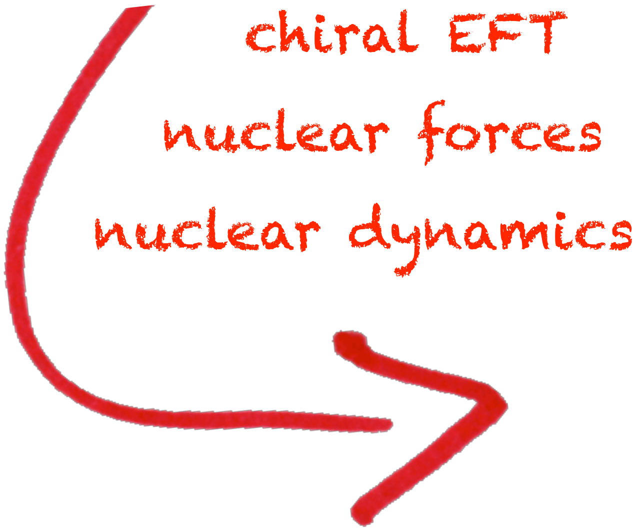
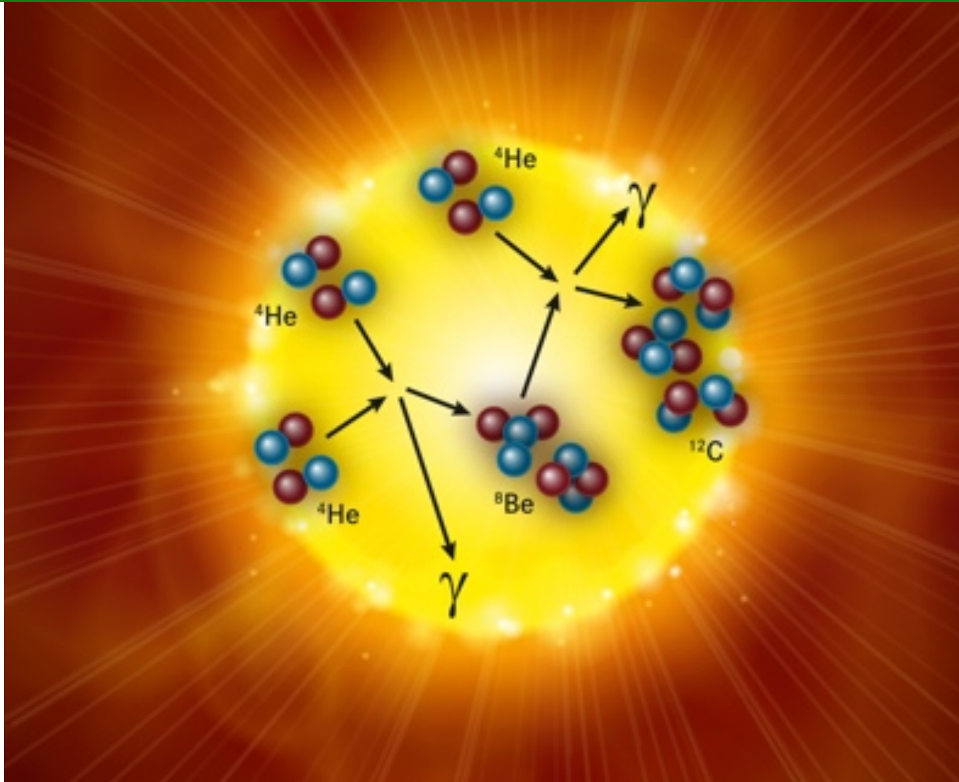
Evgeny Epelbaum, RUB

Quark Confinement and the Hadron Spectrum X, TUM, Oct 8-12, 2012

Nuclear Physics from QCD: State of the Art & Open Challenges





Chiral Perturbation Theory

QCD with 2 light flavors

- Idealized world [$m_u = m_d = 0$], zero-energy limit: non-interacting massless GBs
  (+ strongly interacting matter fields)
- Real world [$m_u,\ m_d \ll \Lambda_{QCD}$], low energy: weakly interacting light GBs
  (+ strongly interacting matter fields)

ChPT: expansion about the ideal world

Write down effective Lagrangian for GBs (pions) ← chiral symmetry

Compute the amplitude up to a given order in $Q \in (p_i/\Lambda_\chi,\ M_\pi/\Lambda_\chi)$ ← power counting

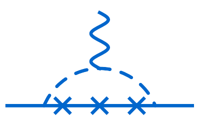
ChPT in the 1N sector: Need to ensure that m_N does not spoil the power counting...

chiral limit →

$$\delta m_N = -\frac{3 g_A^2 m_N^3}{(4\pi F_\pi)^2}\left(16\pi^2 L(\mu) + \frac{1}{2}\ln\frac{m_N^2}{\mu^2}\right) + \mathcal{O}(d-4)$$

Heavy Baryon: use 1/m expanded Lagrangian Jenkins, Manohar, Bernard, Meißner, ...

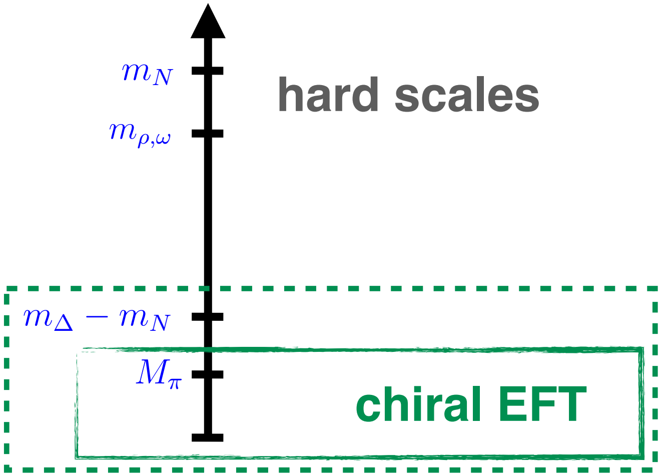
Infrared Reg.: expand the integrand, compute the integrals using DR & resum...
Ellis, Tang, Becher, Leutwyler, ...



EOMS: relativistic propagators + DR + additional subtractions Fuchs, Gegelia, Japaridze, Scherer, ...

Chiral EFT with explicit Δ(1232): assign $m_\Delta - m_N \sim M_\pi$ Jenkins, Manohar, Hemmert, Pascalutsa, ...

Chiral EFT for nuclear systems



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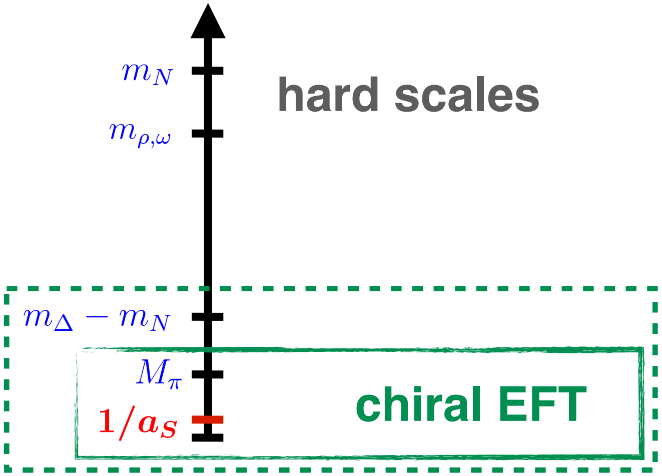

A new, soft scale associated with nuclear binding

$\boldsymbol{Q \sim 1/a_S \simeq 8.5}$ MeV$\boldsymbol{(36}$ MeV$\boldsymbol{)}$ in $^1S_0$ ($^3S_1$)

to be generated dynamically (need resummations...)

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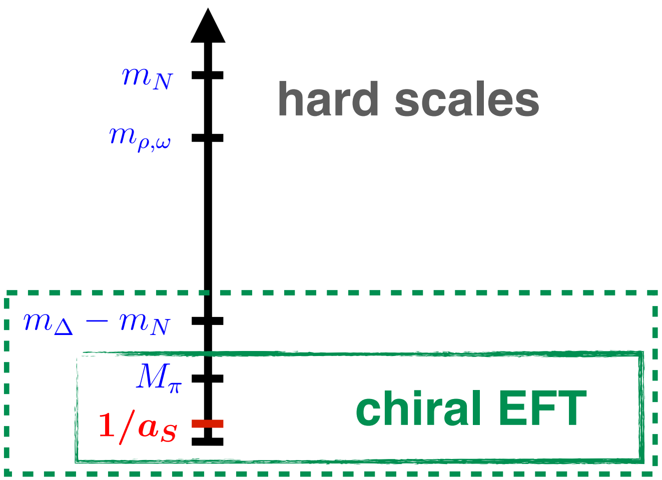

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Pionless EFT (valid for $\sqrt{m_N E_B} \ll Q \ll M_\pi$)

- zero-range forces between nucleons
- for 2N equivalent to Effective Range Theory
- universality, Efimov physics, cold gases, astro,...

