Ab-Initio Spectroscopy of p- and sd-Shell Nuclei with Chiral Two- plus Three-Body Interactions

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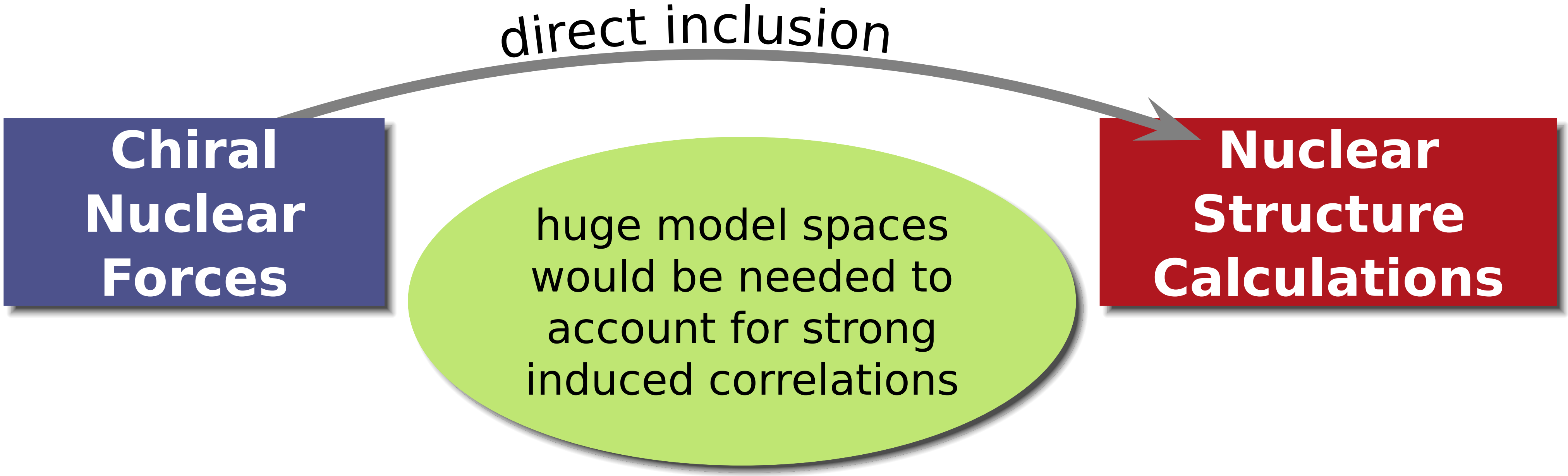
Chiral Hamiltonian



- NN interaction @ N^3LO [Entem, Machleidt, Phys.Rev C68, 041001(R) (2003)]
- 3N interaction @ N^2LO without approximations

- 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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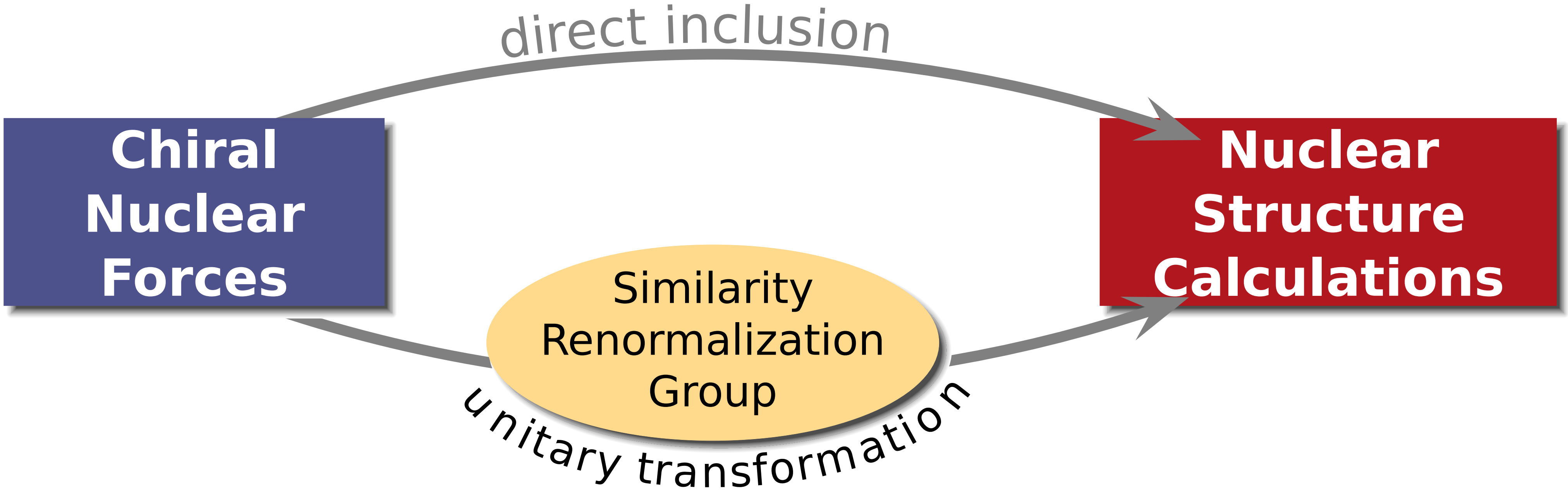

