Evgeny Epelbaum, RUB

Quark Confinement and the Hadron Spectrum XI,
St. Petersburg, September 8-12, 2014

Chiral effective field theory for light nuclei

Introduction

New chiral NN potentials

Chiral 3NF: Ongoing developments

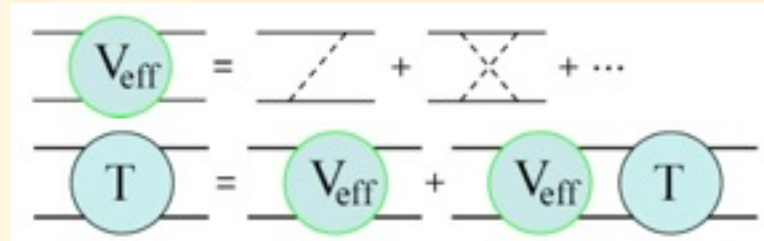
Summary

Nuclear chiral effective field theory

Nuclear chiral EFT

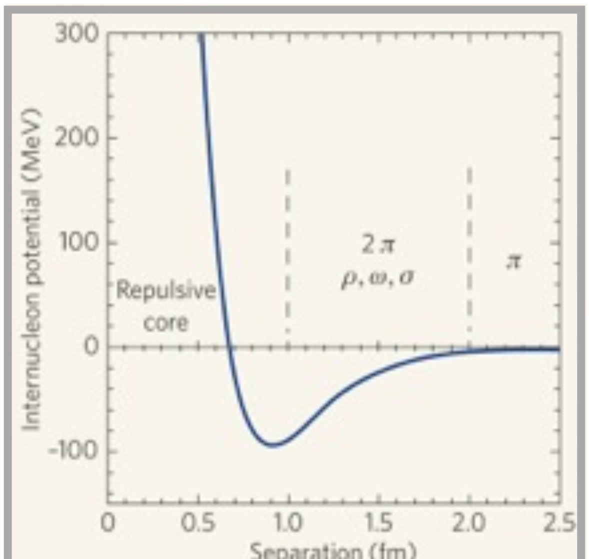
Weinberg, van Kolck, EE, Glöckle, Meißner, Machleidt, Entem...

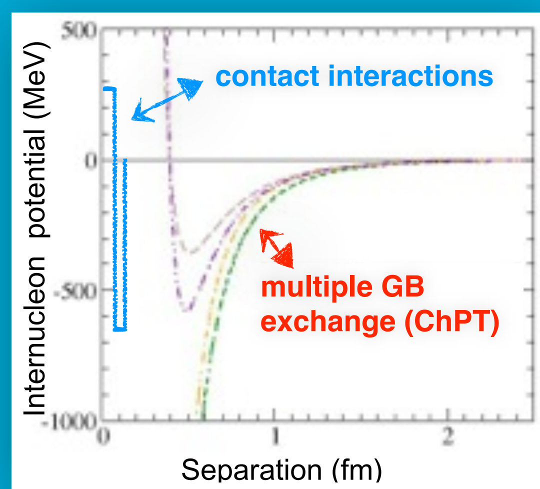
- Schrödinger equation for nucleons interacting via contact forces and long-range potentials (pion exchanges)



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

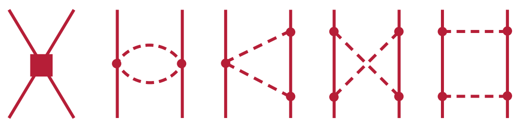
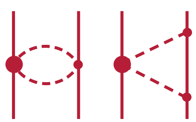
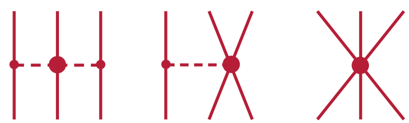
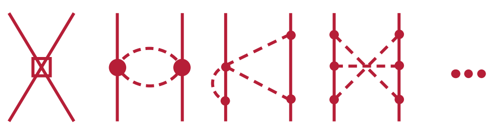
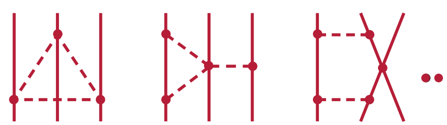
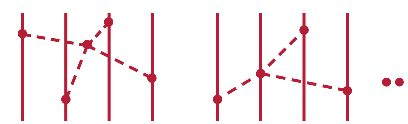
- access to heavier nuclei (ab initio few-/many-body methods)





- 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

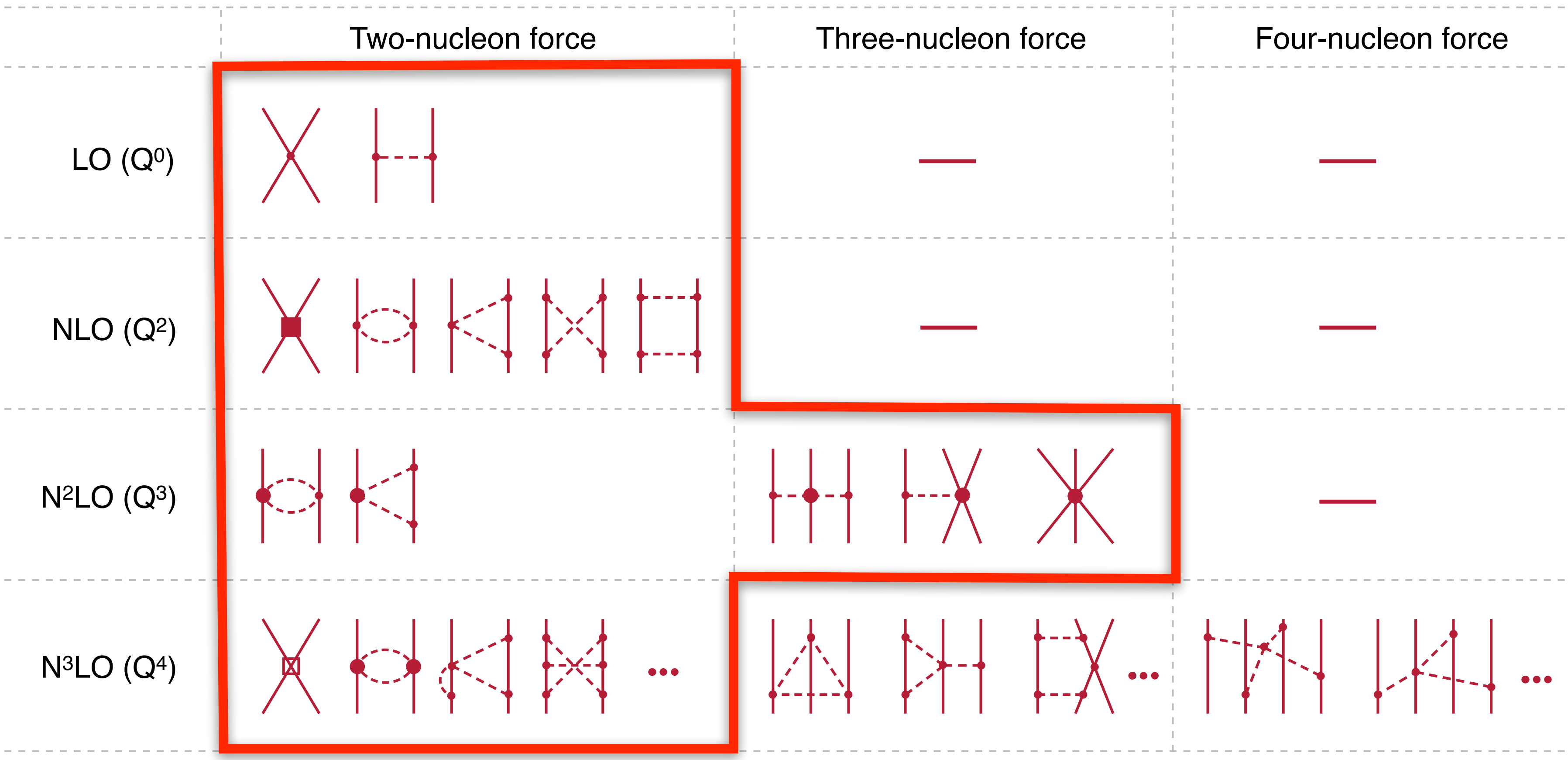
	Two-nucleon force	Three-nucleon force	Four-nucleon force
LO (Q^0)		—	—
NLO (Q^2)		—	—
N^{2}LO (Q^3)			—
N^{3}LO (Q^4)			

2N force: accurate N^{3}LO potentials are available Entem-Machleidt '03; EE-Glöckle-Meißner '04

3N force: N^{2}LO 3NF included in most calculations
N^{3}LO 3NF worked out Bernard, EE, Krebs Meißner '08,'11; (probably) not yet converged → higher orders
numerical PWD developed Golak, Skibinski, Krebs, Hebeler, …, first results available Witala et al.'13

4N force: leading (i.e. N^{3}LO) terms worked out EE '06; contrib. to ^{4}He BE ~ few 100 keV Rospedzik et al. '06

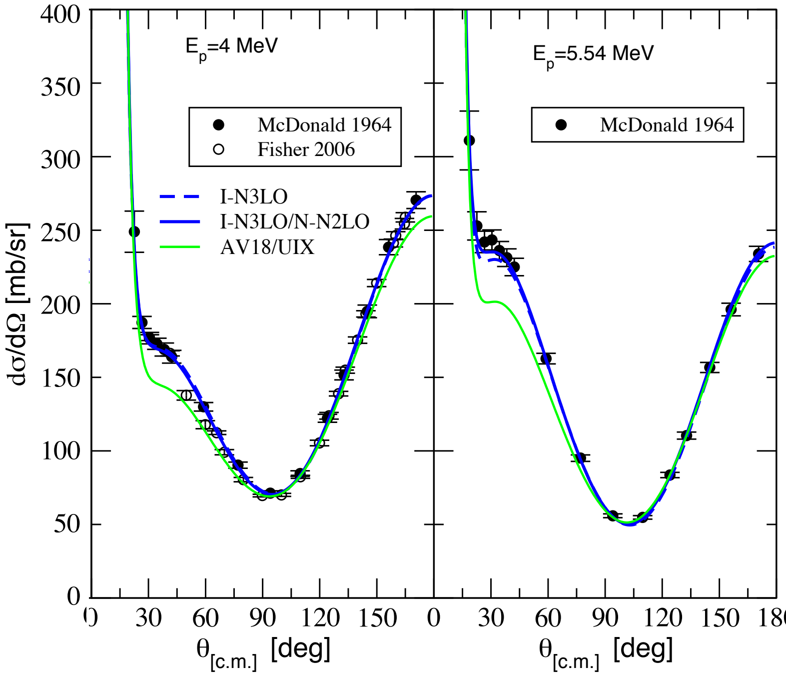
Chiral expansion of nuclear forces



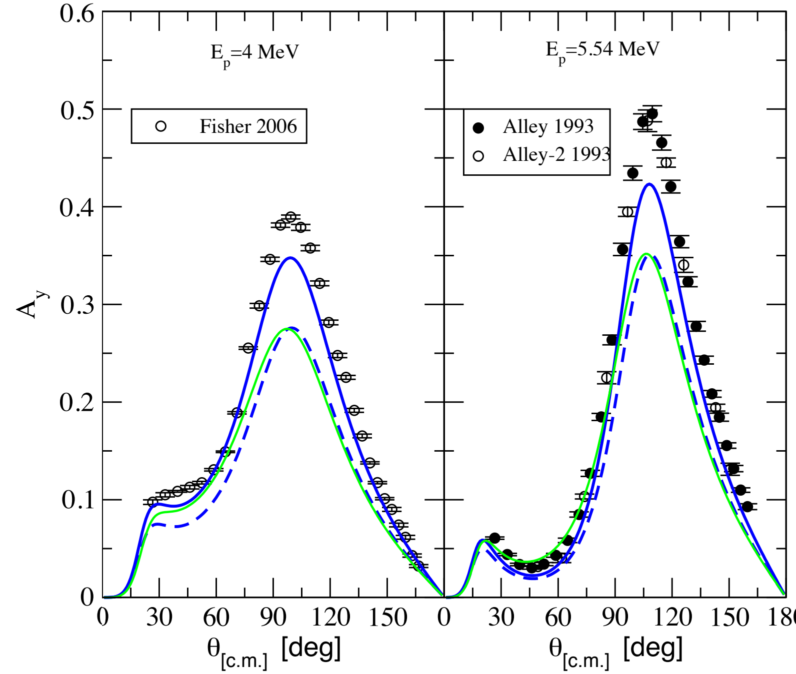
The „standard“ nuclear chiral Hamiltonian has been extensively tested in few- and many-body systems