Hammer, Platter, Grießhammer, Chen, Rupak, Savage, Ando, ...

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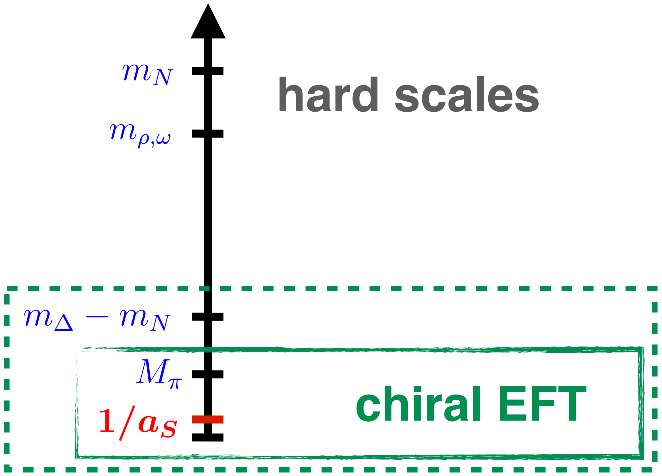

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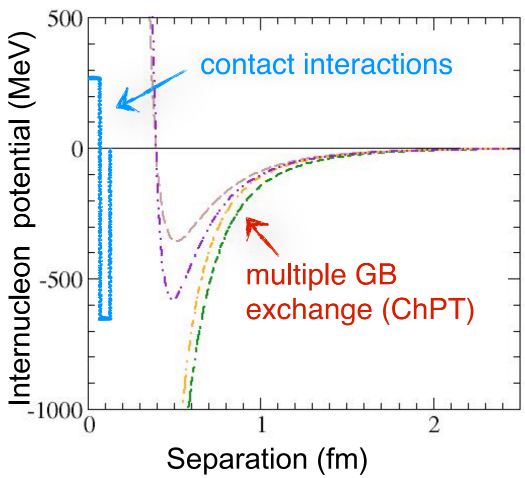
Chiral EFT (valid for $Q \sim M_\pi$) Weinberg, van Kolck, Kaiser, EE, Glöckle, Meißner, Machleidt, Entem, Higa, Robilotta,...

- well below π-production threshold: Schrödinger equation for nucleons interacting via zero-range and long-range potentials (pion exchanges)

$$\left[\left(\sum_{i=1}^{A} \frac{-\vec{\nabla}_i^2}{2m_N} + \mathcal{O}(m_N^{-3}) \right) + \underbrace{V_{2N} + V_{3N} + V_{4N} + \ldots}_{\text{derived in ChPT}} \right] |\Psi\rangle = E|\Psi\rangle$$

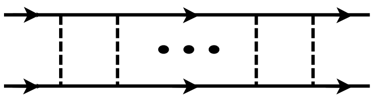


- access to heavier nuclei (ab initio few-/many-body methods)

Barrett, Navratil, Nogga, Roth, Schwenk, Hebeler, Furnstahl, Vary, Schiavilla, ...

Chiral EFT for nuclear systems

Iterations of V in the LS equation generate UV divergences that cannot be absorbed by counterterms in V (truncated at a given order)...



How to renormalize the Schrödinger equation?

Kaplan, Savage, Wise, Fleming, Mehen, Stewart, Phillips, Beane, Cohen, Frederico, Timoteo, Tomio, Birse, Beane, Bedaque, van Kolck, Pavon Valderrama, Ruiz Arriola, Nogga, Timmermanns, EE, Meißner, Entem, Machleidt, Yang, Elster, Long, Gegelia, ...

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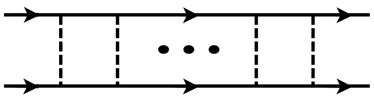

„How to renormalize the Schrödinger equation“, G. P. Lepage, nucl-th/9706029

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⟶ use a finite cutoff, self-consistency checks via „Lepage plots“

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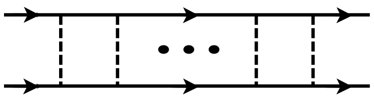

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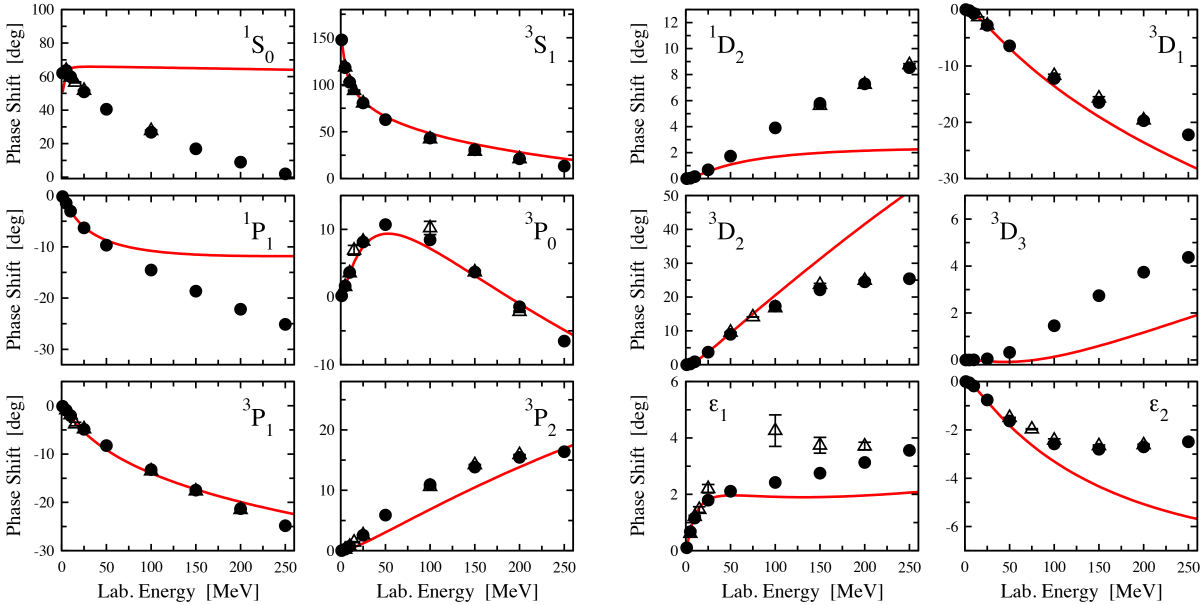
→ use a finite cutoff, self-consistency checks via „Lepage plots“

cutoff-independent results for phase shifts at LO

(i) non-renormalizability of the LO equation is an artifact of the HB expansion
EE, Gegelia, PLB 716 (2012) 338

(ii) renormalizable LO eq. based on manifestly Lorentz invariant Lagrangian

(iii) higher-order corrections (e.g. TPE) to be treated perturbatively in progress...

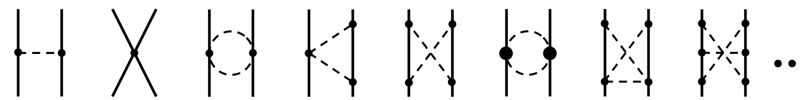


(related work by Pavon Valderrama, van Kolck, Long, Yang, Soto, ...)

Nucleon-nucleon potential at N^{3}LO

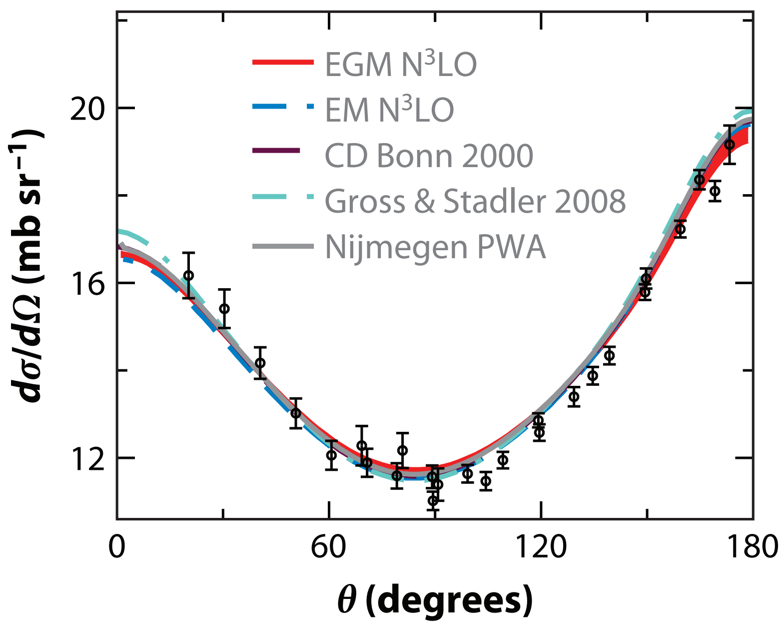
van Kolck et al.'94; Friar & Coon '94; Kaiser et al. '97; E.E. et al. '98,'03; Kaiser '99-'01; Higa, Robilotta '03; …

