CHIRAL NUCLEAR DYNAMICS

Ulf-G. Meißner, Univ. Bonn & FZ Jülich

Supported by DFG, SFB/TR-16 and by DFG, SFB/TR-110 and by EU, I3HP EPOS and by BMBF 05P12PDFTE and by HGF VIQCD VH-VI-417

CONTENTS

- Short Introduction
- Continuum: New developments
- Lattice: New results
- Summary & outlook

Short introduction

NUCLEAR CHIRAL EFFECTIVE FIELD THEORY

- The silver jubilee of Weinberg's work extending chiral EFTs to nuclear physics

> S. Weinberg,
> "Nuclear forces from chiral Lagrangians,"
> Phys. Lett. B **251** (1990) 288 [submitted 14 August 1990].
> 921 citations counted in INSPIRE as of 04 June 2015
>
> S. Weinberg,
> "Effective chiral Lagrangians for nucleon - pion interactions and nuclear forces,"
> Nucl. Phys. B **363** (1991) 3 [submitted 02 April 1991].
> 887 citations counted in INSPIRE as of 04 June 2015

- after 25 years, a mature field? Epelbaum, Hammer, UGM, Rev. Mod. Phys. **81** (2009) 1773

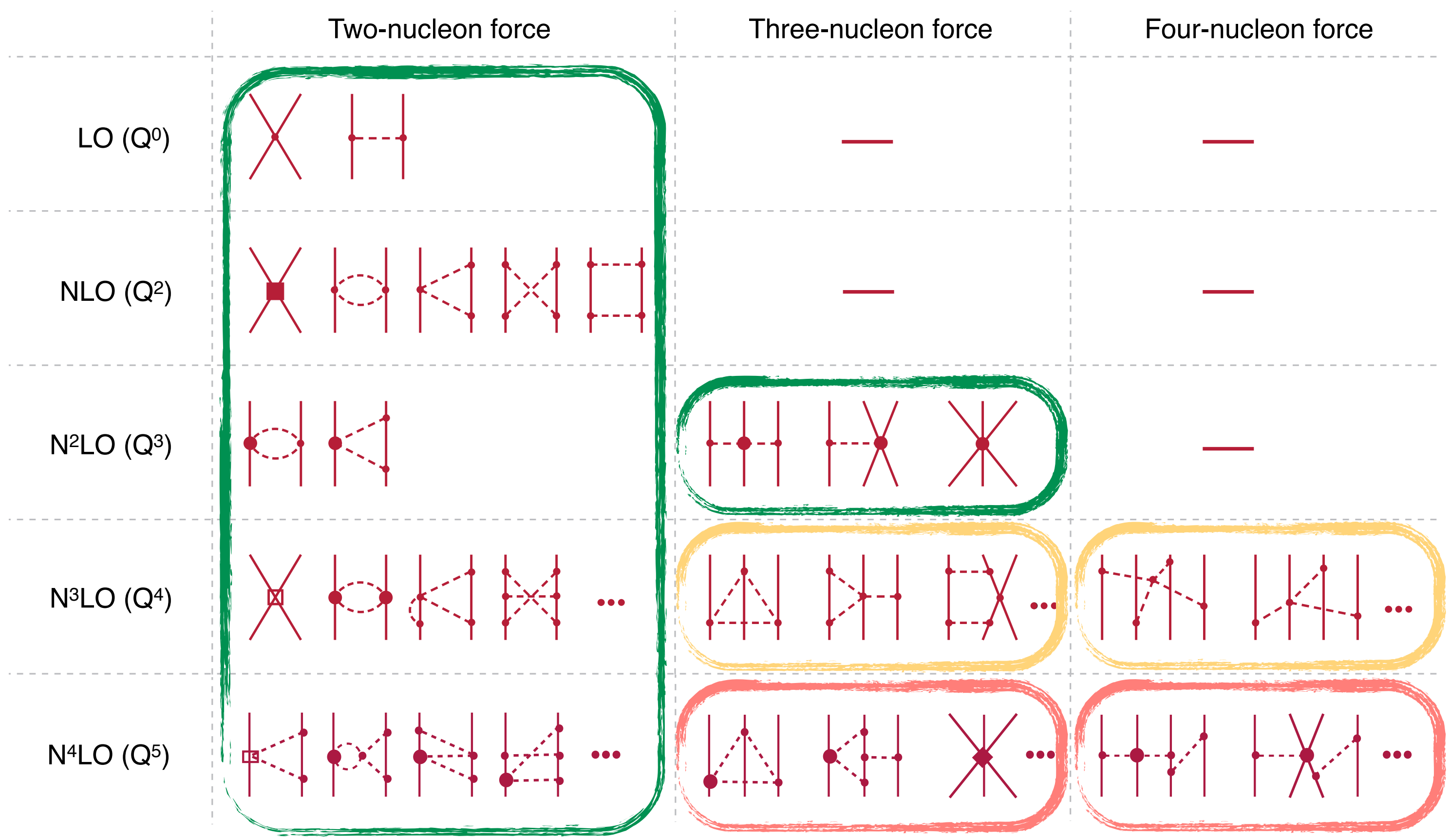
- yes *and* no $\rightarrow$ let's discuss some recent developments

Continuum EFT: new developments

LENPIC

NUCLEAR FORCES in CHIRAL NUCLEAR EFT

- expansion of the potential in powers of Q [small parameter]
- explains observed hierarchy of the nuclear forces



worked out and applied   worked out and to be applied   calculations in progress

NN FORCES to FOURTH ORDER

Epelbaum, Krebs, UGM, Eur. Phys. J. **A 51**: 53 (2015)

- new regularization of long-range physics [coordinate space cut-off]:

$$V^{\rm reg}_{\rm long-range}(\vec{r}) = V_{\rm long-range}(\vec{r}) f_{\rm reg}\left(\frac{r}{R}\right) \;, \quad f_{\rm reg} = \left[1 - \exp\left(-\frac{r^2}{R^2}\right)\right]^6$$

$\Longrightarrow$ No distortion of the long-range potential $\rightarrow$ better at higher energies

$\Longrightarrow$ No additional spectral function regularization in the TPEP required

$\Longrightarrow$ Study of the chiral expansion of multi-pion exchanges: $R = 0.8 \cdots 1.2$ fm

