EXPLORING QUARK MASS DEPENDENT THREE-NUCLEON FORCES IN MEDIUM MASS-NUCLEI

Urban Vernik with Kai Hebeler and Achim Schwenk

arXiv:2512.20454

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Exzellente Forschung für Hessens Zukunft

OUTLINE

TECHNISCHE UNIVERSITÄT DARMSTADT

INTRODUCITON

- Enhanced 3N forces?
- Choice of interaction and calculational details

FITTING STRATEGIES

- Comparison of fitting strategies
- Why is the effect of F_2 large?

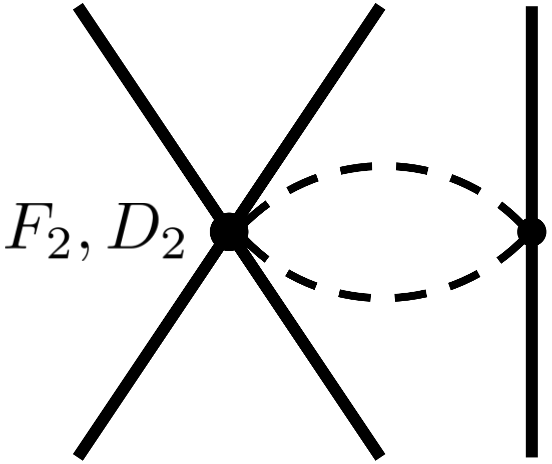
ENERGY AND RADII OF CLOSED-SHELL NUCLEI

CONCLUSIONS

ENHANCED 3N FORCES?

V. Cirigliano et al., Phys. Rev. Lett. 135, (2025)

- Using **KSW** power counting scheme, 3N topologies were identified that:
  - should contribute at N^3LO rather than N^5LO (enhanced by Q^{-2} compared to naive dimensional analysis)
  - include a quark-mass dependant $m_\pi^2(\bar{N}N)^2\pi^2$ vertex (D_2),
  - and a momentum dependent $(\bar{N}N)^2\pi^2$ vertex (F_2)
  - seem to play an important role in symmetric and neutron matter
- The suggested range is $\pm 1/(5f_\pi^4)$ → our normalization $\pm 1/5 = \pm 0.2$



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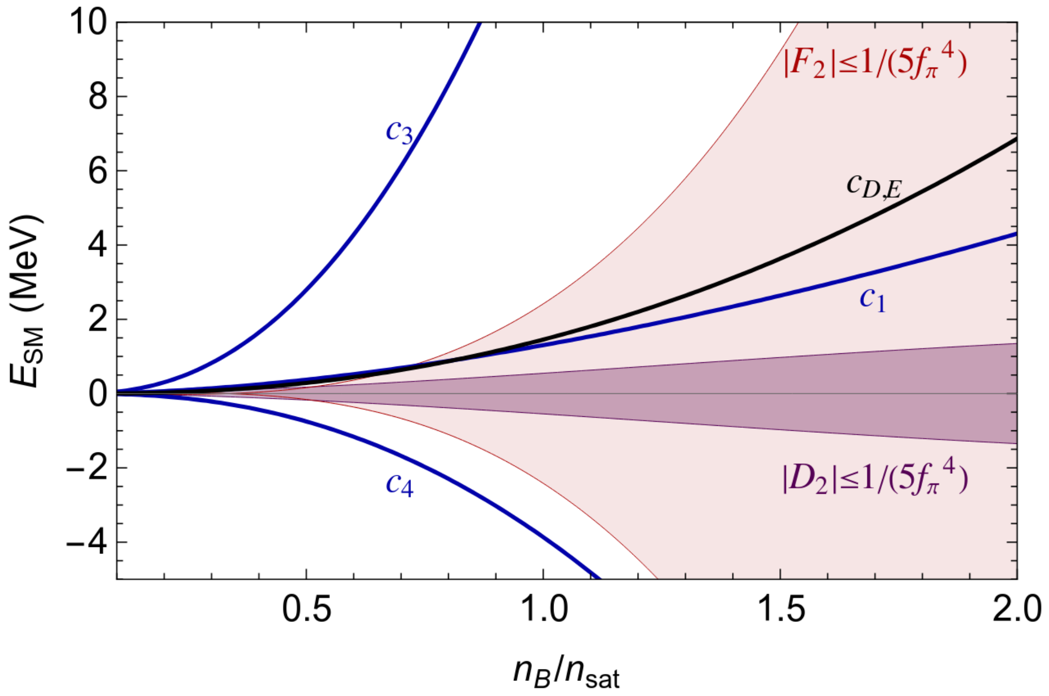

