Study of the electroweak processes in the two- and three-nucleon systems with local chiral forces

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Outline

Introduction:
Model of NN interaction
Formalism (states, currents)

Results
^{2}H photodisintegration
nucleon-deuteron radiative capture
^{3}He photodisintegration
muon capture on ^{2}H,^{3}He

Outlook

Local chiral forces

- 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 arXiv:1412.4623 [nucl-th] – 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
  - 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.

    talk by E.Epelbaum

  - Very good behaviour for Nd elastic scattering and the deuteron breakup

    talk by H.Witała

Do we see improvement also for electroweak processes?

Our approach (1)

- To obtain 2N and 3N states we solve Schrödinger, Lippmann-Schwinger and Faddeev equations in the momentum space.
  (see J.Golak et al., Phys Rep. 415 (2005) 89 and W.Glöckle et al., Phys Rep. 274 (1996) 107)

- d+ $\gamma \to$ p + n $\quad N_\tau^{np} = \left\langle \phi_{np} \left| (1 + tG_0)\, j_\tau(\vec{Q}) \right| \Psi_{deuteron} \right\rangle$

- ^{3}He+$\gamma \to$ p+d, ^{3}He+$\gamma \to$ p+p+n, p+d$\to$ ^{3}He+γ

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

$$N_\tau^{3N} = \left\langle \phi_0 \left| (1+P)\, j_\tau(\vec{Q}) \right| \Psi_{bound} \right\rangle + \left\langle \phi_0 \left| tG_0 (1+P)\, j_\tau(\vec{Q}) \right| \Psi_{bound} \right\rangle + \left\langle \phi_0 \left| P \right| U \right\rangle + \left\langle \phi_0 \left| tG_0 P \right| U \right\rangle$$

$$\left| U \right\rangle = (tG_0 + 0.5(1+P)V_4^{(1)} G_0 (tG_0 + 1))(1+P)\, j_\tau(\vec{Q}) \left| \Psi_{bound} \right\rangle +$$
$$+ (tG_0 P + 0.5(1+P)V_4^{(1)} G_0 (tG_0 + 1) P) \left| U \right\rangle$$

- pd capture transition amplitude can be obtained from two-body ^{3}He photodisintegration using time reversal symmetry

- In the following we put $V_4^{(1)}$=0

Our approach (2)

- In the presented here results the Siegert theorem is used as an alternative way to include many-body contributions to the nuclear current. This corresponds to taking into account all electric and magnetic multipoles up to E7 and M7

  (more in J.Golak et al. Phys. Rev. C62 (2000) 054005).

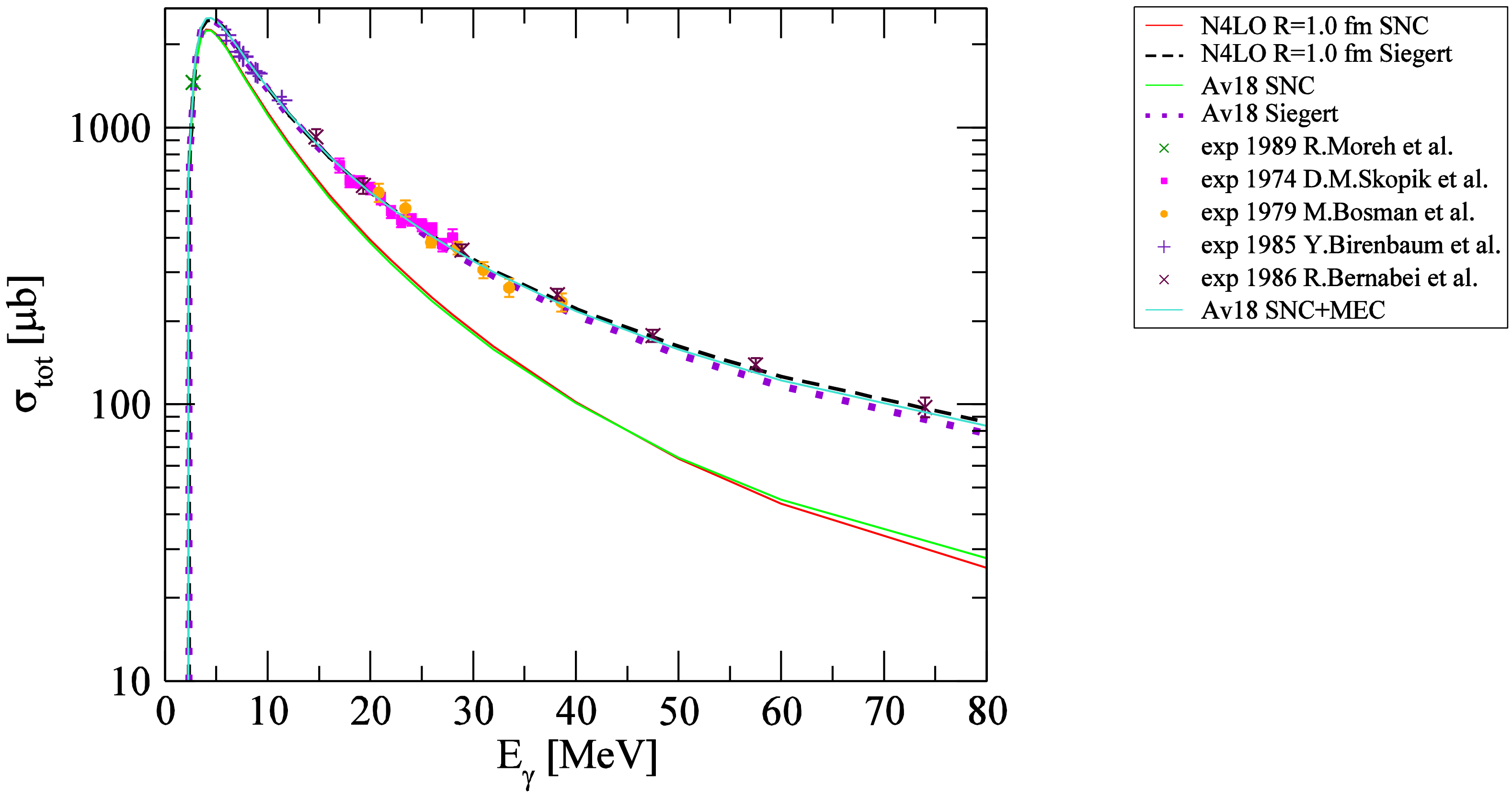
- A weak decay of the muonic atoms: $\mu^- d \rightarrow \nu_\mu + n + n$, $\mu^- {}^3He \rightarrow \nu_\mu + {}^3H$
- The only difference is in the current operator; here we use SNC