Baru et al., EPJ A48 (12) 69

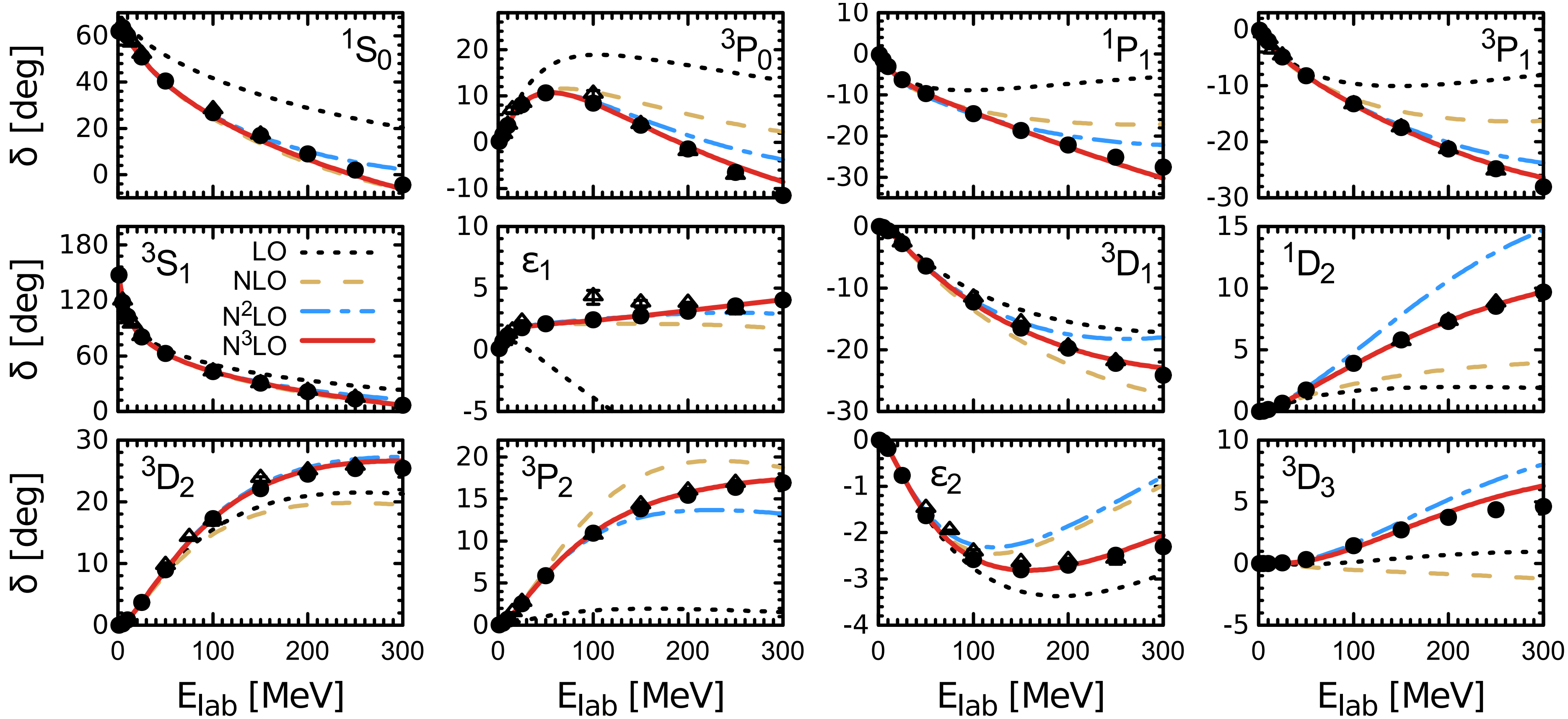
- new way of estimation the theoretical uncertainty [before: only cut-off variations]

$\Longrightarrow$ Expansion parameter depending on the region: $Q = \max\left(\frac{M_\pi}{\Lambda_b}, \frac{p}{\Lambda_b}\right)$

$\Longrightarrow$ Breakdown scale $\Lambda_b = 600$ MeV for $R = 0.8 \cdots 1.0$ fm

CONVERGENCE of the CHIRAL SERIES

- phase shifts show expected convergence [large N2LO corrections understood]

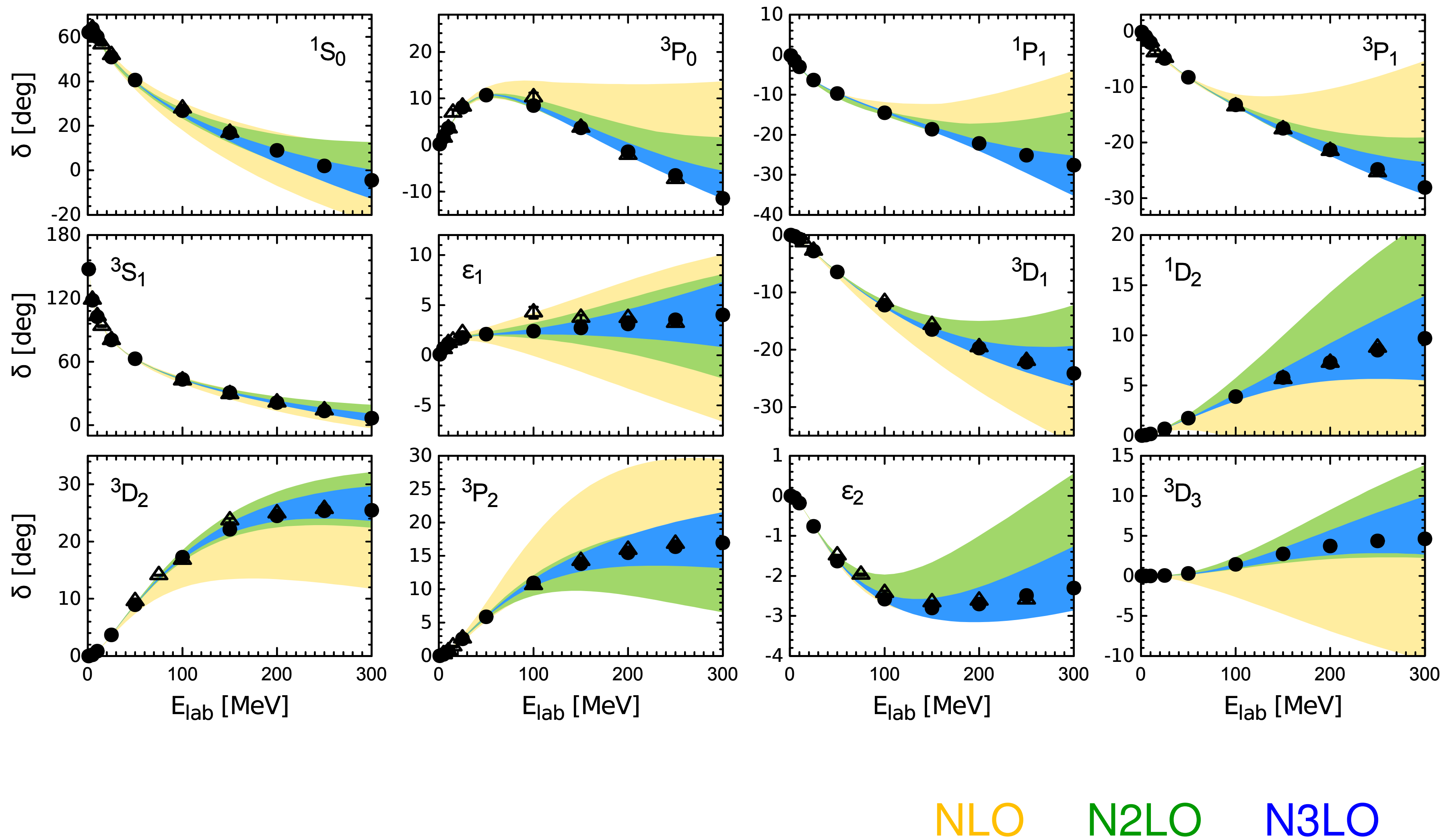


$\Longrightarrow$ clear improvement comp. to earlier N3LO potentials [momentum space reg.]

