Elastic nucleon-deuteron scattering and breakup with chiral forces

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Summary of results obtained with standard NN potentials and 3NF's:

- Quite good descritption of low energy data (below about 30 MeV): it seems that at these energies one does not need a 3NF.

- For some observables different effects of TM99 and UIX 3NF's (in spite of the fact that both are of 2π-exchange origin. That can imply that consistency between NN- and 3N-forces is important.

- Higher energies: large discrepancies between data and theory based only on NN forces start to appear:

  Total nd cross section:

  - up to ~ 50 MeV good agreement with predictions based on 2N forces
  - adding 3NF (TM abd Urbana IX – of 2π-exchange type) provides explanation of the disagreement up to ~ 150 MeV
  - at even larger energies a clear disagreement which increases with energy

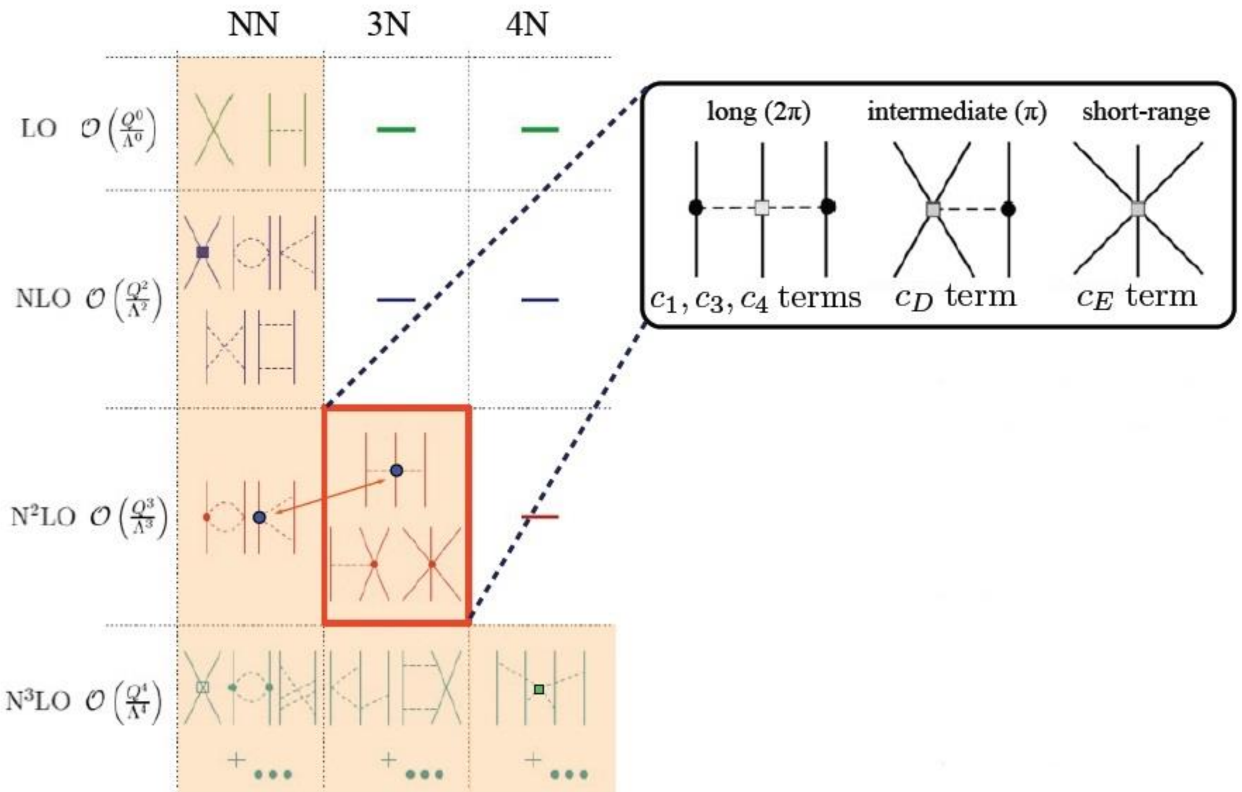
- Relativistic Faddeev calculations:
  - effects of relativity seen only in Nd elastic scattering backward cross section
  - relativistic effects are not responsible for large discrepancies in elastic Nd scattering cross section

It follows that:

- **relativistic effects are not responsible for large discrepancies in elastic Nd scattering**

- **those discrepancies must come from neglection of short-range 3NF components which become active at higher energies**

Challenge: apply NN and 3NF's derived consistently in the framework of chiral perturbation theory



Chiral EFT for nuclear forces

perturbation in $(Q/\Lambda)^{\nu}$

LENPIC (Low Energy Nuclear Physics International Collaboration): to understand nuclear structure and reactions with chiral forces

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Few remarks on chiral forces:

