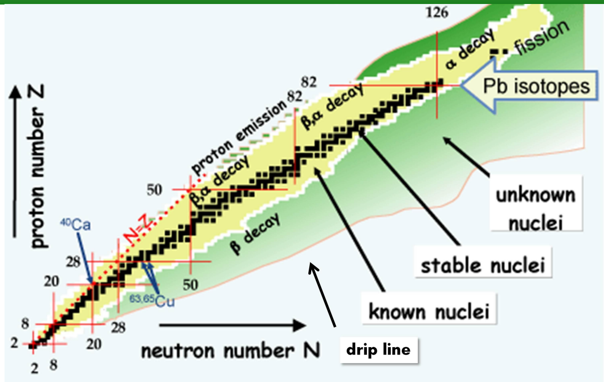
Evgeny Epelbaum, RUB

XIIIth Quark Confinement and the Hadron Spectrum,
31 Jul to 6 Aug 2018, Maynooth University

Chiral effective field theory for few- and many-nucleon systems

Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft
erc European Research Council

Why (precision) nuclear physics?



After discovery of Higgs boson,

the strong sector remains the only poorly understood part of the SM!

Interesting topic on its own. Some current frontiers:

— the nuclear chart and limits of stability FAIR, GANIL, ISOLDE,…

— EoS for nuclear matter (gravitational waves from n-star mergers) LIGO/Virgo,…

— hypernuclei (neutron stars) JLab, JSI/FAIR, J-PARC, MAMI,…

But also highly relevant for searches for BSM physics, e.g.:

— direct Dark Matter searches (WIMP-nucleus scattering)

— searches for 0νββ decays

— searches for nucleon/nuclear EDMs

— proton radius puzzle (complementary experiments with light nuclei…)

→ need a reliable approach to nuclear structure with quantified uncertainties!

From QCD to nuclei

QCD → **lattice**

symmetries (especially the chiral symmetry);
lost of information (LECs)

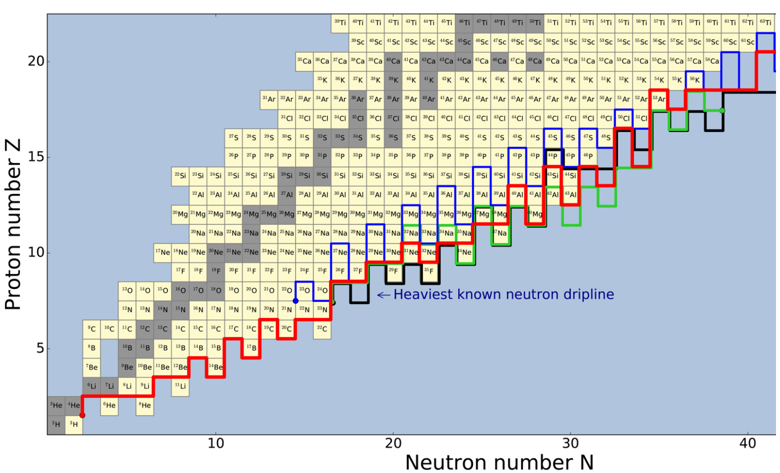
effective chiral Lagrangian $\mathcal{L}_{\text{eff}}(\pi, N)$

integrate out $|\vec{p}\,| \sim \sqrt{M_\pi m_N}$ (but retain $|\vec{p}\,| \sim M_\pi$):
Chiral Perturbation Theory

nuclear forces and currents

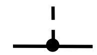
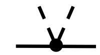
ab initio many-body methods:
lattice, FY, NCSM,…

nuclear structure and dynamics



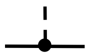
Method of UT for nuclear forces

EE, Glöckle, Meißner, NPA 637 (1998) 107;   EE, PLB 639 (2006) 456

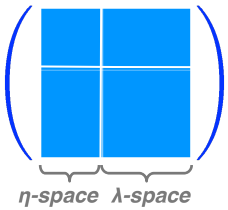
- Begin with the $\mathcal{L}_{\mathrm{eff}}\,[\pi,N]$ without external fields
- Canonical formalism: $\mathcal{L}_{\mathrm{eff}}\,[\pi,N] \longrightarrow H[\pi,N] =$  +  + $\ldots$

Method of UT for nuclear forces

EE, Glöckle, Meißner, NPA 637 (1998) 107;   EE, PLB 639 (2006) 456

- Begin with the $\mathcal{L}_{\rm eff}\,[\pi,N]$ without external fields
- Canonical formalism: $\mathcal{L}_{\rm eff}\,[\pi,N] \longrightarrow H[\pi,N] =$  +  + …
- Apply UT in Fock space to decouple purely nucleonic states [model space] from the rest

$$H \;\to\; \tilde H \;=\; U^\dagger$$



$$U \;=\; \begin{pmatrix} \tilde H_{\rm nucl} & 0 \\ 0 & \tilde H_{\rm rest} \end{pmatrix}$$

Using Okubo's minimal parametrization of U in terms of $A = \lambda A \eta$ leads to the

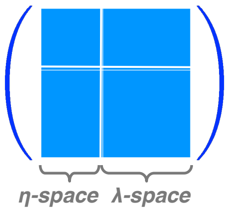
decoupling equation: $$\lambda(H - [A,\; H] - AHA)\eta = 0$$

which is solved perturbatively employing the chiral expansion

Method of UT for nuclear forces

EE, Glöckle, Meißner, NPA 637 (1998) 107;   EE, PLB 639 (2006) 456

- Begin with the $\mathcal{L}_{\rm eff}\,[\pi,N]$ without external fields
- Canonical formalism: $\mathcal{L}_{\rm eff}\,[\pi,N] \longrightarrow H[\pi,N] =$  $+\ \dots$
- Apply UT in Fock space to decouple purely nucleonic states [model space] from the rest

$H \to \tilde{H} = U^\dagger$  $U = \begin{pmatrix} \tilde{H}_{\rm nucl} & 0 \\ 0 & \tilde{H}_{\rm rest} \end{pmatrix}$

Using Okubo's minimal parametrization of U in terms of $A = \lambda A \eta$ leads to the

decoupling equation: $\boxed{\lambda(H - [A,\ H] - AHA)\eta = 0}$

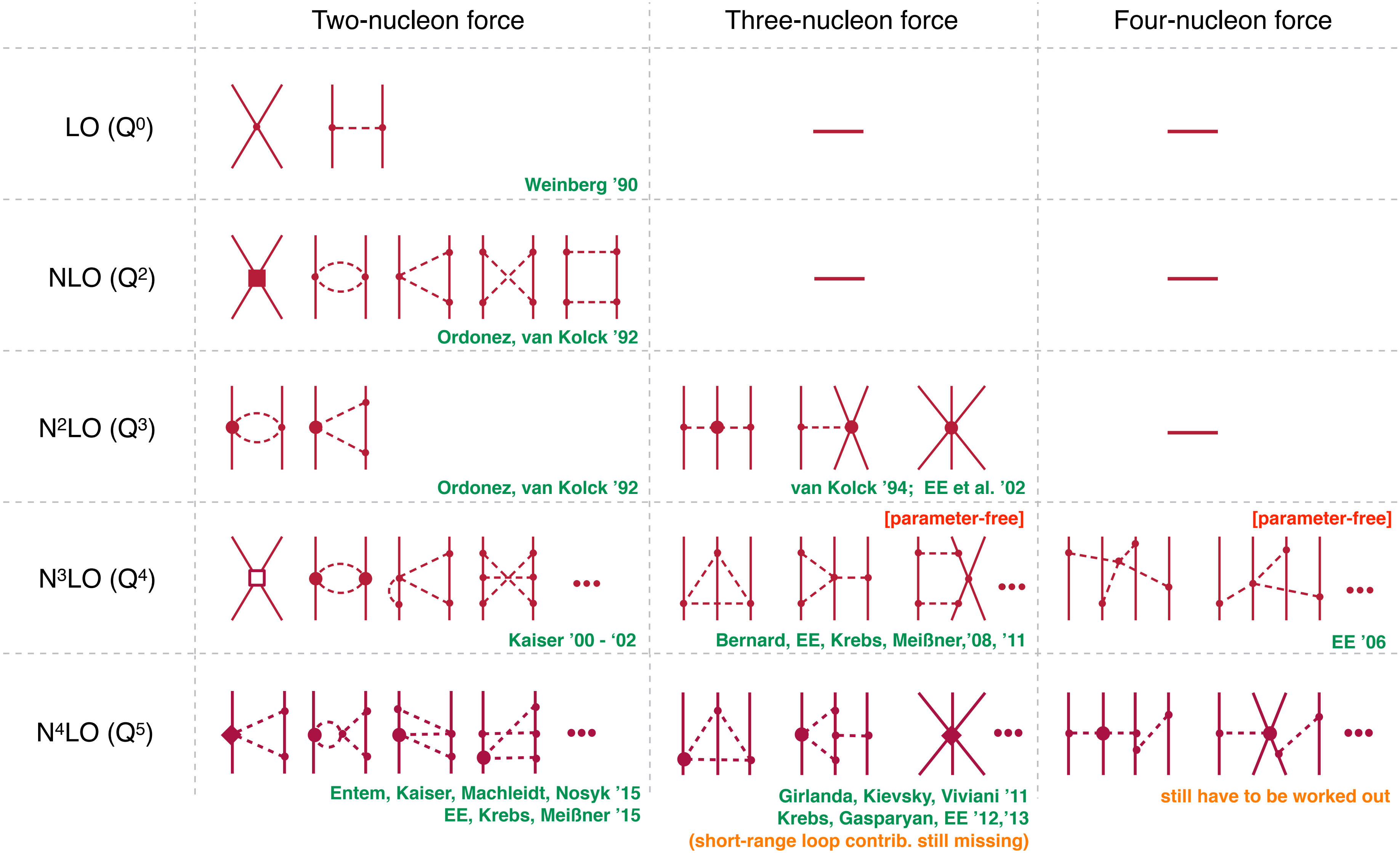
which is solved perturbatively employing the chiral expansion

- Apply all possible additional UTs on the η-subspace consistent with a given chiral order [6 angles α_i for static N^3LO contributions]
- Renormalizability of the potentials [all 1/(d-4) poles must be canceled by the c.t. from $\mathcal{L}_{\rm eff}$]

$\longrightarrow$ fixes some of the α_i and leads to unique (static) expressions

For more details see: EE, *Nuclear Forces from Chiral Effective Field Theory: A Primer*, arXiv:1001.3229[nucl-th]

Chiral expansion of nuclear forces [W-counting]



