Evgeny Epelbaum, Ruhr-University Bochum

KHuK Jahrestagung, Bad Honnef, 5. Dezember 2015

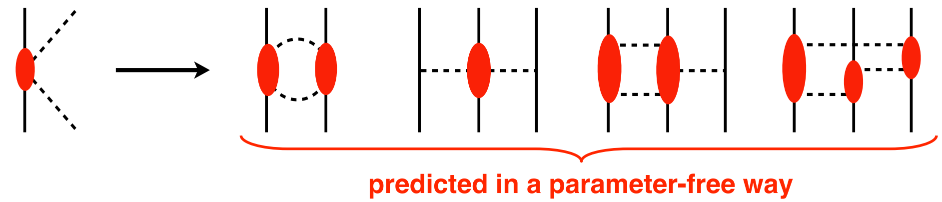
Aktuelle Entwicklungen in der Theorie:
Ab initio Beschreibung der Kerne

- Low-energy pion-nucleon dynamics
- Chiral nuclear forces in the precision era
- Nuclear lattice simulations: recent highlights
- Medium-mass nuclei and nuclear matter
- Nuclear systems from lattice QCD
- Summary

Disclaimer: apologies for not being able to show other results…

Low-energy pion-nucleon dynamics

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



Pion-nucleon Roy-Steiner equations

M. Hoferichter, J. Ruiz de Elvira, B. Kubis, U.-G. Meißner, PRL 115 (2015) 092301; arXiv:1510.06039 [hep-ph]

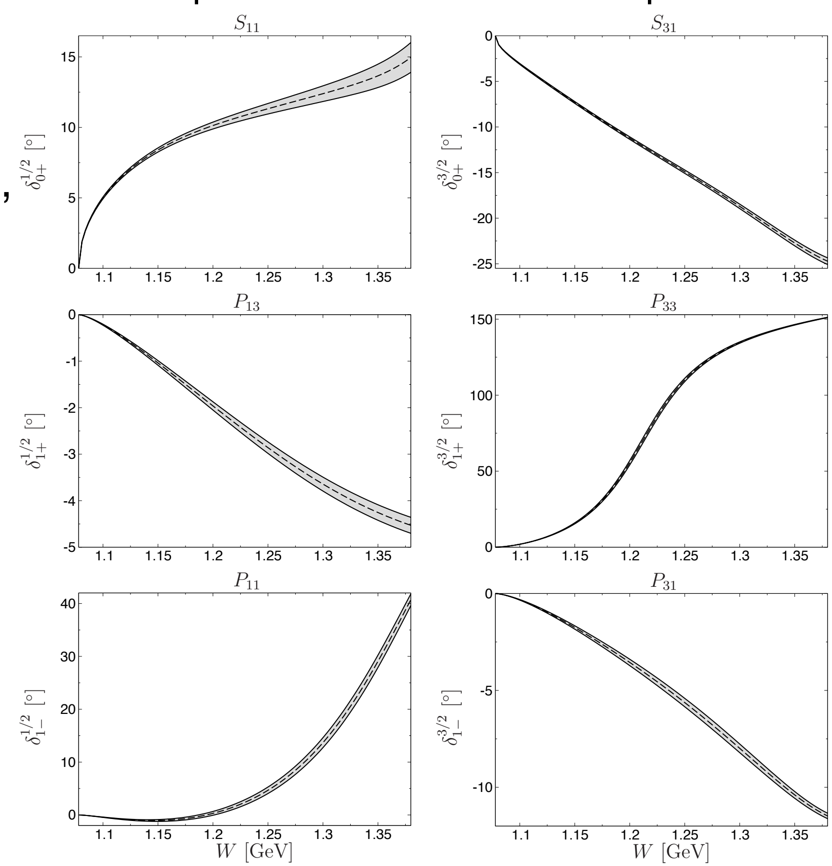
Integral equations in the form of dispersion relations which incorporate constraints from analyticity, unitarity & crossing symmetry

Input: S-,P-waves at high energy, inelasticities, D- and higher waves + scatt. lengths from hadronic atoms

Output: reliable results for S-,P-waves with systematic uncertainties; subthreshold coef-ficients, determination of the σ-term:

$$\sigma_{\pi N} = 59.1 \pm 3.5\,\text{MeV}$$

πN phase shifts from the RS equations



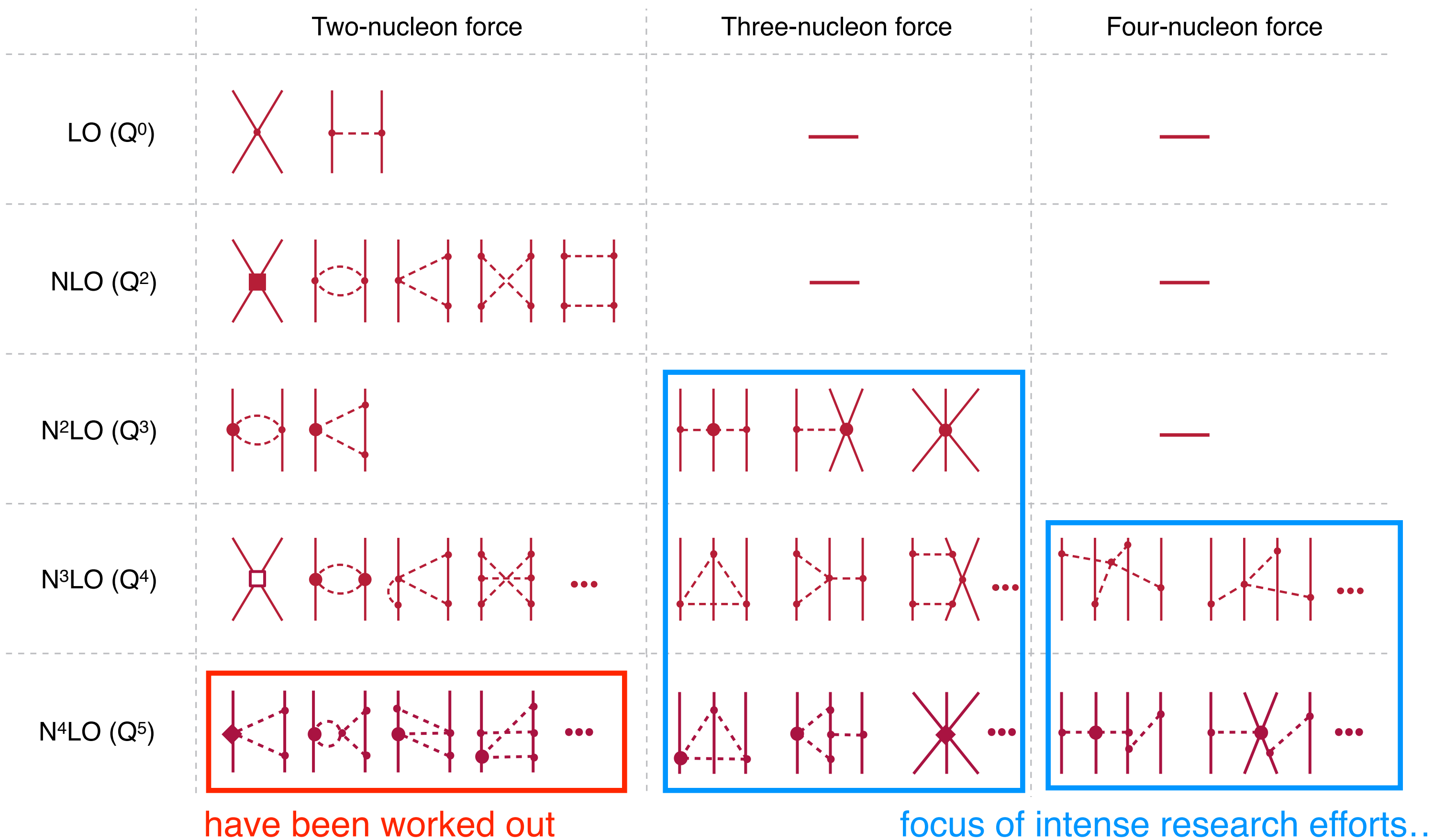
ChPT for πN, πN → $\pi\pi$N with/without Δ(1232)

