

Chiral Dynamics of Few-Nucleon Systems

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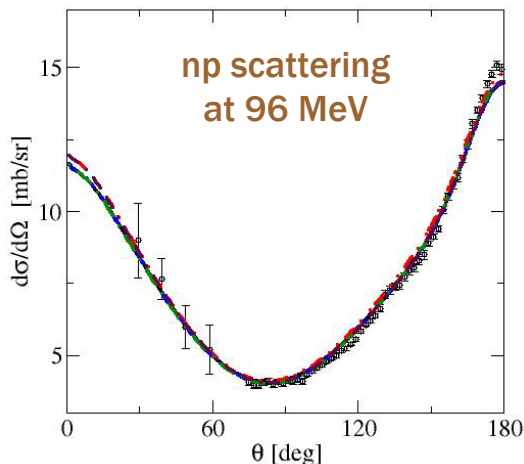
Outline

- 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, ...*)



⇒ 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

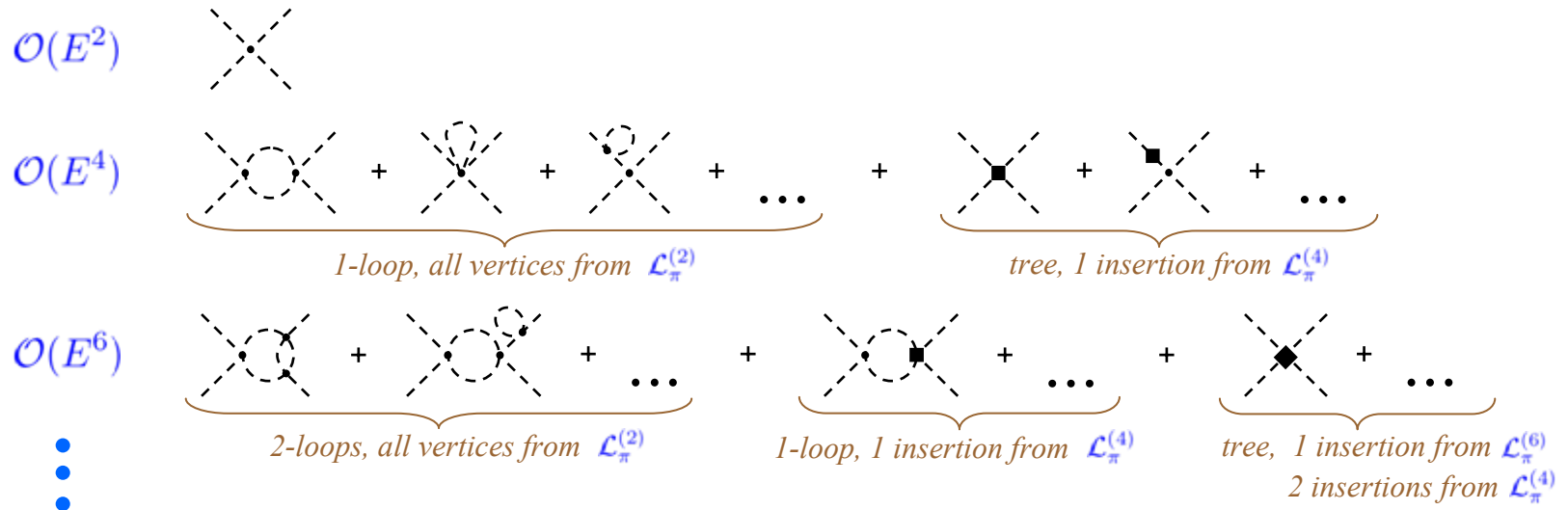
Weinberg, Gasser, Leutwyler, Bernard, Kaiser, Meißner, ...

Goldstone bosons + matter fields

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

- write down the most general \mathcal{L}_{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



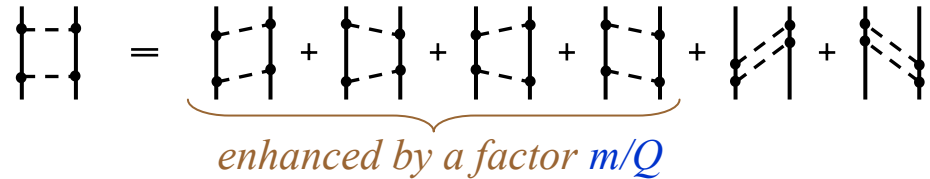
Model-independent & systematically improvable approach!

Generalization to few nucleons

Non-perturbative physics (${}^2\text{H}$, ${}^3\text{H}$, ${}^3\text{He}$, ...).

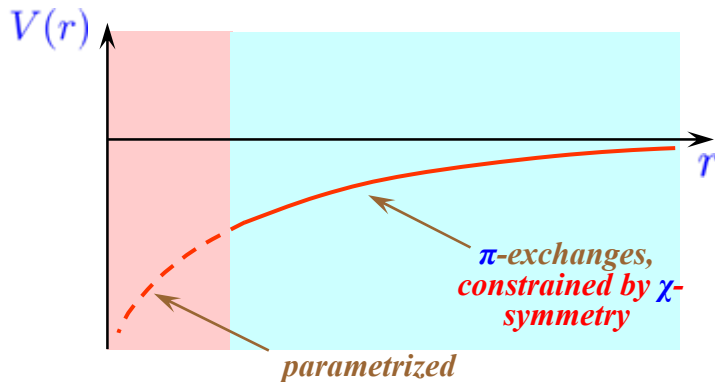
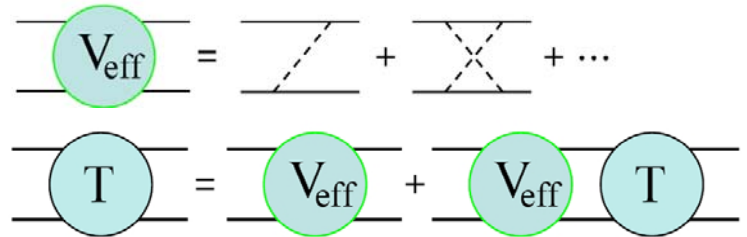
- NN interaction does not vanish in the limit: $E \rightarrow 0$, $M_\pi \rightarrow 0$

