Three-nucleon reactions with improved chiral forces

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Outline

Introduction:
NN interaction
Formalism (states, currents)

Results
nucleon-deuteron elastic scattering
nucleon-deuteron radiative capture
muon capture on ^{3}He

Outlook

Nucleon-nucleon interaction

- 1935 meson theory begins with Yukawa potential
- One-boson exchange
- Many-bosons exchange BonnB (CDBonn)

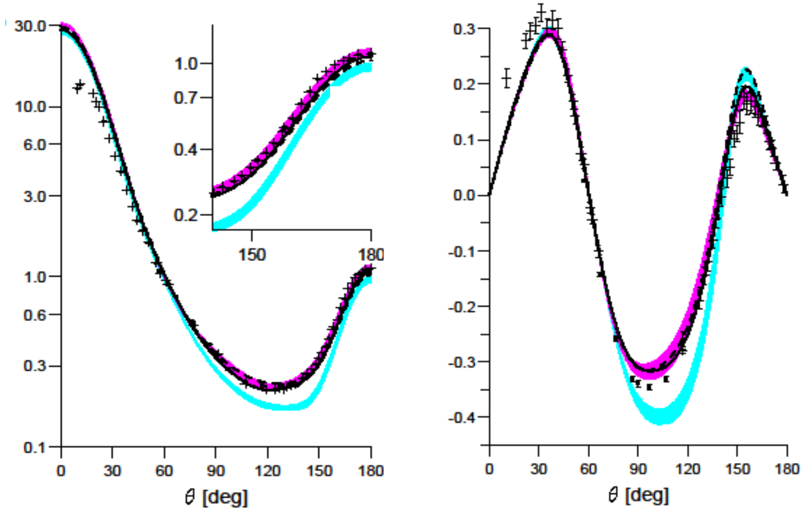
Quite successful,

however

- Not connected to QCD
- Strong dependence of predictions on the model, especially, for polarization observables at N>2
- Not obvious systematic way to introduce improvements
- Not obvious how to derive consistent 3NF and electroweak currents
- Not obvious way how to estimate theoretical errors

Elastic Nd scattering at E=135 MeV

$d\sigma/d\Theta$ [mb/sr] iT_{11}



H.Witała et al.,
Phys. Rev. C63
(2001) 024007

Chiral nuclear interactions

- 1990's meson exchange but within the chiral efffective field theory (S.Weinberg, U. van Kolck)

- Lagrangian for pions and nucleons with symmetries from QCD
  → perturbative expansion and power counting
  → decoupling pions and nucleons
  → effective Hamiltonian
  → effective two-nucleon and many-nucleon potential (in perturbative expansion)

E.Epelbaum, Prog. Part. Nucl. Phys. 57 (2006) 654–741

E.Epelbaum, arXiv:1001.3229v1 [nucl-th] lectures given at the 2009 Joliot-Curie School, Lacanau, France

E.Epelbaum, H-W.Hammer, U.-G.Meißner Rev. Mod. Phys. 81 (2009) 1773

R.Machleidt, D.R.Entem, Phys. Rep. 503 (2011) 1–75

- Currently two groups dominates in developing nucleon-nucleon forces from χEFT:

1. D.R.Entem, R.Machleidt (dominant N5LO contributions, only NN force, two values of regularizator Λ=500 MeV and Λ=600 MeV)

2. E.Epelbaum, Ulf-G.Meißner (up to N4LO, but with consistent 3NF up to N4LO).

Chiral forces with semi-local regularization

- However, after inclusion of 3NF at N3LO to the 3N systems the strong parameter dependence has been observed (J.Golak, Eur. Phys. J. A50 (2014) 177).
  It was traced back, that problems origin in nonlocal regularization of NN and 3N potentials.

