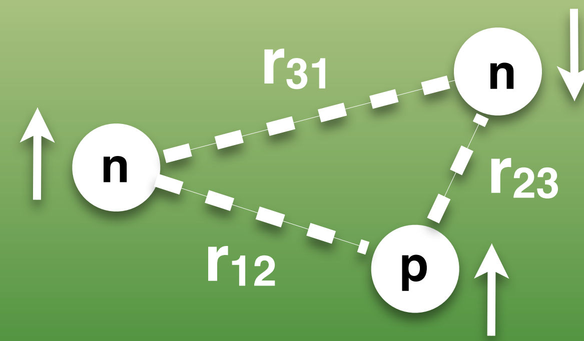
Status of three-nucleon forces



Evgeny Epelbaum, RUB

μ-Workshop, CRC 110, TU München, October 25, 2012

Outline

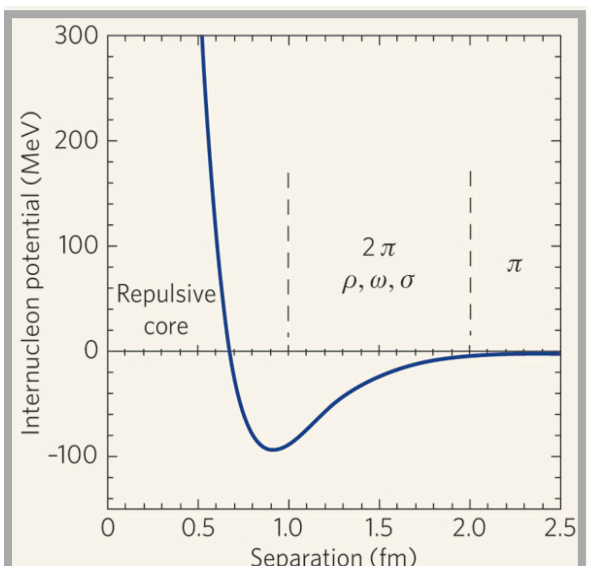
- Introduction
- 3NF: Where do we stand
- 3NF beyond leading order
- Summary and outlook

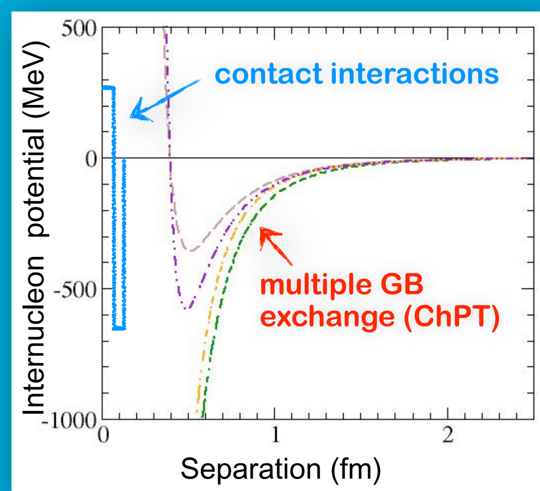
From QCD to nuclear physics

The roadmap: QCD → Chiral Perturbation Theory → hadron dynamics

- **Pions and up to 1 nucleon: ChPT for the scattering amplitude**
- **2 and more nucleons: ChPT for nuclear forces/currents** Weinberg '91

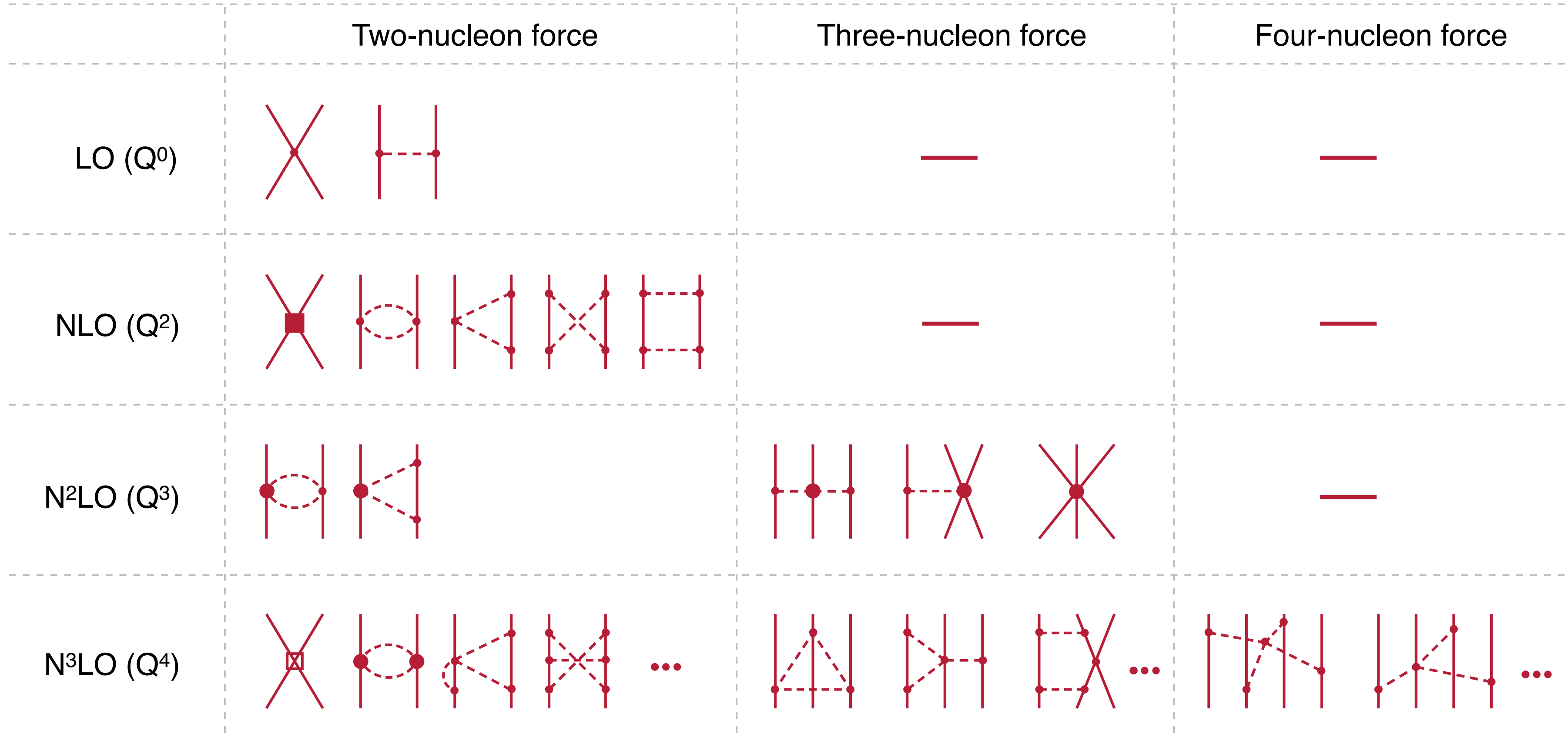
$$\left[\left(\sum_{i=1}^{A}\frac{-\vec{\nabla}_i^2}{2m_N}+\mathcal{O}(m_N^{-3})\right)+\underbrace{V_{2N}+V_{3N}+V_{4N}+\ldots}_{\text{derived within ChPT}}\right]|\Psi\rangle=E|\Psi\rangle$$





- **unified description of $\pi\pi$, πN and NN**
- **consistent many-body forces and currents**
- **systematically improvable**
- **bridging different reactions (electroweak, π-prod., ...)**
- **precision physics with/from light nuclei**

Chiral expansion of nuclear forces



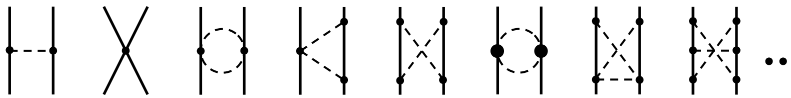
$\langle V_{2\mathrm{N}} \rangle \sim 20\ \mathrm{MeV/pair}$ $\langle V_{3\mathrm{N}} \rangle \sim 1\ \mathrm{MeV/triplet}$ $\langle V_{4\mathrm{N}} \rangle \sim 0.1\ \mathrm{MeV/quartet}$

(numbers from Pudliner et al. PRL 74 (95) 4396)

Nucleon-nucleon potential at N^3LO

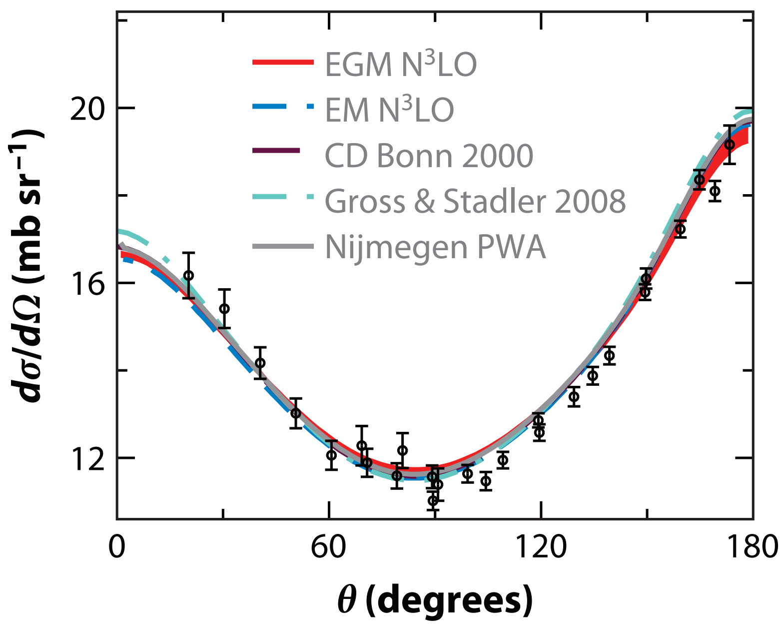
van Kolck et al.'94; Friar & Coon '94; Kaiser et al. '97; E.E. et al. '98,'03; Kaiser '99-'01; Higa, Robilotta '03; ...

