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55. International Winter Meeting on Nuclear Physics,
23 - 27 Januar 2017, Bormio, Italy

Status and perspectives of nuclear chiral EFT

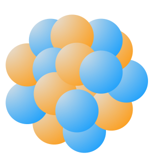
- Chiral NN forces
- Uncertainty quantification
- Few-N systems and the quest for 3NF
- Electroweak current operators

Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft
erc

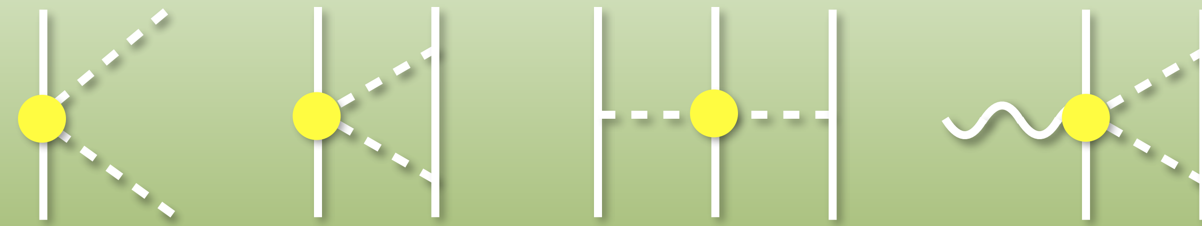
EFTs for nuclear physics

A = 0,1: Chiral perturbation theory

A > 1: Halo-EFT ($Q \ll (\Delta E_{core}\, m)^{1/2}$), pionless EFT ($Q \ll M_\pi$), chiral EFT ($Q \sim M_\pi$)



A >> 1: In-medium chiral EFT; EFTs using collective DOFs (e.g. to describe deformed nuclei)



Chiral perturbation theory

- **Ideal world [$m_u = m_d = 0$], zero-energy limit:** non-interacting massless GBs
  (+ strongly interacting massive hadrons)

- **Real world [$m_u,\ m_d \ll \Lambda_{QCD}$], low energy:** weakly interacting light GBs
  (+ strongly interacting massive hadrons)

→ expand about the ideal world (ChPT)

Chiral Perturbation Theory

Weinberg, Gasser, Leutwyler, Meißner, ...

Expansion of the scattering amplitude in powers of

$$Q = \frac{\text{momenta of pions and nucleons or } M_\pi \sim 140 \text{ MeV}}{\text{hard scales [at best } \Lambda_\chi = 4\pi F_\pi \sim 1 \text{ GeV]}}$$

Manohar, Georgi '84

Tool: Feynman calculus using the effective chiral Lagrangian

low-energy constants

$$\mathcal{L}_\pi = \mathcal{L}_\pi^{(2)} + \mathcal{L}_\pi^{(4)} + \ldots$$

$$\mathcal{L}_{\pi N} = \underbrace{\bar N \Big(i\gamma^\mu D_\mu[\pi] - m + \frac{g_A}{2}\gamma^\mu \gamma_5 u_\mu[\pi] \Big) N}_{\mathcal{L}_{\pi N}^{(1)}} + \underbrace{\sum_i \boldsymbol{c_i}\, \bar N \hat O_i^{(2)}[\pi] N}_{\mathcal{L}_{\pi N}^{(2)}} + \underbrace{\sum_i \boldsymbol{d_i}\, \bar N \hat O_i^{(3)}[\pi] N}_{\mathcal{L}_{\pi N}^{(3)}} + \ldots$$

Pion-nucleon scattering up to Q^4

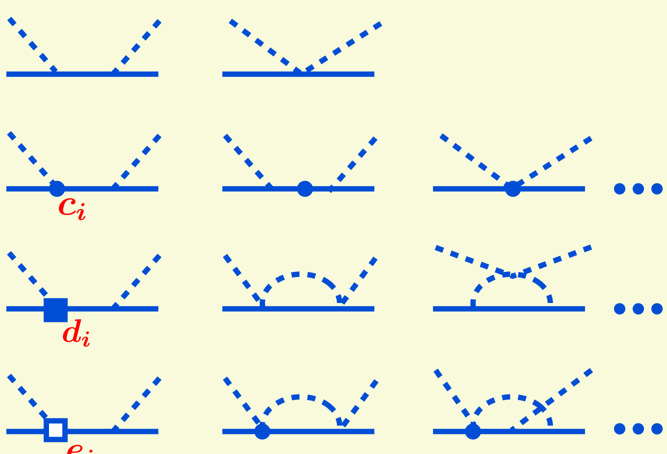
Fettes, Meißner '00; Becher, Leutwyler '01; Krebs, Gasparyan, EE '12; Alarcon, Camalich, Oller '12; Chen, Yao, Zheng '13; Wendt et al. '14; Siemens et al. '16; Yao et al. '16, …

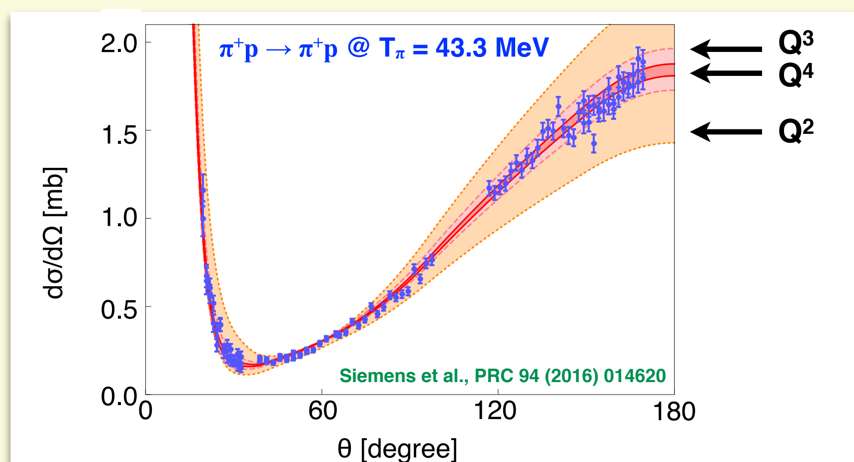
Order Q:

Order Q^2:

Order Q^3:

Order Q^4:



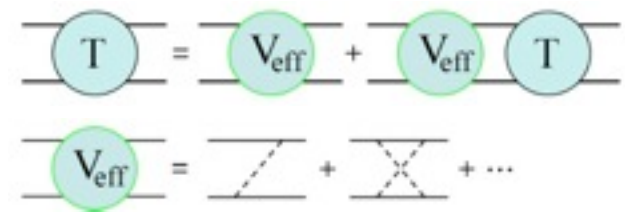


Nuclear chiral EFT

Chiral EFT for nuclear systems: expansion for nuclear forces + resummation (Schrödinger eq.)

Weinberg, van Kolck, Kaiser, EE, Glöckle, Meißner, Entem, Machleidt, Krebs, ...

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



Notice:

- Much more involved than calculating Feynman diagrams (unitary trafos, TOPT, S-matrix-matching, …), potentials are not unique, renormalizability is not guaranteed a priori…

- LS equation is linearly divergent already at LO ⟶ infinitely many CTs are needed to absorb all UV divergences from iterations!

  Commonly used approach **[EGM, EM, EKM, Gezerlis et al.'14, Piarulli et al.'15, Carlsson et al.'16, …]**:

  — Introduce a finite UV regulator R ~ R_b (Λ_b ~ 600 MeV)

  — Include short-range operators in V_{NN} according to NDA ⟵ minimal possible set; alternatives have been proposed…

  — Solve the LS equation & tune the **bare** LECs $C_i(R)$ to data (implicit renormalization)

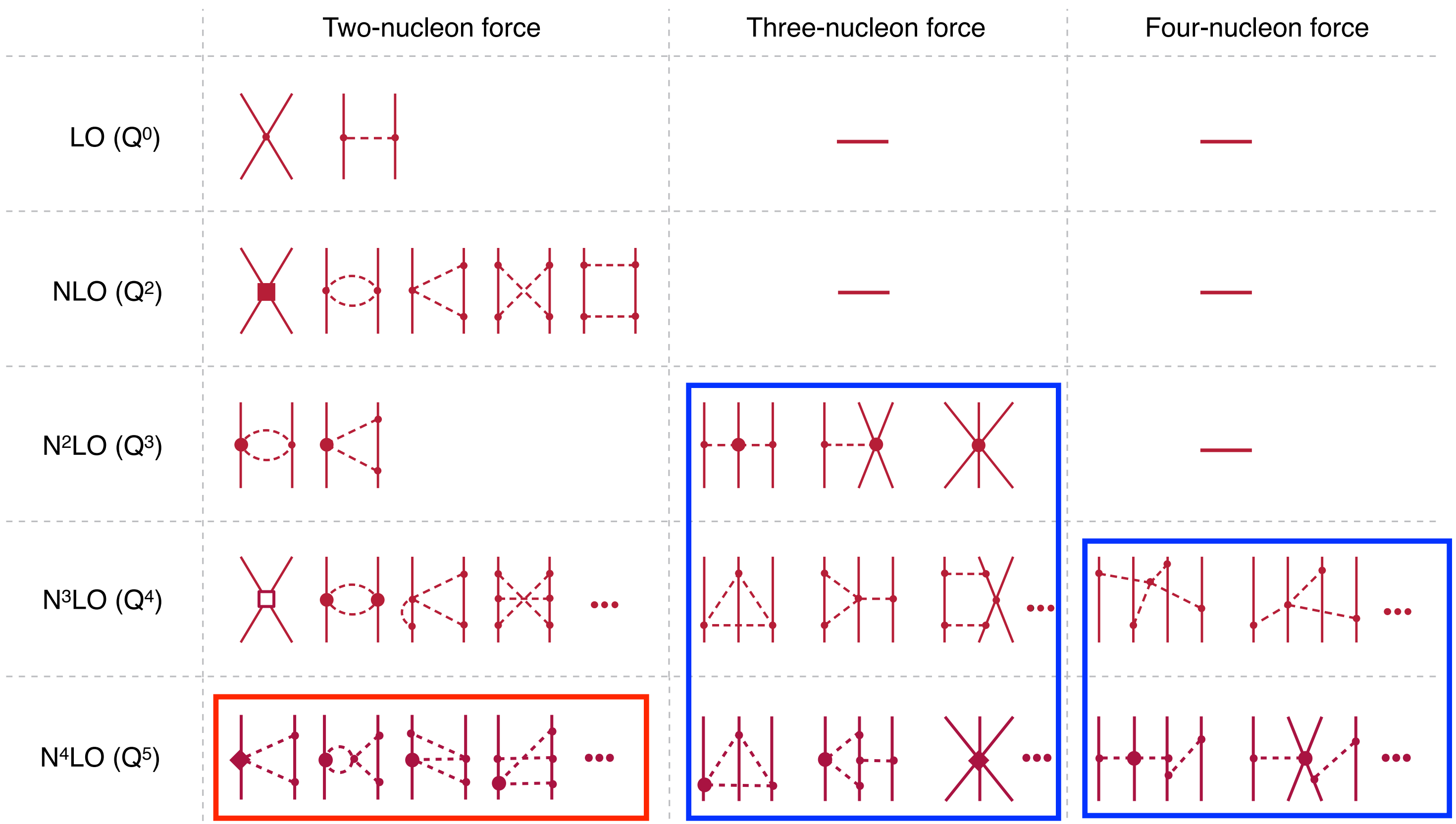
  — (Numerical) self-consistency checks via error analysis and R-variation