— A similar program is being pursued for in chiral EFT with explicit Δ(1232) DOF

Application 1:
A new generation of chiral NN potentials

— semi-local, coordinate-space-regularized up to N^4LO

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

— semi-local, momentum-space-regularized up to N^4LO^+

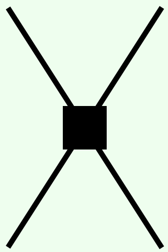
Reinert, Krebs, EE, EPJA 54 (2018) 88

— nonlocal, momentum-space-regularized up to N^4LO^+

Entem, Machleidt, Nosyk, PRC 96 (2017) 024004

The long and short of nuclear forces

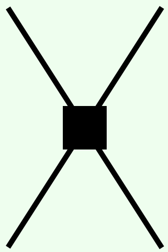
- Short-range interactions have to be tuned to experimental data. In the isospin limit, one has according to NDA:



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 terms
N^{3}LO [Q^4]:	+ **12 operators** (S-, P-, D-waves and ε_1, ε_2)
N^{4}LO [Q^5]:	no new terms

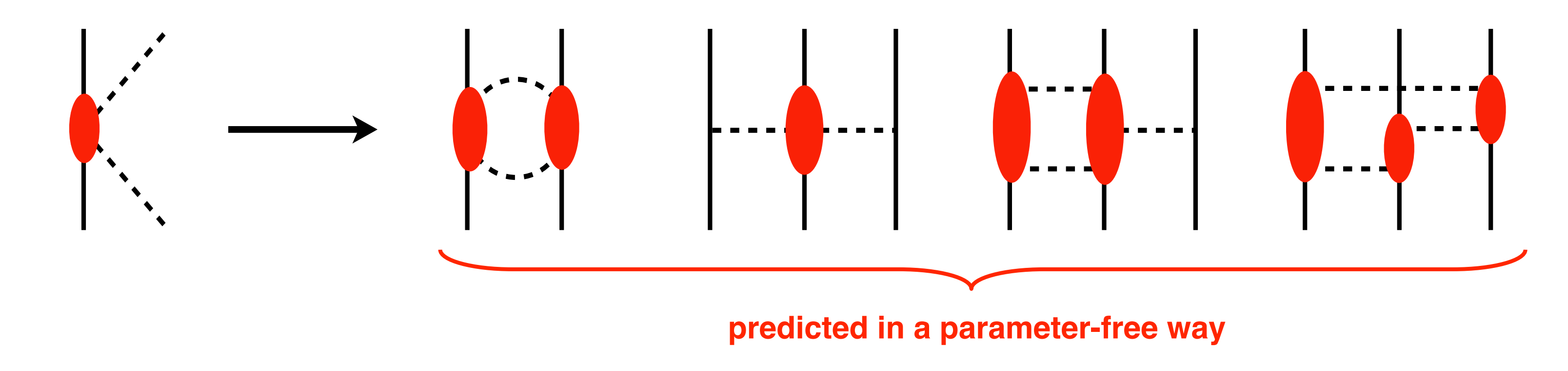
The long and short of nuclear forces

- Short-range interactions have to be tuned to experimental data. In the isospin limit, one has according to NDA:



LO [Q^0]:	2 operators (S-waves)
NLO [Q^2]:	+ 7 operators (S-, P-waves and ε_1)
N^2LO [Q^3]:	no new terms
N^3LO [Q^4]:	+ **12 operators** (S-, P-, D-waves and ε_1, ε_2)
N^4LO [Q^5]:	no new terms

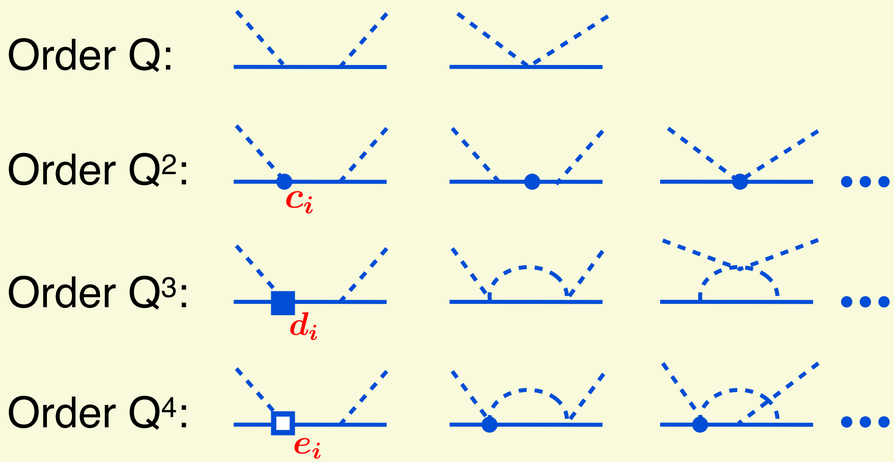
- The long-range part of nuclear forces and currents is completely determined by the chiral symmetry of QCD + experimental information on πN scattering

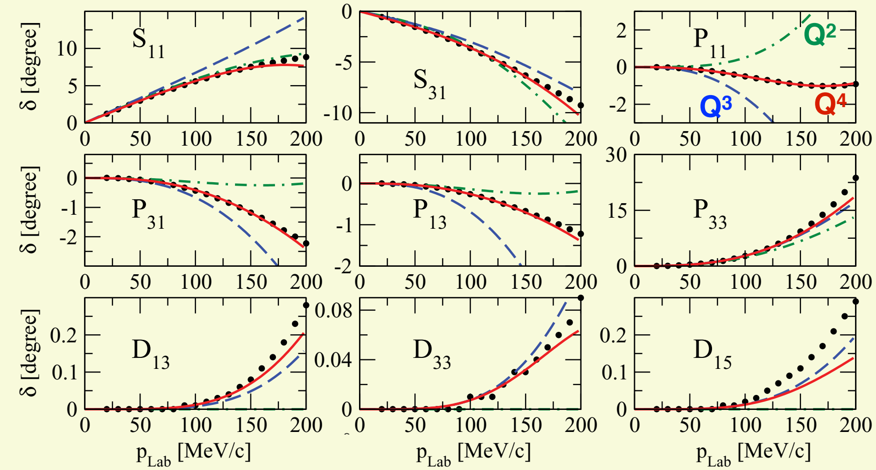


Determination of πN LECs

Pion-nucleon scattering up to Q⁴ in heavy-baryon ChPT

Fettes, Meißner '00; Krebs, Gasparyan, EE '12

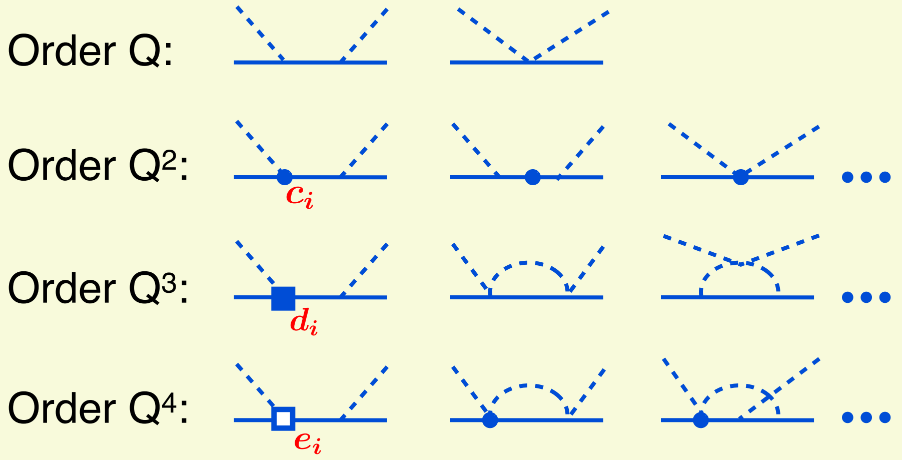


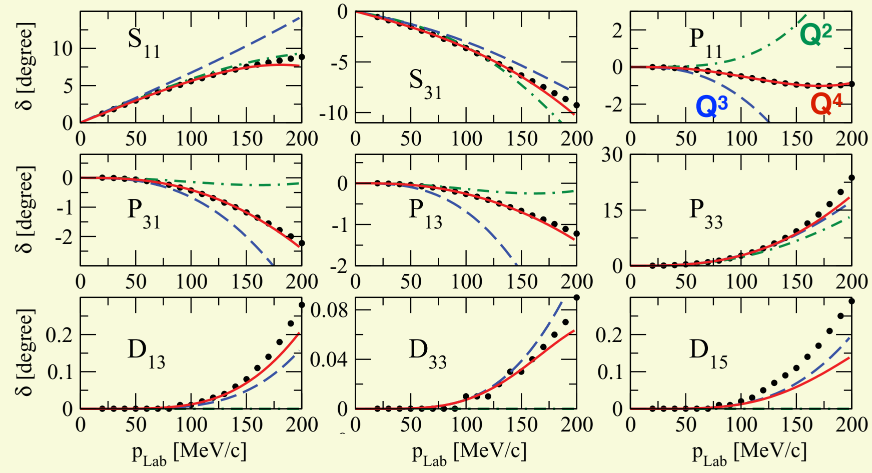


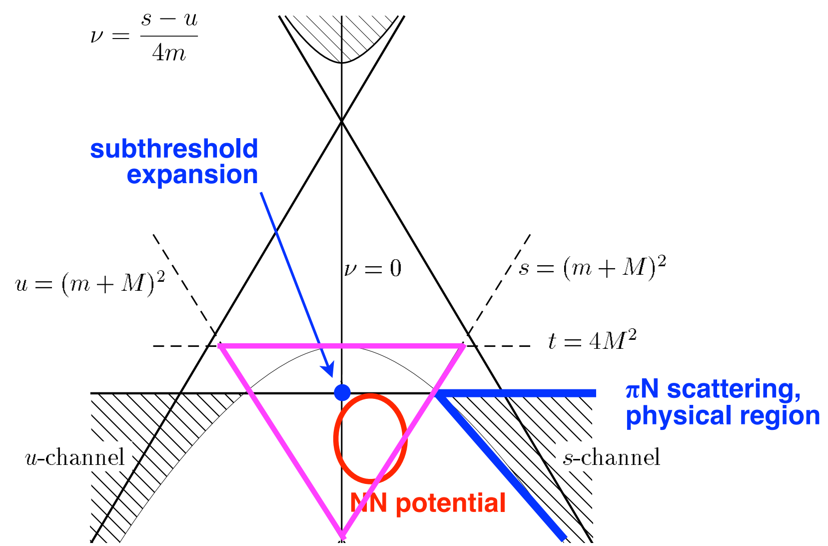
Determination of πN LECs

Pion-nucleon scattering up to Q^4 in heavy-baryon ChPT

Fettes, Meißner '00; Krebs, Gasparyan, EE '12







Matching ChPT to πN Roy-Steiner equations

Hoferichter, Ruiz de Elvira, Kubis, Meißner, PRL 115 (2015) 092301

- χ expansion of the πN amplitude expected to converge best within the Mandelstam triangle
- Subthreshold coefficients (from RS analysis) provide a natural matching point to ChPT

$$\bar{X} = \sum_{m,n} x_{mn}\, \nu^{2m+k} t^n, \qquad X = \{A^\pm, B^\pm\}$$

- Closer to the kinematics relevant for nuclear forces…

Determination of πN LECs

Pion-nucleon scattering up to Q⁴ in heavy-baryon ChPT

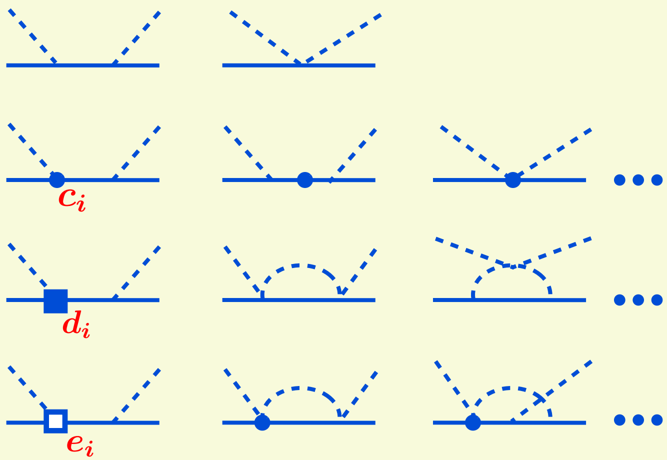
Fettes, Meißner '00; Krebs, Gasparyan, EE '12