- Long-range: parameter-free (all LECs from πN)
- Short-range part: 24 LECs tuned to NN data
- Accurate description of NN data up to ~ 200 MeV

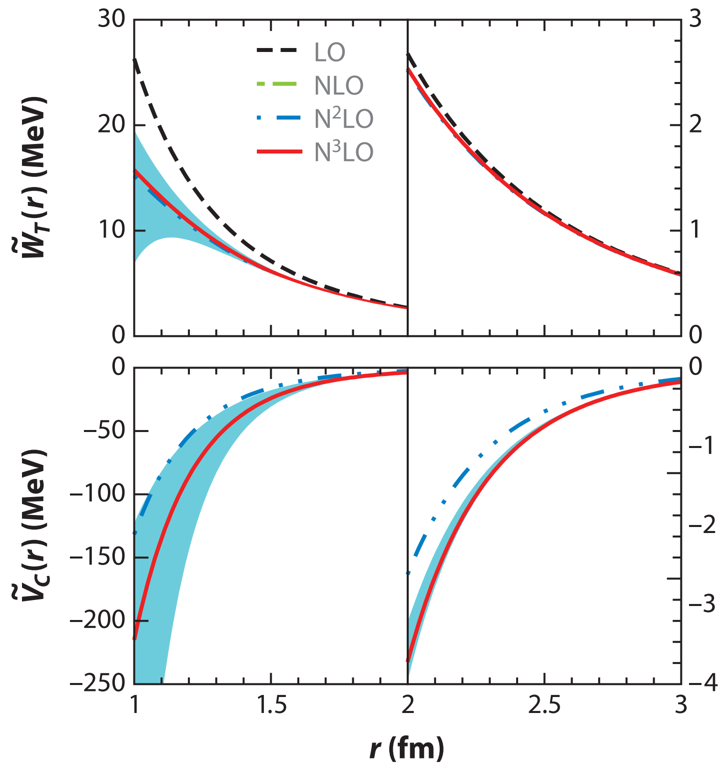


Entem-Machleidt, EE-Glöckle-Meißner

np cross section @ 50 MeV



χ expansion of the long-range force



Recent reviews:

EE, Prog. Part Nucl. Phys. 57 (06) 654;
EE, Hammer, Meißner, Rev. Mod. Phys. 81 (09) 1773;
Entem, Machleidt, Phys. Rept. 503 (11) 1;
EE, Meißner, Ann. Rev. Nucl. Part. Sci. 62 (2012) 159.

The challenge: Understanding the 3N force

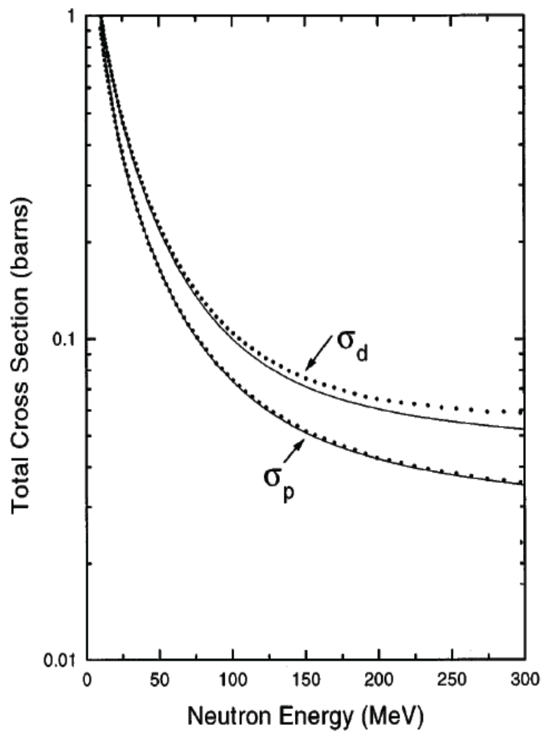
- Today's few- and many-body calculations have reached the level of accuracy at which it is necessary to include 3NFs
- Inspite of decades of efforts, the structure of the 3NF is still poorly understood

  Kalantar-Nayestanaki, EE, Messchendorp, Nogga, Rev. Mod. Phys. 75 (2012) 016301

- All the necessary ingredients for a precision description of the 3NF are available:

  Chiral EFT + authom. PWD + FY equations + few-body data

  → first results already coming...



Most general structure of a local 3NF

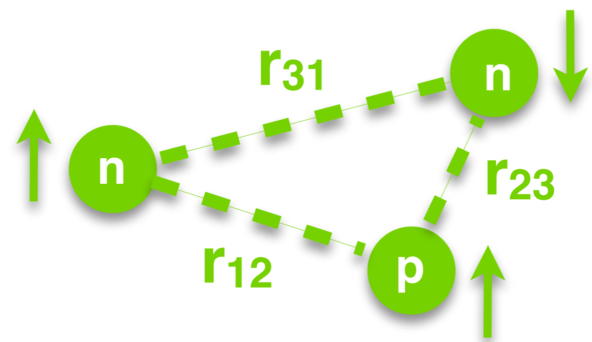
Krebs, Gasparyan, EE, in preparation

A meaningful comparison of 3NF terms requires a complete set of independent operators.

Most general local 3NF involves 89 operators, can be generated (by permutations) from 22 structures:

$$V_{3N} = \sum_{i=1}^{22} \mathcal{G}_i \, F_i(r_{12}, r_{23}, r_{31}) + \text{ perm.}$$

calculated in ChPT; long-range terms parameter free...



Generators $\mathcal{G}$ of 89 independent operators	S	A	G_1	G_2	$G_1(12)$	$G_2(12)$
1	$\boldsymbol{O}_1$	0	0	0	0	0
$\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$	$\boldsymbol{O}_2$	0	$\boldsymbol{O}_3$	$\boldsymbol{O}_4$	O_3	O_4
$\vec{\sigma}_1 \cdot \vec{\sigma}_3$	$\boldsymbol{O}_5$	0	$\boldsymbol{O}_6$	$\boldsymbol{O}_7$	$-\frac{1}{2}O_6$	$-\frac{1}{2}O_7$
$\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{\sigma}_1 \cdot \vec{\sigma}_3$	$\boldsymbol{O}_8$	0	$\boldsymbol{O}_9$	$\boldsymbol{O}_{10}$	$-\frac{1}{2}O_9$	$-\frac{1}{2}O_{10}$
$\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{\sigma}_1 \cdot \vec{\sigma}_2$	$\boldsymbol{O}_{11}$	$\boldsymbol{O}_{12}$	$\boldsymbol{O}_{13}$	$\boldsymbol{O}_{14}$	$\boldsymbol{O}_{15}$	$\boldsymbol{O}_{16}$
$\boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$	$\boldsymbol{O}_{17}$	0	0	0	0	0
$\boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\boldsymbol{O}_{18}$	0	$\boldsymbol{O}_{19}$	$\boldsymbol{O}_{20}$	$-\frac{1}{2}O_{19}$	$-\frac{1}{2}O_{20}$
$\vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_3$	$\boldsymbol{O}_{21}$	$\boldsymbol{O}_{22}$	$\boldsymbol{O}_{23}$	$\boldsymbol{O}_{24}$	$\boldsymbol{O}_{25}$	$\boldsymbol{O}_{26}$
$\vec{q}_1 \cdot \vec{\sigma}_3 \vec{q}_3 \cdot \vec{\sigma}_1$	$\boldsymbol{O}_{27}$	0	$\boldsymbol{O}_{28}$	$\boldsymbol{O}_{29}$	$-\frac{1}{2}O_{28}$	$-\frac{1}{2}O_{29}$
$\vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_3$	$\boldsymbol{O}_{30}$	0	$\boldsymbol{O}_{31}$	$\boldsymbol{O}_{32}$	$-\frac{1}{2}O_{31}$	$-\frac{1}{2}O_{32}$
$\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2$	$\boldsymbol{O}_{33}$	$\boldsymbol{O}_{34}$	$\boldsymbol{O}_{35}$	$\boldsymbol{O}_{36}$	$\boldsymbol{O}_{37}$	$\boldsymbol{O}_{38}$
$\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_2$	$\boldsymbol{O}_{39}$	$\boldsymbol{O}_{40}$	$\boldsymbol{O}_{41}$	$\boldsymbol{O}_{42}$	$\boldsymbol{O}_{43}$	$\boldsymbol{O}_{44}$
$\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2$	$\boldsymbol{O}_{45}$	$\boldsymbol{O}_{46}$	$\boldsymbol{O}_{47}$	$\boldsymbol{O}_{48}$	$\boldsymbol{O}_{49}$	$\boldsymbol{O}_{50}$
$\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_2$	$\boldsymbol{O}_{51}$	$\boldsymbol{O}_{52}$	$\boldsymbol{O}_{53}$	$\boldsymbol{O}_{54}$	$\boldsymbol{O}_{55}$	$\boldsymbol{O}_{56}$
$\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_2 \vec{q}_1 \cdot \vec{\sigma}_3$	$\boldsymbol{O}_{57}$	0	$\boldsymbol{O}_{58}$	$\boldsymbol{O}_{59}$	$-2\,O_{58}$	$-2\,O_{59}$
$\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_2 \vec{q}_3 \cdot \vec{\sigma}_3$	$\boldsymbol{O}_{60}$	$\boldsymbol{O}_{61}$	$\boldsymbol{O}_{62}$	$\boldsymbol{O}_{63}$	$\boldsymbol{O}_{64}$	$\boldsymbol{O}_{65}$
$\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_2 \vec{q}_3 \cdot \vec{\sigma}_3$	$\boldsymbol{O}_{66}$	$-O_{61}$	$\boldsymbol{O}_{67}$	$\boldsymbol{O}_{68}$	$-2\,O_{62} - O_{64} - 2\,O_{67}$	$-2\,O_{63} - O_{65} - 2\,O_{68}$
$\boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{\sigma}_2 \vec{\sigma}_3 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\boldsymbol{O}_{69}$	0	$\boldsymbol{O}_{70}$	$\boldsymbol{O}_{71}$	O_{70}	O_{71}
$\boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_3 \cdot \vec{q}_1 \vec{q}_1 \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)$	$\boldsymbol{O}_{72}$	$\boldsymbol{O}_{73}$	$\boldsymbol{O}_{74}$	$\boldsymbol{O}_{75}$	$\boldsymbol{O}_{76}$	$\boldsymbol{O}_{77}$
$\boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_2 \cdot \vec{q}_1 \vec{\sigma}_3 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\boldsymbol{O}_{78}$	$\boldsymbol{O}_{79}$	$\boldsymbol{O}_{80}$	$\boldsymbol{O}_{81}$	$\boldsymbol{O}_{82}$	$\boldsymbol{O}_{83}$
$\boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{q}_3 \vec{\sigma}_2 \cdot \vec{q}_3 \vec{\sigma}_3 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\boldsymbol{O}_{84}$	0	$\boldsymbol{O}_{85}$	$\boldsymbol{O}_{86}$	O_{85}	O_{86}
$\boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_2 \cdot \vec{q}_3 \vec{\sigma}_3 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\boldsymbol{O}_{87}$	$-O_{79}$	$\boldsymbol{O}_{88}$	$\boldsymbol{O}_{89}$	$O_{80} - O_{82} + O_{88}$	$O_{81} - O_{83} + O_{89}$

