Chiral Nuclear Forces at N4LO

R. Machleidt, University of Idaho

Outline

- Introduction
- Some misconceptions concerning (chiral) nuclear forces
- What's next? The chiral expansion at N4LO
- Outlook

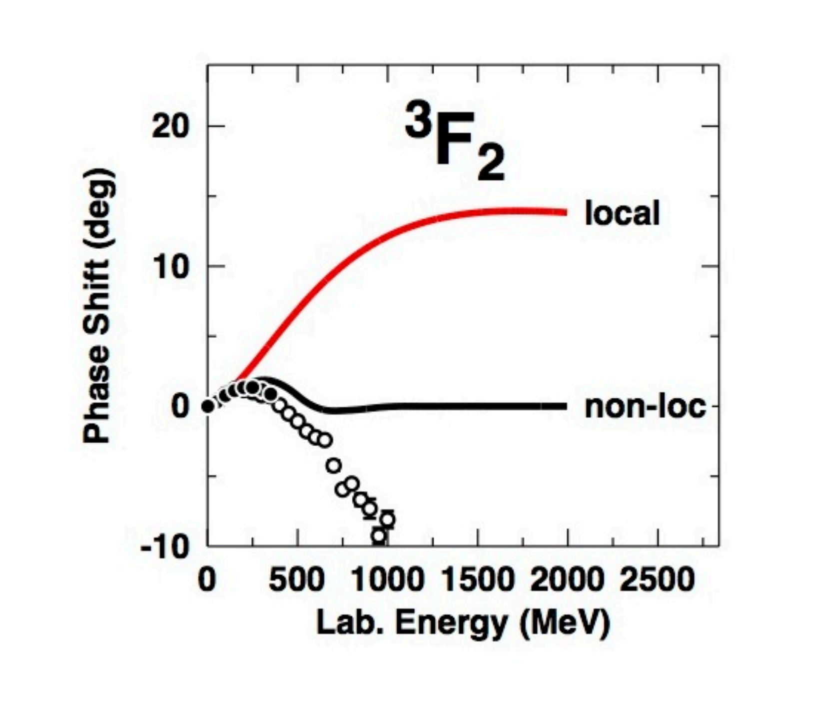
History and current status of chiral nuclear forces

- Since 20+ years, the idea of using chiral EFT for the derivation of nuclear forces is around (Weinberg, van Kolck). The ideas are by now well-known in this community, and I will not repeat them.
- Since 10+ years, quantitative chiral NN potentials exist up to N3LO.
- With these potentials (+chiral 3NFs), numerous exact few-body and *ab initio* many-body calculations have been performed---with some success. But there are also unsolved problems.
- What are the reasons for the open problems?
- The current nuclear forces may be still deficient.
- Thus, the current research on nuclear forces is characterized by attempts to improve those forces.
- Let's look at the facts and address some common misconceptions.

Myth #1: Local cutoffs are better than non-local ones.

Wrong! Why?

- Potentials with local cutoffs never go to zero on-shell and, thus, the phase shifts grow forever.



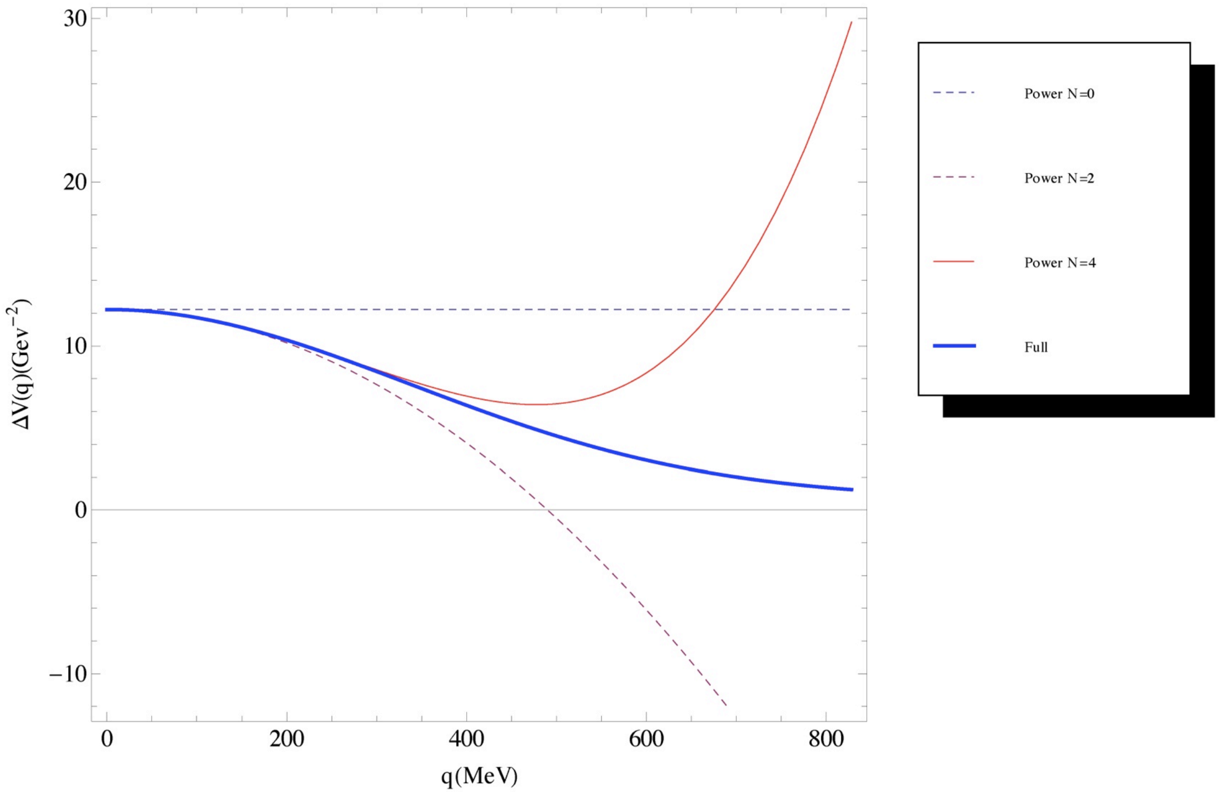
Myth #1: Local cutoffs are better than non-local ones.

Wrong! Why?

- Potentials with local cutoffs never go to zero on-shell and, thus, the phase shifts grow forever.
- Chiral EFT is an expansion in momenta. What power in momentum is the local cutoff function equivalent to?

$$f\left(\frac{r}{R}\right) = \left[1 - \exp\left(-\frac{r^2}{R^2}\right)\right]^n$$

Myth #1: Local cutoffs are better than non-local ones.



Blue curve: The piece that a local regulator cuts out of OPE, Fourier transformed into momentum space.
Dashed curves and red curve: Approximating the blue curve by contacts of various powers as denoted.

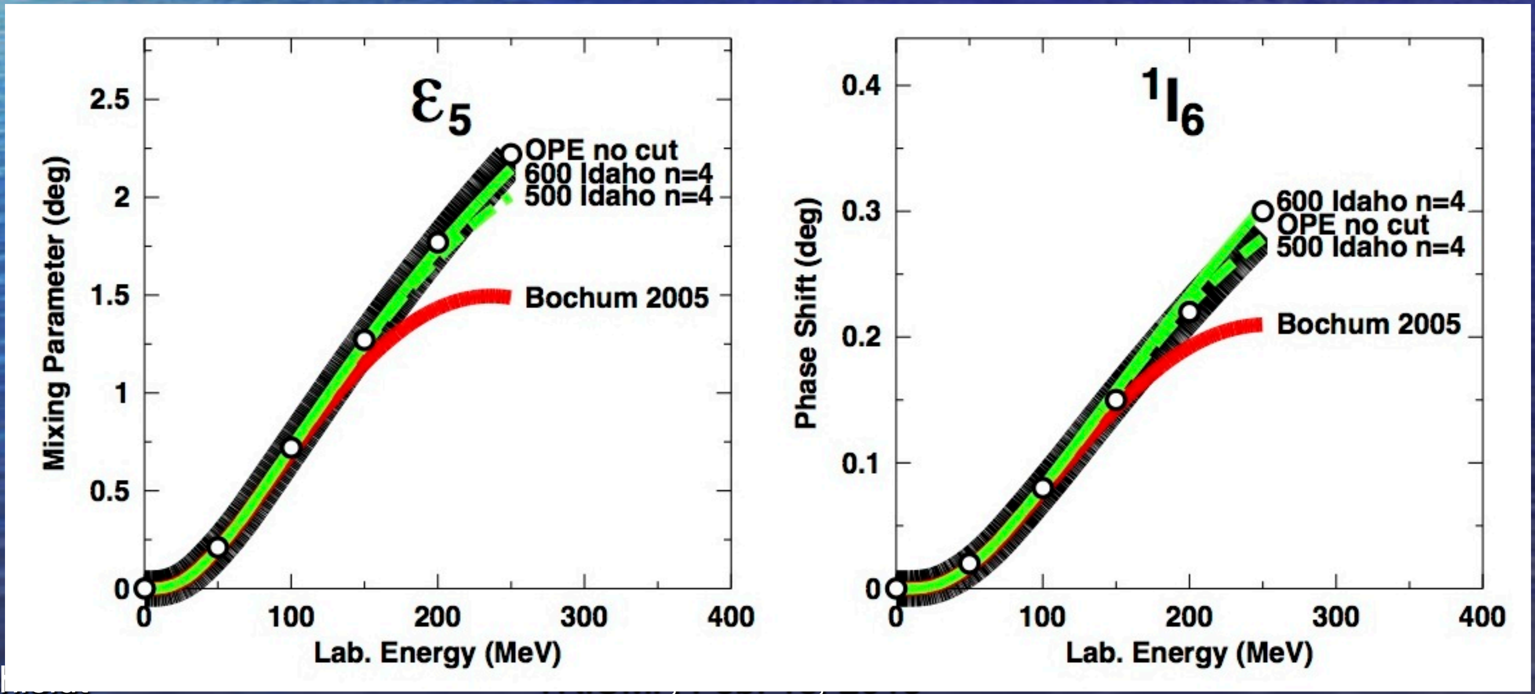
- Pot … ero on-she … ver.
- Chi … hat pow … ction equ …
- **Inconsistent with proper power counting!**

Myth #2: Non-local cutoffs are cutting down the long-range part too much.

Wrong! Why?

- **It depends on the power of the non-local regulator:**

$$f(p', p) = \exp[-(p'/\Lambda)^{2n} - (p/\Lambda)^{2n}]$$



Myth #3: When local cutoffs are used in the 3NF then, consistency requires, that local cutoffs are also used in the 2NF .

Wrong! Why?

- **Cutoffs generate powers of momenta beyond the given order; the coefficients don't matter (as long as they are natural). Local vs. non-local differ only by those coefficients:**

$$
\begin{aligned}
f_{\rm nonlocal}(p',p) &= \exp[-(p'/\Lambda)^{2n} - (p/\Lambda)^{2n}] \\
&\approx 1 - \left[\left(\frac{p'}{\Lambda}\right)^{2n} + \left(\frac{p}{\Lambda}\right)^{2n}\right] + \frac{1}{2}\left[\left(\frac{p'}{\Lambda}\right)^{2n} + \left(\frac{p}{\Lambda}\right)^{2n}\right]^2 - + \dots \\
f_{\rm local}(q) &= \exp[-(\vec{q}/\Lambda)^{2n}] \\
&\approx 1 - \left[\left(\frac{p'}{\Lambda}\right)^{2} + \left(\frac{p}{\Lambda}\right)^{2} - 2\,\frac{\vec{p}\,'\cdot\vec{p}}{\Lambda^2}\right]^{n} + \frac{1}{2}\left[\left(\frac{p'}{\Lambda}\right)^{2} + \left(\frac{p}{\Lambda}\right)^{2} - 2\,\frac{\vec{p}\,'\cdot\vec{p}}{\Lambda^2}\right]^{2n} - + \dots
\end{aligned}
$$

with $\vec{q} = \vec{p}\,' - \vec{p}$, the momentum transfer; $q = |\vec{q}|$.

