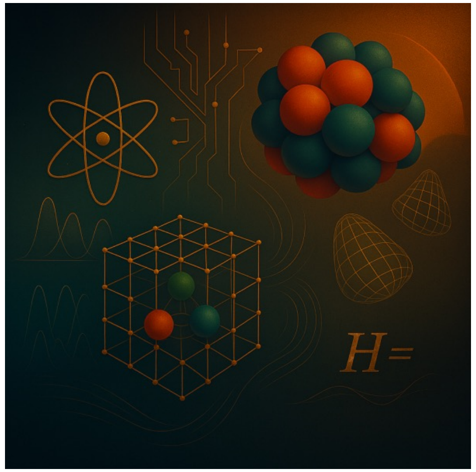
Ab initio calculations with sub-leading three-nucleon interaction

INT Program 26-1
Nuclear Hamiltonians for Advancing Nuclear Physics and Beyond
April 29, 2026

Petr Navratil

TRIUMF



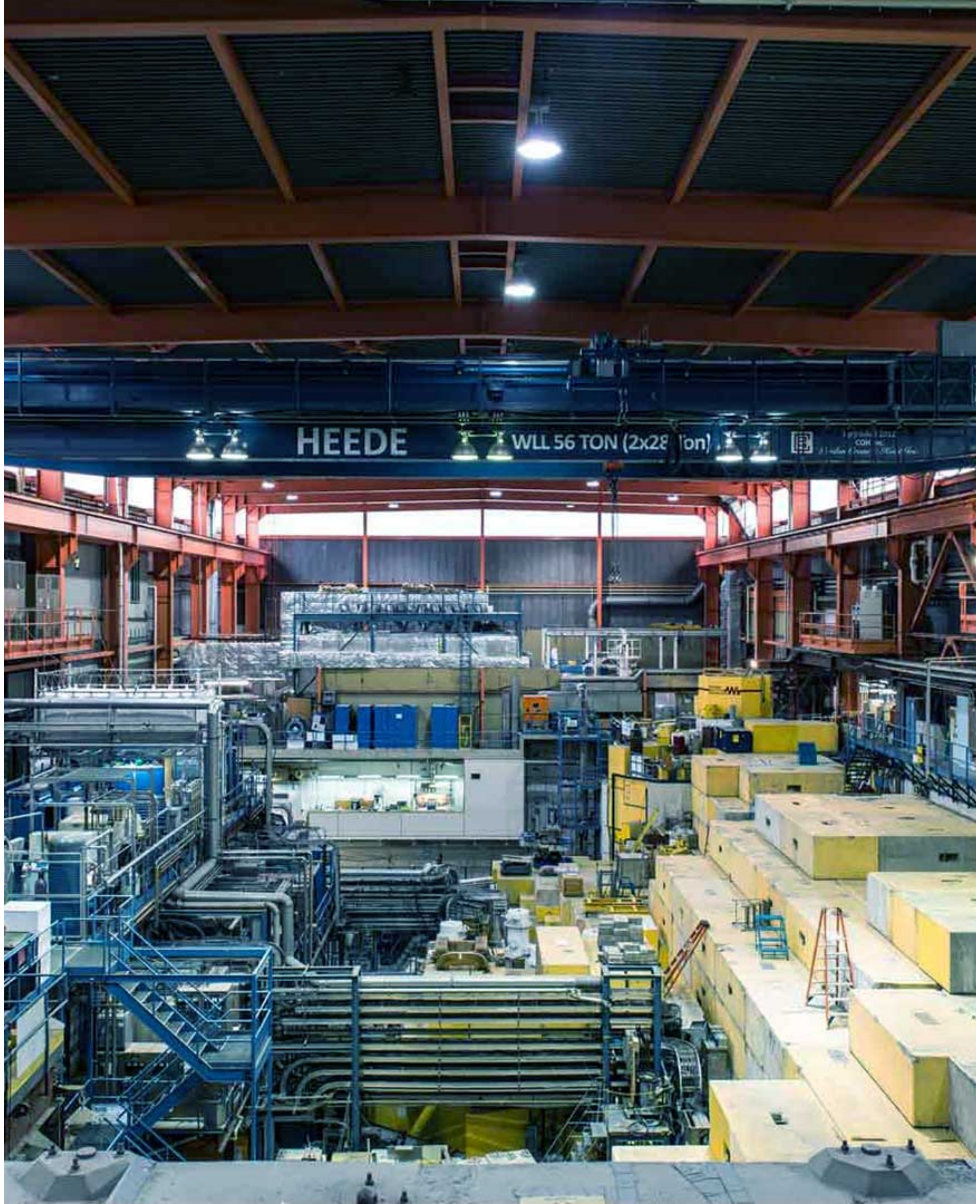
2026-04-29

Discovery, accelerated

Outline

- *Ab initio* nuclear theory – no-core shell model with continuum (NCSMC)
- Precision chiral EFT NN N^3LO + $3N_{lnl}$ interaction
- Precision chiral EFT NN Hamiltonian - order by order convergence
- Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term
  - Energies of light nuclei
  - n+^{4}He scattering
  - ^{7}Be(p,γ)^{8}B radiative capture
  - p+^{12}C scattering and capture, n+^{12}C cross section
  - Ground-state energies of medium mass nuclei
- Enhanced short-range 3N interaction with two-pion exchange
  - Results for 3H
- Conclusions

Ab initio nuclear theory - no-core shell model with continuum (NCSMC)



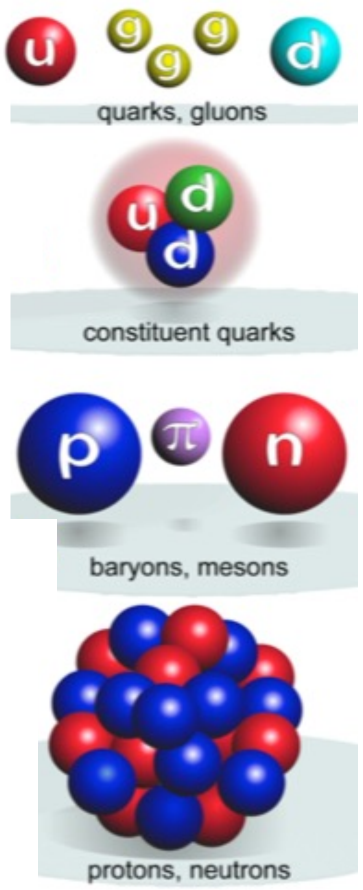
First principles or *ab initio* nuclear theory

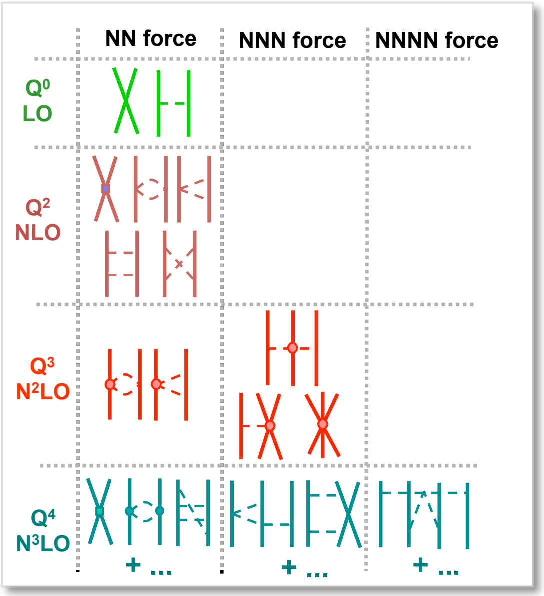
Quantum Chromodynamics (QCD)

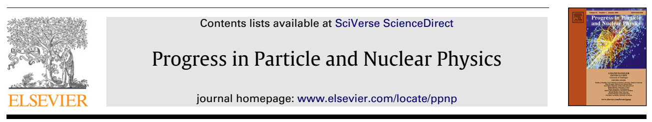
Chiral Effective Field Theory (parameters fitted to NN data)

Many-body *ab initio* nuclear theory

$$H\,\Psi^{(A)} = E\,\Psi^{(A)}$$

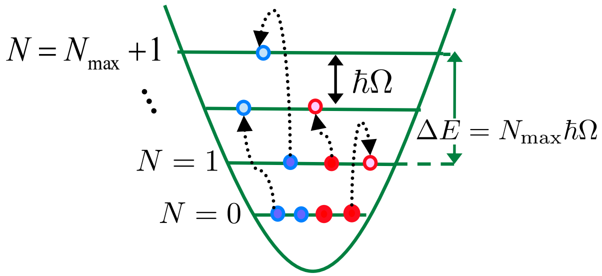


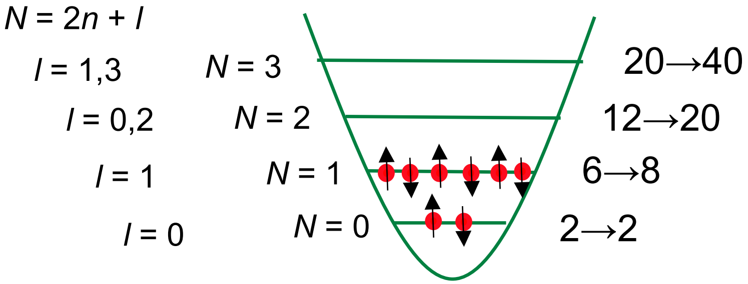



Progress in Particle and Nuclear Physics 69 (2013) 131–181
Contents lists available at SciVerse ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp
Review
Ab initio no core shell model
Bruce R. Barrett[a], Petr Navrátil[b], James P. Vary[c,*]

Conceptually simplest *ab initio* method: No-Core Shell Model (NCSM)

- Basis expansion method (CI)
  - Harmonic oscillator (HO) basis truncated in a particular way (N_{max})
  - Why HO basis?
    - Lowest filled HO shells match magic numbers of light nuclei (2, 8, 20 – ^{4}He, ^{16}O, ^{40}Ca)
    - Equivalent description in relative(Jacobi)-coordinate and Slater determinant basis – nuclei self-bound, $[H,P_{CM}]=0$
      - Exact factorization of CM and intrinsic eigenfunctions at each N_{max}
- Good for well-bound states, approximation of weakly-bound states and narrow resonances





$$E = (2n + l + \tfrac{3}{2})\hbar\Omega$$

Ab initio **calculations of structure including weakly bound halo states, scattering, reactions**

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} , \lambda \right\rangle + \sum_{\nu} \int d\vec{r}\; \gamma_{\nu}(\vec{r}\,)\; \hat{A}_{\nu} \left| {}_{(A-a)} \;\; \vec{r} \;\; {}_{(a)} , \nu \right\rangle$$


IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta
Phys. Scr. **91** (2016) 053002 (38pp) doi:10.1088/0031-8949/91/5/053002

Invited Comment

Unified *ab initio* approaches to nuclear structure and reactions

Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

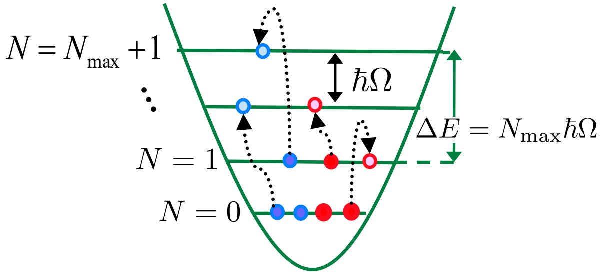
S. Baroni, P. Navratil, and S. Quaglioni,
PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

Ab initio calculations of structure including weakly bound halo states, scattering, reactions

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)}, \lambda \right\rangle + \sum_{\nu} \int d\vec{r}\; \gamma_{\nu}(\vec{r})\; \hat{A}_{\nu} \left| {}_{(A-a)} \; \vec{r} \; {}_{(a)}, \nu \right\rangle$$



Static solutions for aggregate system, describe all nucleons close together


IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta
Phys. Scr. 91 (2016) 053002 (38pp) doi:10.1088/0031-8949/91/5/053002

Invited Comment

Unified *ab initio* approaches to nuclear structure and reactions

Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

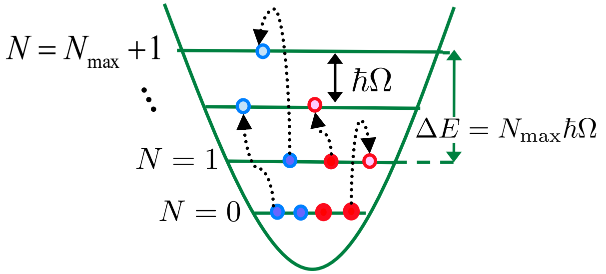
S. Baroni, P. Navratil, and S. Quaglioni, PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

***Ab initio* calculations of structure including weakly bound halo states, scattering, reactions**

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)}, \lambda \right\rangle + \sum_{\nu} \int d\vec{r}\ \gamma_{\nu}(\vec{r}\,)\ \hat{A}_{\nu} \left| {}_{(A-a)}\ \vec{r}\ {}_{(a)}, \nu \right\rangle$$



Static solutions for aggregate system, describe all nucleons close together

Continuous microscopic cluster states, describe long-range projectile-target


IOP Publishing | Royal Swedish Academy of Sciences — Physica Scripta

Phys. Scr. 91 (2016) 053002 (38pp) — doi:10.1088/0031-8949/91/5/053002

Invited Comment

Unified *ab initio* approaches to nuclear structure and reactions

Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

S. Baroni, P. Navratil, and S. Quaglioni, PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

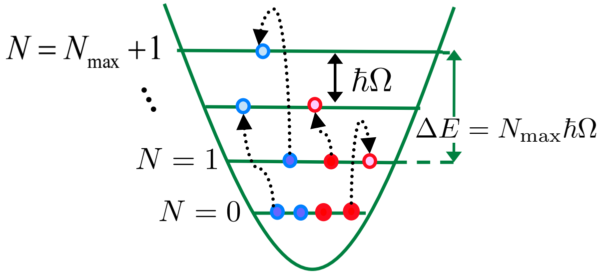
Ab initio calculations of structure including weakly bound halo states, scattering, reactions

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

NCSM　　　　NCSM

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} \,\text{[nucleus]}, \lambda \right\rangle + \sum_{\nu} \int d\vec{r}\, \gamma_{\nu}(\vec{r})\, \hat{A}_{\nu} \left| {}_{(A-a)}\,\text{[cluster]} \xleftrightarrow{\vec{r}} \text{[cluster]}\,{}_{(a)}, \nu \right\rangle$$



Static solutions for aggregate system, describe all nucleons close together

Continuous microscopic cluster states, describe long-range projectile-target


IOP Publishing | Royal Swedish Academy of Sciences　Physica Scripta

Phys. Scr. **91** (2016) 053002 (38pp)　doi:10.1088/0031-8949/91/5/053002

Invited Comment

Unified *ab initio* approaches to nuclear structure and reactions

Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

S. Baroni, P. Navratil, and S. Quaglioni,
PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

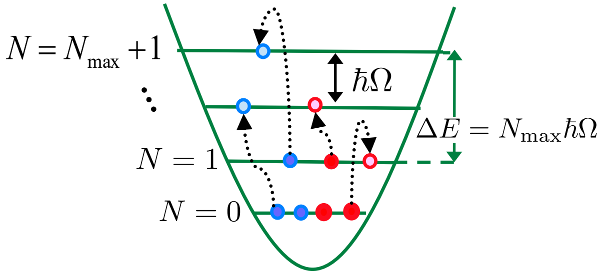
Ab initio calculations of structure including weakly bound halo states, scattering, reactions

Unified approach to bound & continuum states

No-Core Shell Model with Continuum (NCSMC)

Unknowns

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} \, , \lambda \right\rangle + \sum_{\nu} \int d\vec{r}\; \gamma_{\nu}(\vec{r}\,)\; \hat{A}_{\nu} \left|_{(A-a)} \;\; \vec{r} \;\; (a) \, , \nu \right\rangle$$



Static solutions for aggregate system, describe all nucleons close together

Continuous microscopic cluster states, describe long-range projectile-target


IOP Publishing | Royal Swedish Academy of Sciences

Physica Scripta

Phys. Scr. **91** (2016) 053002 (38pp)

doi:10.1088/0031-8949/91/5/053002

Invited Comment

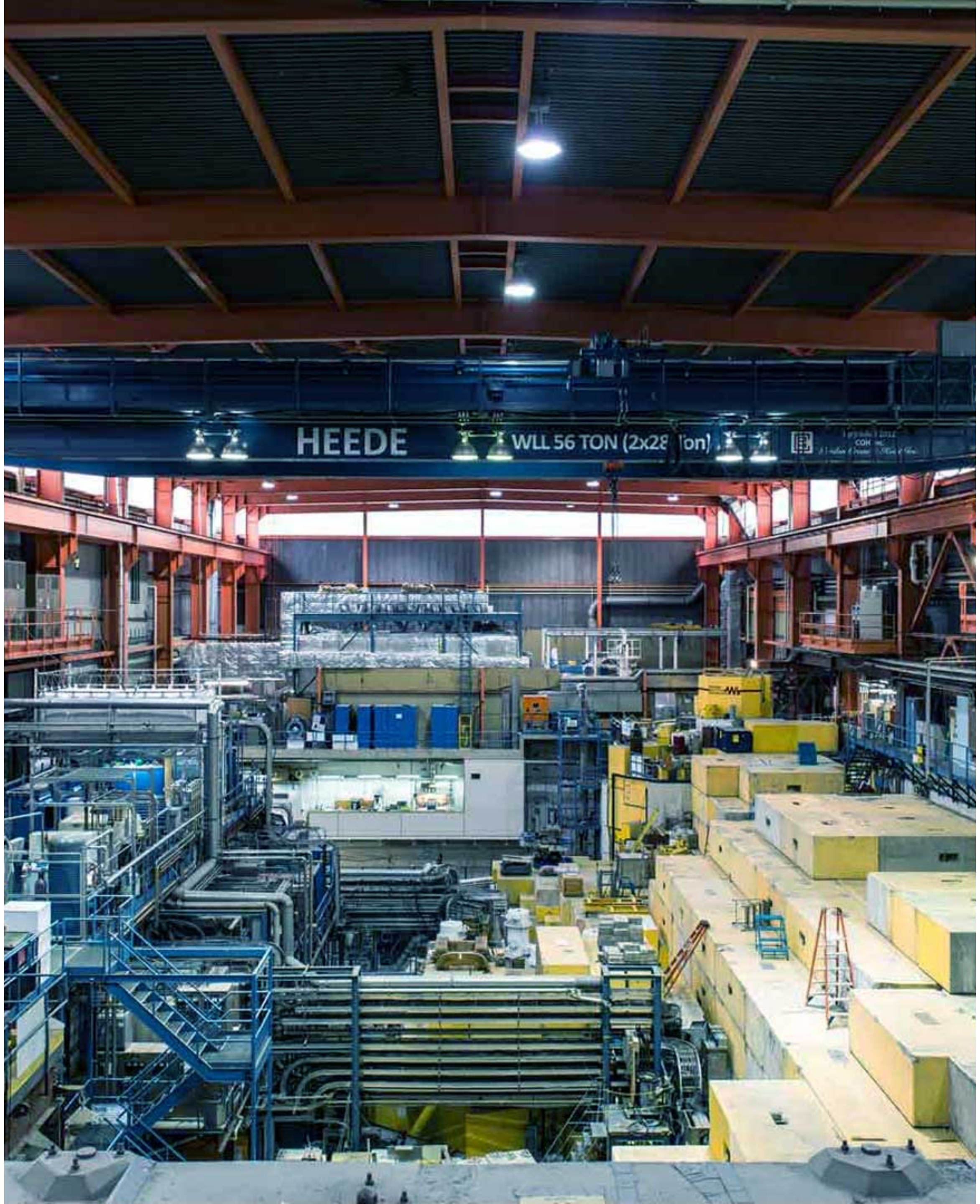
Unified *ab initio* approaches to nuclear structure and reactions

Petr Navrátil[1], Sofia Quaglioni[2], Guillaume Hupin[3,4], Carolina Romero-Redondo[2] and Angelo Calci[1]

S. Baroni, P. Navratil, and S. Quaglioni, PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

Precision chiral EFT

NN N^{3}LO + 3N$_{lnl}$ interaction



PHYSICAL REVIEW C **101**, 014318 (2020)

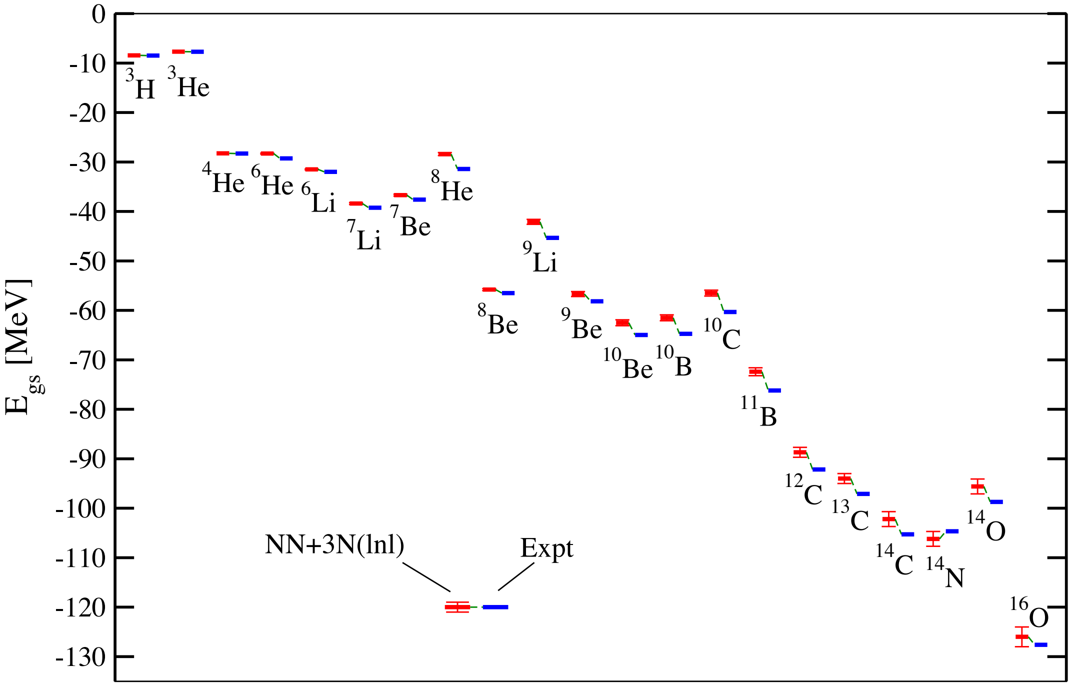
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