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

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

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

The total cross section in the deuteron photodisintegration
→ improved chiral force works well for this process



The deuteron tensor analyzing powers $T_{11}(d)$ and $T_{21}(d)$ in the deuteron photodisintegration at 100 MeV photon lab. energies.

→ improved chiral force works well for this process

$$LO: \quad \delta X^{(0)} = Q^2 \left| X^0 \right|$$

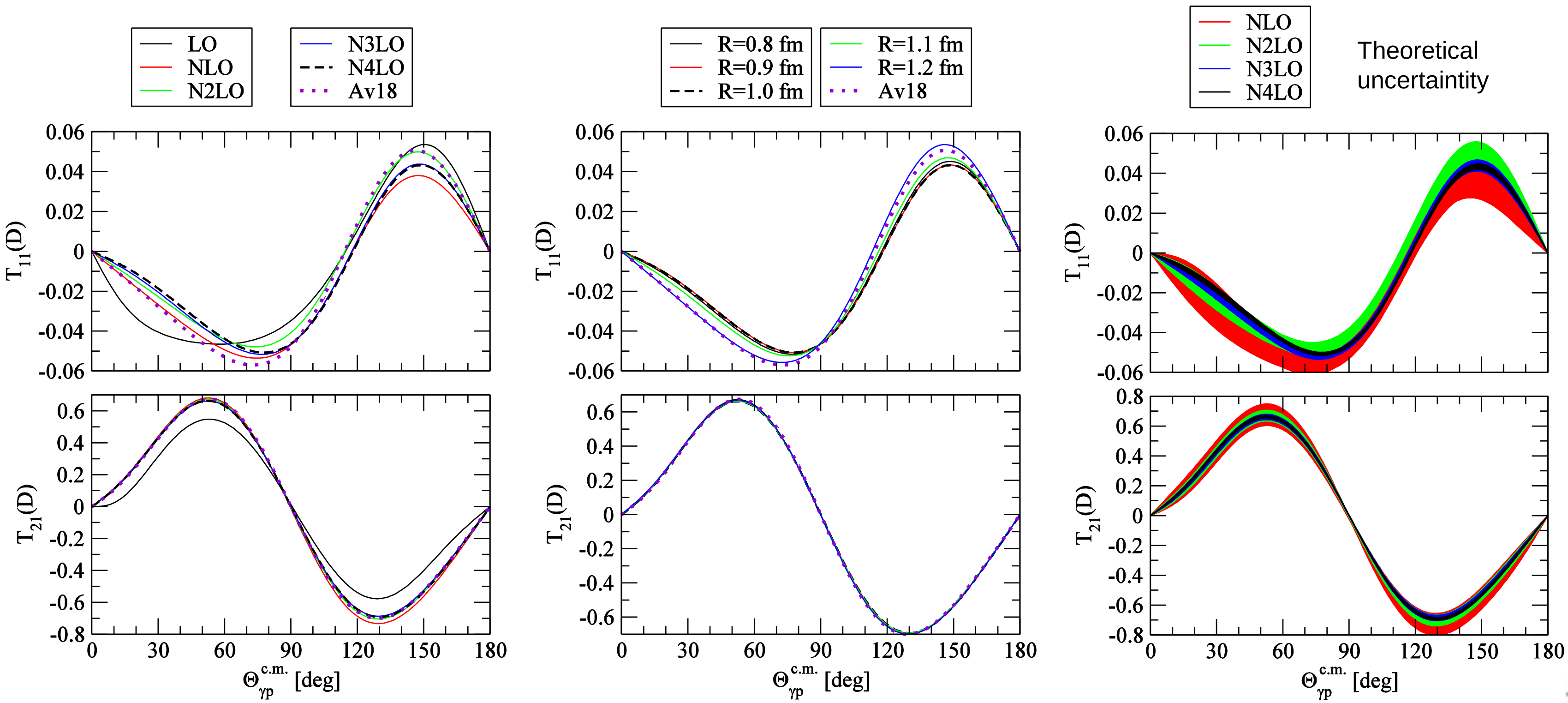
$$NLO: \quad \delta X^{(2)} = \max\left(Q^3 \left| X^0 \right|, Q^1 \left| \Delta X^{(2)} \right|\right)$$