Myth #4: For 3NFs, local cutoffs are better than non-local ones.

Wrong! **Why?**

- **Both are equally good or bad. Use what works best for you.**
- **In the NCSM, locals seem to work better (Navratil, FBS 41, 117 (2007)).**
- **In CC calculations of nuclear matter, locals showed bad convergence (Hagen et al., PRC 89, 014319 (2014)).**

Myth #5: Fitting phase shifts (and not data) is good enough for a high-precison potential.

Wrong! Why?

- **As pointed out correctly by the Nijmegen group some 20 years ago, phase shift chi2 can be very misleading concerning the true reproduction of the NN data.**
- **Example:**

Neutron-proton chi2/datum 0-200 MeV

	Idaho N3LO 500	Idaho N3LO 600	Bochum N3LO 550/600
Using data	1.1	1.2	1.3
Using phase shifts	2.2	5.3	2.1

Myth #6: Fitting a NN potential to just one NN data set is sufficient to demonstrate "high precision".

Wrong! **Why?**

- **Even the craziest NN potential can fit one data set.**
- **The point is to fit all 5000+ NN data.**

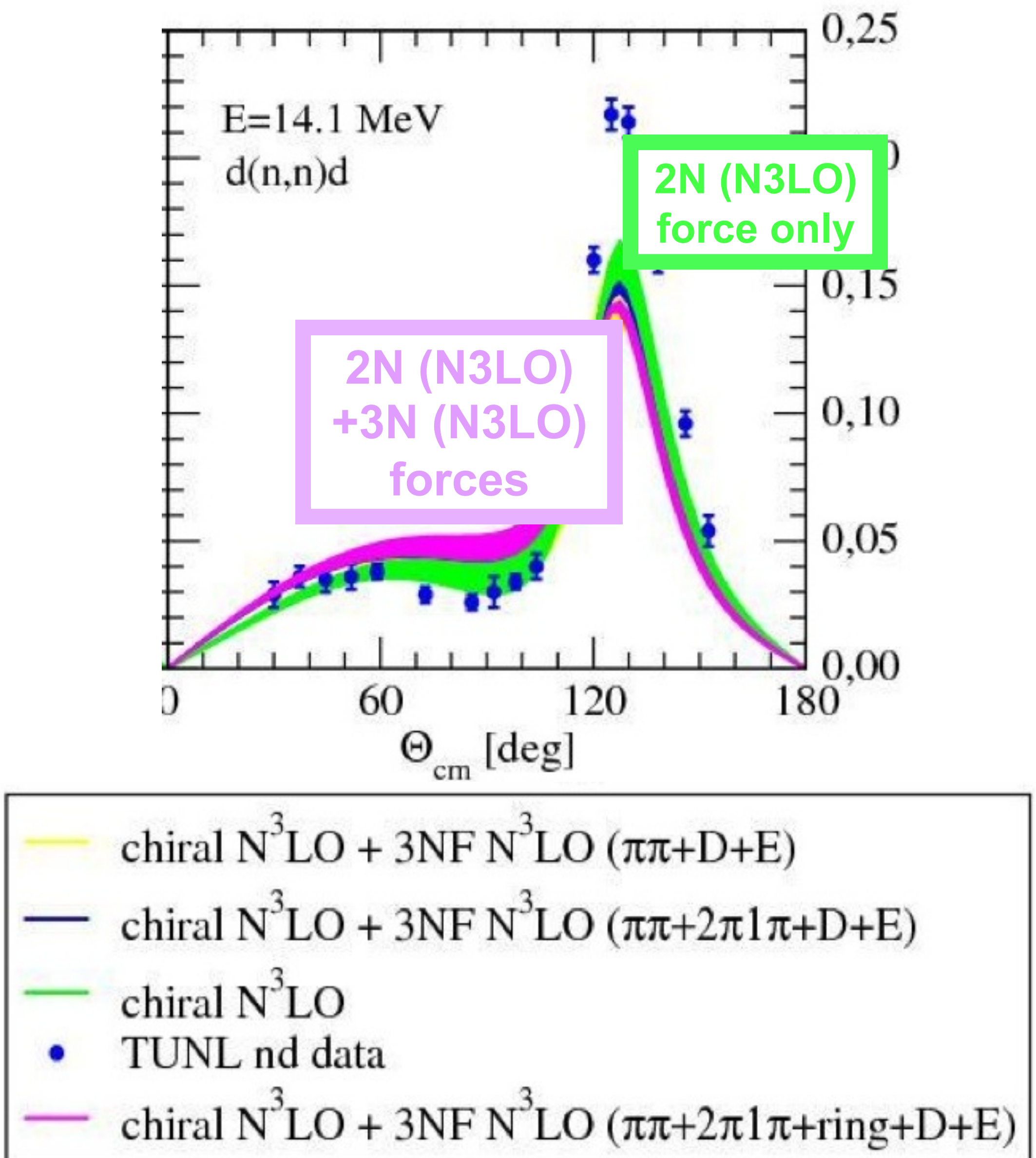
Now that we know what NOT to do.

What should we do?

Evaluate current status. Anything left to do in the nuclear force business?

- **Current status: 2NFs and 3NFs up to N3LO are applied in nuclear few- and many-body systems.**
- **In general, quite a bit of success, but some persistent problems remain.**
- **In the few-body sector: Ay puzzle, N-d break-up, …**

N-d A_y calculations by Witala et al.

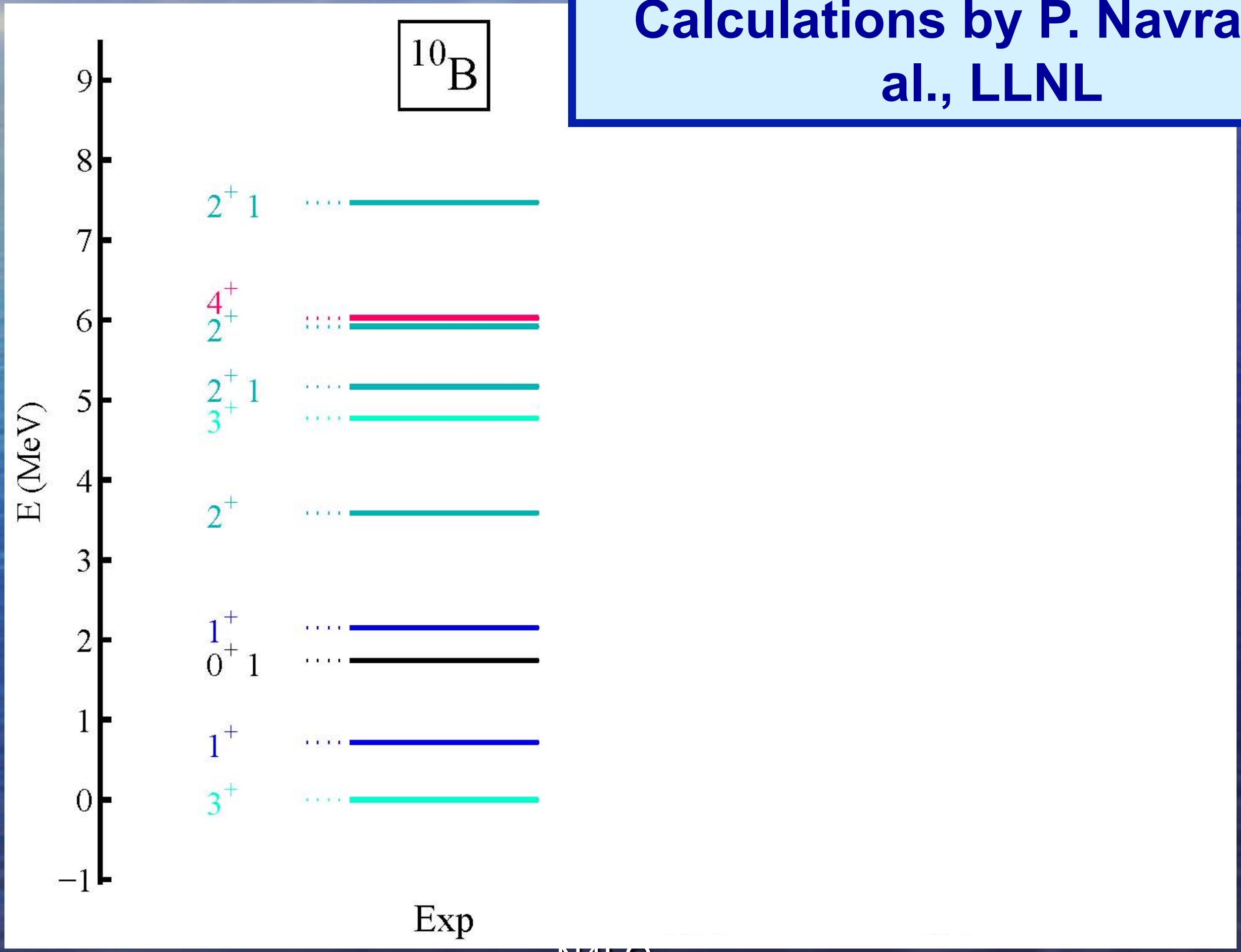


Evaluate current status. Anything left to do in the nuclear force business?

- Current status: 2NFs and 3NFs up to N3LO are applied in nuclear few- and many-body systems.
- In general, quite a bit of success, but some persistent problems remain.
- In the few-body sector: Ay puzzle, N-d break-up, …
- Light nuclei: Spectra not perfect.

