

Three-nucleon forces at low energy

Hermann Krebs

Ruhr-Universität-Bochum

Electron Nucleus Scattering XII

June 28, 2012, Marciana Marina, Isola d'Elba

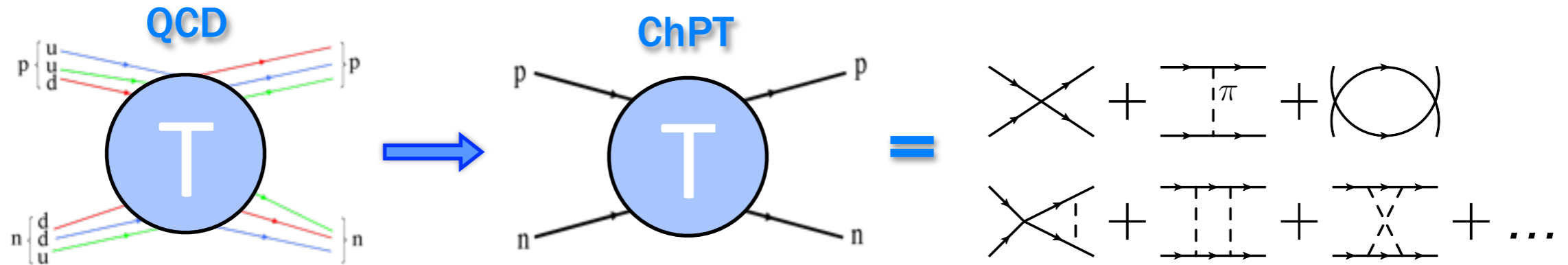
With V. Bernard, E. Epelbaum, A. Gasparyan, U.-G. Meißner



Outline

- From QCD to nuclear physics
- Nuclear forces in chiral EFT
- Three-nucleon forces up to $N^3\text{LO}$
- Long-range part of three-nucleon forces up to $N^4\text{LO}$
- Summary & Outlook

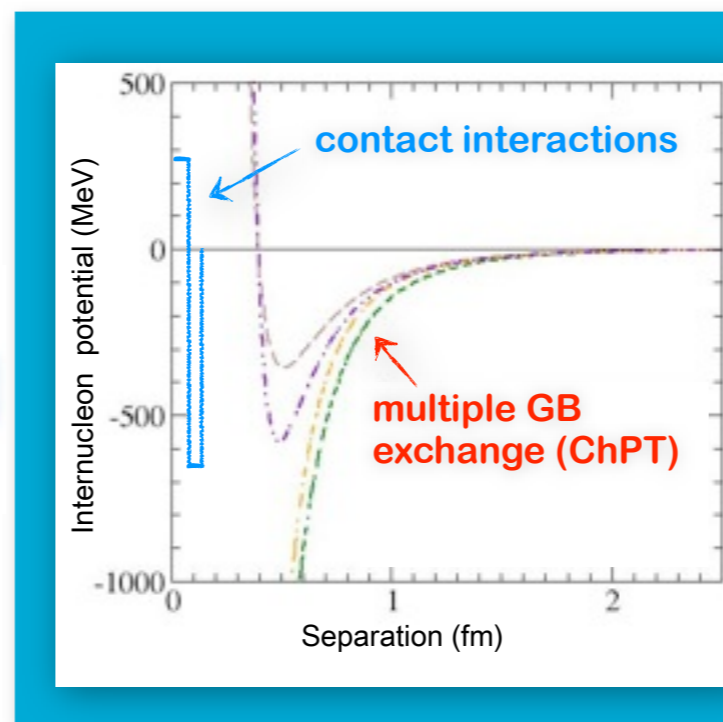
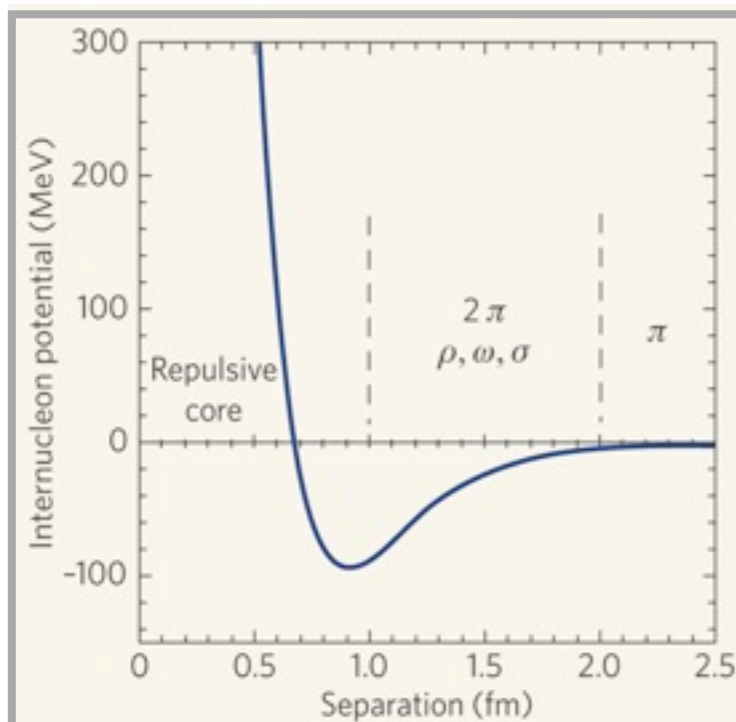
From QCD to nuclear physics



- **NN interaction is strong:** resummations/nonperturbative methods needed
- $1/m_N$ - expansion: nonrelativistic problem ($|\vec{p}_i| \sim M_\pi \ll m_N$) \implies the QM A-body problem

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

Weinberg '91



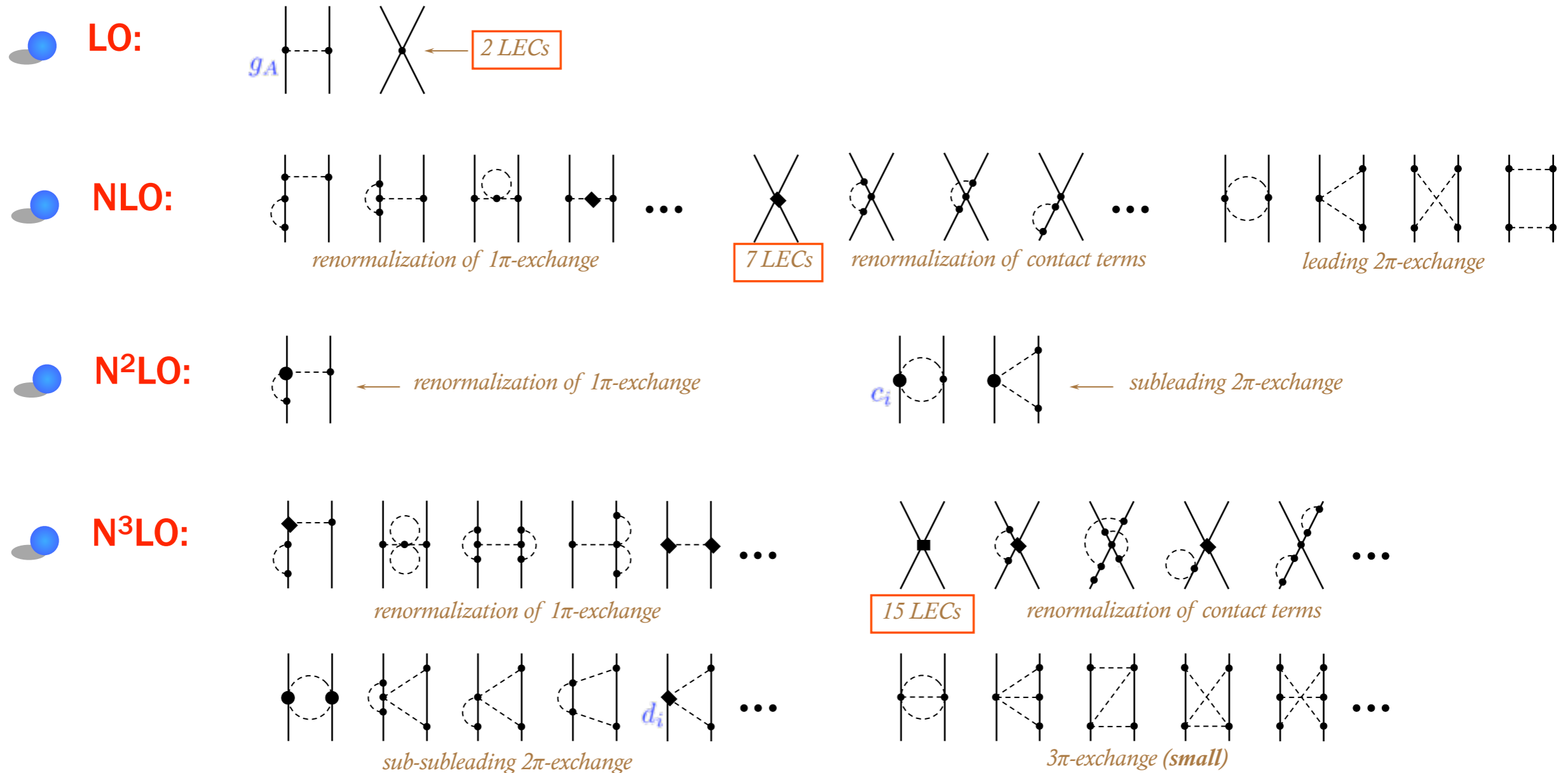
- unified description of $\pi\pi$, πN and NN
- consistent many-body forces and currents
- systematically improvable
- bridging different reactions (electroweak, π -prod., ...)
- precision physics with/from light nuclei

Nucleon-nucleon force up to N³LO

Ordóñez et al. '94; Friar & Coon '94; Kaiser et al. '97; Epelbaum et al. '98, '03; Kaiser '99-'01; Higa et al. '03; ...

