Ab Initio Spectroscopy of p- and sd-Shell Nuclei and Sensitivity on Chiral 3N Interactions

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Workshop on "Perspectives of the Ab Initio No-Core Shell Model"

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Road Map

Nuclear
Structure & Reaction Observables

Importance Truncated NCSM

ab initio studies in the p- & sd-shell

Applications to Nuclear Spectra

spectroscopy and sensitivity on 3N

Coupled Cluster Approach

systematic extension to heavy nuclei

•••

Similarity Renormalization Group

pre-diagonalization of Hamiltonian by unitary transformation
computational technology for 3N matrix elements

Chiral Effective Field Theory

systematic low-energy effective theory of QCD
consistent & improvable NN, 3N,... interactions

Low-Energy Quantum Chromodynamics

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Outline

- Reminders: SRG and Importance-Truncated NCSM
- Spectra of p-Shell Nuclei
  - LEC-Sensitivity
  - Cutoff Sensitivity
- Outlook: The Carbon Isotopic Chain
- Conclusions

Reminder: Similarity Renormalization Group

...yields an evolved Hamiltonian with **improved convergence properties** in many-body calculations

- **unitary transformation** of Hamiltonian driven by

$$\frac{d}{d\alpha}\widetilde{H}_\alpha = \left[\eta_\alpha, \widetilde{H}_\alpha\right] \qquad \eta_\alpha = (2\mu)^2 \left[T_{\text{int}}, \widetilde{H}_\alpha\right]$$

- NN interaction @ N^3LO [Entem, Machleidt, Phys.Rev C68, 041001(R) (2003)]
- 3N interaction @ N^2LO
  - c_D & c_E fixed by binding energy and β-decay halflife of triton

    [Gazit et.al., Phys.Rev.Lett. 103, 102502 (2009)]

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Different SRG-Evolved Hamiltonians

- **NN only**: start with NN initial Hamiltonian and keep two-body terms only
- **NN+3N-induced**: start with NN initial Hamiltonian and keep two- and three-body terms
- **NN+3N-full**: start with NN+3N initial Hamiltonian and keep two- and three-body terms

Reminder: Importance-Truncated NCSM

...**extends the range of NCSM** to
larger N_{max} and particle numbers A

❶ choose $|\Psi_{ref}\rangle$ as initial approximation of the target state(s)

❷ **sample relevance of individual basis states** $|\Phi_\nu\rangle$ by a priori importance measure from 1st order perturbation theory

$$\kappa_\nu = -\frac{\langle \Phi_\nu | H | \Psi_{ref} \rangle}{\epsilon_\nu - \epsilon_{ref}}$$

❸ solve eigenvalue problem in truncated model space including states with $\kappa_\nu > |\kappa_{min}|$

access to complete spectroscopy of
p- and sd-shell nuclei

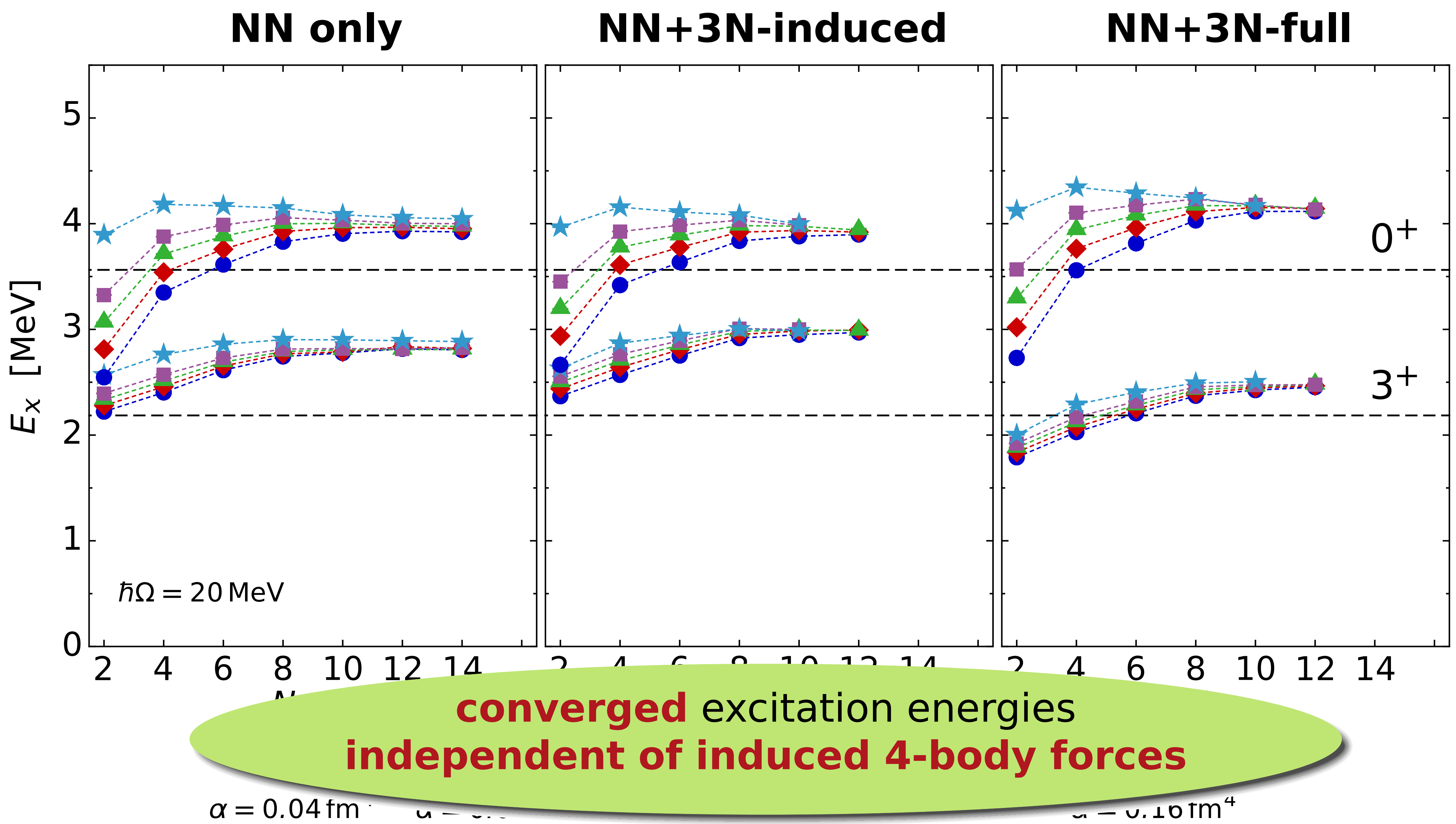
❹ **all relev** ... ates

❺ robust **extrapolatio** ...