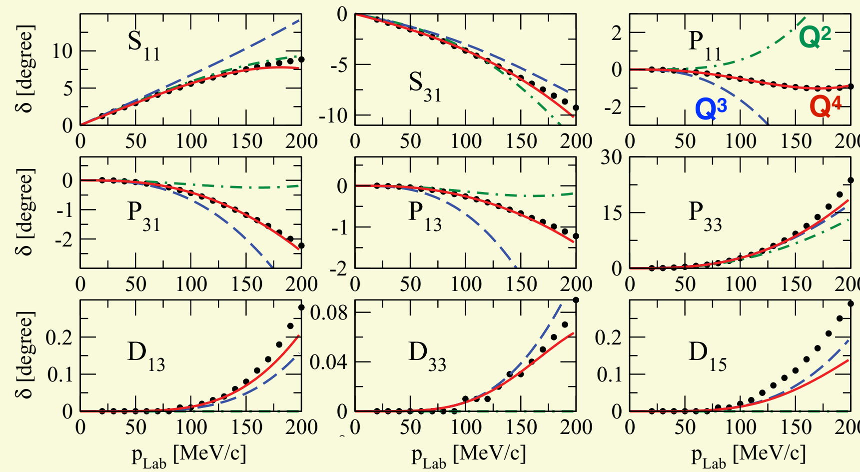
Order Q:

Order Q^2:

Order Q^3:

Order Q^4:





Relevant LECs (in GeV⁻ⁿ) extracted from πN scattering

	c_1	c_2	c_3	c_4	$\bar d_1 + \bar d_2$	$\bar d_3$	$\bar d_5$	$\bar d_{14} - \bar d_{15}$	$\bar e_{14}$	$\bar e_{17}$	
$[Q^4]_{\mathrm{HB,\,NN}}$, GW PWA	−1.13	3.69	−5.51	3.71	5.57	−5.35	0.02	−10.26	1.75	−0.58	Krebs, Gasparyan, EE, PRC85 (12) 054006
$[Q^4]_{\mathrm{HB,\,NN}}$, KH PWA	−0.75	3.49	−4.77	3.34	6.21	−6.83	0.78	−12.02	1.52	−0.37	
$[Q^4]_{\mathrm{HB,\,NN}}$, Roy-Steiner	−1.10	3.57	−5.54	4.17	6.18	−8.91	0.86	−12.18	1.18	−0.18	Hoferichter et al., PRL 115 (15) 092301
$[Q^4]_{\mathrm{covariant}}$, data	−0.82	3.56	−4.59	3.44	5.43	−4.58	−0.40	−9.94	−0.63	−0.90	Siemens et al., PRC94 (16) 014620

Notice:

— some LECs show sizable correlations (especially c_1 and c_3)…

— KH PWA and Roy-Steiner LECs lead to comparable results in the NN sector

Determination of πN LECs

Pion-nucleon scattering up to Q^4 in heavy-baryon ChPT

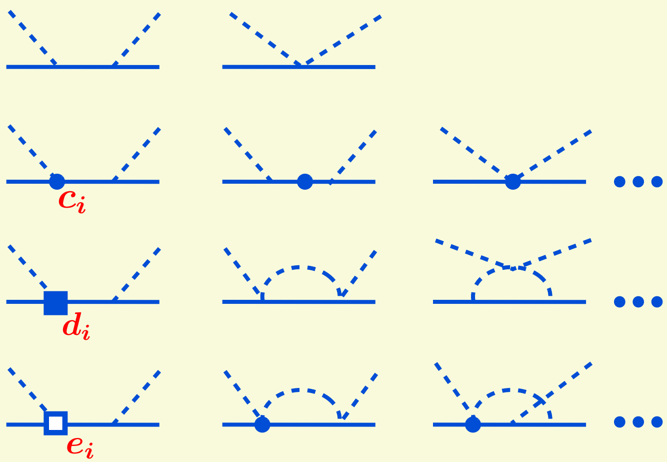
Fettes, Meißner '00; Krebs, Gasparyan, EE '12

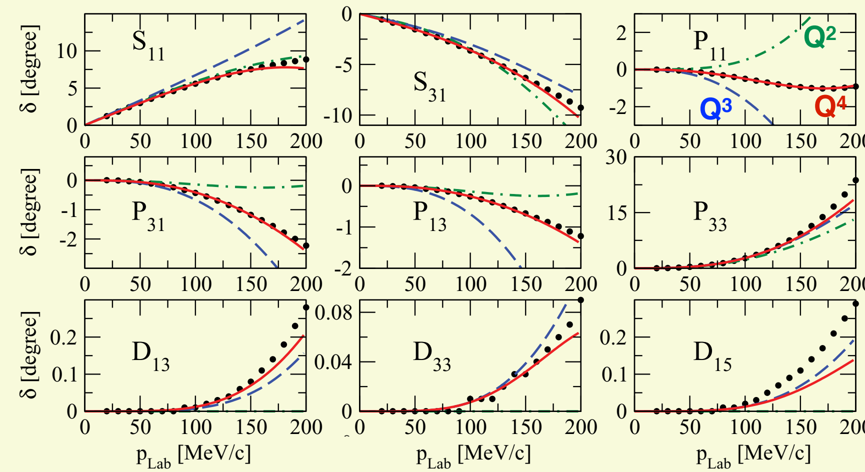
Order Q:

Order Q^2:

Order Q^3:

Order Q^4:





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

	c_1	c_2	c_3	c_4	$\bar d_1 + \bar d_2$	$\bar d_3$	$\bar d_5$	$\bar d_{14} - \bar d_{15}$	$\bar e_{14}$	$\bar e_{17}$
$[Q^4]_{\rm HB,NN}$, GW PWA	−1.13	3.69	−5.51	3.71	5.57	−5.35	0.02	−10.26	1.75	−0.58
$[Q^4]_{\rm HB,NN}$, KH PWA	−0.75	3.49	−4.77	3.34	6.21	−6.83	0.78	−12.02	1.52	−0.37
$[Q^4]_{\rm HB,NN}$, Roy-Steiner	−1.10	3.57	−5.54	4.17	6.18	−8.91	0.86	−12.18	1.18	−0.18
$[Q^4]_{\rm covariant}$, data	−0.82	3.56	−4.59	3.44	5.43	−4.58	−0.40	−9.94	−0.63	−0.90

Krebs, Gasparyan, EE, PRC85 (12) 054006 (GW PWA, KH PWA)

Hoferichter et al., PRL 115 (15) 092301 (Roy-Steiner)

Siemens et al., PRC94 (16) 014620 (covariant, data)

Notice:

— some LECs show sizable correlations (especially c_1 and c_3)…

— KH PWA and Roy-Steiner LECs lead to comparable results in the NN sector

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

Regularization

The cutoff Λ has to be kept finite, $\Lambda \sim \Lambda_b$ (unless all counterterms are taken into account in the calculations) **[Lepage '97; EE, Gegelia '09]**. In practice, low values of Λ are preferred:

— many-body methods require soft interactions,

— spurious deeply-bound states for $\Lambda > \Lambda^{crit}$ make calculations for $A > 3$ unfeasible…

⟶ it is crucial to employ a regulator that minimizes finite-Λ artifacts!

Regularization

The cutoff Λ has to be kept finite, $\Lambda \sim \Lambda_b$ (unless all counterterms are taken into account in the calculations) **[Lepage '97; EE, Gegelia '09]**. In practice, low values of Λ are preferred:

— many-body methods require soft interactions,

— spurious deeply-bound states for $\Lambda > \Lambda^{\rm crit}$ make calculations for $A > 3$ unfeasible…

⟶ it is crucial to employ a regulator that minimizes finite-Λ artifacts!

Nonlocal: $$V_{1\pi}^{\rm reg} \propto \frac{e^{-\frac{p'^4 + p^4}{\Lambda^4}}}{\vec q^{\,2} + M_\pi^2} \longrightarrow \frac{1}{\vec q^{\,2} + M_\pi^2} \underbrace{\left(1 - \frac{p'^4 + p^4}{\Lambda^4} + \mathcal{O}(\Lambda^{-8}) \right)}_{\text{affect long-range interactions...}}$$

EE, Glöckle, Meißner '04; Entem, Machleidt '03; Entem, Machleidt, Nosyk '17; …

Regularization

The cutoff Λ has to be kept finite, $\Lambda \sim \Lambda_b$ (unless all counterterms are taken into account in the calculations) **[Lepage '97; EE, Gegelia '09]**. In practice, low values of Λ are preferred:

— many-body methods require soft interactions,

— spurious deeply-bound states for $\Lambda > \Lambda^{\rm crit}$ make calculations for A > 3 unfeasible…

⟶ it is crucial to employ a regulator that minimizes finite-Λ artifacts!