Siemens et al., PRC 89 (2014) 065211; to appear

Baryon ChPT beyond the low-energy region

EE, J. Gegelia, U.-G. Meißner, D.-L. Yao, EPJ C75 (2015) 499

Chiral nuclear forces



Entem, Kaiser, Machleidt, Nosyk, PRC 91 (2015) 014002
EE, Krebs, Meißner, PRL 115 (2015) 122301

Why is it necessary/interesting to extend the χ-expansion of the NN potential to Q^5?

— no additional parameters (except for 1 IB term) ➙ testing the theory (long-range physics)

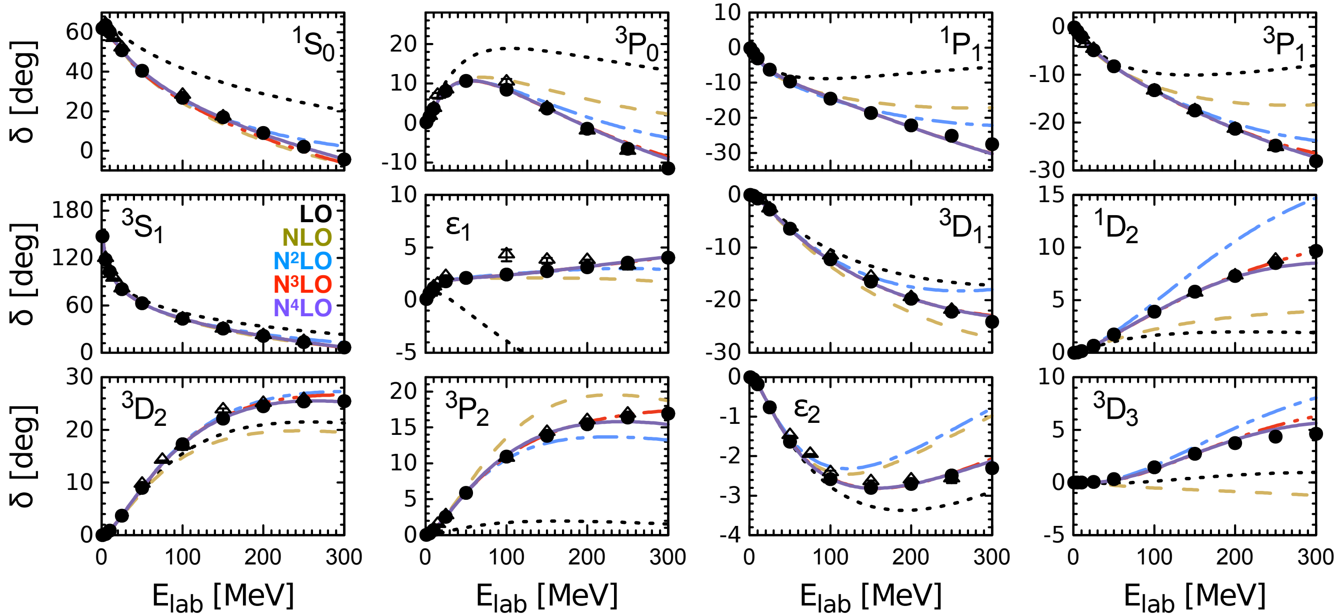
— there is evidence that χ-expansion for the 3NF is not yet converged at Q^4

— understanding fine details of the 3NF requires accurate and precise NN forces

Chiral nuclear forces

New state-of-the-art chiral NN potentials up to N⁴LO

EE, Krebs, Meißner, EPJA 51 (2015) 53; PRL 115 (2015) 122301



— improved UV regulator maintains the analytic structure of the amplitude

— all LECs in the long-range part are taken from πN scattering, no fine tuning!

— coupled with the novel approach for uncertainty quantification, provides the tool for next-generation precision ab initio studies

Quality of the reproduction of the Nijmegen PWA („χ^2_{datum}“)

E_{lab} bin	LO [Q^0]	NLO [Q^2]	N^{2}LO [Q^3]	N^{3}LO [Q^4]	N^{4}LO [Q^5]
neutron-proton phase shifts					
0–100	360	31	4.5	0.7	0.3
0–200	480	63	21	0.7	0.3
proton-proton phase shifts					
0–100	5750	102	15	0.8	0.3
0–200	9150	560	130	0.7	0.6

NLO → N²LO: no new LECs (np); N³LO → N⁴LO: 1 LEC ($^1S_0$) (np); N³LO → N⁴LO: no new LECs (pp)