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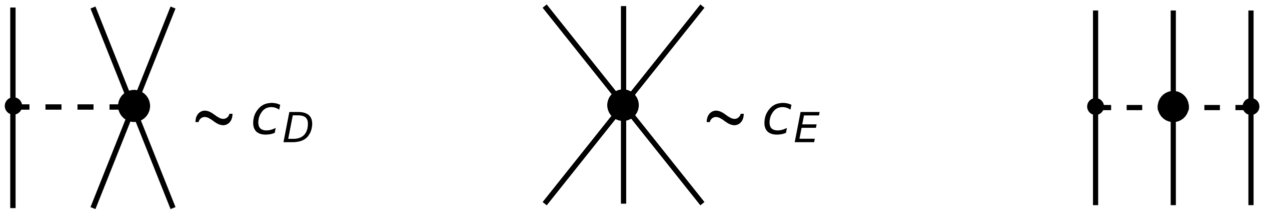

$\sim c_D$ $\sim c_E$ $\sim c_1, c_3, c_4$ fixed in NN system

- c_D & c_E fixed by binding energy and β-decay halflife of triton
  [Gazit et.al., Phys.Rev.Lett. 103, 102502 (2009)]

Similarity Renormalization Group

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

- **unitary transformation** of Hamiltonian driven by

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

for details

→ HK 10.5 A. Calci

- SRG induces irreducible n-body contributions $\widetilde{H}_\alpha^{[n]}$

$$\widetilde{H}_\alpha = \widetilde{H}_\alpha^{[1]} + \widetilde{H}_\alpha^{[2]} + \widetilde{H}_\alpha^{[3]} + \ldots + \widetilde{H}_\alpha^{[n]} + \ldots$$

  - we can keep cluster-orders up to $n = 3$ from evolution in 2B or 3B space

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

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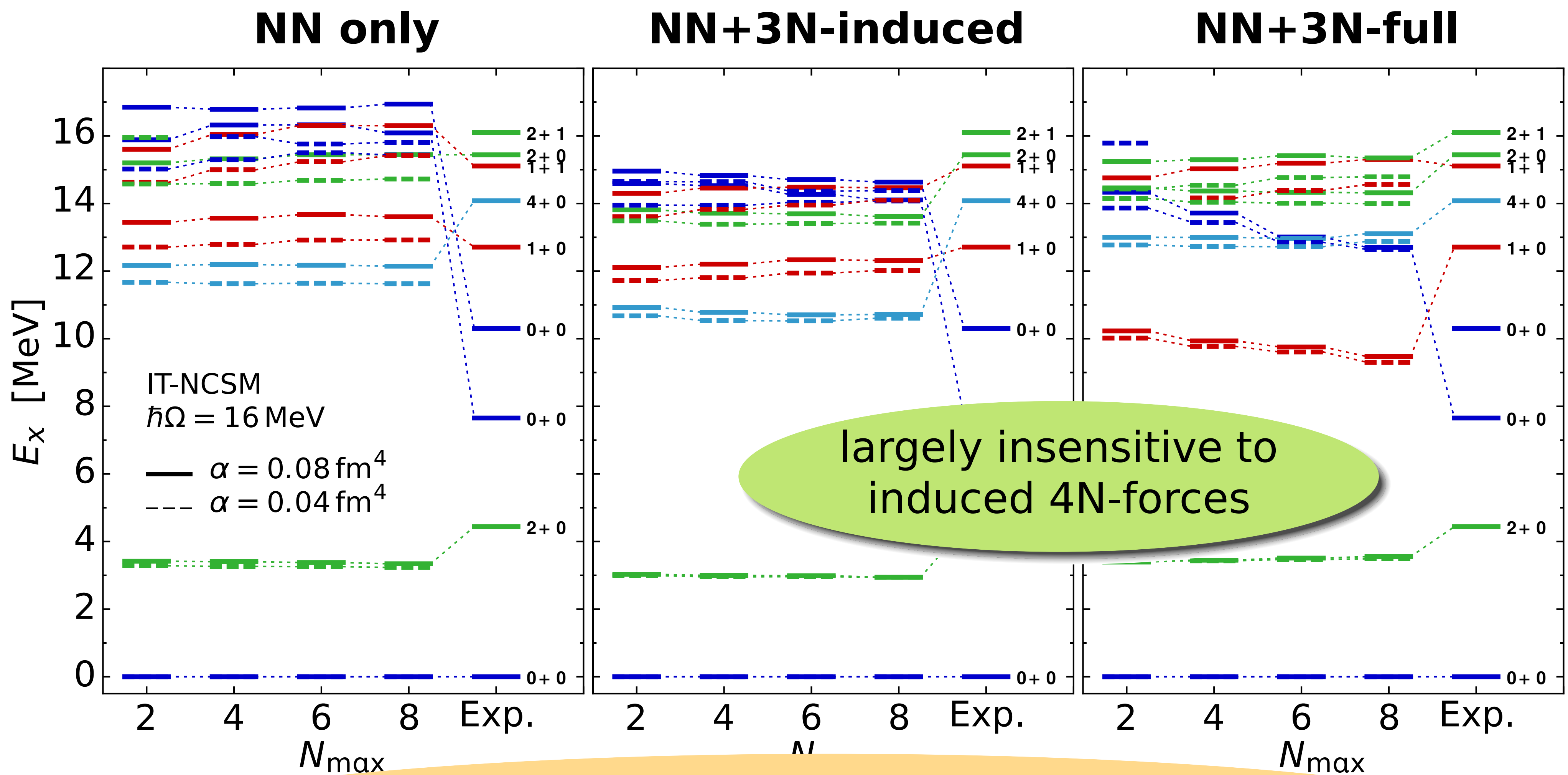
Different SRG-Evolved Hamiltonians

