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High-precision nuclear forces from chiral EFT: Where do we stand?

Introduction

PWA of NN data in chiral EFT

Beyond NN: challenges and open problems

Bundesministerium für Bildung und Forschung

DFG Deutsche Forschungsgemeinschaft

From QCD to nuclei

QCD → **lattice**

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

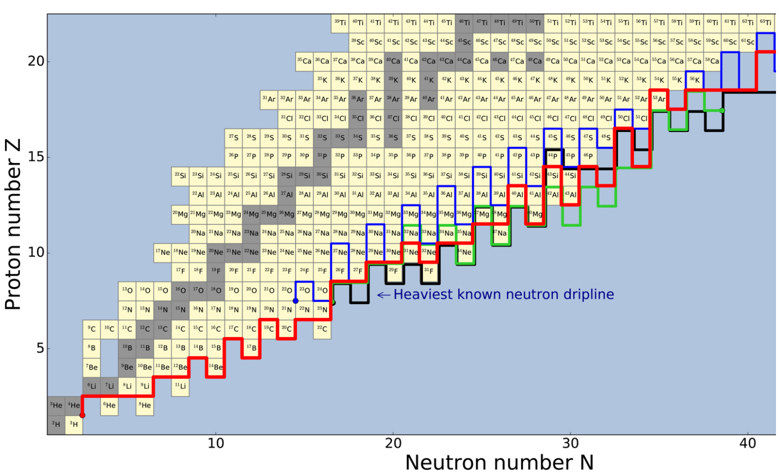
effective chiral Lagrangian $\mathcal{L}_{\text{eff}}(\pi, N)$

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



From chiral Lagrangians to nuclei

Step 1: Derive nuclear forces and currents in ChPT **[Method of UT, S-matrix matching, TOPT].**
Nontrivial: ensure renormalizability of the nuclear potentials…

Step 2: Introduce a cutoff Λ which in a nonrelativistic approach must be kept finite, $\Lambda \sim \Lambda_b$ **[Lepage '97; EE, Meißner '06; EE, Gegelia '09]**. Nontrivial: symmetries…

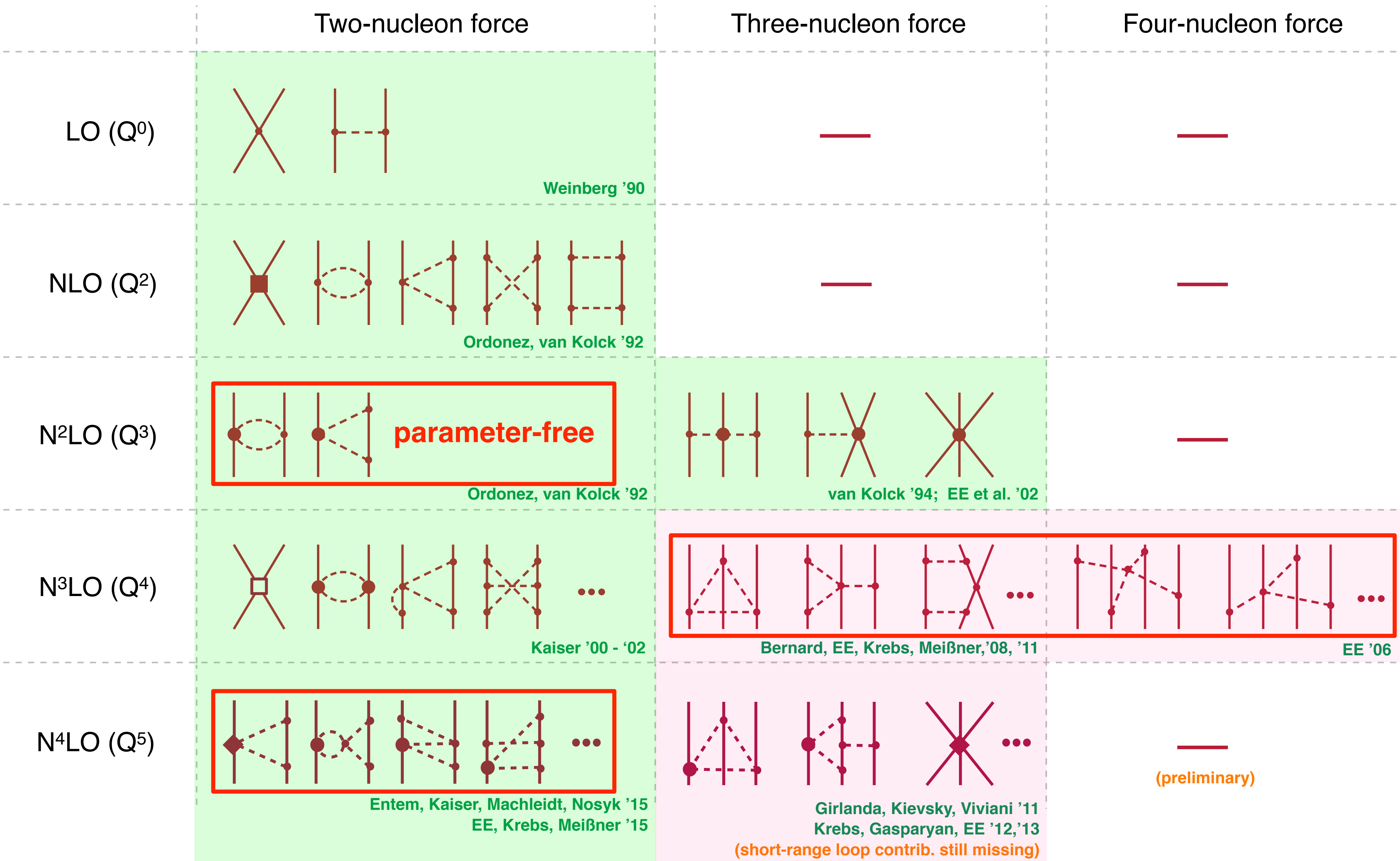
Step 3: PWA of NN scattering data to fix bare LECs $C_i(\Lambda)$ (i.e. implicit renormalization)

Step 4: Compute observables using ab initio methods **[FY, Lattice, NCSM, GFMC, CC, IMSRG, …]** **(talks by Maria Piarulli, Saori Pastore)** and perform error analysis

Renormalization, power counting and all that

- **EE, Gegelia, Meißner, NPB 925 (2017) 161:** identified renormalization conditions yielding a consistent expansion for systems close to the unitary limit with NDA scaling of LECs (W. counting). No contradiction with the KSW/RG-based counting (different renormalization conditions).
- A renormalizable formulation based on the Lorenz-invariant L_{eff} is available (requires contributions beyond V_{LO} to be treated perturbatively) **EE, Gegelia PLB 716 (2012) 338.**
- For a general discussion see materials of the KITP Program Frontiers in Nuclear Physics (2016): **http://online.kitp.ucsb.edu/online/nuclear16/**

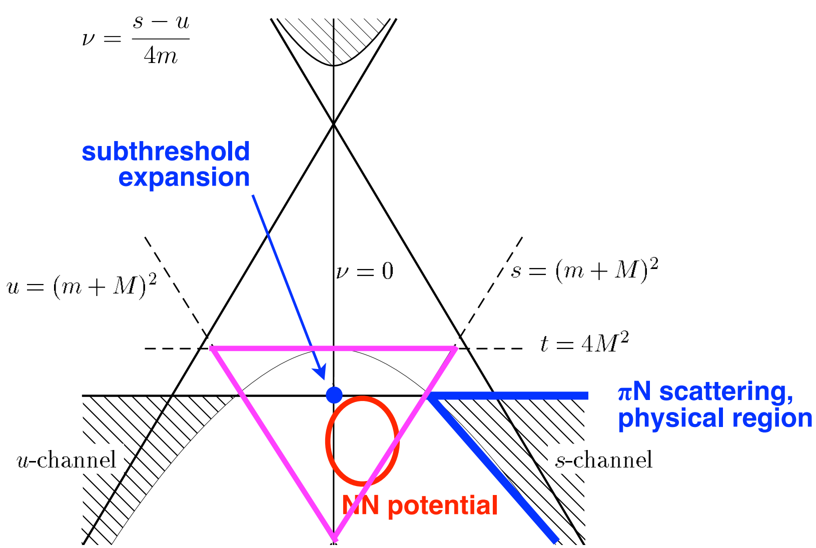
Chiral expansion of the nuclear forces [W-counting]