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

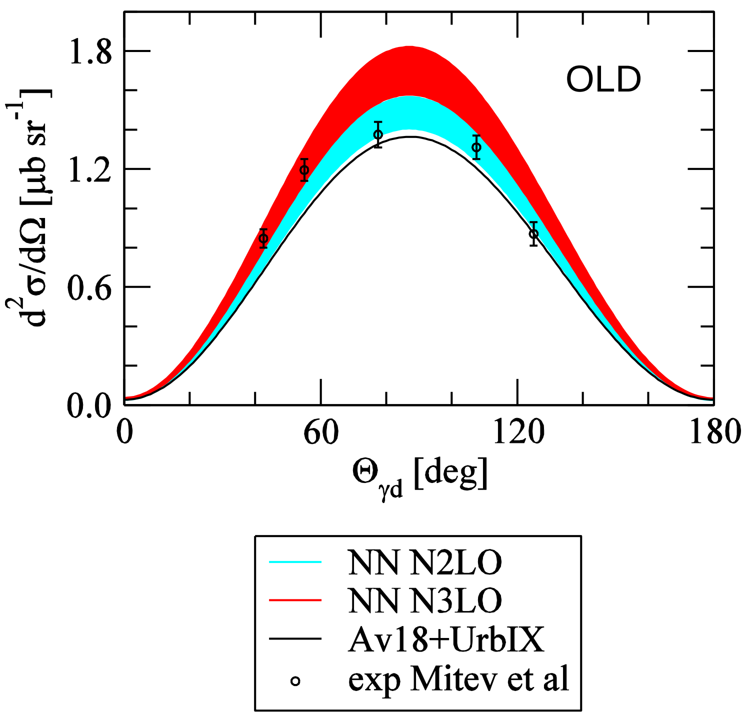
$$\Delta X^{(i)} = X^{(i)} - X^{(i-1)}$$

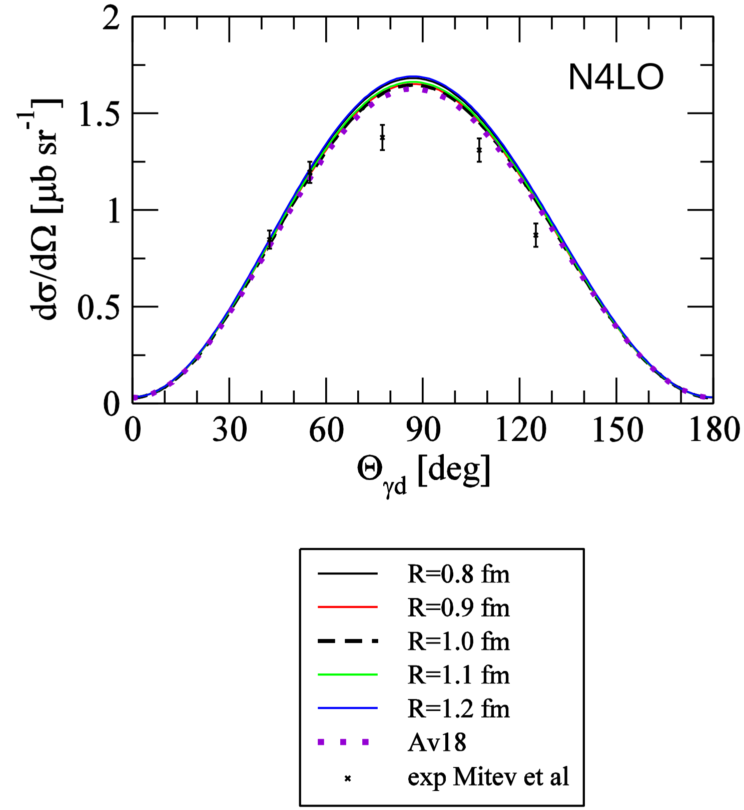
$$N^{(i-1)}LO \quad (i \geq 3): \ \delta X^{(i)} = \max\left(Q^{i+1} \left| X^{(0)} \right|, Q^{i-1} \left| \Delta X^{(2)} \right|, Q^{i-2} \left| X^{(3)} \right|\right)$$

