N^3LO chiral predictions for spin observables in nd elastic scattering and the deuteron breakup at low energies.

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Outline

Introduction:

- Formalism for few nucleons

3NF from χEFT

- 3NF at N^2LO and N^3LO
- Automatized partial wave decomposition (aPWD)
- Fixing free parameters (LECs) at N^3LO

Observables

- Nd elastic scattering cross section
- Deuteron breakup – SST cross section
- Polarization observables for Nd elastic scattering

Outlook

- Another ways to fix LECs
- New regularization scheme for nuclear forces

Introduction – 2N and 3N systems

- Nonrelativistic formalism
- 2N:

  Schrödinger equation,

  Lippmann-Schwinger equation for the t-matrix

  (interaction + free propagation)

$$t(E) = V + VG_0(E)V + VG_0VG_0(E)V + \dots$$

$$G_0(E) \equiv \lim_{\varepsilon \to 0^+} \frac{1}{E - H_0 + i\varepsilon}$$

- 3N: Faddeev equation

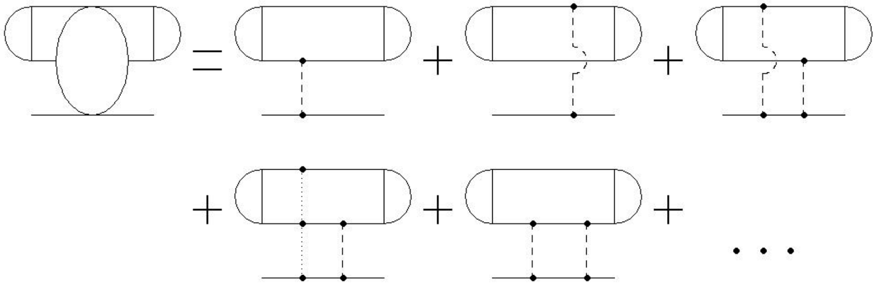
$$T = tP\phi + (1 + tG_0)V_{123}^{(1)}(1 + P)\phi + tPG_0T + (1 + tG_0)V_{123}^{(1)}(1 + P)G_0T$$

Transition amplitudes

$$U = PG_0^{-1} + V_{123}^{(1)}(1 + P)\phi +$$

$$+ PT + V_{123}^{(1)}(1 + P)G_0T$$

$$U_0 = (1 + P)T$$



3NF at N^{2}LO

- N^{2}LO (E.Epelbaum, Prog.Part.Nucl.Phys. 57, 654(2006)):

$$V_{123} = V_{2\pi}^{(3)} + V_{1\pi,cont}^{(3)} + V_{cont}^{(3)}$$

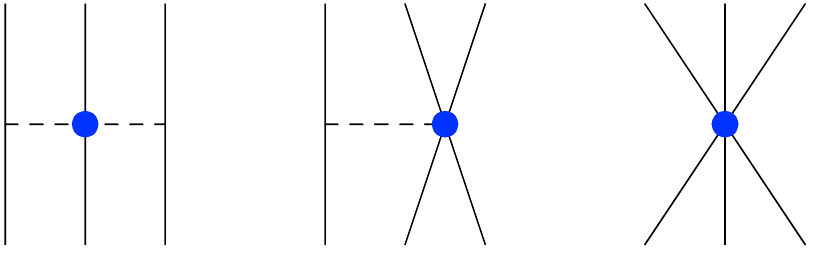
$$V_{2\pi}^{(3)} = \sum_{i \neq j \neq k} \frac{1}{2} \left(\frac{g_A}{2F_\pi}\right)^2 \frac{(\vec{\sigma}_i \circ \vec{q}_i)(\vec{\sigma}_j \circ \vec{q}_j)}{(\vec{q}_i^{\,2} + M_\pi^2)(\vec{q}_j^{\,2} + M_\pi^2)} F_{ijk}^{\alpha\beta} \tau_i^\alpha \tau_j^\beta$$

$$\vec{q}_i \equiv \vec{p}_i\,' - \vec{p}_i$$

$$F_{ijk}^{\alpha\beta} = \delta^{\alpha\beta}\left[-\frac{4c_1 M_\pi^2}{F_\pi^2} + \frac{2c_3}{F_\pi^2}\vec{q}_i \circ \vec{q}_j\right] + \sum_\gamma \frac{c_4}{F_\pi^2}\varepsilon^{\alpha\beta\gamma}\tau_k^\gamma \vec{\sigma}_k \circ \left[\vec{q}_i \times \vec{q}_j\right]$$

$$V_{1\pi,cont}^{(3)} = -\sum_{i \neq j \neq k} \frac{g_A}{8F_\pi^2} D \frac{\vec{\sigma}_j \circ \vec{q}_j}{\vec{q}_j^{\,2} + M_\pi^2}\left(\vec{\tau}_i \circ \vec{\tau}_j\right)\left(\vec{\sigma}_i \circ \vec{q}_j\right)$$

$$V_{cont}^{(3)} = \frac{1}{2}\sum_{j \neq k} E\left(\vec{\tau}_j \circ \vec{\tau}_k\right)$$



Two free parameters: D and E

3NF at N^3LO long range part

N^3LO V.Bernard, E.Epelbaum, H.Krebs, U-G.Meißner,
Phys Rev C77 (2008) 064004.