Spectra of p-Shell Nuclei

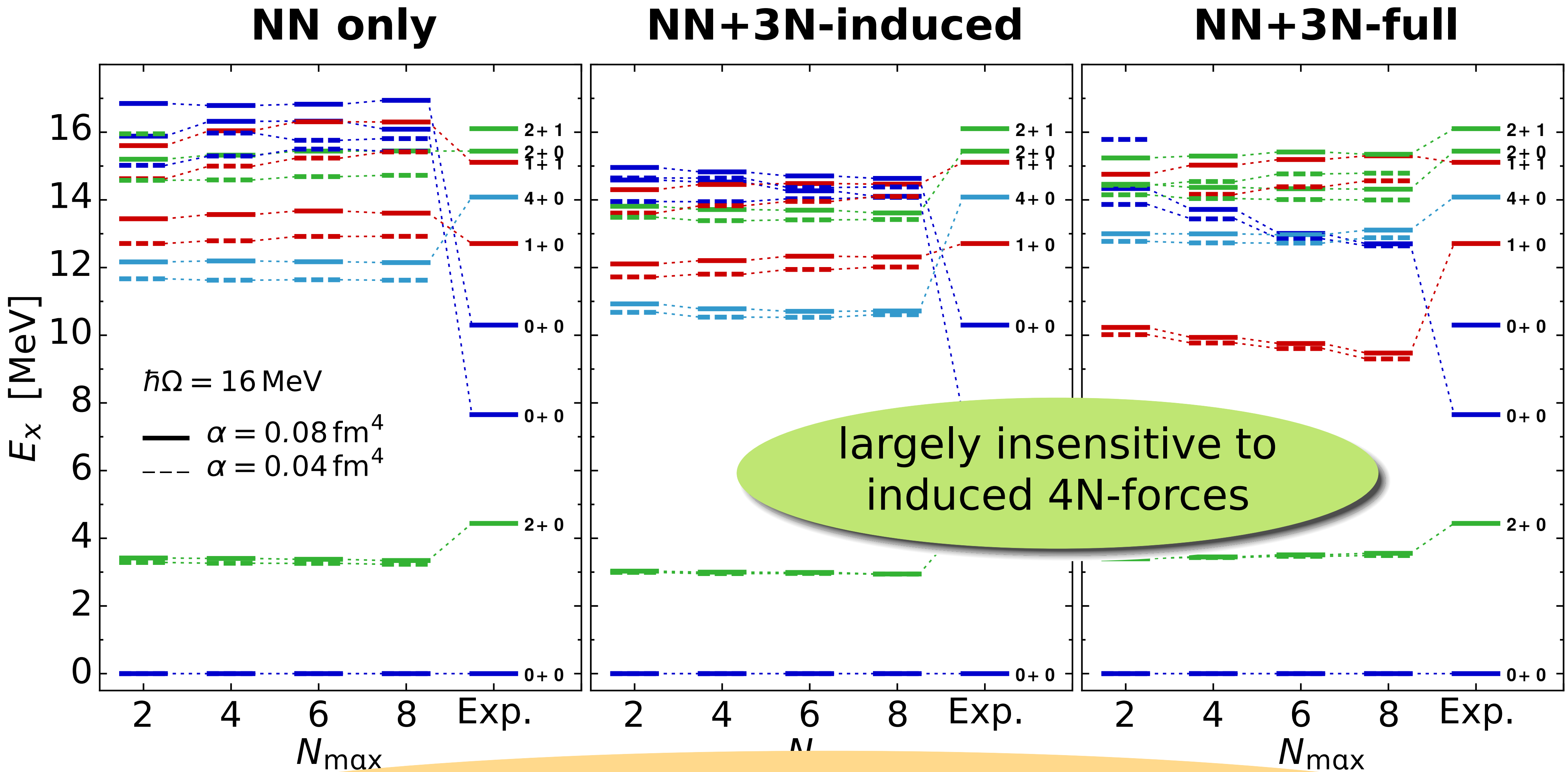
R. Roth, J. Langhammer, A. Calci et al., Phys. Rev. Lett. 107, 072501

Excitations in ^{6}Li



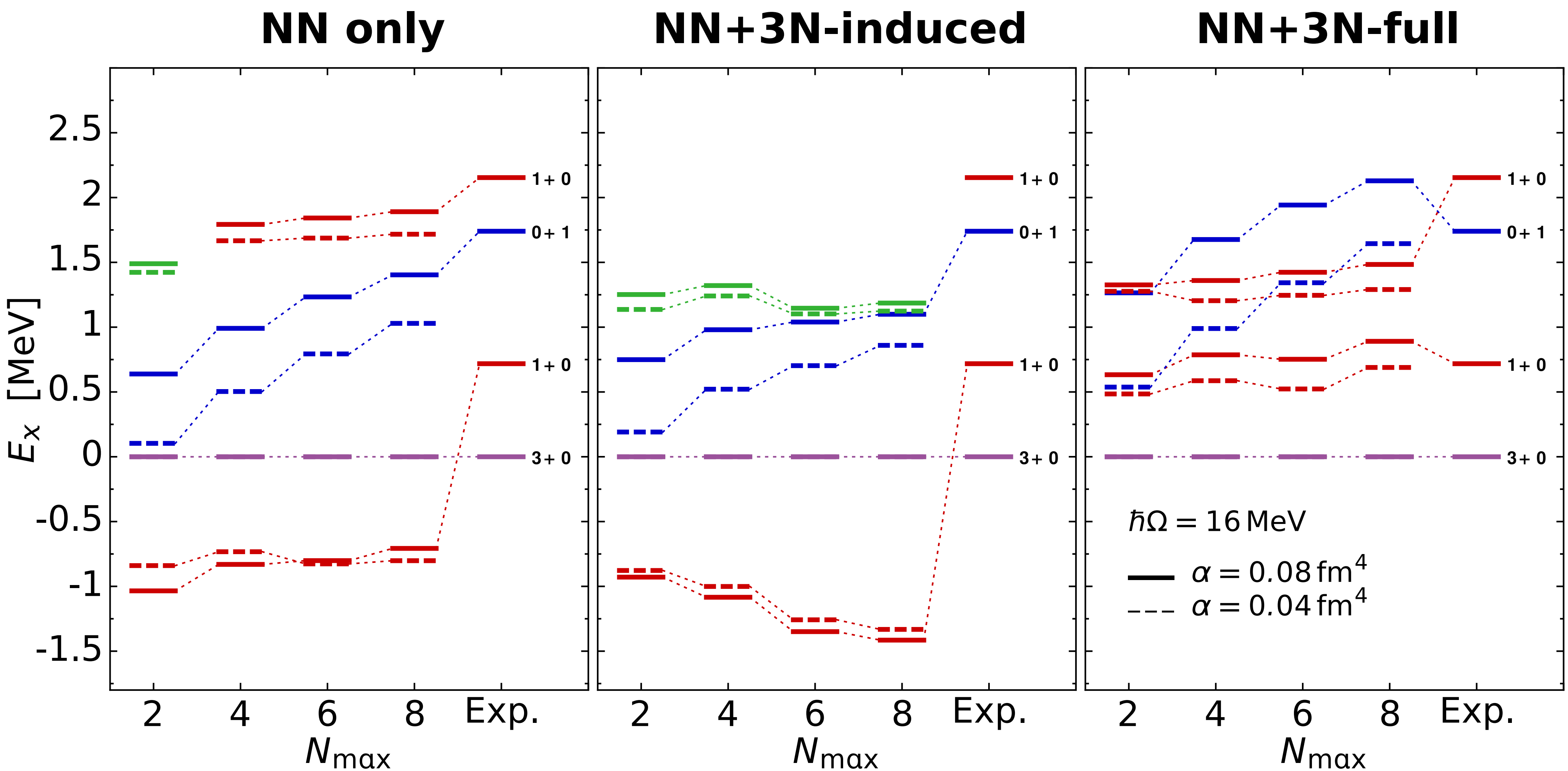
converged excitation energies
independent of induced 4-body forces

Spectroscopy of ^{12}C



⇒ **benchmark of chiral 3N forces possible by spectroscopic studies**

Spectroscopy of ^{10}B



- 3N force indispensable for correct 3^+, 1^+ ordering
- complicated convergence behavior of excited states

Spectra of p-Shell Nuclei
– LEC Sensitivity –

R. Roth, A. Calci, J. Langhammer, S. Binder — in prep.

Why Study the LEC Sensitivity?