Nonlocal: $V_{1\pi}^{\rm reg} \propto \dfrac{e^{-\frac{p'^4+p^4}{\Lambda^4}}}{\vec q^{\,2}+M_\pi^2} \longrightarrow \dfrac{1}{\vec q^{\,2}+M_\pi^2}\underbrace{\left(1-\dfrac{p'^4+p^4}{\Lambda^4}+\mathcal{O}(\Lambda^{-8})\right)}_{\text{affect long-range interactions…}}$

EE, Glöckle, Meißner '04; Entem, Machleidt '03; Entem, Machleidt, Nosyk '17; …

Local: $V_{1\pi}^{\rm reg} \propto \dfrac{e^{-\frac{\vec q^{\,2}+M_\pi^2}{\Lambda^2}}}{\vec q^{\,2}+M_\pi^2} \longrightarrow \dfrac{1}{\vec q^{\,2}+M_\pi^2}\left(1+\text{short-range terms}\right)$

[inspired by Thomas Rijken]

Reinert, Krebs, EE '18;

⟶ does not affect long-range physics **at any order** in $1/\Lambda^2$-expansion

— Application to 2π exchange does not require re-calculating the corresponding diagrams:

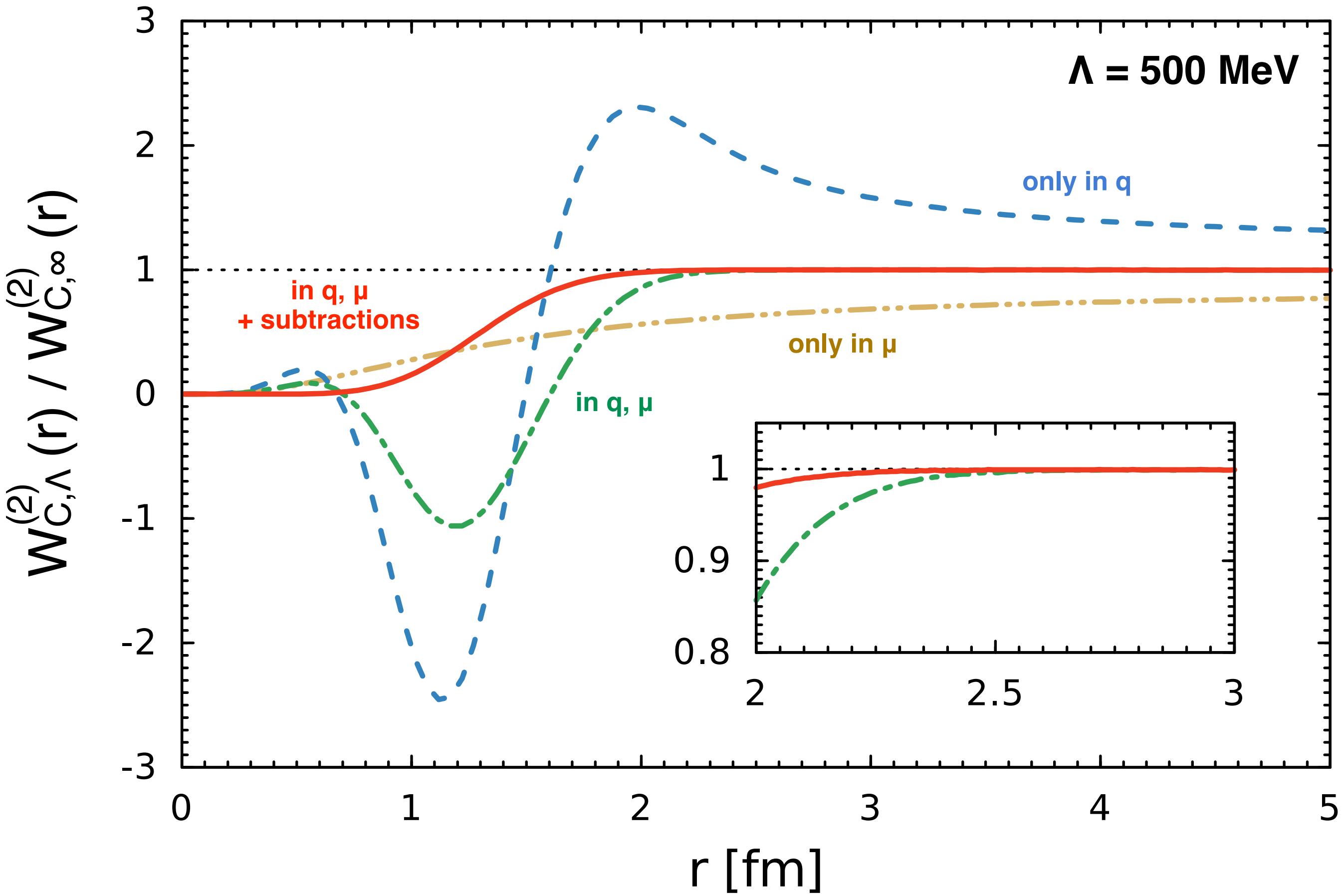
$$V(q) = \frac{2}{\pi}\int_{2M_\pi}^\infty \mu\, d\mu \frac{\rho(\mu)}{q^2+\mu^2} + \ldots \quad \xrightarrow{\text{reg.}} \quad V_\Lambda(q) = e^{-\frac{q^2}{2\Lambda^2}}\frac{2}{\pi}\int_{2M_\pi}^\infty \mu\, d\mu \frac{\rho(\mu)}{q^2+\mu^2}\, e^{-\frac{\mu^2}{2\Lambda^2}} \underbrace{+\ \ldots}_{\substack{\text{polynomial} \\ \text{in } q^2,\, M_\pi}}$$

— Convention: choose polynomial terms such that $\Delta^n V_{\Lambda,\,\rm long}(\vec r)\Big|_{r=0} = 0$

Regularization

Regularized 2π-exchange potential: $W_{C,\Lambda}(q) = e^{-\frac{q^2}{2\Lambda^2}} \frac{2}{\pi} \int_{2M_\pi^2}^{\infty} \mu \, d\mu \, \frac{\rho(\mu)}{q^2 + \mu^2} \, e^{-\frac{\mu^2}{2\Lambda^2}}$

Various regularization approaches



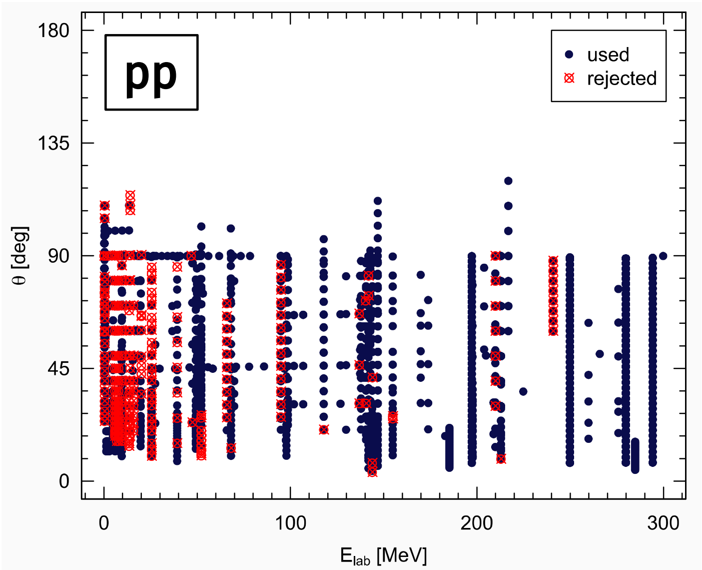
Does it matter in practice?

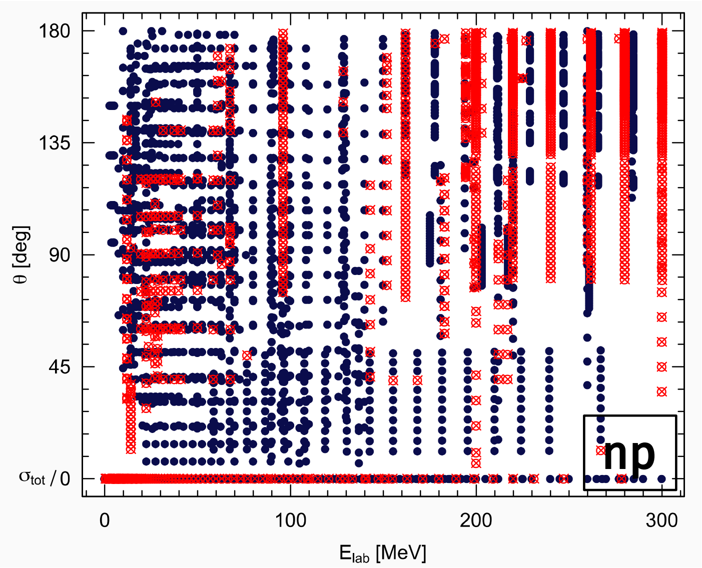
NN data analysis

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88

- Use local/nonlocal regulator for long-range/short-range contributions
- To fix NN contact interactions, use scattering data together with B_d = 2.224575(9) MeV and b_{np} = 3.7405(9) fm.
- Since 1950-es, about 3000 proton-proton + 5000 neutron-proton scattering data below 350 MeV have been measured.
- However, certain data are mutually incompatible within errors and have to be rejected. 2013 Granada database [Navarro-Perez et al., PRC 88 (2013) 064002], rejection rate: 31% np, 11% pp:

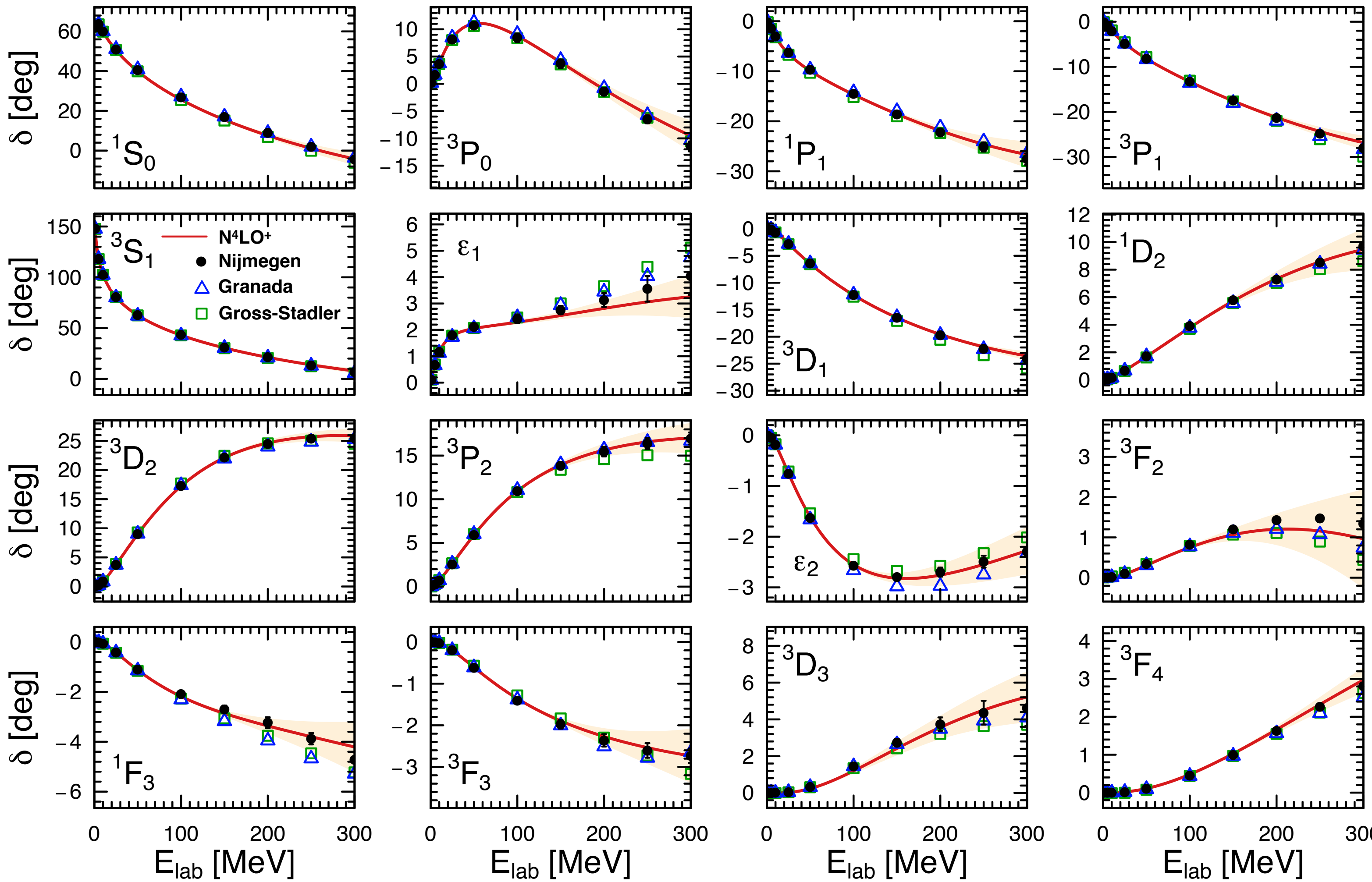
  2158 proton-proton + 2697 neutron-proton data below E_{lab} = 300 MeV