The generators are defined as:

$$S(\mathcal{O}) := \frac{1}{6} \sum_{P \in S_3} P\mathcal{O}$$

$$A(\mathcal{O}) := \frac{1}{6} \sum_{P \in S_3} (-1)^P P\mathcal{O}$$

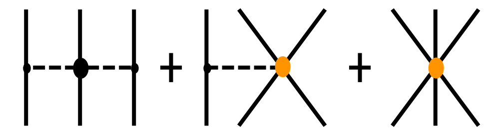
$$G_2(\mathcal{O}) := \frac{\sqrt{3}}{2} \left[S_{23} S_{13} - S_{12} S_{13} \right] (\mathcal{O}).$$

$$G_1(\mathcal{O}) := \left[S_{13} - \frac{1}{2} \left(S_{23} S_{13} + S_{12} S_{13} \right) \right] (\mathcal{O})$$

3N force: Where do we stand

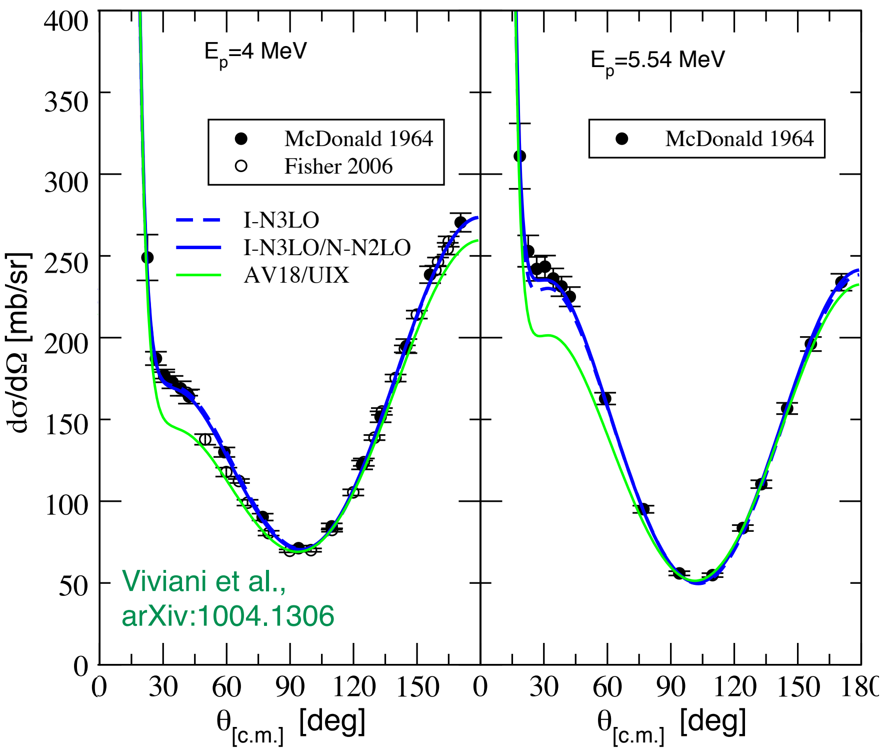
Leading chiral 3NF and 3N/4N continuum

- Nd scattering: accurate description at low energy except for A_y-puzzle (fine tuned) and some breakup configurations
- Uncertainty grows rapidly with energy (higher orders ?)
- 4N continuum: an emerging field...

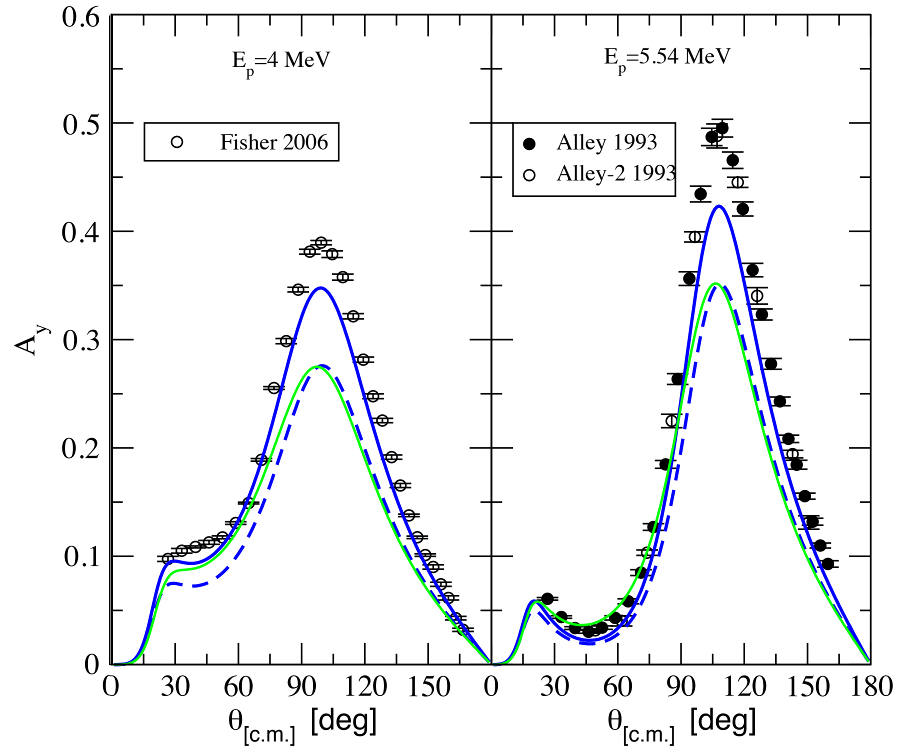


2 LECs tuned to few-N data (e.g. ^{3}H, ^{4}He BEs)

p-^{3}He differential cross section



A_y-puzzle in p-^{3}He elastic scattering



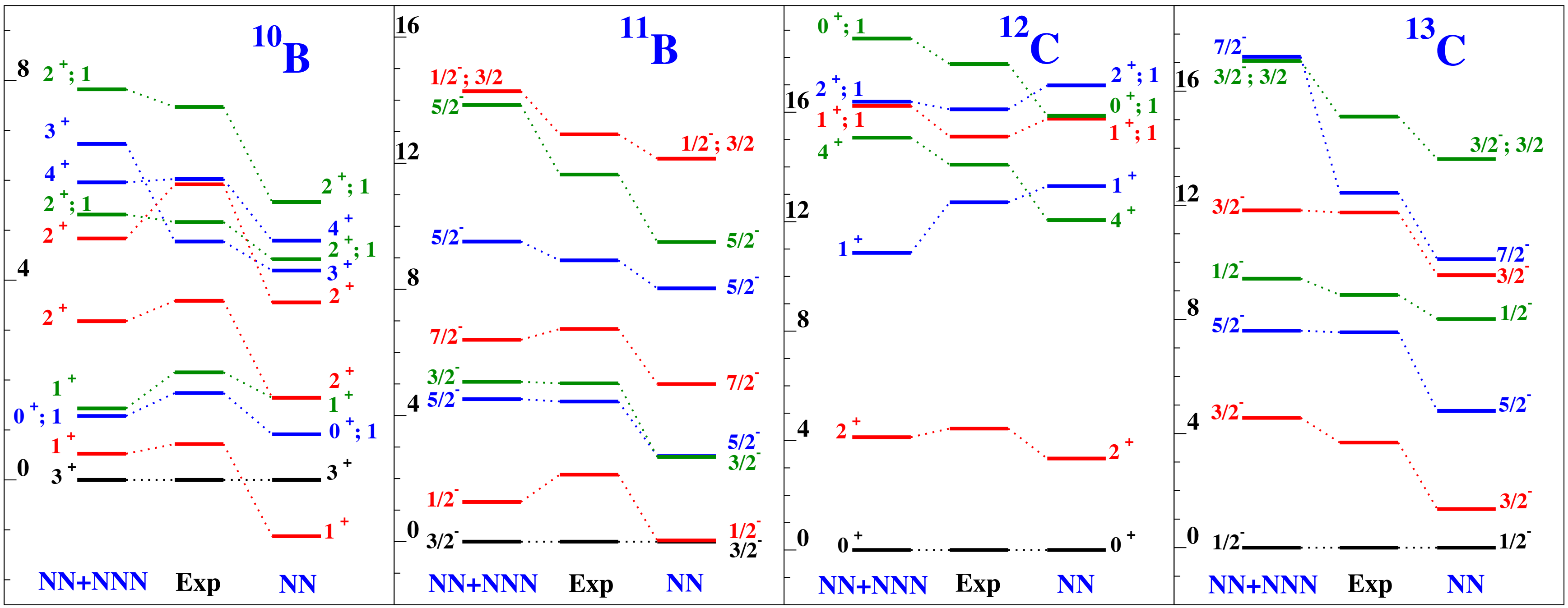
Leading chiral 3NF and nuclear structure

Ab initio methods (NCSM, GFMC, CCM, Lattice, ...) + renormalization ideas (SRG, V_{low-k}, UCOM)

+ computational resources ⟶ precision ab initio nuclear structure calculations

Barrett, Navratil, Nogga, Roth, Schwenk, Hebeler, Furnstahl, Vary, Ormand, ...

