

A02

Report & Perspectives

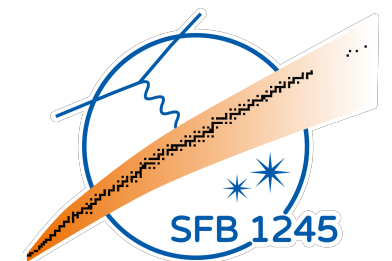
PIs:

Hans-Werner Hammer

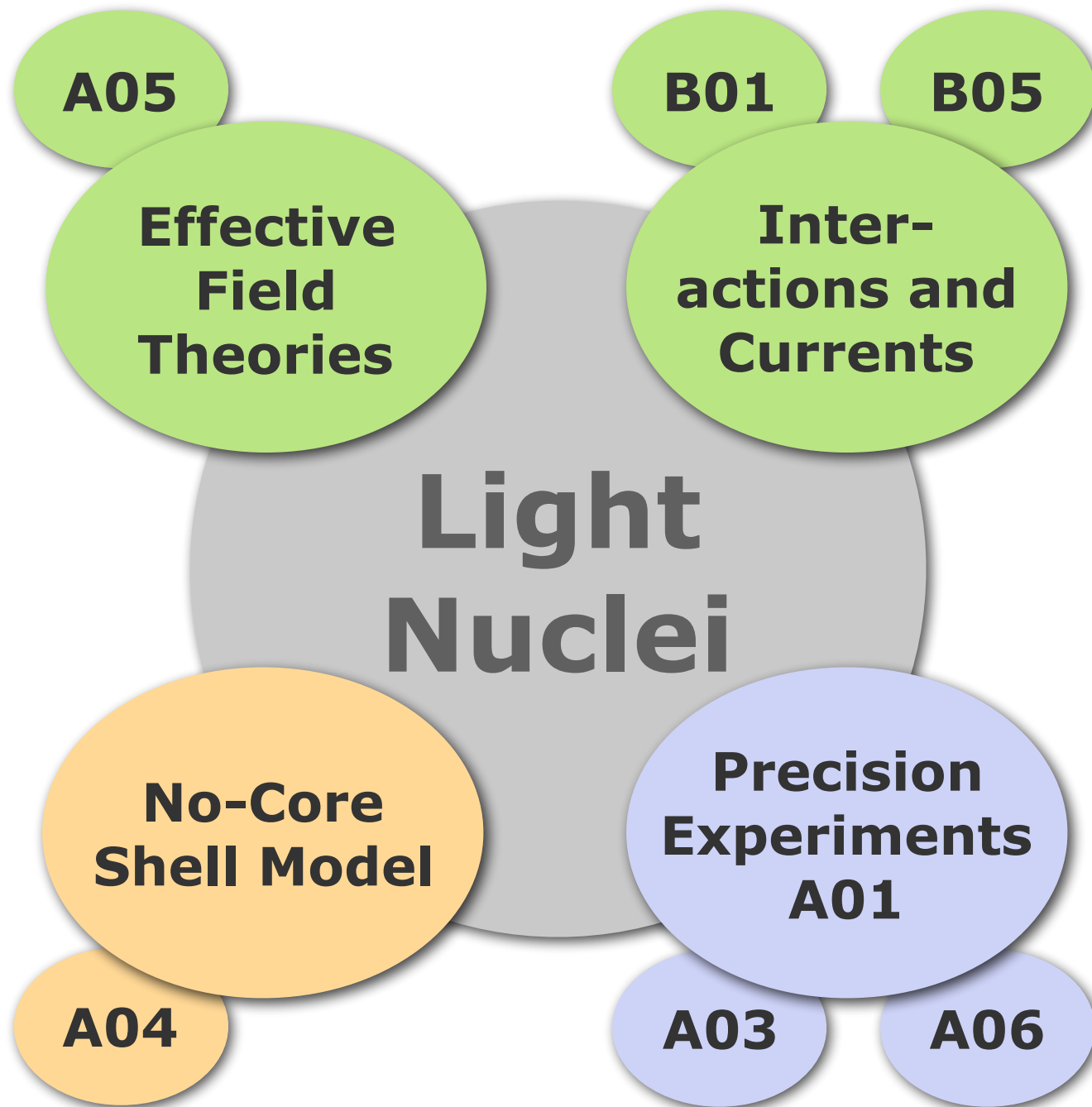
Robert Roth



TECHNISCHE
UNIVERSITÄT
DARMSTADT

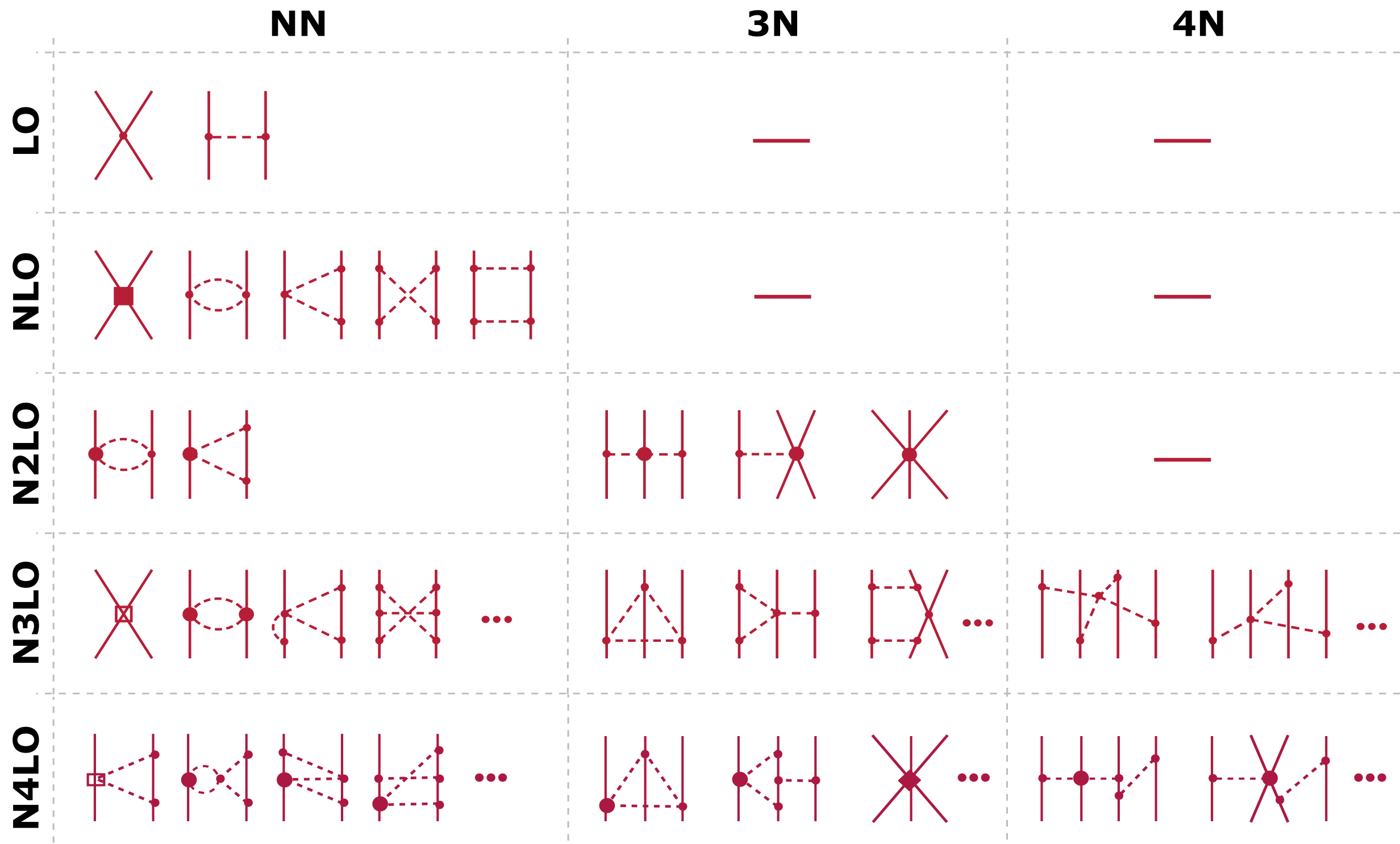


A02: Research Program

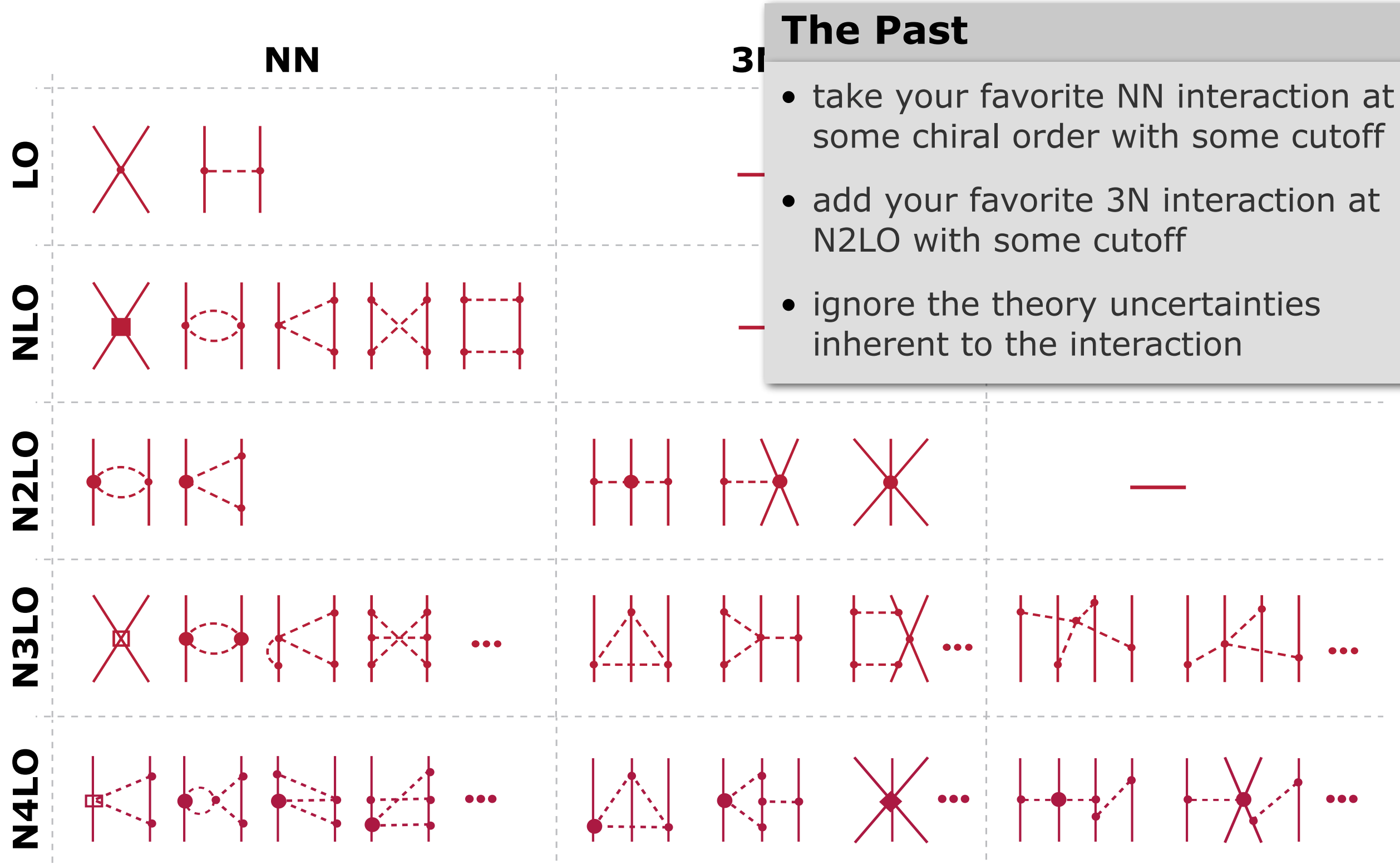


- consistent chiral EFT interactions up to N3LO (NN+3N+4N)
- convergence and uncertainties of chiral EFT interactions
- precision NCSM calculations of radii and electromagnetic observables with quantified uncertainties