  See: Lepage, „How to renormalize the Schrödinger equation", nucl-th/9607029 and talk@INT in 2000

Alternative: renormalizable approach based on the Lorentz invariant $\mathcal{L}_{\rm eff}$ **[EE, Gegelia '12]**

See also: ***Nuclear Effective Field Theories — the crux of the matter***, **open discussion by Mike Birse and EE at the KITP program „Frontiers in Nuclear Physics", August 22 - November 4, 2016, available at** http://online.kitp.ucsb.edu/online/nuclear16/

Chiral expansion of the nuclear forces



have been worked out

being investigated…

Entem, Kaiser, Machleidt, Nosyk, PRC 91 (2015) 014002

EE, Krebs, Meißner, PRL 115 (2015) 122301

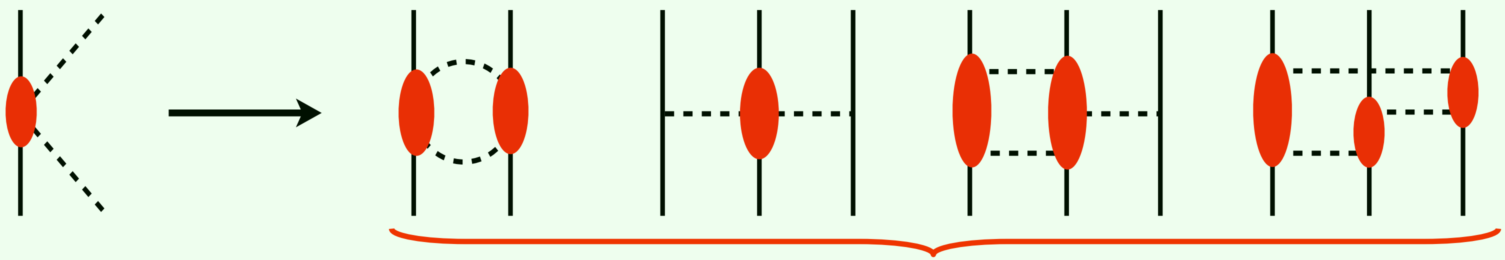
Why go to fifth order (N^{4}LO) in the chiral expansion?

— no additional parameters in the NN force (except for 1 IB term) ➙ testing the theory

— there is evidence that χ-expansion for the 3NF is not yet converged at Q^4

The long-range part of the nuclear forces

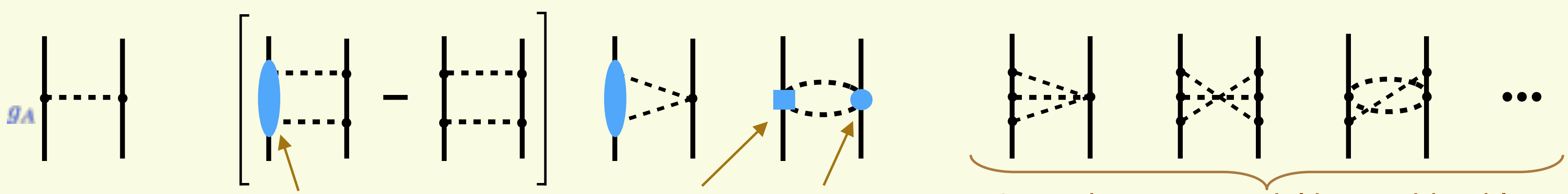
Long-range nuclear forces are completely determined by the
chiral symmetry of QCD + experimental information on πN scattering



predicted in a parameter-free way

The long-range NN force up to N⁴LO [Q⁵]

Ordonez et al.; Kaiser; EE, Krebs, Meißner; Entem, Machleidt; …



πN amplitude up to order Q^4

πN amplitude up to order-Q^3

order-Q^2 πN amplitude

3π-exchange potential is considerably weaker than the 2π-one and is described by contacts

The TPE potential can be derived by taking the phase-space integral of the πN amplitudes computed in ChPT (Lorentz-transformed to the proper kinematics…) Kaiser ’00

Determination of the low-energy constants

All relevant LECs (in GeV^{-n}) extracted from πN scattering

Krebs, Gasparyan, EE '12

	c_1	c_2	c_3	c_4	$\bar{d}_1 + \bar{d}_2$	$\bar{d}_3$	$\bar{d}_5$	$\bar{d}_{14} - \bar{d}_{15}$	$\bar{e}_{14}$	$\bar{e}_{17}$
$[Q^4]_{\text{HB, NN}}$, GW PWA	-1.13	3.69	-5.51	3.71	5.57	-5.35	0.02	-10.26	1.75	-0.58
$[Q^4]_{\text{HB, NN}}$, KH PWA	-0.75	3.49	-4.77	3.34	6.21	-6.83	0.78	-12.02	1.52	-0.37
$[Q^4]_{\text{covariant}}$, data	-0.82	3.56	-4.59	3.44	5.43	-4.58	-0.40	-9.94	-0.63	-0.90

Related recent work (all calculations lead to similar values of the LECs):

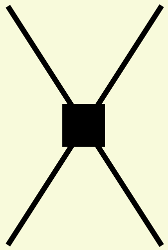
— determination of the LECs from πN data Wendt et al. '14; Siemens et al. '16

— LECs from Roy-Steiner-eq. analysis of πN-scattering Hoferichter et al. '15; Yao et al. '16; Siemens et al. '16

With the LECs taken from πN, the long-range NN force is completely fixed (parameter-free)

The short-range part of the nuclear force (contact interactions)

Organizational principle for contact terms according to NDA (Weinberg's counting)



LO [Q^0]: 2 operators (S-waves)

NLO [Q^2]: + 7 operators (S-, P-waves and ε_1)

N^{2}LO [Q^3]: no new isospin-conserving operators

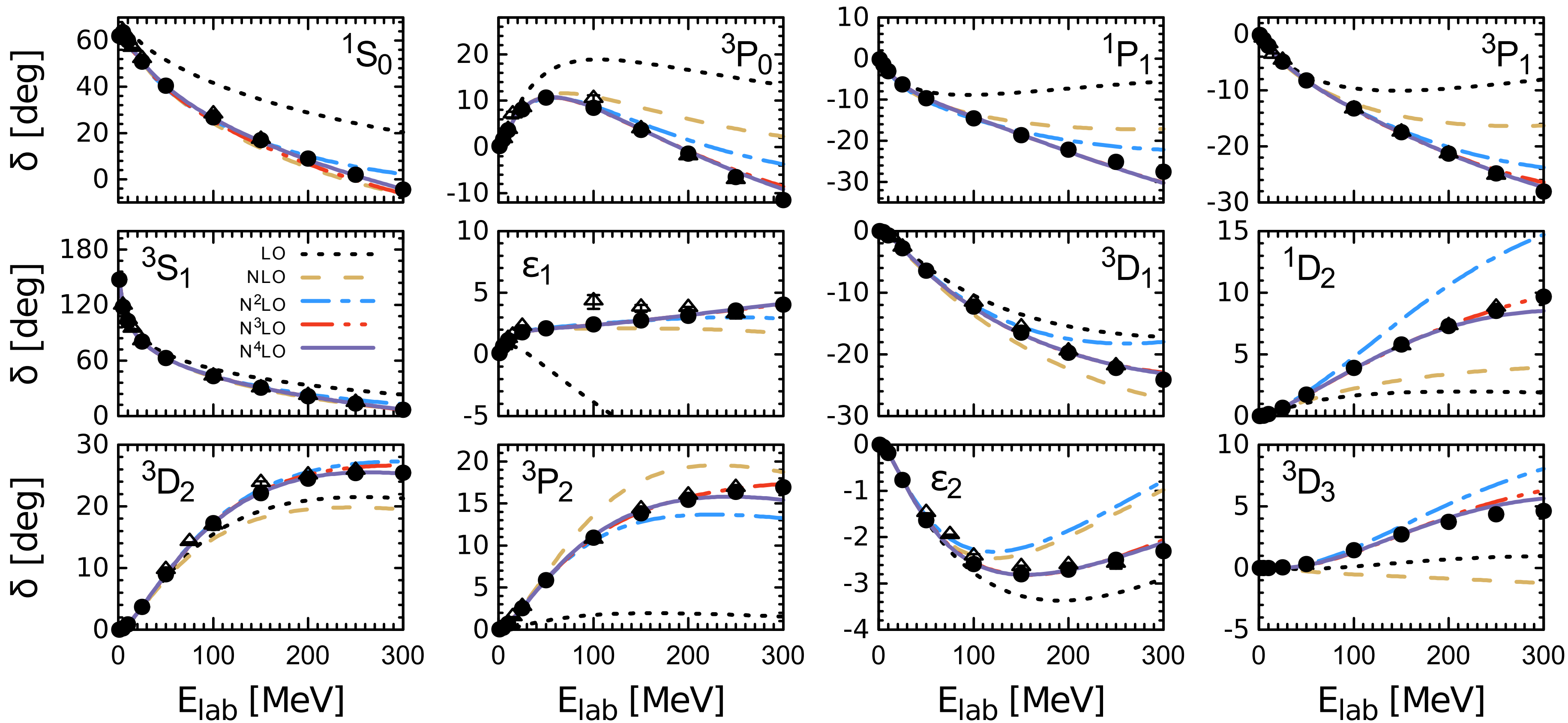
N^{3}LO [Q^4]: + 15 operators (S-, P-, D-waves and ε_1, ε_2)

N^{4}LO [Q^5]: no new isospin-conserving operators

Local r-space regulator for V_π [R = 0.8…1.2 fm], nonlocal Gaussian regulator for V_{cont}

NN phase shifts order by order [R = 0.9 fm]

EE, Krebs, Meißner, EPJ A51 (2015) 5, 53; PRL 115 (2015) 122301



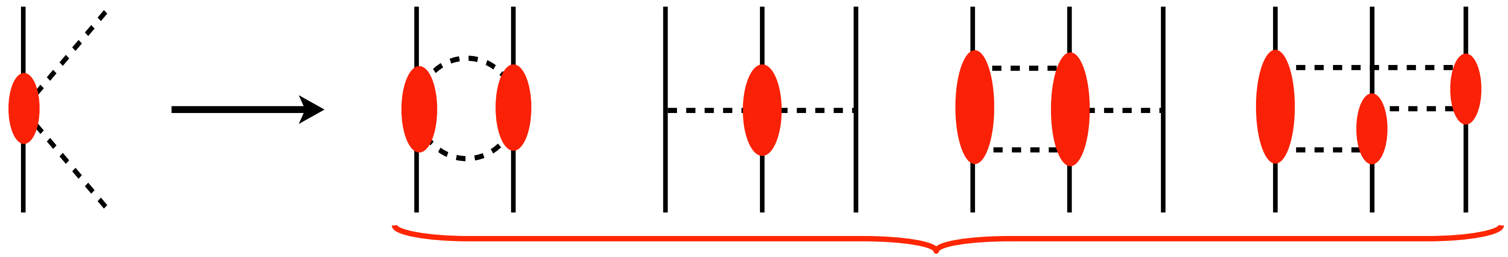
Other chiral NN potentials on the market:

- 1st generation χ N^{3}LO forces (nonlocal) [Epelbaum-Glöckle-Meißner '04, Entem-Machleidt '03]
- fully local potentials up to N^{2}LO [Gezerlis et al. '14]; minimally nonlocal N^{3}LO potential including N^{2}LO Δ(1232) contributions [Piarulli et al.'15]
- N^{2}LO potentials by the Oak Ridge group tuned to heavier nuclei [Ekström, Carlsson et al.]

Evidence of the 2π-exchange

Predictive power?