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

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 $\Lambda_b \sim 600$ MeV

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

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

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

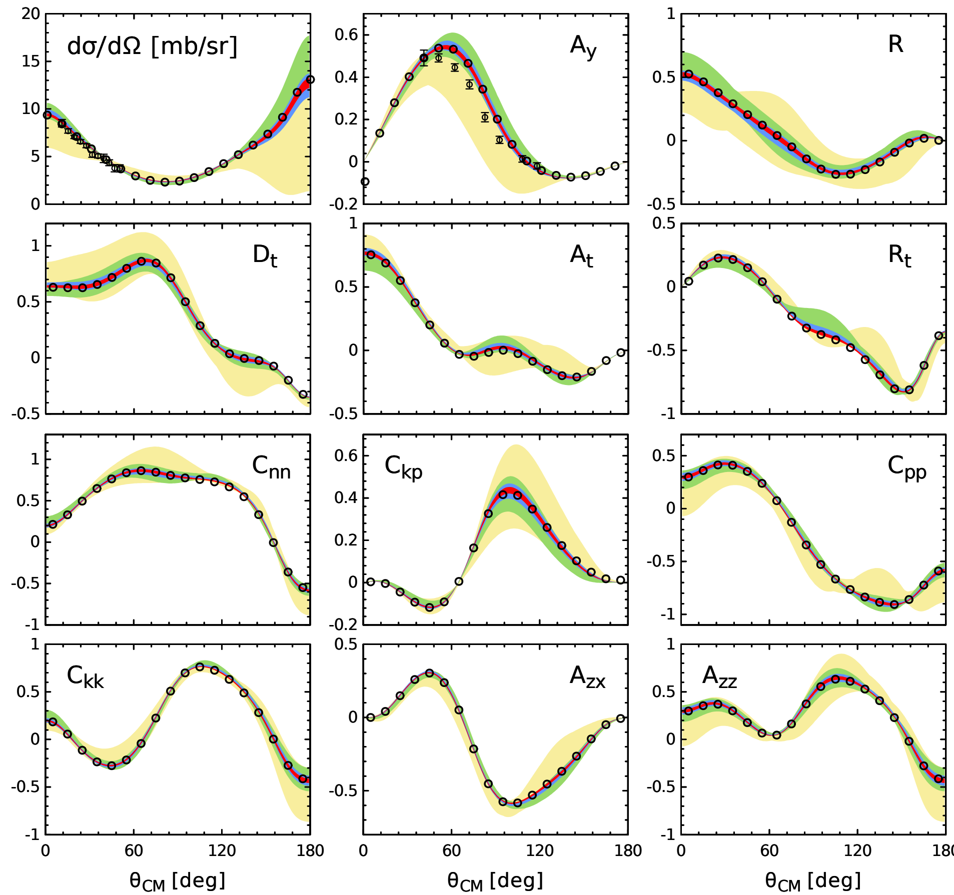
subject to the additional constraint

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

- no reliance on the cutoff variation (not reliable)
- easily applicable to any observable (scattering, bound states, 3N, …)
- error bars 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



3N force studies

With these tools, we are well equipped to tackle the 3N force problem.

Is there any clear evidence for missing 3N forces effects? **Yes!** Binder et al., arXiv: 1505.07218 [nucl-th]

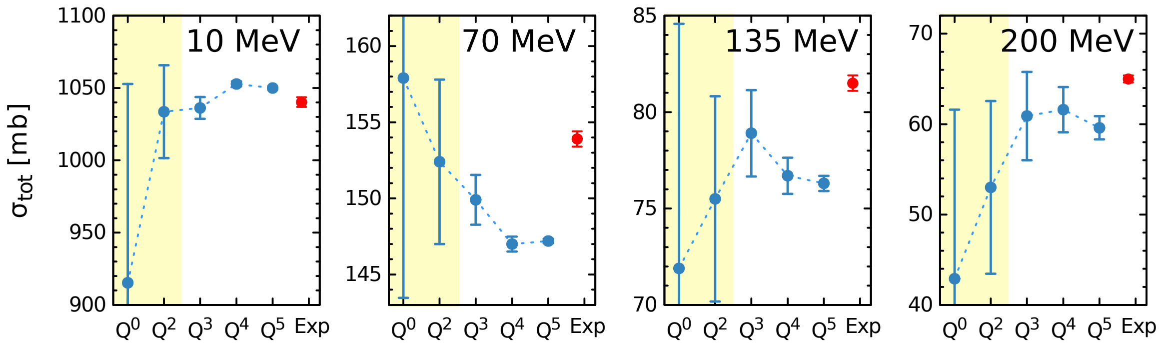
- Discrepancies between theory and data well outside the range of quantified uncertainties

  → unambiguous evidence for missing 3NF effects!

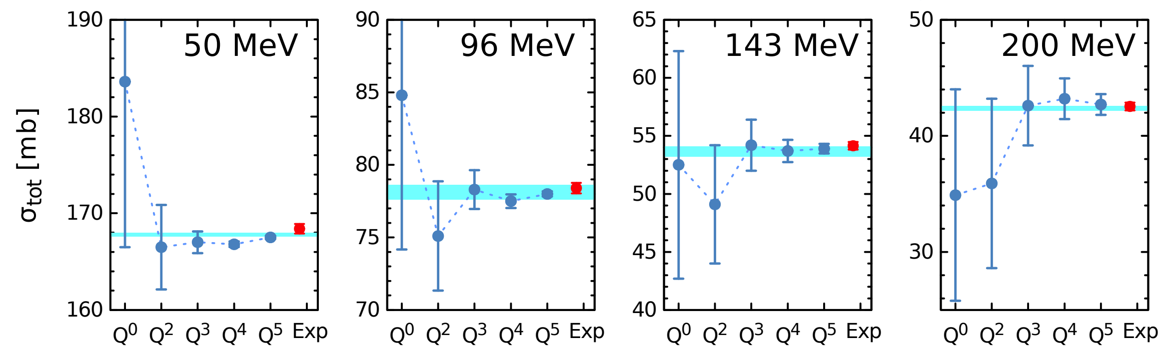
- The magnitude of the required 3NF contributions matches well the estimated size of N^{2}LO terms

  → consistent with the chiral power counting!