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

α-variation provides a **diagnostic tool** to assess the contributions of omitted many-body interactions

Spectroscopy of ^{12}C



largely insensitive to induced 4N-forces

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

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

Spectra of p-Shell Nuclei
– LEC Sensitivity –

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

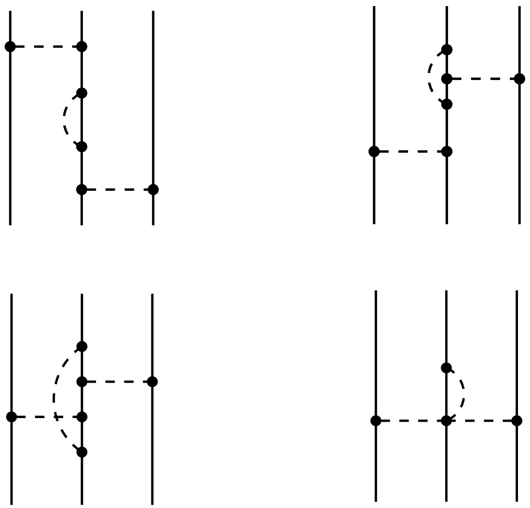
Why Study the LEC Sensitivity?

- 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
Entem et al. – PRC 66,014002	-0.81	-3.40	3.40

  - different c_i combinations have impact on 3NF contributions

- some N^{3}LO corrections to TPE can be included by



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

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

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

change of 20-30%

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

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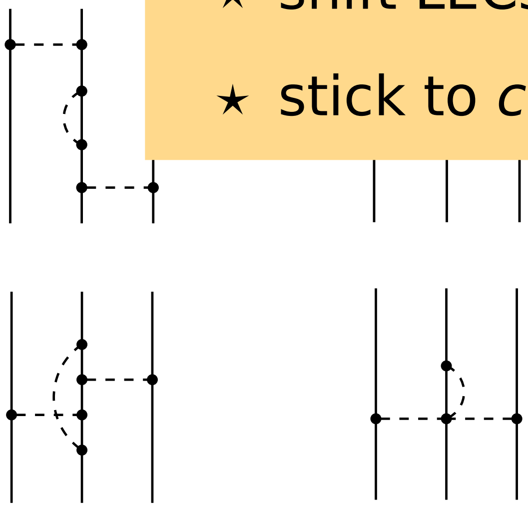
- Are spectra sensitive to different c_i combinations?
- Which LEC is most relevant for spectra?

- In the following
  - ⋆ shift LECs $c_{1/3/4}$
  - ⋆ stick to c_D=-0.2 and refit c_E to ^{4}He binding energy