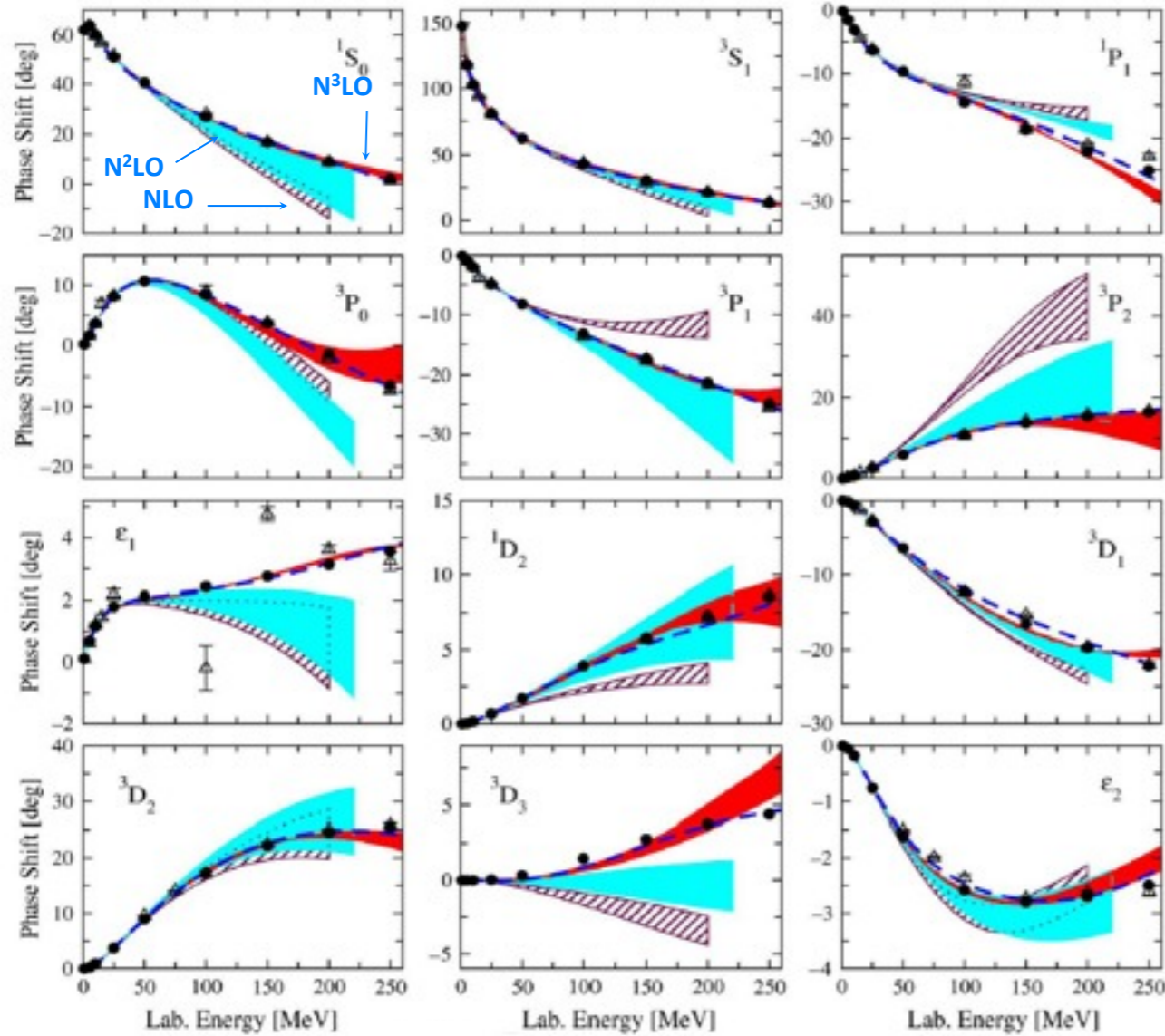
Chiral expansion for the 2N force:

$$V_{2N} = V_{2N}^{(0)} + V_{2N}^{(2)} + V_{2N}^{(3)} + V_{2N}^{(4)} + \dots$$

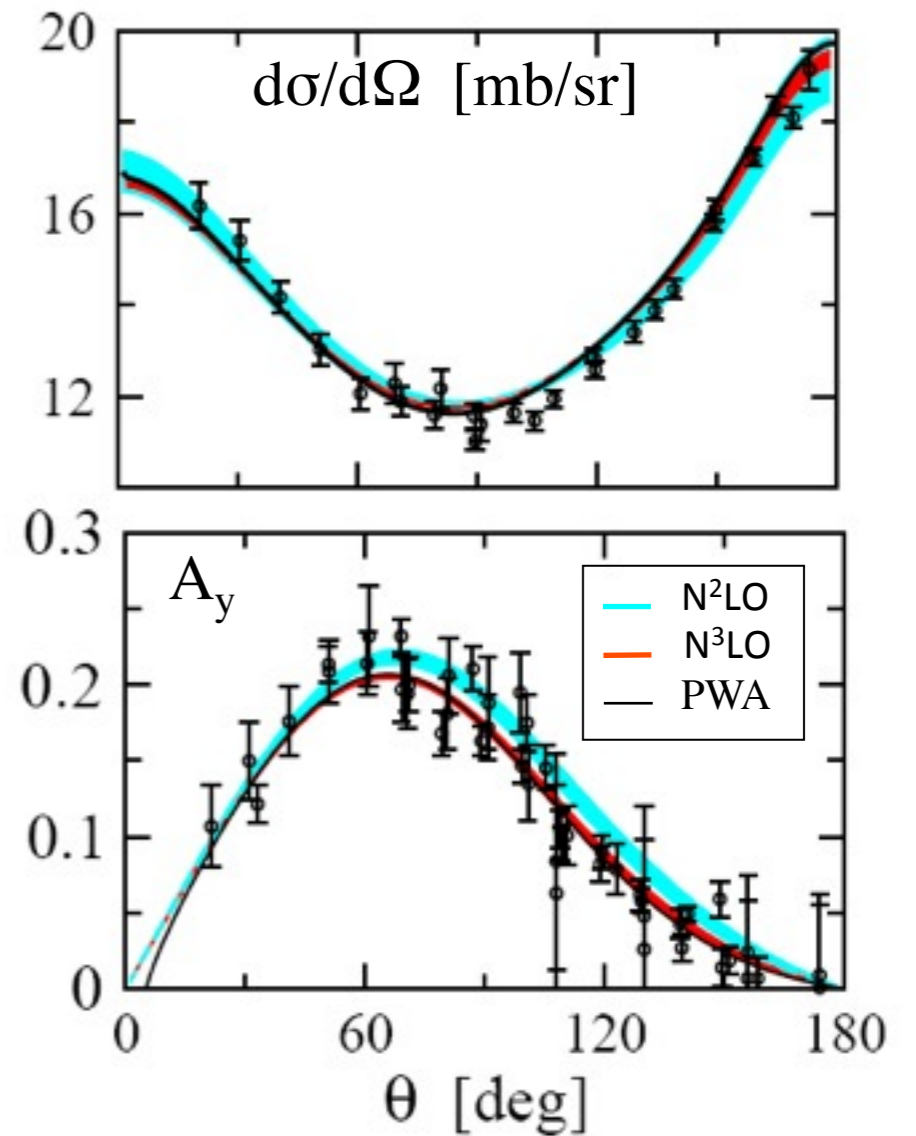


+ 1/m and isospin-breaking corrections...

Neutron-proton phase shifts up to N³LO



np scattering at 50 MeV



Deuteron binding energy & asymptotic normalizations A_s and η_d

	NLO	N ² LO	N ³ LO	Exp
E_d [MeV]	-2.171 ... - 2.186	-2.189 ... - 2.202	-2.216 ... - 2.223	-2.224575(9)
A_S [$\text{fm}^{-1/2}$]	0.868 ... 0.873	0.874 ... 0.879	0.882 ... 0.883	0.8846(9)
η_d	0.0256 ... 0.0257	0.0255 ... 0.0256	0.0254 ... 0.0255	0.0256(4)

Nuclear forces up to N^3LO

dimensional analysis counting

	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)			

- converged
- accurate description of NN at least up to $E_{lab} \sim 200$ MeV

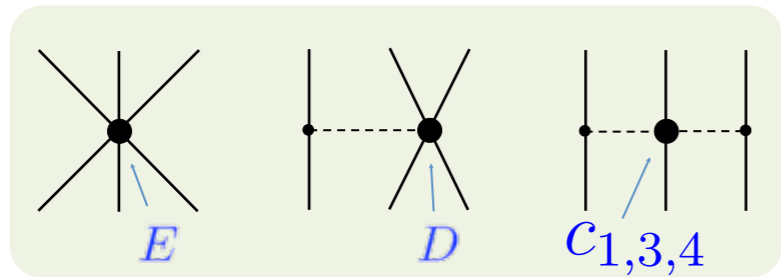
- not yet converged
- higher orders in progress
- impact on few- & many-N systems?

- converged ??
- presently out of reach for few- & many-N studies

Three-nucleon forces

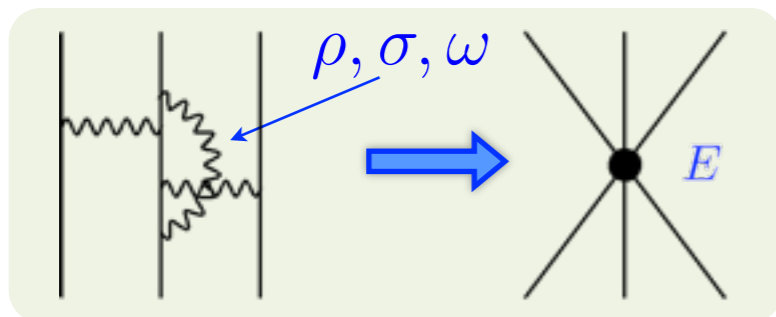
- Three-nucleon forces in chiral EFT start to contribute at NNLO

(U. van Kolck '94; Epelbaum et al. '02; Nogga et al. '05; Navratil et al. '07)

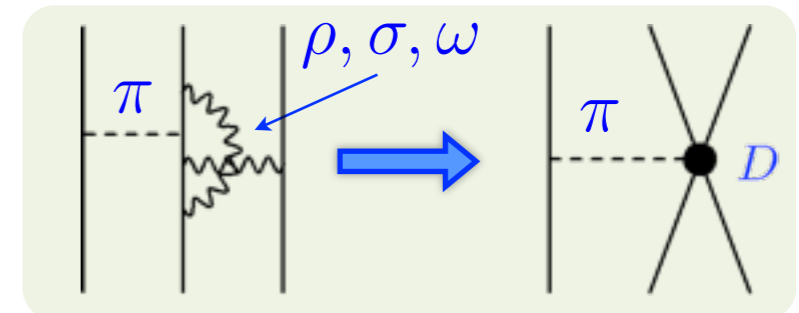


$C_{1,3,4}$ from the fit to πN -scattering data
 D, E from ${}^3\text{H}, {}^4\text{He}, {}^{10}\text{B}$ binding energy + coherent nd -scattering length

- LECs D and E incorporate short-range contr.

