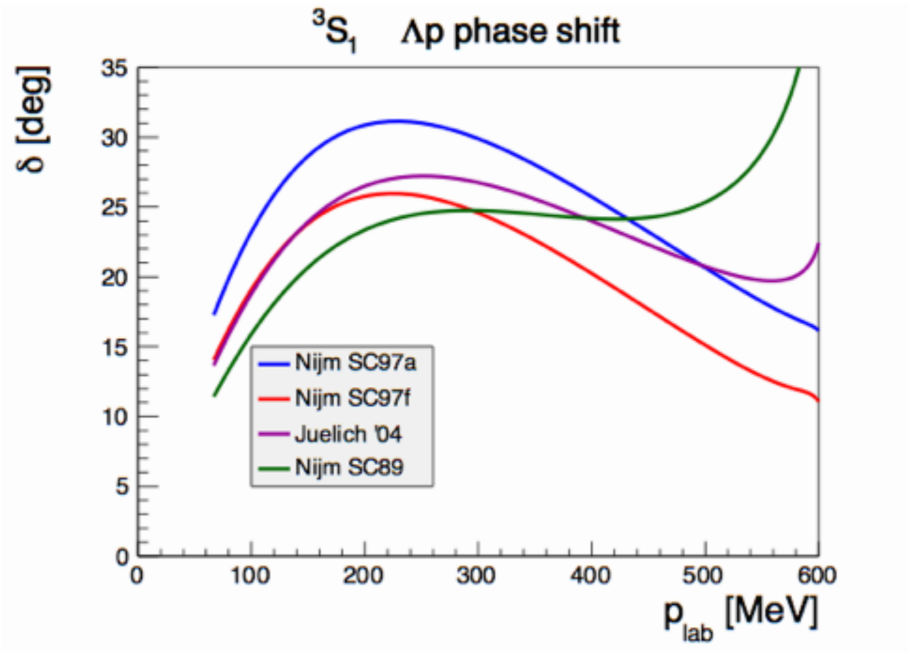
35 YN data, no YN bound state, large uncertainties

→ no partial wave analysis possible

A. Nogga

YN interaction models (Jülich 89/04, Nijmegen 89/97a-f, ESC, …)

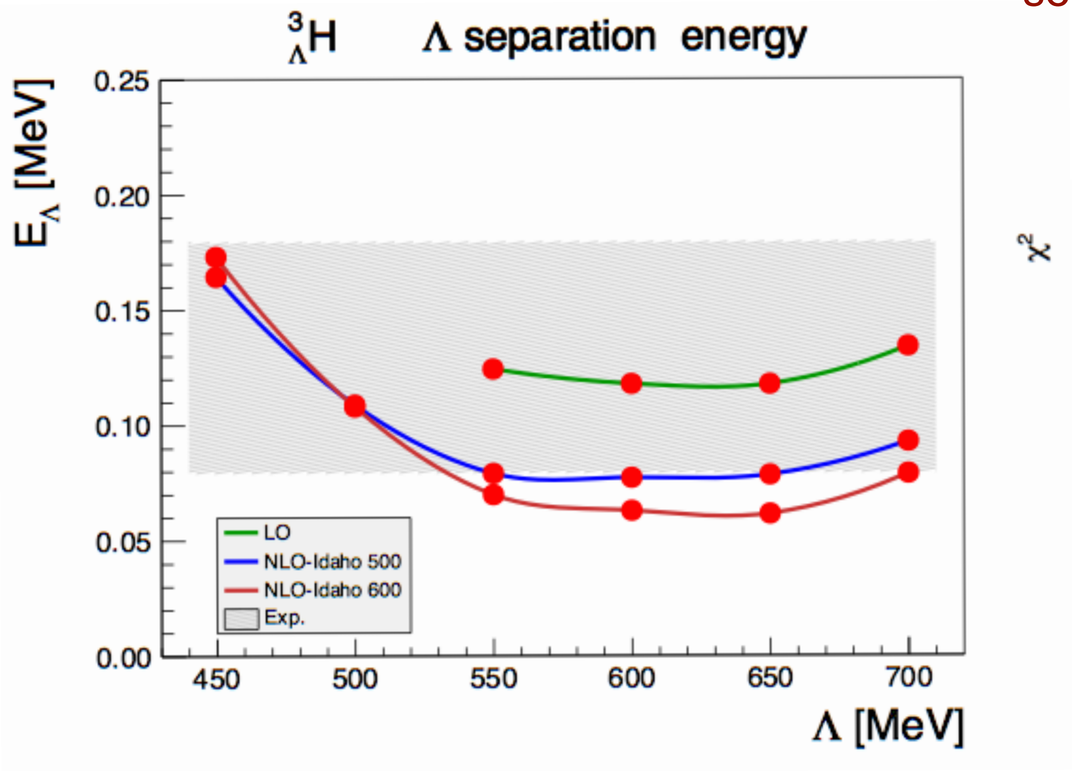
describe all data **more than perfectly**, but are not phase equivalent



	1	3
SC97a	-0.7	-2.15
SC97b	-0.9	-2.11
SC97c	-1.2	-2.06
SC97d	-1.7	-1.93
SC97e	-2.1	-1.83
SC97f	-2.5	-1.73
SC89	-2.6	-1.38
Jülich ´04	-2.6	-1.73

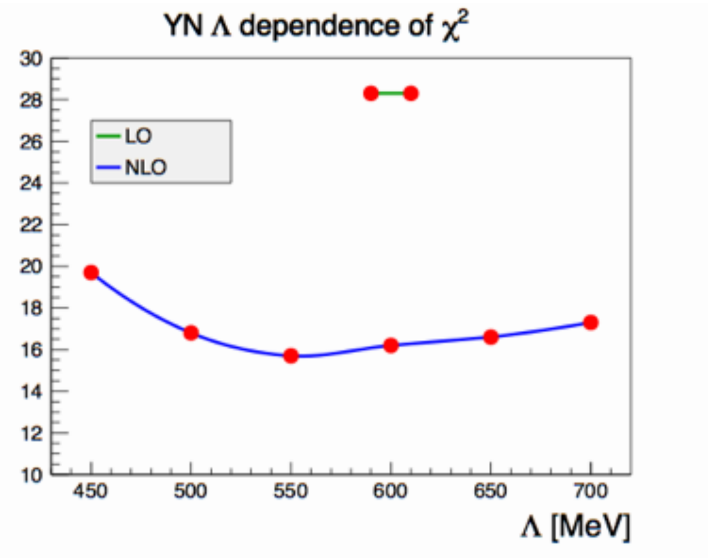
How to further constrain the YN interactions?

Hypertriton separation energies



separation energies:

$$E_\Lambda = E(core) - E(hypernucleus)$$



- singlet scattering length for one cutoff chosen so that hypertriton binding energy is OK

- cutoff variation
  - is **lower bound** for magnitude of higher order contributions
  - correlation with χ^2 of YN interaction ?

- long range 3BFs need to be explicitly estimated

Conclusions & Outlook

A. Nogga

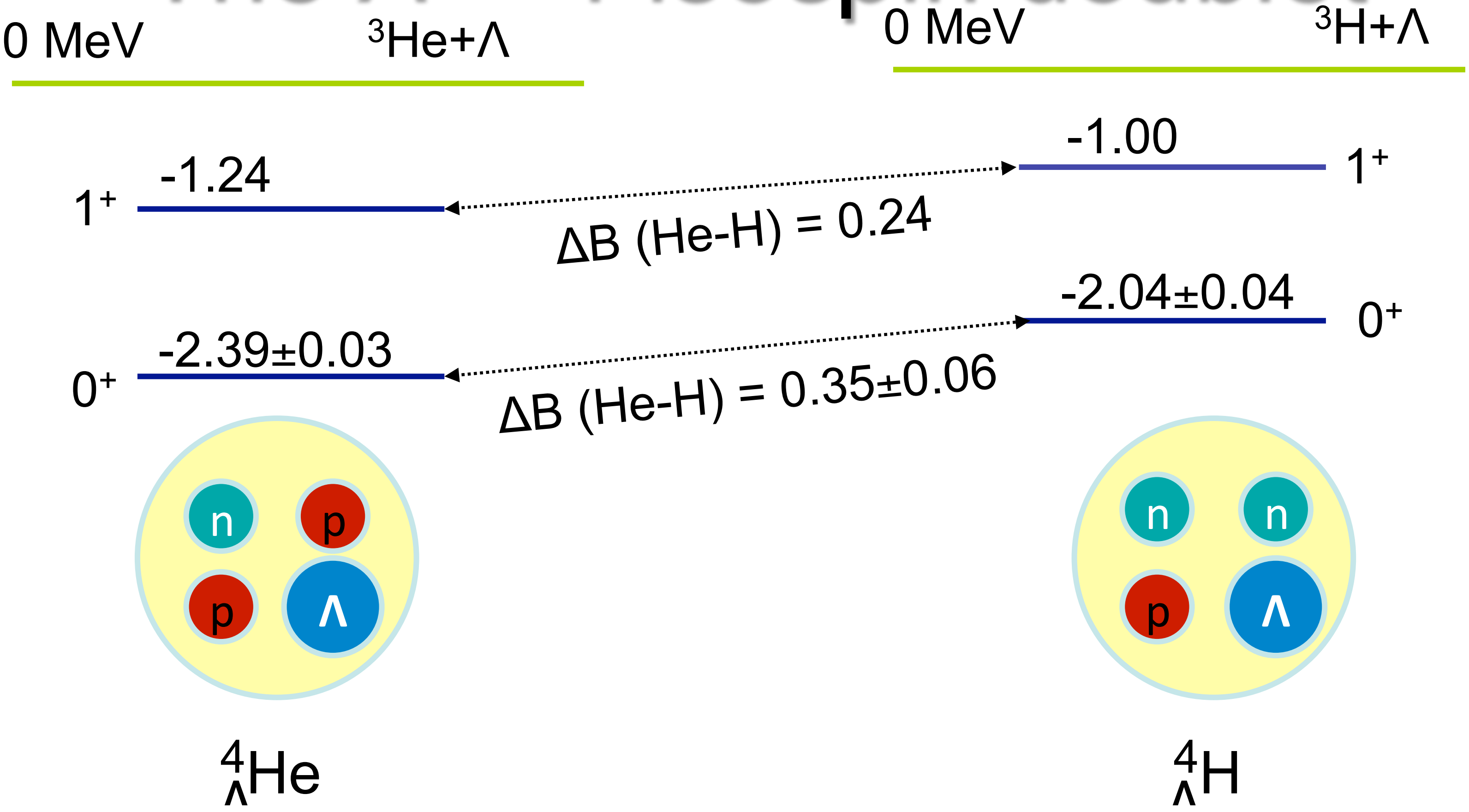
- YN interactions are interesting and not well understood
  - *Λ-Σ conversion, explicit chiral symmetry breaking*
  - *well known: YN models fail*
  - *NLO of chiral interactions: still freedom to adjust YN forces*
  - *but: further estimates of* ***three-baryon interactions*** *(in progress)*

- hypernuclei are an essential source of information on YN
  - *it is not trivial to describe the simplest systems consistently*
  - *experiments for* ***very light*** *hypernuclei are important!*
    The data needs to be ***accurate*** *(better data for the hypertriton?)*
    We need to be sure that these data are ***reliable****.*

- CSB for four-body hypernuclei is a puzzle
  - *obviously related to Λ-Σ conversion*
    Can we engineer chiral interactions with different conversion strength?
  - *experiments for* ***very light*** *hypernuclei are important!*
    Is today's data reliable?

