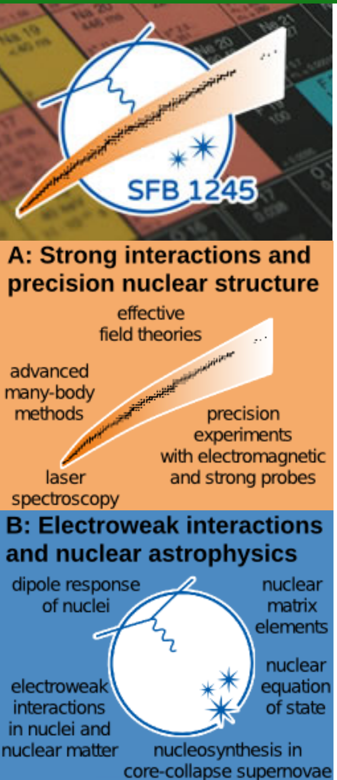
RUB

Evgeny Epelbaum, RUB

SFB 1245 Workshop, Darmstadt, November 21-23, 2016

State-of-the-art nuclear forces & currents from chiral effective field theory



Precision theory for nuclear structure and electroweak reactions requires:

- Ab-initio methods for solving the nuclear A-body problem
- **Accurate and precise nuclear forces**
- Reliable approach to **uncertainty quantification**
- Knowledge of the corresponding **charge/current operators**

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

Chiral Effective Field Theory

Chiral Perturbation Theory: expansion of the scattering amplitude in powers of Q,

Weinberg, Gasser, Leutwyler, Meißner, ...

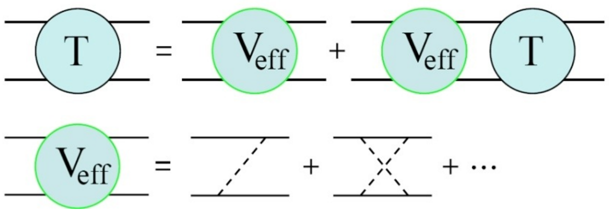
$$Q = \frac{\text{momenta of external particles or } M_\pi \sim 140 \text{ MeV}}{\text{breakdown scale } \Lambda_b}$$

Write down L_{eff} [π, N, …],
identify relevant diagrams at a given order,
do Feynman calculus,
fit LECs to exp data,
make predictions…

Chiral EFT for nuclear systems: expansion for nuclear forces + resummation (Schrödinger eq.)

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

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

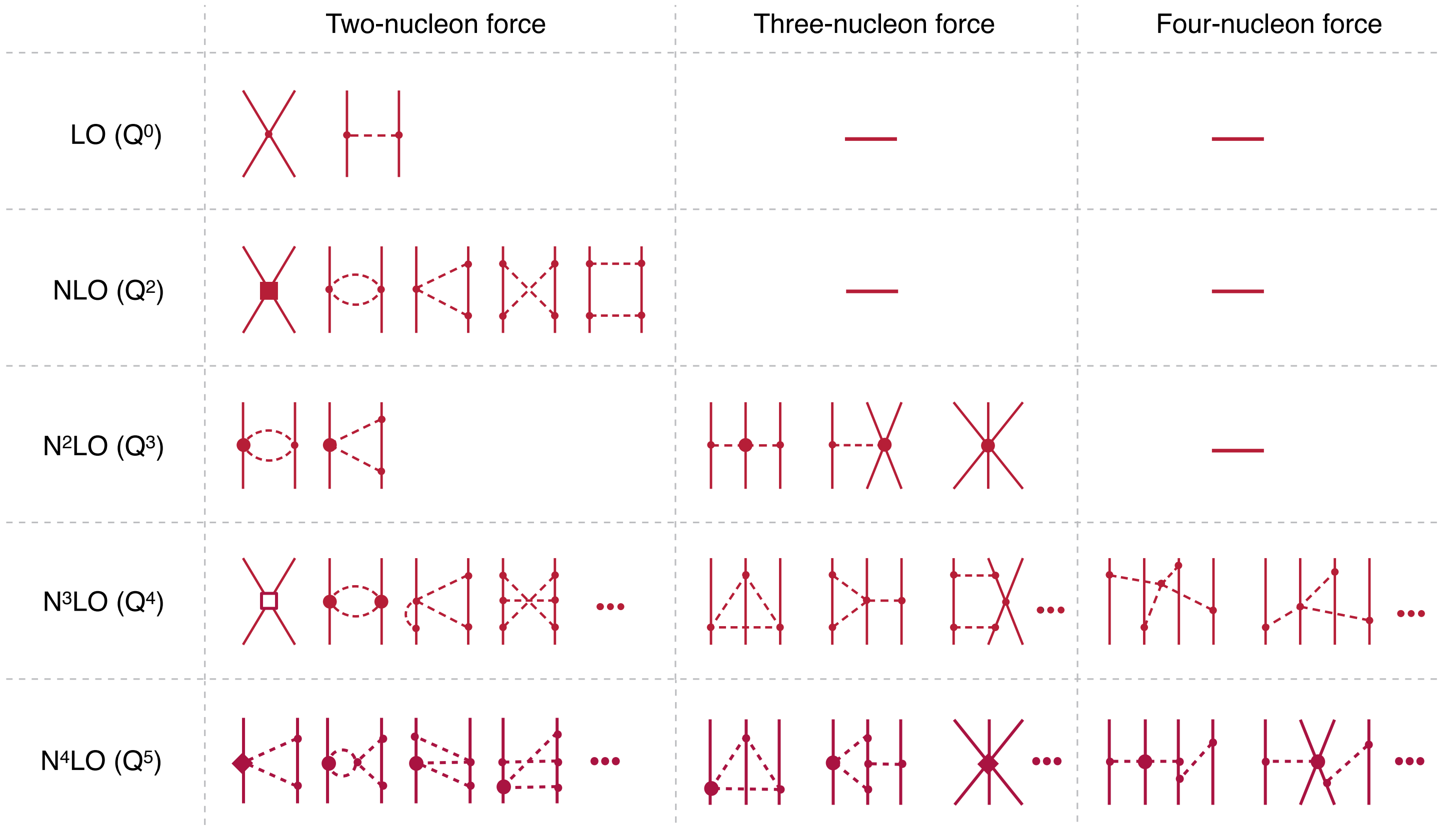


- systematically improvable
- unified approach for $\pi\pi$, πN, NN
- consistent many-body forces and currents
- error estimations

Notice: nonperturbative treatment of chiral nuclear forces in the Schrödinger eq. requires the introduction of a finite cutoff **[Alternatively, use semi-relativistic approach, EE, Gegelia, et al. ’12…’15]**

See also: ***Nuclear Effective Field Theories — the crux of the matter***, **open discussion by Mike Birse and EE at the KITP program „Frontiers in Nuclear Physics“, August 22 - November 4, 2016, available at http://online.kitp.ucsb.edu/online/nuclear16/**

Chiral expansion of the nuclear forces



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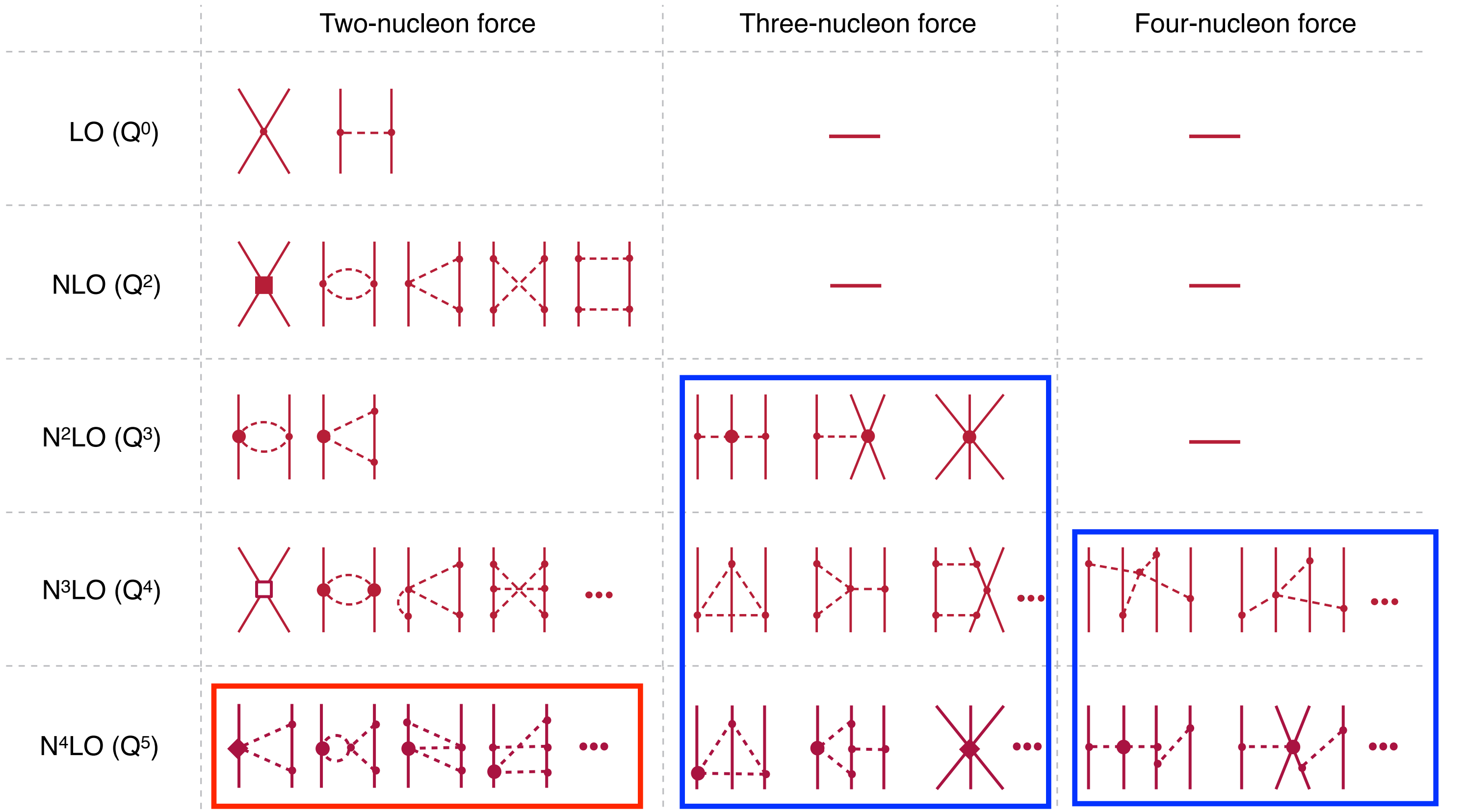

have been worked out

Entem, Kaiser, Machleidt, Nosyk, PRC 91 (2015) 014002
EE, Krebs, Meißner, PRL 115 (2015) 122301

focus of intense research efforts…

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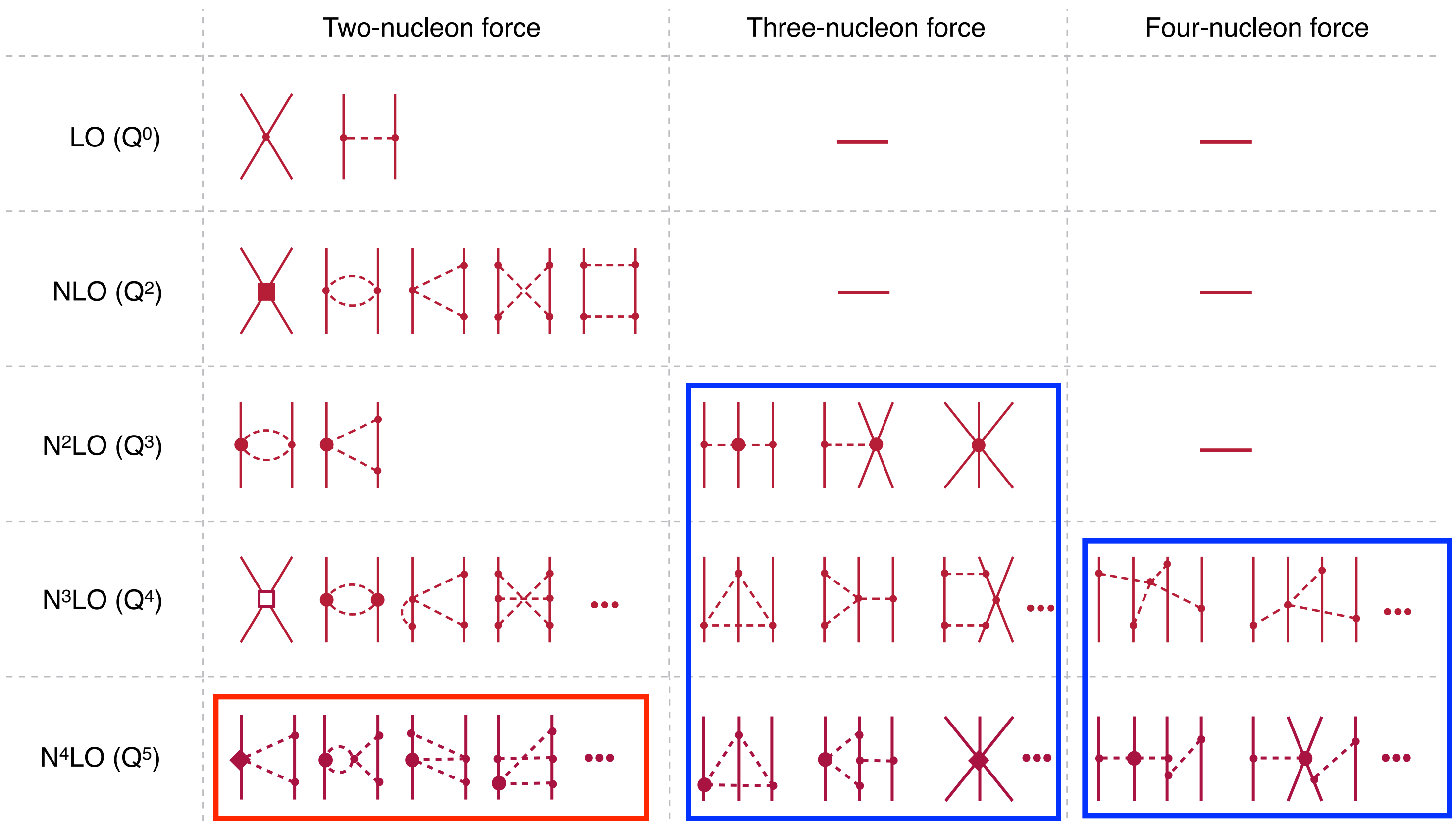

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focus of intense research efforts…

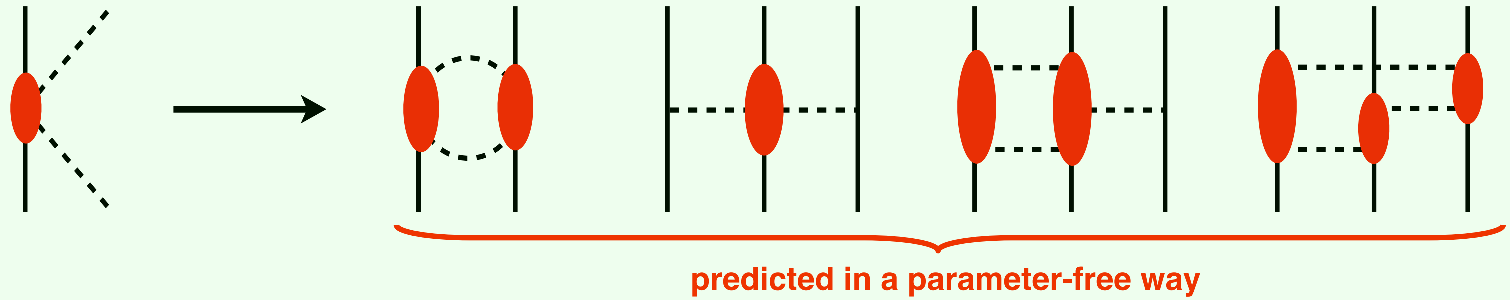
Why go to fifth order (N⁴LO) in the chiral expansion?