Calculating the properties of light nuclei using chiral 2N and 3N forces

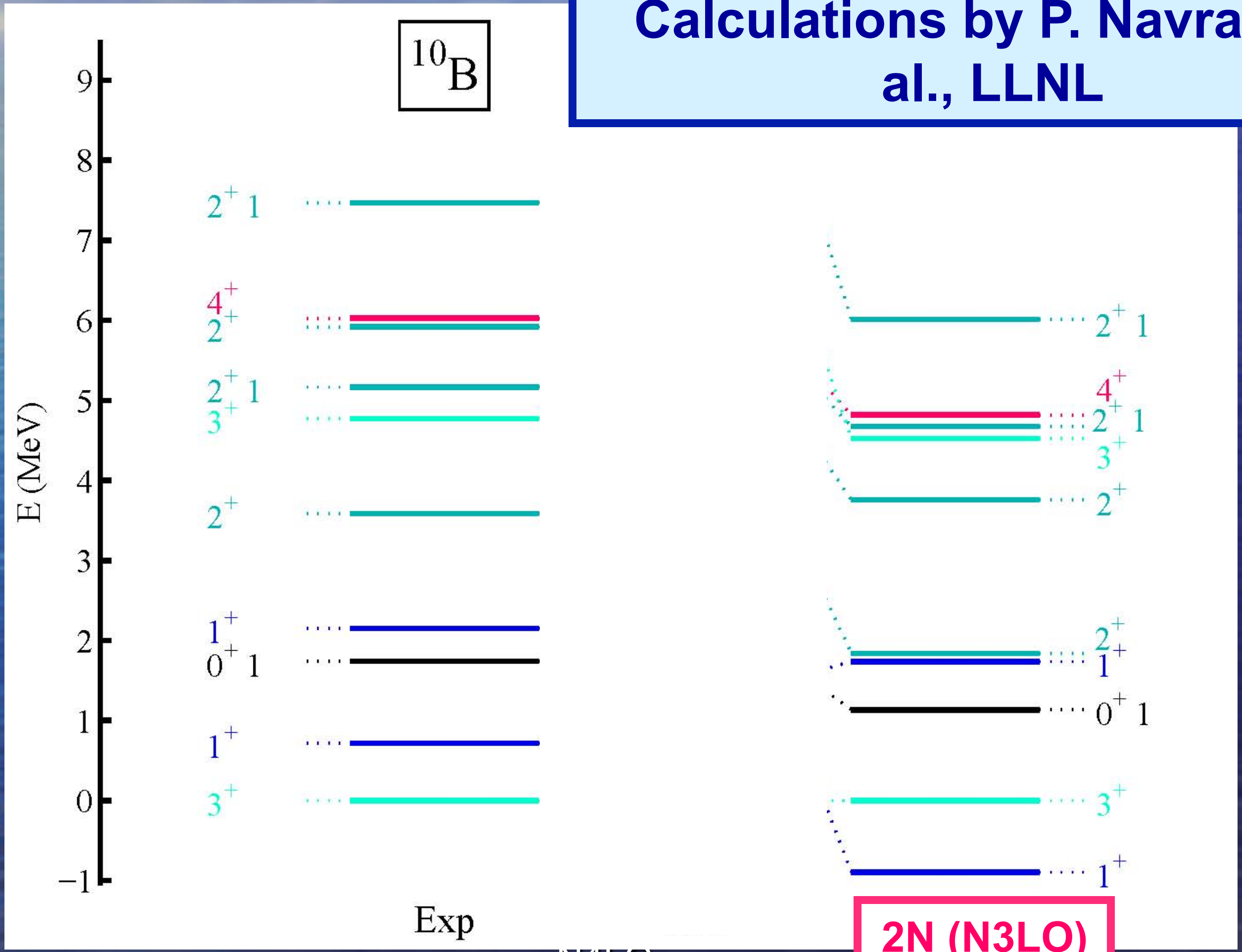
"No-Core Shell Model " Calculations by P. Navratil et al., LLNL



N4LO

Calculating the properties of light nuclei using chiral 2N and 3N forces

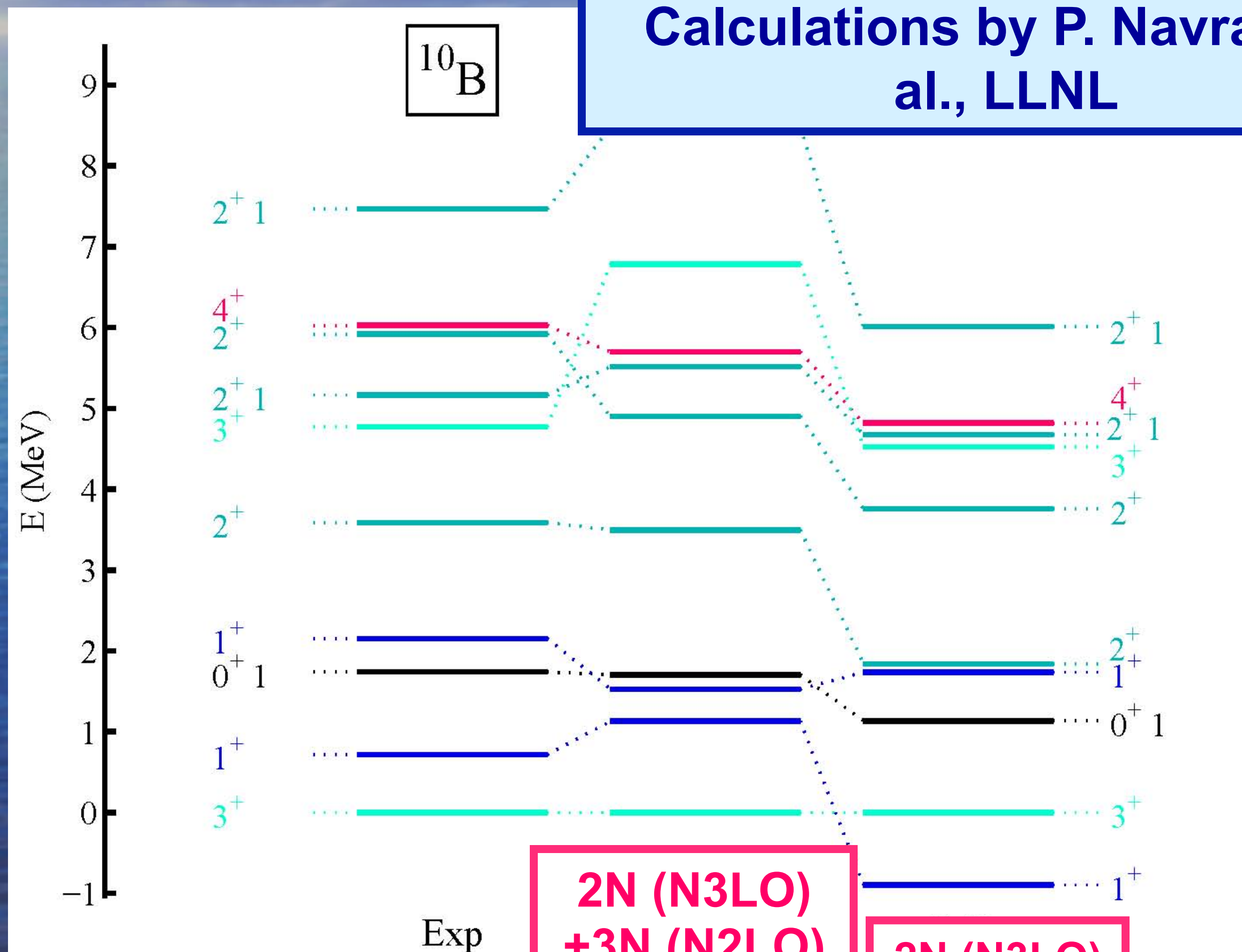
"No-Core Shell Model " Calculations by P. Navratil et al., LLNL



2N (N3LO) force only

Calculating the properties of light nuclei using chiral 2N and 3N forces

"No-Core Shell Model " Calculations by P. Navratil et al., LLNL



2N (N3LO) +3N (N2LO) forces

2N (N3LO) force only

Evaluate current status. Anything left to do in the nuclear force business?

- Current status: 2NFs and 3NFs up to N3LO are applied in nuclear few- and many-body systems.
- In general, quite a bit of success, but some persistent problems remain.
- In the few-body sector: Ay puzzle, N-d break-up, …
- Light nuclei: Spectra not perfect.
- Intermediate nuclei: Overbinding.