total cross section in nD scattering calculated without 3NF



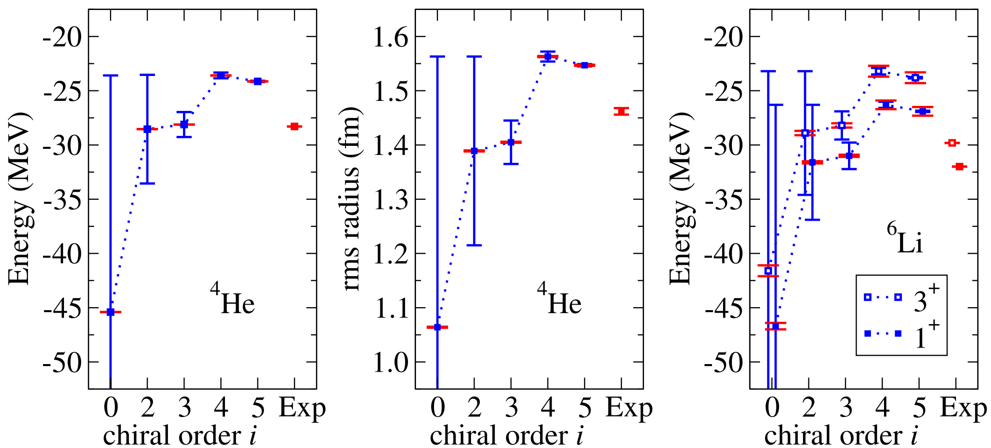
total cross section in np scattering



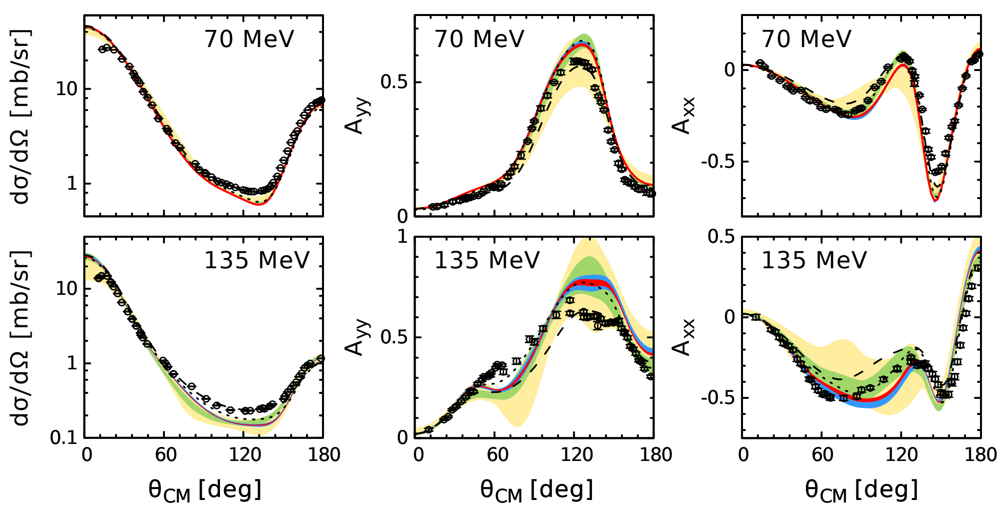
LENPIC: Low **E**nergy **N**uclear **P**hysics **I**nternational **C**ollaboration

RUB universitätbonn TECHNISCHE UNIVERSITÄT DARMSTADT JAGIELLONIAN UNIVERSITY IN KRAKOW STATE JÜLICH FORSCHUNGSZENTRUM Kyutech THE OHIO STATE UNIVERSITY IPN ORSAY TRIUMF OAK RIDGE National Laboratory

3N force studies



Similar pattern is observed for the properties of the light nuclei



Elastic nd scattering at intermediate energies:
The golden window to probe the (spin structure) of the 3NF

Next step: inclusion of the 3NF (LENPIC, work in progress)

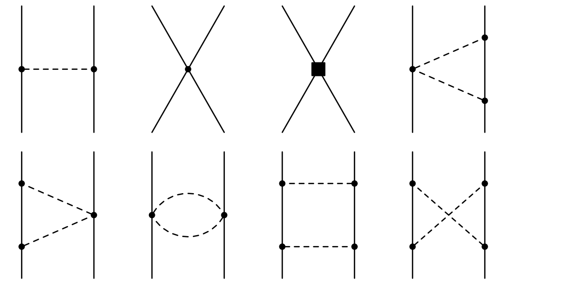
LENPIC: Low **E**nergy **N**uclear **P**hysics **I**nternational **C**ollaboration

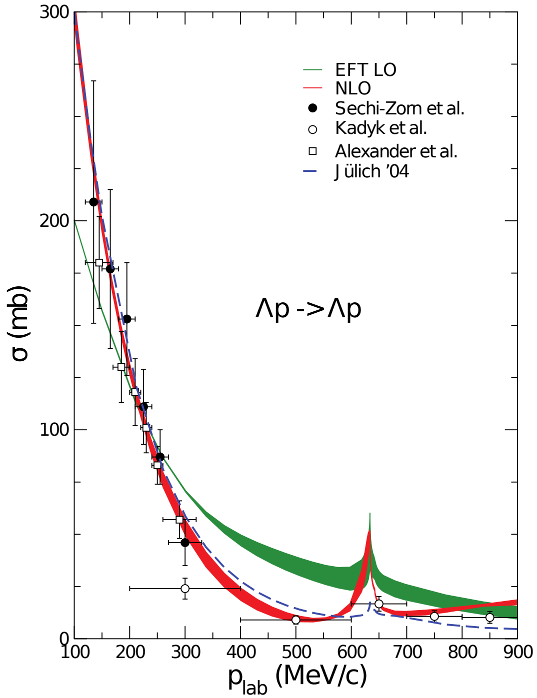
from Norbert Kaiser, TUM

Baryonic forces from SU(3) chiral effective field theory

J. Haidenbauer (FZJ), N. Kaiser (TUM), U.-G. Meißner (Bonn), S. Petschauer (TUM), W. Weise (ECT*)

- extend successful SU(2) χEFT approach to nuclear forces to three flavors
- hyperon-nucleon interaction from SU(3) χEFT at NLO (one- and two-meson exchange + contact terms)



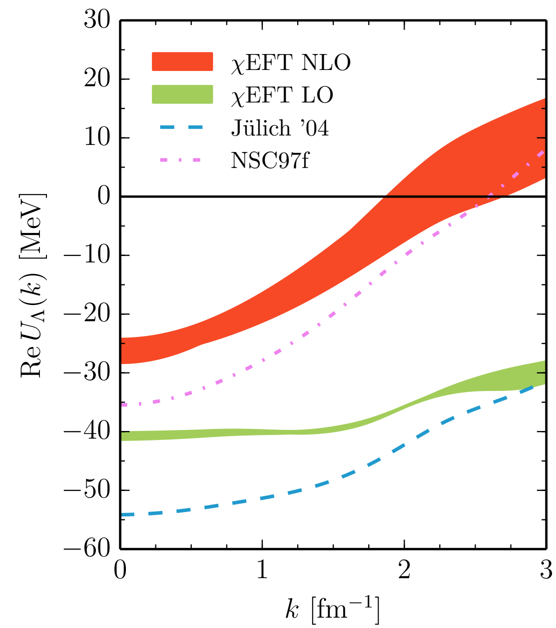


- good description of available *YN* scattering data

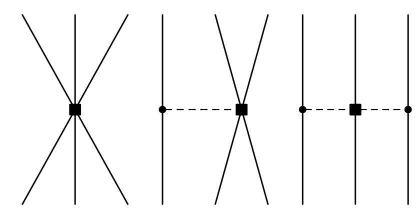
[Nucl.Phys. A915 (2013) 24-58]