- In order to reproduce properly 2N data up to about 250 MeV N3LO order of chiral expansion is required
  - About 2 years ago: NN interaction up to N3LO, 3NF interaction up to N4LO (N3LO used in preliminary calculations at low energies)
  - nonlocal momentum space regularization has been applied:

  V $\rightarrow$ f(p',Λ) V(p',p) f(p,Λ) with $f(p,\Lambda) \equiv e^{-p^6/\Lambda^6}$

  $V^4 \rightarrow$ f(p',q',Λ) V^4(p',q',p',q) f(p,q,Λ) with $f(p,q,\Lambda) \equiv e^{-(p^2+0.75q^2)^3/\Lambda^6}$

  what leads to finite cut-off artefacts (problems when applied to higher energy Nd scattering)

- 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
  - 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
  - Such regularization preserves more long-range OPE and TPE physics
  - All LECs in the long-range part are taken from pion-nucleon scattering without fine tuning
  - Very good description of the deuteron properties, phase shifts etc.

Estimation of theoretical uncertainties (E.Epelbaum et al., arXiv:1412.4623 [nucl-th], arXiv:1505.07218 [nucl.th]):

X(p) - observable and $X^{(i)}, i = 0, 2, 3, \ldots$ prediction at order $Q^{(i)}$ in the chiral expansion

Order-$Q^{(i)}$ correction :

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

$$\Delta X^{(i)} = X^{(i)} - X^{(i-1)} \qquad i \geq 3$$

The chiral expansion for X takes the form:

$X^{(i)} = X^{(0)} + \Delta X^{(2)} + \ldots + \Delta X^{(i)}$ Size of corrections is expected to be $\Delta X^{(i)} = O(Q^{(i)} X^{(0)})$

Quantitative estimates of the theoretical uncertainty $\delta X^{(i)}$ of the prediction $X^{(i)}$ is made using the expected and actual sizes of higher-order contributions:

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

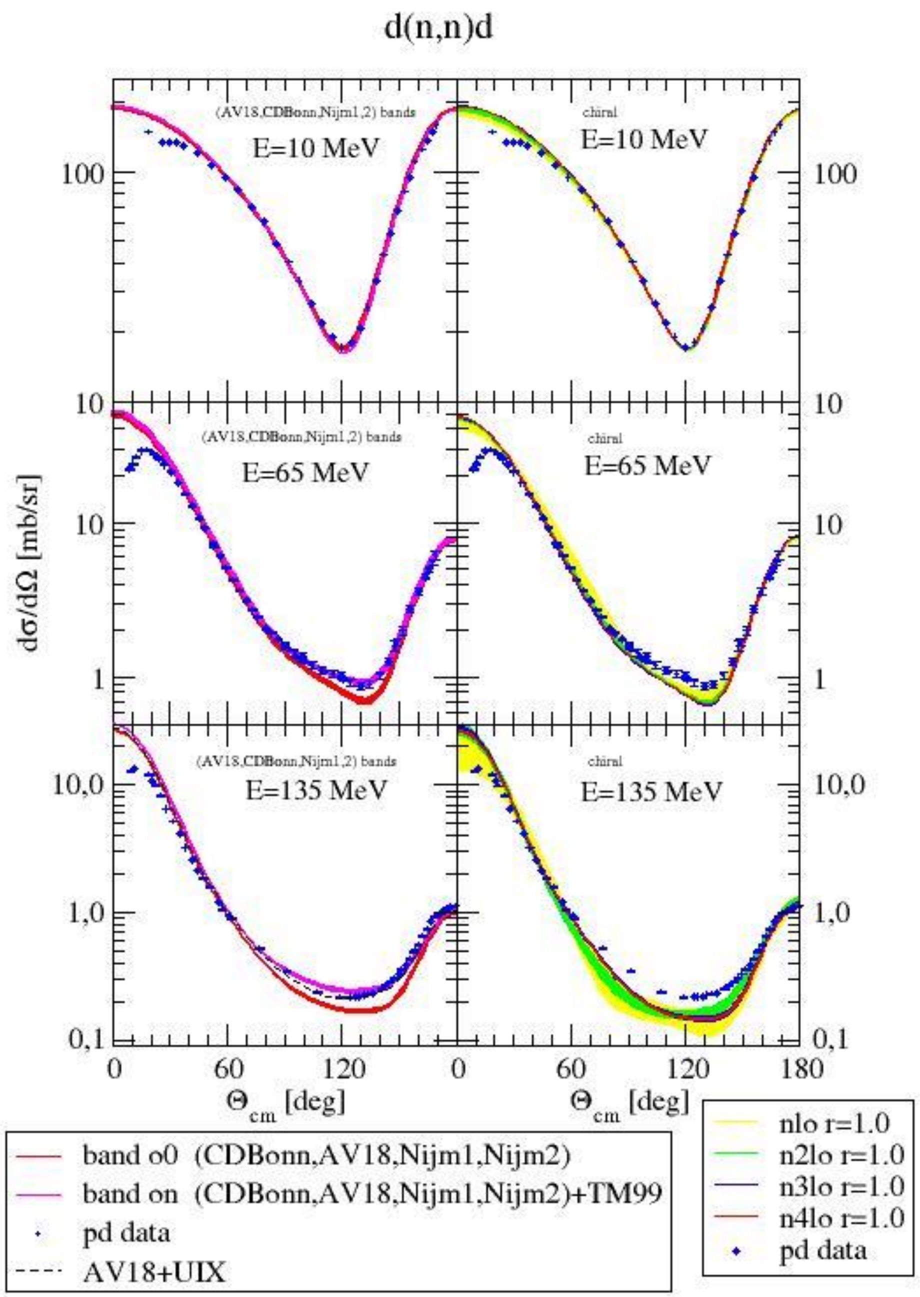
$$\delta X^{(2)} = \max\left(Q^3 \left| X^0 \right|, Q^1 \left| \Delta X^{(2)} \right|\right)$$