Ground-state energies from O-16 to Sn-132 obtained in CC with 2NF + 3NF

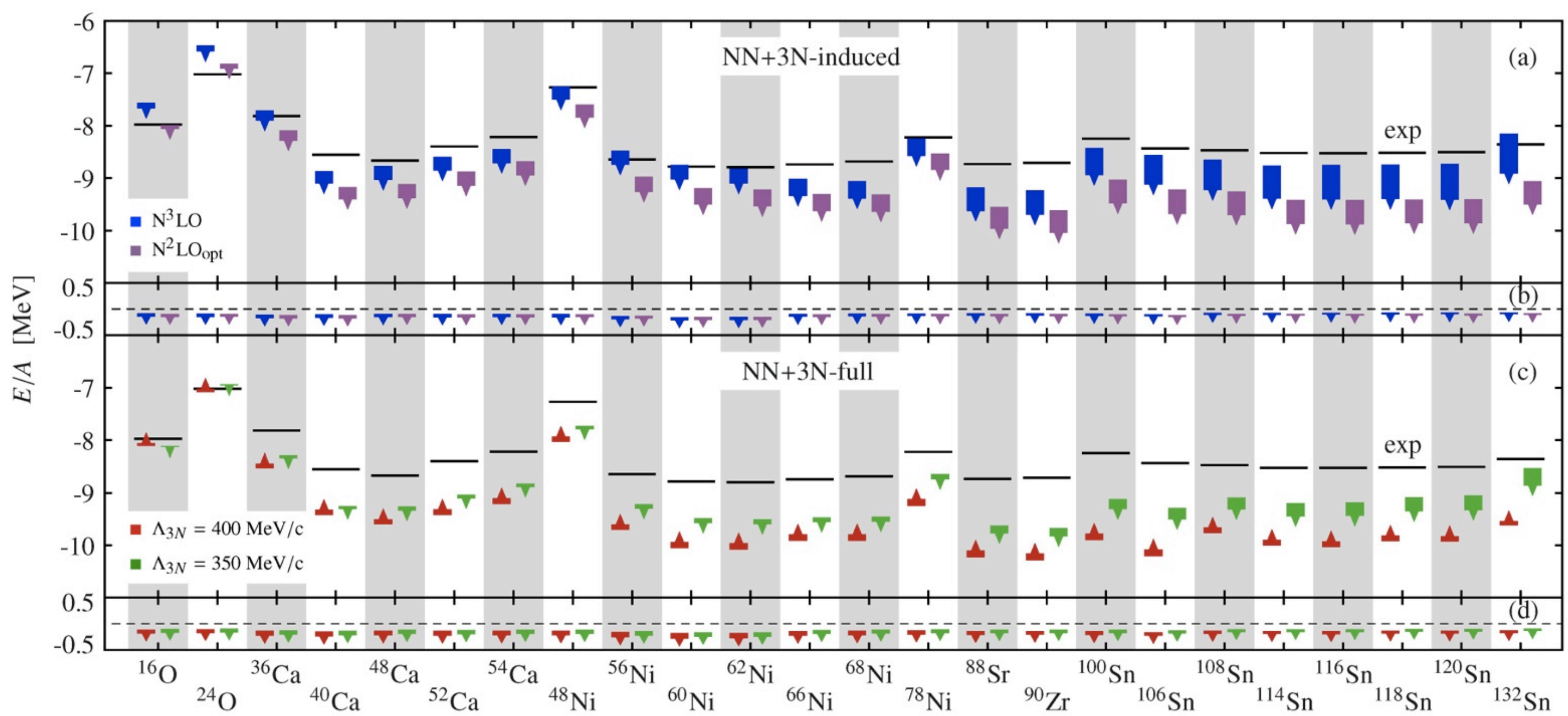


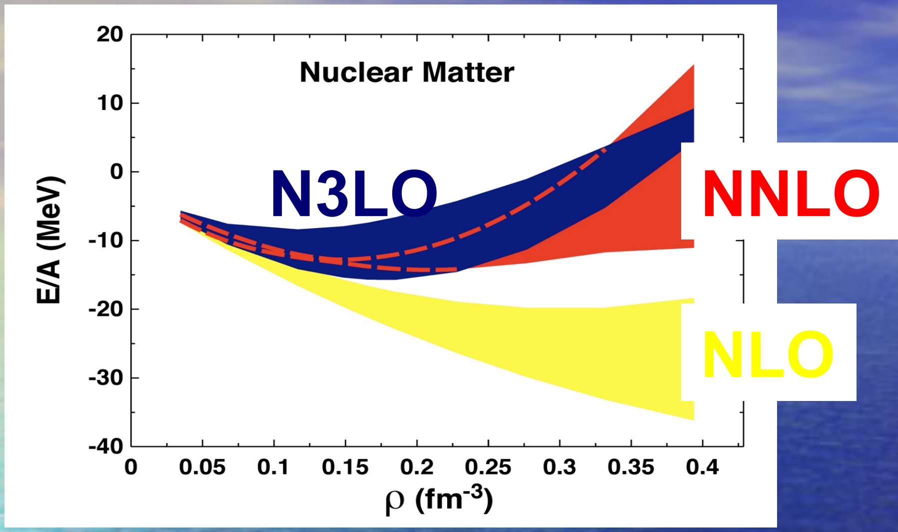
FIG. 5: (Color online) Ground-state energies from CR-CC(2,3) for (a) the NN+3N-induced Hamiltonian starting from the N^3LO and N^2LO-optimized NN interaction and (c) the NN+3N-full Hamiltonian with Λ_{3N} = 400 MeV/c and Λ_{3N} = 350 MeV/c. The boxes represent the spread of the results from $\alpha = 0.04\ \mathrm{fm}^4$ to $\alpha = 0.08\ \mathrm{fm}^4$, and the tip points into the direction of smaller values of α. Also shown are the contributions of the CR-CC(2,3) triples correction to the (b) NN+3N-induced and (d) NN+3N-full results. All results employ $\hbar\Omega$ = 24 MeV and 3N interactions with E_{3max} = 18 in NO2B approximation and full inclusion of the 3N interaction in CCSD up to E_{3max} = 12. Experimental binding energies [32] are shown as black bars.

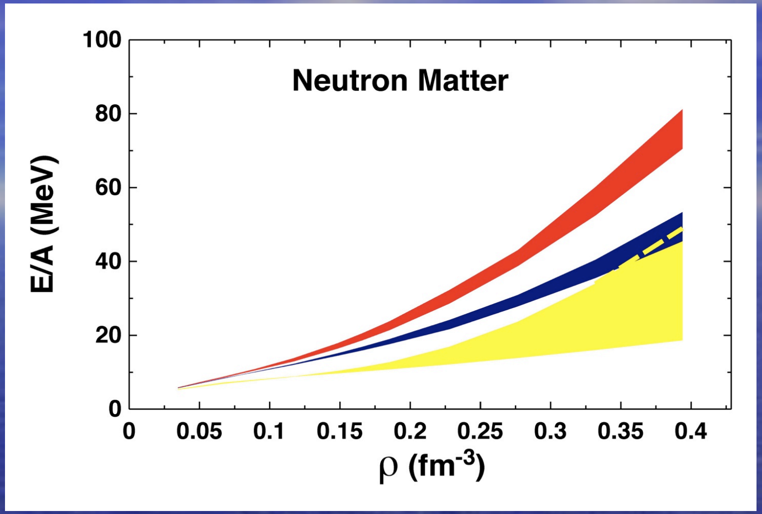
From S. Binder et al., PLB 736, 119 (2014).

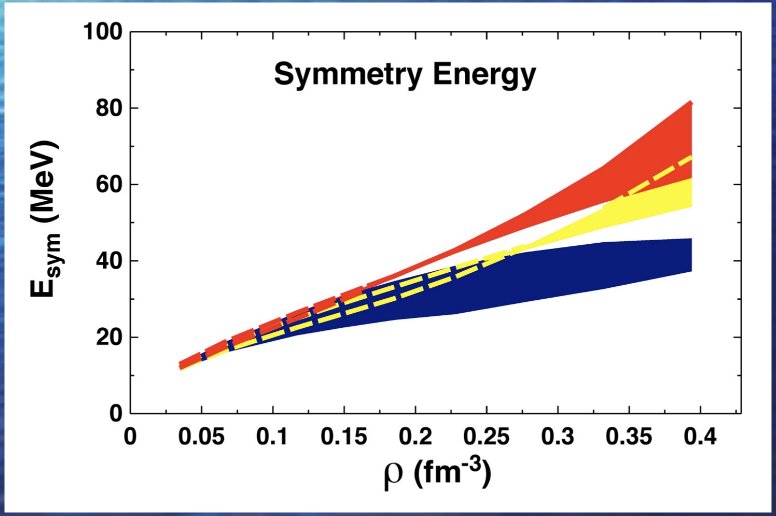
Evaluate current status. Anything left to do in the nuclear force business?

- Current status: 2NFs and 3NFs up to N3LO are applied in nuclear few- and many-body systems.
- In general, quite a bit of success, but some persistent problems remain.
- In the few-body sector: Ay puzzle, N-d break-up, …
- Light nuclei: Spectra not perfect.
- Intermediate nuclei: Overbinding.
- Convergence of the chiral expansion in the many-body system?

Order-by-order convergence ???







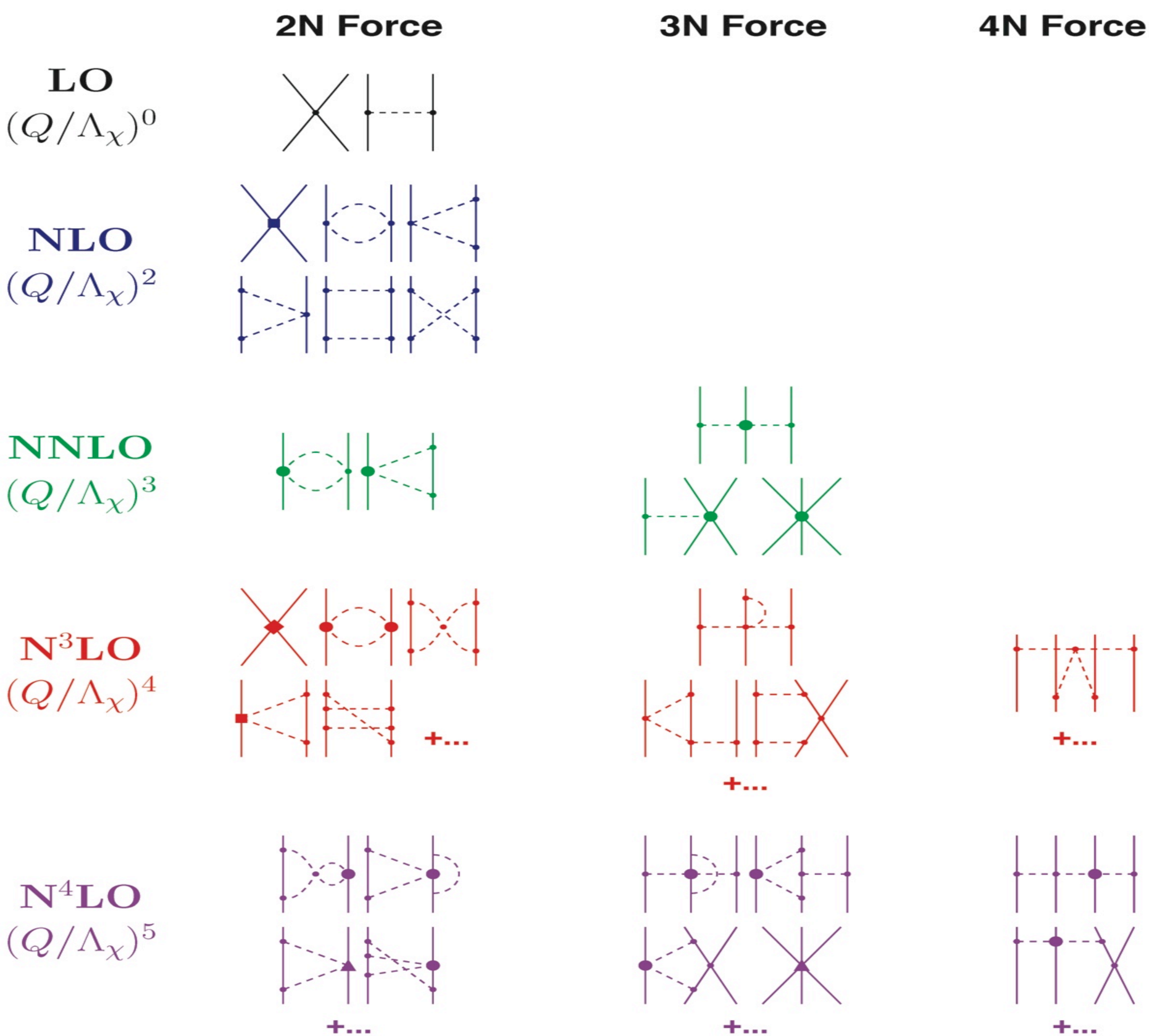
From
F. Sammarruca et al.,
arXiv:1411.0136.

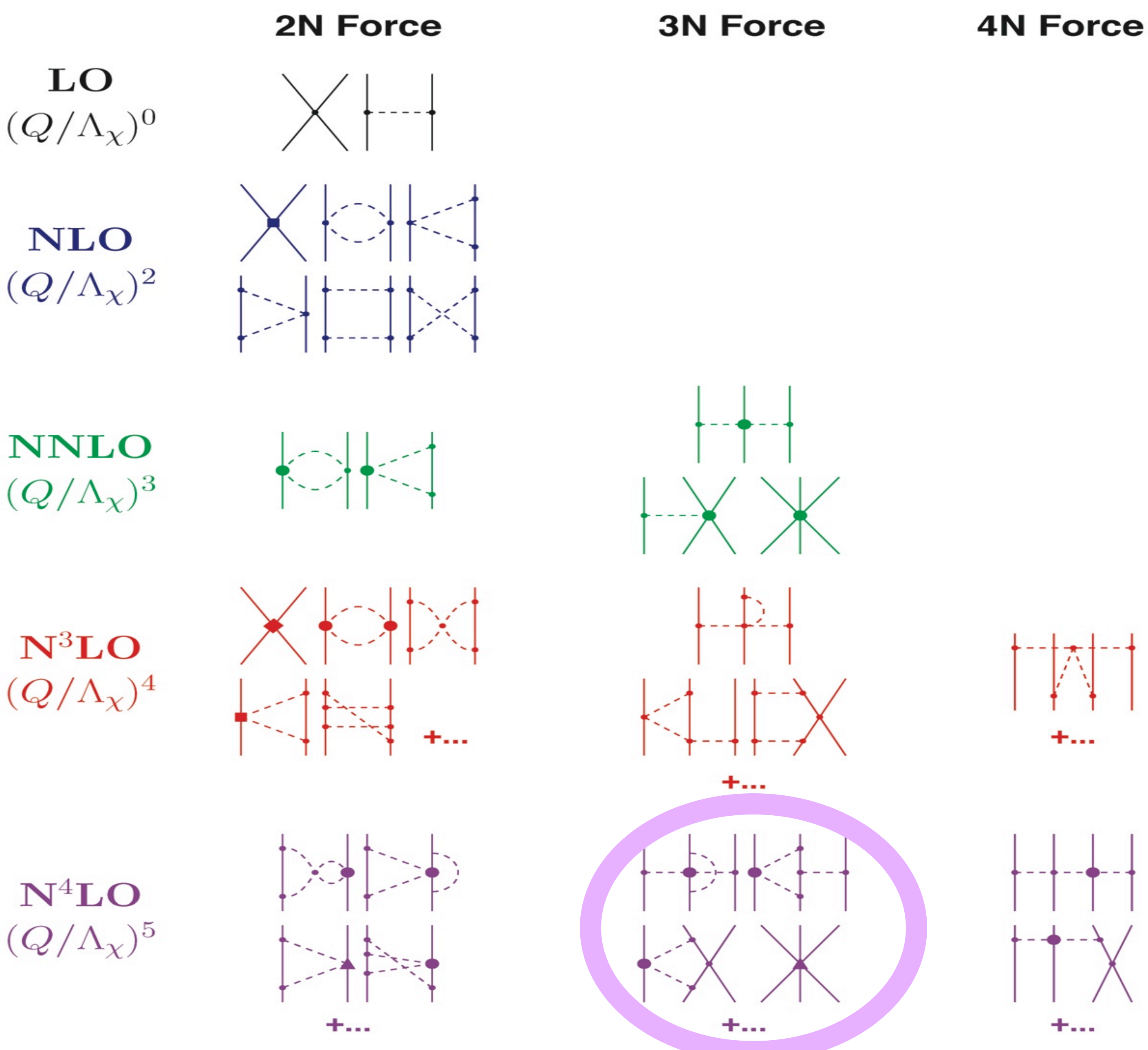
Evaluate current status. Anything left to do in the nuclear force business?