Long-range interactions are completely determined by the chiral symmetry & experimental information on πN scattering



preliminary: Reinert et al., in preparation

Energy bin	LO	NLO	N^2LO	N^3LO	N^4LO
neutron-proton data					
0 – 100 MeV	130.11	3.79	1.46	1.08	1.08
0 – 200 MeV	104.71	19.88	3.21	1.14	1.09
0 – 300 MeV	111.24	52.03	8.78	1.51	1.15
proton-proton data					
0 – 100 MeV	2046.58	33.68	6.67	0.86	0.84
0 – 200 MeV	1649.58	115.60	81.11	1.95	1.34
0 – 300 MeV	1301.41	104.38	84.24	2.73	1.46

NLO → N^2LO (np): no new LECs

N^3LO → N^4LO (np): +1 LEC ($^1S_0$)

N^3LO → N^4LO (pp): no new LECs

2 LECs + 7 + 2 IB LECs + 15 LECs + 1 IB LEC

Clear evidence of the (parameter-free) chiral 2π-exchange!

Uncertainty quantification

A simple algorithm for estimating **uncertainty from the truncation of the chiral expansion:**

EE, Krebs, Meißner, EPJA 51 (2015) 53

For any observable: $\boldsymbol{X^{(i)}(p) = X^{(0)} + \underbrace{\Delta X^{(2)}}_{\sim Q^2 X^{(0)}} + \ldots + \underbrace{\Delta X^{(i)}}_{\sim Q^i X^{(0)}}}$ with $Q = \max(p/\Lambda_b,\, M_\pi/\Lambda_b)$

estimated from the error plots Λb ~ 600 MeV

Use the explicitly calculated $\Delta X^{(i)}$ to estimate the uncertainty $\delta X^{(i)}$ at order Q^i:

$$\boldsymbol{\delta X^{(0)} = Q^2 |X^{(0)}|,}$$

$$\boldsymbol{\delta X^{(i)} = \max_{2 \le j \le i} \left(Q^{i+1} |X^{(0)}|,\, Q^{i+1-j} |\Delta X^{(j)}| \right)}$$

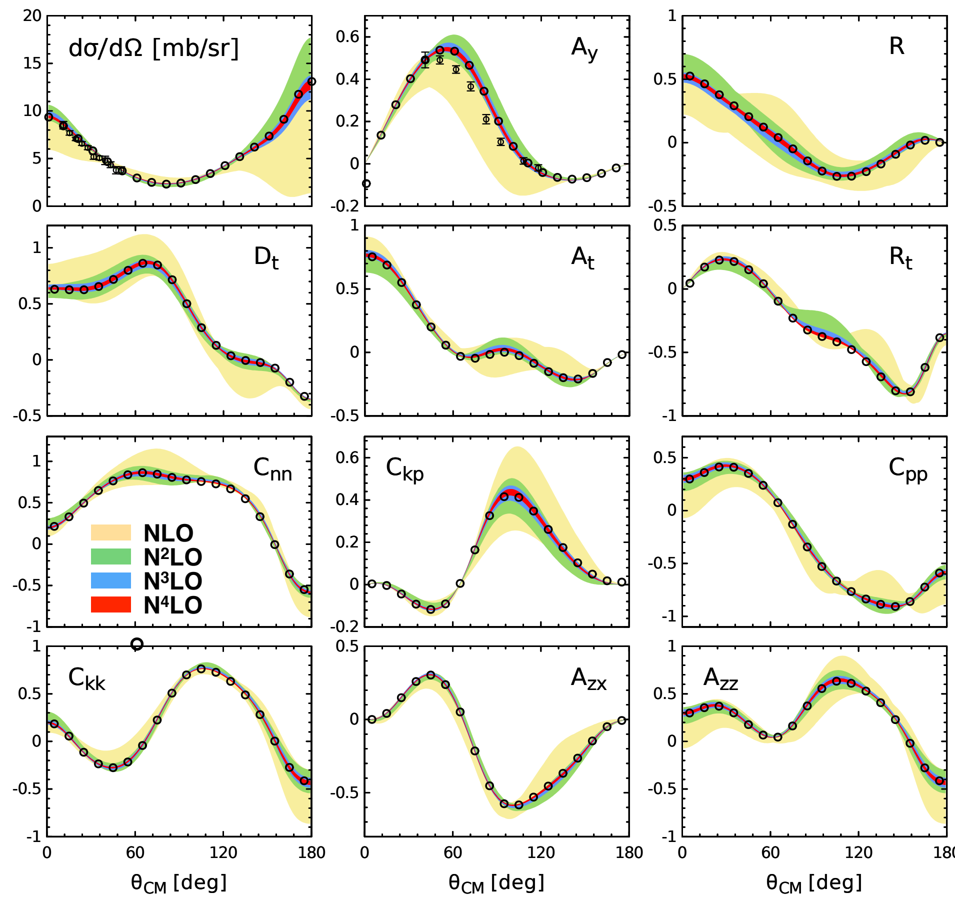
subject to the additional constraint

$$\boldsymbol{\delta X^{(i)} \ge \max_{j,k} \left(|X^{(j \ge i)} - X^{(k \ge i)}| \right).}$$

- no reliance on the cutoff variation (not reliable)
- easily applicable to any observable (scattering, bound states, 3N, …)
- of course, no reliance on exp. data
- for σ_{tot}, errors found to be consistent with 68% degree-of-belief intervals

  Furnstahl et al., PRC 92 (2015) 024005

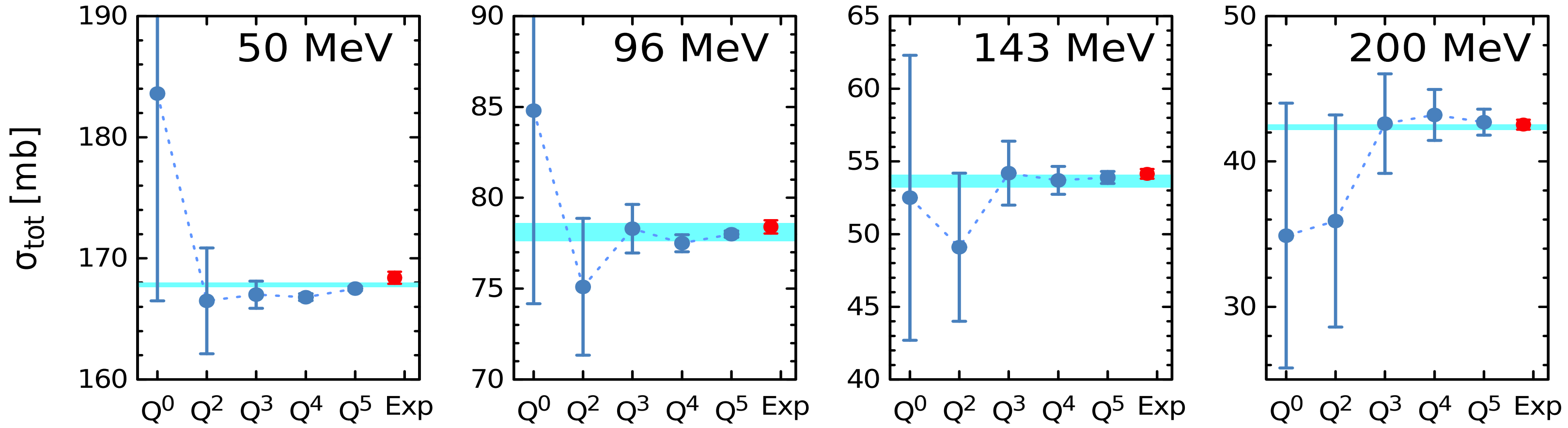
proton-neutron scattering observables at E_{lab}=143 MeV



Examples in the NN sector

What accuracy is achievable?

Chiral expansion of the neutron-proton total cross section



Scattering lengths and effective range parameters extracted from the data

	predictions at N^{4}LO	Experimental/Empirical values
neutron-proton		
$a_{^1S_0}$ [fm]	$-23.733(6)$	$-23.740(20)$
$r_{^1S_0}$ [fm]	$2.677(7)$	$2.77(5)$
$a_{^3S_1}$ [fm]	$5.419(1)$	$5.419(7)$
$r_{^3S_1}$ [fm]	$1.752(0)$	$1.753(8)$
proton-proton		
$a_{^1S_0}$ [fm]	$-7.816(1)$	$-7.817(4)$
$r_{^1S_0}$ [fm]	$2.773(2)$	$2.78(2)$

preliminary: Reinert et al., in preparation

Beyond the 2N system

LENPIC Collaboration

Goal: precision tests of chiral nuclear forces & currents in light nuclei

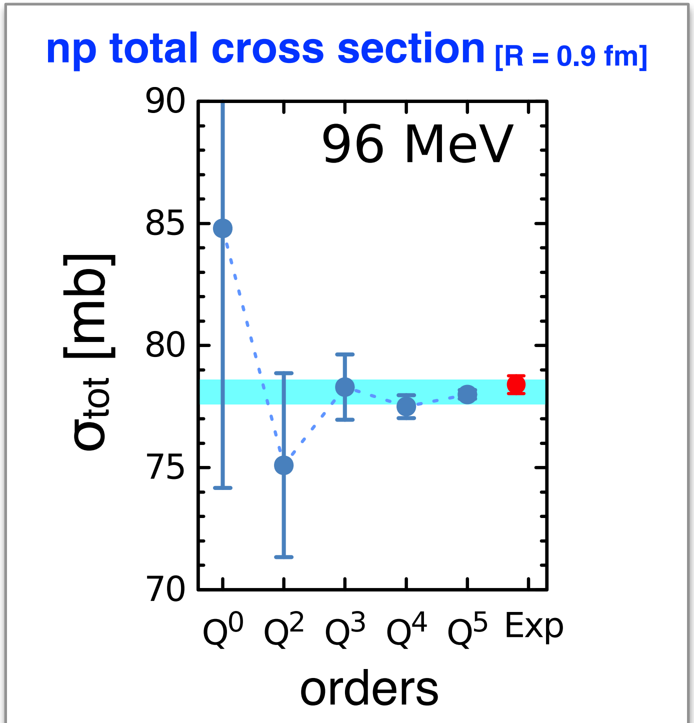
Strategy: go to high orders, do not compromise the πN LECs, no fine tuning to heavy nuclei, careful error analysis

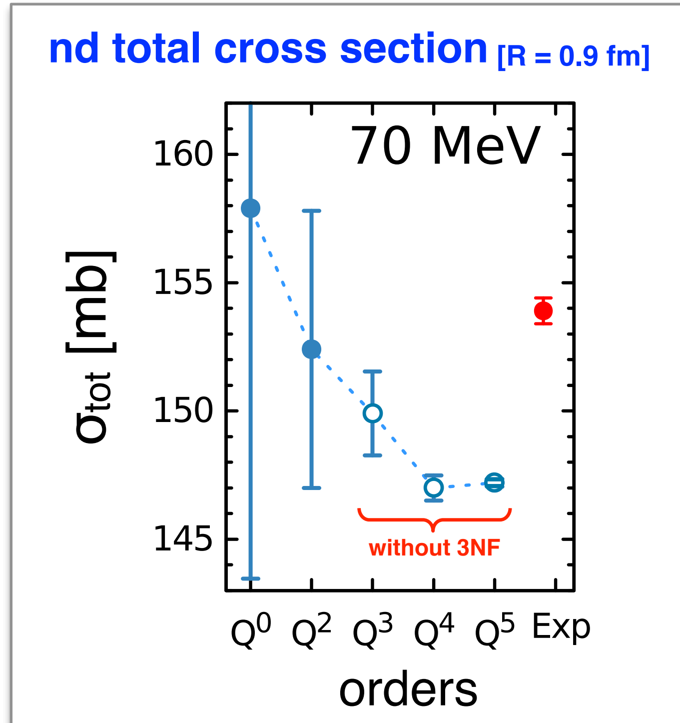
LENPIC: Low **E**nergy **N**uclear **P**hysics **I**nternational **C**ollaboration

Few-N results without 3NF

LENPIC Collaboration (Binder et al.), PRC 93 (2016) 04402

Is there evidence for missing 3N forces effects? Yes!