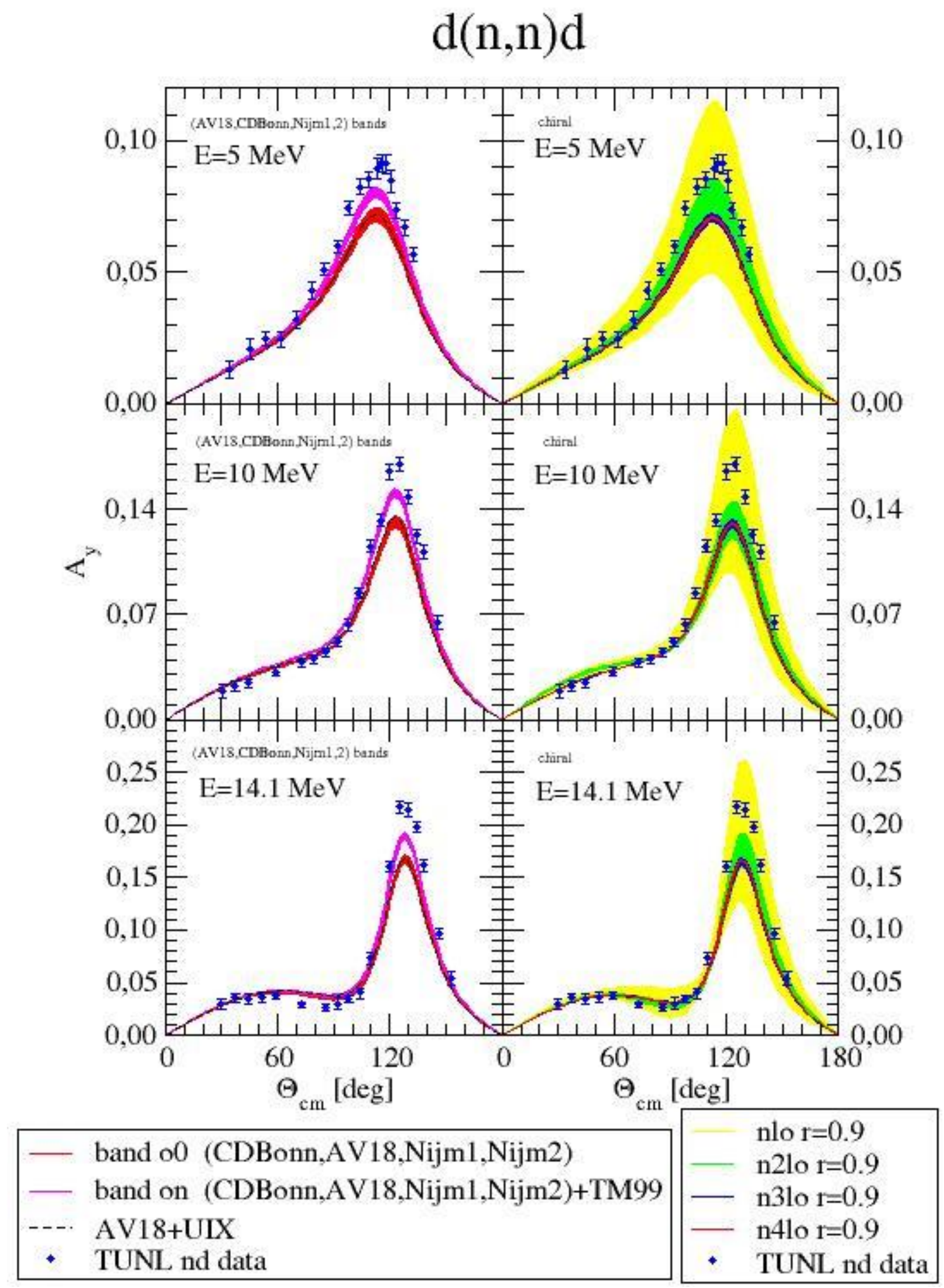
$$i \geq 3: \; \delta X^{(i)} = \max\left(Q^{i+1} \left| X^{(0)} \right|, Q^{i-1} \left| \Delta X^{(2)} \right|, Q^{i-2} \left| \Delta X^{(3)} \right|\right)$$

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

Q=max(p/Λ_b, m_π / Λ_b) with $\Lambda_b = 600, 500$ and 400 MeV
for regulator R=0.8-1.0 fm, R=1.1 fm and R=1.2 fm, respectively.