- New, improved chiral force, presented by Bochum-Bonn group in 2014:
  - E. Epelbaum, H. Krebs, U.-G. Meißner, Eur. Phys. J. A51 (2015) 3,26 – up to N3LO
  - E. Epelbaum, H. Krebs, U.-G. Meißner, Phys. Rev. Lett. 115 (2015) 12, 122301 – up to N4LO

  - **All LECs in the long-range part are taken from pion-nucleon scattering without fine tuning**
  - **Local regularization in the coordinate space** $V_{lr}(\mathbf{r}) \rightarrow V_{lr}(\mathbf{r})f(\mathbf{r})$ with $f(\vec{r}) \equiv \left(1 - e^{-r^2/R^2}\right)^n$
  - R=0.8–1.2 fm what corresponds to Λ=330-500 MeV in an older model
  - Best χ2/(np data up to 300 MeV,) for R=0.9 fm
  - Such regularization preserves more long-range OPE and TPE physics
  - No (unwanted) short-distance part of TPE force (thus no SFR)
  - Very good description of the deuteron properties, phase shifts etc.

Formalism for 3N scattering

- Nonrelativistic formalism, momentum space

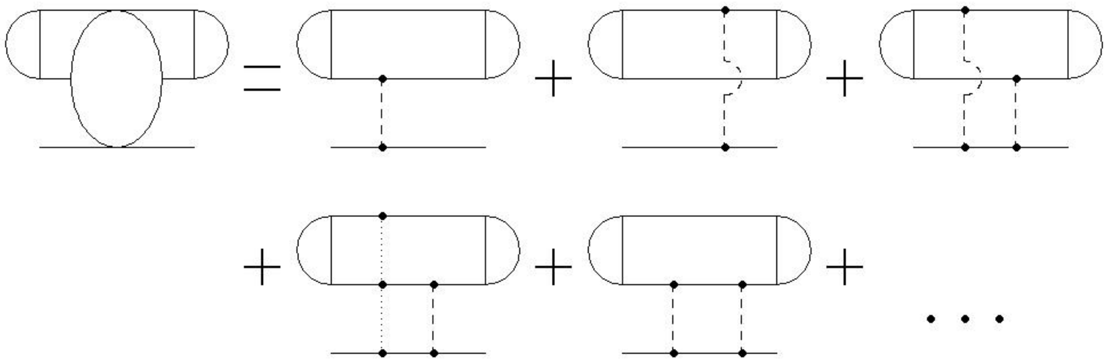
3N: Faddeev equation

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

Lippmann-Schwinger equation for the t-matrix

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

Transition amplitudes:



for elastic Nd scattering

$$U = PG_0^{-1} + V_{123}^{(1)}(1+P)\phi + PT + V_{123}^{(1)}(1+P)G_0T$$

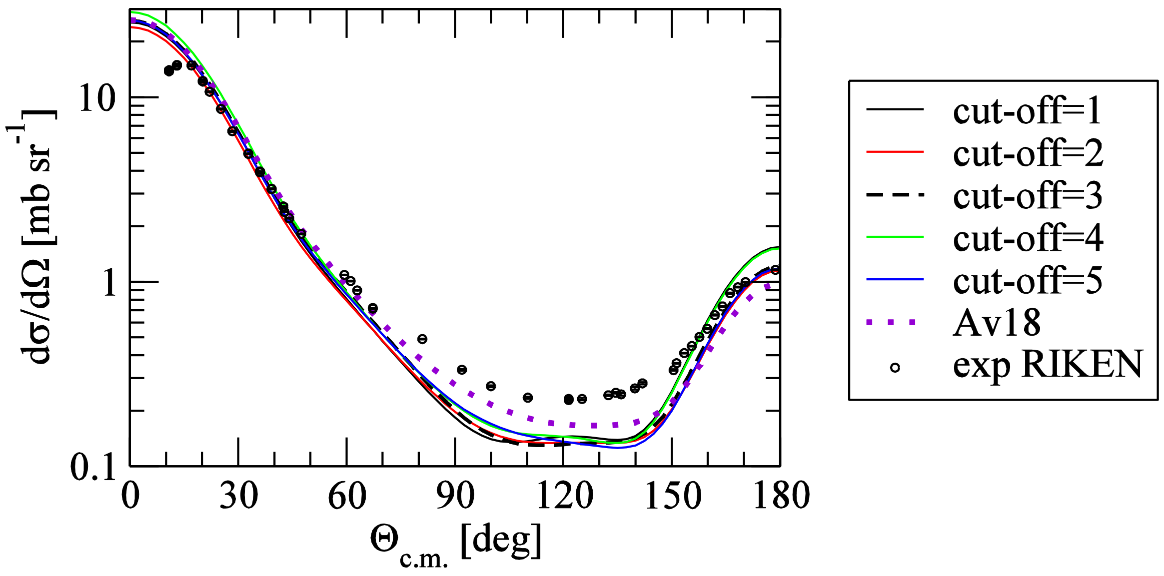
for deuteron breakup

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

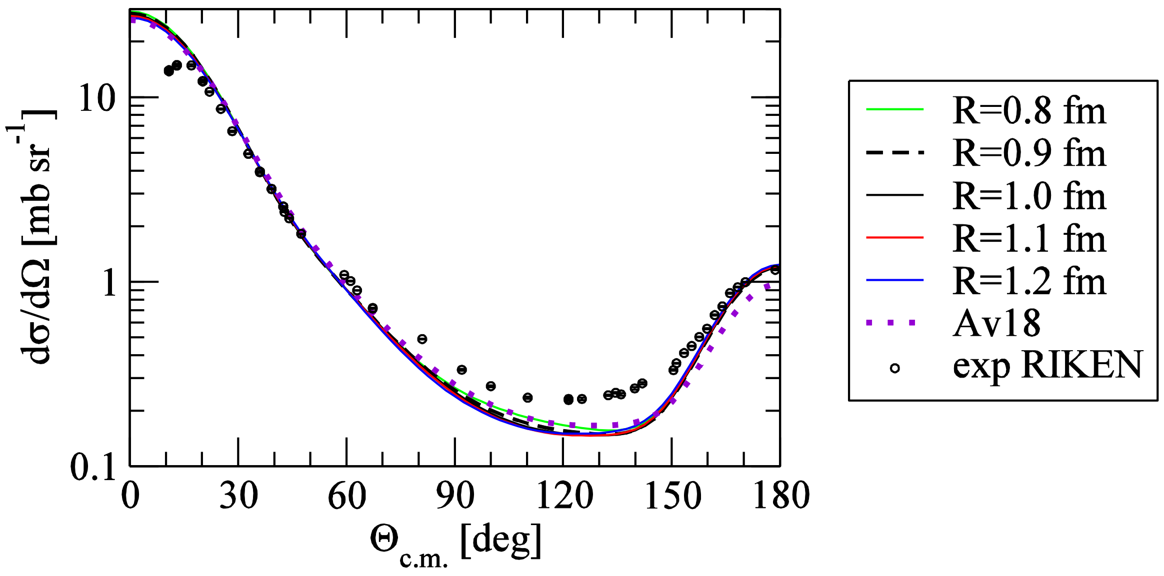
The elastic nucleon-deuteron cross section at 135.0 MeV nucleon lab. energy

→ newer interaction performs better

OLD N3LO
(nonlocal reg.)

