Chiral EFT for nuclear forces with Δ(1232) degrees of freedom

Hermann Krebs

FZ Jülich & Universität Bonn

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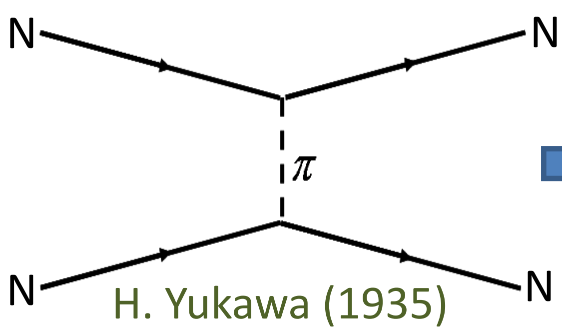
With V. Bernard, E. Epelbaum, U. Meißner

Outline

- Nuclear forces in chiral EFT
- The role of Δ(1232)-isobar
- Summary & Perspectives

Nucleon-Nucleon forces

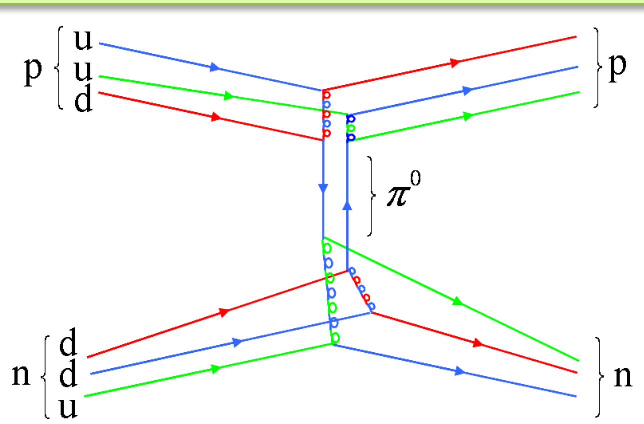
Phenomenological description by Meson-exchange



- Boson-Exchange Models as basis for NN-force
- Highly sophisticated phen. NN potentials
- Excelent description of many experimental data
- Connection to QCD is unclear

QCD Interpretation of NN forces

- NN force as residual strong interaction between handrons



Chiral EFT Interpretation of NN forces

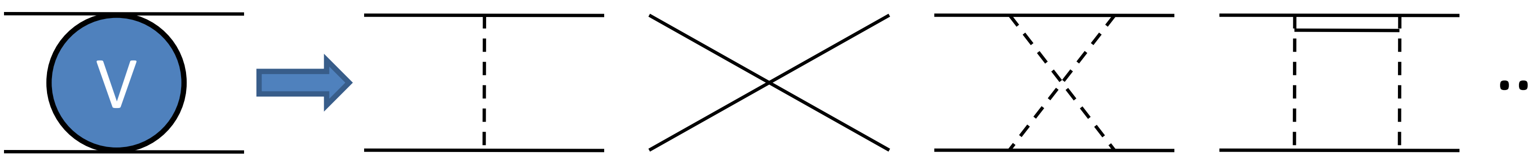
- Model independent treatment
- At low energies NN force dominated by Goldstone Boson dynamics + short range int.
- Systematic perturbative description of few nucleon potentials
- Underlying QCD symmetries implemented by construction

Weinberg's scheme for NN

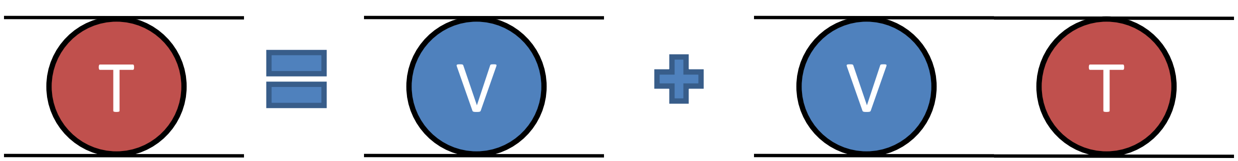
Weinberg, Nucl. Phys. B 363: 3 (1991)