Chiral Hamiltonian & the 3N/4N continuum

p-^{3}He differential cross section



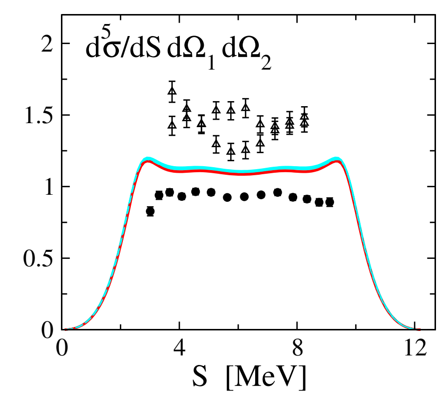
A$_y$-puzzle in p-^{3}He elastic scattering



LECs D,E tuned to the ^{3}H and ^{4}He binding energies, figure from Viviani et al., arXiv:1004.1306

To summarize:

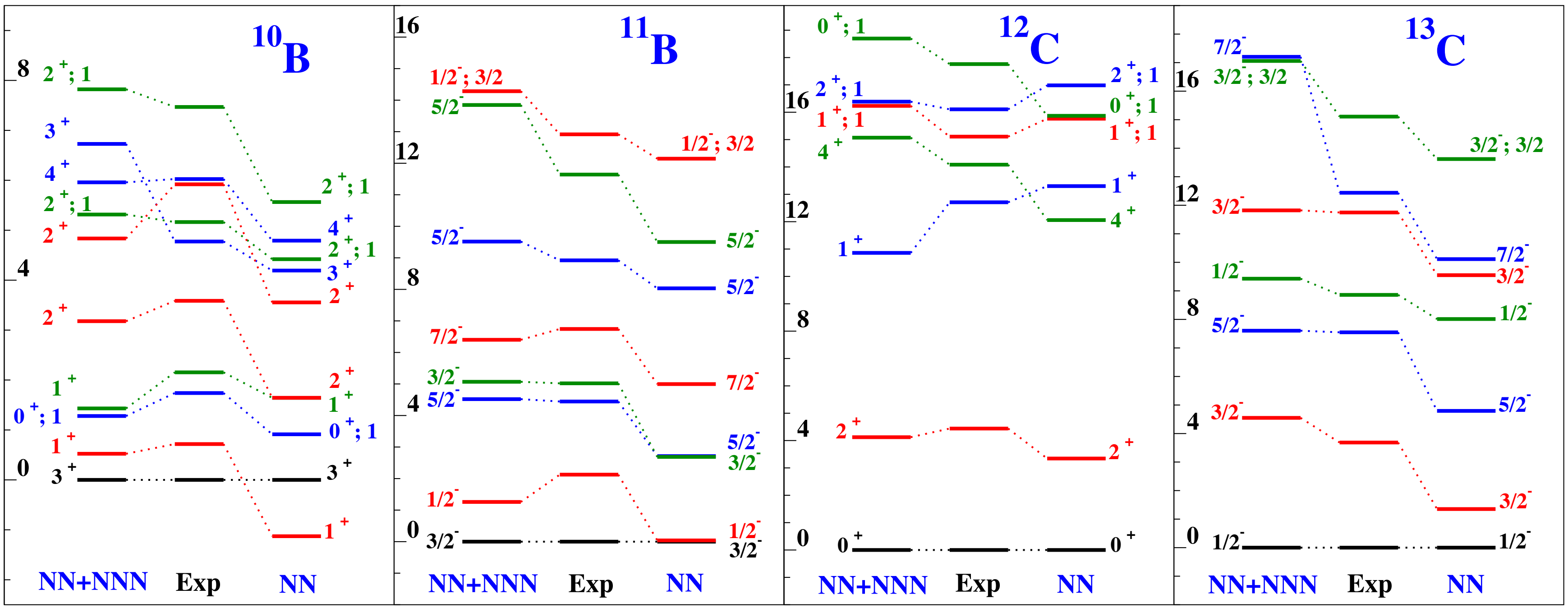
- Nd scattering: accurate description at low energy except for A$_y$ (fine tuned) and Space Star breakup configuration
- Uncertainty increases with energy (higher-order 3NF?)
- 4N continuum: an emerging field...



Chiral Hamiltonian & nuclear structure

Ab initio methods (NCSM, GFMC, CCM, Lattice, ...) + renormalization ideas (SRG, V_{low-k}, UCOM) + computational resources → precision ab initio nuclear structure calculations

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



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

The quest for high-precision chiral Hamiltonian

Corrections to the 3NF beyond N^2LO

Ishikawa, Robilotta ’06; Bernard, EE, Krebs, Meißner ’07,’11; Krebs, Gasparyan, EE’12,’13; EE, Gasparyan, Krebs, Schat, to appear

Convergence, effects of the Δ, partial wave decomposition, determination of the LECs, impact on 3N/4N scattering observables and nuclear structure…

→ **Low Energy Nuclear Physics International Collaboration (LENPIC)**

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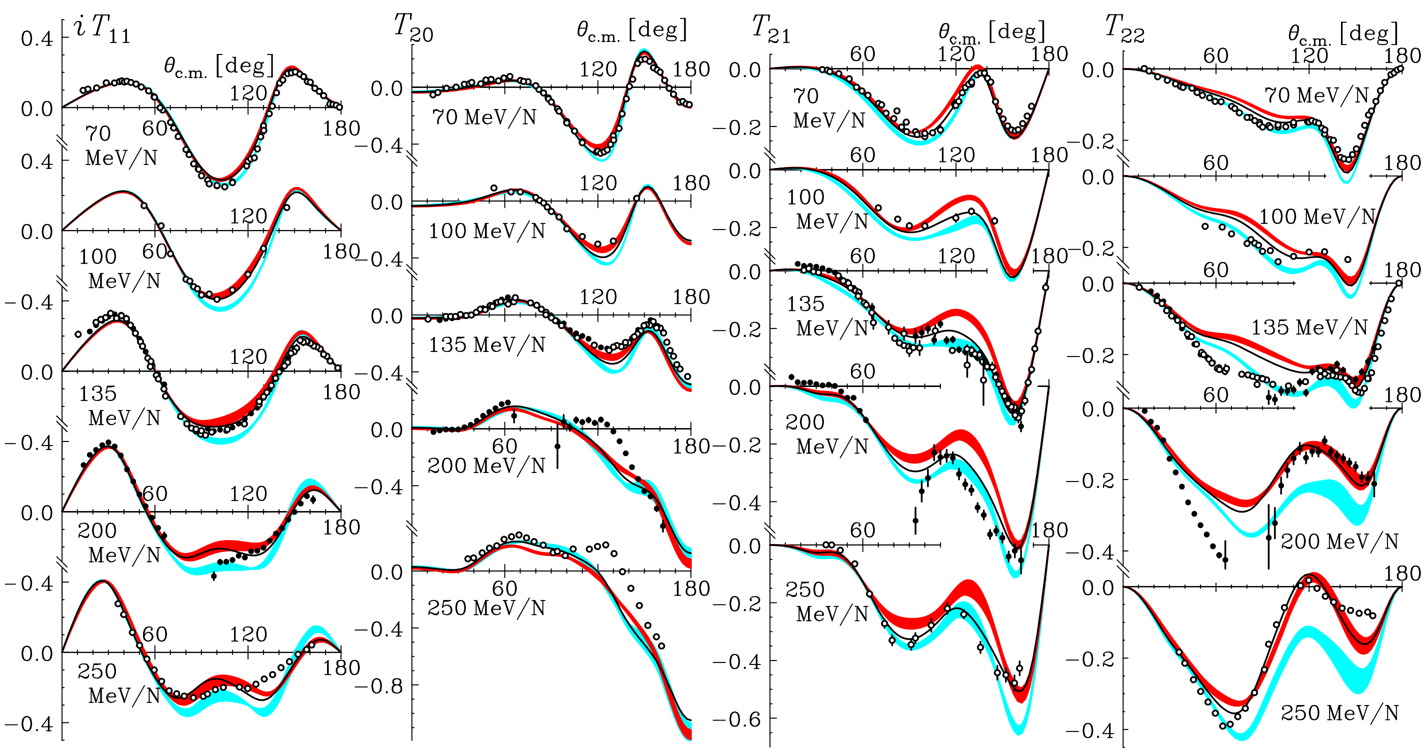
Actually, the spin structure of the 3NF is still poorly understood in spite of decades of effort! (one of the biggest challenges in nuclear physics)



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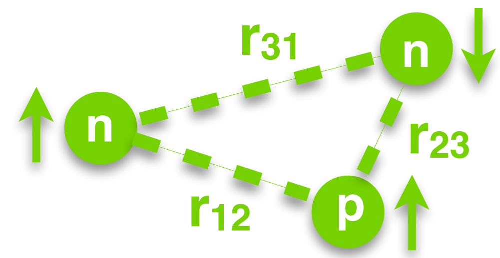
Most general structure of a local, isospin-symmetric 3NF

Krebs, Gasparyan, EE '13; Phillips, Schat '13; EE, Gasparyan, Krebs, Schat, in preparation

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



Assuming hermiticity, time reversal & parity invariance, **20 structure functions** are needed:

$$V(r_{12}, r_{23}, r_{31}) = \sum_{i=1}^{20} \tilde{\mathcal{G}}_i \, F_i(r_{12}, r_{23}, r_{31}) + \text{permutations}$$

$$V(q_1, q_2, q_3) = \sum_{i=1}^{20} \mathcal{G}_i \, F_i(q_1, q_2, q_3) + \text{permutations}$$

The quest for high-precision chiral Hamiltonian

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New generation of chiral NN potentials

Reduce finite-Λ artifacts by employing regularization which maintains the analytic structure of the amplitude ⟶ better performance at higher energies.

l_{ocal}-chiral potentials @ LO, NLO, N^{2}LO

Gezerlis et al, PRL 111 (13) 032501; arXiv:1406.0454; Lynn et al. arXiv:1406.2787

$i_{mproved}$-chiral potentials up to N^{3}LO

EE, Krebs, Meißner, Golak, Skibinski, Witala; work in progress

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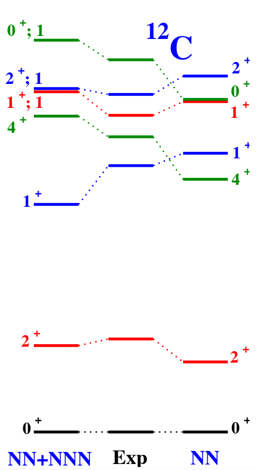
success or failure?

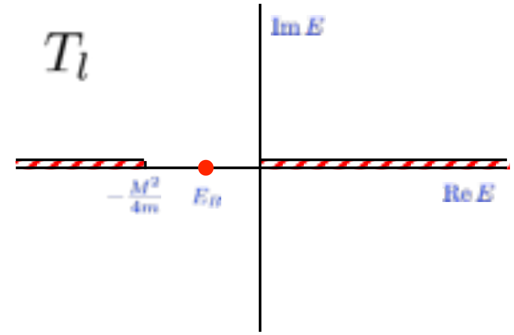


Reliable estimation of theoretical uncertainties

is needed in order to test chiral dynamics in nuclear systems, identify/ resolve possible puzzles (is A_y-puzzle a real puzzle?), make reliable predictions and guide new experiments

New chiral NN potential (preliminary)

- **Regularization which maintains the analytic structure**



Old EM/EGM potentials

$$V^{\rm reg}_{\rm long-range}(\vec{p}\,', \vec{p}\,) = V_{\rm long-range}(\vec{p}\,', \vec{p}\,) \; \exp\left[-\frac{p^n + p'^n}{\Lambda^n}\right]$$

affects the discontinuity across the left-hand cut

New potentials

$$V^{\rm reg}_{\rm long-range}(\vec{r}\,) = V_{\rm long-range}(\vec{r}\,)\; f_{\rm reg}\left(\frac{r}{R}\right) \longrightarrow V^{\rm reg}_{\rm long-range}(\vec{q}\,) = V_{\rm long-range}(\vec{q}\,) - \underbrace{\int d^3 l \; V_{\rm long-range}(\vec{q} - \vec{l}\,)\; \tilde{f}_{\rm reg}(\vec{l}\,)}_{\text{manifestly short-range}}$$

$\tilde{f}_{\rm reg}$: $\mathrm{FourierTransform}[f(r/R) - 1]$

no distortion of the long-range potential!