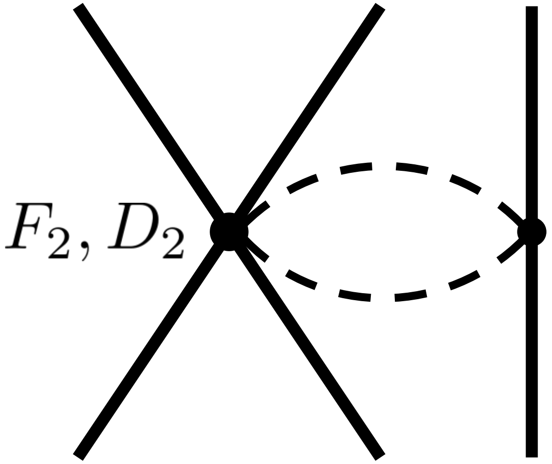

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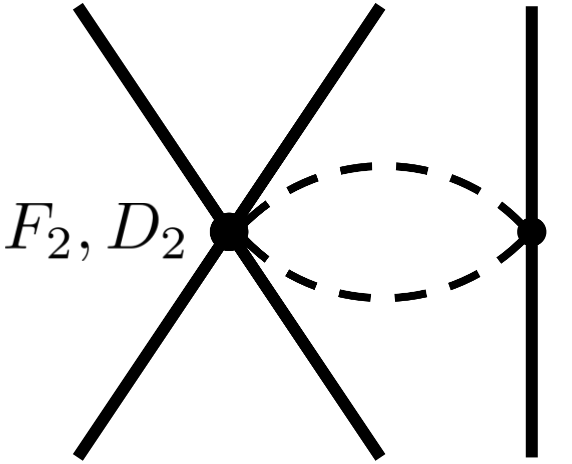

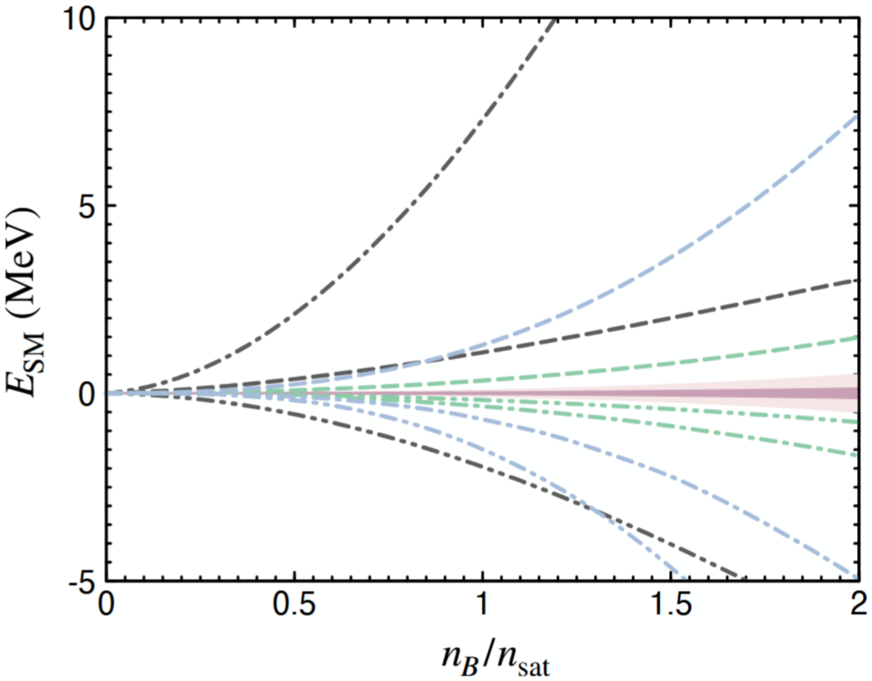

- The effect is however scheme and regulator dependent
- By removing the dependence, the contributions are within the expectations of Weinberg PC and NDA.

E. Epelbaum et al., arXiv:2512.14117 [nucl-th] (2025)

CHOICE OF INTERACTION &CALCULATION DETAILS

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INTERACTION: EMN D. R. Entem, R. Machleidt, and Y. Nosyk, Phys. Rev. C 96, (2017).

- 2N and 3N treated at consistent chiral order → here: both N^{2}LO and N^{3}LO
- Bare ($\lambda_{\mathrm{SRG}} = \infty,\ \Lambda_{2N} = \Lambda_{3N} = 450\ \mathrm{MeV}$) or SRG-evolved ($\lambda^{2N}_{\mathrm{SRG}} = 1.8\ \mathrm{fm}^{-1},\ \Lambda_{3N} = 2.0\ \mathrm{fm}^{-1} \approx 394.\cdots\ \mathrm{MeV}$)

LEC	c_1	c_3	c_4	c_D	c_E	F_2
N^{2}LO/N^{3}LO	-0.74/-1.20	-3.61/-4.43	2.44/2.67	*to fit*	*to fit*	*to fit*

M. Hoferichter, J. Ruiz de Elvira, B. Kubis, and U.-G. Meißner, Phys. Rept. 625, 1 (2016).

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CALCULATION DETAILS

- IMSRG(2), $e_{\max} = 14,\ E_{3\max} = 24,\ \hbar\omega = 16$

REFITTING

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- 2 fitting approaches (few-body only vs. including many-body data)

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1. Choose a value of F_2
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3. Constrain c_D
4. Compute observables

Approach	Constraint on c_D
few-body	^{3}H half-life **(GT)**
many-body	^{16}O charge radius (and BE) **(^{16}O)**