— Consistent vector, axial, pseudoscalar currents at N^{3}LO (2-loop/1-loop/tree for 1N/2N/3N) **talk by H. Krebs**

— A similar program is being pursued in chiral EFT with explicit Δ(1232) **Kaiser et al.; Krebs, Gasparyan, EE, Meißner**

Determination of πN LECs



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…

[talks by Jacobo Ruiz de Elvira, Martin Hoferichter]

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

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

— EKM N^{4}LO [EE, Krebs, Meißner, PRL 115 (2015) 122301]: Q^4 fit to KH PWA

— RKE N^{4}LO [Reinert, Krebs, EE, EPJA 54 (2018) 88]: Q^4 fit to RS and Q^4 fit to KH PWA

With the LECs taken from πN, the long-range NN force is fixed in a parameter-free way

Regularization

The cutoff Λ has to be kept finite, $\Lambda \sim \Lambda_b$. In practice, even 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…

$\longrightarrow$ it is crucial to employ a regulator that minimizes finite-Λ artifacts!

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

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

Local: (implemented in coordinate space)

[inspired by Thomas Rijken]

$$V_\pi(\vec r\,) \longrightarrow V_\pi(\vec r\,)\left[1-\exp(-r^2/R^2)\right]^n$$ used in EE, Krebs, Meißner (EKM) ’15

— still an ad hoc procedure

— (technically) difficult to apply to 3NF and exchange currents

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

Reinert, Krebs, EE ’18;

$\longrightarrow$ 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:

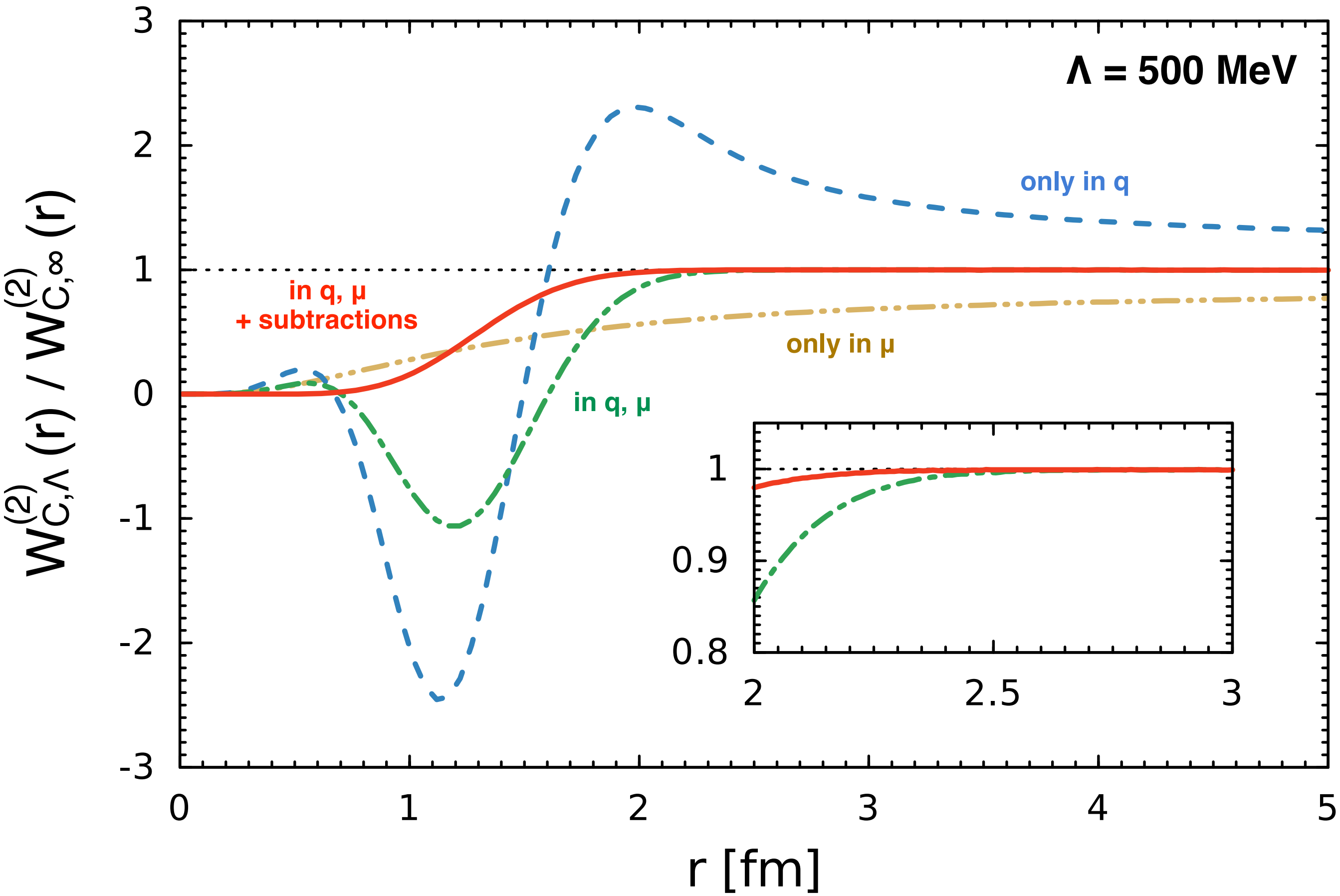
$$V(q)=\frac{2}{\pi}\int_{2M_\pi}^\infty \mu\, d\mu \frac{\rho(\mu)}{q^2+\mu^2}+\ \ldots \xrightarrow{\text{reg.}} V_\Lambda(q)=e^{-\frac{q^2}{2\Lambda^2}}\frac{2}{\pi}\int_{2M_\pi}^\infty \mu\, d\mu \frac{\rho(\mu)}{q^2+\mu^2}\,e^{-\frac{\mu^2}{2\Lambda^2}}+\underbrace{\ldots}_{\substack{\textit{polynomial}\\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

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

Regularization

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

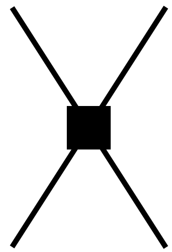
Various regularization approaches



Does it matter in practice?

Contact interactions

- 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~~ 12 operators (S-, P-, D-waves, $\varepsilon_{1,2}$)
N^{4}LO [Q^5]:	no new isospin-conserving operators
N^{4}LO$^+$ [Q^6]:	+ 4 F-wave operators

- Use a simple nonlocal Gaussian regulator for contacts with Λ = 350…500 MeV

- Fits @N^{3}LO & beyond indicate some redundancy [Hammer, Furnstahl; Beane, Savage, Wesolowski et al.]

$$\begin{aligned}
\langle {}^1S_0,\, p'|V_{\rm cont}|{}^1S_0,\, p\rangle &= \tilde{C}_{1S0} + C_{1S0}(p^2+p'^2) + D_{1S0}\, p^2p'^2 + D^{\rm off}_{1S0}\,(p^2-p'^2)^2 \\
\langle {}^3S_1,\, p'|V_{\rm cont}|{}^3S_1,\, p\rangle &= \tilde{C}_{3S1} + C_{3S1}(p^2+p'^2) + D_{3S1}\, p^2p'^2 + D^{\rm off}_{3S1}\,(p^2-p'^2)^2 \\
\langle {}^3S_1,\, p'|V_{\rm cont}|{}^3D_1,\, p\rangle &= C_{\epsilon 1}p^2 + D_{\epsilon 1}\, p^2p'^2 + D^{\rm off}_{\epsilon 1}\, p^2(p^2-p'^2)
\end{aligned}$$

(Short-range) UTs $U = e^{\gamma_1 T_1 + \gamma_2 T_2 + \gamma_3 T_3}$ with

$$T_1 = \vec{k}\cdot\vec{q}, \qquad T_2 = \vec{k}\cdot\vec{q}\;\vec{\sigma}_1\cdot\vec{\sigma}_2, \qquad T_3 = \vec{\sigma}_1\cdot\vec{k}\;\vec{\sigma}_2\cdot\vec{q} \;+\; 1\leftrightarrow 2.$$

Induced terms in the Hamiltonian: $\delta H = U^\dagger H U - H^{(0)} = \underbrace{\sum_i \gamma_i \left[H^{(0)}_{\rm kin},\, T_i\right]}_{}+\;\ldots$

have the form of $V^{(4)}_{\rm cont}$ → *3 terms can be eliminated (modulo higher-order terms…)*

The UT also affects short-range 3NFs and currents starting from N^{4}LO. Changing the off-shell behavior of the interaction in a controlled way is a useful tool!