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

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

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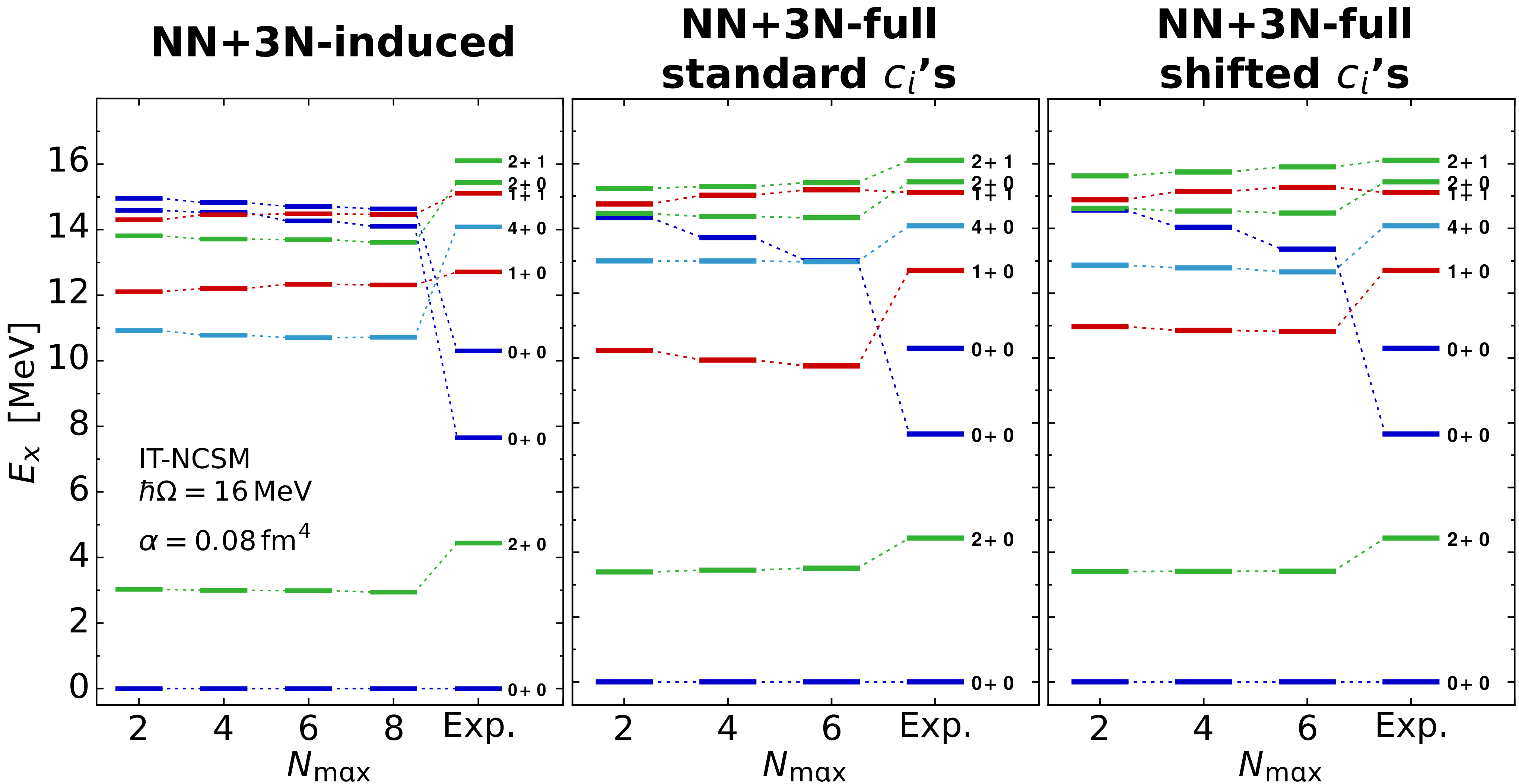
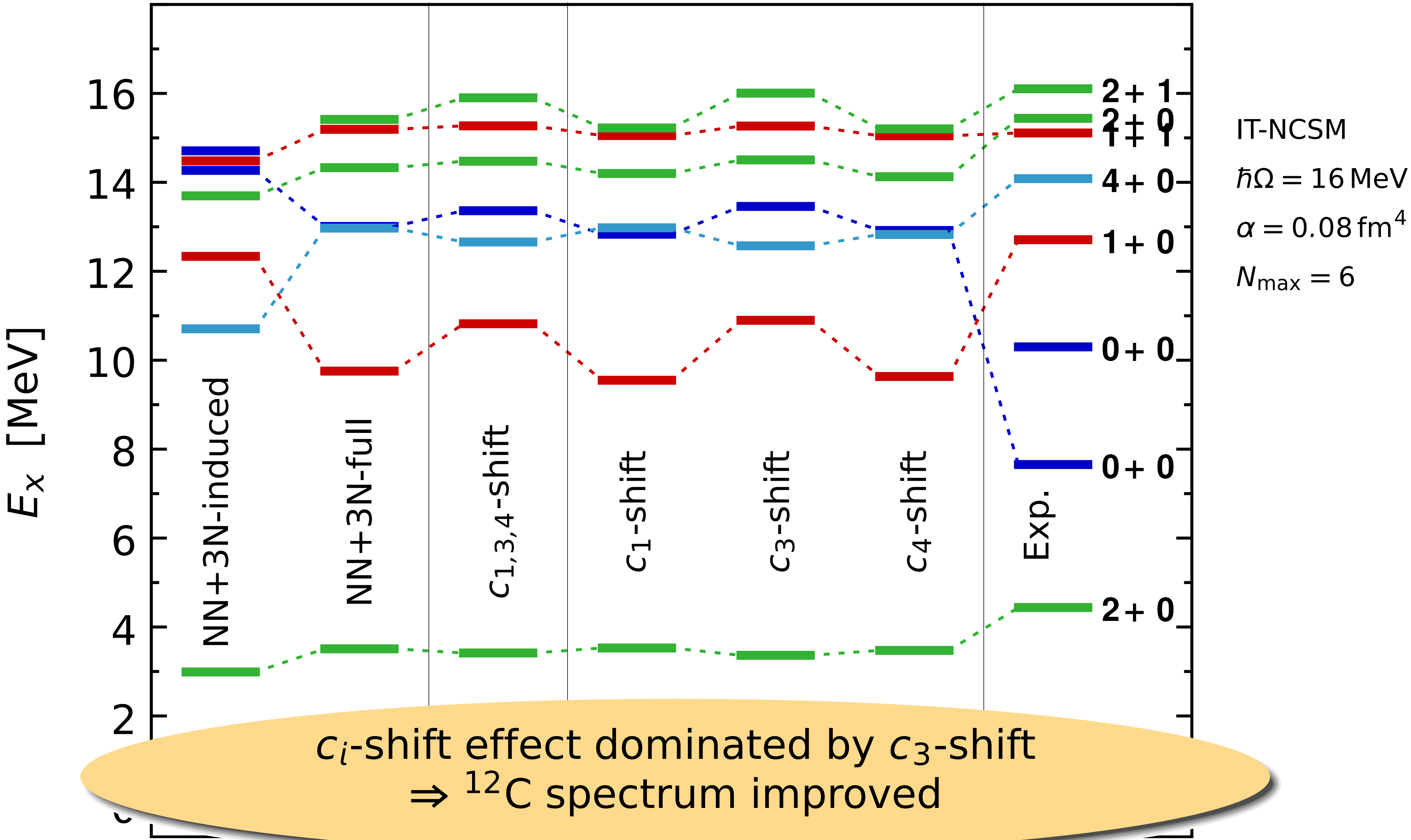
^{12}C – Shifted c_i's