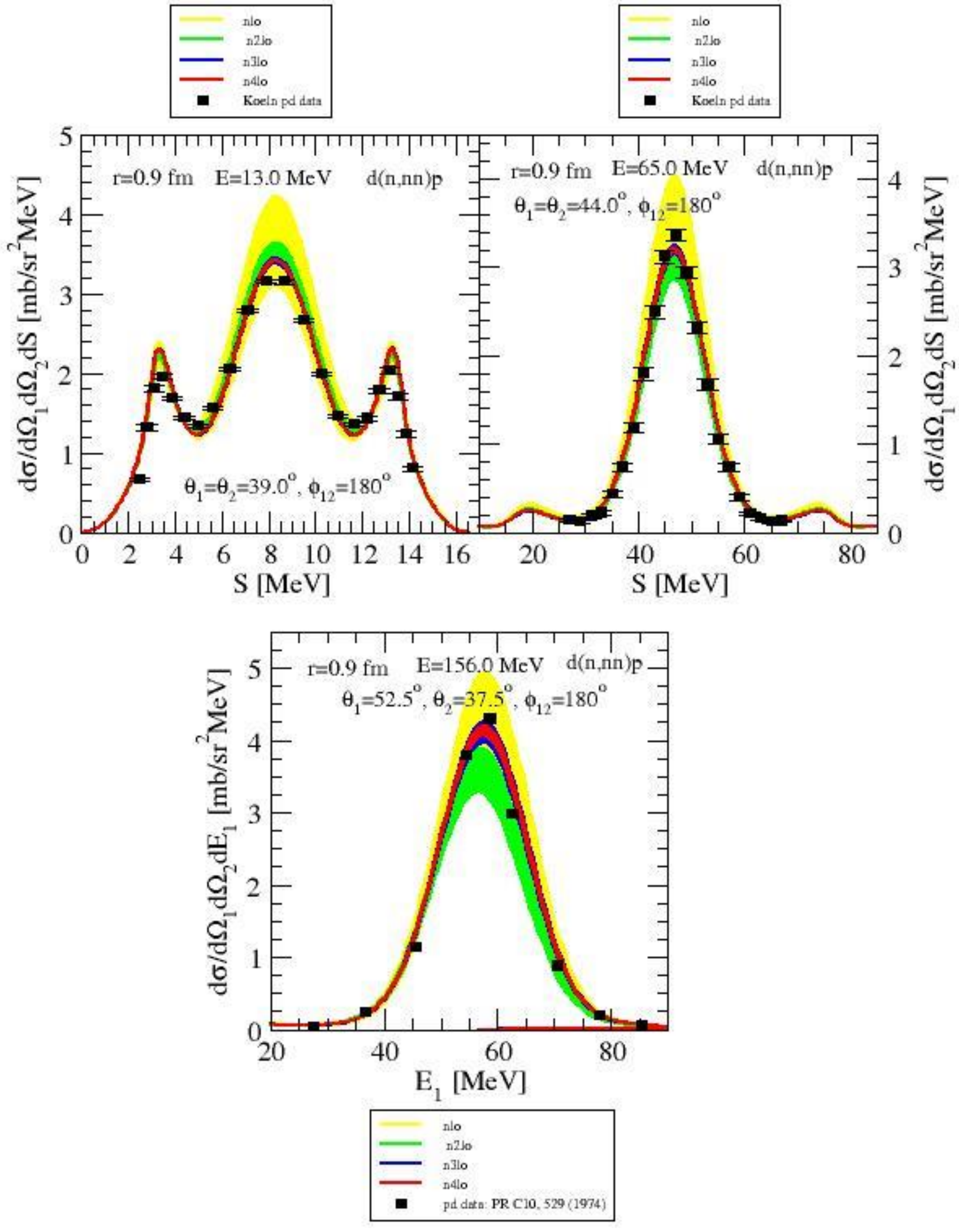
- NN developed up to N4LO: E.Epelbaum et al. arXiv:1412.4623 [nucl-th]
- Novel way of quantifying the theoetical uncertainty due to the truncation of the chiral expansion: E.Epelbaum et al. arXiv:1412.0142 [nucl-th]