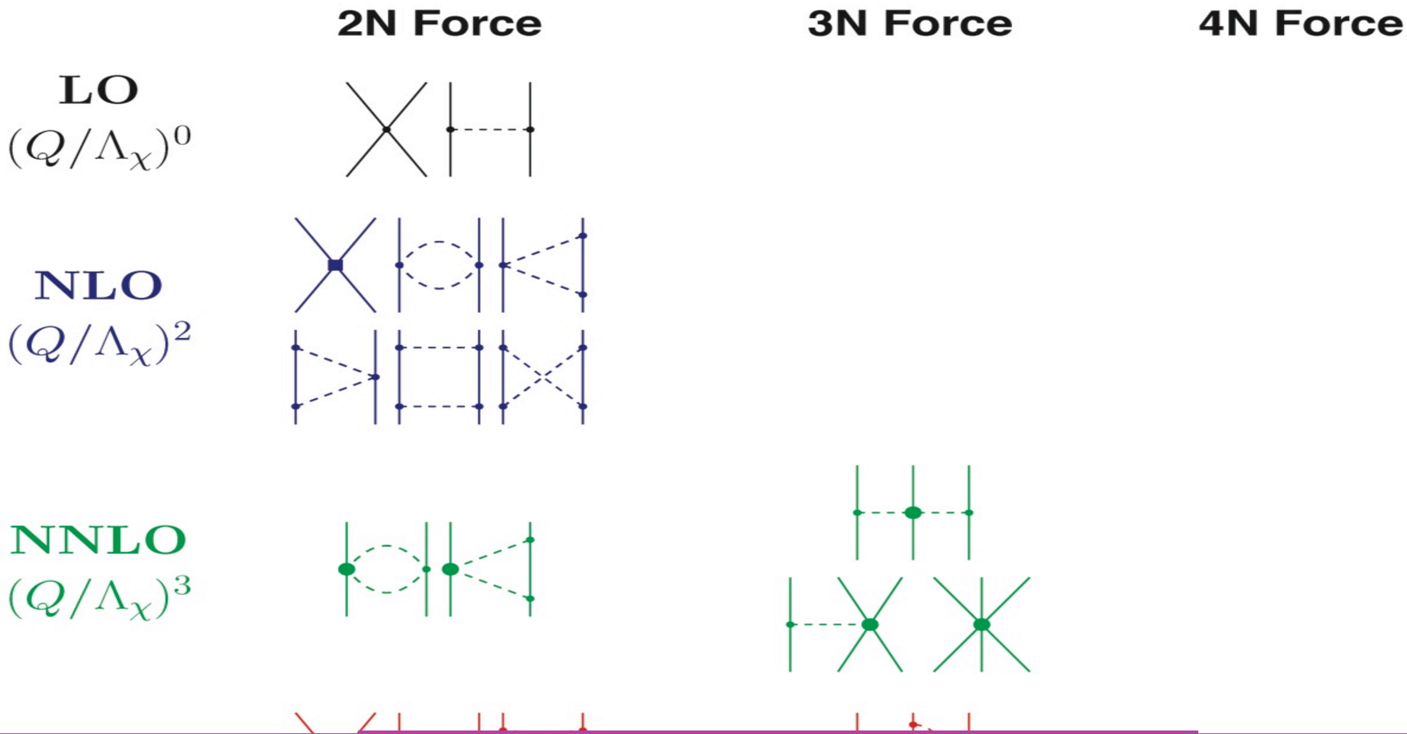
- Current status: 2NFs and 3NFs up to N3LO are applied in nuclear few- and many-body systems.
- In general, quite a bit of success, but some persistent problems remain.
- In the few-body sector: Ay puzzle, N-d break-up, …
- Light nuclei: Spectra not perfect.
- Intermediate nuclei: Overbinding.
- Convergence of the chiral expansion in the many-body system? Not converged at N3LO.

Because of the problems just demonstrated, improvement of current nuclear forces is called for

- How?
- Go to next order!
- That is: Turn to N4LO.
- What can we expect from N4LO?
- Does N4LO have anything to offer we were not offered before?

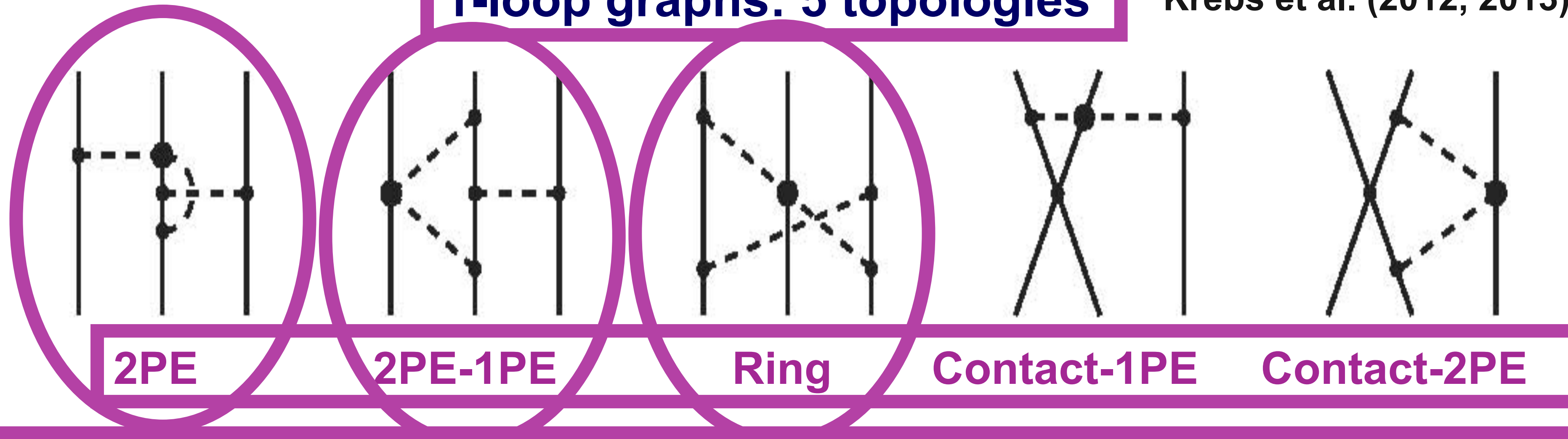

2N Force
3N Force
4N Force
LO
$(Q/\Lambda_\chi)^0$
NLO
$(Q/\Lambda_\chi)^2$
NNLO
$(Q/\Lambda_\chi)^3$
N^{3}LO
$(Q/\Lambda_\chi)^4$
+...
+...
+...
N^{4}LO
$(Q/\Lambda_\chi)^5$
+...
+...
+...

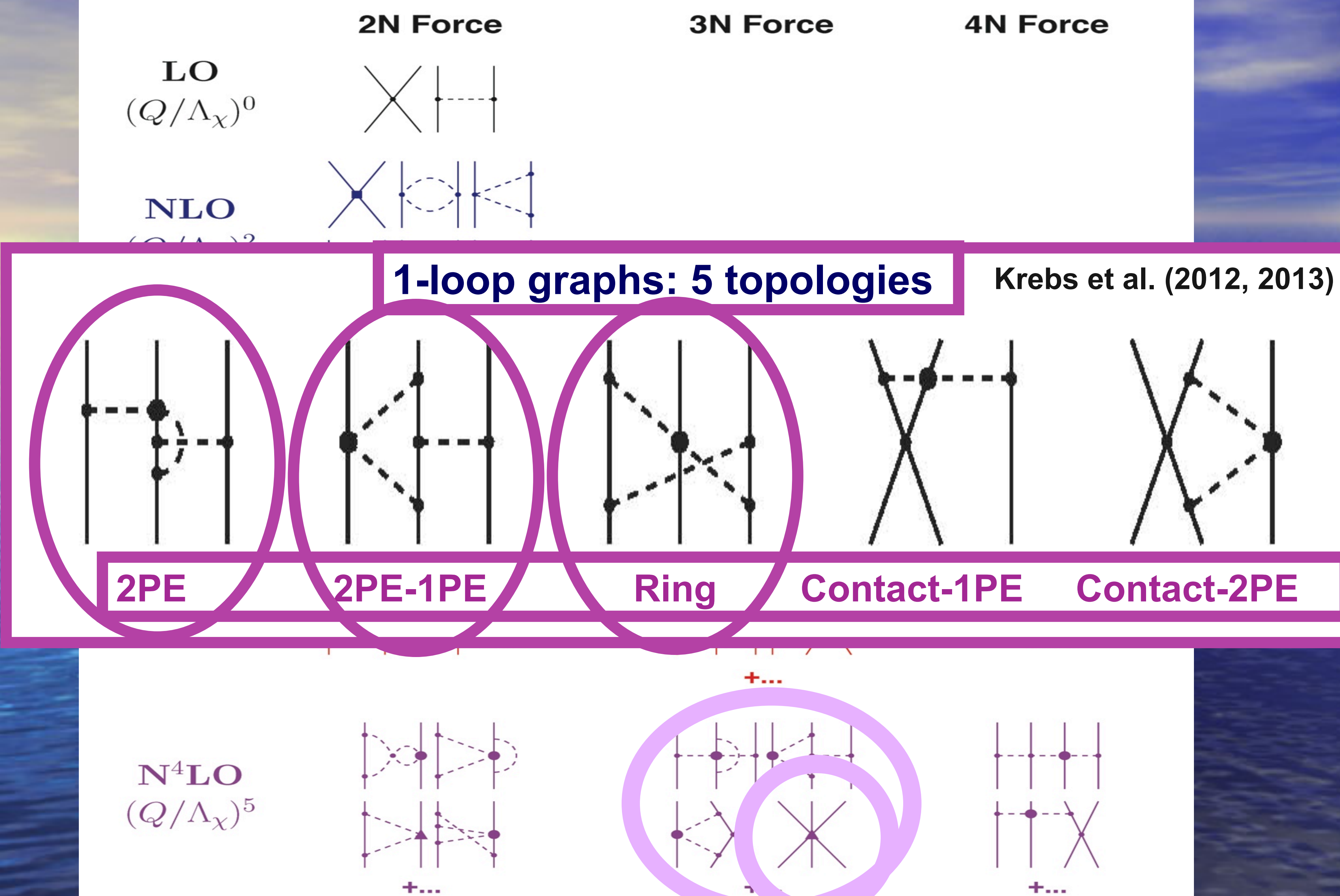

2N Force
3N Force
4N Force
LO
$(Q/\Lambda_\chi)^0$
NLO
$(Q/\Lambda_\chi)^2$
NNLO
$(Q/\Lambda_\chi)^3$
N^{3}LO
$(Q/\Lambda_\chi)^4$
+...
+...
+...
N^{4}LO
$(Q/\Lambda_\chi)^5$
+...
+...
+...