- 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

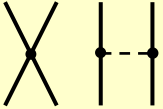


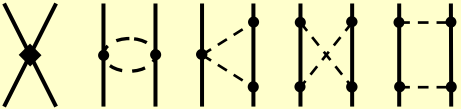


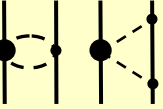
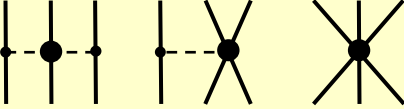

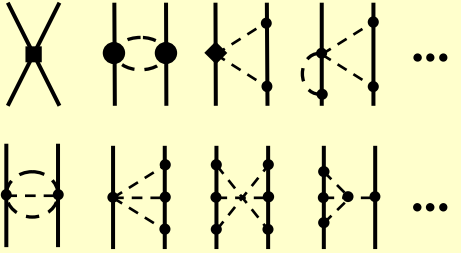
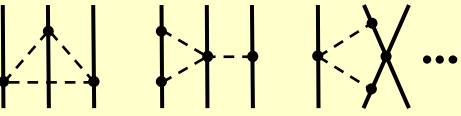
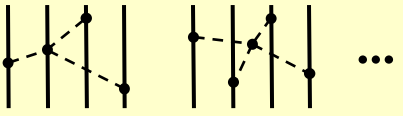


— Chiral NN force has the structure:

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

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

Few-nucleon forces in chiral EFT

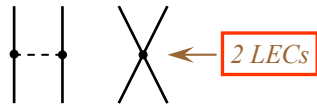
	Two-nucleon force	Three-nucleon force	Four-nucleon force
Q^0			
Q^2			
Q^3			
Q^4		 work in progress...	

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

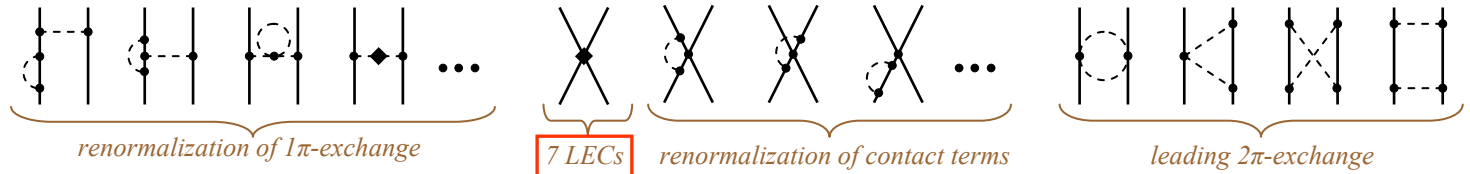
Two-nucleon force

Ordenez 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:



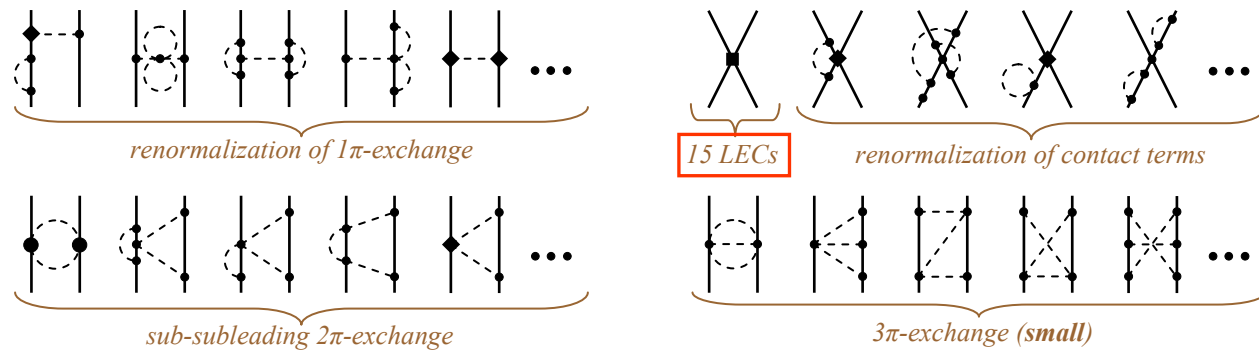
● NLO:



● N²LO:

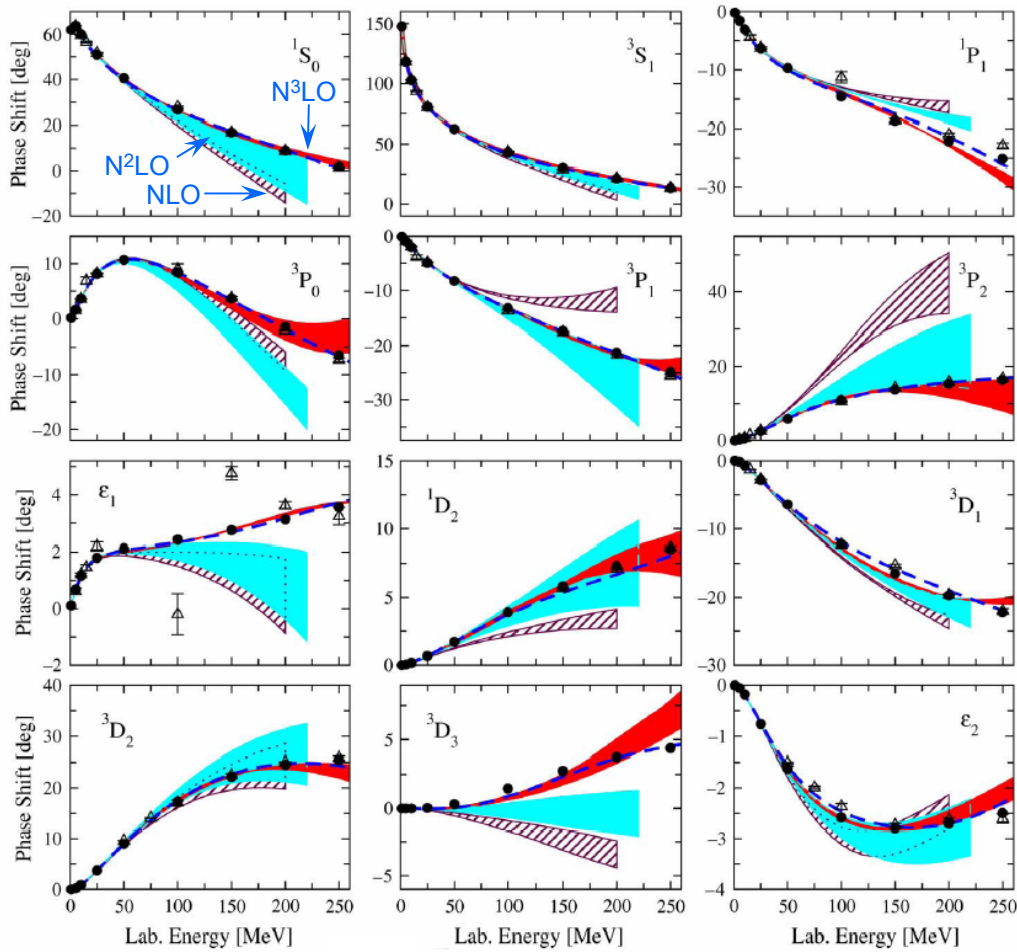


● N³LO:



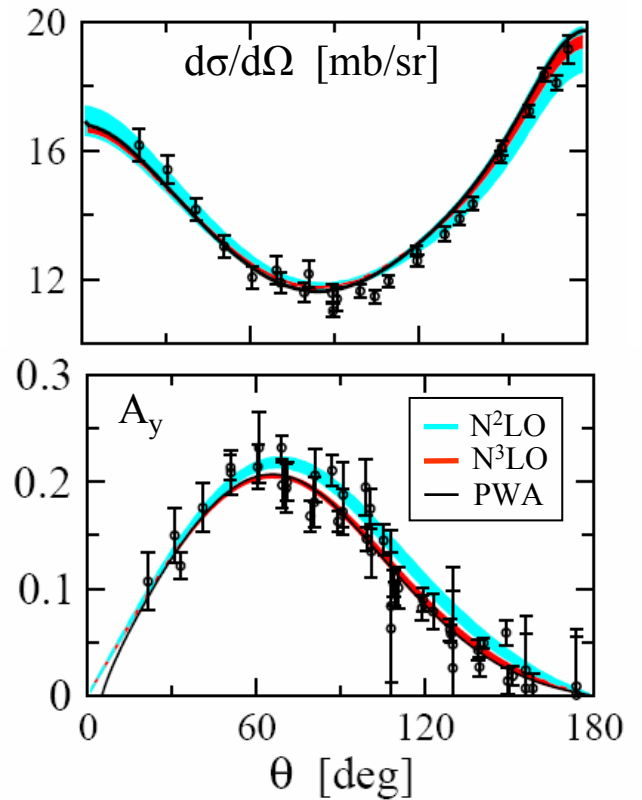
● 1/m - corrections (Friar '99)

Neutron-proton phase shifts up to N³LO



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

np scattering at 50 MeV

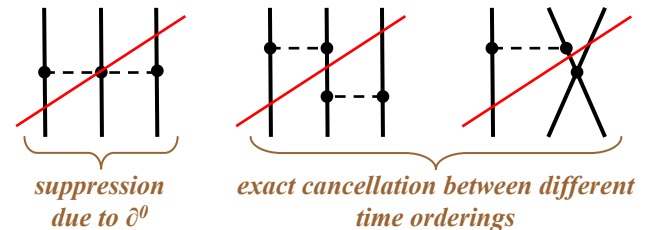


Three-nucleon force

● 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; ...