- No perturbative description for bound states

- Construct effective potential perturbatively



- Solve Lippmann-Schwinger equation nonperturbatively

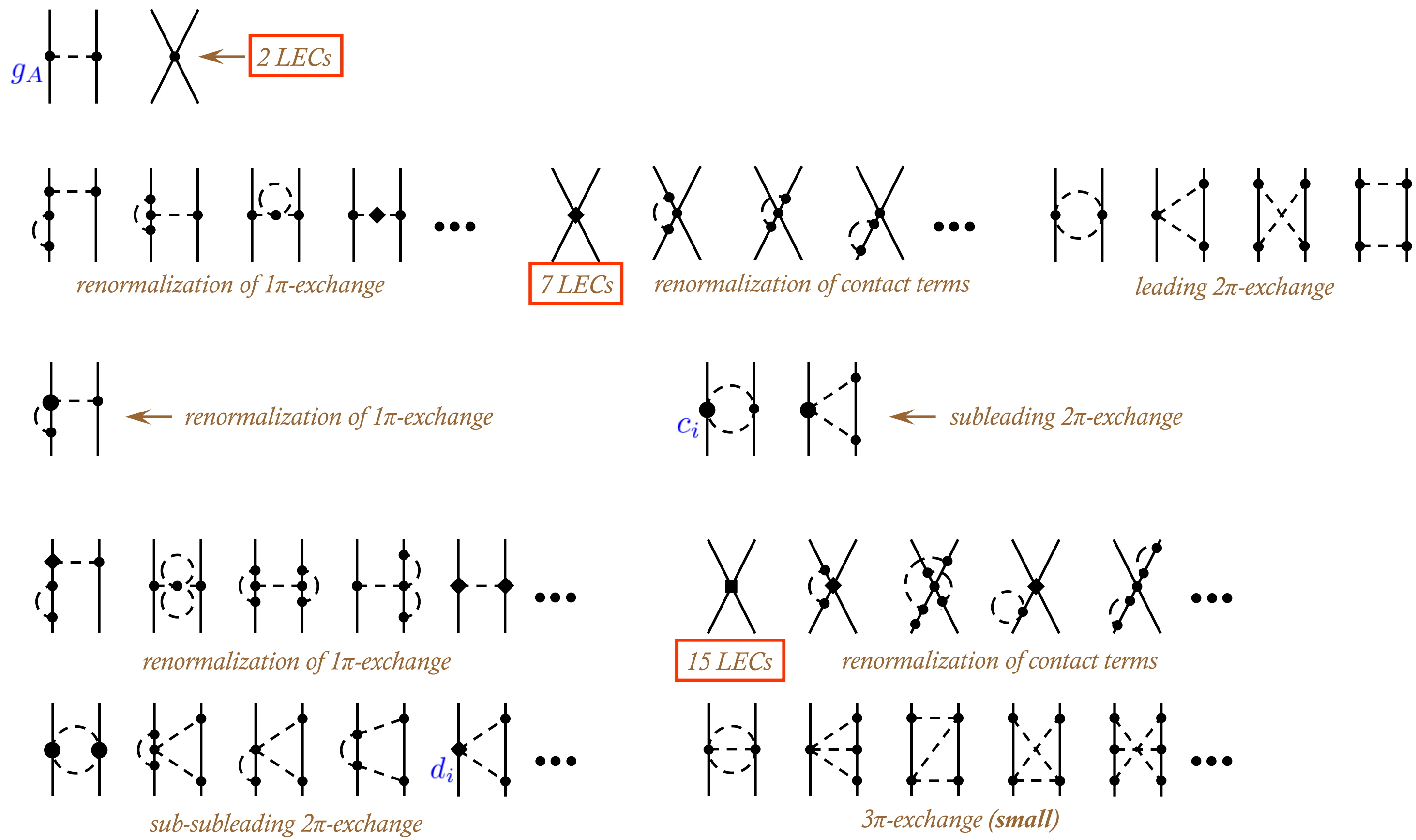


Nucleon-nucleon force up to N^{3}LO

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

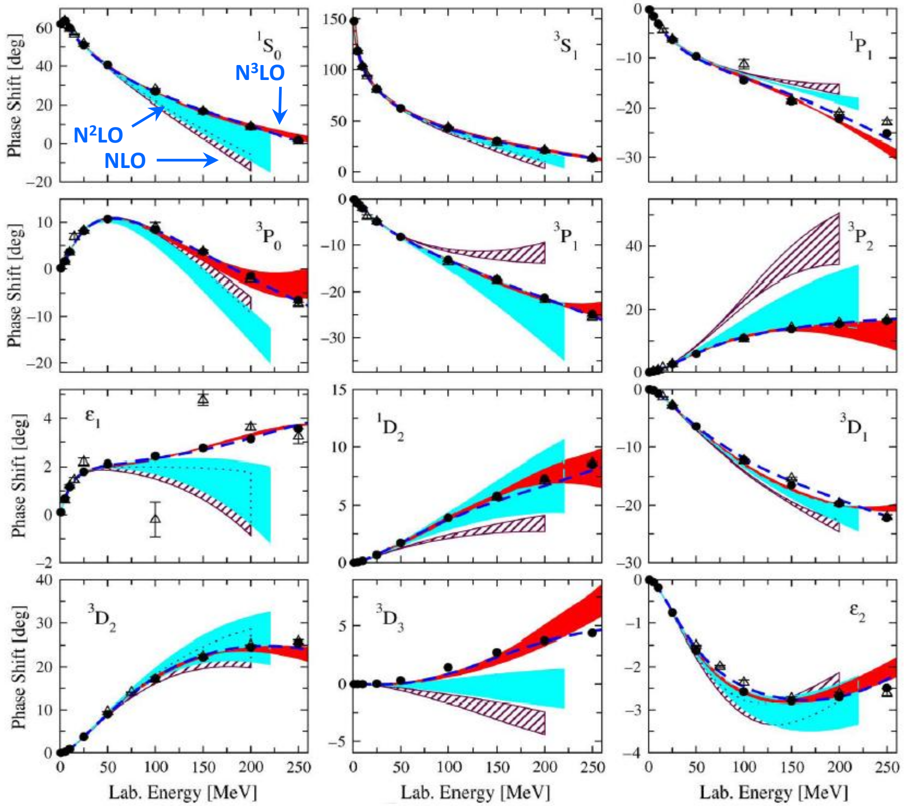
Chiral expansion for the 2N force: $V_{2N} = V_{2N}^{(0)} + V_{2N}^{(2)} + V_{2N}^{(3)} + V_{2N}^{(4)} + \ldots$

- LO:
- NLO:
- N^{2}LO:
- N^{3}LO:

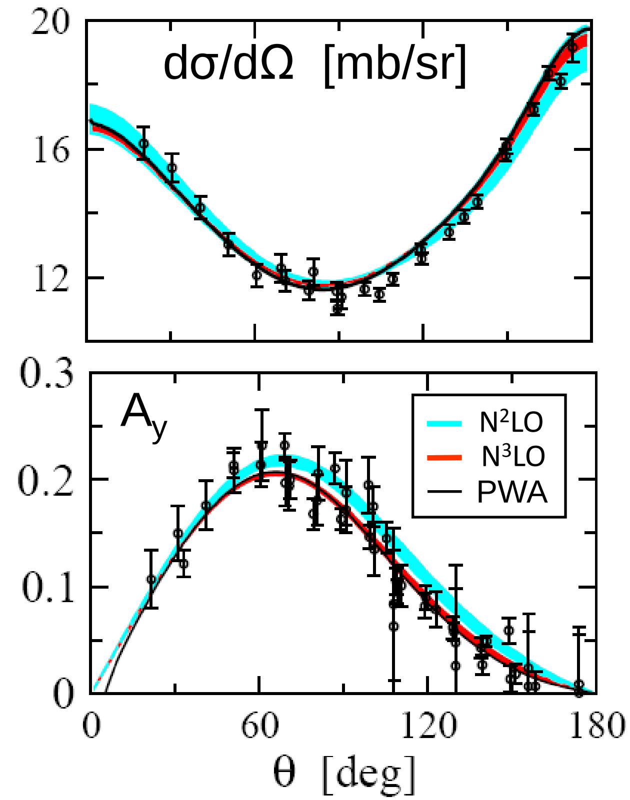


+ 1/m and isospin-breaking corrections…

Neutron-proton phase shifts up to N^{3}LO



np scattering at 50 MeV



Deuteron binding energy & asymptotic normalizations A_s and η_d

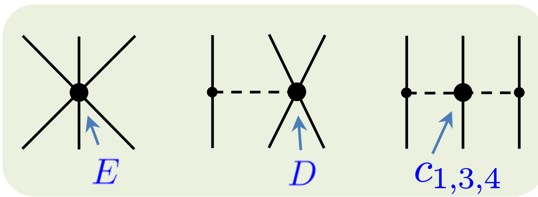
	NLO	N^{2}LO	N^{3}LO	Exp
E_d [MeV]	$-2.171\ldots-2.186$	$-2.189\ldots-2.202$	$-2.216\ldots-2.223$	$-2.224575(9)$
A_S [fm$^{-1/2}$]	$0.868\ldots0.873$	$0.874\ldots0.879$	$0.882\ldots0.883$	$0.8846(9)$
η_d	$0.0256\ldots0.0257$	$0.0255\ldots0.0256$	$0.0254\ldots0.0255$	$0.0256(4)$

Entem & Machleidt '03; Epelbaum, Glöckle & Meißner '05

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

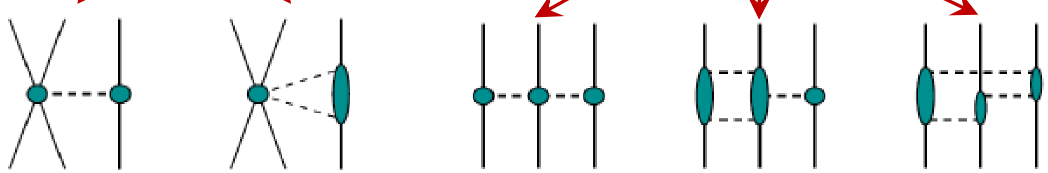
D, E from $^3H, ^4He, ^{10}B$ binding energy + coherent nd scattering length

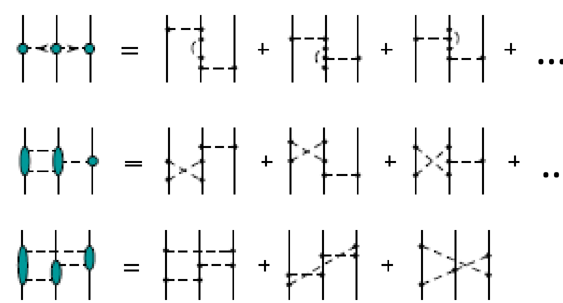
- Three-nucleon forces at N^{3}LO

Short range contr. under construction

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

Long range contributions



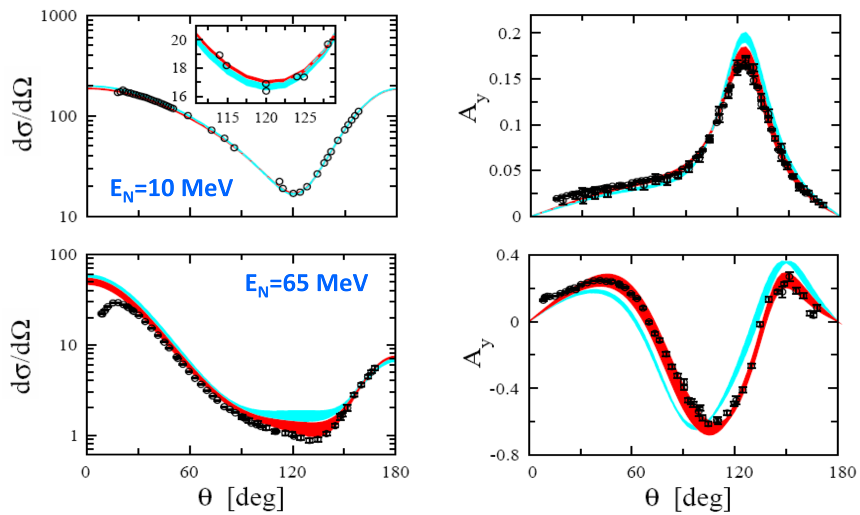


- No additional free parameters at N^{3}LO
- Rich isospin-spin-orbit structure of N^{3}LO 3NF