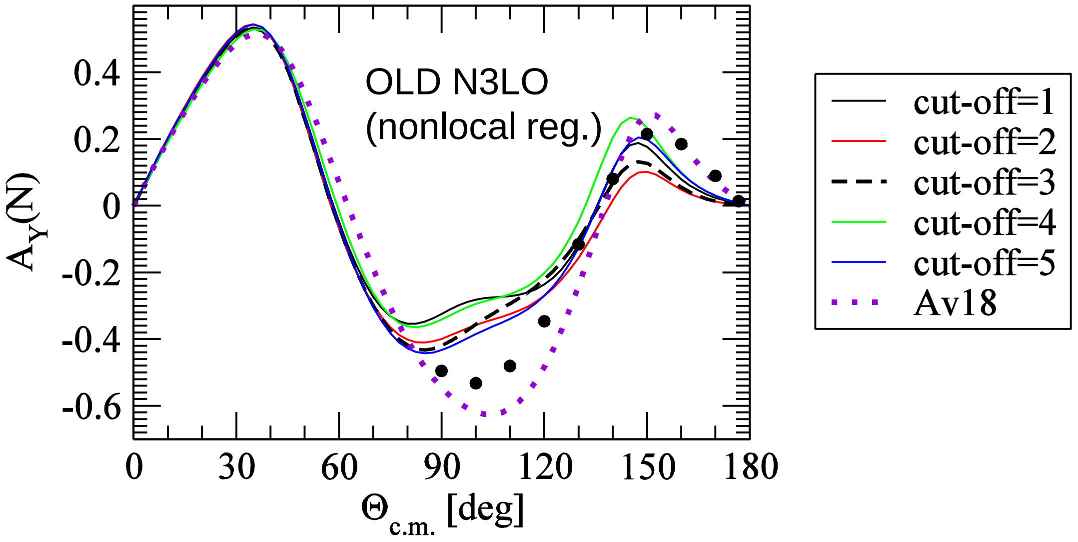


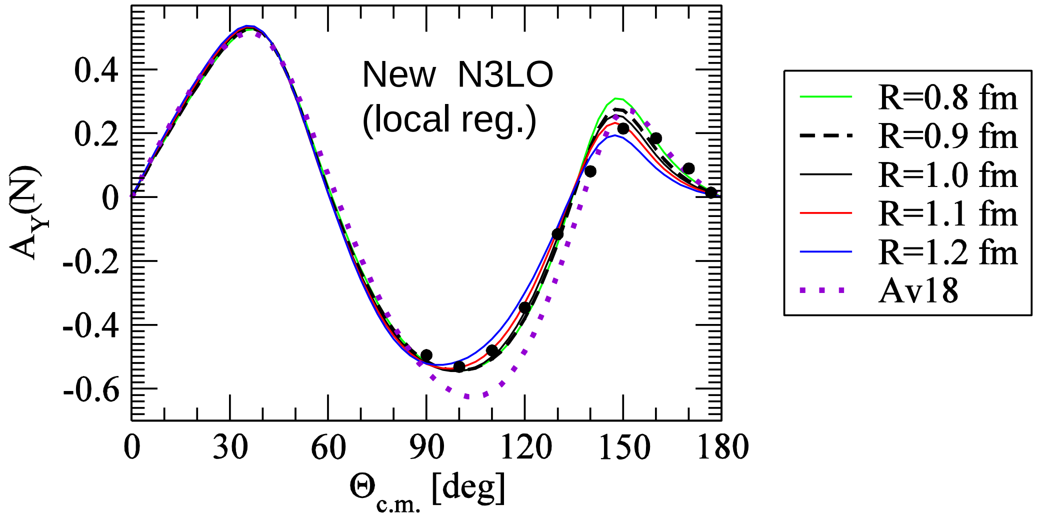
NEW N3LO
(local reg.)

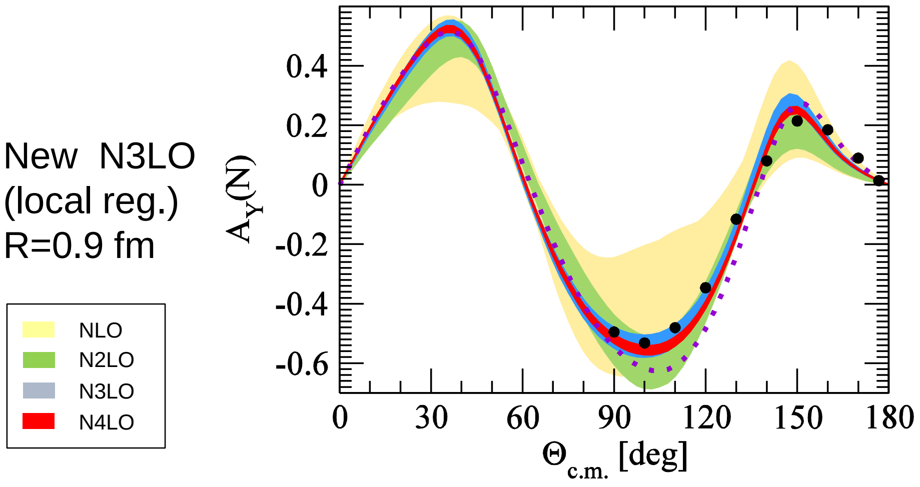


The nucleon analyzing power at 135.0 MeV nucleon lab. energy

→ nice behaviour and improvement also for spin observables







Truncation error estimation:

$$\Delta X^{(2)} = X^{(2)} - X^{(0)}$$

$$\Delta X^{(i)} = X^{(i)} - X^{(i-1)}$$

$$\delta X^{(0)} = Q^2 |X^0|$$

$$\delta X^{(2)} = \max\left(Q^3 |X^0|, Q^1 |\Delta X^{(2)}|\right)$$

$$i \geq 3: \ \delta X^{(i)} = \max\left(Q^{i+1} |X^{(0)}|, Q^{i-1} |\Delta X^{(2)}|, Q^{i-2} |\Delta X^{(3)}|\right)$$

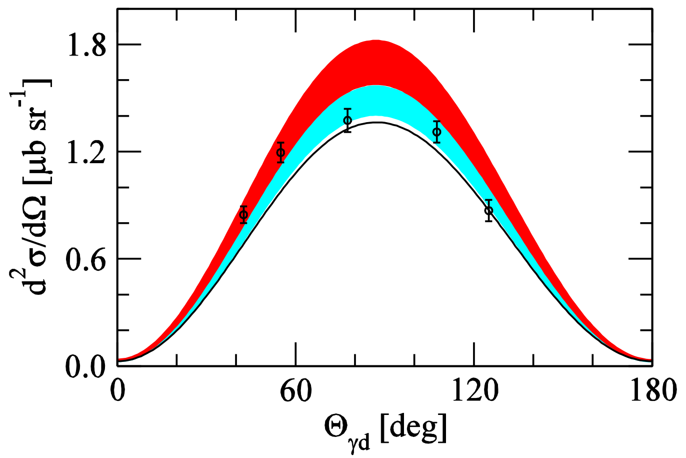
$$\delta X^{(2)} \geq Q \delta X^{(0)}, \qquad \delta X^{(i \geq 3)} \geq Q \delta X^{(i-1)}$$

Electromagnetic and weak processes in 2N and 3N systems

- Strong processes are not only possibility to study nuclear forces

  ➡ Let’s try electromagnetic and weak processes

- Do we see improvement for new chiral forces?



Neutron-deuteron radiative capture at E_n=9 MeV

Old model of interaction:

NN N2LO

NN N3LO

AV18+Urb IX

Exp. data from
G.Mitev et al., Phys. Rev. C34, 389 (1986)

- New component: electroweak current consistent with the interaction.

It combines single nucleon current and many-body contributions.

Formalism for electroweak processes

- Faddeev-like equations, e.g.

$$N_\tau^{Nd} = \langle \phi_{Nd} | (1+P) j_\tau(\vec{Q}) | \Psi_{bound} \rangle + \langle \phi_{Nd} | P | U \rangle$$

$$|U\rangle = tG_0(1+P) j_\tau(\vec{Q}) | \Psi_{bound} \rangle + tG_0 P | U \rangle$$

- In the presented here results the Siegert theorem is used as an alternative way to include many-body contributions to the electric part of nuclear current. In general, our approach corresponds to taking into account all electric and magnetic multipoles up to E7 and M7
(more in J.Golak et al., Phys Rep. 415 (2005) 89; J.Golak et al. Phys. Rev. C62 (2000) 054005).