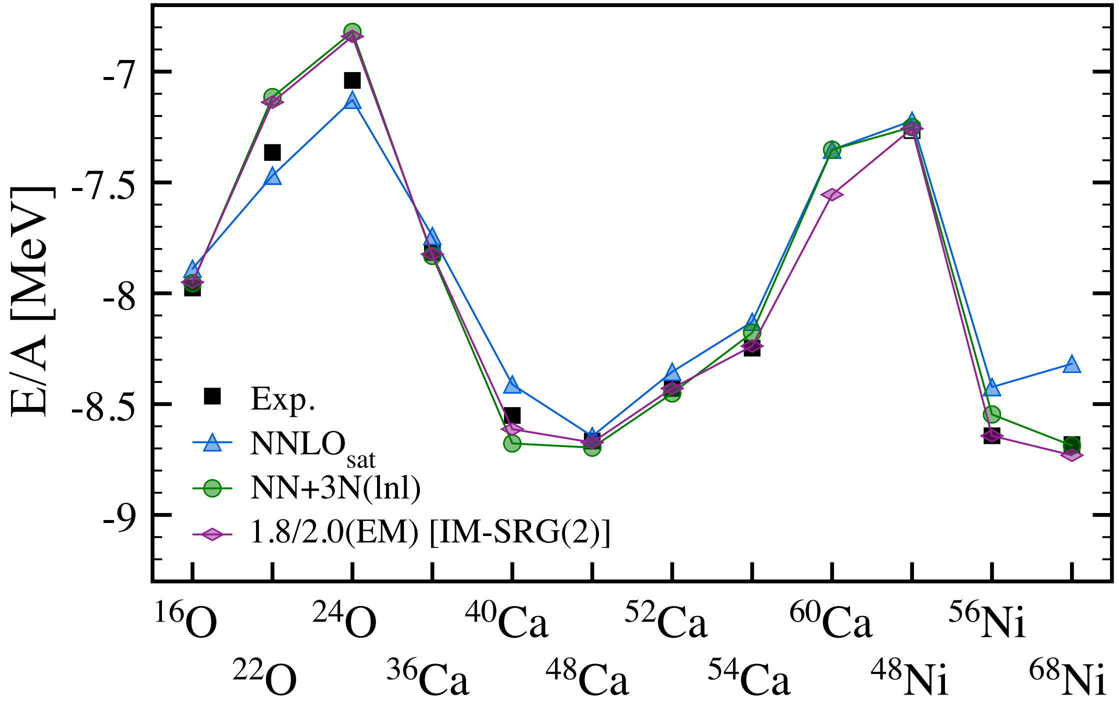
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

Binding energies of atomic nuclei from nuclear forces from chiral Effective Field Theory

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Medium mass nuclei – Self-Consistent Green's Function method

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator

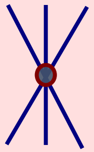




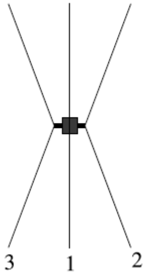
1.8/2.0 (EM) results: J. Simonis, S. R. Stroberg, K. Hebeler, J. D. Holt, and A. Schwenk, Phys. Rev. C 96, 014303 (2017).

Local vs. non-local chiral 3N interaction

- Regulator depending on momentum transfer $\Rightarrow$ local NNN interaction in coordinate space
  - Different space-tensor structure (compared to regulation with nucleon momenta)
  - **Example:** Contact term



$$W_1^{\rm cont} = E\vec{\tau}_2\cdot\vec{\tau}_3\,\delta(\vec{r}_1-\vec{r}_2)\delta(\vec{r}_3-\vec{r}_1)$$
$$= E\vec{\tau}_2\cdot\vec{\tau}_3\frac{1}{(2\pi)^6}\frac{1}{(\sqrt{3})^3}\int d\vec{\pi}_1 d\vec{\pi}_2 d\vec{\pi}_1' d\vec{\pi}_2' |\vec{\pi}_1\vec{\pi}_2\rangle\langle\vec{\pi}_1'\vec{\pi}_2'|$$



- Local

$$W_1^{\rm cont,Q} = E\vec{\tau}_2\cdot\vec{\tau}_3\frac{1}{(2\pi)^6}\frac{1}{(\sqrt{3})^3}\int d\vec{\pi}_1 d\vec{\pi}_2 d\vec{\pi}_1' d\vec{\pi}_2' |\vec{\pi}_1\vec{\pi}_2\rangle F(\vec{Q}^2;\Lambda)F(\vec{Q}'^2;\Lambda)\langle\vec{\pi}_1'\vec{\pi}_2'|$$
$$= E\vec{\tau}_2\cdot\vec{\tau}_3\int d\vec{\xi}_1 d\vec{\xi}_2 |\vec{\xi}_1\vec{\xi}_2\rangle Z_0(\sqrt{2}\xi_1;\Lambda)Z_0(|\tfrac{1}{\sqrt{2}}\vec{\xi}_1+\sqrt{\tfrac{3}{2}}\vec{\xi}_2|;\Lambda)\langle\vec{\xi}_1\vec{\xi}_2|$$

- Non-local

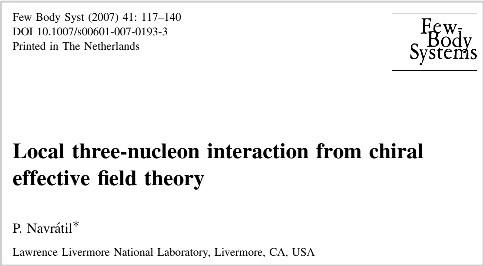
$$W_1^{\rm cont,ENGKMW} = E\,\boldsymbol{\tau}_2\cdot\boldsymbol{\tau}_3\frac{1}{(2\pi)^6}\frac{1}{(\sqrt{3})^3}\int d\boldsymbol{\pi}_1\, d\boldsymbol{\pi}_2\, d\boldsymbol{\pi}_1'\, d\boldsymbol{\pi}_2' |\boldsymbol{\pi}_1\boldsymbol{\pi}_2\rangle$$
$$\times F\left(\frac{1}{2}(\pi_1^2+\pi_2^2);\Lambda\right)F\left(\frac{1}{2}(\pi_1'^2+\pi_2'^2);\Lambda\right)\langle\boldsymbol{\pi}_1'\boldsymbol{\pi}_2'|$$

- Local/Non-local

$$F(\tfrac{1}{2}(\pi_1^2+\pi_2^2);\Lambda_{\rm nonloc})\,W_1^Q(\Lambda_{\rm loc})\,F(\tfrac{1}{2}(\pi_1^2+\pi_2^2);\Lambda_{\rm nonloc})$$

← Use completeness in HO basis to calculate products of *F W F*

$$\vec{\xi}_1 = \frac{1}{\sqrt{2}}(\vec{r}_1-\vec{r}_2)$$
$$\vec{\xi}_2 = \sqrt{\frac{2}{3}}\left(\frac{1}{2}(\vec{r}_1+\vec{r}_2)-\vec{r}_3\right)$$
$$\vec{\pi}_1 = \frac{1}{\sqrt{2}}(\vec{p}_1-\vec{p}_2)$$
$$\vec{\pi}_2 = \sqrt{\frac{2}{3}}\left(\frac{1}{2}(\vec{p}_1+\vec{p}_2)-\vec{p}_3\right)$$
$$\vec{Q} = \vec{p}_2'-\vec{p}_2 = -\frac{1}{\sqrt{2}}(\vec{\pi}_1'-\vec{\pi}_1)+\frac{1}{\sqrt{6}}(\vec{\pi}_2'-\vec{\pi}_2)$$
$$\vec{Q}' = \vec{p}_3'-\vec{p}_3 = \sqrt{\frac{2}{3}}(\vec{\pi}_2-\vec{\pi}_2')$$
$$Z_0(r;\Lambda) = \frac{1}{2\pi^2}\int dq q^2 j_0(qr)F(q^2;\Lambda)$$
$$F(q^2;\Lambda) = \exp[-q^4/\Lambda^4]$$



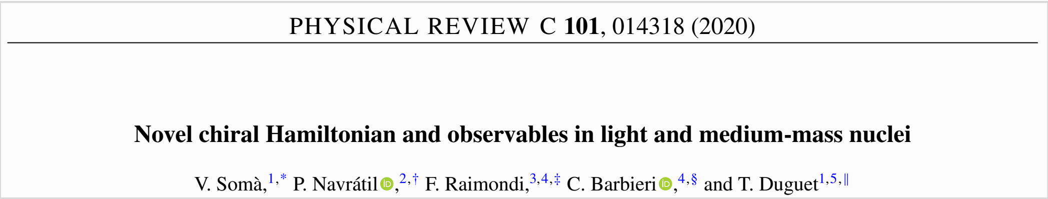
Few Body Syst (2007) 41: 117–140
DOI 10.1007/s00601-007-0193-3
Printed in The Netherlands

Few-Body Systems

Local three-nucleon interaction from chiral effective field theory

P. Navrátil*

Lawrence Livermore National Laboratory, Livermore, CA, USA


PHYSICAL REVIEW C **101**, 014318 (2020)

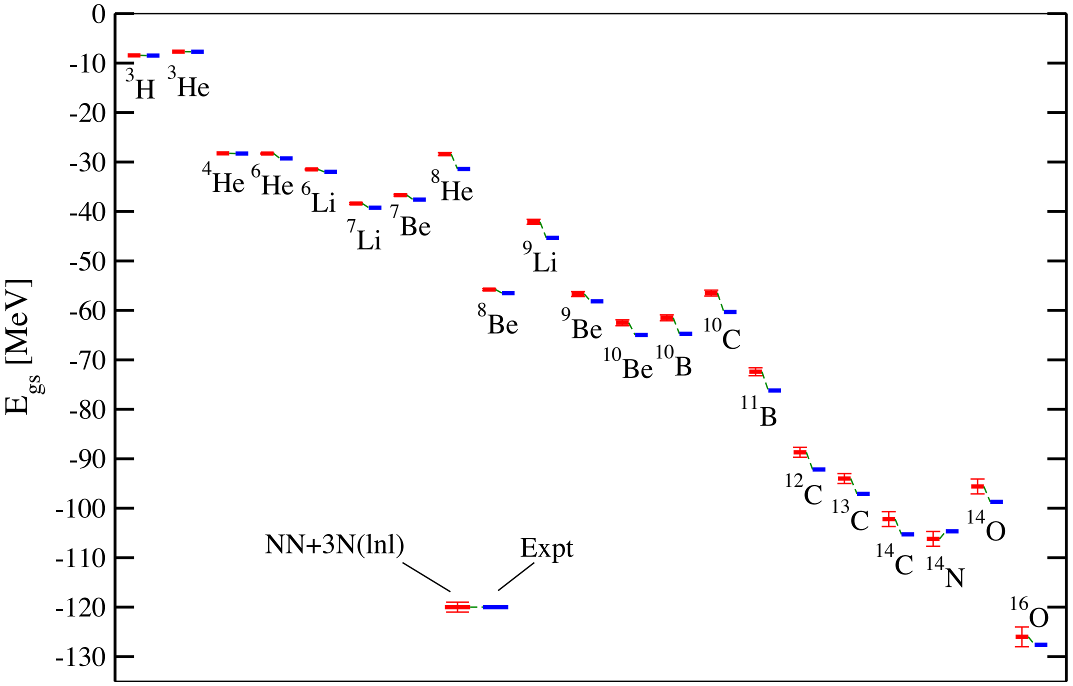
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

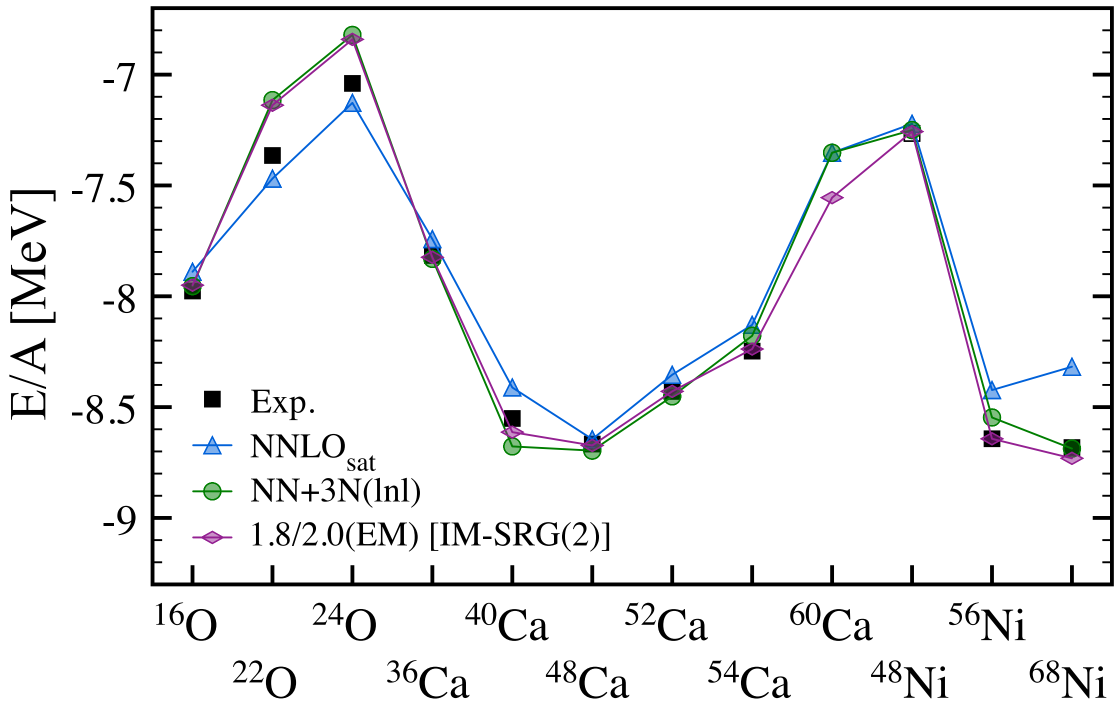
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,∥]

Binding energies of atomic nuclei from nuclear forces from chiral Effective Field Theory

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Medium mass nuclei – Self-Consistent Green's Function method

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator





1.8/2.0 (EM) results: J. Simonis, S. R. Stroberg, K. Hebeler, J. D. Holt, and A. Schwenk, Phys. Rev. C 96, 014303 (2017).

PHYSICAL REVIEW C **101**, 014318 (2020)

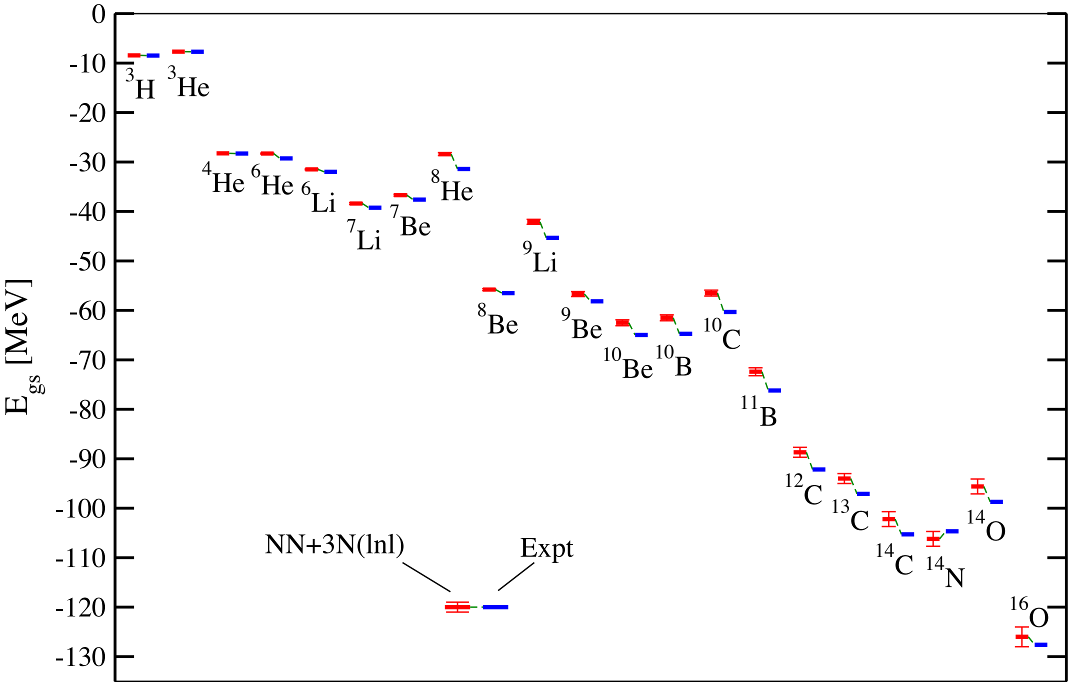
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

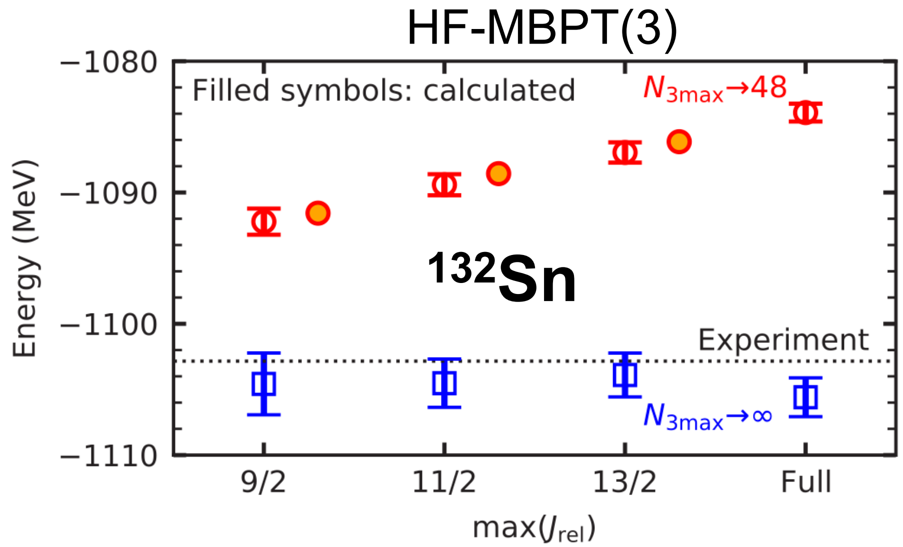
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

Binding energies of atomic nuclei from nuclear forces from chiral Effective Field Theory

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Heavy nuclei – HF-MBPT(3)

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator





PHYSICAL REVIEW C **105**, 014302 (2022)

Converged *ab initio* calculations of heavy nuclei

T. Miyagi,[1,*] S. R. Stroberg,[2,†] P. Navrátil,[1,‡] K. Hebeler,[3,4,5,§] and J. D. Holt[1,6,‖]

PHYSICAL REVIEW C **101**, 014318 (2020)

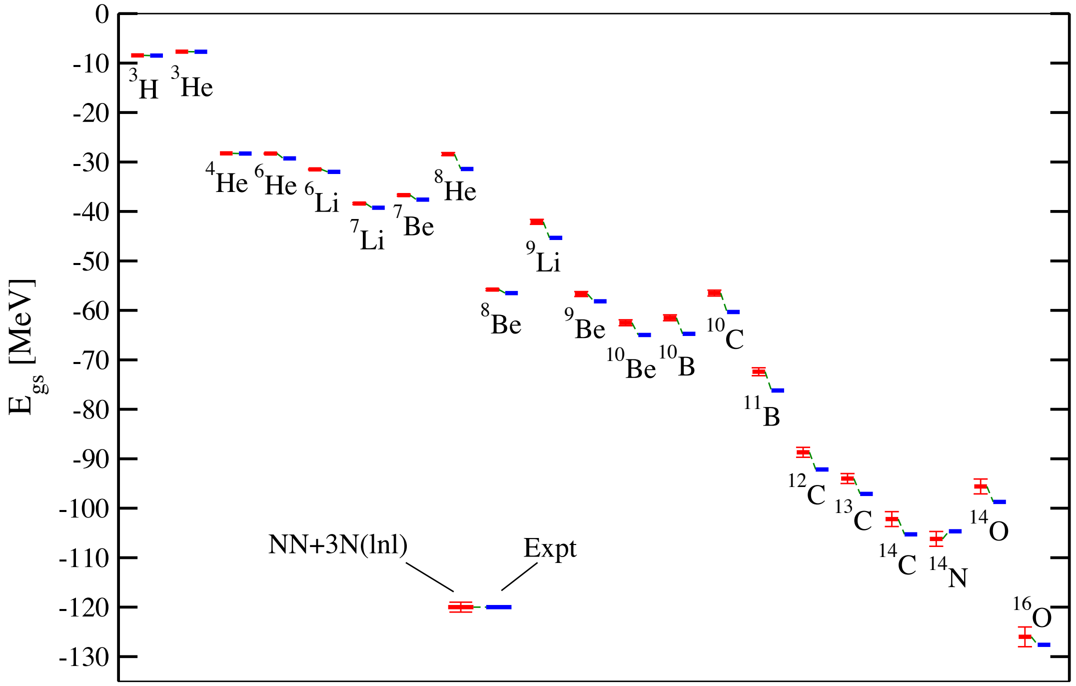
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