Nd elastic scattering

Cross section & vector analyzing power

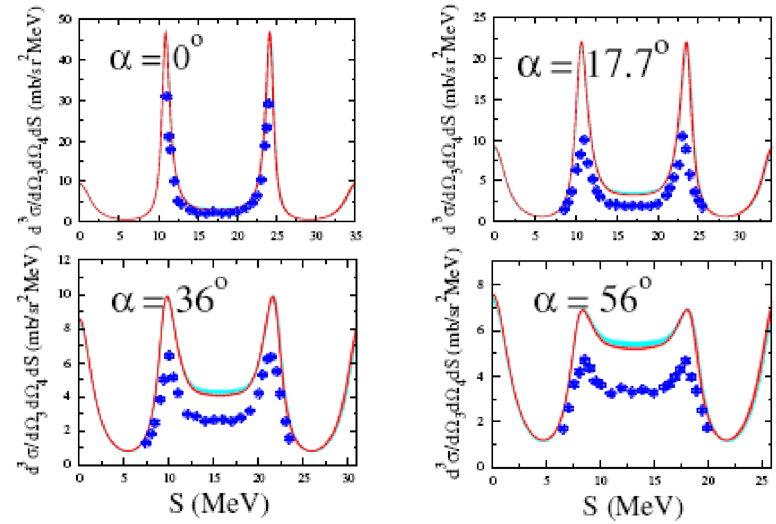
E.pelbaum, PPNP 57 (2006) 654



Deuteron break-up

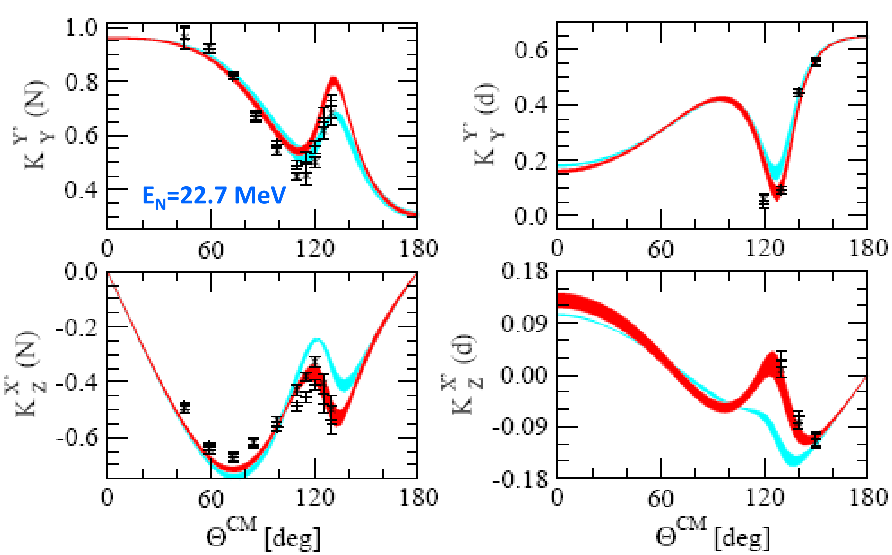
SCRE configuration at E_d=19 MeV

Ley et al., PRC 73 (2006) 064001



Polarization transfer coefficients

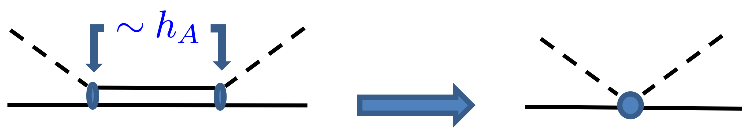
Witała et al., PRC 73 (2006) 044004



- Promising NNLO results for Nd elastic scattering
- Satisfactory A_y description related to overprediction of triplet P-waves
- Systematic overestimation of deuteron break-up data
- Hope for improvement at N^3LO

Delta-less effective potential

- Standard chiral expansion: $Q \sim M_\pi \ll \Delta \equiv m_\Delta - m_N = 293 \text{ MeV}$
- Small scale expansion: $Q \sim M_\pi \sim \Delta \ll \Lambda_\chi$ *(Hemmert, Holstein & Kambor '98)*
- Delta contributions encoded in LECs
  (Bernard, Kaiser & Meißner '97)

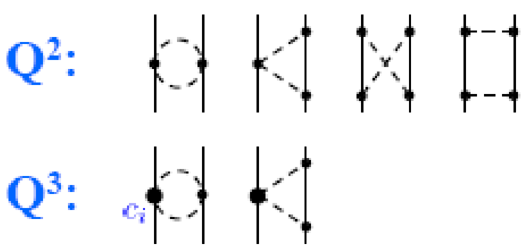


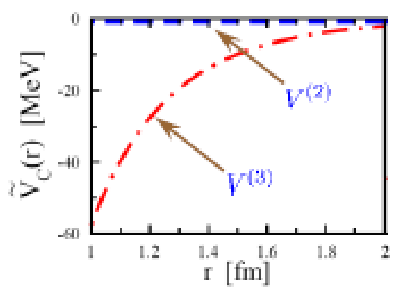
Delta-resonance saturation

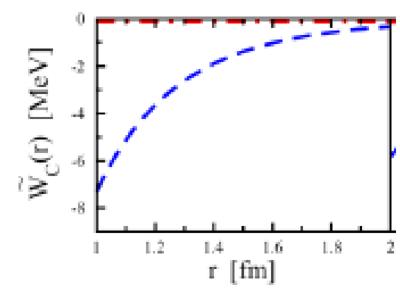
$$c_3 = -2c_4 = c_3(\cancel{\Delta}) - \boxed{\frac{4h_A^2}{9\Delta}}$$

Enlargement due to Delta contribution

- Convergence of EFT potential







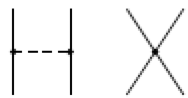
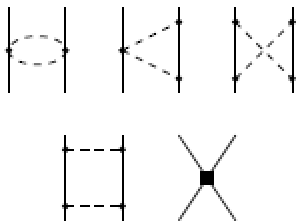
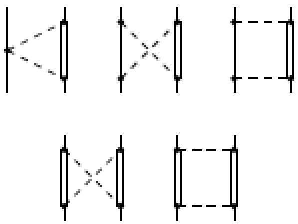
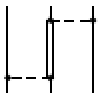
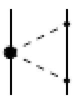
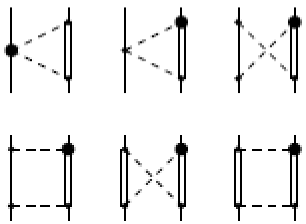
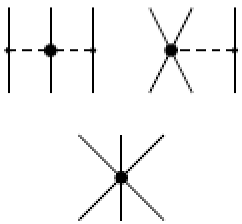
The subleading contribution is bigger than the leading one!