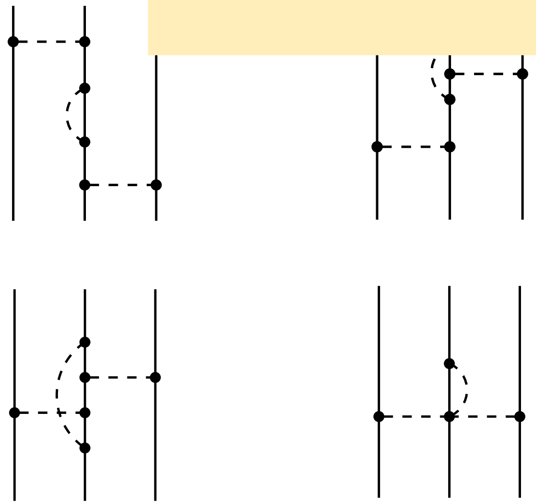
- LECs from πN vertices have sizable uncertainties

	c_1 [GeV^{-1}]	c_3 [GeV^{-1}]	c_4 [GeV^{-1}]
Entem et al. – PRC 68,041001(R)	**-0.81**	**-3.20**	**5.40**
Rentmeester et al. – PRC 67, 044001	-0.76	-4.78	3.96
Büttiker et al. – NPA 668, 97	-0.81	-4.70	3.40
Fettes et al. – NPA 640, 199	-1.23	-5.94	3.47
Ente			0

  - dif

- Are spectra sensitive to different c_i combinations?
- Which LEC is most relevant for spectra?
  - Can we constrain this LEC more precisely?

- som



$$\bar{c}_1 = c_1 - \frac{\cdots}{64\pi F_\pi^2} = -0.81 - 0.13$$

$$\bar{c}_3 = c_3 + \frac{g_A^4 M_\pi}{16\pi F_\pi^2} = -3.2 + 0.89$$

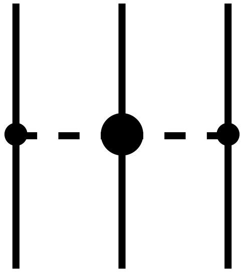
$$\bar{c}_4 = c_4 - \frac{g_A^4 M_\pi}{16\pi F_\pi^2} = 5.4 - 0.89$$

change of 20-30%

[Skibinski, Golak et al.,Phys. Rev. C 84, 054005 (2011)]

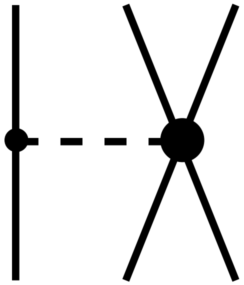
LECs and Corresponding Operators

- chiral 3N interaction @ N^2LO

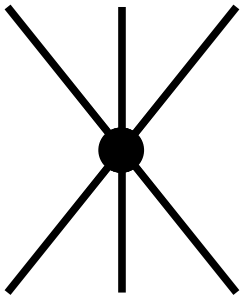


$$\sum_{i\neq j\neq k} \frac{1}{2}\left(\frac{g_A}{2F_\pi}\right)^2 \frac{(\vec{\sigma}_i\cdot\vec{q}_i)(\vec{\sigma}_j\cdot\vec{q}_j)}{(\vec{q}_i^{\,2}+M_\pi^2)(\vec{q}_j^{\,2}+M_\pi^2)} F^{\alpha\beta}_{ijk}\tau_i^\alpha\tau_j^\beta$$

$$F^{\alpha\beta}_{ijk} = \delta^{\alpha\beta}\left[-\frac{4c_1 M_\pi^2}{F_\pi^2} + \frac{2c_3}{F_\pi^2}\vec{q}_i\cdot\vec{q}_j\right] + \sum_\gamma \frac{c_4}{F_\pi^2}\epsilon^{\alpha\beta\gamma}\tau_k^\gamma\vec{\sigma}_k\cdot[\vec{q}_i\times\vec{q}_j]$$



$$-\,c_D \sum_{i\neq j\neq k} \frac{g_A}{8F_\pi^4\Lambda_\chi}\frac{\vec{\sigma}_j\cdot\vec{q}_j}{\vec{q}_j^{\,2}+M_\pi^2}(\vec{\tau}_i\cdot\vec{\tau}_j)(\vec{\sigma}_i\cdot\vec{q}_j)$$

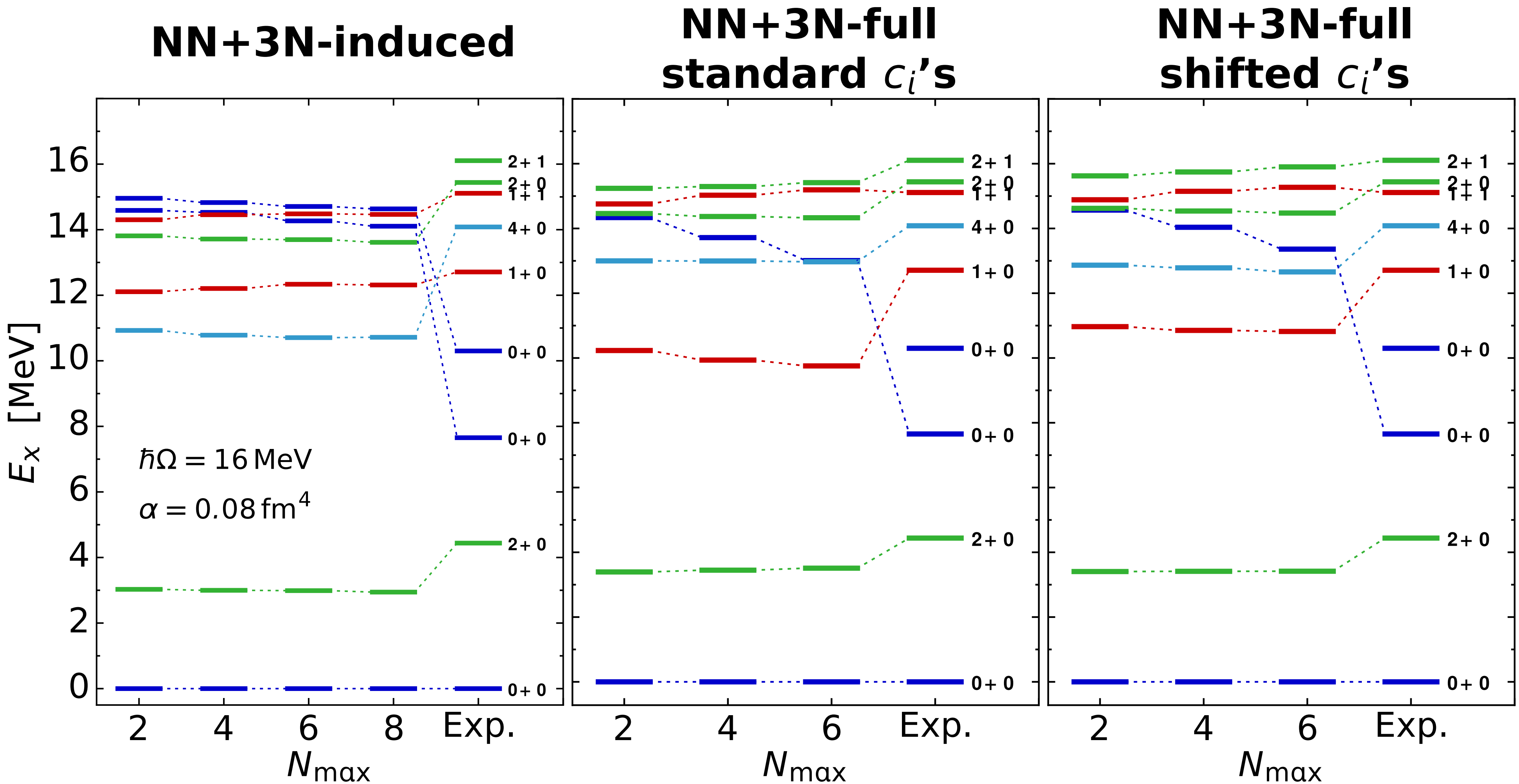


$$c_E \sum_{j\neq k}\frac{1}{2F_\pi^4\Lambda_\chi}(\vec{\tau}_j\cdot\vec{\tau}_k)$$