- Long-range: parameter-free (all LECs from πN)
- Short-range part: 24 LECs tuned to NN data
- Accurate description of NN data up to ~ 200 MeV

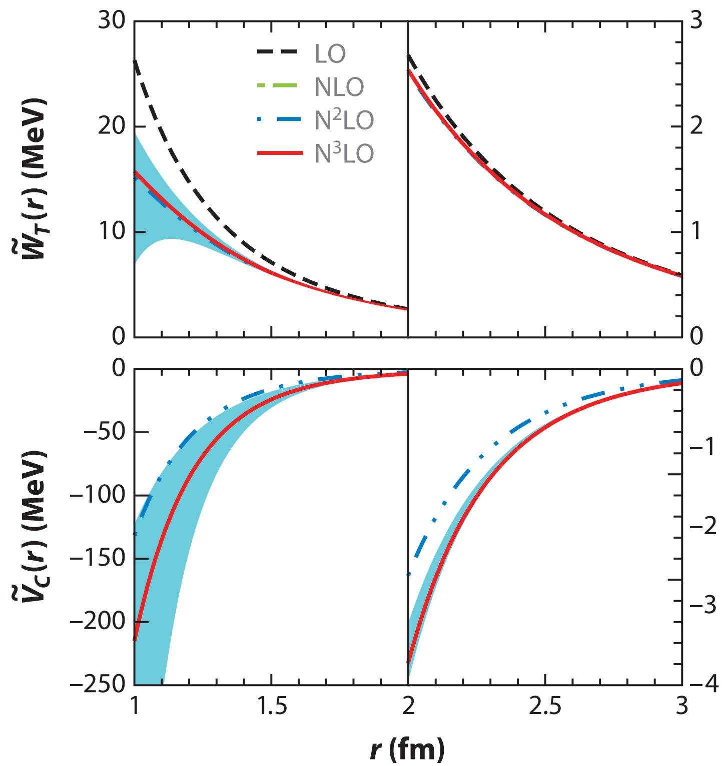


Entem-Machleidt, EE-Glöckle-Meißner

np cross section @ 50 MeV

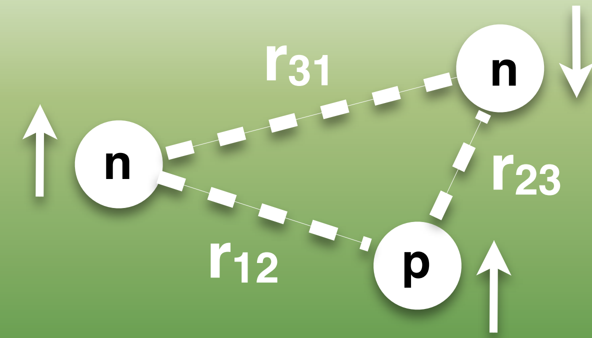


χ expansion of the long-range force



Recent reviews:

EE, Prog. Part Nucl. Phys. 57 (06) 654;
EE, Hammer, Meißner, Rev. Mod. Phys. 81 (09) 1773;
Entem, Machleidt, Phys. Rept. 503 (11) 1;
EE, Meißner, arXiv:1201.2136, Ann. Rev. Nucl. Part. Sci. (in press)



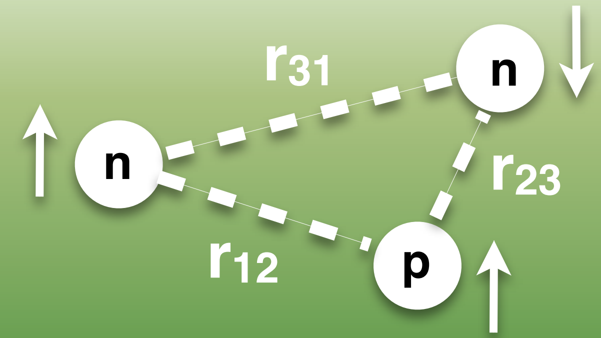
The challenge: Understanding the 3N force

- Today's few- and many-body calculations have reached the level of accuracy at which it is absolutely necessary to include 3NF

- In spite of the decades of efforts, the (spin) structure of the 3NF is still poorely understood
  Kalantar-Nayestanaki, EE, Messchendorp, Nogga, Rev. Mod. Phys. 75 (2012) 016301

- Modeling (phenomenology) is difficult in particular due to the complicated structure of 3NF. E.g. 22 „structure functions" $\mathcal{F}_i(r_{12}, r_{23}, r_{31})$ needed to parametrize only the static part:

$$V_{3N}^{\rm static} = \sum_{i=1}^{22} \mathcal{G}_i(\vec{\sigma}_1, \vec{\sigma}_2, \vec{\sigma}_3, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}_3, \vec{r}_{12}, \vec{r}_{23})\, \mathcal{F}_i(r_{12}, r_{23}, r_{31}) + \text{permutations}$$



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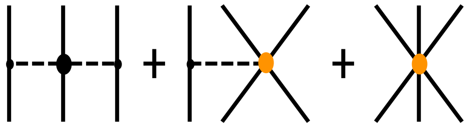
calculated in ChPT; long-range terms parameter free...

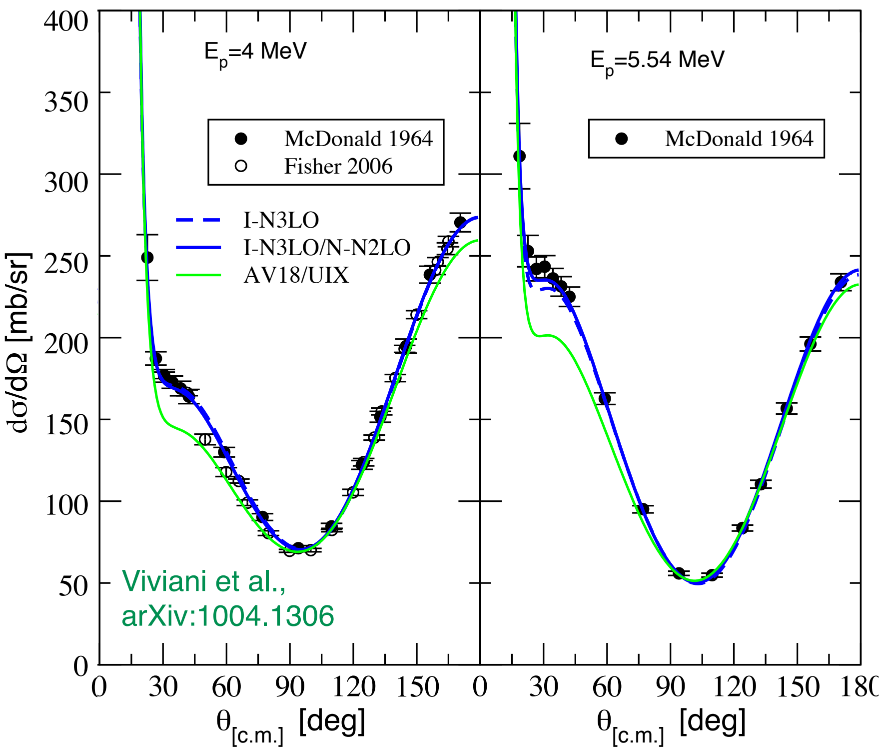
Leading chiral 3NF and 3N/4N continuum

- Nd scattering: accurate description at low energy except for A_y-puzzle (fine tuned) and some breakup configurations
- Uncertainty grows rapidly with energy (higher orders ?)
- 4N continuum: an emerging field...