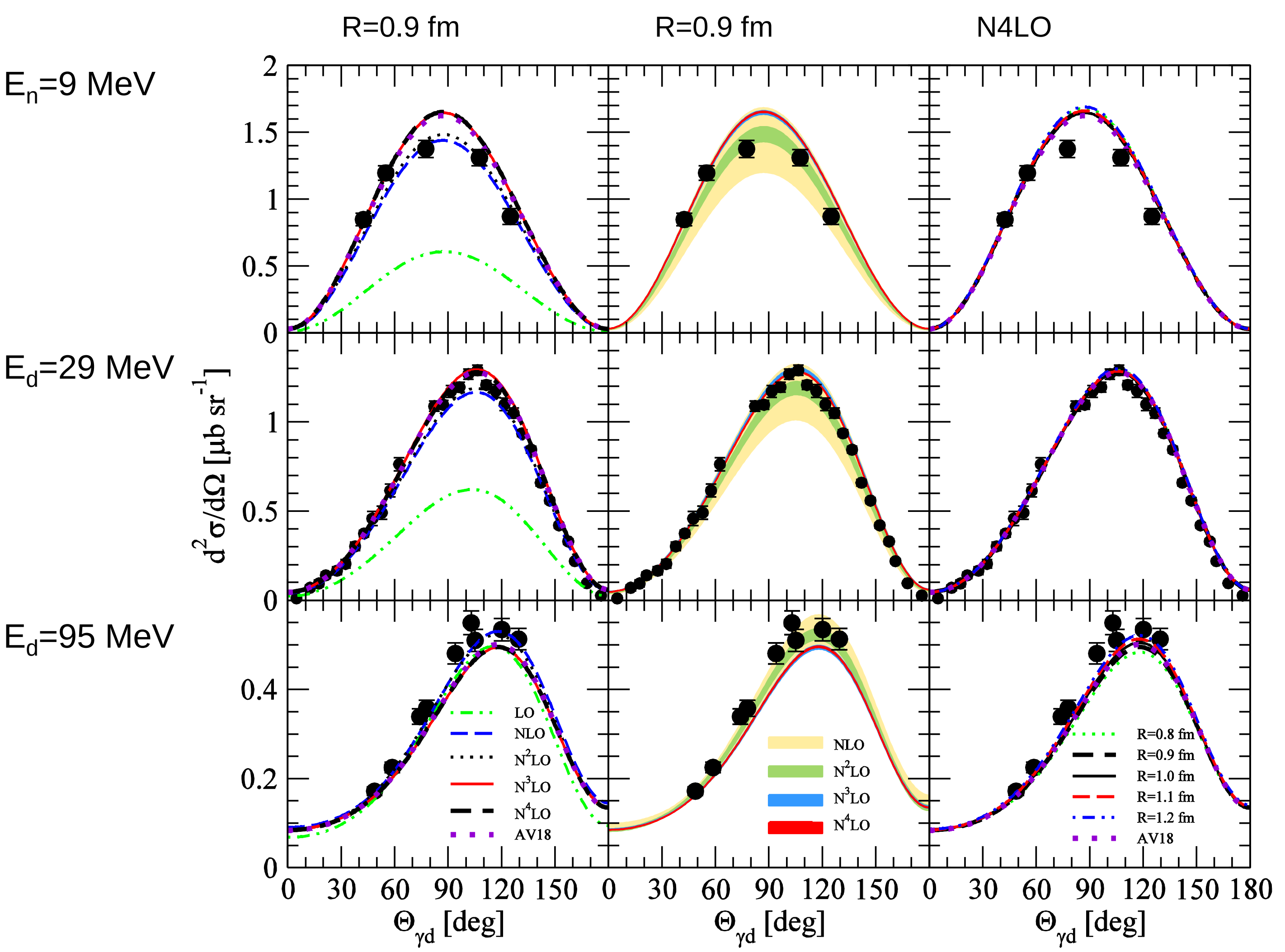
- A weak decay of the muonic atoms: $\mu^- d \rightarrow \nu_\mu + n + n$, $\mu^- {}^3He \rightarrow \nu_\mu + {}^3H$
- The only difference is in the current operator; here we use SNC

$$j^\lambda(\vec{p}', s'; \vec{p}, s) = \bar{u}(\vec{p}', s') \begin{pmatrix} \left(g_1^V - 2m\, g_2^V\right)\gamma^\lambda \\ + g_2^V (p + p')^\lambda \\ + g_1^A \gamma^\lambda \gamma^5 \\ + g_2^A (p - p')^\lambda \gamma^5 \end{pmatrix} \tau_- u(\vec{p}, s)$$

either in the nonrelativistic form or with $1/m^2$ corrections (RC)

(more in J.Golak et al. Phys. Rev. C90 (2014) 024001).