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

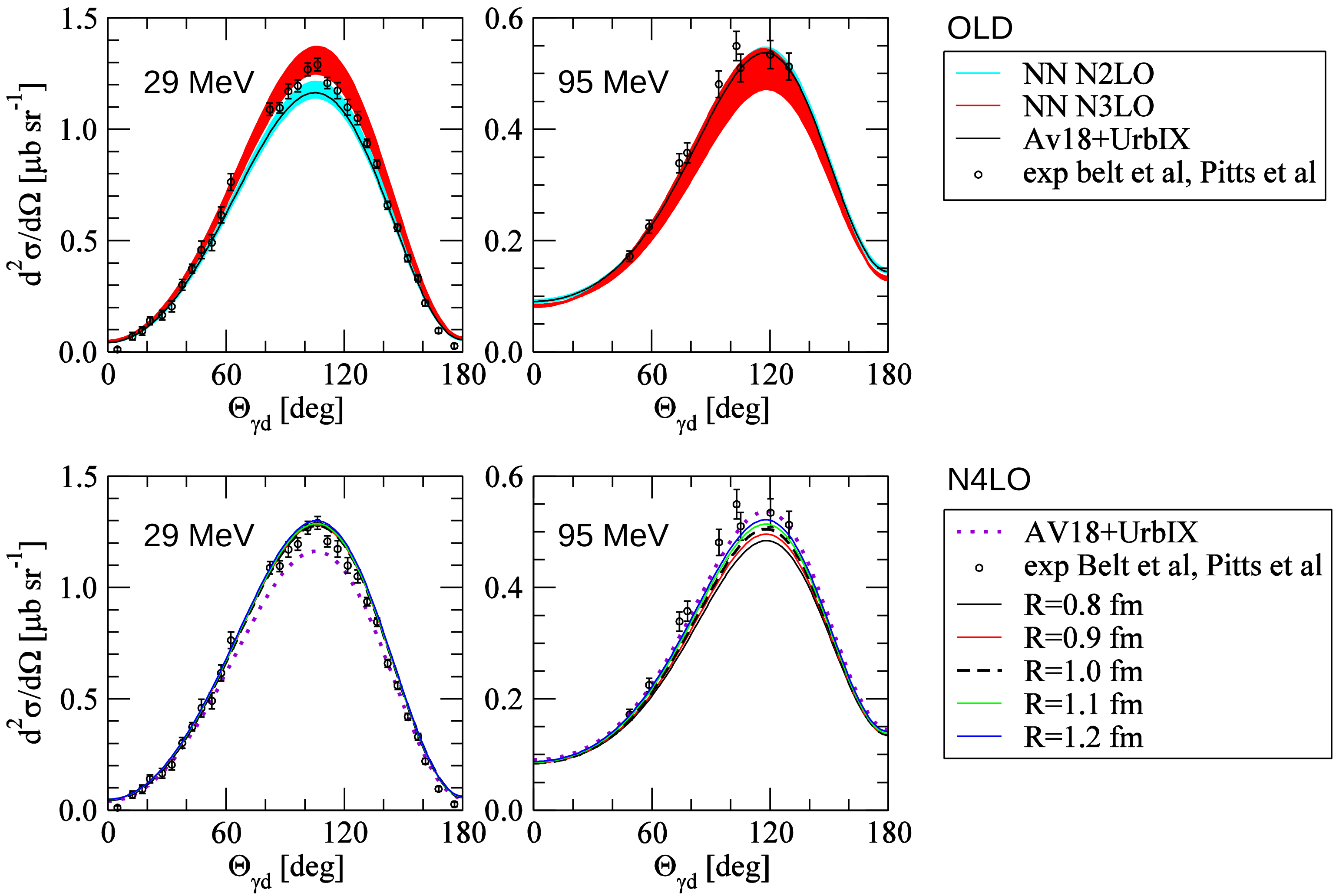


The c.m. neutron-deuteron capture cross section at 9.0 MeV neutron lab. energy.
→ cut-off dependence much smaller at higher orders also for nd-capture