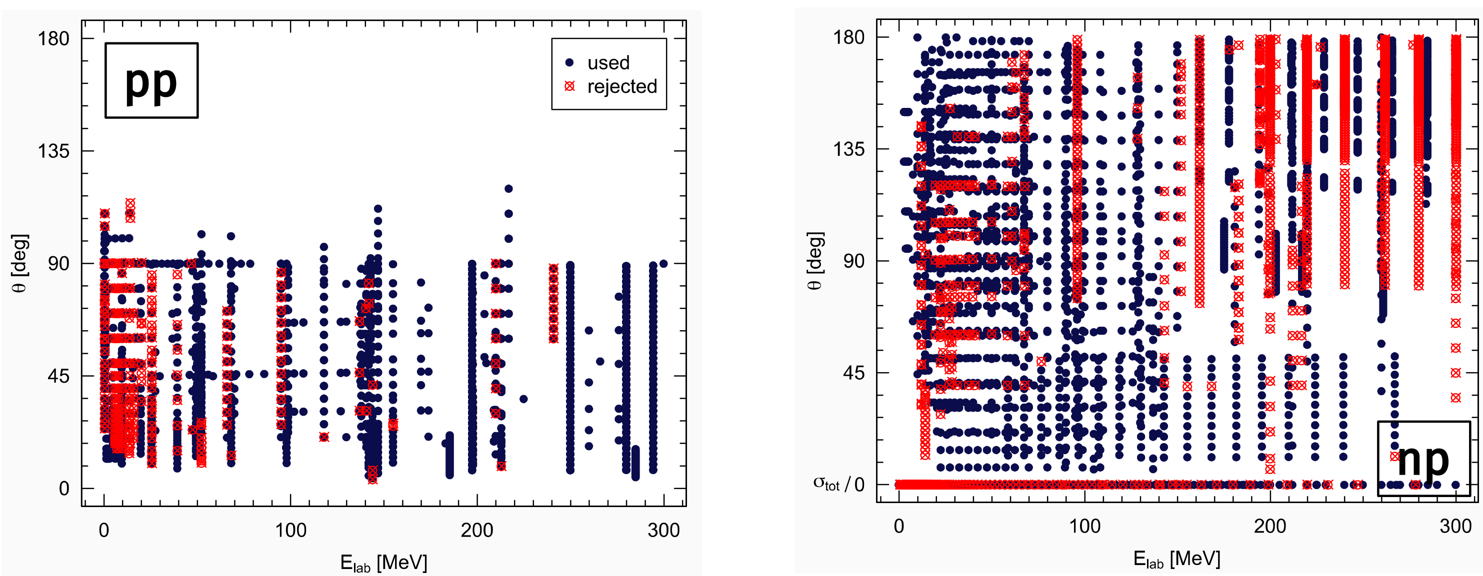
Partial wave analysis of NN data

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

- 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 collected.

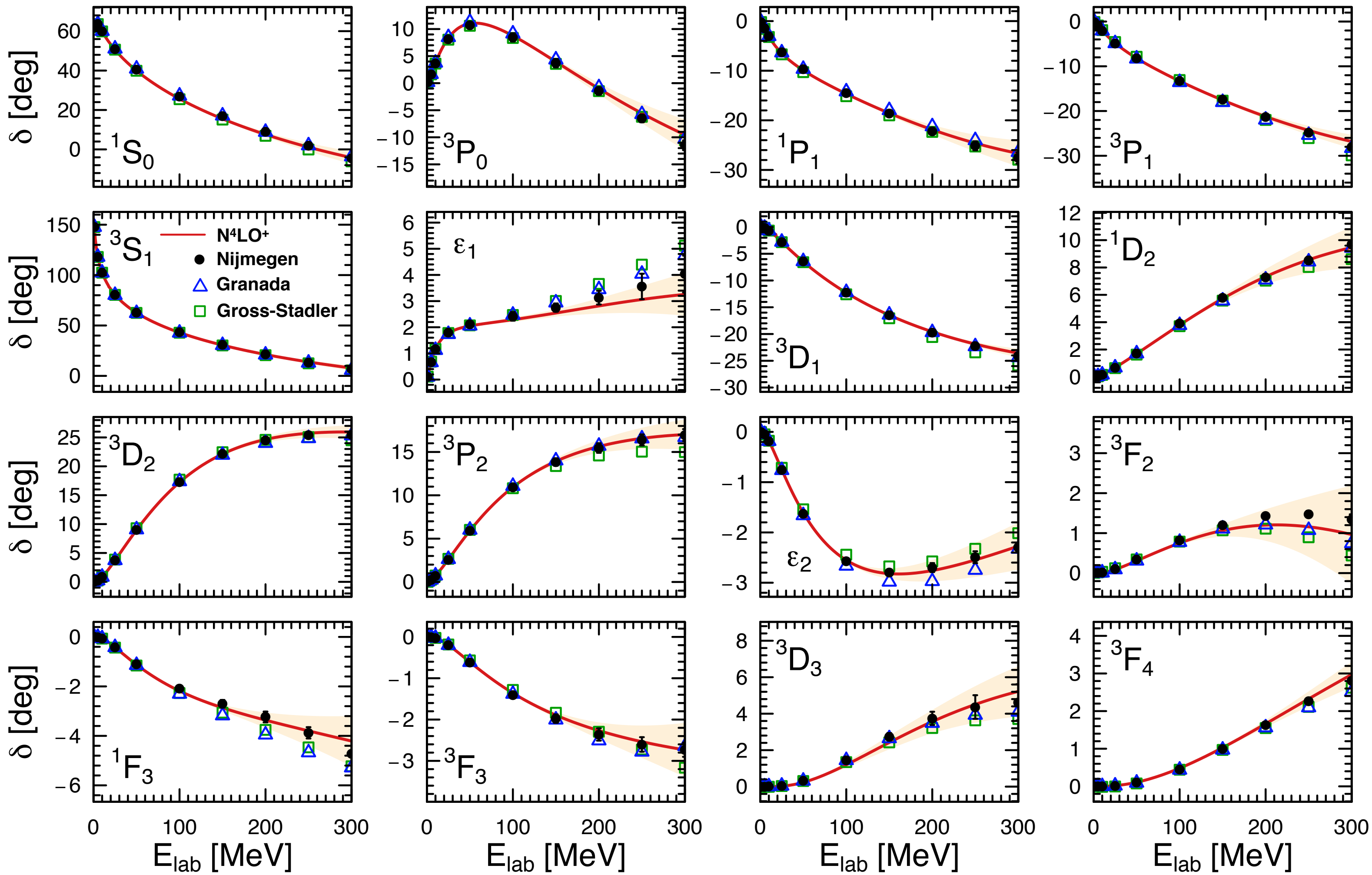
- However, certain data are mutually incompatible within errors and have to be rejected.
  2013 Granada database [Navarro-Perez et al., PRC 88 (2013) 064002], rejection rate: 31% np, 11% pp:
  2158 proton-proton + 2697 neutron-proton data below $E_{lab} = 300$ MeV