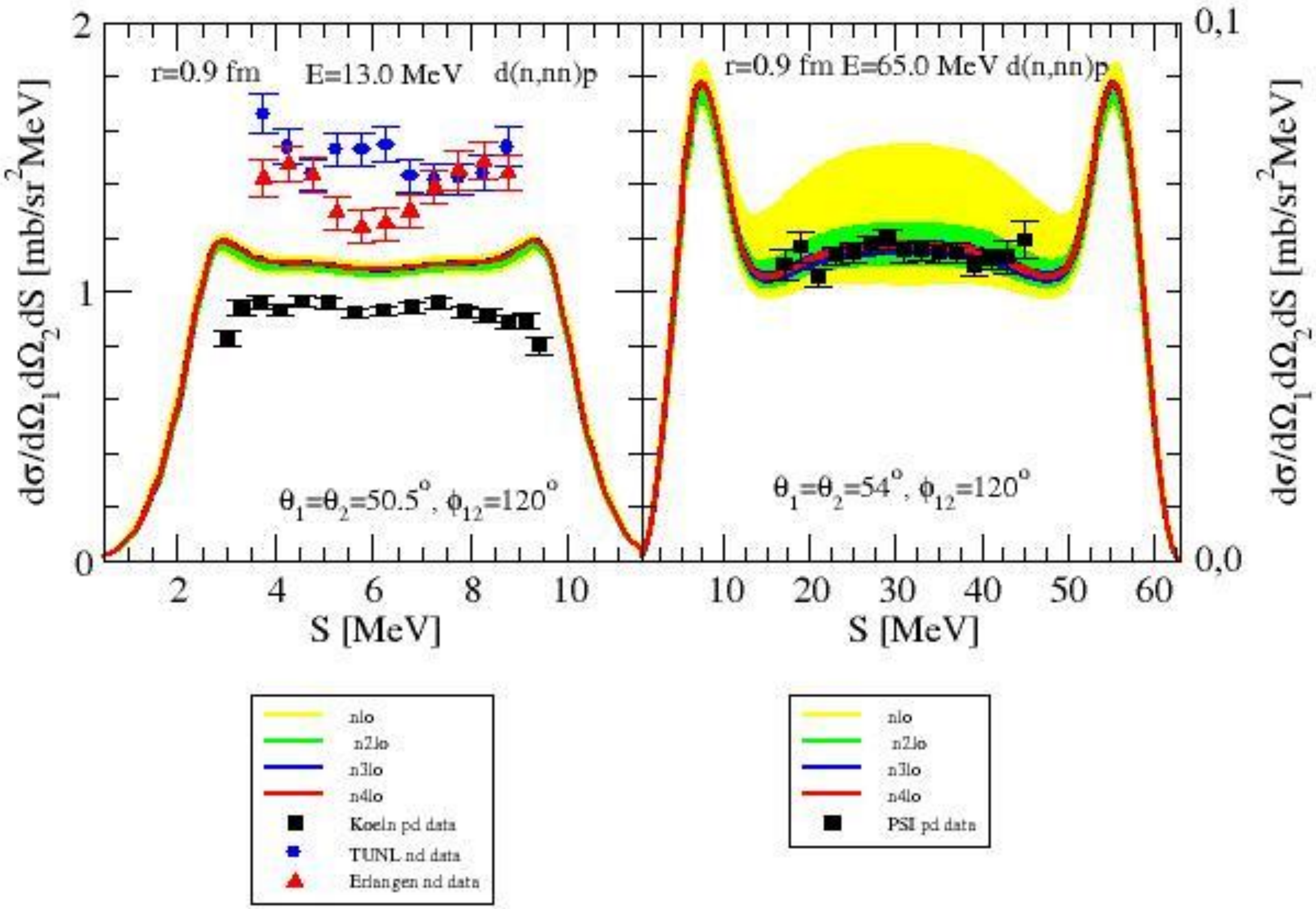


- ❑ Theoretical uncertainty grows with energy and decreases with increasing order

Exclusive breakup reaction: quasi free pp scattering



Exclusive breakup reaction: symmetric space-star configuration



Big challenge: application of full N3LO chiral force: NN + 3NF

QFSnp: d(n,np)n, En=26 MeV

$\Theta_n = 39°$ $\Theta_p = 42°$ $\phi_{np} = 180°$

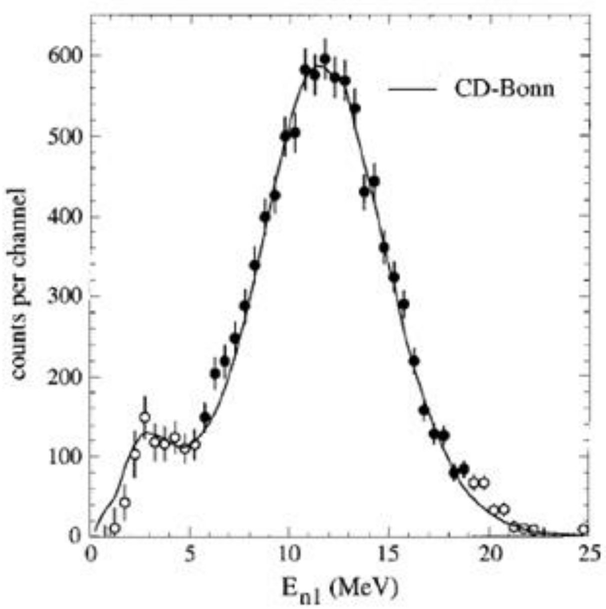


FIG. 2. Data for n-p QFS, projected onto the E_n axis. The solid line is the finite-geometry Monte Carlo prediction, using CD-Bonn for the N-N interaction.