D. Gazit et al., Phys. Rev. Lett. 103, (2009); P. Klos et al Eur. Phys. J. A 53, (2017).

T. Hüther, et al. Phys. Lett. B (2020),
P. Arthuis et al., arXiv:2411.00097 [nucl-th] (2024).
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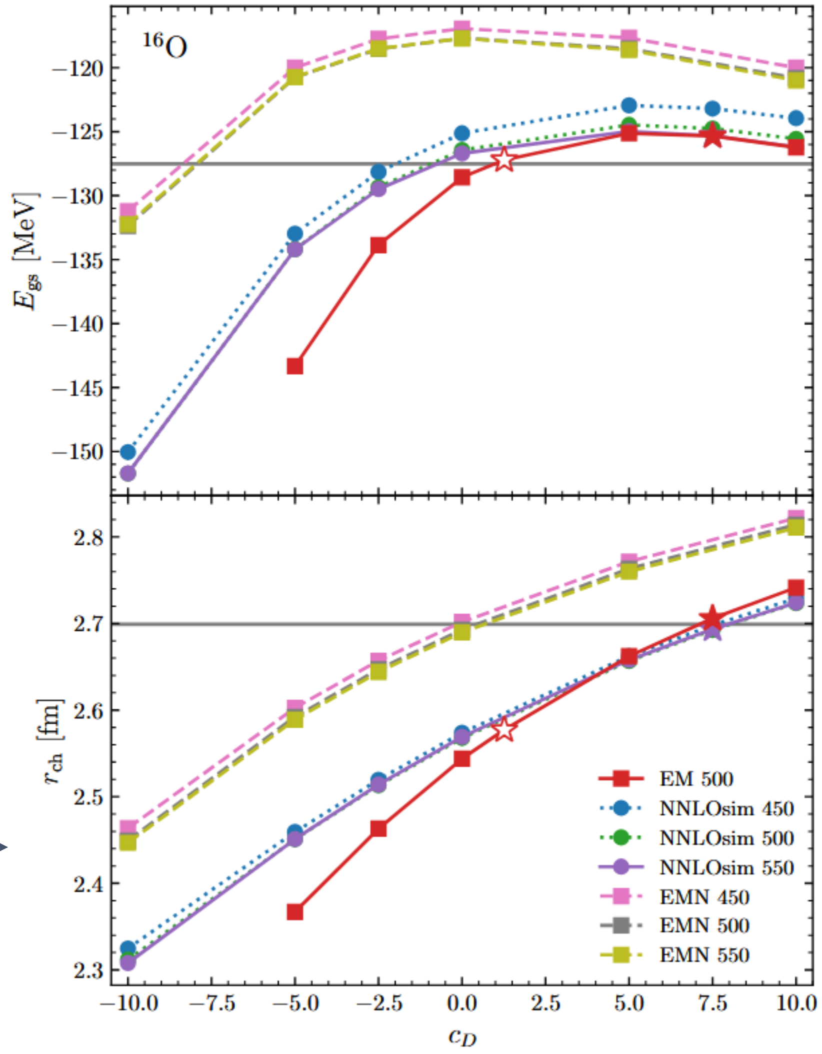

Figure: P. Arthuis et al., arXiv:2411.00097 [nucl-th] (2024)

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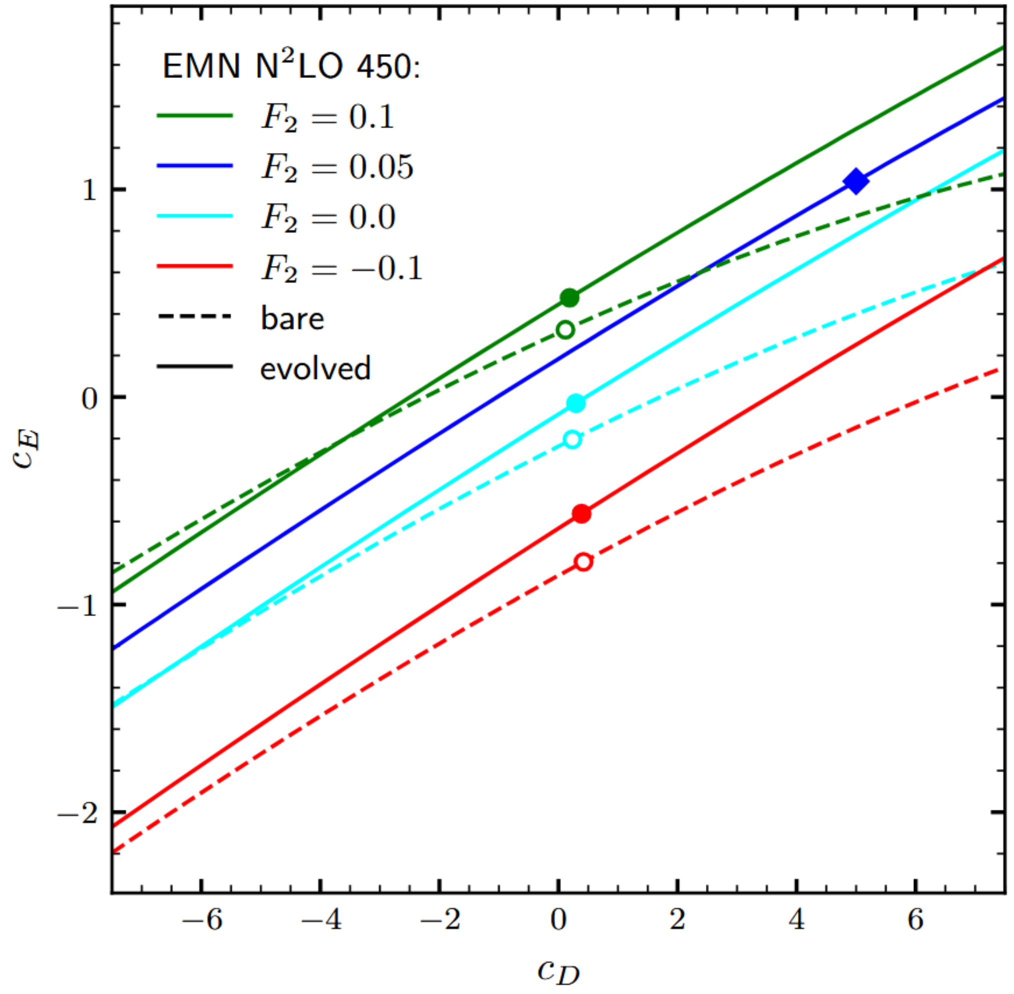
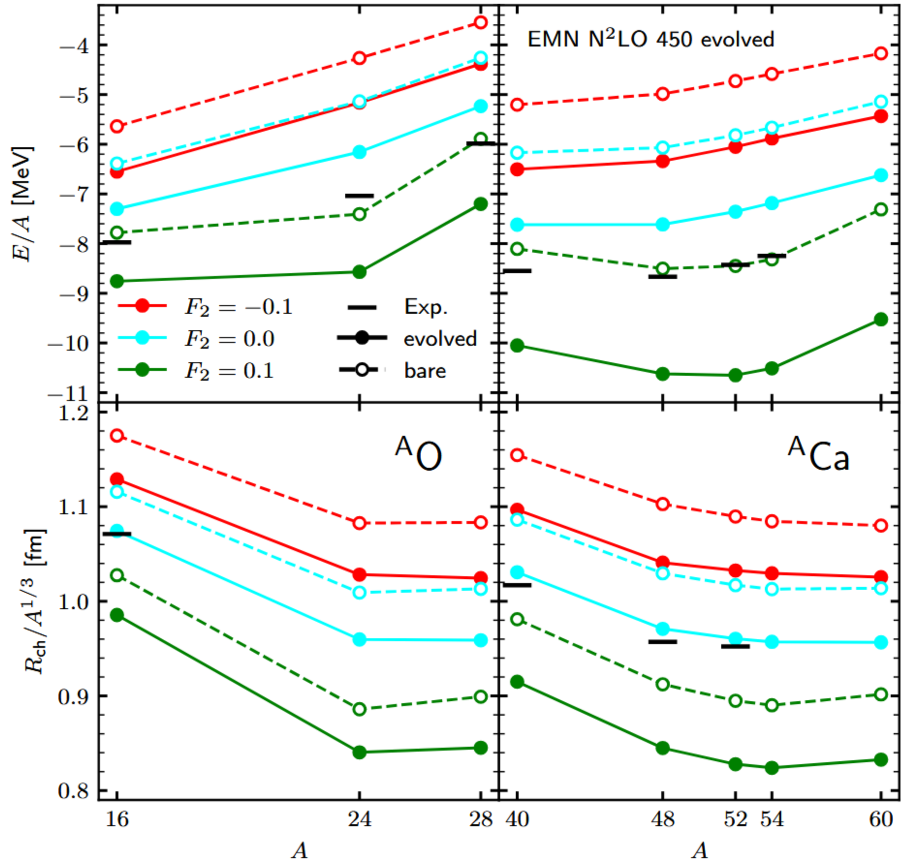