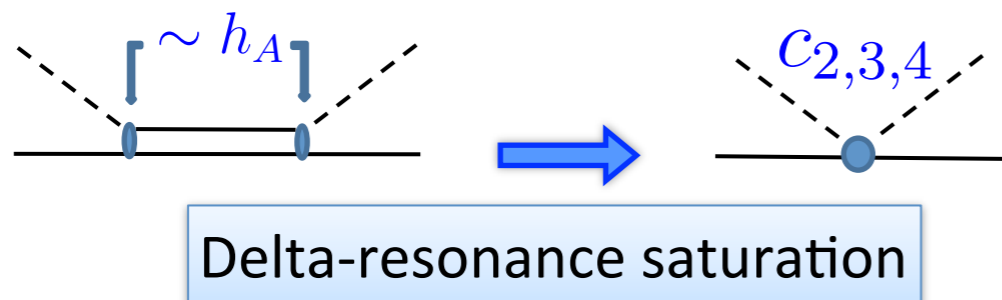


Resonance saturation interpretation of LECs



- Delta contributions encoded in LECs

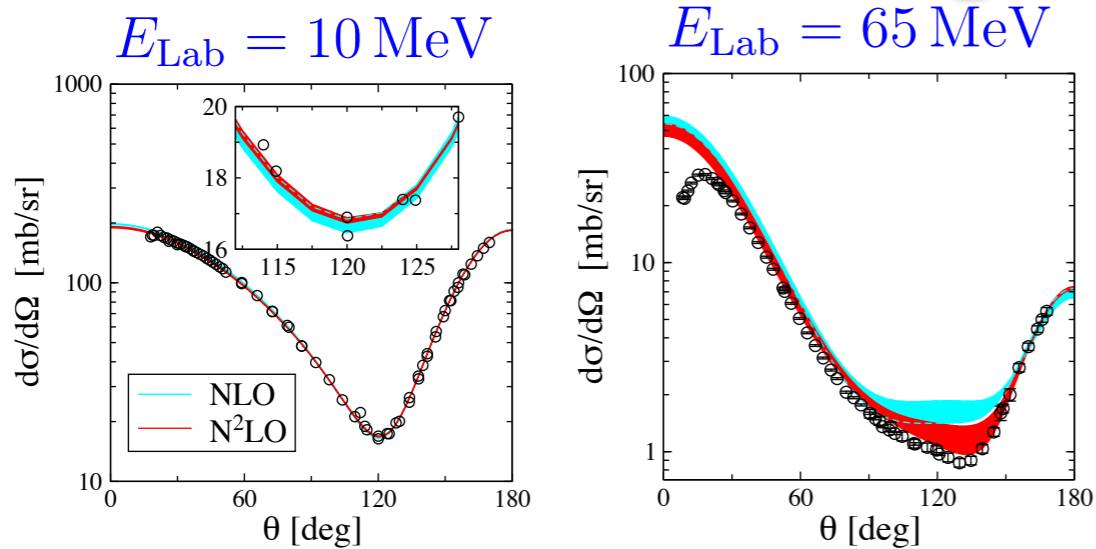
(Bernard, Kaiser & Meißner '97)



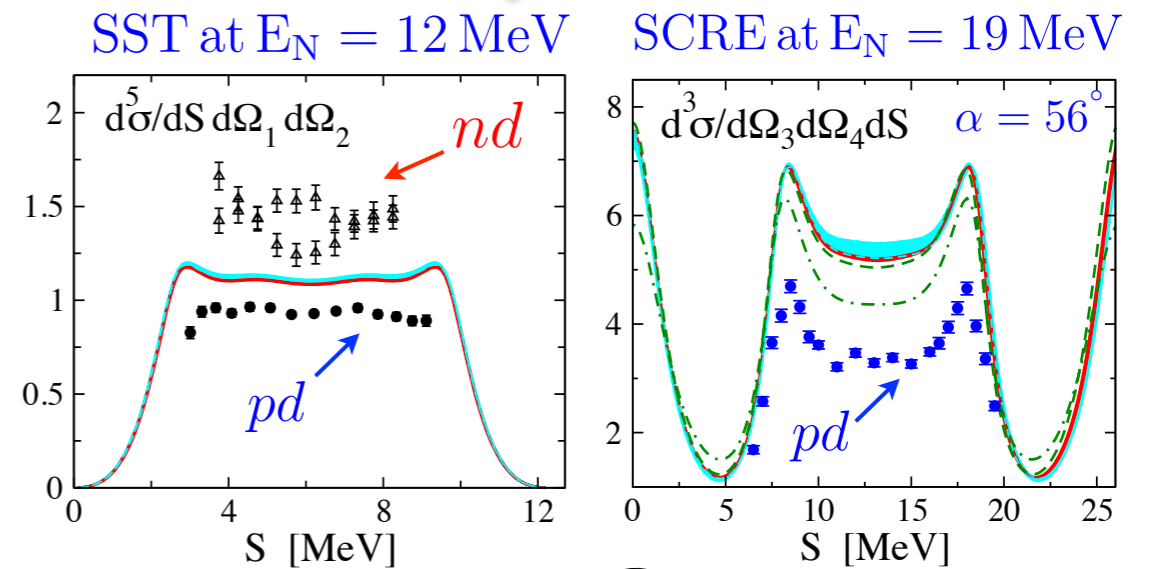
$$c_3 = -2c_4 = c_3(\Delta) - \frac{4h_A^2}{9\Delta}$$

Enlargement due to Delta contribution

nd elastic scattering



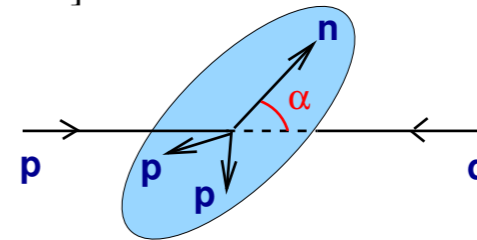
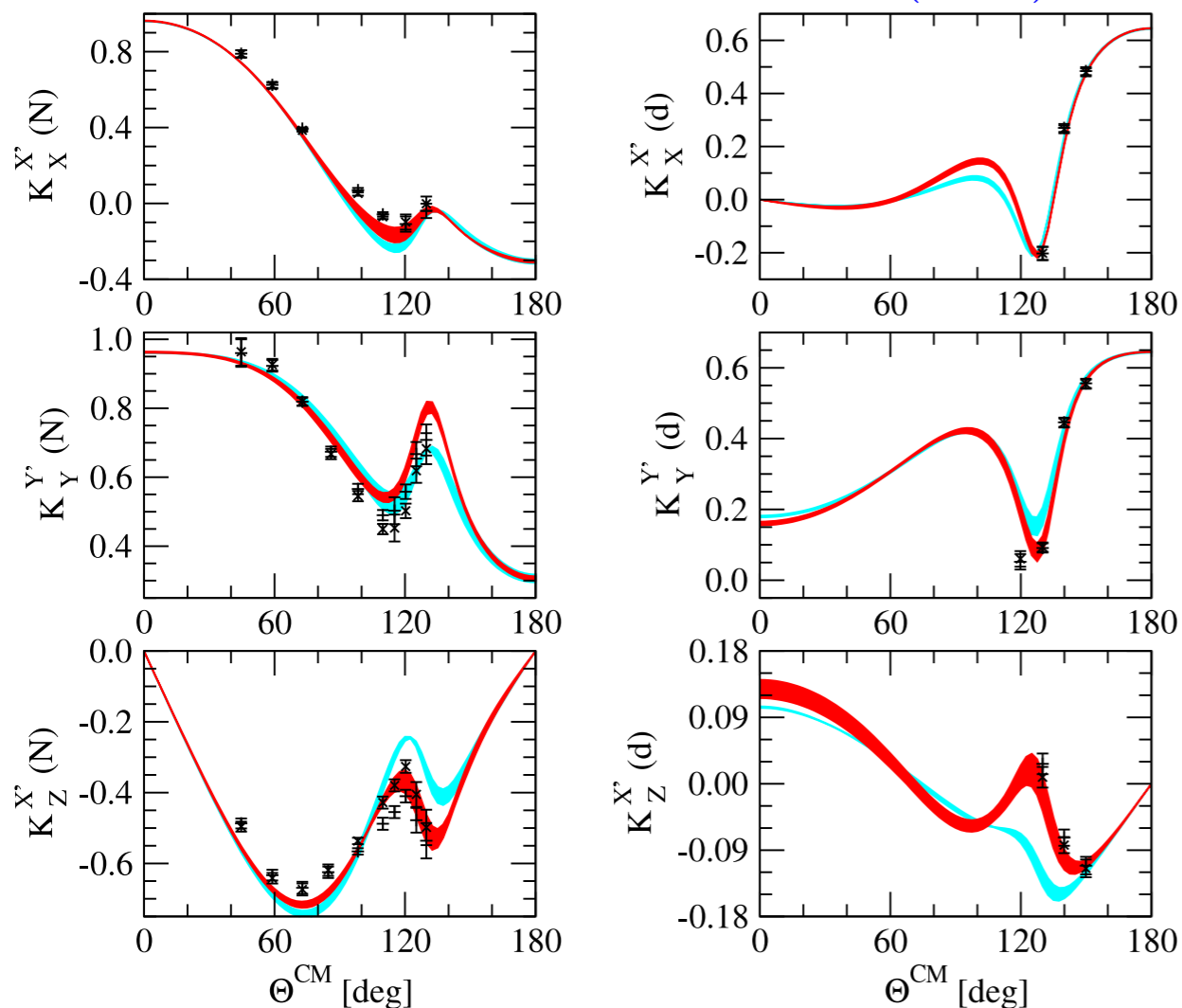
nd break-up [mb MeV⁻¹sr⁻²]



polarization transfer: $E_p^{\text{Lab}} = 22.7 \text{ MeV}$

$$d(\vec{p}, \vec{p})d$$

$$d(\vec{p}, \vec{d})p$$



For references see recent reviews:

- Epelbaum, Prog. Part Nucl. Phys. 57 (06) 654
- Epelbaum, Hammer, Meißner, Rev. Mod. Phys. 81 (09) 1773
- Entem, Machleidt, Phys. Rept. 503 (11) 1
- Epelbaum, Meißner, arXiv:1201.2136,
to appear in Ann. Rev. Nucl. Part. Sci.
- Kalantar et al. Rep. Prog. Phys. 75 (12) 016301

- Generally good description of data. But some discrepancies arise. E.g. break-up observables for SCRE/SST configuration at low energy
- Hope for improvement at N³LO