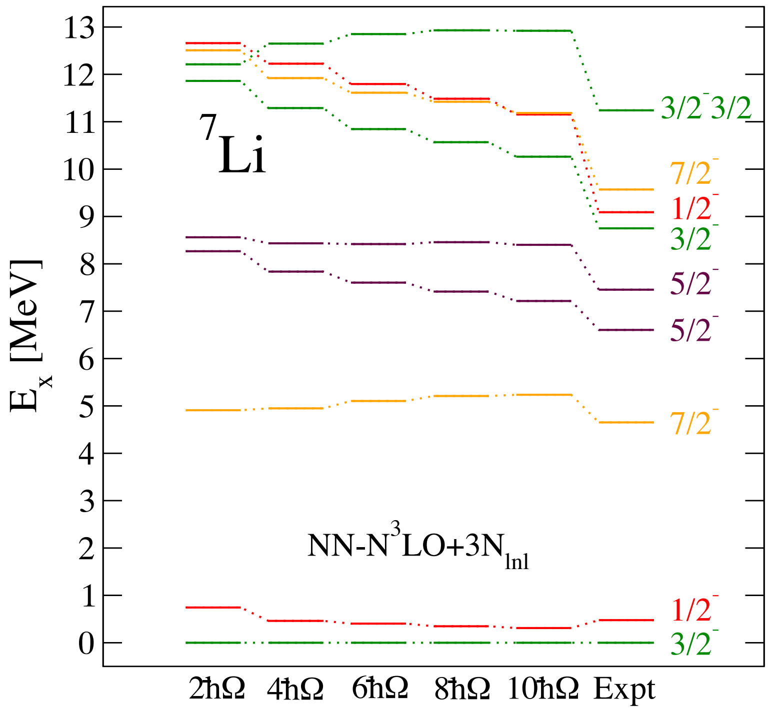
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

Binding and excitation energies of atomic nuclei from nuclear forces from chiral Effective Field Theory

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Denoted as NN N^{3}LO + 3N$_{lnl}$

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator





PHYSICAL REVIEW C **101**, 014318 (2020)

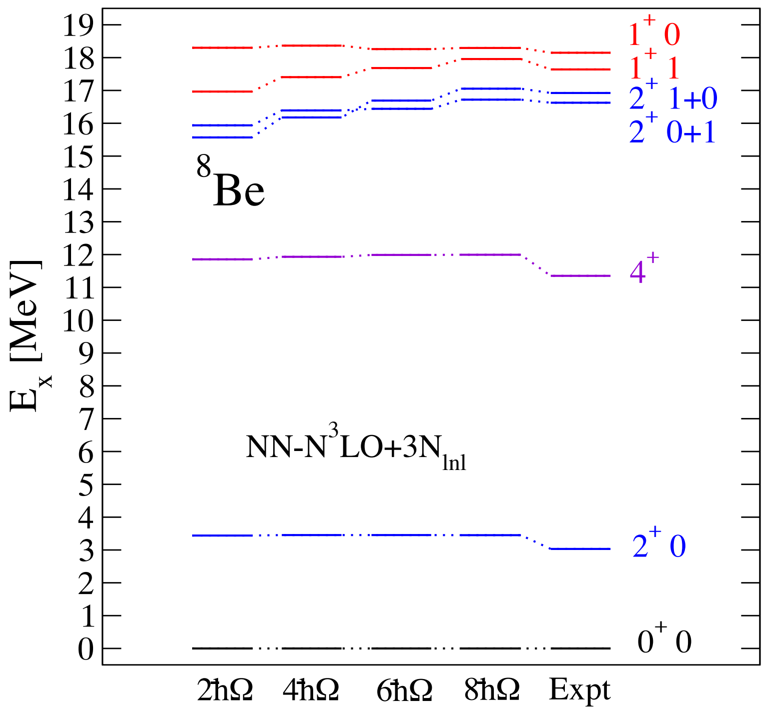
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

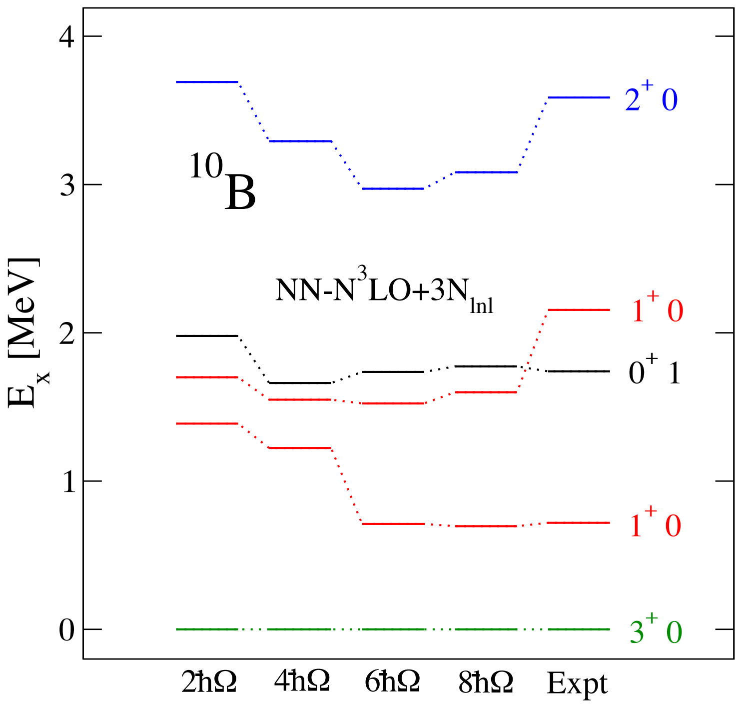
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,||]

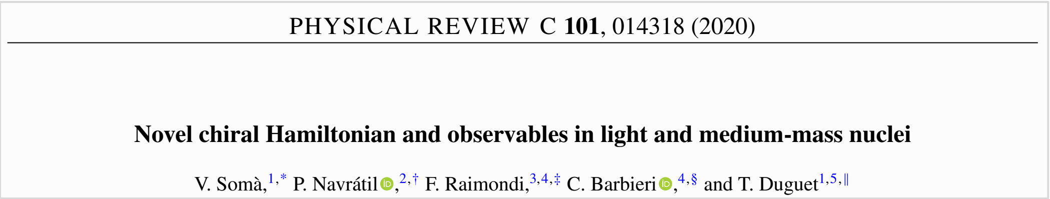
Excitation energies of atomic nuclei from nuclear forces from chiral Effective Field Theory

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Denoted as NN N^{3}LO + 3N$_{\mathrm{lnl}}$

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator






PHYSICAL REVIEW C **101**, 014318 (2020)

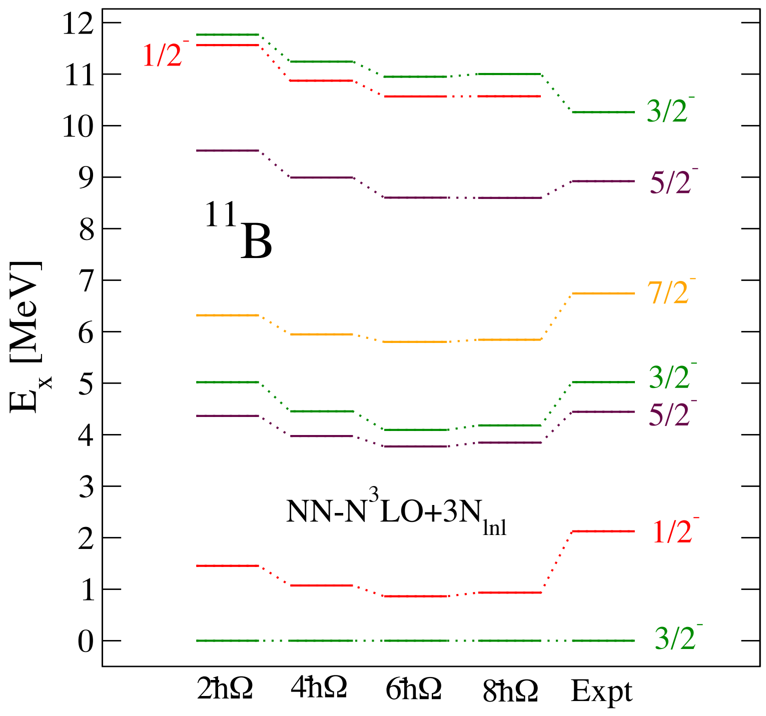
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

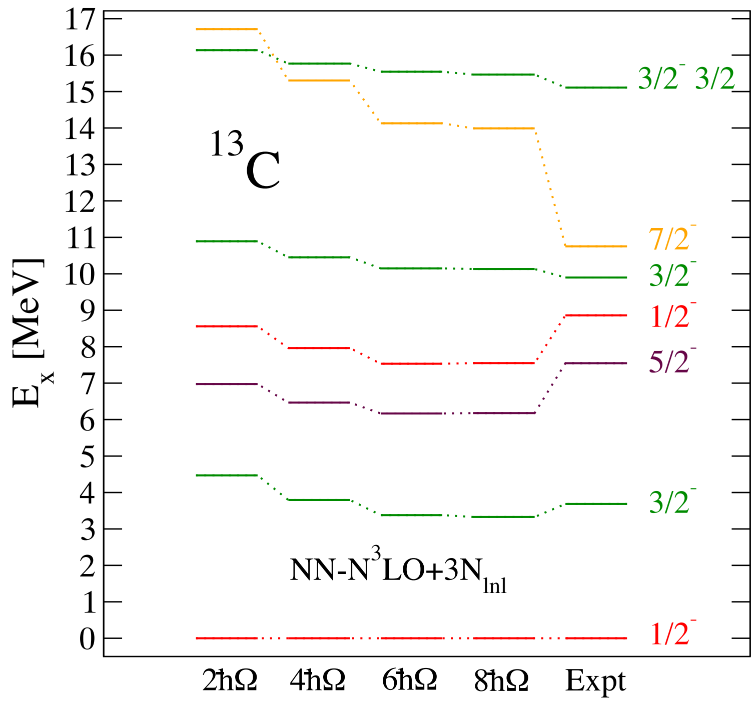
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

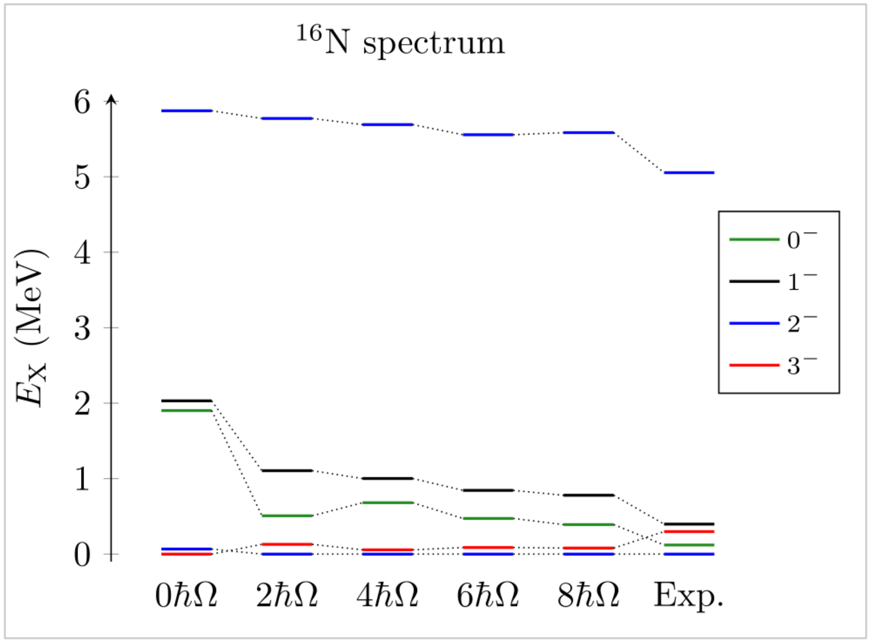
Excitation energies of atomic nuclei from nuclear forces from chiral Effective Field Theory

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Denoted as NN N^{3}LO + 3N$_{lnl}$

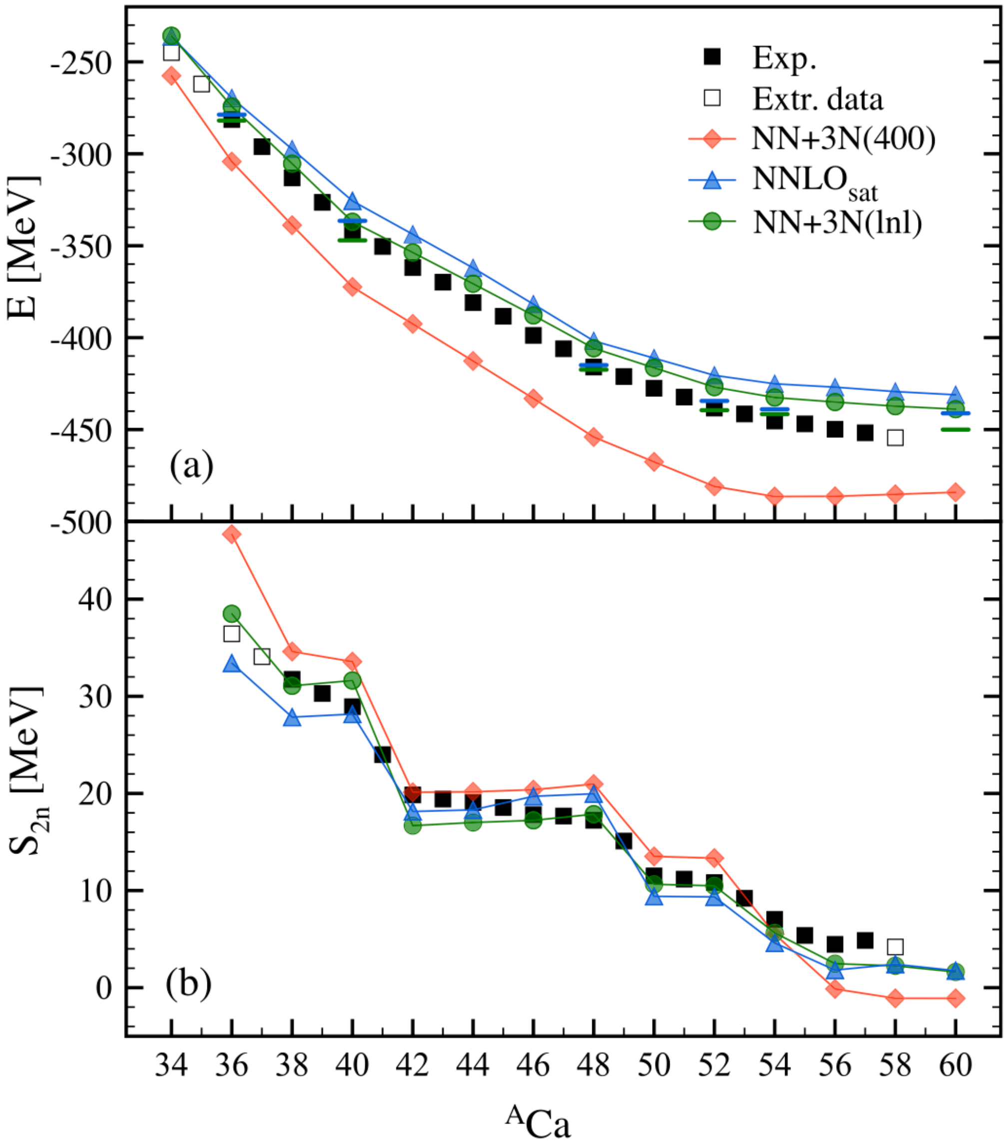
NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator







Performance of NN N^{3}LO + 3N$_{lnl}$ in medium-mass nuclei



PHYSICAL REVIEW C **101**, 014318 (2020)

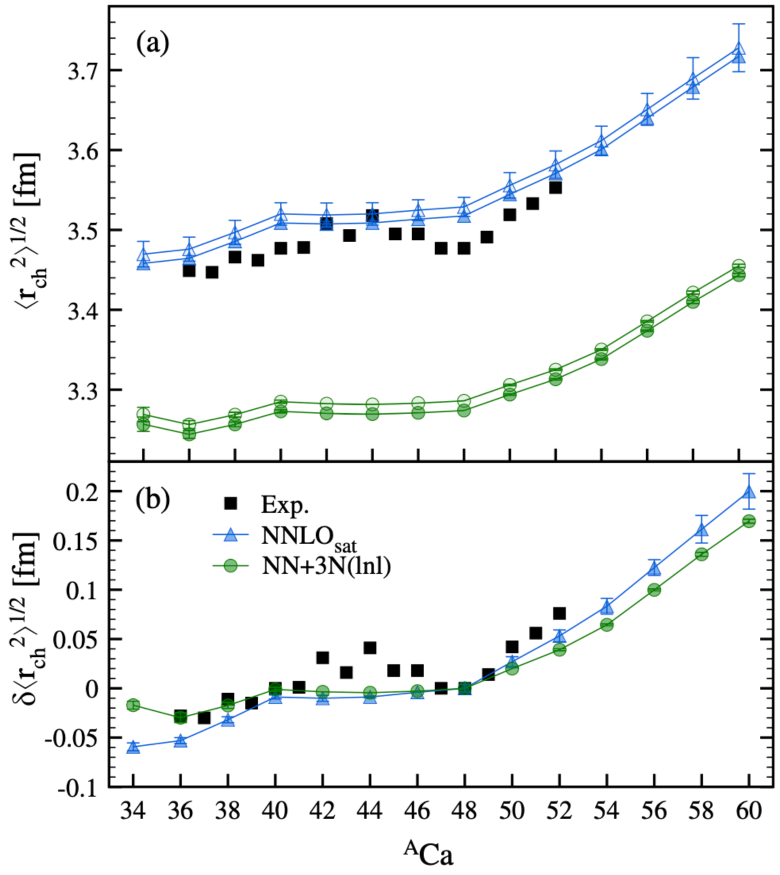
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

Eur. Phys. J. A (2021) 57:135
https://doi.org/10.1140/epja/s10050-021-00437-4
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article -Theoretical Physics

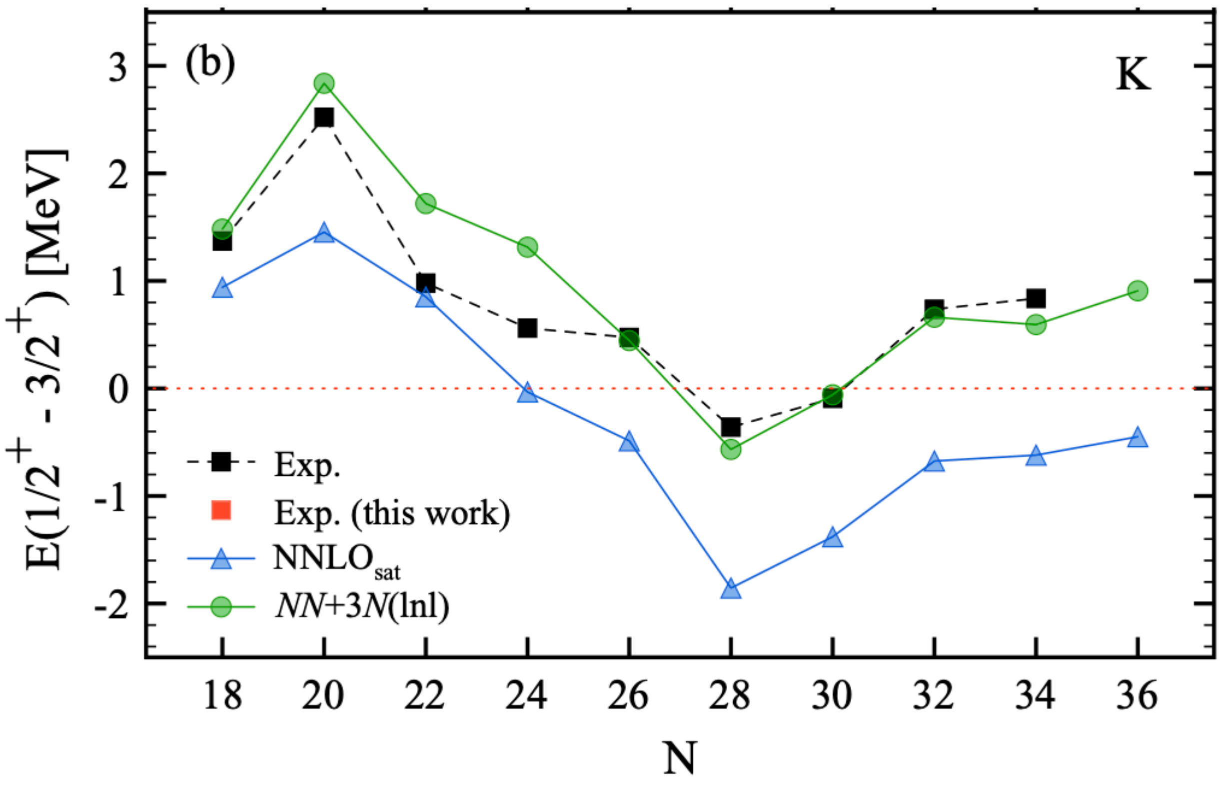
Moving away from singly-magic nuclei with Gorkov Green's function theory

V. Somà[1,a], C. Barbieri[2,3,4], T. Duguet[1,5], P. Navrátil[6]



Performance of NN N^3LO + $3N_{lnl}$ in medium-mass nuclei

- RIKEN experiment on neutron rich odd K isotopes
  - Restoration of the Natural $E(1/2^+)$ - $E(3/2^+)$ Energy Splitting towards N=40



NN N^3LO+3N_{lnl} performs quite well

Physics Letters B 802 (2020) 135215
Contents lists available at ScienceDirect
Physics Letters B
ELSEVIER
www.elsevier.com/locate/physletb