COMPARISON OF FITTING STRATEGIES

GT STRATEGY

- Energies and radii cannot be reproduced at the same time
- To change energy and radius independently, one must be able to vary c_D



Label	Order	λ (fm^{-1})	Λ_{3N}	F_2	c_D	c_E	Fit
○ (red)	N^{2}LO	∞	450 MeV	-0.1	0.421	-0.794	GT
○ (cyan)	N^{2}LO	∞	450 MeV	0.0	0.235	-0.204	GT
○ (green)	N^{2}LO	∞	450 MeV	0.1	0.118	0.324	GT
● (red)	N^{2}LO	1.8	2.0 fm^{-1}	-0.1	0.389	-0.562	GT
● (cyan)	N^{2}LO	1.8	2.0 fm^{-1}	0.0	0.294	-0.030	GT
● (green)	N^{2}LO	1.8	2.0 fm^{-1}	0.1	0.188	0.478	GT

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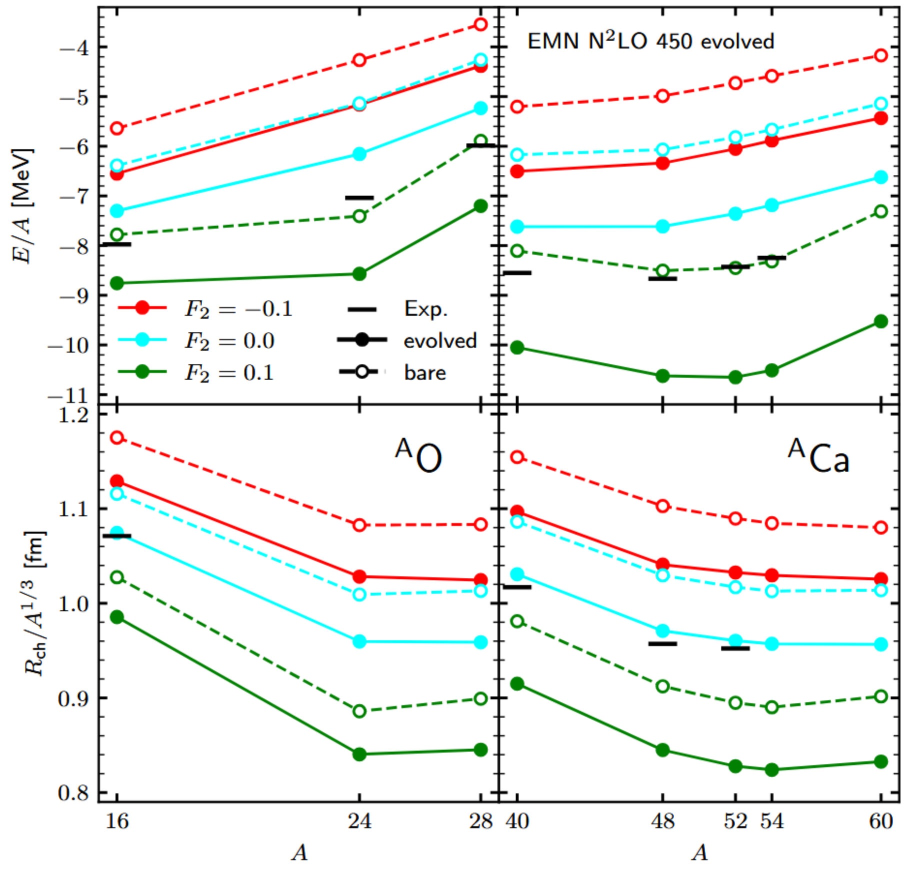
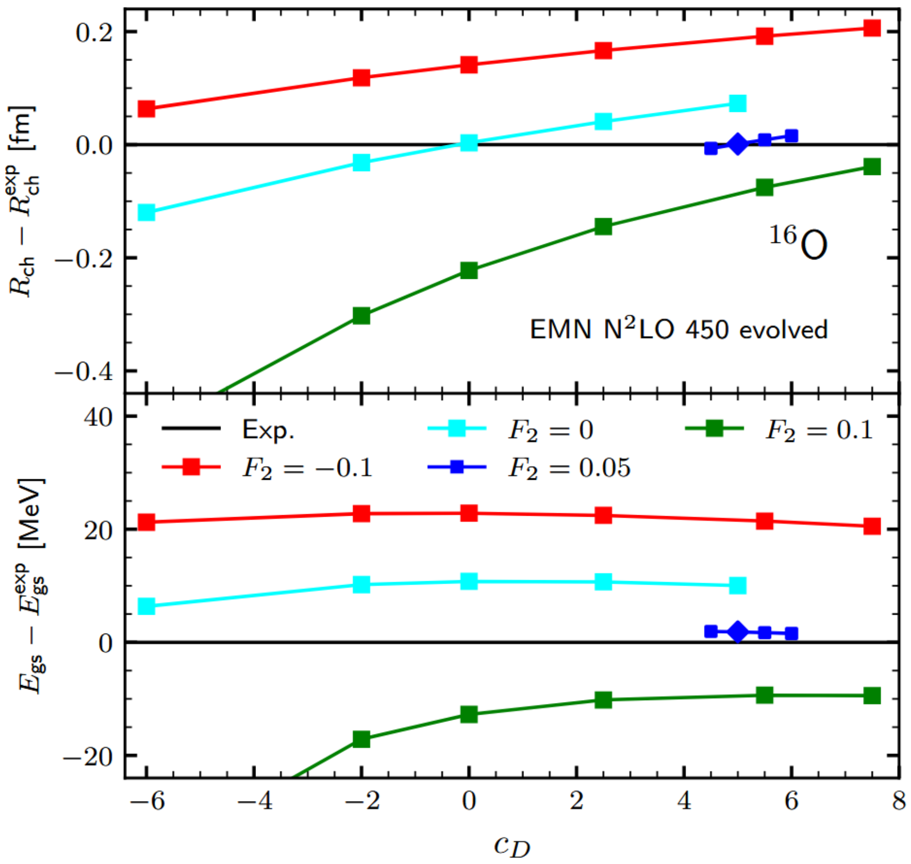


^{16}O STRATEGY

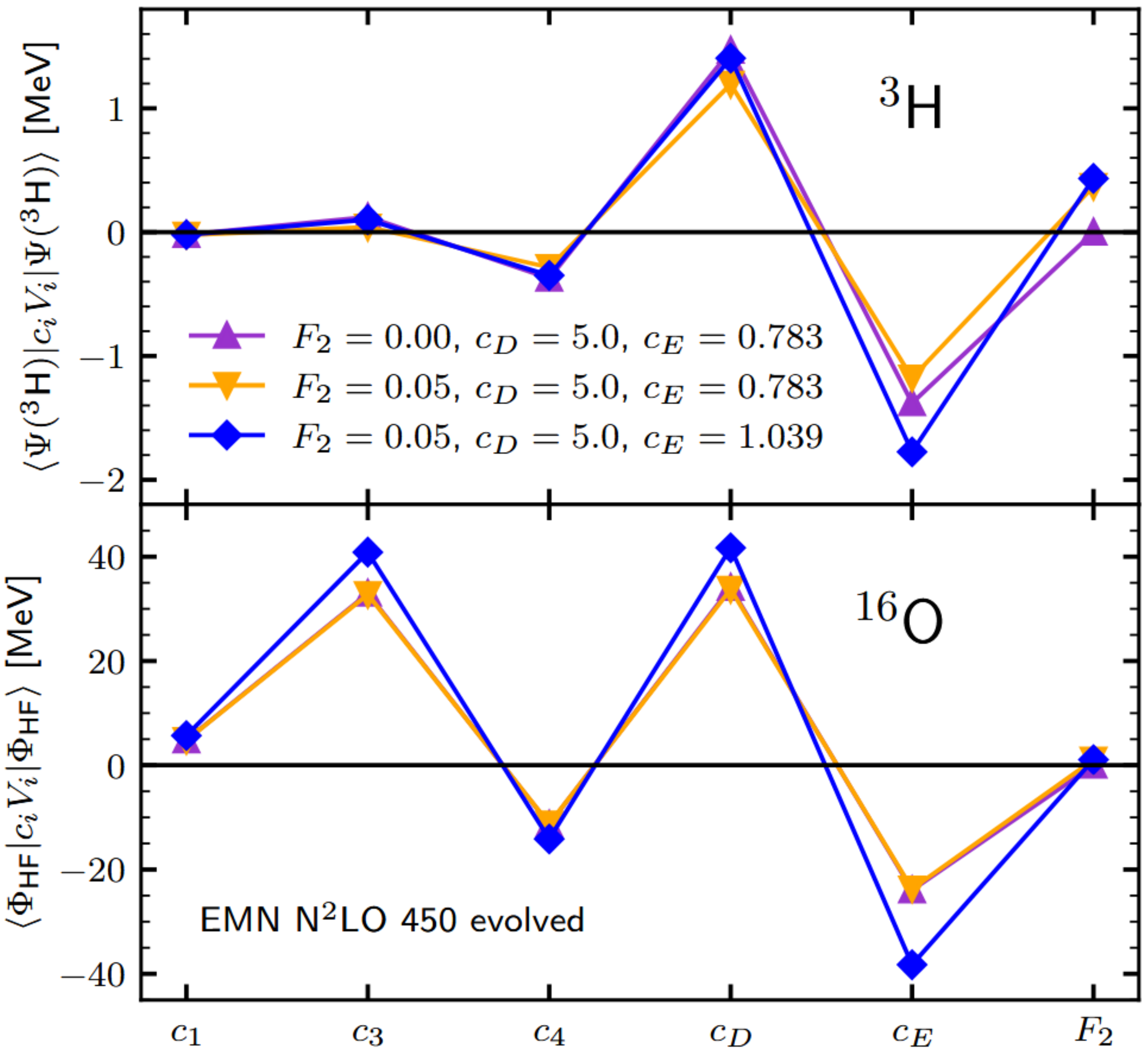
- Energies and radii can be reproduced at the same time
- Works similarly well for both chiral orders for the same F_2