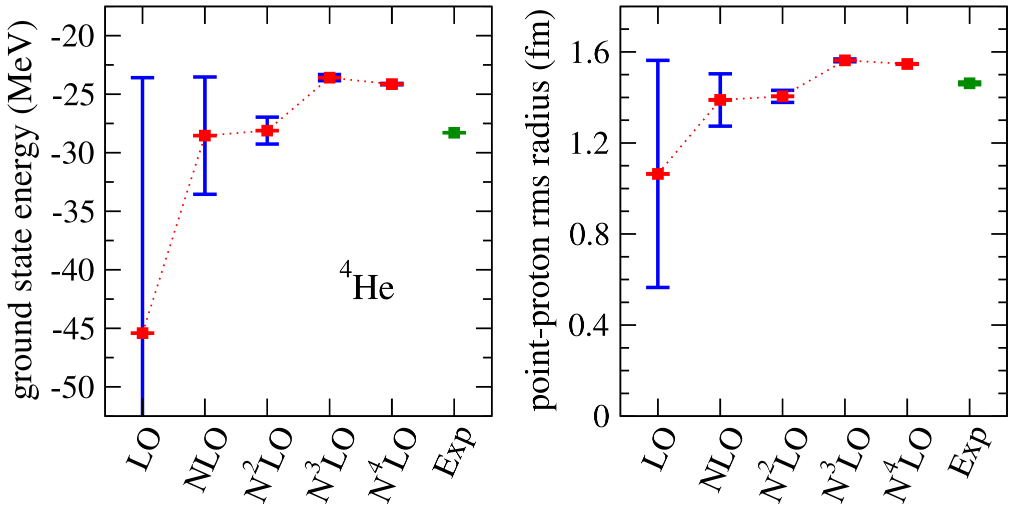


- Discrepancies between theory and data well outside the range of quantified uncertainties
  → **clear evidence for missing 3NF effects**
- Magnitude of the required 3NF contributions matches well the estimated size of N^2LO terms
  → **consistent with the chiral power counting**

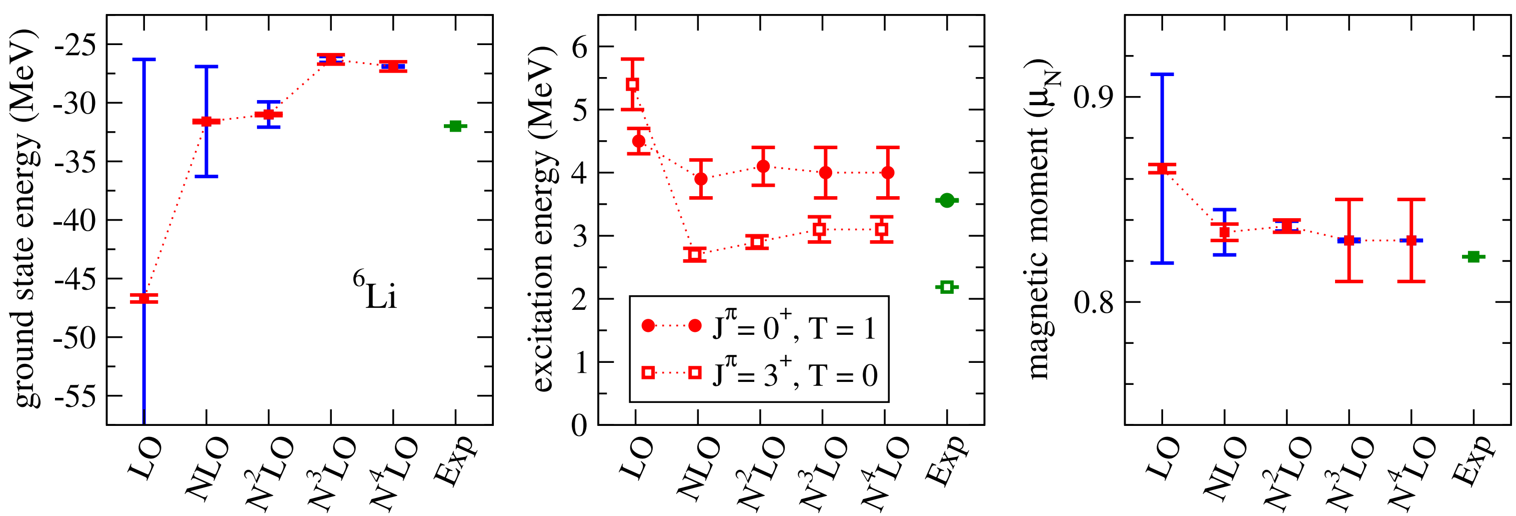
LENPIC: Low Energy Nuclear Physics International Collaboration

Few-N results without 3NF

LENPIC Collaboration (Maris et al.), EPJ Web of Conf. 113 (2016) 04015



Calculations performed by Pieter Maris in the framework of the No-Core Shell Model

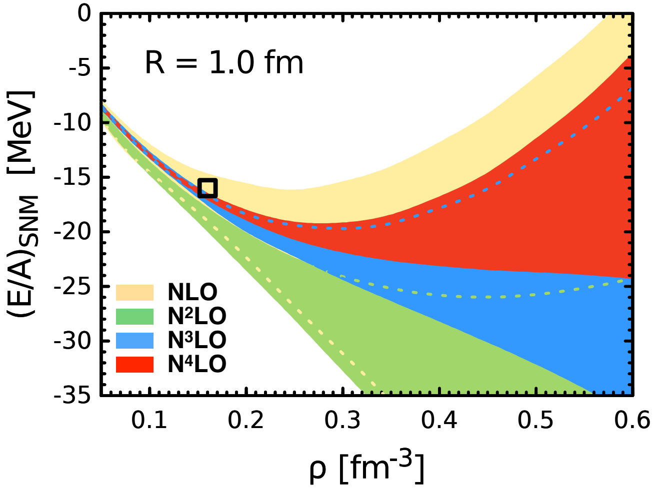


LENPIC: Low Energy Nuclear Physics International Collaboration

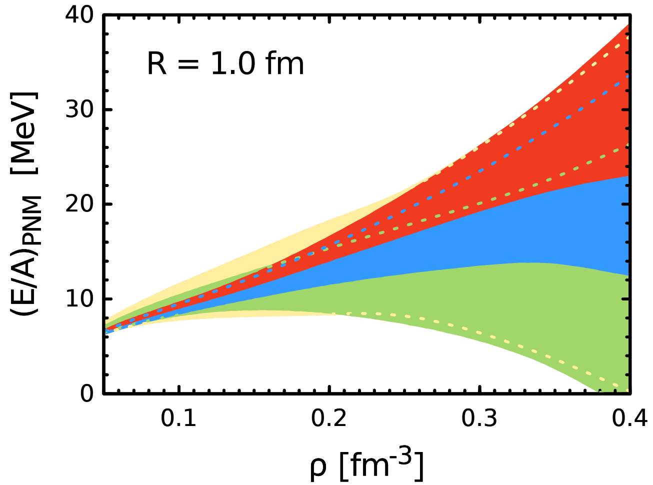
Brueckner-Hartree-Fock without 3NF

Jinniu Hu, Ying Zhang, EE, Ulf-G. Meißner, Jie Meng, arXiv:1612.05433 [nucl-th]

Symmetric nuclear matter



Pure neutron matter

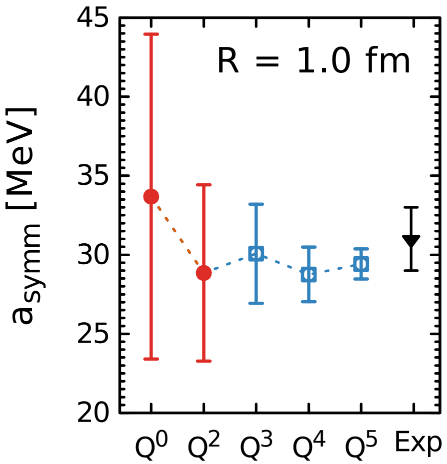


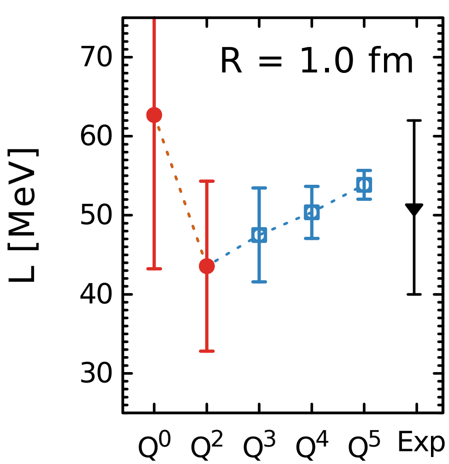
Estimated accuracy at N^{4}LO at the saturation density:

± 0.3 MeV for SNM,

± 0.7 MeV for PNM

Symmetry energy and the slope parameter at the saturation density

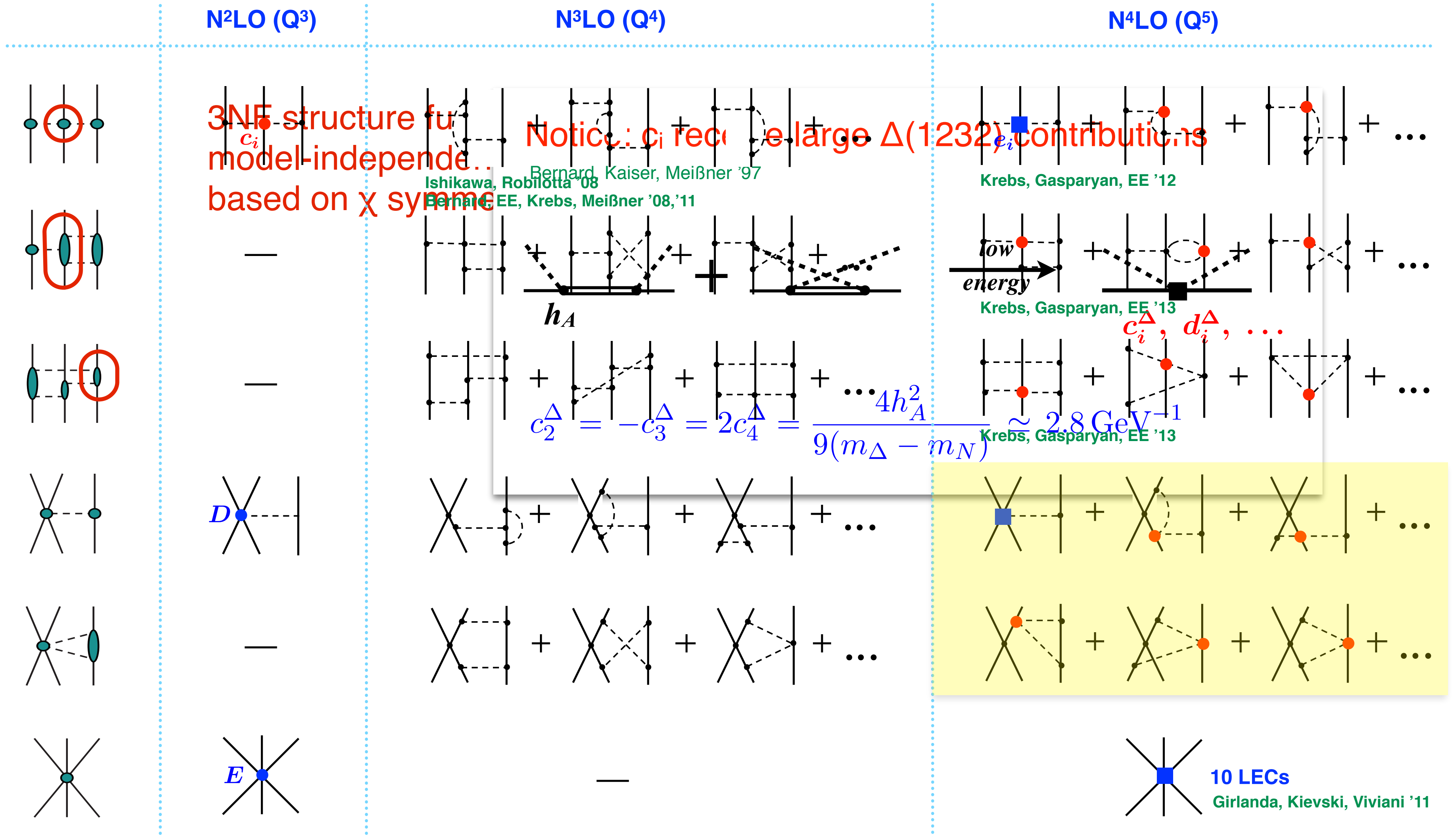




$$a_{\text{symm}}(\rho) = \left(\frac{E}{A}\right)_{\text{PNM}} - \left(\frac{E}{A}\right)_{\text{SNM}}$$

$$L = 3\rho \frac{\partial (E/A)_{\text{SNM}}}{\partial \rho}$$

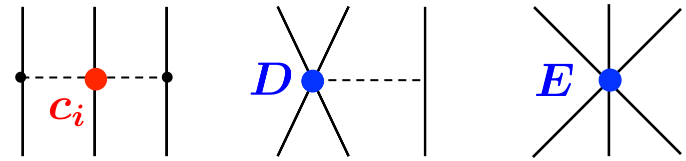
Chiral expansion of the 3NF



Some PRELIMINARY results with 3NF

LENPIC, in progress

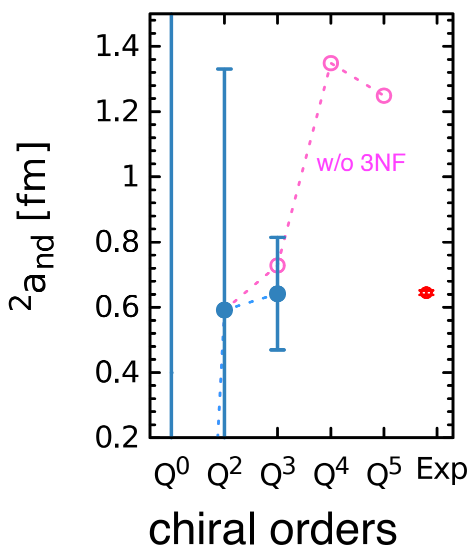
The LECs D, E are determined from the ^{3}H and the Nd cross section minimum @70 MeV (RIKEN data)

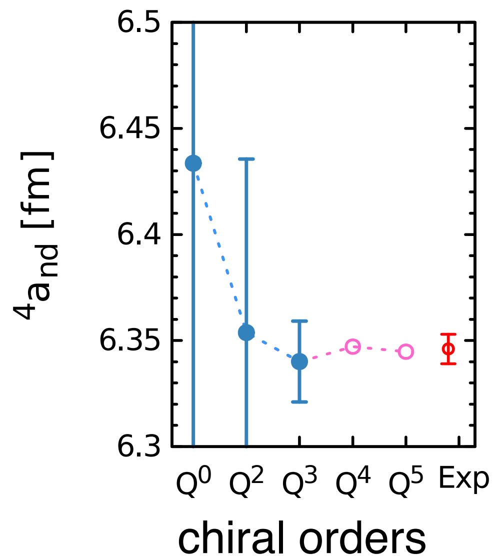


The results are **preliminary:**

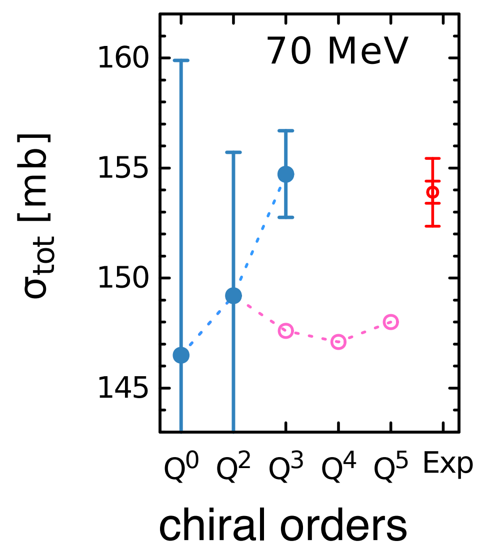
— still have to analyze different ways to determine D and E, check other sources of uncertainties, …

nd scattering lengths [R = 1.0 fm]





nd σ_{tot} at 70 MeV [R = 1.0 fm]



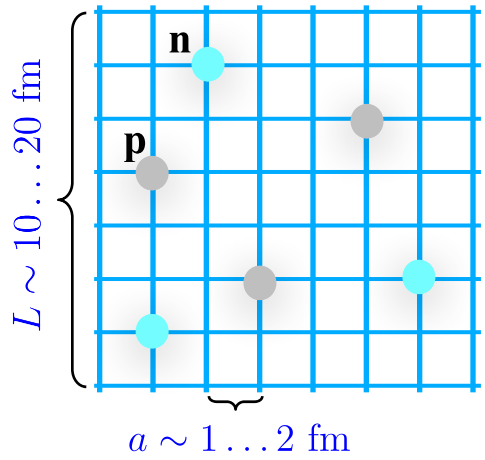
LENPIC: Low Energy Nuclear Physics International Collaboration

Nuclear systems from lattice χEFT

Nuclear lattice simulations:

A novel ab initio approach to nuclei and nuclear reactions

D. Lee, EE, H. Krebs, T. Lähde, T. Luu, U.-G. Meißner, G. Rupak, …



Some recent highlights:

Ab initio calculation of the Hoyle state

EE, H. Krebs, D. Lee, U.-G. Meißner, PRL 106 (11) 192501; EE, H. Krebs, T.A.Lähde, D. Lee, U.-G. Meißner, PRL 109 (12) 252501

Viability of Carbon-based life as a function of light quark masses

EE, H. Krebs, T. A. Lähde, D. Lee, U.-G. Meißner, PRL 110 (13) 112502; EPJA 49 (13) 82

Ab initio calculation of the spectrum and structure of ^{16}O

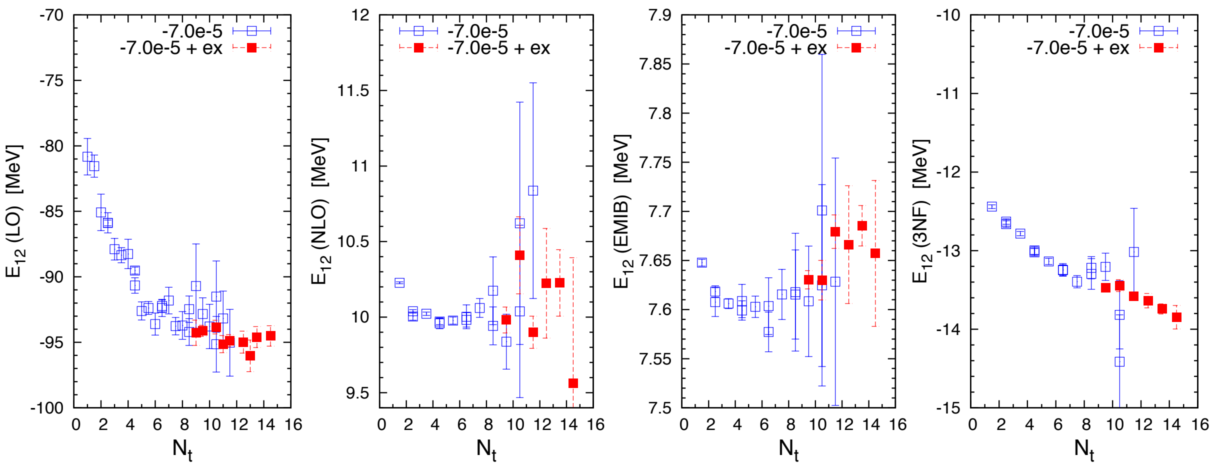
EE, H. Krebs, T. A. Lähde, D. Lee, U.-G. Meißner, G. Rupak, PRL 112 (14) 102501

Lattice EFT for medium-mass nuclei („triangulation“ method for Euclidean-time extrapol.)

T. A. Lähde, EE, H. Krebs, D. Lee, U.-G. Meißner, G. Rupak, PLB 732 (14) 110

$E_{8Be, \text{old}}$ = -55(2) MeV

$E_{8Be, \text{new}}$ = -56.4(2) MeV



Symmetry-sign extrapol.

T.A. Lähde, T. Luu, D. Lee, U.-G. Meißner, EE, H. Krebs, G. Rupak, EPJ A51 (15) 92

Nuclear binding energy near a quantum phase transition

Elhatisari et al., PRL 117 (2016) 132501

Nuclear systems from lattice χEFT

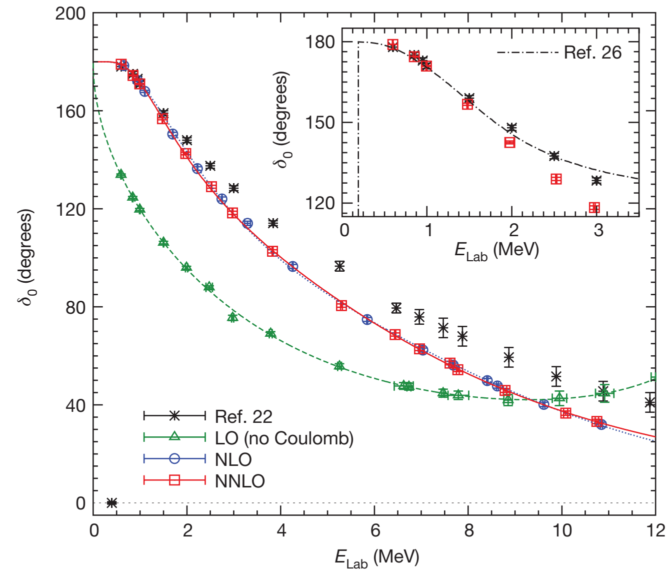

nature International weekly journal of science

Ab initio alpha–alpha scattering

Serdar Elhatisari[1], Dean Lee[2], Gautam Rupak[3], Evgeny Epelbaum[4], Hermann Krebs[4], Timo A. Lähde[5], Thomas Luu[1,5] & Ulf-G. Meißner[1,5,6]