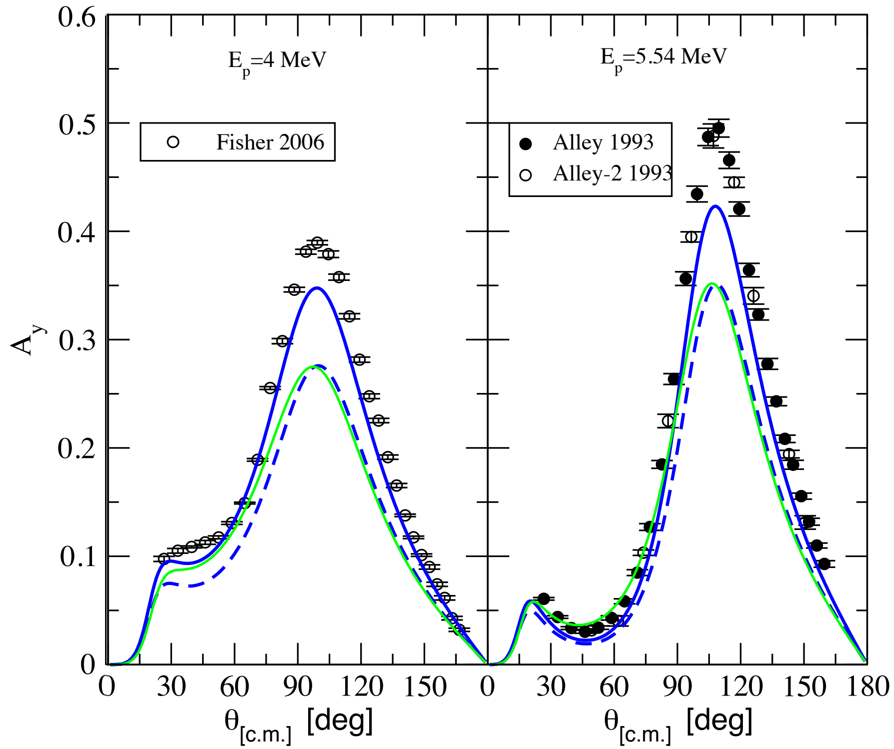


2 LECs tuned to few-N data (e.g. ^3H, ^4He BEs)

p-^{3}He differential cross section



A_y-puzzle in p-^{3}He elastic scattering



Leading chiral 3NF and nuclear structure

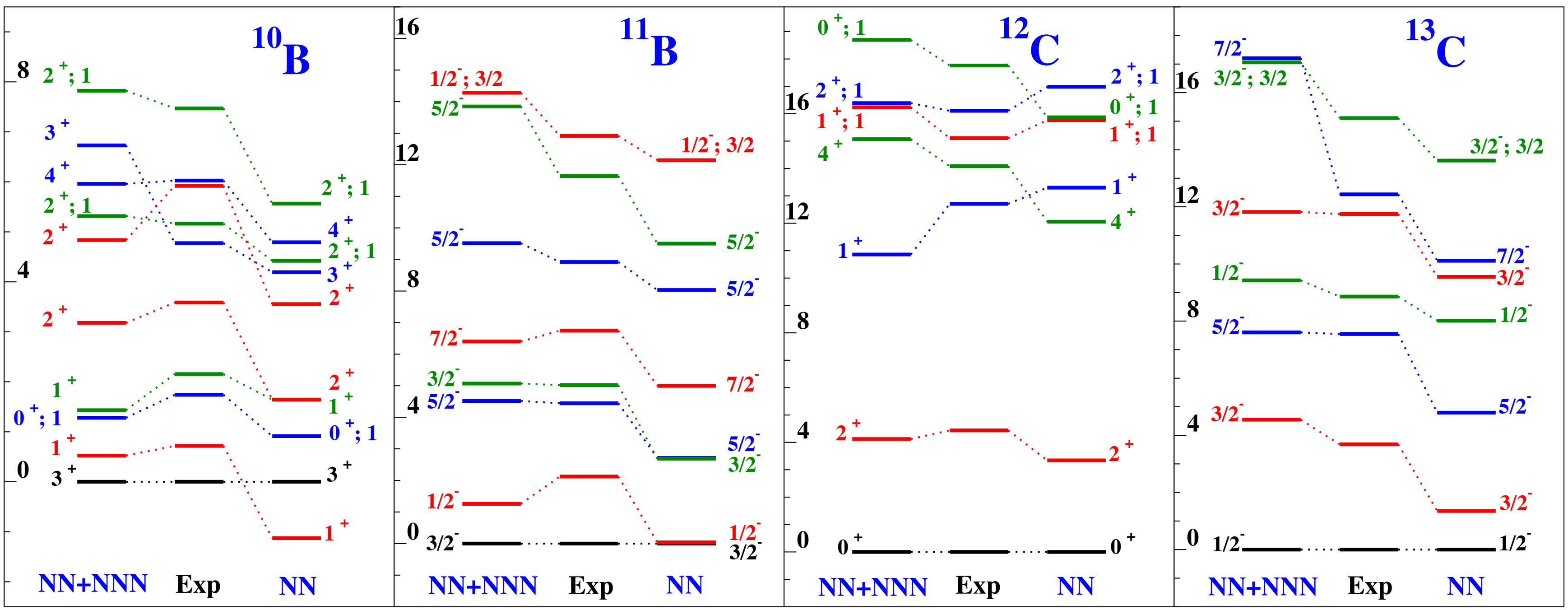
Ab initio methods (NCSM, GFMC, CCM, Lattice, ...) + renormalization ideas (SRG, $V_{low\text{-}k}$, UCOM)

+ computational resources ⟶ precision ab initio nuclear structure calculations

Barrett, Navratil, Nogga, Roth, Schwenk, Hebeler, Furnstahl, Vary, Ormand, ...

NCSM calculation of p-shell nuclei with chiral 2NF+3NF

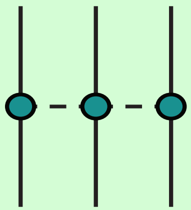
Navratil et al. '07

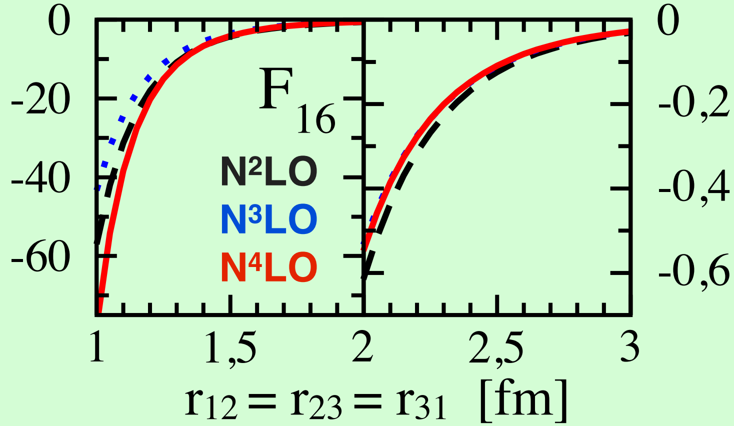


- sensitive to details of the 3NF
- many promising results (neutron-rich nuclei, long lifetime of ^{14}C, neutron star radii, ...)
- still room for improvement and some open questions ⟶ higher-order 3NFs...

Chiral 3NF: higher-order corrections

Bernard, EE, Krebs ’08 ’11; Gasparyan, Krebs, EE ’12





- all LECs determined in πN
- very good convergence of the chiral expansion
- only 10 out of 22 F_i‘s...

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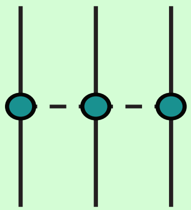

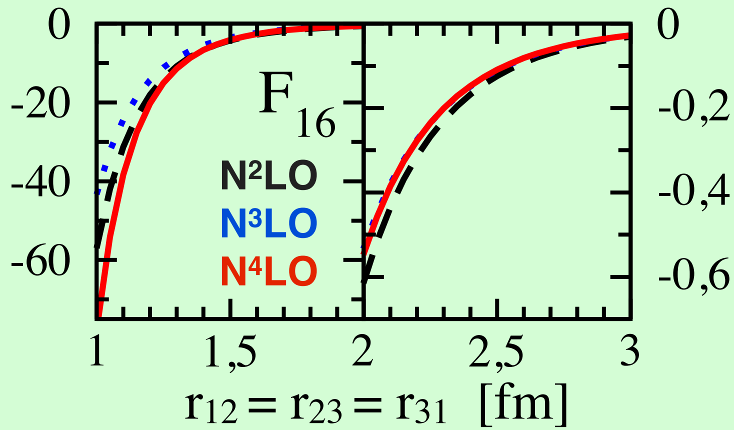

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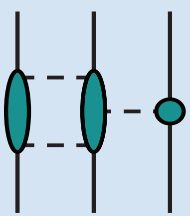

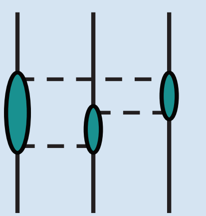

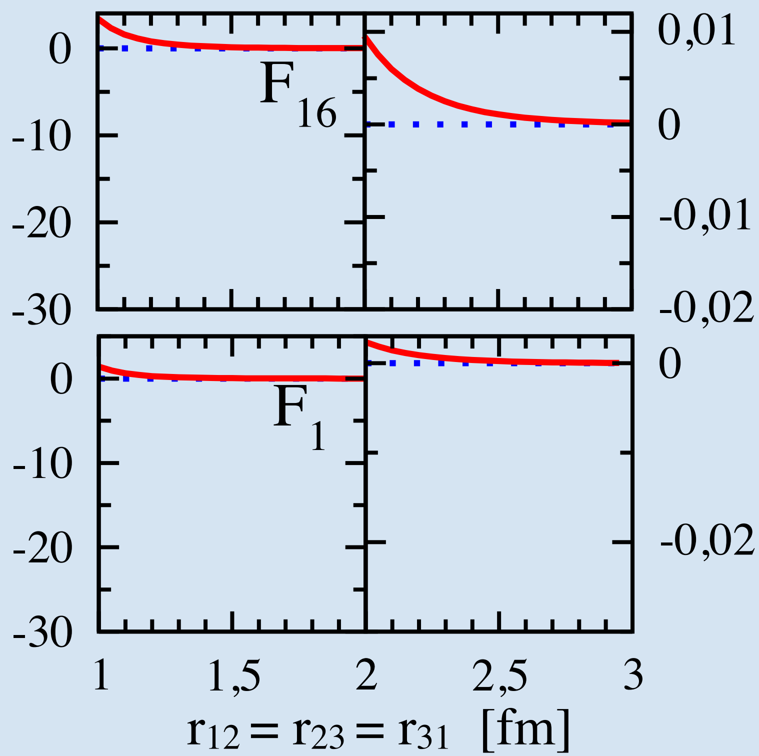

- parameter-free
- rich operator structure (all F_i‘s nonzero)
- not converged at N³LO