QFSnn: d(n,nn)p, En=26 MeV

Both n detectors were at $\Theta_n = 42°$

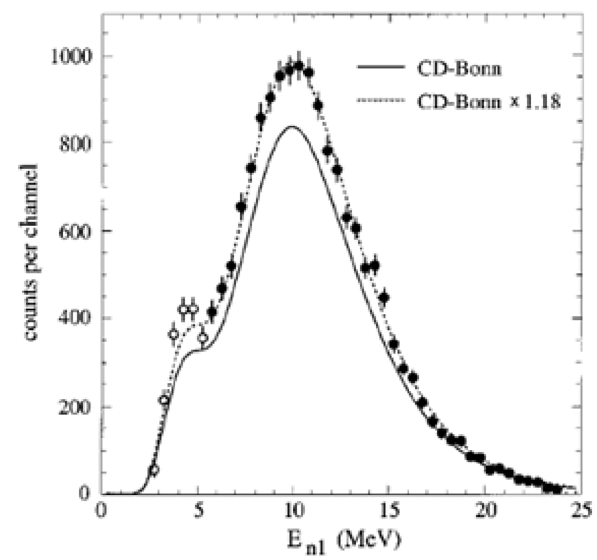
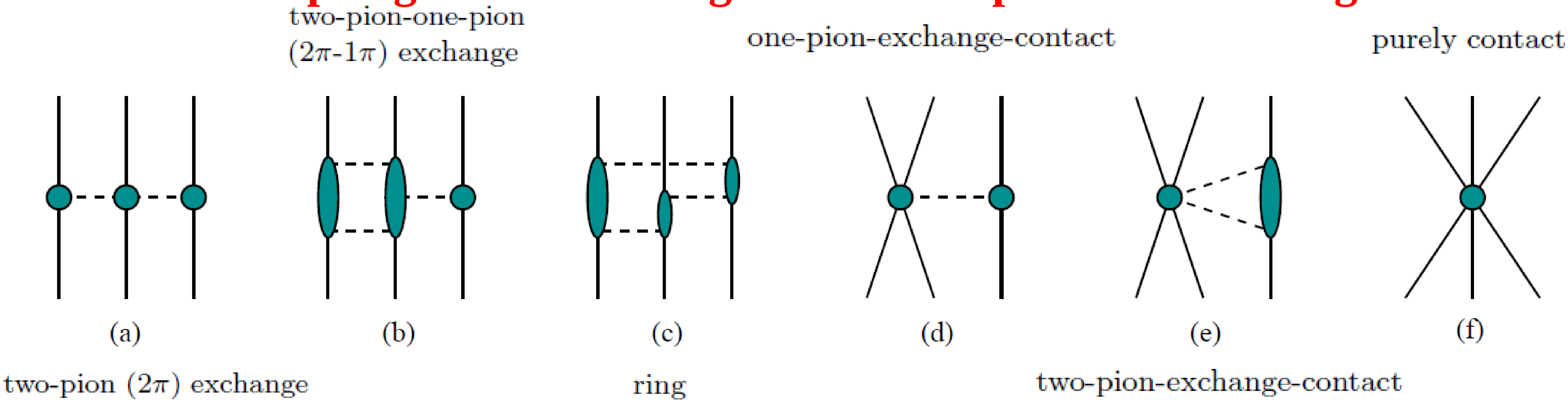


FIG. 4. HE data of Fig. 3, projected onto the E_{n1} axis. The solid curve represents the finite-geometry Monte Carlo prediction using CD-Bonn, the dotted line is the MC result normalized to the experiment by multiplication with a factor of 1.18. Only events with E_{n1} and $E_{n2} > 6$ MeV have been included in the analysis.