- Incomplete treatment of IB effects: $V_\gamma + V_{1\pi} + V_{cont}$ ($^1S_0$)

Partial wave analysis of NN data

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



— For the first time, chiral EFT potentials qualify for being regarded as PWA

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

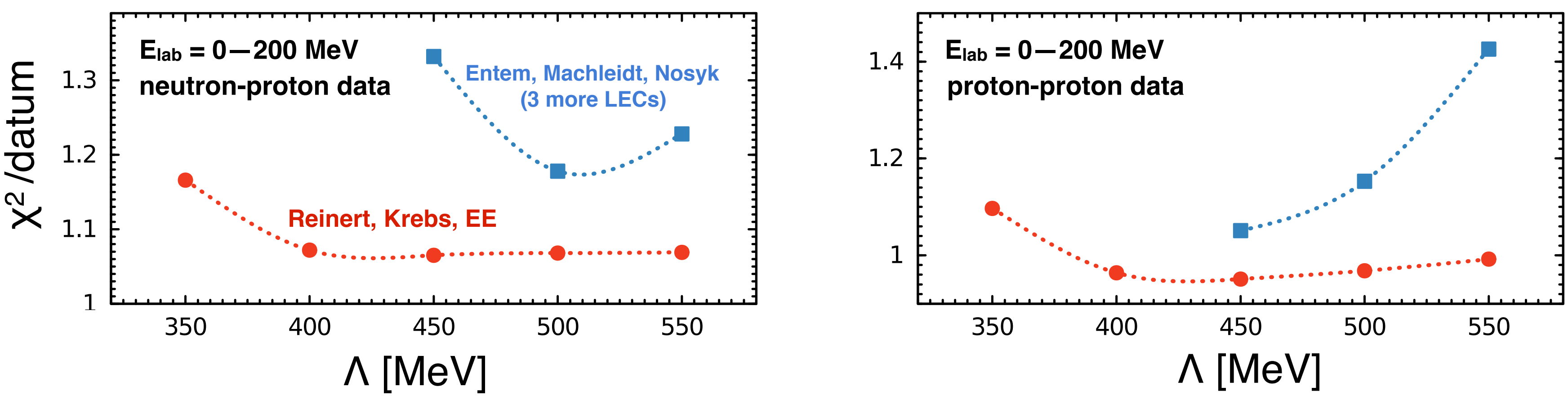
Partial wave analysis of NN data

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

χ^2/datum for the description of the Granada-2013 database: χEFT vs. phenomenology

$E_{\rm lab}$ bin	CD Bonn$_{(43)}$	Nijm I$_{(41)}$	Nijm II$_{(47)}$	Reid93$_{(50)}$	N^{4}LO$^+$$_{(27+1)}$, this work
neutron-proton scattering data					
0 – 100	1.08	1.06	1.07	1.08	1.07
0 – 200	1.08	1.07	1.07	1.09	1.07
0 – 300	1.09	1.09	1.10	1.11	1.06
proton-proton scattering data					
0 – 100	0.88	0.87	0.87	0.85	0.86
0 – 200	0.98	0.99	1.00	0.99	0.95
0 – 300	1.01	1.05	1.06	1.04	1.00

N^{4}LO$^+$: semilocal (Reinert, Krebs, EE) vs. nonlocal (Entem, Machleidt, Nosyk)



Error analysis

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

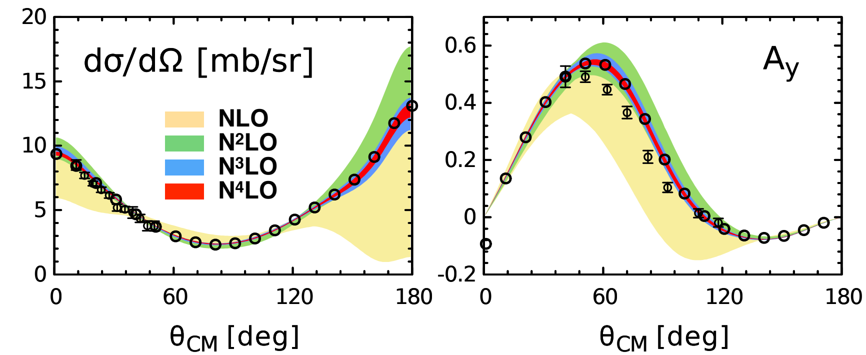
1. Truncation error

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

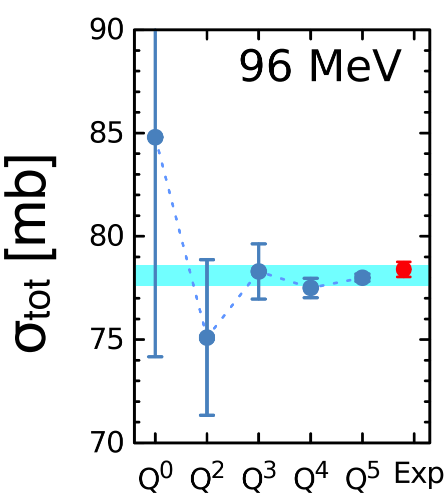
proton-neutron scattering at E_{lab}=143 MeV



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

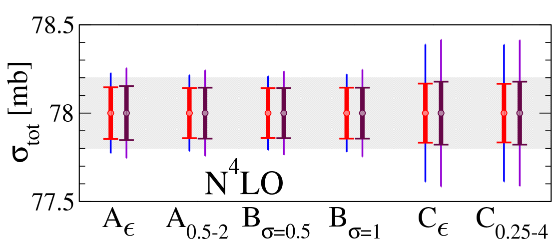
$$\left\{ \delta X^{(0)} = Q^2 |X^{(0)}|, \quad \delta X^{(i)} = \max_{2 \le j \le i} \left(Q^{i+1} |X^{(0)}|, \, Q^{i+1-j} |\Delta X^{(j)}| \right) \right\} \quad \wedge \quad \delta X^{(i)} \geq \max_{j,k} \left(|X^{(j \geq i)} - X^{(k \geq i)}| \right)$$

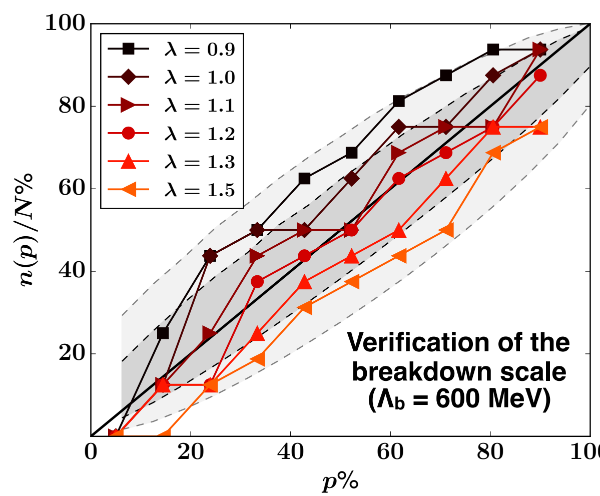
Example: np total cross section at 96 MeV



— calculations based on the EE, Krebs, Meißner, PRL115 (15) 122301

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





Error analysis

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

In most cases, the uncertainty is dominated by truncation errors. At N⁴LO 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, πN LECs, statistical error, 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: $A_S = 0.8781(44)\ \mathrm{fm}^{-1/2}$, $\eta = 0.0256(4)$