NCSM calculation of p-shell nuclei with chiral 2NF+3NF Navratil et al. ’07

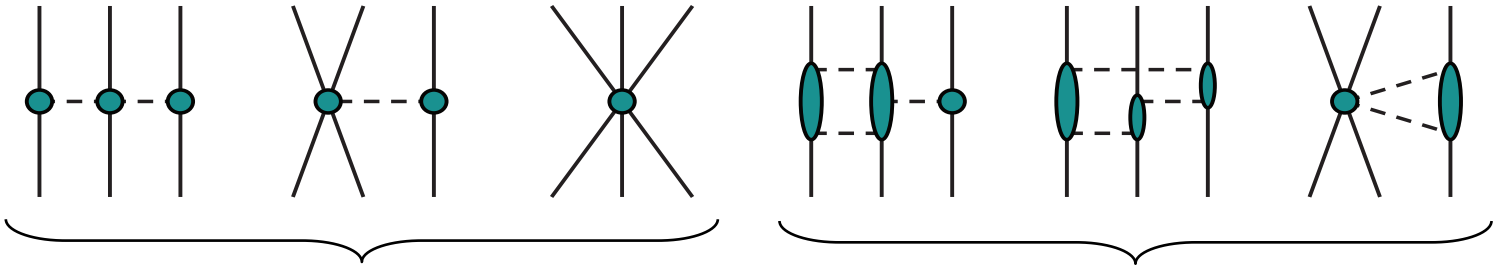


- sensitive to details of the 3NF
- many promising results (neutron-rich nuclei, long lifetime of ^{14}C, neutron star radii, ...)
- still room for improvement and some open questions ⟶ higher-order 3NFs...

3N force beyond leading order

3N force: corrections beyond LO

3NF topologies up to N^4LO (subleading one-loop order)



Q^3 [N^2LO] + Q^4 [N^3LO] + Q^5 [N^4LO] + ...

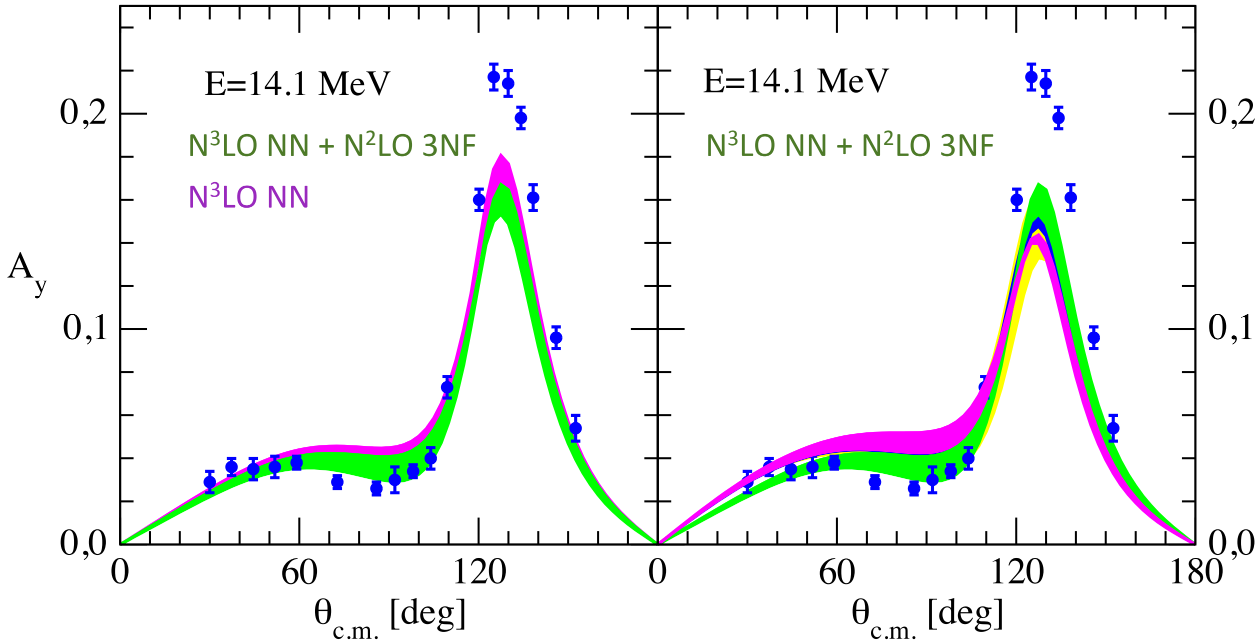
Q^4 [N^3LO] + Q^5 [N^4LO] + ...

- N^2LO contributions (leading 3NF) nowadays included in most few-/many-body calculations
- The leading corrections (N^3LO) have been worked out recently
  Ishikawa, Robilotta, PRC76 (07); Bernard, EE, Krebs, Meißner, PRC77 (08); PRC84 (11)
  - parameter-free!
  - rich spin-momentum structure, especially from the ring diagrams
  - partial wave decomposition is still in progress
    - the technology for numerical PWD has been developed Skibinski et al., PRC84 (11)
    - calculations presently running at JUROPA@FZJ, OSC@OhioState,...
    - estimated need: ~ 10.000.000 CPU hours

3N force: corrections beyond LO

Impact of some of the N^3LO 3NF terms on nd A_y (incomplete)

Witala et al., in proceedings of FB20

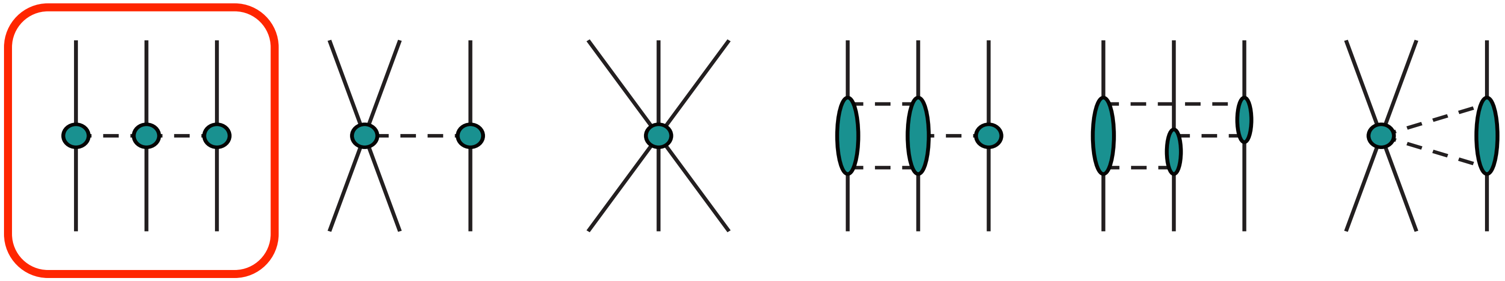


Right panel: X = N^3LO NN + N^2LO 3NF + N^3LO 3NF (1π-cont.) + N^3LO 3NF (cont.)

- (yellow) = X + N^3LO 3NF (2π-exch.)
- (blue) = X + N^3LO 3NF (2π-exch. & 2π-1π-exch.)
- (magenta) = X + N^3LO 3NF (2π-exch. & 2π-1π-exch. & ring)

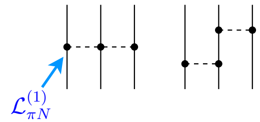
- N^3LO corrections seem to be rather small,
- chiral expansion of the 3NF is NOT yet converged → need to go to higher orders...