Entem, Machleidt; Epelbaum, Glöckle, UGM

UNCERTAINTIES

- uncertainties show expected pattern



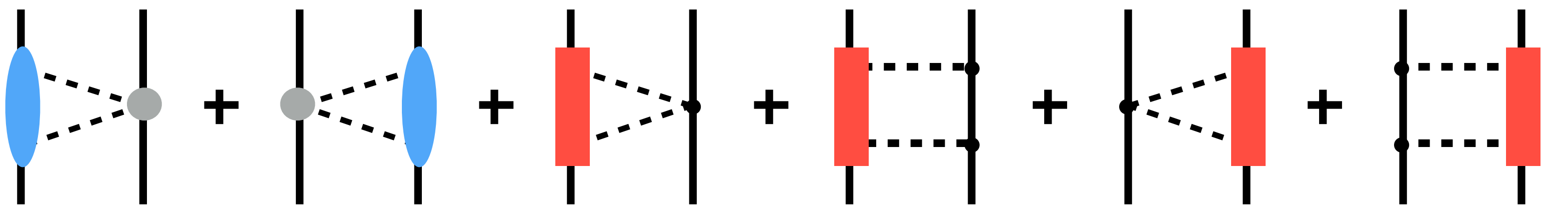
NN FORCES to FIFTH ORDER

Epelbaum, Krebs, UGM, arXiv:1412.4623

- No contact interactions at this order - odd in Q

- New contributions fixed from πN scattering, LECs c_i, d_i, e_i:

Büttiker, Fettes, UGM, Steininger (1998-2000); Krebs, Gasparian, Epelbaum (2012)



$$\mathcal{L}_{\pi N} = \mathcal{L}_{\pi N}^{(1)} + \mathcal{L}_{\pi N}^{(2)}(c_i) + \mathcal{L}_{\pi N}^{(3)}(d_i) + \mathcal{L}_{\pi N}^{(4)}(e_i)$$

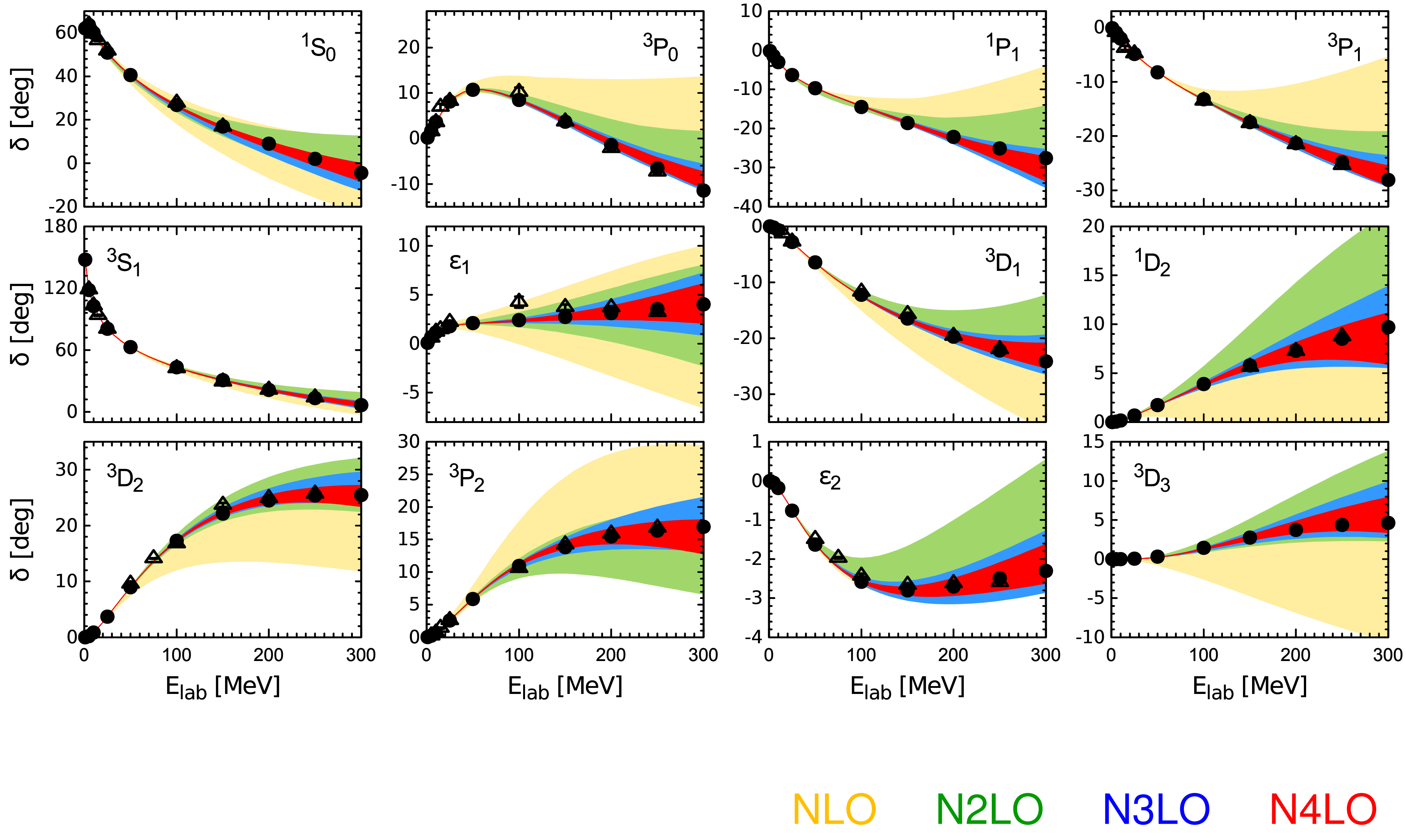
- Three-pion exchange can be neglected

  $\rightarrow$ explicit calculation of the dominant NLO contribution — Kaiser (2001)