- G-matrix calculation of hyperon potentials in isospin-(a)symmetric nuclear matter
  - weak Λ-nuclear spin-orbit
  - repulsive Σ-nuclear potential

[arXiv:1507.08808]



- construction of leading three-baryon forces (e.g. ΛNN) [arXiv:1511.02095]
- constants estimated via decuplet saturation (e.g. Σ^* for ΛNN)

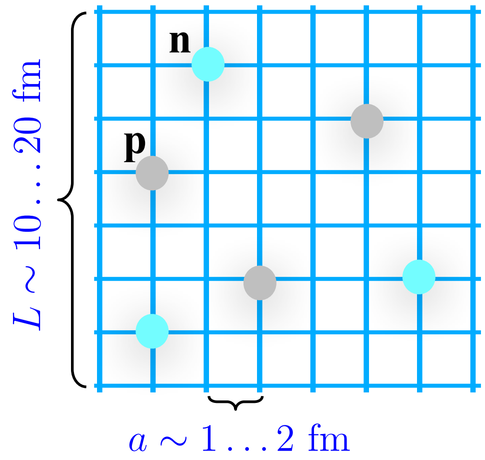


Nuclear systems from lattice χEFT

Nuclear lattice simulations:

A new 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.)

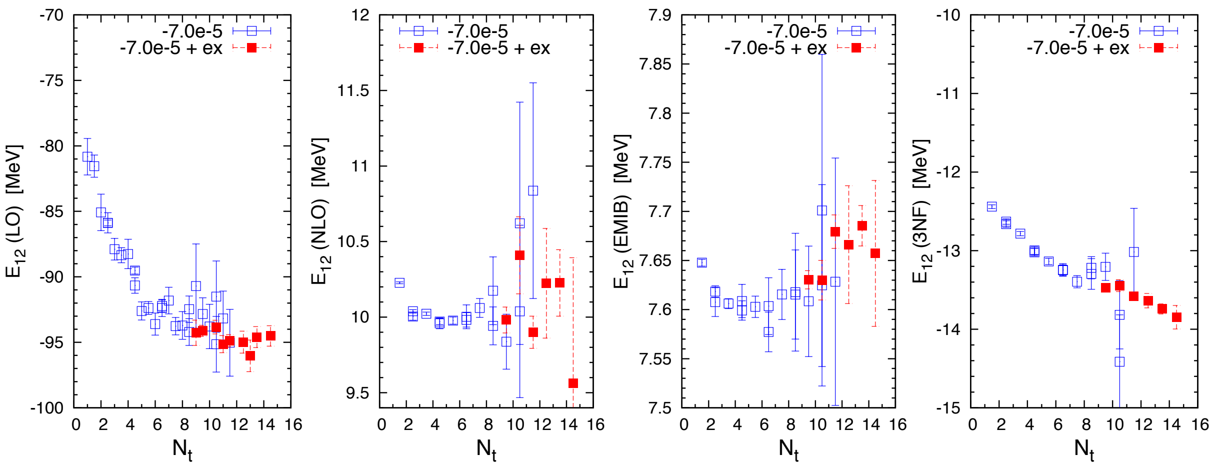
T. A. Lähde, EE, H. Krebs, D. Lee, U.-G. Meißner, G. Rupak, PLB 732 (14) 110

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

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

Symmetry-sign extrapol.

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



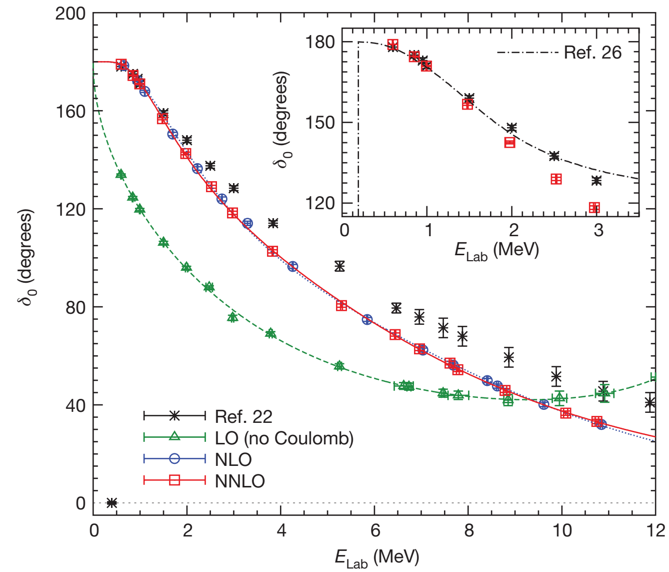
Nuclear systems from lattice χEFT

nature International weekly journal of science

Ab initio alpha–alpha scattering

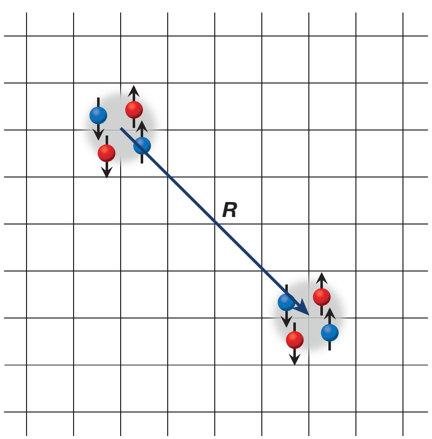
Serdar Elhatisari[1], Dean Lee[2], Gautam Rupak[3], Evgeny Epelbaum[4], Hermann Krebs[4], Timo A. Lähde[5], Thomas Luu[1,5] & Ulf-G. Meißner[1,5,6]

Nature **528**, 111–114 (03 December 2015) | doi:10.1038/nature16067
Received 12 June 2015 | Accepted 30 September 2015 | Published online 02 December 2015