- extension of complete calculations to larger systems **(access more data)**
  (see also Roland Wirth's talk)

The *A* = 4 isospin doublet



0 MeV ^{3}He+Λ

1$^+$ -1.24

0$^+$ -2.39±0.03

ΔB (He-H) = 0.24

ΔB (He-H) = 0.35±0.06

0 MeV ^{3}H+Λ

-1.00 1$^+$

-2.04±0.04 0$^+$

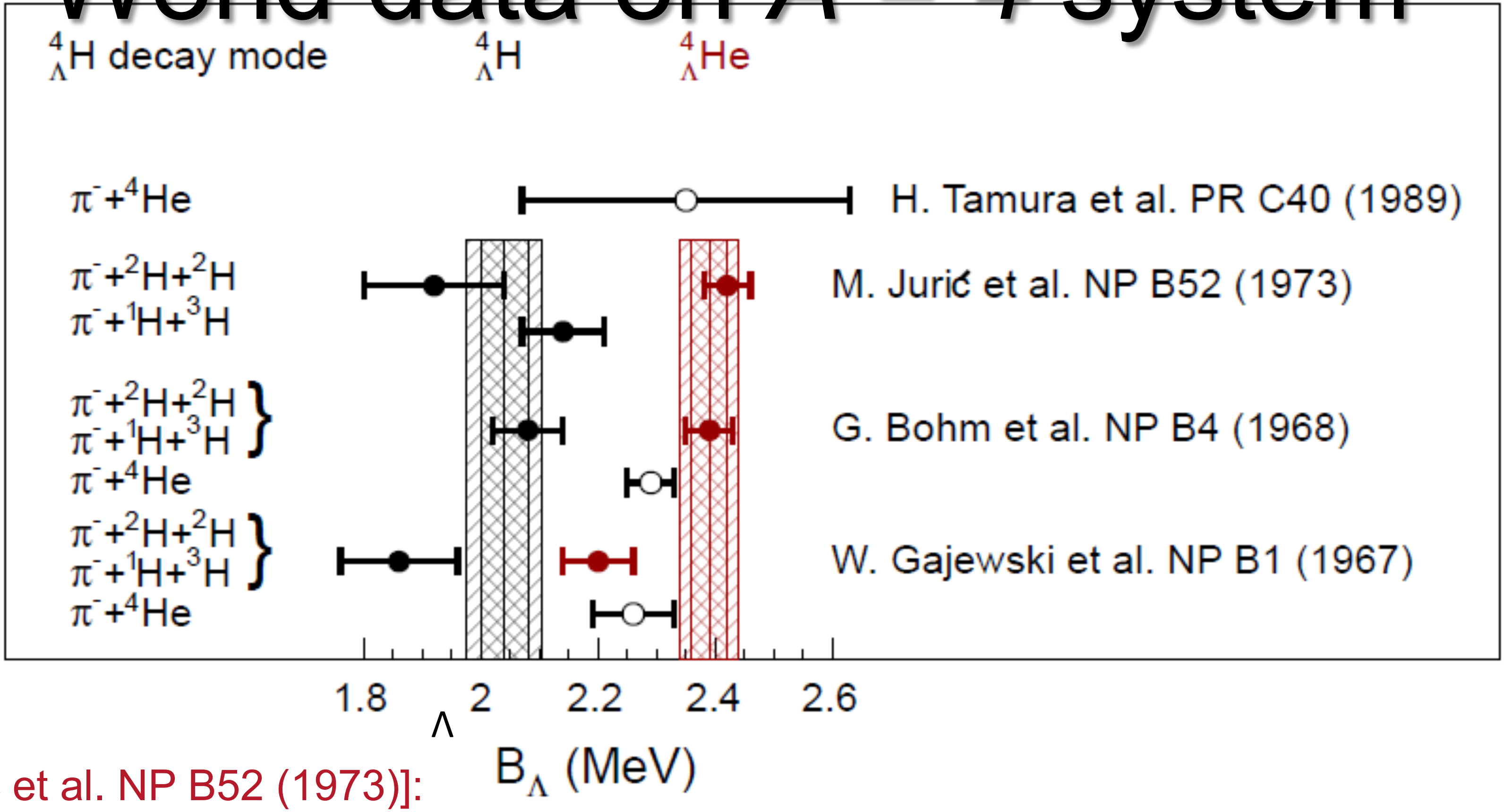
$^4_\Lambda$He

$^4_\Lambda$H

- Nucleon-hyperon interaction can be studied by strange mirror pairs
- Coulomb corrections are < 50 keV for the $^4{}_\Lambda$H - $^4{}_\Lambda$He pair
- Energy differences of $^4{}_\Lambda$H - $^4{}_\Lambda$He pair much > than for ^{3}H - ^{3}He pair

P. Achenbach, Mainz

World data on *A* = *4* system



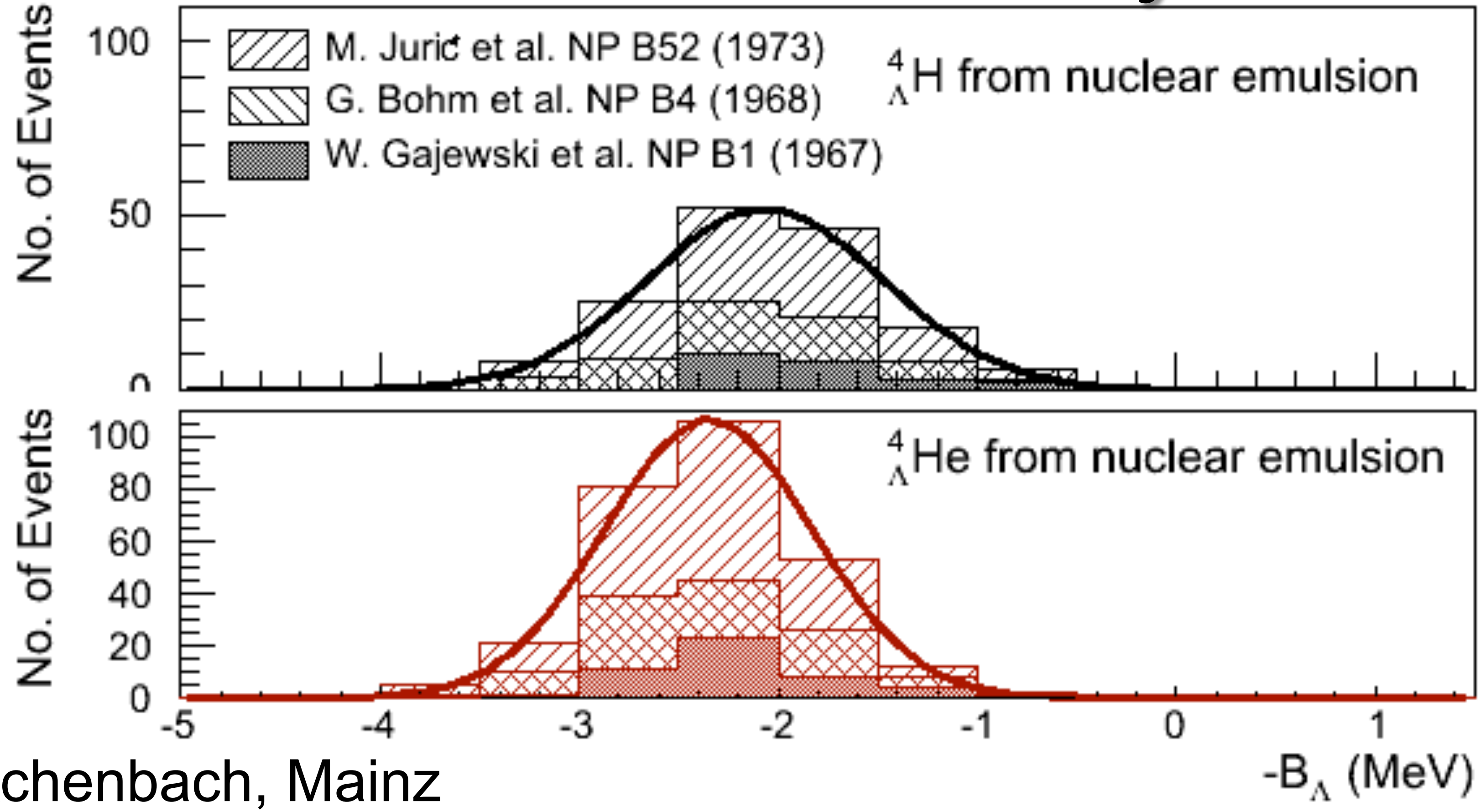
[M. Juric et al. NP B52 (1973)]:

$$\left.\begin{array}{l} {}^4_\Lambda\text{He} \xrightarrow{\text{decay}} \pi^- + {}^1\text{H} + {}^3\text{He}: B = 2.42 \pm 0.05\ \text{MeV} \\ {}^4_\Lambda\text{He} \xrightarrow{\text{decay}} \pi^- + 2\,{}^1\text{H} + {}^2\text{H}: B = 2.44 \pm 0.09\ \text{MeV} \end{array}\right\}\ 0.02\ \text{MeV difference}$$

Total: B = 2.42 ±0.04 MeV

P. Achenbach, Mainz

World data on *A* = *4* system



P. Achenbach, Mainz

- Only three-body decay modes used for hyperhydrogen
- Systematic errors of > 0.04 MeV not included [D. Davis]
- 155 events for hyperhydrogen, 279 events for hyperhelium