— no additional parameters in the NN force (except for 1 IB term) ➙ testing the theory

— there is evidence that χ-expansion for the 3NF is not yet converged at Q^4

The long-range part of the nuclear forces

Long-range nuclear forces are completely determined by the
chiral symmetry of QCD + experimental information on πN scattering



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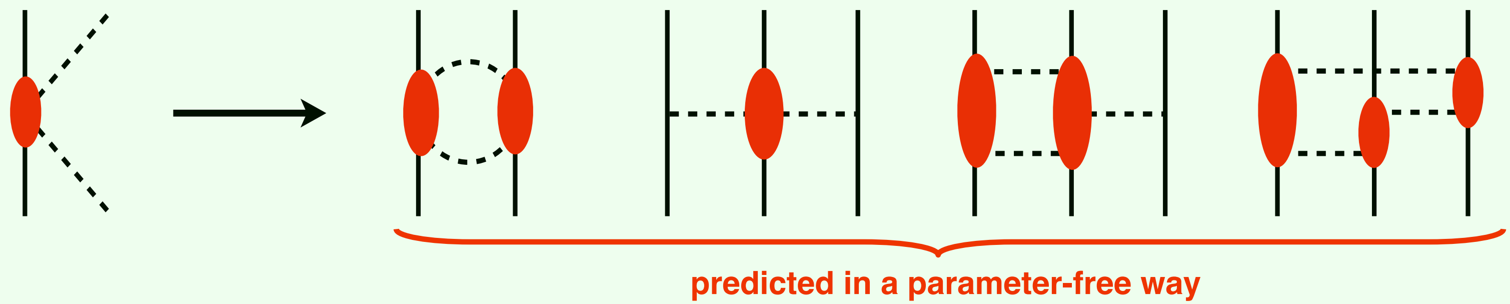
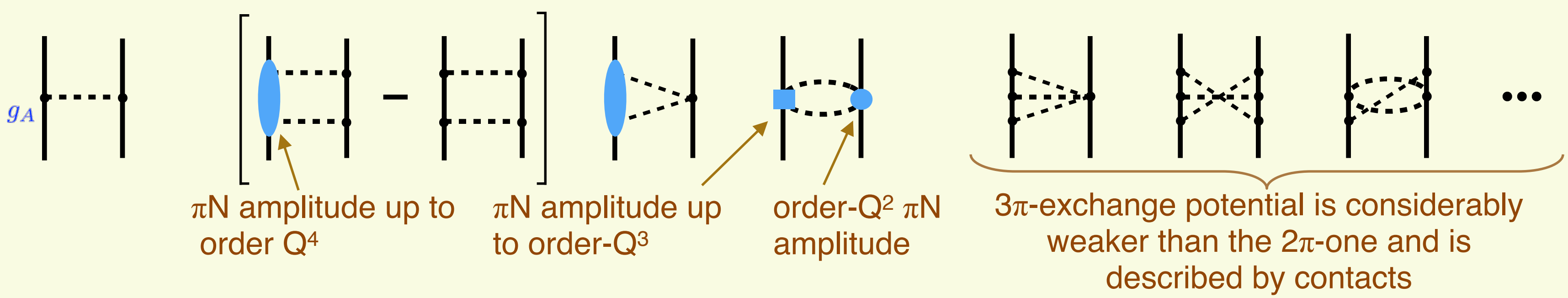


The long-range NN force up to N⁴LO [Q⁵]

Ordonez et al.; Kaiser; EE, Krebs, Meißner; Entem, Machleidt; …



The TPE potential can be derived by taking the phase-space integral of the πN amplitudes computed in ChPT (Lorentz-transformed to the proper kinematics…) Kaiser '00

Determination of the low-energy constants

All relevant LECs (in GeV^{-n}) extracted from πN scattering Krebs, Gasparyan, EE '12

	c_1	c_2	c_3	c_4	$\bar{d}_1 + \bar{d}_2$	$\bar{d}_3$	$\bar{d}_5$	$\bar{d}_{14} - \bar{d}_{15}$	$\bar{e}_{14}$	$\bar{e}_{17}$
$[Q^4]_{\rm HB,\,NN}$, GW PWA	−1.13	3.69	−5.51	3.71	5.57	−5.35	0.02	−10.26	1.75	−0.58
$[Q^4]_{\rm HB,\,NN}$, KH PWA	−0.75	3.49	−4.77	3.34	6.21	−6.83	0.78	−12.02	1.52	−0.37
$[Q^4]_{\rm covariant}$, data	−0.82	3.56	−4.59	3.44	5.43	−4.58	−0.40	−9.94	−0.63	−0.90

Related recent work (all calculations lead to similar values of the LECs):

— determination of the LECs from πN data Wendt et al. '14; Siemens et al. '16

— LECs from Roy-Steiner-eq. analysis of πN-scattering Hoferichter et al. '15; Yao et al. '16; Siemens et al. '16

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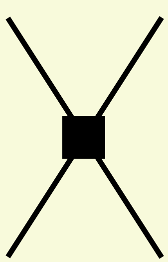
The short-range part of the nuclear force (contact interactions)

Here, the organizational principle for contact terms is assumed to be according to NDA (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

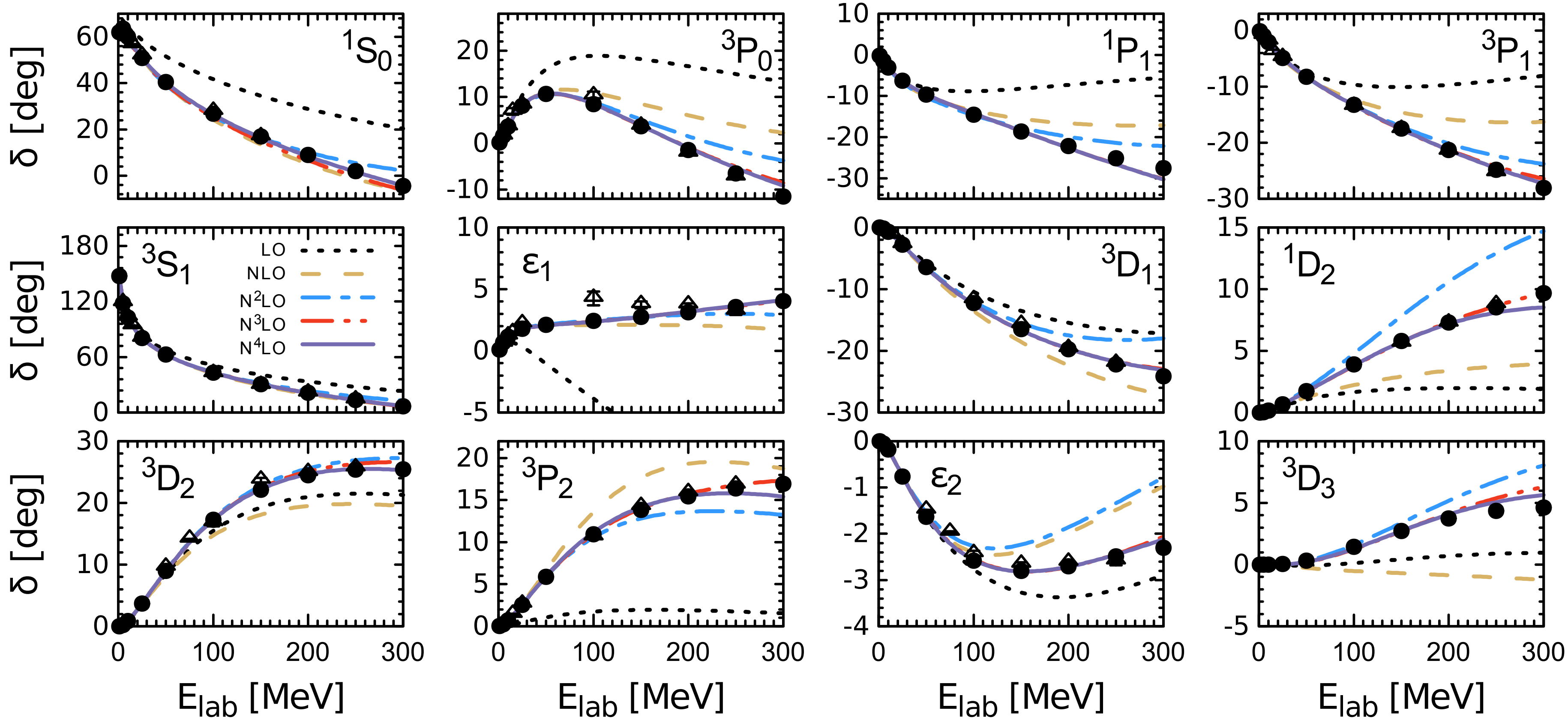
N^{3}LO [Q^4]: + 15 operators (S-, P-, D-waves and ε_1, ε_2)

N^{4}LO [Q^5]: no new isospin-conserving operators

NN phase shifts order by order

EE, Krebs, Meißner, EPJ A51 (2015) 5, 53; PRL 115 (2015) 122301

Convergence of the chiral expansion for np phase shifts [using R = 0.9 fm]



- Use a local r-space regulator for V_π, R = 0.8…1.2 fm, & (nonlocal) Gaussian regulator for V_{cont}
- NN contact interactions are determined from fits to Nijmegen PWA below 200 MeV

Uncertainty quantification

A simple algorithm for estimating **uncertainty from the truncation of the chiral expansion:**

EE, Krebs, Meißner, EPJA 51 (2015) 53

For any observable: $\boldsymbol{X^{(i)}(p) = X^{(0)} + \underbrace{\Delta X^{(2)}}_{\sim Q^2 X^{(0)}} + \ldots + \underbrace{\Delta X^{(i)}}_{\sim Q^i X^{(0)}}}$ with $Q = \max(p/\Lambda_b, M_\pi/\Lambda_b)$

estimated from the error plots Λ_b ~ 600 MeV

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

$$\boldsymbol{\delta X^{(0)} = Q^2 |X^{(0)}|,}$$

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

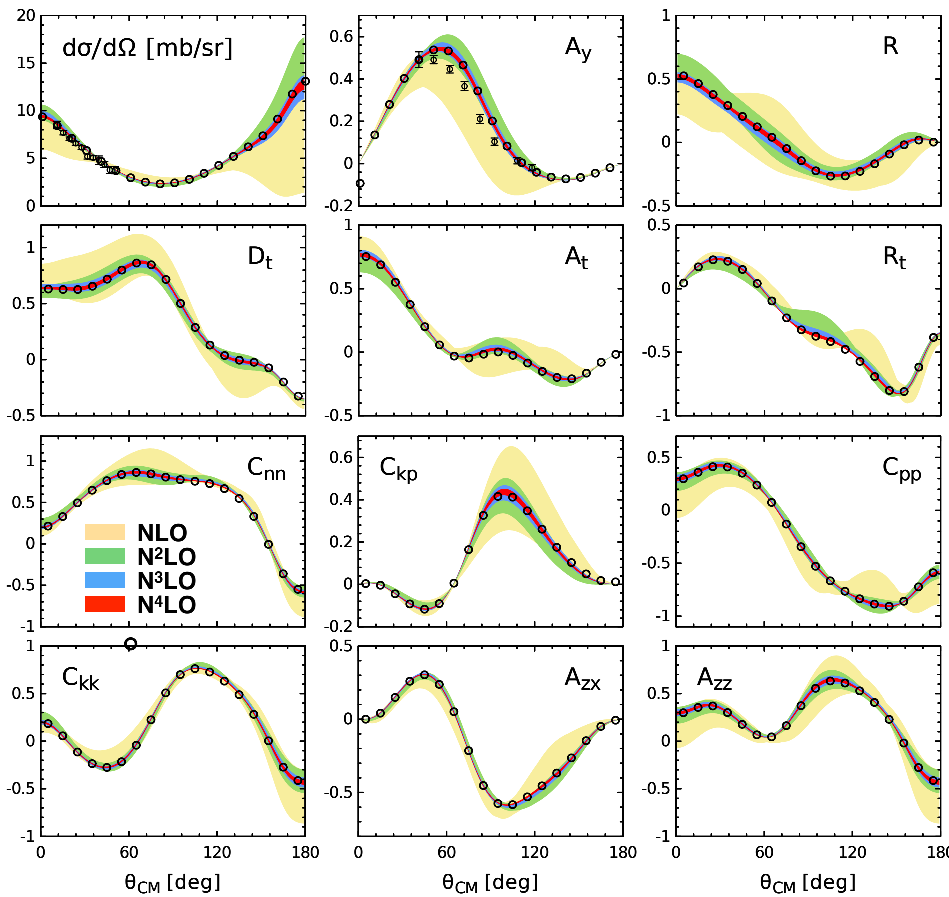
subject to the additional constraint

$$\boldsymbol{\delta X^{(i)} \ge \max_{j,k} \left(|X^{(j \ge i)} - X^{(k \ge i)}| \right).}$$

- **no reliance on the cutoff variation** (not reliable)
- **easily applicable to any observable** (scattering, bound states, 3N, …)
- of course, **no reliance on exp. data**
- **for σ_{tot}, errors found to be consistent with 68% degree-of-belief intervals**

  Furnstahl et al., PRC 92 (2015) 024005

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



Optimization using NN scattering data

Patrick Reinert et al., in preparation

To avoid unnecessary model dependence, it is desirable to use NN scattering data for fixing contacts interactions instead of relying on the Nijmegen PWA

Optimization using NN scattering data

- Used self-consistent data base by the Granada group [Perez et al.'13]
- Optimization at N^3LO and N^4LO is performed with POUNDerS
- Theoretical errors are incorporated (recursively) ⟶ no need to specify the energy range
- In most cases, the results do not change significantly and stay within the estimated uncertainties…