Expectation from inclusion of Δ explicitely

- more natural size of LECs
- better convergence
- applicability at higher energies

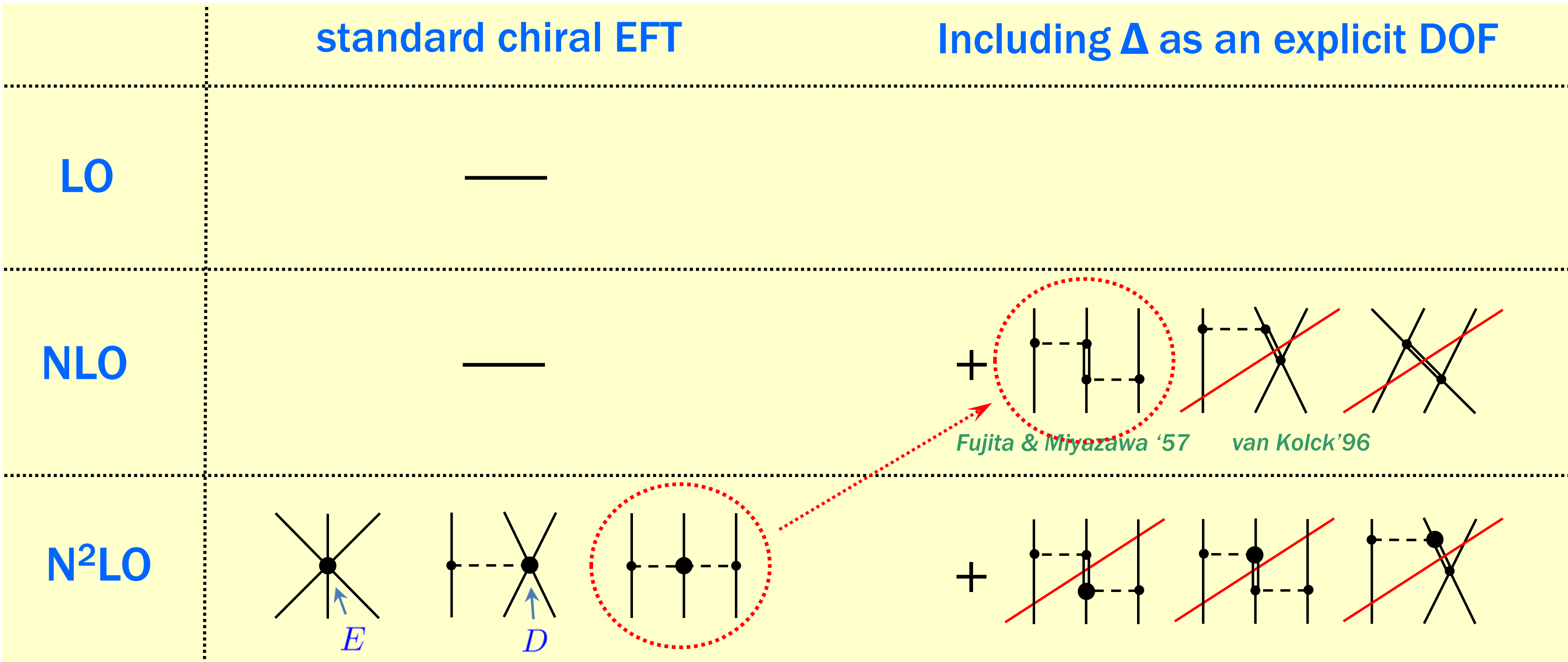
Few-nucleon forces with the Delta

Isospin-symmetric contributions

	Two-nucleon force		Three-nucleon force	
	Δ–less EFT	Δ–contributions	Δ–less EFT	Δ–contributions
LO		—	—	—
NLO		 Ordonez et al.'96, Kaiser et al. '98	—	
NNLO		 H.K., Epelbaum & Meißner '07		—

Delta excitations and the three-nucleon force

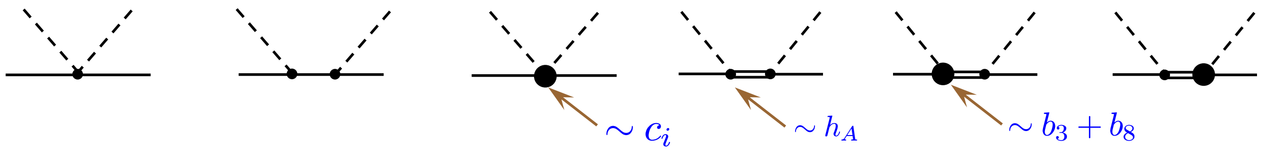
Epelbaum, H.K., Meißner, Nucl. Phys. A806 (2008) 65



- The LO NNNΔ contact interaction $\bar{T}_i^{\mu} N \bar{N} S_\mu \tau^i N + \text{ h.c.}$ vanishes due to the Pauli principle
  ⟹ the LECs D and E are not saturated by the delta.
- No contributions from subleading 2π –exchange due to ∂^0 at the $b_3 + b_8$ vertex.
- The entire effect of the Δ is given by a partial shift of the N²LO TPE 3NF to NLO…