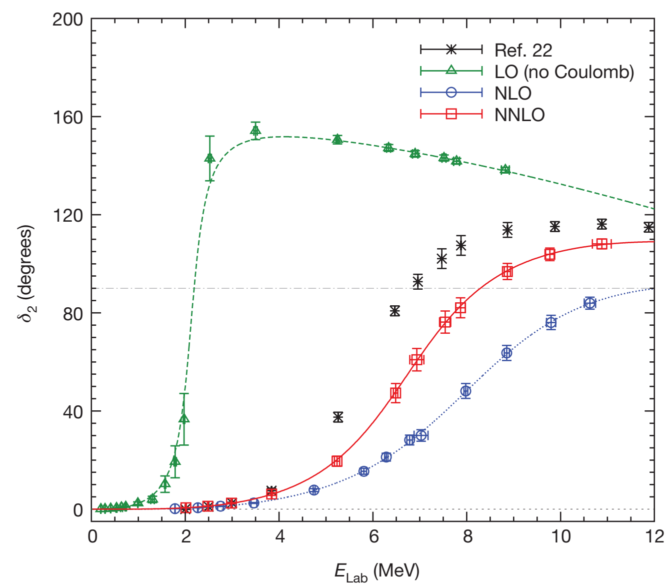
First ab initio calculation of alpha-alpha scattering!

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



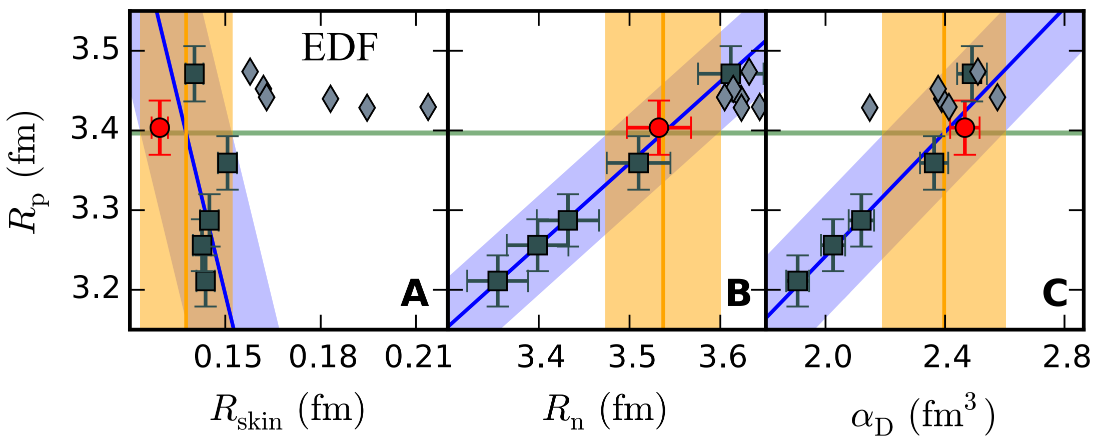
Phase shifts obtained employing a hard spherical wall boundary at asymptotically large distances

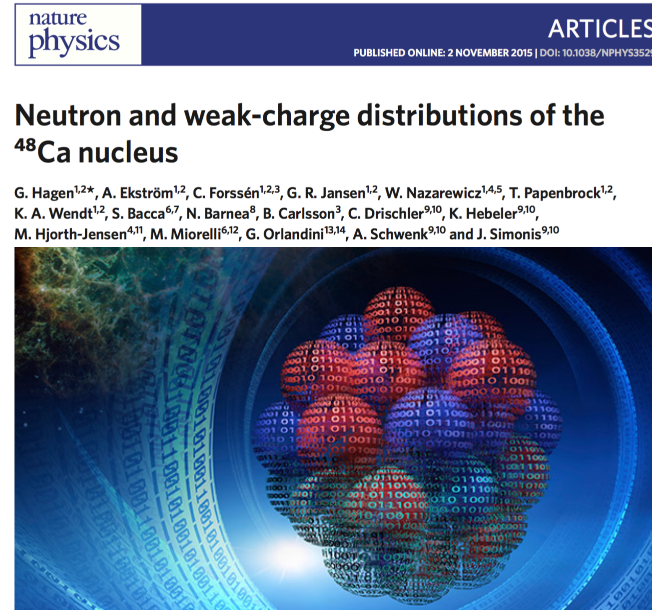
Promising scaling with respect to the number of particles as $\sim (A_1 + A_2)^2$



Frontier of ab initio calculations from Achim Schwenk, TU Darmstadt

- First NN+3N prediction of the **neutron skin, weak form factor, dipole polarizability of ^{48}Ca**




nature physics

ARTICLES

PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529

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

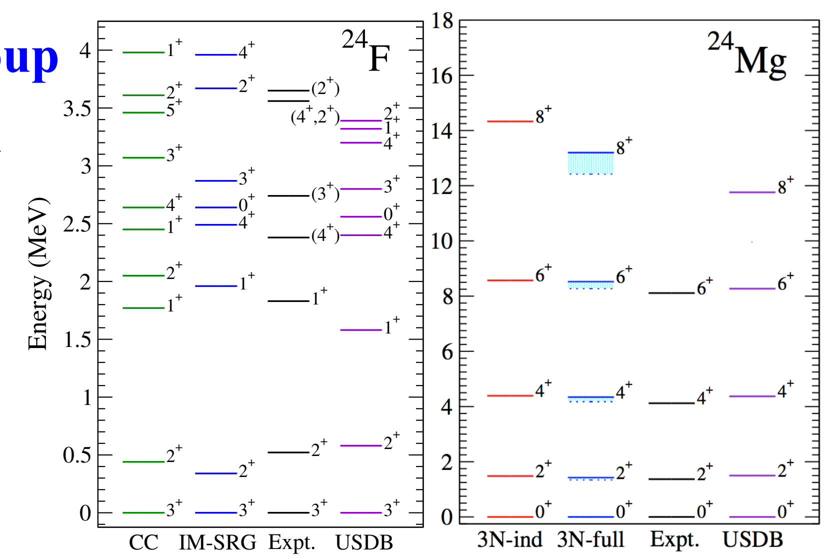
G. Hagen[1,2*], A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

Neutron skin smaller than previously thought! Hagen et al., Nature Phys.

