Chiral Dynamics of Few-Nucleon Systems

Evgeny Epelbaum

Research Center Jülich & Bonn University, Germany

Outline

- Introduction
- The structure of nuclear forces in chiral EFT
- Applications to few-nucleon systems
- Nuclear lattice simulations
- Inclusion of the Δ
- Summary and outlook

What holds nucleons together in a nucleus?

1935 *Yukawa* suggests that nucleons interact via exchange of massive scalar mesons

1946 *Pauli* predicts correct quantum numbers of π-meson

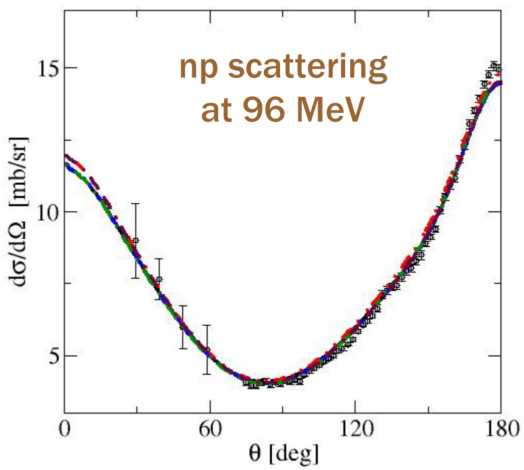
1947 π's observed experimentally *(Lattes, Muirhead, Occhialini and Powell)*

1950's study of 2π-exchange *(Taketani, Mashida, Onuma, Brückner, Watson, ...)*

1960's discovery of heavy mesons, *one-boson-exchnage models*

1970-80's *dispersion theory, boson-exchange models, inverse scattering theory, quark cluster models, phenomenology, ...*

1990's modern high-precision NN potentials *(CD Bonn, Argonne V18, Nijm I,II, ...)*



$\Longrightarrow$ perfect description of low-energy 2N data but:

- Relation to QCD?
- Consistent many-body forces?
- Why do 2N forces dominate?
- What is the theoretical uncertainty?
- How to improve?

Modern approach: chiral effective field theory *(Weinberg '90)*

Chiral Perturbation Theory

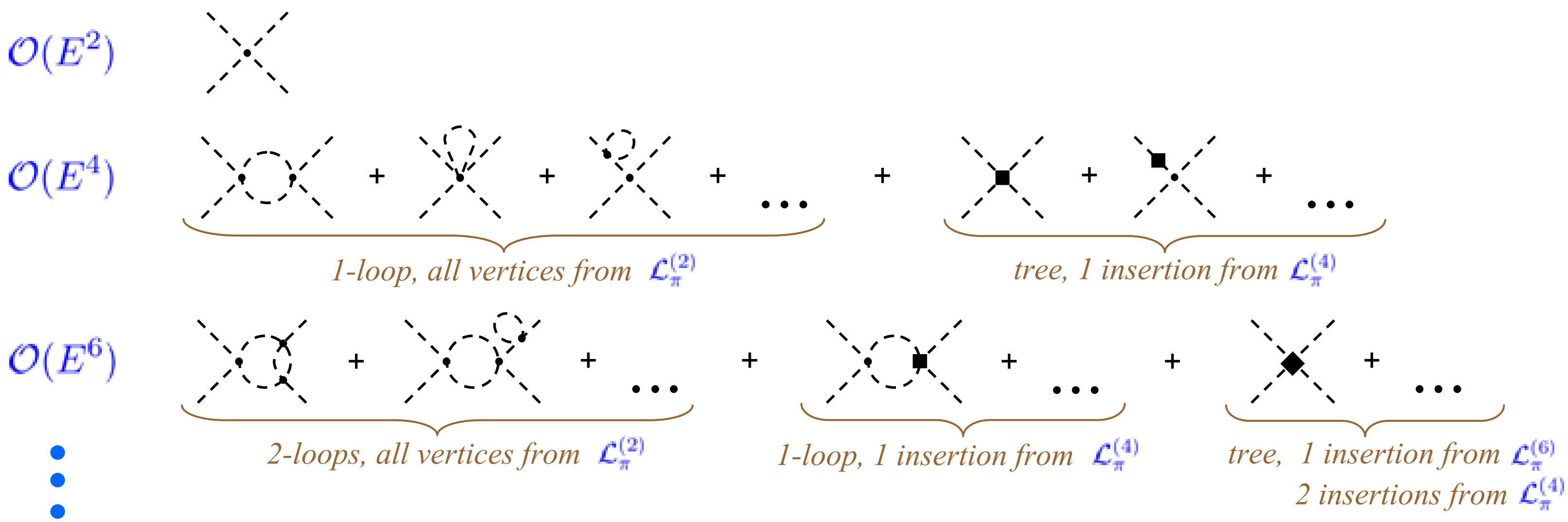
Weinberg, Gasser, Leutwyler, Bernard, Kaiser, Meißner, ...

Goldstone bosons + matter fields

$$e^{iZ[J]} = \int [Dq][D\bar{q}][DG]\, e^{\int i d^4x\, \mathcal{L}_{\rm QCD}[q,\bar{q},G;\, J]} \Leftrightarrow \int [D\Phi]\, e^{\int i d^4x\, \mathcal{L}_{\rm eff}[\Phi;\, J]}$$

- write down the most general $\mathcal{L}_{\rm eff}$ consistent with the χ-symmetry of QCD
- compute S-matrix elements in perturbation theory (power counting)
- fix the low-energy constants & make predictions...

Example: $\pi\pi$ scattering

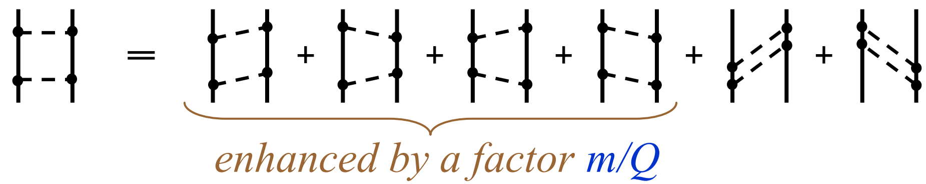


Model-independent & systematically improvable approach!

Generalization to few nucleons

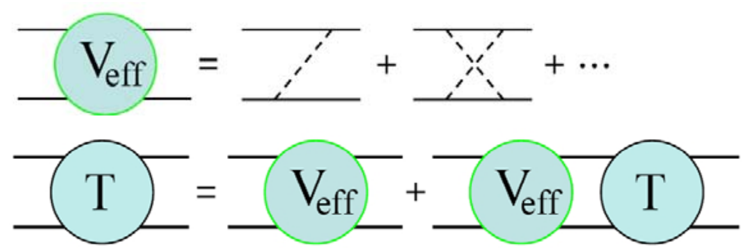
Non-perturbative physics (^{2}H, ^{3}H, ^{3}He, …).