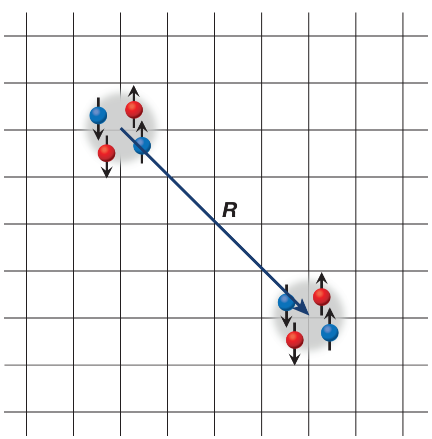
Nature 528, 111–114 (03 December 2015) | doi:10.1038/nature16067

Received 12 June 2015 | Accepted 30 September 2015 | Published online 02 December 2015



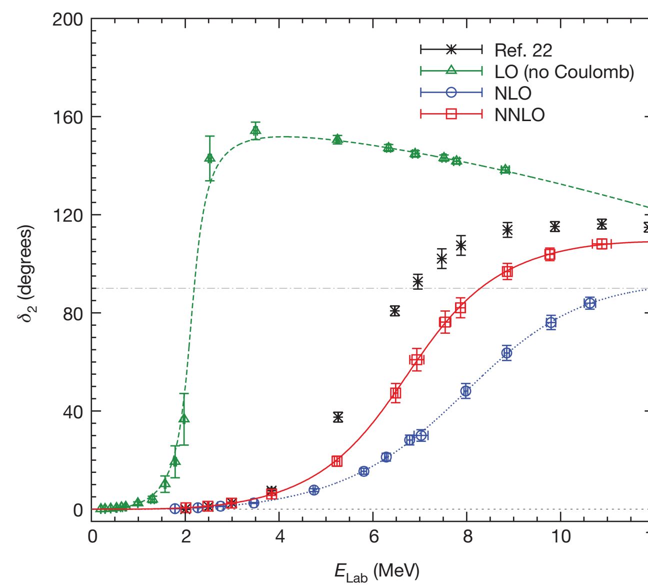
First ab initio calculation of alpha-alpha scattering!

Used lattice EFT to extract the effective Hamiltonian for two interacting α-clusters (adiabatic projection method **[A. Rokash et al., PRC 92 (15) 054612]**)

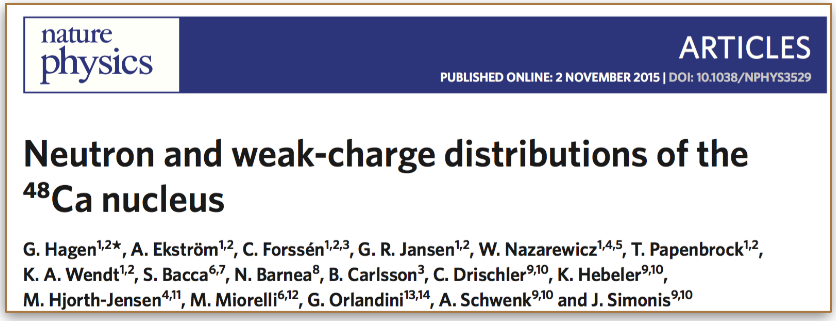


Phase shifts obtained employing a hard spherical wall boundary at asymptotically large distances

Promising scaling with respect to the number of particles as $\sim (A_1 + A_2)^2$



Neutron skin of ^{48}Ca



nature physics

ARTICLES

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Neutron and weak-charge distributions of the ^{48}Ca nucleus

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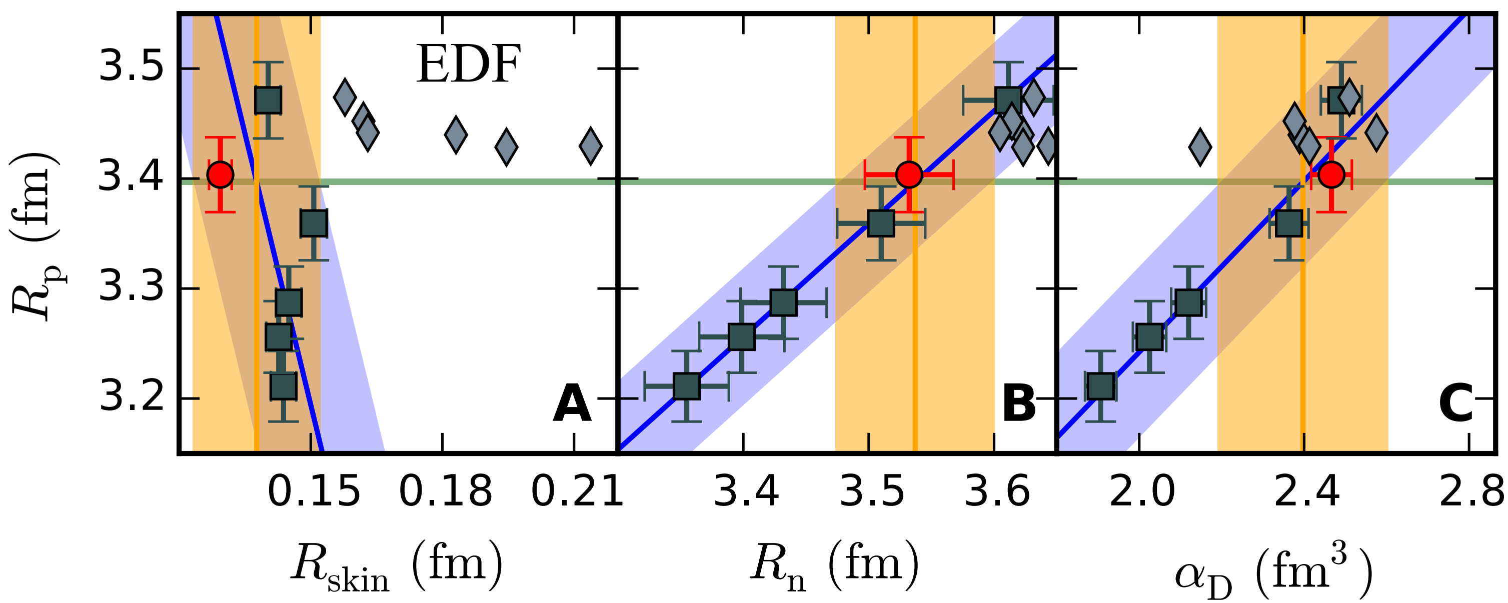
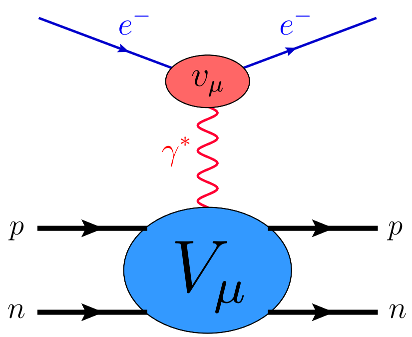
- First ab-initio (coupled-cluster) calculation of the neutron distribution in ^{48}Ca
- Used $\mathrm{NNLO_{sat}}$ NN + 3NF tuned to energies and radii of up to A ~ 25 nuclei (also EM $\mathrm{N^3LO}$ NN + $\mathrm{N^2LO}$ 3NF)



- Neutron skin significantly smaller than expected from DFT and robust (correlations)
- Prediction of the electric dipole polarizability α_D

Nuclear current operators in chiral EFT

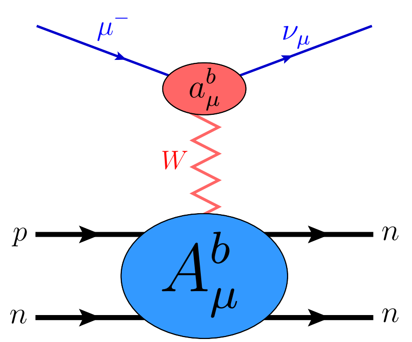


EM currents:

- Kölling, EE, Krebs, Meißner (method of UT), PRC 80 (09) 045502; 86 (12) 047001
- Jlab-Pisa group (TOPT), Pastore et al. '08 - '11

Axial currents:

- Krebs, EE, Meißner (MUT), arXiv:1610.03569, to appear in Annals of Physics
- Jlab-Pisa group (TOPT), Baroni et al. '16
- Hoferichter, Klos, Schwenk '15

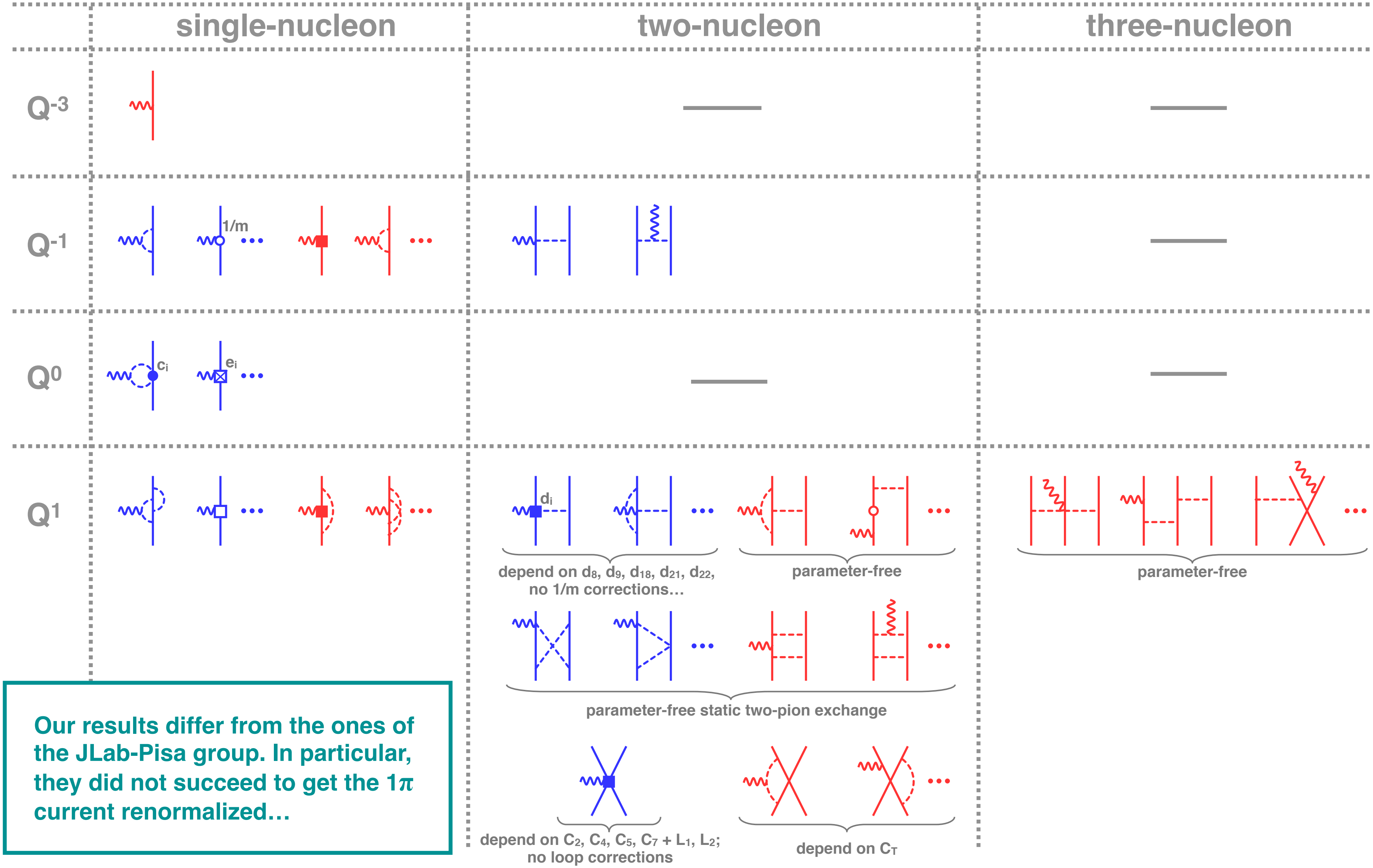


(Our) requirements on the current operators:

- must be **off-shell consistent with the forces**
- should be **renormalized** (exploit unitary ambiguity)
- (cutoff) regularization of the forces and currents should **maintain the symmetry** (cont. equation)

Electromagnetic currents

Chiral expansion of the electromagnetic **current** and **charge** operators



Our results differ from the ones of the JLab-Pisa group. In particular, they did not succeed to get the 1π current renormalized…

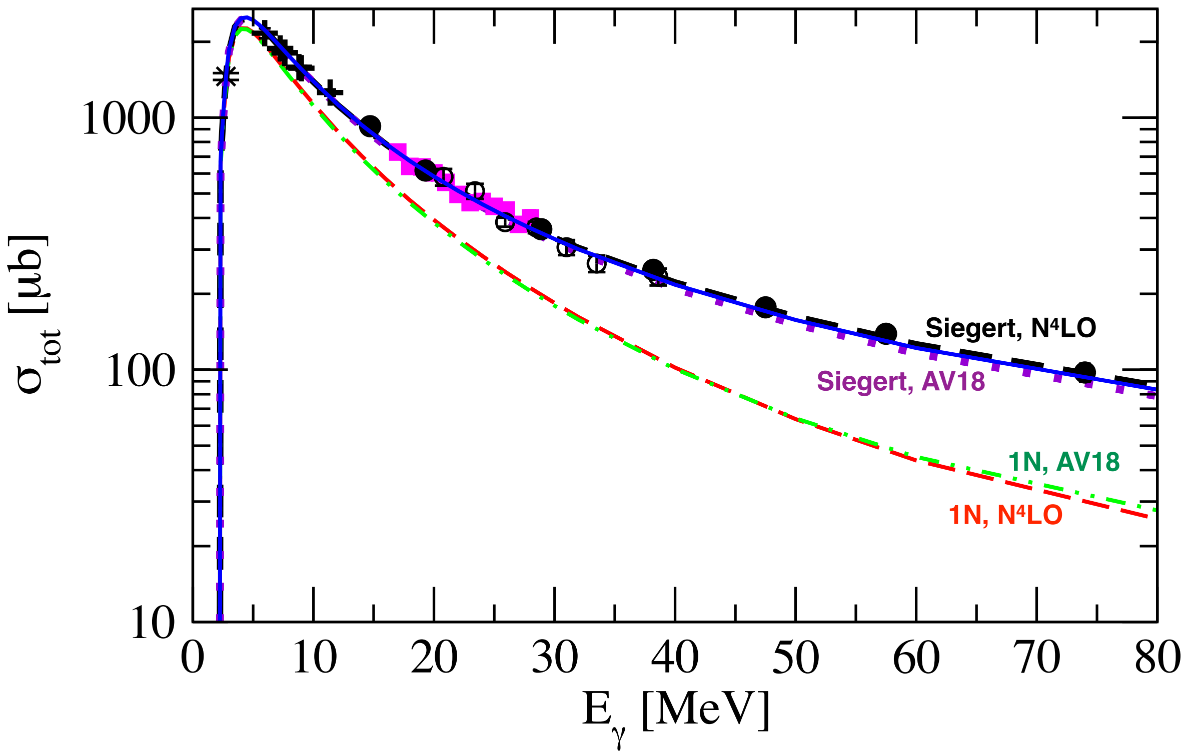
Electromagnetic exchange currents

Skibinski, Golak, Topolnicki, Witala, EE, Krebs, Kamada, Meißner, Nogga, PRC 93 (2016) 064002

- To maintain consistency between currents and forces (symmetry), we generate regularized longitudinal terms in the current via the continuity equation (i.e. Siegert approach).

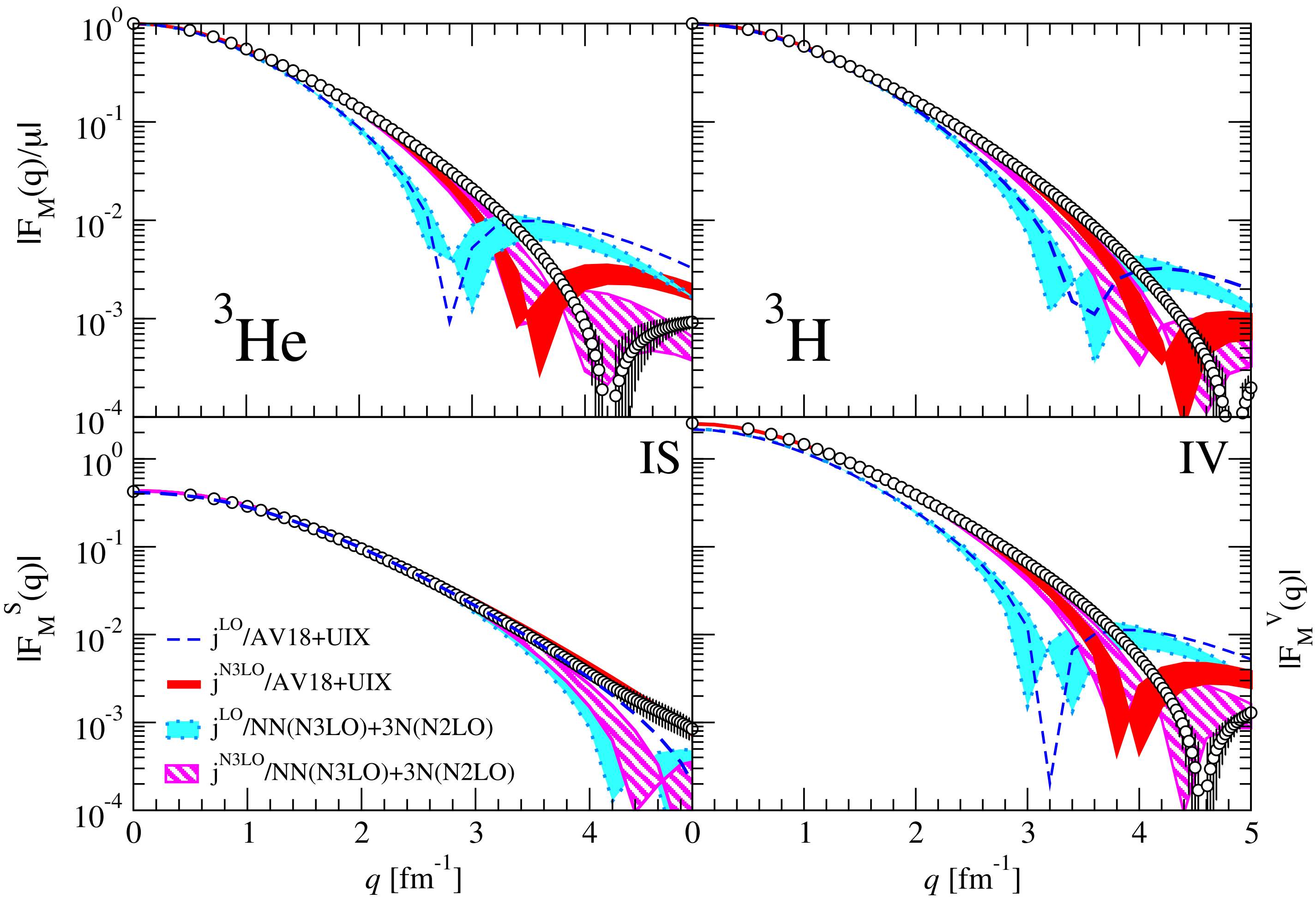
- Transverse terms in the currents are to be regularized and included explicitly (in progress…)

Total cross section for the deuteron photo-disintegration reaction $\gamma + d \rightarrow p + n$



Magnetic form factors of ^{3}He, ^{3}H

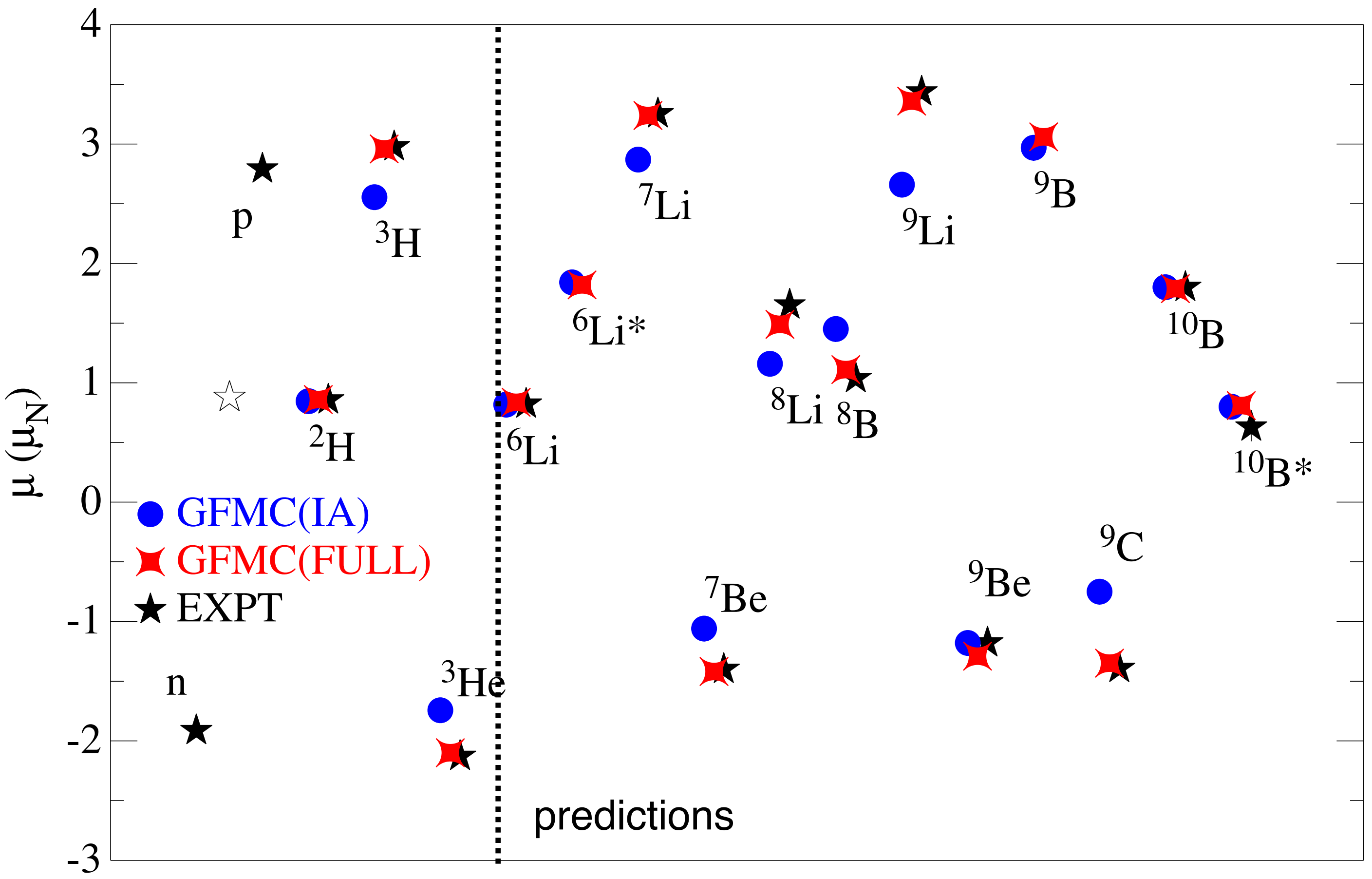
Piarulli, Girlanda, Marcucci, Pastore, Schiavilla, Viviani, Phys. Rev. C87 (2013) 014006