- **No need for an additional spectral function regularization in the TPEP**
- **Use LECs c_i, d_i from πN scattering without any fine tuning**

	Entem-Machleidt potential	Epelbaum-Glöckle-Meißner potential	πN scattering to leading one loop (Q^3)
c_1	-0.81	-0.81	-0.81 ± 0.15^b
c_2	2.80	3.28	3.28 ± 0.23^c
c_3	-3.20	-3.40	-4.69 ± 1.34^b
c_4	5.40	3.40	3.40 ± 0.04^b
$\bar{d}_1 + \bar{d}_2$	3.06	3.06	3.06 ± 0.21^c
$\bar{d}_3$	-3.27	-3.27	-3.27 ± 0.73^c
$\bar{d}_5$	0.45	0.45	0.45 ± 0.42^c
$\bar{d}_{14} - \bar{d}_{15}$	-5.65	-5.65	-5.65 ± 0.41^c

were tuned to improve the fit

taken on the lower side to avoid deeply-bound states

Convergence of the χ-expansion (preliminary)

- **Total cross section for neutron-proton scattering**

E_{lab} = 25 MeV [p = 108 MeV]

R = 0.9 fm [Λ = 440 MeV]: $\sigma_{tot} = \overbrace{396}^{Q^0} - \overbrace{\underbrace{15}_{\sim 40}}^{Q^2} - \overbrace{\underbrace{1}_{\sim 12}}^{Q^3} + \overbrace{\underbrace{0}_{\sim 4}}^{Q^4} = 380$ mbarn

$Q \sim 0.3 \longrightarrow$ expect: ~ 40 ~ 12 ~ 4

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$Q \sim 0.3 \longrightarrow$ expect: ~ 40 ~ 12 ~ 4

E_{lab} = 200 MeV [p = 306 MeV]

R = 0.9 fm [Λ = 440 MeV]: $$\sigma_{tot} = 35 \underbrace{+15}_{\sim 17} \underbrace{-7}_{\sim 12} \underbrace{+0}_{\sim 8} = 43 \text{ mbarn}$$

$Q \sim 0.7 \longrightarrow$ expect: ~ 17 ~ 12 ~ 8

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Q ~ 0.7 ⟶ expect:

R = 1.2 fm [Λ = 330 MeV]: $\sigma_{tot} = 17 + 6 + 1 + 14 = 38 \text{ mbarn}$

Q ~ 1 ⟶ expect no convergence!

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E_{lab} = 200 MeV [p = 306 MeV]

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$Q \sim 0.7 \longrightarrow$ expect:

R = 1.2 fm [Λ = 330 MeV]: $\sigma_{tot} = 17 + 6 + 1 + 14 = 38$ mbarn

$Q \sim 1 \longrightarrow$ expect no convergence!

- **Total cross section for neutron-deuteron scattering**

E_{lab} = 10 MeV [p = 69 MeV]

R = 0.9 fm [Λ = 440 MeV]: $\sigma_{tot} = 918 + \underbrace{85}_{\sim 80} + \underbrace{2}_{\sim 24} + \underbrace{11}_{\sim 7} = 1046$ mbarn

$Q \sim 0.3 \longrightarrow$ expect:

E_{lab} = 200 MeV [p = 306 MeV]

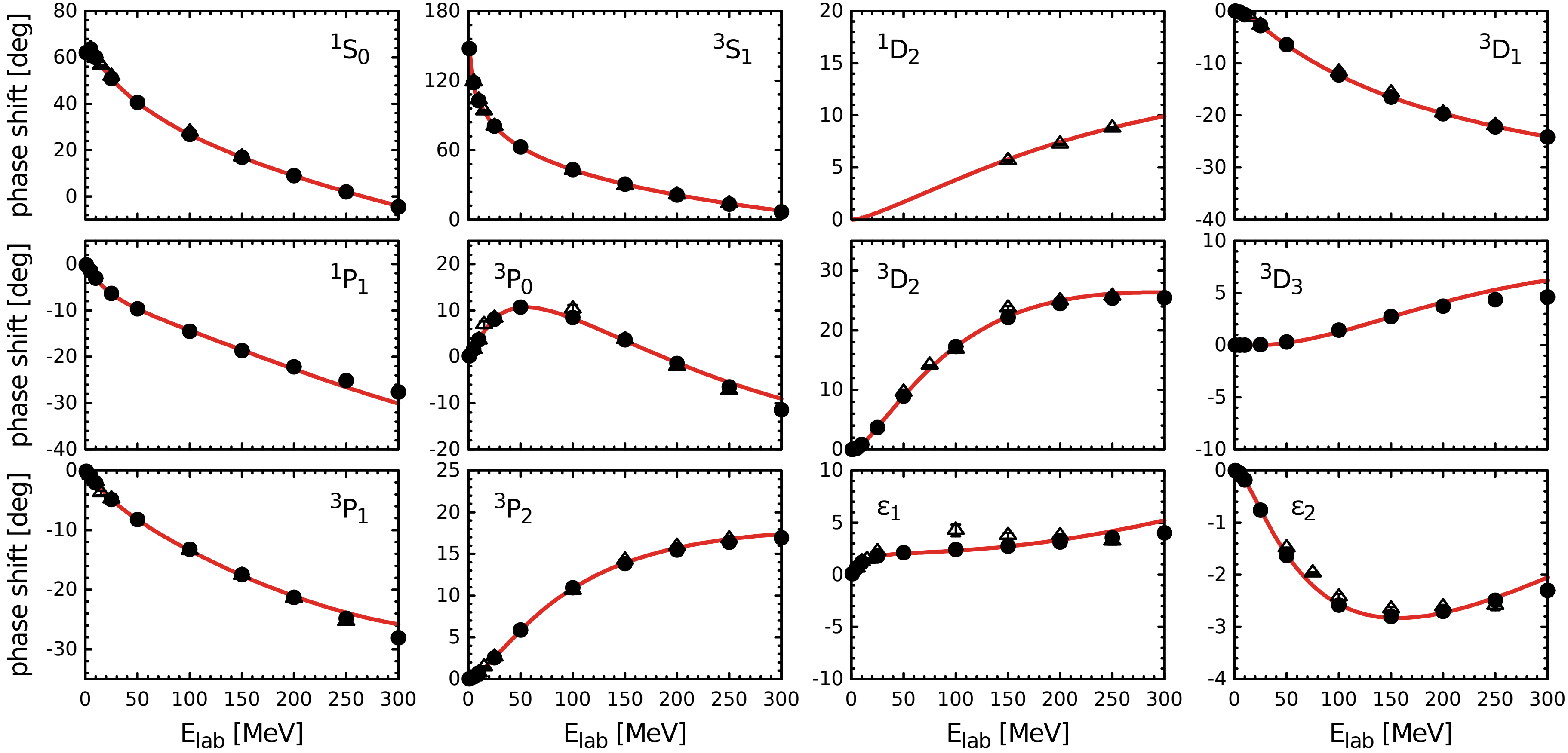
R = 0.9 fm [Λ = 440 MeV]: $\sigma_{tot} = 43 + \underbrace{11}_{\sim 21} + \underbrace{8}_{\sim 14} - \underbrace{1}_{\sim 10} = 61$ mbarn

$Q \sim 0.7 \longrightarrow$ expect:

R = 1.2 fm [Λ = 330 MeV]: $\sigma_{tot} = 20 + 10 + 4 + 20 = 54$ mbarn

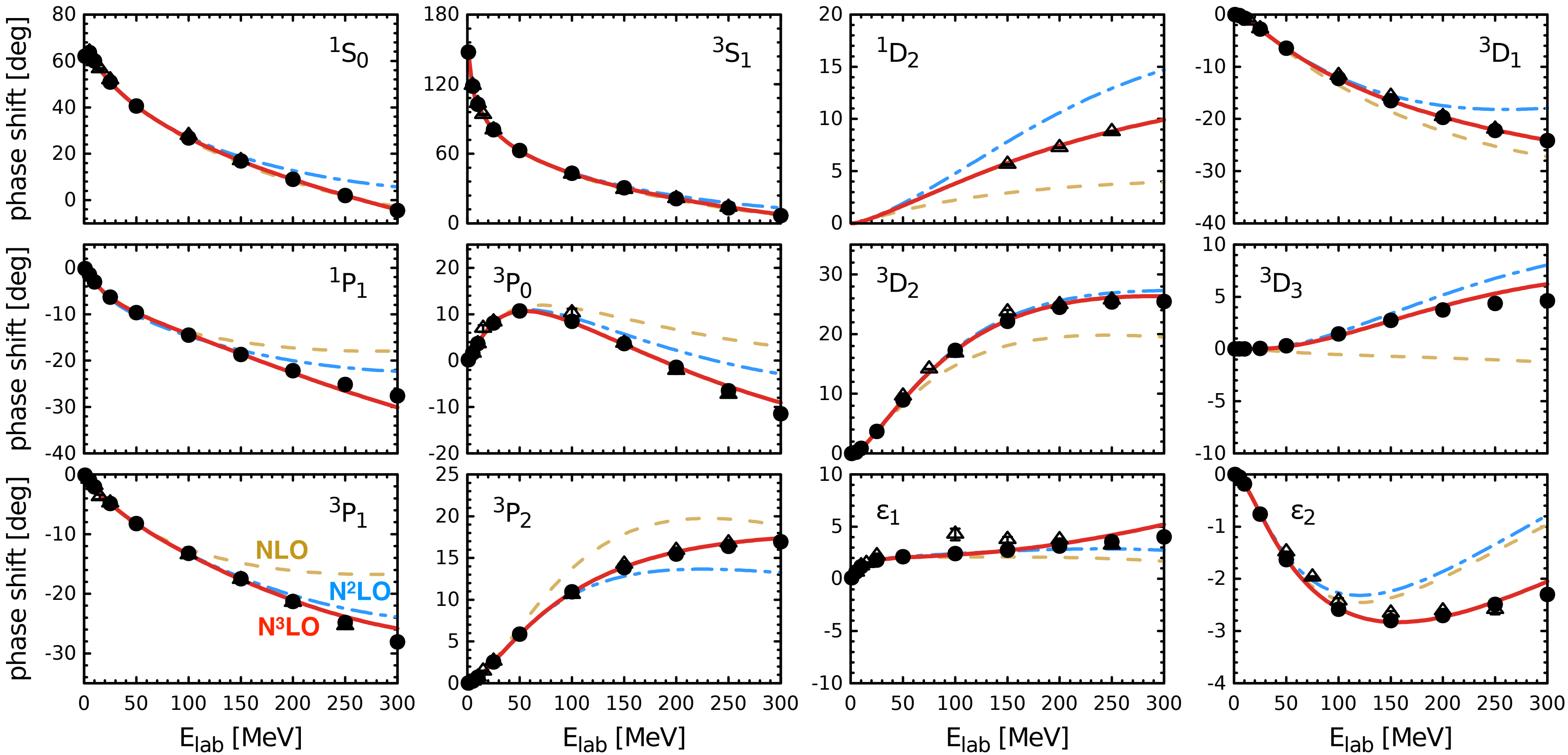
$Q \sim 1 \longrightarrow$ expect no convergence!