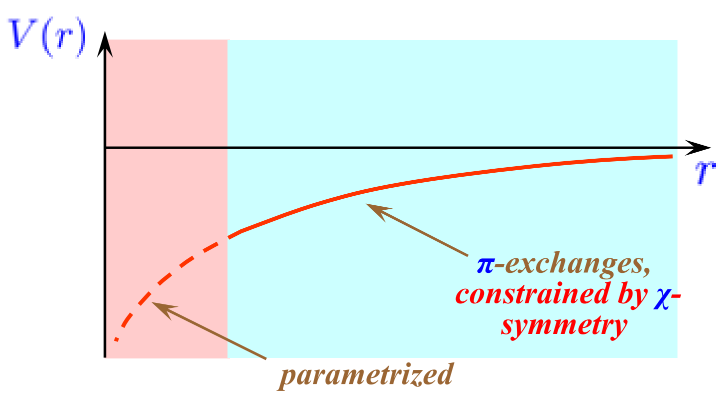
- NN interaction does not vanish in the limit: $E \to 0,\ M_\pi \to 0$
- Infrared enhancement for reducible diagrams



Weinberg's approach

- Irreducible contributions can be calculated using ChPT
- Enhanced reducible contributions should be summed up to infinite order



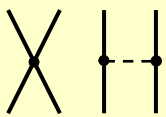
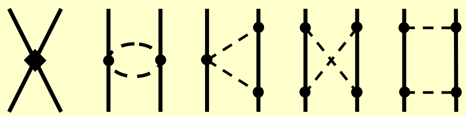
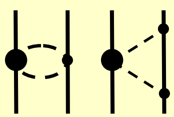
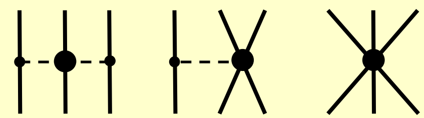
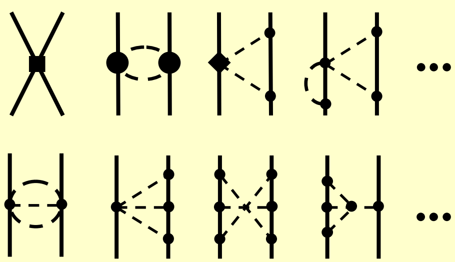
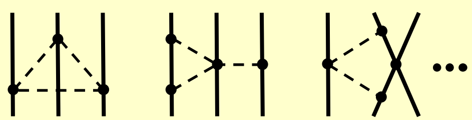
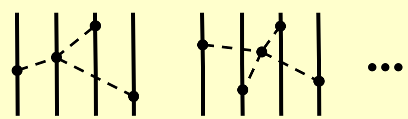


— Chiral NN force has the structure:

$$V_{\text{eff}} = \sum_\nu \left[V^{(\nu)}_{\text{long-range}} + V^{(\nu)}_{\text{short-range}} \right]$$

— Possible large anomalous dimensions of contact terms are currently under investigation

Few-nucleon forces in chiral EFT

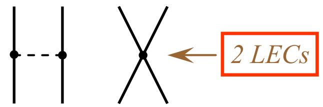
	Two-nucleon force	Three-nucleon force	Four-nucleon force
Q^0		—	—
Q^2		—	—
Q^3			—
Q^4		 work in progress…	

2 nucleon force $\gg$ 3 nucleon force $\gg$ 4 nucleon force . . .

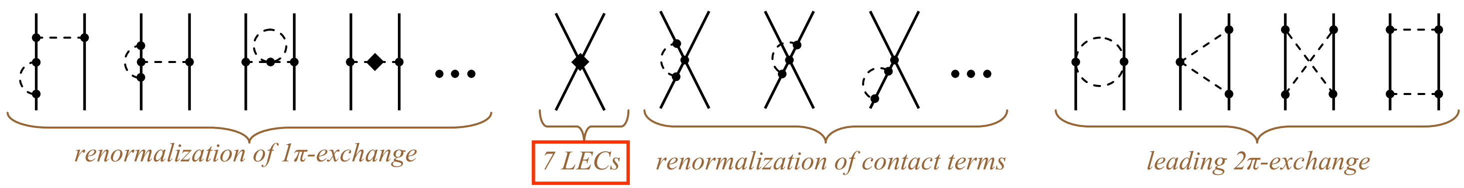
Two-nucleon force

Ordonez et al. '94; Friar & Coon '94; Kaiser et al. '97; E.E. et al. '98, '03; Kaiser '99,'00,'01; Higa et al. '03