- **In-Medium Similarity Renormalization Group**

  First nonperturbative derivation of shell-model interactions from NN+3N interactions
  Bogner et al., PRL 113, 142501 (2014)

  First ab initio description of deformed nuclei
  Stroberg et al., 1511.02802

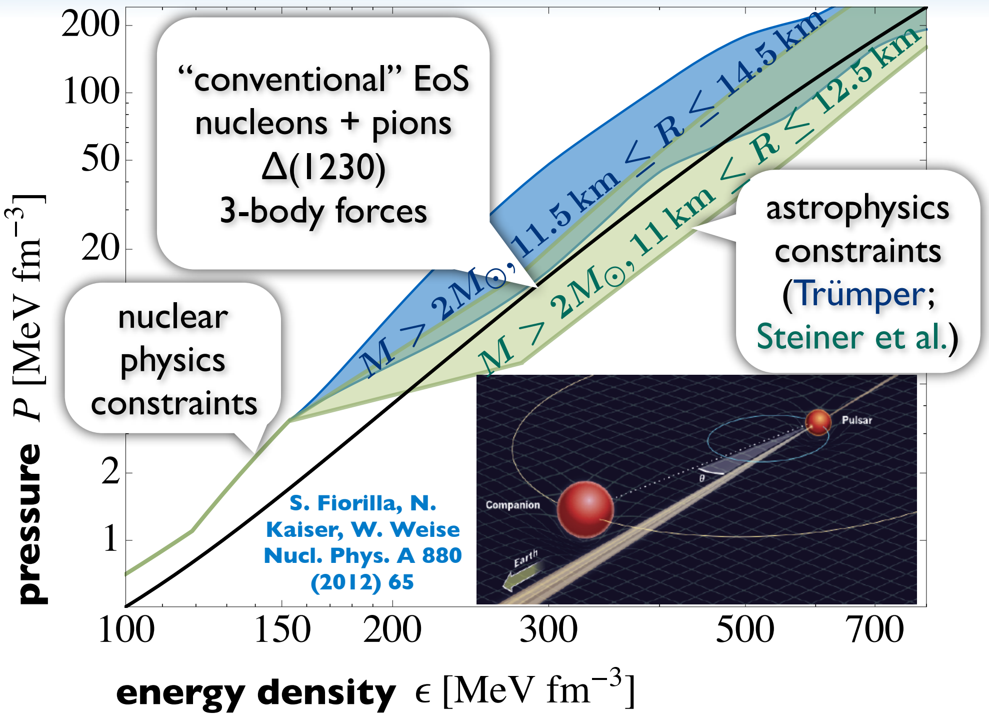


- **Quantum Monte Carlo** with local chiral 3N
  Lynn, Tews et al., 1507.05561, 1509.0347

from Norbert Kaiser, TUM

Neutron-Star Matter

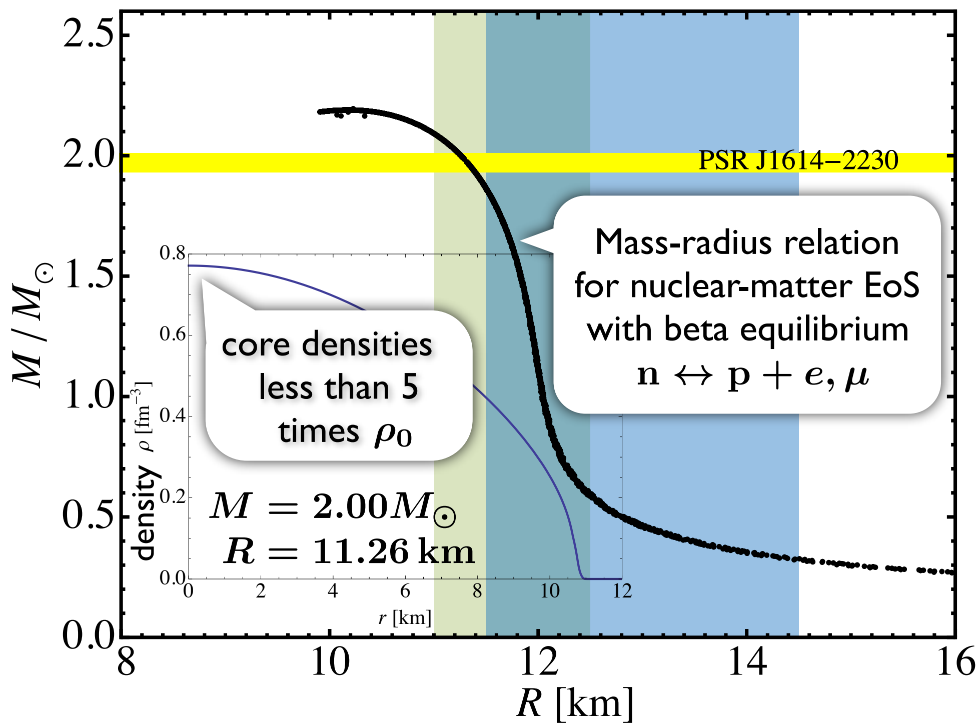
T. Hell, N. Kaiser, B. Röttgers, S. Schulteß, W. Weise
PRC 90 (2014) 045801



- Very precise measurement of a neutron star (PSR J1614-2230) P.B. Demorest et al., Nature, 467, 1081 (2010)

$$M = (1.97 \pm 0.04) M_\odot$$

- Sets new constraints on the equation of state (EoS) of nuclear matter
- Inclusion of neutron star constraints plus **C**hiral **E**ffective **F**ield **T**heory at lower density



- Mass-radius relation R.C. Tolman (1939) J.R. Oppenheimer, G.M. Volkoff (1939)

$$\frac{dP(r)}{dr} = -\frac{\mathcal{G}}{c^2}\,\frac{[\epsilon(r)+P(r)]\,[M(r)+4\pi r^3 P(r)/c^2]}{r\,[r-2\mathcal{G}M(r)/c^2]}$$

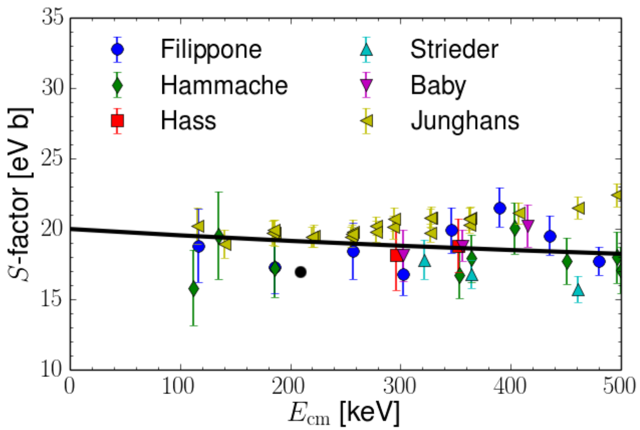
- Conventional (baryonic and mesonic) degrees of freedom are sufficient to describe massive neutron stars
- no "exotic" matter needed (or excluded)