Fit of LECs to πN scattering data

Epelbaum, H.K., Meißner, Eur. Phys. J. A32 (2007) 127



+ crossed graphs

Two possible values for h_A

- fit 1: $h_A = \frac{3 g_A}{2\sqrt{2}} \sim 1.34$ *(SU(4), large N_c)*
- fit 2: $h_A = 1.05$ *(Fettes & Meißner '01)*

LECs	Q^2, no Δ	Q^2, fit 1	Q^2, fit 2
c_1	-0.57	-0.57	-0.57
c_2	2.84	-0.25	0.83
c_3	-3.87	-0.79	-1.87
c_4	2.89	1.33	1.87
h_A	–	$1.34^\star$	$1.05^\star$
$b_3 + b_8$	–	1.40	2.95

Results of the fit

- Improved description of P-wave parameters when Δ is included
- Strongly reduced values for c_i
- Resulting c_i depend strongly on h_A while the thresh. param. do not

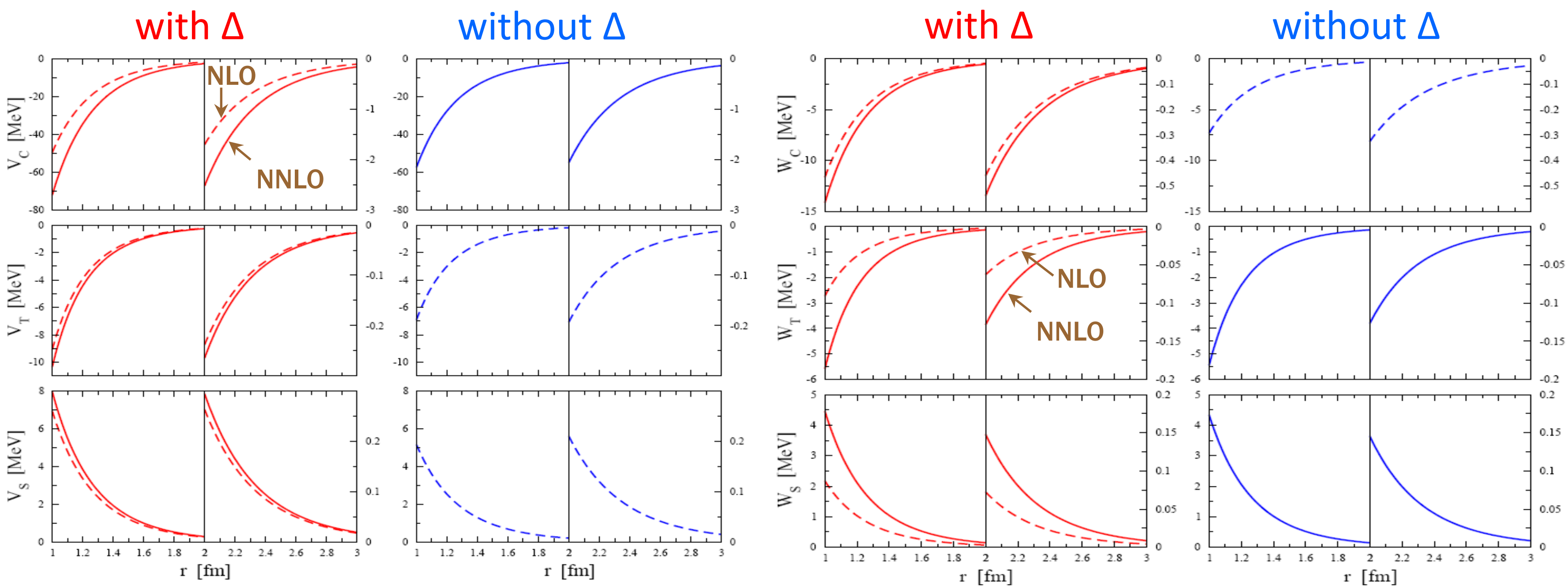
S- and P-wave threshold parameters

	Q^2, no Δ	Q^2 fits 1, 2	EM98
a^+_{0+}	0.41	0.41	0.41 ± 0.09
b^+_{0+}	-4.46	-4.46	-4.46
a^-_{0+}	7.74	7.74	7.73 ± 0.06
b^-_{0+}	3.34	3.34	1.56
a^-_{1-}	-0.05	-1.32	-1.19 ± 0.08
a^+_{1-}	-2.81	-5.30	-5.46 ± 0.10
a^-_{1+}	-6.22	-8.45	-8.22 ± 0.07
a^+_{1+}	9.68	12.92	13.13 ± 0.13

NN potential with explicit Δ

$$V_{\text{eff}} = V_C + W_C \vec{\tau}_1 \cdot \vec{\tau}_2 + [V_S + W_S \vec{\tau}_1 \cdot \vec{\tau}_2] \vec{\sigma}_1 \cdot \vec{\sigma}_2 + [V_T + W_T \vec{\tau}_1 \cdot \vec{\tau}_2](3\, \vec{\sigma}_1 \cdot \hat{r} \vec{\sigma}_2 \cdot \hat{r} - \vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