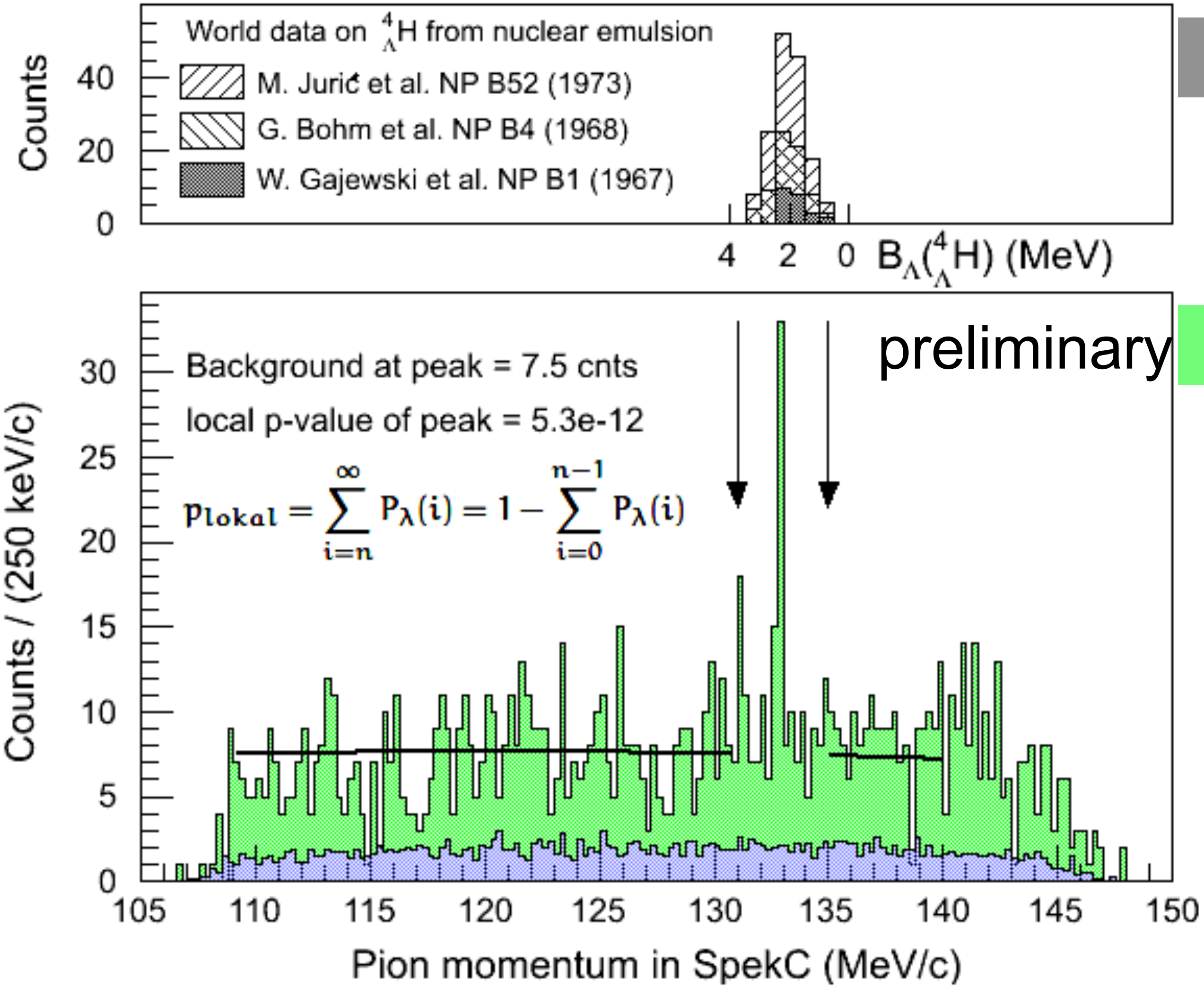
Modern calculations on A = 4 system

Calculation	Interaction	${}^{4}_{\Lambda}\mathrm{H}_{gs}$	${}^{4}_{\Lambda}\mathrm{He}_{gs}$	Δ (He-H)
A. Nogga, H. Kamada and W. Gloeckle, PRL 88, 172501 (2002)	SC97e	1.47	1.54	0.07
	SC89	2.14	1.80	0.34
H. Nemura. Y. Akaishi and Y. Suzuki, PRL 89, 142504 (2002)	SC97d	1.67	1.62	-0.05
	SC97e	2.06	2.02	-0.04
	SC97f	2.16	2.11	-0.05
	SC89	2.55	2.47	-0.08
E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yama PRC 65, 011301 (R) (2001)	AV8	2.33	2.28	-0.05