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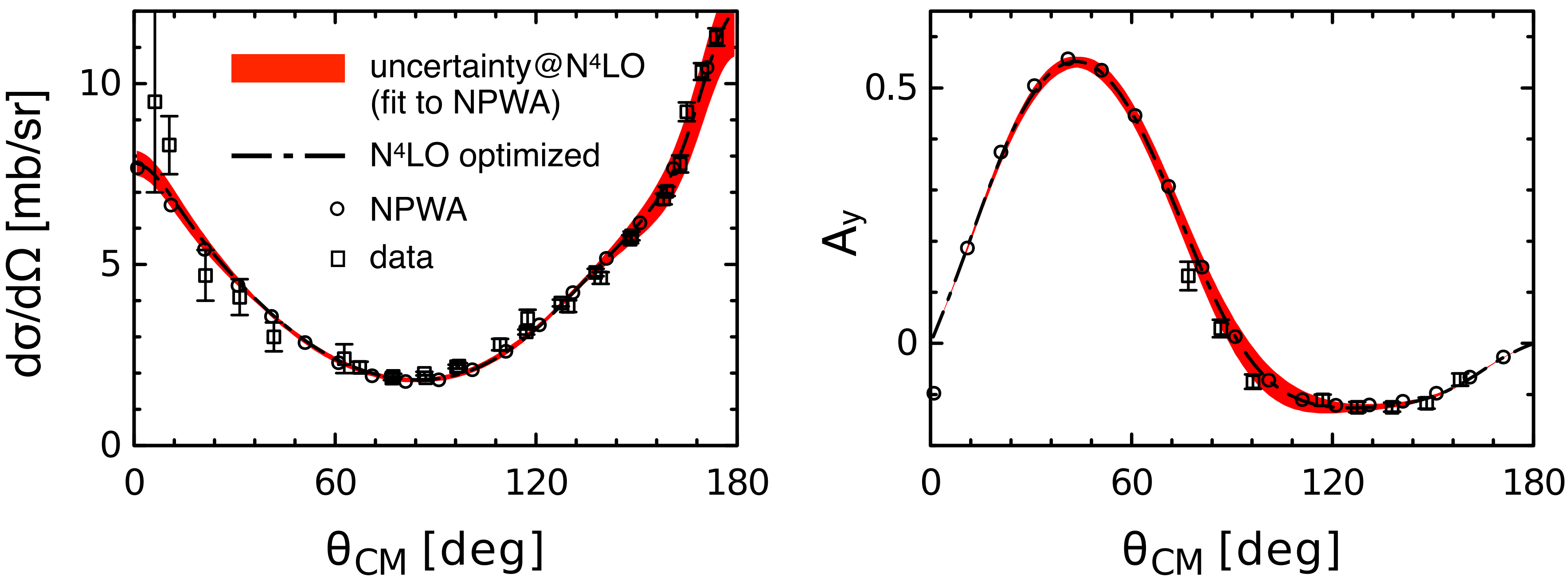
Impact of optimization on the np diff. cross section and A_y at 200 MeV [for R=0.9fm]



χ^2 per datum for the description of the np and pp scattering data [R = 0.9 fm]

Energy bin	LO	NLO	N^2LO	N^3LO	N^4LO
neutron-proton data					
0 − 100 MeV	**130.11**	**3.79**	**1.46**	**1.08**	**1.08**
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proton-proton data					
0 − 100 MeV	**2046.58**	**33.68**	**6.67**	**0.86**	**0.84**
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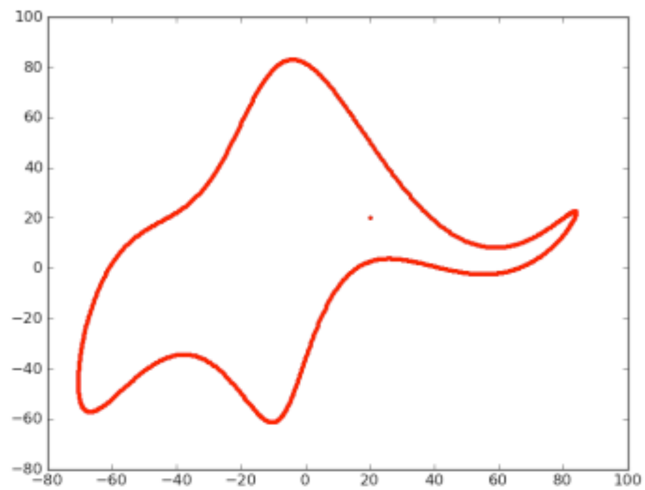

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neutron-proton data: NLO → N^2LO: no new LECs; N^3LO → N^4LO: +1 LEC ($^1S_0$)

proton-proton data: N^3LO → N^4LO: no new LECs

Clear evidence of the (parameter-free) chiral 2π-exchange!

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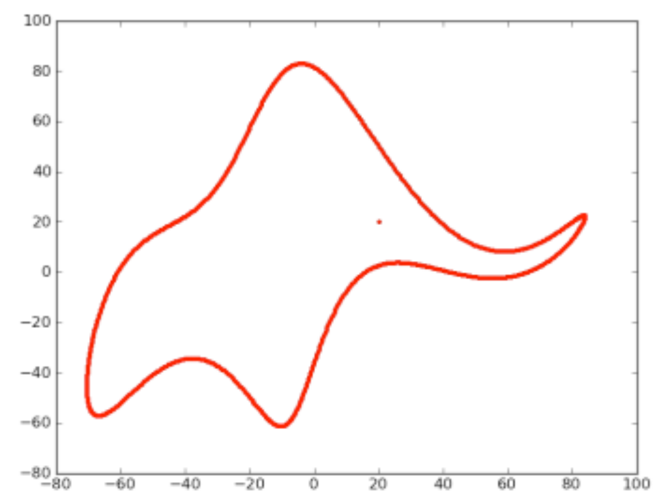

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What is the origin of the still somewhat large χ^2 for pp data @ N^4LO?

χ^2 per datum for the description of the np and pp scattering data [R = 0.9 fm]

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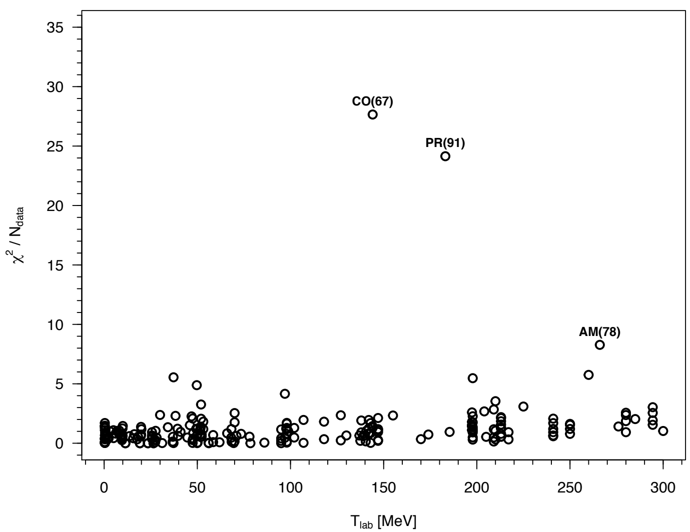

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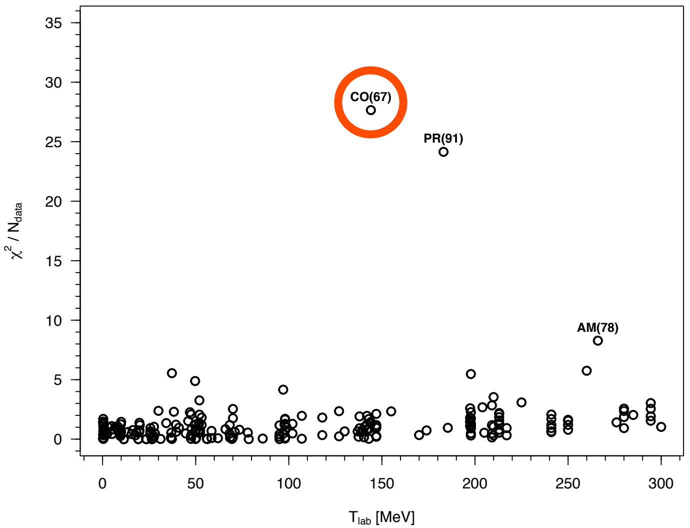

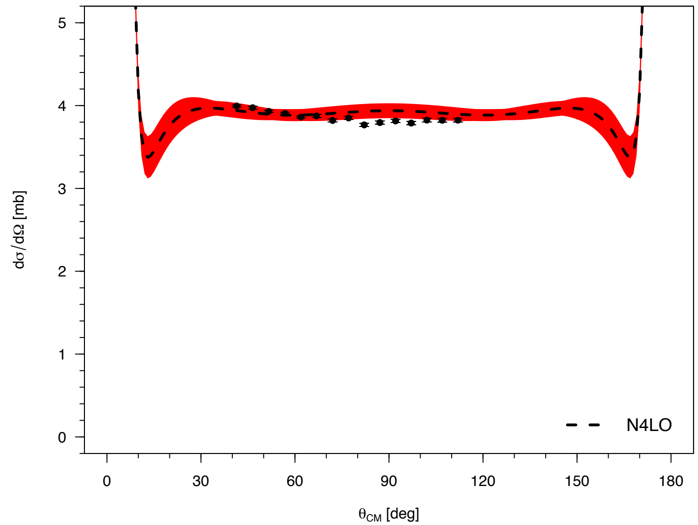

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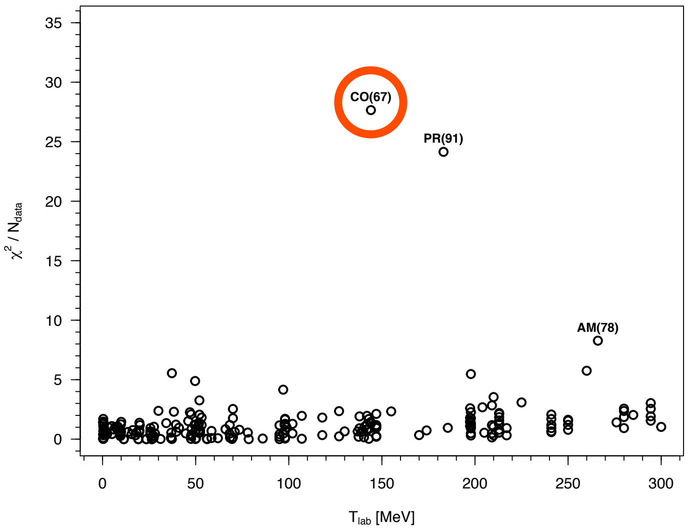

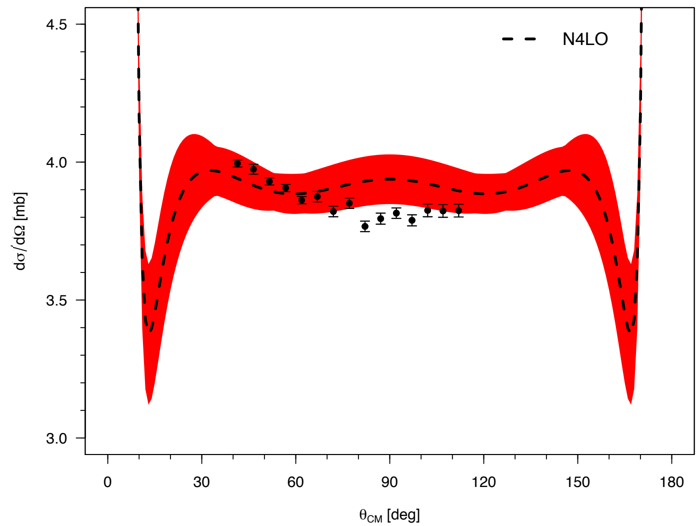

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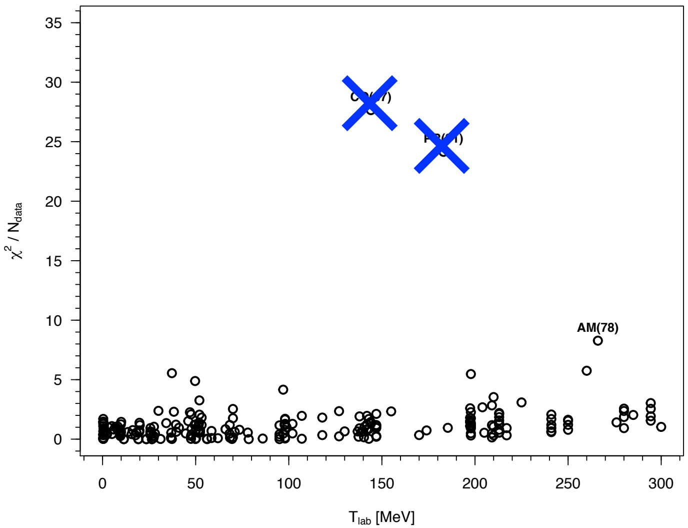

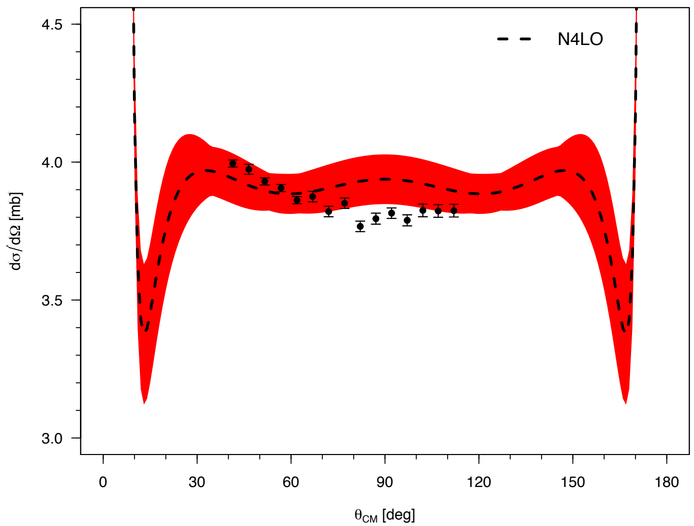

- much lower χ^2 per datum without the outliers

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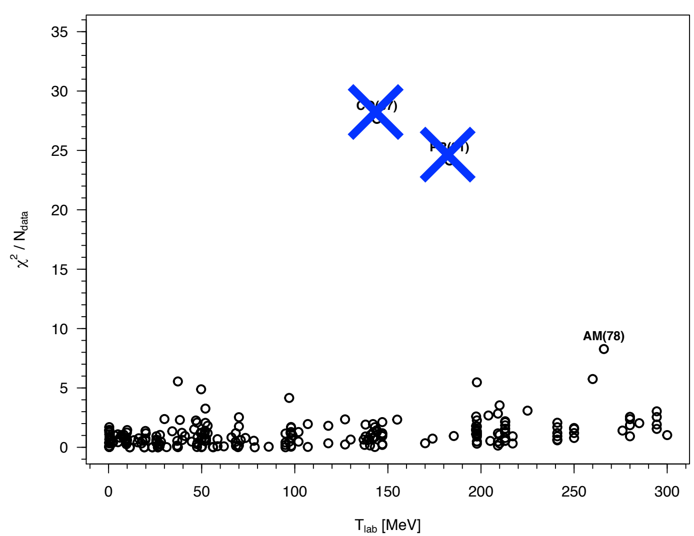
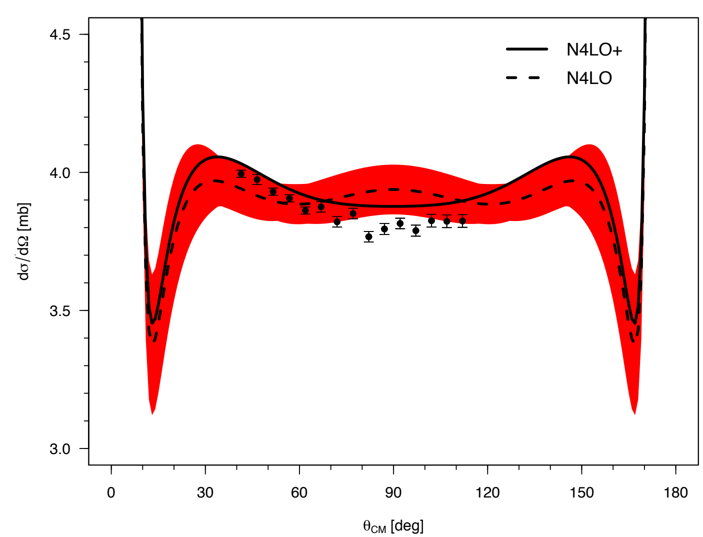
0 – 300 MeV	**1301.41**	**104.38**	**84.24**	**2.73**	**1.46** (**1.28**)
	2 LECs	**+ 7 + 2 IB LECs**		**+ 15 LECs**	**+ 1 IB LEC**

What is the origin of the still somewhat large χ^2 for pp data @ N^4LO?