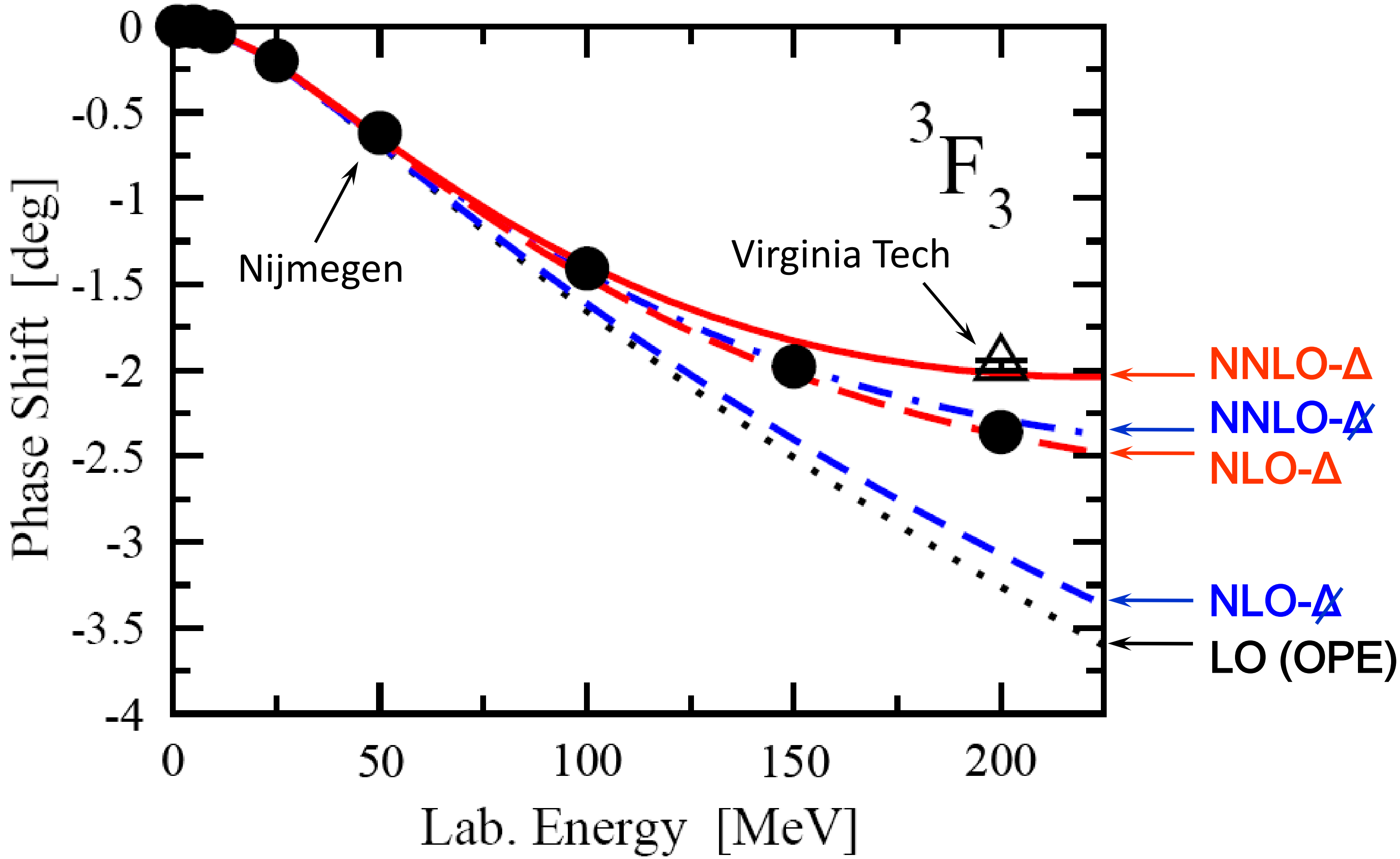
Chiral 2π- exchange potential up to NNLO



Advantages when Δ is included explicitly

- Dominant contributions already at NLO
- Much better convergence in all potentials

$^3F_3$ partial waves up to NNLO with and without Δ

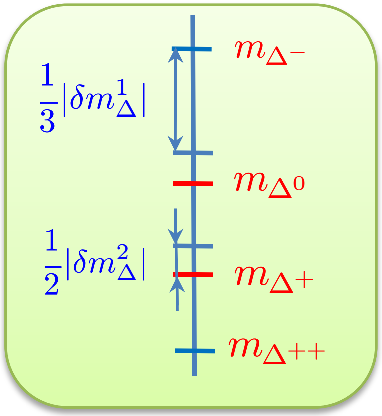


(calculated in the first Born approximation)

Δ-mass splitting in chiral EFT

Epelbaum, H.K., Meißner, Nucl. Phys. A806 (2008) 65
Tiburzi, Walker-Loud, Nucl. Phys. A 764 (2006) 274 (strong splitting)

$$\mathcal{L}^{\rm LO}_{\Delta,\rm mass} = -\bar{T}^\mu_i \left[-\delta m^1_\Delta \frac{1}{2}\tau^3\delta_{ij} - \delta m^2_\Delta \frac{3}{4}\delta_{i3}\delta_{j3} \right] g_{\mu\nu} T^\nu_j \, .$$



Equidistant splitting: strong & em

$$\delta m^1_\Delta = -4 M_\pi^2 \epsilon c_5^\Delta - F_\pi^2 e^2 f_2^\Delta$$

Non-equidistant splitting: em

$$\delta m^2_\Delta = -\frac{4}{3} F_\pi^2 e^2 f_2^\Delta$$

- Most recent data from the PDG: $m_{\Delta^{++}} = 1230.80 \pm 0.30$ MeV, $m_{\Delta^0} = 1233.45 \pm 0.35$ MeV

  In addition, PDG‘s recommended value for the average mass:

$$m_\Delta = \frac{1}{4}\left(m_{\Delta^{++}} + m_{\Delta^+} + m_{\Delta^0} + m_{\Delta^-}\right) = \tilde{m}_\Delta + \frac{1}{4}\delta m^2_\Delta = 1231 \ldots 1233 \,\text{MeV}$$

  On the other hand: $m_\Delta = 1233.4 \pm 0.4$ MeV *(Arndt et al. '06)* ⟹ use: $m_\Delta = 1233$ MeV

⟹ $\boxed{\tilde{m}_\Delta = 1233.4 \pm 0.7 \text{ MeV}\,, \quad \delta m^1_\Delta = -5.3 \pm 2.0 \text{ MeV}\,, \quad \delta m^2_\Delta = -1.7 \pm 2.7 \text{ MeV}}$