World data average 2.04±0.04 2.39±0.03 0.35±0.06

With precise spectroscopy details of *NY*-interaction can be inferred

Hyperhydrogen peak search



Emulsion data

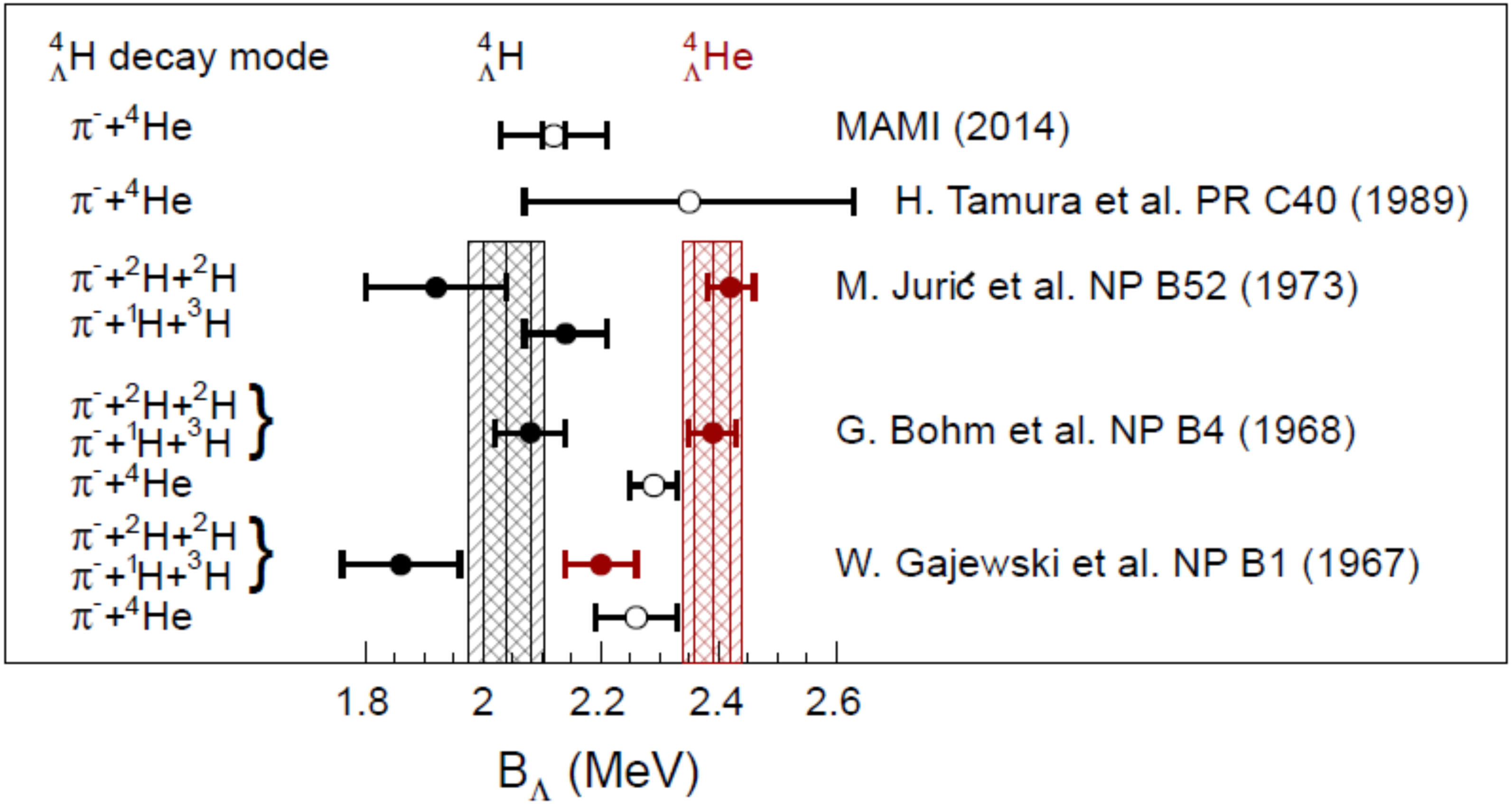
preliminary

MAMI data

local excess observed inside the hyperhydrogen search region

P. Achenbach, Mainz

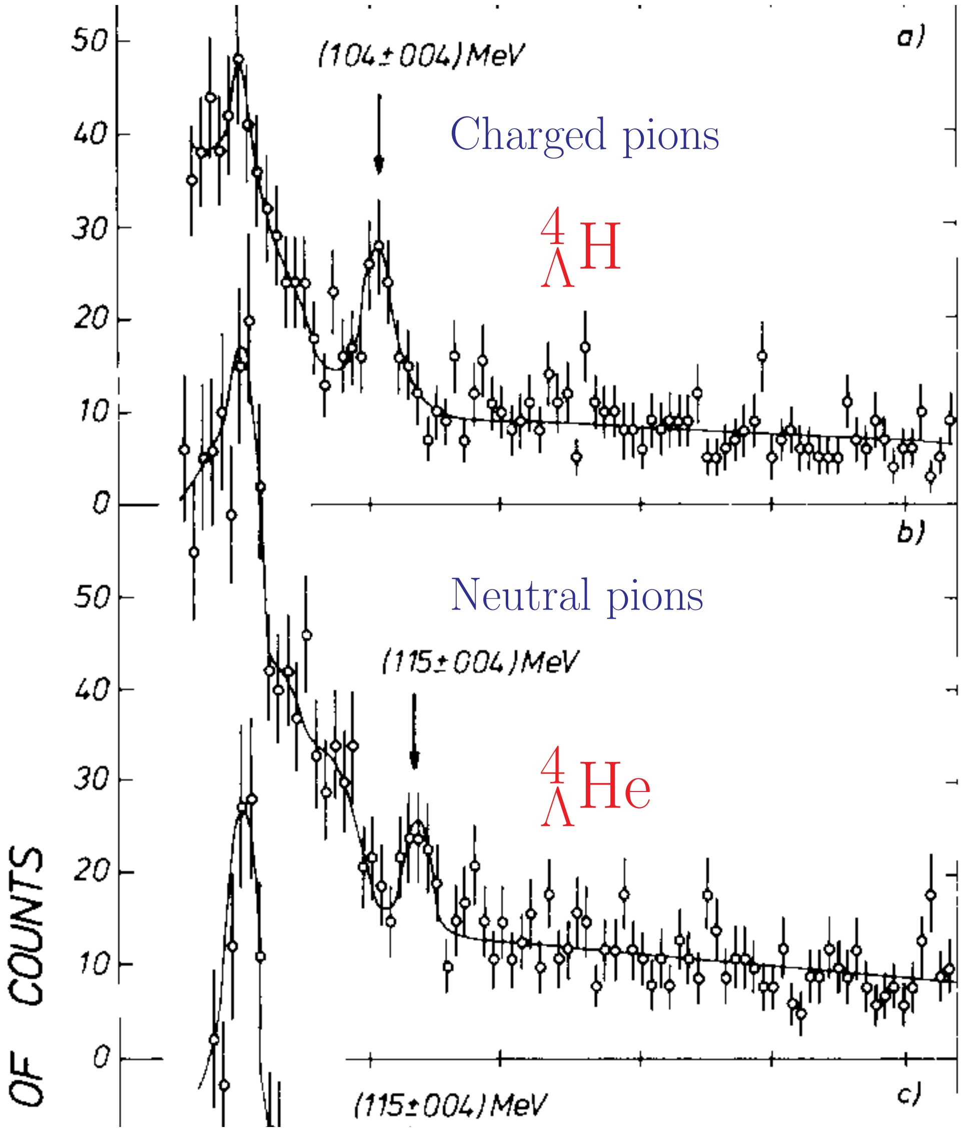
World data on *A* = *4* system



MAMI experiment confirmed Λ separation energy of ${}_{\Lambda}{}^{4}$H

P. Achenbach, Mainz

Millener



M. Bedjidian et al., Phys. Lett. B 83, 252 (1979)

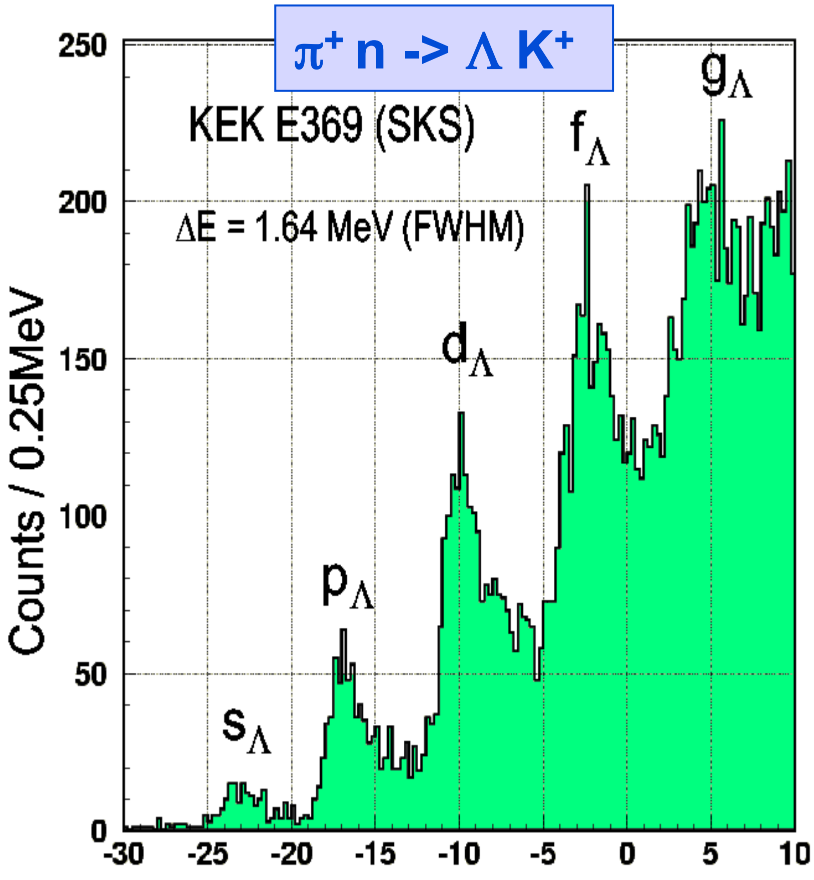
Tamura

Previous (π^+,K^+) data and ΛN interaction

SKS at KEK-PS

^{89}Y (π^+,K^+) $^{89}_{\Lambda}$Y

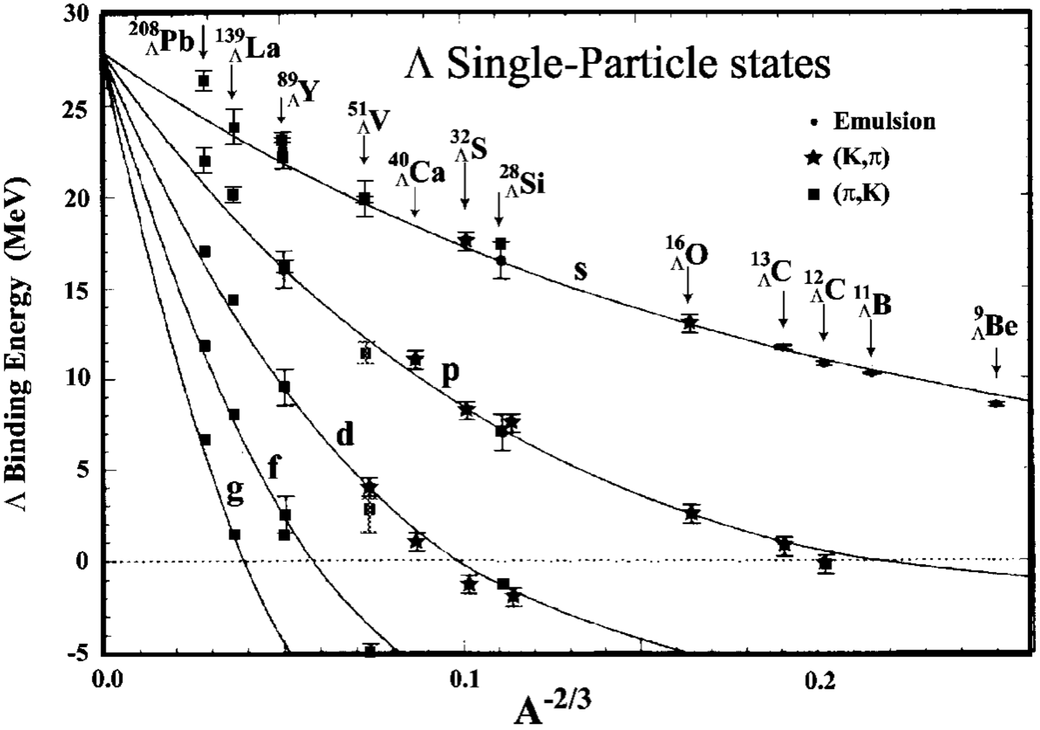
π^+ n -> Λ K^+



Mass of hypernucleus $-B_\Lambda$ (MeV)

Hotchi et al., PRC 64 (2001) 044302

Data as of 1996



U_Λ = - 30 MeV (< U_N = -50 MeV) established

better resolution
n-rich hypernuclei

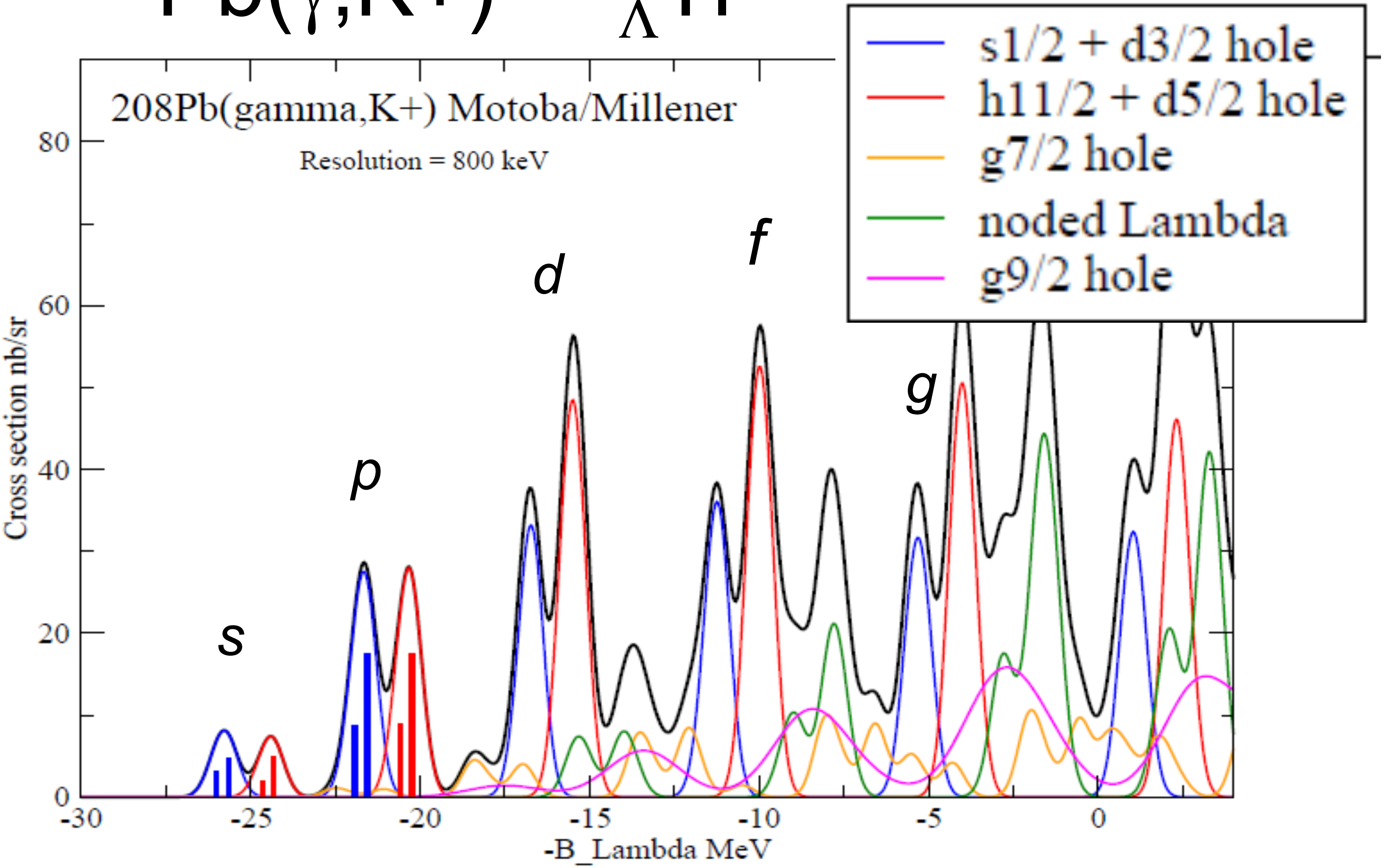
for further info. on ΛN int.