  $\rightarrow$ no influence on phase shifts or deuteron properties

PHASE SHIFTS at N4LO

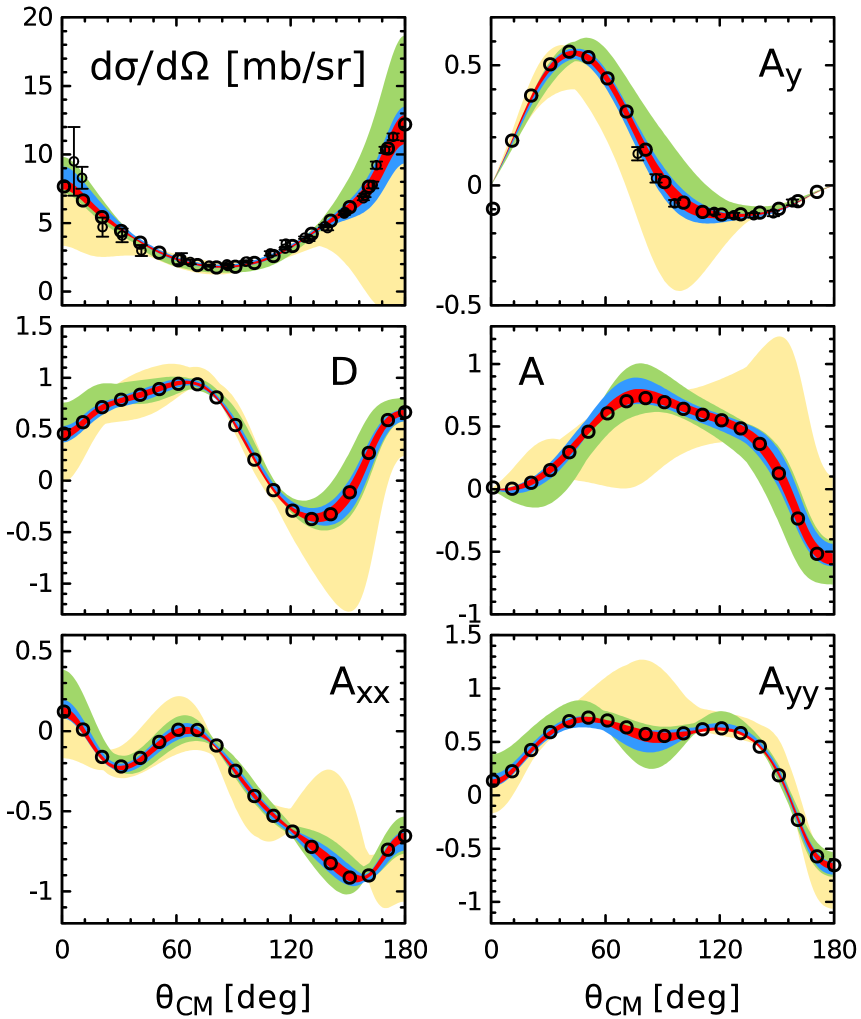
$\Rightarrow$ Precision phase shifts with small uncertainties up to $E_{\rm lab} = 300$ MeV



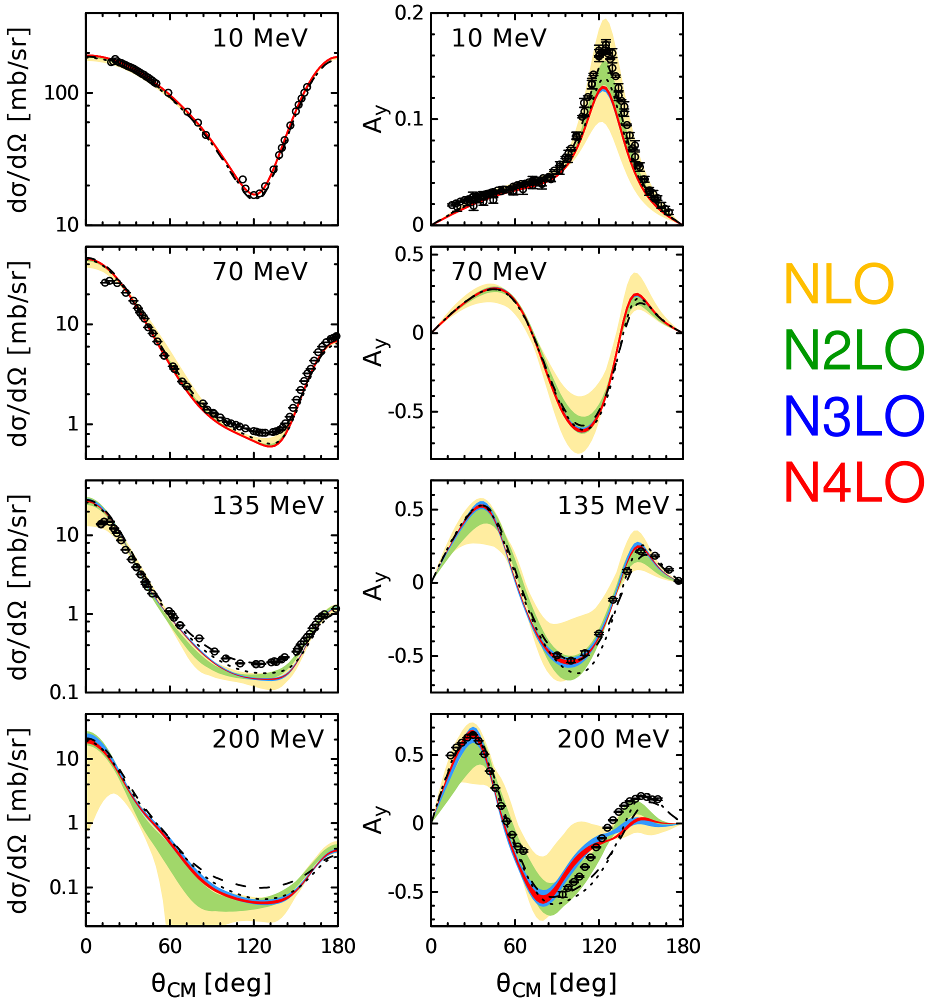
EVIDENCE for THREE-NUCLEON FORCES

- Two-nucleon system under control, three-nucleon system requires 3NFs!
  → being implemented [LENPIC collaboration]

- np scattering at 200 MeV



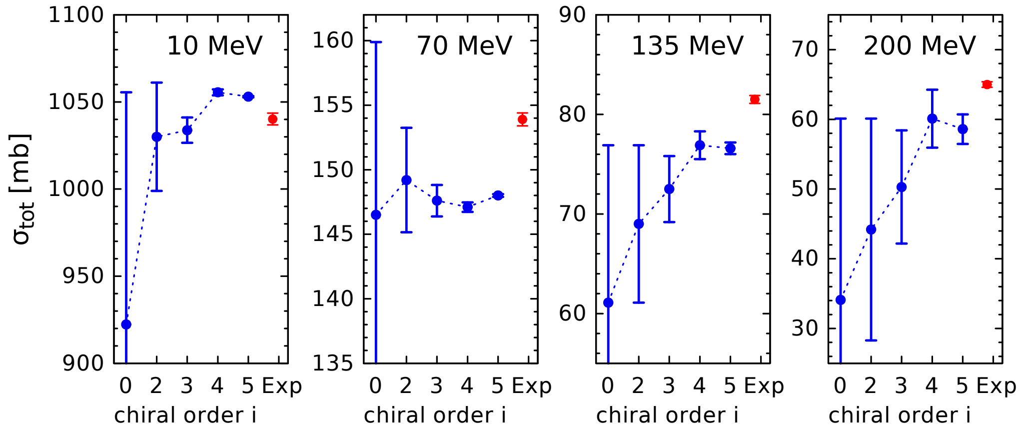
- nd scattering [2NFs only]