- bridge to effective field theories to address difficult observables and exploit correlations
- inclusion of continuum degrees of freedom in the NCSM

Nuclear Interactions from Chiral EFT



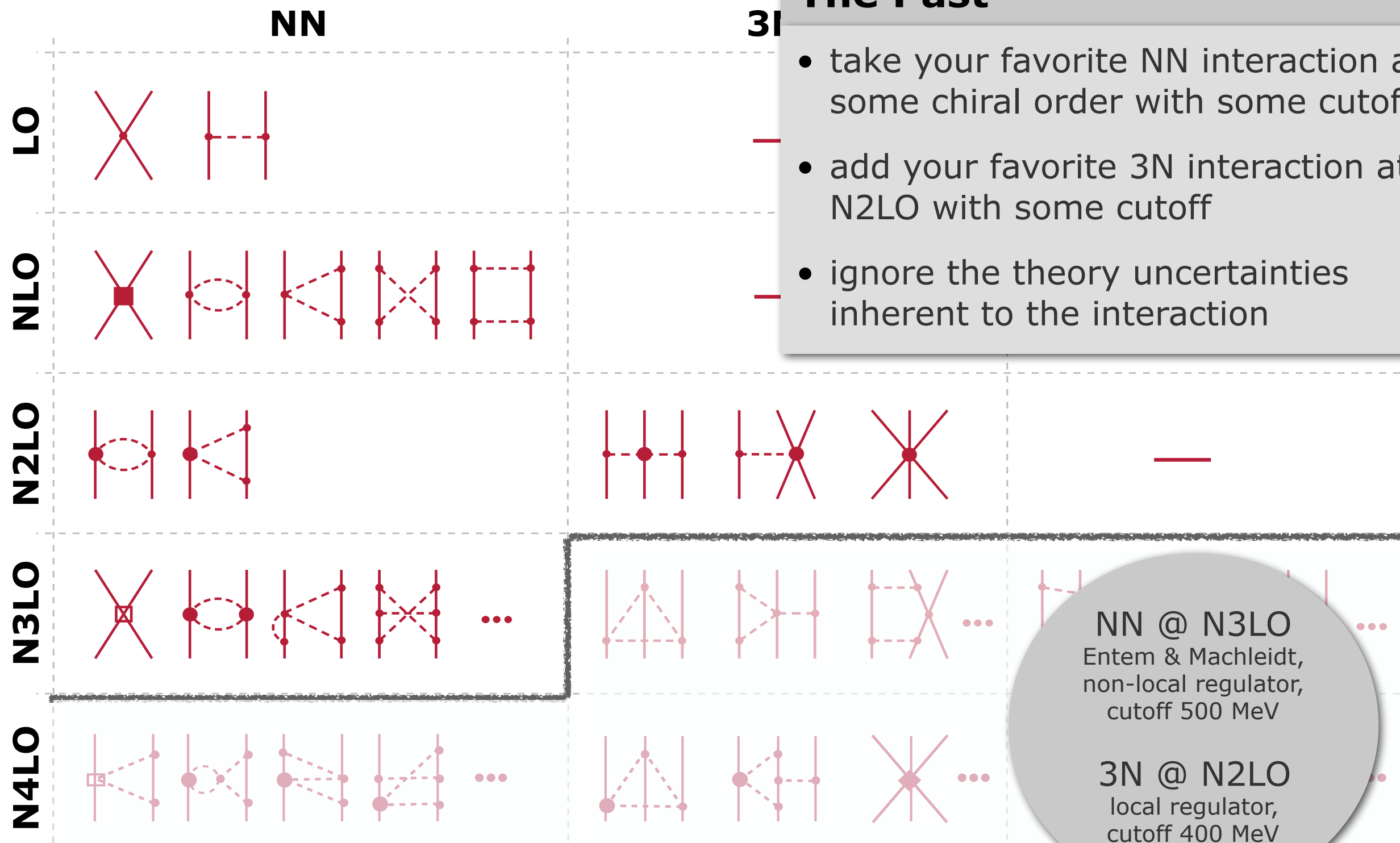
Nuclear Interactions from Chiral EFT



The Past

- take your favorite NN interaction at some chiral order with some cutoff
- add your favorite 3N interaction at N2LO with some cutoff
- ignore the theory uncertainties inherent to the interaction