- ∃ some very precise pp data… which are, however, still well described by the theory!





- much lower χ^2 per datum without the outliers
- probe $l > 2$ waves which are parameter-free at N^4LO…

N^4LO^+: include N^5LO contacts in $^3F_2$, $^1F_3$, $^3F_3$, $^3F_4$ & ε_3

χ^2 per datum for the description of the np and pp scattering data [R = 0.9 fm]

Energy bin	LO	NLO	N^2LO	N^3LO	N^4LO	N^4LO+
neutron-proton data						
0 – 100 MeV	130.11	3.79	1.46	1.08	1.08	1.08
0 – 200 MeV	104.71	19.88	3.21	1.14	1.09	1.10
0 – 300 MeV	111.24	52.03	8.78	1.51	1.15	1.13
proton-proton data						
0 – 100 MeV	2046.58	33.68	6.67	0.86	0.84	0.84
0 – 200 MeV	1649.58	115.60	81.11	1.95	1.34 (1.08)	0.97
0 – 300 MeV	1301.41	104.38	84.24	2.73	1.46 (1.28)	1.18
	2 LECs	+ 7 + 2 IB LECs		+ 15 LECs	+ 1 IB LEC	+ 5 LEC

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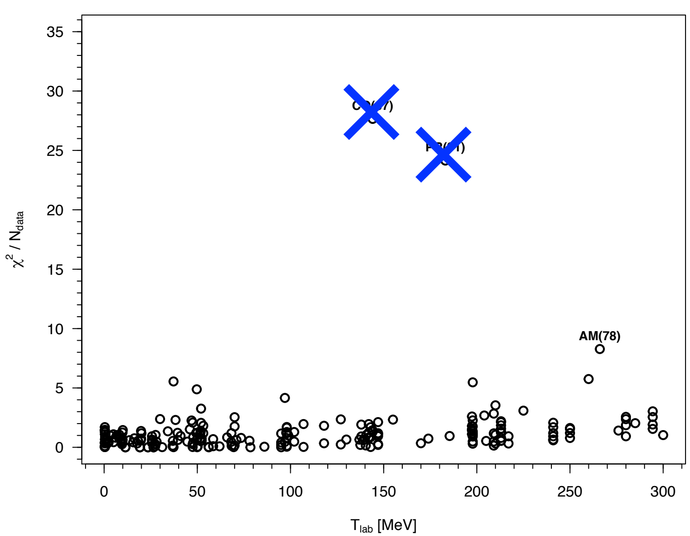

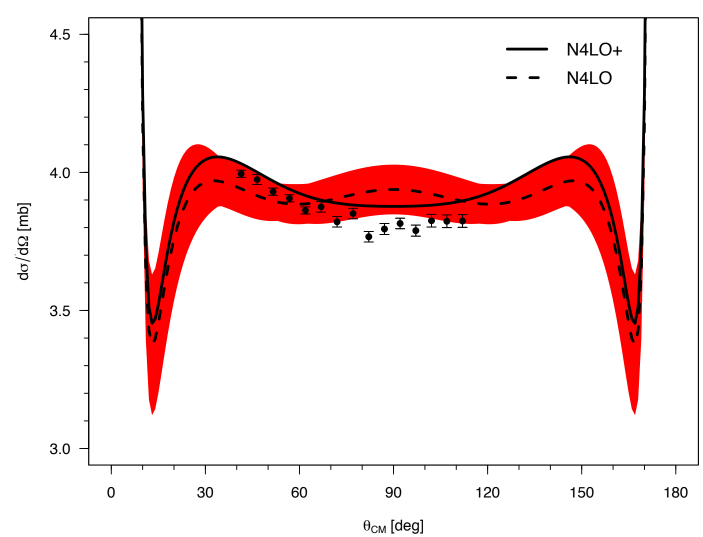

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χ^2 per datum for the description of the np and pp scattering data [R = 0.9 fm]

Energy bin	N^3LO Idaho 500/600	N^4LO/N^4LO+	CD Bonn 2000	Nijm II
neutron-proton data				
0 – 100 MeV	**1.17/1.35**	**1.08/1.08**	**1.08**	**1.08**
0 – 200 MeV	**1.17/1.33**	**1.09/1.10**	**1.07**	**1.07**
0 – 300 MeV	**1.24/1.38**	**1.15/1.13**	**1.09**	**1.11**
proton-proton data				
0 – 100 MeV	**0.96/1.28**	**0.84/0.84**	**0.84**	**0.83**
0 – 200 MeV	**1.28/1.55**	**1.34/0.97**	**0.95**	**0.96**
0 – 300 MeV	**1.37/2.04**	**1.46/1.18**	**0.99**	**1.03**

χ^2 per datum for the description of the np and pp scattering data [R = 0.9 fm]

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0 – 300 MeV	**1.37/2.04**	**1.46/1.18**	**0.99**	**1.03**

Predictions for the scattering lengths and effective range parameters [R = 0.9 fm]
(with respect to Riccati-Bessel/Coulomb functions)

	predictions at N^4LO	Experimental/Empirical values
neutron-proton		
$a_{^1S_0}$ [fm]	**−23.733(6)**	**−23.740(20)**
$r_{^1S_0}$ [fm]	**2.677(7)**	**2.77(5)**
$a_{^3S_1}$ [fm]	**5.419(1)**	**5.419(7)**
$r_{^3S_1}$ [fm]	**1.752(0)**	**1.753(8)**
proton-proton		
$a_{^1S_0}$ [fm]	**−7.816(1)**	**−7.817(4)***
$r_{^1S_0}$ [fm]	**2.773(2)**	**2.78(2)***

* Recommended values, Bergervoet et al., Phys. Rev. C38 (1988) 15

Work in progress:

Inclusion of the chiral 3NF

Having developed these tools, namely

— accurate and precise NN potentials up to N^4LO

— reliable approach for quantifying theoretical uncertainties,

we are well equipped to address the three-nucleon force problem.

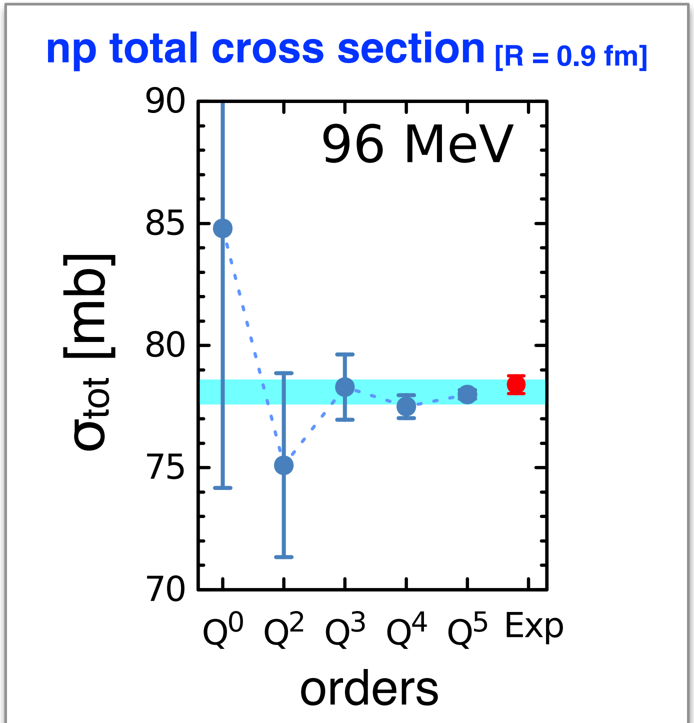
Notice: none of the existing 3NF models is able to reproduce 3N scattering observables **[Kalantar-Naestanaki, EE, Messchendorp, Nogga, Rept. Prog. Phys. 75 (12) 016301]**

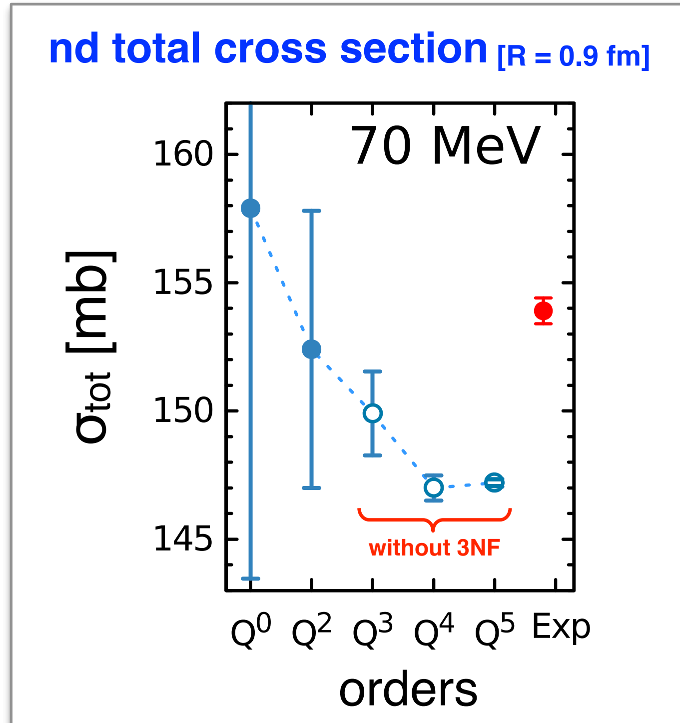
LENPIC: Low **E**nergy **N**uclear **P**hysics **I**nternational **C**ollaboration

Few-N results without 3NF

LENPIC Collaboration (Binder et al.), PRC 93 (2016) 04402

Is there evidence for missing 3N forces effects? Yes!





- Discrepancies between theory and data well outside the range of quantified uncertainties
  → **clear evidence for missing 3NF effects**
- Magnitude of the required 3NF contributions matches well the estimated size of N^2LO terms
  → **consistent with the chiral power counting**

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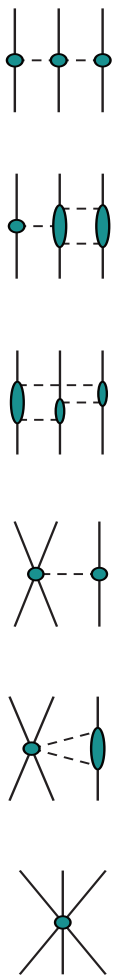
Chiral expansion of the 3NF



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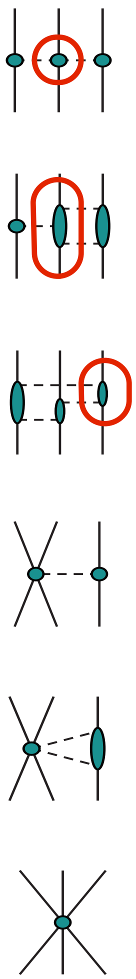
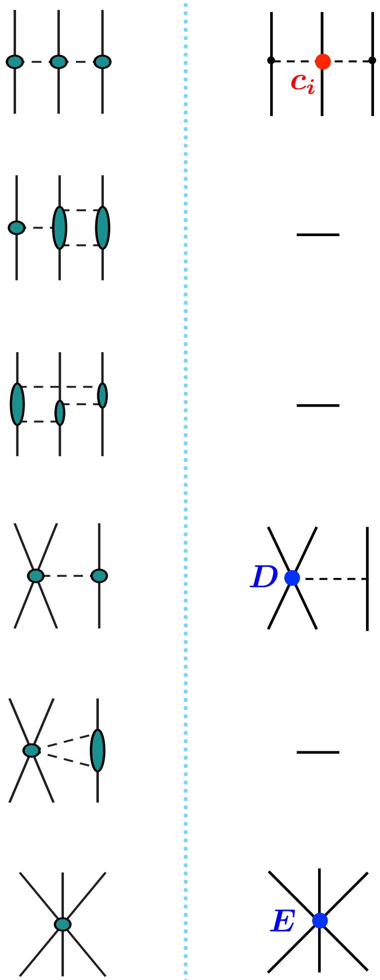


3NF structure functions at large distance are
model-independent and parameter-free predictions
based on χ symmetry of QCD + exp. information on πN system

Chiral expansion of the 3NF

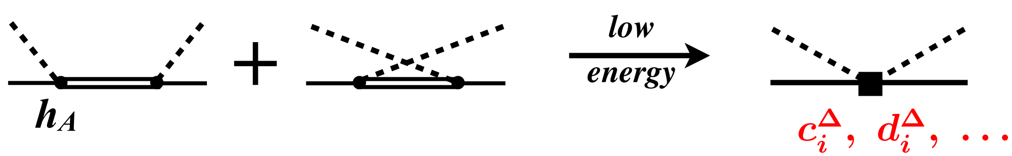
Chiral expansion of the 3NF

N²LO (Q^3)



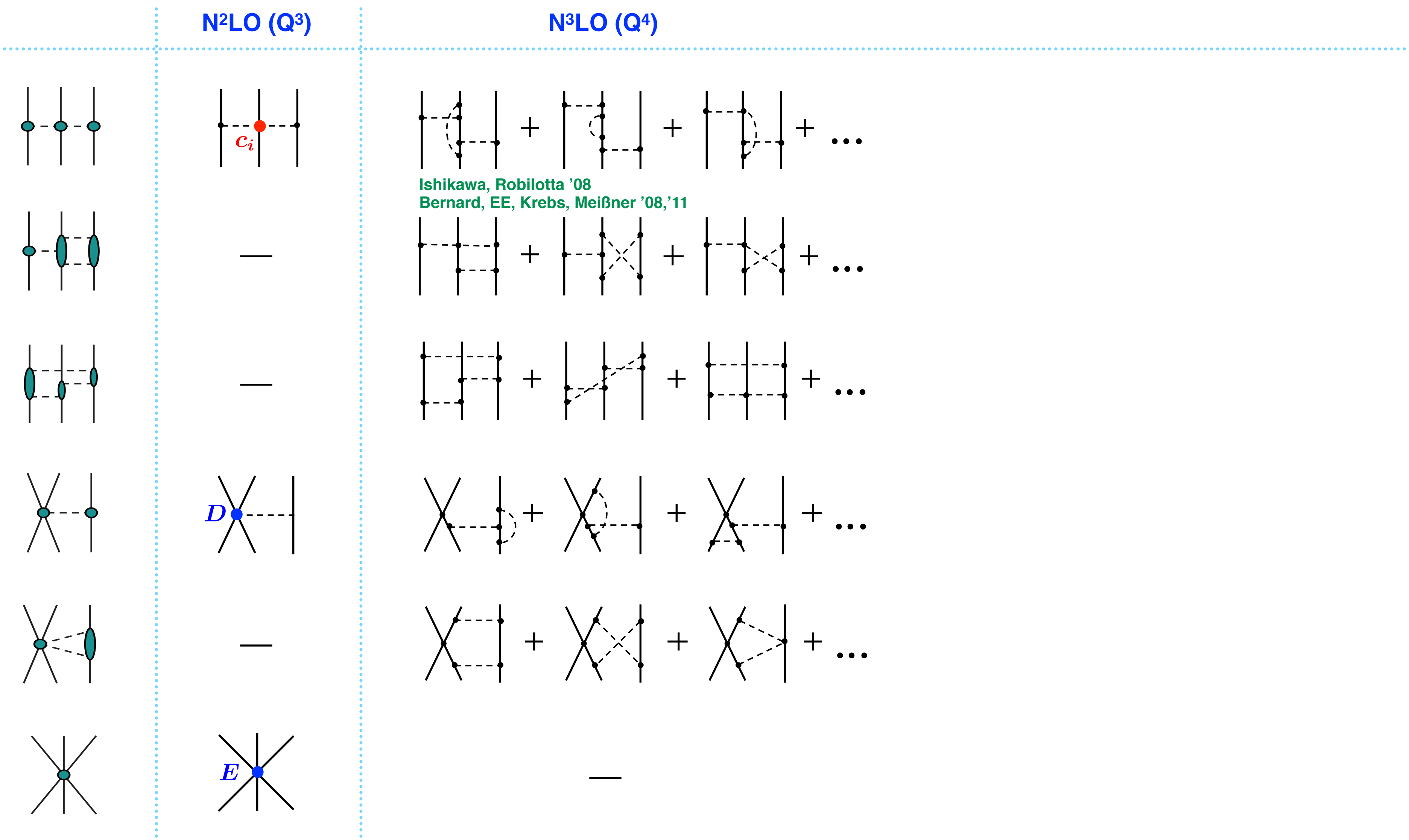
Notice: c_i receive large Δ(1232) contributions