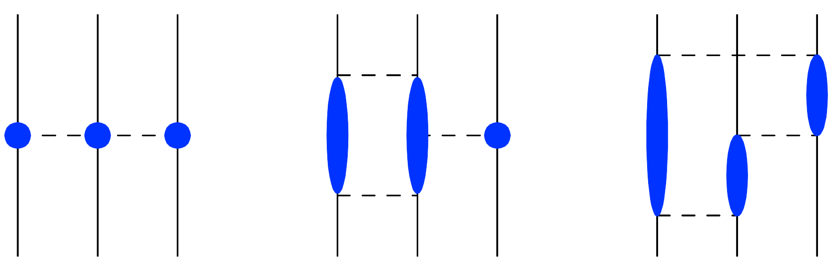
- $V_{2\pi}$ – already at N^2LO, at N^3LO the same operator structure but new values of C_1, C_3, C_4 and momentum dependance in formfactors

Two new topologies:

- Two pion – one pion exchange $V_{2\pi\text{-}1\pi}$
- The ring term V_{ring}

No new free parameters

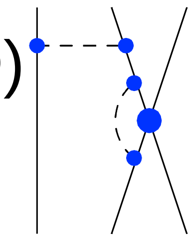
More operator structures and more complicated momentum dependece



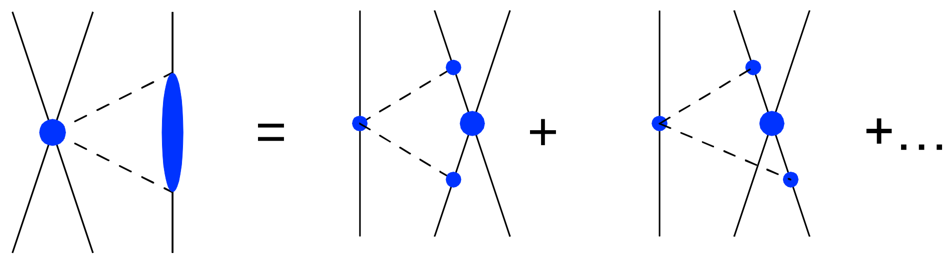
3NF at N^{3}LO short range part

N^{3}LO: V.Bernard, E.Epelbaum, H.Krebs, U-G.Meißner,
Phys Rev C84 (2011) 054001.

- 1π-contact – already at N^{2}LO (one free parameter D)
  at N^{3}LO all terms cancel thus no new contributions at this order

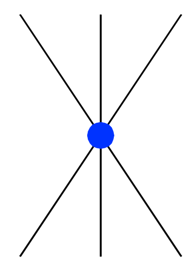


- 2π-contact



No new free parameters

- Three nucleon contact term – already at N^{2}LO
  One free parameter E

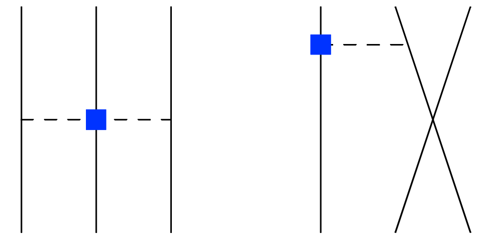


3NF at N^{3}LO short range part

N^{3}LO: V.Bernard, E.Epelbaum, H.Krebs, U-G.Meißner,
Phys Rev C84 (2011) 054001.

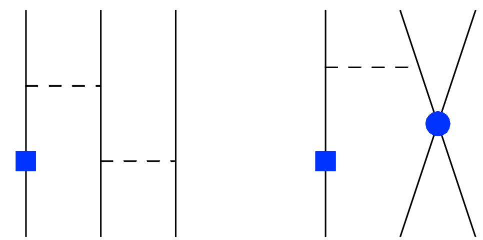
- Relativistic 1/m corrections to 2π and 1π-contact terms coming from:

corrections to πNN
and $\pi\pi$NN vertices



retardation effects

No new free parameters



In total: two free parameters at N^{3}LO.

The chiral 3NF depends also on additional regularization parameter.

aPWD (automatized partial wave decomposition)

- The efficient method of partial wave decomposition is required to include many operator structures present in 3NF into calculations.

- aPWD reduces partial wave decomposition to 1-dim integration for NN force and 5-dim integration for 3NF. However this integration has to be repeated for different momenta and three-body partial waves.

- The integrands can be relatively easy prepared using e.g. Mathematica®.