Uncertainty in phase shifts (preliminary)

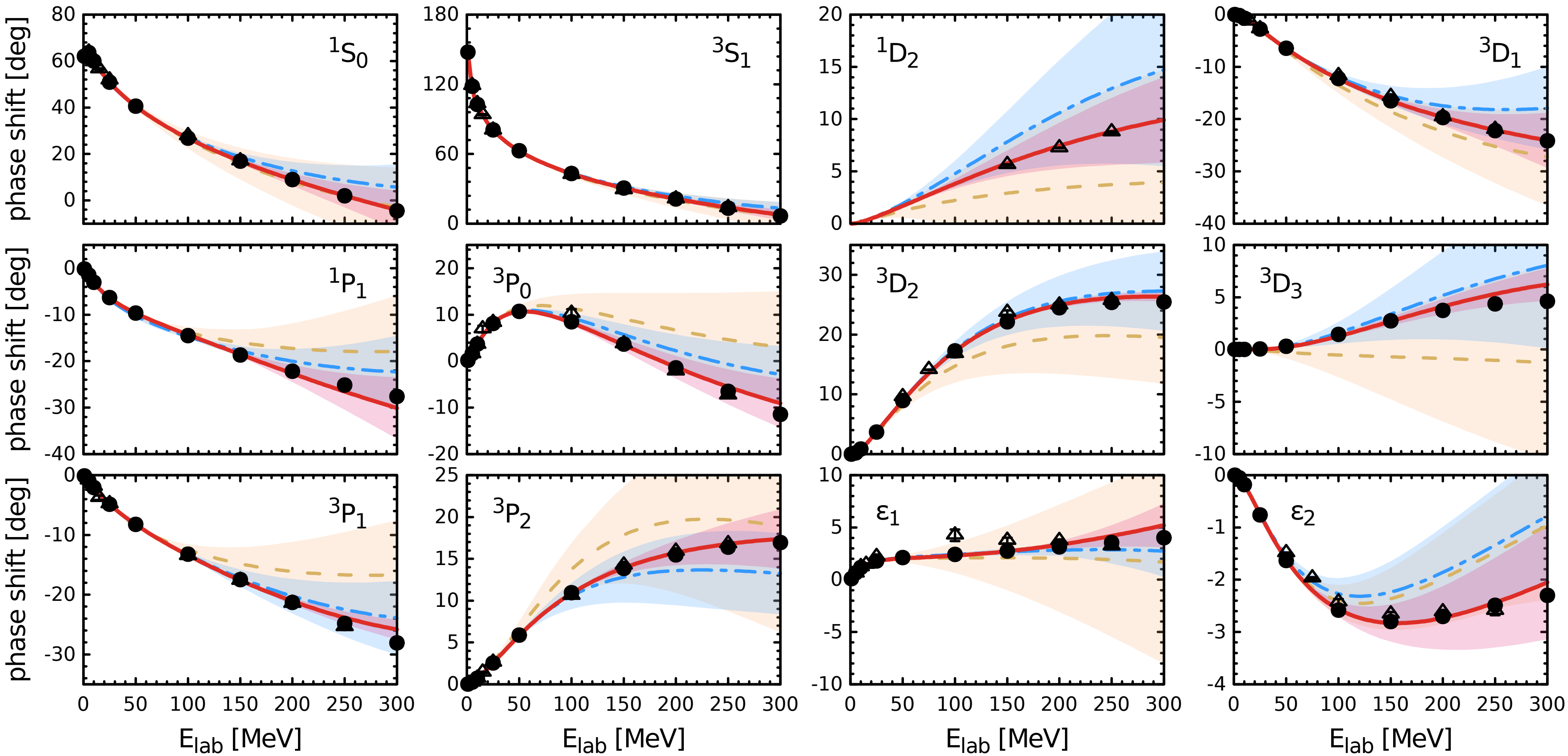


The description of phase shifts at N³LO is nearly perfect. **But what is the expected theoretical uncertainty?**

Uncertainty in phase shifts (preliminary)



Uncertainty in phase shifts (preliminary)



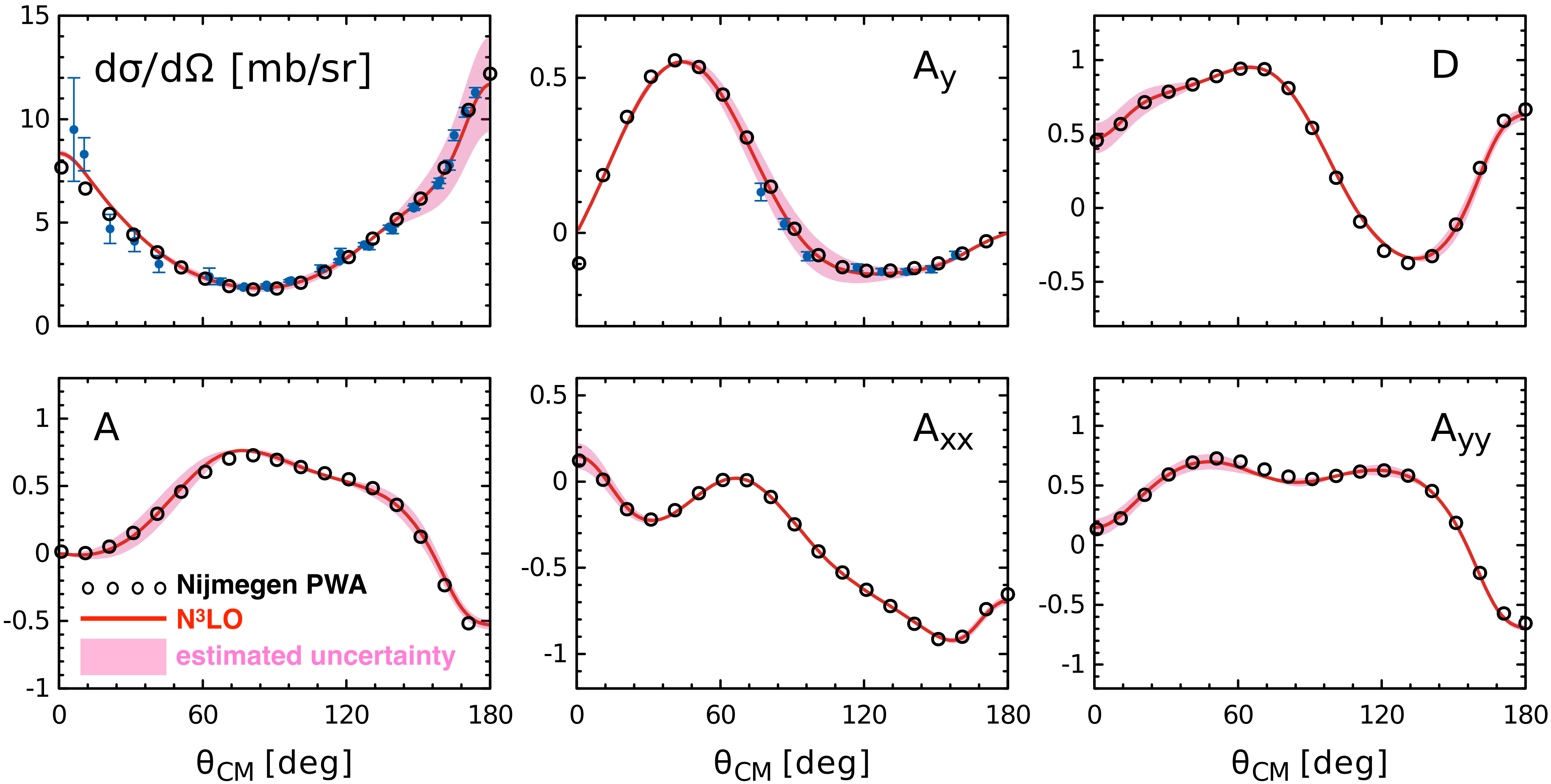
For an observable $X(p)$, we assign: $\Delta X^{(n)}(p) = \mathrm{Abs}\Big(X^{(n)}(p) - X^{(n-1)}(p)\Big) \times \mathrm{Max}\left(\frac{p}{\Lambda}, \frac{M_\pi}{\Lambda}\right)$

to estimate the size of corrections beyond the order Q^n.

(if higher-order corrections are available, we use them as a lower bound)

Nucleon-nucleon scattering (preliminary)

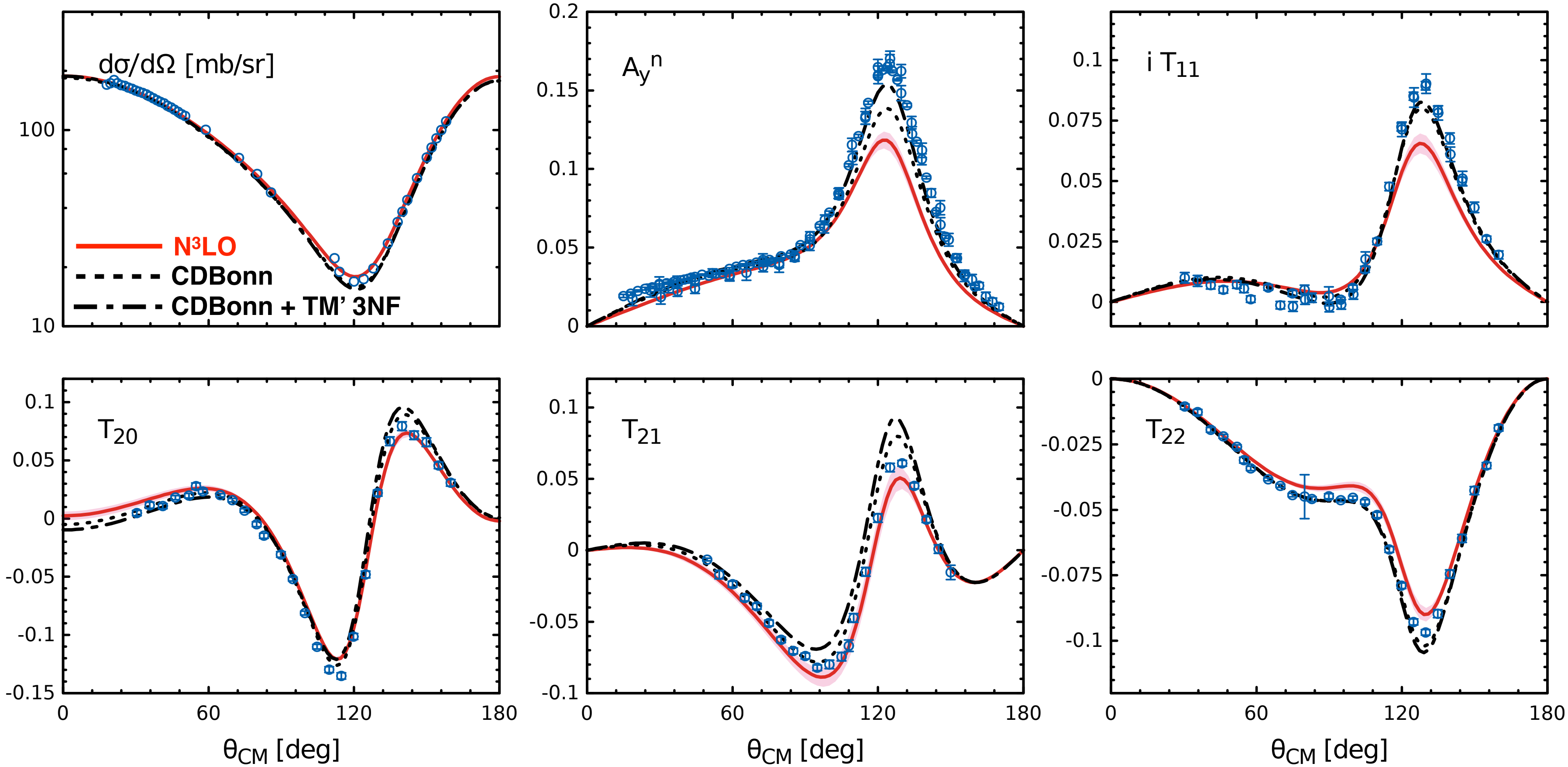
Selected neutron-proton scattering observables at E_{lab} = 200 MeV
(preliminary results with $i_{improved}$-chiral N³LO potential)



At N³LO, 2N observables are accurately described up to at least E_{lab} ~ 200 MeV

Elastic Nd scattering with N^3LO 2NF

Selected neutron-deuteron scattering observables at E_{lab} = 10 MeV
(preliminary results with $i_{mproved}$-chiral N^3LO potential)