Nuclear Interactions from Chiral EFT



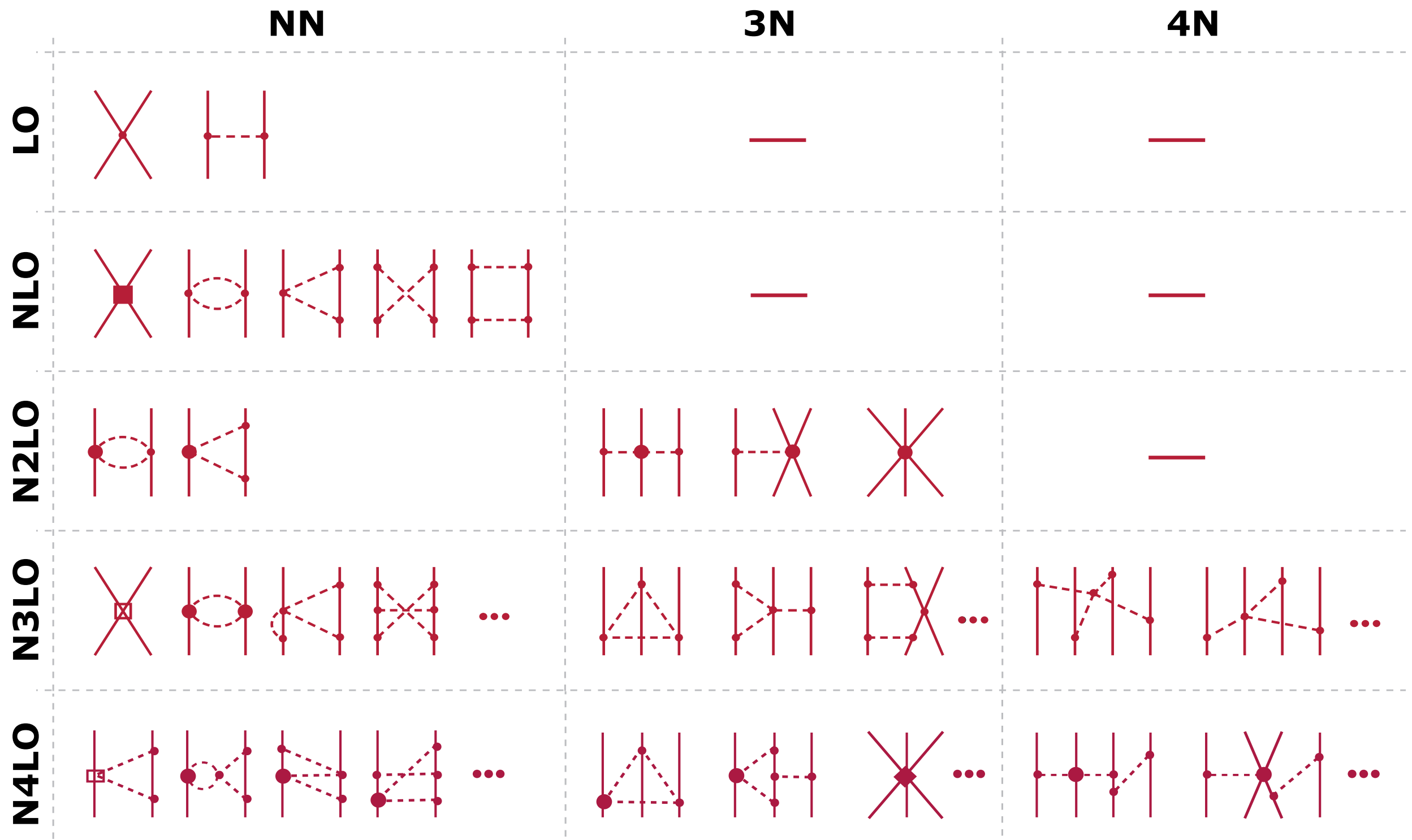
The Past

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- add your favorite 3N interaction at N2LO with some cutoff
- ignore the theory uncertainties inherent to the interaction

NN @ N3LO
 Entem & Machleidt,
 non-local regulator,
 cutoff 500 MeV

3N @ N2LO
 local regulator,
 cutoff 400 MeV

Nuclear Interactions from Chiral EFT



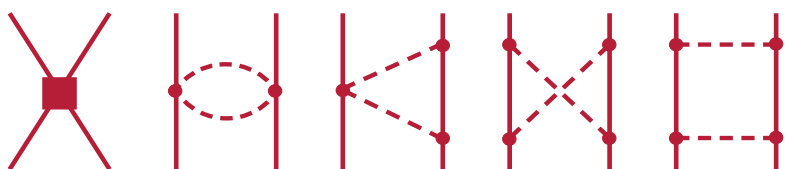
Nuclear Interactions from Chiral EFT

NN

LO



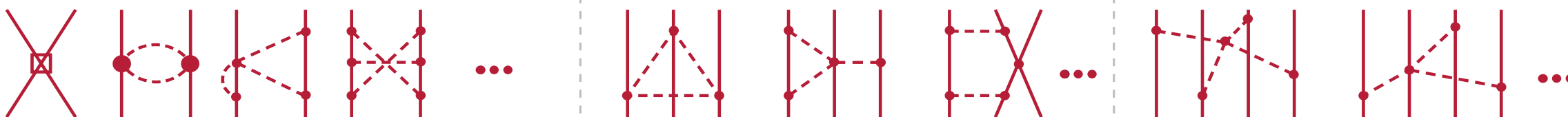
NLO



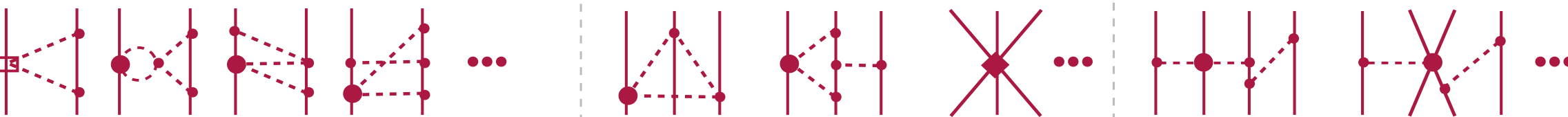
N2LO



N3LO



N4LO

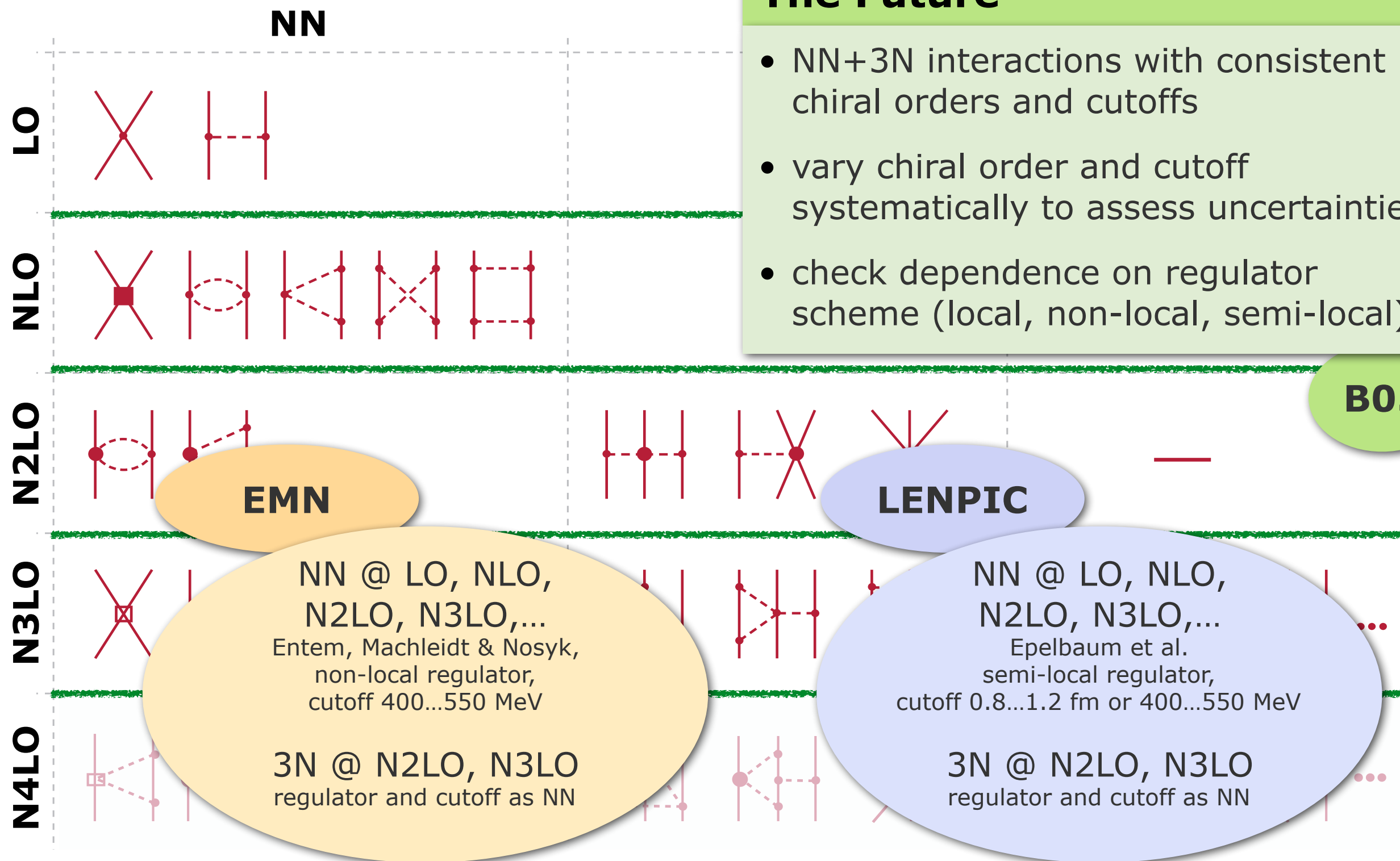


The Future

- NN+3N interactions with consistent chiral orders and cutoffs
- vary chiral order and cutoff systematically to assess uncertainties
- check dependence on regulator scheme (local, non-local, semi-local)