Restoration of the natural $E(1/2^+_1)$ - $E(3/2^+_1)$ energy splitting in odd-K isotopes towards $N = 40$

Y.L. Sun[a,b,*], A. Obertelli[a,b,c], P. Doornenbal[c], C. Barbieri[d], Y. Chazono[e], T. Duguet[b,f], H.N. Liu[a,b,g], P. Navrátil[h], F. Nowacki[i,j], K. Ogata[e,k], T. Otsuka[l,m], F. Raimondi[d,n], V. Somà[b], Y. Utsuno[o], K. Yoshida[o], N. Achouri[p], H. Baba[c], F. Browne[c], D. Calvet[b], F. Château[b], S. Chen[q,c,r], N. Chiga[c], A. Corsi[b], M.L. Cortés[c], A. Delbart[b], J.-M. Gheller[b], A. Giganon[b], A. Gillibert[b], C. Hilaire[b], T. Isobe[c], T. Kobayashi[s], Y. Kubota[c,m], V. Lapoux[b], T. Motobayashi[c], I. Murray[c], H. Otsu[c], V. Panin[c], N. Paul[b], W. Rodriguez[t,c], H. Sakurai[c,l], M. Sasano[c], D. Steppenbeck[c], L. Stuhl[m], Y. Togano[u], T. Uesaka[c], K. Wimmer[l], K. Yoneda[c], O. Aktas[g], T. Aumann[a,v], L.X. Chung[w], F. Flavigny[p], S. Franchoo[p], I. Gašparić[x,c], R.-B. Gerst[y], J. Gibelin[z], K.I. Hahn[aa], D. Kim[aa,c], T. Koiwai[l], Y. Kondo[ab], P. Koseoglou[a,v], J. Lee[r], C. Lehr[a], B.D. Linh[w], T. Lokotko[r], M. MacCormick[p], K. Moschner[y], T. Nakamura[ab], S.Y. Park[aa,c], D. Rossi[a], E. Sahin[ac], D. Sohler[ad], P.-A. Söderström[a], S. Takeuchi[ab], H. Törnqvist[a,v], V. Vaquero[ae], V. Wagner[a], S. Wang[af], V. Werner[a], X. Xu[r], H. Yamada[ab], D. Yan[af], Z. Yang[c], M. Yasuda[ab], L. Zanetti[a]

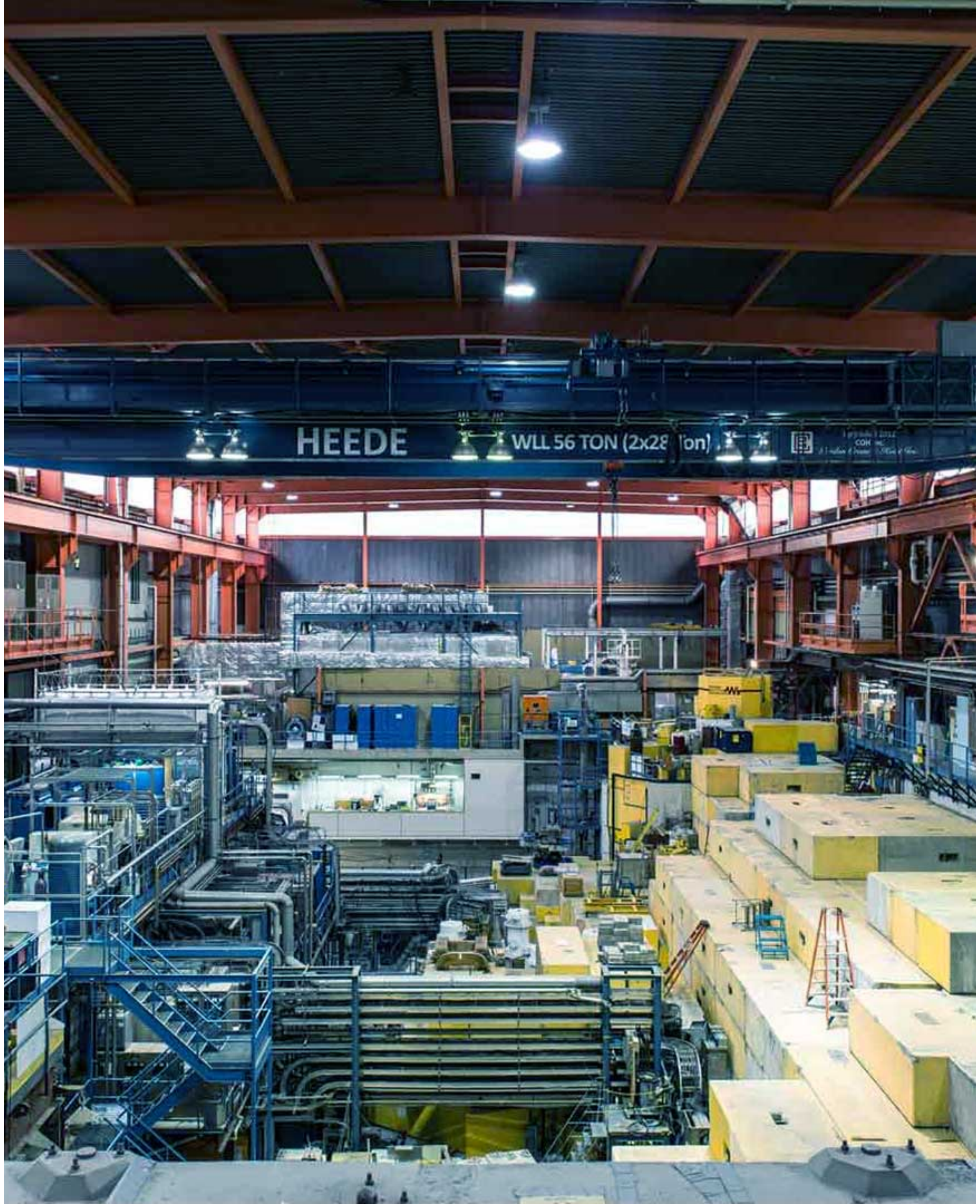
PHYSICAL REVIEW C **104**, 044331 (2021)

Investigation of the ground-state spin inversion in the neutron-rich ^{47,49}Cl isotopes

B. D. Linh,[1] A. Corsi,[2] A. Gillibert,[2,*] A. Obertelli,[2,3,4] P. Doornenbal,[3] C. Barbieri,[5,6,7] S. Chen,[8,3,9] L. X. Chung,[1] T. Duguet,[2,10] M. Gómez-Ramos,[4,11] J. D. Holt,[12,13] A. Moro,[11] P. Navrátil,[12] K. Ogata,[14,15] N. T. T. Phuc,[16,17] N. Shimizu,[18] V. Somà,[2] Y. Utsuno,[18,19] N. L. Achouri,[20] H. Baba,[3] F. Browne,[3] D. Calvet,[2] F. Château,[2] N. Chiga,[3] M. L. Cortés,[3] A. Delbart,[2] J.-M. Gheller,[2] A. Giganon,[2] C. Hilaire,[2] T. Isobe,[3] T. Kobayashi,[21] Y. Kubota,[3,18] V. Lapoux,[2] H. N. Liu,[2,4,22] T. Motobayashi,[3] I. Murray,[23,3] H. Otsu,[3] V. Panin,[3] N. Paul,[2,24] W. Rodriguez,[3,25,26] H. Sakurai,[3,27] M. Sasano,[3] D. Steppenbeck,[3] L. Stuhl,[18,28,29] Y. L. Sun,[2,4] Y. Togano,[30] T. Uesaka,[3] K. Wimmer,[27,3] K. Yoneda,[3] O. Aktas,[22] T. Aumann,[4,31] F. Flavigny,[23,20] S. Franchoo,[23] I. Gašparić,[32,4,3] R.-B. Gerst,[33] J. Gibelin,[20] K. I. Hahn,[34,29] N. T. Khai,[35] D. Kim,[34,3,29] T. Koiwai,[27] Y. Kondo,[36] P. Koseoglou,[4,31] J. Lee,[8] C. Lehr,[4] T. Lokotko,[8] M. MacCormick,[23] K. Moschner,[33] T. Nakamura,[36] S. Y. Park,[34,29] D. Rossi,[4] E. Sahin,[37] D. Sohler,[28] P.-A. Söderström,[4] S. Takeuchi,[36] N. D. Ton,[1] H. Törnqvist,[4,31] V. Vaquero,[38] V. Wagner,[4] H. Wang,[39] V. Werner,[4] X. Xu,[8] Y. Yamada,[36] D. Yan,[39] Z. Yang,[3] M. Yasuda,[36] and L. Zanetti[4]

Precision chiral EFT NN Hamiltonian

- order by order convergence

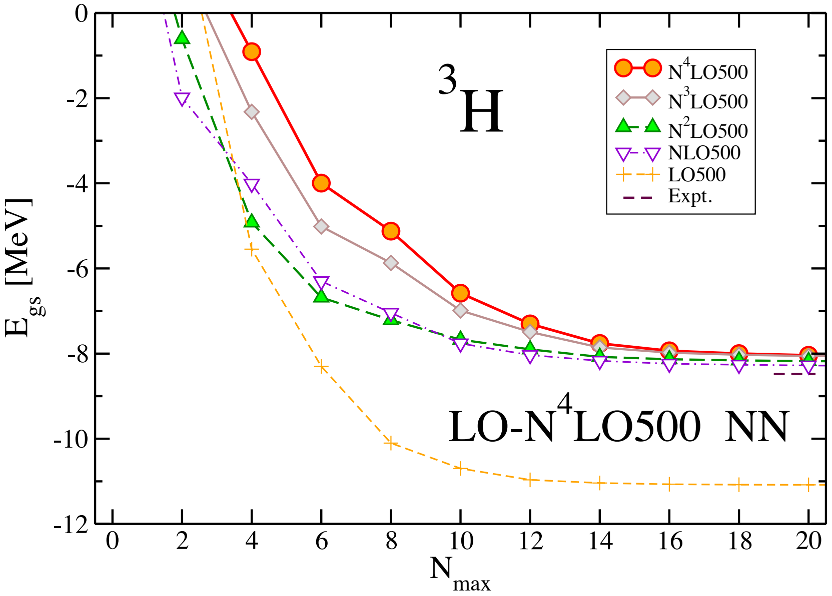


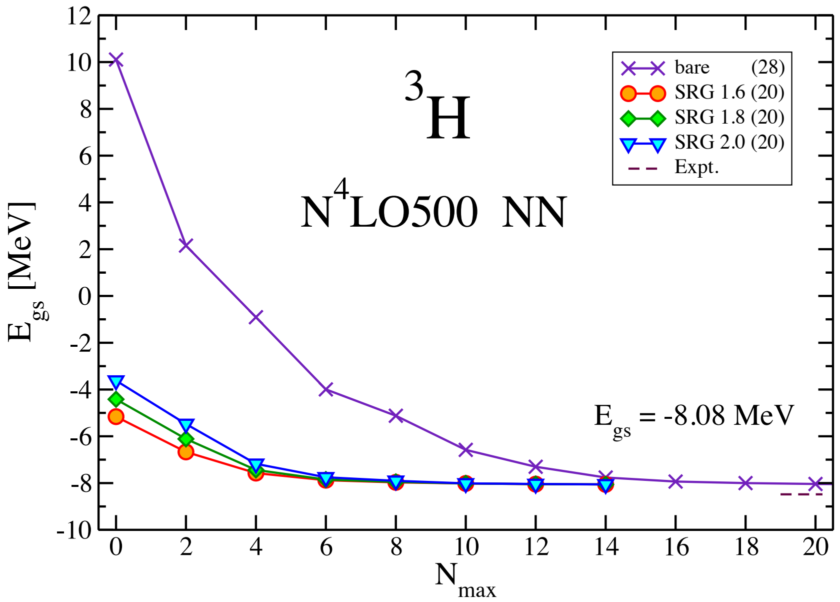
PHYSICAL REVIEW C **96**, 024004 (2017)

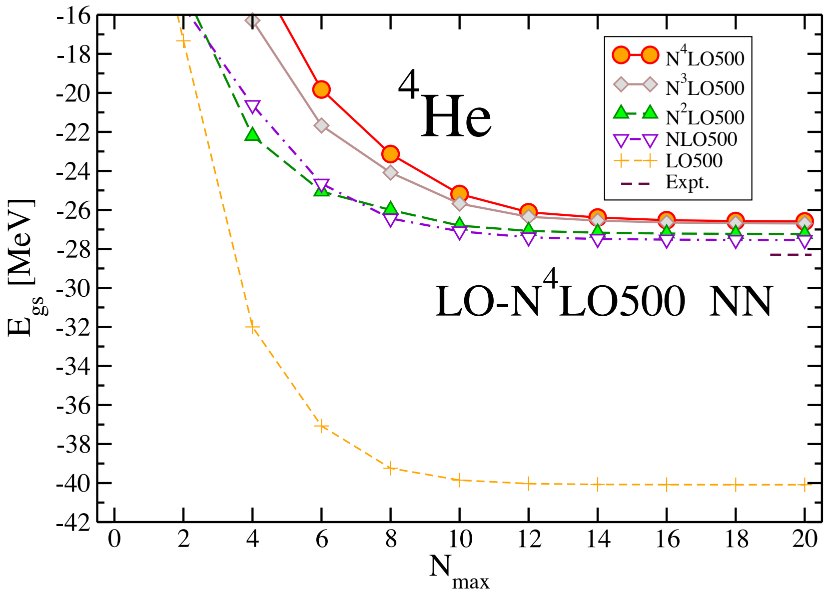
High-quality two-nucleon potentials up to fifth order of the chiral expansion

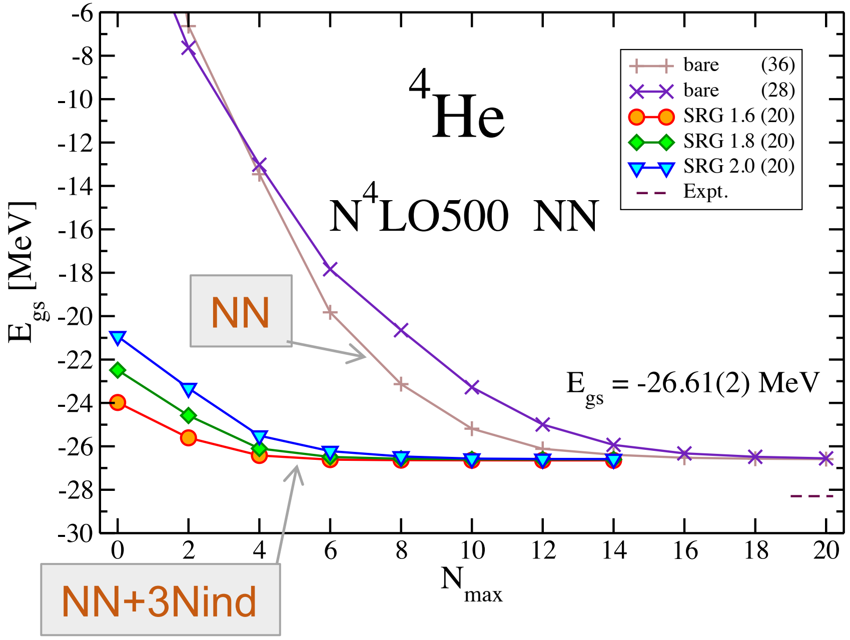
D. R. Entem,[1,*] R. Machleidt,[2,†] and Y. Nosyk[2]

^{3}H and ^{4}He with chiral EFT interactions up to N^{4}LO

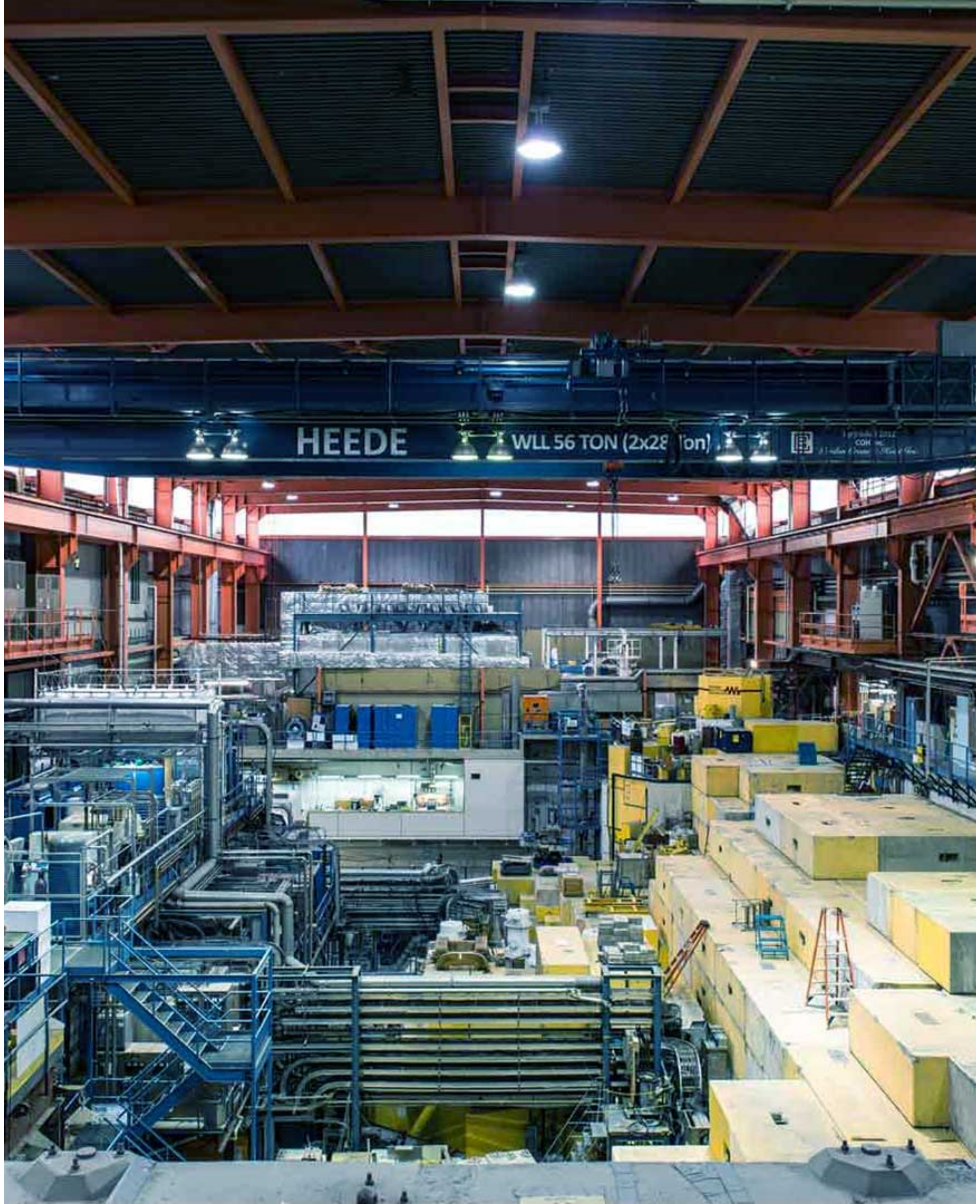








Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term



Precision chiral EFT Hamiltonian with sub-leading 3N interaction terms

- NN N^{4}LO 500 interaction by Entem-Machleidt-Nosyk (2017)
- 3N N^{2}LO plus a sub-leading spin-orbit enhancing term with a new LEC (E_7) – Girlanda 2011
  - local/non-local regulator
  - **The Hamiltonian fully determined in *A*=2, *A*=3,4, and ^{6}Li systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
    - New LEC (E_7) fitted to improve excitation levels in ^{6}Li
  - Denoted as NN N^{4}LO + 3N$_{\mathrm{lnlE7}}$

PHYSICAL REVIEW C, VOLUME 60, 034001

Phenomenological spin-orbit three-body force

A. Kievsky*

$$V = \sum_{i\neq j\neq k} (E_1 + E_2 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j + E_3 \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j + E_4 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\left[Z_0''(r_{ij}) + 2\frac{Z_0'(r_{ij})}{r_{ij}}\right]Z_0(r_{ik})$$
$$+ (E_5 + E_6 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j)S_{ij}\left[Z_0''(r_{ij}) - \frac{Z_0'(r_{ij})}{r_{ij}}\right]Z_0(r_{ik}) + (E_7 + E_8 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_k)(\mathbf{L}\cdot\mathbf{S})_{ij}\frac{Z_0'(r_{ij})}{r_{ij}}Z_0(r_{ik})$$
$$+ [(E_9 + E_{10}\boldsymbol{\tau}_j\cdot\boldsymbol{\tau}_k)\boldsymbol{\sigma}_j\cdot\hat{\mathbf{r}}_{ij}\boldsymbol{\sigma}_k\cdot\hat{\mathbf{r}}_{ik} + (E_{11} + E_{12}\boldsymbol{\tau}_j\cdot\boldsymbol{\tau}_k + E_{13}\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j)\boldsymbol{\sigma}_k\cdot\hat{\mathbf{r}}_{ij}\boldsymbol{\sigma}_j\cdot\hat{\mathbf{r}}_{ik}]Z_0'(r_{ij})Z_0'(r_{ik})$$

$$Z_0(r;\Lambda) = \int \frac{d\mathbf{p}}{(2\pi)^3} e^{i\mathbf{p}\cdot\mathbf{r}} F(\mathbf{p}^2;\Lambda)$$

PHYSICAL REVIEW C **84**, 014001 (2011)

Subleading contributions to the three-nucleon contact interaction

L. Girlanda,[1] A. Kievsky,[2] and M. Viviani[2]

PHYSICAL REVIEW C **102**, 019903(E) (2020)

Erratum: Subleading contributions to the three-nucleon contact interaction [Phys. Rev. C 84, 014001 (2011)]