in the following

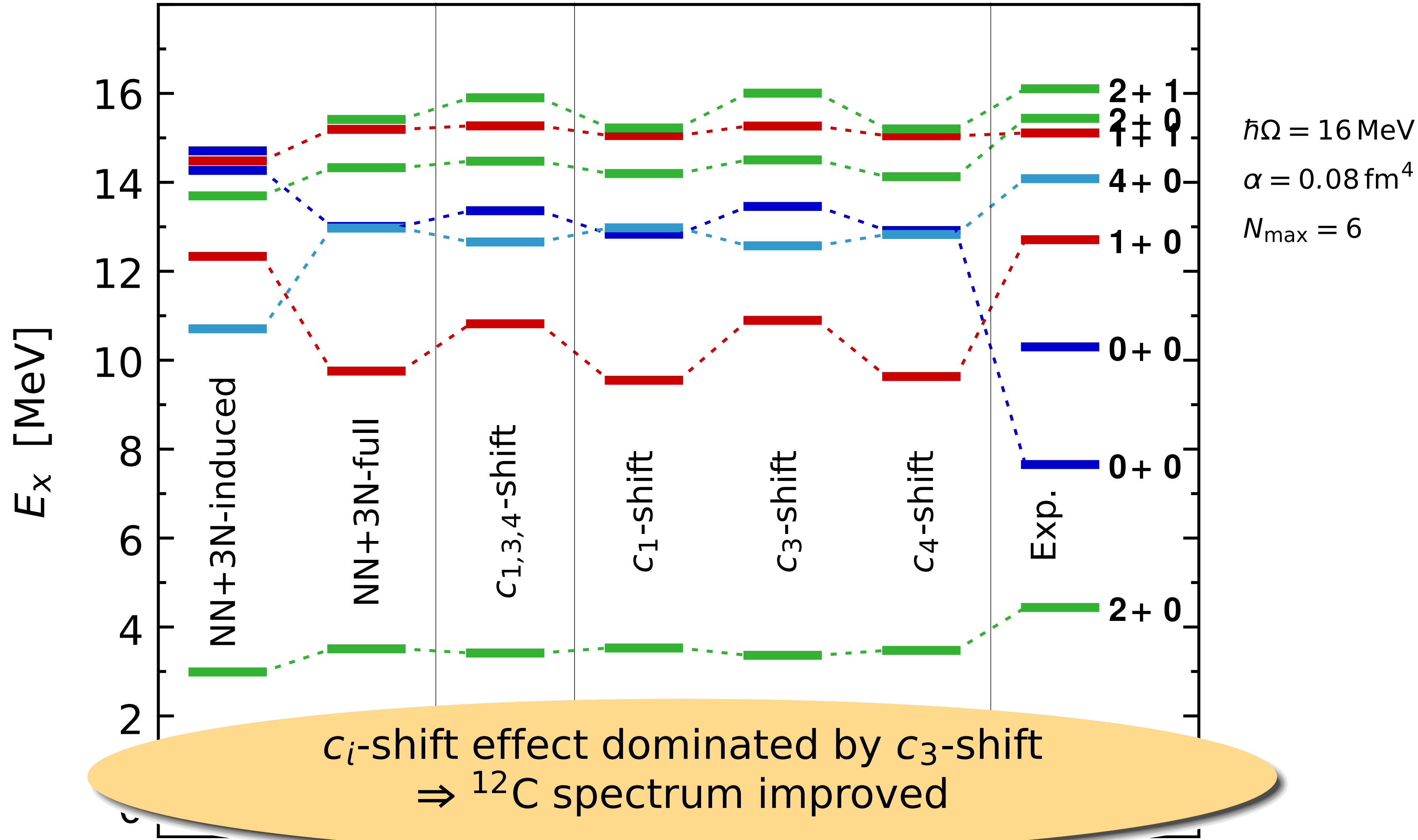
1. shift LECs $c_{1/3/4}$
2. stick to $c_D = -0.2$
3. refit c_E to ^{4}He binding energy

