AFDMC Calculations on Medium-Heavy Hypernuclei

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In collaboration with:

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- ✓ Francesco Pederiva, Trento
- ✓ Francesco Catalano, Uppsala

NSCL

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MICHIGAN STATE UNIVERSITY

FRIB

SciDAC Scientific Discovery through Advanced Computing

NUCLEI Nuclear Computational Low-Energy Initiative

NERSC

JLab, March 15, 2016

AFDMC for strange systems

✓ AFDMC wave function: single particle representation

$$\psi_T(R,S) = \prod_{\lambda i} f_c^{\Lambda N}(r_{\lambda i})\, \psi_T^N(R_N,S_N)\, \psi_T^\Lambda(R_\Lambda,S_\Lambda)$$

$$\begin{cases} \psi_T^\kappa(R_\kappa,S_\kappa) = \prod_{i<j} f_c^{\kappa\kappa}(r_{ij})\, \Phi_\kappa(R_\kappa,S_\kappa) & \kappa = N,\Lambda \\ \Phi_\kappa(R_\kappa,S_\kappa) = \mathcal{A}\left[\prod_{i=1}^{\mathcal{N}_\kappa} \varphi_\epsilon^\kappa(\boldsymbol{r}_i,s_i)\right] = \det\left\{\varphi_\epsilon^\kappa(\boldsymbol{r}_i,s_i)\right\} \end{cases}$$

→ s.p. orbitals
→ plane waves

$$s_i = \begin{pmatrix} a_i \\ b_i \\ c_i \\ d_i \end{pmatrix}_i = a_i|p\uparrow\rangle_i + b_i|p\downarrow\rangle_i + c_i|n\uparrow\rangle_i + d_i|n\downarrow\rangle_i$$

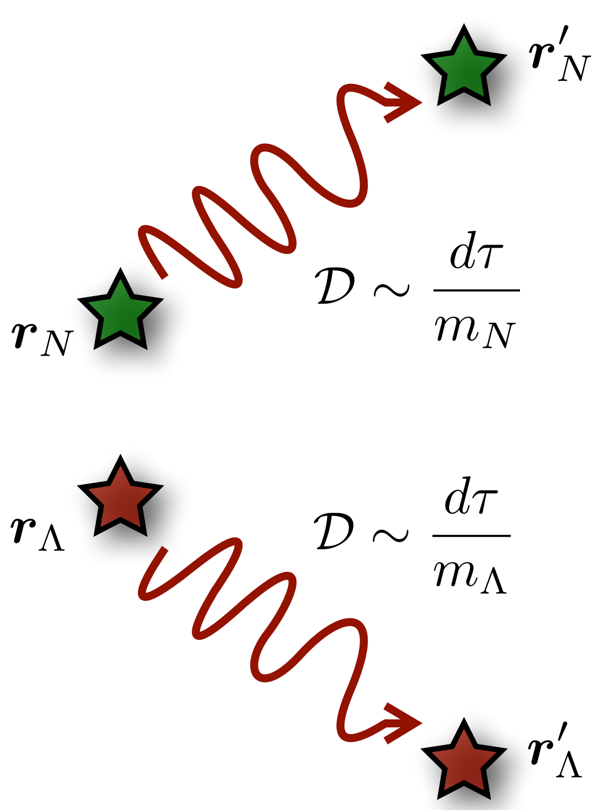
$$s_\lambda = \begin{pmatrix} u_\lambda \\ v_\lambda \end{pmatrix}_\lambda = u_\lambda|\Lambda\uparrow\rangle_\lambda + v_\lambda|\Lambda\downarrow\rangle_\lambda$$

AFDMC for strange systems

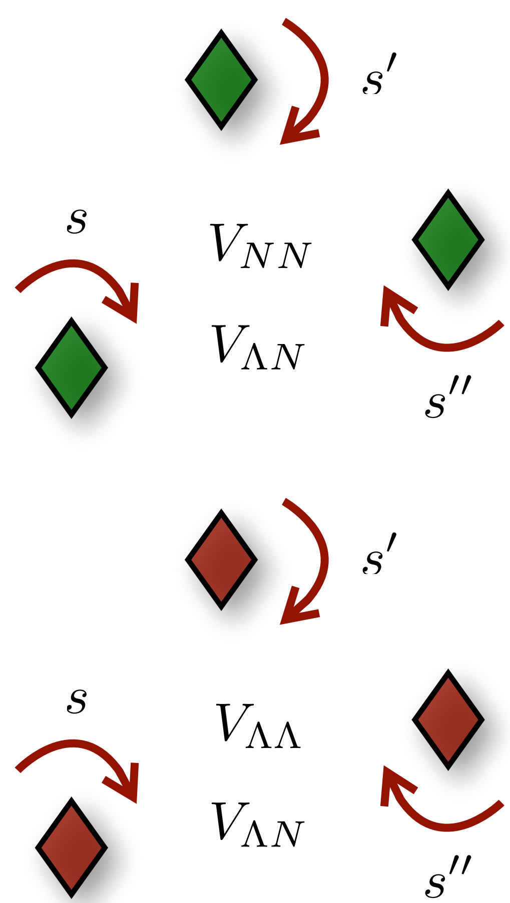
- ✓ AFDMC propagation

$$\underbrace{\langle SR|\psi(\tau+d\tau)\rangle}_{\text{final walkers}} = \int dR'\,dS' \underbrace{\langle SR|\,\mathrm{e}^{-(H-E_0)d\tau}\,|R'S'\rangle}_{\text{propagator}} \underbrace{\langle S'R'|\psi_T(\tau)\rangle}_{\text{initial walkers}}$$

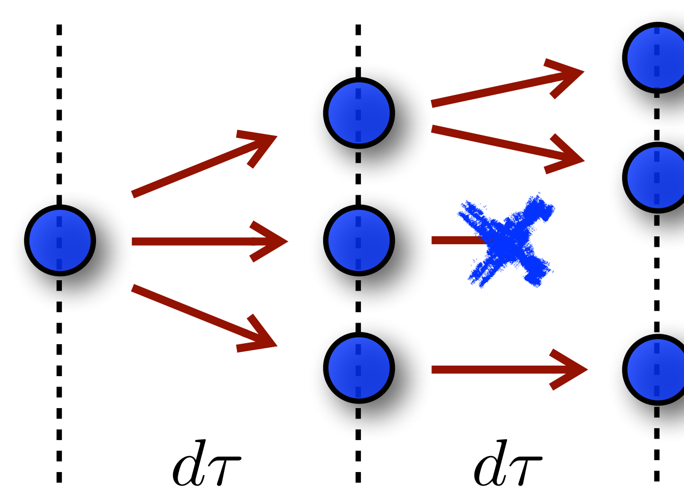
diffusion (DMC): $d\tau$



rotation (AF): $\sqrt{d\tau}$



branching: $d\tau$



AFDMC for strange systems

✓ AFDMC algorithm

- imaginary time projection ⟶ exact ground state
- single particle wf + HS transformation ⟶ large number of particles
- stochastic method ⟶ error estimate: $\sigma \sim 1/\sqrt{\mathcal{N}}$

✓ AFDMC Hamiltonians

- nucleon-nucleon phenomenological interaction: Argonne & Urbana

$$H = \sum_i \frac{p_i^2}{2m_N} + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

2B: NN scattering + deuteron

3B: nuclei + nuclear matter

AFDMC for strange systems

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- ✓ AFDMC Hamiltonians
  - nucleon-nucleon phenomenological interaction: Argonne & Urbana
  - hyperon-nucleon phenomenological interaction: Argonne like

$$H = \sum_i \frac{p_i^2}{2m_N} + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

$$+ \sum_\lambda \frac{p_\lambda^2}{2m_\Lambda} + \sum_{\lambda,i} v_{\lambda i} + \sum_{\lambda,i<j} v_{\lambda ij}$$

2B: Λp scattering + $A = 4$ CSB*

3B: no unique fit

AFDMC for strange systems

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$$+ \sum_\lambda \frac{p_\lambda^2}{2m_\Lambda} + \sum_{\lambda,i} v_{\lambda i} + \sum_{\lambda,i<j} v_{\lambda ij}$$