B05

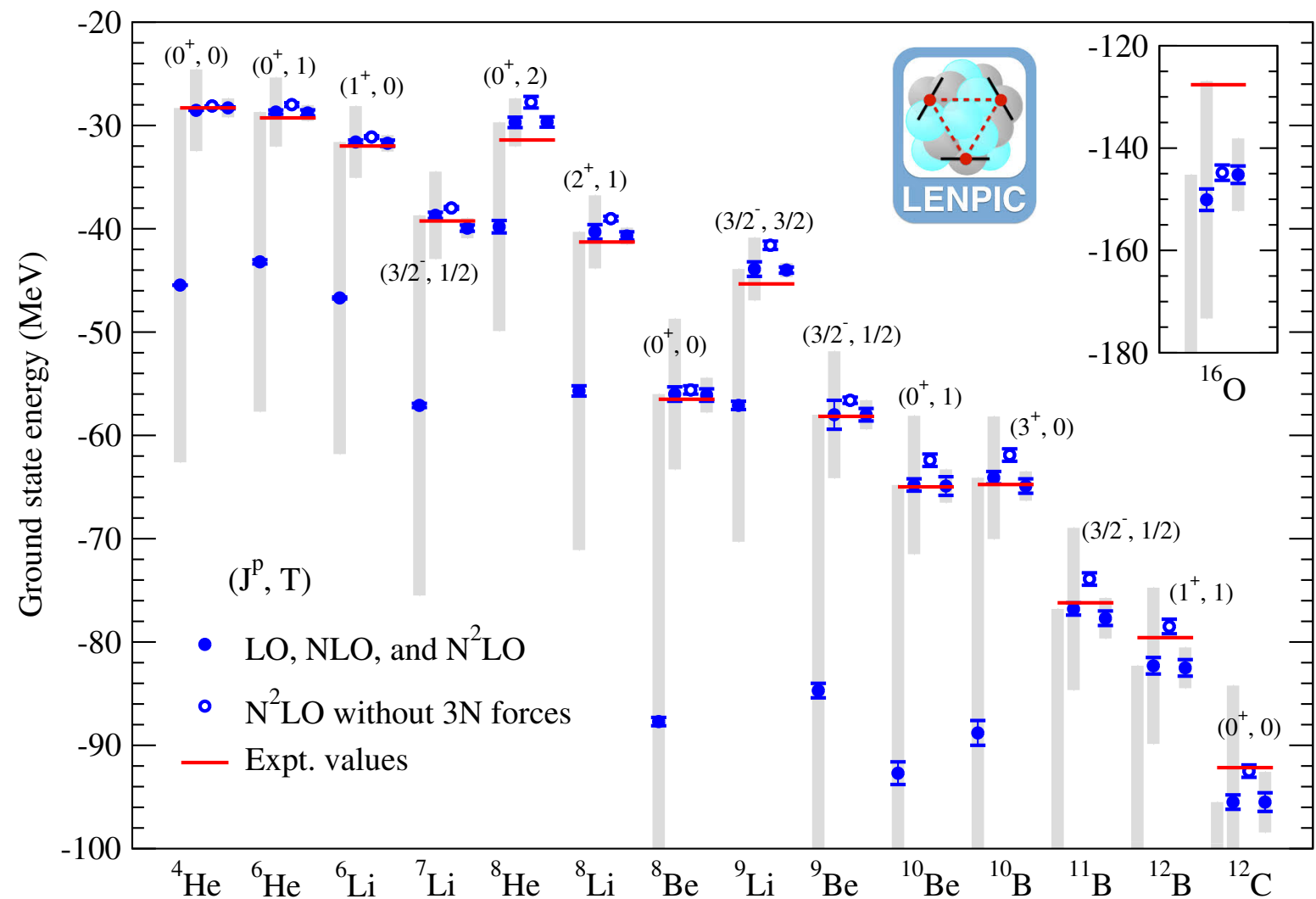
Nuclear Interactions from Chiral EFT



Order-by-Order Calculations

Epelbaum, Golak, Hebeler, H ther et al.; PRC 99, 024313 (2019)

- systematic order-by-order calculations of nuclear observables in the NCSM
- quantification of theory uncertainties from chiral inputs and from many-body method
- unexpectedly large impact of regulator scheme, especially for the 3N force



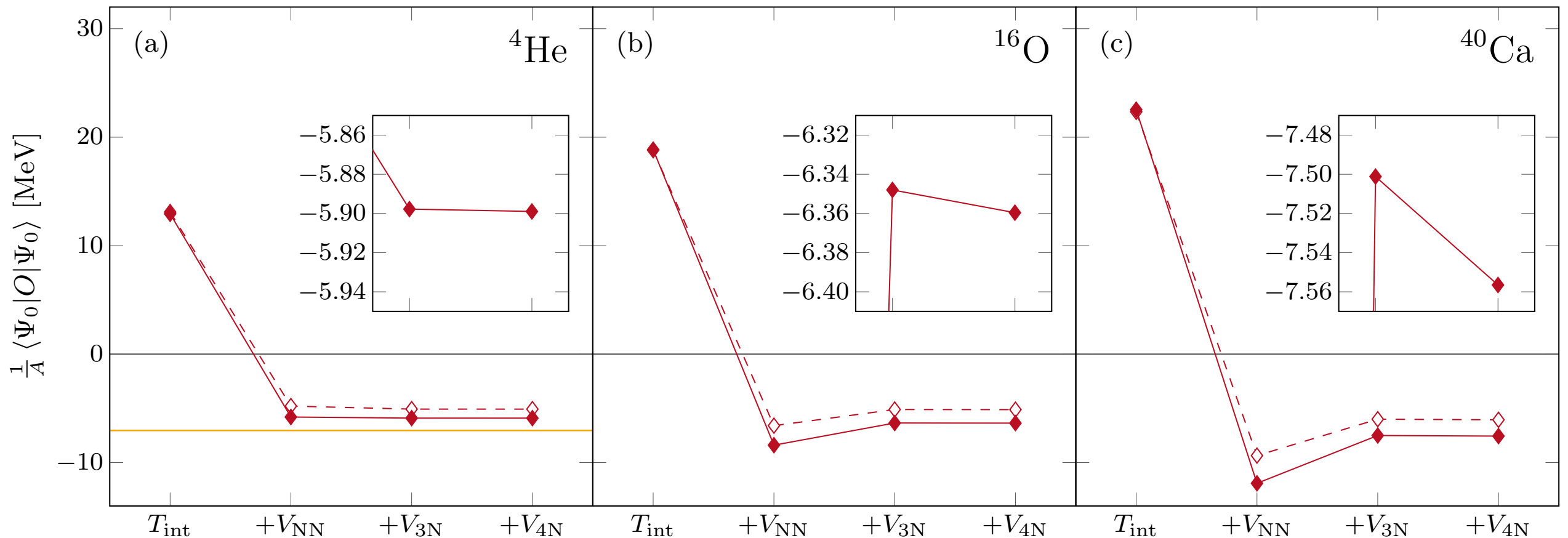
new standard protocol for
ab initio nuclear structure
calculations