PR C65, 034010 (2002)

Various topologies contributing to the 3NF up to and including N^4LO



- ❑ N^2LO: (a) + (d) + (f) (E.Epelbaum et al., PR C66, 064001 (2002))

- ❑ N^3LO: (a) + (b) + (c) + (d) + (e) + (f) + rel
  V.Bernard et al., PR C77, 064004 (2008) - long range contributions (a), (b), (c)
  V.Bernard et al., PR C84, 054001 (2011) - short range terms (e)
  and leading relativistic corrections

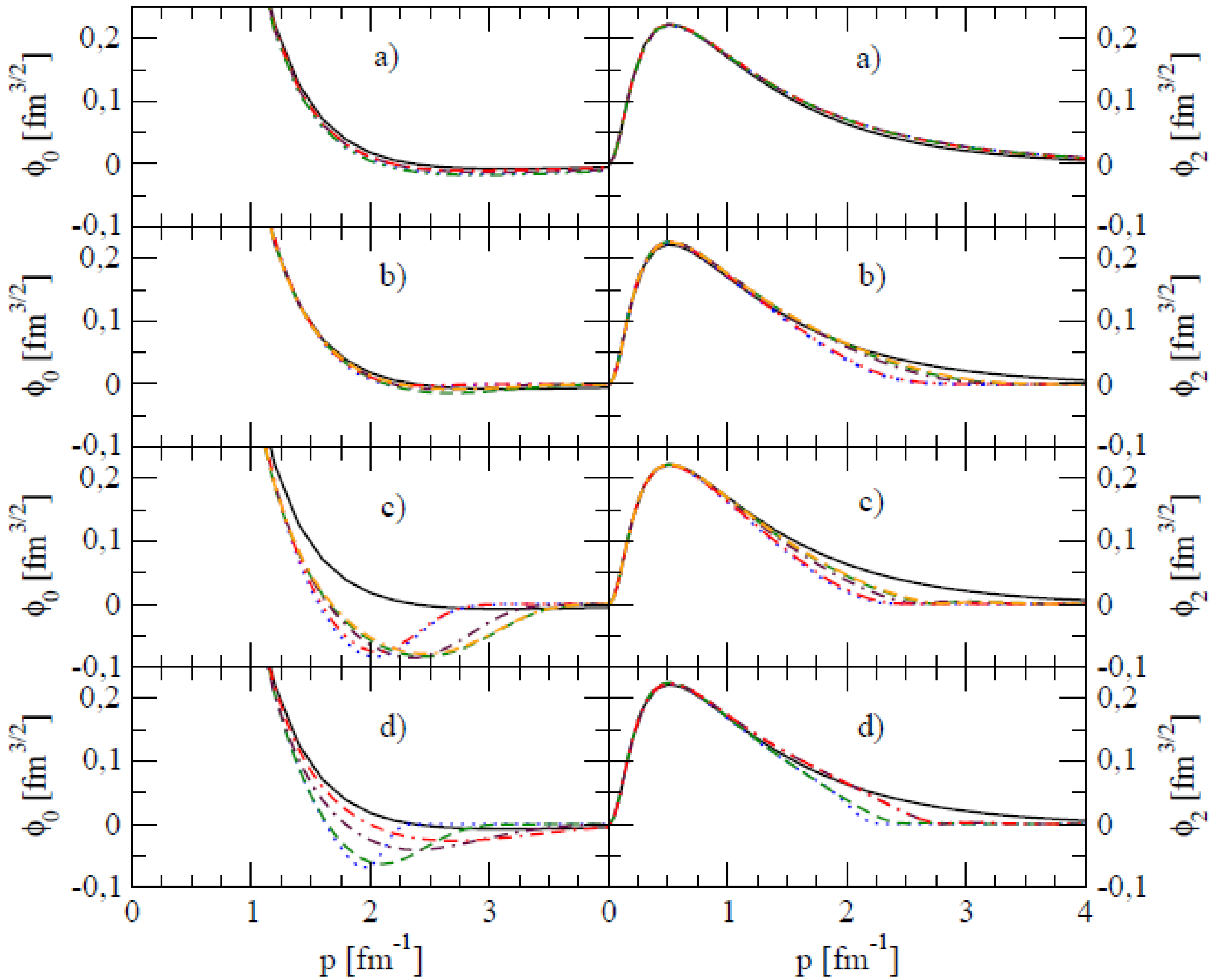
N^3LO contributions do not involve any unknown low energy constants !

The full N^3LO 3NF depends on two parameters c_D and c_E coming with (d) and (f) terms, respectively. They are adjusted to two chosen 3N observables.

- ❑ N^4LO (longest range contributions): (a) + (b) + (c) + (d) + (e) + (f) (H.Krebs et al., arXiv:1203.0067)

Summary:

- Nd elastic scattering and deuteron breakup reaction reveal large sensitivity to underlying nuclear forces --> good tools to test nuclear Hamiltonian
- it is clear that in nuclear Hamiltonian 3NF is needed
- 3NF models, derived independently from NN potentials, can account in some cases for discrepancies between theory and data
- call for consistency between 2N and 3N forces: support and guidance --> chiral perturbation theory
- Big challenge: application of chiral N^3LO forces (2- and 3-body) to 3N continuum



Standard NN pot.