use QMC to fit hyp. exp. data

$$B_\Lambda = E(^{A-1}Z) - E(^{A}_{\Lambda}Z)$$

3B: no unique fit

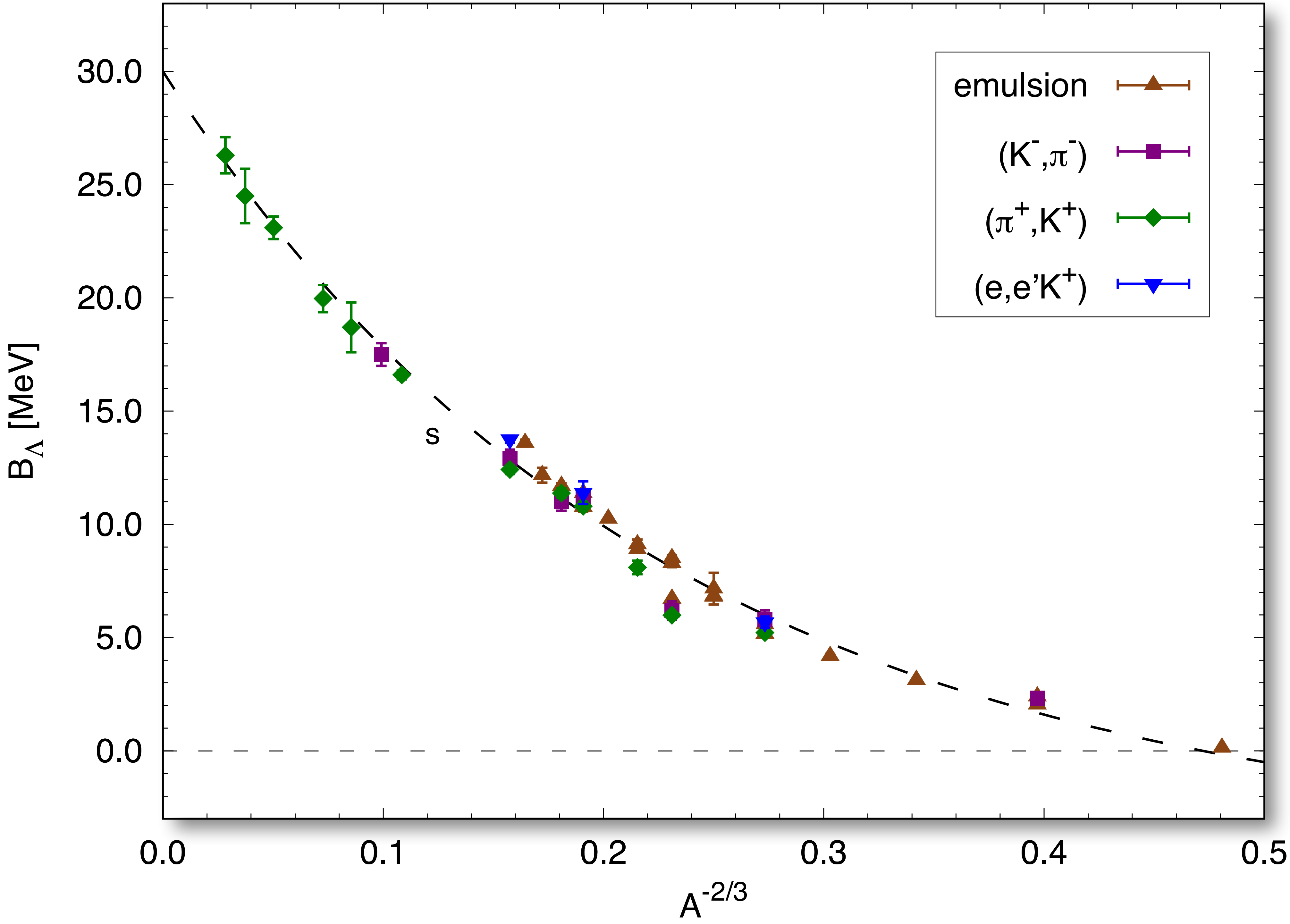
AFDMC results: nuclei

nucleon-nucleon interaction

nucleus	AV4′	AV6′	AV7′	AV4′+UIX$_c$	exp
^{4}He (0^+)	-32.83(5)	-27.09(3)	-25.7(2)	-26.63(2)	-28.295
^{15}O $(\frac{1}{2}^-)$	–	–	–	-99.43(2)	-111.955
^{16}O (0^+)	-180.1(4)	-115.6(3)	-90.6(4)	-119.9(2)	-127.619
^{39}K $(\frac{3}{2}^+)$	–	–	–	-360.8(2)	-333.724
^{40}Ca (0^+)	-597(3)	-322(2)	-209(1)	-383.3(3)	-342.051
^{44}Ca (0^+)	–	–	–	-397.8(5)	-380.960
^{47}K $(\frac{1}{2}^+)$	–	–	preliminary –	-386.3(2)	-400.199
^{48}Ca (0^+)	-645(3)	–	–	-413.2(3)	-416.001

S. Gandolfi, A. Lovato, J. Carlson, K. E. Schmidt, Phys. Rev. C 90, 061306(R) (2014)
F. Pederiva, F. Catalano, D. L., A. Lovato, S. Gandolfi, arXiv:1506.04042 (2015)

AFDMC results: hypernuclei



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

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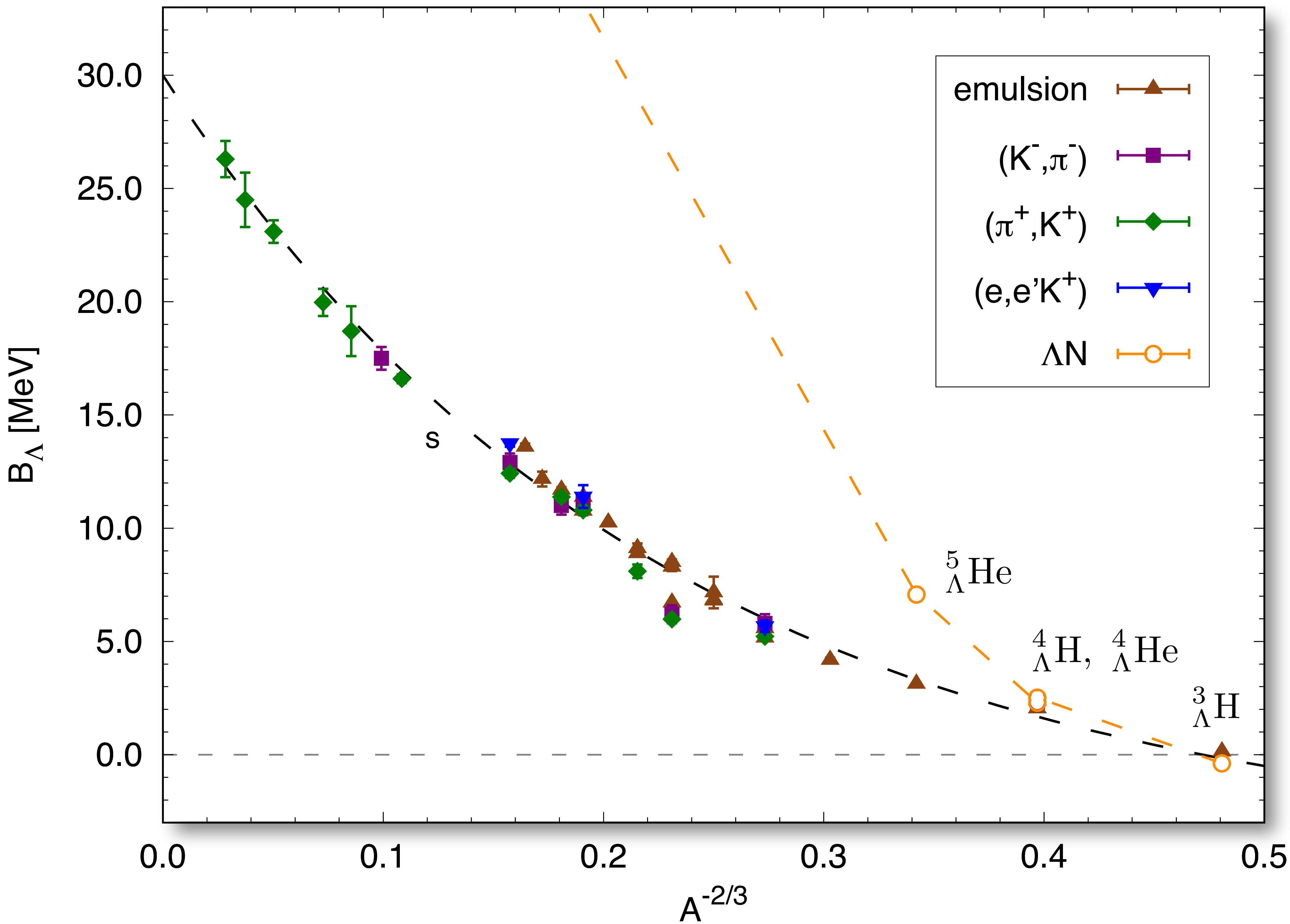

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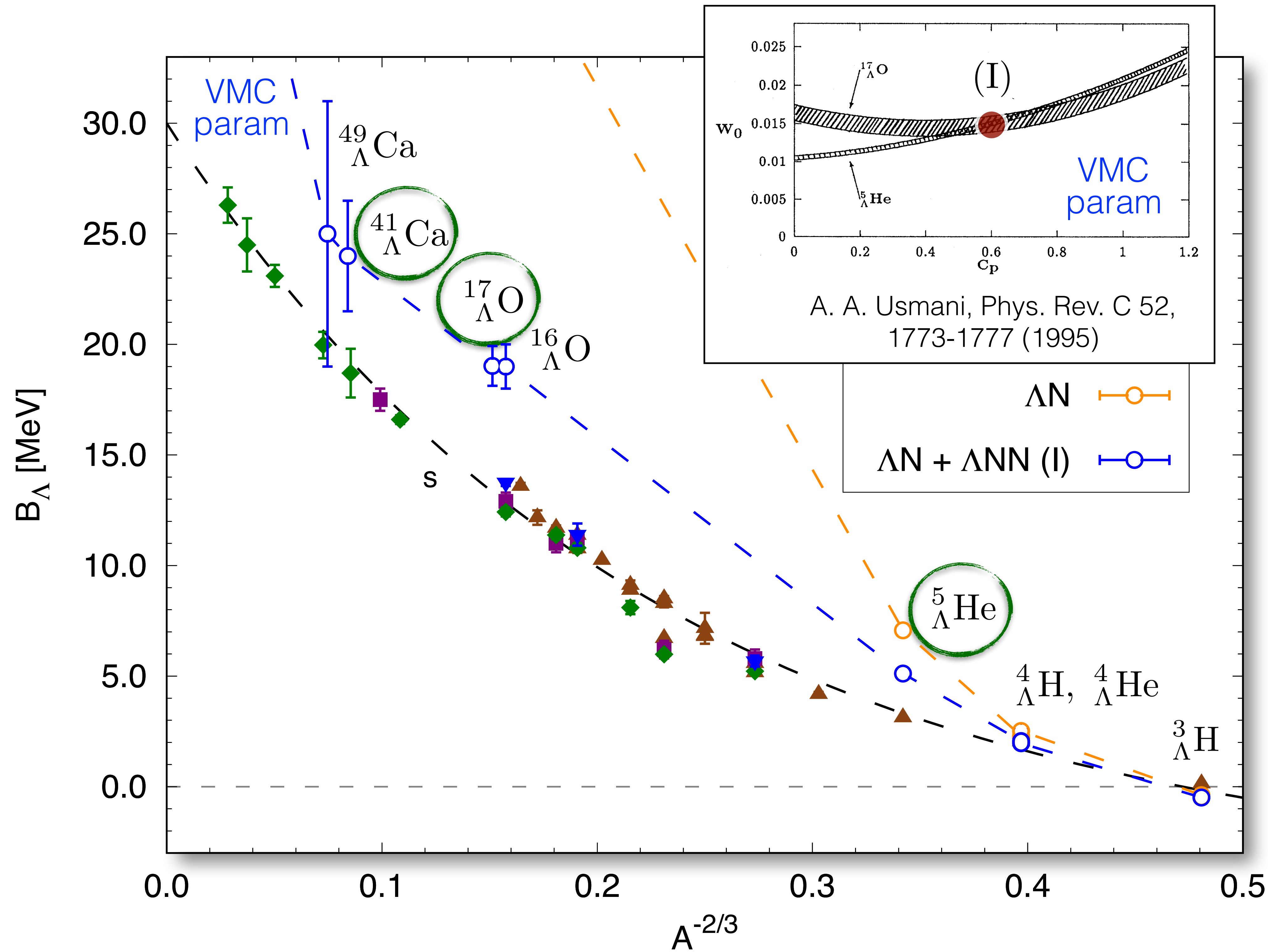