Bernard, Kaiser, Meißner '97



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

Chiral expansion of the 3NF



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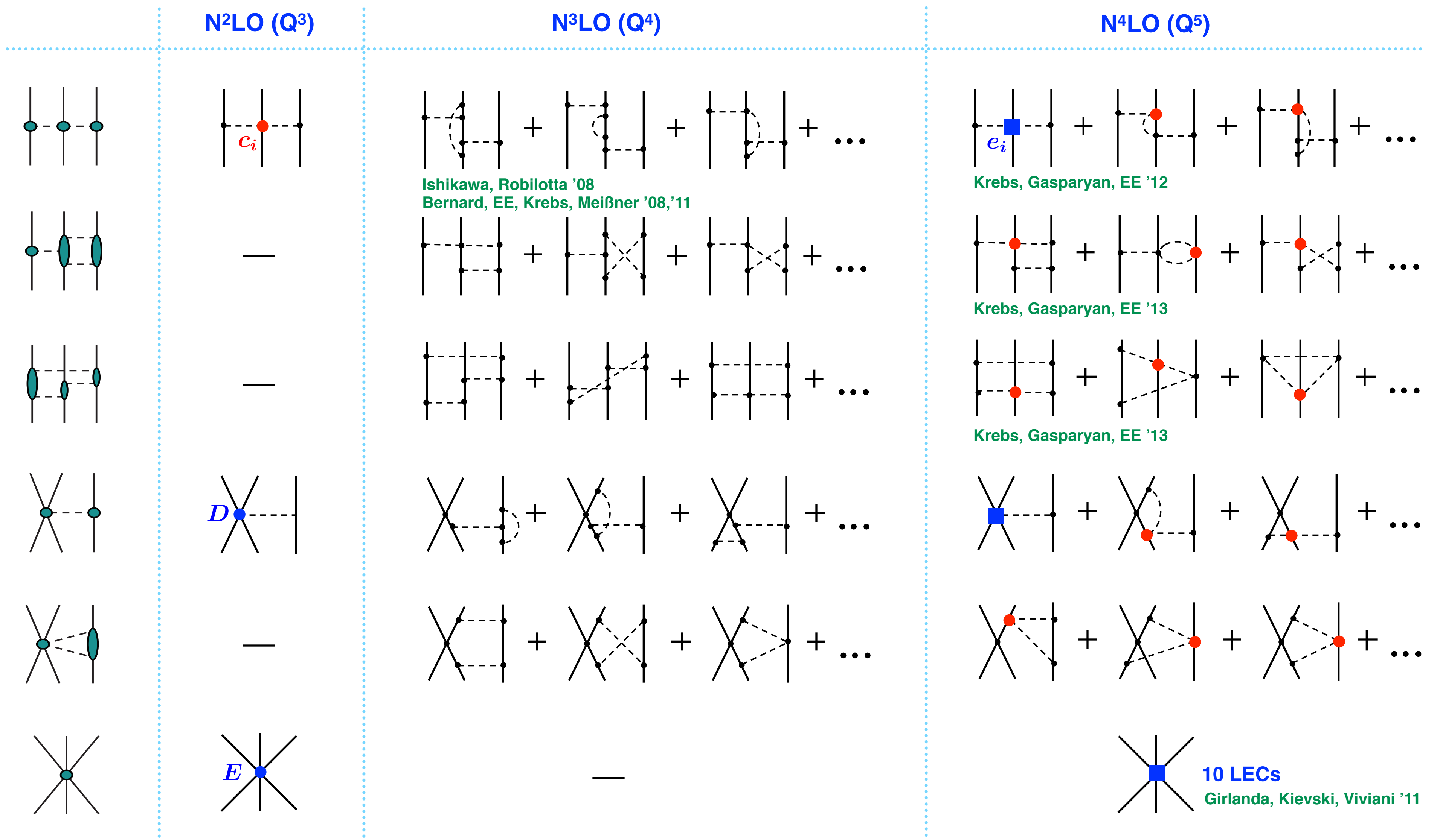

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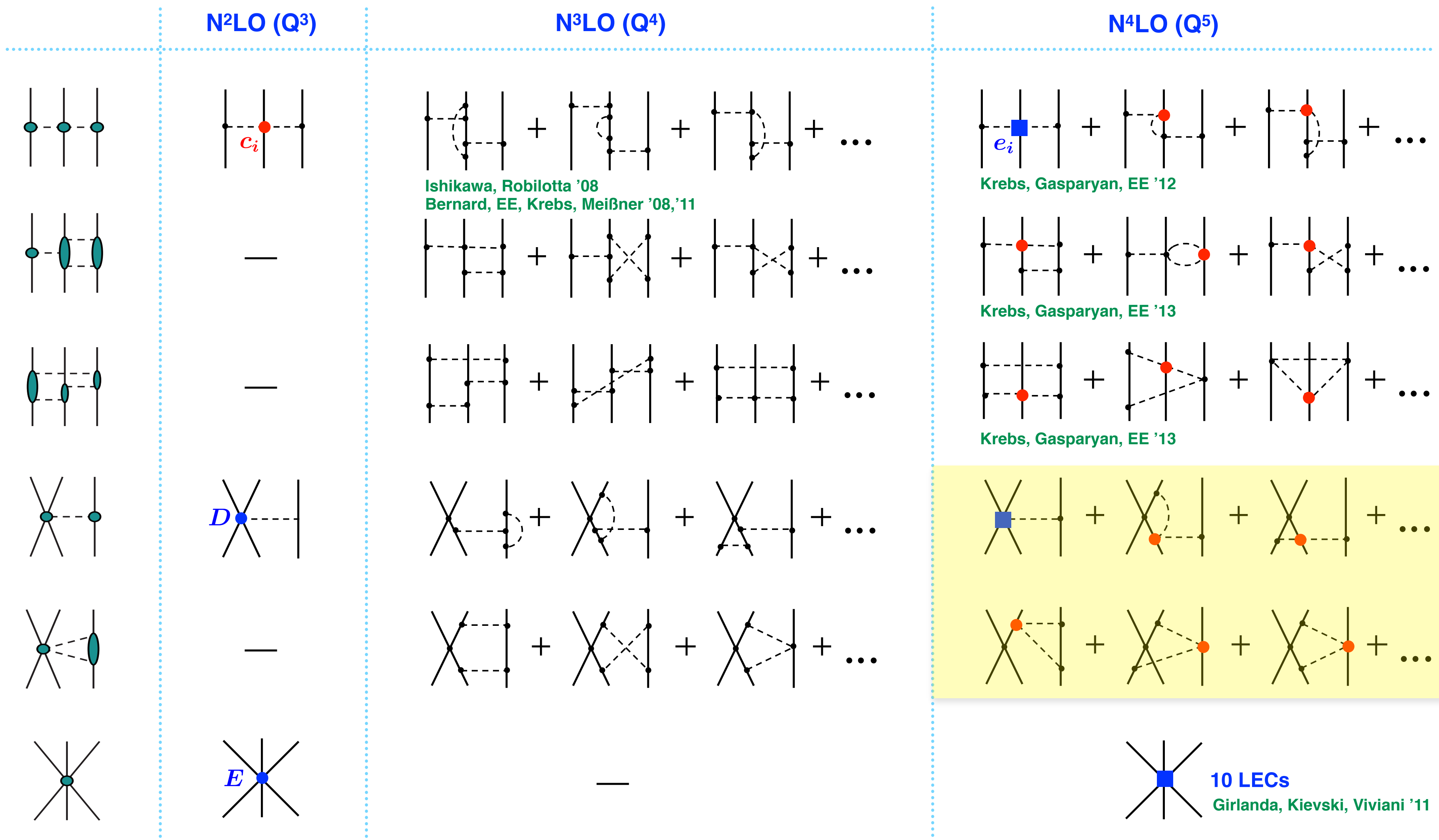
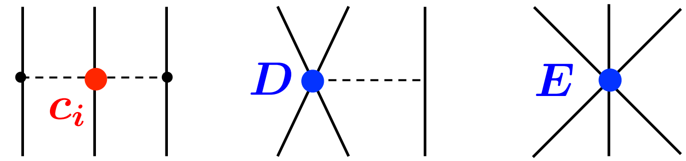


Some PRELIMINARY results with 3NF

LENPIC, in progress

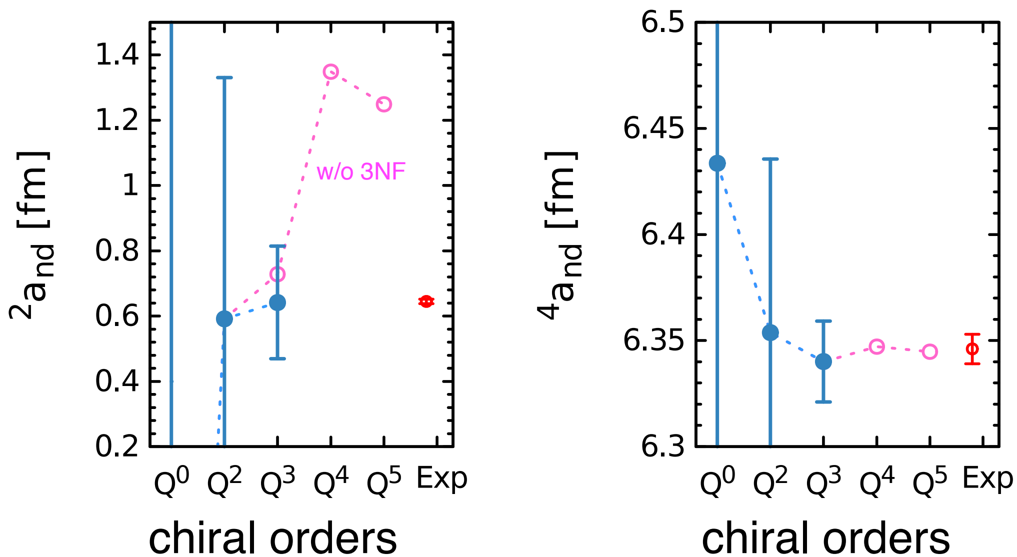
The LECs D, E are determined from the ^{3}H and the Nd cross section minimum @70 MeV (RIKEN data)



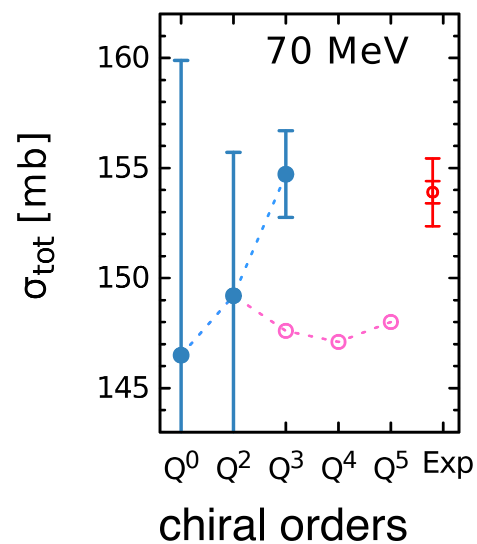
The results are preliminary:

— still have to analyze different ways to determine D and E, check other sources of uncertainties, …

nd scattering lengths [R = 1.0 fm]

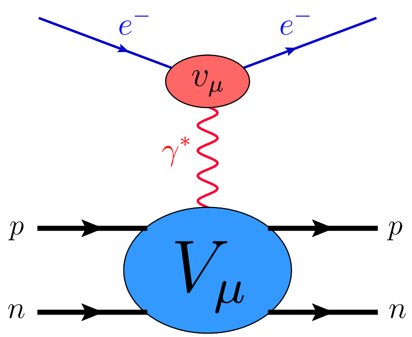


nd σ_{tot} at 70 MeV [R = 1.0 fm]



LENPIC: Low Energy Nuclear Physics International Collaboration

Nuclear current operators
in chiral EFT

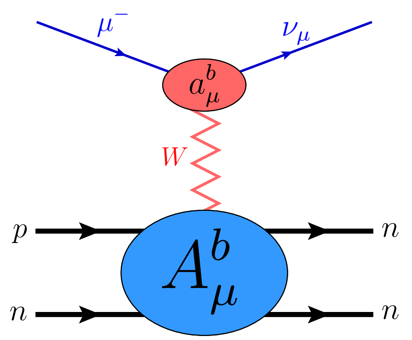


EM currents:

- Kölling, EE, Krebs, Meißner, PRC 80 (09) 045502; 86 (12) 047001
- Jlab-Pisa group (TOPT), Pastore et al. '08 - '11

Axial currents:

- Krebs, EE, Meißner, arXiv:1510.03569 [nucl-th]
- Jlab-Pisa group (TOPT), Baroni et al. '16
- Hoferichter, Klos, Schwenk '15