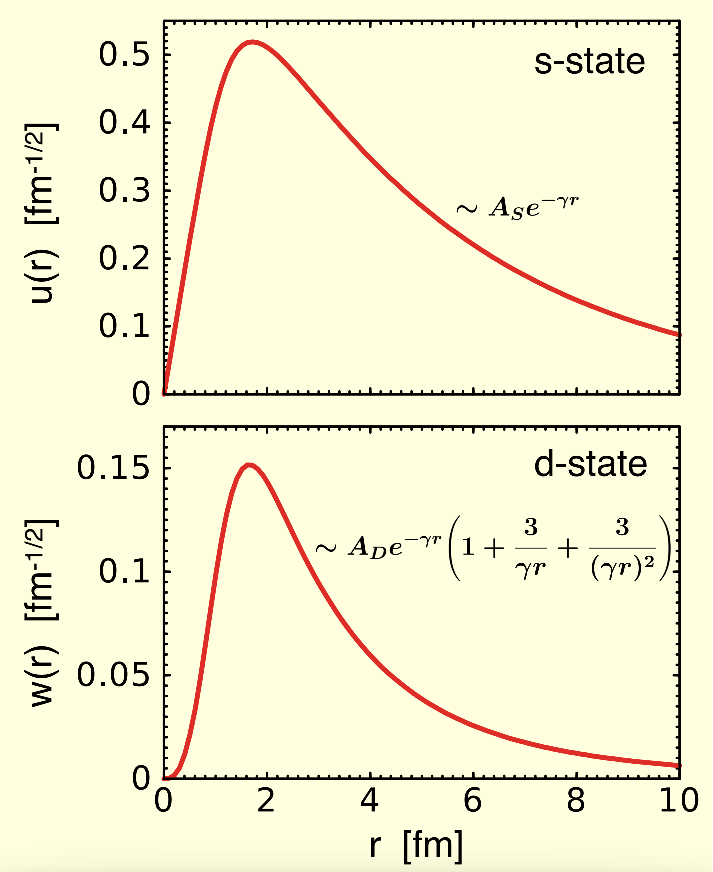
Borbely et al. '85 — Rodning, Knutson '90

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

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



Isospin-breaking effects

talk by Patrick Reinert

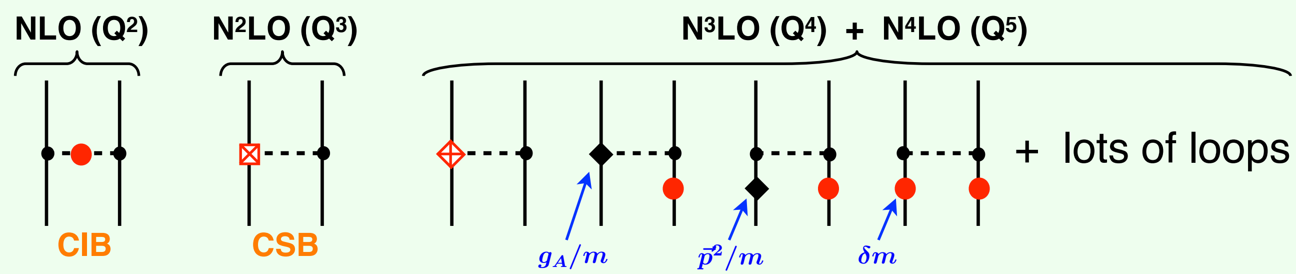
chiral order	two-nucleon forces	three-nucleon forces
NLO $[Q^2]$	$V_{1\gamma} + V_{1\pi}$	—
N^{2}LO $[Q^3]$	$V_{1\pi} + V_{\rm cont}$	—
N^{3}LO $[Q^4]$	$V_{1\gamma} + V_{\pi\gamma} + V_{1\pi} + V_{2\pi} + V_{\rm cont}$	$V_{2\pi} + V_{1\pi-{\rm cont}}$
N^{4}LO $[Q^5]$	$V_{1\pi} + V_{2\pi} + V_{\rm cont}$	$V_{2\pi} + V_{1\pi-{\rm cont}}$

The only unknown LECs up to N^{4}LO are charge-dependent πN coupling constants and $V_{\rm cont}$

IB 1-pion exchange

class II (CIB): $\tau_1^3 \tau_2^3$

class III (CSB): $\tau_1^3 + \tau_2^3$

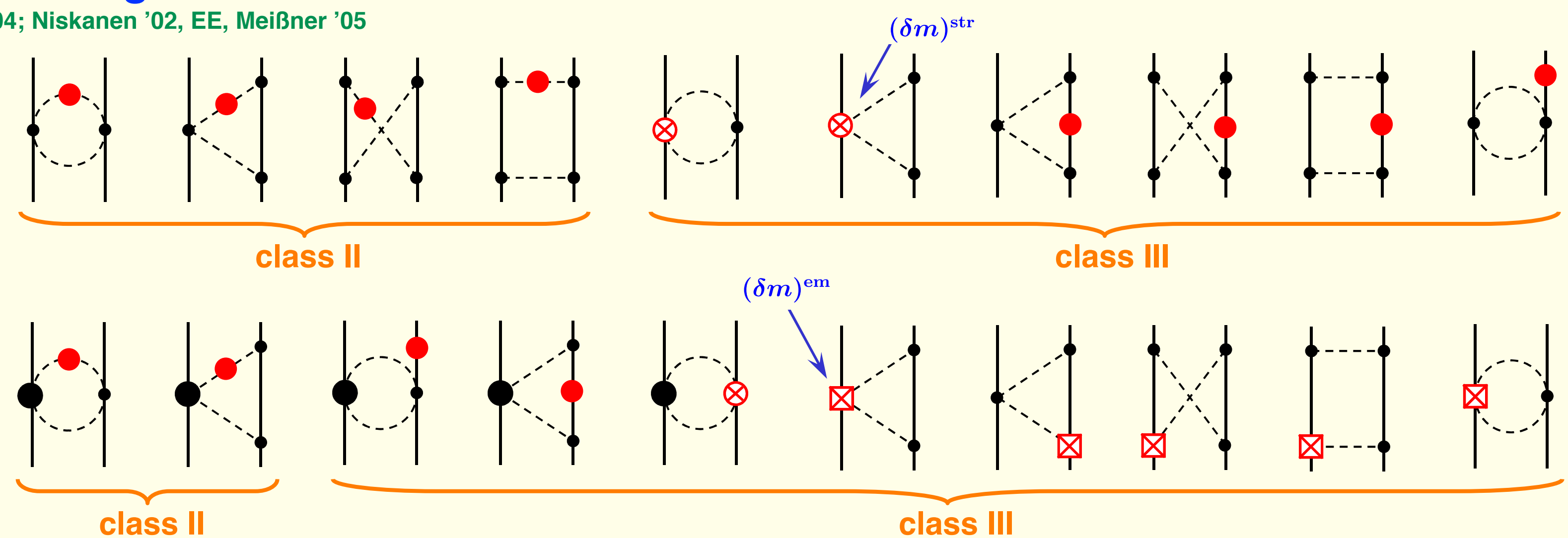


IB 2-pion exchange

Friar et al. ’99,’03,’04; Niskanen ’02, EE, Meißner ’05

N^{3}LO (Q^4):