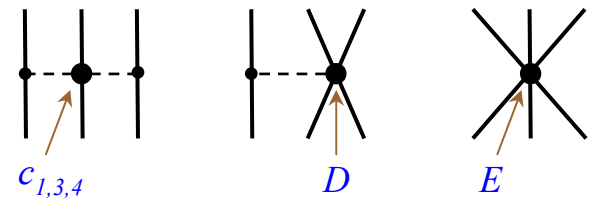


● N²LO: first nonvanishing 3NF

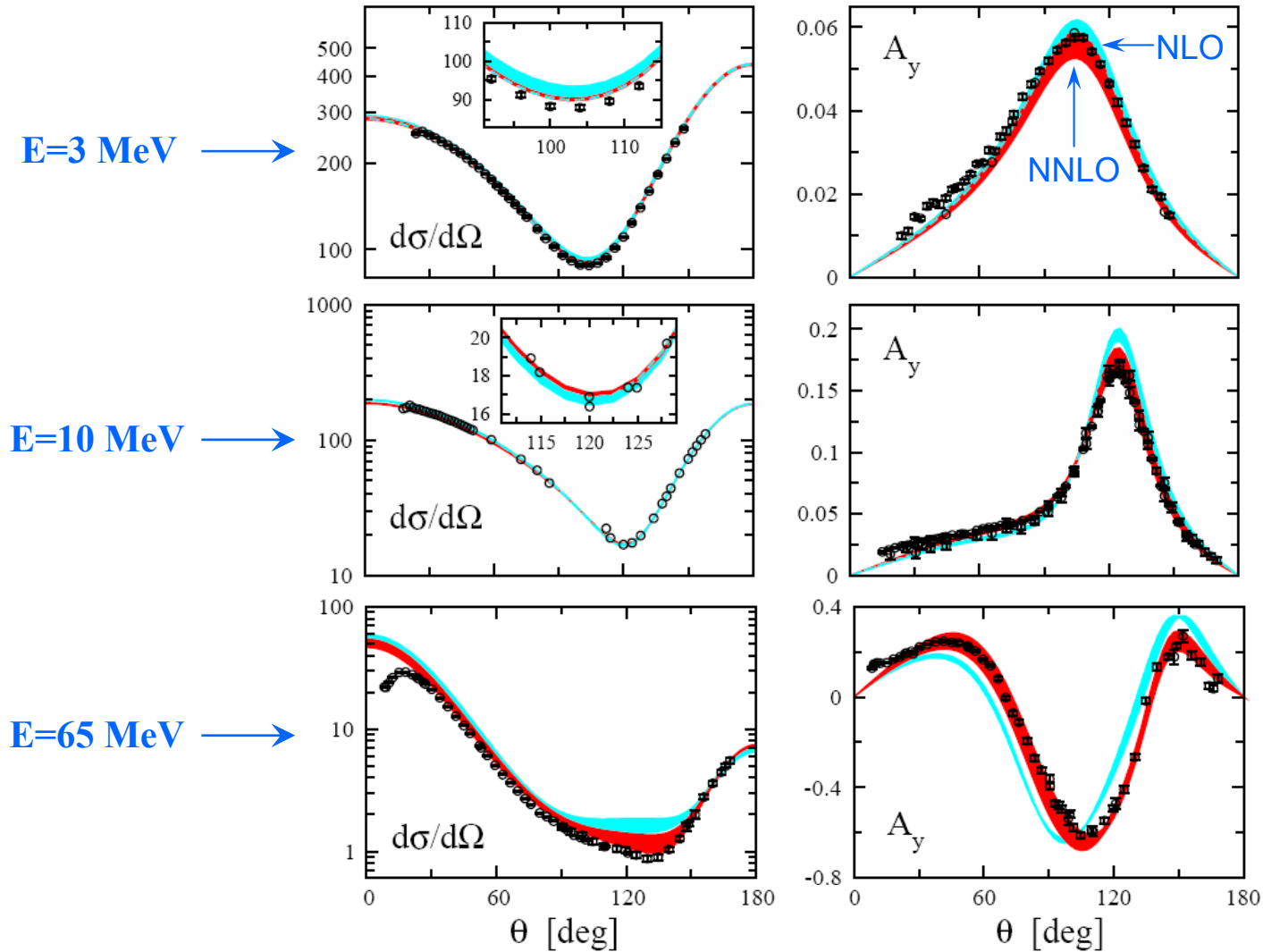
van Kolck '94; E.E. et al. '02

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
 - ^3H binding energy and nd doublet scatt. length (E.E. et al. '02)
 - ^3H and ^4He binding energies (Nogga et al. '05)
 - ^3H and ^{10}B binding energies (Navratil et al. '07)