- ^{3}He/^{3}H m.m's used to fix EM LECs; ~15% correction from two-body currents
- Exchange currents crucial to improve agreement with exp data

Magnetic moments of light nuclei

Pastore, Pieper, Schiavilla, Wiringa, Phys. Rev. C87 (2013) 035503

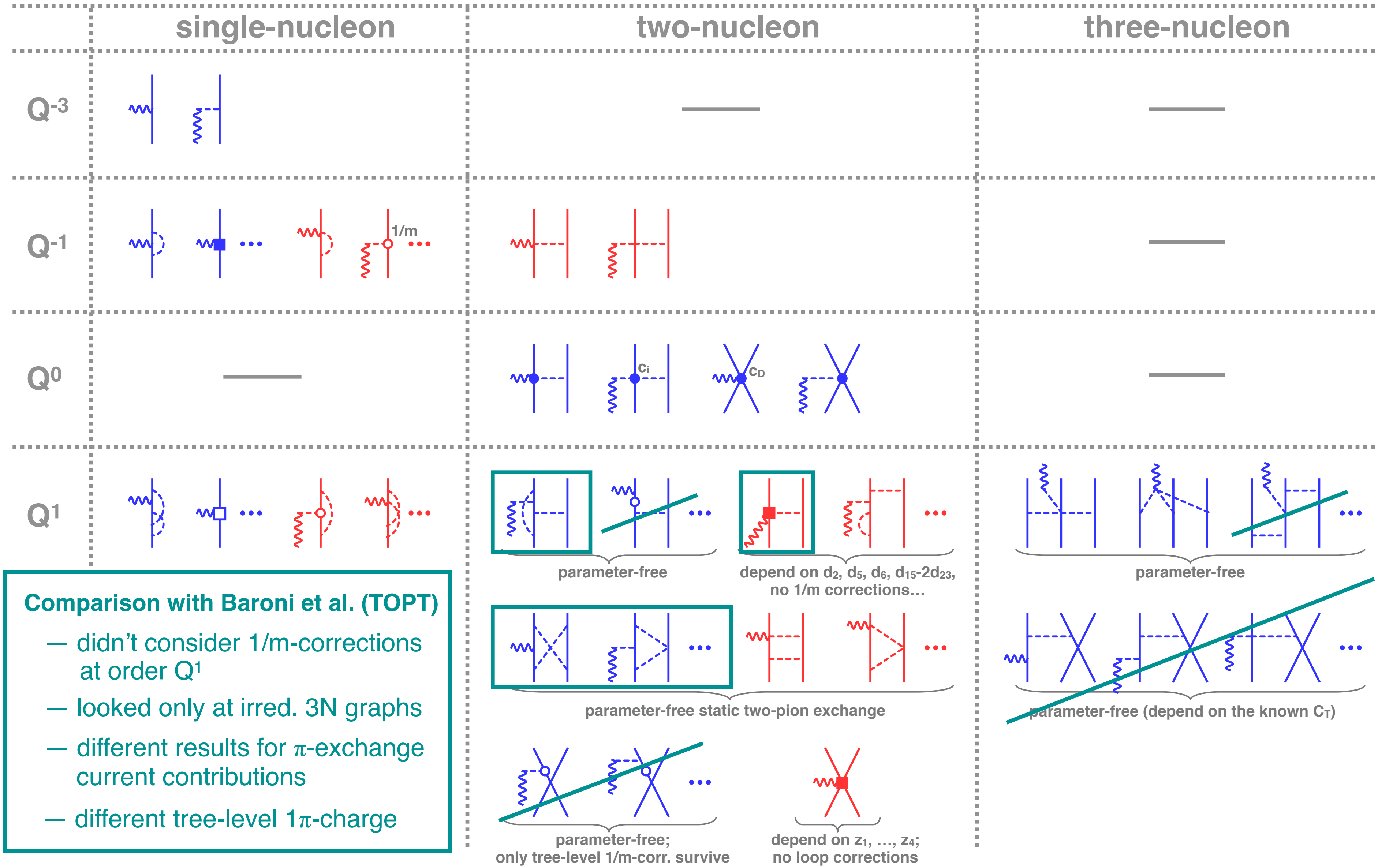


- Hybrid GFMC calculations using AV18 + Urbana 3NF
- Magnetic moments of A = 2, 3 nuclei used to fix EM LECs
- Theoretical uncertainties?

Exchange axial currents

Krebs, EE, Meißner, arXiv:1610.03569

Chiral expansion of the axial current and charge operators



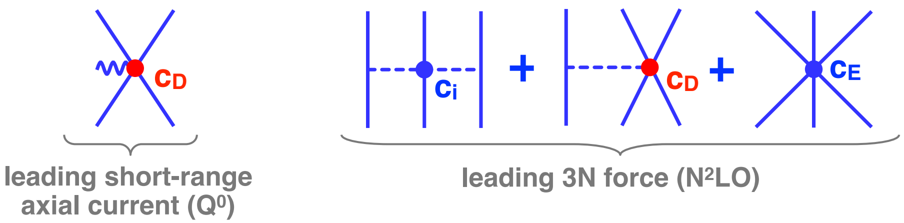
Comparison with Baroni et al. (TOPT)

- didn't consider 1/m-corrections at order Q^1
- looked only at irred. 3N graphs
- different results for π-exchange current contributions
- different tree-level 1π-charge

Tritium β-decay [Skibinski et al., in progress]

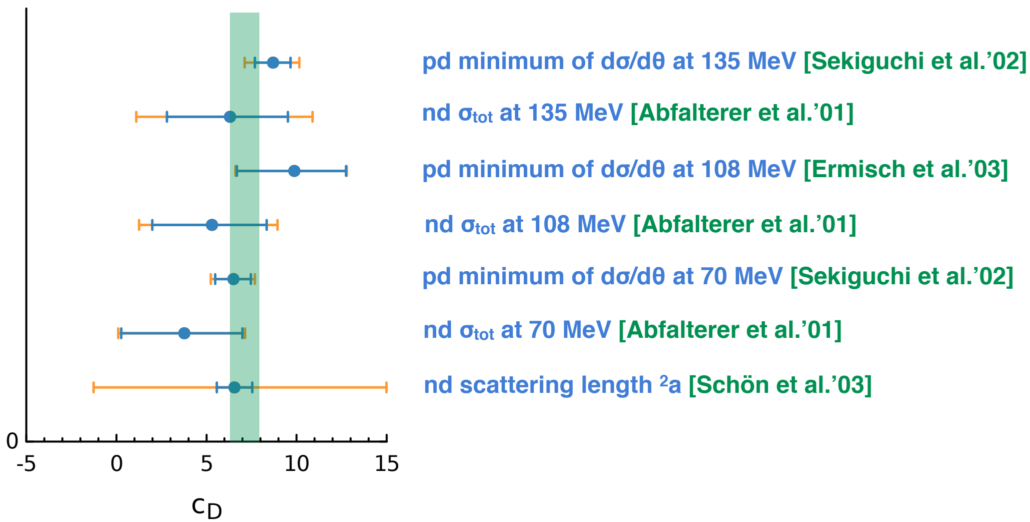
- Half-life of ^{3}H (up to known radiative corrections): $$ft = \frac{K}{G_V^2\langle F\rangle^2 + g_A^2\langle GT\rangle^2} = 1129.6 \pm 3.0\ \mathrm{s}$$
  ⟶ constraints on the Gamow-Teller ME

- Using 1N current, the ***ft*** value is off by ~ 5% ⟵ exchange current contribution!
  Up to Q^1 (i.e. N^{3}LO), no LECs except for known c_i and c_D involved. Fixing c_D in the strong sector allows one to predict ***ft***!
  (it is crucial to maintain the symmetry)
  ⟶ test axial exchange currents



- Within the LENPIC, work is in progress on the determination of c_D.

- Being validated in ^{3}H β-decay, the same currents can be used to predict the μ capture rate on ^{2}H being measured in MuSun



LENPIC: Low Energy Nuclear Physics International Collaboration

Relevance for WIMP-nucleus scattering

Assuming the WIMP χ to be fermion and a SM singlet, the dimension-6 and -7 effective Lagrangian for χ-SM fields has the form **[Goodman et al. '10; Hoferichter et al. '15]**:

Wilson coefficients

$$
\begin{aligned}
\mathcal{L}_\chi \; = \; & \frac{1}{\Lambda^3}\sum_q \Big[C_q^{SS}\bar\chi\chi\, m_q\bar q q + C_q^{PS}\bar\chi i\gamma_5\chi\, m_q\bar q q + C_q^{SP}\bar\chi\chi\, m_q\bar q i\gamma_5 q + C_q^{PP}\bar\chi i\gamma_5\chi\, m_q\bar q i\gamma_5 q \Big] \\
& + \frac{1}{\Lambda^2}\sum_q \Big[C_q^{VV}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q + C_q^{AV}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu q + C_q^{VA}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu\gamma_5 q + C_q^{AA}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu\gamma_5 q \\
& \qquad + C_q^{TT}\bar\chi\sigma^{\mu\nu}\chi\,\bar q\sigma_{\mu\nu} q + \tilde C_q^{TT}\bar\chi\sigma^{\mu\nu} i\gamma_5\chi\,\bar q\sigma_{\mu\nu} q \Big] \\
& + \frac{1}{\Lambda^3}\Big[C_g^S\bar\chi\chi\,\alpha_s G^a_{\mu\nu}G_a^{\mu\nu} + C_g^P\bar\chi i\gamma_5\chi\,\alpha_s G^a_{\mu\nu}G_a^{\mu\nu} + \tilde C_g^S\bar\chi\chi\,\alpha_s G^a_{\mu\nu}\tilde G_a^{\mu\nu} + \tilde C_g^P\bar\chi i\gamma_5\chi\,\alpha_s G^a_{\mu\nu}\tilde G_a^{\mu\nu} \Big]
\end{aligned}
$$

scale of new physics

…can be viewed as external sources in QCD…

- Vector, axial-vector and pseudoscalar 2N currents have been worked out at order Q^4 (leading 1-loop) **[Pastore et al.'08; Kölling et al.'09,'11; Krebs et al.'15; Hoferichter et al.'15]**

- Scalar exchange currents are only available at tree level **[Cirigliano et al.'14]**, derivation of the leading loop corrections in progress **[Krebs et al., in preparation…]**

The future

What are the frontiers/challenges for the near future?

Precision physics beyond the 2N system: challenge the theory

- Lots of predictive power (N^3LO contributions to the 3NF and 4NF are parameter-free, ^3H β-decay & μ-capture reactions are parameter-free up to N^3LO once the short-range 3NF@N^2LO is fixed, …)
- 3NF & long-standing puzzles in 3N continuum
- Push theory to heavier nuclei (underbinding? radii?)
- More reliable error analysis
- Test different power counting schemes

Nuclear reactions

Chiral EFT as a tool to deal with nuclear effects when looking at physics of/beyond the SM (parity violation, EDM, 0νββ, proton charge radius,…)

EFT for lattice QCD (extrapolations), lattice QCD for EFT (quark mass dependence, „data“, …)