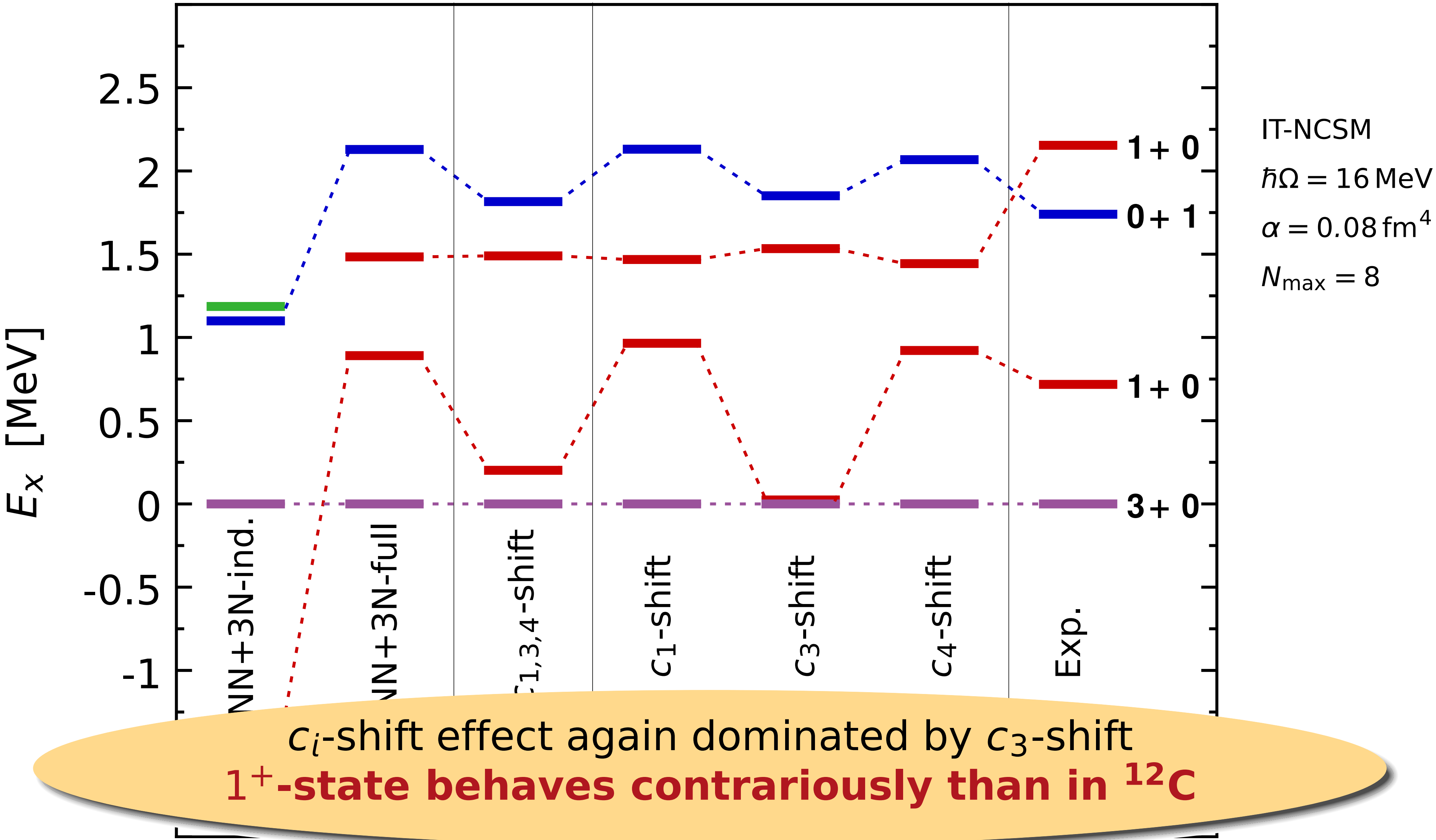
- 1^+ state: very sensitive to c_i-shift
- other states: minor effects