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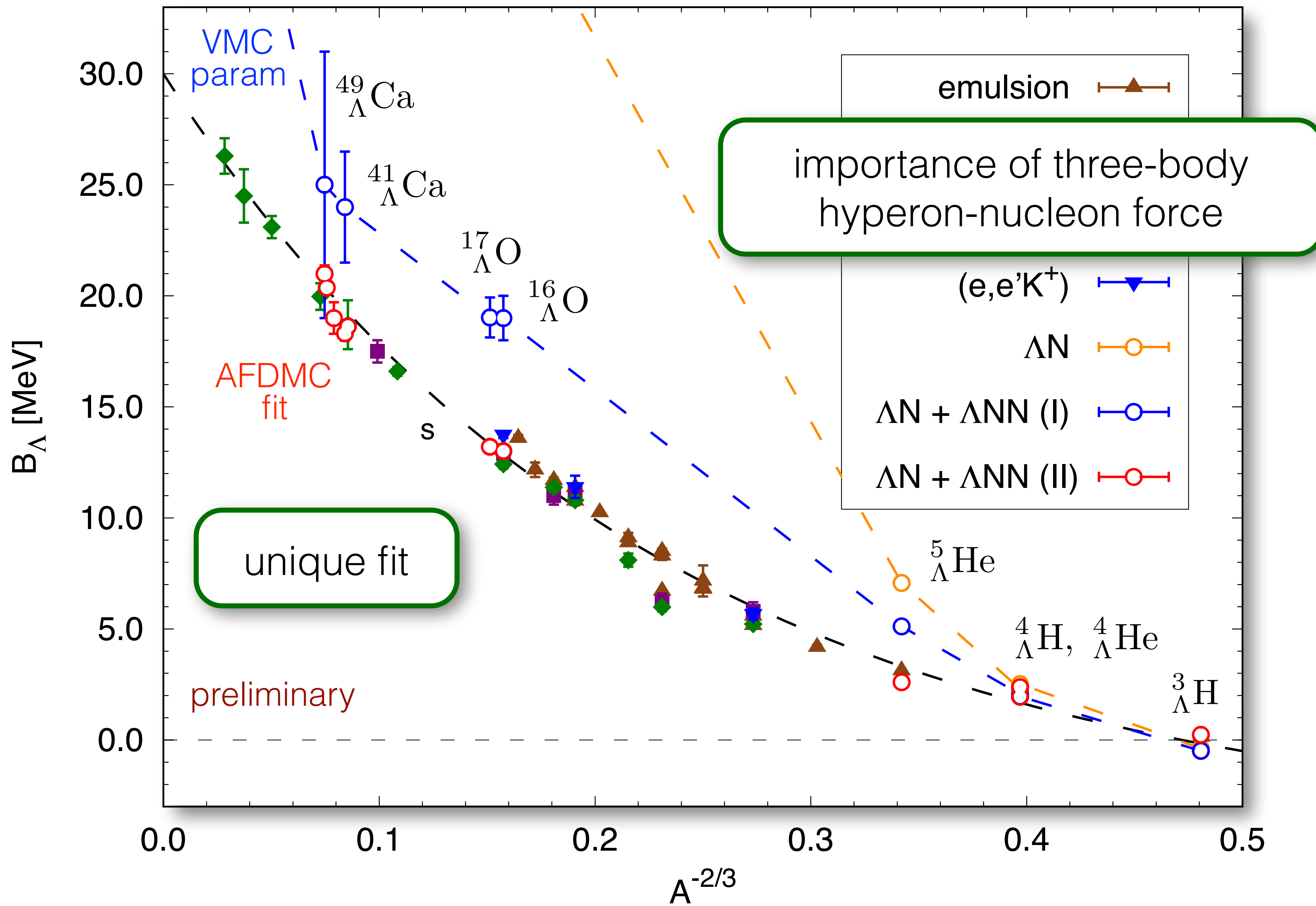

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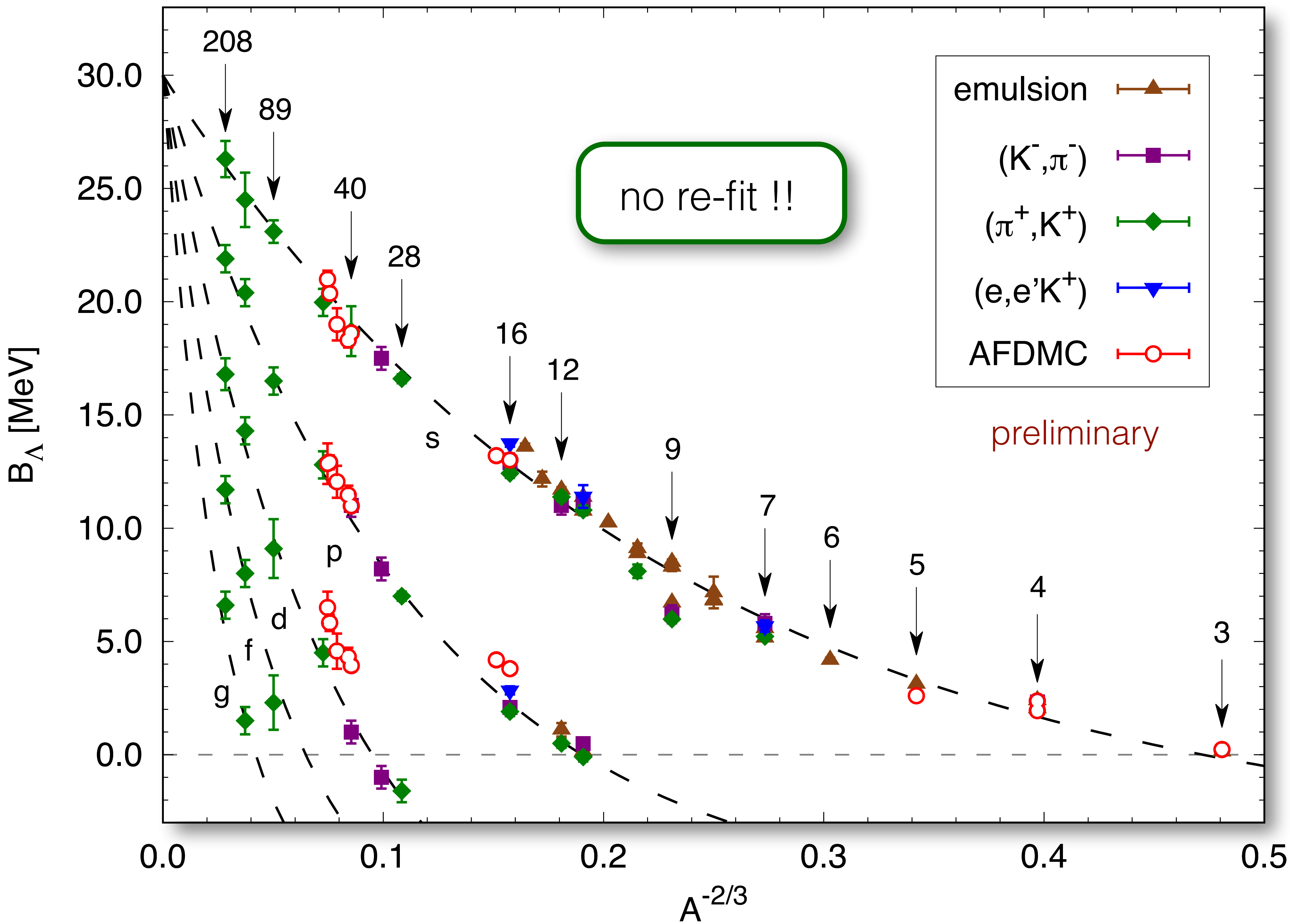

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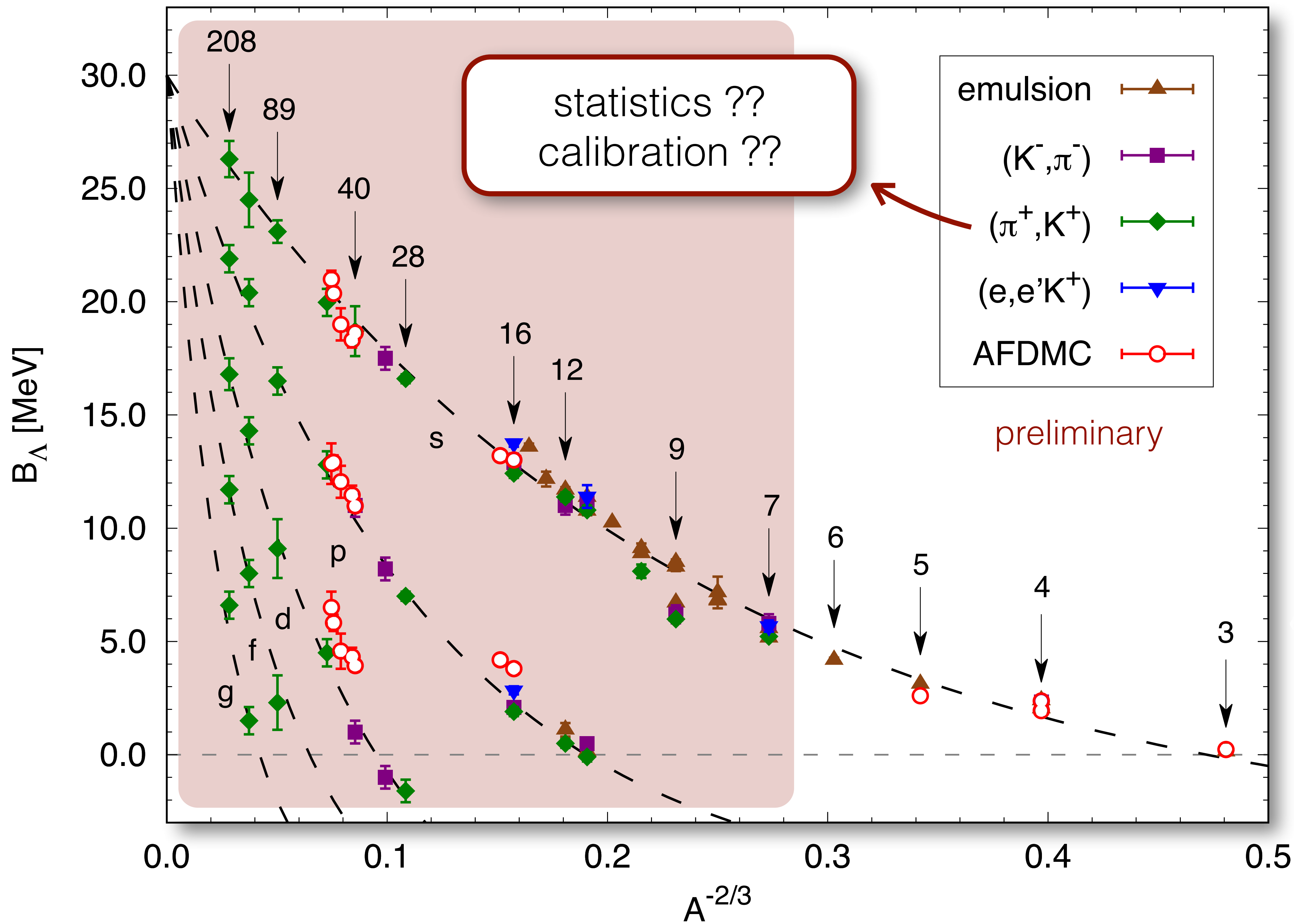