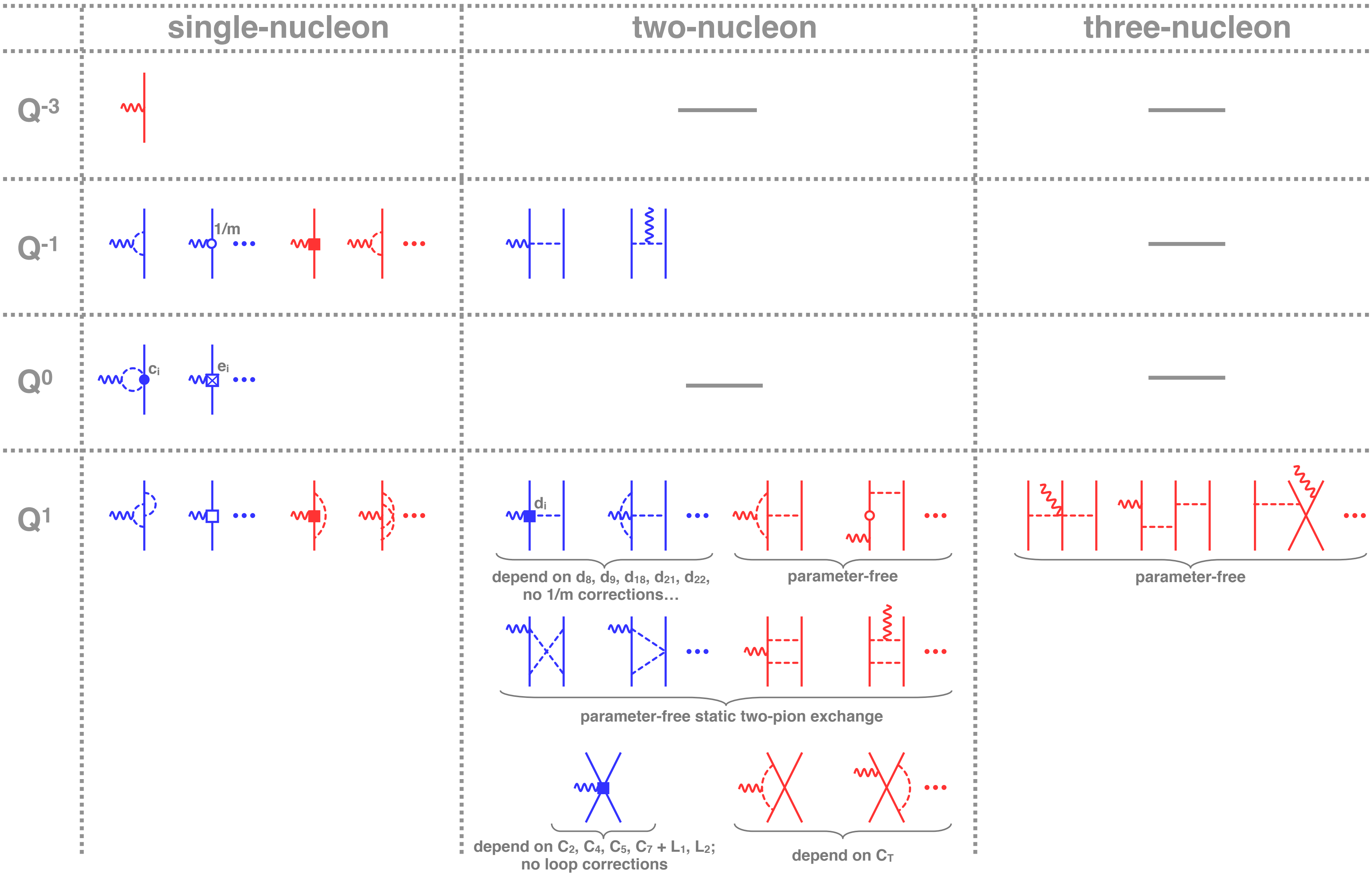


(Our) requirements on the current operators

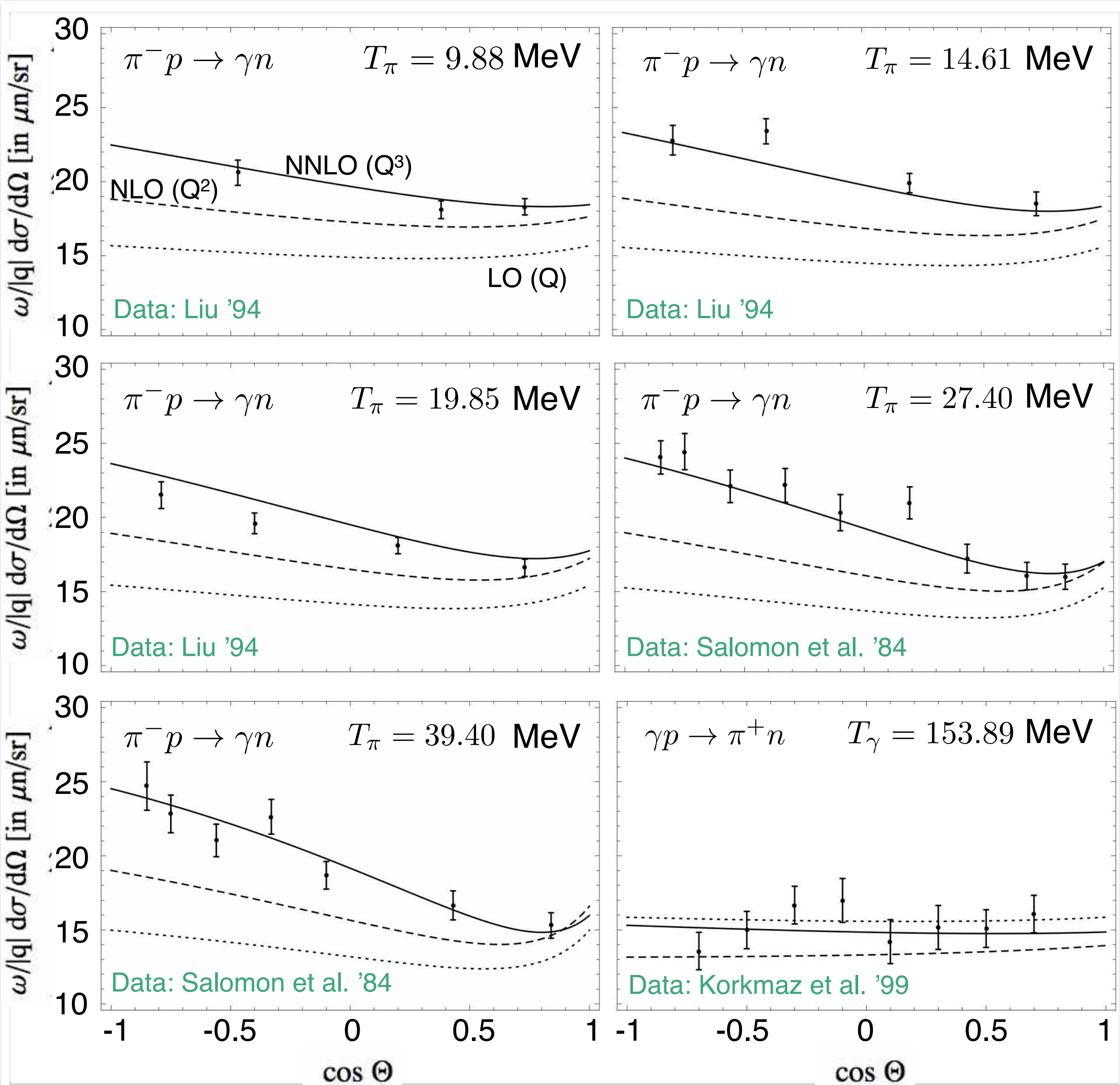
- must be **off-shell consistent with the forces**
- should be **renormalized** (exploit unitary ambiguity)
- (cutoff) regularization of the forces and currents should **maintain the symmetry** (cont. equation)

Electromagnetic currents

Chiral expansion of the electromagnetic **current** and **charge** operators



The low-energy constants



LECs entering the 1**π** current:

$$\bar{l}_6,\ \bar{d}_8,\ \bar{d}_9,\ \bar{d}_{18},\ \bar{d}_{21},\ \bar{d}_{22}$$

$\bar{l}_6$ - known from the **π** sector

$\bar{d}_{18}$ - known from GTD

$\bar{d}_{22}$ - from the axial radius:

$$\bar{d}_{22} = 2.2 \pm 0.2\ \text{GeV}^{-2}$$

$\bar{d}_9,\ \bar{d}_{21},\ \bar{d}_{22}$ - contribute to charged pion photoproduction (radiative capture)

Fearing et al.'00
Till Wolf, master thesis, Bochum, 2013

LEC [GeV⁻²]	Fearing *et al.*	Wolf
$\bar{d}_9$	2.5 ± 0.8	2.2 ± 0.9
$\bar{d}_{20}$	-1.5 ± 0.5	-3.2 ± 0.5
$2\bar{d}_{21} - \bar{d}_{22}$	5.7 ± 0.8	6.8 ± 1.0

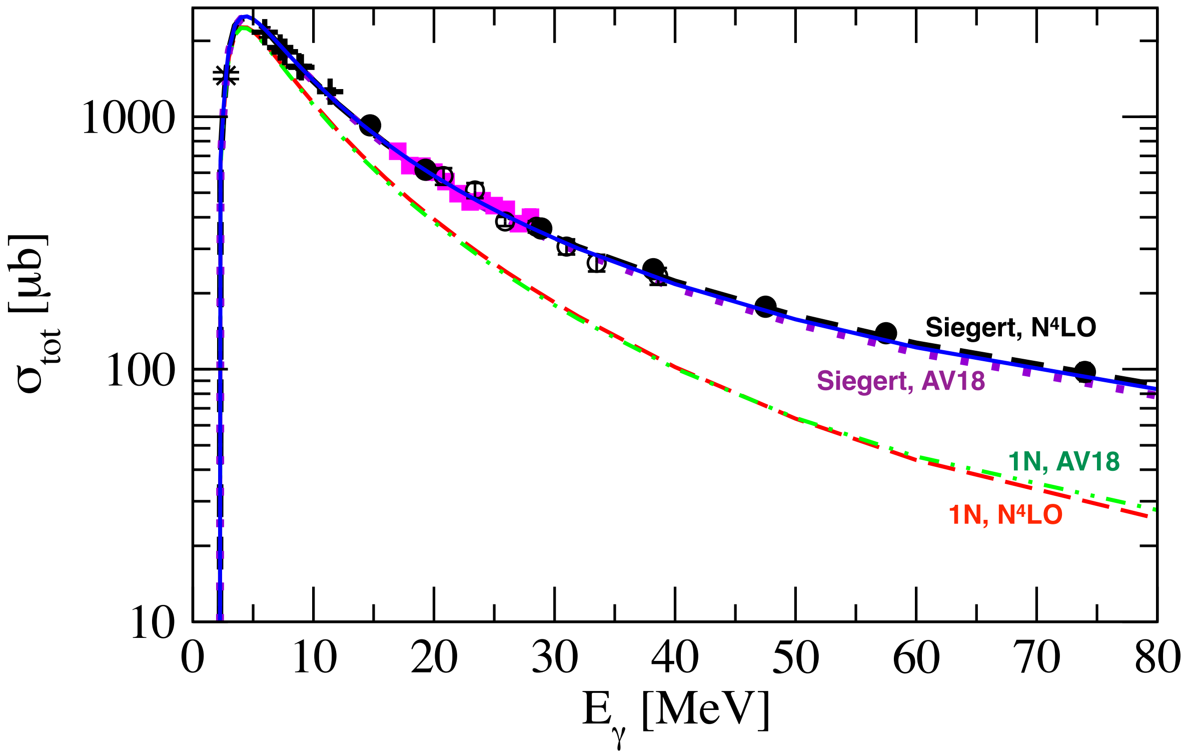
Some d_i's have been determined by Gasparyan, Lutz '10 (ChPT + disp. relations)

Electromagnetic exchange currents

Skibinski, Golak, Topolnicki, Witala, EE, Krebs, Kamada, Meißner, Nogga, PRC 93 (2016) 064002

- To maintain consistency between currents and forces (symmetry), we generate regularized longitudinal terms in the current via the continuity equation (i.e. Siegert approach).
- Transverse terms in the currents are to be regularized and included explicitly (in progress…)

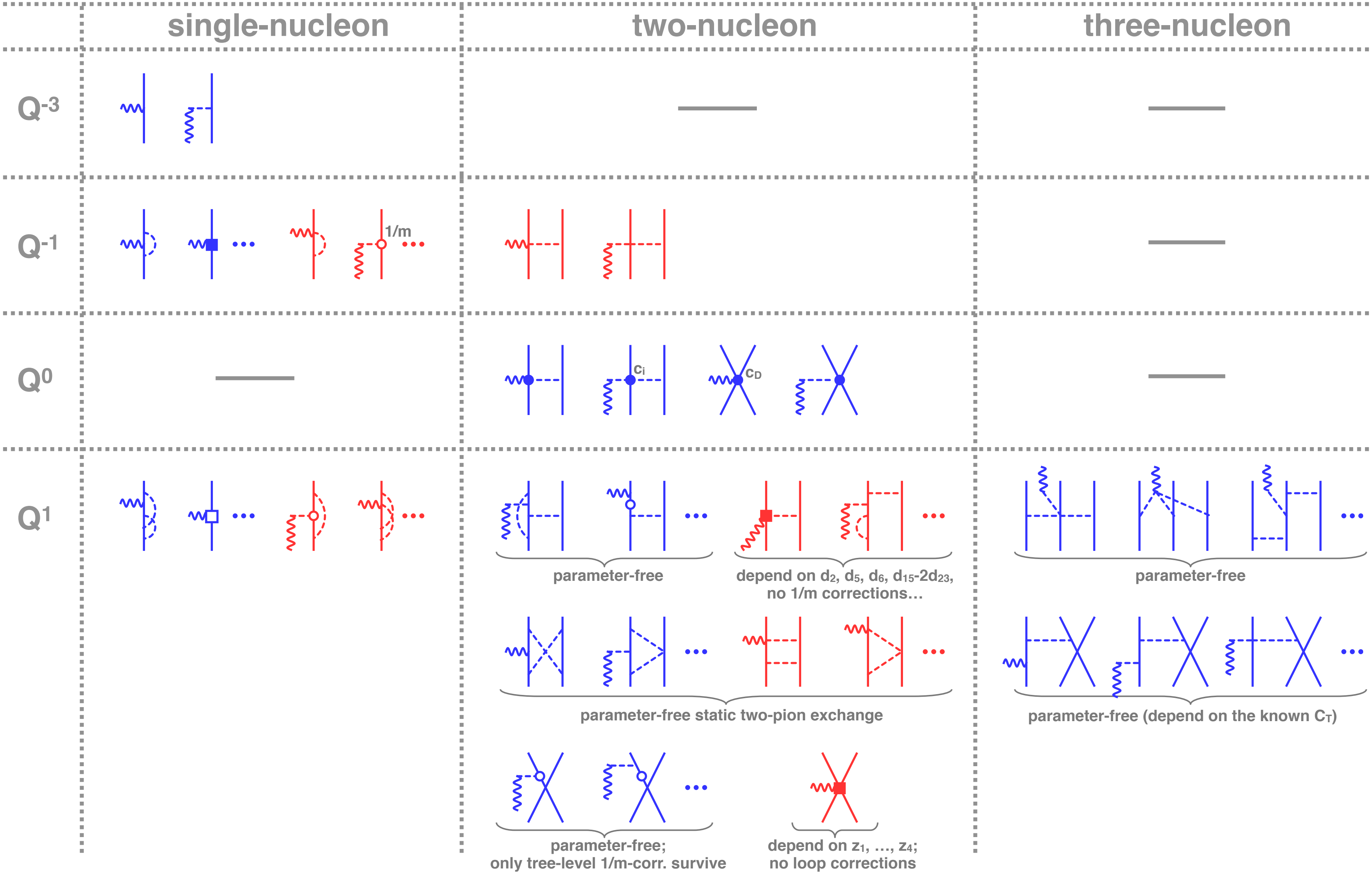
Total cross section for the deuteron photo-disintegration reaction $\gamma + d \to p + n$