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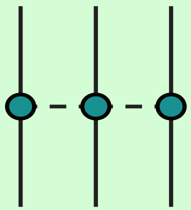
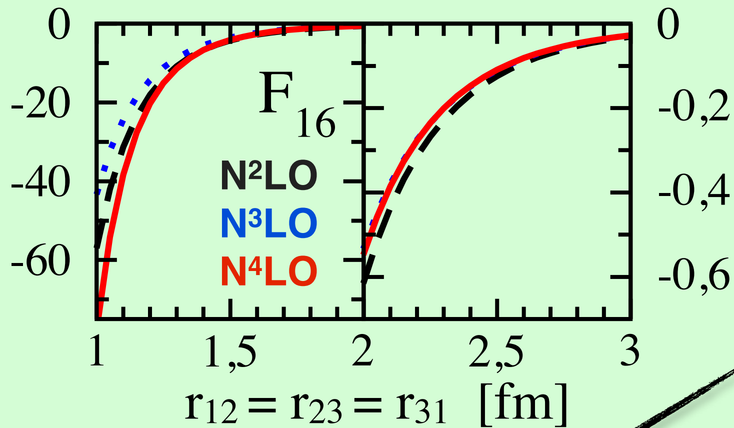
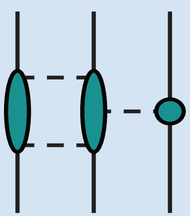


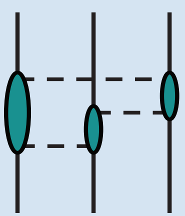


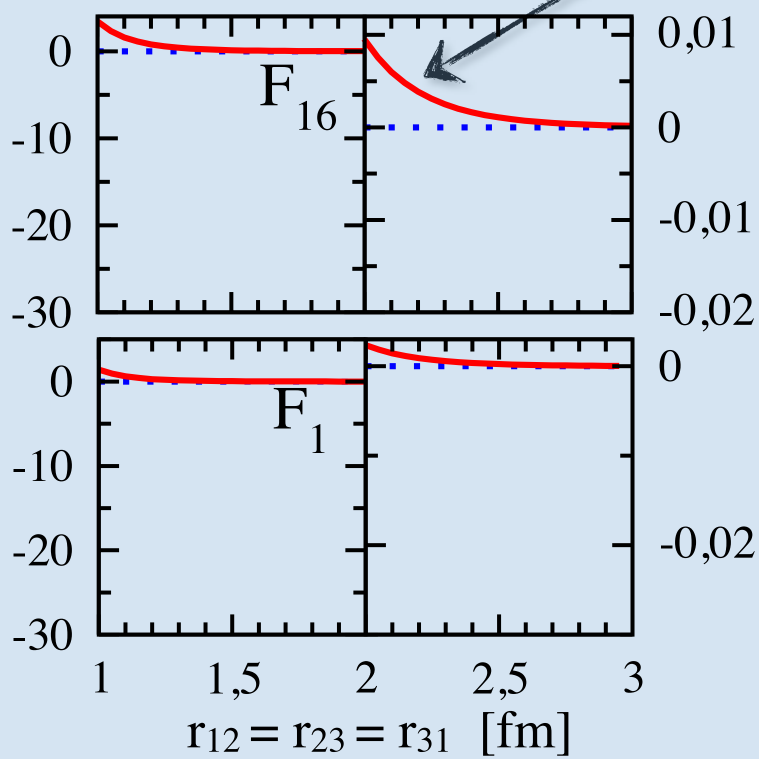
includes terms $\sim \frac{1}{m_\Delta - m_N}$

(Δ-saturation of c_3, c_4)

but NOT $\sim \frac{1}{(m_\Delta - m_N)^2}, \; \cdots$







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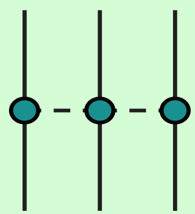

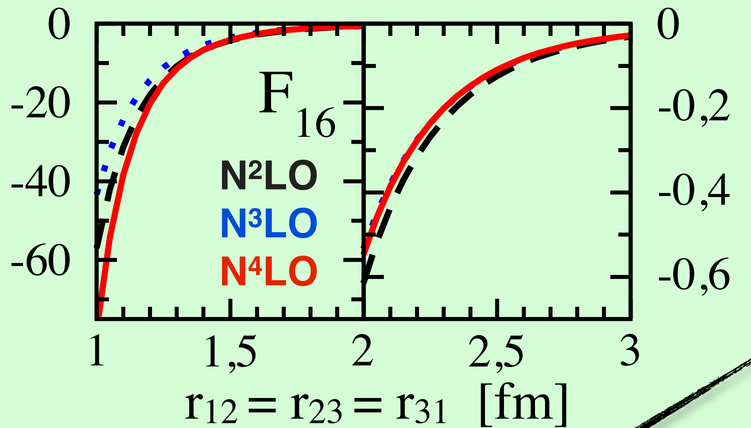

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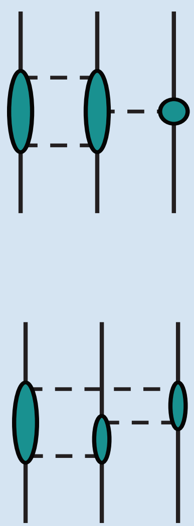
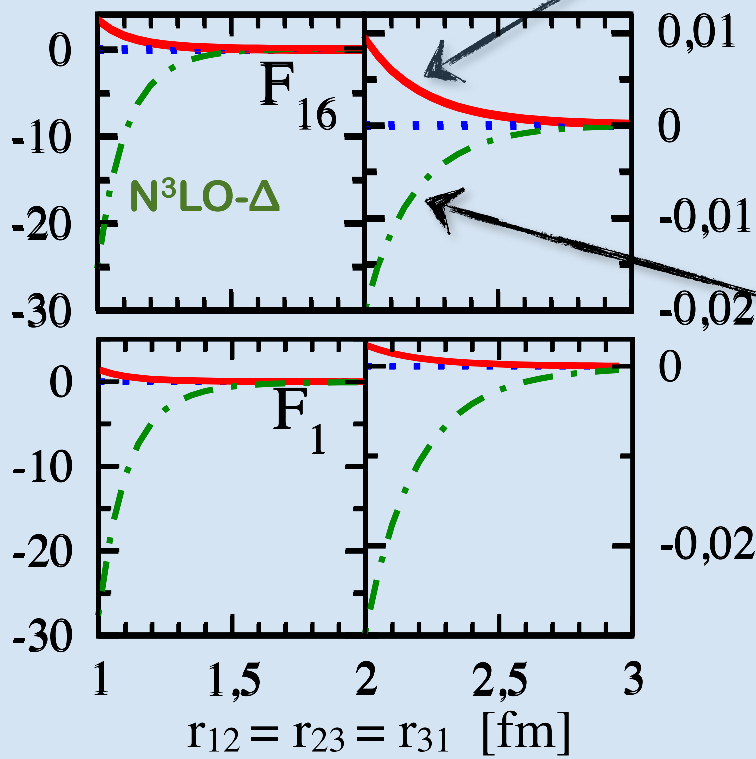




Chiral EFT with Δ(1232):

a (partial) resummation of terms:

$\sim \frac{1}{m_\Delta - m_N}, \; \frac{1}{(m_\Delta - m_N)^2}, \; \cdots$

Precision physics with light nuclei: Recent examples

Pion-deuteron scattering

Pion-nucleon amplitude at threshold (in the isospin limit): $T^{ba}_{\pi N} \propto \left[\delta^{ab} \boldsymbol{a}^+ + i\epsilon^{bac}\tau^c \boldsymbol{a}^-\right]$

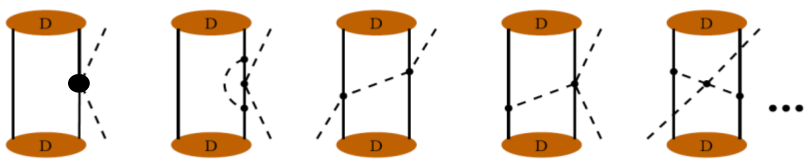
Recent data on hadronic atoms:

πH: $\epsilon_{1s} = (-7.120 \pm 0.012)\,\text{eV}, \quad \Gamma_{1s} = (0.823 \pm 0.019)\,\text{eV}$ Gotta et al., Lect. Notes. Phys. 745 (08) 165

πD: $\epsilon^D_{1s} = (2.356 \pm 0.031)\,\text{eV}$ Strauch et al., Eur. Phys. J A47 (11) 88

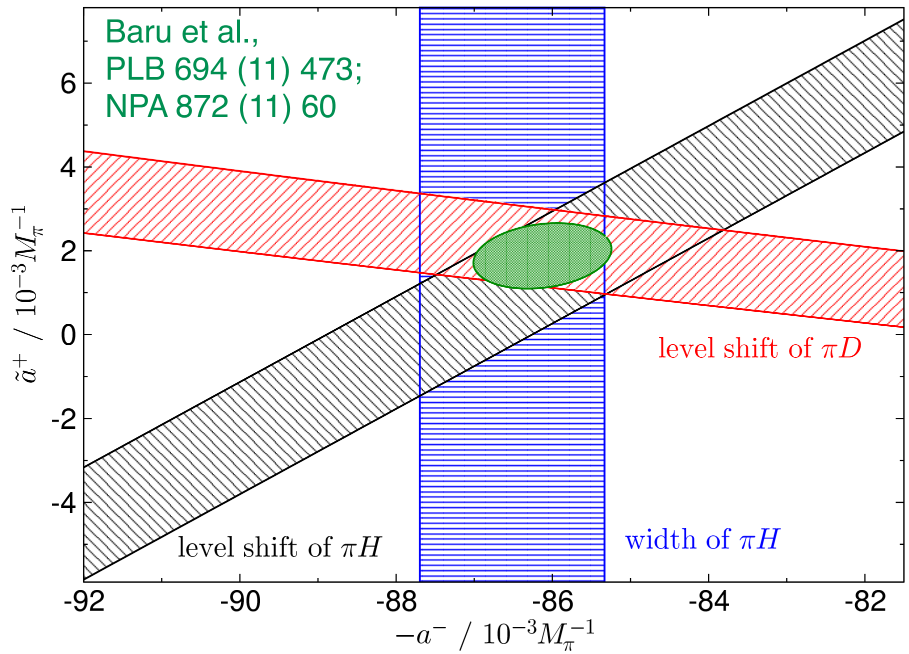
Use chiral EFT to extract information on a^+ and a^- from $a_{\pi d}$

Weinberg; Beane, Bernard, Lee, Meißner, EE, Phillips;
Baru, Liebig, Hoferichter, Hanhart, Nogga, ...



- careful analysis of IB effects
- radiative corrections included

$$a^+ = (7.6 \pm 3.1) \times 10^{-3} M_\pi^{-1}$$
$$a^- = (86.1 \pm 0.9) \times 10^{-3} M_\pi^{-1}$$



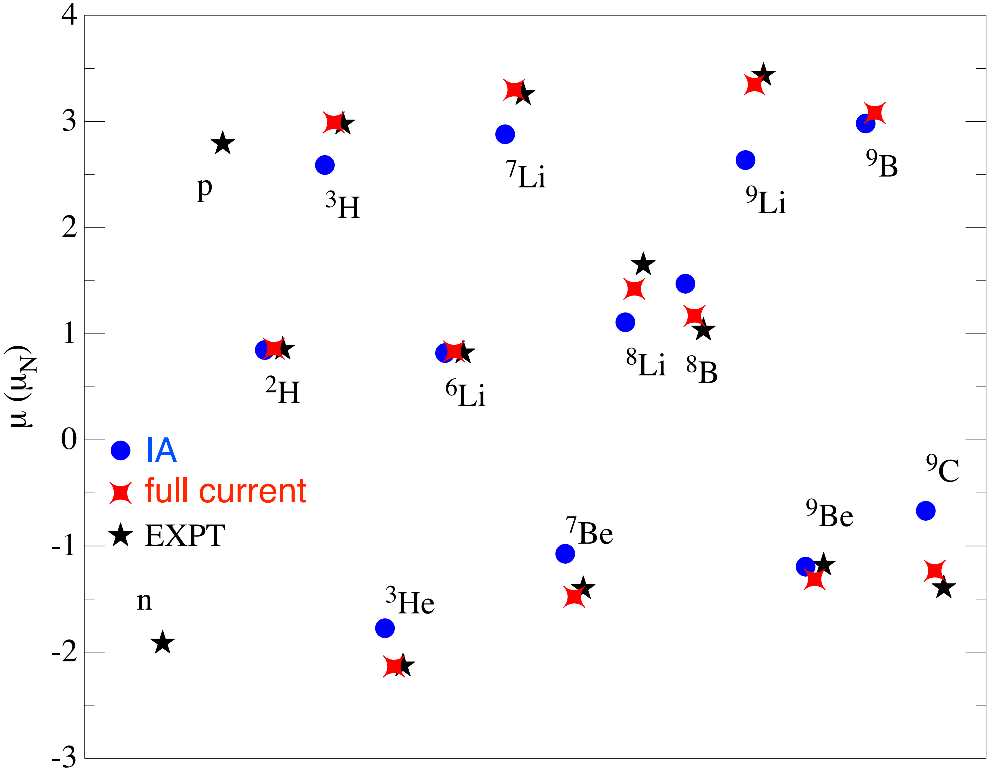
Magnetic moments of light nuclei

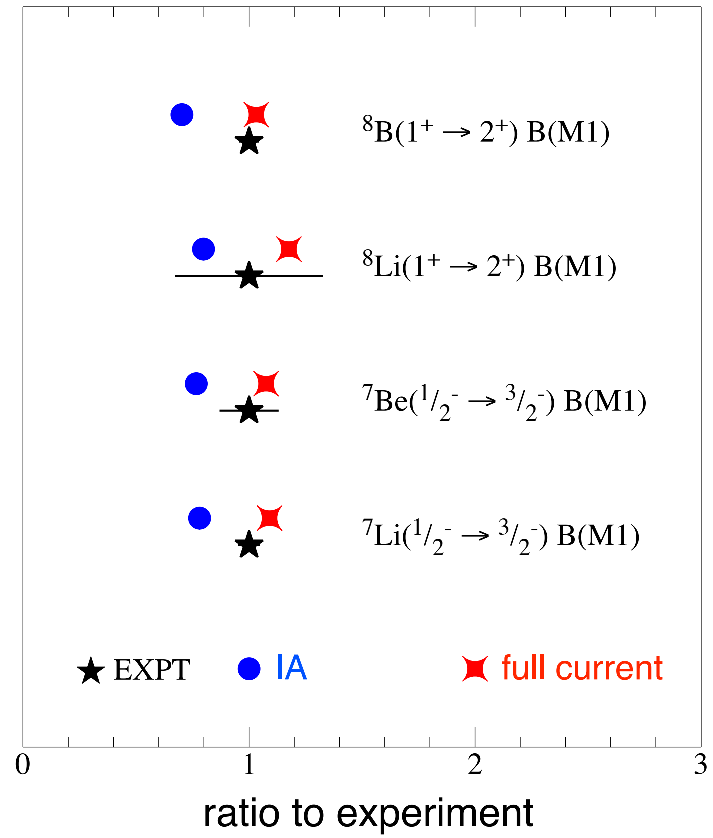
Use chiral EFT to compute EM and weak nuclear currents

Park-Min-Rho, Girlanda-Pastore-Schiavilla-Viviani-Wiringa, Kölling-EE-Krebs-Meißner, Lazauskas, Phillips, ...