...same analysis in progress for
EMN family of interactions
up to N3LO

Chiral 4N Interaction

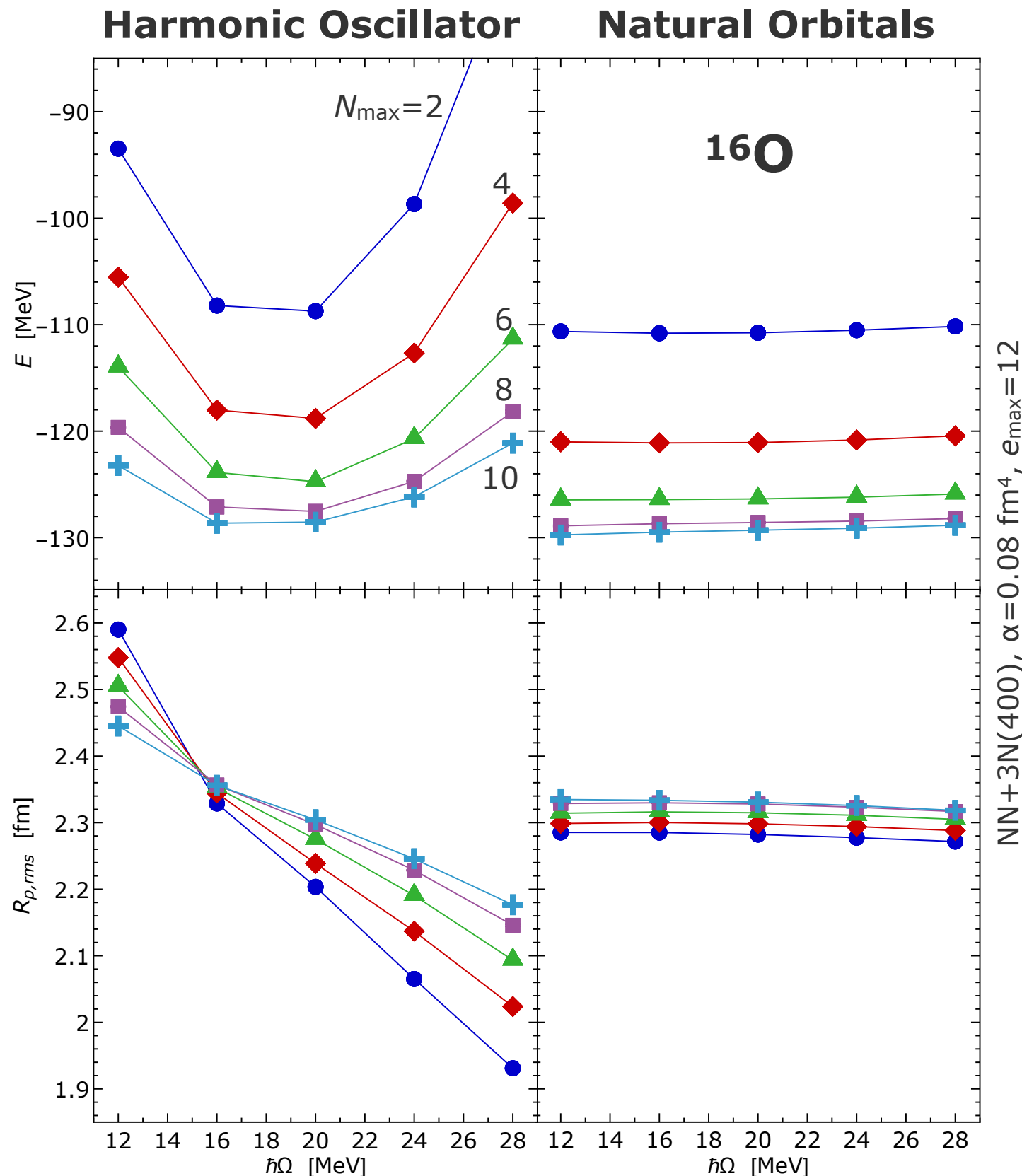
Schulz; PhD Thesis (2017) & in preparation

- parameter-free chiral 4N interactions appear at N3LO: how significant is their effect in light or medium mass nuclei?
- implementation in nuclear-structure calculations requires tedious partial-wave decomposition and complete matrix-element technology at 4N level
- effect in ground-state energies is negligible, even for calcium isotopes!



NCSM with Natural-Orbital Basis

Tichai, Müller, Vobig, Roth; PRC 99, 034321 (2019) - Editors' Suggestion



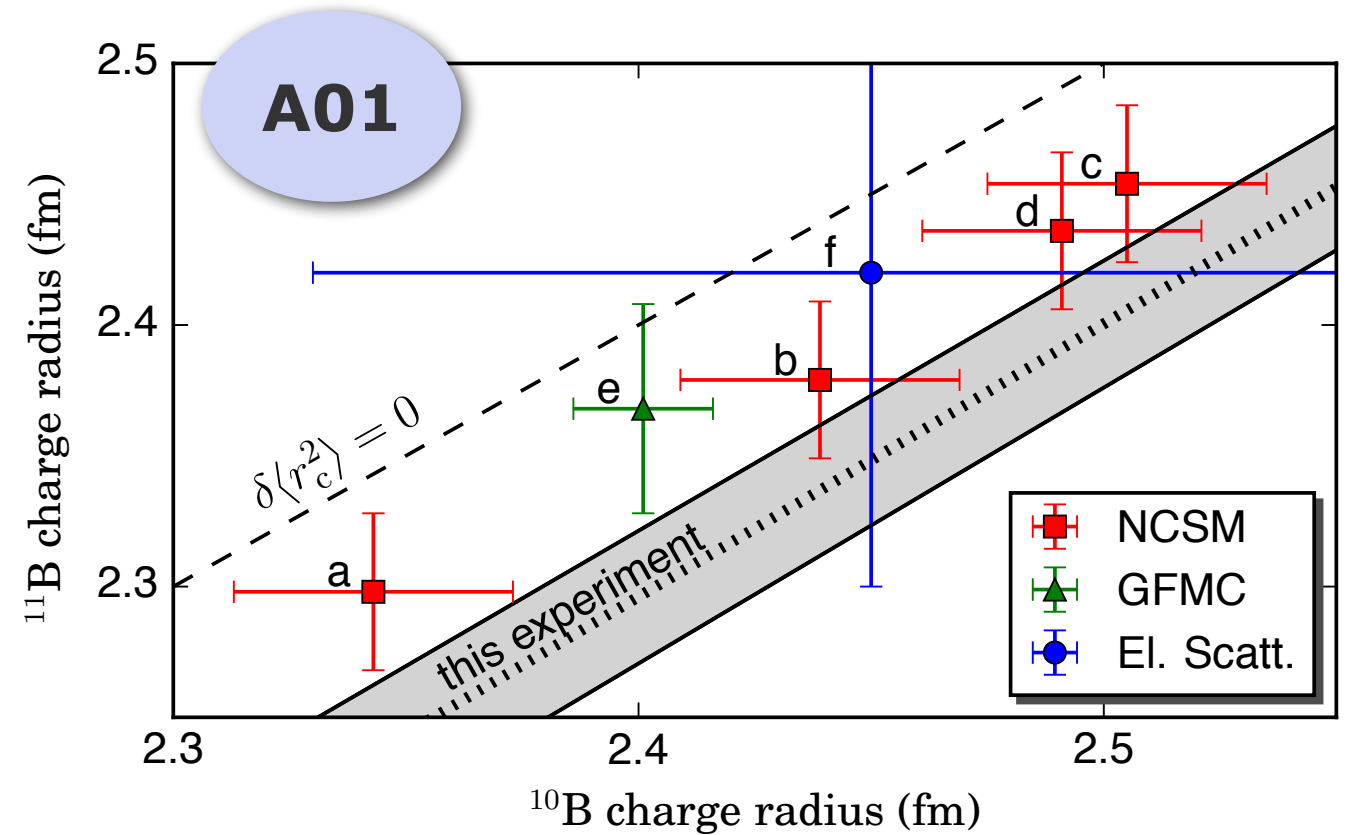
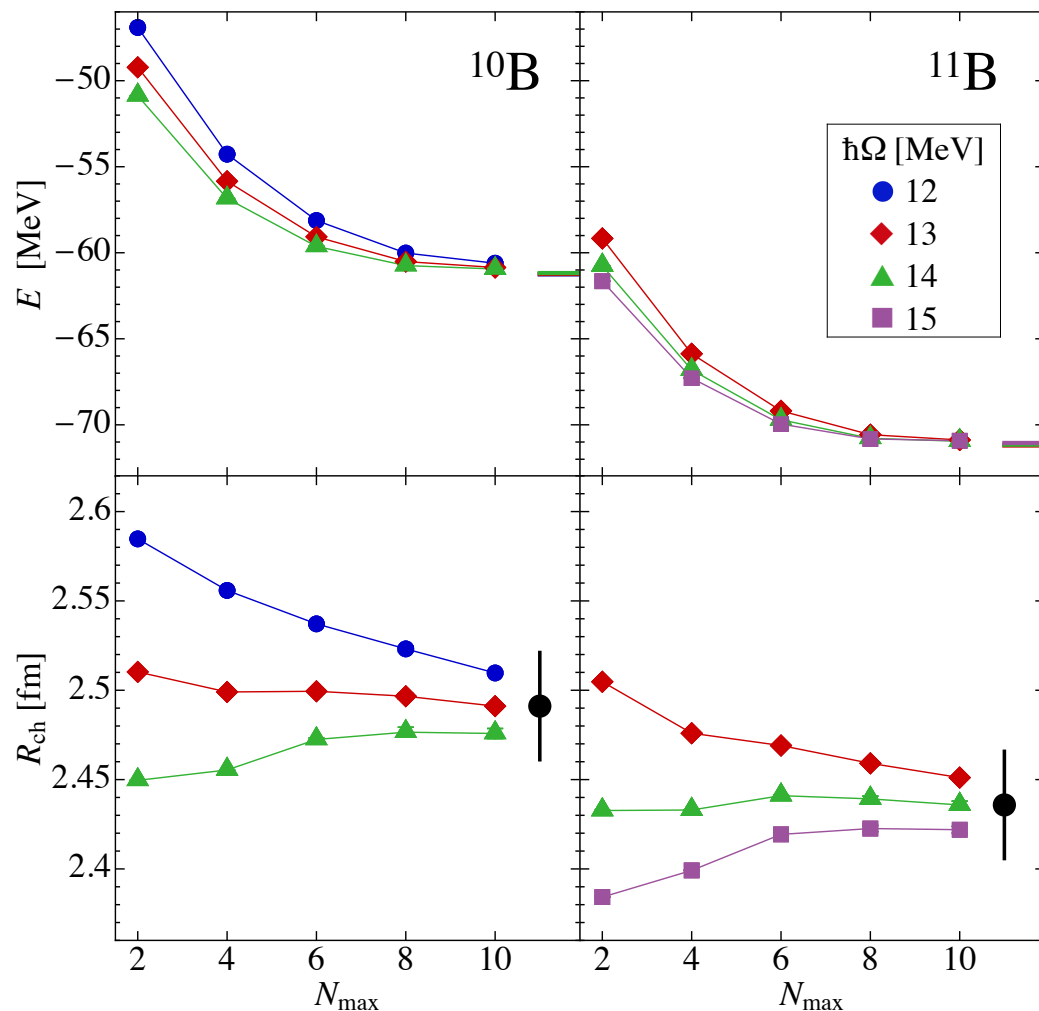
- model-space convergence is *the* limiting factor in all NCSM calculations
- depends on choice of single-particle basis
- natural orbitals constructed from a correlated ground-state obtained in low-order MBPT
- optimal convergence and independence of HO frequency

default for medium-mass,
optional for light nuclei

Charge Radii of ^{10}B and ^{11}B

Maaß, Hüther, et al.; arXiv:1901.06323 (2019)