- This can be further reduced for local 3NF

- Details are given in:

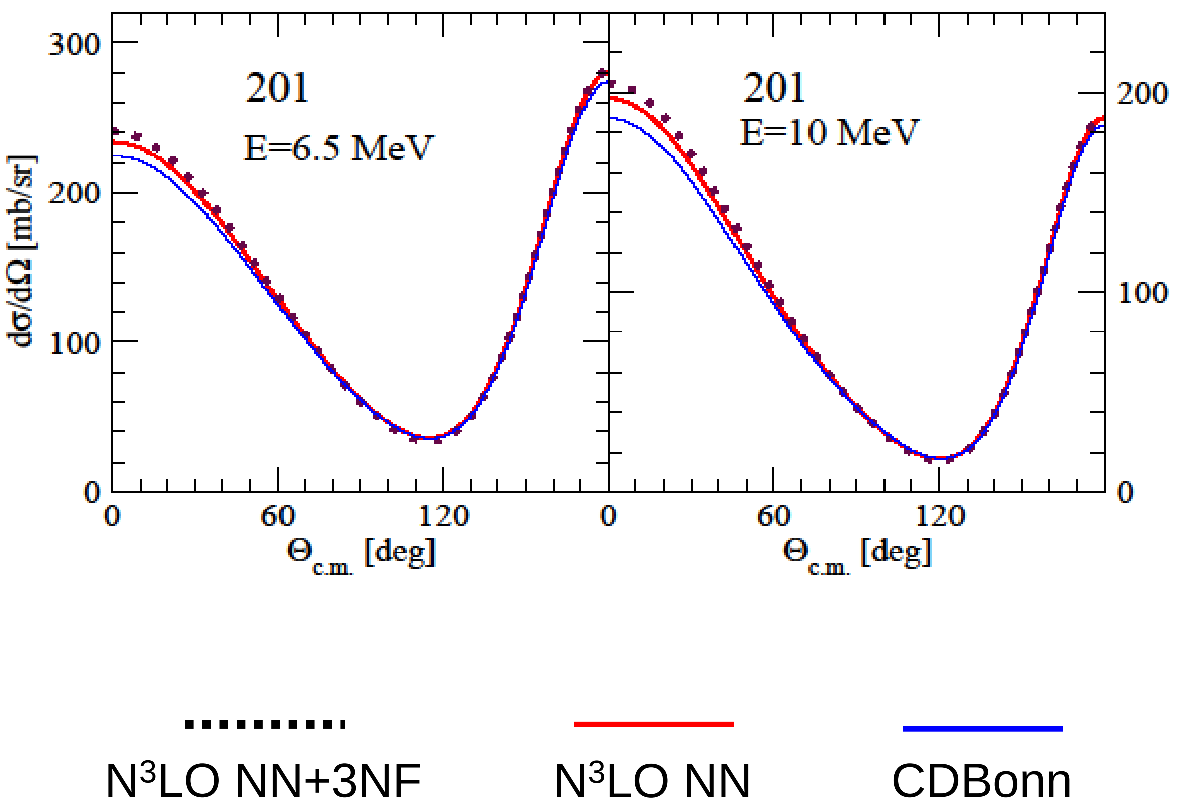
  J.Golak et al., Eur. Phys. J. A43, (2010) 241

  R.Skibiński et al., Eur. Phys J. A47 (2011) 48.