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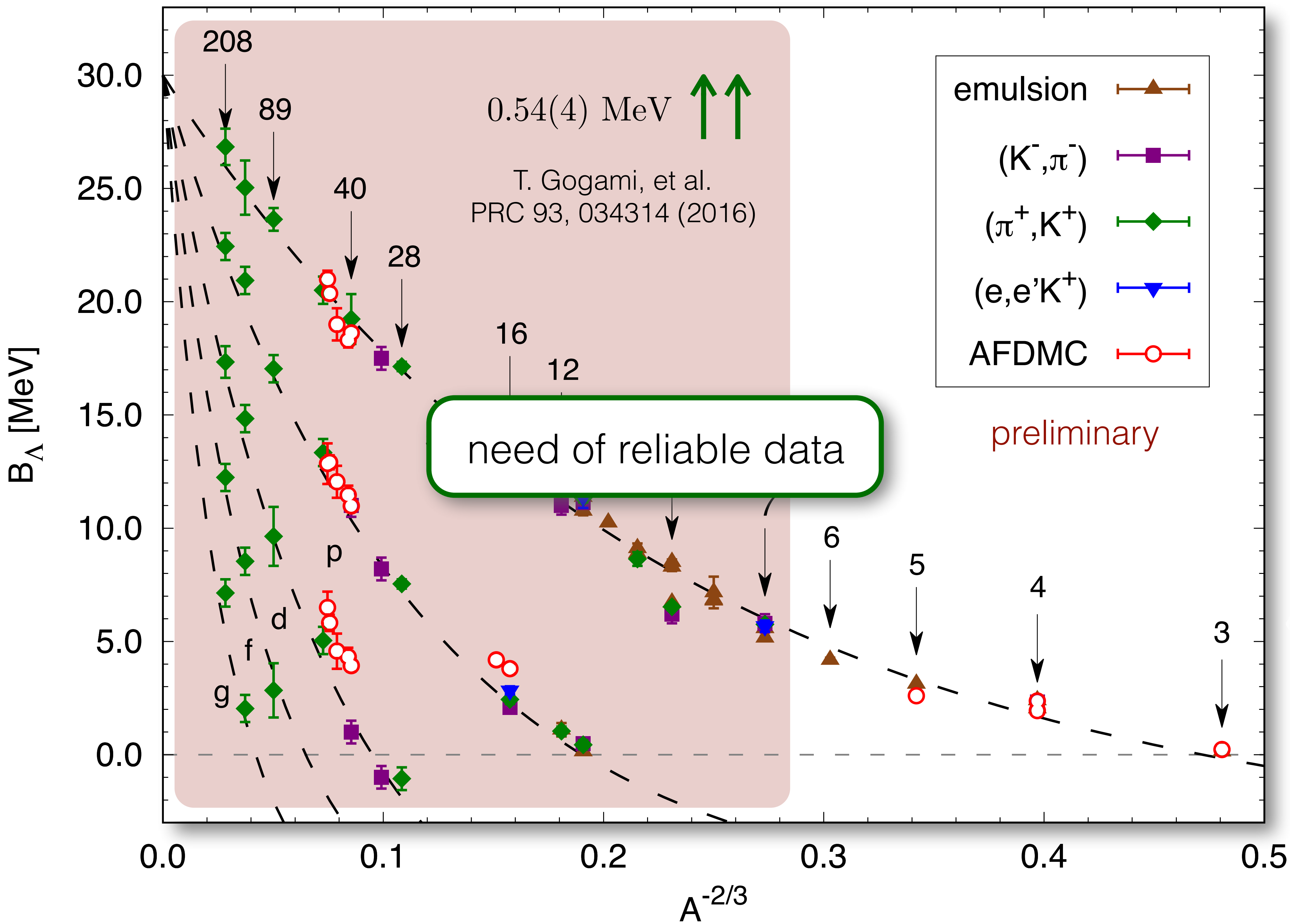

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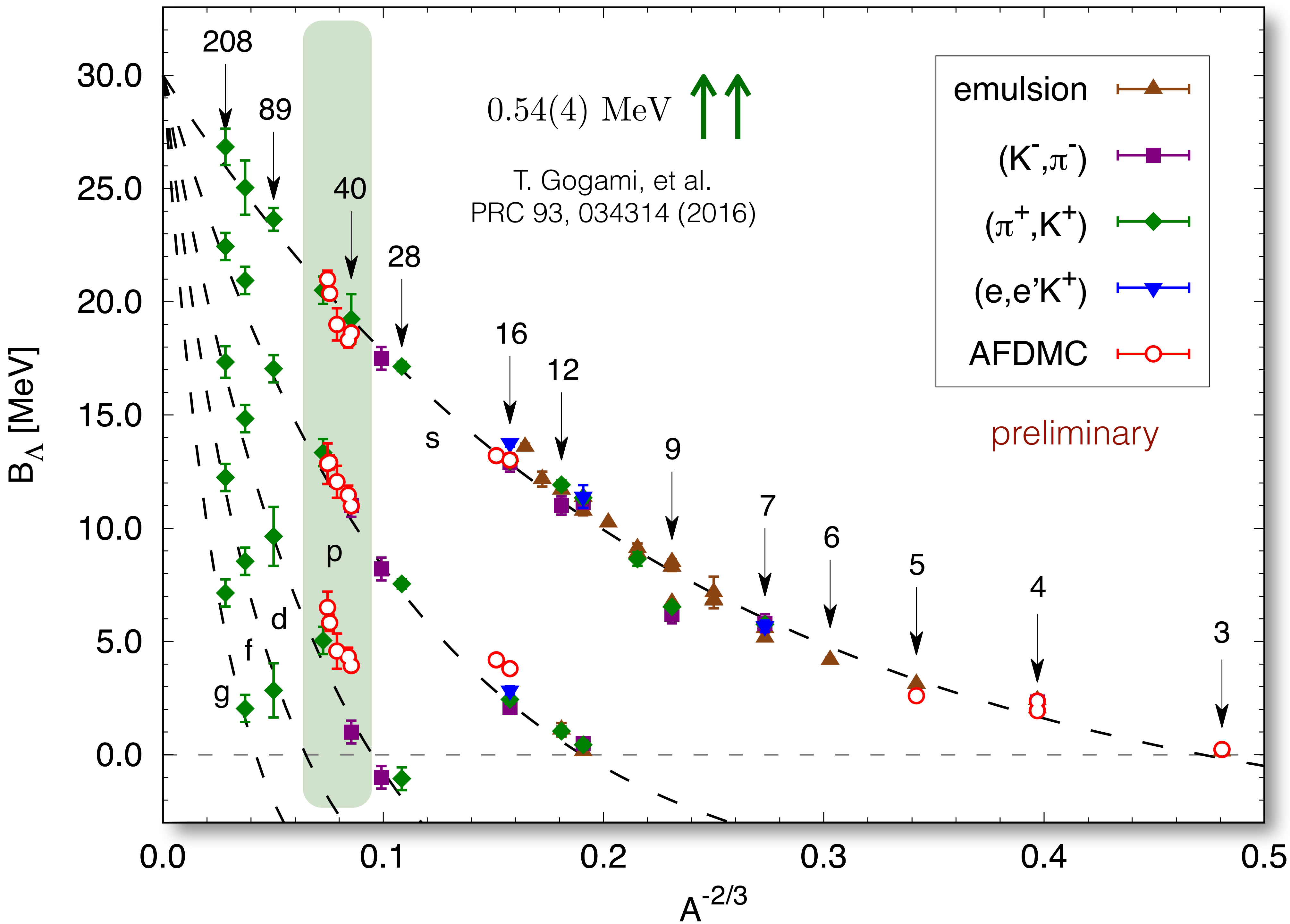

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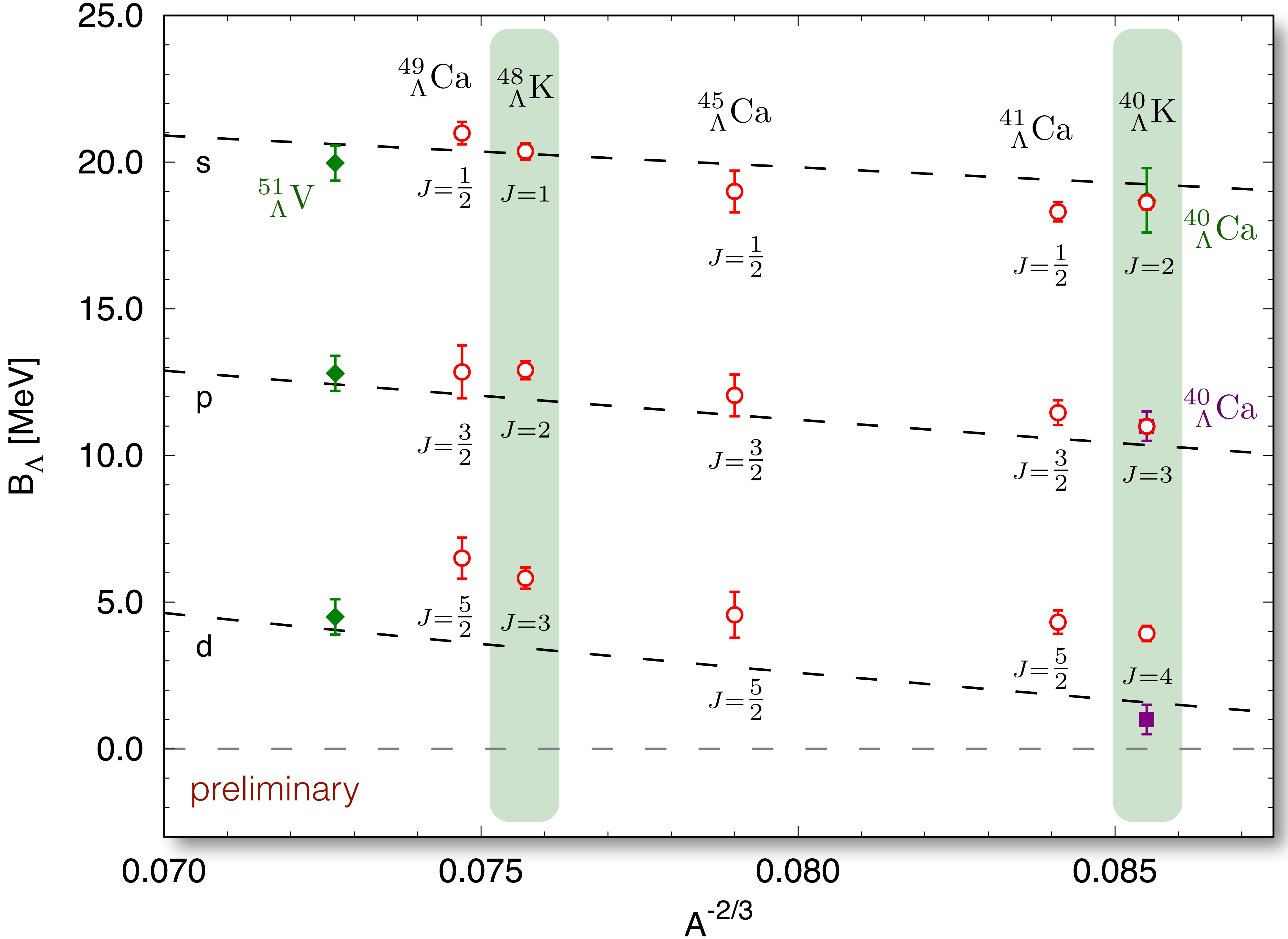
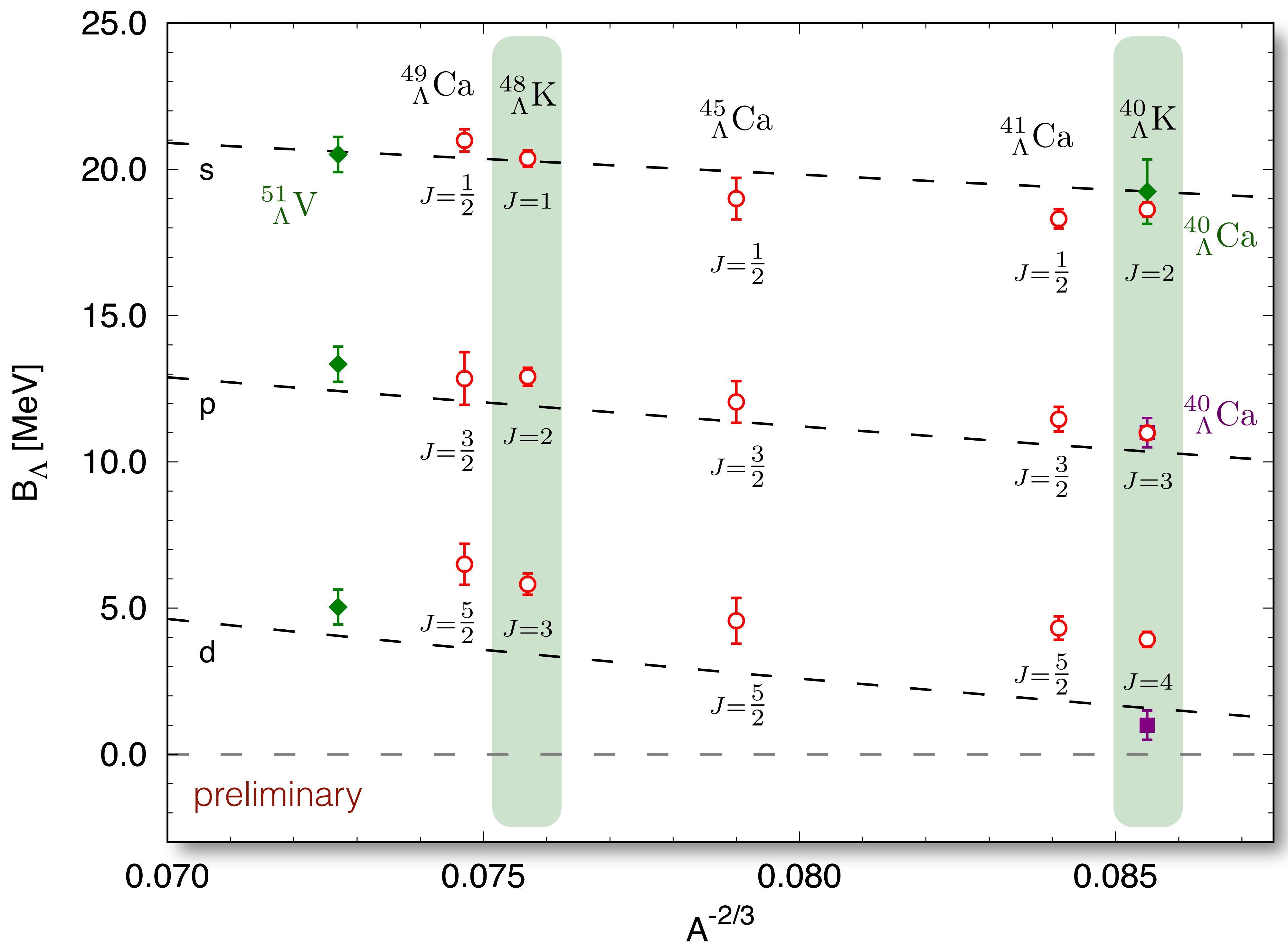