- precision NCSM calculations for charge radii of $^{10,11}\text{B}$
- using different next-generation chiral NN+3N interactions with improved p-shell radii



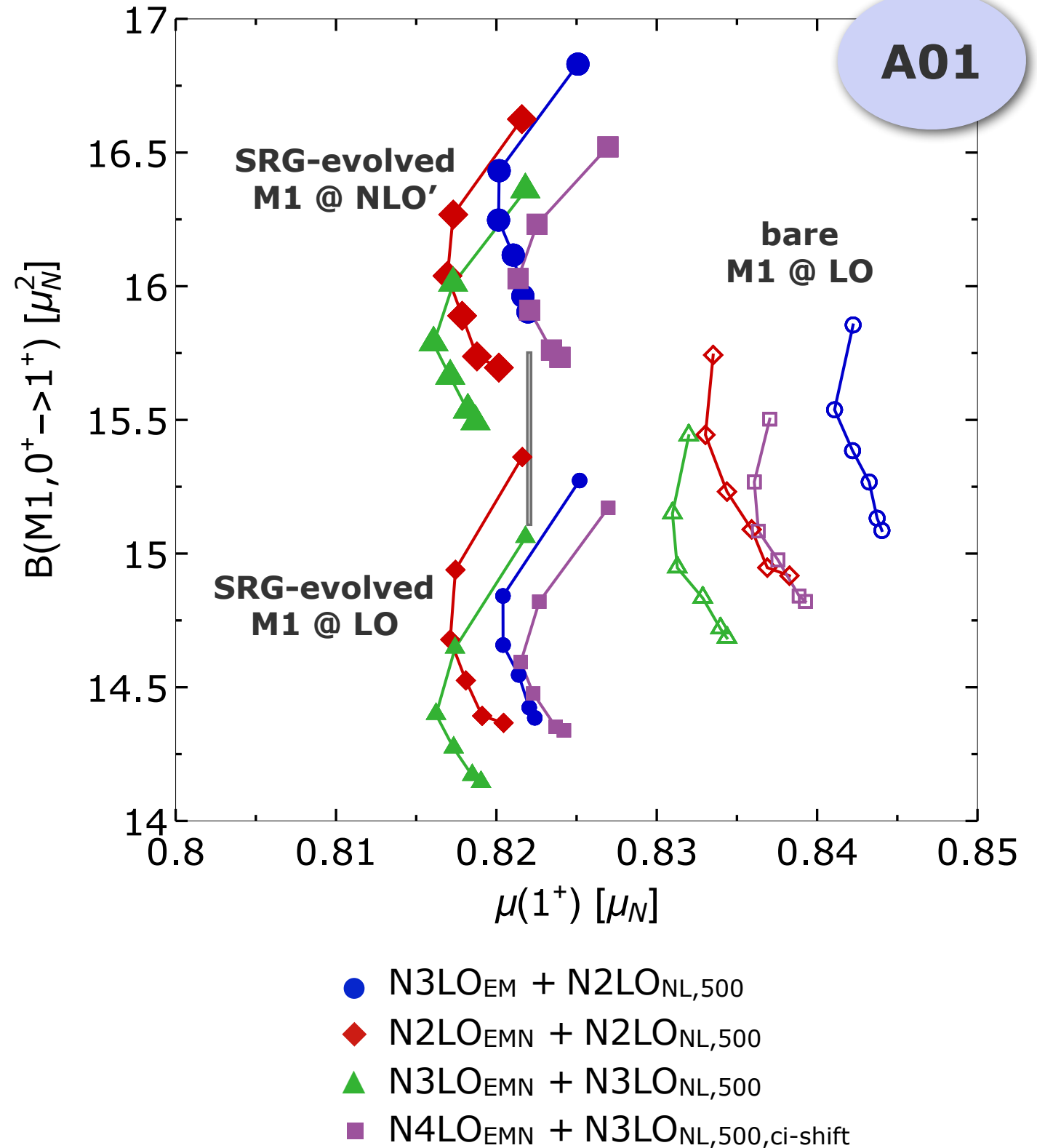
- comparison to precision laser spectroscopy for radius difference from A01 and GFMC calculations
- theory and experiment consistent within uncertainties, however, theory tends towards smaller radius differences

B(M1) Transition Strength in ${}^6\text{Li}$

Gayer et al.; in preparation

- use next-generation chiral interactions for precision study of M1 observables in NCSM
- new elements:
 - consistent SRG evolution of M1 operator
 - inclusion of partial NLO two-body current contributions
- effects of SRG (5%) and currents (10%) on B(M1) are significant

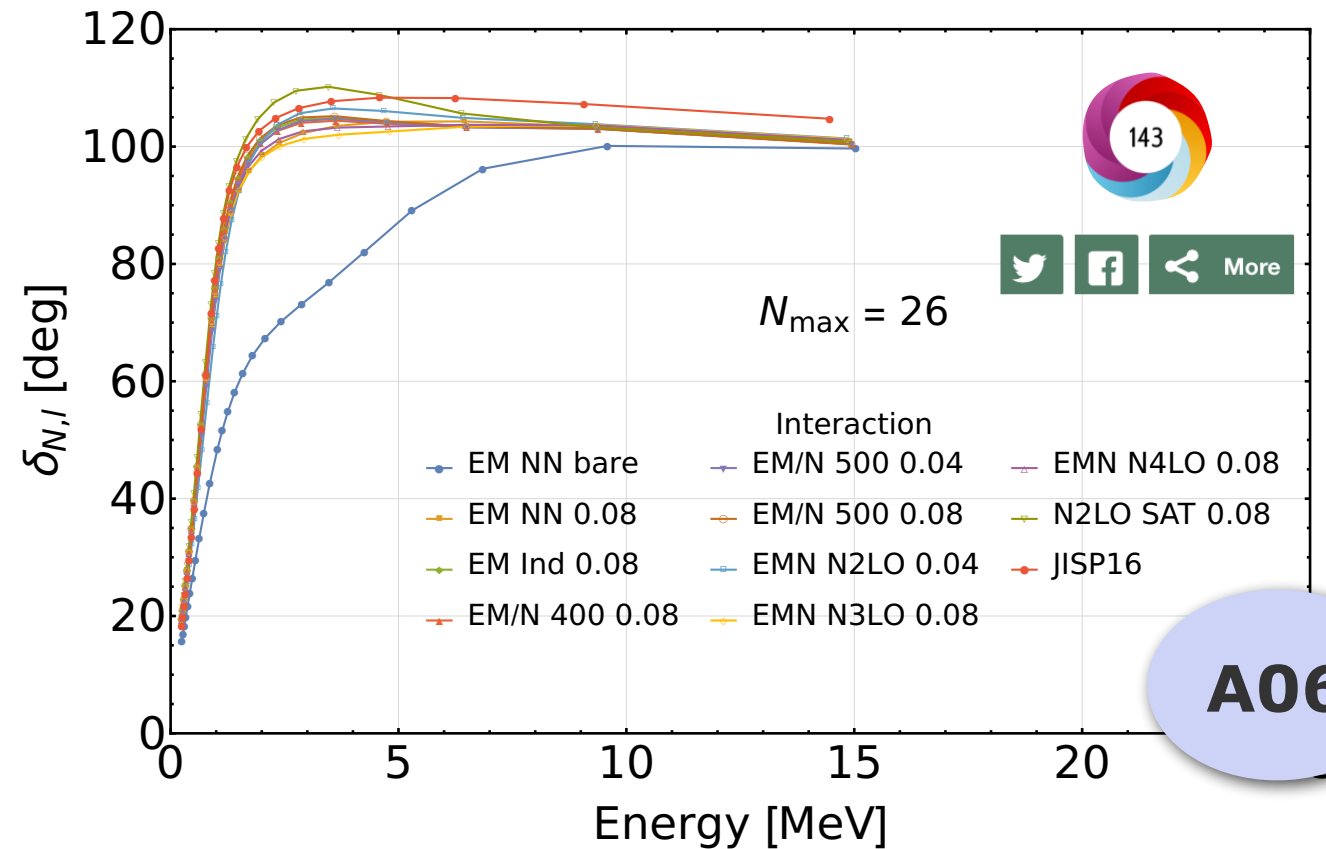
theory consistent with experiment within uncertainties iff both are included