(e,e'K^+) at JLab

γ spectroscopy and (π^-,K^+) at J-PARC

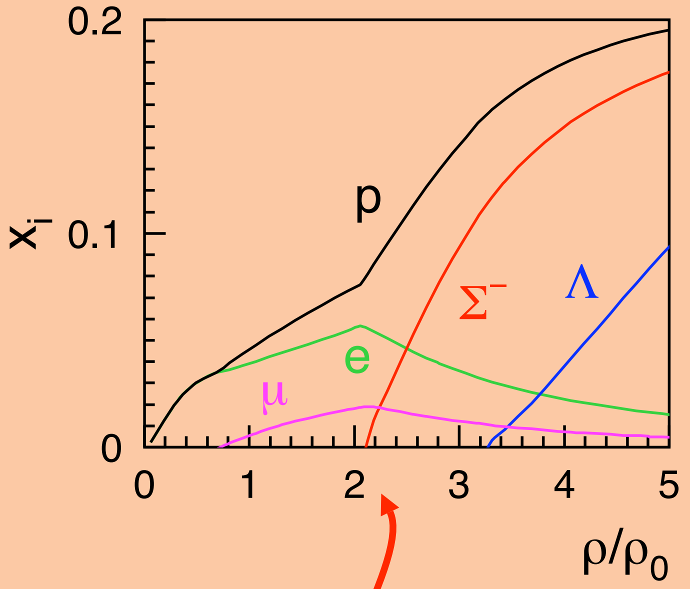
$^{208}Pb(\gamma,K+)\ ^{208}_{\Lambda}Tl$

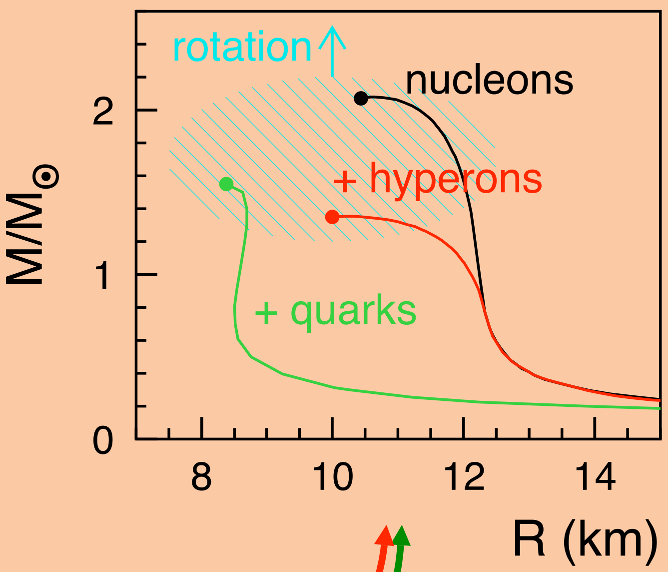
Motoba



We have an opportunity to observe a series of Lambda orbits ?

Generic implications for EOS and stellar structure:





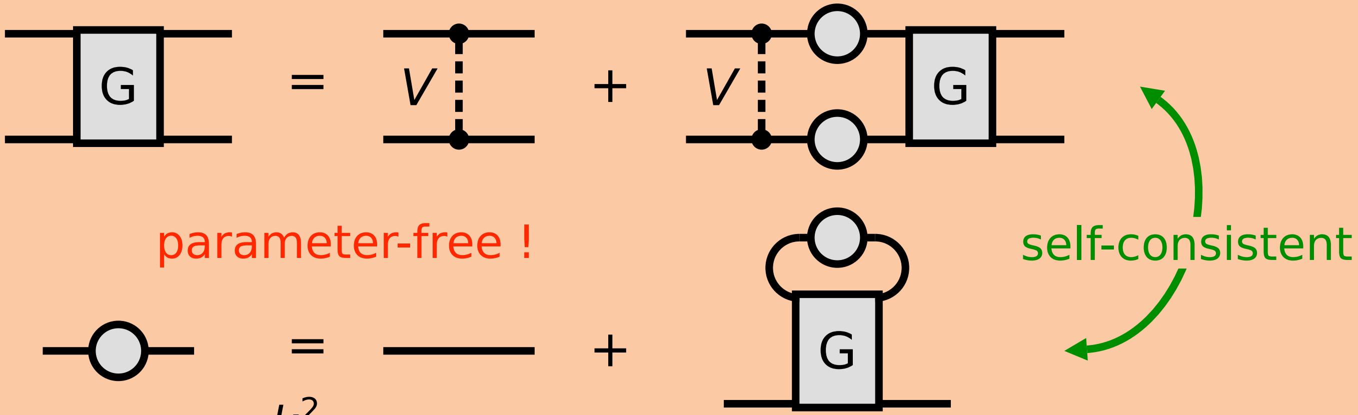
- Hyperon onset occurs at $\rho \sim 2 \ldots 3\, \rho_0$
- Softer EOS
- NS structure including hyperons

  . . . and including quark matter

H.-J. Schulze

Brueckner Theory of (Hyper)Nuclear Matter:

- Effective in-medium interaction G from potential V:



parameter-free !

self-consistent

$$e_k = m + \frac{k^2}{2m} + U(k)$$

Results: binding energy $\epsilon(\rho_n,\rho_p,\rho_\Lambda,\rho_\Sigma) = \sum_i \sum_{k<k_F^{(i)}} \left[e_k^{(i)} - \frac{U_i(k)}{2} \right]$

s.p. properties, cross sections, ...

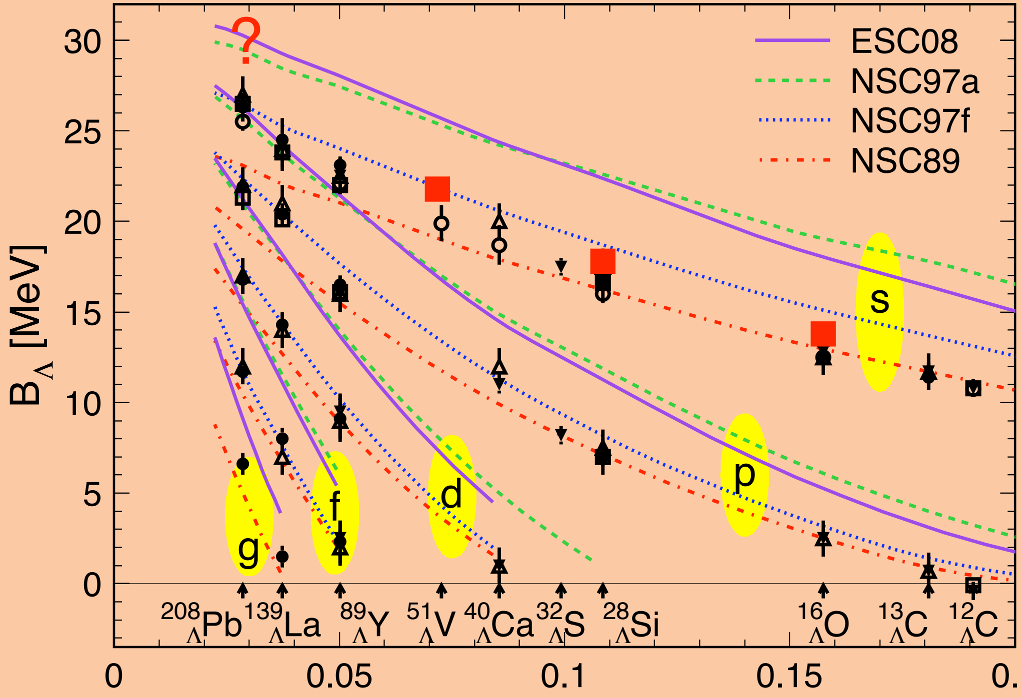
K.A. Brueckner and J.L. Gammel; PR 109, 1023 (1958) for nuclear matter

Extension to hypernuclear matter ...

H.-J. Schulze

Results: Single-Λ Hypernuclei:

- Lambda single-particle levels:



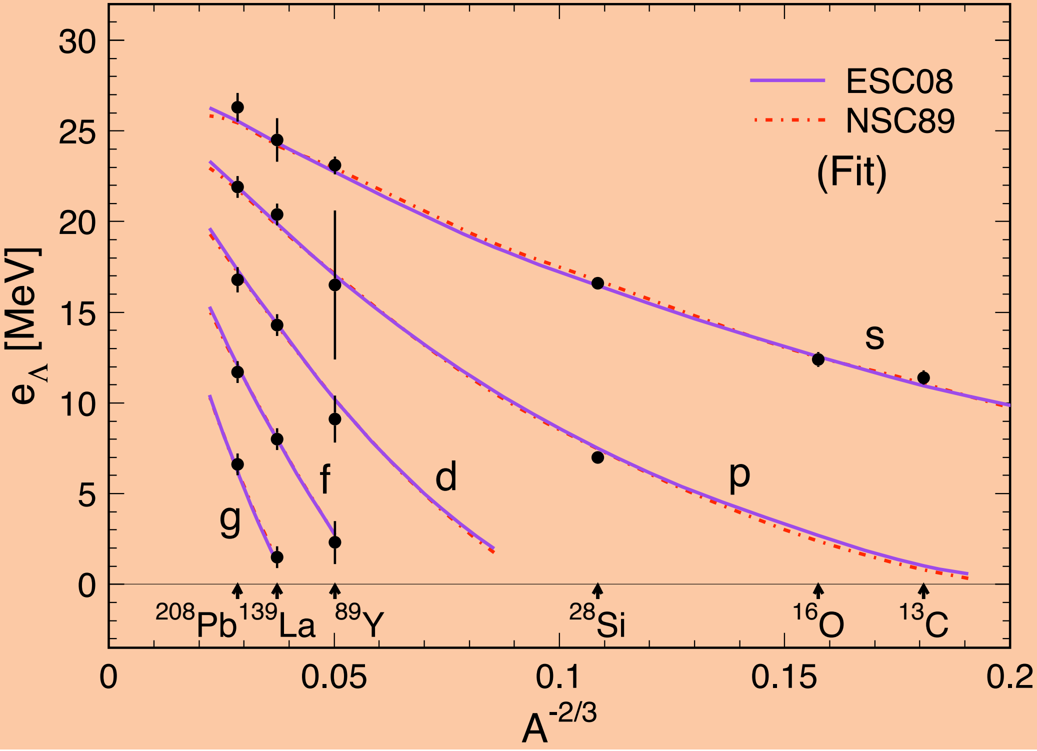
→ Best agreement with NSC89 and NSC97f potentials
No indication of strong hyperon TBF

H.-J. Schulze

Fit of empirical hyperon TBF:

$$\epsilon_{N\Lambda}(\rho_N,\rho_\Lambda) = \epsilon^{\mathrm{BHF}}_{N\Lambda}(\rho_N,\rho_\Lambda) + \tilde{\epsilon}_1\rho_N\rho_N\rho_\Lambda + \tilde{\epsilon}_2\rho_N\rho_\Lambda\rho_\Lambda + \tilde{\epsilon}_3\rho_\Lambda\rho_\Lambda\rho_\Lambda$$