The radiative Nd capture $n+d \to \gamma + {}^3H$, $p+d \to \gamma + {}^3He$



Exp. data from:

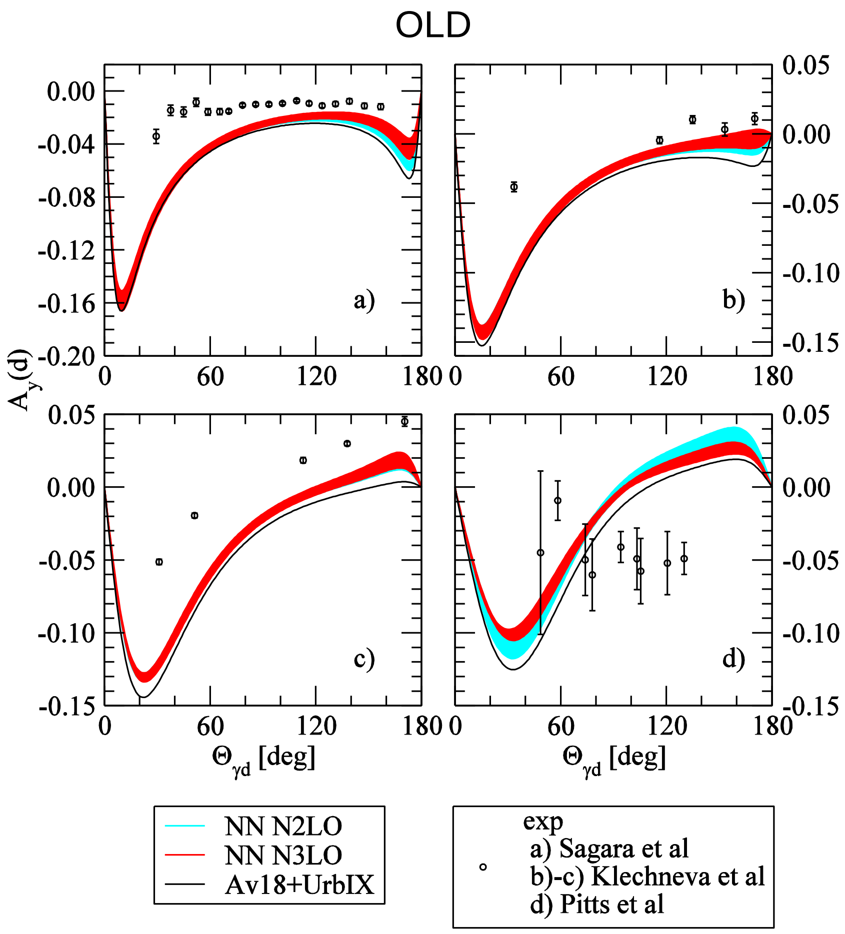
E_n=9 MeV
G.Mitev et al.
Phys. Rev. C34, 389 (1986)