1-loop graphs: 5 topologies

Krebs et al. (2012, 2013)



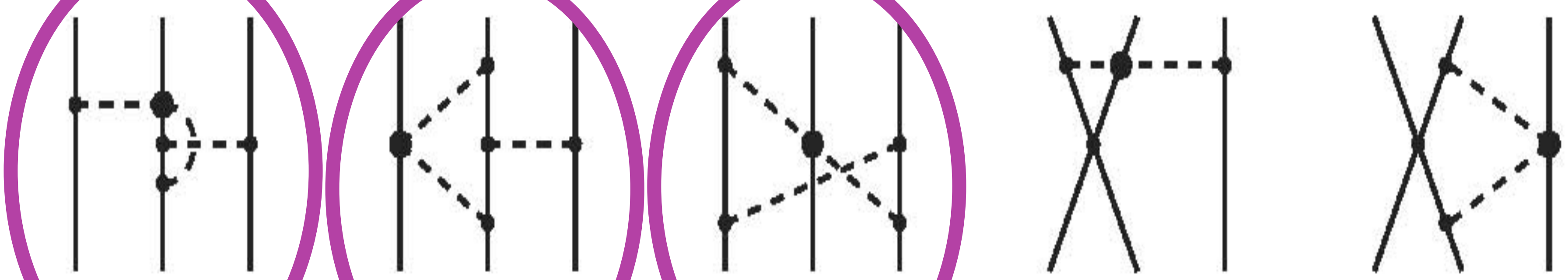


2N Force
3N Force
4N Force
LO
$(Q/\Lambda_\chi)^0$
NLO
1-loop graphs: 5 topologies
Krebs et al. (2012, 2013)
2PE
2PE-1PE
Ring
Contact-1PE
Contact-2PE
+...
N^{4}LO
$(Q/\Lambda_\chi)^5$
+...
+...

2N Force | 3N Force | 4N Force

1-loop graphs: 5 topologies

Krebs et al. (2012, 2013)



2PE | 2PE-1PE | Ring | Contact-1PE | Contact-2PE

3NF contacts at N4LO

Girlanda, Kievsky, Viviani, PRC 84, 014001 (2011)

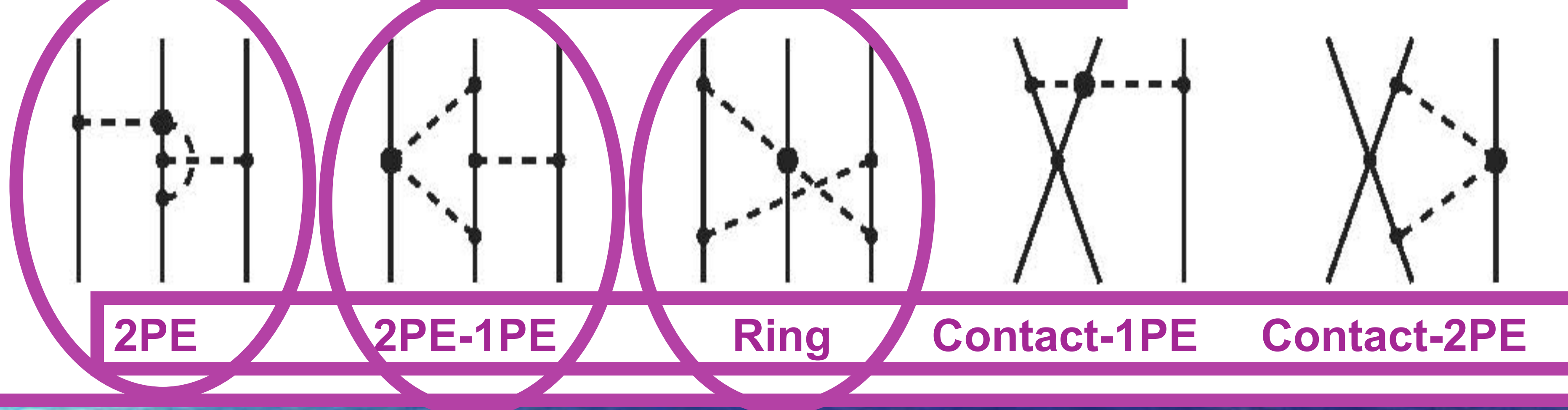
$\mathbf{k}_i = \mathbf{p}_i - \mathbf{p}'_i$ and $\mathbf{Q}_i = \mathbf{p}_i + \mathbf{p}'_i$, $\mathbf{p}_i$ and $\mathbf{p}'_i$ being the initial and final momenta of nucleon i, the potential in momentum space is found to be

$$V = \sum_{i \neq j \neq k} \Big[-E_1 \mathbf{k}_i^2 - E_2 \mathbf{k}_i^2 \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j - E_3 \mathbf{k}_i^2 \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j - E_4 \mathbf{k}_i^2 \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$$
$$- E_5 \left(3 \mathbf{k}_i \cdot \boldsymbol{\sigma}_i \mathbf{k}_i \cdot \boldsymbol{\sigma}_j - \mathbf{k}_i^2 \right) - E_6 \left(3 \mathbf{k}_i \cdot \boldsymbol{\sigma}_i \mathbf{k}_i \cdot \boldsymbol{\sigma}_j - \mathbf{k}_i^2 \right)) \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$$
$$+ \frac{i}{2} E_7 \mathbf{k}_i \times (\mathbf{Q}_i - \mathbf{Q}_j) \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j) + \frac{i}{2} E_8 \mathbf{k}_i \times (\mathbf{Q}_i - \mathbf{Q}_j) \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j) \boldsymbol{\tau}_j \cdot \boldsymbol{\tau}_k$$
$$- E_9 \mathbf{k}_i \cdot \boldsymbol{\sigma}_i \mathbf{k}_j \cdot \boldsymbol{\sigma}_j - E_{10} \mathbf{k}_i \cdot \boldsymbol{\sigma}_i \mathbf{k}_j \cdot \boldsymbol{\sigma}_j \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j \Big], \quad (15)$$

The 3NFs at N4LO

1-loop graphs: 5 topologies

Krebs et al. (2012, 2013)



3NF contacts at N4LO

Girlanda, Kievsky, Viviani, PRC 84, 014001 (2011)

$\mathbf{k}_i = \mathbf{p}_i - \mathbf{p}'_i$ and $\mathbf{Q}_i = \mathbf{p}_i + \mathbf{p}'_i$, $\mathbf{p}_i$ and $\mathbf{p}'_i$ being the initial and final momenta of nucleon i, the potential in momentum space is found to be

$$V = \sum_{i \neq j \neq k} \Big[-E_1 \mathbf{k}_i^2 - E_2 \mathbf{k}_i^2 \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j - E_3 \mathbf{k}_i^2 \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j - E_4 \mathbf{k}_i^2 \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$$
$$-E_5 \left(3 \mathbf{k}_i \cdot \boldsymbol{\sigma}_i \mathbf{k}_i \cdot \boldsymbol{\sigma}_j - \mathbf{k}_i^2\right) - E_6 \left(3 \mathbf{k}_i \cdot \boldsymbol{\sigma}_i \mathbf{k}_i \cdot \boldsymbol{\sigma}_j - \mathbf{k}_i^2\right)) \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j$$
$$+\frac{i}{2} E_7 \mathbf{k}_i \times (\mathbf{Q}_i - \mathbf{Q}_j) \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j) + \frac{i}{2} E_8 \mathbf{k}_i \times (\mathbf{Q}_i - \mathbf{Q}_j) \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j) \boldsymbol{\tau}_j \cdot \boldsymbol{\tau}_k$$
$$-E_9 \mathbf{k}_i \cdot \boldsymbol{\sigma}_i \mathbf{k}_j \cdot \boldsymbol{\sigma}_j - E_{10} \mathbf{k}_i \cdot \boldsymbol{\sigma}_i \mathbf{k}_j \cdot \boldsymbol{\sigma}_j \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j \Big], \quad (15)$$

The 3NFs at N4LO

All possible 20 isospin-spin-momentum/position structures occur!

Krebs, Gasparyan, Epelbaum, PRC 87, 054007 (2013)