GFMC results for magnetic moments of light nuclei with chiral MECs

Pastore, Pieper, Schiavilla, Wiringa, arXiv:1208.6034





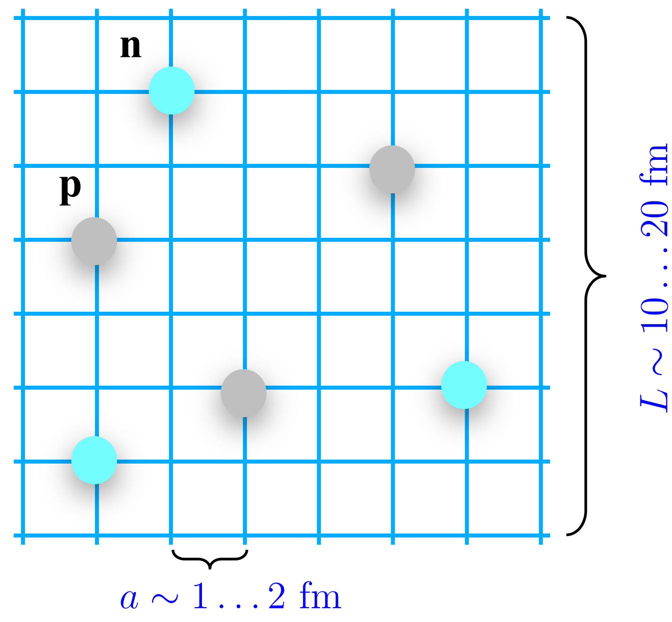
Nuclear Lattice Effective Field Theory

The Collaboration: E.E. (Bochum), Hermann Krebs (Bochum), Timo Lahde (Jülich), Dean Lee (NC State), Ulf-G. Meißner (Bonn/Jülich)

Discretized version of chiral EFT for nuclear dynamics

$$\left[\left(\sum_{i=1}^{A}\frac{-\vec{\nabla}_i^2}{2m_N}+\mathcal{O}(m_N^{-3})\right)+\underbrace{V_{2N}+V_{3N}+V_{4N}+\ldots}_{\text{derivable within ChPT}}\right]|\Psi\rangle=E|\Psi\rangle$$

Borasoy, E.E., Krebs, Lee, Meißner, Eur. Phys. J. A31 (07) 105,
Eur. Phys. J. A34 (07) 185,
Eur. Phys. J. A35 (08) 343,
Eur. Phys. J. A35 (08) 357,
E.E., Krebs, Lee, Meißner, Eur. Phys. J A40 (09) 199,
Eur. Phys. J A41 (09) 125,
Phys. Rev. Lett 104 (10) 142501,
Eur. Phys. J. 45 (10) 335,
Phys. Rev. Lett. 106 (11) 192501
arXiv:1208.1328

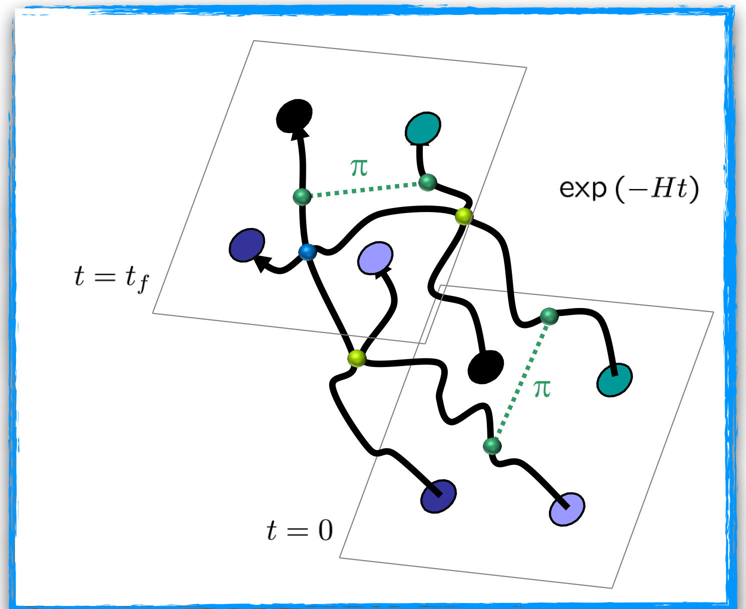


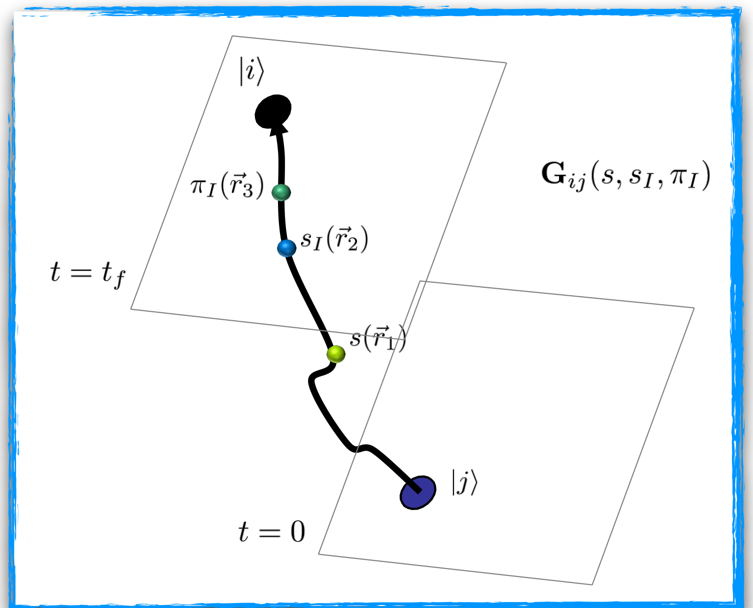
Calculation strategy

$: \exp(-H_{\rm LO}\alpha_t) :$

- Simulation based on LO action (1π + LO contacts), higher orders perturbatively
- Eucl.-time propagation of A nucleons → transition amplitude $Z_{\rm LO}(t) = \langle \Psi(t')| \left(M_{\rm LO}\right)^{L_t} |\Psi(t')\rangle$

  → ground- (and excited-) state energies $\exp\left(-E_0^{\rm LO}\alpha_t\right) = \lim_{t\to\infty} Z(t+\alpha_t)/Z(t)$
- Auxiliary-field formulation: nucleons propagating in the background of (instantaneous) pion + auxiliary fields...

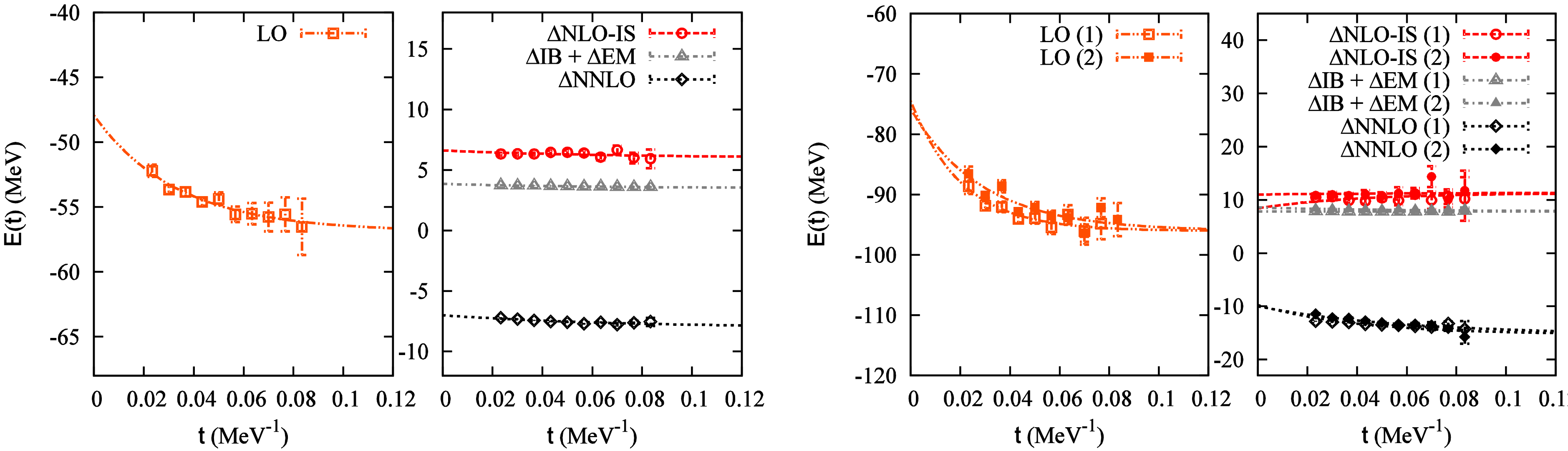




Ground states of ^{8}Be and ^{12}C

E.E., Krebs, Lee, Meißner, PRL 106 (11) 192501

Simulations for ^{8}Be and ^{12}C, L=11.8 fm

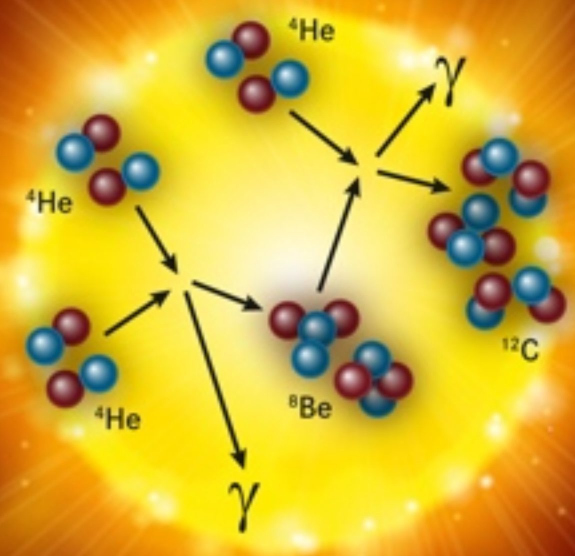


Ground state energies (L=11.8 fm) of ^{4}He, ^{8}Be, ^{12}C & ^{16}O

	^{4}He	^{8}Be	^{12}C	^{16}O
LO $[Q^0]$, in MeV	$-28.0(3)$	$-57(2)$	$-96(2)$	$-144(4)$
NLO $[Q^2]$, in MeV	$-24.9(5)$	$-47(2)$	$-77(3)$	$-116(6)$
NNLO $[Q^3]$, in MeV	$-28.3(6)$	$-55(2)$	$-92(3)$	$-135(6)$
Experiment, in MeV	-28.30	-56.5	-92.2	-127.6