- **LO:**

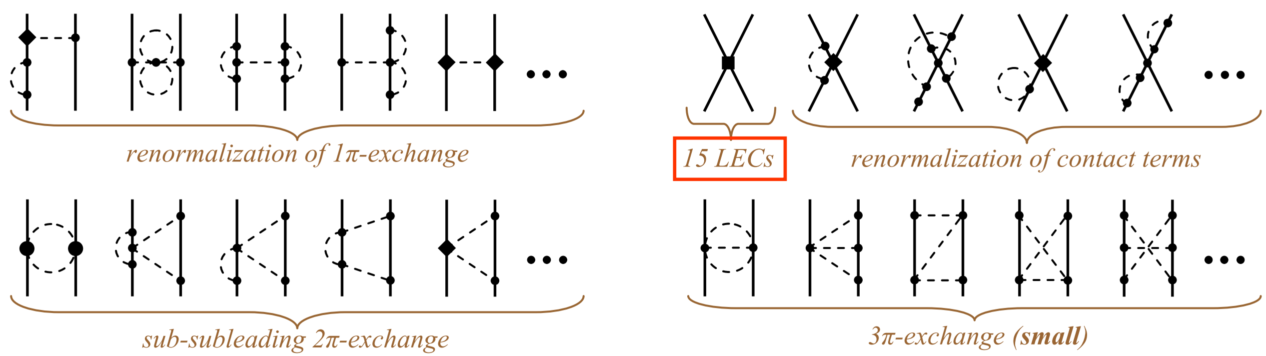


- **NLO:**



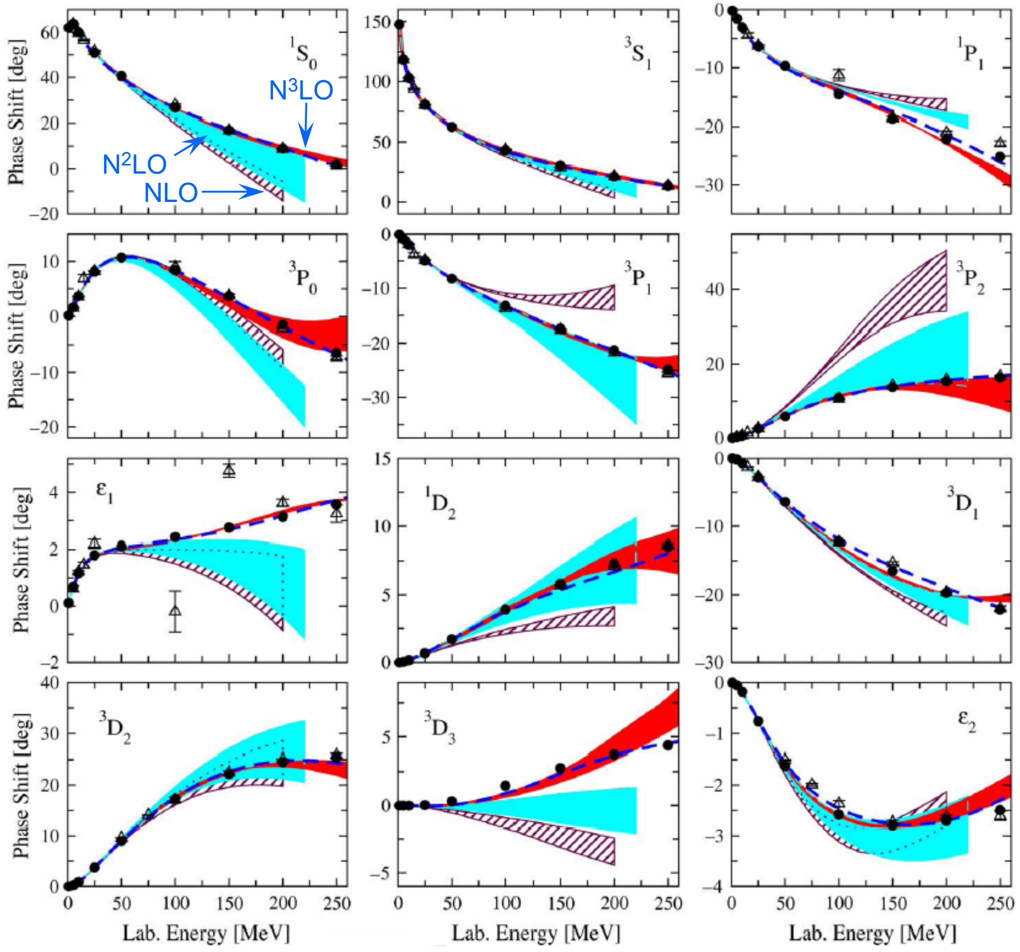
- **N^{2}LO:**

- **N^{3}LO:**

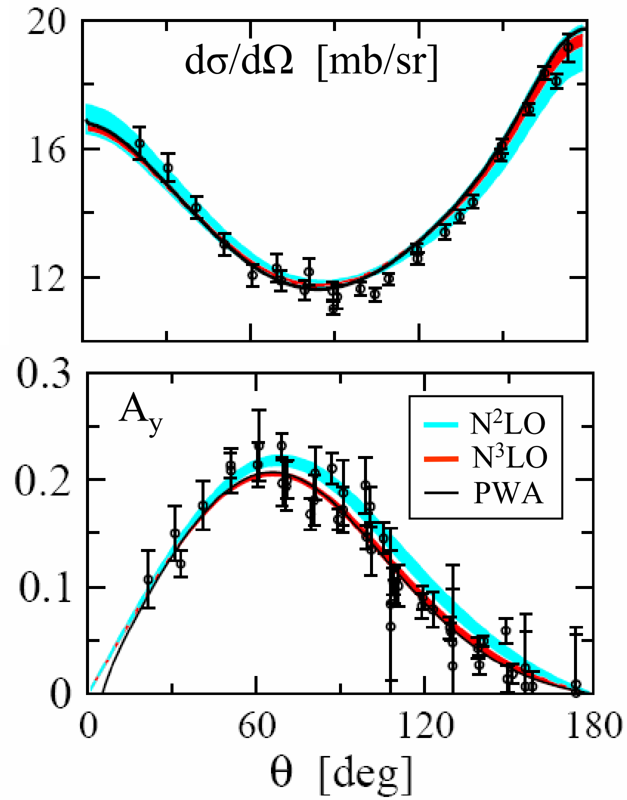


- **1/m - corrections** *(Friar '99)*

Neutron-proton phase shifts up to N^3LO



np scattering at 50 MeV

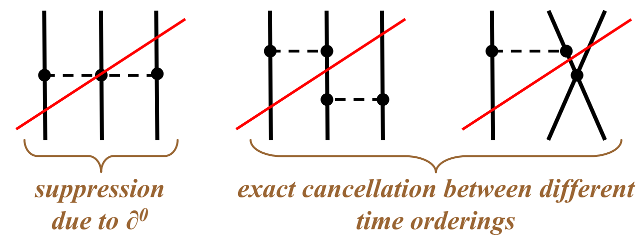


Entem & Machleidt '03; E.E., Meißner & Glöckle '05

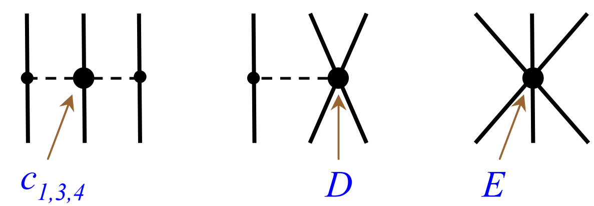
Three-nucleon force

- **LO:** no 3NF

- **NLO:** 3NF vanishes
  (if one uses energy-independent formulation)
  Weinberg '91; Coon & Friar '94; van Kolck '94; E.E. et al.,'98; ...



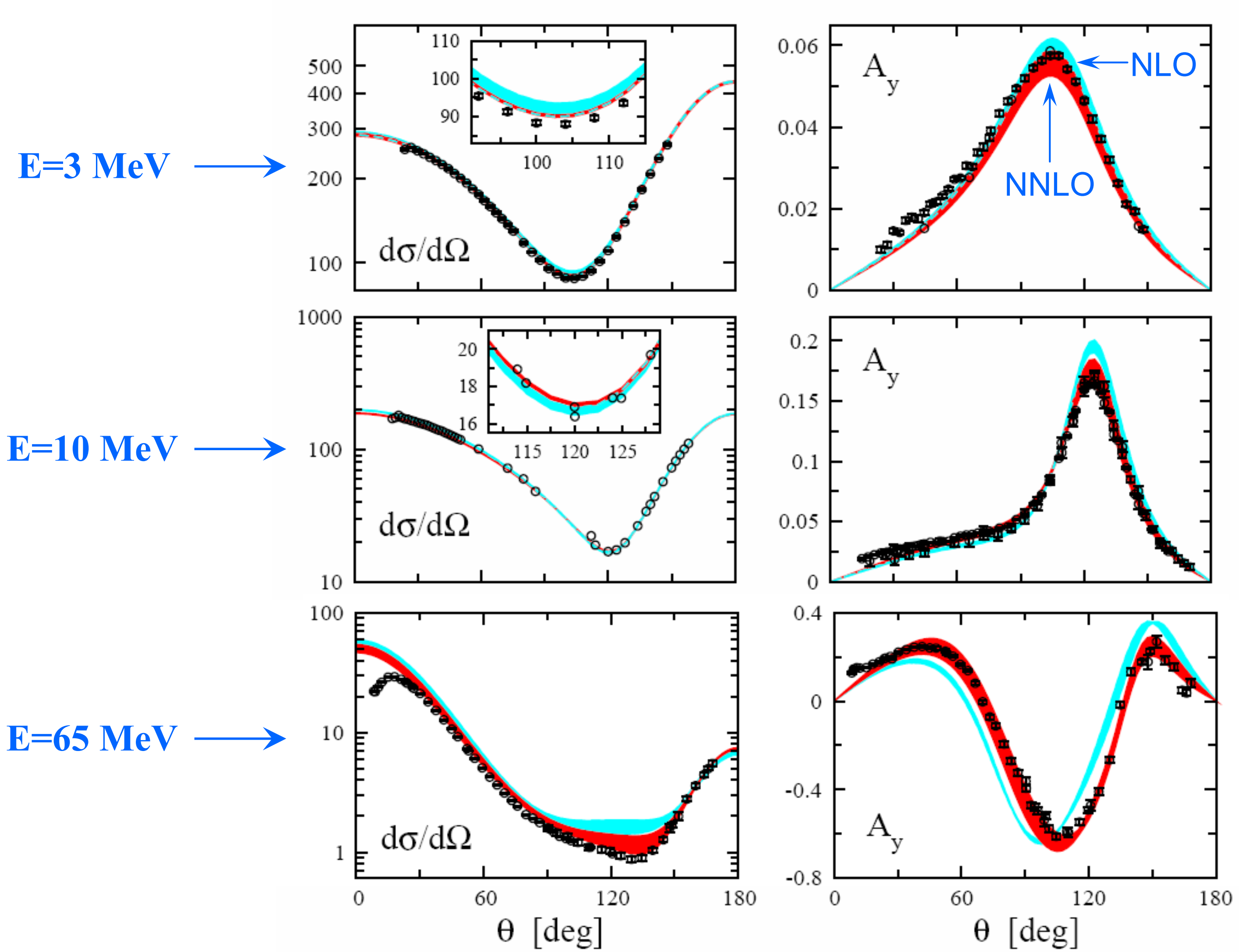
- **N²LO:** first nonvanishing 3NF
  van Kolck '94; E.E. et al. '02