3NF: chiral expansion of the longest-range piece (2π)



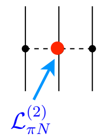
Two-pion exchange 3NF up to N^{4}LO

Next-to-leading order

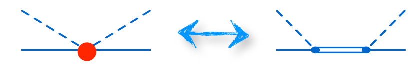


yield vanishing 3NF contributions

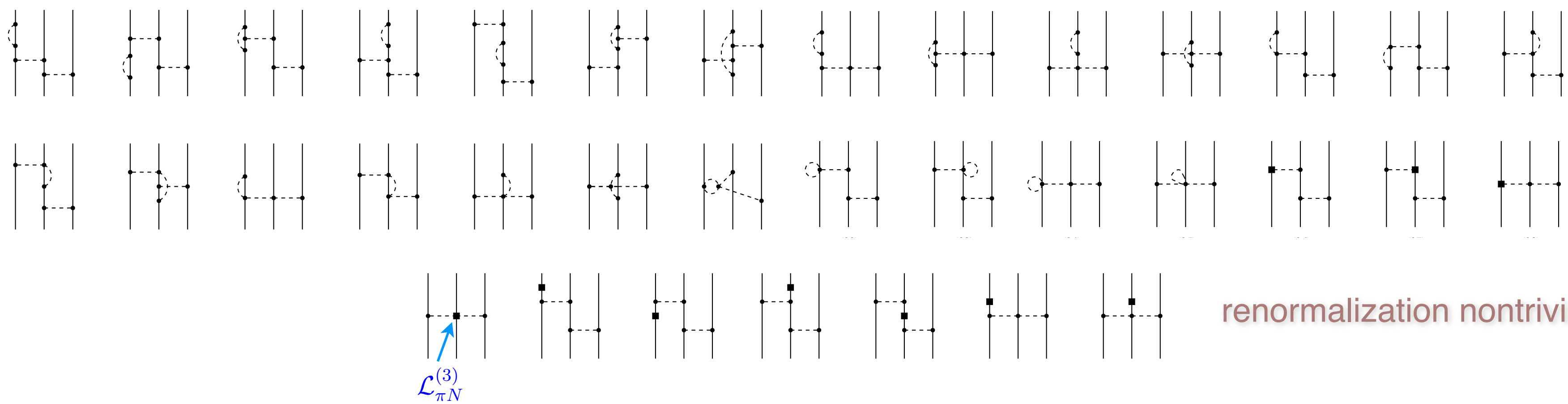
Next-to-next-to-leading order



first nonvanishing 3NF,
encodes information about the Δ:

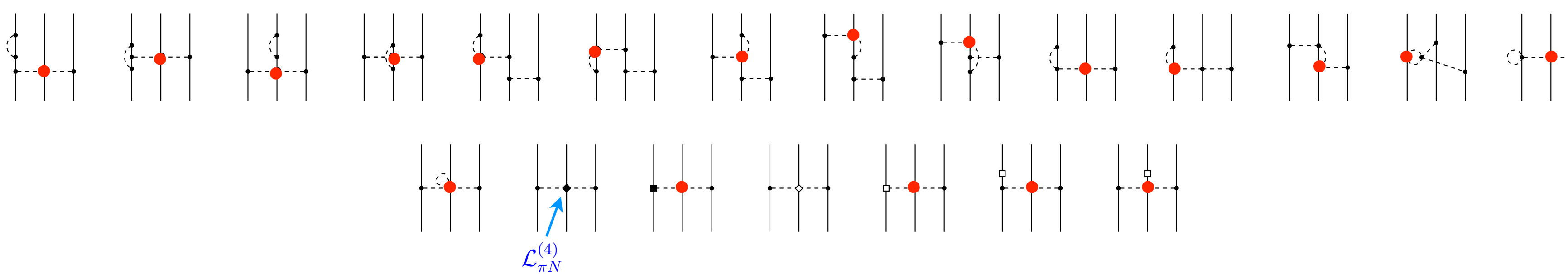


Next-to-next-to-next-to-leading order (leading 1 loop)



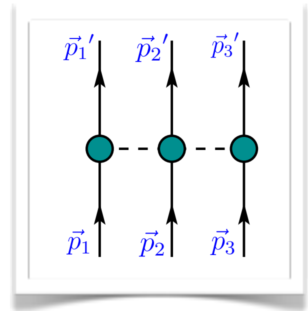
renormalization nontrivial !

Next-to-next-to-next-to-next-to-leading order (subleading 1 loop)



Two-pion exchange 3NF up to N⁴LO

The TPE 3NF has the form (modulo 1/m-terms):



$$V_{2\pi} = \frac{\vec{\sigma}_1 \cdot \vec{q}_1 \, \vec{\sigma}_3 \cdot \vec{q}_3}{[q_1^2 + M_\pi^2]\,[q_3^2 + M_\pi^2]} \Big(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \mathcal{A}(q_2) + \boldsymbol{\tau}_1 \times \boldsymbol{\tau}_3 \cdot \boldsymbol{\tau}_2 \, \vec{q}_1 \times \vec{q}_3 \cdot \vec{\sigma}_2 \, \mathcal{B}(q_2) \Big)$$

- leading-order:
  van Kolck '94

$$\mathcal{A}^{(3)}(q_2) = \frac{g_A^2}{8F_\pi^4} \Big((2c_3 - 4c_1) M_\pi^2 + c_3 q_2^2 \Big) \,, \qquad \mathcal{B}^{(3)}(q_2) = \frac{g_A^2 c_4}{8F_\pi^4}$$

- subleading:

$$\mathcal{A}^{(4)}(q_2) = \frac{g_A^4}{256\pi F_\pi^6} \Big[A(q_2) \left(2M_\pi^4 + 5M_\pi^2 q_2^2 + 2q_2^4 \right) + \left(4g_A^2 + 1 \right) M_\pi^3 + 2 \left(g_A^2 + 1 \right) M_\pi q_2^2 \Big] \,,$$

$$\mathcal{B}^{(4)}(q_2) = -\frac{g_A^4}{256\pi F_\pi^6} \Big[A(q_2) \left(4M_\pi^2 + q_2^2 \right) + (2g_A^2 + 1) M_\pi \Big]$$

Ishikawa, Robilotta '07
Bernard, EE, Krebs, Meißner '08

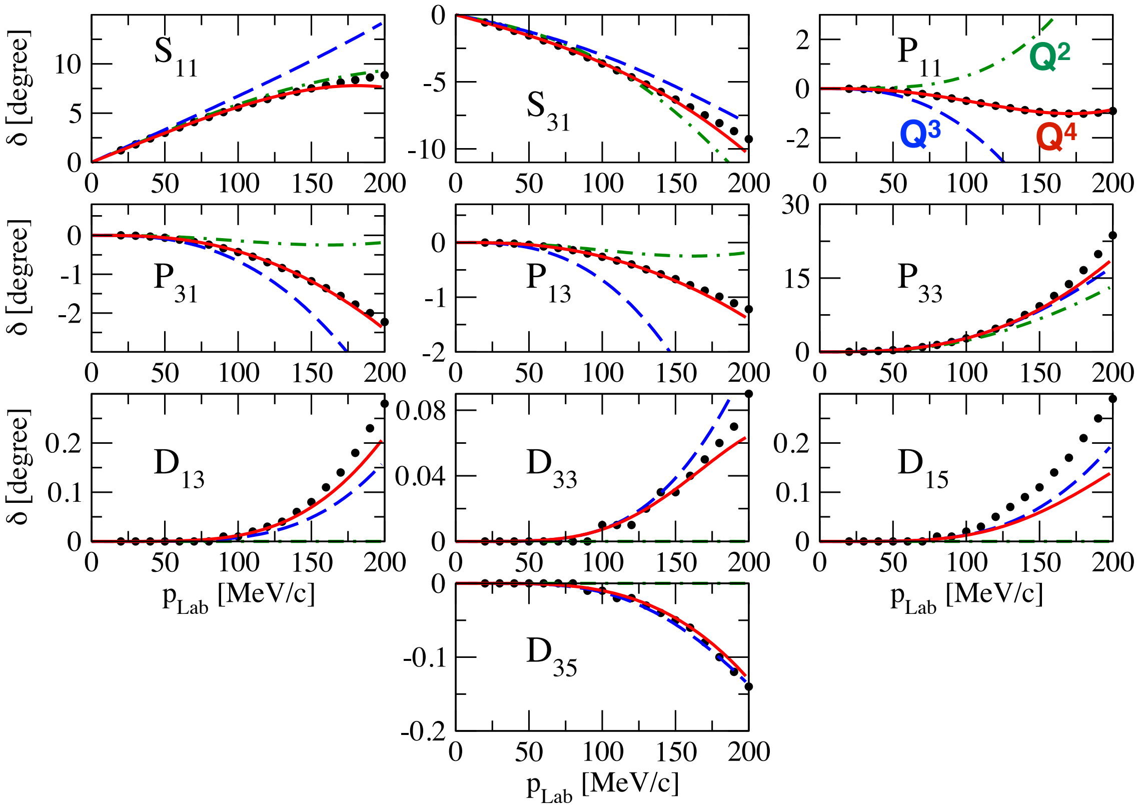
- sub-subleading:
  Krebs, Gasparyan, EE '12

$$\begin{aligned}
\mathcal{A}^{(5)}(q_2) &= \frac{g_A}{4608\pi^2 F_\pi^6} \Big[M_\pi^2 q_2^2 (F_\pi^2 \left(2304\pi^2 g_A (4\bar{e}_{14} + 2\bar{e}_{19} - \bar{e}_{22} - \bar{e}_{36}) - 2304\pi^2 \bar{d}_{18} c_3 \right) \\
&+ g_A (144 c_1 - 53 c_2 - 90 c_3)) + M_\pi^4 \left(F_\pi^2 \left(4608\pi^2 \bar{d}_{18} (2c_1 - c_3) + 4608\pi^2 g_A (2\bar{e}_{14} + 2\bar{e}_{19} - \bar{e}_{36} - 4\bar{e}_{38}) \right) \right. \\
&+ \left. g_A \left(72 \left(64\pi^2 \bar{l}_3 + 1 \right) c_1 - 24 c_2 - 36 c_3 \right) \right) + q_2^4 \left(2304\pi^2 \bar{e}_{14} F_\pi^2 g_A - 2g_A (5c_2 + 18 c_3) \right) \Big] \\
&- \frac{g_A^2}{768\pi^2 F_\pi^6} L(q_2) \left(M_\pi^2 + 2q_2^2 \right) \left(4M_\pi^2 (6c_1 - c_2 - 3c_3) + q_2^2 (-c_2 - 6c_3) \right) \,, \\
\mathcal{B}^{(5)}(q_2) &= -\frac{g_A}{2304\pi^2 F_\pi^6} \Big[M_\pi^2 \left(F_\pi^2 \left(1152\pi^2 \bar{d}_{18} c_4 - 1152\pi^2 g_A (2\bar{e}_{17} + 2\bar{e}_{21} - \bar{e}_{37}) \right) + 108 g_A^3 c_4 + 24 g_A c_4 \right) \\
&+ q_2^2 \left(5 g_A c_4 - 1152\pi^2 \bar{e}_{17} F_\pi^2 g_A \right) \Big] + \frac{g_A^2 c_4}{384\pi^2 F_\pi^6} L(q_2) \left(4M_\pi^2 + q_2^2 \right)
\end{aligned}$$