State-of-the-art NN potentials

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88



— N^4LO^+ yields currently the best description of the 2013 Granada database ($E_{lab} < 300$ MeV)

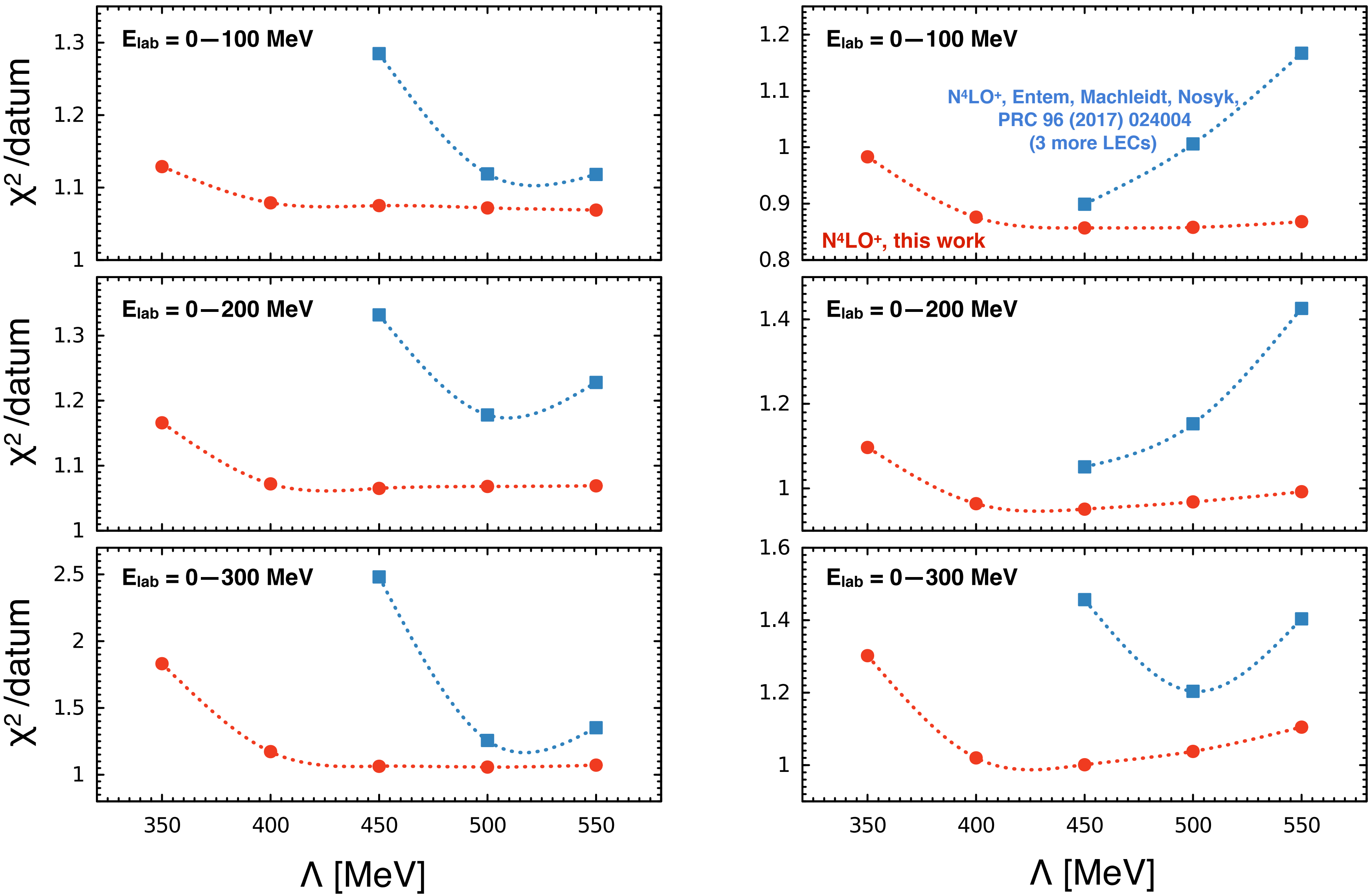
— 40% less parameters (27+1) compared to high-precision potentials

— Clear evidence of the parameter-free chiral 2π exchange

State-of-the-art NN potentials

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88

neutron-proton data | **proton-proton data**



Error analysis

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88

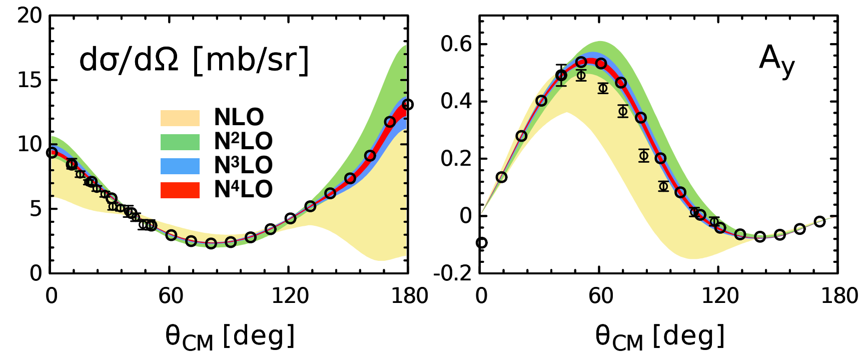
1. Truncation error

EE, Krebs, Meißner, EPJA 51 (2015) 53

$$X^{(i)}(p) = X^{(0)} + \underbrace{\Delta X^{(2)}}_{\sim Q^2 X^{(0)}} + \ldots + \underbrace{\Delta X^{(i)}}_{\sim Q^i X^{(0)}}$$

Expansion parameter: $Q = \max\left\{ \frac{p}{\underbrace{\Lambda_b}_{\simeq 600\ \mathrm{MeV}}}, \frac{M_\pi}{\Lambda_b} \right\}$

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



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

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

Has been validated/extended within a Bayesian approach BUQEYE Collaboration, Furnstahl et al.,'15 - '18

Error analysis

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88

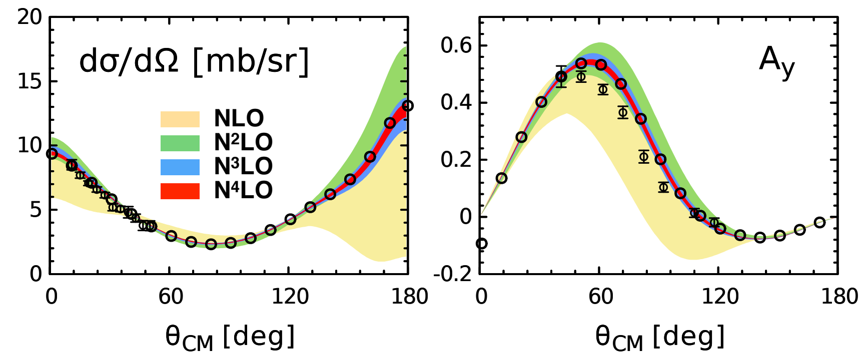
1. Truncation error

EE, Krebs, Meißner, EPJA 51 (2015) 53

$$X^{(i)}(p) = X^{(0)} + \underbrace{\Delta X^{(2)}}_{\sim Q^2 X^{(0)}} + \ldots + \underbrace{\Delta X^{(i)}}_{\sim Q^i X^{(0)}}$$

Expansion parameter: $Q = \max\left\{\frac{p}{\Lambda_b}, \frac{M_\pi}{\Lambda_b}\right\}$, $\Lambda_b \simeq 600\ \text{MeV}$

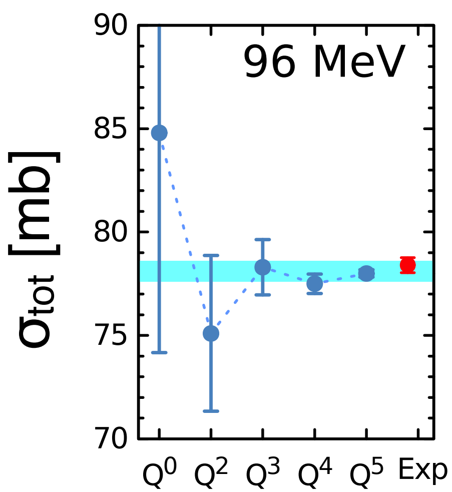
proton-neutron scattering at E_{lab}=143 MeV



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

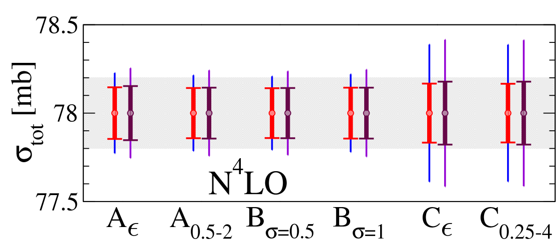
$$\left\{\delta X^{(0)} = Q^2|X^{(0)}|,\ \ \delta X^{(i)} = \max_{2\le j\le i}\left(Q^{i+1}|X^{(0)}|,\ Q^{i+1-j}|\Delta X^{(j)}|\right)\right\} \ \wedge\ \ \delta X^{(i)} \ge \max_{j,k}\left(|X^{(j\ge i)} - X^{(k\ge i)}|\right)$$