Determination of the LECs

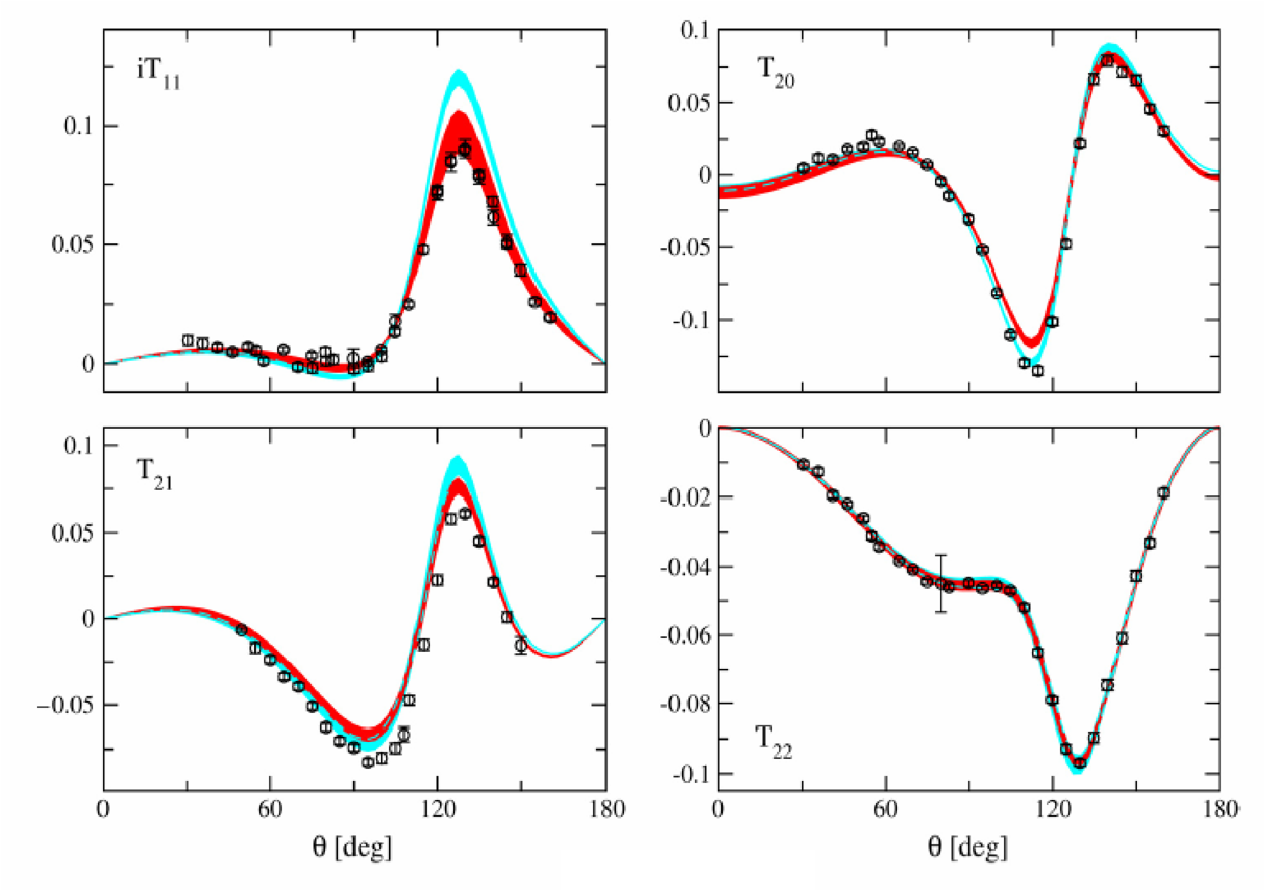
- $c_{1,3,4}$ are known from πN scattering (also enter the NN force)
- The LECs D and E have been fixed from
  — ^{3}H binding energy and nd doublet scatt. length *(E.E. et al. '02)*
  — ^{3}H and ^{4}He binding energies *(Nogga et al.'05)*
  — ^{3}H and ^{10}B binding energies *(Navratil et al.'07)*

Elastic nucleon-deuteron scattering observables



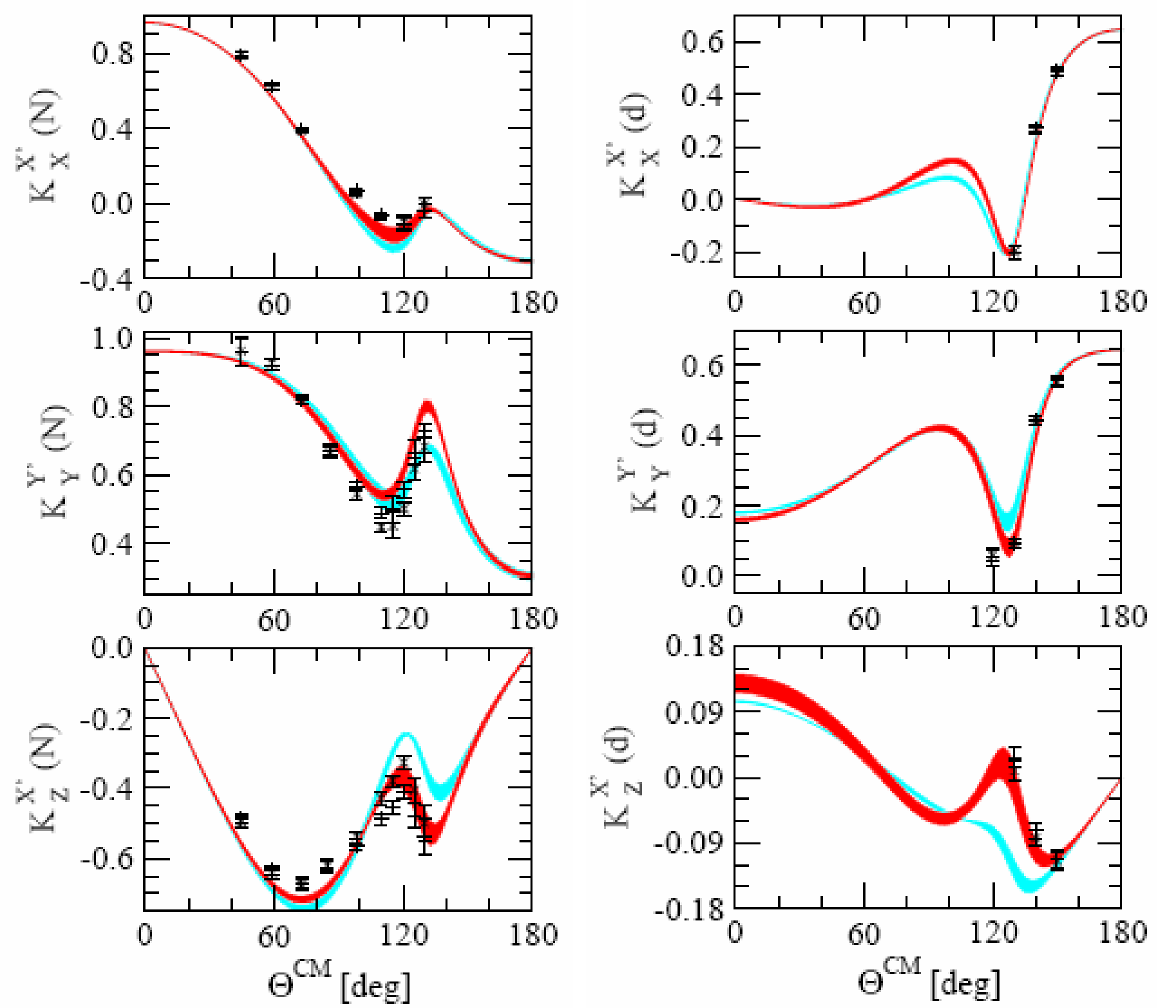
Data shown are np and Coulomb-corrected pd data