^{12}C – LEC Sensitivity Analysis



c_i-shift effect dominated by c_3-shift
⇒ ^{12}C spectrum improved

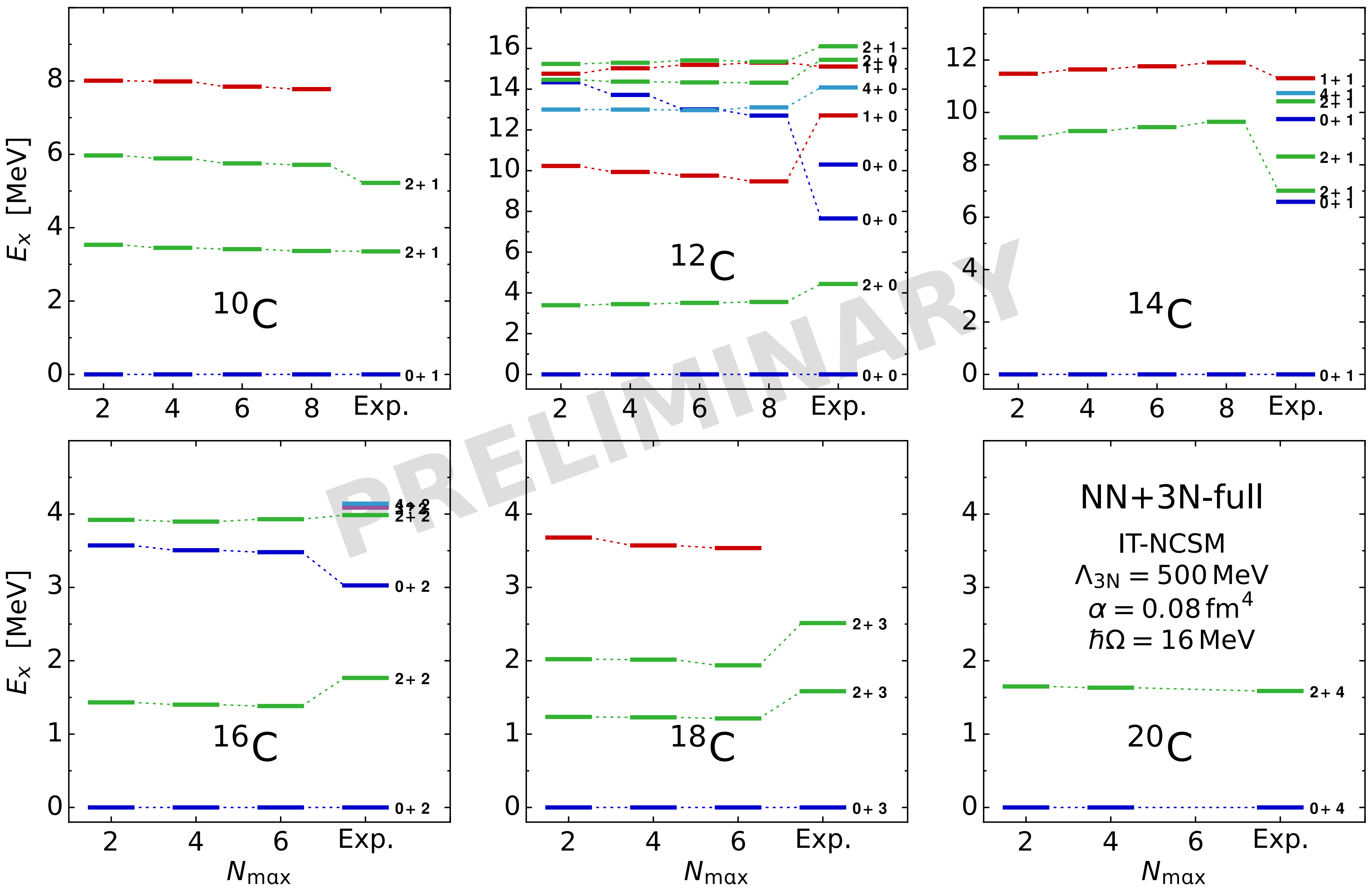