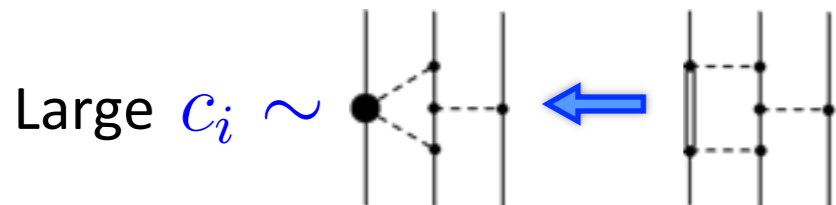
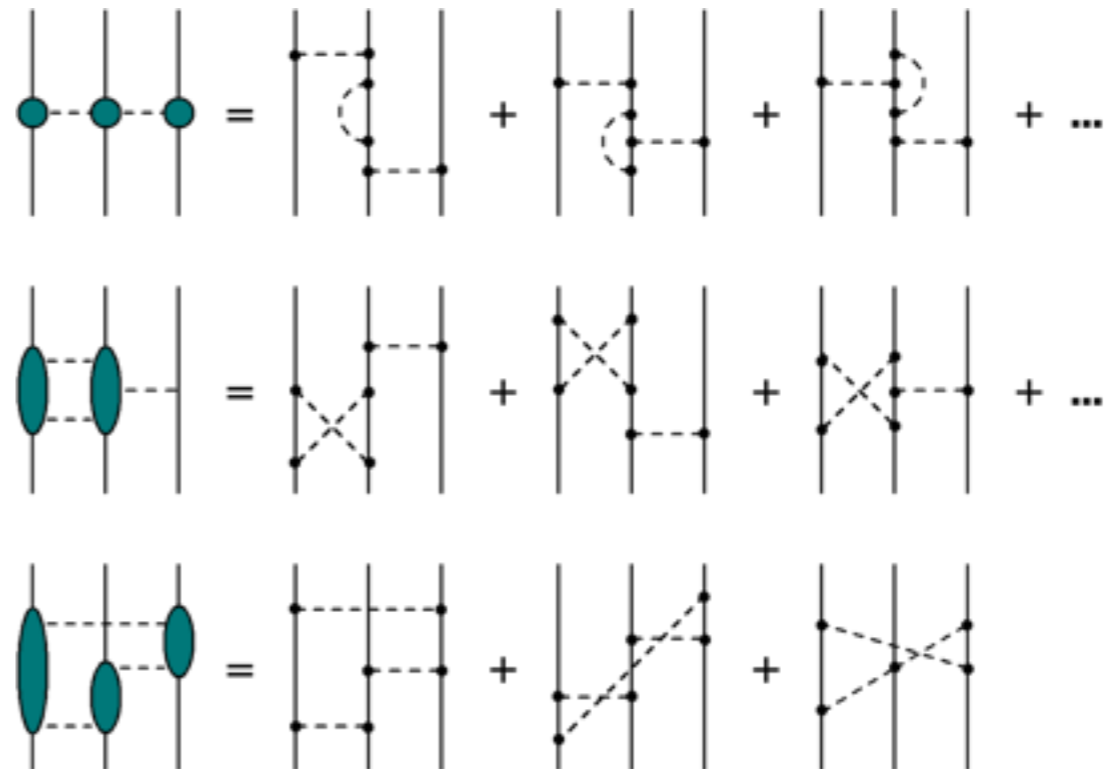
Three-nucleon forces

Three-nucleon forces at $N^3\text{LO}$

Long range contributions

Bernard, Epelbaum, H.K., Meißner '08; Ishikawa, Robilotta '07

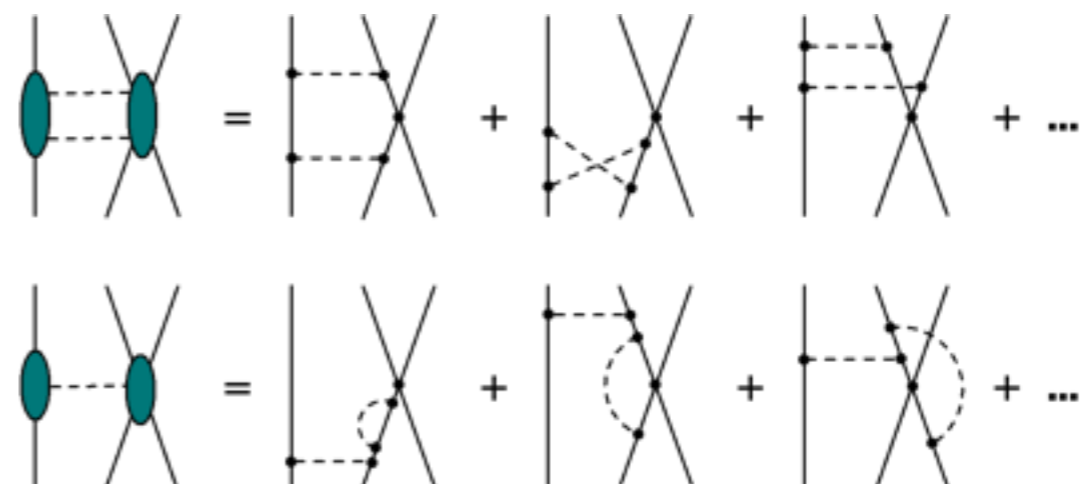
- No additional free parameters
- Expressed in terms of g_A, F_π, M_π
- Rich isospin-spin-orbit structure
- $\Delta(1232)$ -contr. are important



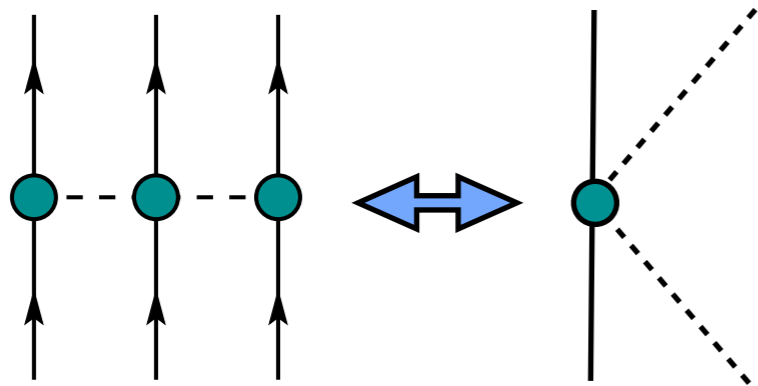
Shorter range contributions

Bernard, Epelbaum, H.K., Meißner '11

- LECs needed for shorter range contr.
 g_A, F_π, M_π, C_T
- Central NN contact interaction does not contribute
- Unique expressions in the static limit for a renormalizable 3NF



Two-pion-exchange 3NF



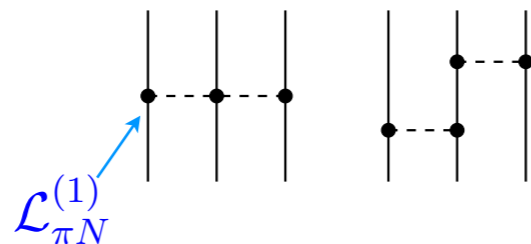
- Two-pion-exchange 3NF is connected to pion-nucleon scattering amplitude

Robilotta '07

- The same linear combinations of LECs
- The same renormalization

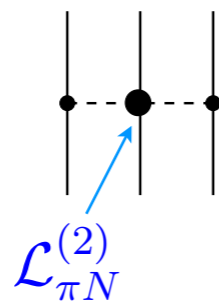
$$V_{2\pi} = \frac{\vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_3 \cdot \vec{q}_3}{[q_1^2 + M_\pi^2][q_3^2 + M_\pi^2]} \left(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \mathcal{A}(q_2) + \boldsymbol{\tau}_1 \times \boldsymbol{\tau}_3 \cdot \boldsymbol{\tau}_2 \vec{q}_1 \times \vec{q}_3 \cdot \vec{\sigma}_2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

NLO - contr.



← yield vanishing 3NF contributions

N²LO - contr.



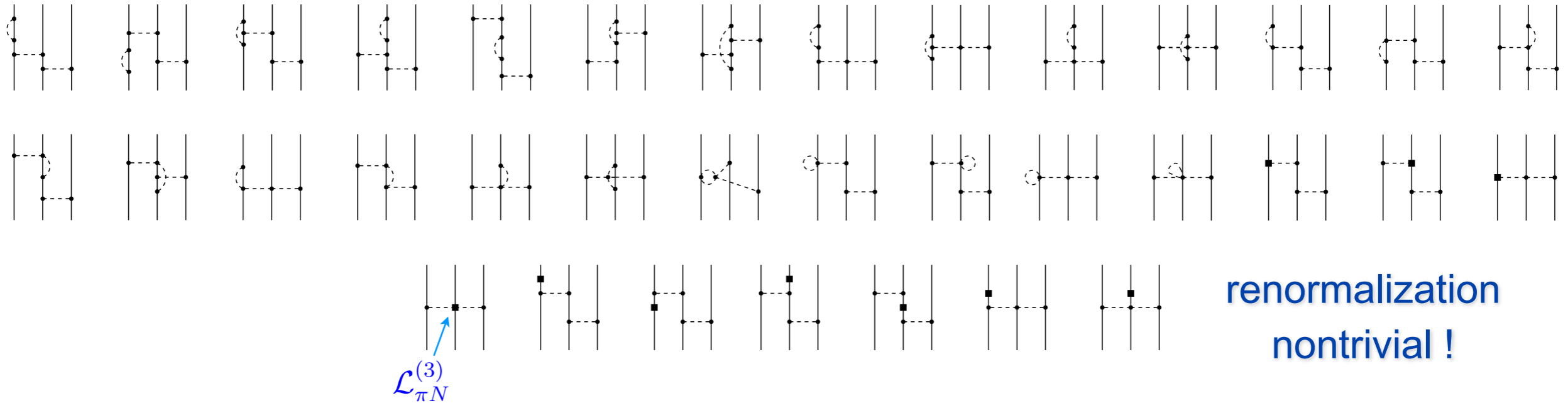
← first nonvanishing 3NF, encodes information about the Δ :



$$\mathcal{A}^{(3)}(q_2) = \frac{g_A^2}{8F_\pi^4} \left((2c_3 - 4c_1)M_\pi^2 + c_3 q_2^2 \right), \quad \mathcal{B}^{(3)}(q_2) = \frac{g_A^2 c_4}{8F_\pi^4} \quad \text{van Kolck '94}$$

Two-pion-exchange 3NF

N³LO - contr. (leading 1 loop)