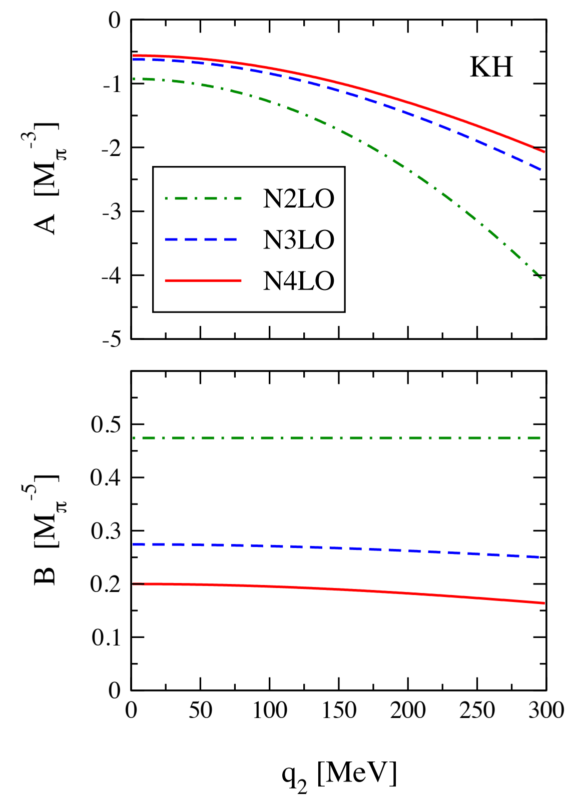
Two-pion exchange 3NF up to N^4LO

Krebs, Gasparyan, EE ’12

πN phase shifts in HB ChPT up to Q^4 (KH PWA)



3NF „structure functions“



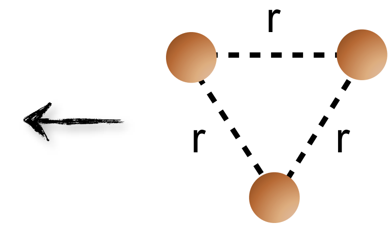
The determined values of LECs

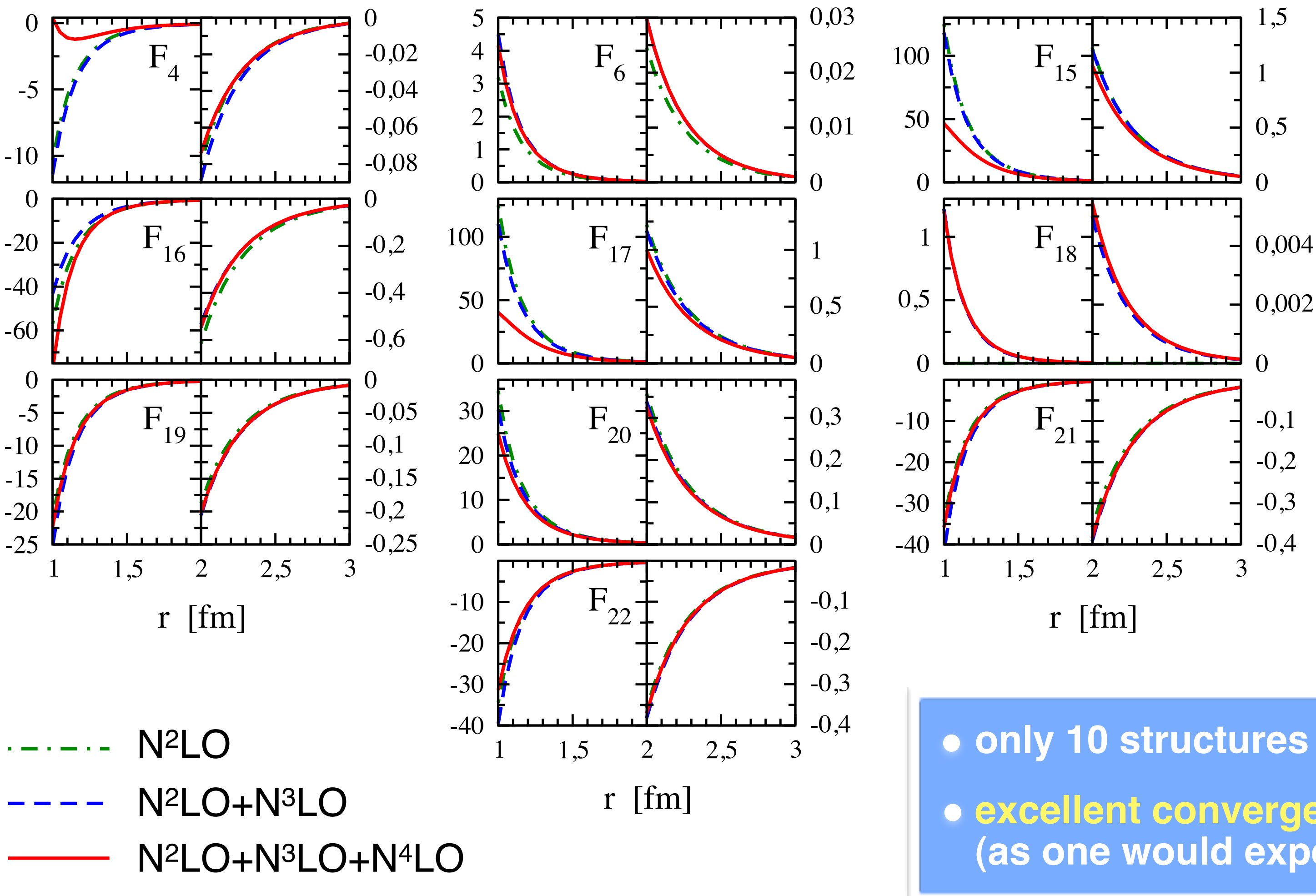
	c_1	c_2	c_3	c_4	$\bar{d}_1 + \bar{d}_2$	$\bar{d}_3$	$\bar{d}_5$	$\bar{d}_{14} - \bar{d}_{15}$	$\bar{e}_{14}$	$\bar{e}_{15}$	$\bar{e}_{16}$	$\bar{e}_{17}$	$\bar{e}_{18}$
Q^4 fit to GW	-1.13	3.69	-5.51	3.71	5.57	-5.35	0.02	-10.26	1.75	-5.80	1.76	-0.58	0.96
Q^4 fit to KH	-0.75	3.49	-4.77	3.34	6.21	-6.83	0.78	-12.02	1.52	-10.41	6.08	-0.37	3.26

Two-pion exchange 3NF up to N⁴LO

Krebs, Gasparyan, EE ’12

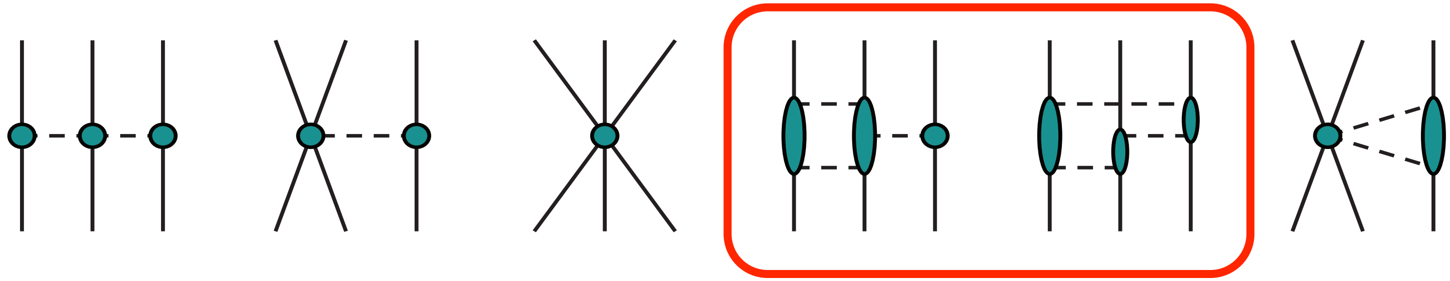
Chiral expansion of TPE „structure functions“ F_i (in MeV) in the equilateral-triangle configuration





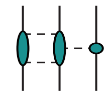
- only 10 structures out of 22...
- excellent convergence for r > 1.5 fm (as one would expect)