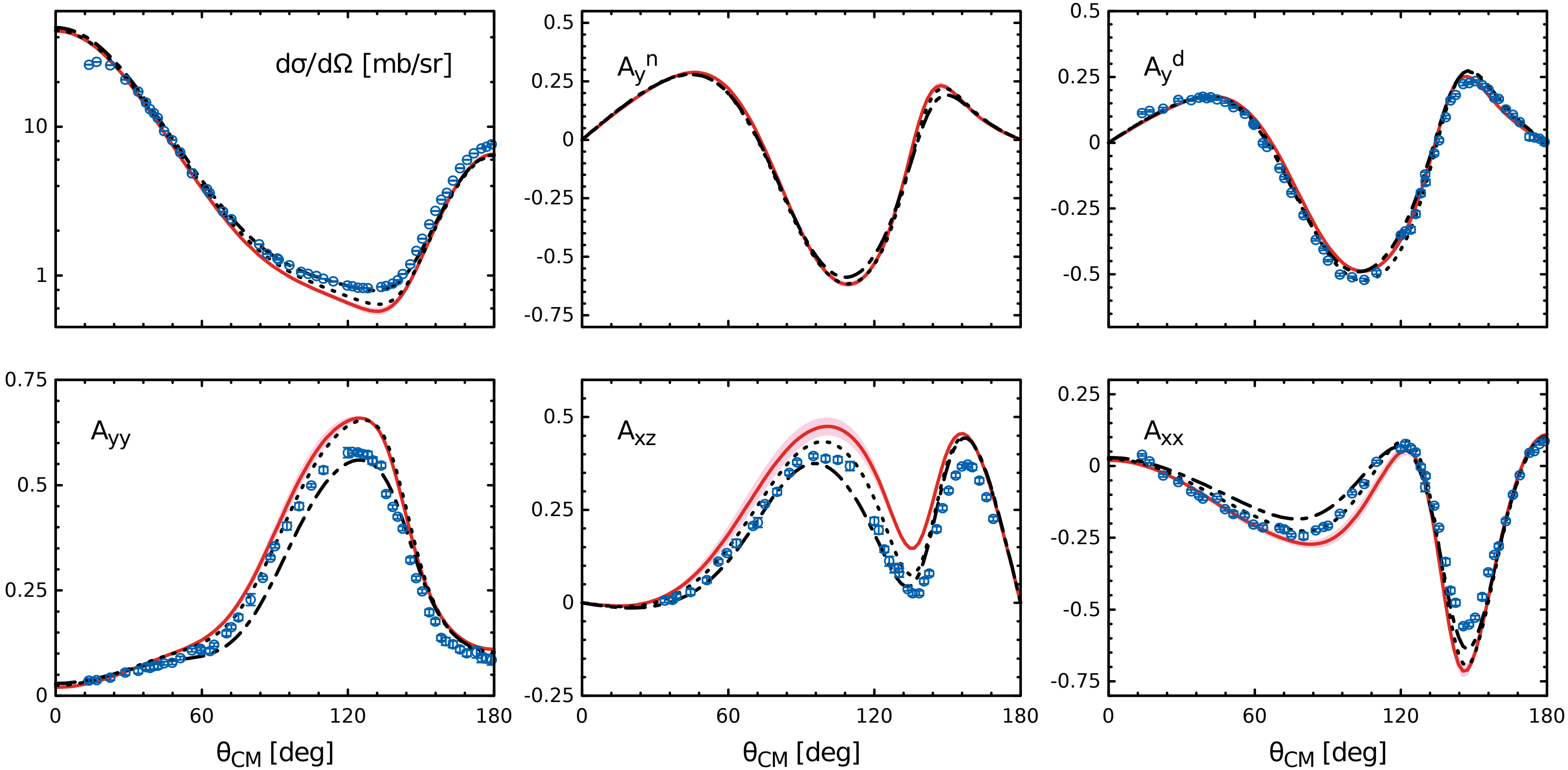


Clear room for 3NF effects in A_y and iT_{11}

Most of the data are Coulomb-corrected pd data

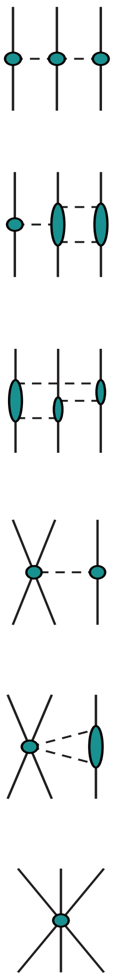
Elastic Nd scattering with N^{3}LO 2NF

Selected neutron-deuteron scattering observables at E_{lab} = 70 MeV
(preliminary results with $i_{improved}$-chiral N^{3}LO potential)

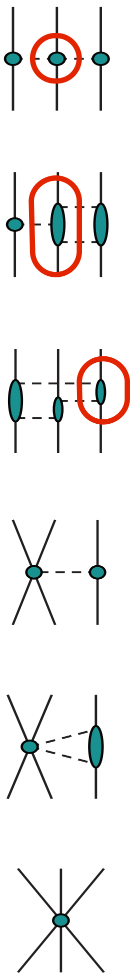


Clear room for 3NF effects in the cross section and A_{ij}

Chiral expansion of the 3NF (Δ-less EFT)

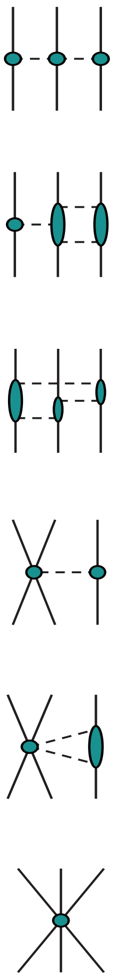


Chiral expansion of the 3NF (Δ-less EFT)



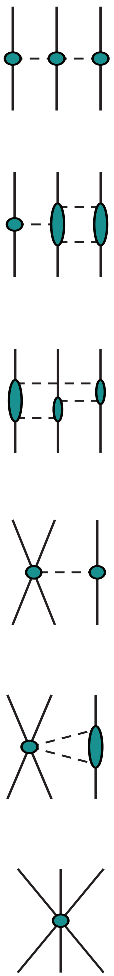
3NF structure functions at large distance are
model-independent and parameter-free predictions
based on χ symmetry of QCD + exp. information on πN system

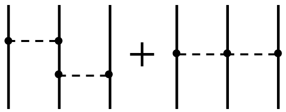
Chiral expansion of the 3NF (Δ-less EFT)



Chiral expansion of the 3NF (Δ-less EFT)

NLO (Q^2)





Weinberg ’91, van Kolck ’94

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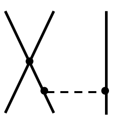

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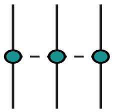
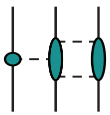
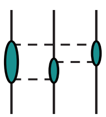
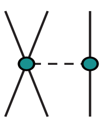
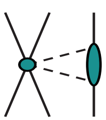
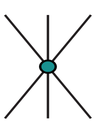
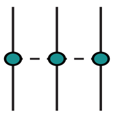
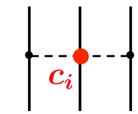
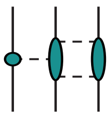
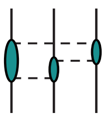
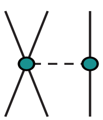
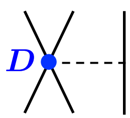
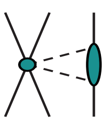
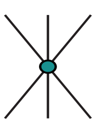
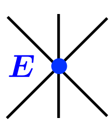
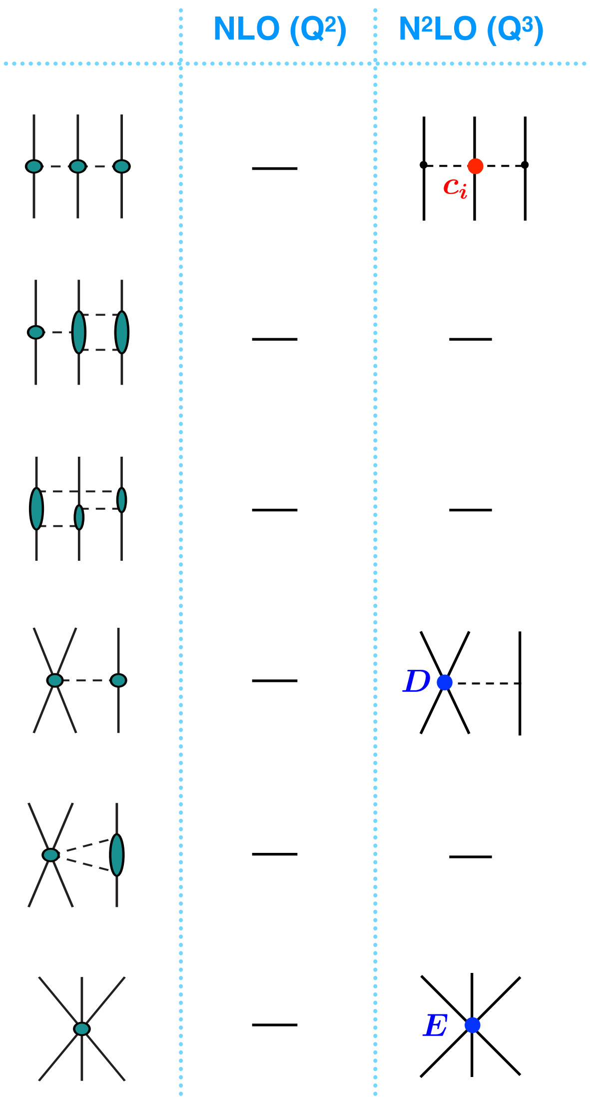
Chiral expansion of the 3NF (Δ-less EFT)

	NLO (Q^2)
	—
	—
	—
	—
	—
	—

Chiral expansion of the 3NF (Δ-less EFT)

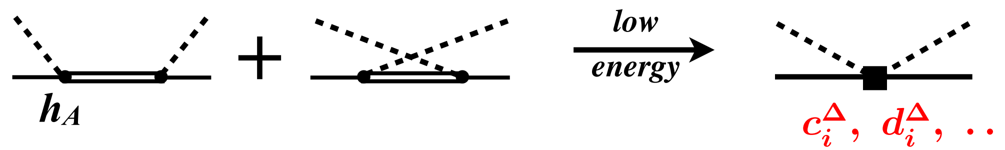
	NLO (Q^2)	N²LO (Q^3)
	—	
	—	—
	—	—
	—	
	—	—
	—	

Chiral expansion of the 3NF (Δ-less EFT)



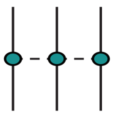
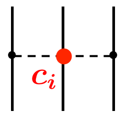
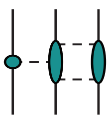
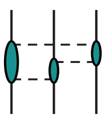
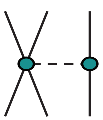
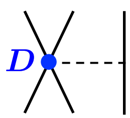
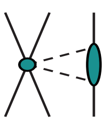
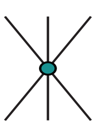
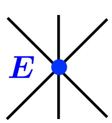
Notice: c_i receive large Δ(1232) contributions