^{12}C – Shifted c_i's



- 1^+ state: very sensitive to c_i-shift
- other states: minor effects

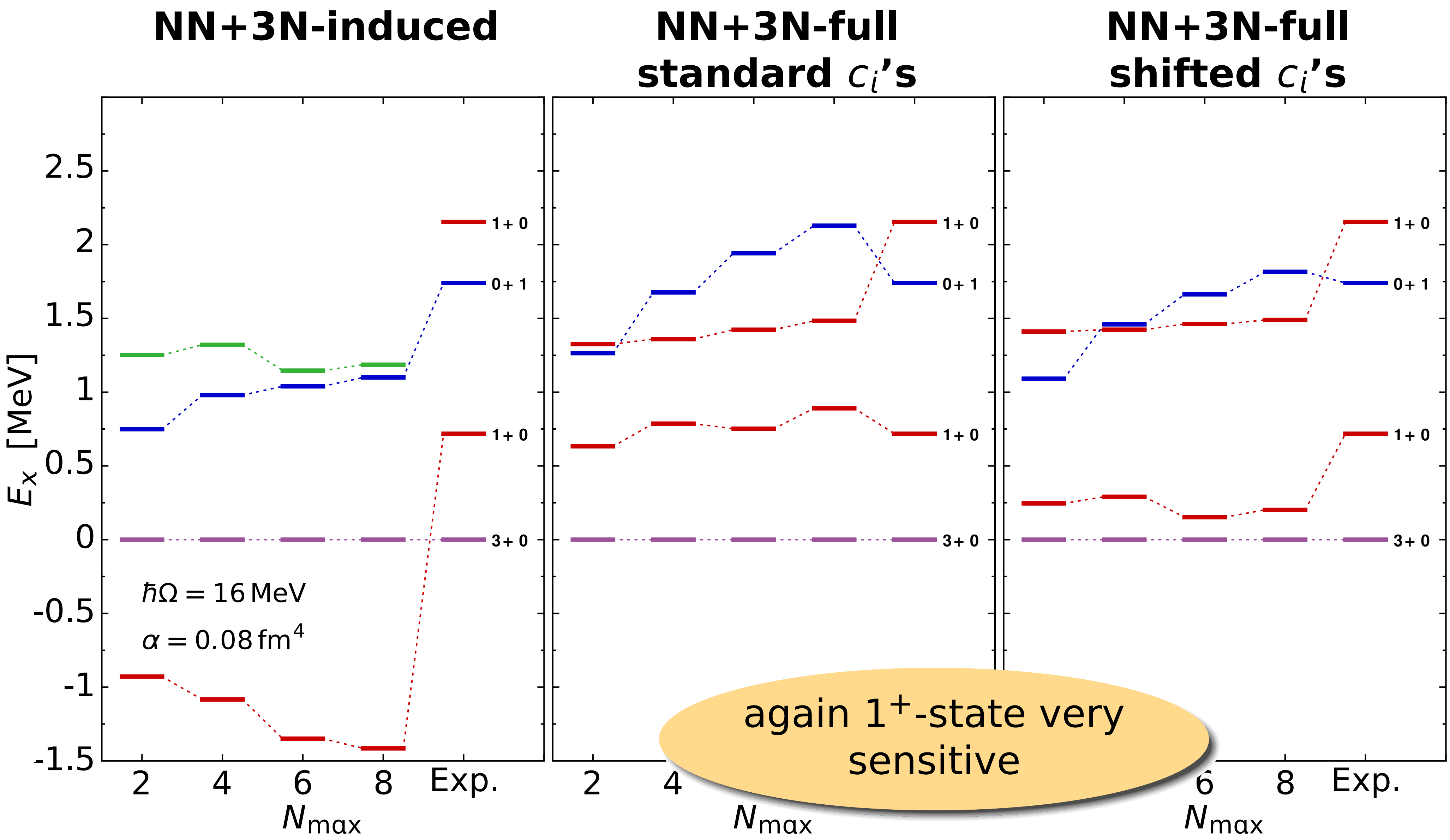
^{12}C – LEC Sensitivity Analysis



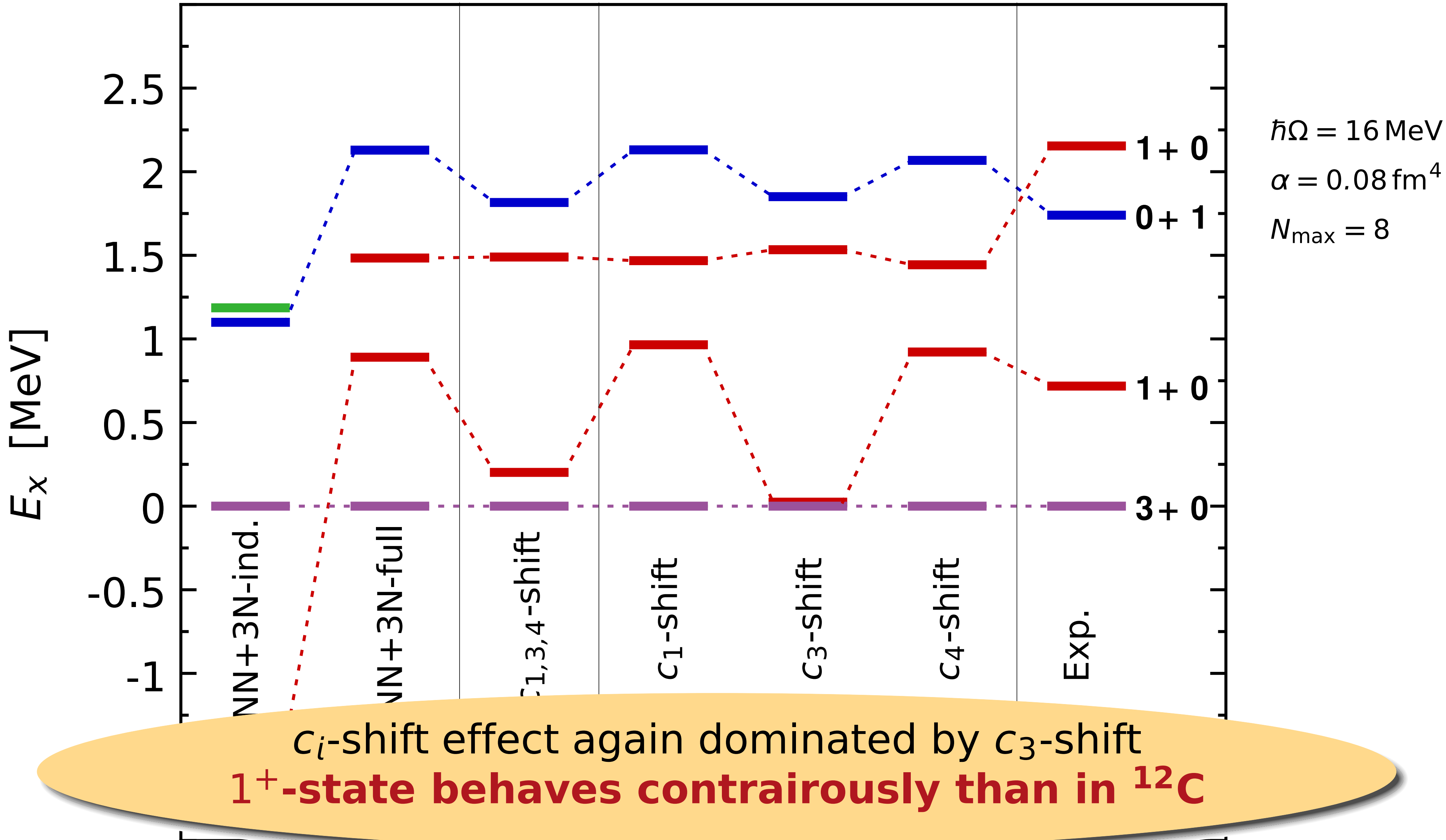
c_i-shift effect dominated by c_3-shift

⇒ ^{12}C spectrum improved

^{10}B – Shifted c_i's



^{10}B – LEC Sensitivity Analysis



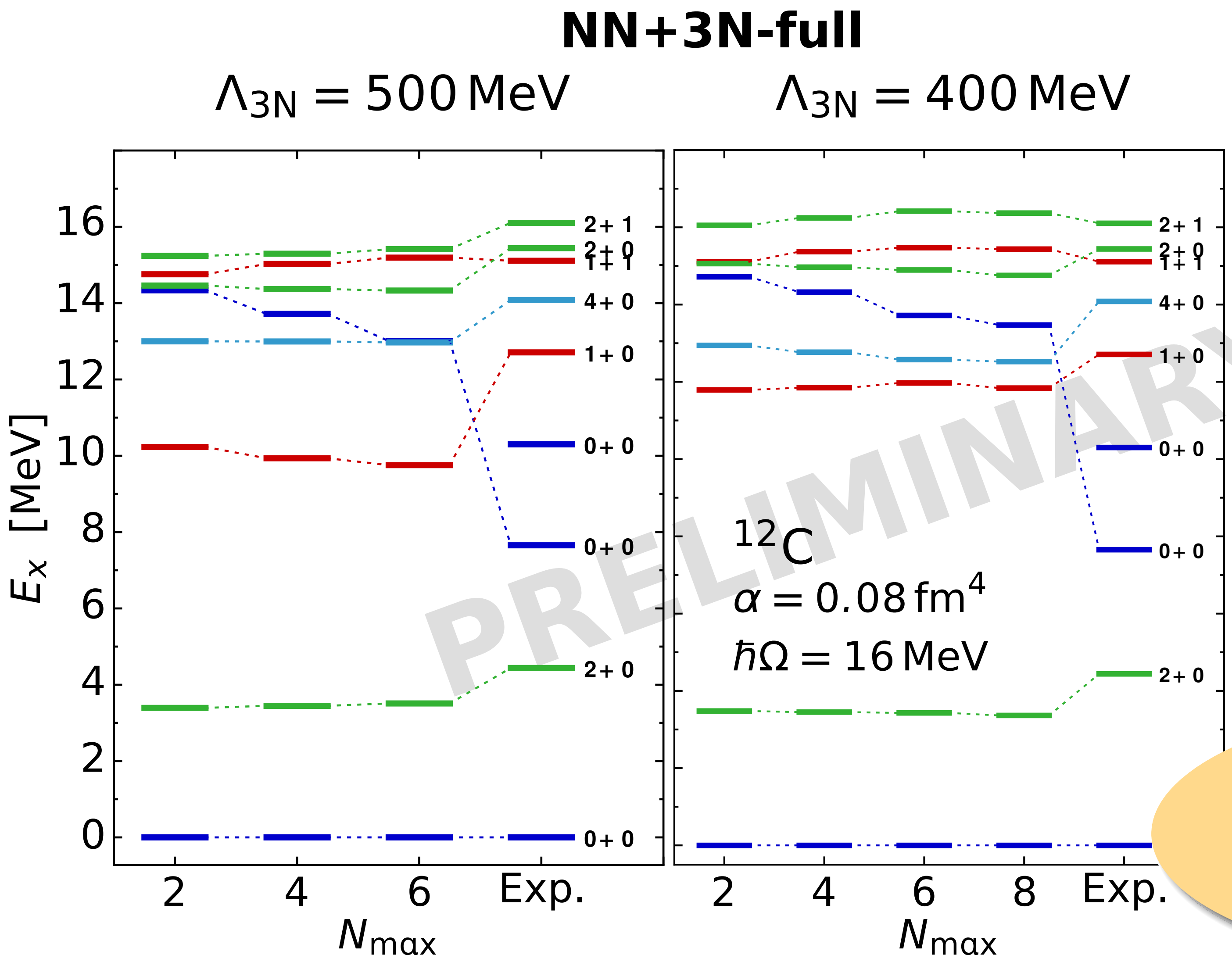
c_i-shift effect again dominated by c_3-shift