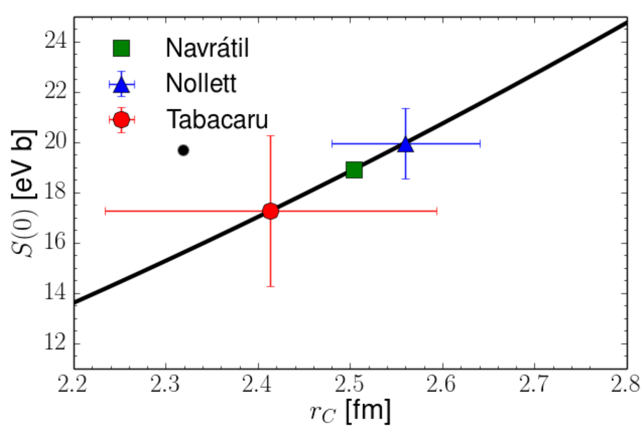
EFT for Proton Halos

from Hans-Werner Hammer, TU Darmstadt

TECHNISCHE UNIVERSITÄT DARMSTADT

- Delicate interplay between strong and Coulomb interaction
  $\Longrightarrow$ two fine tunings required to obtain shallow halo states
  $\Longrightarrow$ proton halos are rarer in nature than neutron halos
- Range corrections in proton halos
  Ryberg, Forssen, Hammer, Platter, arXiv:1507.08675
- Explore universal correlations between observables
- S-factor for ^{7}Be$(p,\gamma)^8$B and charge radius of ^{8}B are correlated





Ryberg, Forssen, Hammer, Platter, Eur. Phys. J. A **50** (2014) 170

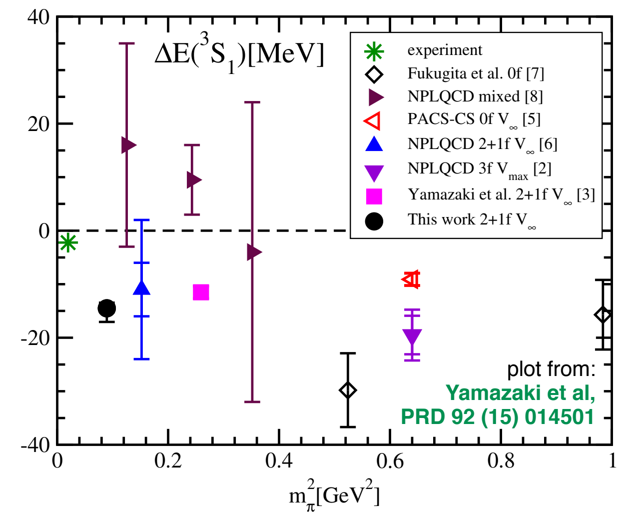
Nuclear physics from lattice QCD

- Lattice QCD results for light nuclei start to emerge (at high M_π)
- Controversial results: more binding **[NPLQCD, Yamazaki et al.]** versus no binding at all **[HAL QCD]**

→ **consistency checks are needed!**

— π-less EFT & extrapolations in the # of nucl. **[Barnea et al.'15]**

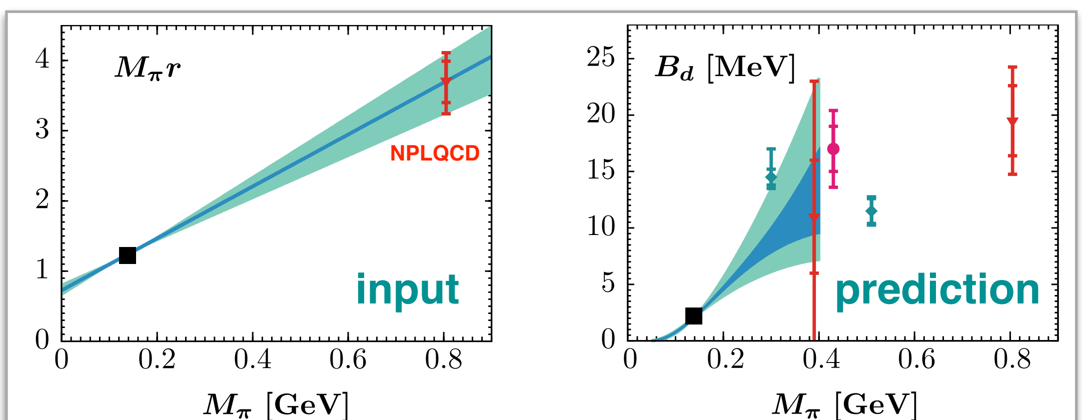
— **Low-energy theorems:** long-range interactions imply correlations between coefficients in the effective range expansion

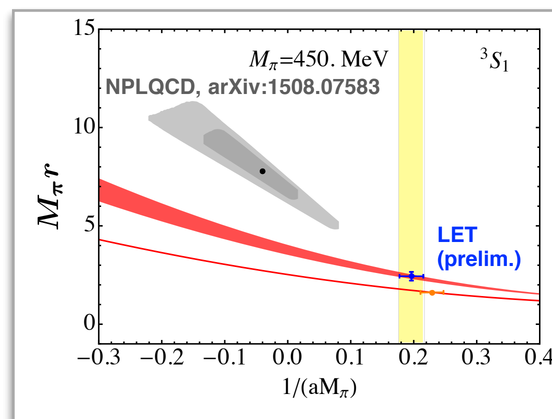


- model-independent; no reliance on the χ-expansion
- good predictive power in $^3S_1$ for physical M_π →
- can be extended to heavier M_π

[Baru et al., PRC99 (15) 014001]

	a [fm]	r [fm]	v_2 [fm^3]	v_3 [fm^5]	v_4 [fm^7]
LO LET	input	1.60	−0.05	0.82	−5.0
NLO LET	input	input	0.06	0.70	−4.0
Nijmegen PWA	5.42	1.75	0.04	0.67	−4.0





Summary

New generation of accurate and precise chiral nuclear forces

+ Reliable approach to uncertainty quantifications

+ Exciting progress in ab initio methods
  (Nuclear lattice simulations, Coupled cluster, In-Medium SRG, Green Function Monte Carlo, …)

+ Growing computational resources

Low energy nuclear theory is entering precision era:
Reliable ab initio few- and many-body calculations based on chiral EFT with quantified theoretical uncertainties.