$$F_2^{\text{evolved}} = 0.05,\ F_2^{\text{bare}} = 0.15$$

WHY IS THE EFFECT OF F_2 SO LARGE?

- Is it safe/consistent to promote individual topologies?
  - case study: c_D and c_E exhibit fine cancellations
  - counter terms to F_2 might need to be promoted
- F_2 has a small contribution to the energy but fitting rearranges other topologies significantly



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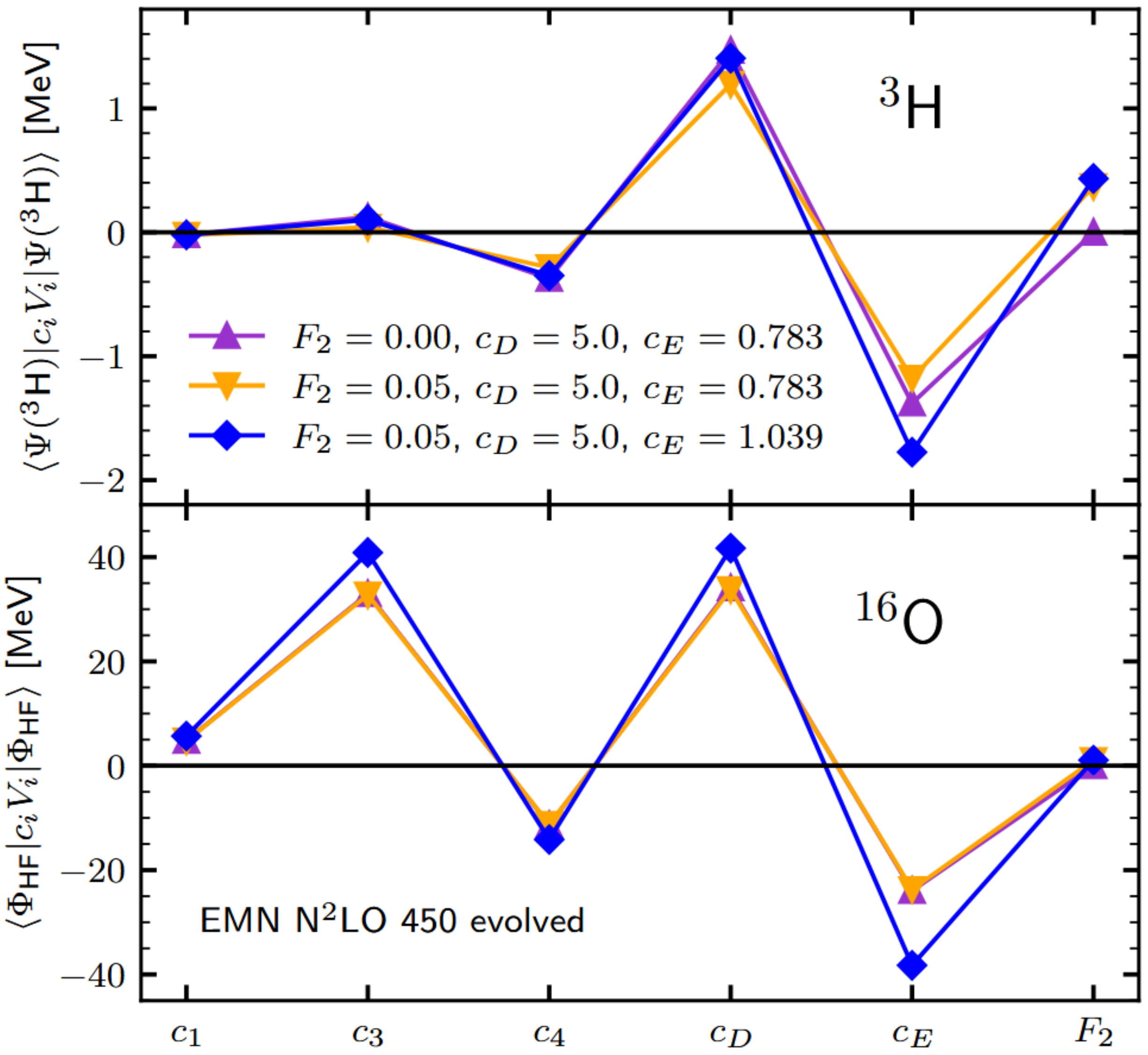
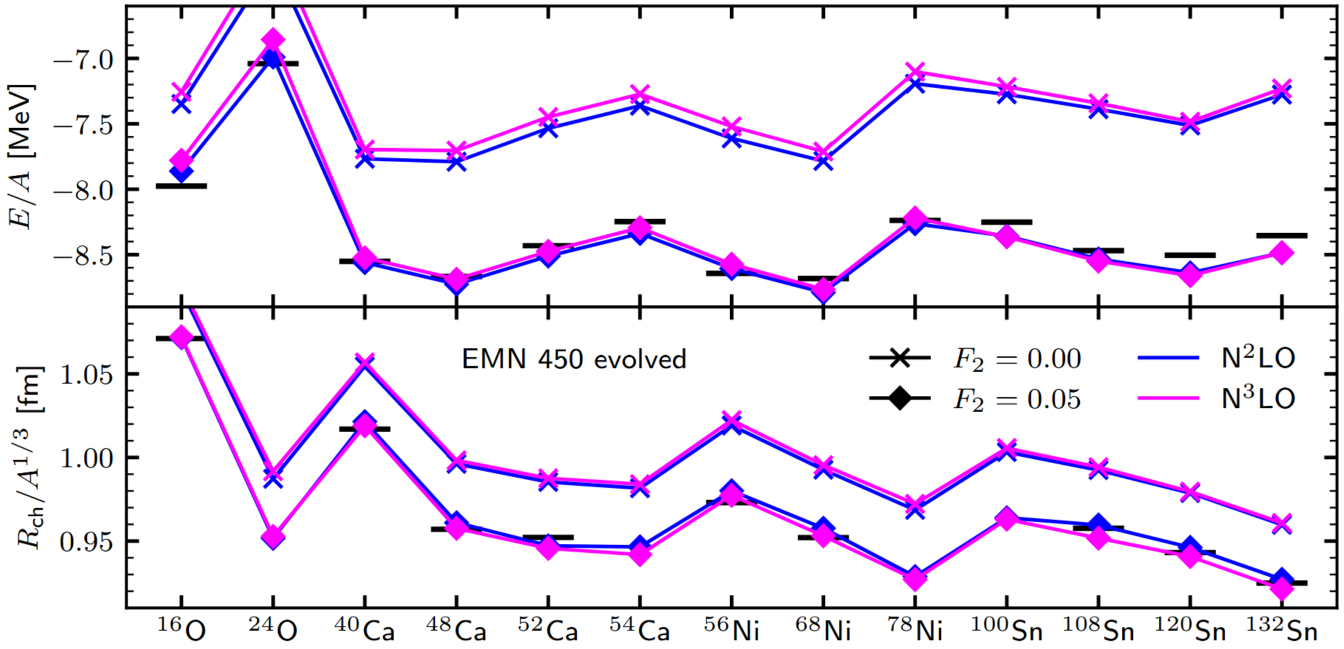