L. Girlanda, A. Kievsky, and M. Viviani

Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

- NN N^{4}LO 500 interaction by Entem-Machleidt-Nosyk (2017)
- 3N N^{2}LO plus a sub-leading spin-orbit enhancing term with a new LEC (E_7) – Girlanda 2011
  - local/non-local regulator
  - **The Hamiltonian fully determined in *A*=2, *A*=3,4, and ^{6}Li systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
    - New LEC (E_7) fitted to improve excitation levels in ^{6}Li
  - Denoted as NN N^{4}LO + 3N$_{\mathrm{lnlE7}}$

- Successfully applied to ^{7}Be(p,γ)^{8}B, muon capture on ^{6}Li, ^{12}C, and ^{16}O, ^{11}Li structure, ^{19}F structure and exotic moments, N=20 isotones

Physics Letters B 845 (2023) 138156
Contents lists available at ScienceDirect
Physics Letters B
journal homepage: www.elsevier.com/locate/physletb
ELSEVIER

Ab initio informed evaluation of the radiative capture of protons on ^{7}Be

K. Kravvaris[a,*], P. Navrátil[b], S. Quaglioni[a], C. Hebborn[c,a], G. Hupin[d]

PHYSICAL REVIEW C **109**, 065501 (2024)

Muon capture on ^{6}Li, ^{12}C, and ^{16}O from *ab initio* nuclear theory

Lotta Jokiniemi[1,*] Petr Navrátil[1,2,†] Jenni Kotila[3,4,5,‡] and Kostas Kravvaris[6,§]

PHYSICAL REVIEW LETTERS **136**, 112501 (2026)

Nuclear Schiff Moment of the Fluorine Isotope ^{19}F

Kia Boon Ng[1,*] Stephan Foster[1,2] Lan Cheng[3] Petr Navrátil[1] and Stephan Malbrunot-Ettenauer[1,4]

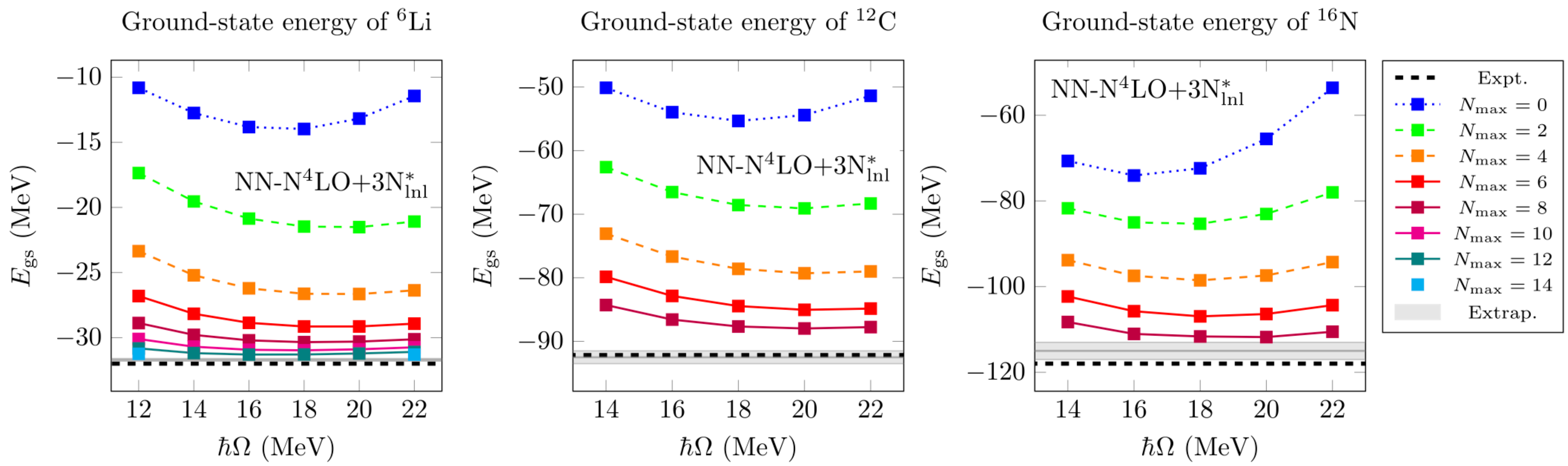
Halo Nuclei from *Ab Initio* Nuclear Theory

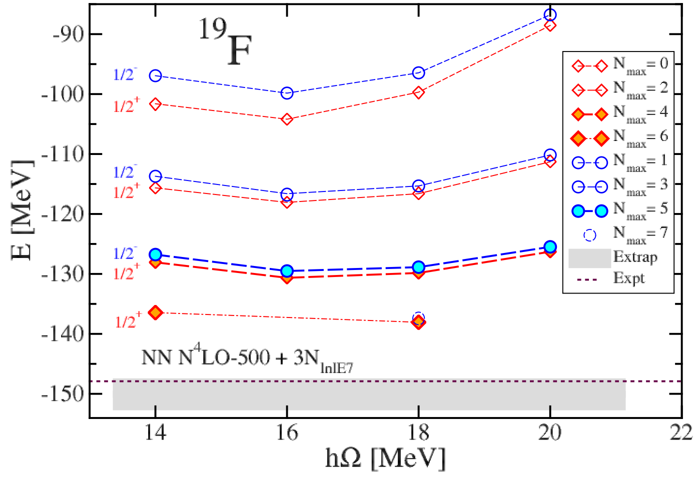
Petr Navrátil[1,2,*], Sofia Quaglioni[3], Guillaume Hupin[4], Michael Gennari[5] and Kostas Kravvaris[3]

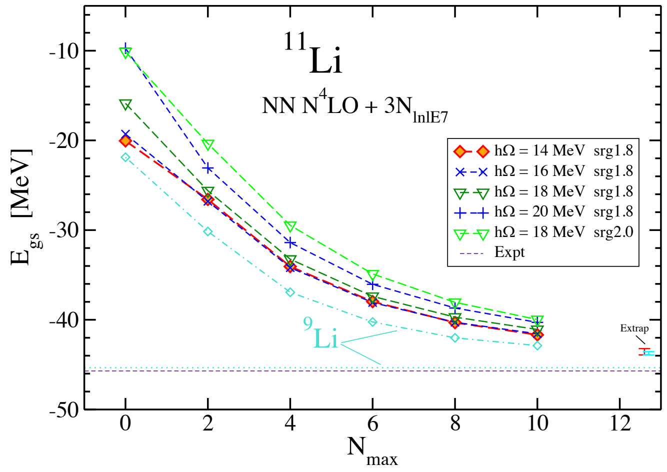
arXiv:2604.02612

Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

- Energies of light nuclei







Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

- Energies of light nuclei

TABLE IV. The extrapolated ground-state energies of ^{6}He, ^{6}Li, ^{12}C, ^{12}B, ^{16}O, and ^{16}N.

Nucleus	Interaction	$E_{\rm g.s.}$ (MeV)	Expt. (MeV) [48]
^{6}He	NN-N^{3}LO+3N$_{\rm lnl}$	−28.3(1)	−29.27
	NN-N^{4}LO+3N$_{\rm lnl}$	−28.3(1)	
	NN-N^{4}LO+3N$^{*}_{\rm lnl}$	−28.6(1)	
^{6}Li	NN-N^{3}LO+3N$_{\rm lnl}$	−31.5(1)	−31.99
	NN-N^{4}LO+3N$_{\rm lnl}$	−31.4(1)	
	NN-N^{4}LO+3N$*_{\rm lnl}$	−31.7(1)	
^{12}C	NN-N^{3}LO+3N$_{\rm lnl}$	−88.7(10)	−92.16
	NN-N^{4}LO+3N$_{\rm lnl}$	−88.6(10)	
	NN-N^{4}LO+3N$^{*}_{\rm lnl}$	−92.5(10)	
^{12}B	NN-N^{3}LO+3N$_{\rm lnl}$	−76.1(10)	−79.57
	NN-N^{4}LO+3N$_{\rm lnl}$	−76.0(10)	
	NN-N^{4}LO+3N$^{*}_{\rm lnl}$	−79.5(10)	
^{16}O	NN-N^{3}LO+3N$_{\rm lnl}$	−126(2)	−127.62
	NN-N^{4}LO+3N$_{\rm lnl}$	−127(2)	
	NN-N^{4}LO+3N$^{*}_{\rm lnl}$	−127(2)	
^{16}N	NN-N^{3}LO+3N$_{\rm lnl}$	−114(2)	−116.58
	NN-N^{4}LO+3N$_{\rm lnl}$	−114(2)	
	NN-N^{4}LO+3N$^{*}_{\rm lnl}$	−115(2)	

	NN N^{4}LO+3N$_{\rm lnlE7}$			Expt. (MeV)
	Bare	srg2.0	srg1.8	
^{3}H	-8.49			-8.481795
^{3}He	-7.73			-7.71804
^{4}He	-28.23(5)	-28.38	-28.45	-28.29566

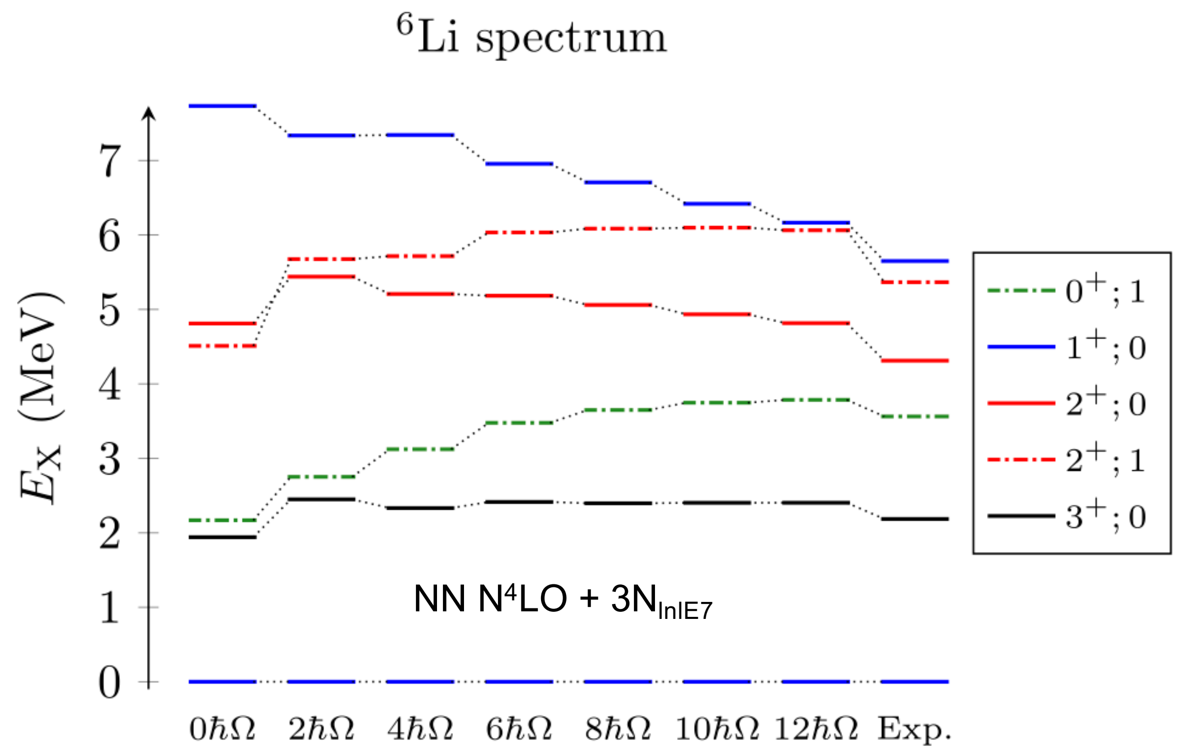
PHYSICAL REVIEW C **109**, 065501 (2024)

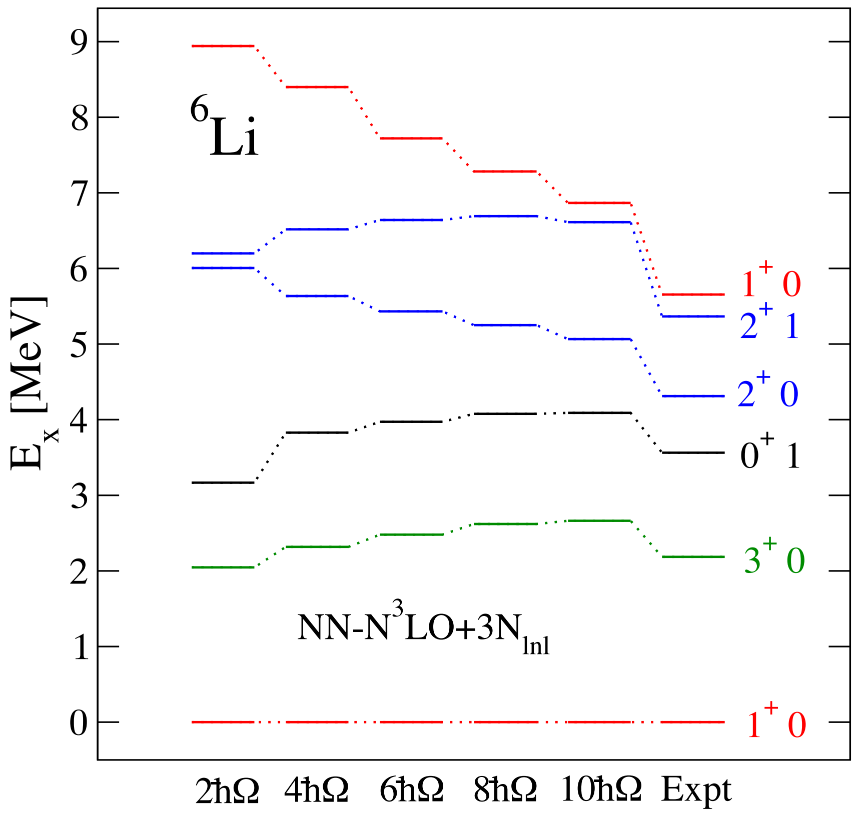
Muon capture on ^{6}Li, ^{12}C, and ^{16}O from *ab initio* nuclear theory

Lotta Jokiniemi[1,*] Petr Navrátil[1,2,†] Jenni Kotila[3,4,5,‡] and Kostas Kravvaris[6,§]

Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

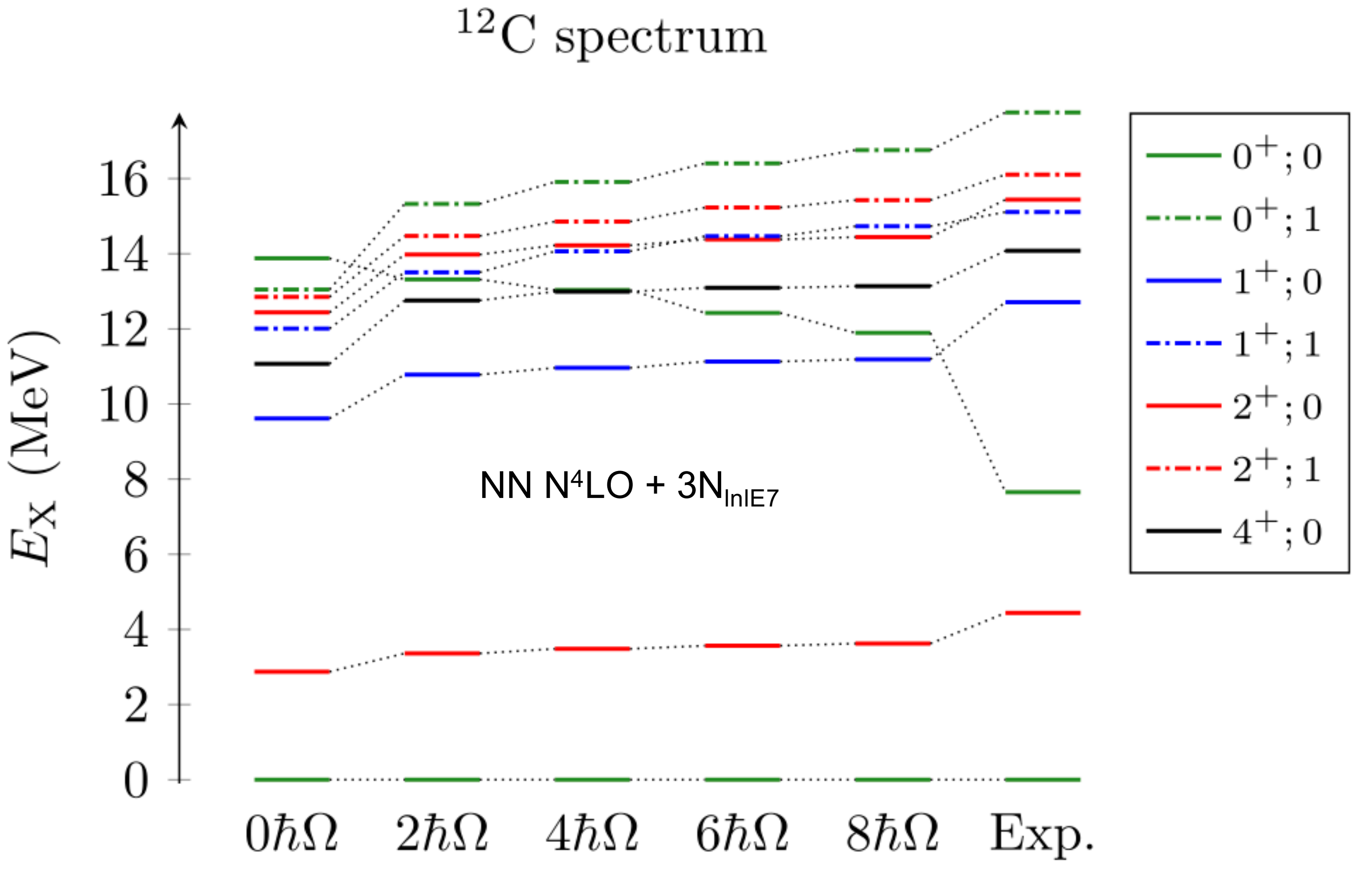
- Excitation energies of light nuclei

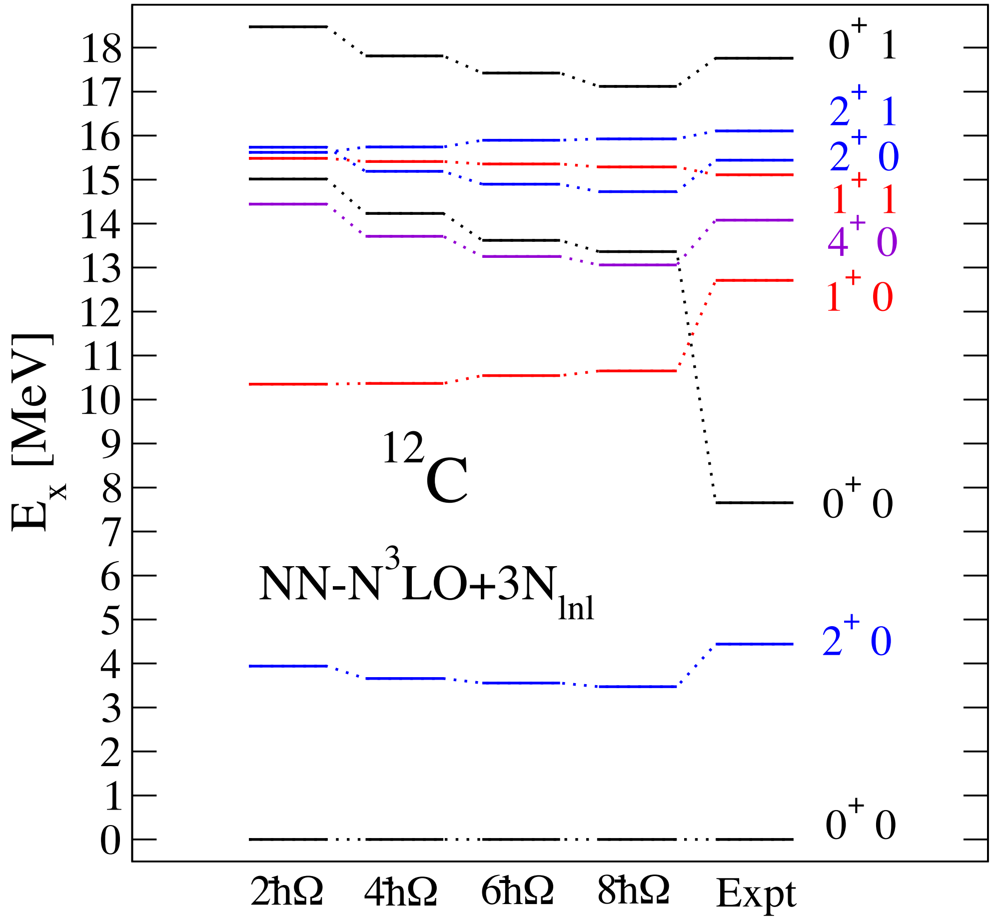




Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

- Excitation energies of light nuclei

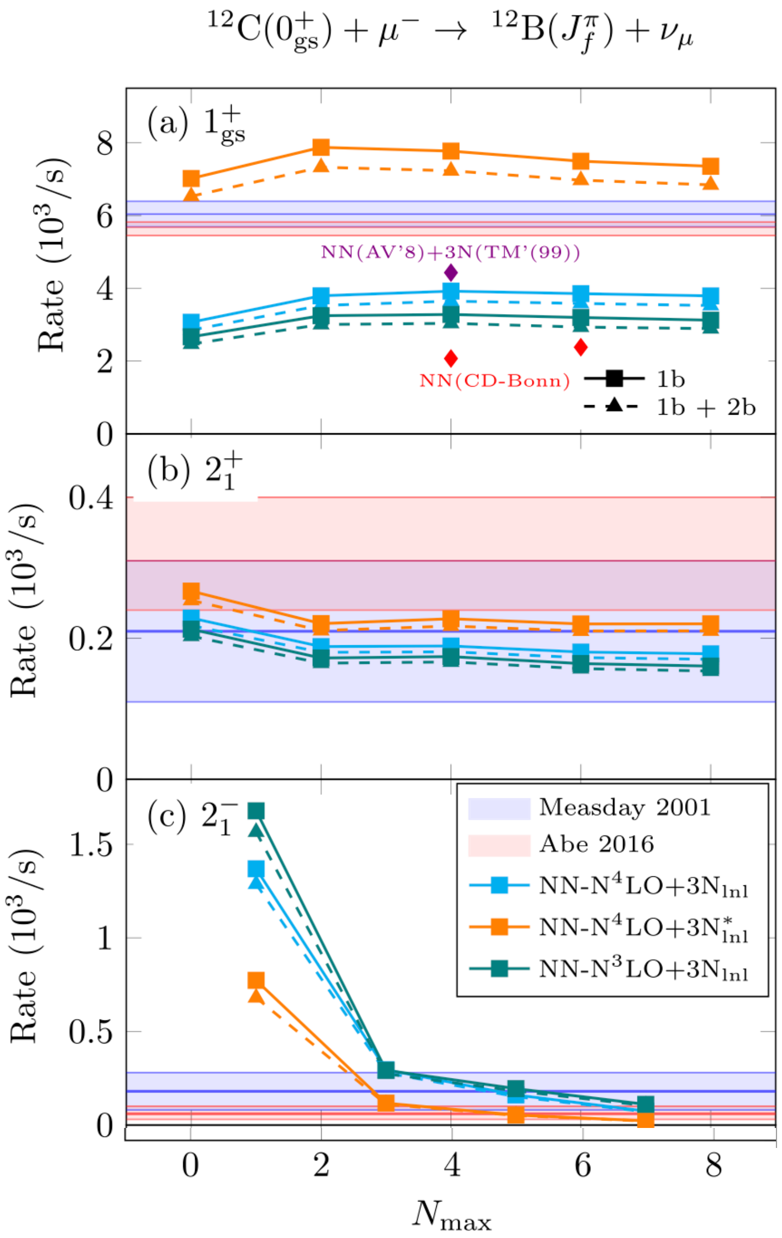


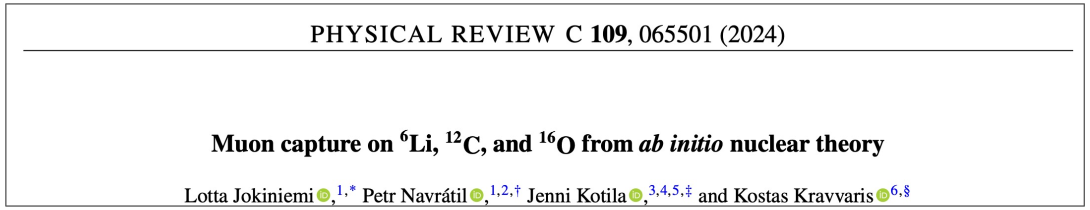


Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

- Muon capture rate on ^{12}C

Improvement for ^{12}C muon capture rate compared to other interactions



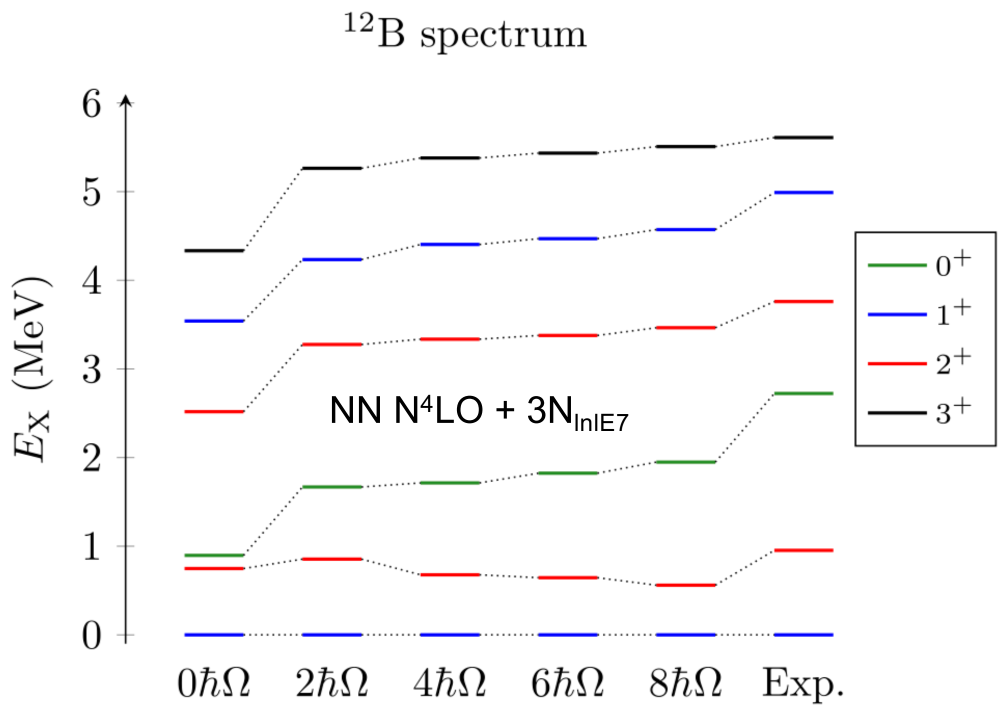

PHYSICAL REVIEW C **109**, 065501 (2024)

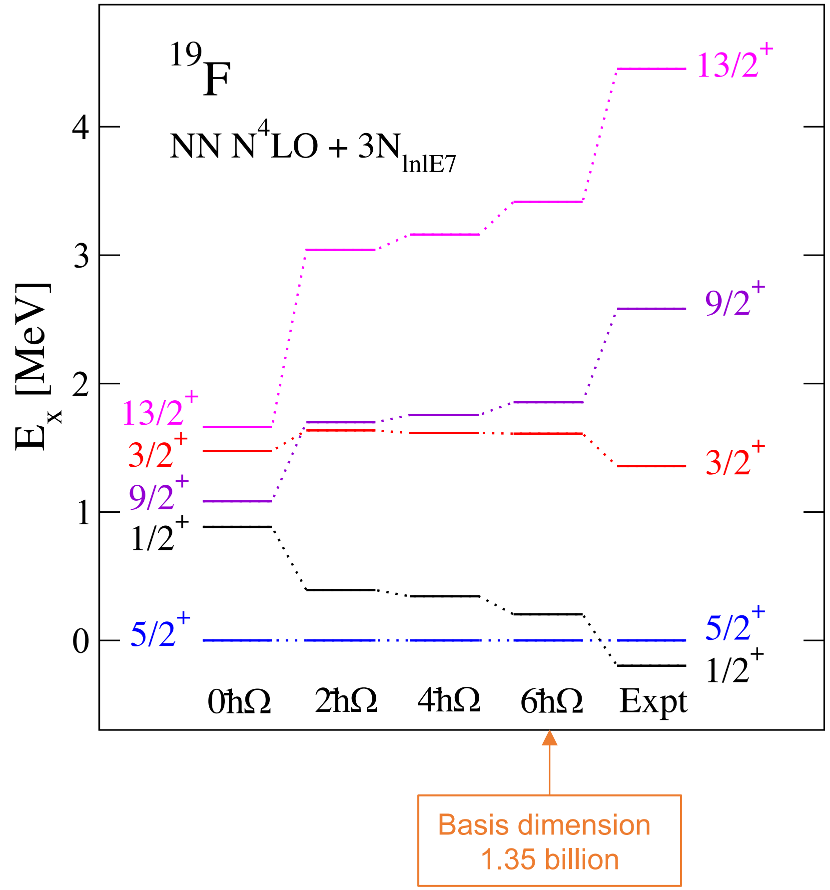
Muon capture on ^{6}Li, ^{12}C, and ^{16}O from *ab initio* nuclear theory

Lotta Jokiniemi[1,*] Petr Navrátil[1,2,†] Jenni Kotila[3,4,5,‡] and Kostas Kravvaris[6,§]

Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

- Excitation energies of light nuclei

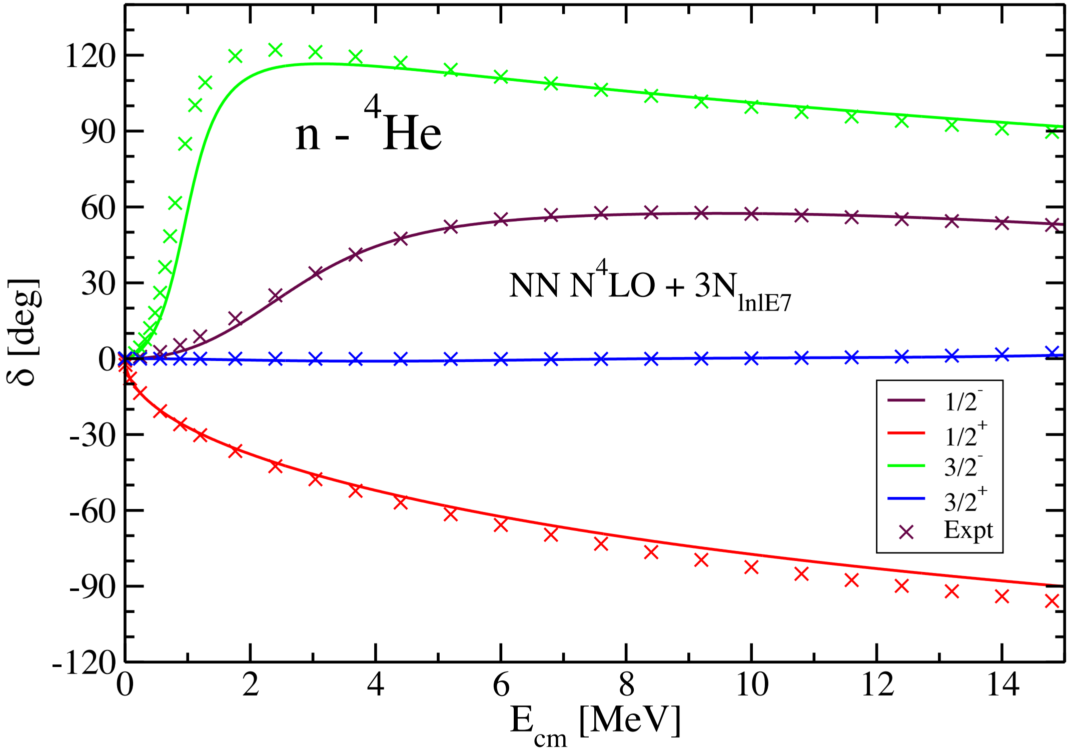


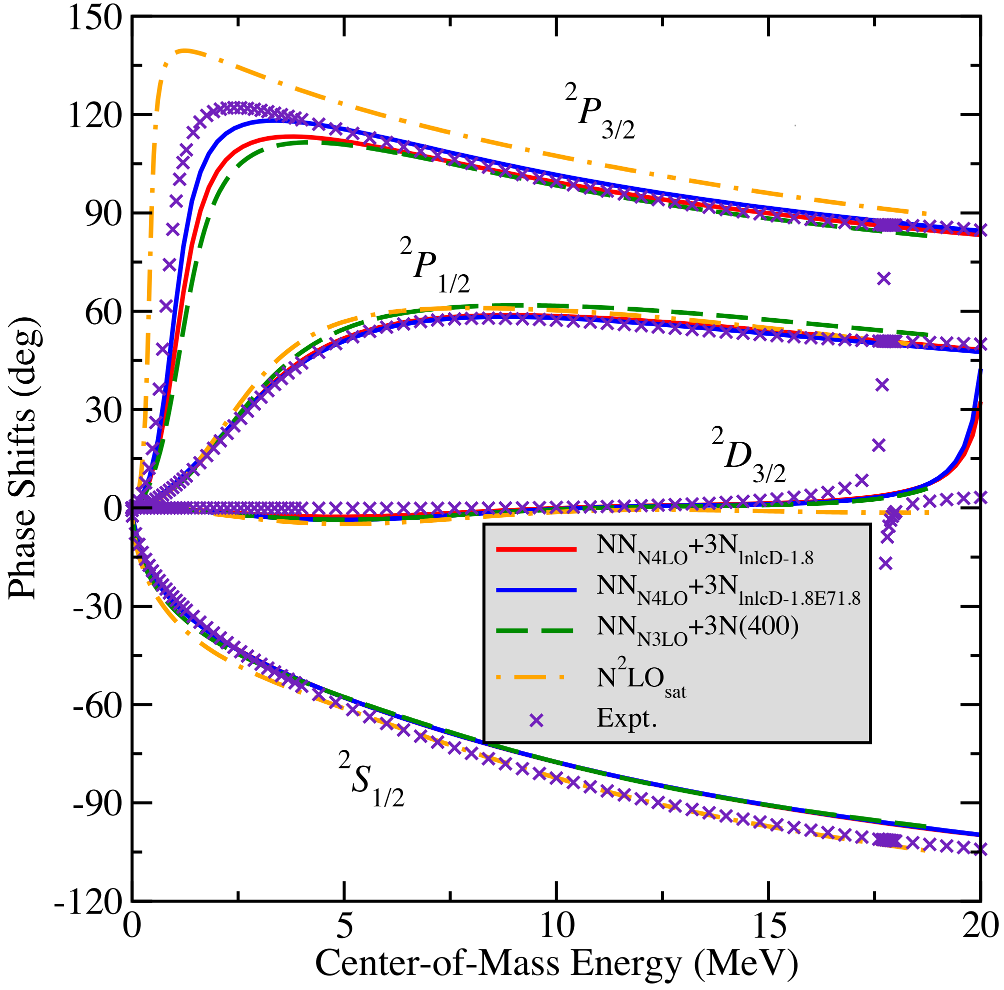


Describes well ground-state energies & excitation levels of light nuclei

Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

- n+^{4}He scattering

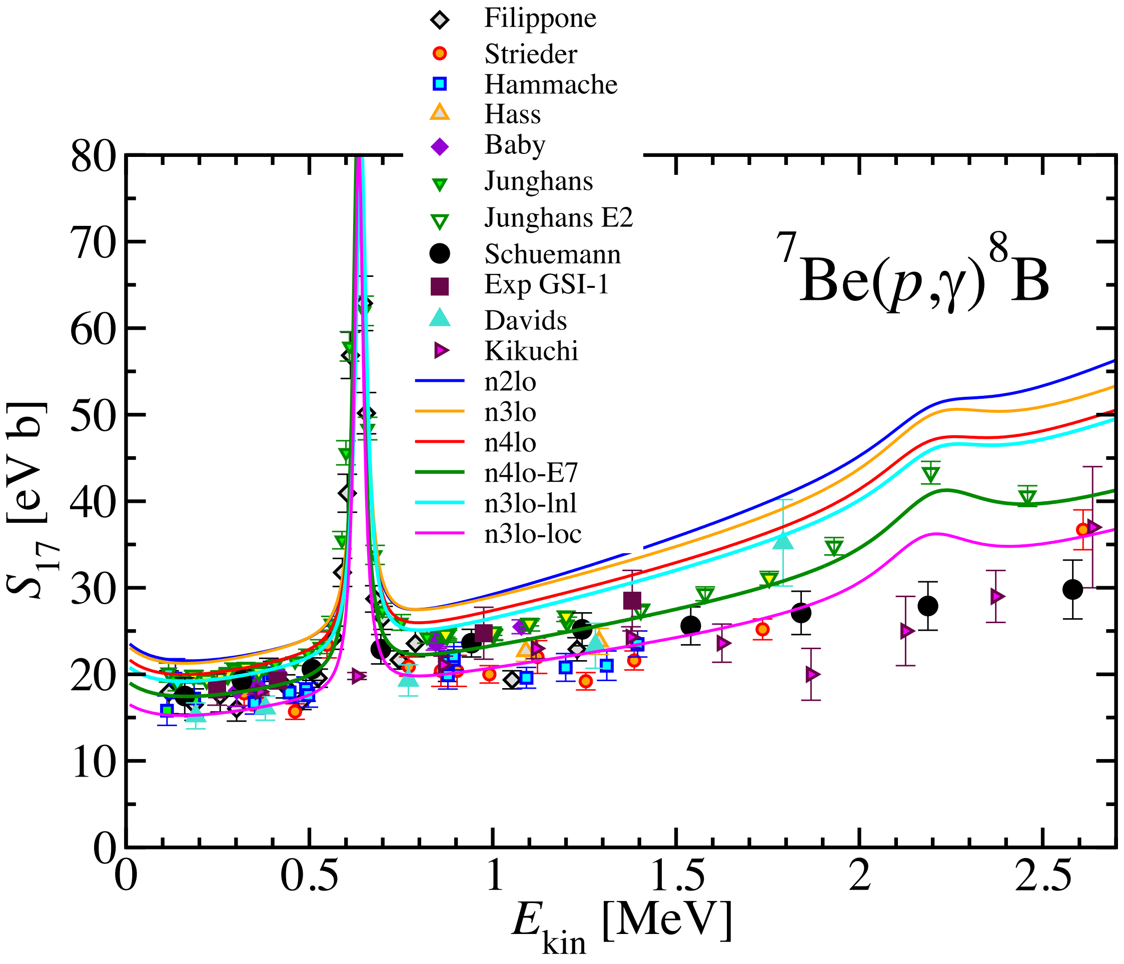


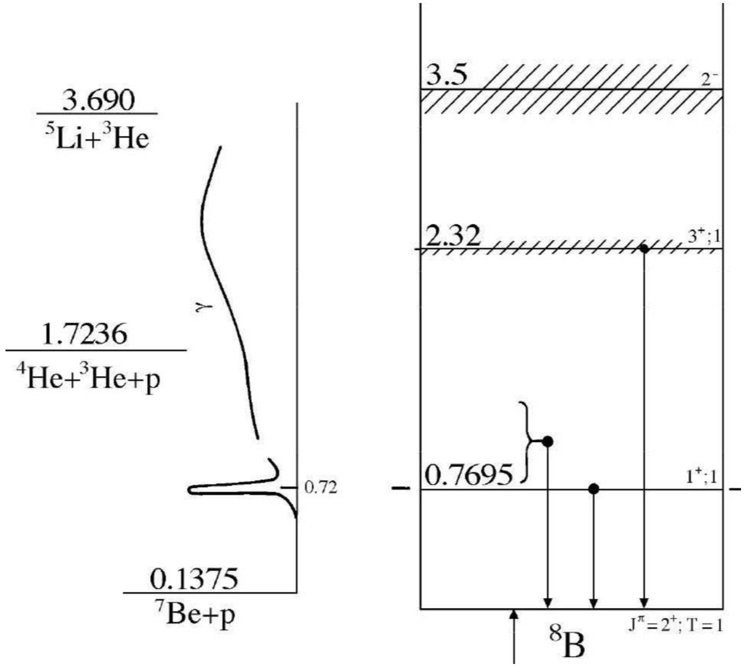


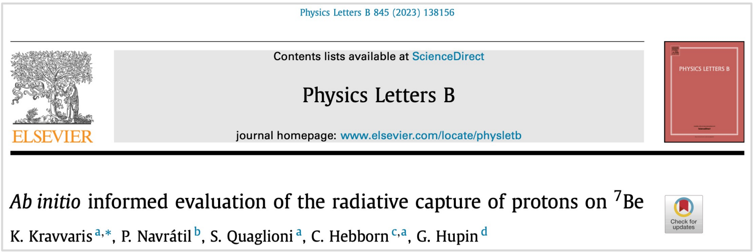
Improvement for ^{5}He *P*-wave resonances compared to other interactions

Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

- ^{7}Be(p,γ)^{8}B radiative capture






Physics Letters B 845 (2023) 138156

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

Ab initio informed evaluation of the radiative capture of protons on ^{7}Be

K. Kravvaris[a,*], P. Navrátil[b], S. Quaglioni[a], C. Hebborn[c,a], G. Hupin[d]

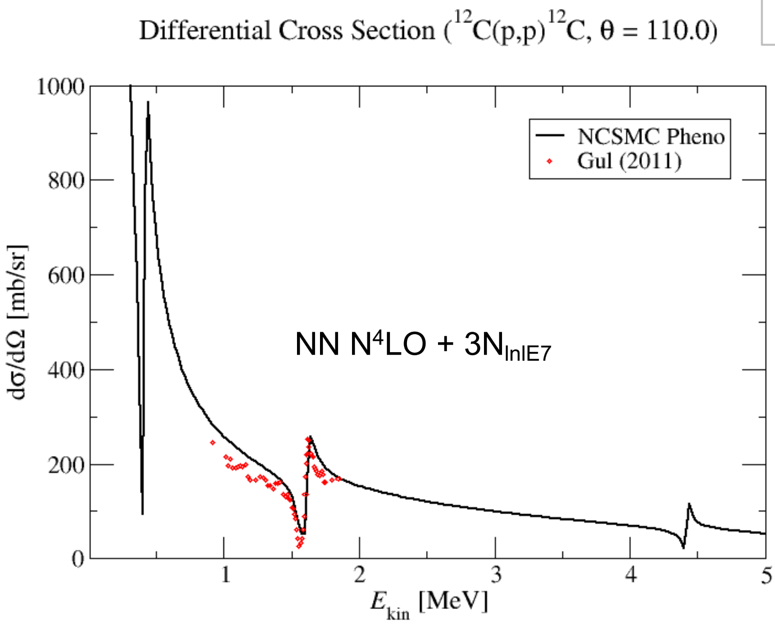
Improvement for ^{7}Be(p,γ)^{8}B S-factor compared to other interactions