^{10}B – LEC Sensitivity Analysis



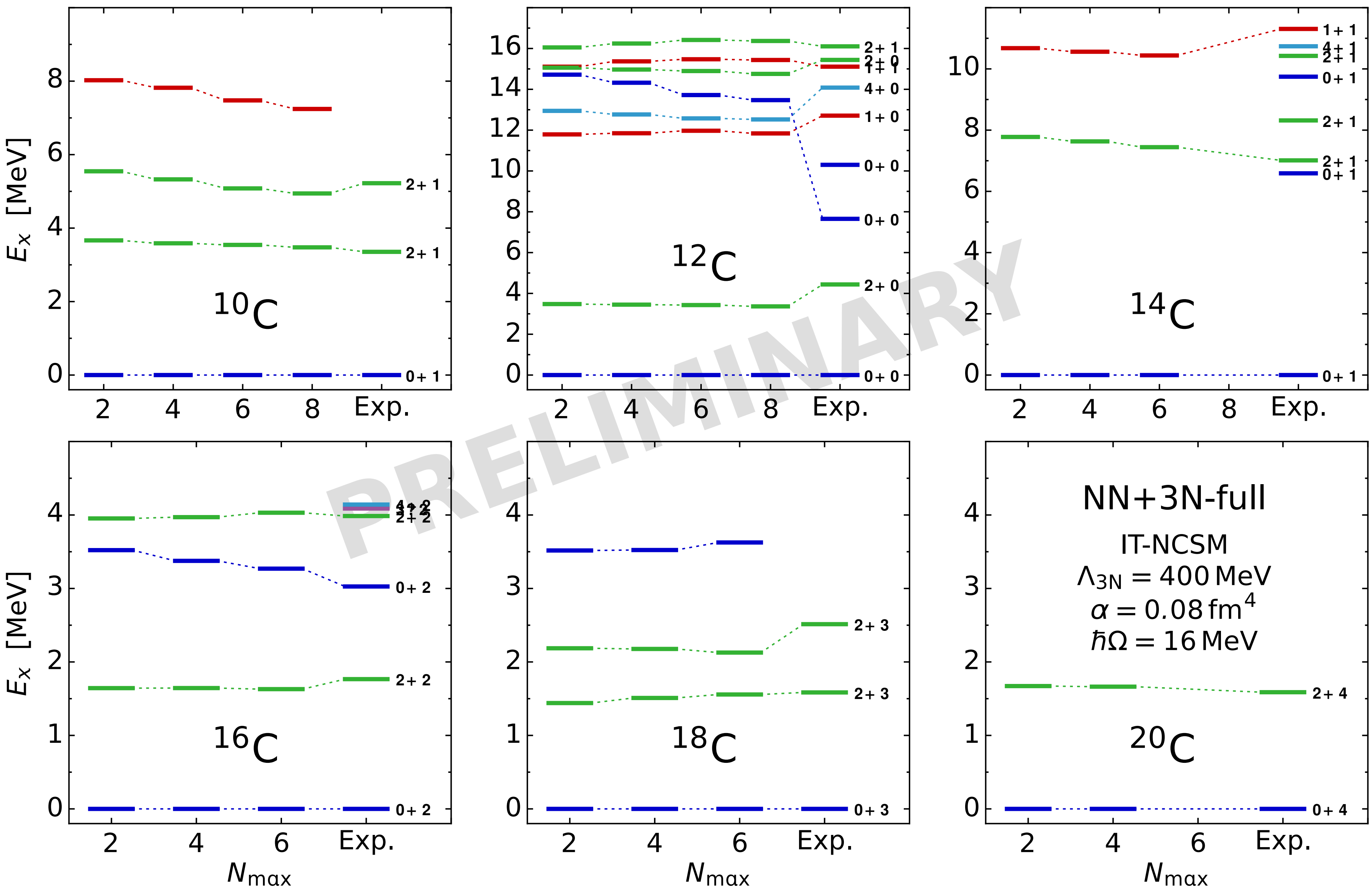
c_i-shift effect again dominated by c_3-shift
1^+-state behaves contrariously than in ^{12}C