Bernard, Kaiser, Meißner '97

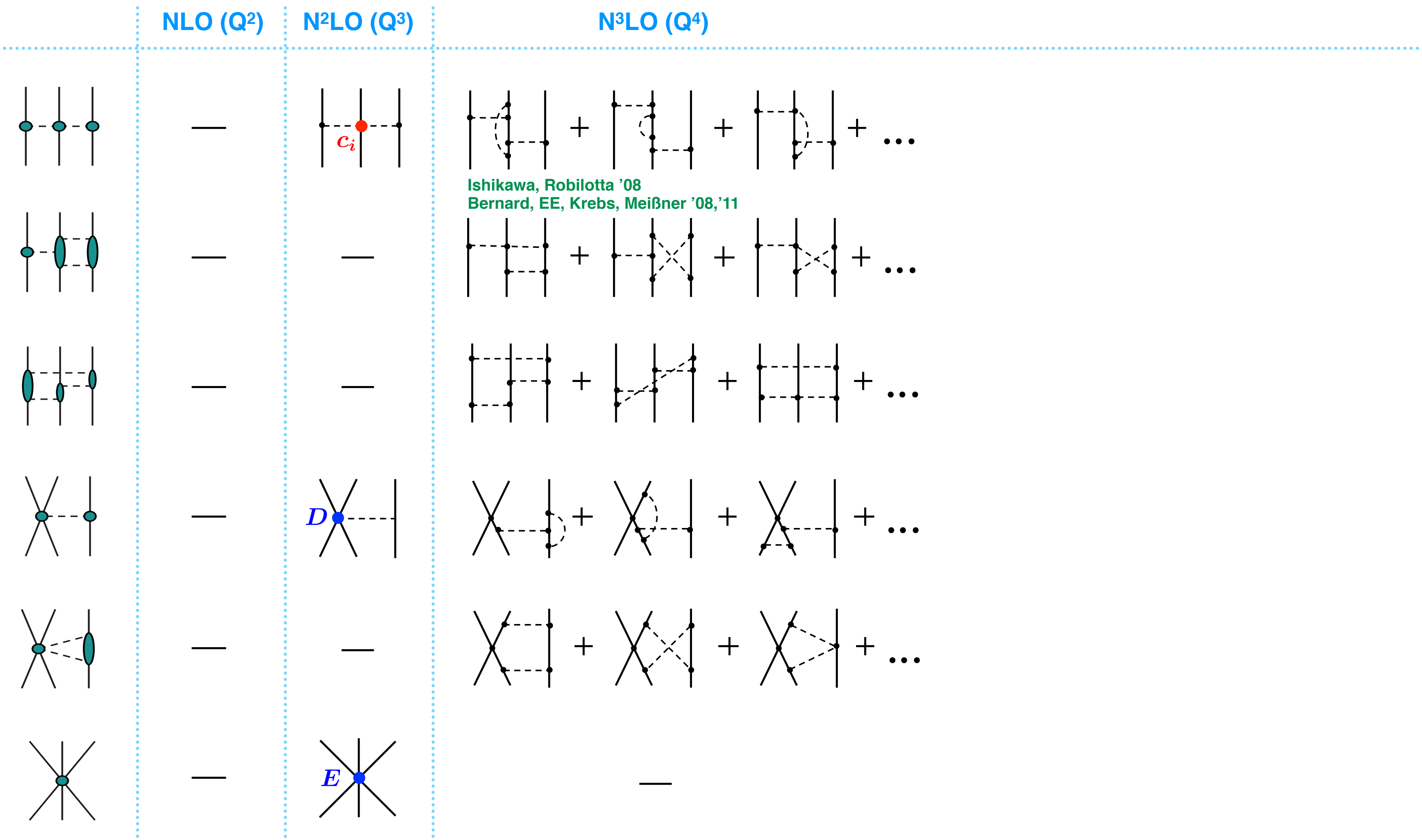


$$c_2^\Delta = -c_3^\Delta = 2c_4^\Delta = \frac{4h_A^2}{9(m_\Delta - m_N)} \simeq 2.8\,\mathrm{GeV}^{-1}$$

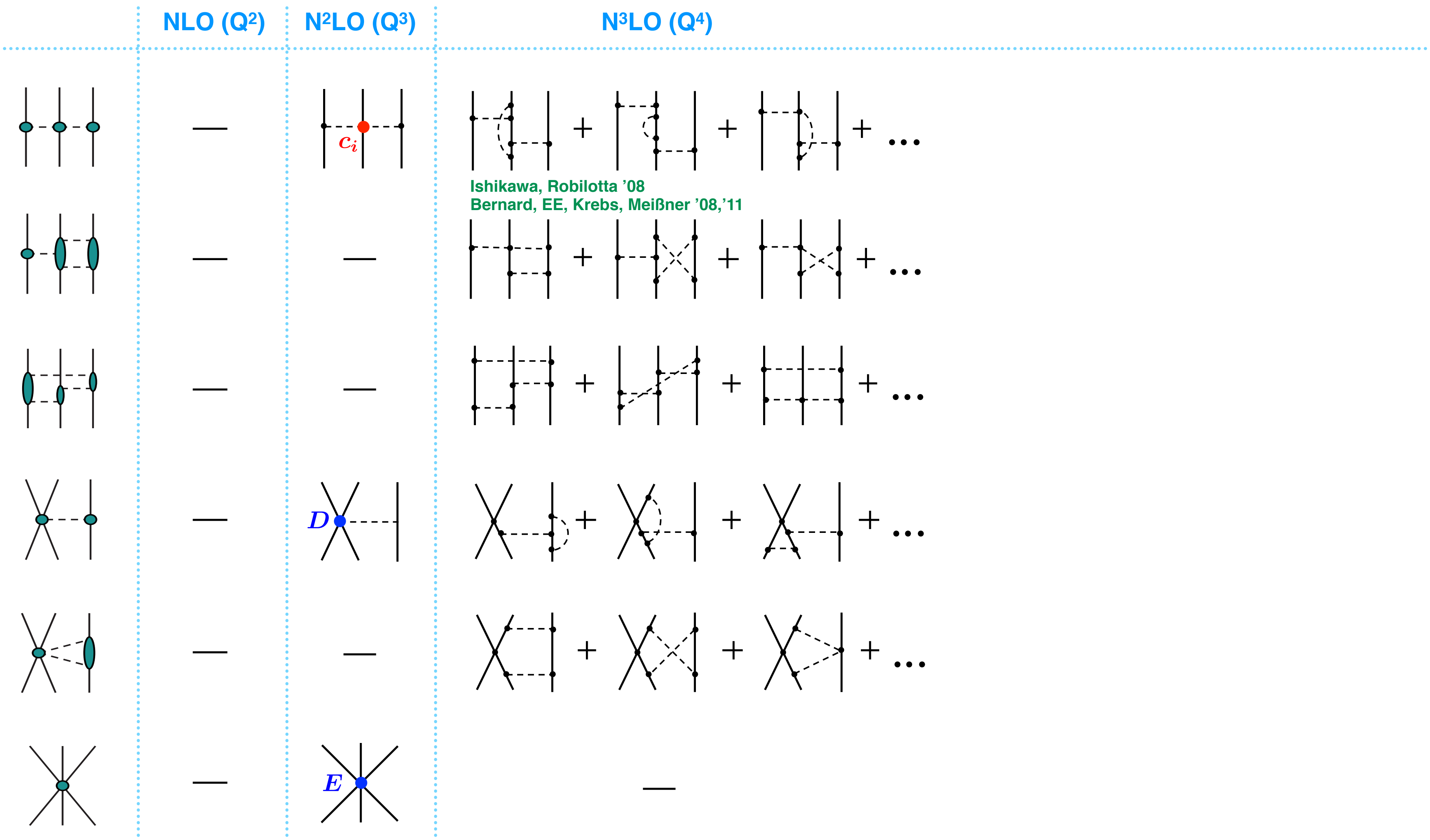
Chiral expansion of the 3NF (Δ-less EFT)

	NLO (Q^2)	N^2LO (Q^3)
	—	
	—	—
	—	—
	—	
	—	—
	—	

Chiral expansion of the 3NF (Δ-less EFT)

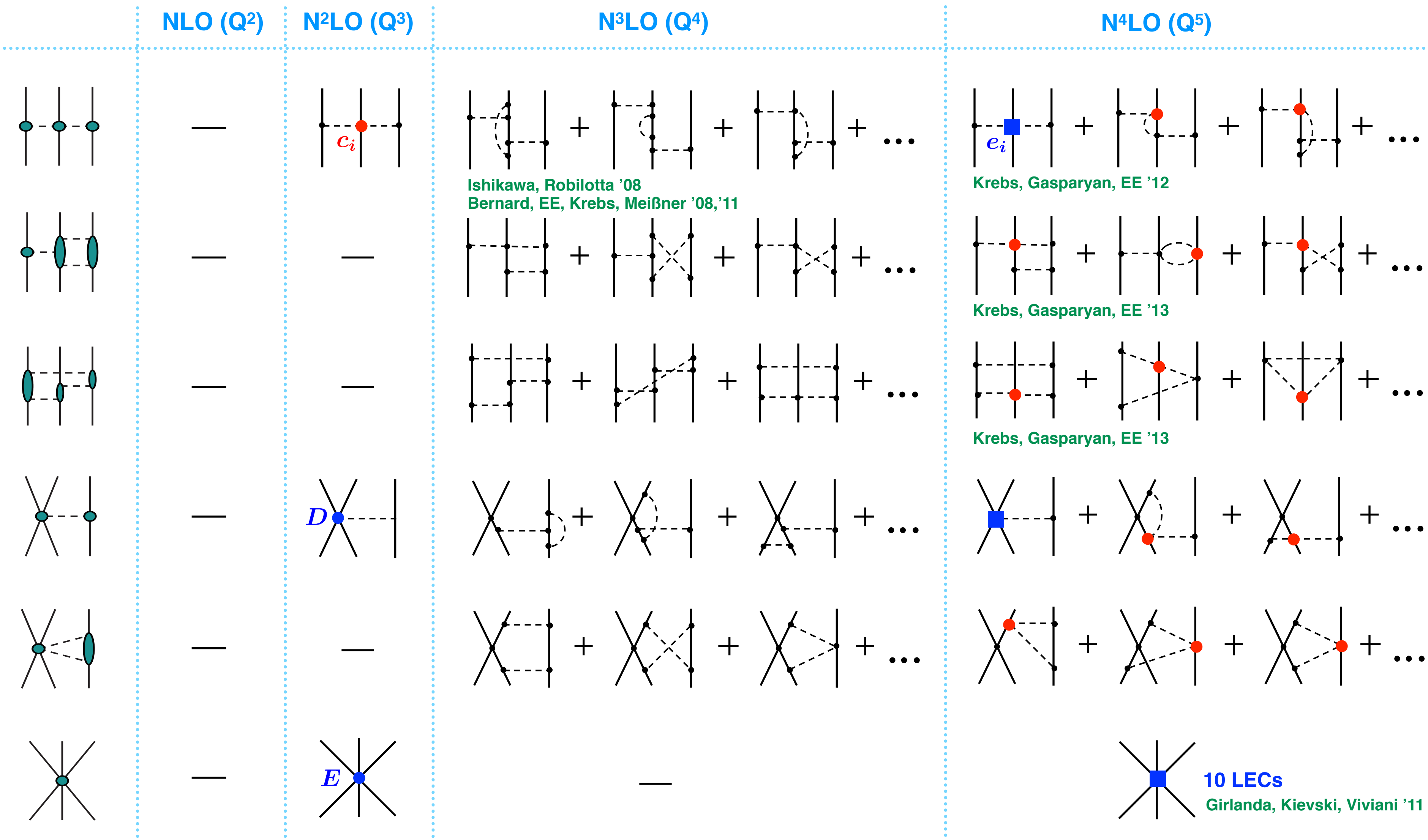


Chiral expansion of the 3NF (Δ-less EFT)