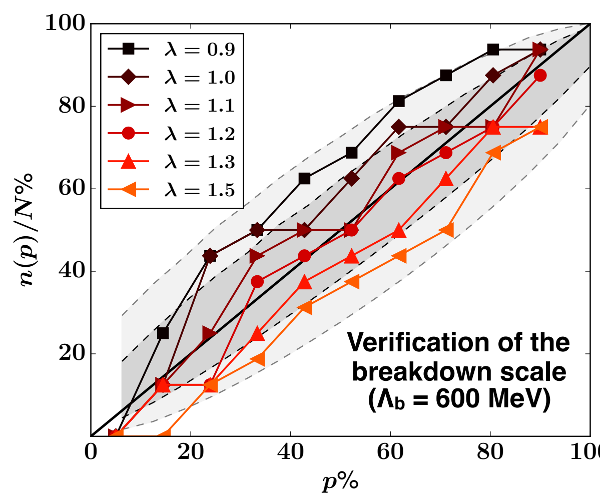
Example: np total cross section at 96 MeV



— calculations based on the EE et al., PRL 115 (2015) 122301

— Bayseian analysis [BUQEYE], Furnstahl et al., PRC92 (15) 024005





Verification of the breakdown scale (Λ_b = 600 MeV)

Error analysis

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88

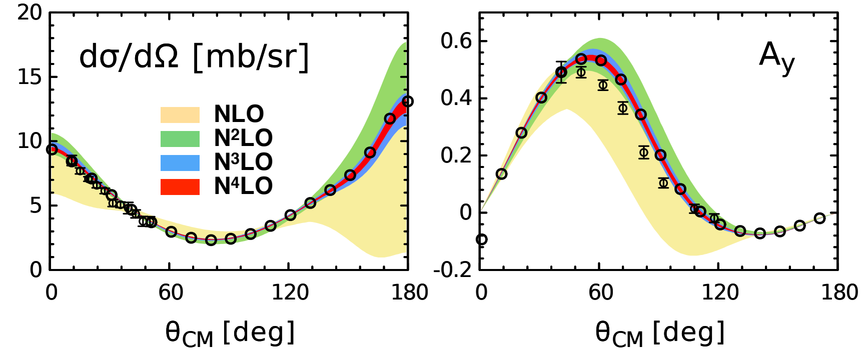
1. Truncation error

EE, Krebs, Meißner, EPJA 51 (2015) 53

$$X^{(i)}(p) = X^{(0)} + \underbrace{\Delta X^{(2)}}_{\sim Q^2 X^{(0)}} + \ldots + \underbrace{\Delta X^{(i)}}_{\sim Q^i X^{(0)}}$$

Expansion parameter: $Q = \max \left\{ \frac{p}{\Lambda_b}, \frac{M_\pi}{\Lambda_b} \right\}$, $\Lambda_b \simeq 600$ MeV

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



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

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

Has been validated/extended within a Bayesian approach BUQEYE Collaboration, Furnstahl et al.,'15 - '18

2. Statistical uncertainties

Estimated in the standard way using the covariance matrix (quadratic approximation)

3. Uncertainties due to πN LECs $c_{1,2,3,4}$, $d_{1,2,3,5,14,15}$ and $e_{14,17}$

Estimated using 2 sets of πN LECs (Roy-Steiner equation analysis & KH PWA)

4. Choice of E_{max} in the fits

Uncertainty estimated at N⁴LO/N⁴LO⁺ by performing fits with E_{max} = 220…300 MeV

Error analysis

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88

In most cases, the uncertainty is dominated by truncation errors. At N^{4}LO and at very low energies, other sources of errors become comparable (especially πN LECs…).

Example: deuteron asymptotic normalizations (relevant for nuclear astrophysics)

Our determination:

truncation error, statistical error, πN LECs, variation of E_{max}

$$A_S = 0.8847^{(+3)}_{(-3)}(3)(5)(1)\ \mathrm{fm}^{-1/2}$$

$$\eta \equiv \frac{A_D}{A_S} = 0.0255^{(+1)}_{(-1)}(1)(4)(1)$$

Exp: $A_S = 0.8781(44)\ \mathrm{fm}^{-1/2}$, $\eta = 0.0256(4)$

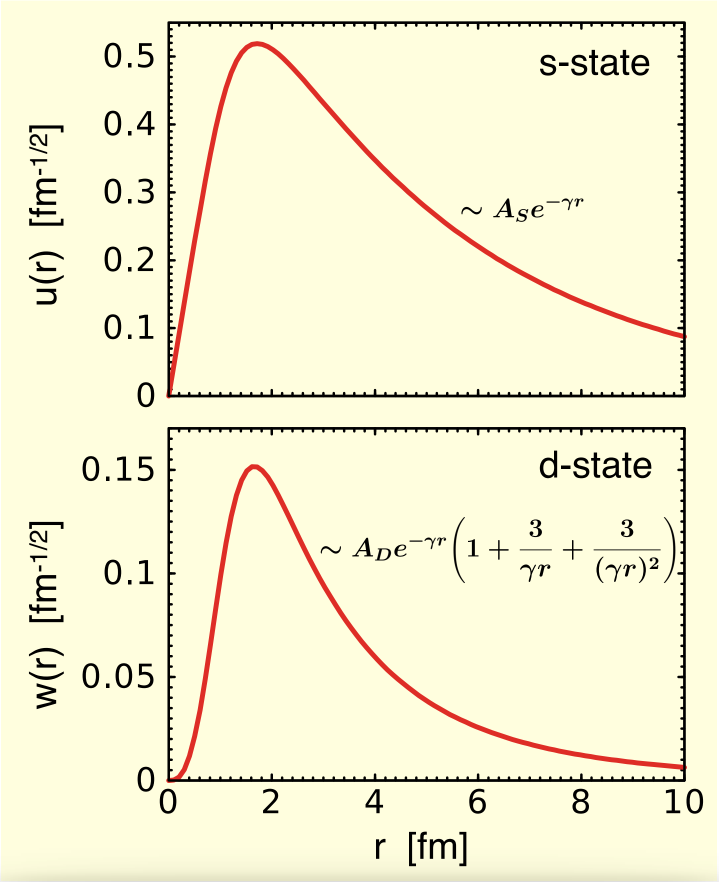
Borbely et al. '85 — Rodning, Knutson '90

Nijmegen PWA [errors are „educated guesses"] Stoks et al. '95

$$A_S = 0.8845(8)\ \mathrm{fm}^{-1/2}, \quad \eta = 0.0256(4)$$

Granada PWA [errors purely statistical] Navarro Perez et al. '13

$$A_S = 0.8829(4)\ \mathrm{fm}^{-1/2}, \quad \eta = 0.0249(1)$$



Applications 2: Beyond the 2N system

— LENPIC Collaboration —

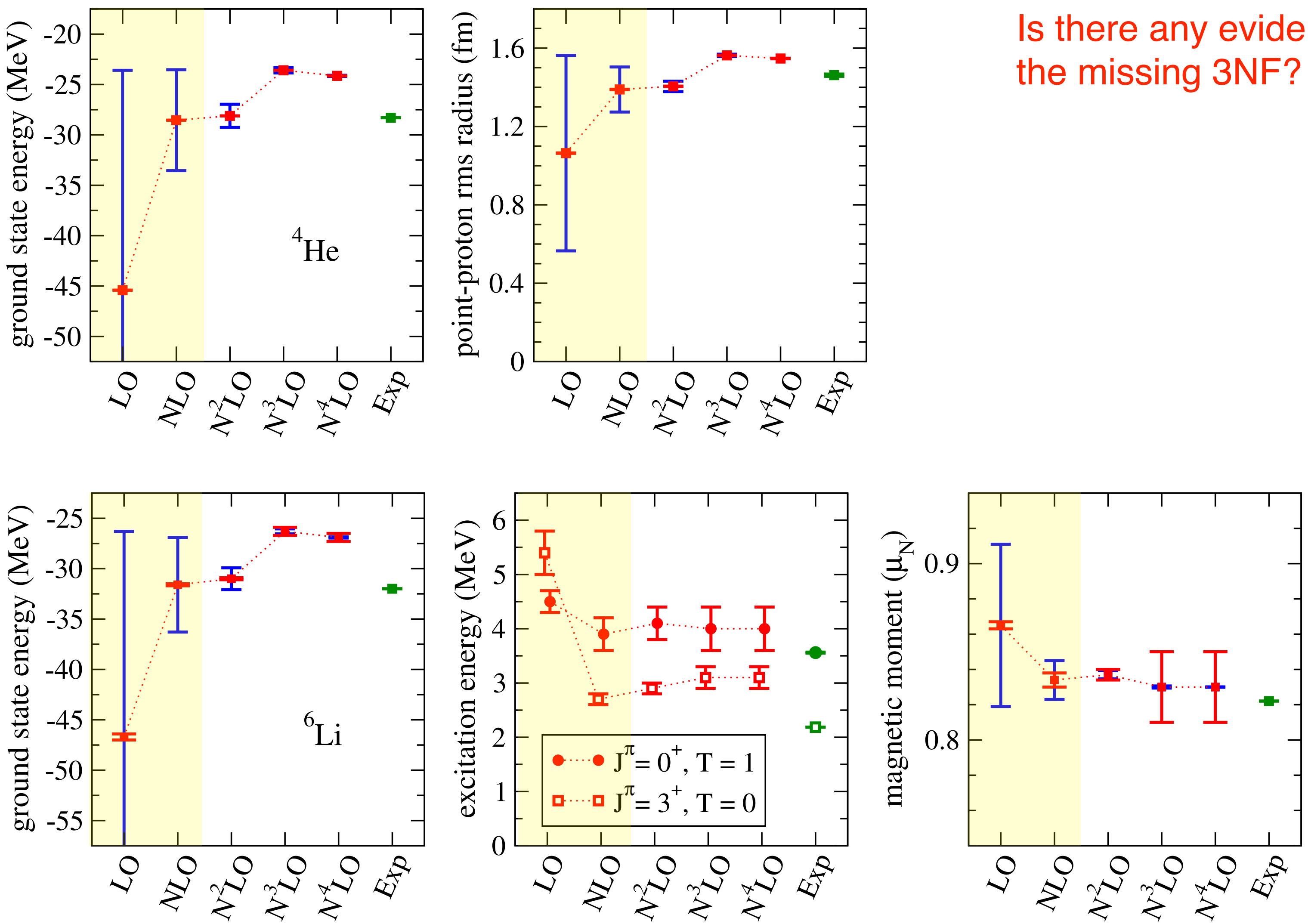
Goal: precision tests of chiral nuclear forces & currents in light nuclei