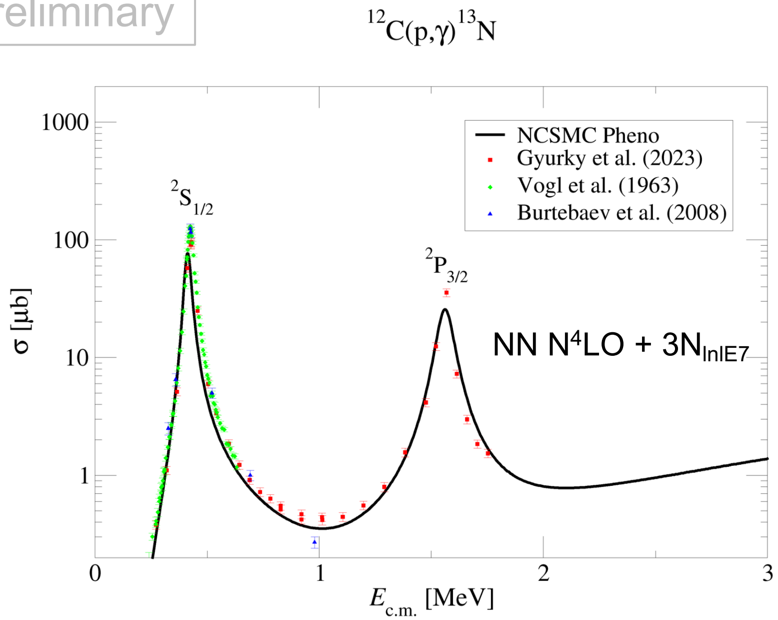
Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

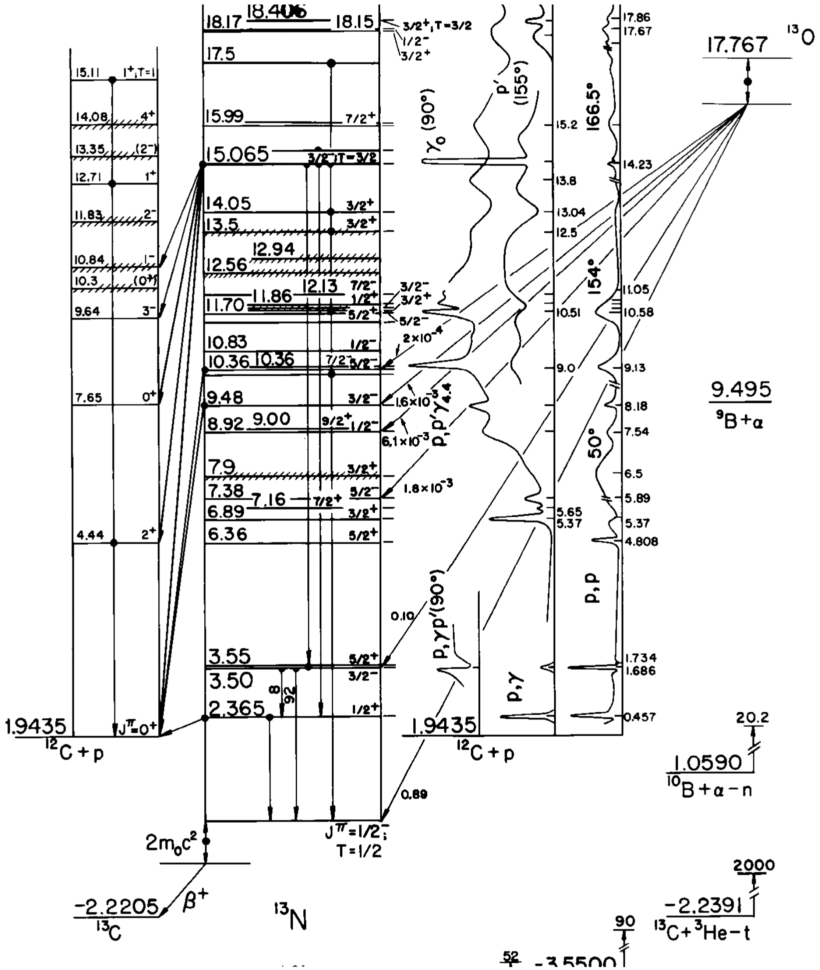
- p+^{12}C scattering and capture

  Calculations in collaboration with Marshall Kodar (UVic undergrad)

Preliminary







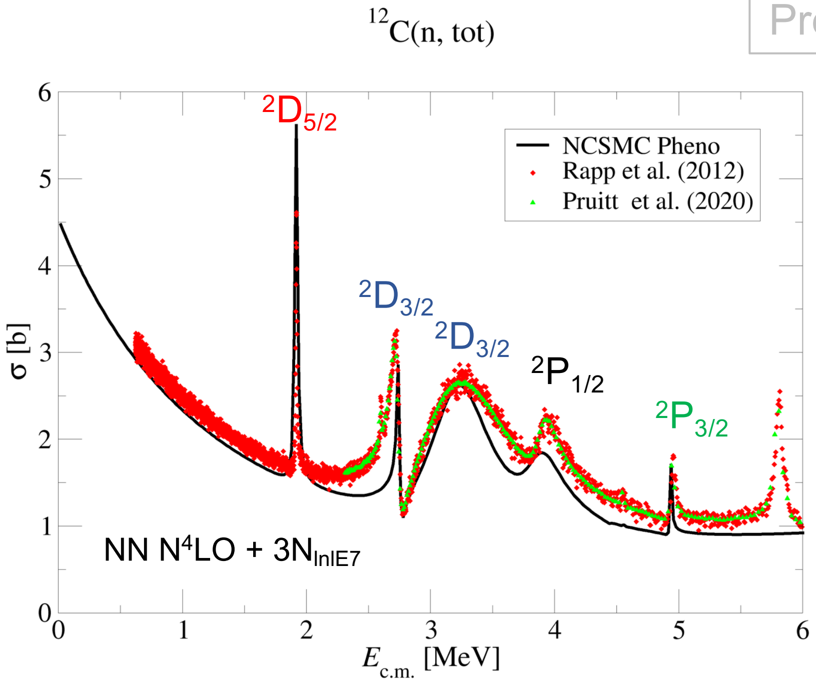
Excellent agreement with experimental data

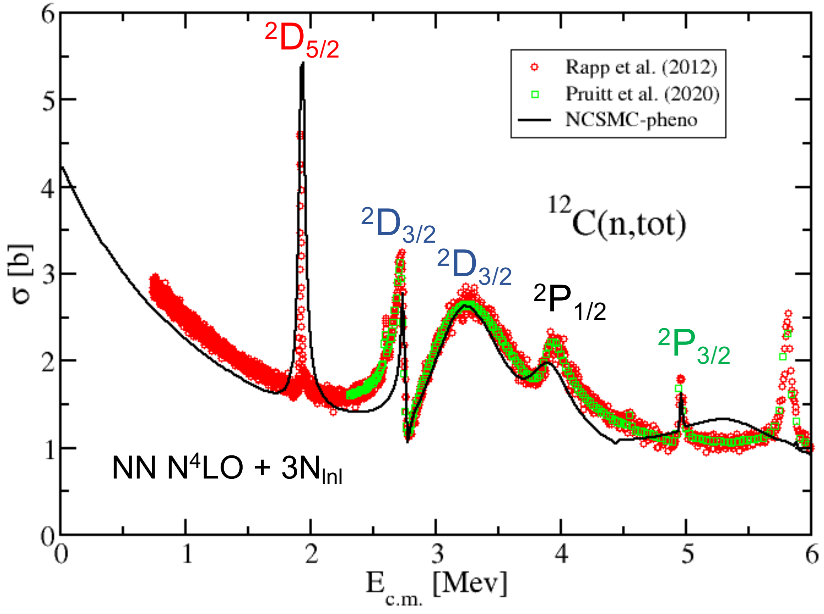
Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term

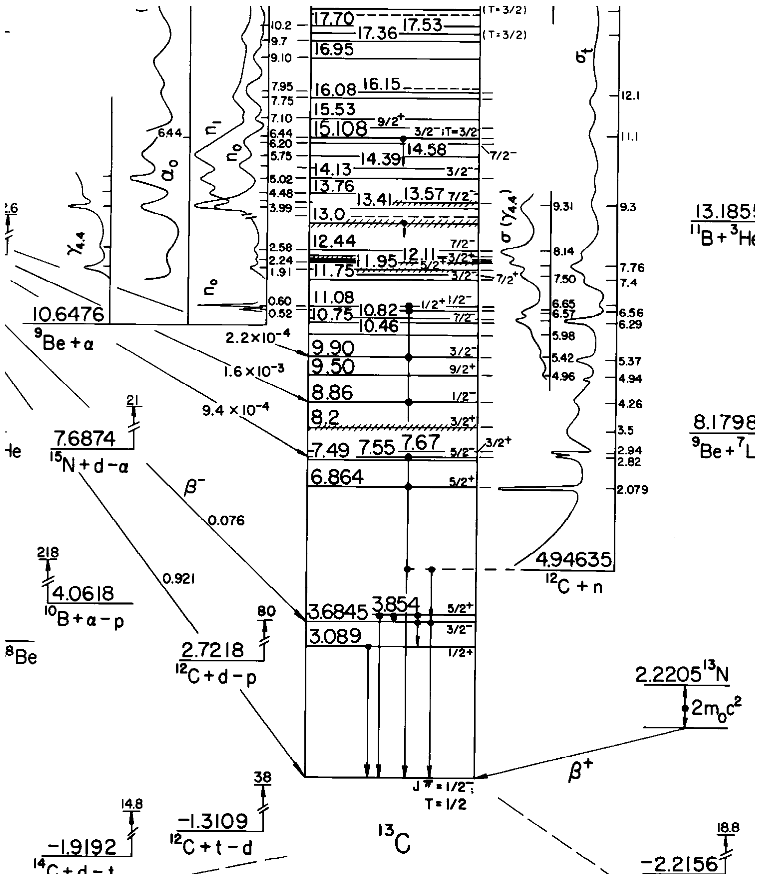
- n+^{12}C cross section

Calculations in collaboration with Marshall Kodar (UVic undergrad), Matteo Vorabbi (Surrey)

Preliminary

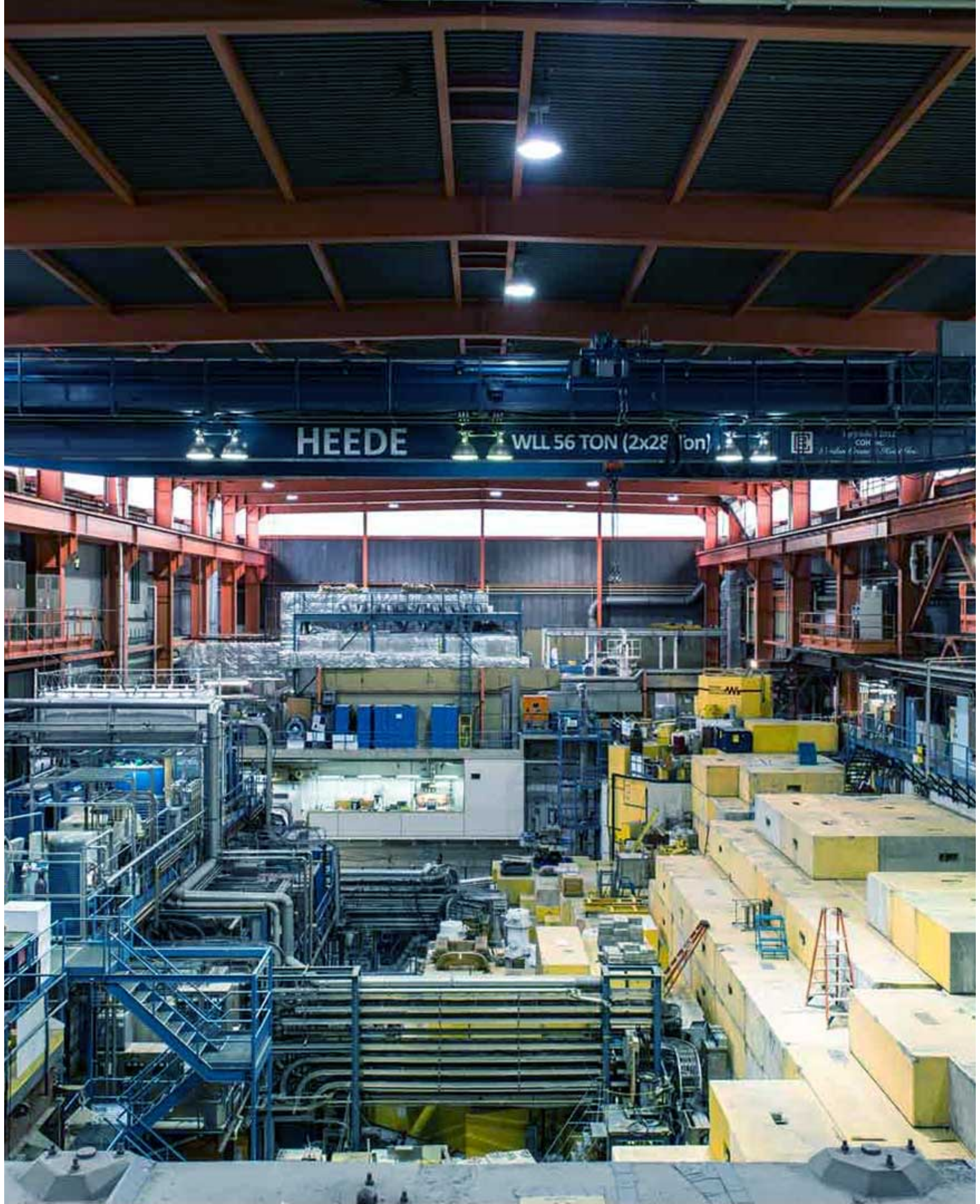






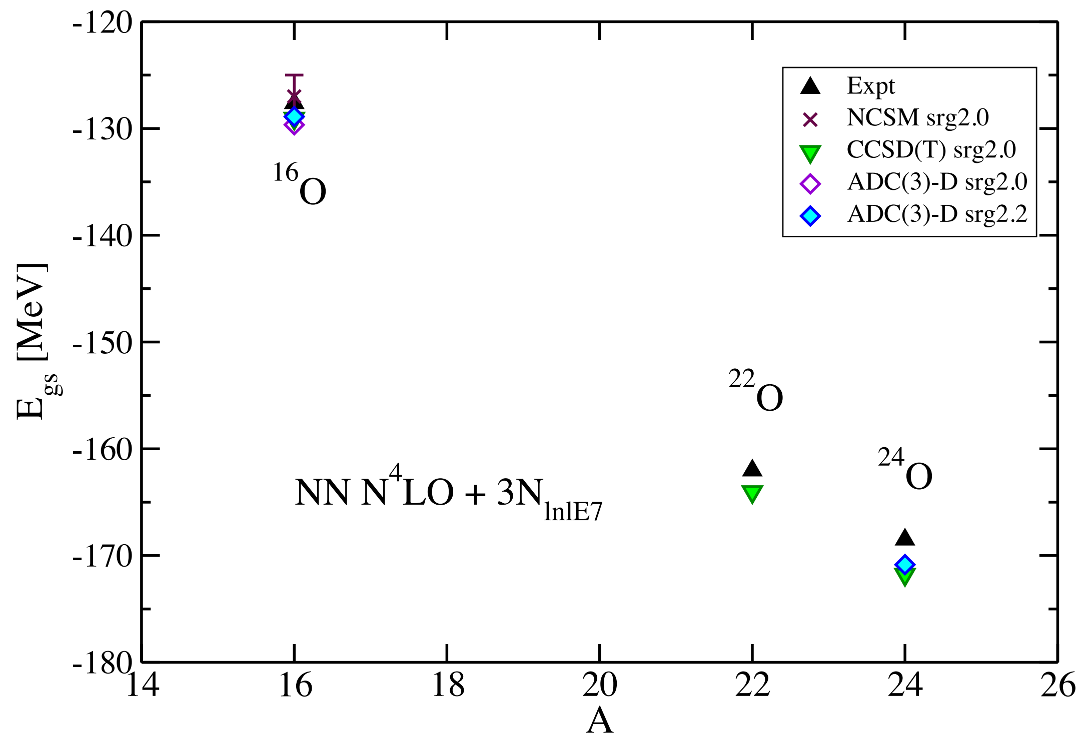
Excellent agreement with experimental data. Impact of E_7 term in progress.

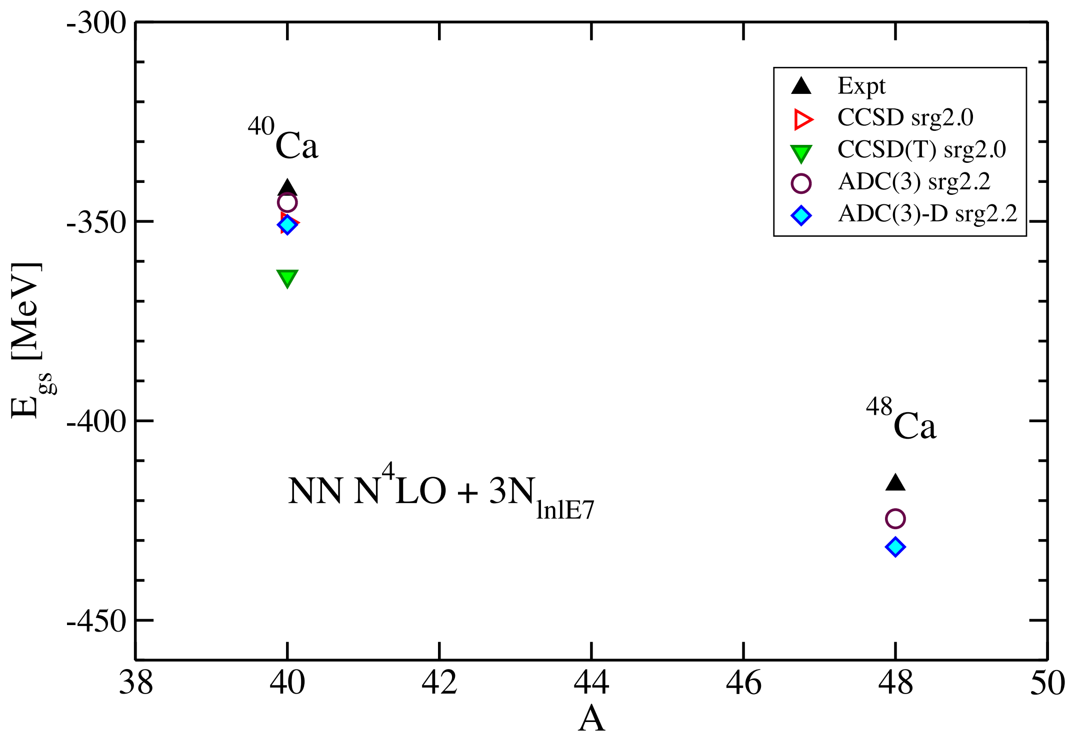
Precision chiral EFT Hamiltonian with a sub-leading 3N interaction term - medium mass nuclei



Coupled cluster and Self-Consistent Green's Function calculations for O and Ca isotopes

Calculations by Gaute Hagen and Carlo Barbieri





^{16}O	srg1.8	srg2.0	srg2.2	Expt.	(MeV)
CCSD(T)	-130.76	-129.05			
ADC(3)-D		-129.65	-128.89	-127.619	

Overall slight overbinding – SRG effect or LECs re-fit needed?