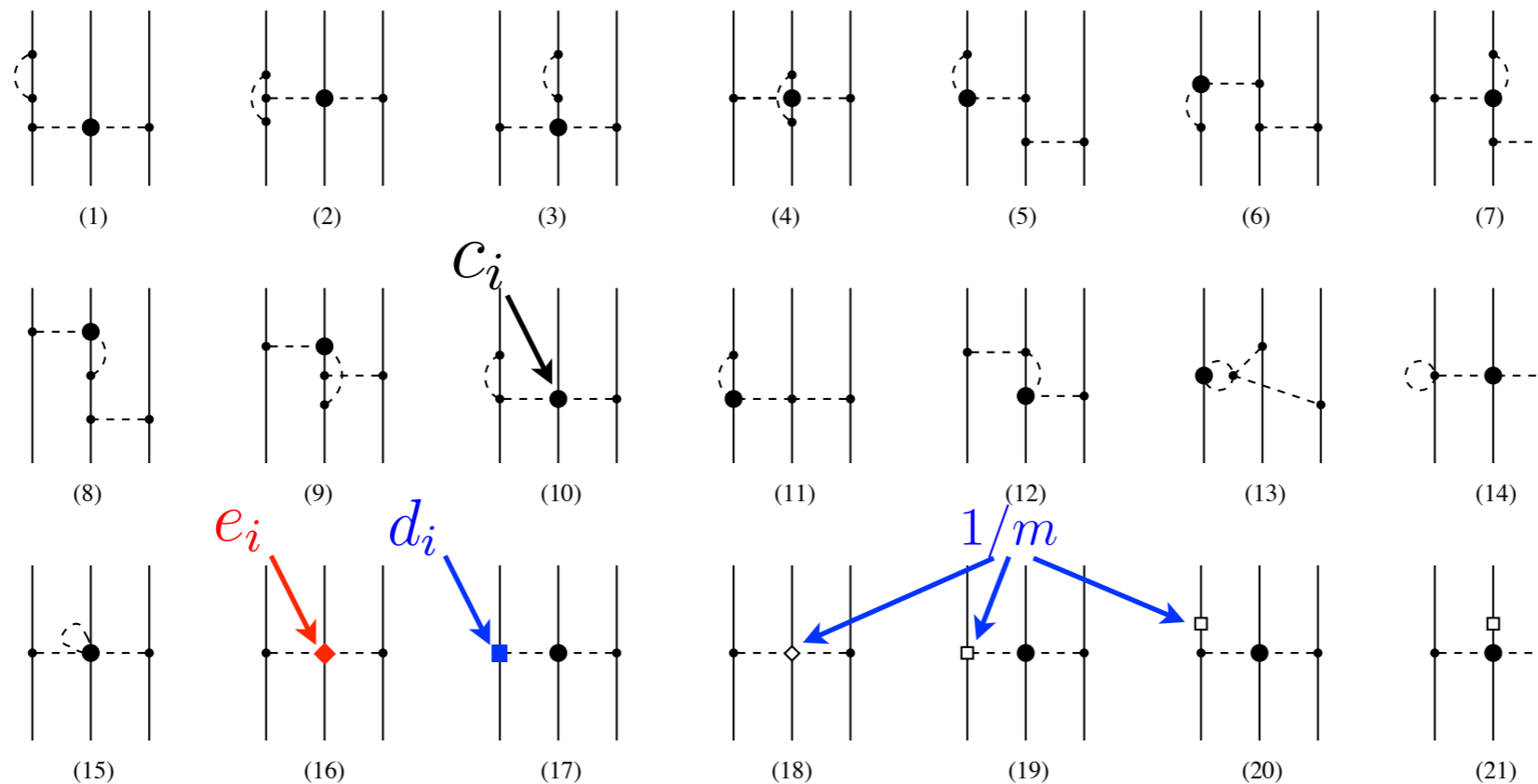
$$\mathcal{A}^{(4)}(q_2) = \frac{g_A^4}{256\pi F_\pi^6} \left[A(q_2) \left(2M_\pi^4 + 5M_\pi^2 q_2^2 + 2q_2^4 \right) + \left(4g_A^2 + 1 \right) M_\pi^3 + 2 \left(g_A^2 + 1 \right) M_\pi q_2^2 \right],$$

$$\mathcal{B}^{(4)}(q_2) = -\frac{g_A^4}{256\pi F_\pi^6} \left[A(q_2) \left(4M_\pi^2 + q_2^2 \right) + \left(2g_A^2 + 1 \right) M_\pi \right] \text{ Robilotta '07, Bernard, Epelbaum, HK, Meißner '07}$$

- No unknown parameters at this order
- Everything is expressed in terms of loop function $A(q) = \frac{1}{2q} \arctan \frac{q}{2M_\pi}$
- Additional unitarity transformations required for proper renormalization

Two-pion-exchange 3NF

N⁴LO - contr. (subleading 1 loop) *Epelbaum, Gasparyan, H.K., '12*



C_i 's LECs from $\mathcal{L}_{\pi N}^{(2)}$, d_i 's LECs from $\mathcal{L}_{\pi N}^{(3)}$, e_i 's LECs from $\mathcal{L}_{\pi N}^{(4)}$: fitted to πN - scattering data

- Leading Δ - contributions are taken into account through C_i 's
- Vanishing $1/m$ - contributions at this order

Two-pion-exchange 3NF at N⁴LO

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

Some LECs can be absorbed by shifting c_i 's

$$\begin{aligned}
 c_1 &\rightarrow c_1 - 2M_\pi^2 \left(\bar{e}_{22} - 4\bar{e}_{38} - \frac{\bar{l}_3 c_1}{F_\pi^2} \right), \\
 c_3 &\rightarrow c_3 + 4M_\pi^2 \left(2\bar{e}_{19} - \bar{e}_{22} - \bar{e}_{36} + 2\frac{\bar{l}_3 c_1}{F_\pi^2} \right), \\
 c_4 &\rightarrow c_4 + 4M_\pi^2 (2\bar{e}_{21} - \bar{e}_{37}),
 \end{aligned}$$

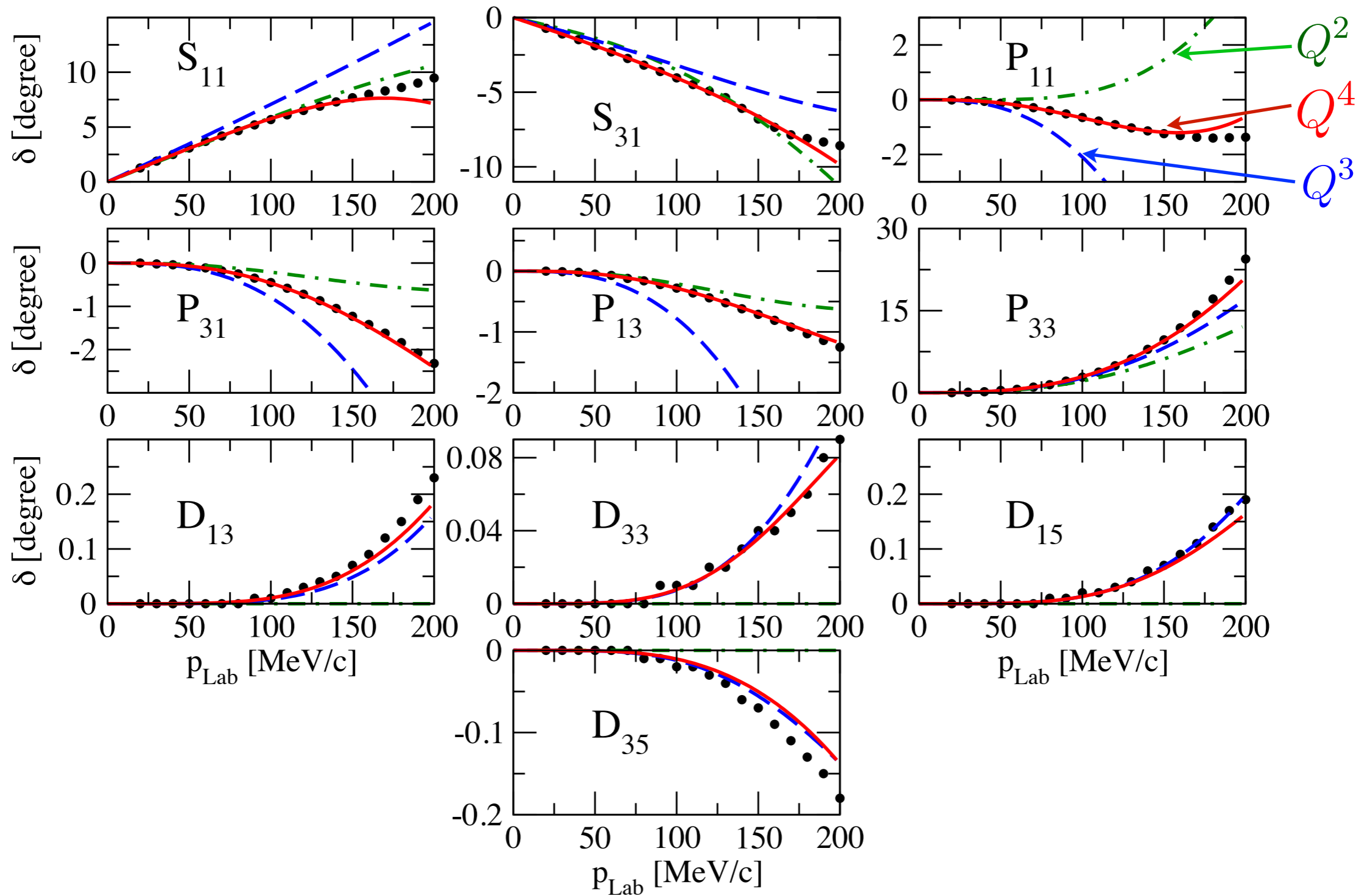
$$g_{\pi NN} = \frac{g_A m}{F_\pi} \left(1 - \frac{2M_\pi^2 \bar{d}_{18}}{g_A} \right) \leftarrow \text{Violation of Goldberger-Treiman relation}$$

$$L(q) = \frac{\sqrt{q^2 + 4M_\pi^2}}{q} \log \frac{\sqrt{q^2 + 4M_\pi^2} + q}{2M_\pi}$$

- No d_i dependence of TPE-contr. besides d_{18}
- Pion-nucleon scattering does strongly depend on d_i 's