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

Light nuclei based on 2NF alone

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



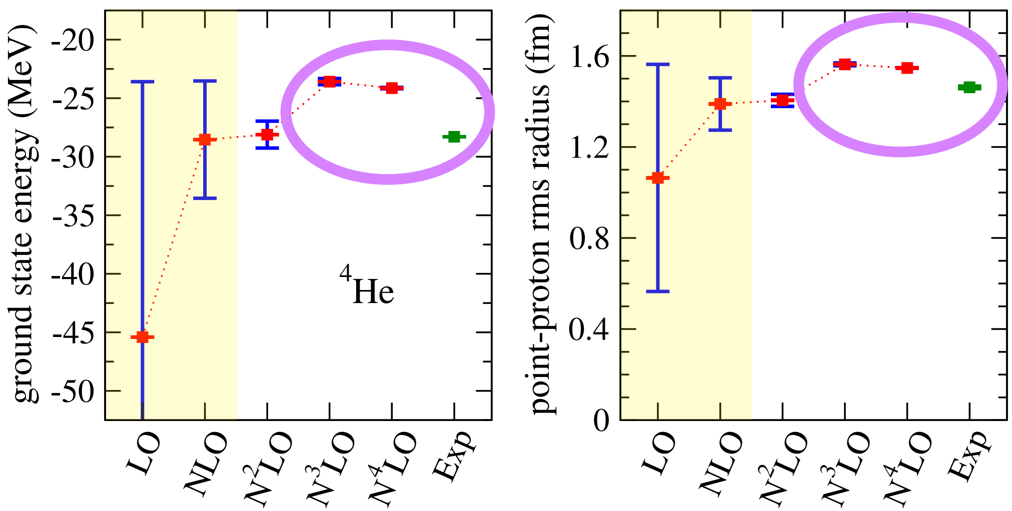
Is there any evidence of the missing 3NF?

LENPIC: Low Energy Nuclear Physics International Collaboration

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

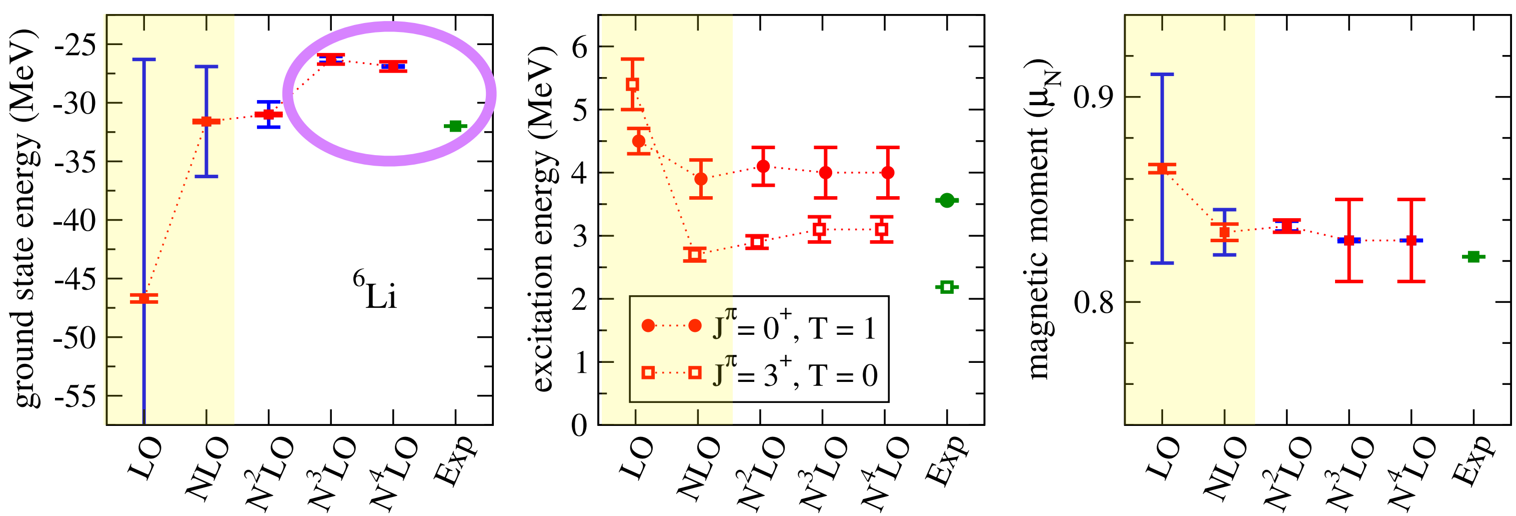
Light nuclei based on 2NF alone

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



Is there any evidence of the missing 3NF?

Deviations from the data are consistent with the estimated size of the 3N forces

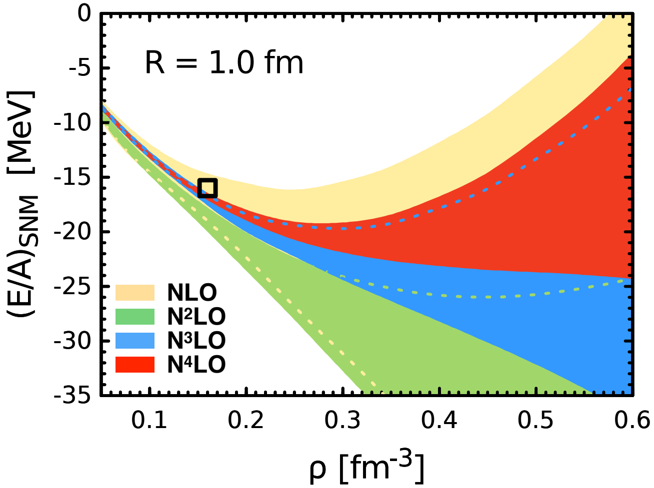


LENPIC: Low Energy Nuclear Physics International Collaboration

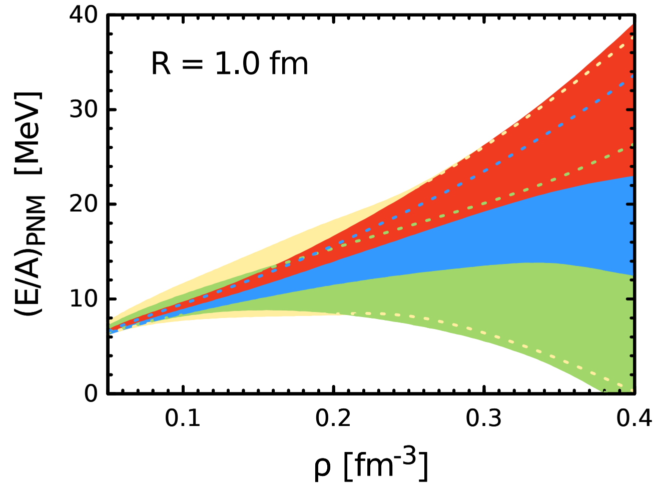
Brueckner-Hartree-Fock based on 2NF alone

Jinniu Hu, Ying Zhang, EE, Ulf-G. Meißner, Jie Meng, PRC 96 (2017) 034307

Symmetric nuclear matter



Pure neutron matter

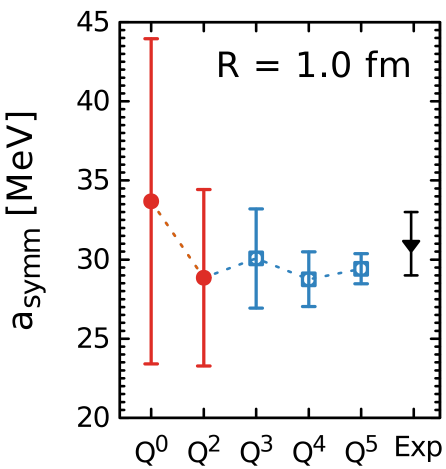


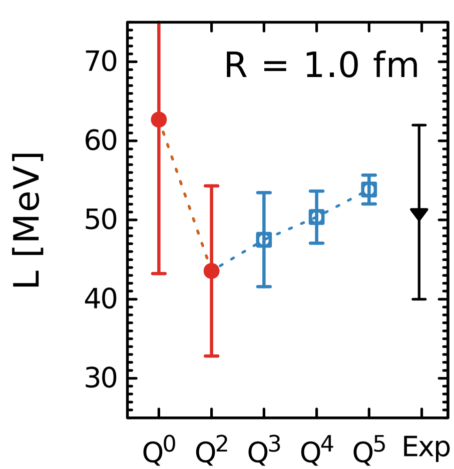
Achievable accuracy at N^4LO at ρ_0:

$\pm$ 0.3 MeV for SNM,
$\pm$ 0.7 MeV for PNM,

semi-quantitative up to ~ $2\rho_0$ …

Symmetry energy and the slope parameter at the saturation density



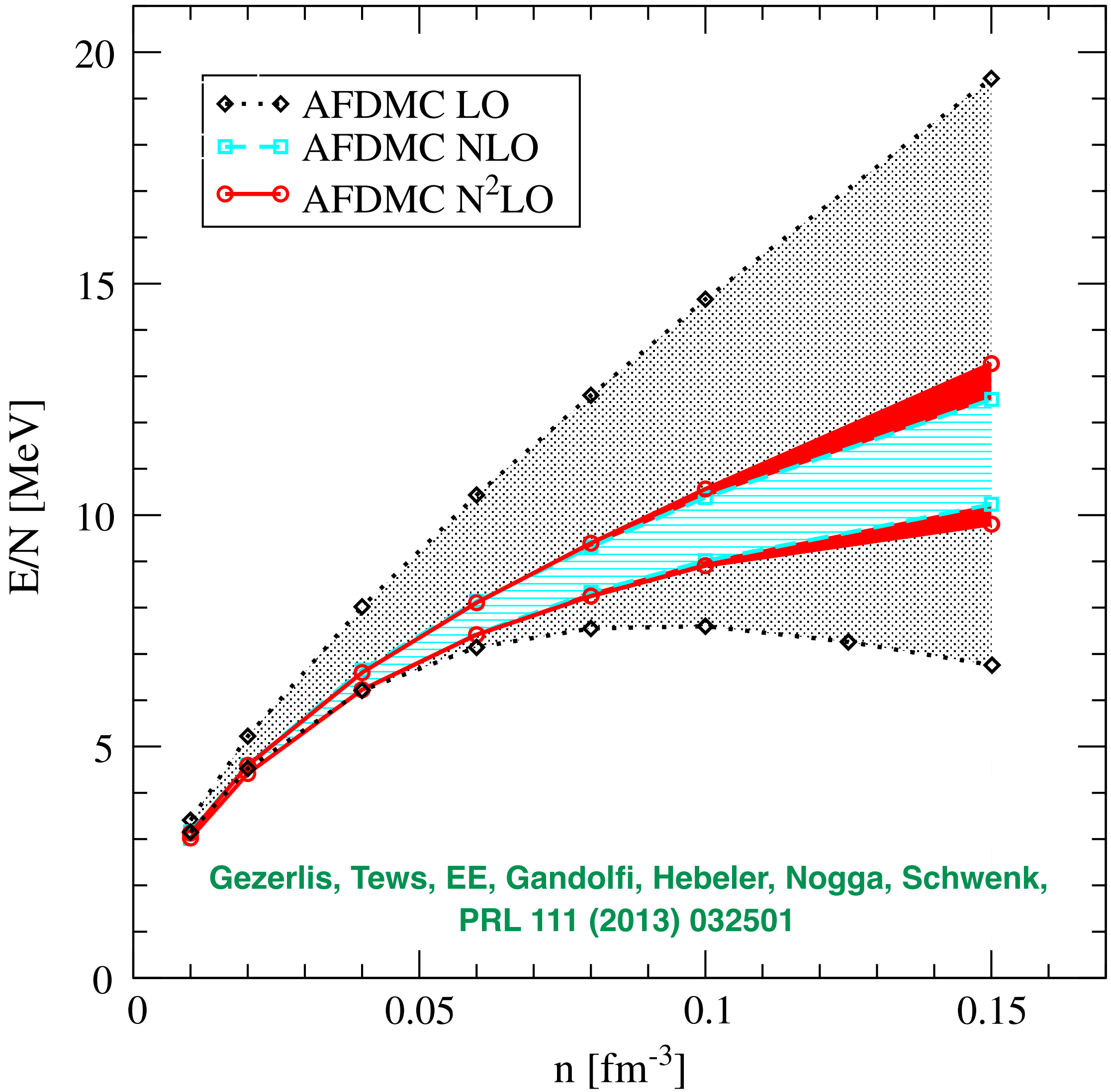


$$a_{\rm symm}(\rho) = \left(\frac{E}{A}\right)_{\rm PNM} - \left(\frac{E}{A}\right)_{\rm SNM}$$

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

Brueckner-Hartree-Fock based on 2NF alone

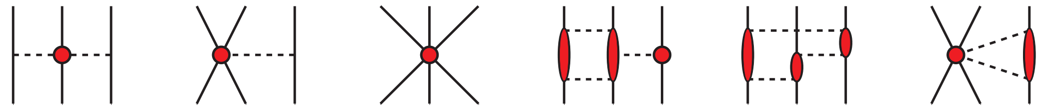
Jinniu Hu, Ying Zhang, EE, Ulf-G. Meißner, Jie Meng, PRC 96 (2017) 034307



Estimated truncation error at N^{4}LO

Three-nucleon forces

N²LO: tree-level graphs, 2 new LECs
van Kolck '94; EE et al '02

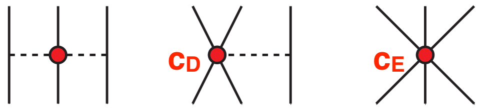


N³LO: leading 1 loop, parameter-free
Ishikawa, Robilotta '08; Bernard, EE, Krebs, Meißner '08, '11

N⁴LO: full 1 loop, almost completely worked out, several new LECs
Girlanda, Kievski, Viviani '11; Krebs, Gasparyan, EE '12,'13; EE, Gasparyan, Krebs, Schat '14

Three-nucleon forces

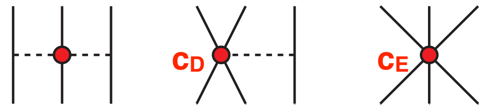
N²LO: tree-level graphs, 2 new LECs
van Kolck '94; EE et al '02



Determination of the LECs c_D, c_E: Triton BE & pd elastic cross section minimum @70 MeV

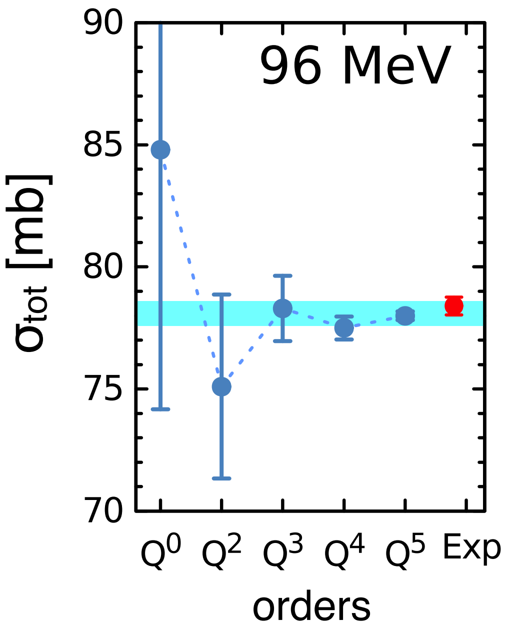
Three-nucleon forces

N²LO: tree-level graphs, 2 new LECs
van Kolck '94; EE et al '02

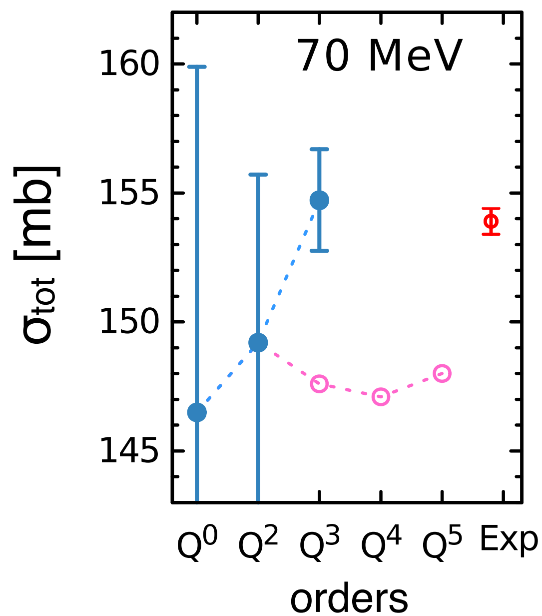


Determination of the LECs c_D, c_E: Triton BE & pd elastic cross section minimum @70 MeV

np total cross section



nd total cross section



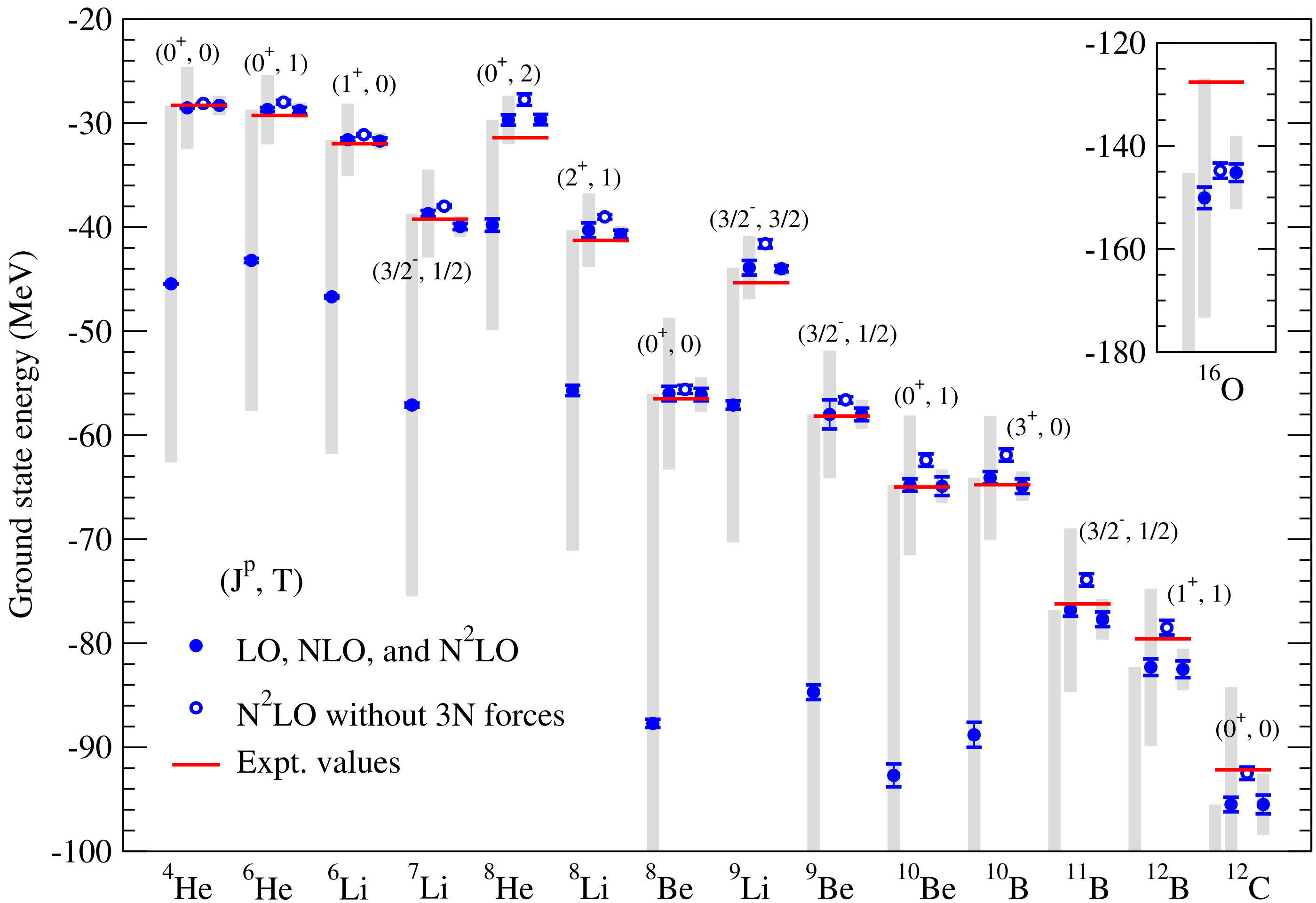
LENPIC, preliminary

LENPIC: Low Energy Nuclear Physics International Collaboration

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

Light nuclei

EE et al. (LENPIC), arXiv:1807.02848



[based on EKM potential, R = 1.0 fm]

LENPIC: Low Energy Nuclear Physics International Collaboration

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

Summary and outlook

Nuclear Hamiltonian:

— derivation of contributions up to N^3LO completed already in 2011; derivation of N^4LO corrections done for V_{2N} and almost done for V_{3N} (new LECs…) and V_{4N}

— accurate & precise 2N potentials at N^4LO^+ are available,

— promising results for few-N systems based on 2NF + 3NF@N^2LO [LENPIC]

Work in progress:

— regularization of 3NF & currents beyond N^2LO (nontrivial to maintain χ-symm!)

Next steps:

— Precision tests of the theory for ^3H β decay & μ capture (validation)

— Extension to other processes, heavier nuclei, N^4LO, explicit Δ's, …