1^+-state behaves contrairously than in ^{12}C

Spectra of p-Shell Nuclei
– Cutoff Sensitivity –

R. Roth, S. Binder, K. Vobig, A. Calci, JL, P. Navratil — arXiv:1112.0287

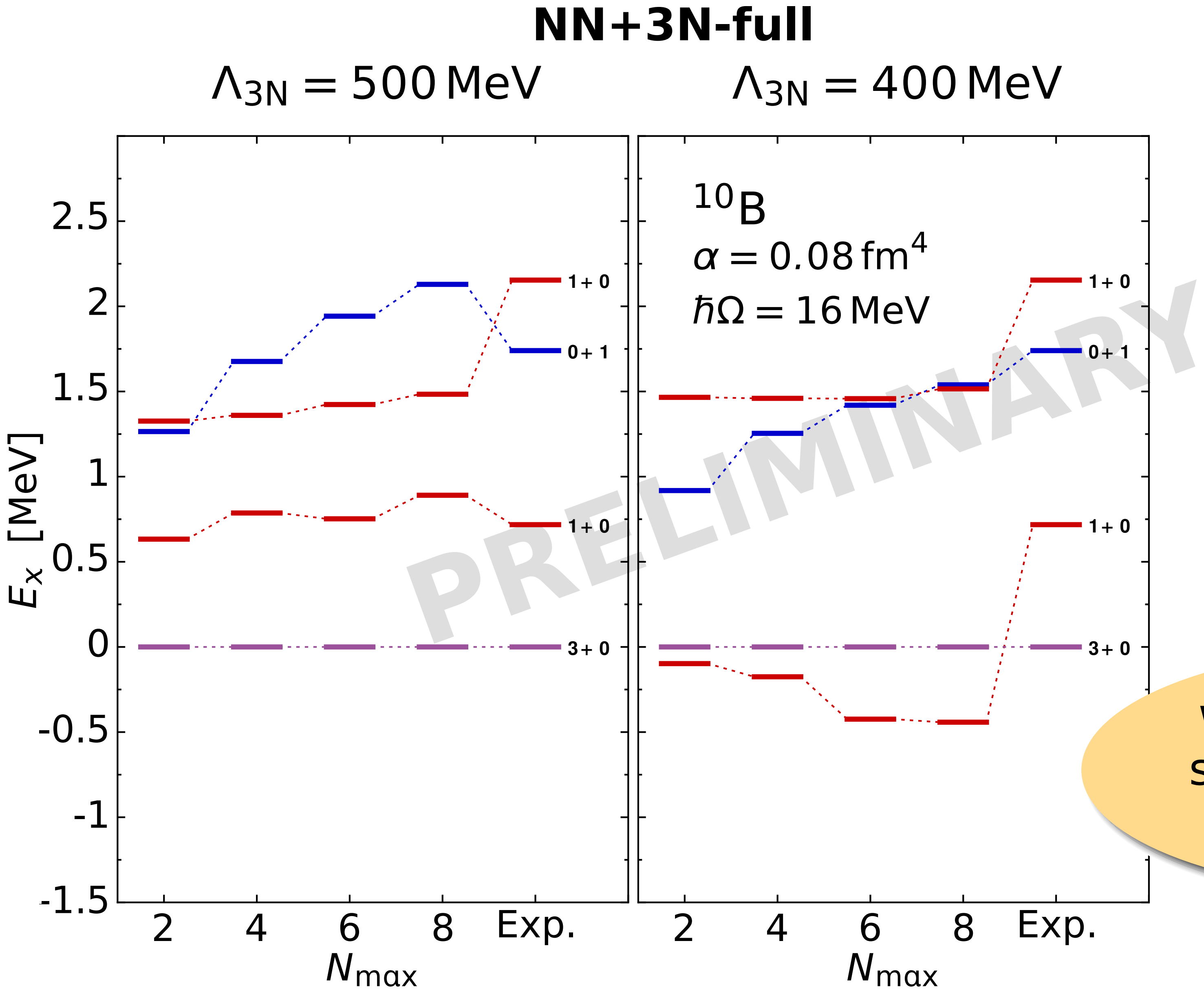
Impact of Reduced Cutoff Λ_{3N}



- use standard c_i's
- lower the cutoff to $\Lambda_{3N} = 400\,\text{MeV}$
- refit c_E to ^{4}He binding energy
- **first 1^+ state very sensitive**