Parameters $\tilde{\epsilon}_1, \tilde{\epsilon}_2, \tilde{\epsilon}_3$



H.-J. Schulze

Summary:

- Consistent theoretical BHF+SHF framework for hypernuclei and neutron star structure
- Nijmegen *NY* potentials are consistent with hypernuclear structure: Required corrections (TBF etc.) are small
- JLAB key experiment: ${}^{208}_{\Lambda}\mathrm{Pb}$ to fine-tune the *NY* interaction in bulk matter

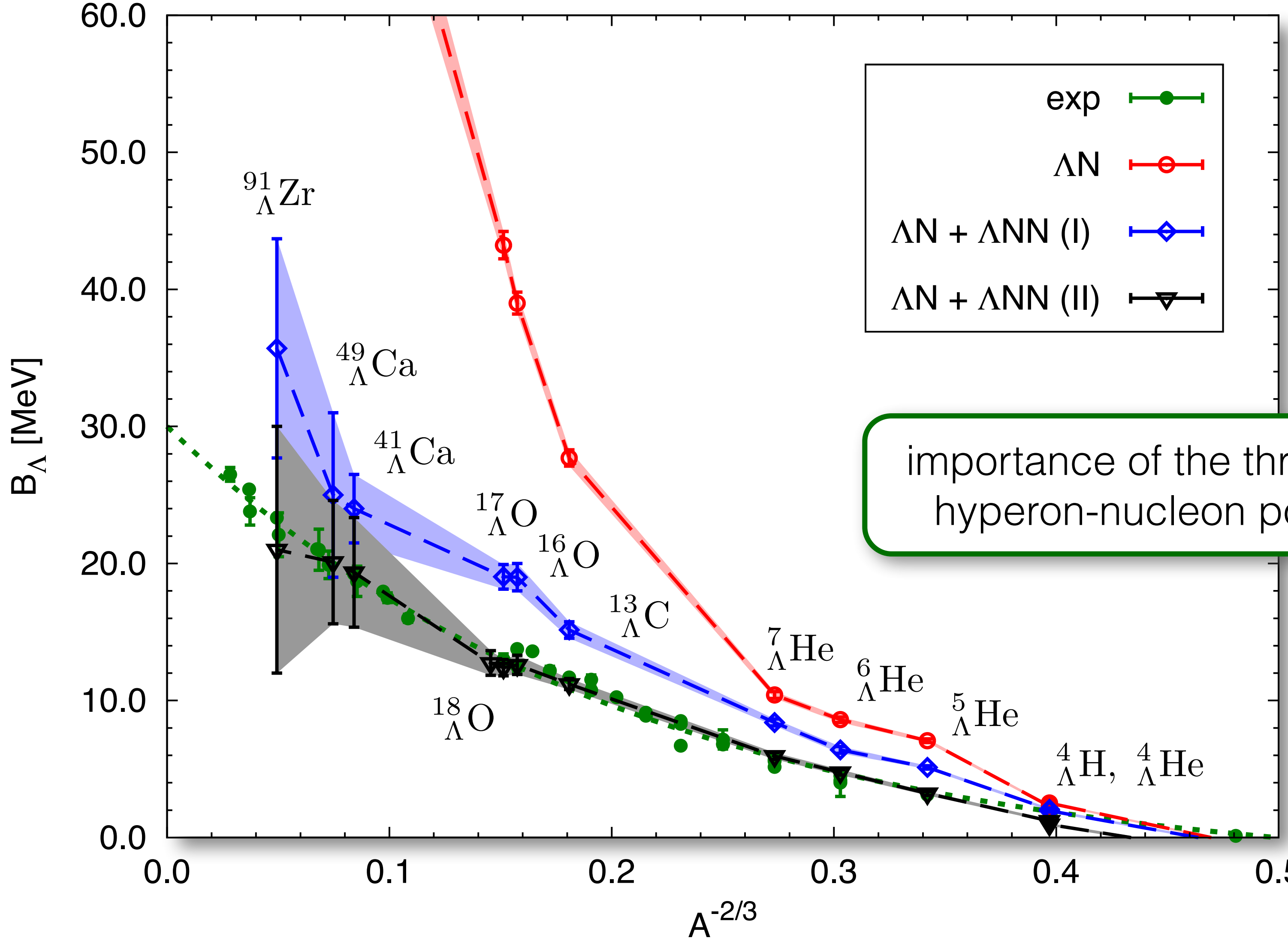
---

- Hyperons cannot be ignored in neutron stars !
- BHF EOS with hyperons predicts M_{max} not above $\sim 1.4\,M_{\odot}$
- Need “quark matter” to reach higher masses
- Currently $M_{\mathrm{max}} \approx 1.9\,M_{\odot}$ for hybrid stars in this approach

Results: hypernuclei

Diego Lonardoni, ANL

closed + open shell: new parametrization

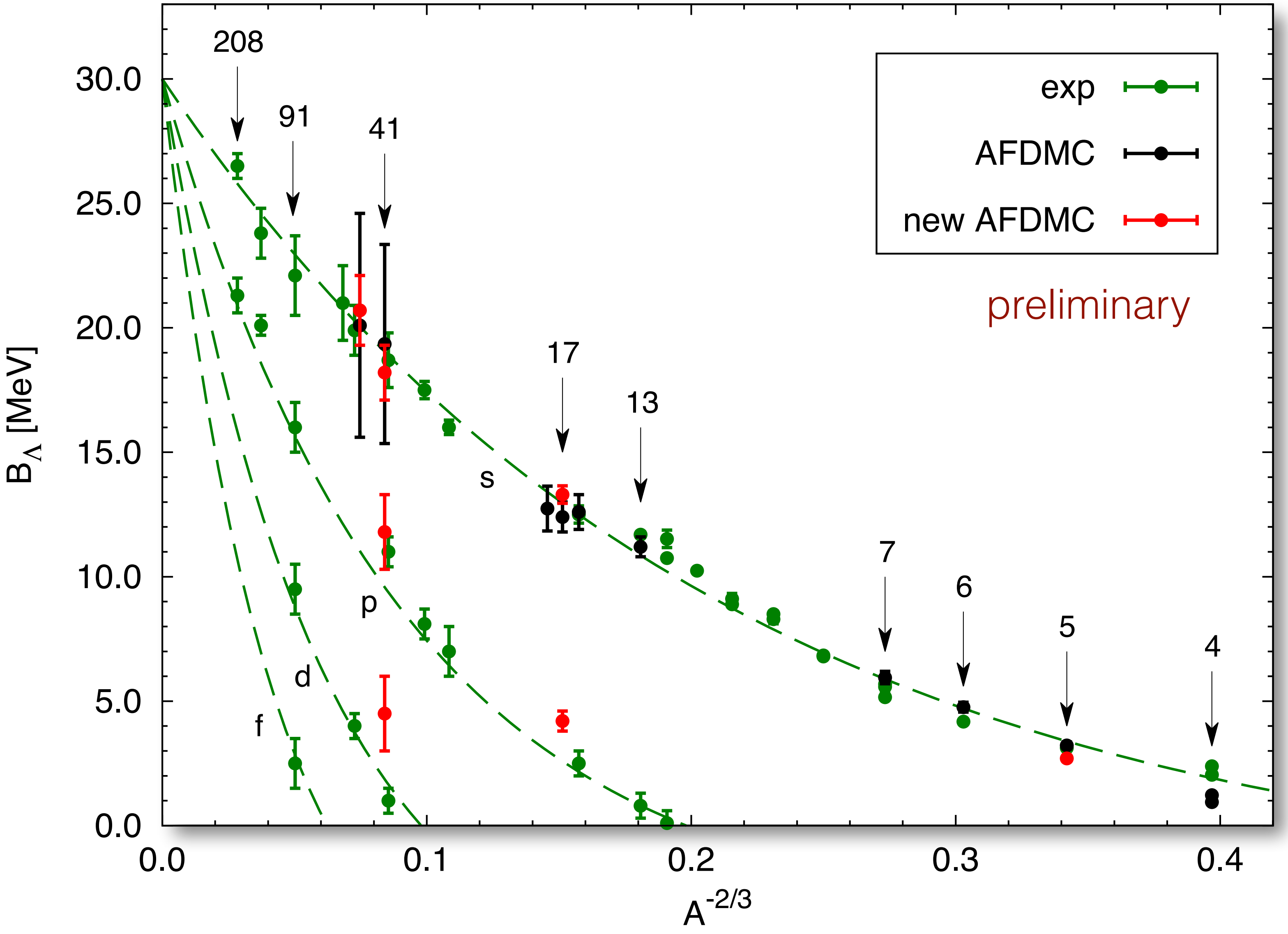


importance of the three-body hyperon-nucleon potential

D. L., F. Pederiva, S. Gandolfi, Phys. Rev. C 89, 014314 (2014)

Results: hypernuclei (improved^2)

s, p, d wave **Diego Lonardoni, ANL**



Results: hypernuclei (improved^2)