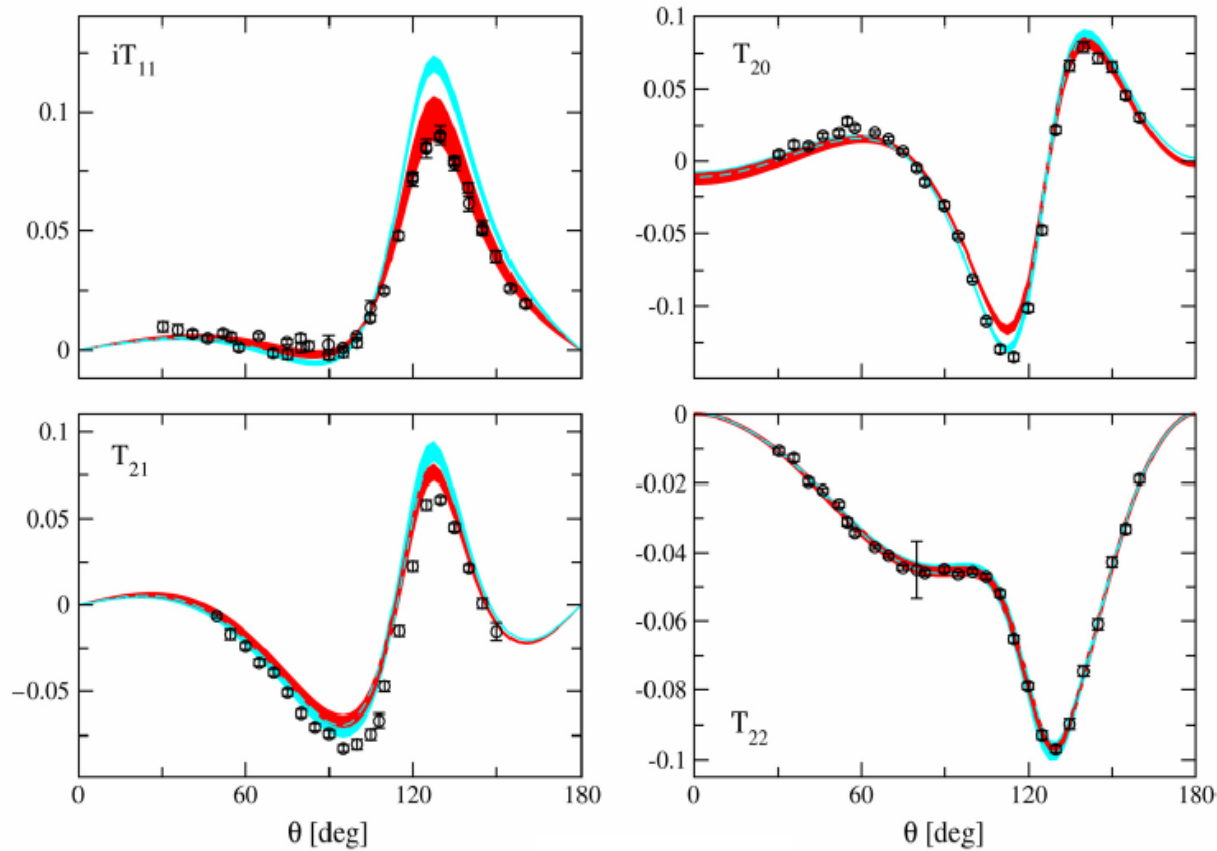


Elastic nucleon-deuteron scattering observables



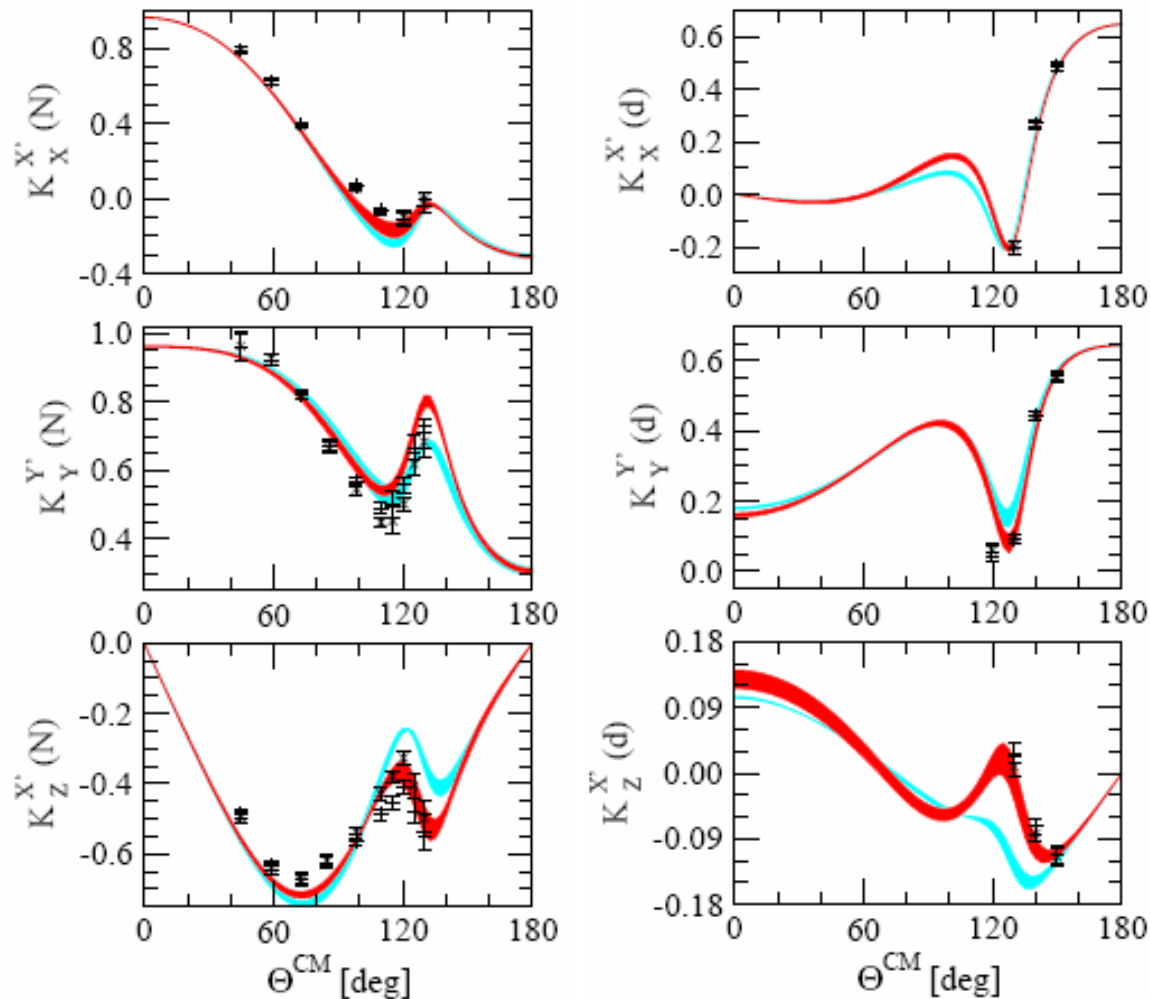
Data shown are np and Coulomb-corrected pd data

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



Data shown are Coulomb-corrected pd data

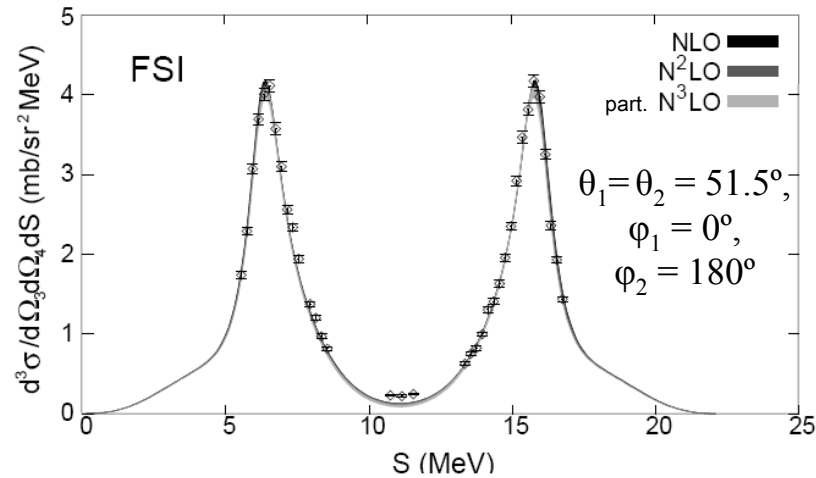
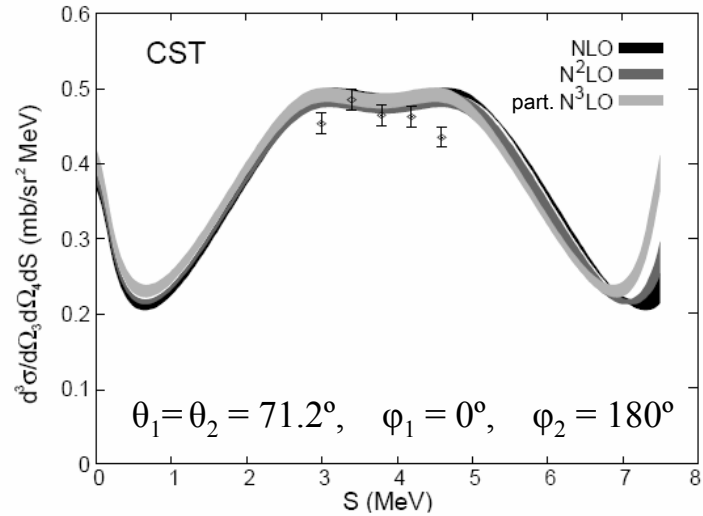
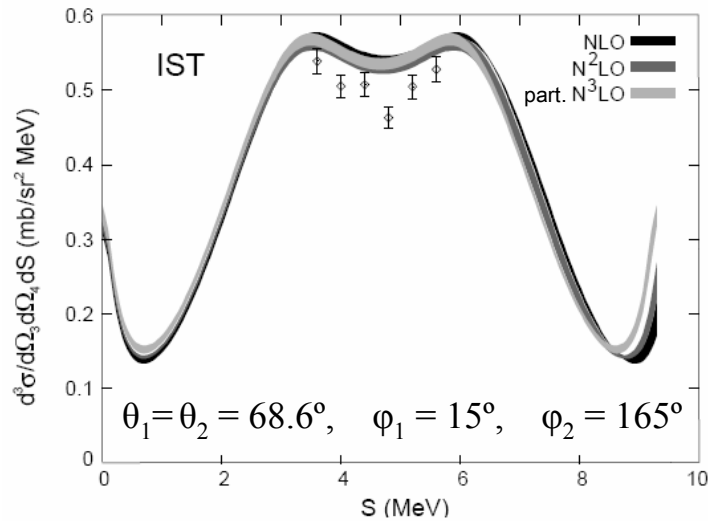
Polarization transfer coefficients in $d(\vec{p}, \vec{p})d$ and $d(\vec{p}, \vec{d})p$ at $E_p=22.7$ MeV