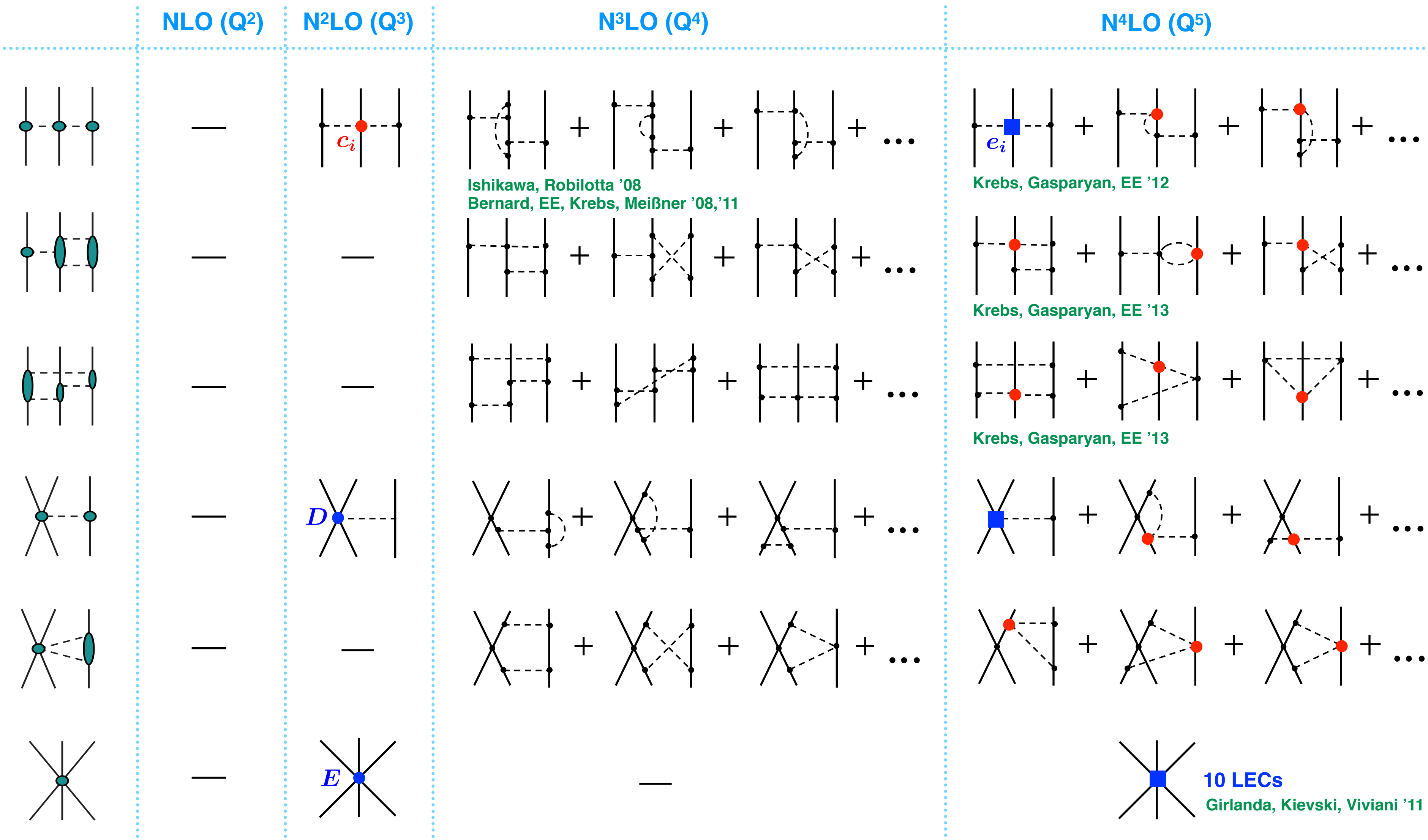
- parameter-free!
- Δ-effects are missing (except for the 2π 3NF) → expect large N⁴LO corrections

Chiral expansion of the 3NF (Δ-less EFT)



- parameter-free!
- Δ-effects are missing (except for the 2π 3NF) → expect large N^{4}LO corrections

Chiral expansion of the 3NF (Δ-less EFT)



- parameter-free!
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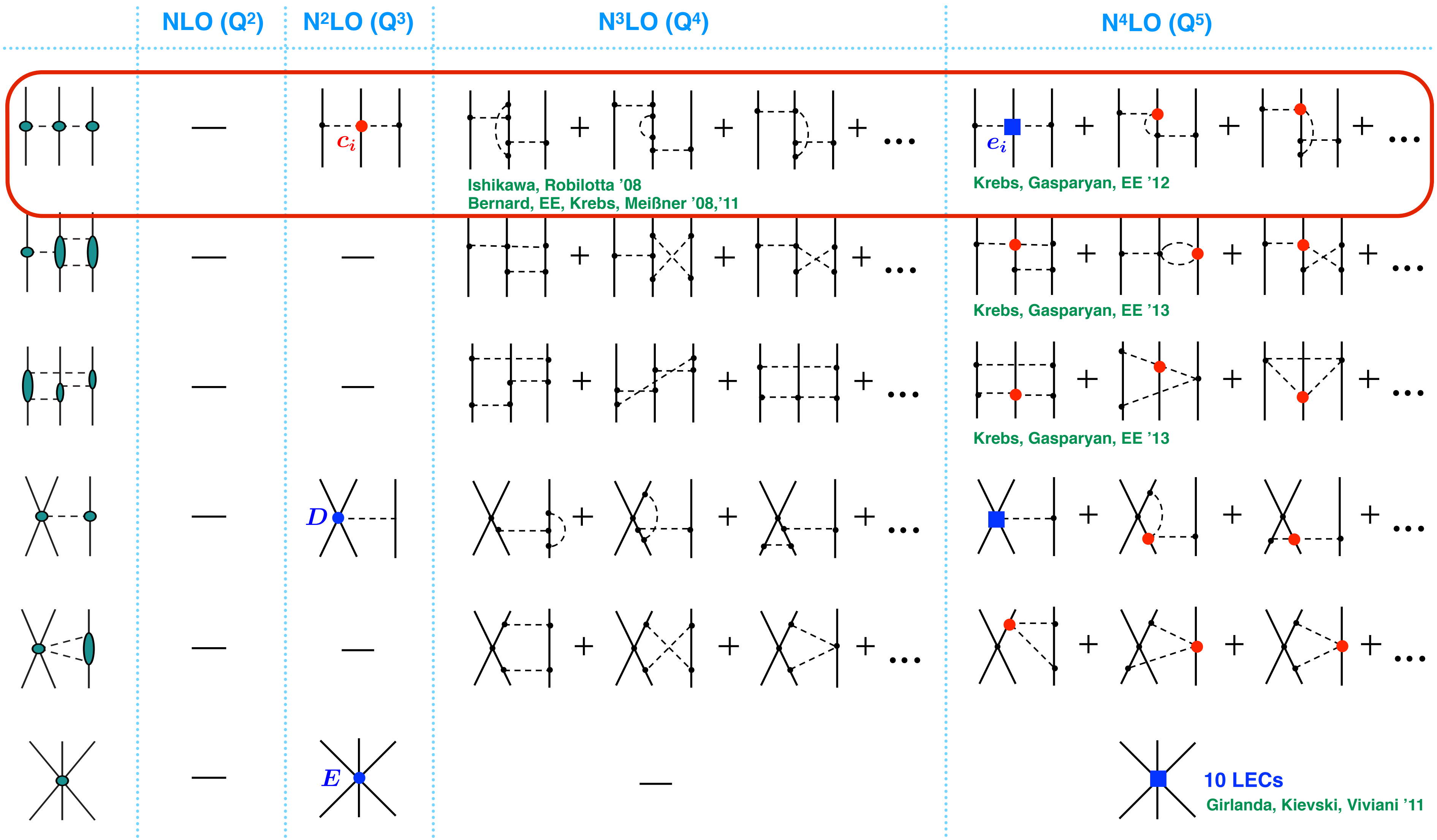
- long range parameter-free (after determination of LECs in πN)
- converged?? (graphs ~ c_i^2, c_i^3…)

Chiral expansion of the 3NF (Δ-less EFT)



- parameter-free!
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- long range parameter-free (after determination of LECs in πN)
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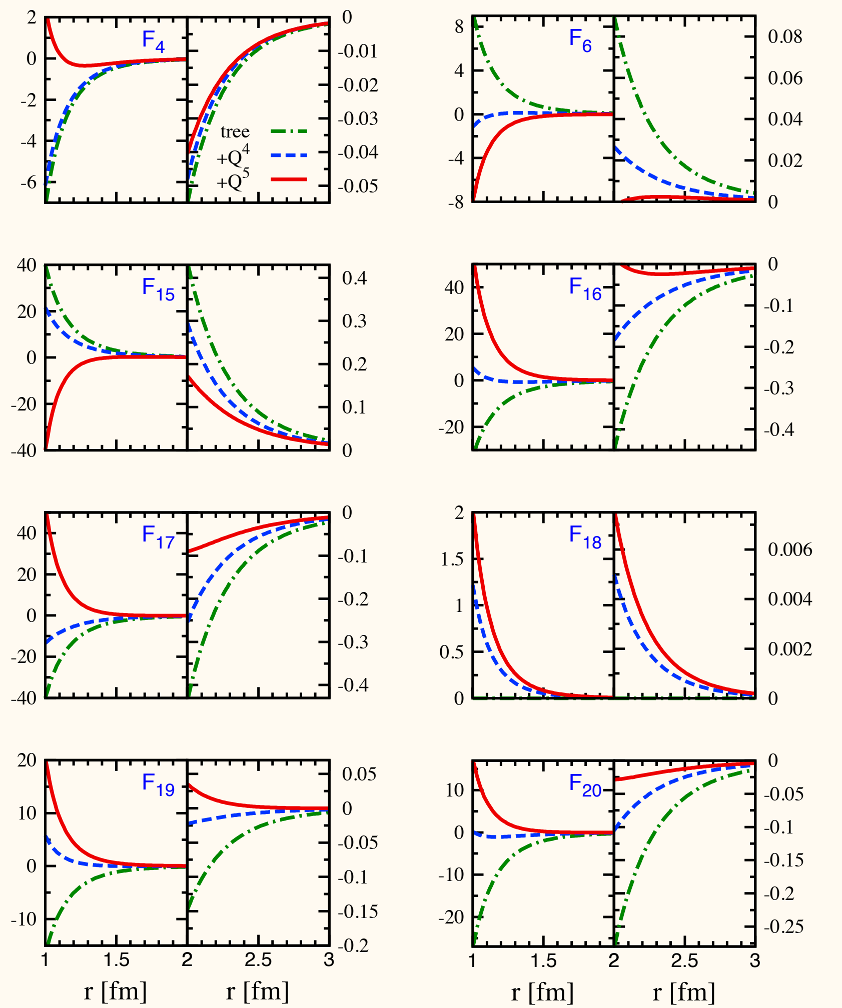
2π 3NF: Δ-full vs Δ-less (preliminary)

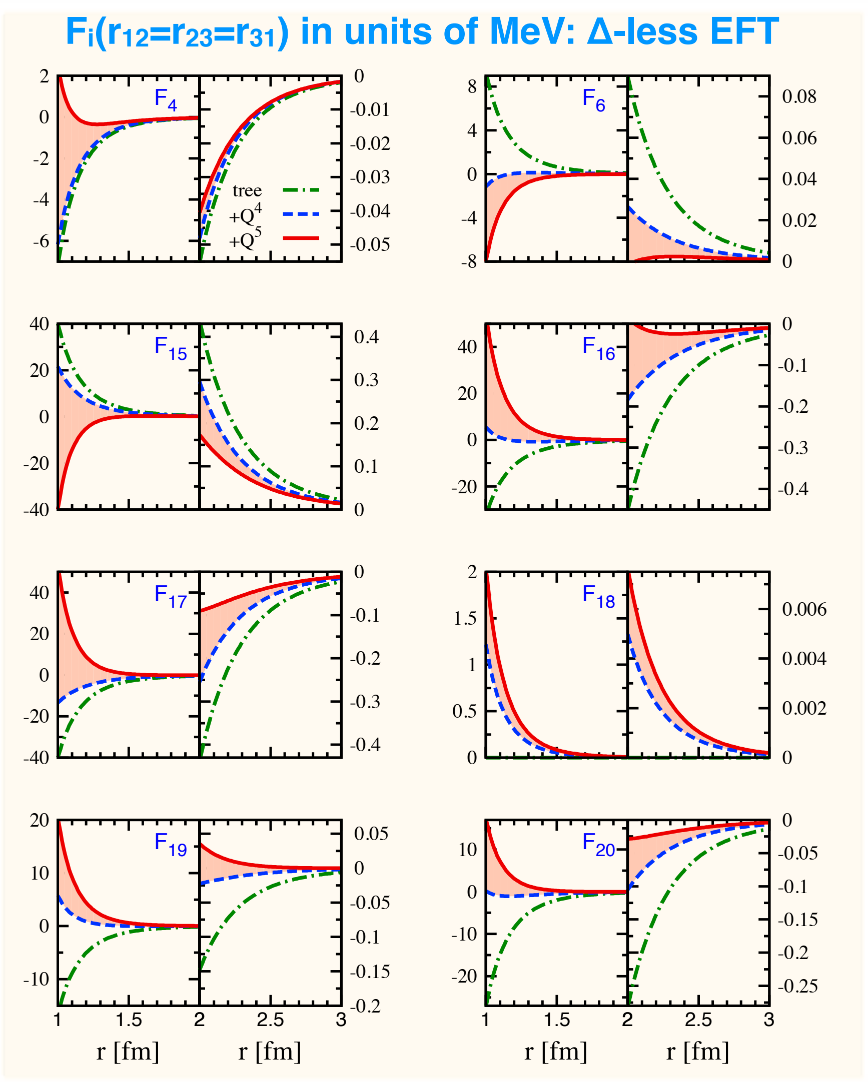
Krebs, Gasparyan, EE, to appear

$F_i(r_{12}=r_{23}=r_{31})$ in units of MeV: Δ-less EFT



2π 3NF: Δ-full vs Δ-less (preliminary)