computing time **Diego Lonardoni, ANL**

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

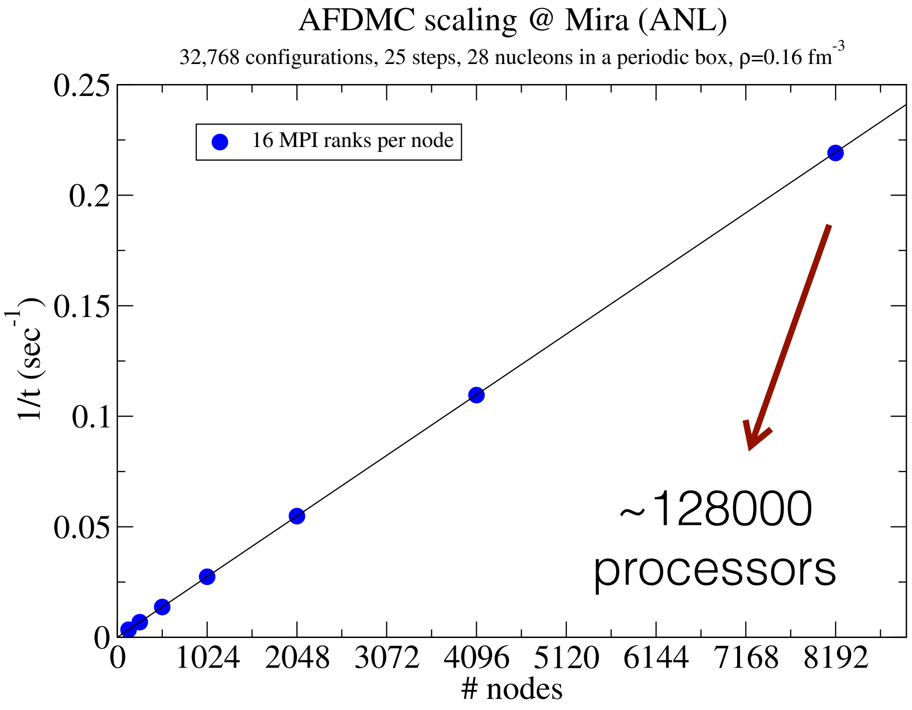
→ 128 processors

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

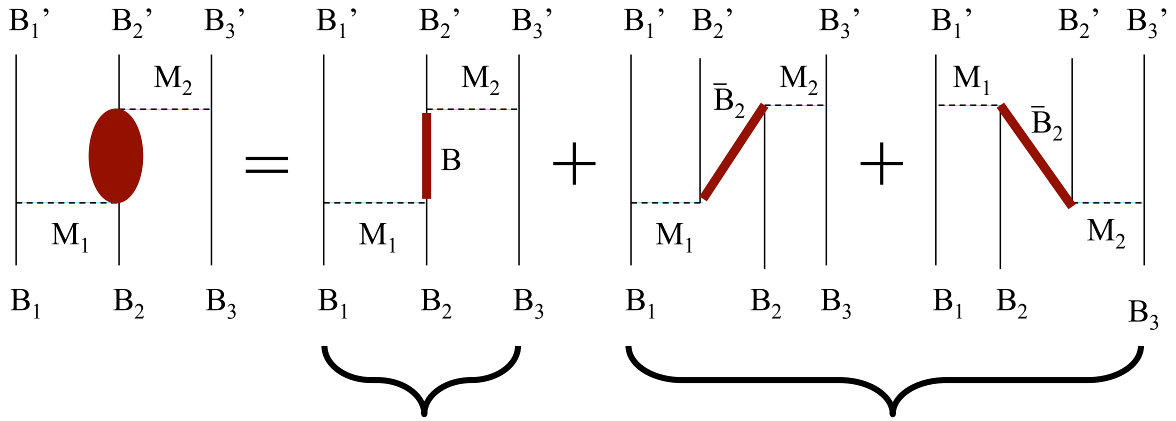


~128000 processors

S. Gandolfi, unpublished

Isaac Vidana: uses BHF

Two-meson exchange Hyperonic TBF



B_i B_i': N, Λ, Σ   B - excitation   Z – diagram

M_i: π, K, σ, ω   B: Λ, Σ, Δ, Σ* $\bar{B}_2$: $\bar{N}$, $\bar{\Lambda}$, $\bar{\Sigma}$

Vertices: consistent with YN and YY

Repulsion at high densities due to Z-diagram as in NNN

- Simple model to establish numerical lower and upper limits to the effect of hyperonicTBF on the maximum mass of NS.

Assuming the strength of hyperonic TBF ≤ nucleonic TBF:

$1.27\ M_\odot < M_{max} < 1.60\ M_\odot$ compatible with 1.4-1.5 $M_\odot$

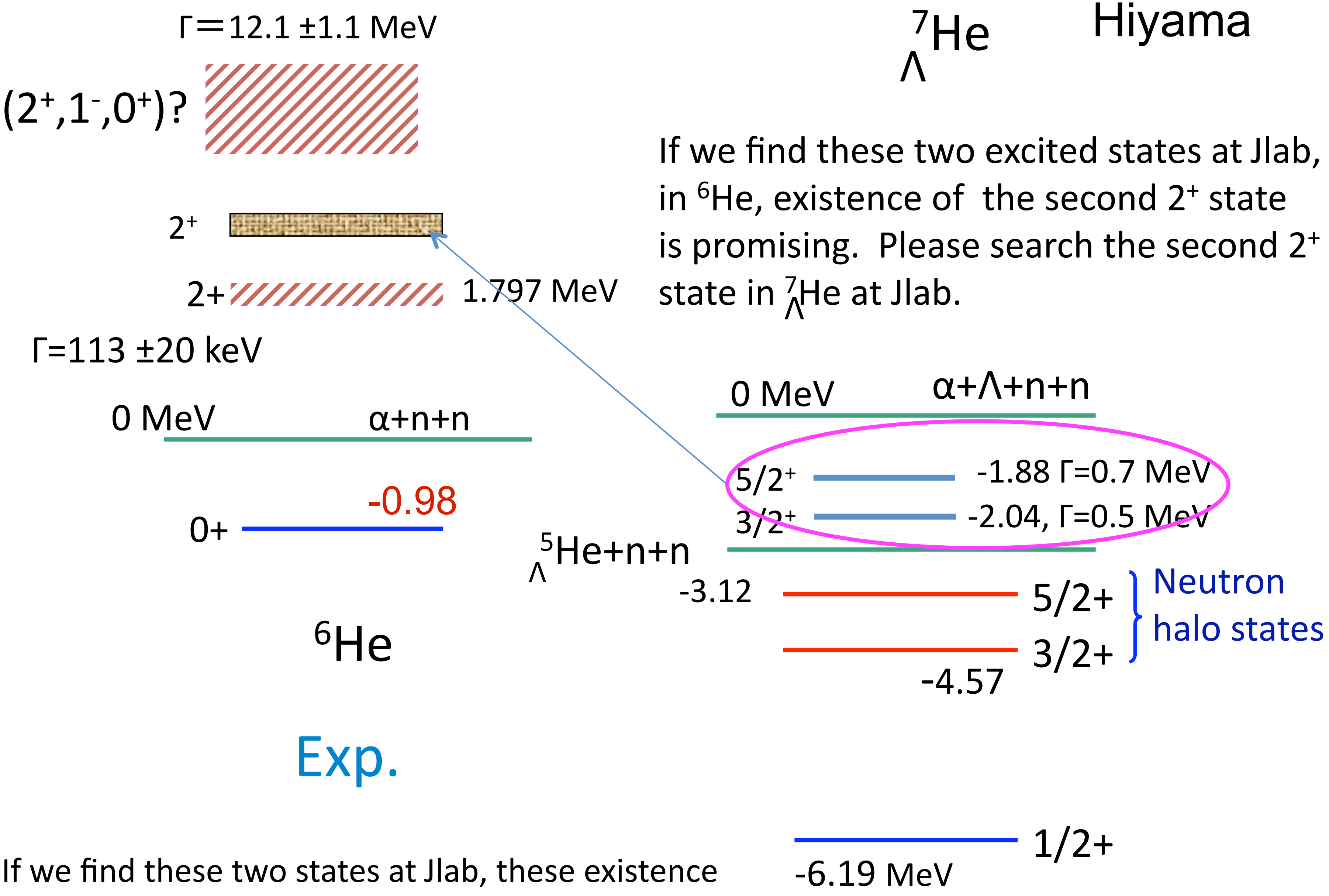
but incompatible with observation of very massive NS

Nuclear Structure through Hypernuclei

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

Hiyama

If we find these two excited states at Jlab, in ^{6}He, existence of the second 2^+ state is promising. Please search the second 2^+ state in ${}^{7}_{\Lambda}$He at Jlab.



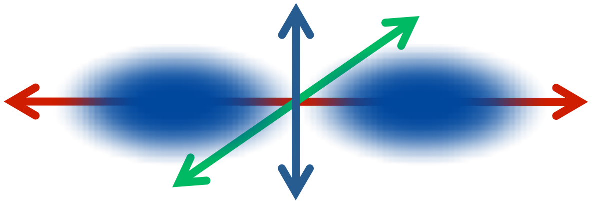
If we find these two states at Jlab, these existence contribute to unstable nuclear physics.

Triaxial deformation

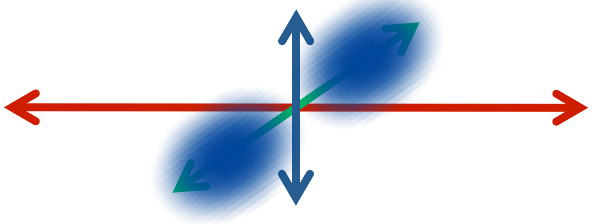
Isaka

If ^{24}Mg is triaxially deformed nuclei

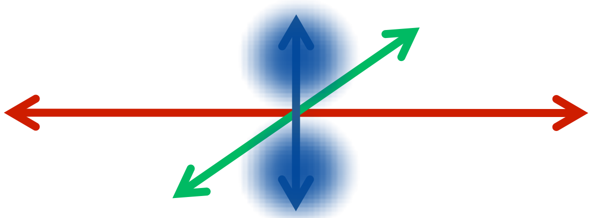
→ ***p*-states split into 3 different state**



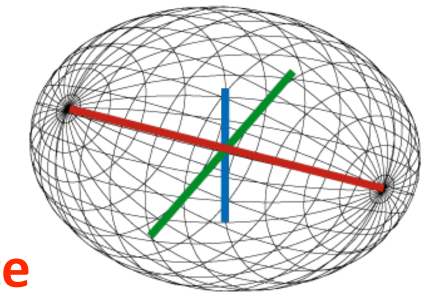
Large overlap leads to deep binding



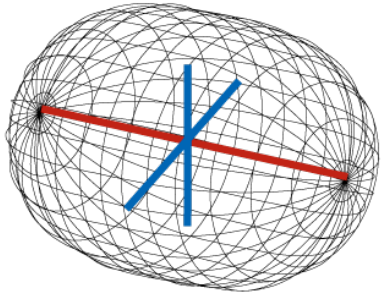
Middle



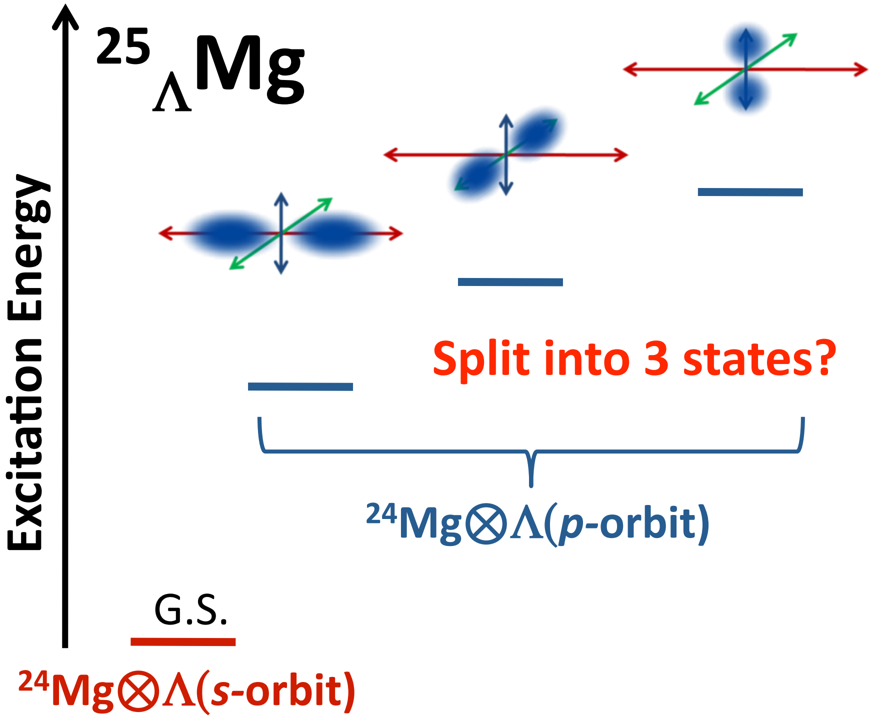
Small overlap leads to shallow binding



Triaxial deformation



Prolate deformation



Observing the 3 different *p*-states is strong evidence of triaxial deformation

Our (first) task: To predict the level structure of the *p*-states in $^{25}{}_{\Lambda}$Mg