➢ It is the refitted c_E that affects the observables

➢ At the cost of reproducing triton data, $c_D = 5.0,\ c_E = 1.039$ would be an example of EMN interaction with great reproduction of oxygen properties



RESULTS FOR ^{16}O - ^{132}Sn



- Both energies and charge radii are very well reproduced at both chiral orders
- No significant changes in trends as a function of mass and proton-to-neutron ratio

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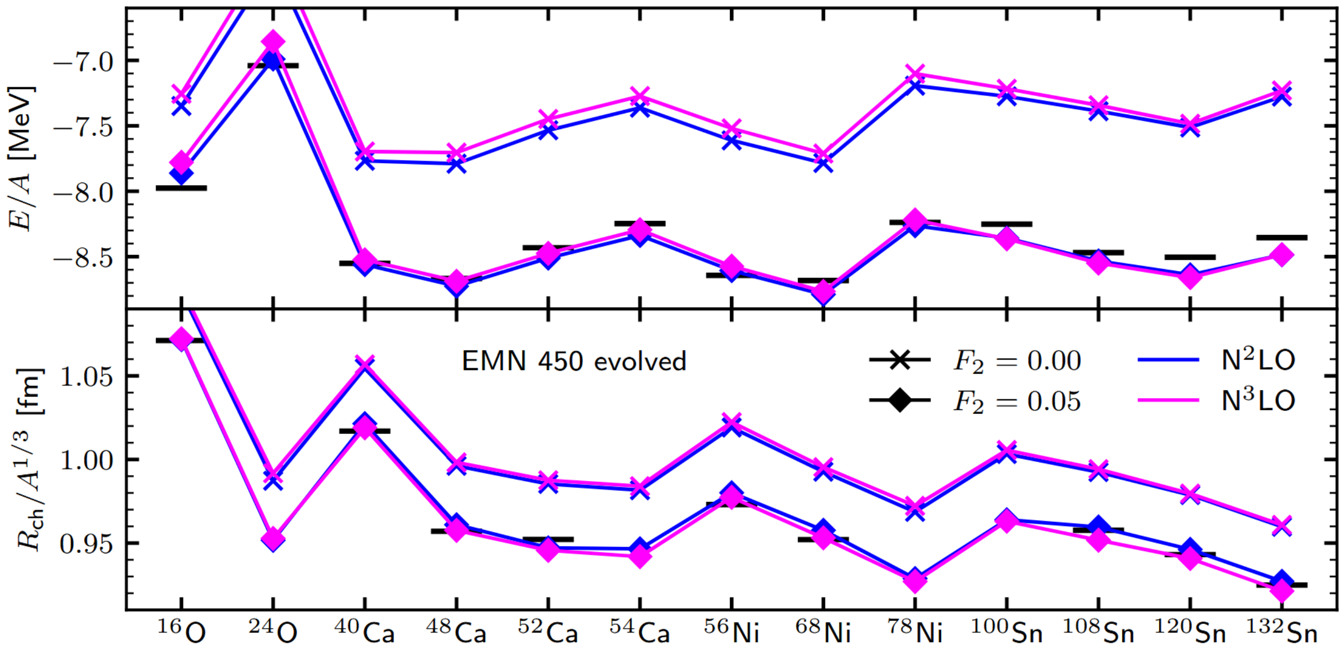