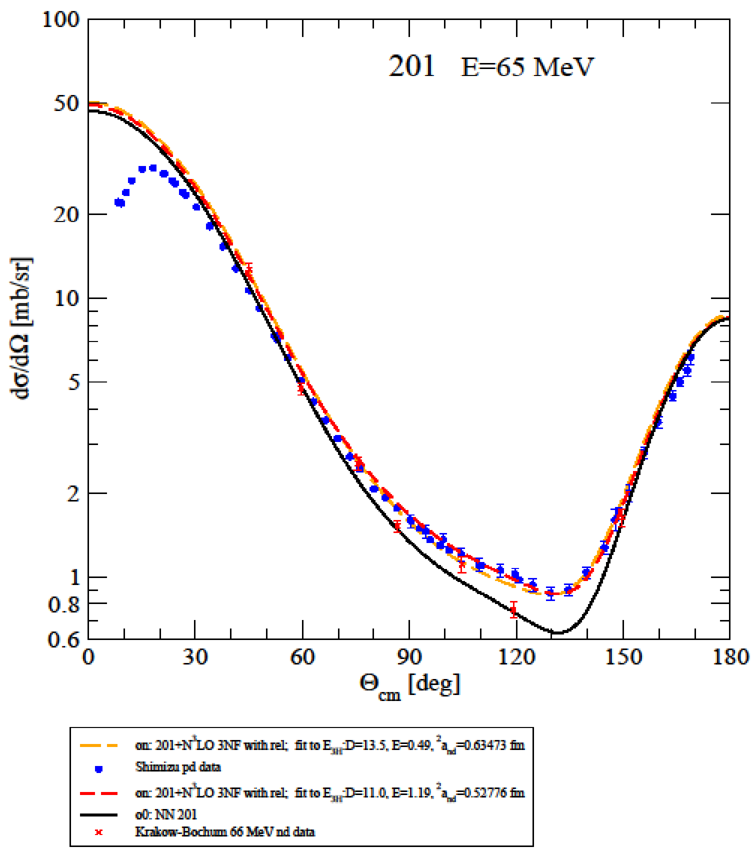
Fixing LECs

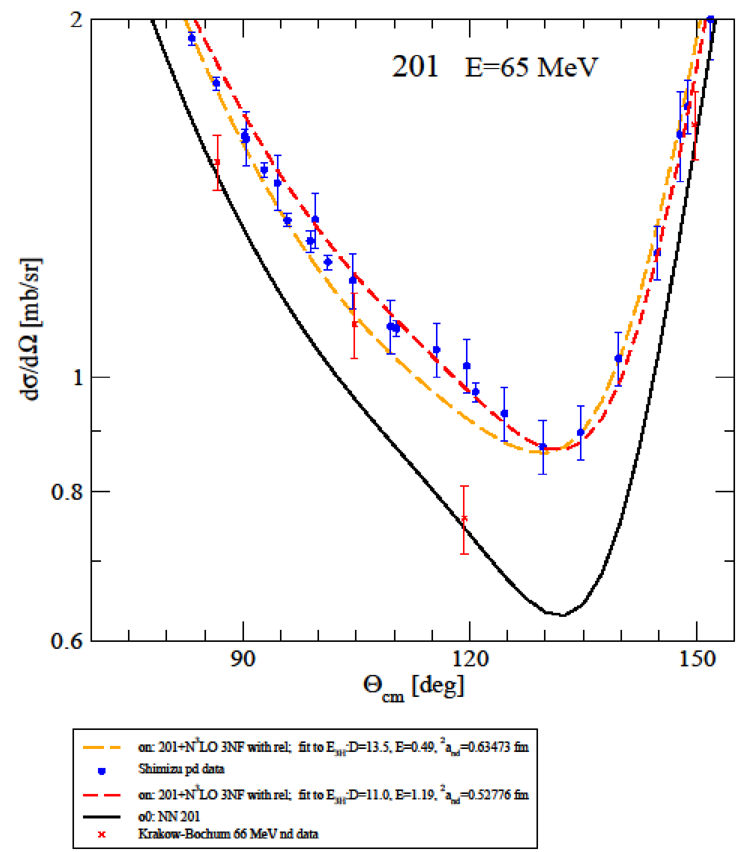
- At this moment we use the ^3H binding energy and the $^2a_{nd}$ scattering lenght to fix D and E LECs, which arise from short range terms.
- Such a procedure requires a solution of the Faddeev and Schrödinger equations but only for J=1/2+ states.
- Neutron-duteron system – there is no Coulomb force.
- In principle other observables can also be used to determine D and E, for example μ-capture on ^3He (J=1/2+, first step in this direction in J.Golak et al., arXiv:1406.6781)
- For cut-offs =1 and 4 (regularization parameter Λ=450 MeV) we are able to fix D and E, obtaining D=13.78 and E=0.372 and D=9.095 and E=-0.0845, respectively. For other cut-offs (with bigger Λ) one have to go to too big (absolute values) of D and E to reproduce $^2a_{nd}$. There are also problems with the convergence of the Faddeev equation in some non-physical range of values of D and E.
- More details in: R.Skibiński et al., Phys. Rev. C84 (2011) 054005
  H.Witała et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 094011
  J.Golak et al., arXiv:1410.0756