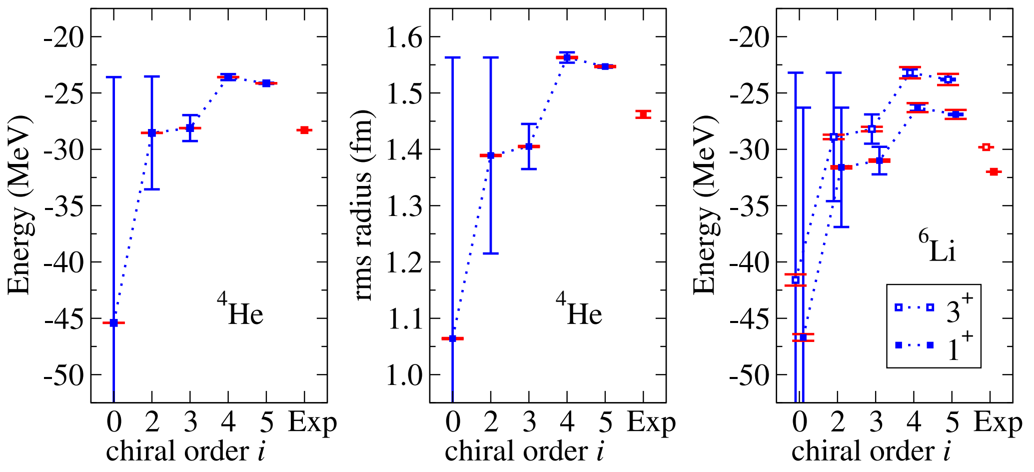
MORE EVIDENCE for THREE-NUCLEON FORCES

Binder et al. [LENPIC collaboration], arXiv:1505.07218

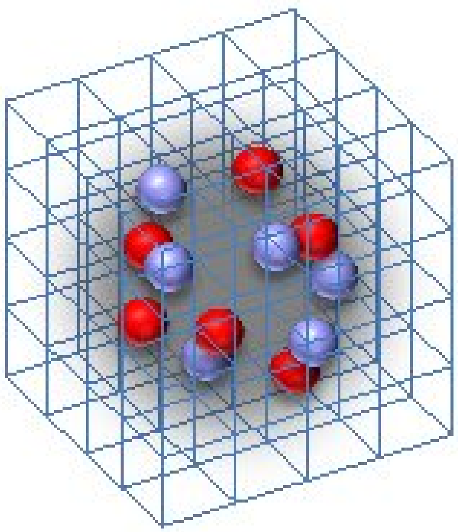
- Total cross section for Nd scattering [2NFs only]



- Binding energy and rms radius of ^{4}He, lowest levels in ^{6}Li [2NFs only]



Lattice: new results



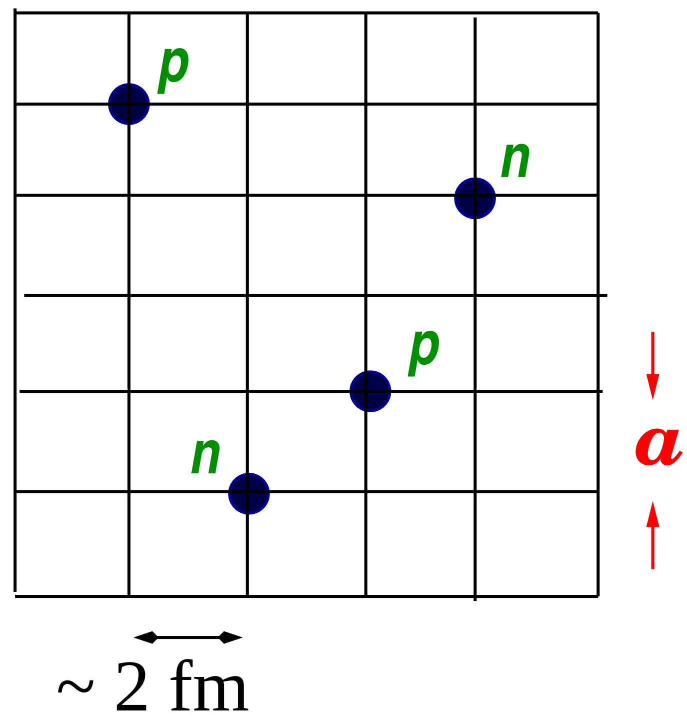
NLEFT

THE TOOL: NUCLEAR LATTICE SIMULATIONS

Frank, Brockmann (1992), Koonin, Müller, Seki, van Kolck (2000) , Lee, Schäfer (2004), . . .
Borasoy, Krebs, Lee, UGM, Nucl. Phys. **A768** (2006) 179; Borasoy, Epelbaum, Krebs, Lee, UGM, Eur. Phys. J. **A31** (2007) 105

- *new method* to tackle the nuclear many-body problem
- discretize space-time $V = L_s \times L_s \times L_s \times L_t$:
  nucleons are point-like fields on the sites
- discretized chiral potential w/ pion exchanges
  and contact interactions + Coulomb
- typical lattice parameters

$$\Lambda = \frac{\pi}{a} \simeq 300 \text{ MeV [UV cutoff]}$$

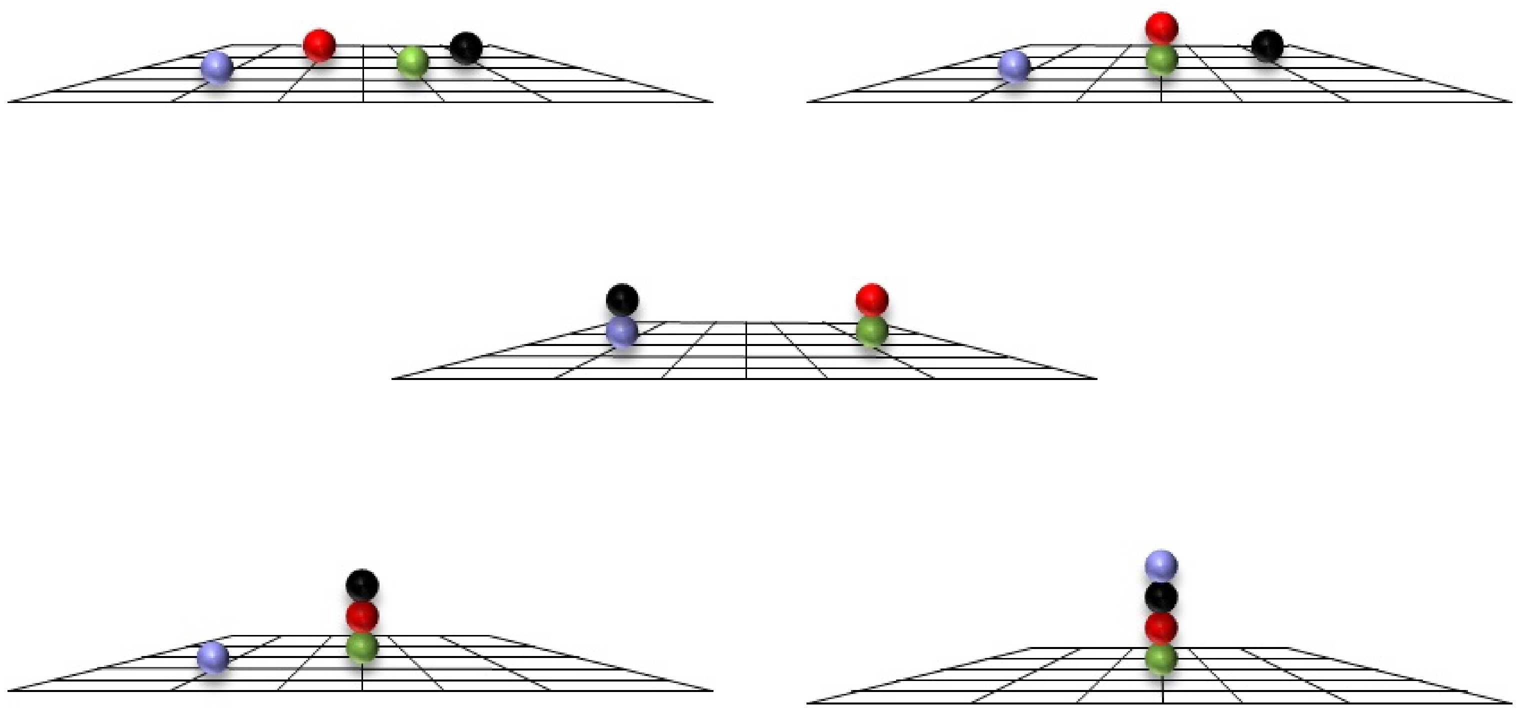


- strong suppression of sign oscillations due to approximate Wigner SU(4) symmetry