Tensor analyzing powers for elastic nucleon-deuteron scattering observables at E_p=10 MeV



Data shown are Coulomb-corrected pd data

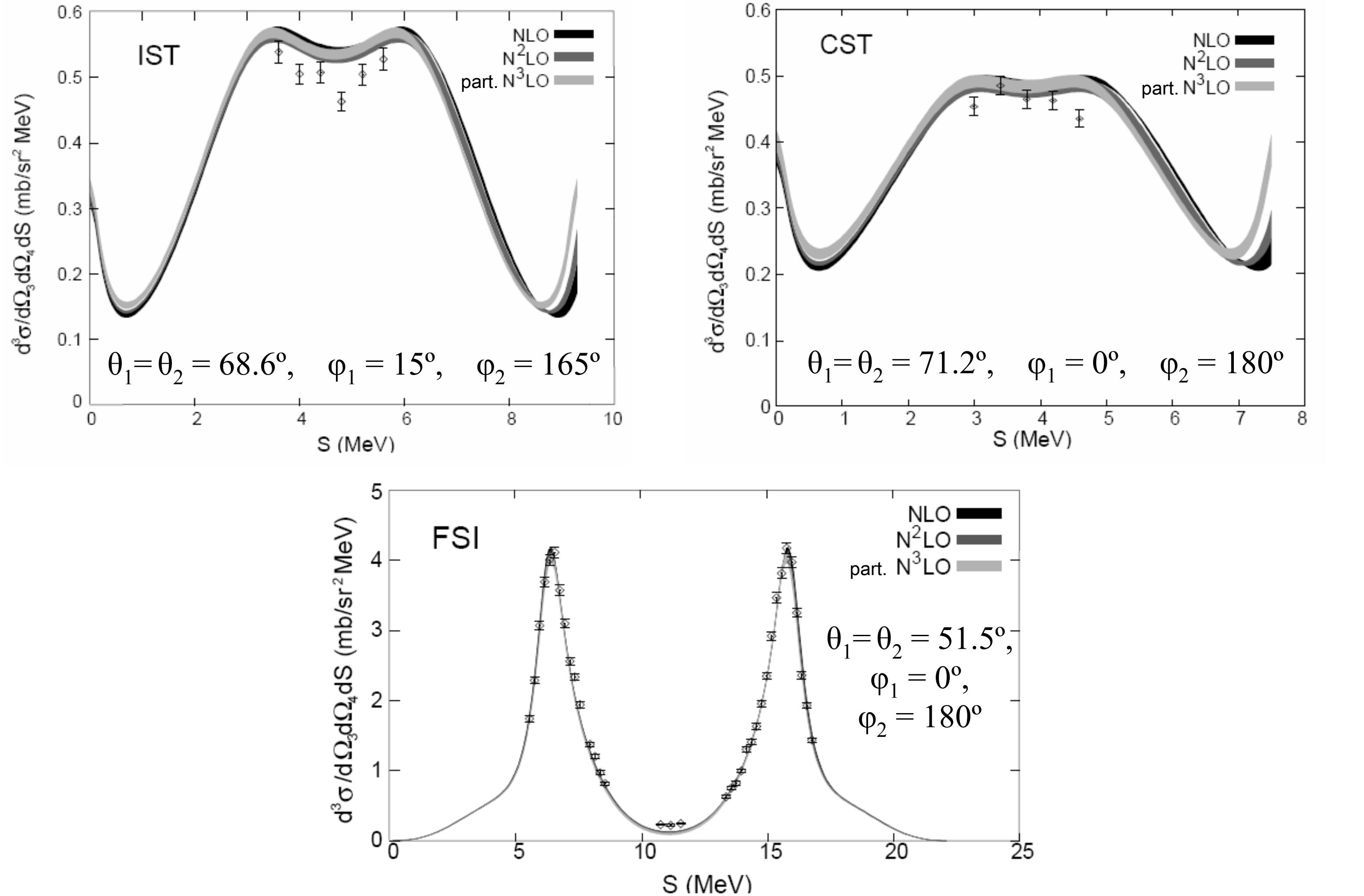
Polarization transfer coefficients in $d(\vec{p}, \vec{p})d$ and $d(\vec{p}, \vec{d})p$ at E_p=22.7 MeV