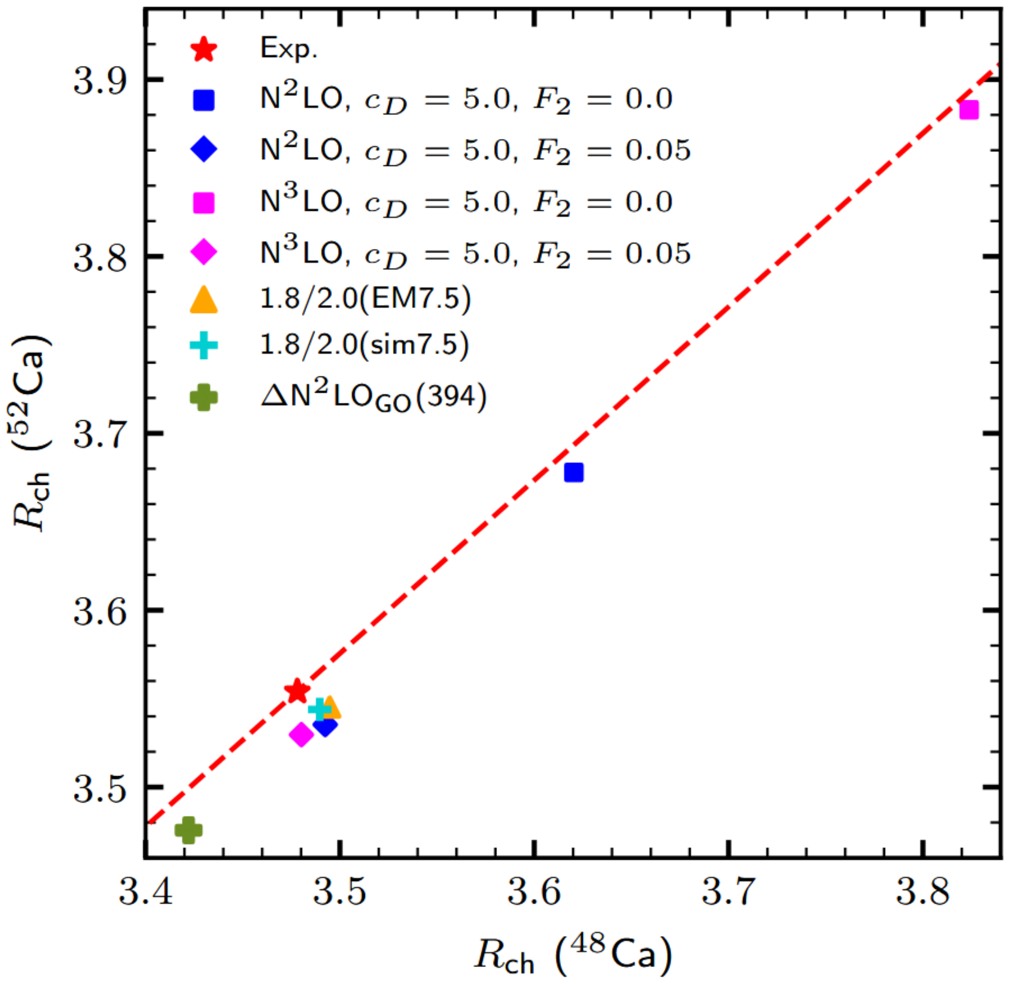

- Both energies and charge radii are very well reproduced at both chiral orders
- No significant changes in trends as a function of mass and proton-to-neutron ratio
- Inclusion of F_2 cannot resolve the theoretical discrepancy to the experimental value of $\delta\langle R_{\mathrm{ch}}^2\rangle^{48,52}$

CONCLUSIONS

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- We investigated the impact of new 3N forces on the properties of medium-mass nuclei.
- Many-body energies and radii are noticeably impacted by F_2 → but due to refit of c_E.
- Employing the ^{16}O fitting strategy and adding F_2 to the EMN interactions brings it in a very good agreement with the experimental results along the chain of closed-shell nuclei.
- While F_2 improves the EMN interaction, this is mainly due to shifts in c_D and c_E rather than new physics hiding in F_2.

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THANK YOU FOR YOUR ATTENTION!