overall quite good agreement with experiment

Impact of Reduced Cutoff Λ_{3N}

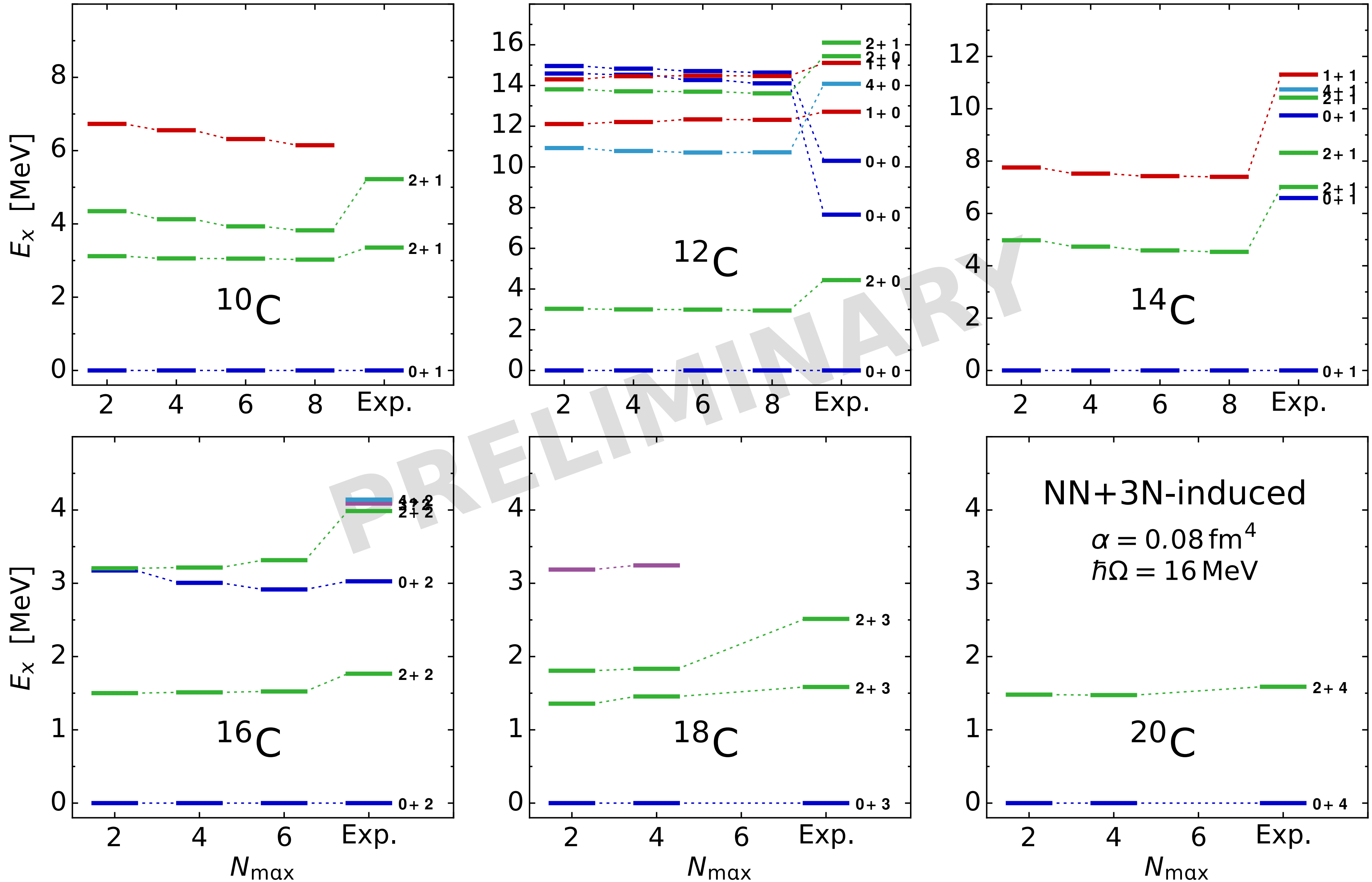


- use standard c_i's
- lower the cutoff to $\Lambda_{3N} = 400\,\text{MeV}$
- refit c_E to ^{4}He binding energy

wrong ^{10}B ground state with reduced cutoff

Application
– Carbon Isotopic Chain –

Outlook: Carbon Isotopic Chain



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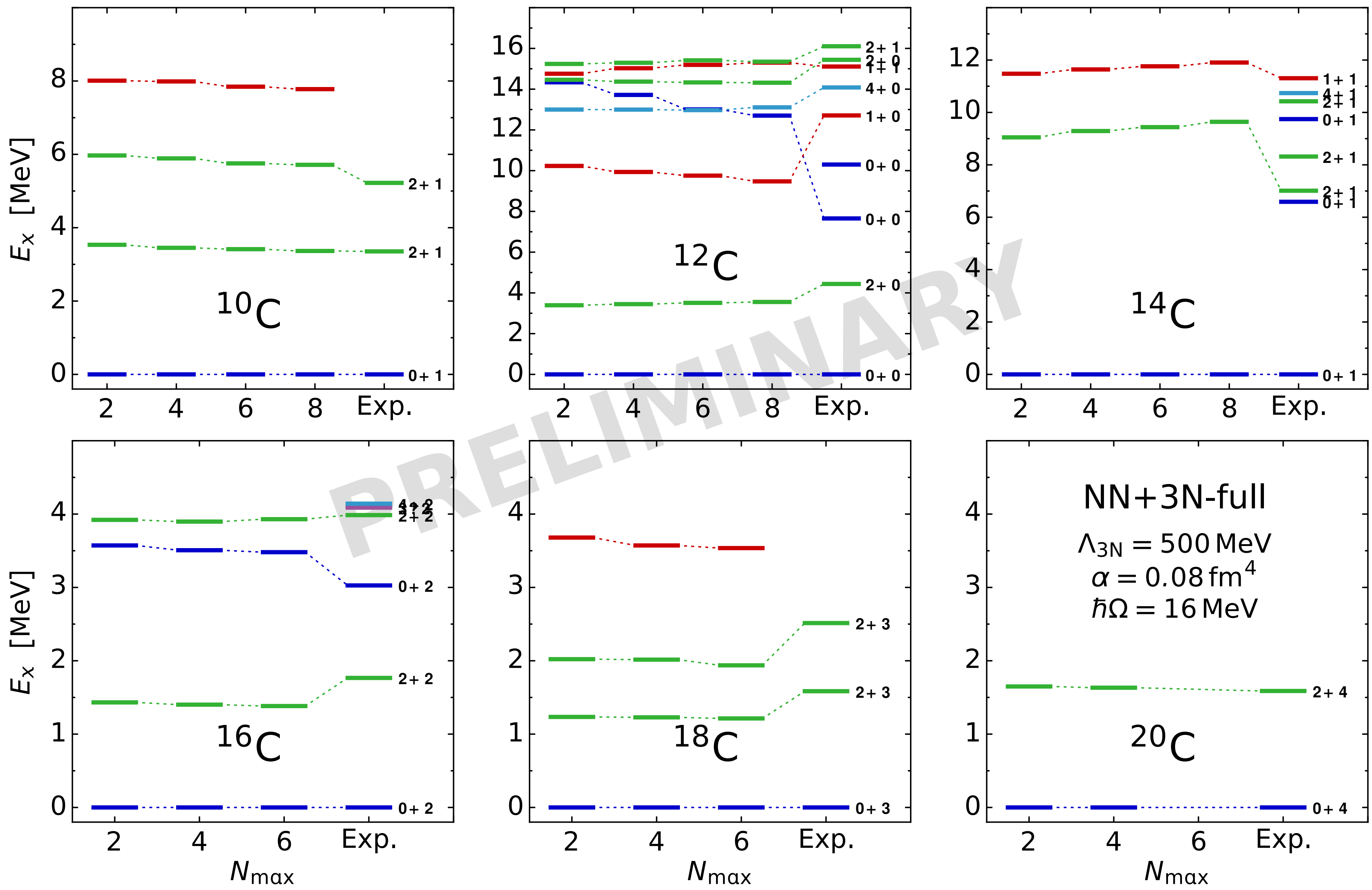