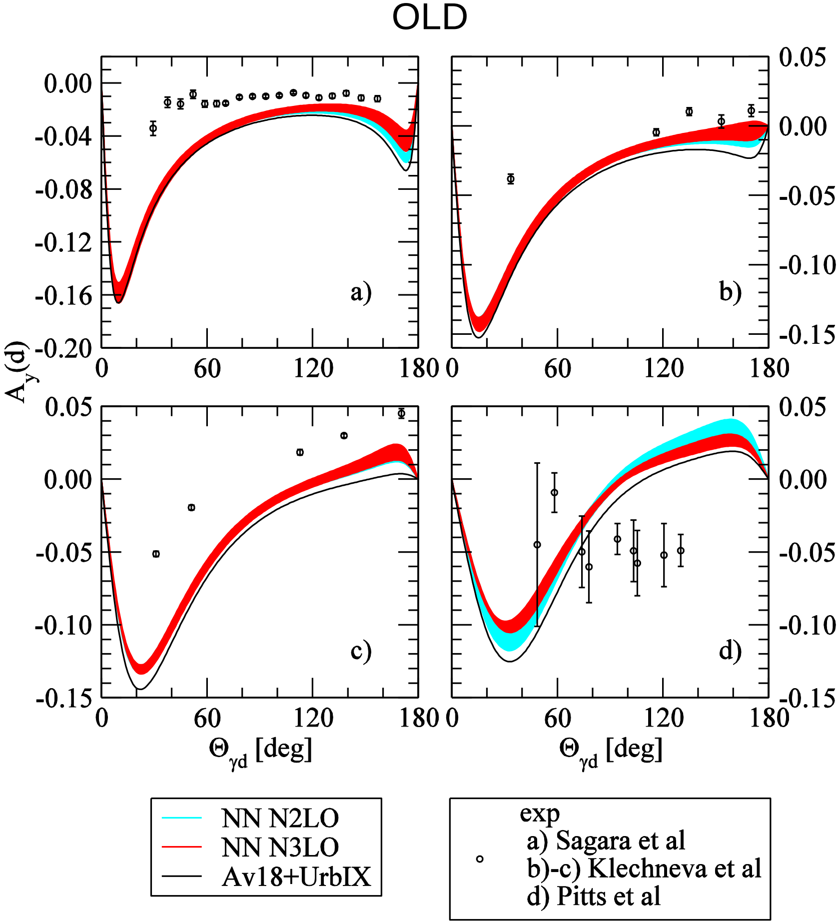


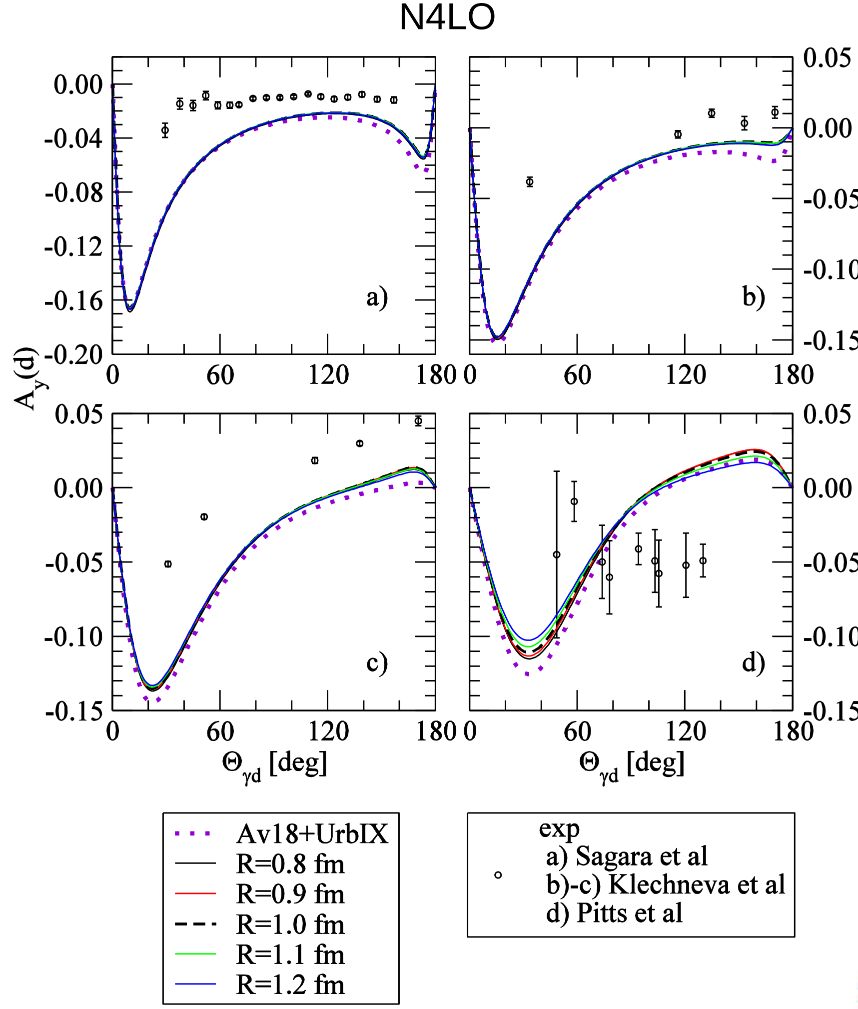
The c.m. proton-deuteron capture cross section at: 29.0 MeV and 95 MeV deuteron lab. energies → smaller cut-off dependence at higher energies



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

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





Total (2body+3body) ^{3}He photodisintegration cross section and it's theoretical uncertainty

$$LO: \quad \delta X^{(0)} = Q^2 \left| X^0 \right|$$

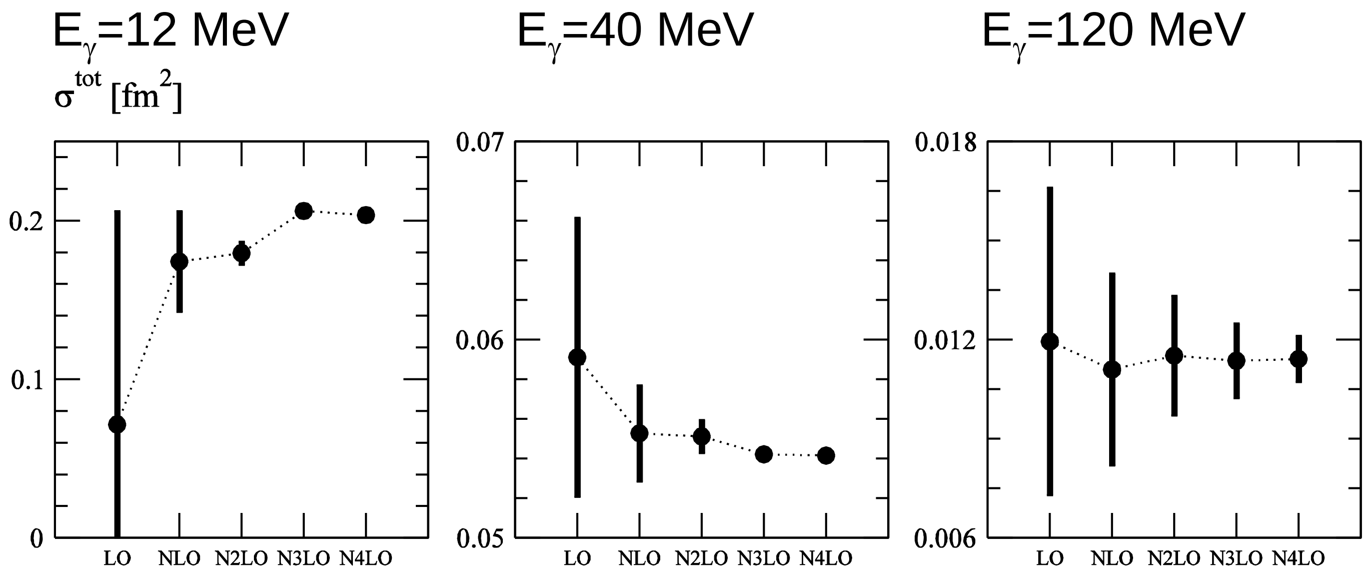
$$NLO: \quad \delta X^{(2)} = \max\left(Q^3 \left| X^0 \right|, Q^1 \left| \Delta X^{(2)} \right|\right)$$