Outlook
– The Carbon Isotopic Chain –

Carbon Isotopic Chain



Carbon Isotopic Chain



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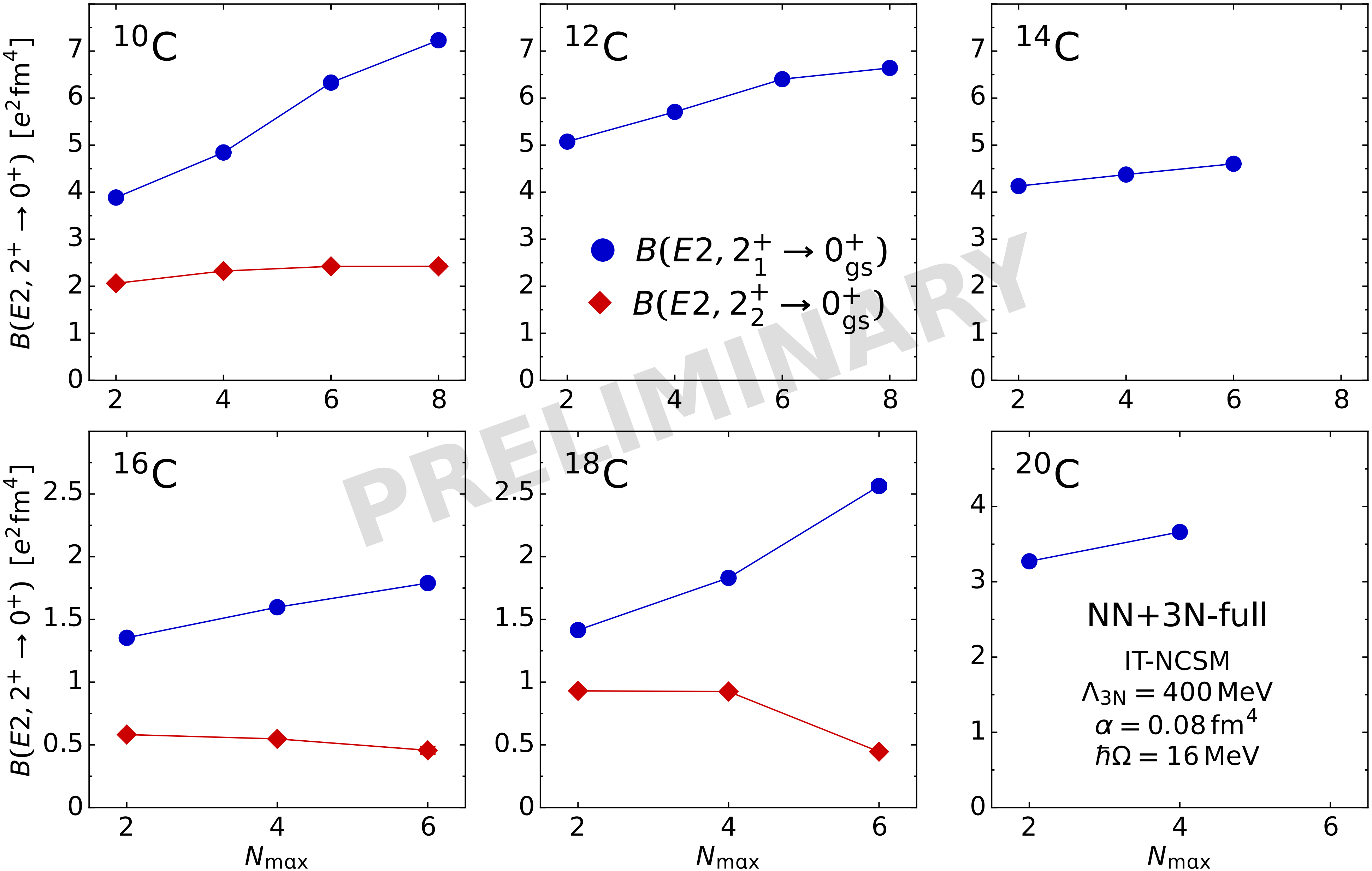

Conclusions

- access to **complete spectroscopy** of p- and lower sd-shell nuclei **with full 3N forces**
  - SRG-induced 4N forces negligible for converged spectra
  - IT-NCSM is the key many-body method of these studies

$\Rightarrow$ powerful **benchmark for chiral forces**

- 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
  - inclusion of chiral 3N forces at N^3LO necessary

Epilogue

- **thanks to our group & collaborators**

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  - H. Fe…
    GSI H…
  - C. Forssén
    Chalmers University, Sweden
  - H. Hergert
    Ohio State University, USA
  - P. Piecuch
    Michigan State University, USA

Thank you for your attention!

COMPUTING TIME

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Center for Scientific Computing Frankfurt

SFB 634

Deutsche Forschungsgemeinschaft
DFG

HIC for FAIR
Helmholtz International Center

LOEWE – Landes-Offensive zur Entwicklung Wissenschaftlich-ökonomischer Exzellenz

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