$^{48}\mathrm{Ca}(e,e'K^+)^{48}_{\Lambda}\mathrm{K}$ $\qquad$ $^{40}\mathrm{Ca}(e,e'K^+)^{40}_{\Lambda}\mathrm{K}$

AFDMC results: hypernuclei



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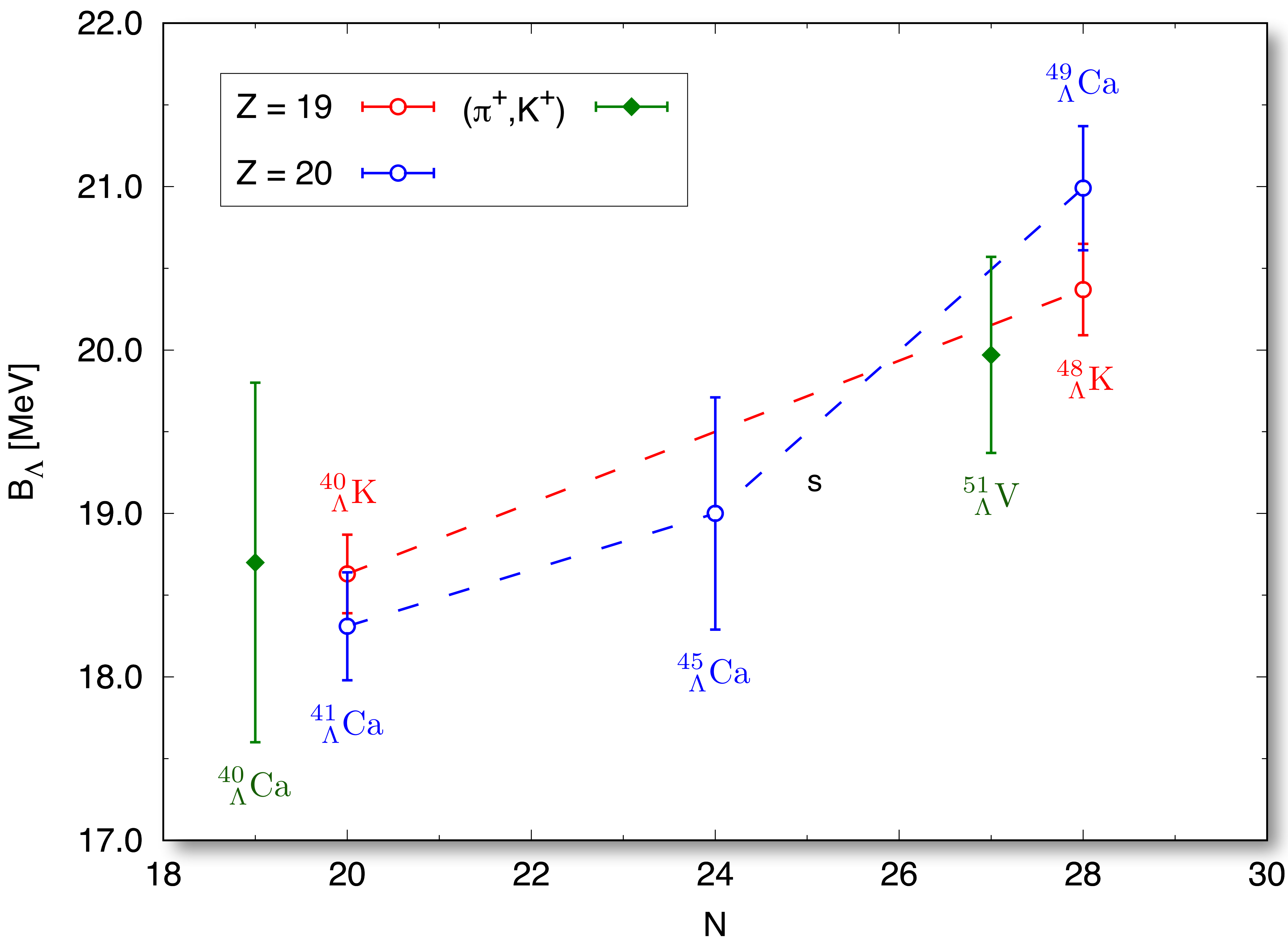
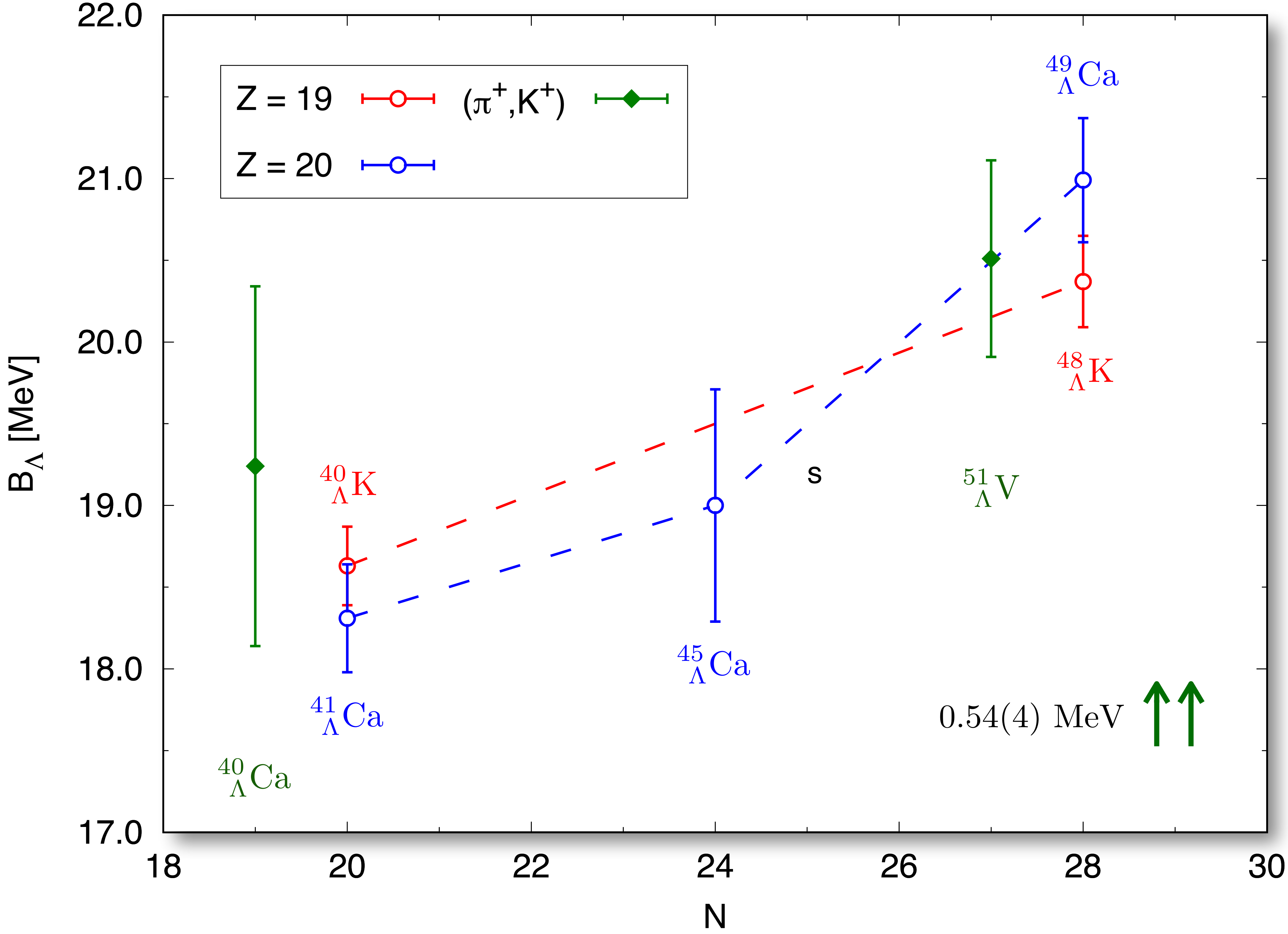