J. W. Chen, D. Lee and T. Schäfer, Phys. Rev. Lett. **93** (2004) 242302, T. Lähde et al., *arXiv:1502.06787*

- hybrid Monte Carlo & transfer matrix (similar to LQCD)

CONFIGURATIONS



⇒ all *possible* configurations are sampled

⇒ *clustering* emerges *naturally*

COMPUTATIONAL EQUIPMENT

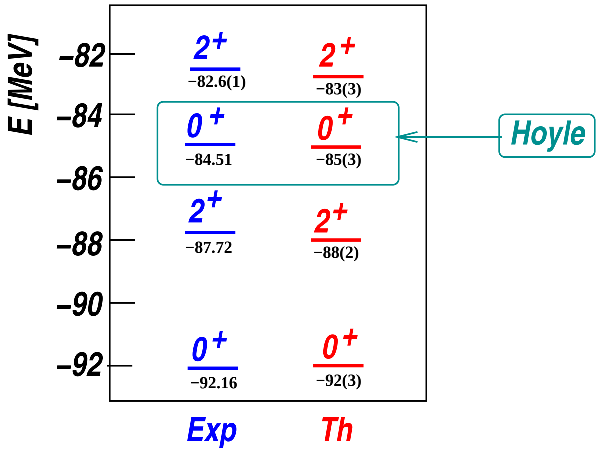
- Present = JUQUEEN (BlueGene/Q)

6 Pflops

RESULTS from LATTICE NUCLEAR EFT

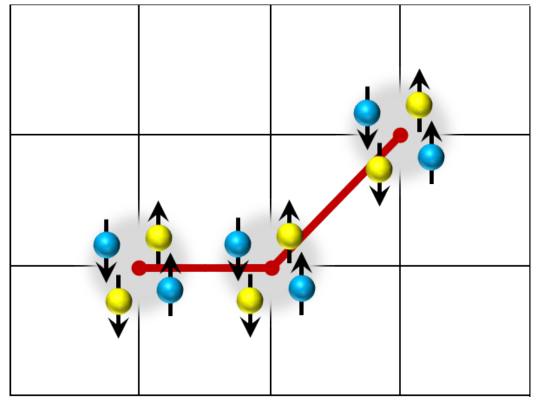
- Hoyle state in ^{12}C

PRL 106 (2011)



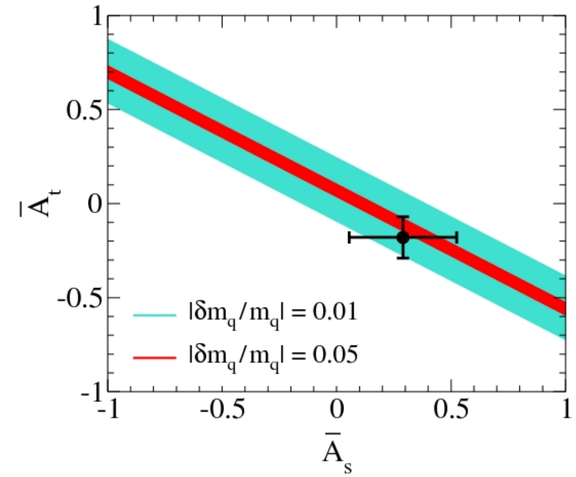
- Structure of the Hoyle state

PRL 109 (2012)



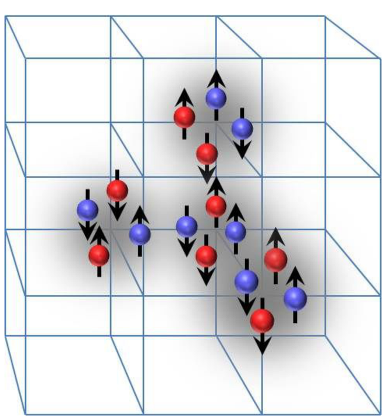
- Fate of carbon-based life

PRL 110 (2013), EPJ A49 (2013)



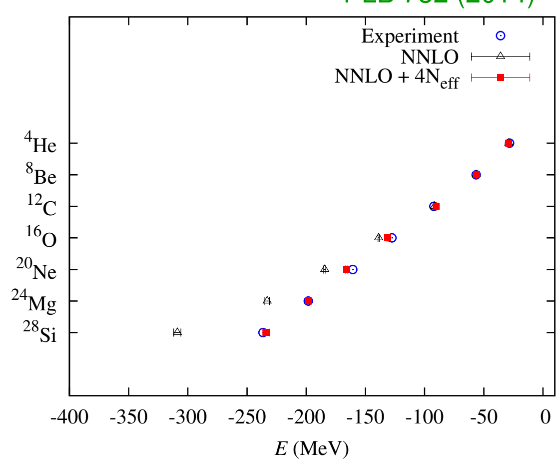
- Spectrum of ^{16}O

PRL 112 (2014)



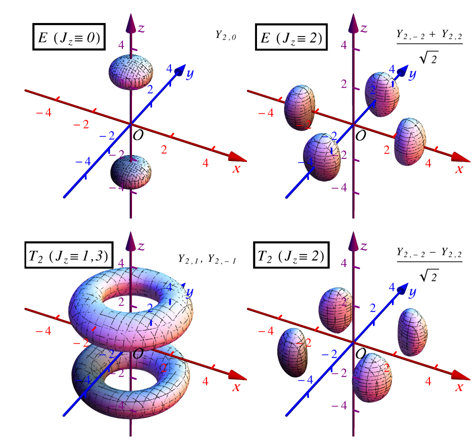
- Going up the α-chain

PLB 732 (2014)



- Rot. symmetry breaking

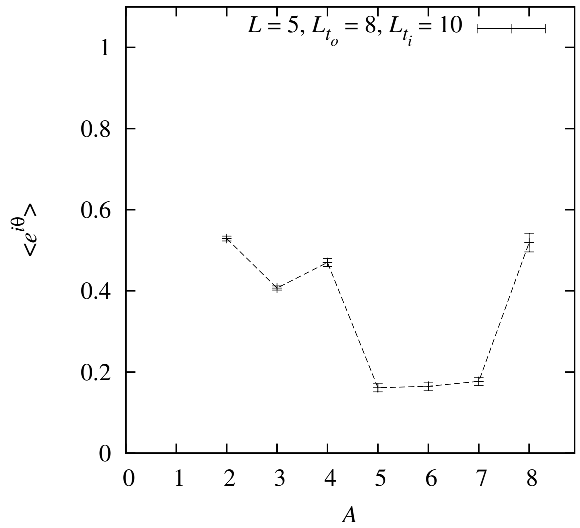
PRD 90 (2014)