Data shown are Coulomb-corrected pd data

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

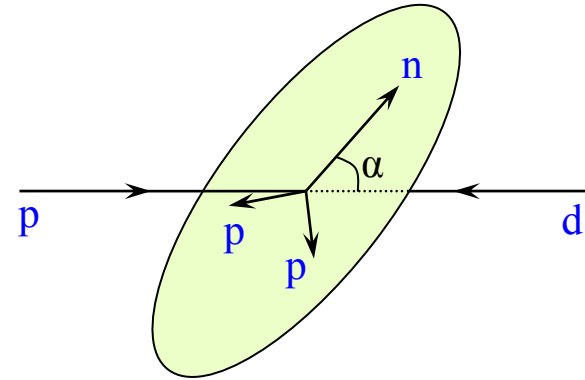
Breakup cross section in the reaction $d(p, pp)n$ at $E_p=16$ MeV



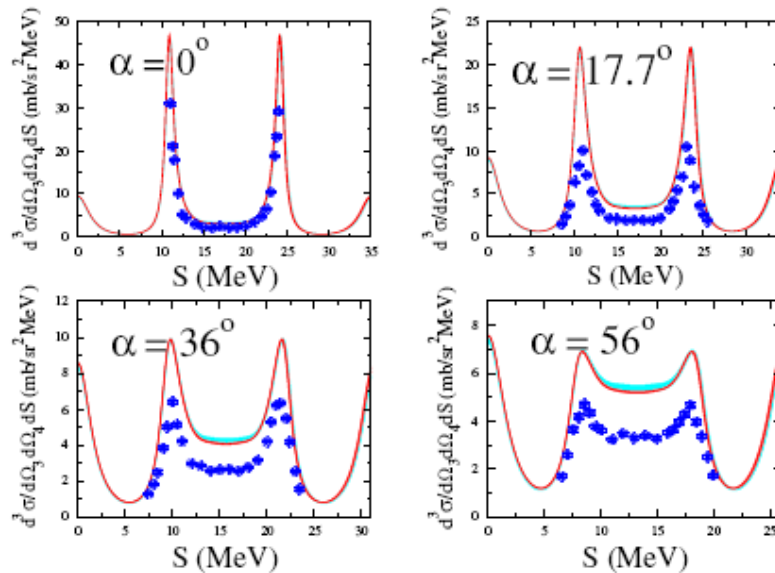
Some open problems...

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

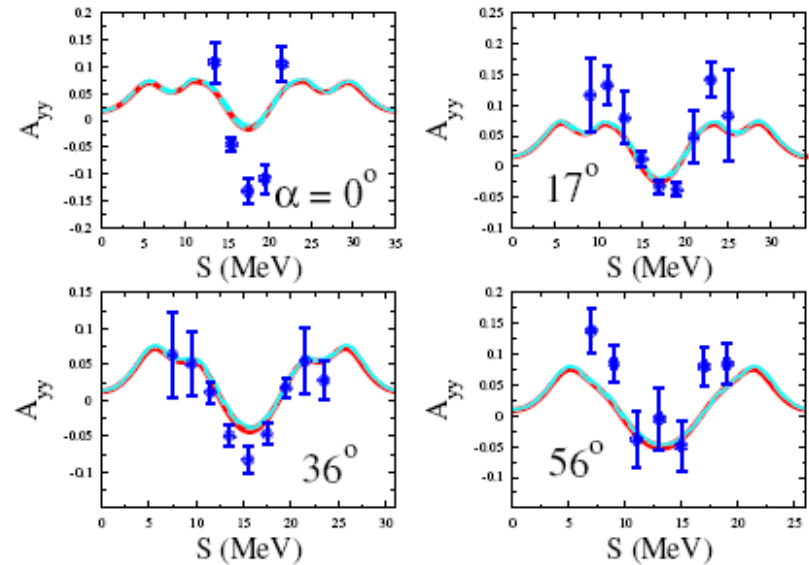
Ley et al., PRC 73 (2006) 064001



Differential cross section



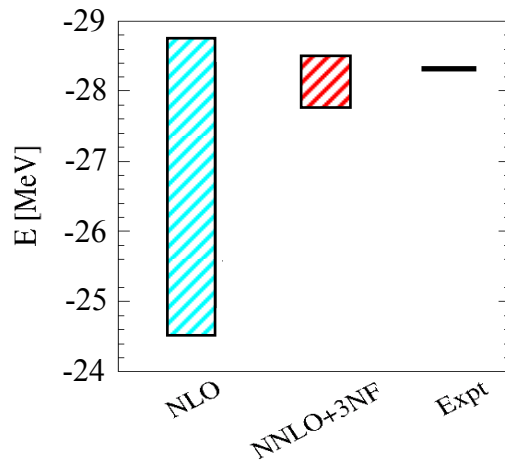
Tensor analyzing power A_{yy}



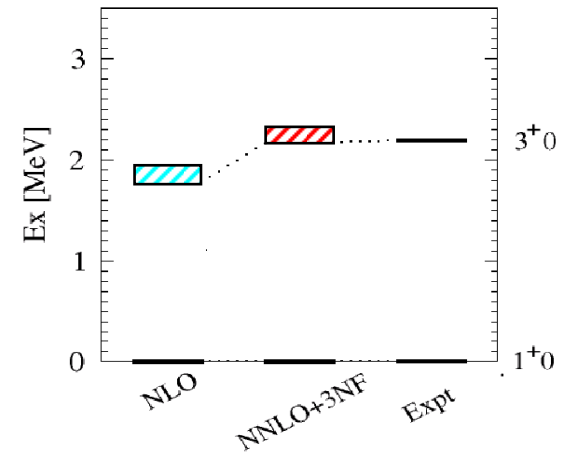
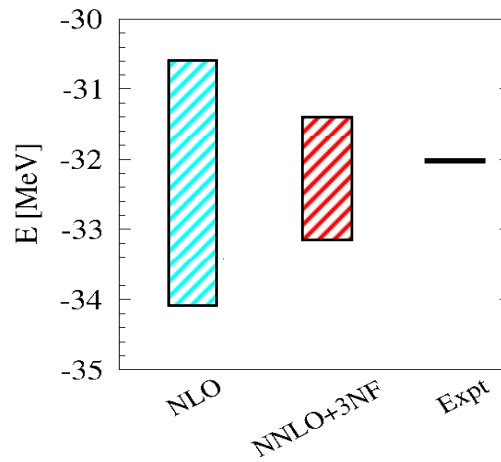
Notice: including Coulomb interaction reduces the discrepancy for the cross section by about 30% and improves the description of A_{yy}

More nucleons...