Resonances Based on the NCSM

Shirokov, Papadimitriou, Mazur, Mazur, Roth, Vary; PRL 117, 182502 (2016) & in preparation

- NCSM is a bound-state method, but can be used as backend for continuum extensions
- focus on tetraneutron
- Single-State HORSE: provides phase-shifts based on NCSM energy eigenvalues
- Full HORSE: extract S-matrix based on full NCSM spectrum
- ACCC: provides S-matrix pole based on NCSM energies for modified Hamiltonian
- complementarity to overcome limitations of individual methods



A06

Puzzleteile für kosmische Rätsel

Sie untersuchen äußerst exotische Atomkerne, um die Entstehung schwerer Elemente besser zu verstehen. Nun haben Forscher der TU Darmstadt eine Erklärung für die kurzzeitige Existenz des so genannten Tetraneutrons und Indizien, die helfen könnten, ein wichtiges Rätsel der Neutronensterne zu lösen.

Von Christian Meier

Robert Roth studierte Physik, weil ihn Astronomie begeistert. Die größten Dinosaurier, die er studiert, sind die ersten Sterne, die sich bilden konnten. Er forscht an der TU Darmstadt über die Entstehung schwerer Elemente. In seinem Team forschen er und sein Team an der TU Darmstadt über die Entstehung schwerer Elemente. In seinem Team forschen er und sein Team an der TU Darmstadt über die Entstehung schwerer Elemente.

erschmelzen. Doch schwerere Elemente als Eisen, etwa Blei oder Gold, können so nicht gebildet werden.

Nur kosmische Katastrophen, Supernova-Explosionen oder Kollisionen von so genannten Neutronensternen erzeugen die notwendigen Bedingungen. „Dabei werden sehr viele Neutronen frei“, sagt Roth. Diese sind wie ein Rohstoff für neue Atomkerne. Denn die entstehenden Kerne müssen binnen Bruchteilen von Millisekunden immer neue Neutronen einfangen. Wenn dies zu langsam geschieht, zerfallen instabile Zwischenprodukte, bevor sie zu stabilen Atomkernen wie etwa Blei oder Gold anwachsen können. „Wir müssen wissen, wie unter solchen extremen Bedingungen Neutronen mit anderen Neutronen wechselwirken“, sagt der Physiker.

Sein Darmstädter Team geht neue Wege. Es simuliert etwa mit dem Lichtenberg-Hochleistungsrechner an der TU Darmstadt höchst exotische Kerne, das „Tetraneutron“ etwa, das aus nur vier Neutronen besteht. Weil Neutronen sich nur sehr schwach anziehen, sollte so ein Gebilde gleich wieder auseinanderfallen. Jüngst zeigten Experimente Hinweise auf kurzzeitige Existenz des Tetraneutrons. „Unsere Rechnungen liefern eine mögliche Erklärung dafür“, sagt Roth. Die Forscher haben dafür erstmals in den ohnehin komplexen quantentheoretischen

Methoden auch noch den Zerfall des Tetraneutrons berücksichtigt. So fanden die Forscher, dass eine so genannte Resonanz die vier Neutronen für eine unvorstellbar kurze Zeit (ein Milliardstel Milliardstel einer Zehntausendstel Sekunde) zusammenhält. „Das Tetraneutron kann also existieren“, resümiert Roth. Im Rahmen des von der Deutschen Forschungsgemeinschaft geförderten Sonderforschungsbereichs 1245 laufen diese Untersuchungen weiter. Dazu gehören auch neue Experimente in Japan, durchgeführt von der experimentellen Gruppe um Professor Thomas Aumann, die das Tetraneutron zweifelsfrei nachweisen sollen.

Unterdessen untersucht Roths Team noch exotischere Atomkerne, die neben Neutronen und Protonen auch so genannte Hyperonen enthalten, weshalb man sie Hyperkerne nennt. Hyperonen enthalten ein so genanntes Strange-Quark, das Protonen oder Neutronen fehlt. „Wir haben Indizien gefunden, die zur Lösung des so genannten Hyperon-Rätsels beitragen“, sagt Roth. In Neutronensternen, die mehr als doppelt soviel Masse haben können wie die Sonne, müssten sich eigentlich Hyperonen bilden. Doch dann könnten so schwere Neutronensterne nicht existieren. Tun sie aber.

Es kann gut sein, dass Robert Roth und sein Team ein Rätsel über diese Himmelskörper lösen, indem sie deren winzigste Bausteine besser verstehen.

Der Autor ist Wissenschaftsjournalist und promovierter Physiker.



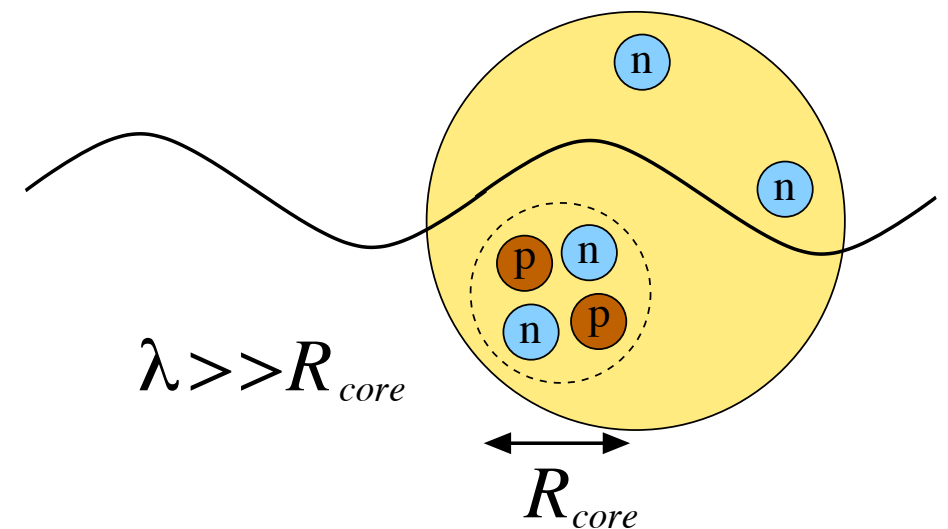
Physik-Professor Robert Roth

Publikationen:
Shirokov, A.M. et al: Physical Review Letters, 117, 182502 (2016).
Wirth, R., Roth, R.: Physical Review Letters, 117, 182501 (2016).



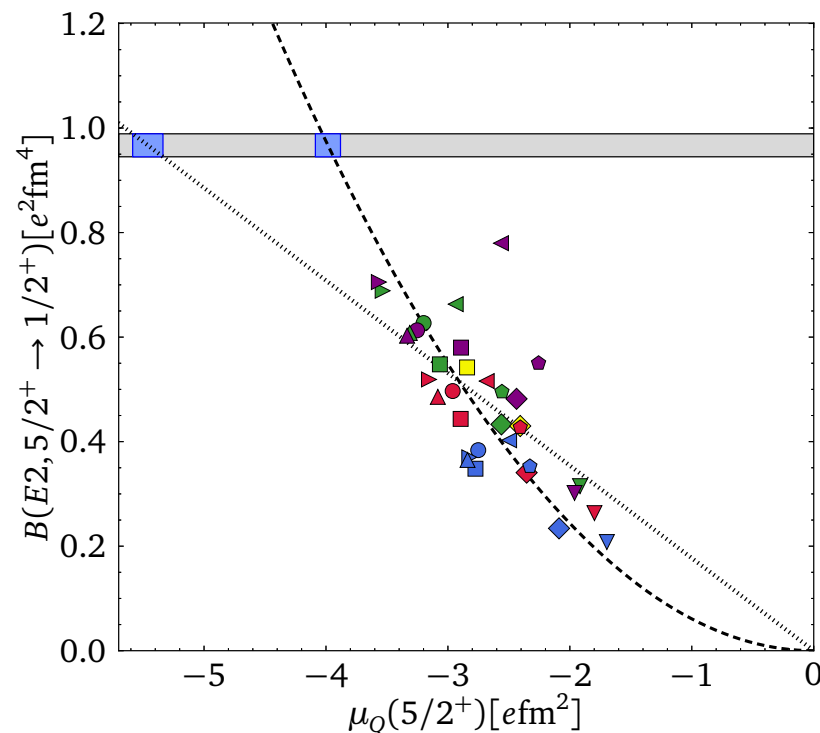
Halo Effective Field Theory

- Scales: $E \sim p^2/(2\mu) \sim 1/(2\mu R^2)$
 - Separation of scales:
 $1/k = \lambda \gg R_{core}$
 - Limited resolution at low energy:
→ expand in powers of kR_{core}
 - Short-distance physics not resolved
→ capture in low-energy constants using renormalization
→ include long-range physics explicitly
- Review article:** HWH, Ji, Phillips, J. Phys. G **44** (2017) 103002
- Halo nuclei: P - and higher partial waves
 - Universality: hadronic molecules, ultracold atoms, ...