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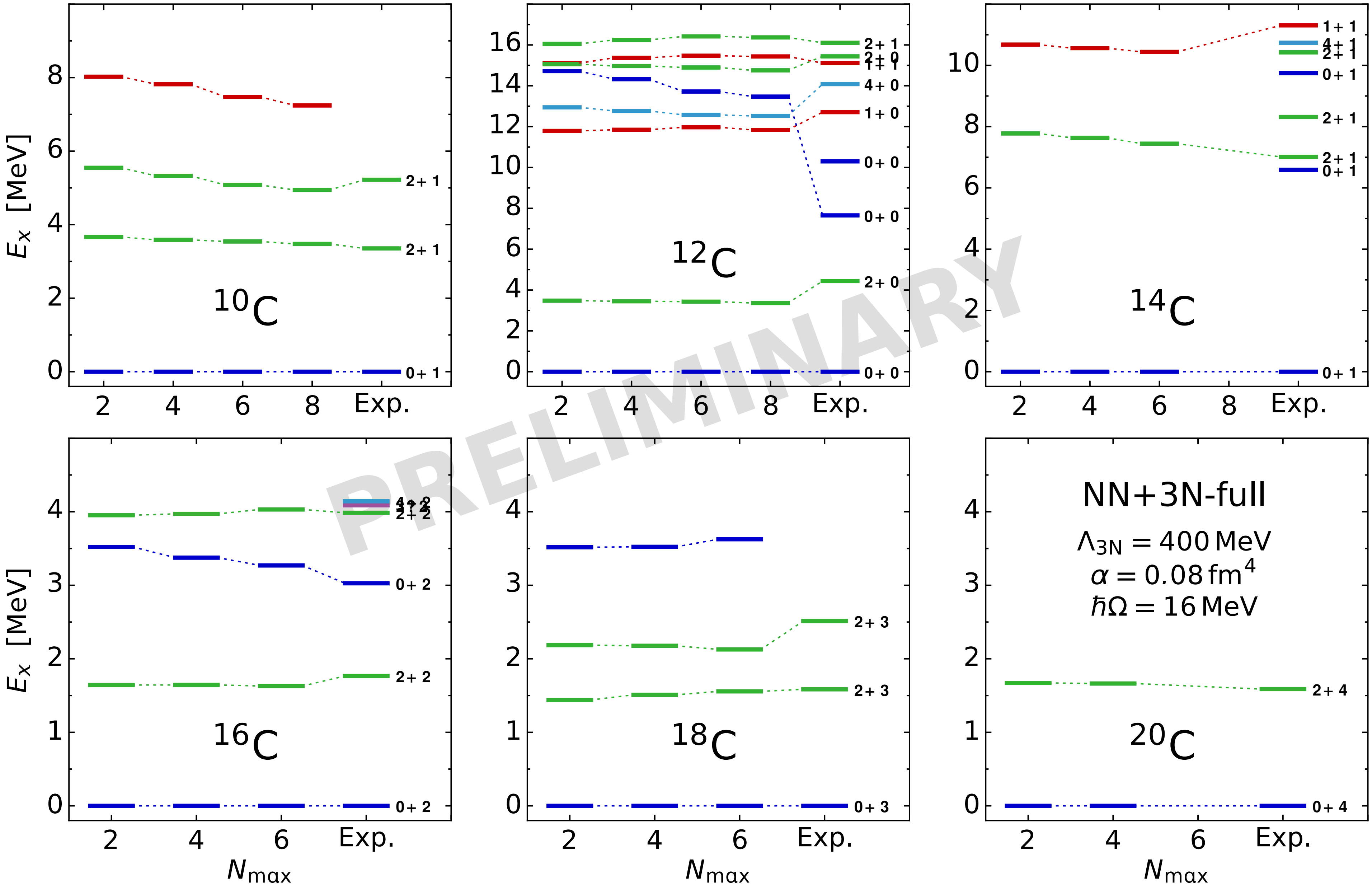

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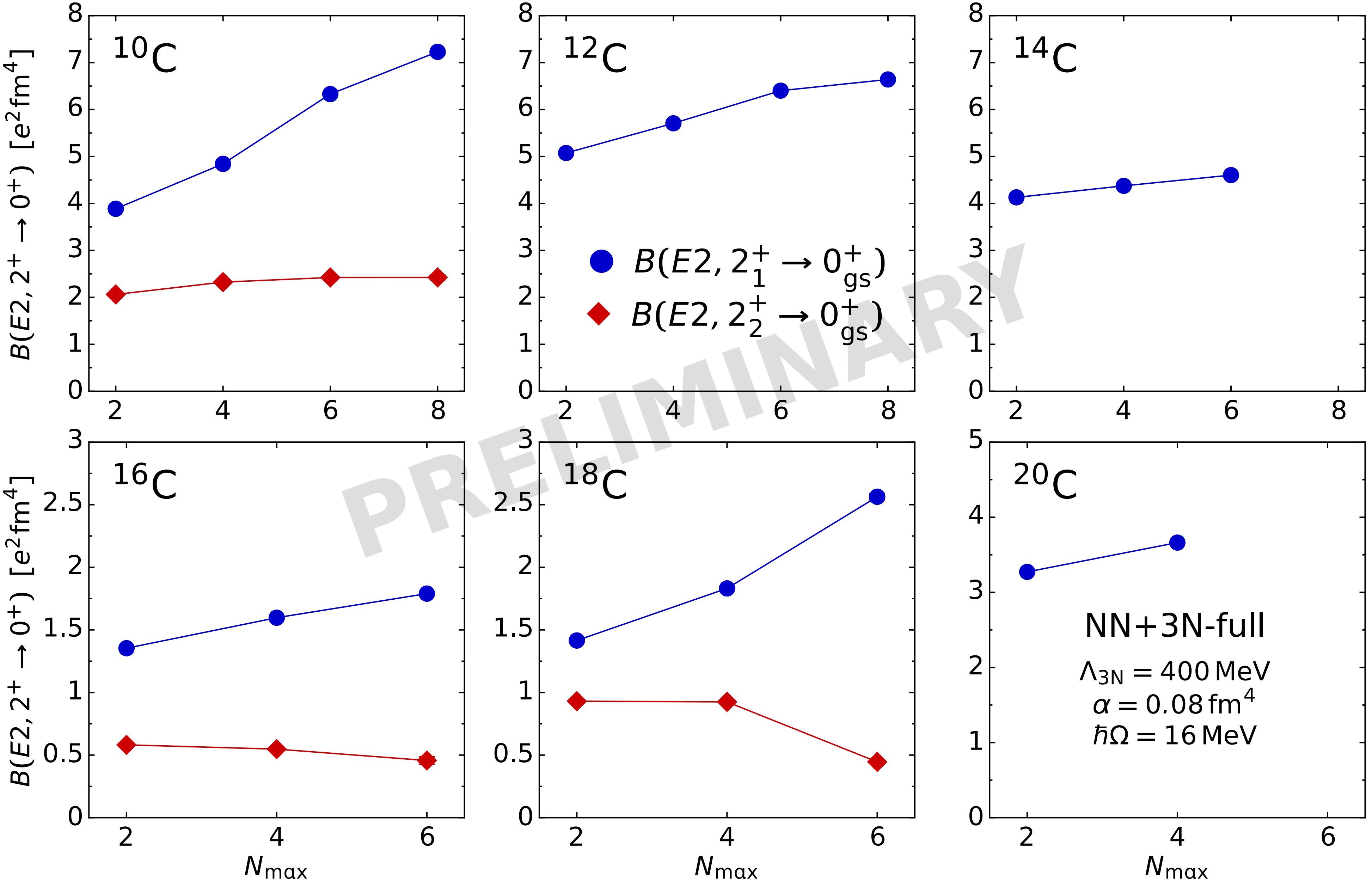

Conclusions

- spectra of p- & sd-shell nuclei powerful **benchmark for chiral forces**
  - induced 4N-forces negligible if excitation energies are converged
  - IT-NCSM enables these studies with **manageable computational cost**
- LEC c_3 has a strong influence on spectra
  - with 3N @ N^2LO not possible to describe the first 1^+-states in ^{10}B and ^{12}C simultaneously
  - may be we should aim at **better constraints for c_3**
- lower cutoff $\Lambda_{3N} = 400\,\text{MeV}$ yields quite good description of the low-lying states throughout the carbon isotopic chain (but not ^{10}B)

Epilogue

- **thanks to our group & collaborators**
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Thank you for your attention!

COMPUTING TIME

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