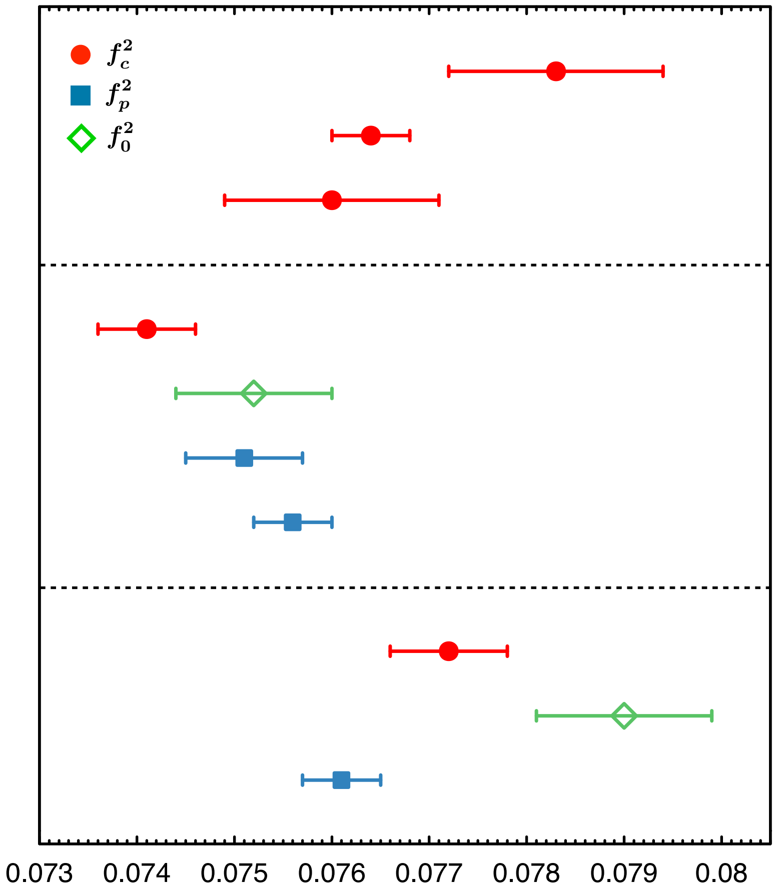
N^{4}LO (Q^5):



Charge dependence of the πN couplings

talk by Patrick Reinert

Notation: $f_p^2 \equiv f_{\pi^0 pp} f_{\pi^0 pp}, \qquad f_0^2 \equiv -f_{\pi^0 nn} f_{\pi^0 pp}, \qquad 2f_c^2 \equiv f_{\pi^- pn} f_{\pi^+ np}$



Goldberger-Miyazawa-Oehme (GMO) sum rule **[Ericson et al. '02]**

fixed-t dispersial relations **[Arndt et al. '06]**

π^-d scattering + GMO sum rule **[Baru et al. '11]**

NN PWA by the Nijmegen Group
[Klomp, Stoks, de Swart '91]

— np + pp data up to E_{lab} = 350 MeV
— V_γ + $V_{1\text{-boson}}$ + V_{phen}

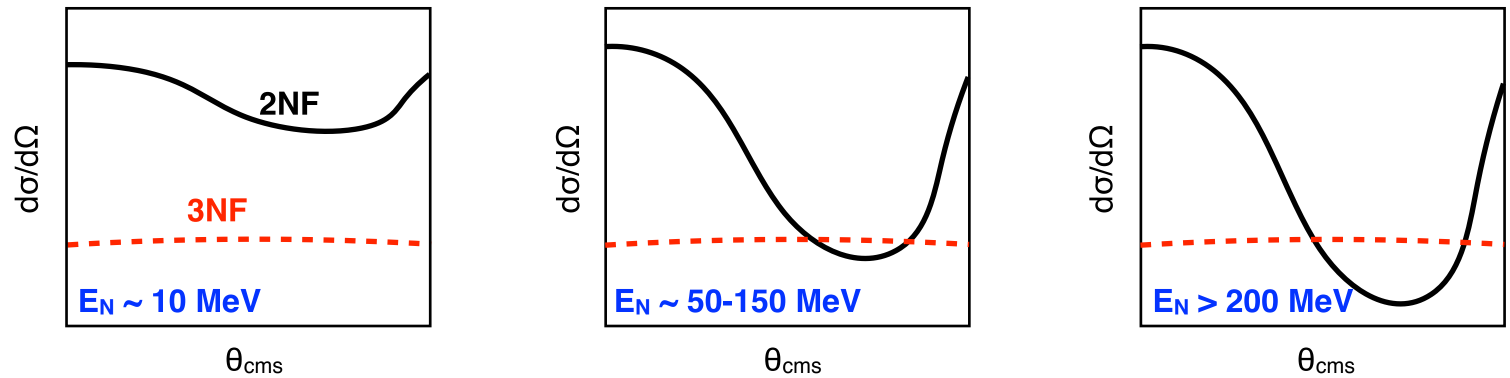
[Rentmeester et al. '99]

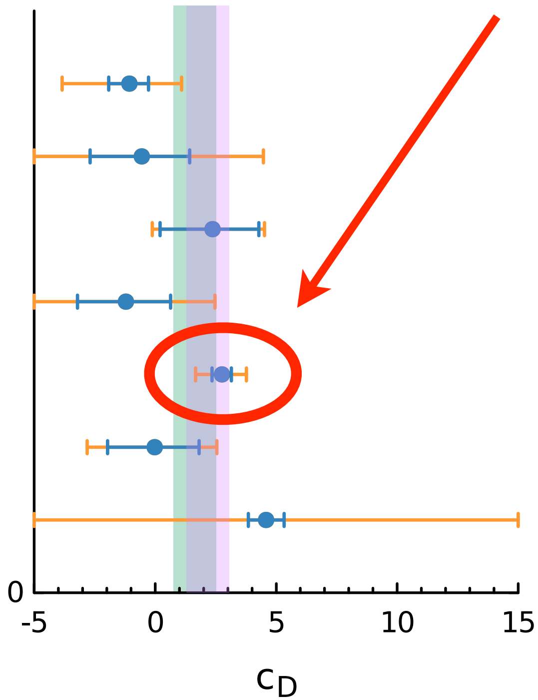
— pp data, including 2π-exchange from χEFT

NN PWA by the Granada Group
[Navarro-Perez, Amaro, Ruiz Arriola '17]

— Granada-2013 np + pp database
— E_{lab} = 0…350 MeV
— V_γ + $V_{1\pi}$ + δ-shells

Beyond the two-nucleon system





pd minimum of dσ/dθ at 135 MeV [Sekiguchi et al.'02]

nd σ_{tot} at 135 MeV [Abfalterer et al.'01]

pd minimum of dσ/dθ at 108 MeV [Ermisch et al.'03]

nd σ_{tot} at 108 MeV [Abfalterer et al.'01]

pd minimum of dσ/dθ at 70 MeV [Sekiguchi et al.'02]

nd σ_{tot} at 70 MeV [Abfalterer et al.'01]