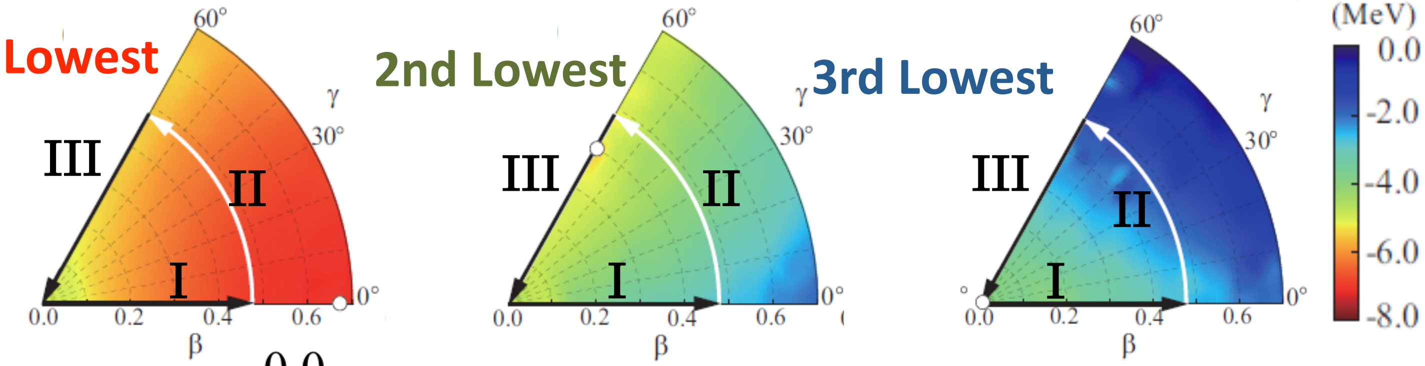
Results： Single particle energy of Λ hyperon ε_Λ

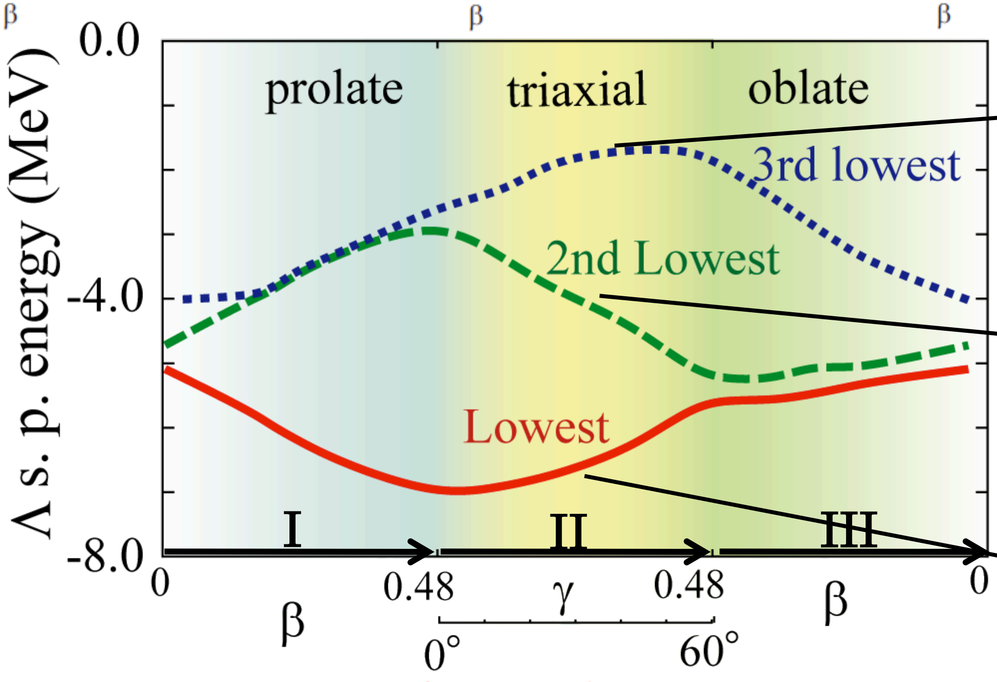
Isaka

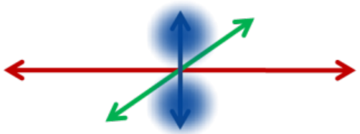
$^{25}_{\Lambda}$Mg (AMD)

$$\varepsilon_\Lambda(\beta_i,\gamma_i)=\left\langle \Psi^\pi(\beta_i,\gamma_i)\right|\left(\hat{T}_\Lambda+\hat{V}_{\Lambda N}\right)\left|\Psi^\pi(\beta_i,\gamma_i)\right\rangle$$

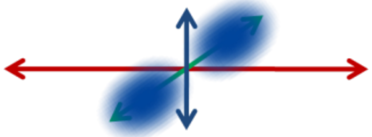
3 *p*-states with different spatial distributions of Λ in *p*-orbit



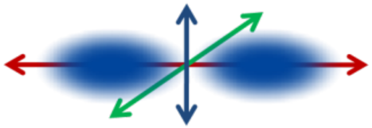




3rd lowest p state
(Parallel to short axis)



2nd lowest p state
(Parallel to middle axis)



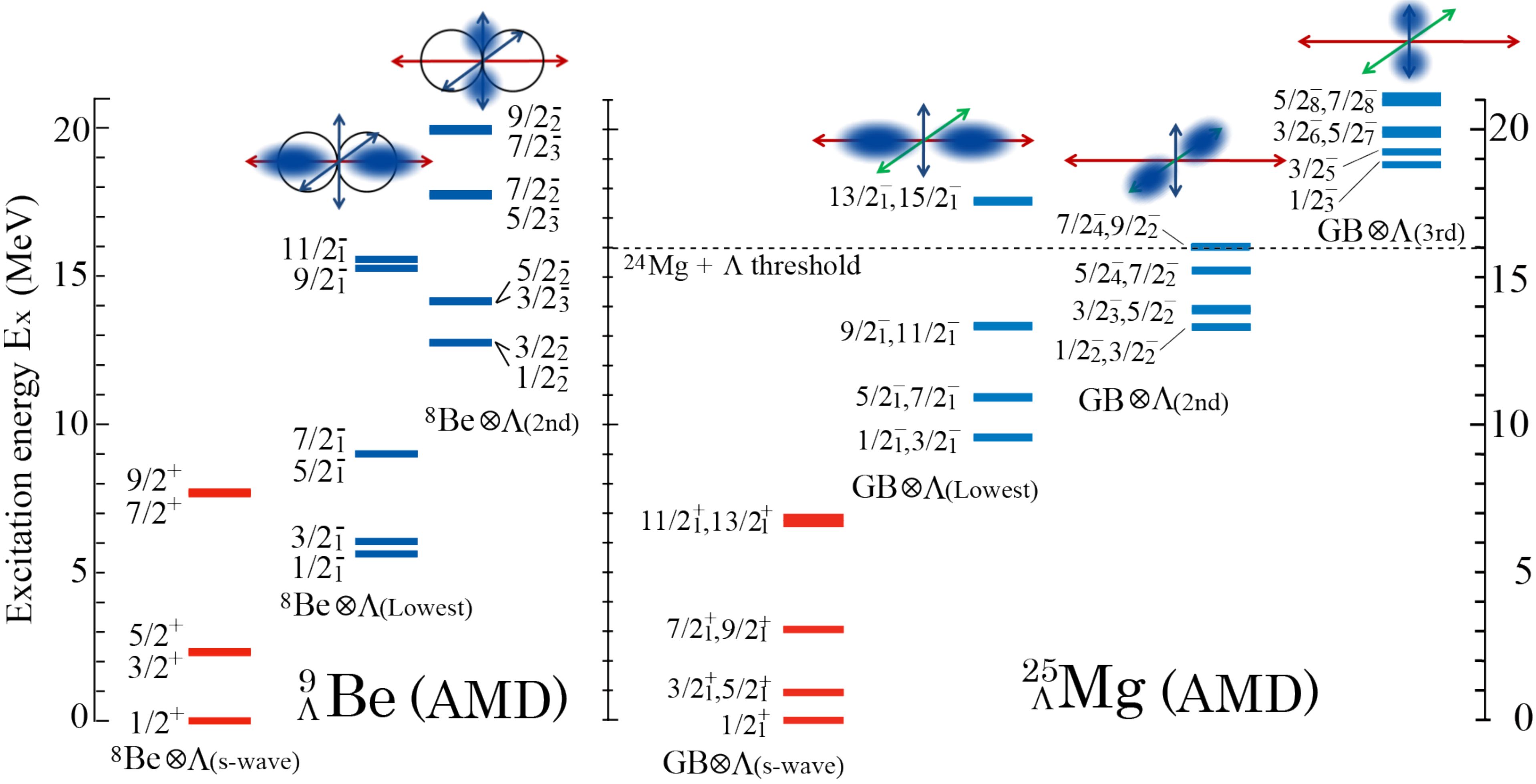
Lowest p state
(Parallel to long axis)

Λ s. p. energy is different from each other with triaxial deformation

Results: Excitation spectra

Isaka

- **3 bands are obtained by Λ hyperon in *p*-orbit** → **Splitting of the *p* states**
  - **^{24}Mg⊗Λp(lowest), ^{24}Mg⊗Λp(2nd lowest), ^{24}Mg⊗Λp(3rd lowest)**



Lowest threshold ${}^{21}_{\Lambda}\mathrm{Ne} + \Lambda$: in between 8.3 and 12.5 MeV

Summary
(a personal view)

- Someone really should measure Λp
- Remeasure A=3,4 system with <50 keV; MAMI or JLab, whoever can do it best
- Mass dependence of single particle levels all the way to Pb (several targets.)
- Keep theorists on their toes: calculations in support of a proposal need to explore more than just one parameter set.