D-Wave States in Halo EFT

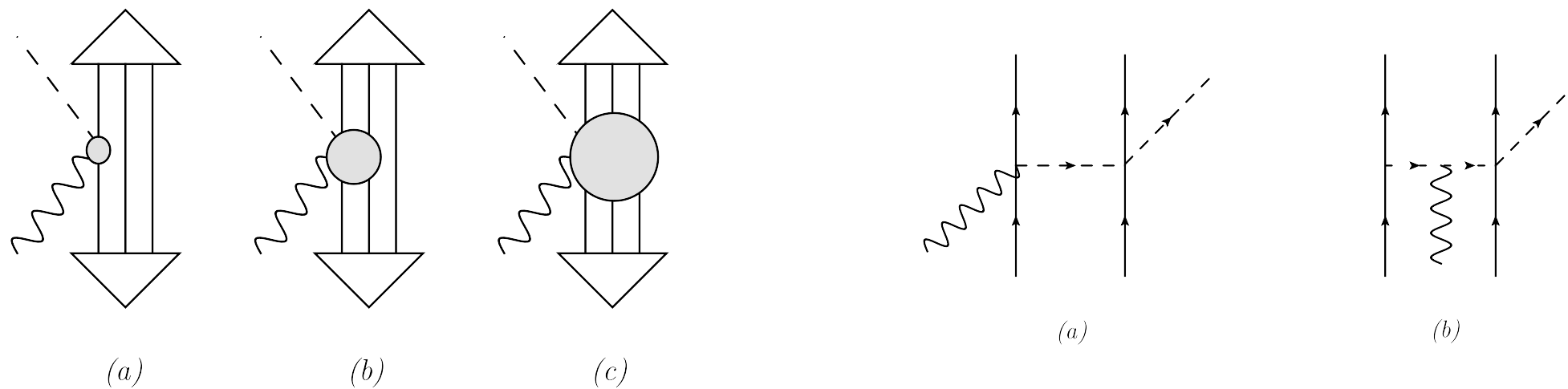
- **Example:** ^{15}C
 - ^{15}C ground state: $J^P = 1/2^+$, $S_n = 1218$ keV
 - ^{15}C excited state: $J^P = 5/2^+$, $S_n = 478$ keV
- **Calculated $E2$ transitions, form factors,...**
(Braun, Elkamhawy, Roth, HWH, arXiv:1803.02169)
- **Correlations:** combine with ab initio input (NCSM)



- **Halo EFT:** $B(E2) \propto \mu_Q^{(d)}$
- **Rigid rotor model** $B(E2) \propto (\mu_Q^{(d)})^2$
- **No clear conclusion**
- **Physical information from unphysical data**

Neutral Pion Production off Nuclei

- Further playing field for chiral EFT
- Direct test of chiral dynamics in nuclei
- Evaluate pion production operator between NCSM wave functions



- Density matrix formalism

$$\langle \Psi_f | \hat{O}^{(1N)} | \Psi_i \rangle = \sum_{ss'} o_{s',s} \langle \Psi_f | \hat{a}_{s'}^\dagger \hat{a}_s | \Psi_i \rangle = \text{Tr} \left(\mathbf{O}^{(1N)} \boldsymbol{\rho}_{\Psi_f \Psi_i}^{(1N)} \right)$$

Neutral Pion Production off Nuclei

- Two-nucleon contribution is factor 2-3 larger than 1N
- Results

nucleus	$E_{0+} [10^{-3}/M_{\pi^+}]$	
	our result	literature
^2H	-1.31(22)	-1.53(5) [Beane et al., 1997]
^3H	-4.48(43)	-4.94(5) [Lenkewitz et al. 2013]
^3He	-1.77(44)	-2.25(4) [Lenkewitz et al., 2013]
^6Li	-1.26(19)	

(Braun, Roth, HWG, in preparation)

Publications: A02

- J. Braun, W. Elkamhawy, R. Roth, H.-W. Hammer
Electric structure of shallow D-wave states in Halo EFT
submitted to J. Phys. G (2019)
- B. Maaß, T. Hüther, J. Krause, J. Krämer, K. König, A. Lovato, P. Müller, M. Puchalski, K. Pachucki, R. Roth, R. Sanchez, F. Sommer, R.B. Wiringa, W. Nörtershäuser
Nuclear Charge Radii of 10,11-B
submitted to Phys. Rev. Lett. (2019) - **with A01**
- A. Tichai, J. Müller, K. Vobig, R. Roth
Natural orbitals for ab initio no-core shell model calculations
Phys. Rev. C 99, 034321 (2019) - Editors' Suggestion
- E. Epelbaum, J. Golak, K. Hebeler, T. Hüther, H. Kamada, H. Krebs, P. Maris, U.-G. Meißner, A. Nogga, R. Roth, R. Skibinski, K. Topolnicki, J. P. Vary, K. Vobig, H. Witala
Few- and many-nucleon systems with semilocal coordinate-space regularized chiral two- and three-body forces
Phys. Rev. C 99, 024313 (2019)
- A. Tichai, E. Gebrerufael, K. Vobig, R. Roth
Open-Shell Nuclei from No-Core Shell Model with Perturbative Improvement
Phys. Lett. B 786, 448 (2018) - **with A04**

Publications: A02

- S. Binder, A. Calci, E. Epelbaum, R.J. Furnstahl, J. Golak, K. Hebeler, T. Huether, H. Kamada, H. Krebs, P. Maris, U.-G. Meißner, A. Nogga, R. Roth, R. Skibinski, ...
Few- and Many-Nucleon Systems with Semilocal Coordinate-Space Regularized Chiral Nucleon-Nucleon Forces
Phys. Rev. C 98, 014002 (2018)
- S. König, H.W. Griedhammer, H.W. Hammer, U. van Kolck
Nuclear Physics Around the Unitarity Limit
Phys. Rev. Lett. 118, 202501 (2017) - Editors' Suggestion
- A. Kumar, R. Kanungo, A. Calci, P. Navratil, A. Sanetullaev, M. Alcorta, V. Bildstein, G. Christian, B. Davids, J. Dohet-Eraly, J. Fallis, A. T. Gallant, ...
Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C
Phys. Rev. Lett. 118, 262502 (2017)
- A. Calci, P. Navratil, R. Roth, J. Dohet-Eraly, S. Quaglioni, G. Hupin
Can Ab Initio Theory Explain the Phenomenon of Parity Inversion in ^{11}Be ?
Phys. Rev. Lett. 117, 242501 (2016)
- A.M. Shirokov, G. Papadimitriou, A.I. Mazur, I.A. Mazur, R. Roth, J.P. Vary
Prediction for a Four-Neutron Resonance
Phys. Rev. Lett. 117, 182502 (2016)

Future Plans

Consistent Chiral EFT Interactions

- establish families of consistent chiral interactions from LO up to N3LO; explore non-local and semi-local regulators and cutoff dependence
- develop effective 4N interactions to capture initial and SRG-induced four-body contributions
- continue work on chiral two-body corrections to electromagnetic multipole operators and charge radii

Precision NCSM Studies

- large-scale survey of p-shell spectroscopy to validate uncertainty estimation protocol (including order-by-order and many-body uncertainties)
- precision radii of p-shell nuclei with full uncertainty quantification
... special focus on ${}^8\text{B}$, ${}^{10,11}\text{B}$, ${}^{12}\text{C}$ in-sync with the program in A01
- survey of electromagnetic structure of neutron-rich carbon isotopes, particularly ${}^{16}\text{C}$, ${}^{18}\text{C}$, ${}^{20}\text{C}$ plus update on ${}^{12}\text{C}$

Future Plans

Resonances in an NCSM Framework

- apply the ACCC+NCSM for a study of potential resonances in 3,4n and for extraction of resonance parameters of the excited 0^+ in ${}^4\text{He}$
- develop the full HORSE approach for extracting S-matrix pole for 4n directly
- continue with the development of the Gamow-NCSM and study above-threshold states in light p-shell nuclei

Resonances in an EFT Framework

- low-energy neutron systems well-described in by pionless EFT
- extract few-neutron resonance properties from integral equations for scattering amplitudes
- analytically continue into complex energy plane preparatory work in the 3n systems, extension to the 4n system
- multiple complementarities to fully resolve 4n controversy