KH-Fit to pion-nucleon scattering

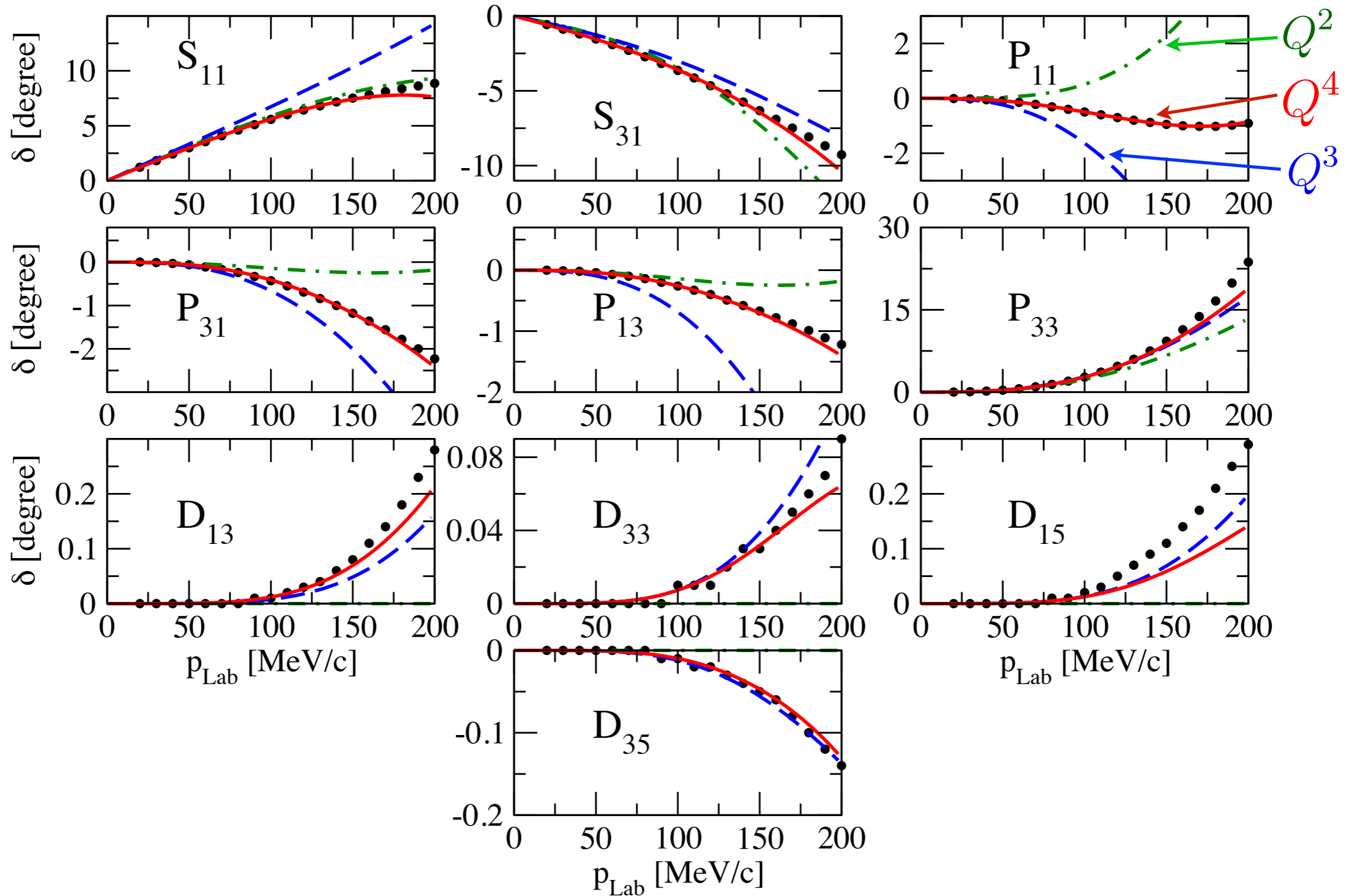
KH-PWA: R. Koch Nucl. Phys. A 448 (1986) 707



Data fitted for $p_{\text{Lab}} < 150$ MeV

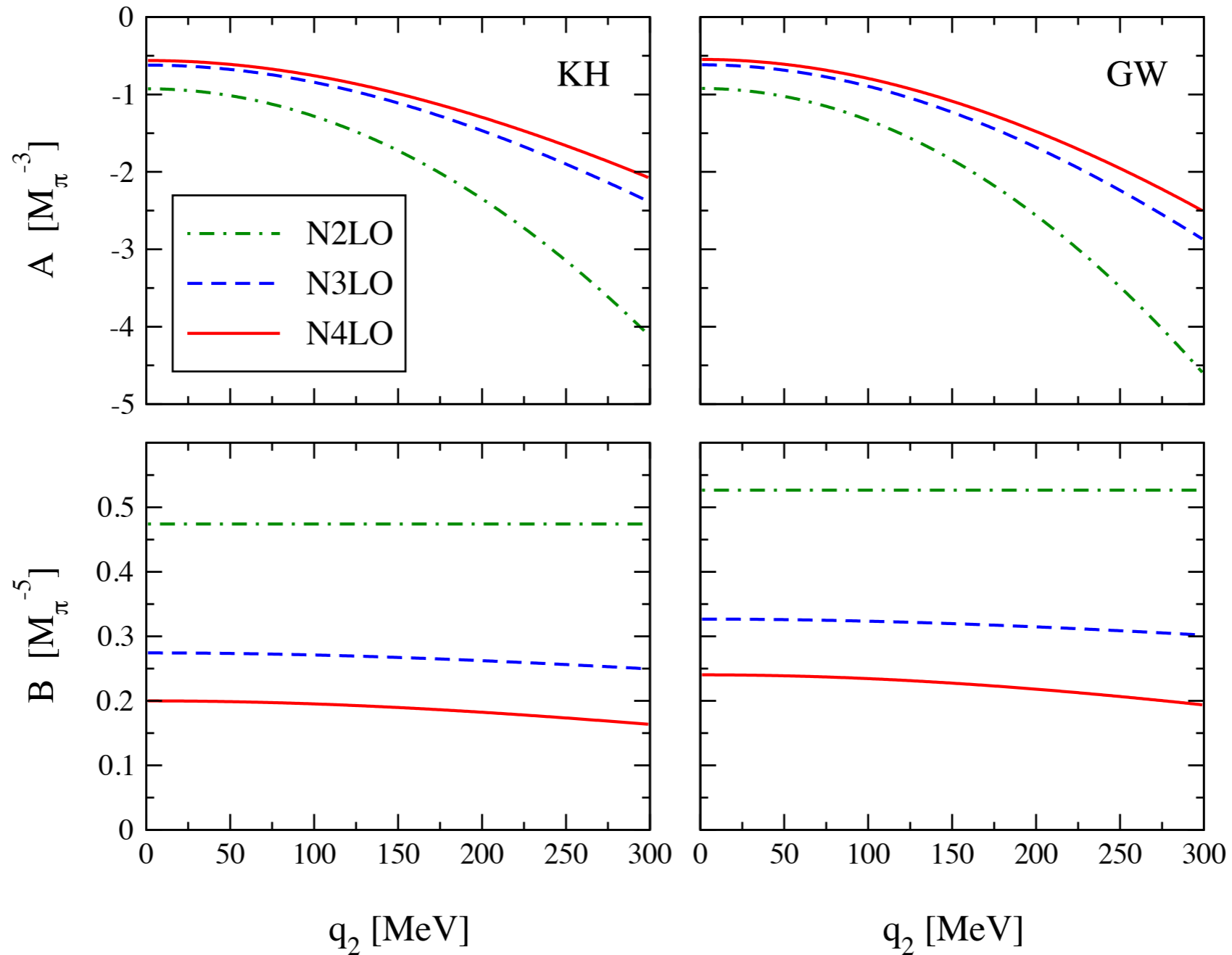
GW-Fit to pion-nucleon scattering

GW-PWA: Arndt et al. Phys. Rev. C 74 (2006) 045205



Data fitted for $p_{\text{Lab}} < 150$ MeV

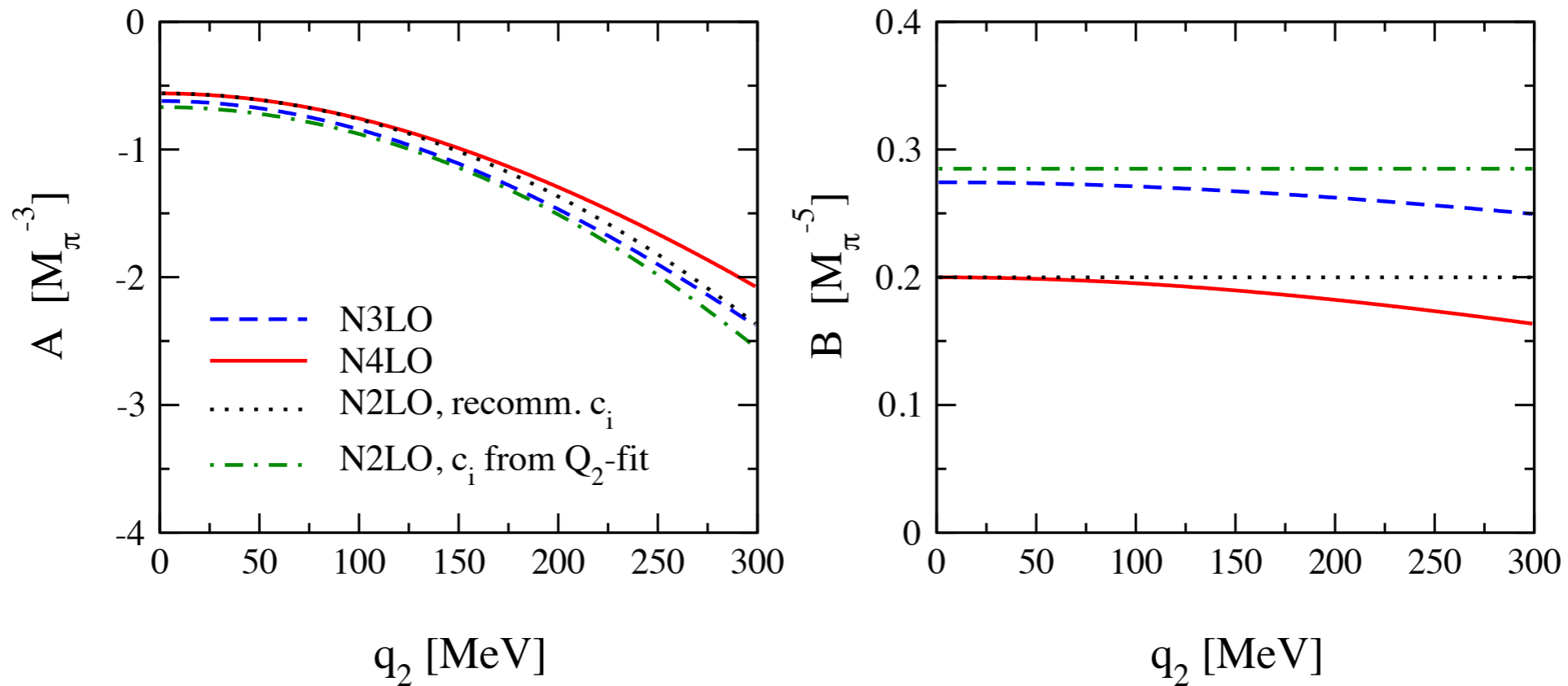
Two-pion-exchange at N⁴LO



	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}
GW-fit	-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
KH-fit	-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