α -particle



${}^6\text{Li}$ 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 $N^3\text{LO}$ 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

$2\pi-1\pi$ - exchange

2π - exchange between all three nucleons

contact- 1π - exchange

contact- 2π - exchange

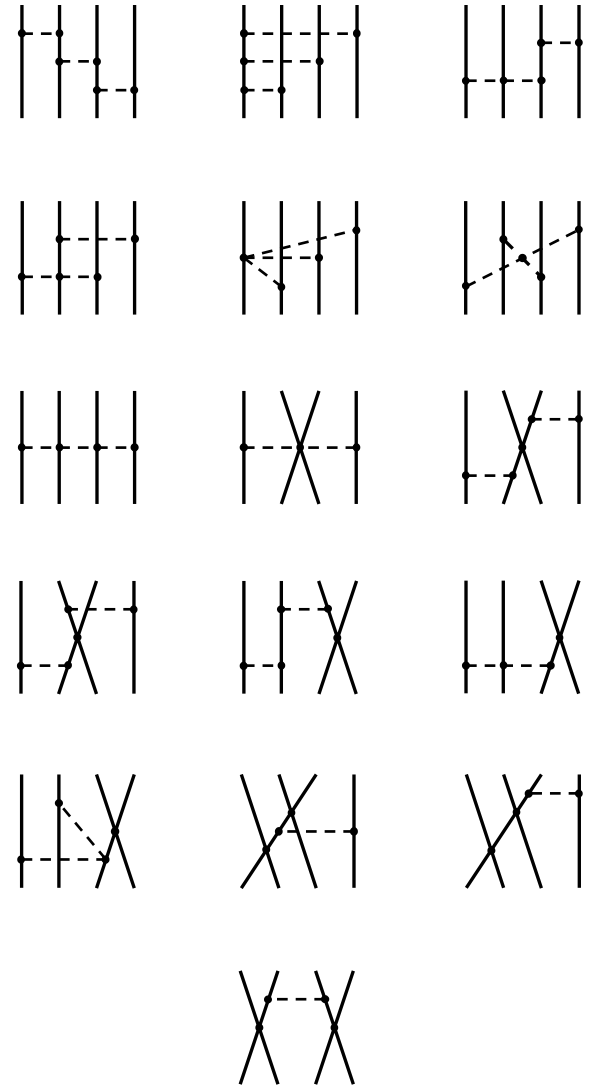
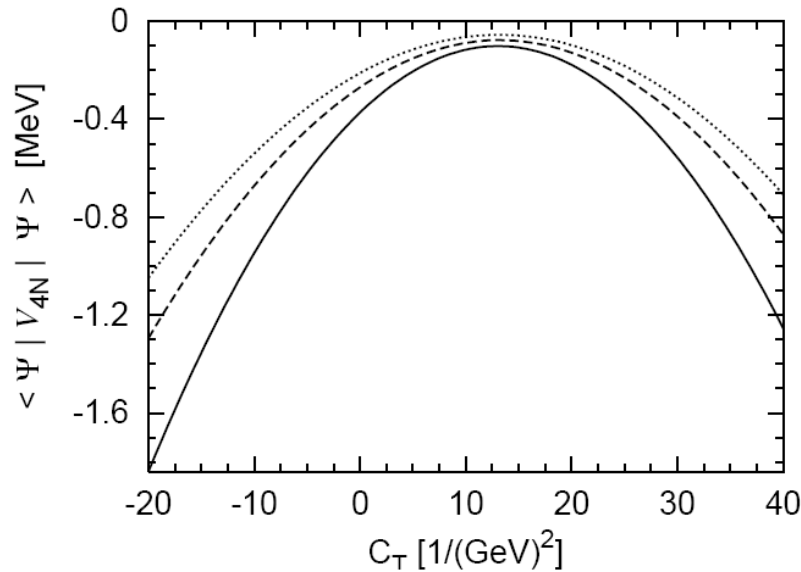
+ $1/m$ - corrections

- no new 3N contact interactions \implies **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^3LO
- chiral symmetry plays a crucial role
- **parameter-free**

Contribution of the 4NF to the ${}^4\text{He}$ 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:

$$V_{NN}^{LO} = \text{X} + \text{---}$$

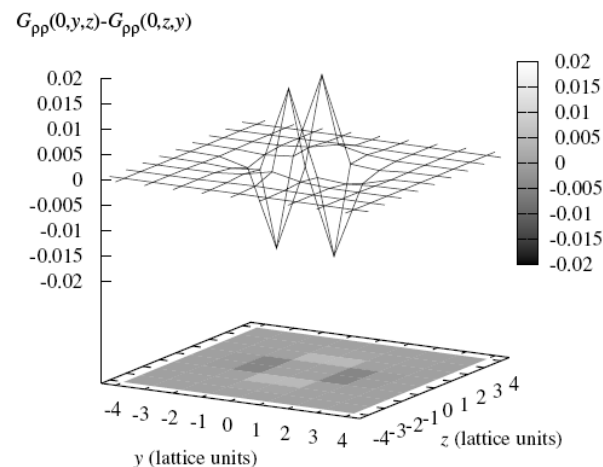
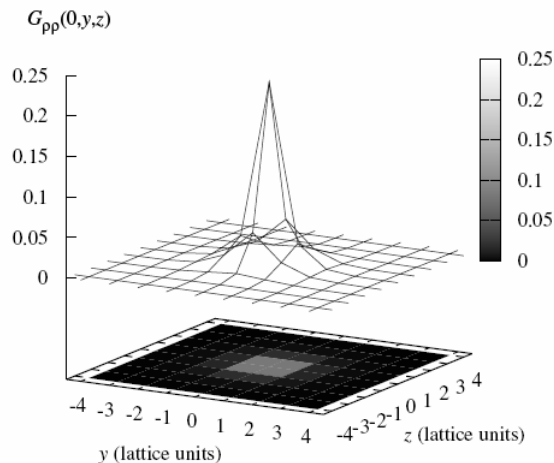
We found:

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

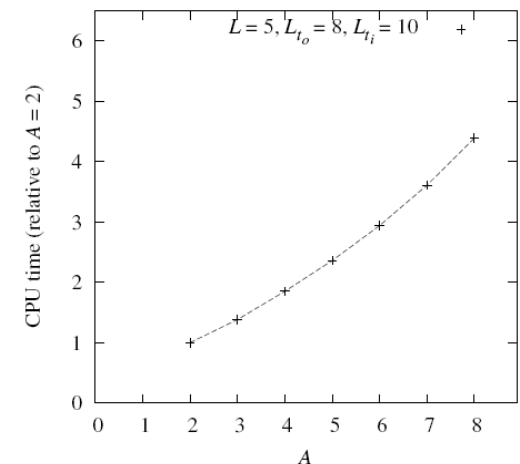
Deuteron properties

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

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



CPU time scaling



Inclusion of the Δ

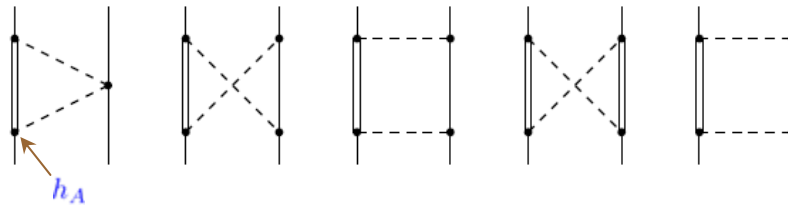
Krebs, E.E., Meißner, EPJA 2007, in press

Δ -isobar is known to be important due to:

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

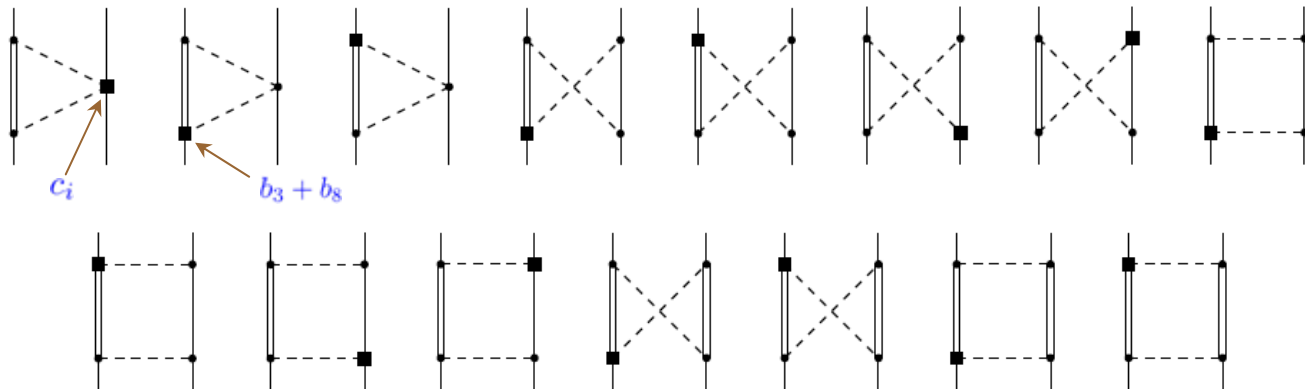
⇒ expect: better convergence & applicability at higher energy in EFT with Δ 's

NLO



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

NNLO

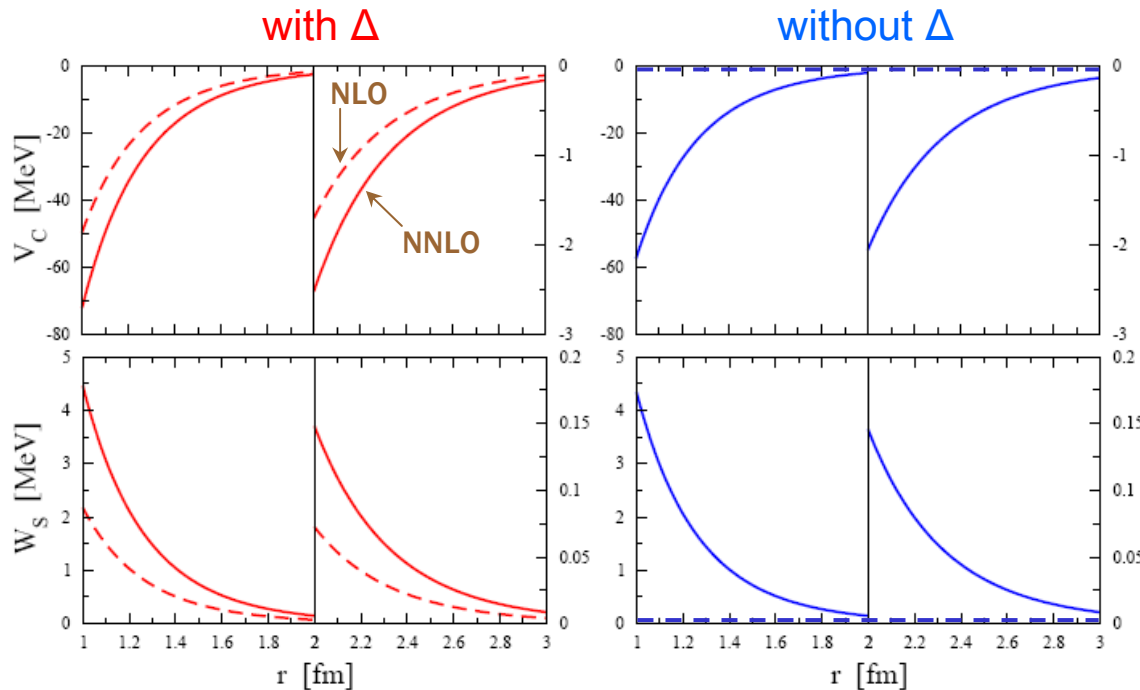


The LECs c_i and $b_3 + b_8$ are fixed from πN S- and P-wave threshold coefficients.

Chiral 2π -exchange potential up to NNLO:

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

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 $N^3\text{LO}$ are in very good agreement with the data. $N^2\text{LO}$ calculations in $>2\text{N}$ systems yield promising results.
- The leading 4NF has been worked out (contributes at $N^3\text{LO}$). Calculation of the $N^3\text{LO}$ 3NF corrections are underway.
- First results are obtained for nuclear lattice simulations at LO in chiral EFT
- The $N^2\text{LO}$ 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 $N^3\text{LO}$.
- The role of Δ -isobar for nuclear forces and few-nucleon systems.
- Further work on nuclear lattice lattice simulations.