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

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

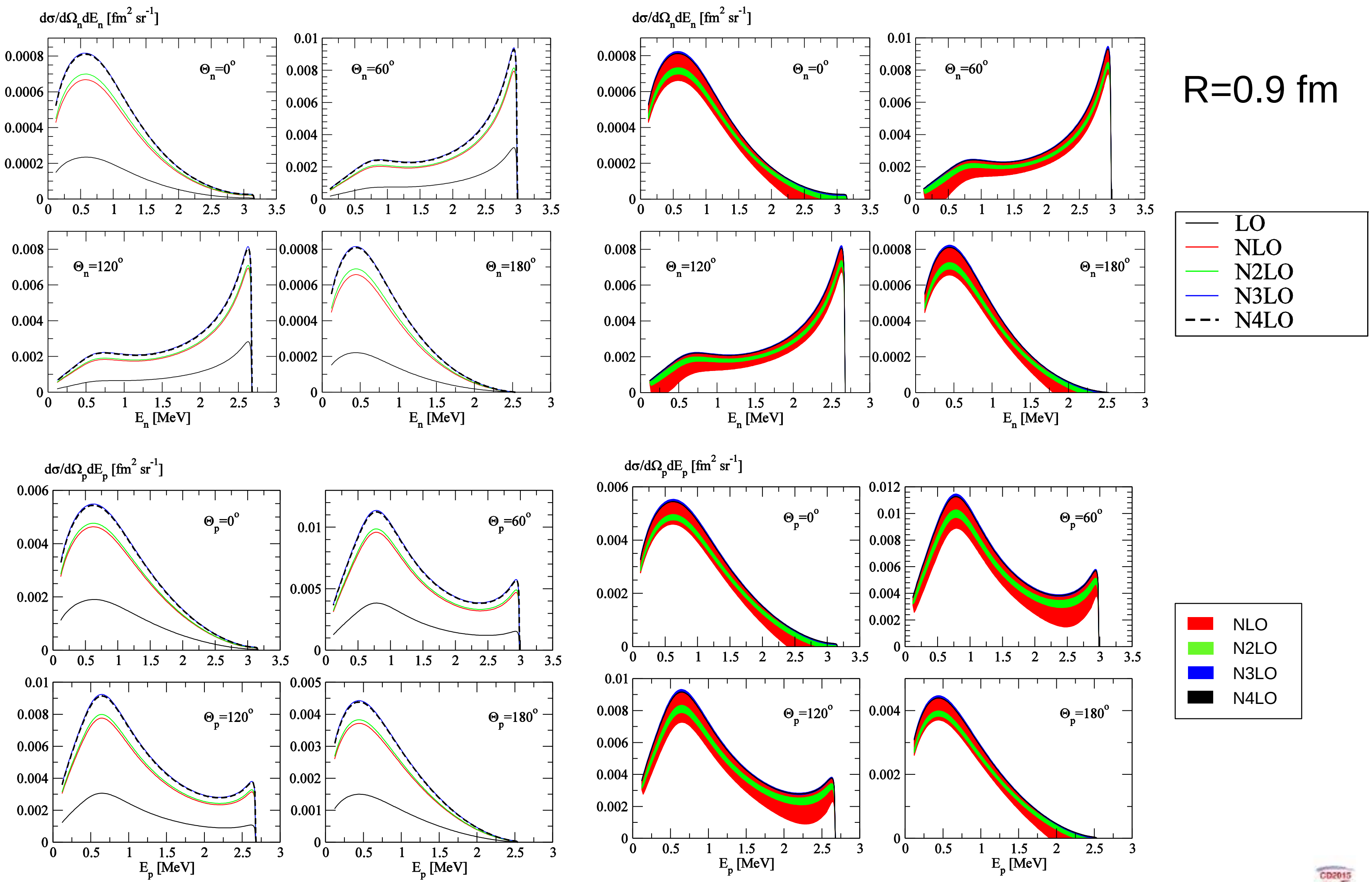
$$\Delta X^{(2)} = X^{(2)} - X^{(0)}$$

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

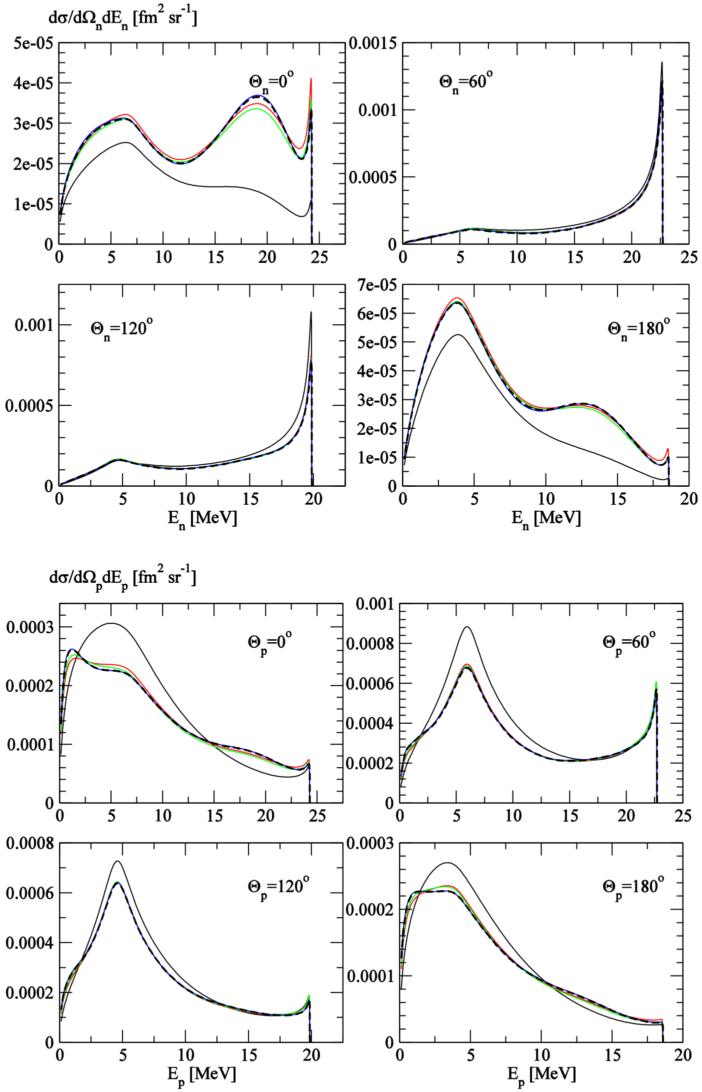


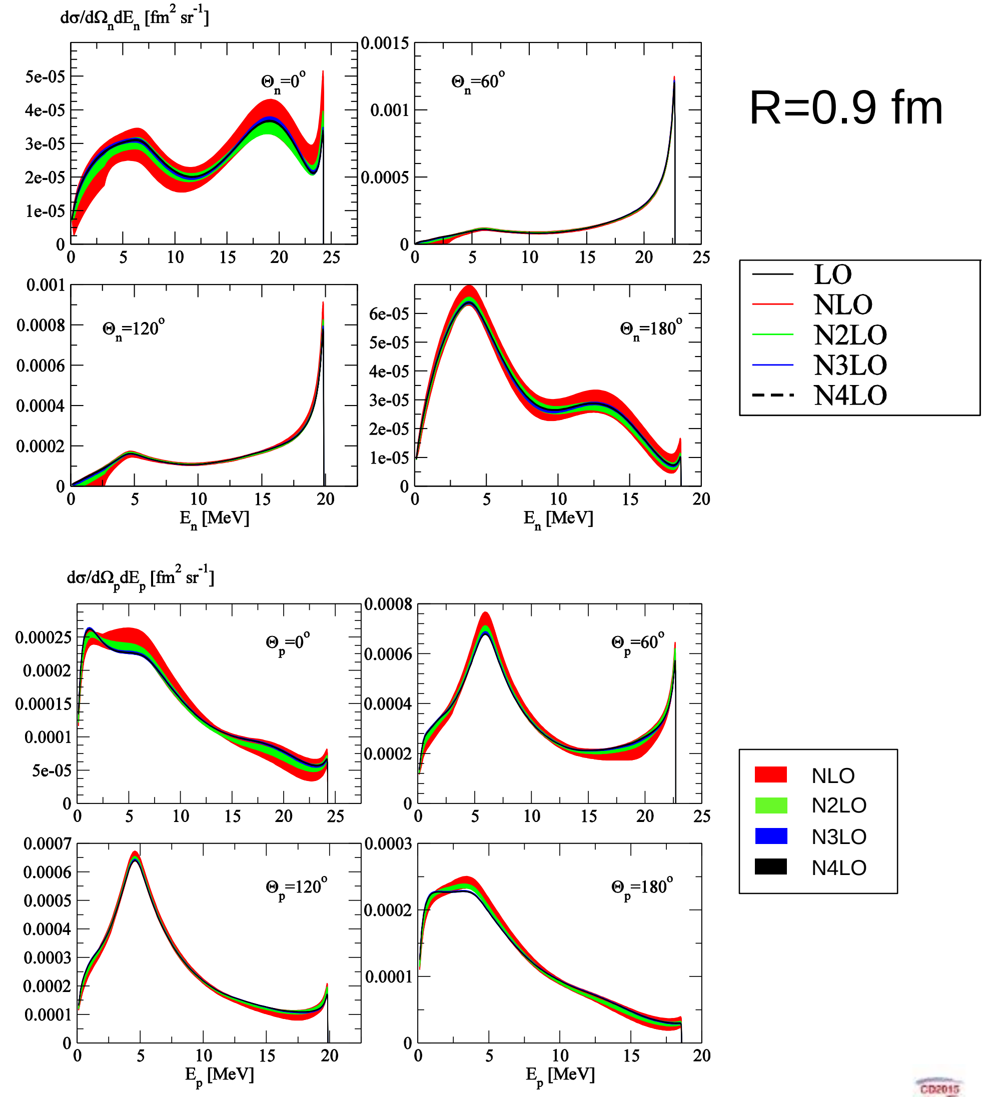
R=0.9 fm

Inclusive three-body ^{3}He photodisintegration at E_γ=12 MeV

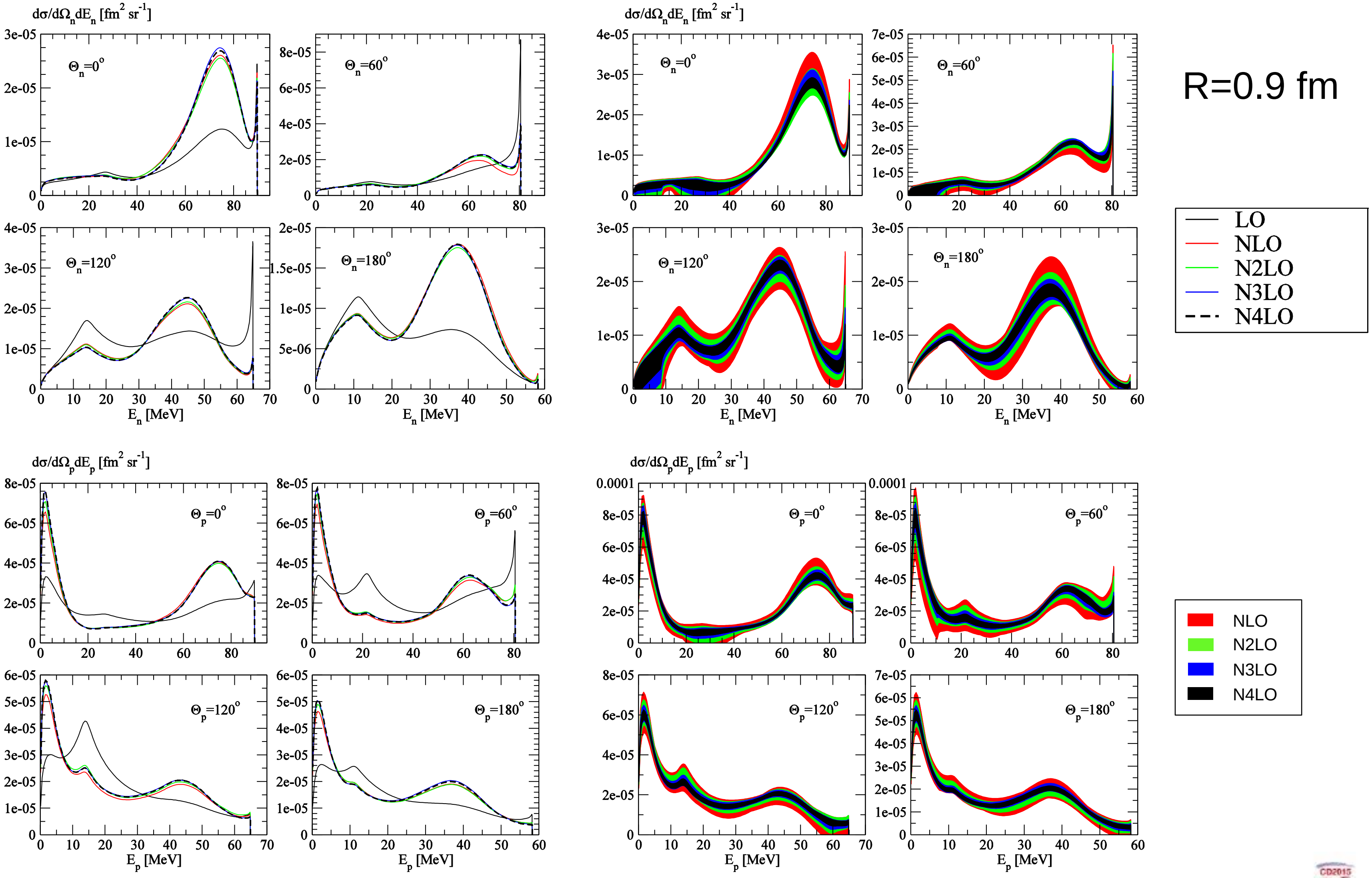


Inclusive three-body ^{3}He photodisintegration at E_γ=40 MeV





Inclusive three-body ^3He photodisintegration at E_γ=120 MeV



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Results for decay of muonic atoms (d and ^{3}He)

Doublet capture rates (F=½) in [s^{-1}] for $\mu^- + d \rightarrow \nu_\mu + n + n$ (SNC with RC)