preliminary

AFDMC results: hypernuclei



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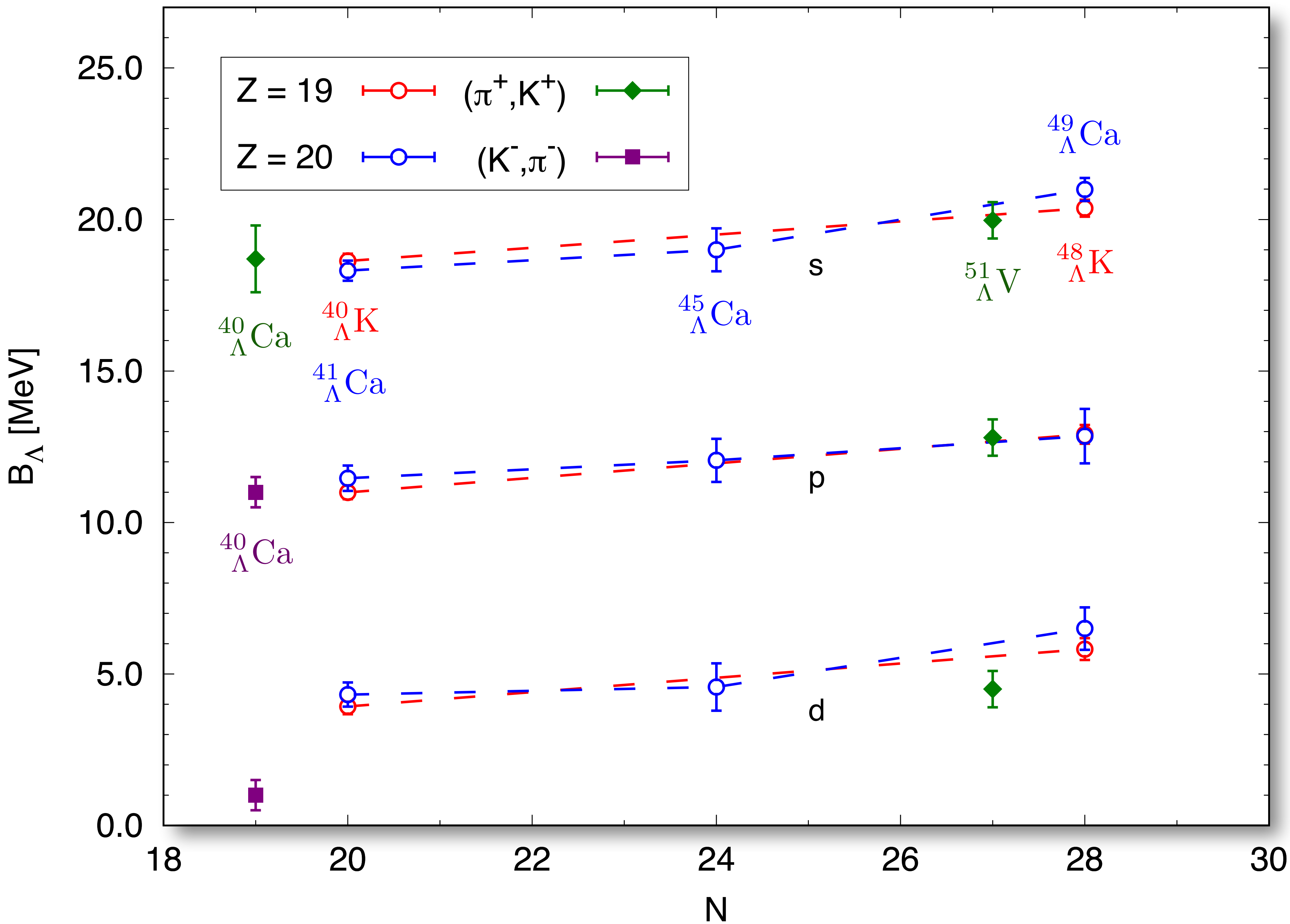

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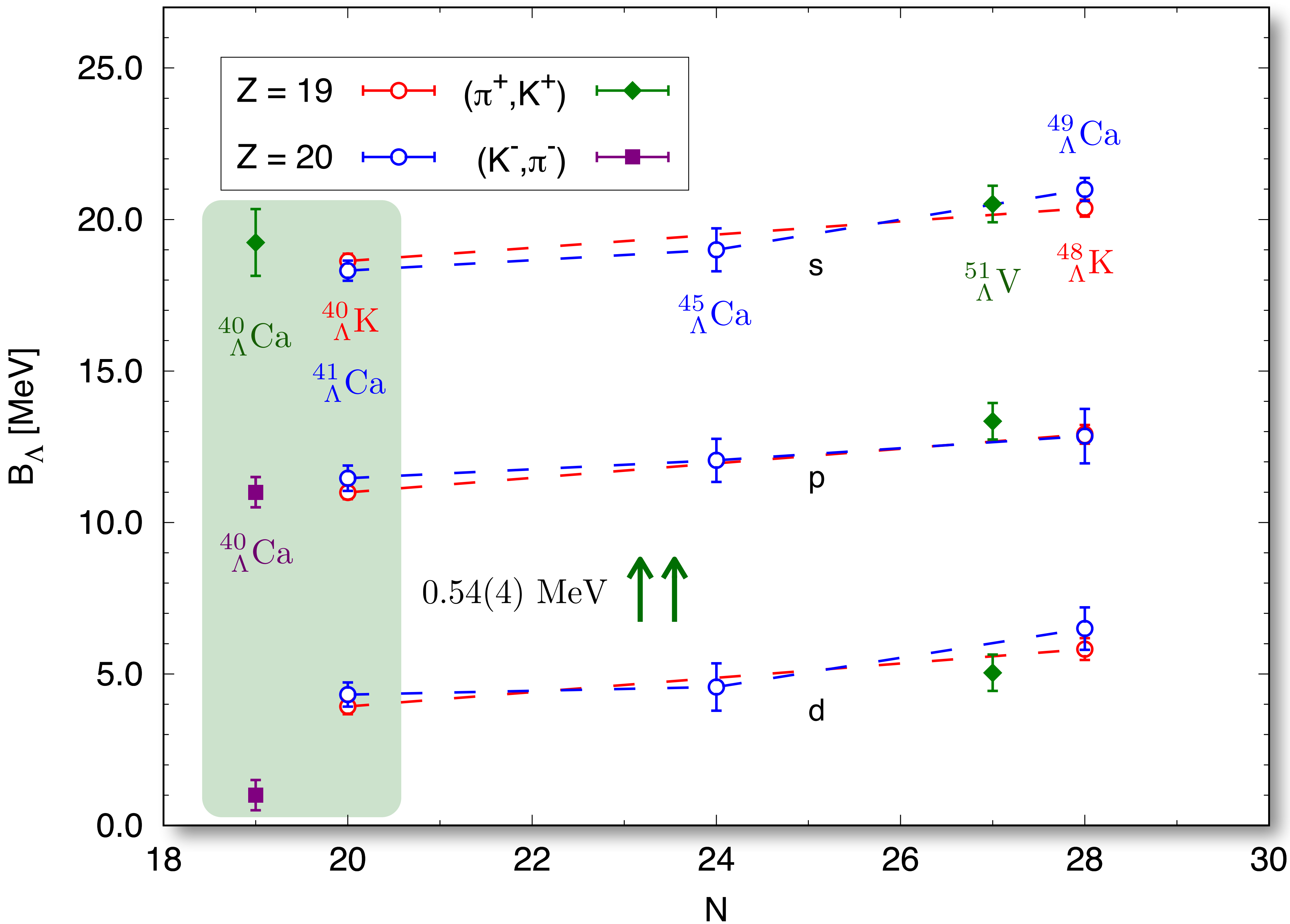

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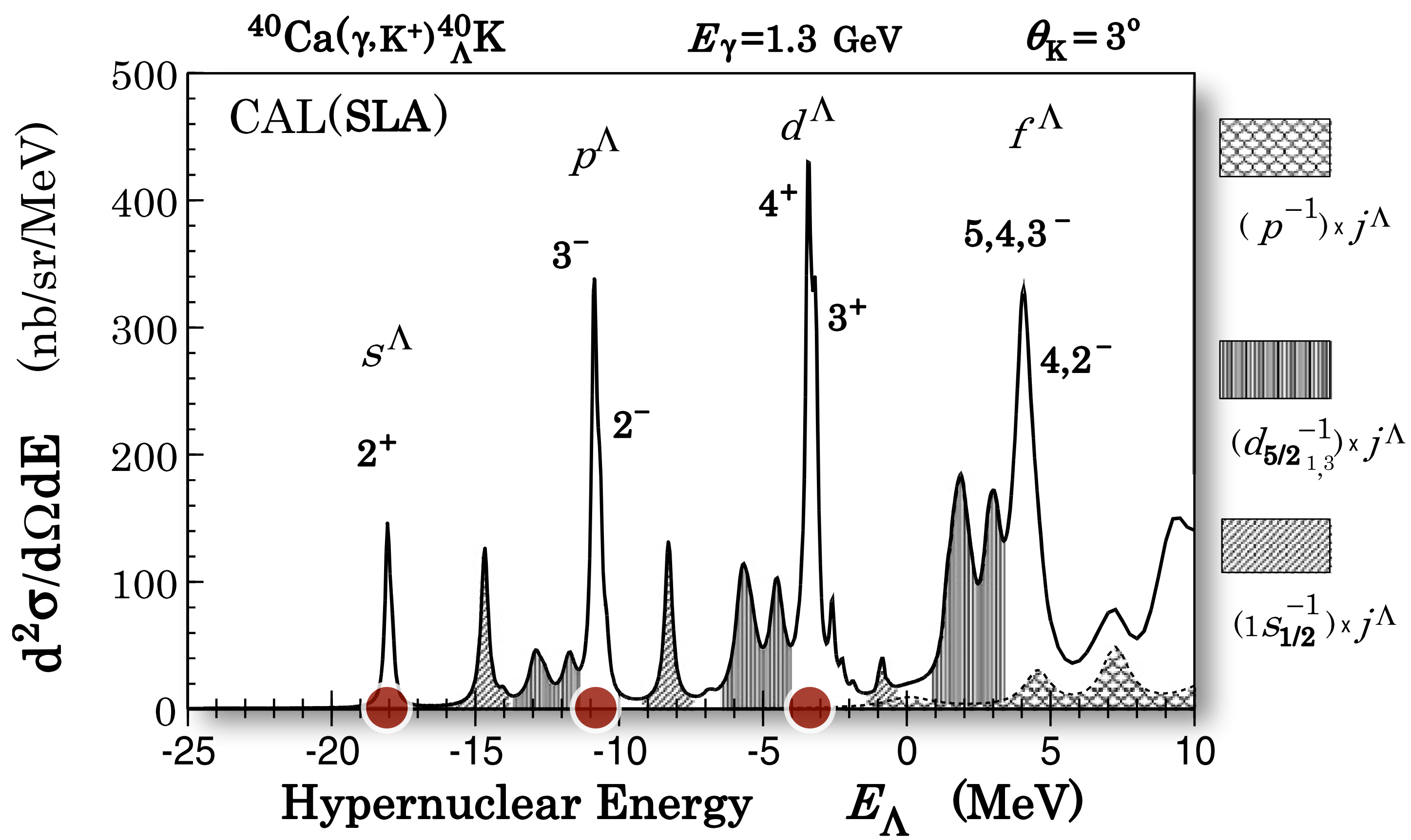