Daata shown are Coulomb-corrected pd data

H. Witała et al., PRC 73 (2006) 044004

Breakup cross section in the reaction *d(p, pp)n* at E_p=16 MeV

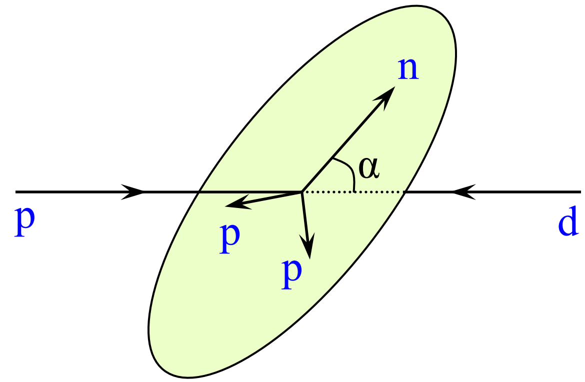


C. Düwecke et al., PRC 72 (2006) 044001

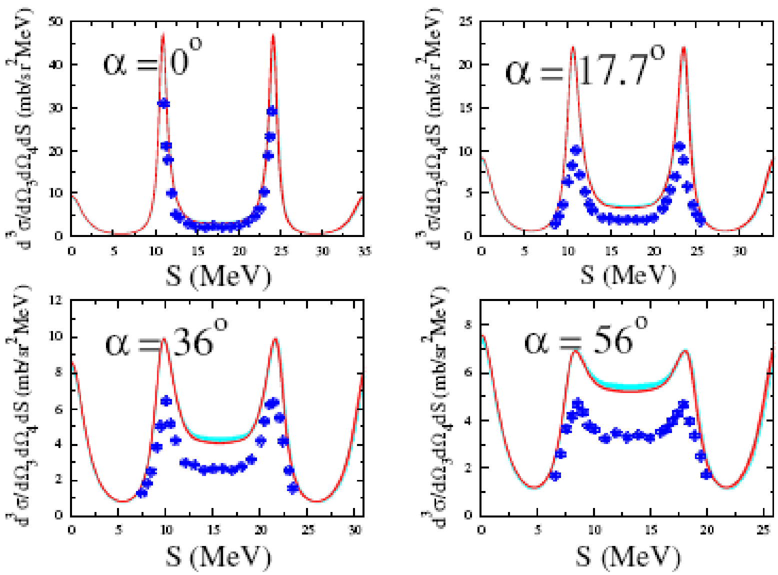
Some open problems…

Deuteron breakup in the Symmetric Constant Relative Energy (SCRE) configuration at E_d=19 MeV

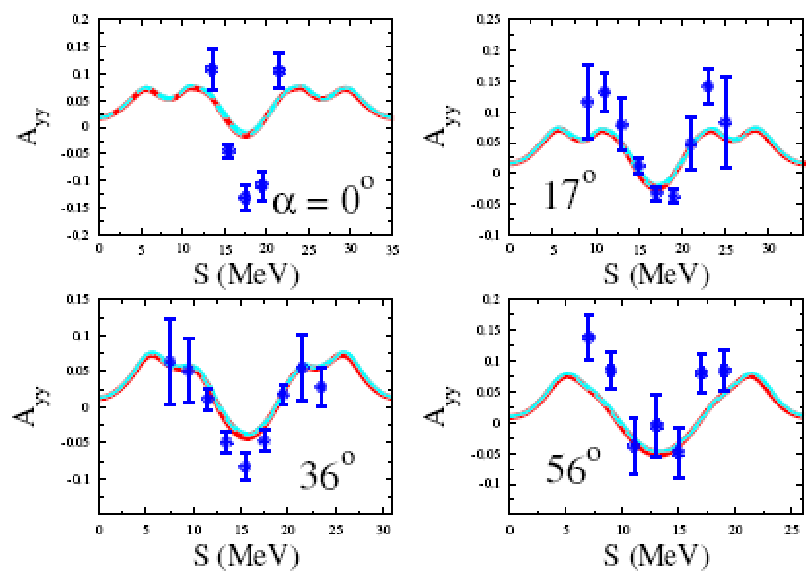
Ley et al., PRC 73 (2006) 064001



Differential cross section



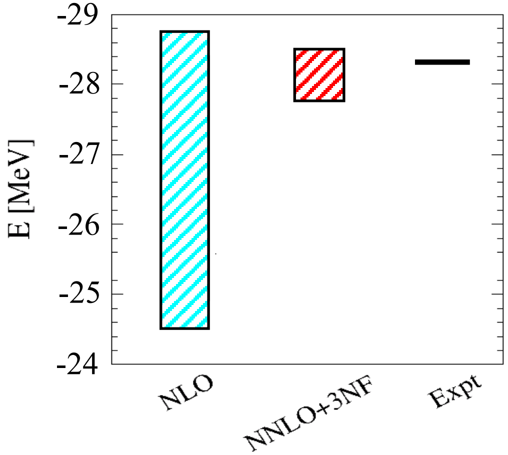
Tensor analyzing power A_{yy}



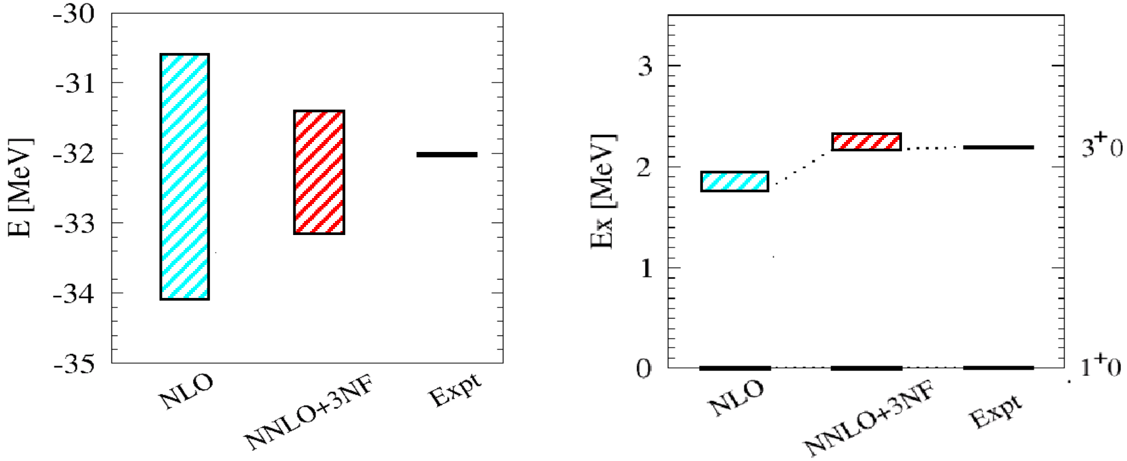
<u>Notice</u>: including Coulomb interaction reduces the discrepancy for the cross section by about 30% and improves the description of A_{yy}

More nucleons...

α-particle



^{6}Li ground and excited states



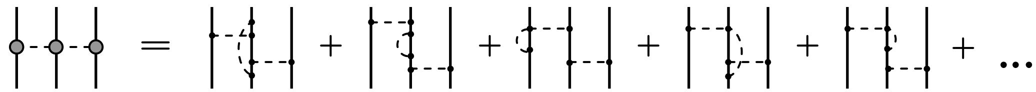
Calculations based on chiral forces up to A=13 carried out by *Navratil et al., ’06,‘07*

It is very important to go to N^{3}LO to further test chiral EFT in the few-nucleon sector and to see whether the remaining problems can be solved!

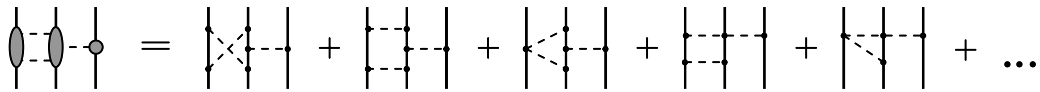
The structure of the 3NF at N^3LO

(Ishikawa & Robilotta '07; EE, Bernard & Meißner, in preparation)