The Hoyle state

EE, Krebs, Lee, Meißner, PRL 106 (11) 192501; EE, Krebs, Lähde, Lee, Meißner, arXiv:1208.1328



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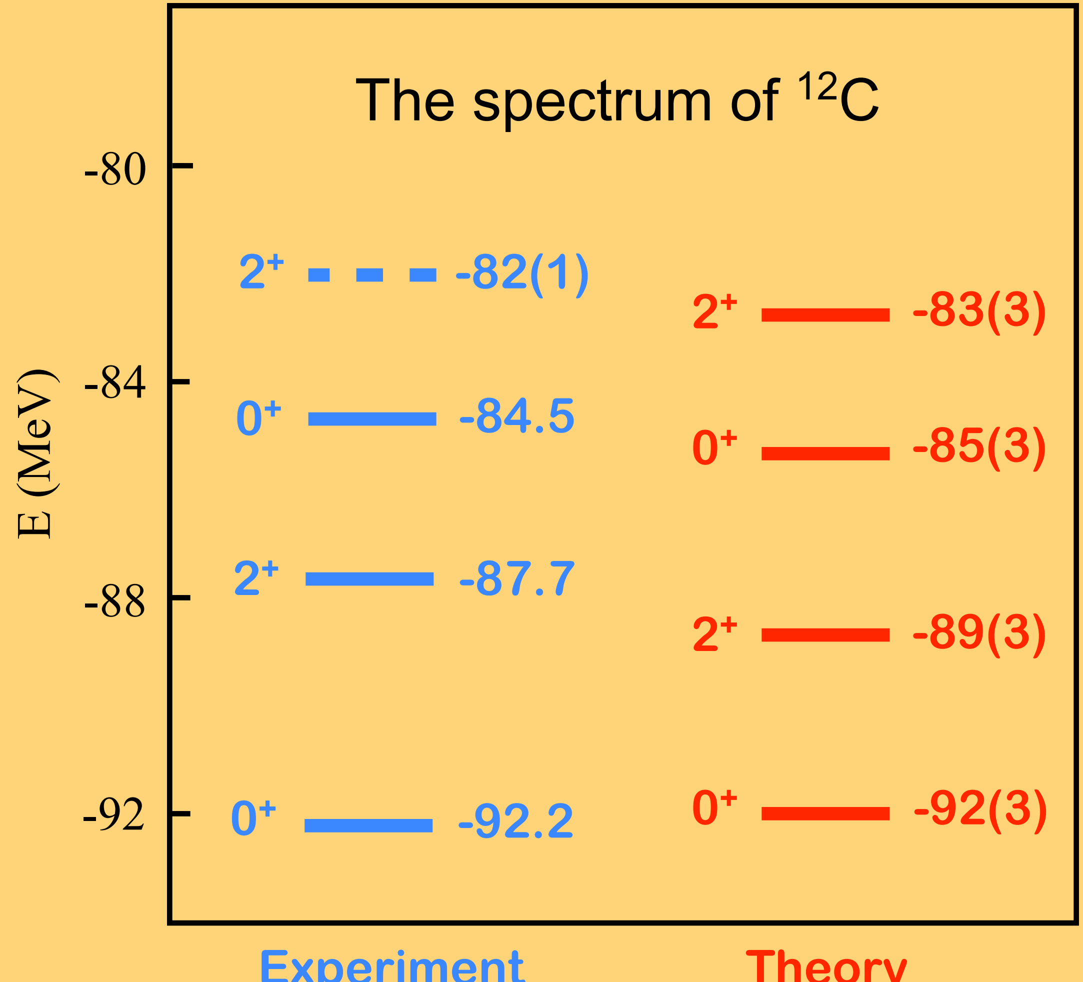
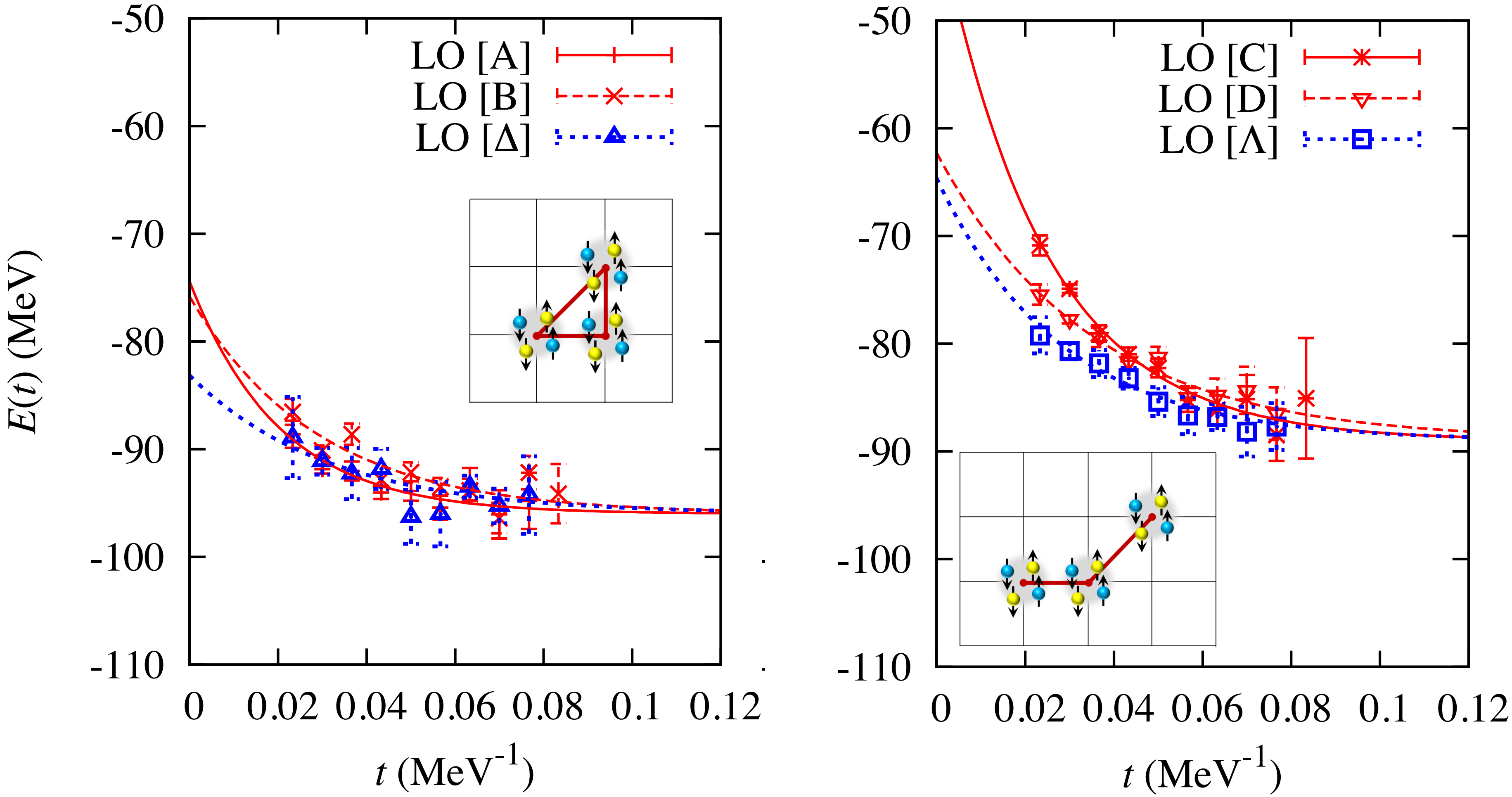


Structure of the Hoyle state

EE, Krebs, Lähde, Lee, Meißner, arXiv:1208.1328

Probing (α-cluster) structure of the 0_1^+, 0_2^+ states



Summary and outlook

Nuclear chiral dynamics enters precision era:

- low-energy NN scattering is accurately described at N^3LO
- many high-precision few-N studies: pion-N scatt. lengths, Compton scattering, pion photoproduction, FFs, radiative/muon capture...
- impressive progress in ab initio many-body methods, precise nuclear structure calculations for light nuclei become reality!
- The main source of uncertainty is presently due to the 3NF...
  (higher-order corrections in progress)

Nuclear lattice simulations:

- combining EFT and lattice simulations → access to (light) nuclei
- exciting results for the ^{12}C spectrum, first ab initio calculation of the Hoyle state

  Work in progress: quark mass dependence of the Hoyle state, spectrum of ^{16}O, volume dependence, reactions ...