SYMMETRY-SIGN EXTRAPOLATION METHOD

Epelbaum, Krebs, Lähde, Lee, Luu, UGM, Rupak, arXiv:1502.06787

- so far: nuclei with $N = Z$, and $A = 4 \times \text{int}$
  as these have the least sign problem
  due to the approximate SU(4) symmetry



Borasoy et al. (2007)

$$\langle \text{sign} \rangle = \langle \exp(i\theta) \rangle = \frac{\det M(t_o, t_i, \ldots)}{|\det M(t_o, t_i, \ldots)|}$$

$M(t_o, t_i, \ldots)$ is the transition matrix

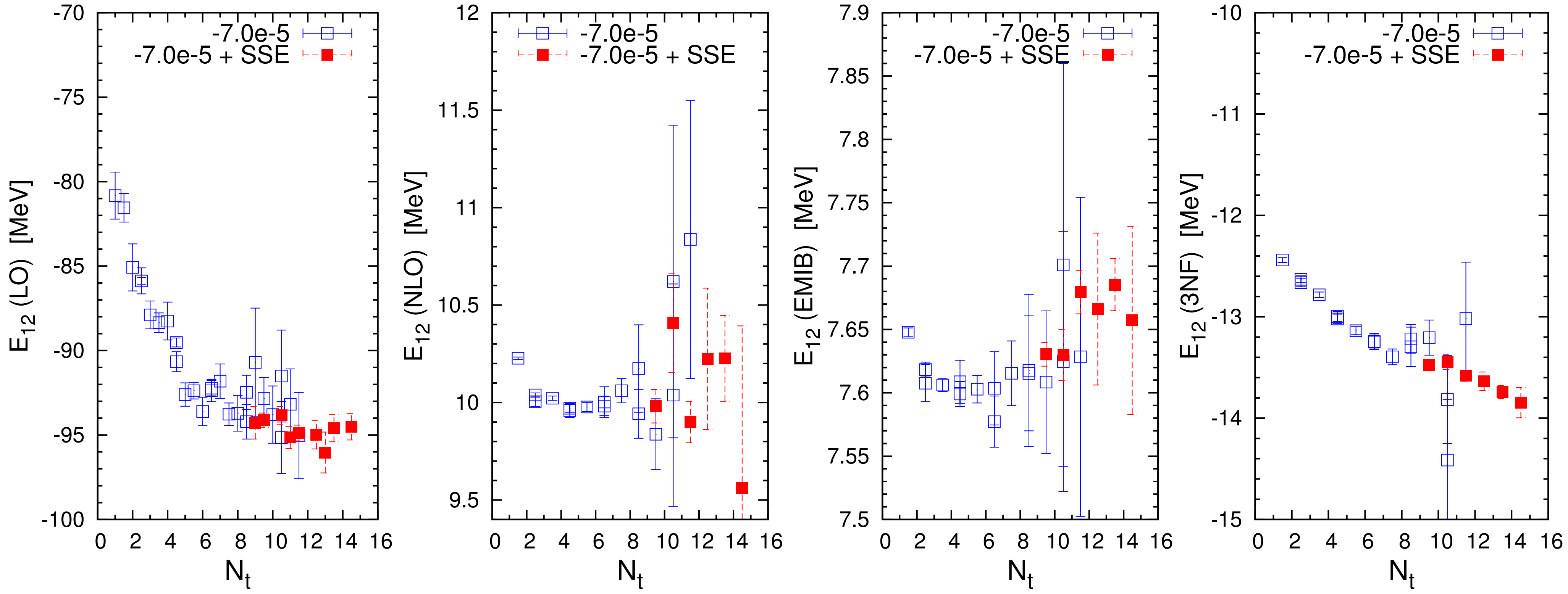
- Symmetry-sign extrapolation (SSE) method: control the sign oscillations

$$H_{d_h} = d_h \cdot H_{\text{phys}} + (1 - d_h) \cdot H_{\text{SU}(4)} \qquad H_{\text{SU}(4)} = \frac{1}{2} C_{\text{SU}(4)} \, (N^\dagger N)^2$$

$\hookrightarrow$ family of solutions for different SU(4) couplings $C_{\text{SU}(4)}$
that converge on the physical value for $d_h = 1$

RESULTS for ^{12}C

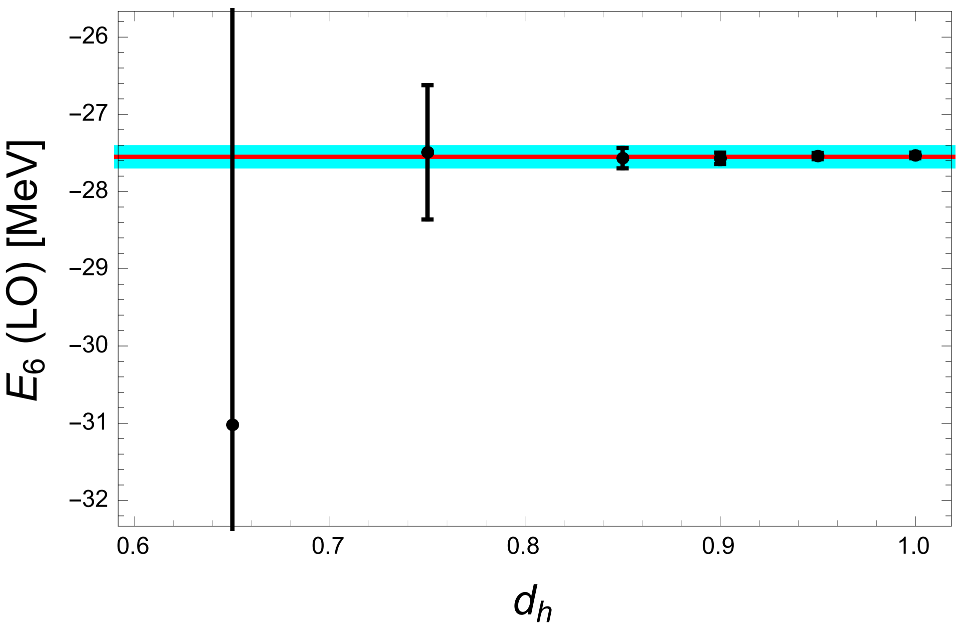
- generate a few more MC data at large N_t using SSE