- No dependence on d_i 's
- e_i 's are of natural size
- Good convergence of TPE 3NF

Working with N²LO 3NF



Recommended c_i 's by working with N²LO 3NF

$$c_1^{\text{KH}} = -0.37 \text{ GeV}^{-1}, \quad c_3^{\text{KH}} = -2.71 \text{ GeV}^{-1}, \quad c_4^{\text{KH}} = 1.41 \text{ GeV}^{-1},$$

$$c_1^{\text{GW}} = -0.73 \text{ GeV}^{-1}, \quad c_3^{\text{GW}} = -3.38 \text{ GeV}^{-1}, \quad c_4^{\text{GW}} = 1.69 \text{ GeV}^{-1}.$$

- With these parameters we get at $q_2 = 0$ the value and slope of N⁴LO result
- c_i 's fitted to pion-nucleon Q^2 (KH-fit) lead to slightly different results for B-function

$$c_1 = -0.25 \text{ GeV}^{-1}, \quad c_2 = 2.02 \text{ GeV}^{-1}, \quad c_3 = -2.80 \text{ GeV}^{-1}, \quad c_4 = 2.01 \text{ GeV}^{-1}.$$

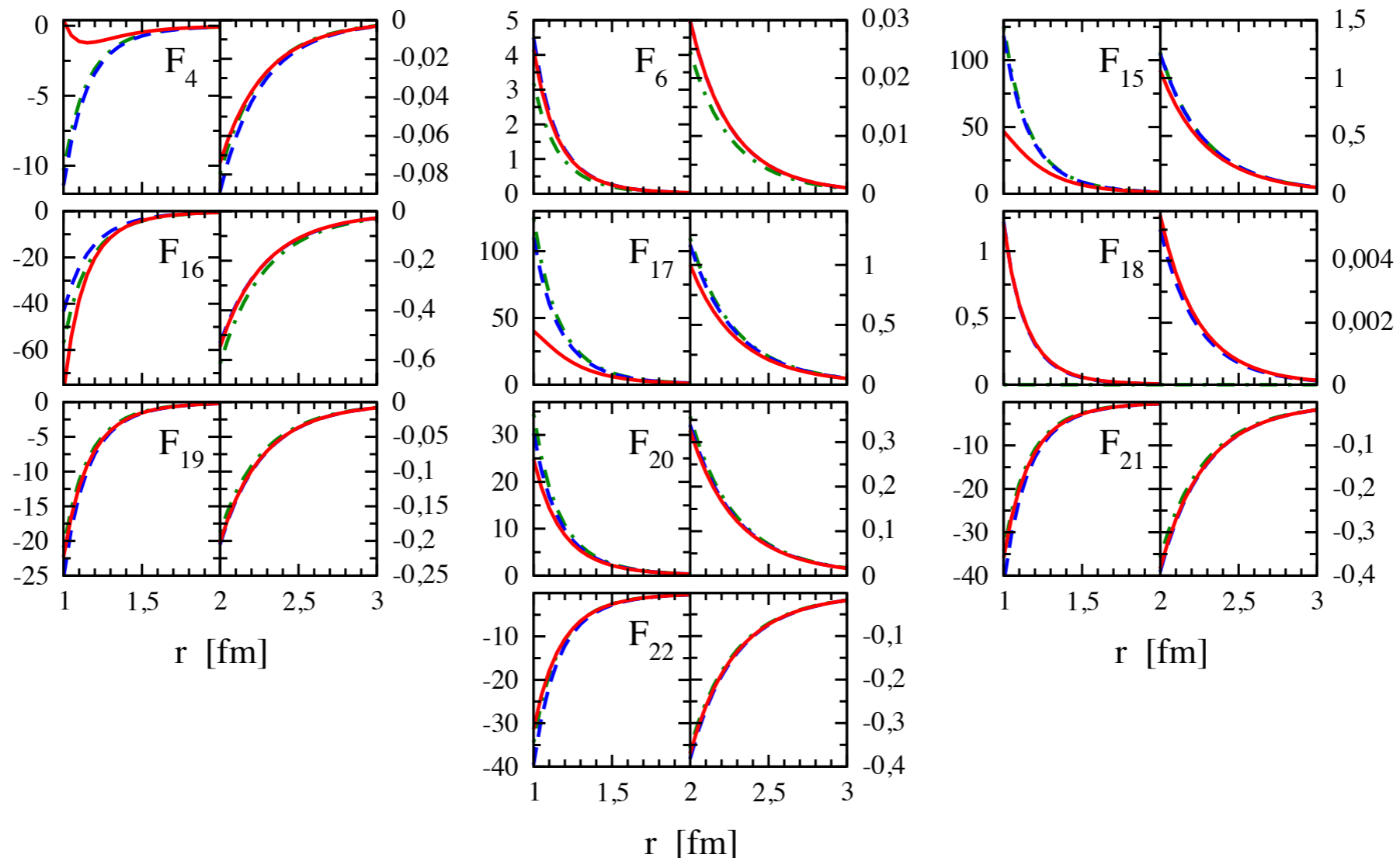
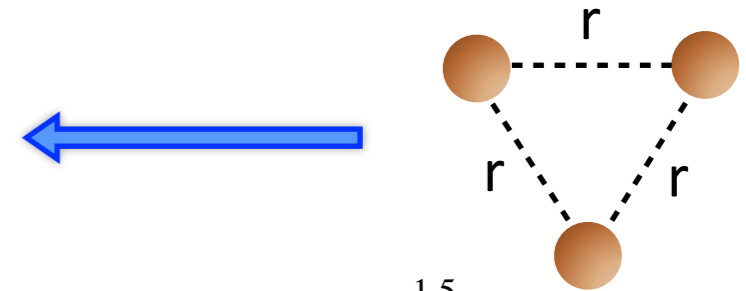
Two-pion-exchange up to N⁴LO

Epelbaum, Gasparyan, H.K., in preparation

Most general, local 3NF involves 89 operators, can be generated (by perm.) from **22 structures**

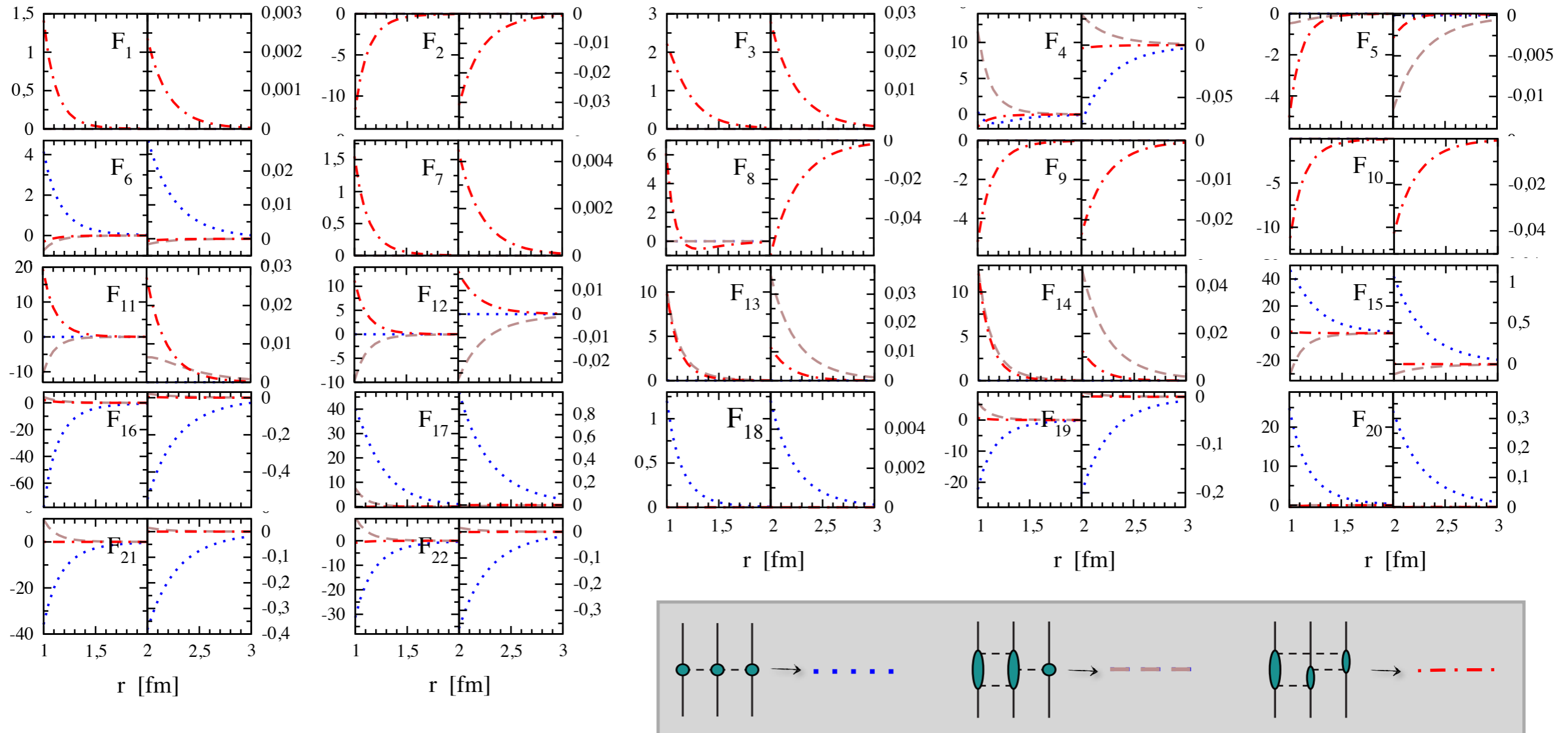
$$V_{3N}^{\text{loc.}} = \sum_{i=1}^{22} \mathcal{G}_i F_i(r_{12}, r_{23}, r_{31}) + 5 \text{ perm.} \quad \text{with} \quad \mathcal{G}_1 = 1, \quad \mathcal{G}_2 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2, \quad \mathcal{G}_3 = \vec{\sigma}_1 \cdot \vec{\sigma}_3, \quad \dots$$

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



Complete long-range 3NF up to N⁴LO

Epelbaum, Gasparyan, H.K., in preparation



- Predictions based entirely on chiral symmetry + input from πN , benchmarks for lattice-QCD
- Implications for Nd, light nuclei & nuclear matter? (*work in progress ...*)
- $2\pi - 1\pi$ and ring-topology: already converged? ChPT with explicit Δ 's (*work in progress ...*)

Summary

- Chiral nuclear forces are analyzed up to N^3LO
- Long-range part of chiral three-nucleon forces is analyzed up to N^4LO
- In general there are 89 spin-isospin structures in local 3NF's built out of 22 + perm.
- Two-pion-exchange part dominates 3NF but does not fill all 22 structures
- With two-pion-one-pion-exchange and ring diagrams all 22 structures are filled

Outlook

- Partial wave decomposition of N^3LO three-nucleon forces
- Complete study of 3NF and 4NF up to N^4LO with explicit delta-isobar
- Implementations in Nd, light nuclei & nuclear matter

Most general structure of a local 3NF

Epelbaum, Gasparyan, H.K., in preparation

Up to N⁴LO, the computed contributions are local \longrightarrow it is natural to switch to r-space.