Exchange axial currents

Krebs, EE, Meißner, arXiv:1610.03569

Chiral expansion of the axial **current** and **charge** operators



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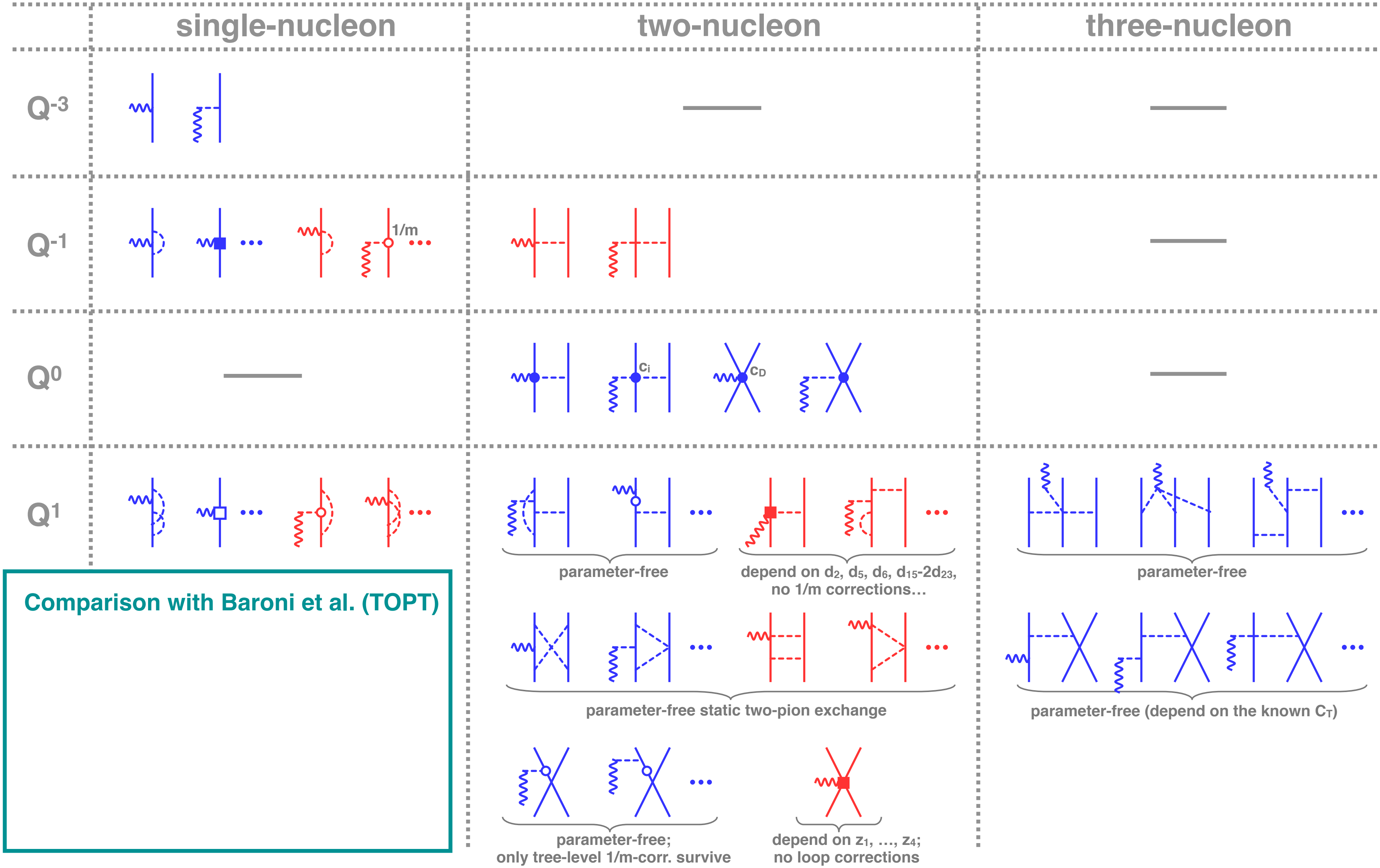

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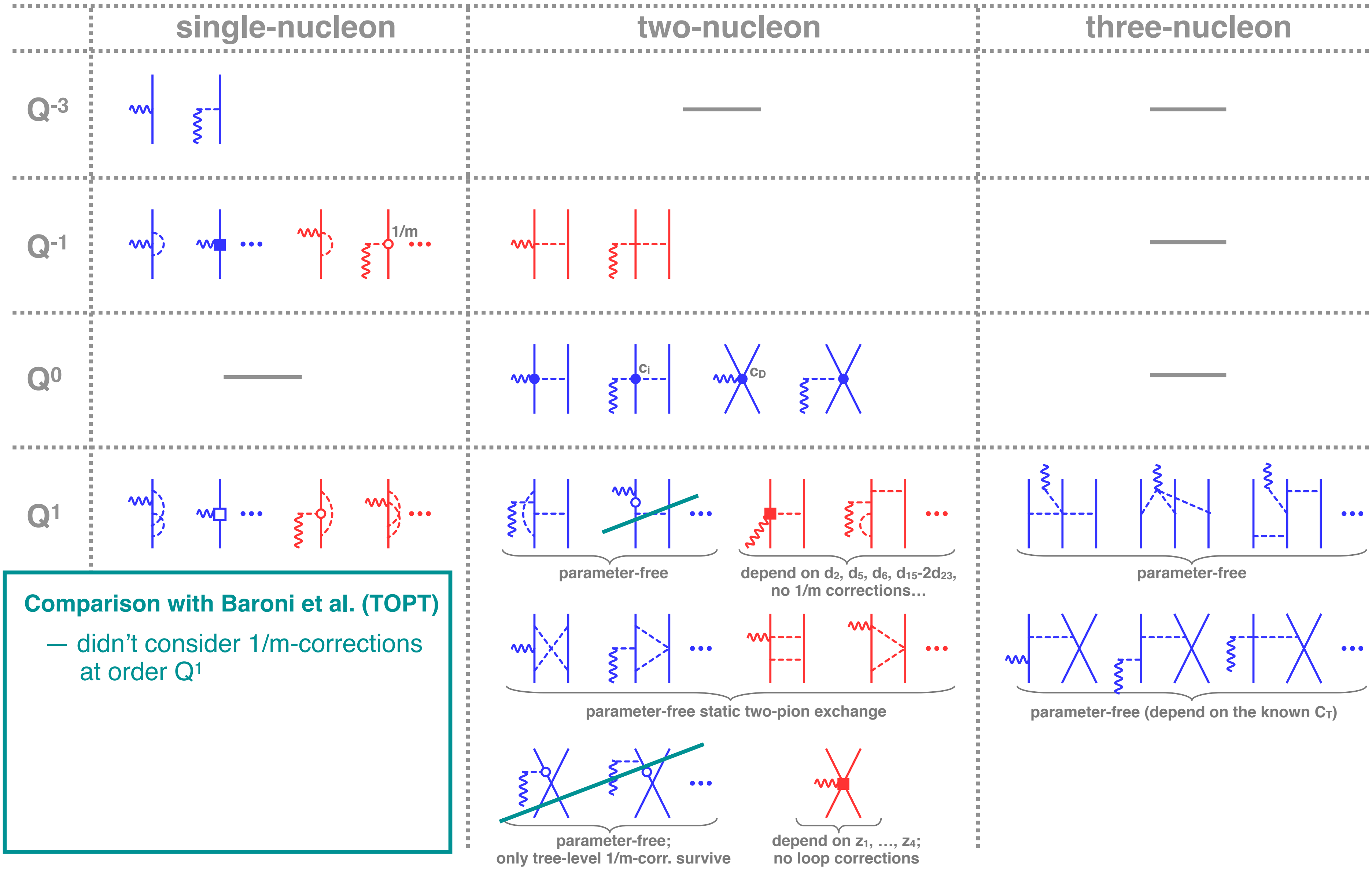

Comparison with Baroni et al. (TOPT)

— didn't consider 1/m-corrections at order Q^1

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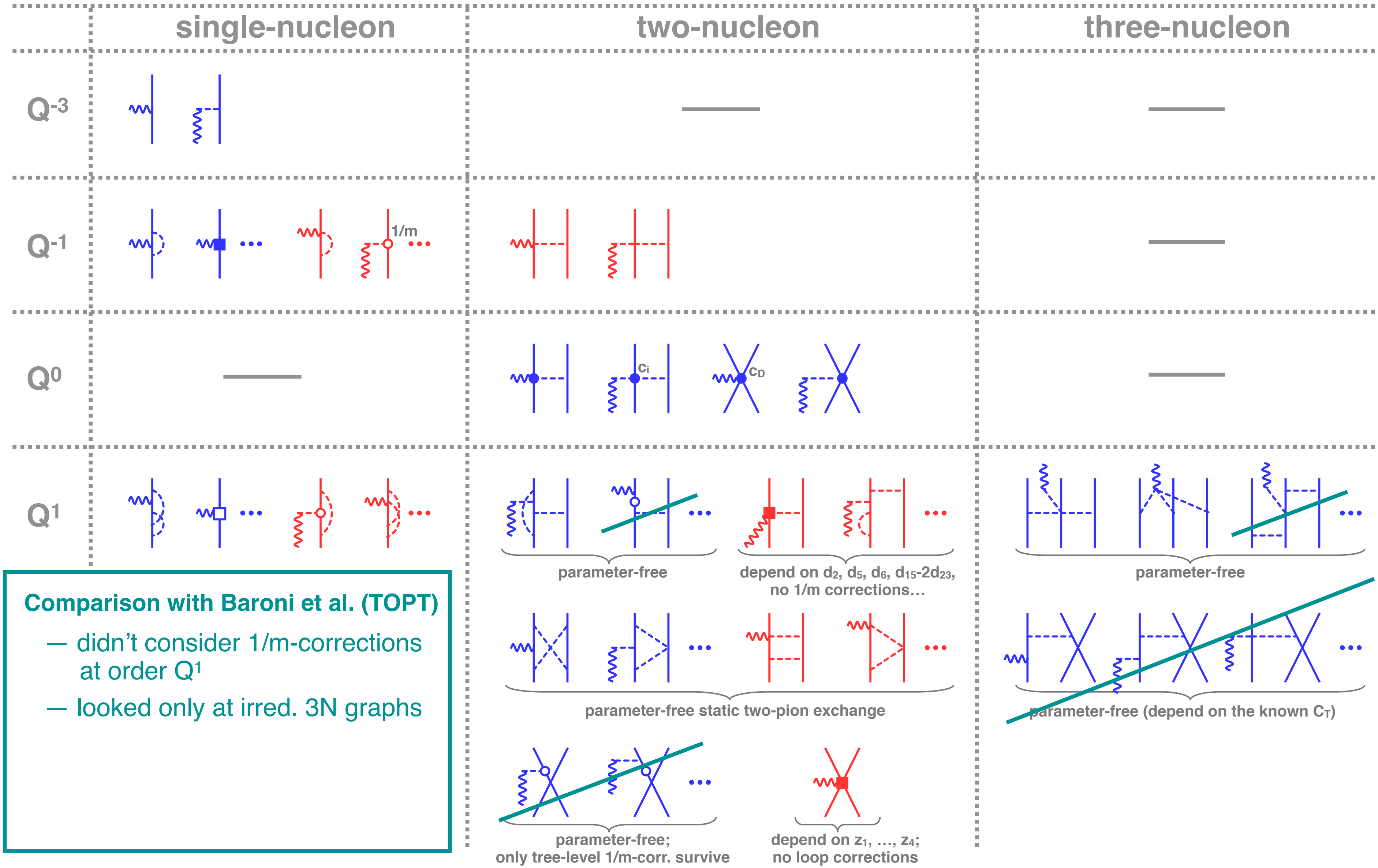

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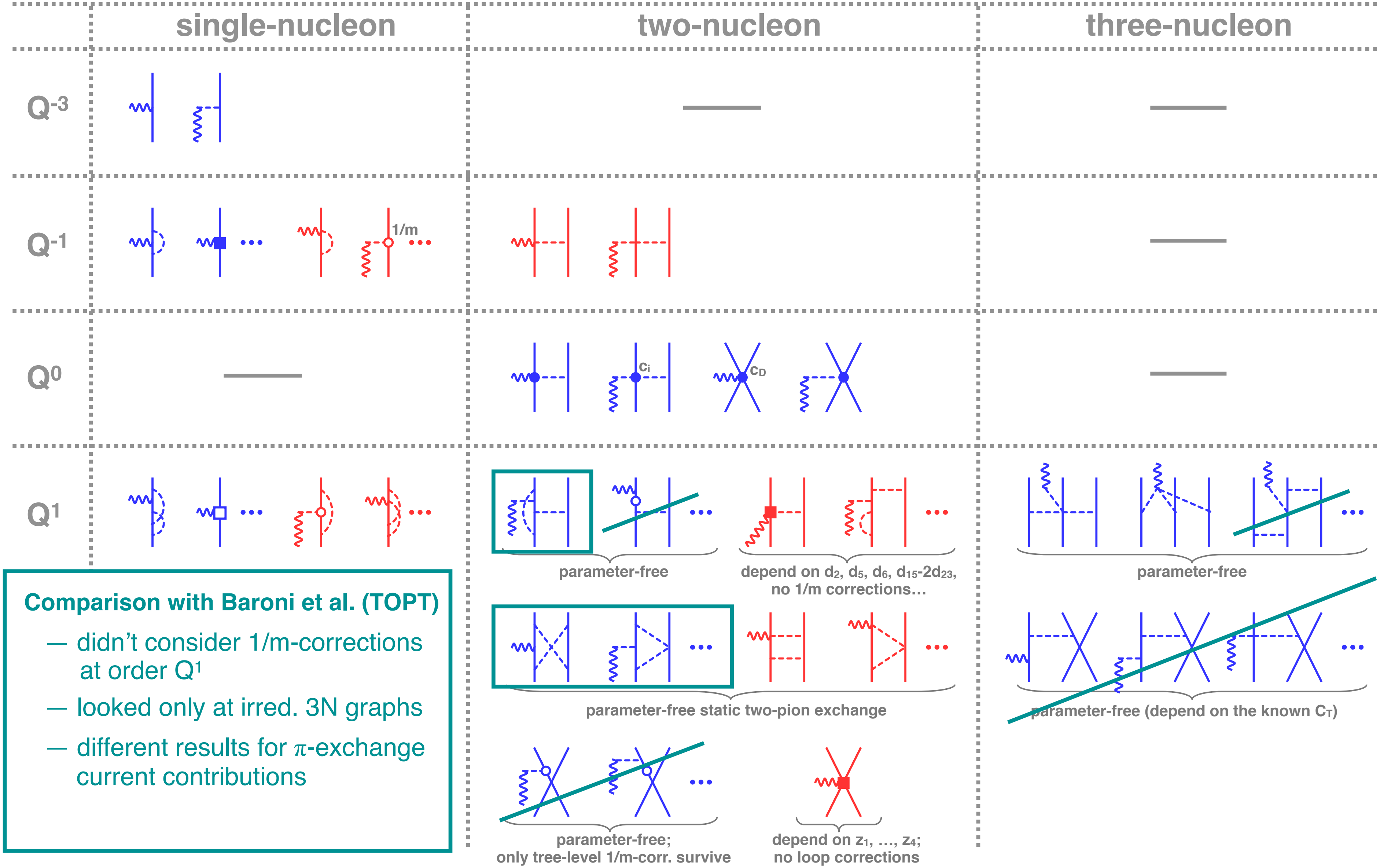