P. Bydžovský, M. Sotona, T. Motoba, K. Itonaga, K. Ogawa, O. Hashimoto, Nucl. Phys. A 881 (2012) 199-217

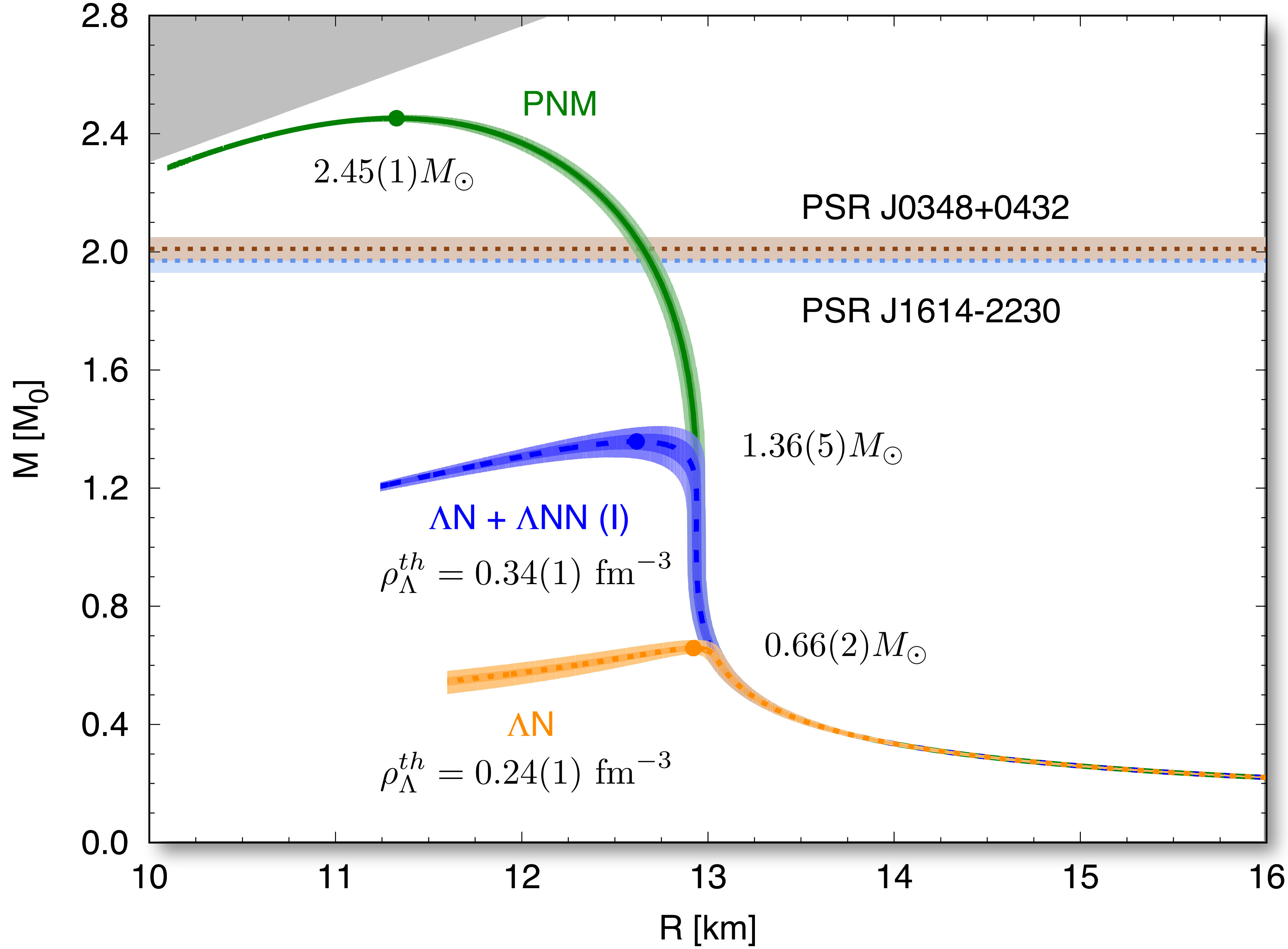
$$B_\Lambda^s \simeq 18.0 \text{ MeV}$$

$$B_\Lambda^p \simeq 10.7 \text{ MeV}$$

$$B_\Lambda^d \simeq 3.3 \text{ MeV}$$

hypernucleus	s-wave	p-wave	d-wave
$^{40}_{\Lambda}$K AFDMC	18.63(24)	10.99(22)	3.93(26)
$^{41}_{\Lambda}$Ca AFDMC	18.31(33)	11.46(42)	4.32(40)
$^{40}_{\Lambda}$Ca (π^+, K^+)	18.7(1.1)	–	–
$^{40}_{\Lambda}$Ca (K^-, π^-)	–	11.0(5)	1.0(5)

AFDMC results: neutron stars



D. L., A. Lovato, S. Gandolfi, F. Pederiva, Phys. Rev. Lett. 114, 092301 (2015)

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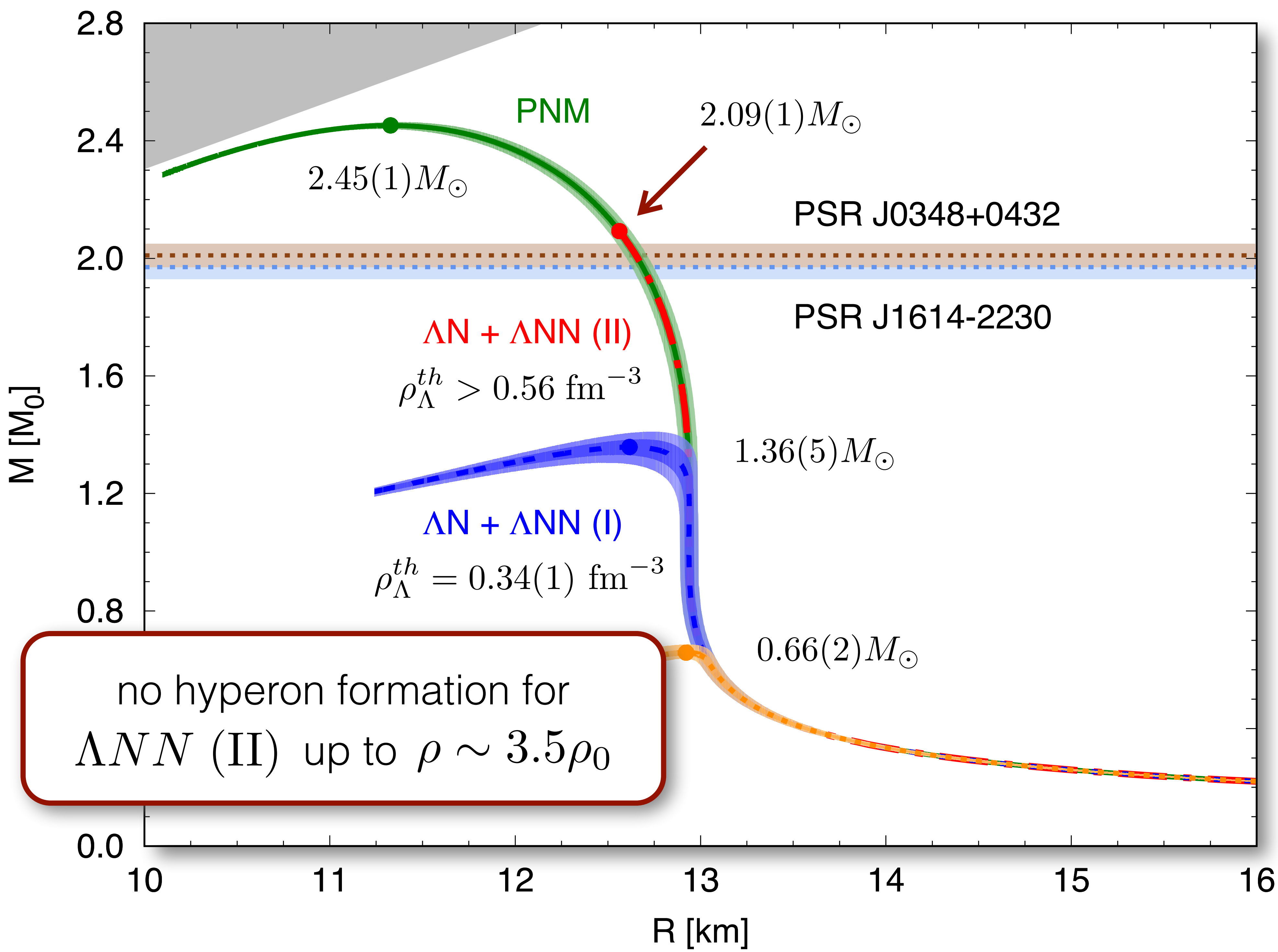

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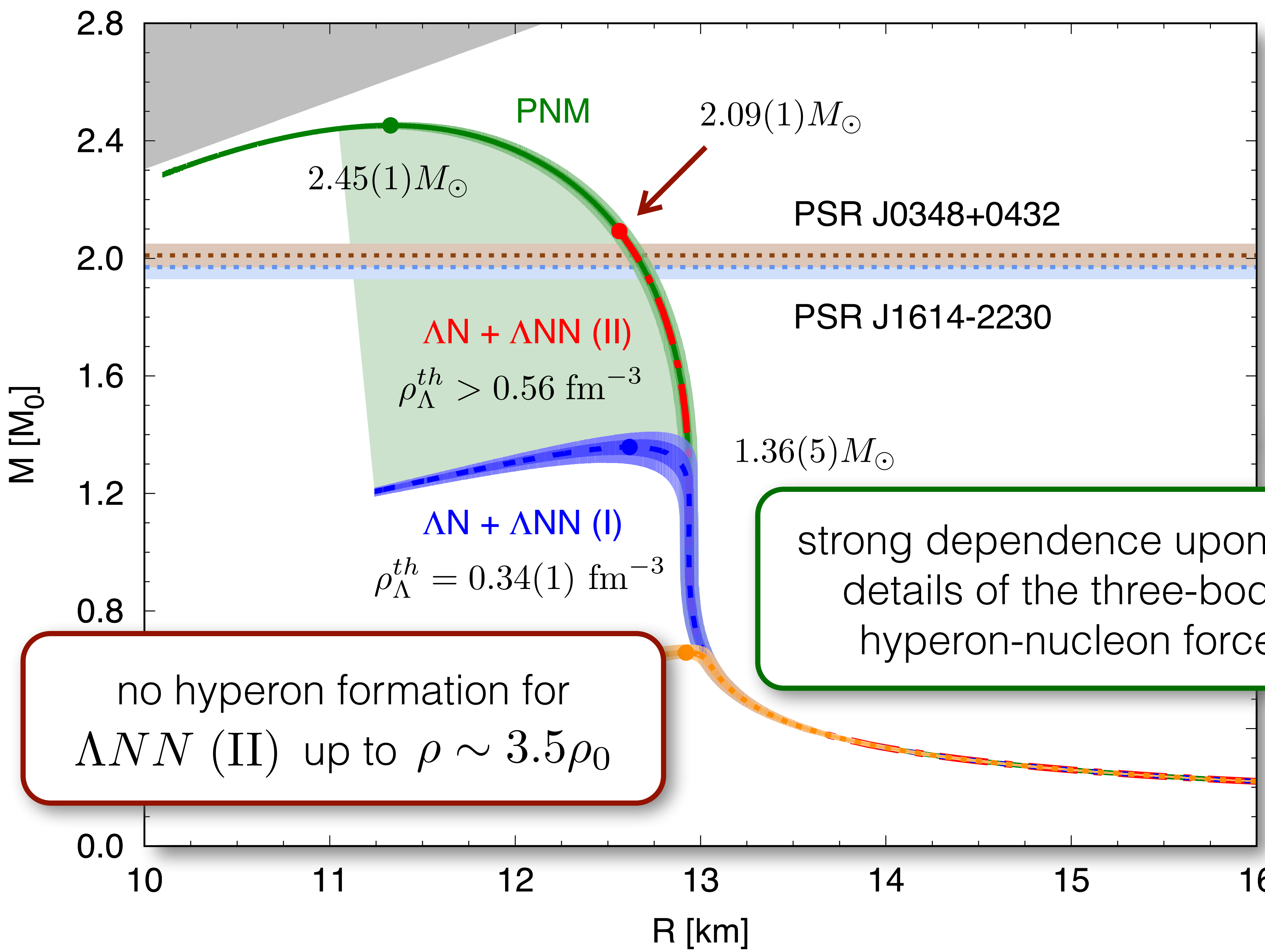