3NF: chiral expansion of the intermediate-range terms

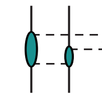


2π-1π & ring graphs up to N^4LO

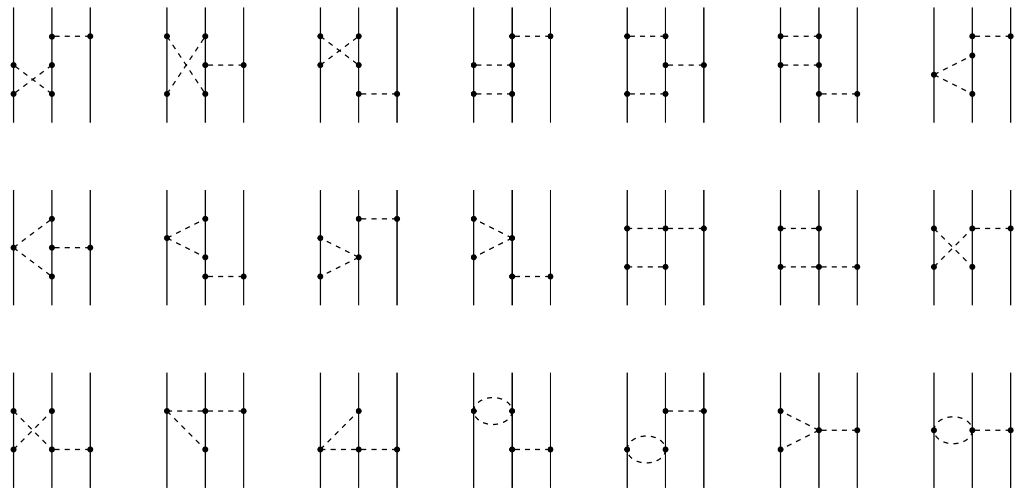
The 2π-1π-exchange 3NF topology

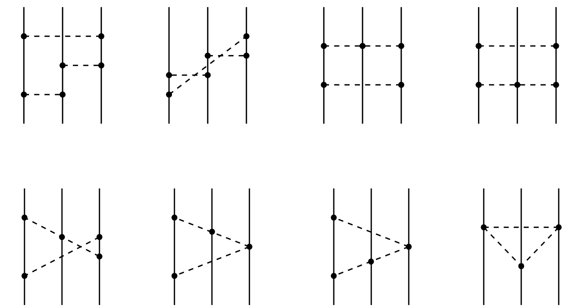


Ring 3NF diagrams



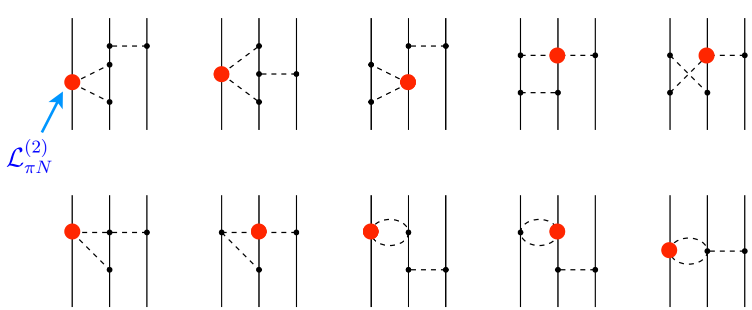
N^3LO

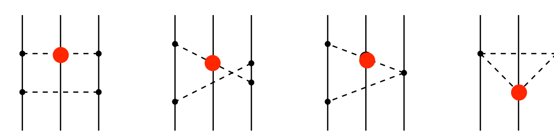




Bernard, EE, Krebs, Meißner PRC 77 (2008) 064004

N^4LO



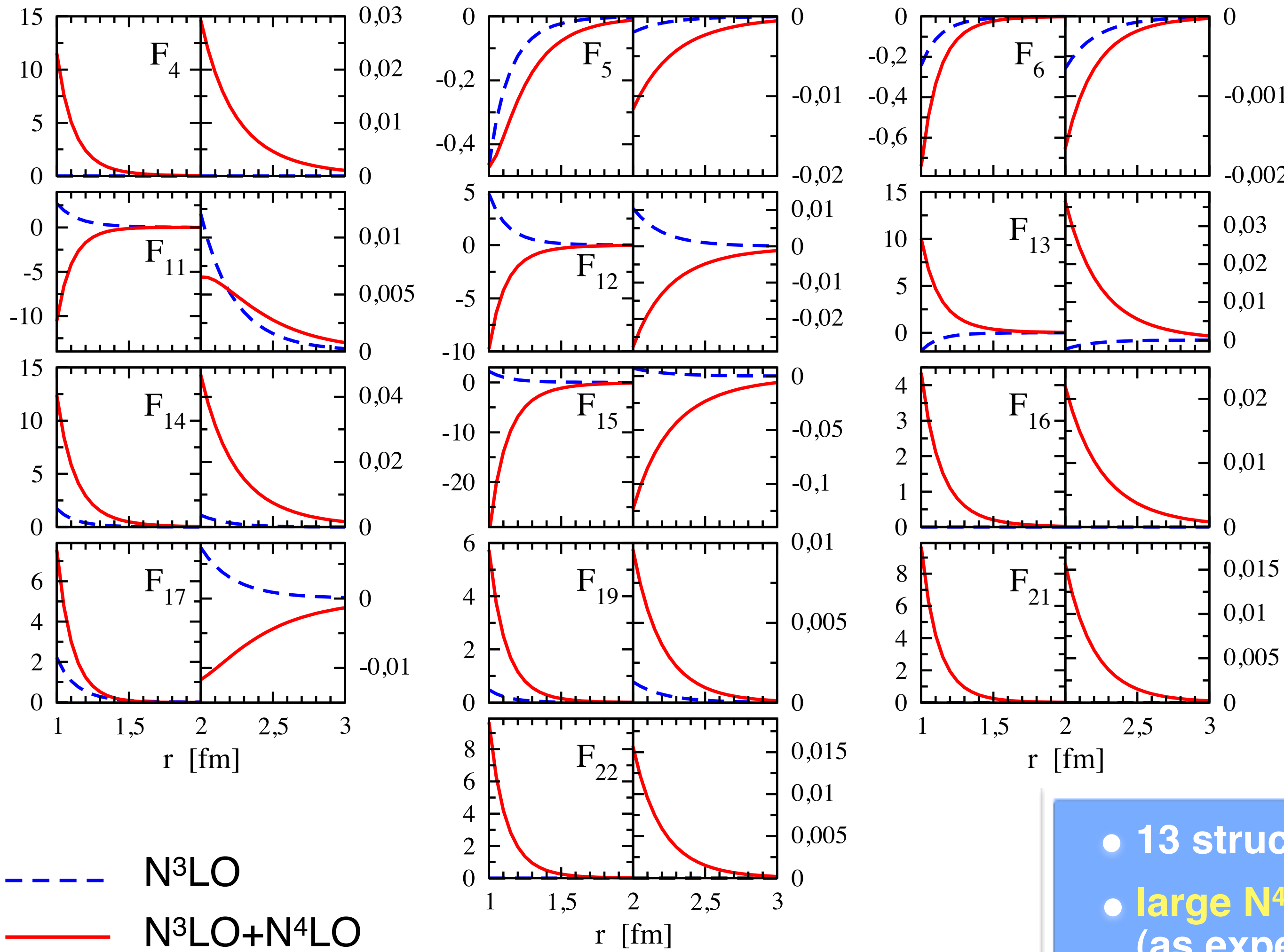


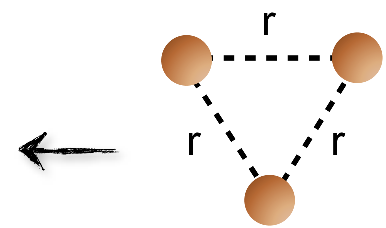
Krebs, Gasparyan, EE, in preparation

2π-1π-exchange 3NF at N⁴LO

Krebs, Gasparyan, EE, in preparation

Chiral expansion of 2π-1π „structure functions“ F_i (in MeV) in the equilateral-triangle configuration