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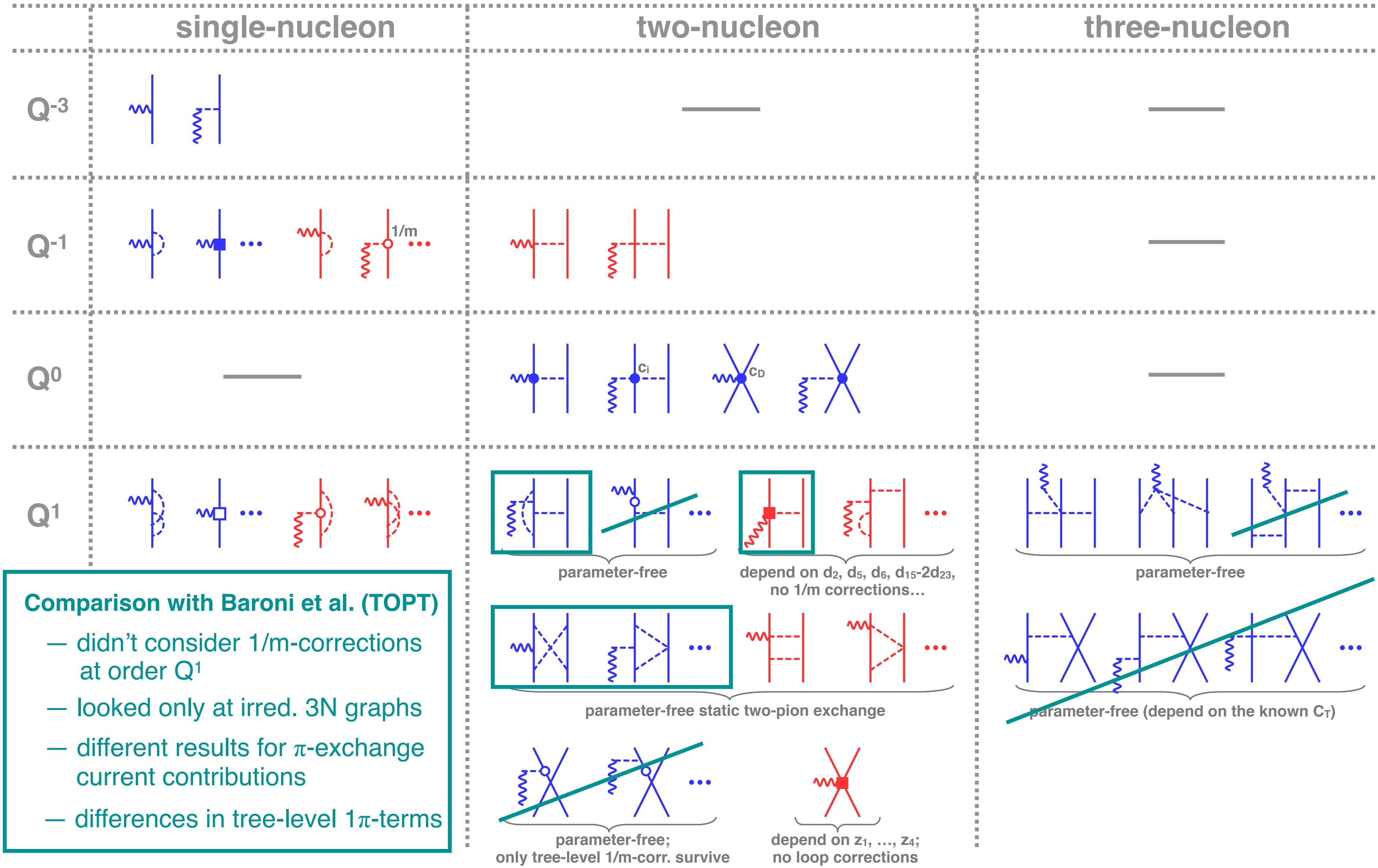

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- different results for π-exchange current contributions
- differences in tree-level 1π-terms

Tritium β-decay [Skibinski et al., in progress]

- Half-life of ^{3}H (up to known radiative corrections): $$ft = \frac{K}{G_V^2 \langle F \rangle^2 + g_A^2 \langle GT \rangle^2} = 1129.6 \pm 3.0 \text{ s}$$

  ⟶ constraints on the Gamow-Teller ME

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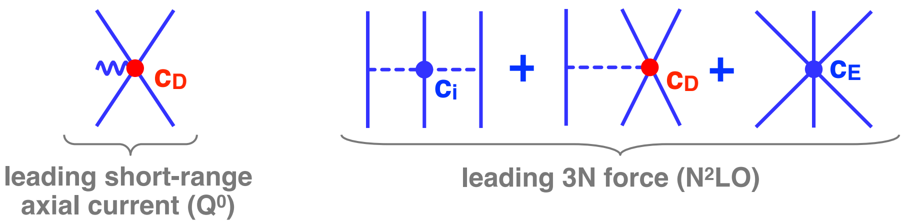
  ⟶ constraints on the Gamow-Teller ME

- Using 1N current, the ***ft*** value is off by ~ 5% ⟵ exchange current contribution!
  Up to Q^1 (i.e. N^{3}LO), no LECs except for known c_i and c_D involved. Fixing c_D in the strong sector allows one to predict ***ft***!
  (it is crucial to maintain the symmetry)

  ⟶ test axial exchange currents



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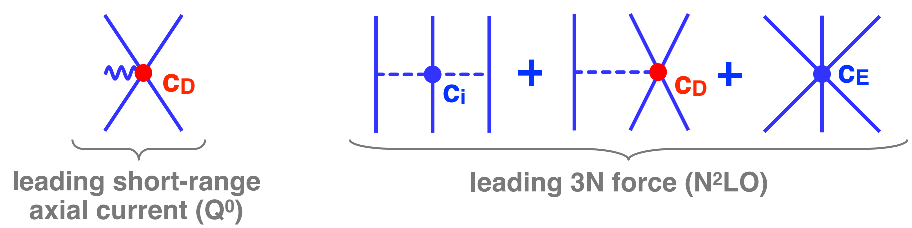
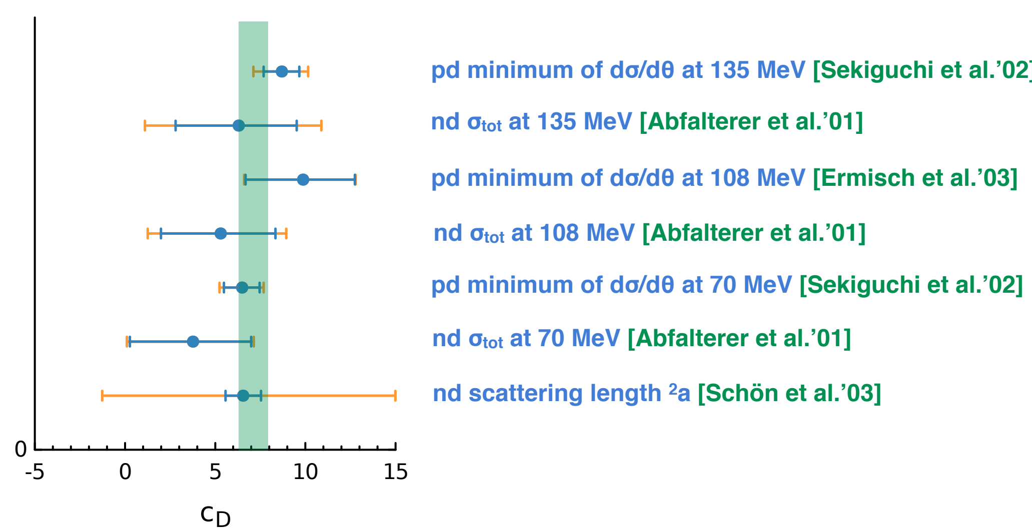


- Within the LENPIC, work is in progress on the determination of c_D. ⟶



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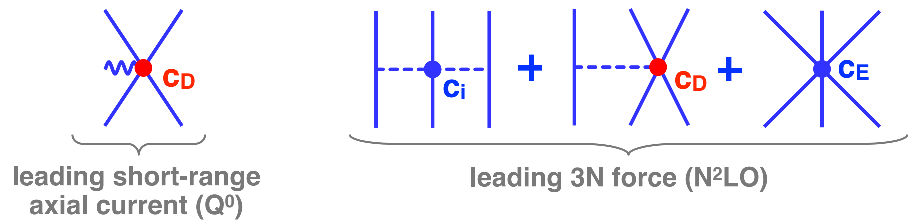

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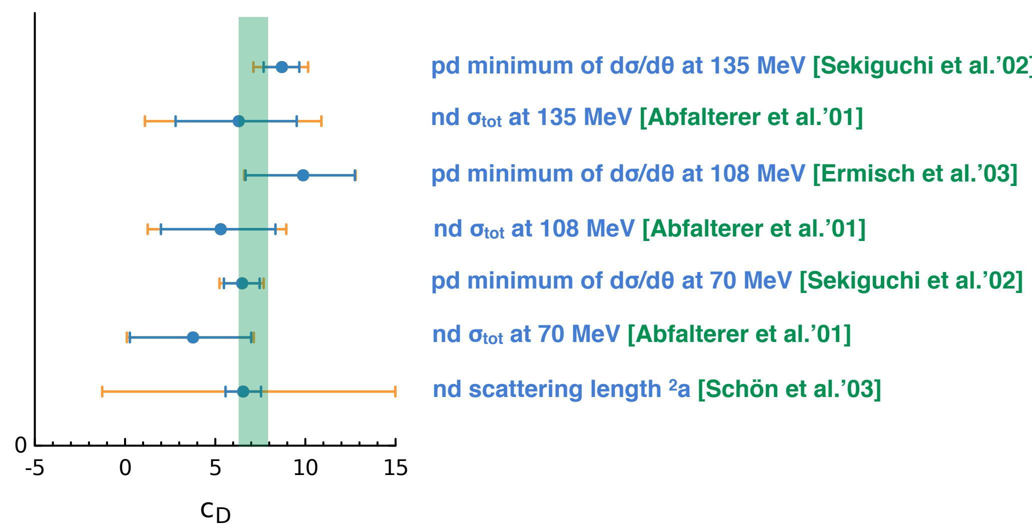

- Being validated in ^{3}H β-decay, the same currents can be used to predict the μ capture rate on ^{2}H being measured in MuSun

LENPIC: Low Energy Nuclear Physics International Collaboration

RUB · universität bonn · Technische Universität Darmstadt · Jagiellonian University in Krakow · Iowa State · Jülich Forschungszentrum · Kyutech · The Ohio State University · IPN Orsay · TRIUMF · Oak Ridge National Laboratory

Comparison with Baroni et al.

For ^{3}H β-decay ($\vec{k} \simeq 0$), the N^{3}LO contribution to the 2N current by Baroni et al. is:

$$\vec{A}^a_{\text{Baroni et al.}} = \frac{g_A^3}{32\pi F_\pi^4}\tau_2^a \left[W_1(q_1)\vec{\sigma}_1 + W_2(q_1)\vec{q}_1\,\vec{\sigma}_1\cdot\vec{q}_1 + Z_1(q_1)\left(2\frac{\vec{q}_1\,\vec{\sigma}_2\cdot\vec{q}_1}{q_1^2+M_\pi^2} - \vec{\sigma}_2\right)\right]$$
$$+ \frac{g_A^5}{32\pi F_\pi^4}\tau_1^a W_3(q_1)(\vec{\sigma}_2\times\vec{q}_1)\times\vec{q}_1 - \frac{g_A^3}{32\pi F_\pi^4}[\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2]^a Z_3(q_1)\frac{\vec{\sigma}_1\times\vec{q}_1\vec{\sigma}_2\cdot\vec{q}_1}{q_1^2+M_\pi^2} + 1\leftrightarrow 2\,,$$

Baroni et al., PRC93 (2016) 015501; PRC94 (2016) 024003

where the various loop functions are defined as:

$$W_1(q_1) = \frac{1}{2}A(q_1)\left[4(1-2g_A^2)M_\pi^2 + (1-5g_A^2)q_1^2\right] + \frac{1}{2}M_\pi\left[g_A^2\left(\frac{4M_\pi^2}{4M_\pi^2+q_1^2}-9\right)+1\right],$$

$$W_2(q_1) = \frac{M_\pi\left(4(2g_A^2+1)M_\pi^2+(3g_A^2+1)q_1^2\right)}{2q_1^2(4M_\pi^2+q_1^2)} - \frac{A(q_1)\left(4(2g_A^2+1)M_\pi^2+(g_A^2-1)q_1^2\right)}{2q_1^2},$$

$$W_3(q_1) = -\frac{4A(q_1)}{3} - \frac{1}{6M_\pi},$$

← does not exist in the chiral limit!
(in contrast to our results)

$$Z_1(q_1) = 2A(q_1)(2M_\pi^2+q_1^2) + 2M_\pi,$$

$$Z_3(q_1) = \frac{1}{2}A(q_1)(4M_\pi^2+q_1^2) + \frac{M_\pi}{2},$$

$$A(q_1) = \frac{1}{2q_1}\arctan\left(\frac{q_1}{2M_\pi}\right).$$

Comparison with Baroni et al.

For ^{3}H β-decay ($\vec{k} \simeq 0$), the N^{3}LO contribution to the 2N current by Baroni et al. is:

$$\begin{aligned}\vec{A}^a_{\text{Baroni et al.}} &= \frac{g_A^3}{32\pi F_\pi^4}\tau_2^a \left[W_1(q_1)\vec{\sigma}_1 + W_2(q_1)\vec{q}_1\,\vec{\sigma}_1\cdot\vec{q}_1 + Z_1(q_1)\left(2\frac{\vec{q}_1\,\vec{\sigma}_2\cdot\vec{q}_1}{q_1^2+M_\pi^2} - \vec{\sigma}_2\right)\right] \\ &+ \frac{g_A^5}{32\pi F_\pi^4}\tau_1^a W_3(q_1)(\vec{\sigma}_2\times\vec{q}_1)\times\vec{q}_1 - \frac{g_A^3}{32\pi F_\pi^4}[\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2]^a Z_3(q_1)\frac{\vec{\sigma}_1\times\vec{q}_1\vec{\sigma}_2\cdot\vec{q}_1}{q_1^2+M_\pi^2} + 1\leftrightarrow 2\,,\end{aligned}$$

Baroni et al., PRC93 (2016) 015501; PRC94 (2016) 024003

where the various loop functions are defined as:

$$\begin{aligned}W_1(q_1) &= \frac{1}{2}A(q_1)\left[4(1-2g_A^2)M_\pi^2 + (1-5g_A^2)q_1^2\right] + \frac{1}{2}M_\pi\left[g_A^2\left(\frac{4M_\pi^2}{4M_\pi^2+q_1^2} - 9\right) + 1\right], \\ W_2(q_1) &= \frac{M_\pi\left(4(2g_A^2+1)M_\pi^2 + (3g_A^2+1)q_1^2\right)}{2q_1^2(4M_\pi^2+q_1^2)} - \frac{A(q_1)\left(4(2g_A^2+1)M_\pi^2 + (g_A^2-1)q_1^2\right)}{2q_1^2}, \\ W_3(q_1) &= -\frac{4A(q_1)}{3} - \frac{1}{6M_\pi}, \\ Z_1(q_1) &= 2A(q_1)(2M_\pi^2+q_1^2) + 2M_\pi, \\ Z_3(q_1) &= \frac{1}{2}A(q_1)(4M_\pi^2+q_1^2) + \frac{M_\pi}{2}, \\ A(q_1) &= \frac{1}{2q_1}\arctan\left(\frac{q_1}{2M_\pi}\right).\end{aligned}$$

← does not exist in the chiral limit! (in contrast to our results)

We find:

$$\vec{A}^a_{\text{Baroni et al.}} - \vec{A}^a_{\text{KEM}} = -\frac{g_A^5 A(q_1)\left(\vec{\sigma}_2\tau_1^a q_1^4 + 2\vec{q}_1(6M_\pi^2+q_1^2)\vec{q}_1\cdot\vec{\sigma}_2\tau_1^a\right)}{96\pi F_\pi^4 q_1^2} + \text{rational function of } \vec{q}_1 + 1\leftrightarrow 2$$

→ the currents have different long-range parts!

Summary and outlook

- A new generation of accurate and precise chiral NN potentials up to N^{4}LO
  [good convergence of the chiral expansion, **not much room for improvement beyond N^{4}LO/N^{4}LO$^+$…**]
- A simple approach to estimate truncation error (validated in the NN system)
- Expressions for vector and axial-vector currents worked out up to N^{3}LO

These developments open the way for highly nontrivial
precision tests of nuclear chiral EFT
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Ongoing work and outlook for the near future:

- Inclusion of 3NFs at N^{3}LO and N^{4}LO (LENPIC). The unsolved discrepancies in Nd scattering will pose a challenge for the theory…
- Precision tests of chiral forces in light & medium-mass nuclei (spectra, radii)
- Symmetry-preserving regularization of the current operators (continuity eq.)
- Validating the theory for ^{3}H β-decay (parameter-free up to N^{3}LO), μ-capture reactions, …
- Photodisintegration and radiative capture few-N reactions (beyond Siegert)