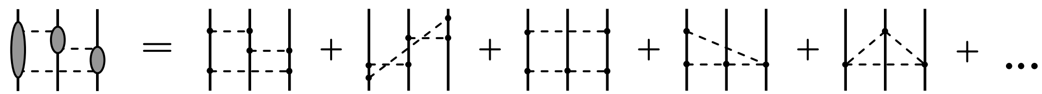
2π – exchange



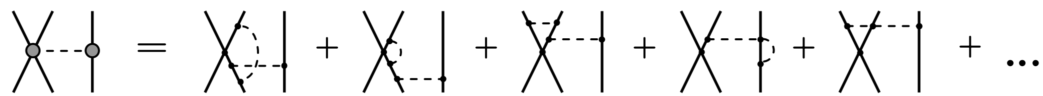
2π-1π – exchange



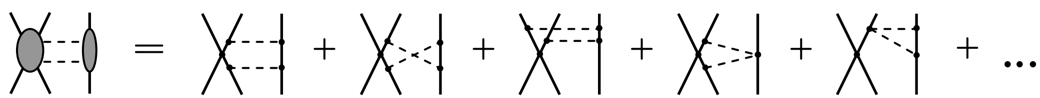
2π – exchange between all three nucleons



contact-1π – exchange



contact-2π – exchange



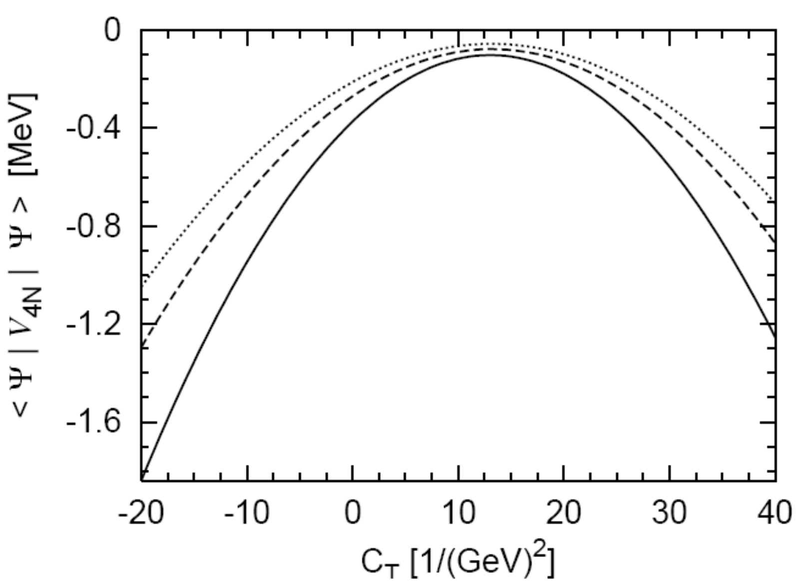
+ $1/m$ - corrections

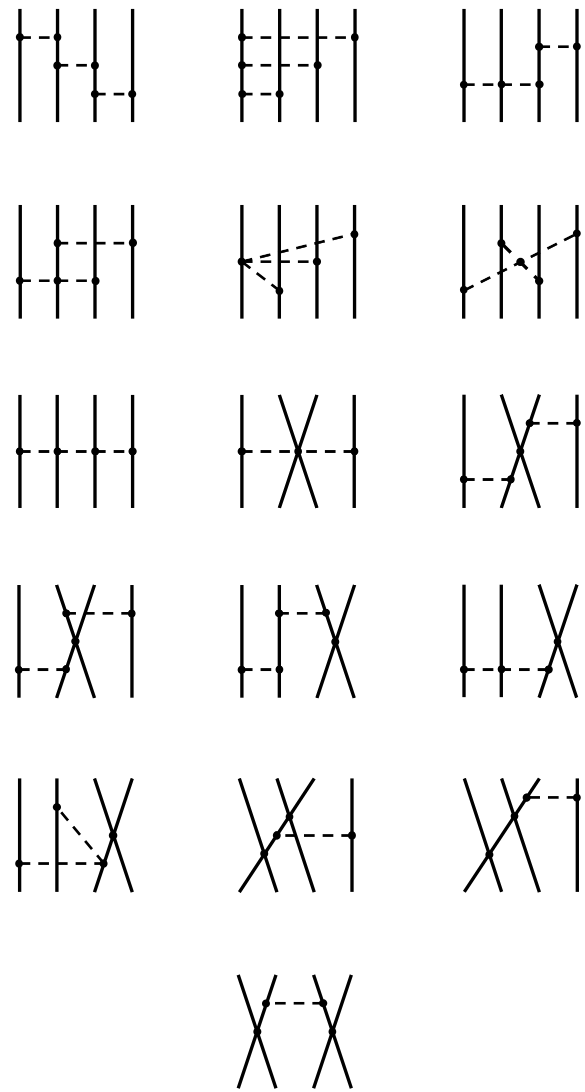
- no new 3N contact interactions ⟹ parameter-free results !
- new isospin & spin-space structures, not included in the conventional 3NF models

Four-nucleon force *(E.E. '06)*

- first shows up at N^{3}LO
- chiral symmetry plays a crucial role
- parameter-free

Contribution of the 4NF to the ^{4}He BE is attractive and of the order of few 100 keV
(Rozpedzik et al. ´06)

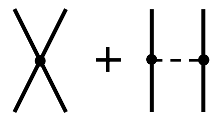




Nuclear lattice simulations

Borasoy, E.E., Krebs, Lee, Meißner, '06

We used the Lagrangian for nucleons and instantaneous pions which reproduces the LO NN interaction:

V_{NN}^{LO} =


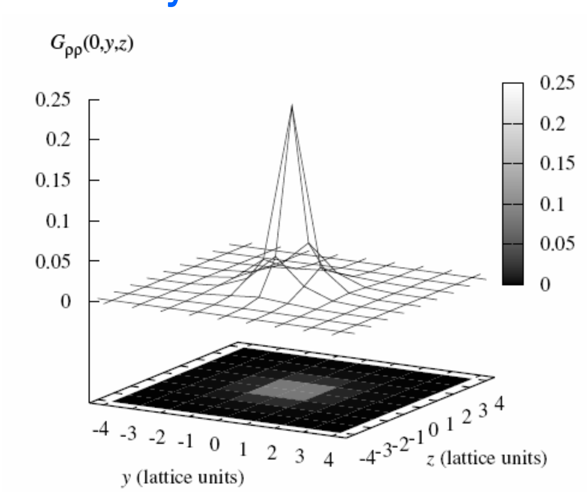
Deuteron properties

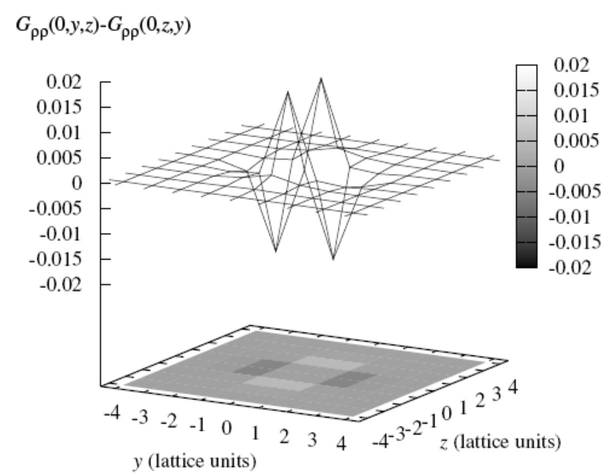
	r_d (fm)	Q_d (fm^2)
lattice	1.989(1)	0.278(1)
experiment	1.9671(6)	0.2859(3)

We found:

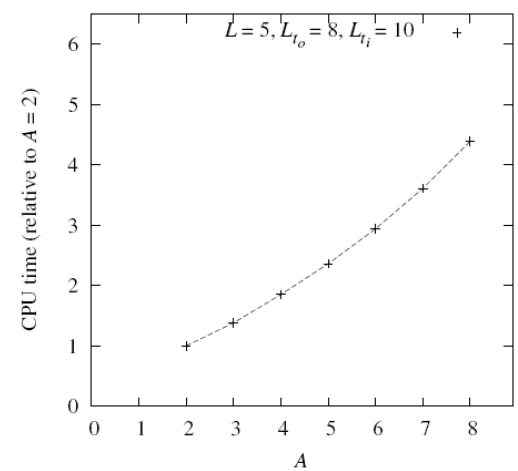
- good agreement with the data in the 2N sector;
- promising results for 3N, 4N systems: $E_{3N} = -8.9(2)\ \mathrm{MeV}$, $E_{4N} = -21.5(9)\ \mathrm{MeV}$
- encouraging results for CPU time scaling with the number of particles

Density correlations for the deuteron with spin in the +z direction





CPU time scaling



Inclusion of the Δ

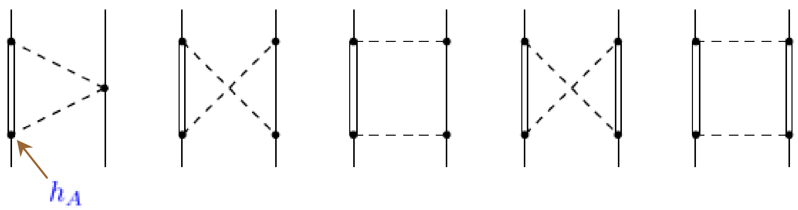
Krebs, E.E., Meißner, EPJA 2007, in press

Δ-isobar is known to be important due to:

- low excitation energy: $\Delta m = m_\Delta - m_N = 293\ \mathrm{MeV} \sim 2M_\pi$
- strong coupling to the πN–system ($g_{\pi N \Delta}$ large)

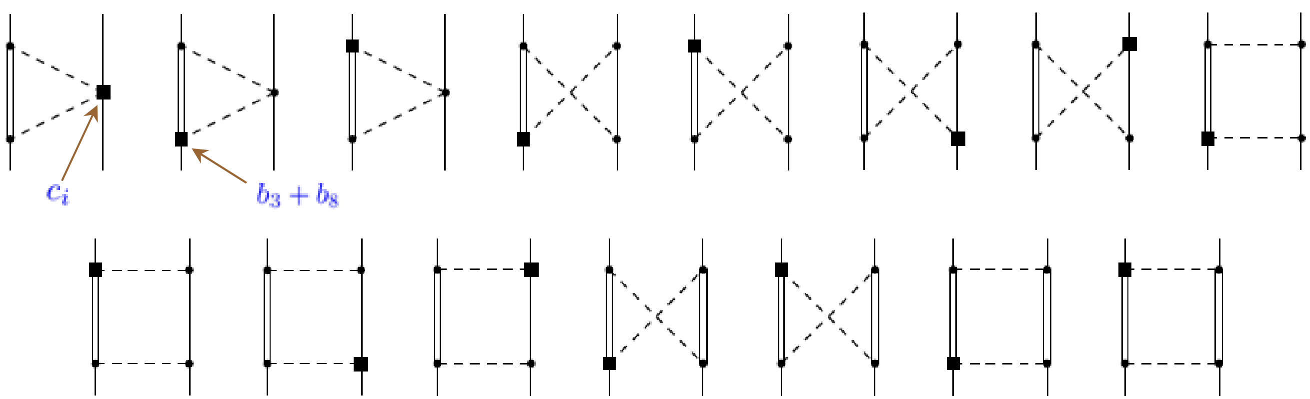
⇨ expect: better convergence & applicability at higher energy in EFT with Δ's

NLO



Ordonez, Ray & van Kolck '96
Kaiser, Gerstendorfer & Weise '98

NNLO

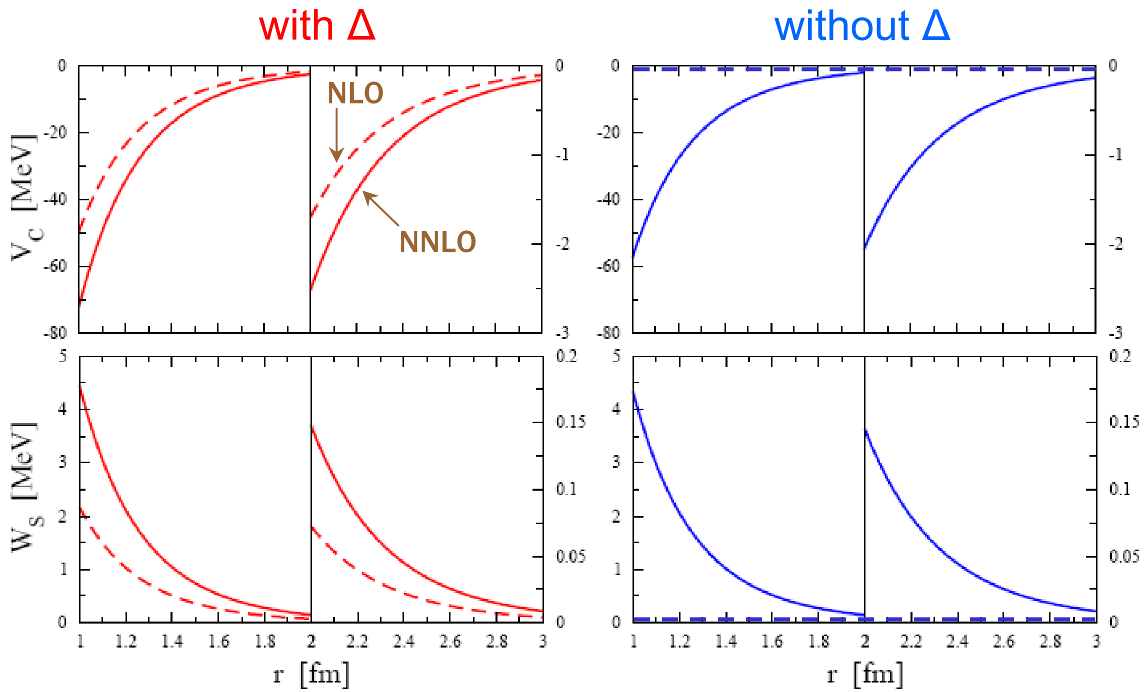


The LECs c_i and $b_3 + b_8$ are fixed from πN S- and P-wave threshold coefficients.

Chiral 2π–exchange potential up to NNLO:

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

Chiral 2π-exchange up to NNLO with and without explicit Δ



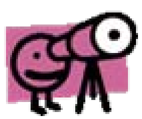
⇨ much better convergence when Δ is included explicitly!

work on implications for 2N observables, 3N forces & isospin breaking effects in progress…

Summary

- Chiral EFT results for the 2N sector at N^3LO are in very good agreement with the data. N^2LO calculations in >2N systems yield promising results.
- The leading 4NF has been worked out (contributes at N^3LO). Calculation of the N^3LO 3NF corrections are underway.
- First results are obtained for nuclear lattice simulations at LO in chiral EFT
- The N^2LO contributions to the 2NF due to explicit Δ have been worked out. Improved convergence of the chiral expansion for the 2NF is demonstrated.

Outlook



- Few-nucleon systems at N^3LO.
- The role of Δ-isobar for nuclear forces and few-nucleon systems.
- Further work on nuclear lattice lattice simulations.