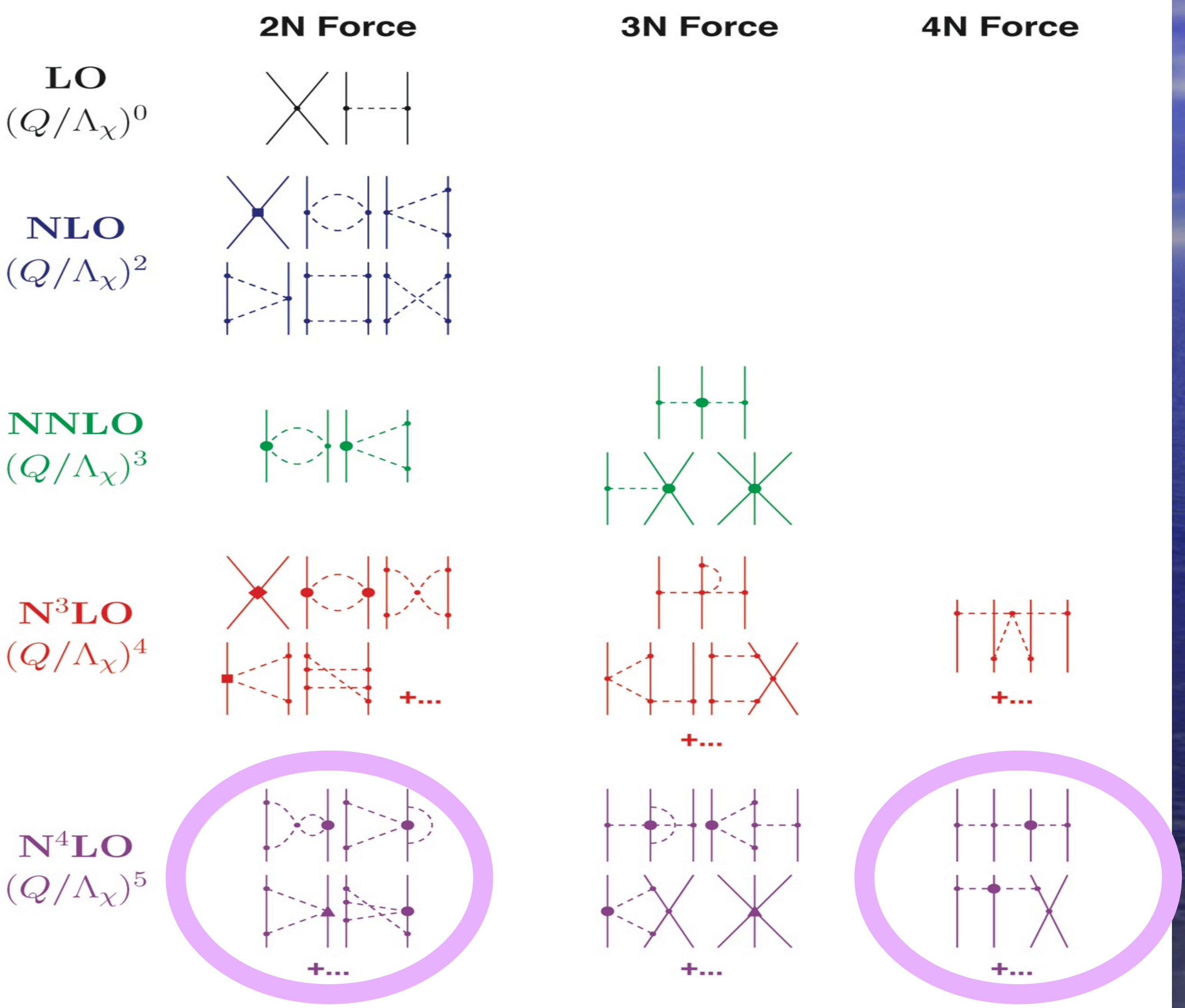
Generators $\mathcal{G}$ in momentum space	Generators $\tilde{\mathcal{G}}$ in coordinate space
$\mathcal{G}_1 = 1$	$\tilde{\mathcal{G}}_1 = 1$
$\mathcal{G}_2 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3$	$\tilde{\mathcal{G}}_2 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3$
$\mathcal{G}_3 = \vec{\sigma}_1 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_3 = \vec{\sigma}_1 \cdot \vec{\sigma}_3$
$\mathcal{G}_4 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{\sigma}_1 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_4 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \vec{\sigma}_1 \cdot \vec{\sigma}_3$
$\mathcal{G}_5 = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{\sigma}_1 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_5 = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \vec{\sigma}_1 \cdot \vec{\sigma}_2$
$\mathcal{G}_6 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$	$\tilde{\mathcal{G}}_6 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$
$\mathcal{G}_7 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\tilde{\mathcal{G}}_7 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23})$
$\mathcal{G}_8 = \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_8 = \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_3$
$\mathcal{G}_9 = \vec{q}_1 \cdot \vec{\sigma}_3 \vec{q}_3 \cdot \vec{\sigma}_1$	$\tilde{\mathcal{G}}_9 = \hat{r}_{23} \cdot \vec{\sigma}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1$
$\mathcal{G}_{10} = \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_{10} = \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_3$
$\mathcal{G}_{11} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_{11} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_2$
$\mathcal{G}_{12} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_{12} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_2$
$\mathcal{G}_{13} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_{13} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_2$
$\mathcal{G}_{14} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_{14} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_2$
$\mathcal{G}_{15} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{q}_2 \cdot \vec{\sigma}_1 \vec{q}_2 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_{15} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{13} \cdot \vec{\sigma}_1 \, \hat{r}_{13} \cdot \vec{\sigma}_3$
$\mathcal{G}_{16} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_2 \vec{q}_3 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_{16} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_2 \, \hat{r}_{12} \cdot \vec{\sigma}_3$
$\mathcal{G}_{17} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_{17} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_3$
$\mathcal{G}_{18} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{\sigma}_3 \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\tilde{\mathcal{G}}_{18} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot \vec{\sigma}_3 \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23})$
$\mathcal{G}_{19} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_3 \cdot \vec{q}_1 \vec{q}_1 \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)$	$\tilde{\mathcal{G}}_{19} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_3 \cdot \hat{r}_{23} \, \hat{r}_{23} \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)$
$\mathcal{G}_{20} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_3 \cdot \vec{q}_3 \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\tilde{\mathcal{G}}_{20} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot \hat{r}_{23} \, \vec{\sigma}_3 \cdot \hat{r}_{12} \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23})$

Because of the problems demonstrated, improvement of current nuclear forces indicated

- **How?**
- **Go to next order!**
- **That is: Turn to N4LO.**
- **What can we expect from N4LO?**
- **Does N4LO have anything to offer we were not offered before?**

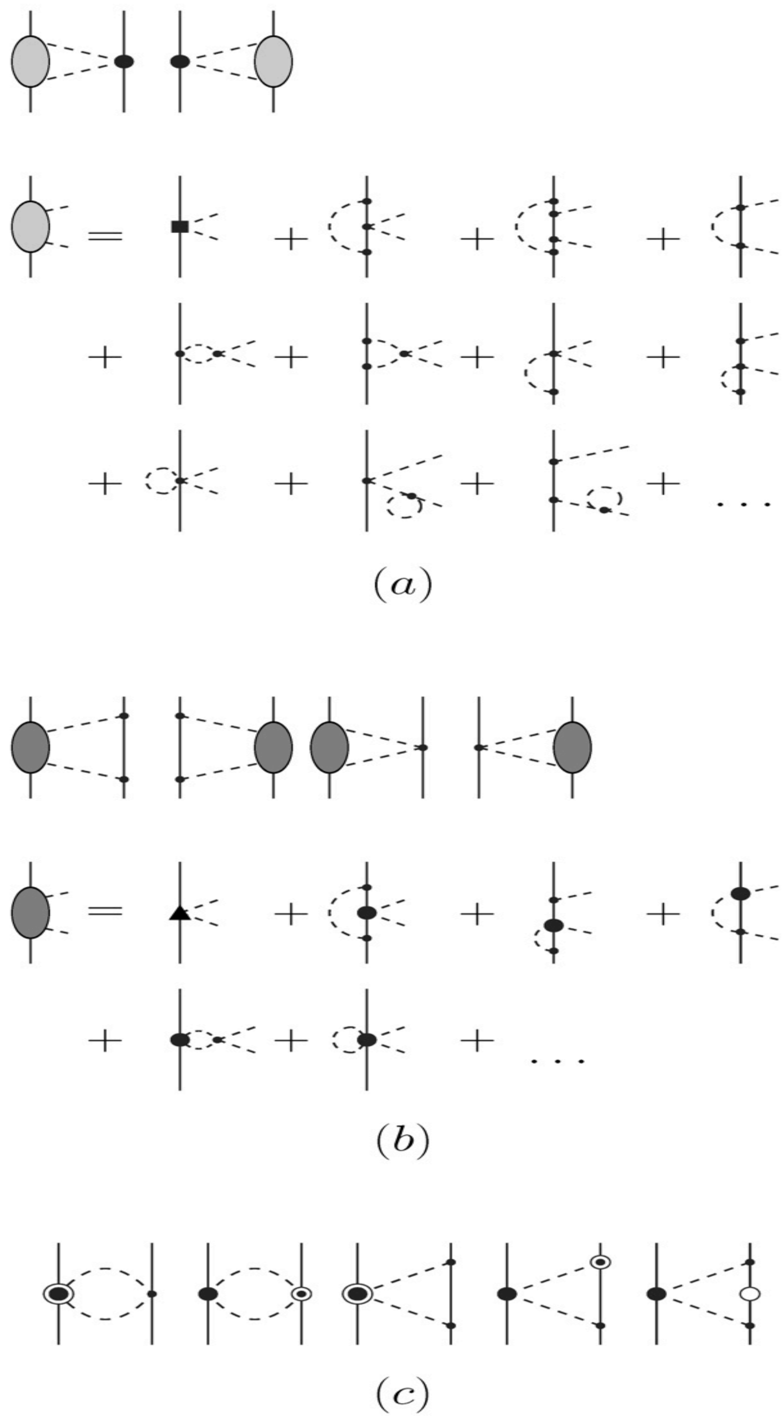
Oh yes! All 3NFs you have ever dreamed of!

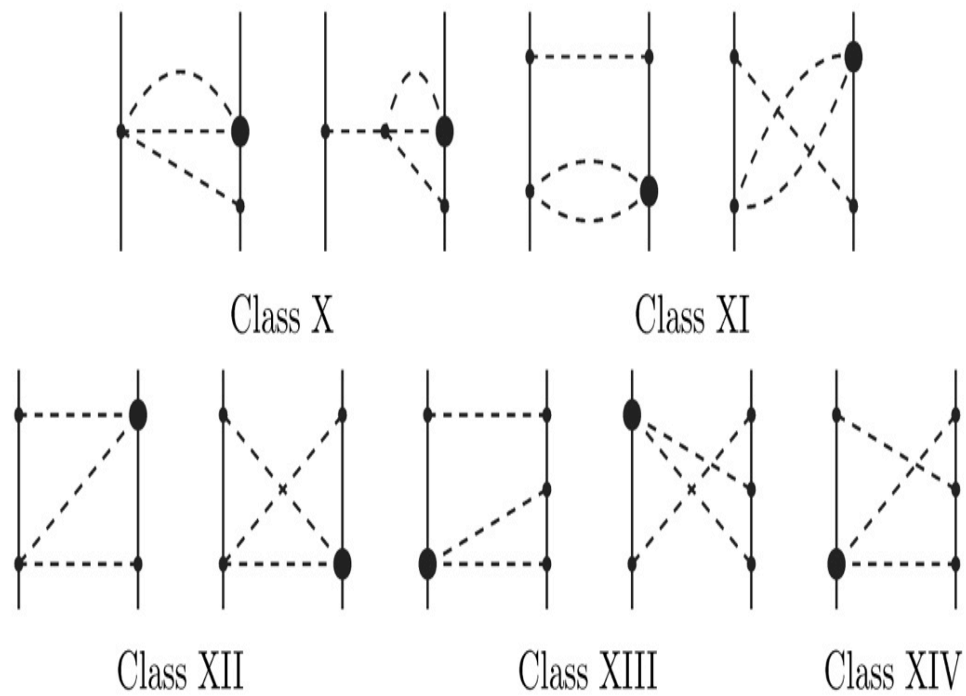
What else is there at N4LO?


2N Force
3N Force
4N Force
LO
$(Q/\Lambda_\chi)^0$
NLO
$(Q/\Lambda_\chi)^2$
NNLO
$(Q/\Lambda_\chi)^3$
N^{3}LO
$(Q/\Lambda_\chi)^4$
+...
N^{4}LO
$(Q/\Lambda_\chi)^5$
+...