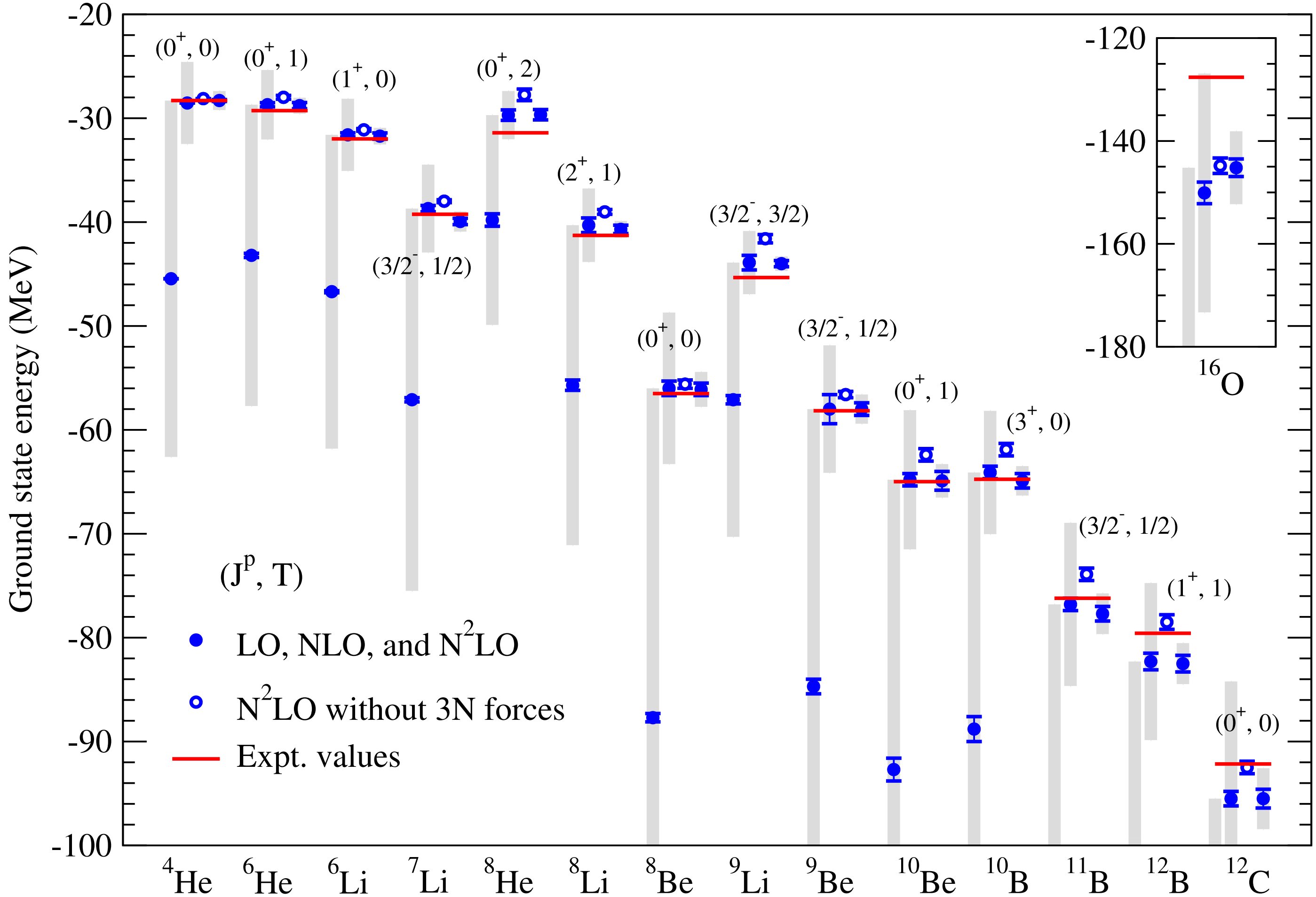
nd scattering length ^2a [Schoen et al.'03]

LENPIC, 1807.02848 [based on EKM, R = 0.9 fm]

yields the strongest constraint…

Light nuclei

EE et al. (LENPIC), arXiv:1807.02848



[based on the EKM potential, R = 1.0 fm]

LENPIC: Low Energy Nuclear Physics International Collaboration

Intermediate summary

- The 2N sector is in a good shape: chiral potentials at N^4LO^+ yield nearly perfect description of np and pp data up to 300 MeV. No significant improvement can be achieved by going to even higher orders.

- 3NF extensively explored at N^2LO. The results are promising, but the truncation error is still large at this order. **Things to be avoided:**

  — optimization beyond the actual accuracy of the theory by compromising the rigor (inconsistent combinations of the interactions, LECs incompatible with πN, lack of error analysis, …)

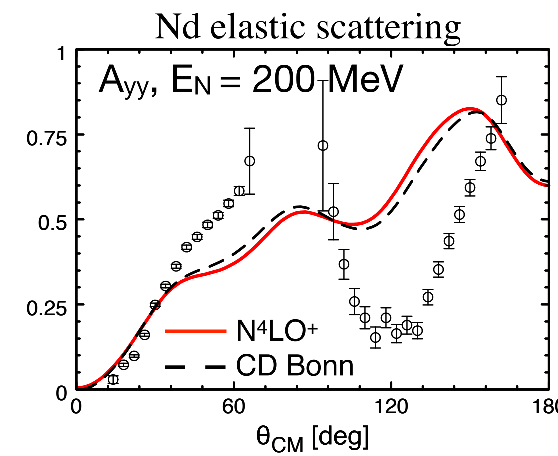
  — focusing on a too restricted set of observables (spectra + radii of nuclei + EOS). Cannot claim to understand 3NF unless Nd data are properly described.

The quest for high-precision calculations beyond the 2N system: a <u>major</u> challenge for chiral EFT!

The 3NF challenge

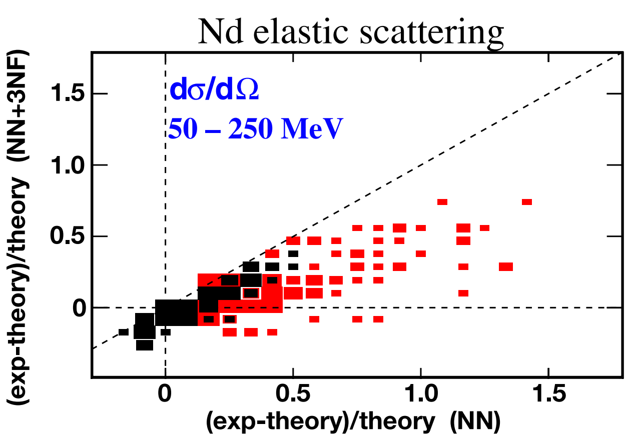
Nd scattering studies have revealed: [Glöckle, Witala, Kievsky, Viviani, Deltuva, …]

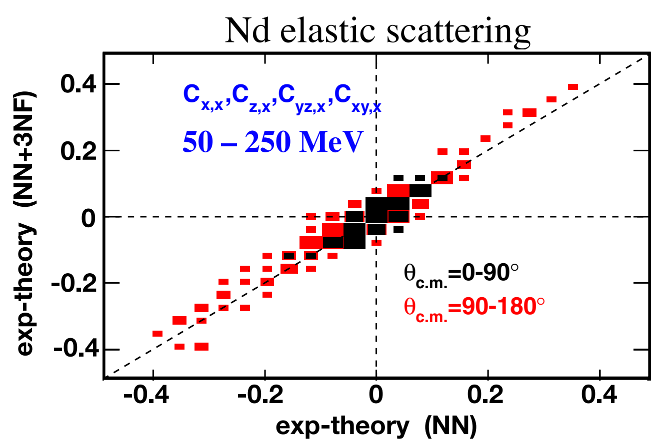
- High-precision 2N potentials alone (N^4LO^+, CDBonn, Nijm, AV18,…) yield similar predictions.
- Good description of data at low E_N (except for A_y and SST).
- Discrepancies set in at $E_N \sim 50$ MeV and become large at $E_N \sim 200$ MeV. Phenomenological 3NFs do not help. χEFT 3NF@N^2LO inconclusive (too large uncertainty).

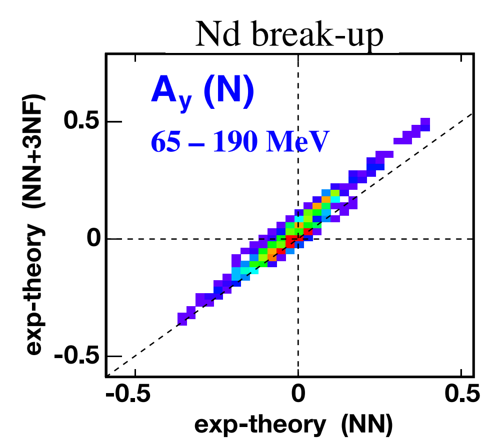


→ **The simplest system beyond NN is poorly understood!** [talk by Kimiko Sekiguchi]

One needs to push chiral EFT to N^4LO and perform a PWA of Nd scattering (similar to NN).
Computational ($2_{[N2LO]}$ + $>10_{[N4LO]}$ LECs) & conceptual (consistent regularization) challenges!







from: Kalantar-Nayestanaki, EE, Messchendorp, Nogga, Rept. Prog. Phys. 75 (2012) 016301

Regularization and the symmetries

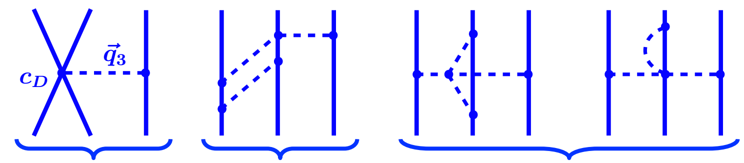
talk by Hermann Krebs in the FB WG

$$V(q) = \frac{2}{\pi}\int_{2M_\pi}^{\infty} \mu\, d\mu \frac{\rho(\mu)}{q^2+\mu^2} + \ldots \quad \longrightarrow \quad V_\Lambda(q) = e^{-\frac{q^2}{2\Lambda^2}}\, \frac{2}{\pi}\int_{2M_\pi}^{\infty} \mu\, d\mu \frac{\rho(\mu)}{q^2+\mu^2}\, e^{-\frac{\mu^2}{2\Lambda^2}} + \ldots$$

Regulator artifacts can <u>always</u> be absorbed into NN LECs (<u>no constraints from χ-symm.</u>).