Nd elastic scattering at low energies

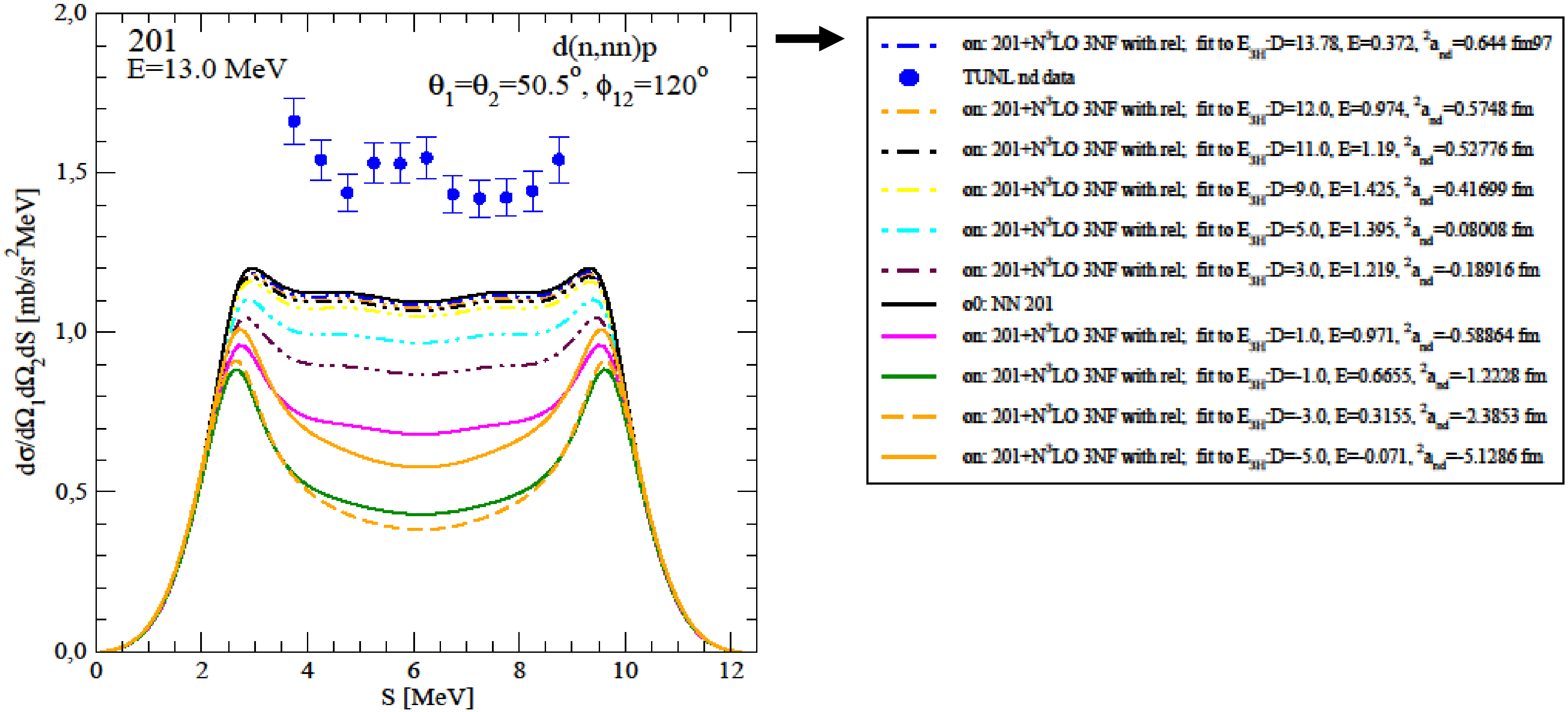


Nd elastic scattering at E=65 MeV, cut-off=1

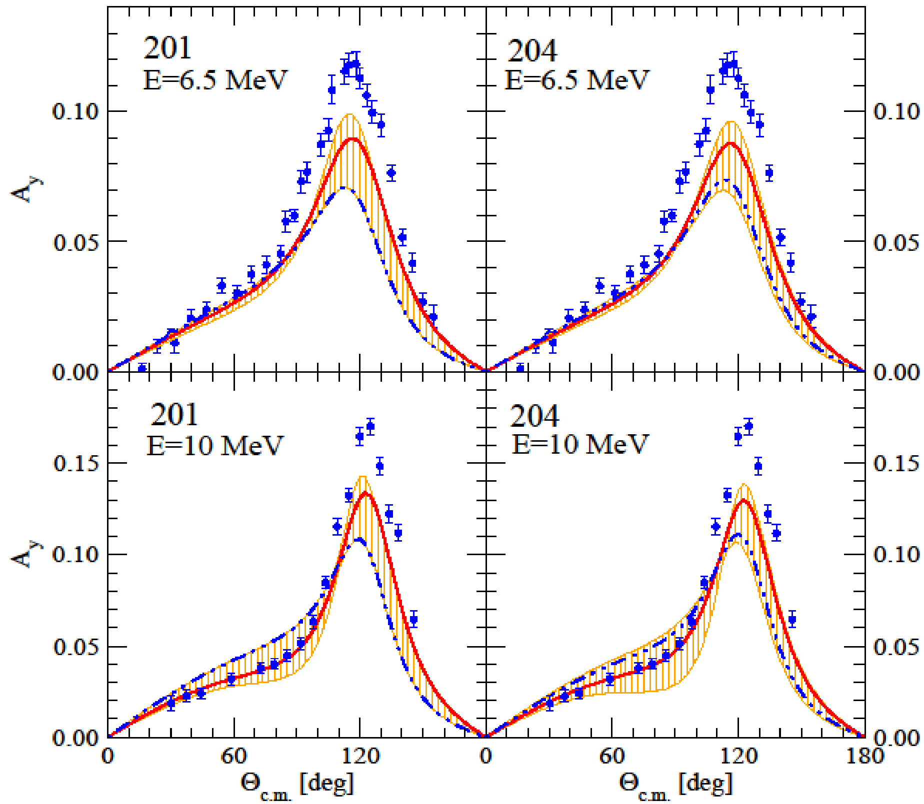




SST cross section at E=13 MeV, cut-off=1



The nucleon analyzing power A_y

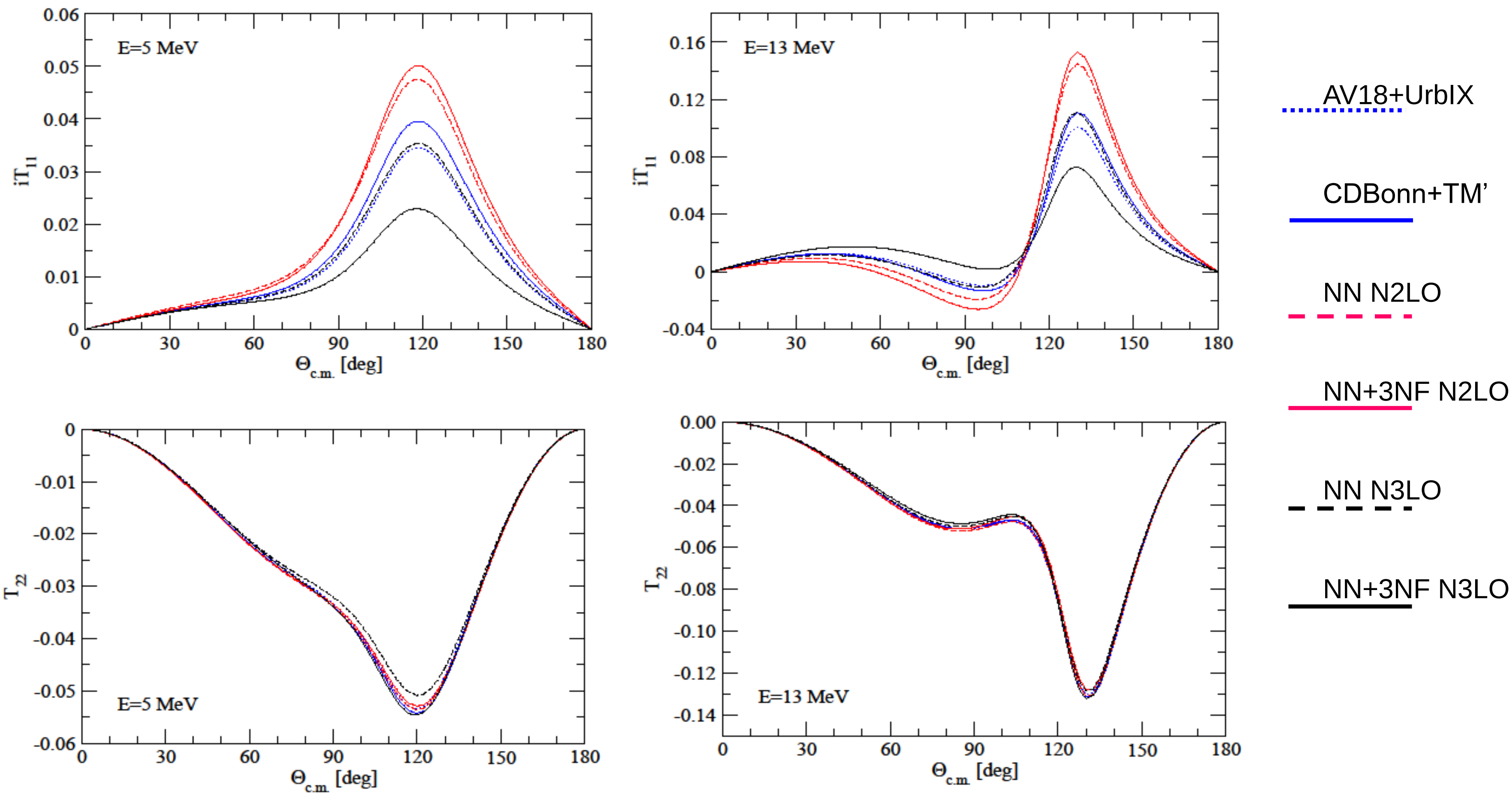


N^3LO NN+3NF

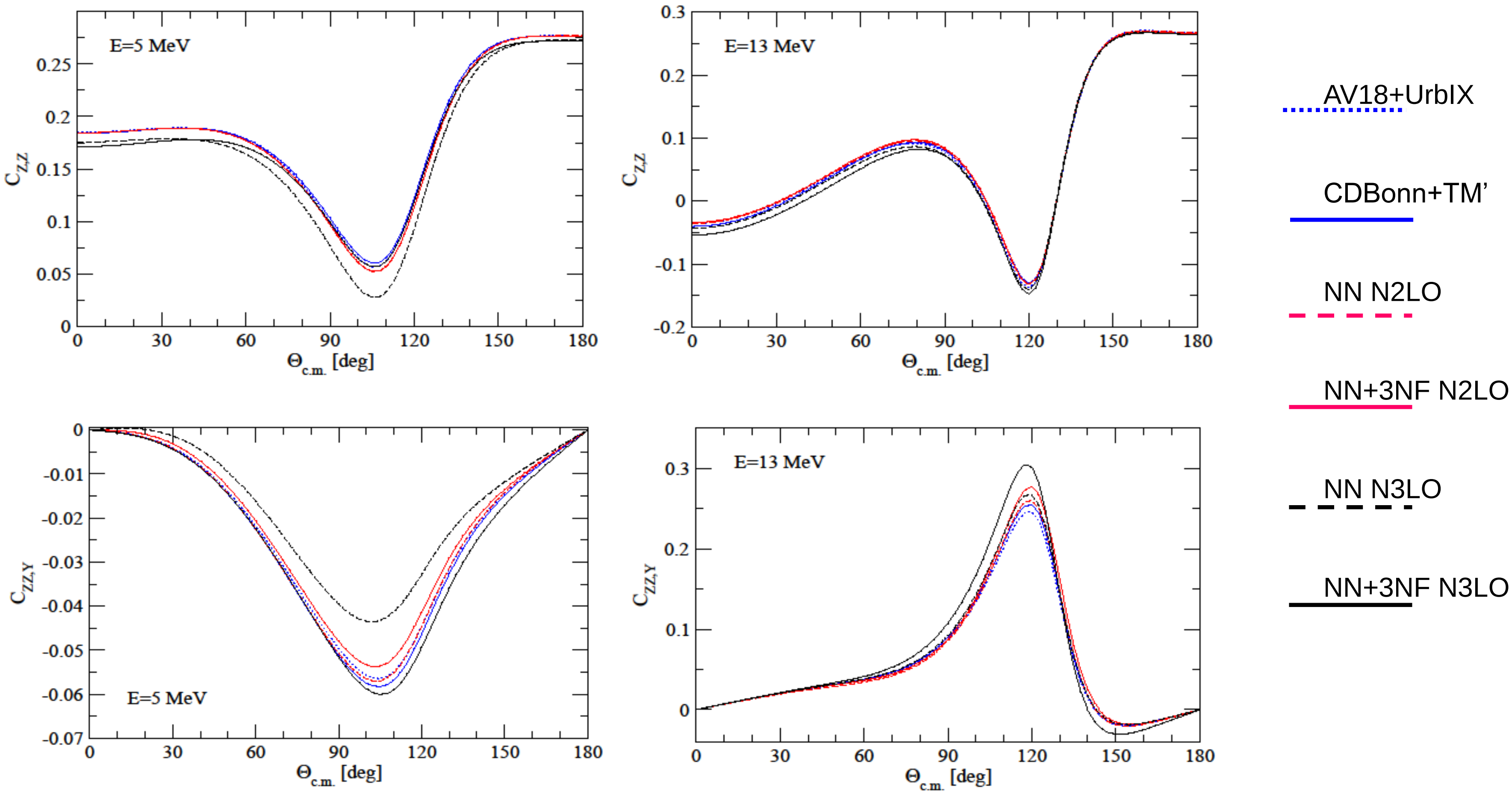
N^3LO NN

N^3LO NN+3NF, only ^3H reproduced

The deuteron tensor analyzing powers iT_{11} and T_{22}