- Alternatively, use $m_{\Delta^{++}}/m_{\Delta^0}$ & the QM relation: $m_{\Delta^+} - m_{\Delta^0} = m_p - m_n$ *(Rubinstein et al. '67)*

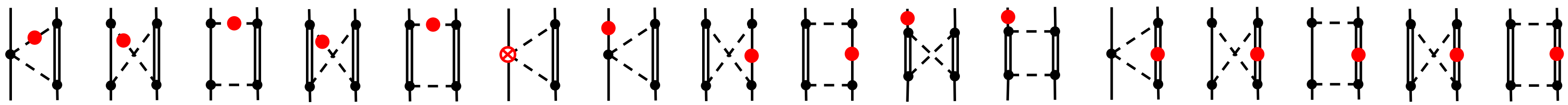
⟹ $\tilde{m}_\Delta = 1232.7 \pm 0.3$ MeV, $\delta m^1_\Delta = -3.9$ MeV, $\delta m^2_\Delta = 0.3 \pm 0.3$ MeV

Isospin-breaking NN potential

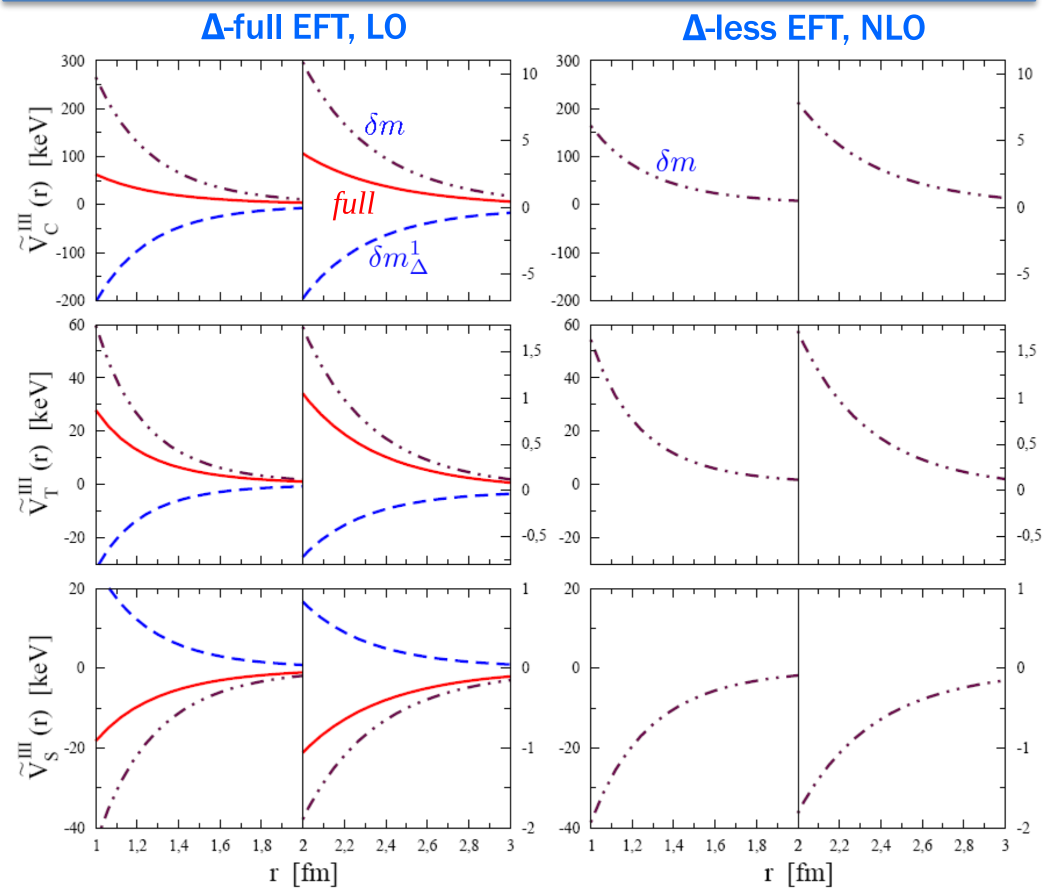
Epelbaum, H.K., Meißner, Phys. Rev. C77 (2008) 034006

2π – exchange contributions with expicit Δ

$$V = (\tau_1^3+\tau_2^3)\left[V_C^{\rm III} + V_S^{\rm III}\vec{\sigma}_1\cdot\vec{\sigma}_2 + V_T^{\rm III}\vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}\right] + \ldots$$



Charge-symmetry-breaking 2π–exchange potential



- Similar $\sim \delta m$ contr. to $\tilde{V}^{\rm III}_{\rm S,T}$ in the Δ-less and Δ-full EFT
- Sizeable deviation in $\sim \delta m$ contr. for $\tilde{V}^{\rm III}_{\rm C}$
- Strong cancelations between $\sim \delta m$ and $\sim \delta m^1_\Delta$ terms

⇓

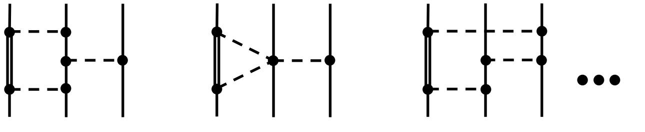
Big contributions beyond the subleading corrections in the Δ-less EFT

Summary

- Quantitative description of few-nucleon forces within chiral EFT
- Promising results for few-nucleon dynamics
- Better convergence of nuclear forces if Δ-isobar is included explicitely

Perspectives

- Complete numerical studies with 3NF and 4NF upto N^3LO
- Few-nucleon forces with Δ-DOF upto N^3LO: important effects expected for 3NF and 4NF



- Electroweak reactions with few-nucleon systems