Chiral order	R=0.8 fm	R=0.9 fm	R=1 fm	R=1.1fm	R=1.2 fm	$\Gamma_{max} - \Gamma_{min}$
LO	396.0	397.4	398.4	398.9	399.2	3.3
NLO	384.2	385.8	387.2	388.6	389.8	5.7
N2LO	385.0	386.1	387.2	388.3	389.3	4.3
N3LO	386.8	386.4	385.2	384.3	383.2	3.6
N4LO	385.5	386.1	386.3	385.6	384.6	1.7

AV18
382.3 s^{-1}

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

Chiral order	R=0.8 fm	R=0.9 fm	R=1 fm	R=1.1fm	R=1.2 fm	$\Gamma_{max} - \Gamma_{min}$
LO	1610	1618	1610	1594	1572	46
NLO	1330	1357	1381	1405	1427	97
N2LO	1337	1356	1376	1395	1415	78
N3LO	1314	1304	1289	1278	1266	48
N4LO	1296	1307	1308	1299	1285	23

AV18
1295 s^{-1}

very weak dependence on the regulator parameter R

(obtained in collaboration with L.Marcucci, H.Kamada, A.Nogga, more details in J.Golak et al. Phys. Rev. C90 (2014) 024001 and in poster by A.E.Elmeshneb)

Summary and Outlook

1. New generation of NN potentials has occurred in 2014

2. First applications to the deuteron and 3He photodisintegrations as well as to muon capture on the deuteron and 3He 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. More systematic study (energies, observables) and error estimation
2. Applications to the nuclear structure calculations
3. Inclusion of the 3NF (regularized in the same way)
4. Consistent chiral electromagnetic and weak currents
5. We hope for the precise measurements (ongoing MuSun experiment or the capture rates in the μ-^{3}He break-up channels)

Thank you for your attention