The spin correlation coefficients $C_{Z,Z}$ and $C_{ZZ,Y}$



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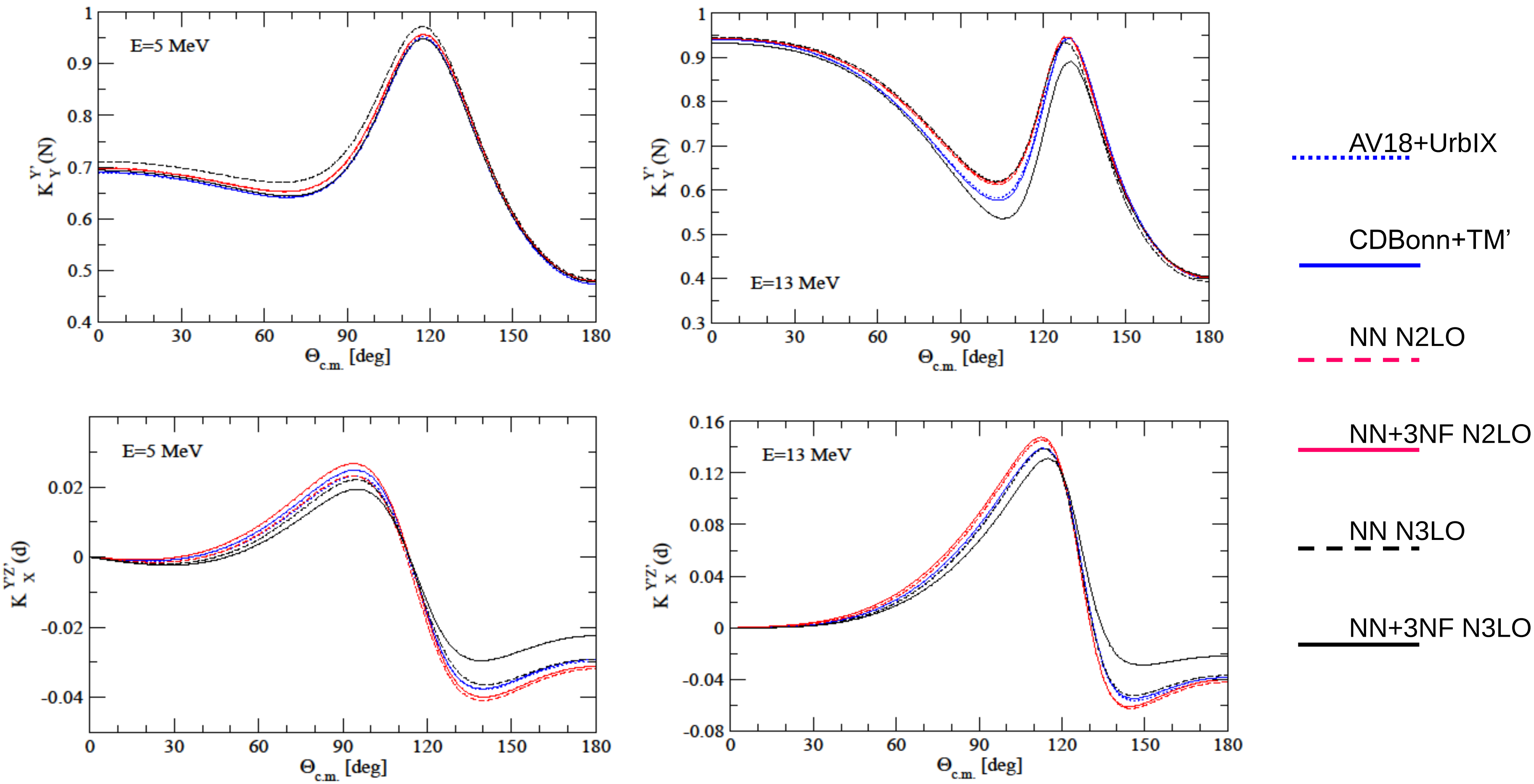
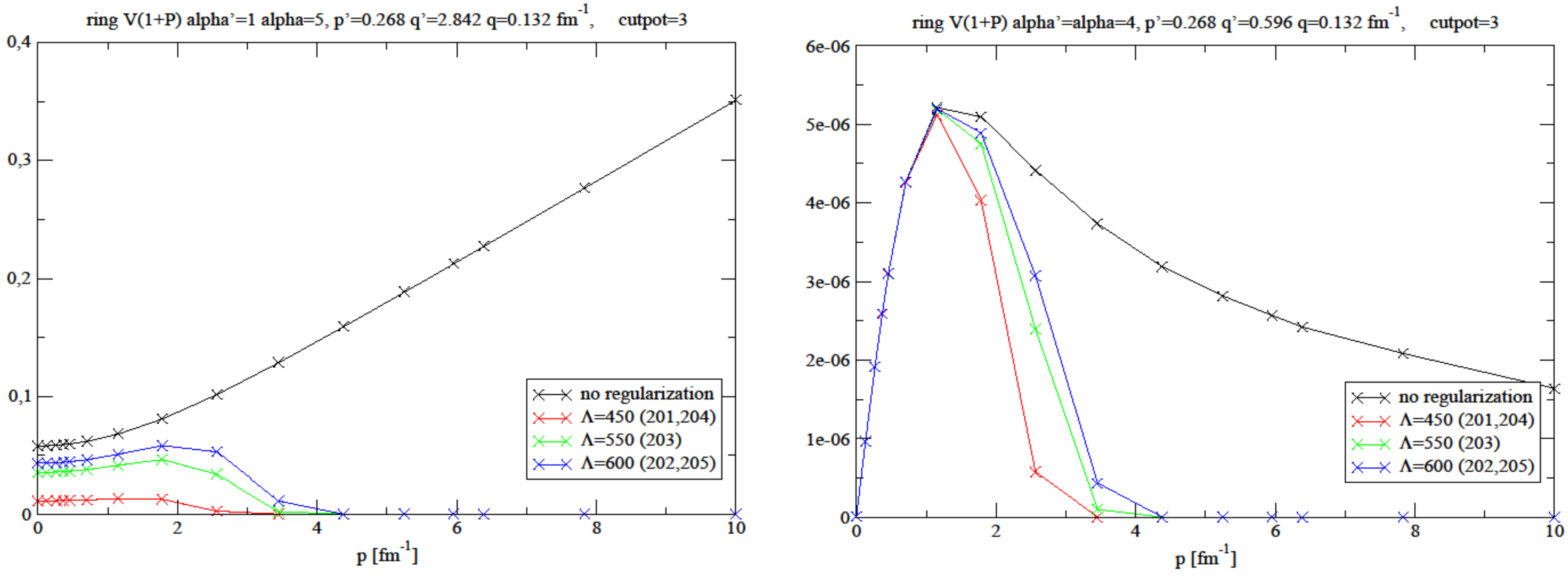
The spin transfer coefficients $K_Y^{Y'}(N)$ and $K_X^{Y'Z'}$



Importance of regularization

- Regularization $V^4 \rightarrow f(p',q',\Lambda)\, V^4(p',q',p',q)\, f(p,q,\Lambda)$ with

$$f(p,q,\Lambda) \equiv e^{-(p^2+0.75q^2)^3/\Lambda^6}$$



- New, local regularization scheme for NN and 3N forces is under construction (E.Epelbaum). The preliminary results for NN and Nd scattering show much smaller dependance on cut-off parameters, then presented here.

Summary and Outlook

1. The full chiral N^3LO potential with standard nonlocal regularization has been applied to the elastic Nd scattering and the deuteron breakup reaction. Unfortunatelly, there is no improvement in data description.

2. The strong dependence on cut-off parameters is seen and unnaturaly large values of free parameters (not shown in my talk) have been obtained for some cut-offs.

The above calls for modifications of current forces:

1. The new, local regularization scheme for NN and 3N forces will be used .

2. LECs will be fixed using also weak processes.

3. New 3NFs, especially ones from chiral EFT with explicit Δ will be included.

Thank you for your attention