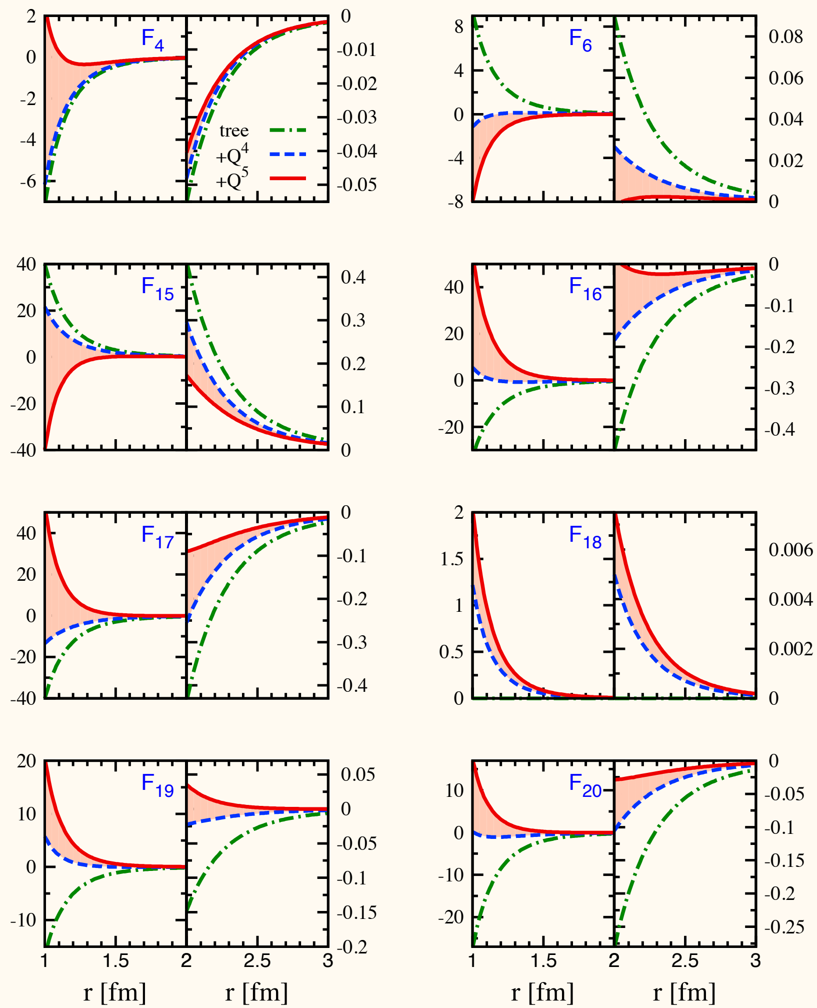
Krebs, Gasparyan, EE, to appear



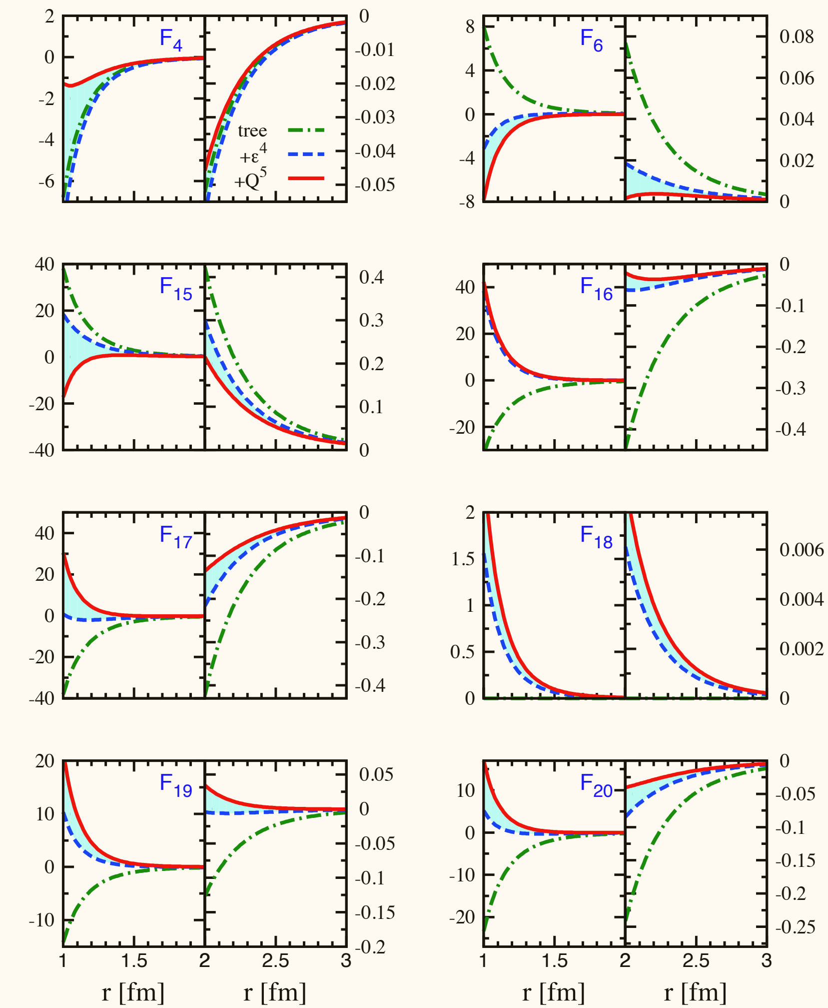
2π 3NF: Δ-full vs Δ-less (preliminary)

Krebs, Gasparyan, EE, to appear

$F_i(r_{12}=r_{23}=r_{31})$ in units of MeV: Δ-less EFT



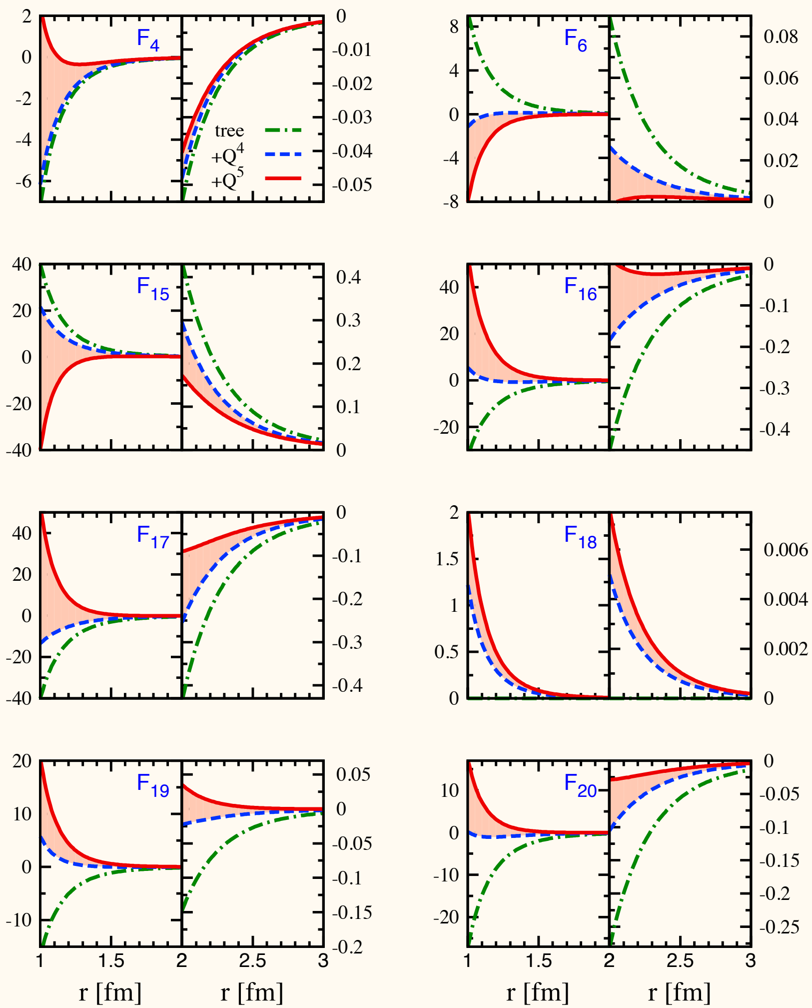
$F_i(r_{12}=r_{23}=r_{31})$ in units of MeV: Δ-full EFT



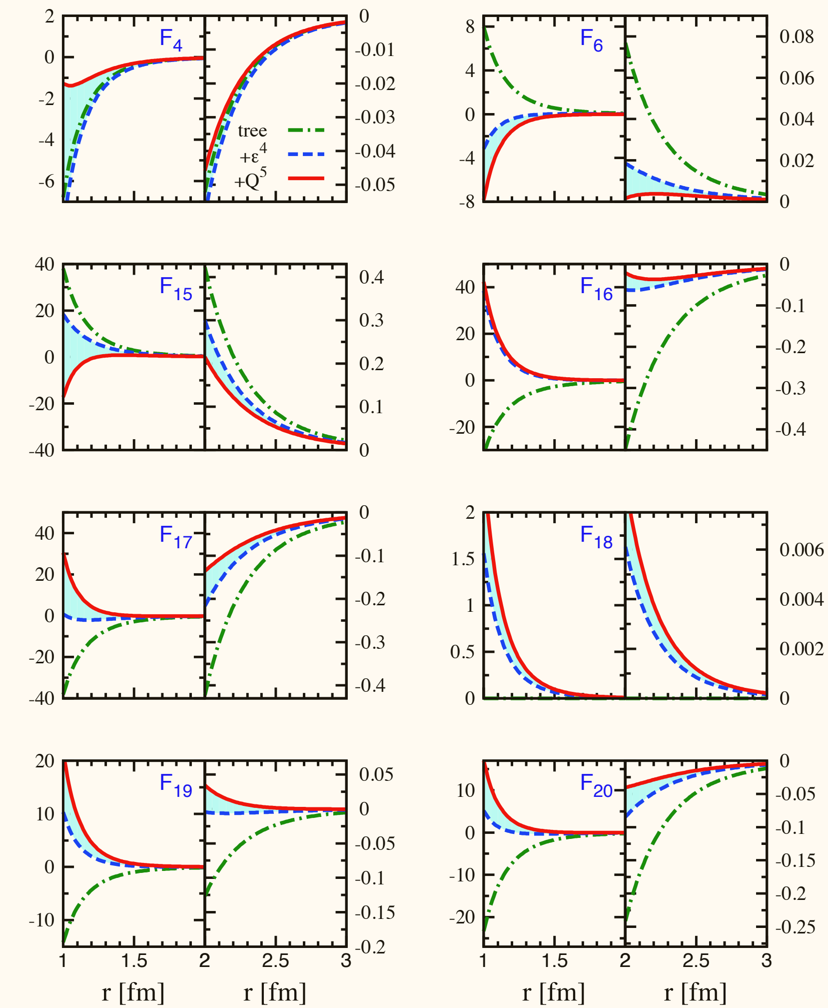
2π 3NF: Δ-full vs Δ-less (preliminary)

Krebs, Gasparyan, EE, to appear

$F_i(r_{12}=r_{23}=r_{31})$ in units of MeV: Δ-less EFT



$F_i(r_{12}=r_{23}=r_{31})$ in units of MeV: Δ-full EFT



- Δ-full and Δ-less EFT predictions agree well with each other
- Δ-full approach shows clearly a superior convergence
- remarkably, the final 2π 3NF turns out to be rather weak at large distances…

Summary

Chiral two-nucleon force

- A new generation of chiral NN potentials is underway
  - regulator maintains analytic structure of the ampl. ⟶ better performance at high E
  - no need for additional spectral function regularization
  - LECs from πN without fine tuning

Error estimations

- Instead of a cutoff variation, we suggest to use a standard ChPT procedure by estimating the size of the (missing) higher-order corrections.

Three-nucleon force

- Clear evidence for missing 3NF effects in elastic Nd scattering at E~70-150 MeV
- 3NF beyond N2LO:
  - Worked out completely at N^3LO and, to a large extent, at N^4LO. The N^4LO contributions are driven by the Δ and appear to be large (as expected).
  - Alternatively, EFT with explicit Δ DOF. For 2π 3NF both approaches yield similar results (with the Δ-full approach converging faster). Other topologies in progress.
- Good progress on the PWD of the 3NF.