no hyperon formation for ΛNN (II) up to $\rho \sim 3.5\rho_0$

strong dependence upon the details of the three-body hyperon-nucleon force

D. L., A. Lovato, S. Gandolfi, F. Pederiva, Phys. Rev. Lett. 114, 092301 (2015)

AFDMC results: hypernuclei

3-body interaction → fit on symmetric hypernuclei

ΛNN force: no dependence on singlet or triplet nucleon isospin state

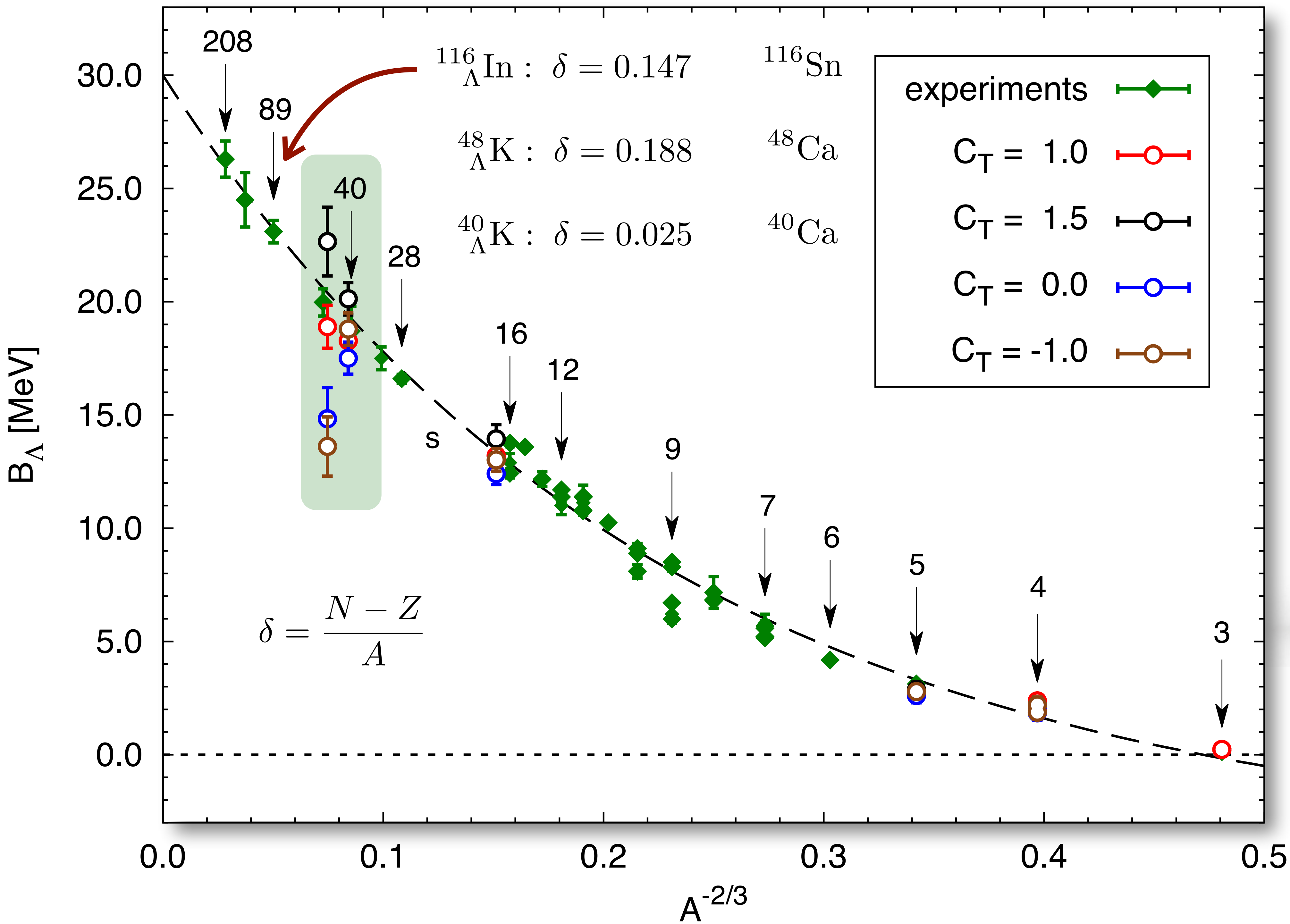
$$\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j = -3\,\mathcal{P}^{T=0} + \mathcal{P}^{T=1} \quad \longrightarrow \quad -3\,\mathcal{P}^{T=0} + C_T\,\mathcal{P}^{T=1}$$

isospin projectors

control parameter:
strength and sign of the nucleon isospin triplet channel

sensitivity study:
light- & medium-heavy hypernuclei

AFDMC results: hypernuclei



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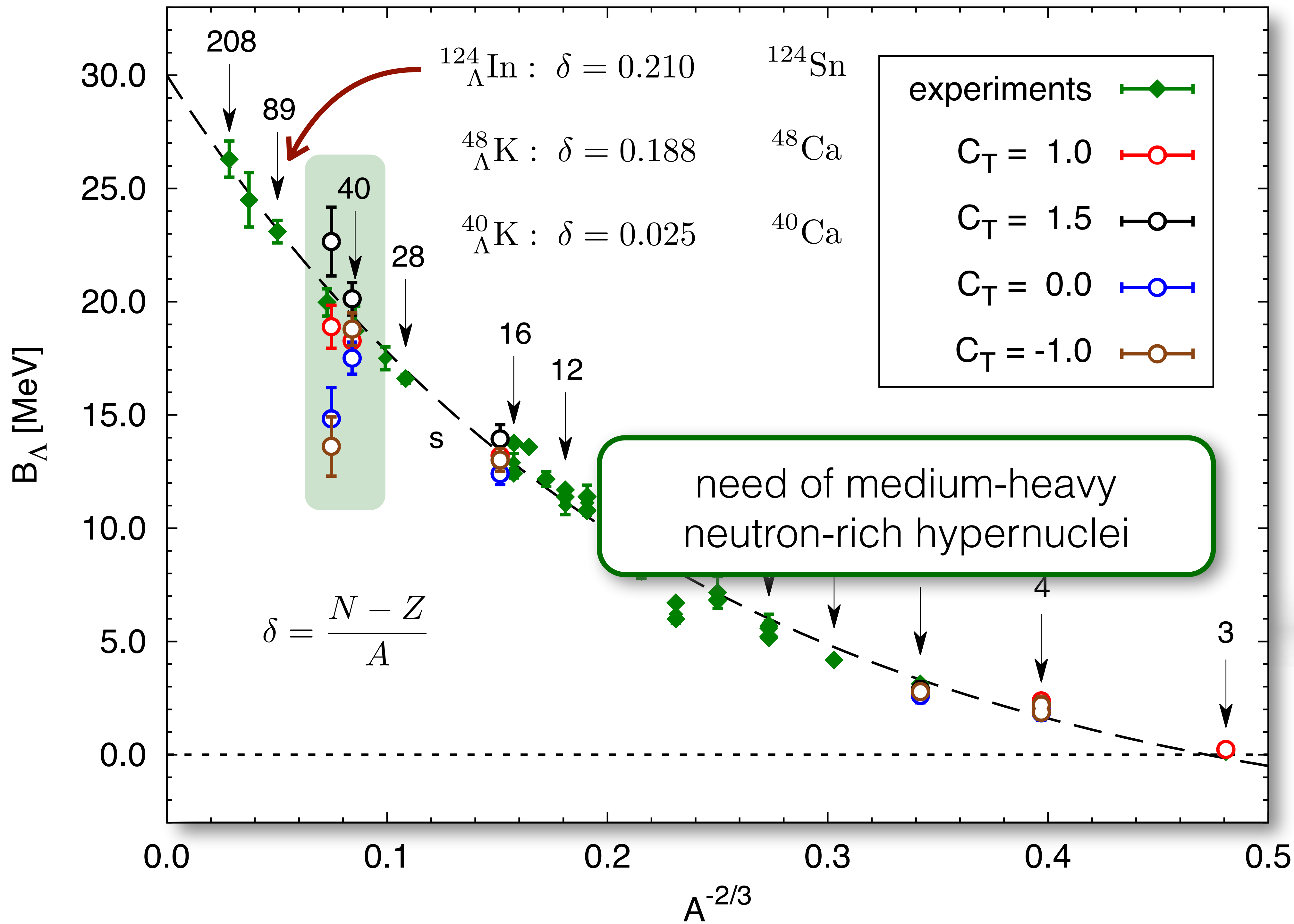

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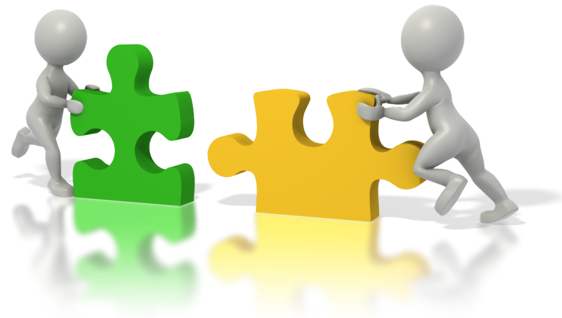
Conclusions & Perspectives



- ✓ Present status

  Substantial improvements in AFDMC calculations for strange systems

  - better performance & better accuracy
  - the medium-mass region (A=40-50) can be used to constrain the hyperon-nucleon interaction
  - need of precise experimental input ⟶ pin down the isospin dependence of the hyperon-nucleon force

- ✓ What's next

  - How does the experimental uncertainty of the Λ separation energy affect the prediction of the neutron star structure?
  - Produce a second generation of results extending the progresses reached in AFDMC calculations for nuclei and nuclear matter to the strange sector
  - Use of the hypernuclear EoS in dynamical general relativity calculations

Thank you!!