Bogoliubov many-body perturbation theory (BMBPT) calculations for N=20 isotones

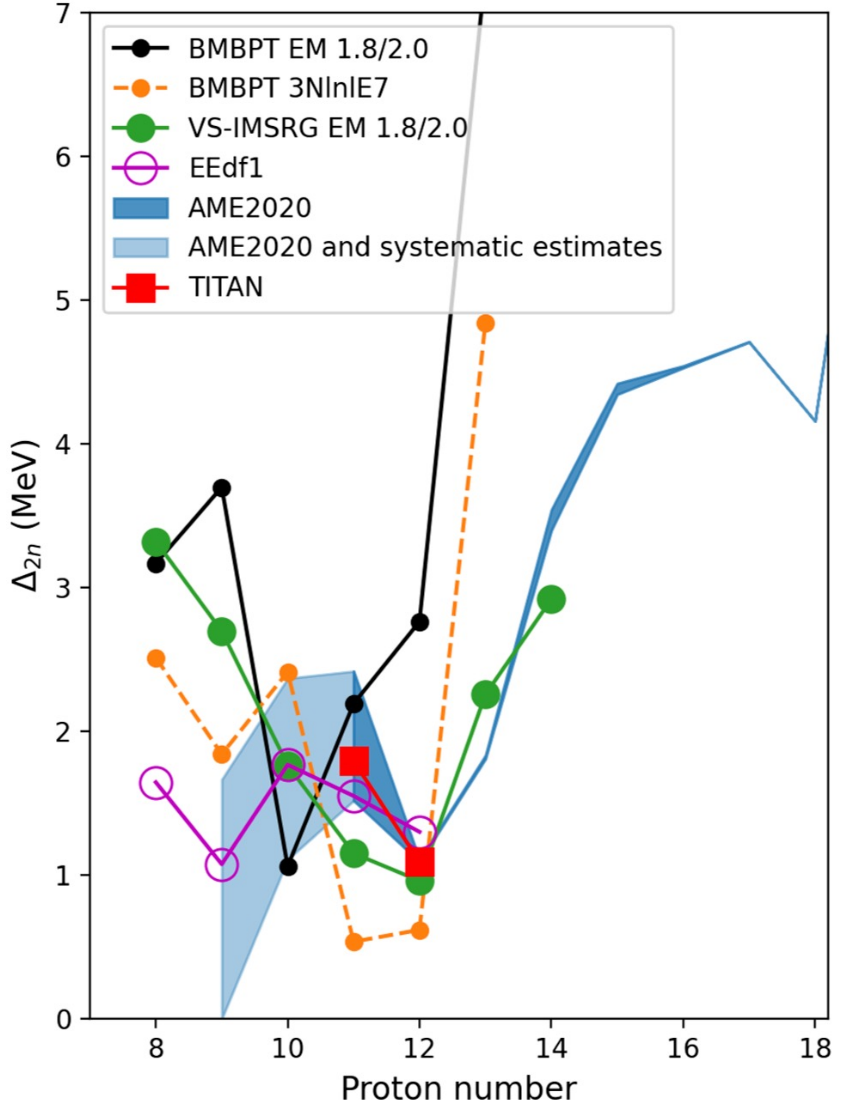
Calculations by Vittorio Soma

PHYSICAL REVIEW LETTERS **134,** 052503 (2025)

Refined Topology of the $N = 20$ Island of Inversion with High Precision Mass Measurements of $^{31-33}$Na and $^{31-35}$Mg

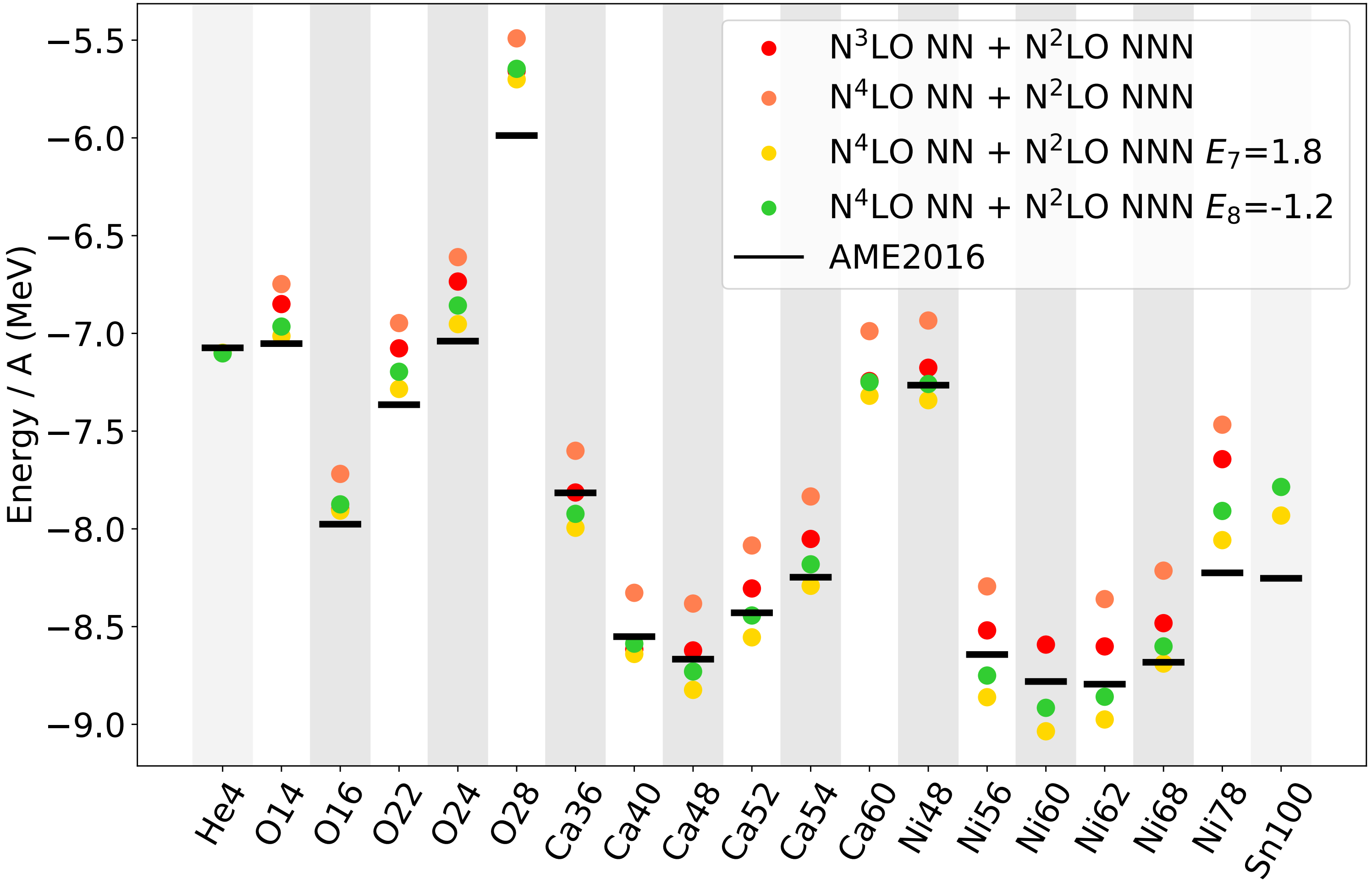
E. M. Lykiardopoulou,[1,2] C. Walls,[1,3] J. Bergmann,[4] M. Brodeur,[5] C. Brown,[6] J. Cardona,[1,3] A. Czihaly,[1,7] T. Dickel,[8,4] T. Duguet,[9,10] J.-P. Ebran,[11,12] M. Frosini,[13] Z. Hockenbery,[1,14] J. D. Holt,[1,14] A. Jacobs,[1,2] S. Kakkar,[1,3] B. Kootte,[15] T. Miyagi,[1,16] A. Mollaebrahimi,[1,4] T. Murboeck,[4] P. Navratil,[1,7] T. Otsuka,[17,18] W. R. Plaß,[4,8] S. Paul,[1,19] W. S. Porter,[5] M. P. Reiter,[6] A. Scalesi,[9] C. Scheidenberger,[8,4,20] V. Somà,[9] N. Shimizu,[21] Y. Wang,[1,2] D. Lunney,[22] J. Dilling,[1,2,23,24] and A. A. Kwiatkowski[1,7]

NN N^{4}LO + 3N$_{\text{lnlE7}}$ predictions resembling those of the successful phenomenological EEdf1 with the same trend for Z = 8 - 10



MBPT calculations up to 3rd order for (semi-)magic medium mass nuclei

- Calculations by Takayuki Miyagi

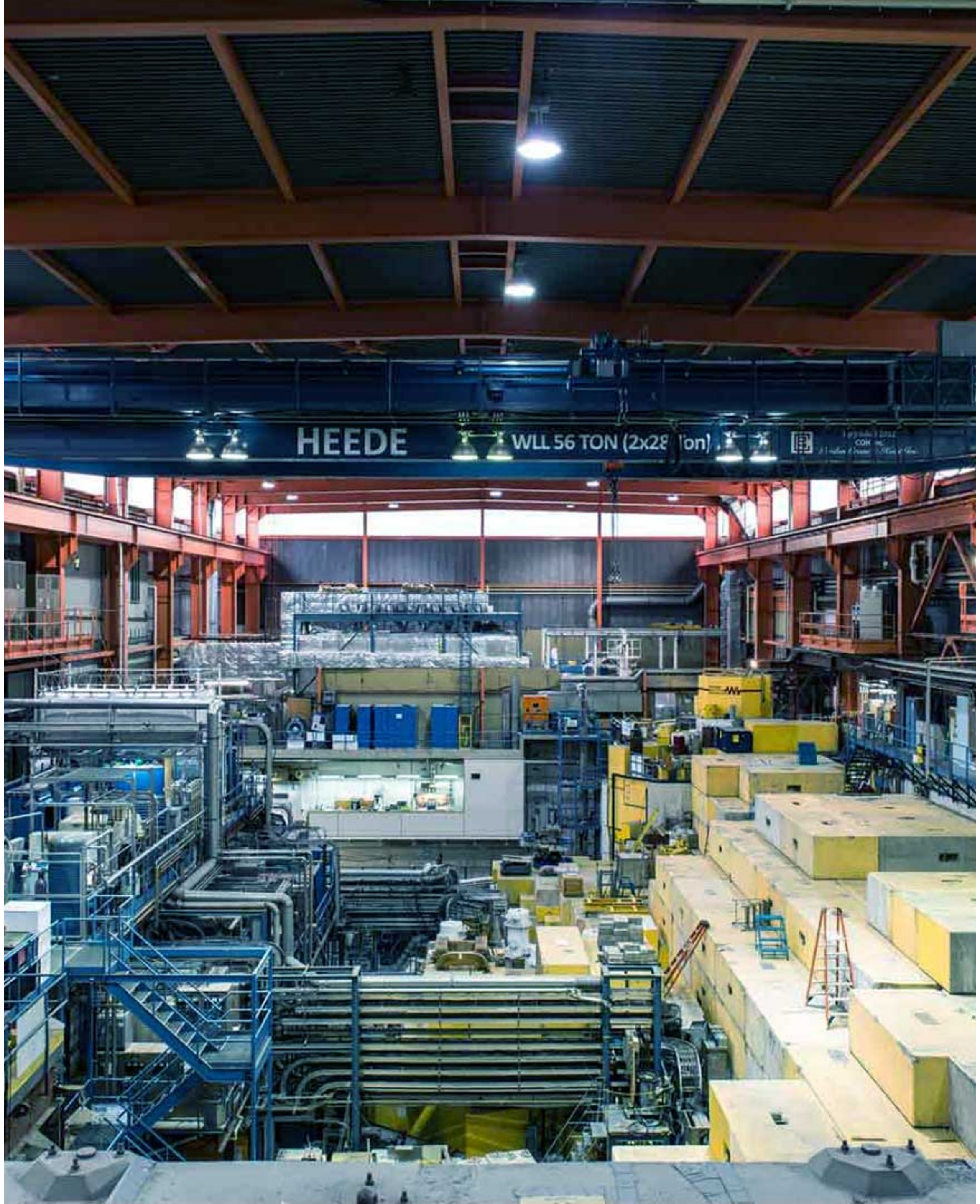


N^{4}LO 3N contact contributions worth further exploring!

TRIUMF

Enhanced short-range 3N interaction with two-pion exchange

Results for ^3H



Discovery, accelerated

A new class of three-nucleon forces – enhanced sub-leading terms?

PHYSICAL REVIEW LETTERS 135, 022501 (2025)

New Class of Three-Nucleon Forces and Their Implications

Vincenzo Cirigliano,* Maria Dawid,† Wouter Dekens,‡ and Sanjay Reddy§

Closer look at enhanced three-nucleon forces

E. Epelbaum,[1] A. M. Gasparyan,[1] J. Gegelia,[1,2] D. Hog,[1] and H. Krebs[1]

arXiv:2512.14117

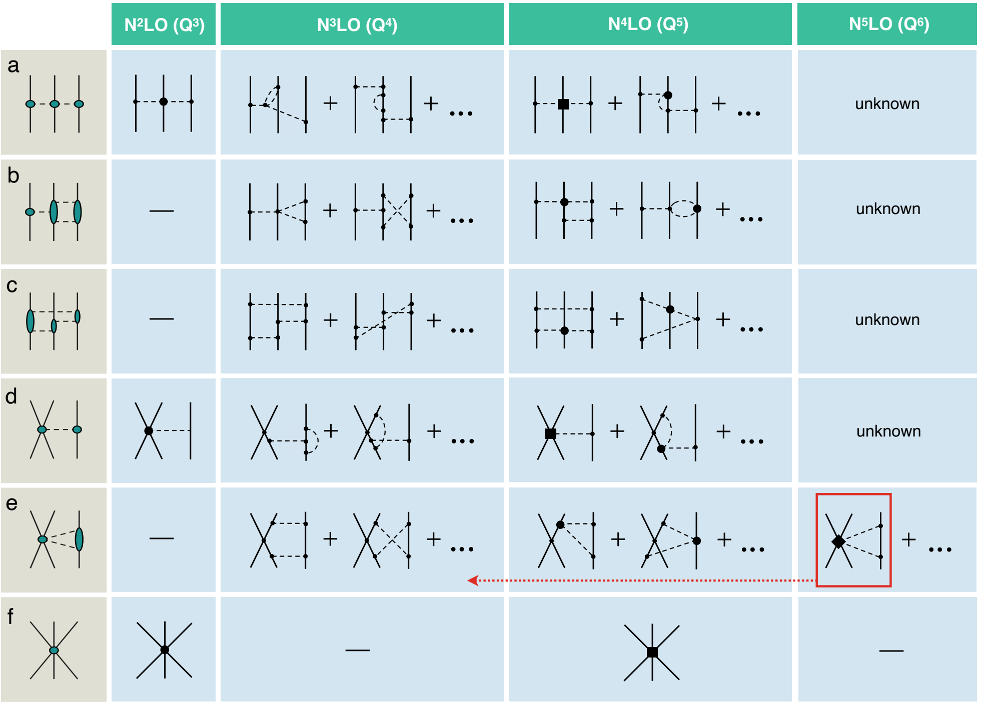
- Enhanced short-range 3N interaction with two-pion exchange

$$W_{D_2} = \sum_{i\neq j\neq k} \frac{9 g_A^2 D_2 m_\pi^3}{128\pi f_\pi^4} \frac{(d_2^S + d_2^T \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)}{d_2^S - 3 d_2^T} \mathcal{I}\left(\frac{q_k^2}{4m_\pi^2}\right)$$

$$W_{F_2} = -\sum_{i\neq j\neq k} \frac{15 g_A^2 m_\pi^3}{16\pi f_\pi^4} (f_2^S + f_2^T \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)\, \mathcal{J}\left(\frac{q_k^2}{4m_\pi^2}\right)$$

$$D_2 = \frac{c_{D_2}}{5F_\pi^4} \qquad \longleftarrow \qquad D_2 = \frac{c_{D_2}}{F_\pi^2 \Lambda_\chi^2}$$

$$F_2 = \frac{c_{F_2}}{5F_\pi^4} \qquad\qquad F_2 = \frac{c_{F_2}}{F_\pi^2 \Lambda_\chi^2}$$



Exploring quark mass dependent three-nucleon forces in medium-mass nuclei

Urban Vernik,[1,2,*] Kai Hebeler,[1,2,3,†] and Achim Schwenk[1,2,3,‡]

A new class of three-nucleon forces – enhanced sub-leading terms?

PHYSICAL REVIEW LETTERS 135, 022501 (2025)

New Class of Three-Nucleon Forces and Their Implications

Vincenzo Cirigliano,* Maria Dawid,† Wouter Dekens,‡ and Sanjay Reddy§

Closer look at enhanced three-nucleon forces

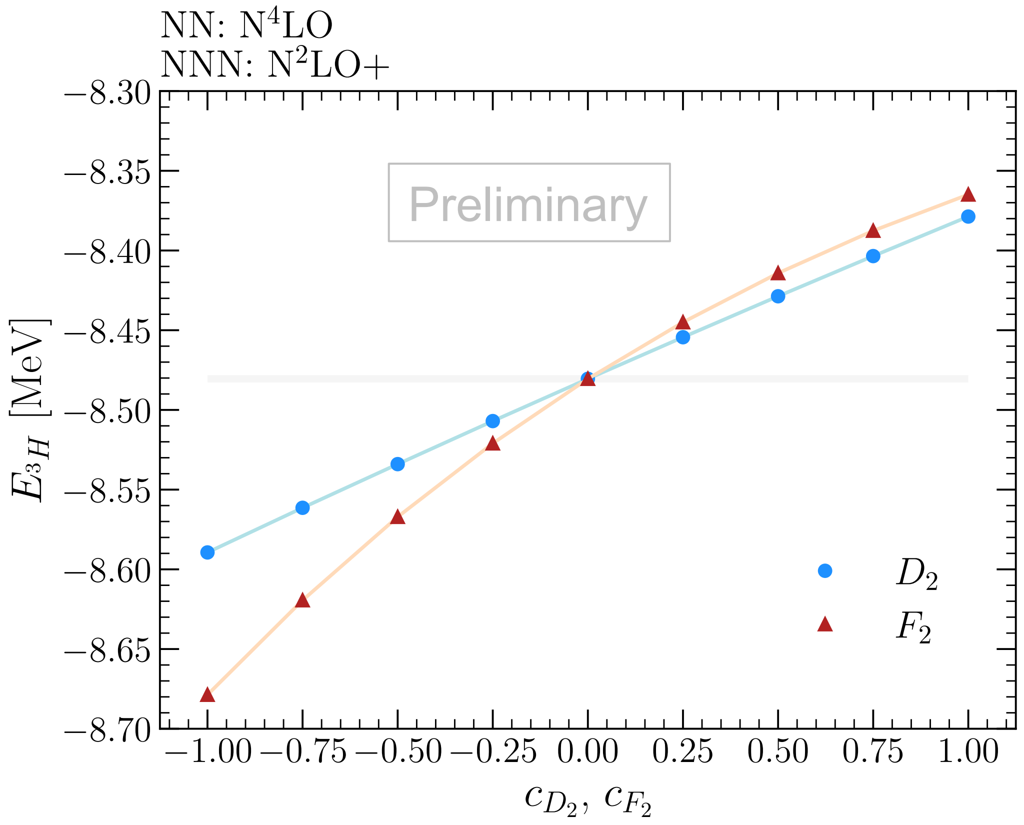
E. Epelbaum,[1] A. M. Gasparyan,[1] J. Gegelia,[1,2] D. Hog,[1] and H. Krebs[1]

arXiv:2512.14117

- Application to ^{3}H gs energy – Jacobi NCSM

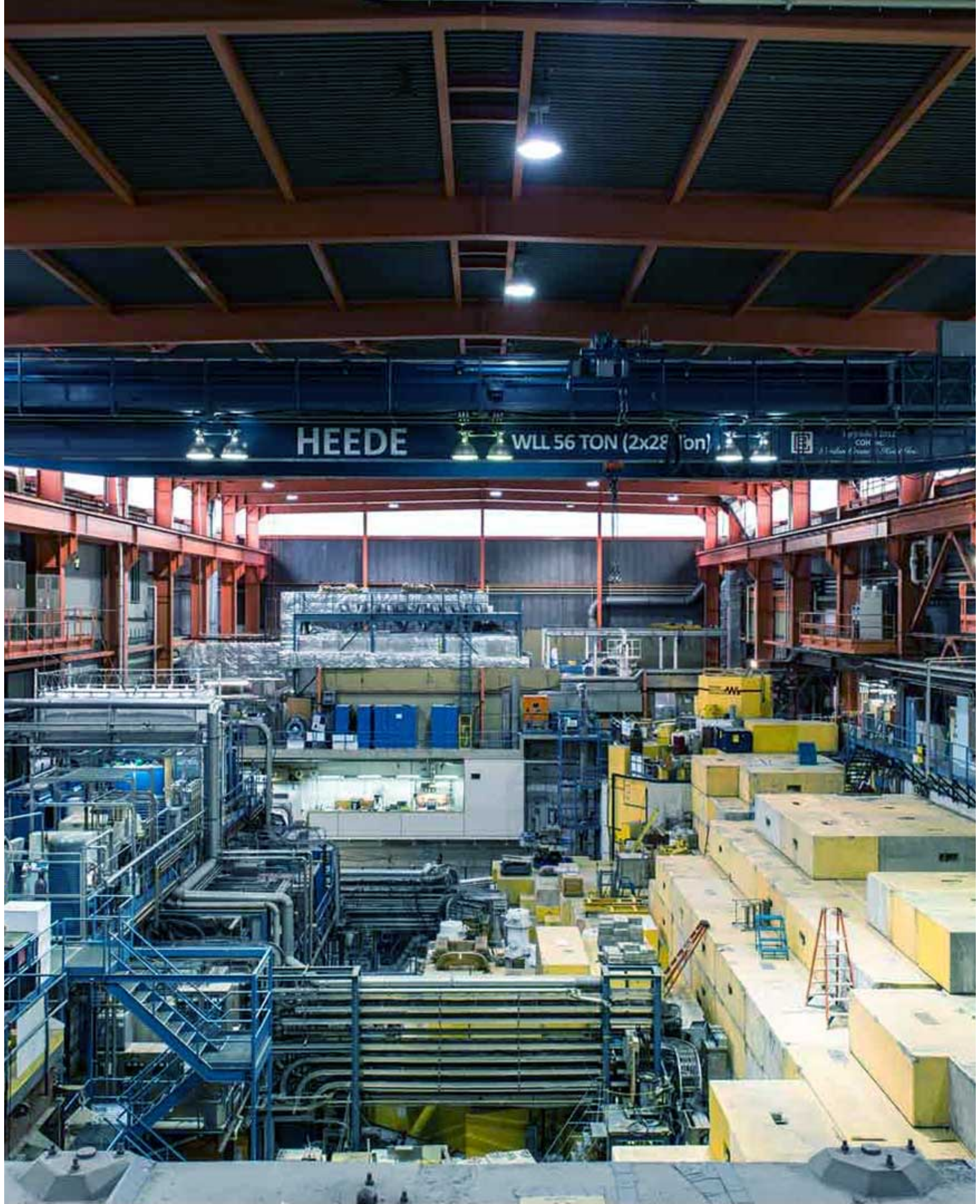
Georgios Palkanoglou (TRIUMF)

Calculations for ^{4}He, p-shell nuclei in progress



TRIUMF

Conclusions



Discovery, accelerated

Conclusions

- Big picture
  - High-order (N^3LO and N^4LO) chiral NN interactions are OK
  - 3N interactions need to be improved
  - Including N^4LO 3N contact terms straightforward and a logical thing to do
  - Spin-orbit enhancing E_7 and/or E_8 terms important, should be included
    - Optimally fitted to n+^{4}He phase shifts
  - Good evidence that there is a correlation between ^{4}He, ^{16}O, ^{40}Ca binding energy
    - Important to get the ^{4}He binding energy properly
    - Beware that SRG induced 4N can play a role
  - Neutron rich nuclei seems to be underbound – add T=3/2 3N contact(s)?

- More medium-mass and heavy nuclei calculations needed to test Hamiltonians with subleading 3N interactions

- Open question
  - How important is the “enhanced short-range 3N interaction with two-pion exchange”?
    - Applied to ^{3}H
    - Calculations for ^{4}He and p-shell nuclei in progress