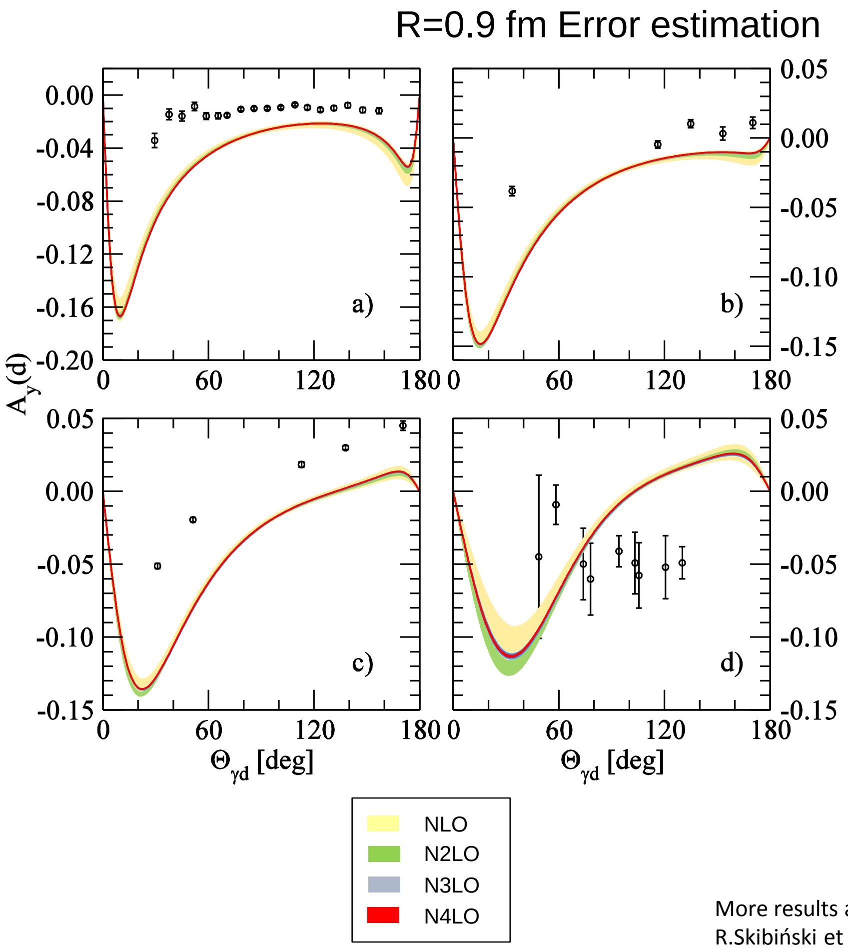
E_d=29 MeV
B.D.Belt et al.,
Phys. Rev. Lett. 24, 1120 (1970)

E_d=95 MeV
W.K.Pitts et al.,
Phys. Rev. C37,1 (1988)

The deuteron analyzing power $A_y(d)$ at: 17.5, 29.0, 45 and 95 MeV deuteron lab. energies

→ smaller cut-of depenence also for el-mag spin observables





More results and details:
R.Skibiński et al., Phys. Rev. C93 (2016) 064002

Results for decay of muonic ^{3}He atom

Total capture rates in [s^{-1}] for $\mu^-{+}^3He \rightarrow \nu_\mu + p + n + n$ (SNC with RC)

Chiral order	R=0.8 fm	R=0.9 fm	R=1 fm	R=1.1 fm	R=1.2 fm	$\delta(\Gamma)$	$\Gamma_{max} - \Gamma_{min}$
LO	95	99	105	113	120	70.0	26
NLO	159	157	154	151	148	16.1	11
N2LO	161	159	157	154	151	3.7	10
N3LO	169	169	171	172	175	0.9	6
N4LO	170	169	169	170	173	0.2	4

AV18
169 s^{-1}

(obtained in collaboration with L.Marcucci)

more details in
J.Golak et al., Phys. Rev. C90 (2014) 024001,
J.Golak et al., arXiv:1605.05668 [nucl-th], accepted to Phys. Rev. C)

very weak dependence on the regulator parameter R

Summary and Outlook

1. New generation of NN potentials, arising from χEFT, has occurred in 2014

2. First applications to the nucleon-deuteron elastic scattering, the radiative Nd capture, the muon capture on the ^{3}He as well as to other, not shown here processes, are very promising

3. Weak dependence on cut-off parameter R

4. Nice convergence with respect to the order of chiral expansion

5. Comparing to old forces, new ones works much better at higher energies

Future:

1. Inclusion of consistent 3NF at N2LO and N3LO (ongoing).
2. Derivation of consistent electroweak currents (ongoing) → processes with electrons.
3. The Gamow-Teller ME will be used to determine LECs in 3NF
4. We hope for the precise measurements (MuSun experiment or the capture rates in the μ-^{3}He break-up channels, phtodisintegration)

Thank you for your attention