A meaningful comparison requires a **complete set of independent operators**

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

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

$$V_{3N}^{\text{loc.}} = \sum_{i=1}^{22} \mathcal{G}_i + 5 \text{ perm.}$$

The generators \mathcal{G}_i are defined as:

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

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

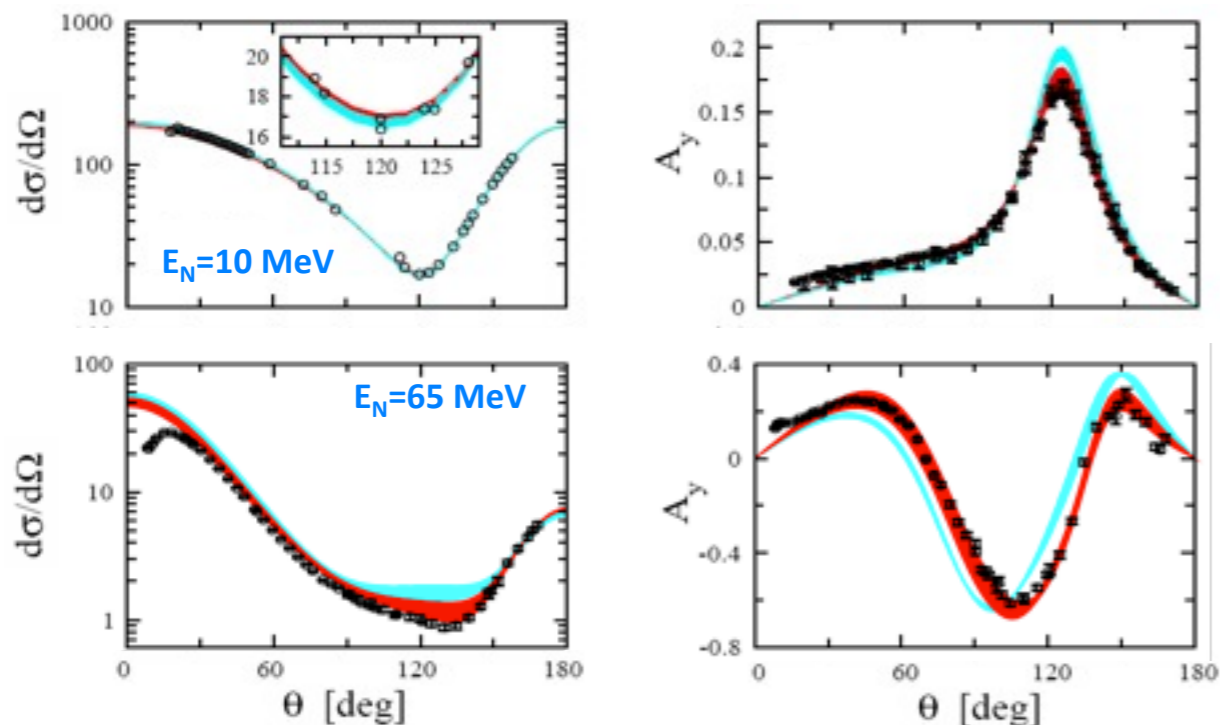
$$G_2(\mathcal{O}) := \frac{\sqrt{3}}{2} [S_{23} S_{13} - S_{12} S_{13}] (\mathcal{O})$$

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

Nd elastic scattering

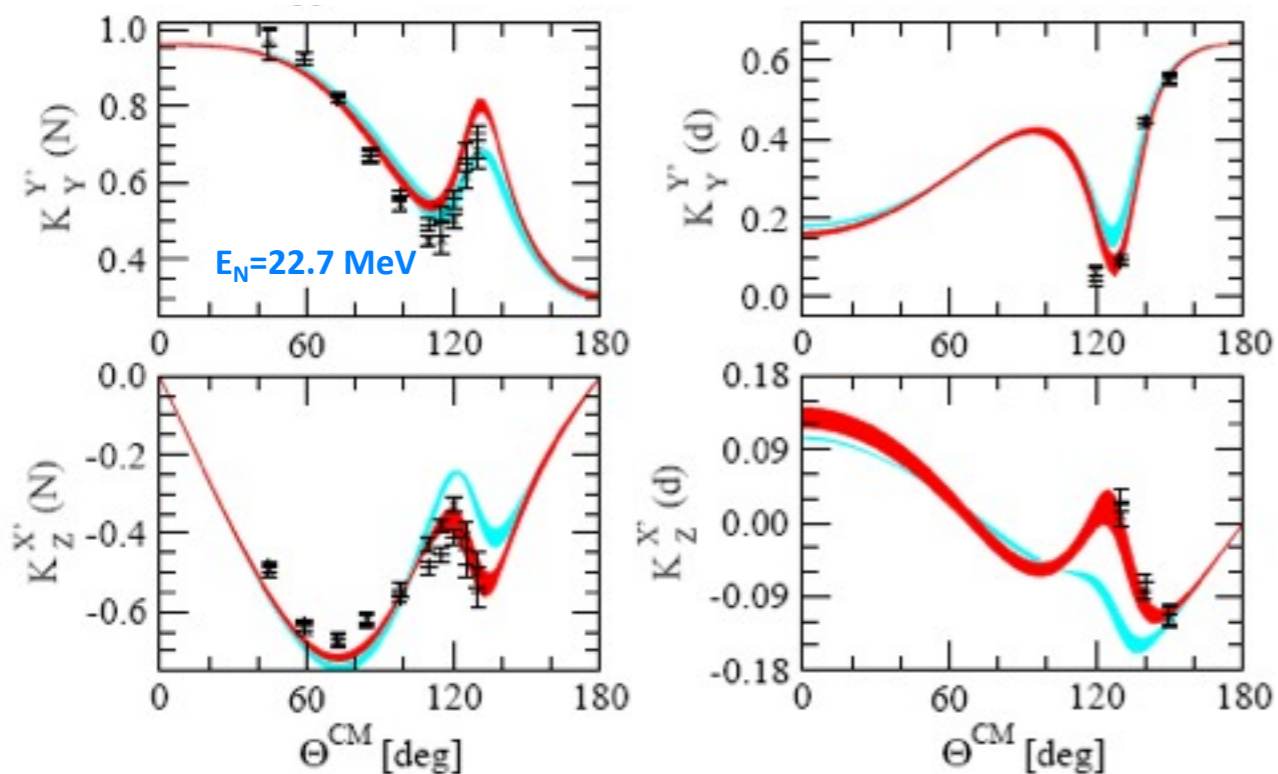
Cross section & vector analyzing power

E. pelbaum, PPNP 57 (2006) 654



Polarization transfer coefficients

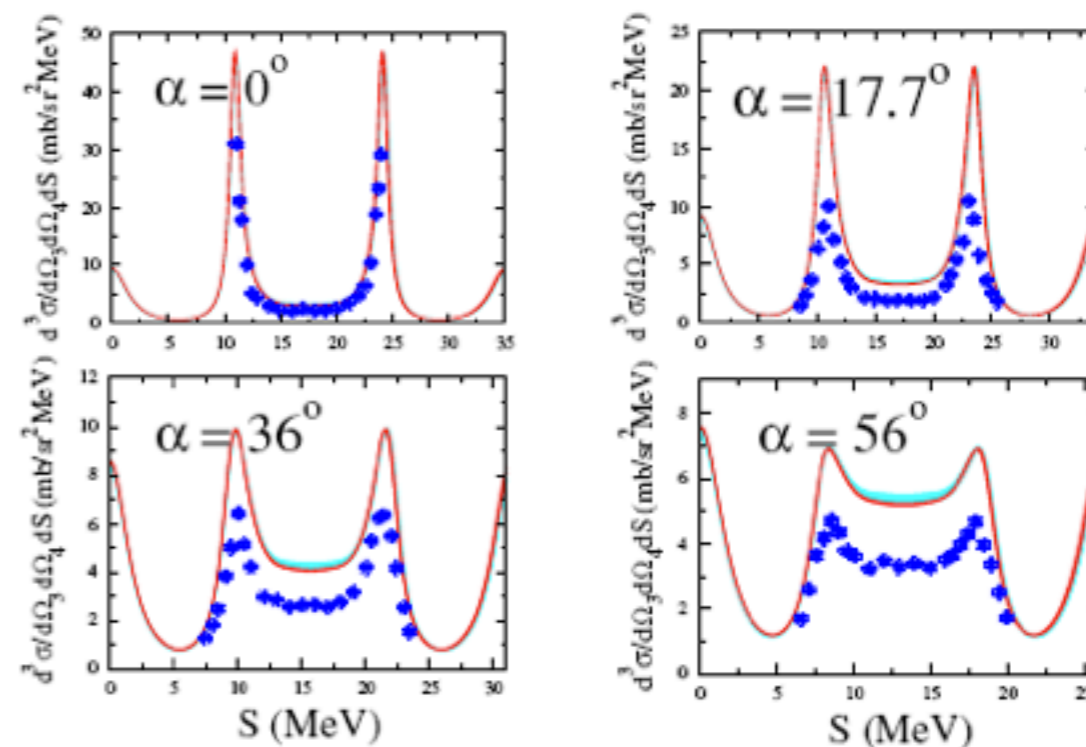
Witala et al., PRC 73 (2006) 044004



Deuteron break-up

SCRE configuration at Ed=19 MeV

Ley et al., PRC 73 (2006) 064001



- Promising NNLO results for Nd elastic scattering
- Generally good description of break-up observables except for SCRE/SST break-up configuration at low energy
- Hope for improvement at N³LO