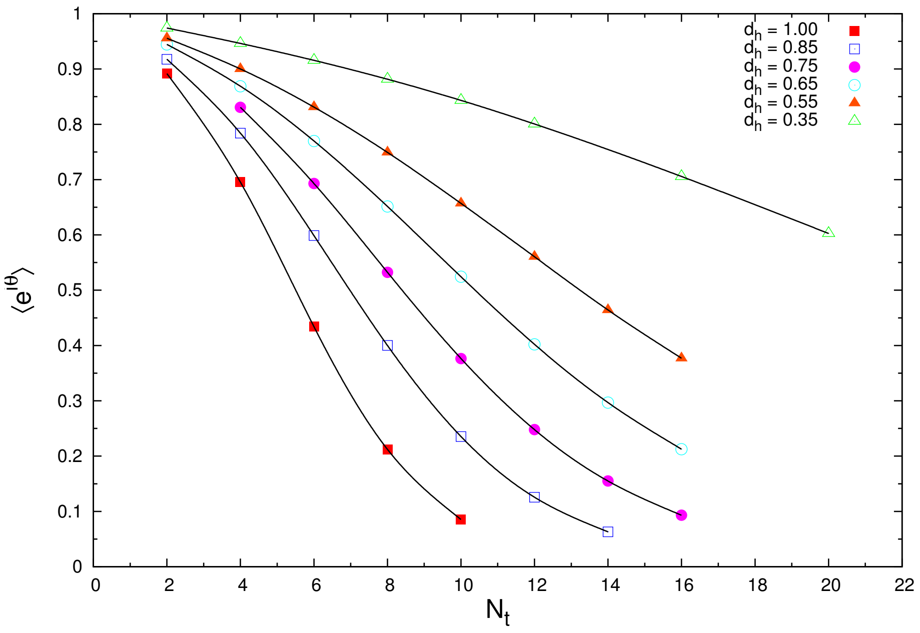


- promising results $\rightarrow$ no more exponential deterioration of the MC data
- results w/ small uncertainties for $d_h \geq 0.8$

RESULTS for $A = 6$

- Simulations for ^{6}He and ^{6}Be





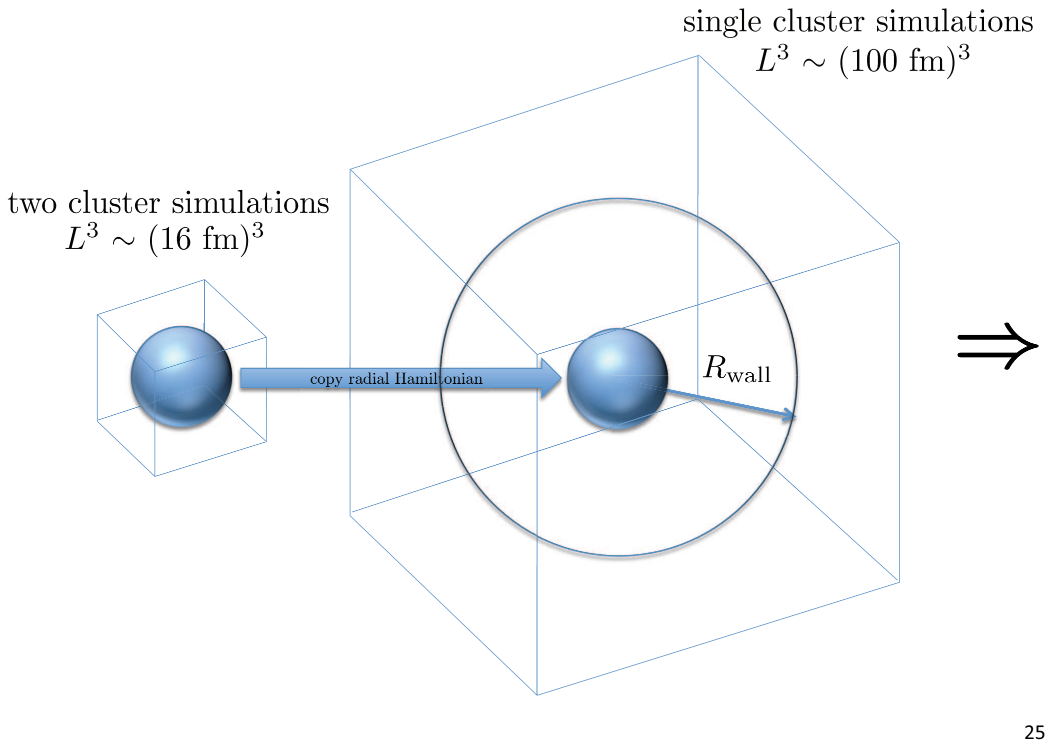
⇒ methods works for nuclei with $A \neq Z$

⇒ neutron-rich nuclei can now be systematically explored (larger volumes)

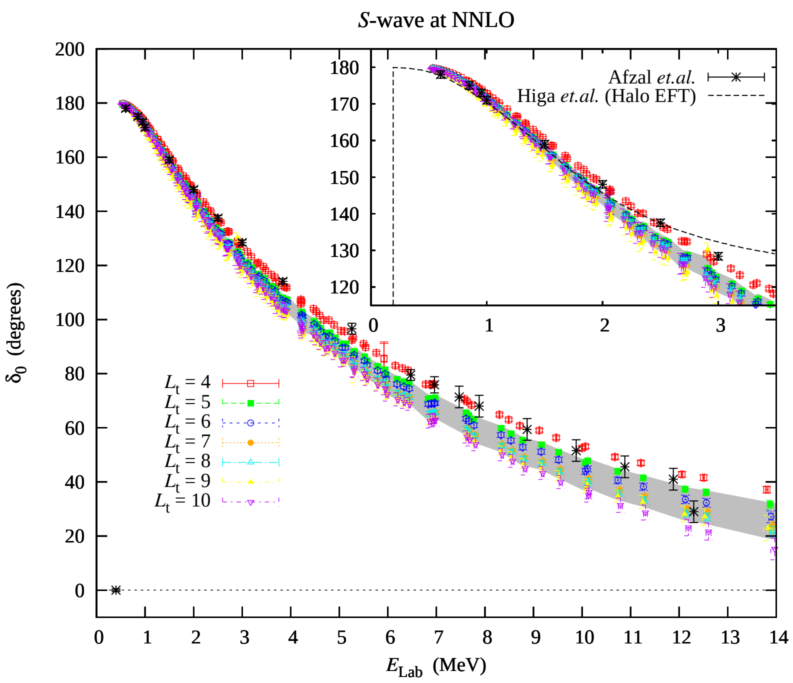
AB INITIO CALCULATION of α-α SCATTERING

- use lattice MC to construct an ab-initio cluster (adiabatic) Hamiltonian
- Use adiabatic Hamiltonian to compute scattering/reaction amplitudes

Elhatisari et al. 2015



$\Rightarrow$



- D-wave equally well described

SUMMARY & OUTLOOK

- Chiral nuclear EFT: best approach to nuclear forces and few-body systems
  - $\rightarrow$ new, solid method to estimate the theoretical uncertainties
  - $\rightarrow$ high-precision NN potential to fifth order available
  - $\rightarrow$ pinning down the 3NFs under way
- Nuclear lattice simulations as a new quantum many-body approach
  - $\rightarrow$ clustering emerges naturally, α-cluster nuclei
  - $\rightarrow$ symmetry-sign extrapolation method allows to go to the drip lines
  - $\rightarrow$ holy grail of nuclear astrophysics (α+^{12}C $\rightarrow$ ^{16}O+γ) in reach