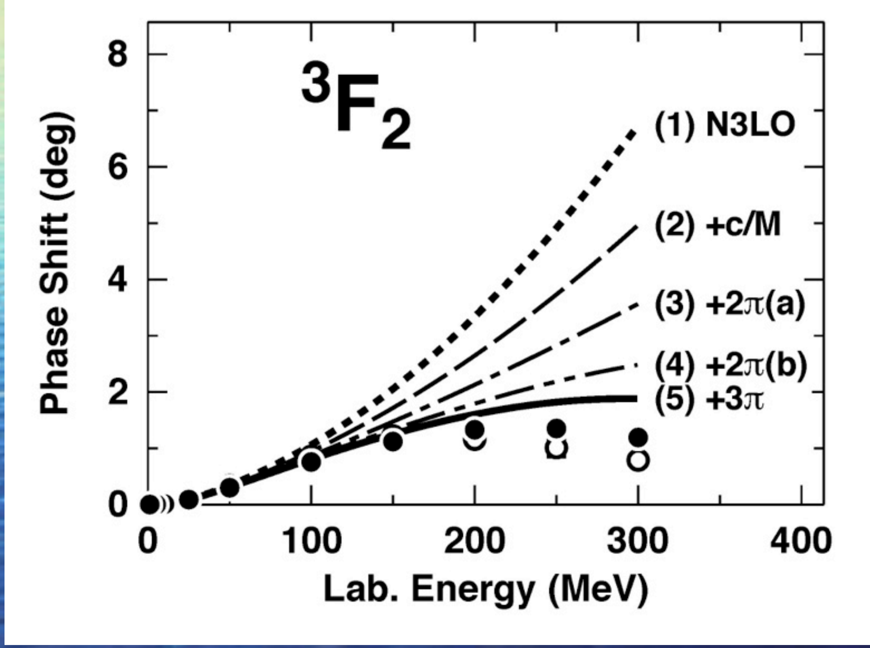
N4LO 2NF Contributions

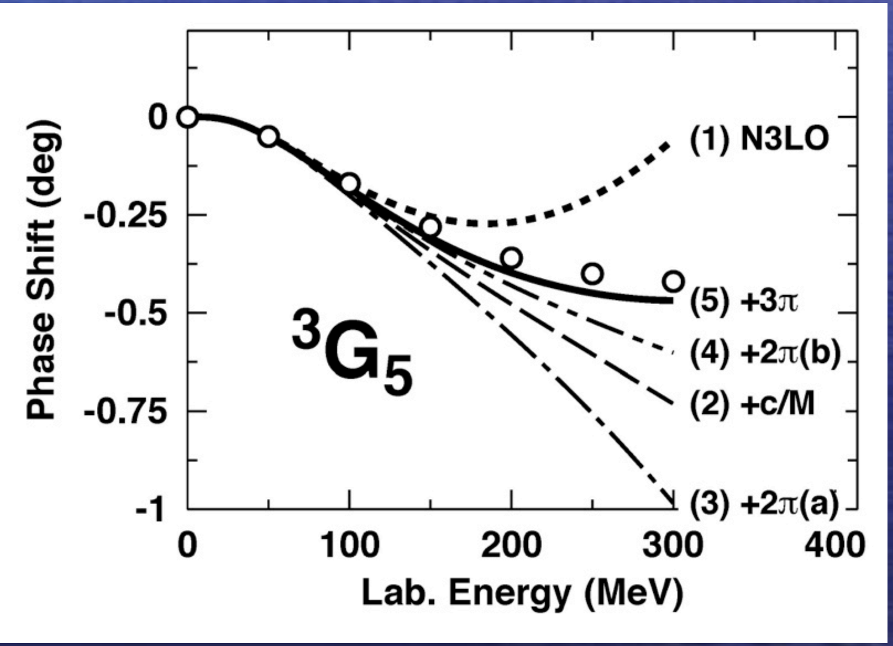
Entem, Kaiser, Machleidt, Nosyk,
PRC 91, 014002 (2015)



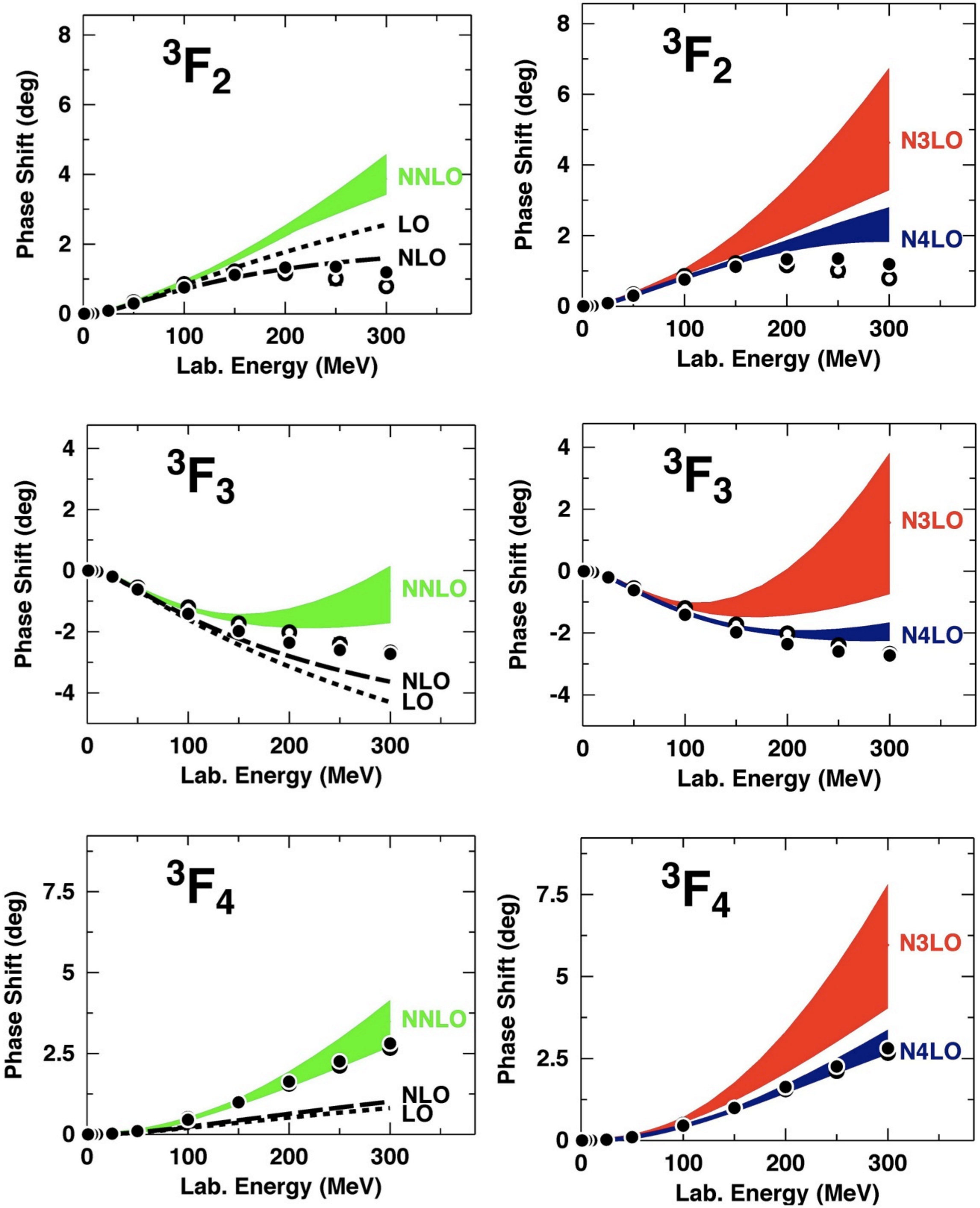


N4LO effects on NN scattering in peripheral partial waves



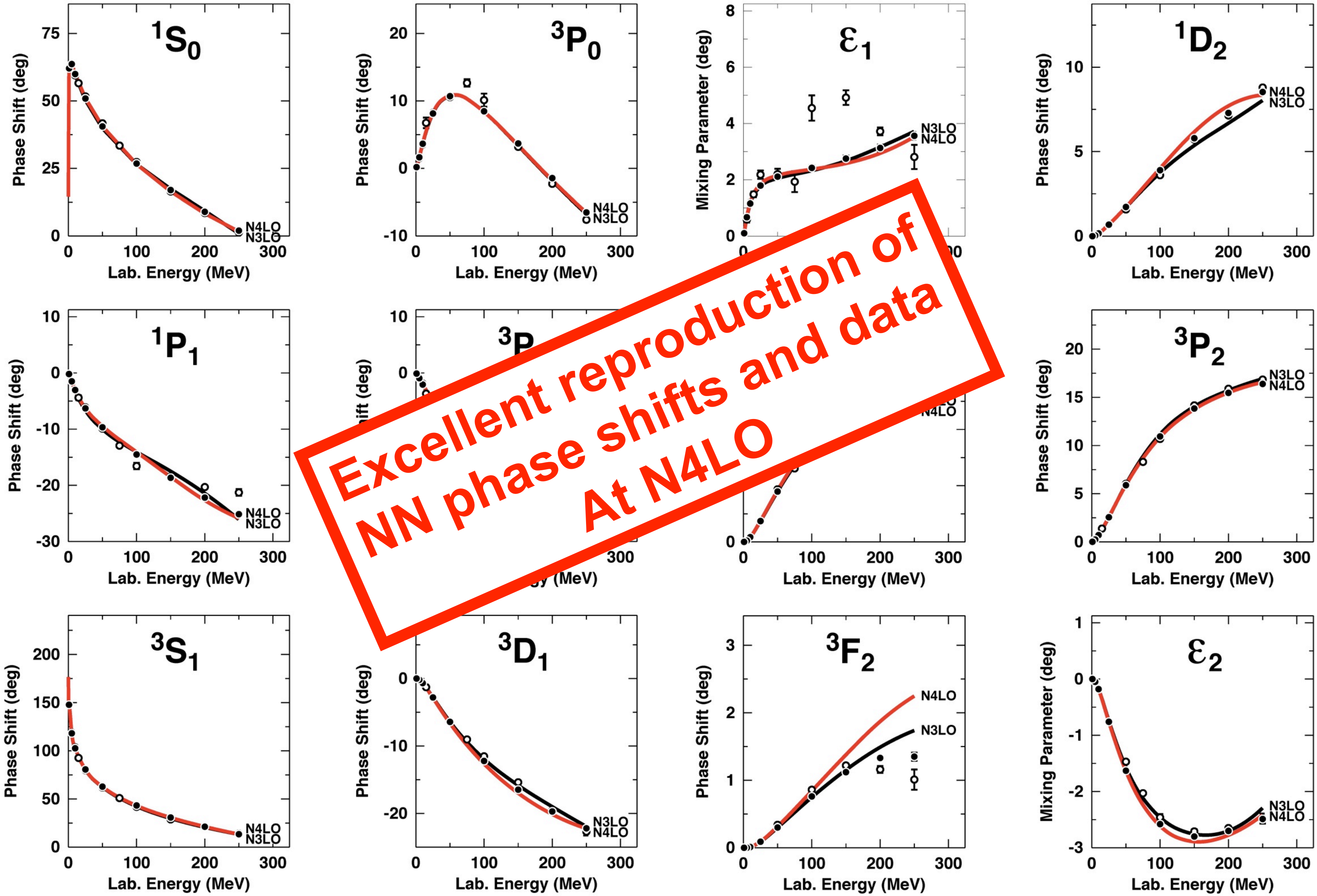


From Entem, Kaiser, Machleidt, Nosyk, PRC 91, 014002 (2015)



Using LECs from pi-N Analysis at order four.

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



Excellent reproduction of
NN phase shifts and data
At N4LO
$^1S_0$
$^3P_0$
ε_1
$^1D_2$
$^1P_1$
$^3P_2$
$^3S_1$
$^3D_1$
$^3F_2$
ε_2
Phase Shift (deg)
Mixing Parameter (deg)
Lab. Energy (MeV)
N4LO
N3LO

Conclusions

- **Be aware of misconceptions!**
- **N3LO won't solve all our problems.**
- **Turn to N4LO: Complete set of 3NFs and new 3NF contacts.**
- **2NF at N4LO promises to be very quantitative including the peripheral waves (N4LO NN pots soon available).**
- **The new challenge and the new hope in microscopic nucear structure: N4LO**