This is **NOT** true anymore beyond the NN system!

— may encounter χ-symmetry breaking divergences (ambiguous). Using DR to compute 3NFs/currents and cutoff in ladder graphs (iterations) is problematic.



— naive cutoff regularization breaks χ-symmetry (dependence on π-parametrization).

These issues affect >2N forces & exchange currents beyond tree level (i.e. beyond N²LO)!

Solution: higher-derivative regularization [Slavnov, Nucl. Phys. B31 (1971) 301]

(designed to coincide with the employed local regularization in the NN sector)

$$\mathcal{L}^{(2)}_{\pi,\Lambda} = \mathcal{L}^{(2)}_{\pi} + \frac{F^2}{4}\mathrm{Tr}\left[\mathrm{EOM}\, \frac{1-\exp\left(\frac{\mathrm{ad}_{D_\mu}\mathrm{ad}_{D^\mu}+\frac{1}{2}\chi_+}{\Lambda^2}\right)}{\mathrm{ad}_{D_\mu}\mathrm{ad}_{D^\mu}+\frac{1}{2}\chi_+}\,\mathrm{EOM}\right], \qquad \mathcal{L}^{(2)}_{\pi} = \frac{F^2}{4}\mathrm{Tr}\left[u_\mu u^\mu + \chi_+\right]$$

Hermann Krebs et al. (preliminary)

with $\mathrm{EOM} \equiv -[D_\mu, u^\mu] + \frac{i}{2}\chi_- - \frac{i}{4}\mathrm{Tr}(\chi_-)$ and $\mathrm{ad}_X Y \equiv [X, Y]$

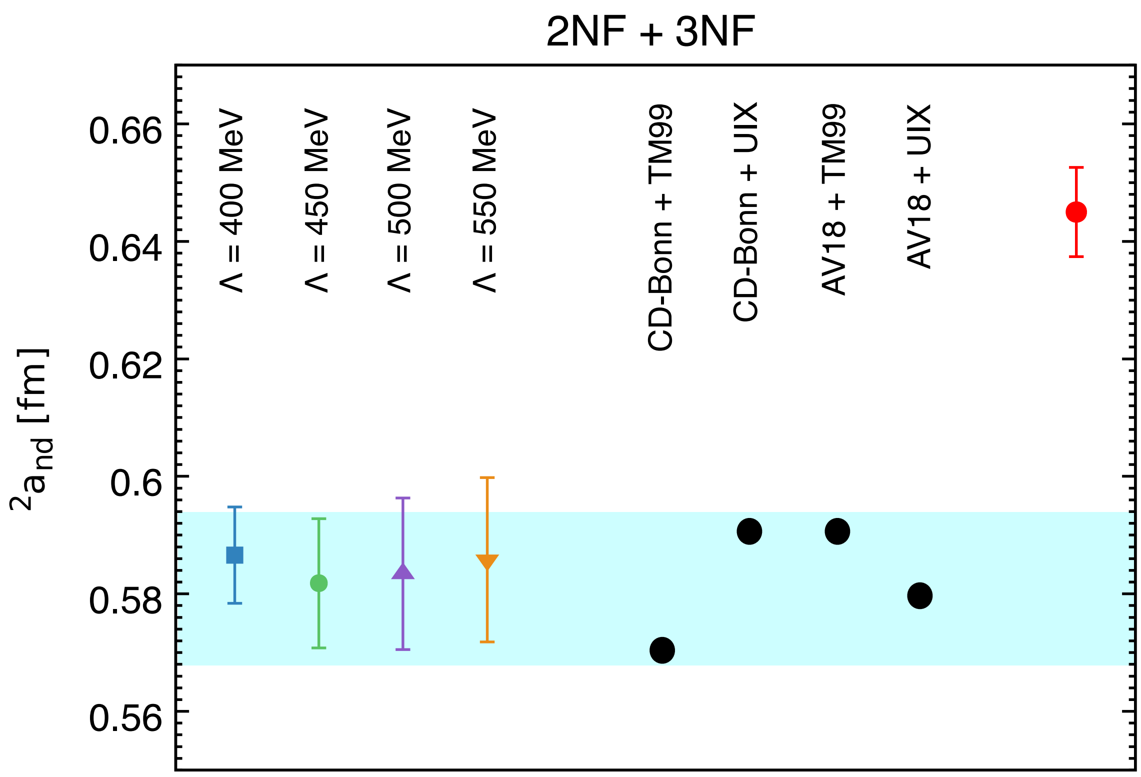
Requires recalculation of the loop contributions to the 3NF/exchange currents (in progress)

IB effects and precision few-N physics

- **Neutron-neutron scattering length from few-N reactions**

$\pi^- + {}^2\mathrm{H} \to n + n + \gamma \longrightarrow$ $a_{nn} = -18.50 \pm 0.53$ fm Howell et al. ’98

$n + {}^2\mathrm{H} \to n + n + p \longrightarrow$ $\begin{cases} a_{nn} = -18.7 \pm 0.6 \text{ fm} & \text{Gonzales Trotter et al. ’99} \\ a_{nn} = -16.3 \pm 0.4 \text{ fm} & \text{Huhn et al. ’00} \end{cases}$



Can reproduce $^2a_{nd}$ using $a_{nn} \sim -16.5$ fm! Alternatives (3NF beyond N^{2}LO, IB effects) need to be checked.
Can one then still understand the BE differences of mirror nuclei?

Radii of medium-mass nuclei: A smoking gun?

- Preliminary results indicate that radii of heavier nuclei are underestimated (~ 15% for ^{16}O)
- Calculations are incomplete: **3NFs** beyond N^2LO **and MECs** are missing…
- High-precision 2NF + 3NF yield similar results in light nuclei, deviations increase with A

	r_D, ^2H (fm)	r_p, ^3H (fm)	r_p, ^4He (fm)
AV18 + UIX	1.967 (−0.4%)	1.584 (−1%)	1.44 (−2%)
CD-Bonn + TM99	1.966		1.42
N^4LO^+ + 3NF@N^2LO	1.967	1.580	1.43

Can the remaining discrepancies be removed by MECs?

- What could be the reason that the N^2LO potentials by Ekström et al. are doing a good job?

$NNLO_{sat}$: r_D = 1.978 fm (+0.13%)
Ekström et al., PRC91 (2015) 051301

$\Delta NNLO(450)$: r_D = 1.982 fm (+0.3%)
Ekström et al., PRC97 (2018) 024332

However, NN data seem to prefer smaller r_D:

	RKE N^4LO^+	Granada PWA (δ-shell)	Nijm I	Nijm II	Reid93	CD-Bonn	Exp.
r_D, ^2H (fm)	1.965 … 1.968	1.965	1.967	1.968	1.969	1.966	1.975

- Work in progress: calculations of the EM FFs of A = 2…16 nuclei including consistent MECs
  with Vadim Baru, Arseniy Filin, Daniel Möller + LENPIC Collaboration

Summary and outlook

- The most precise NN forces finally come from chiral EFT
- Pushing the accuracy/precision frontier in >2N systems requires addressing the 3NF problem: A computational and conceptual challenge
- Exciting field full of opportunities, unsolved problems and puzzles!

— hope to provide some answers at CD21 :-) —

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