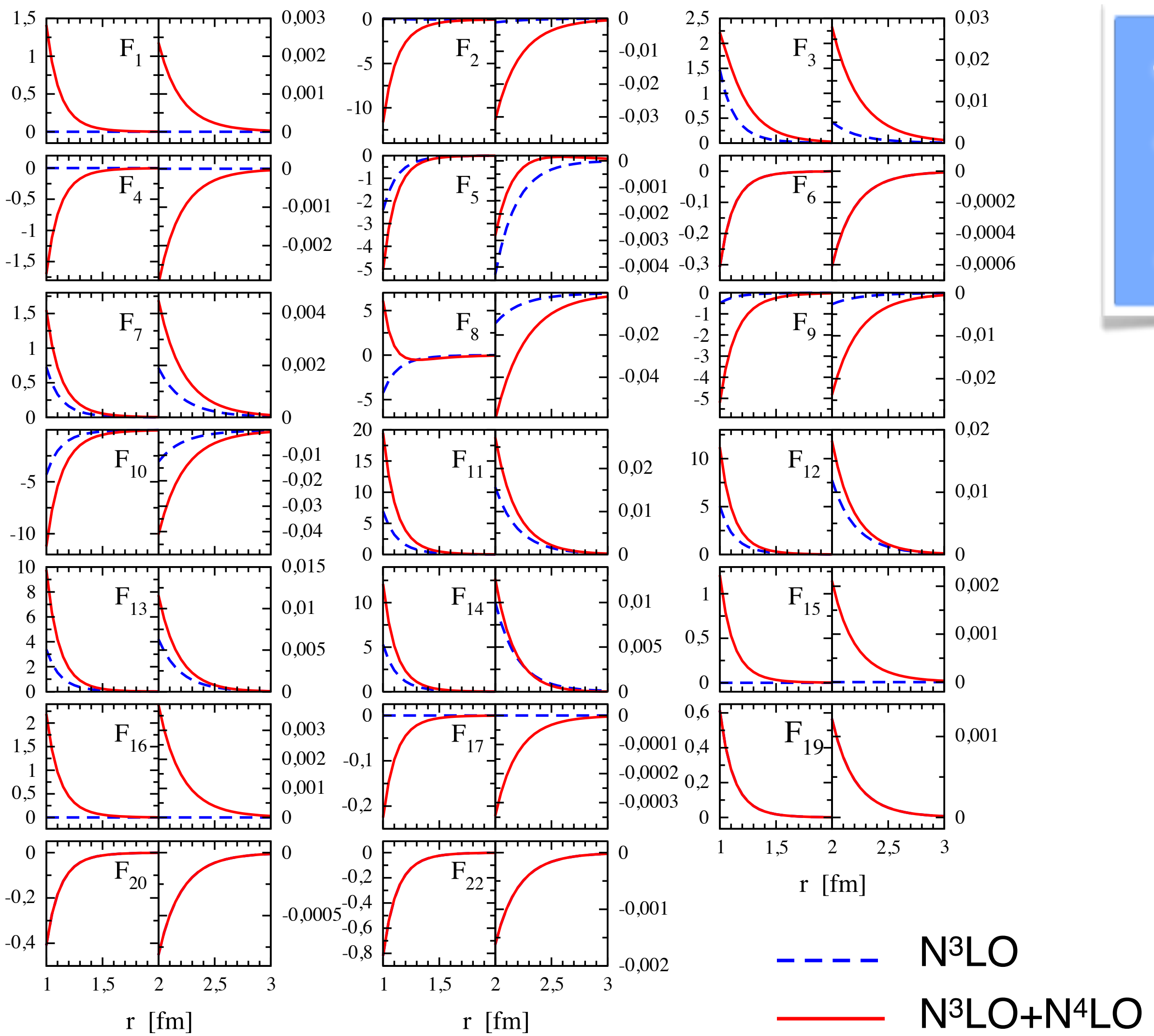


- 13 structures out of 22...
- large N⁴LO contributions (as expected)

Ring 3NF topology at N^4LO

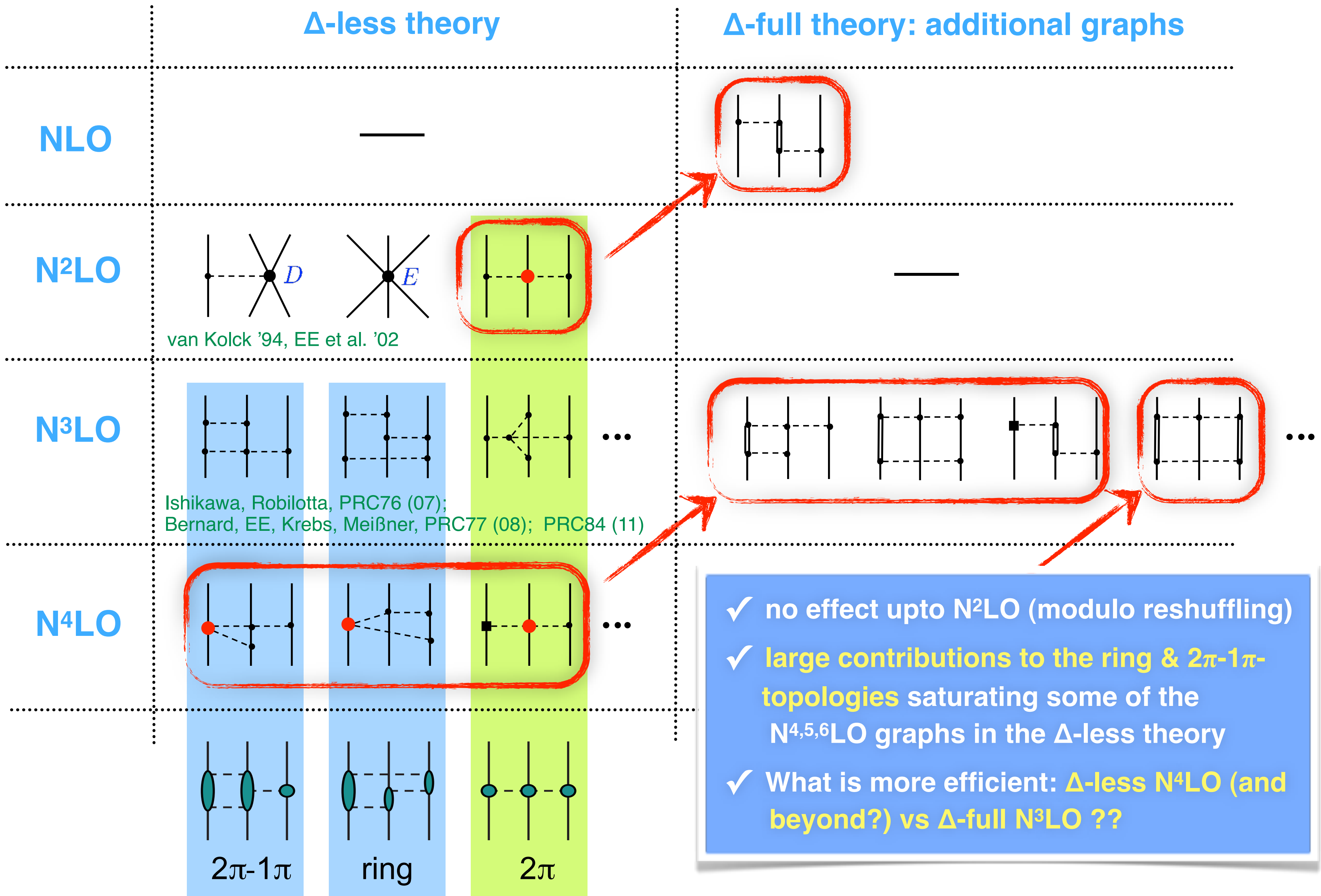
Krebs, Gasparyan, EE, in preparation

Ring „structure functions" F_i (in MeV) in the equilateral-triangle configuration



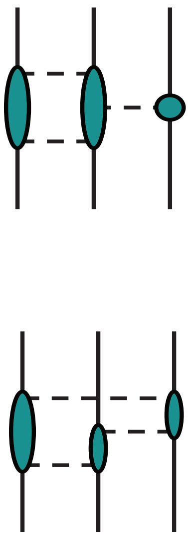
- 20 structures out of 22…
- large N^4LO contributions (as expected)
- N^4LO converged ??

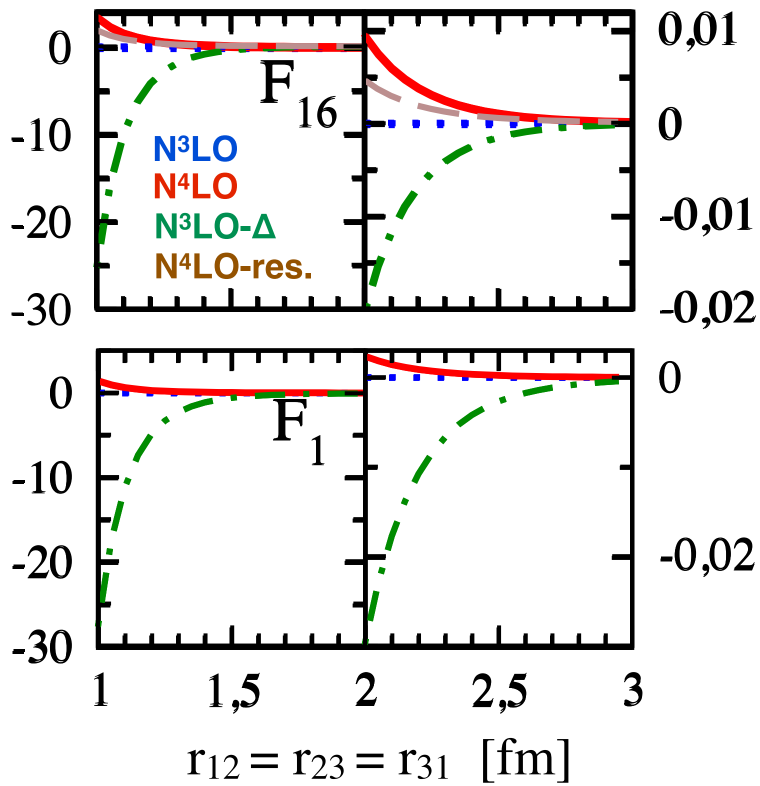
Chiral expansion of the 3NF



Chiral 3NF: Δ-less vs. Δ-full

Krebs, Gasparyan, EE, to appear





include terms $\sim \frac{1}{m_\Delta - m_N}$

(Δ-saturation of c_3, c_4)

but NOT $\sim \frac{1}{(m_\Delta - m_N)^2}, \ldots$

Chiral EFT with Δ(1232): (partial) resummation of terms:

$\sim \frac{1}{m_\Delta - m_N}, \frac{1}{(m_\Delta - m_N)^2}, \ldots$

N^4LO, resonance saturation (only effects of the Δ)

- N^4LO contributions still miss important physics of double and triple Δ-excitations
  → it is more efficient to include Δ as an explicit DOF
- there are indications that N^3LO-Δ results for F_i already provide a good approximation
- intermediate and short-range topologies in progress...

Summary and outlook

Towards high-precision chiral three-nucleon forces

- technology to (numerically) carry out PWD for ANY 3NF has been developed (but requires huge computational recources...)

- **3NF at N^2LO:** nowadays standard, promising results, room for improvement

- **3NF at N^3LO:** work in progress (PWD, determination of D, E). First results indicate that N^3LO corrections might be small; evidence for significant higher-order contributions (2π-1π, ring)

- **3NF beyond N^3LO:** long-range terms (parameter-free) worked out completely at N^4LO and N^3LO-Δ (seems to be the most efficient approach); shorter-range contributions in progress

Future: determination of LECs in the short-range parts of the 3NF, effects of the novel structures in the 3N and 4N continuum and light nuclei, lots of interesting physics...