N^2LO - Bochum

N^3LO - Bochum

N^3LO - Idaho

FIG. 9: (color online) The momentum space deuteron wave function for different NN potentials. The S- and D-components (ϕ_0 and ϕ_2, respectively) are shown in the left and right columns, respectively. In a) wave functions for standard NN potentials are shown by different lines: AV18 - dotted (blue), CD Bonn - solid (black), Nijm 93 - dashed (maroon), Nijm I - dashed-dotted (red), and Nijm II - dashed-double-dotted (green). In b) and c) wave functions for the Bochum N^2LO and N^3LO NN potentials with different cut-off parameters from Table I are shown, respectively: (450,500) - dotted (blue) line, (600,500) - dashed (green) line, (550,600) - dashed-dotted (maroon) line, (450,700) - dashed-double-dotted (red) line, (600,700) - double-dashed-dotted (orange) line. The Idaho N^3LO wave functions for different cut-off parameters from Table II are shown in d): 414 - dotted (blue) line, 450 - dashed (green) line, 500 - dashed-dotted (maroon) line, 600 - dashed-double-dotted (red) line. For comparison in b), c) and d) also the CD Bonn wave function is shown by solid (black) line.

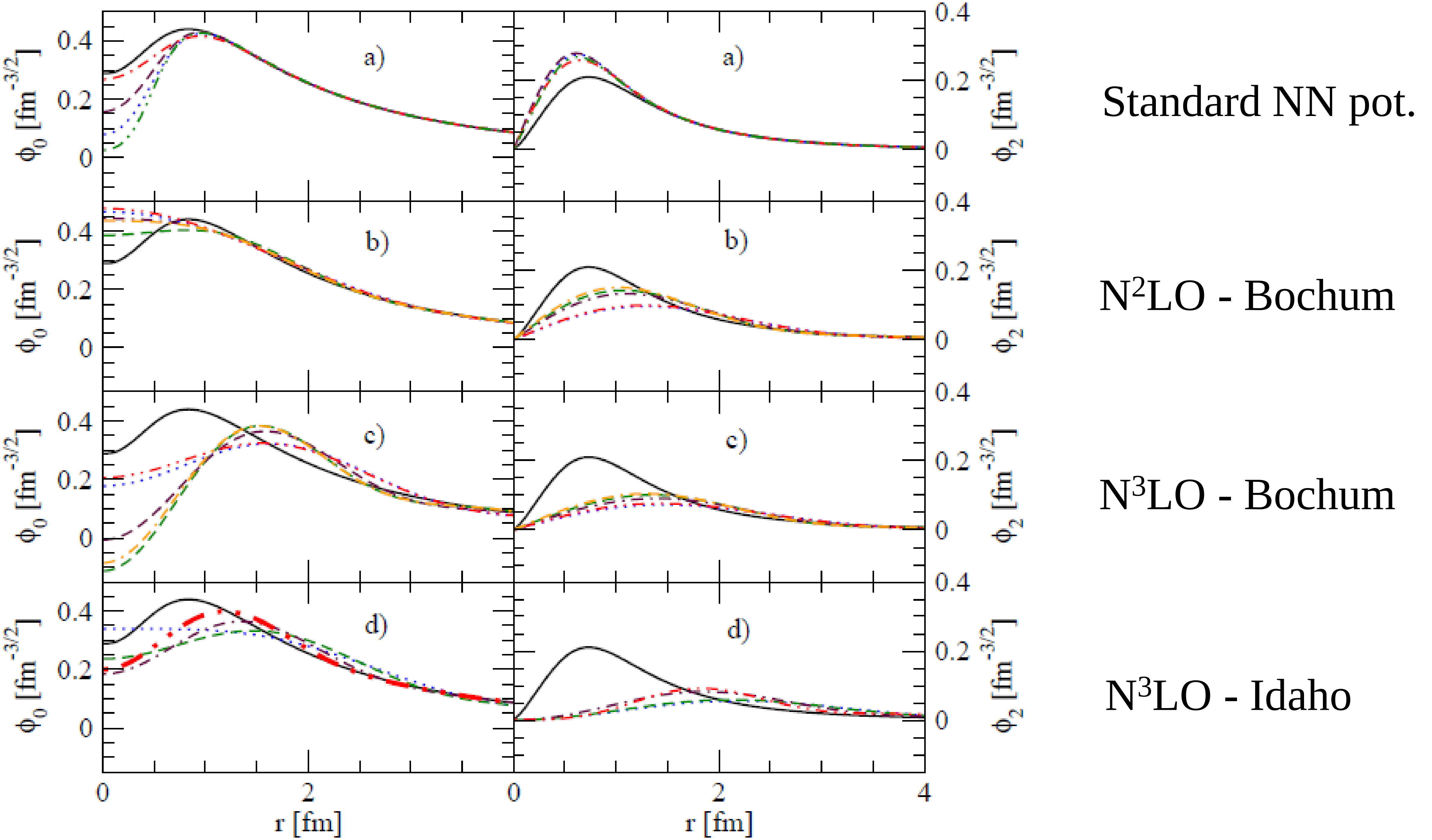
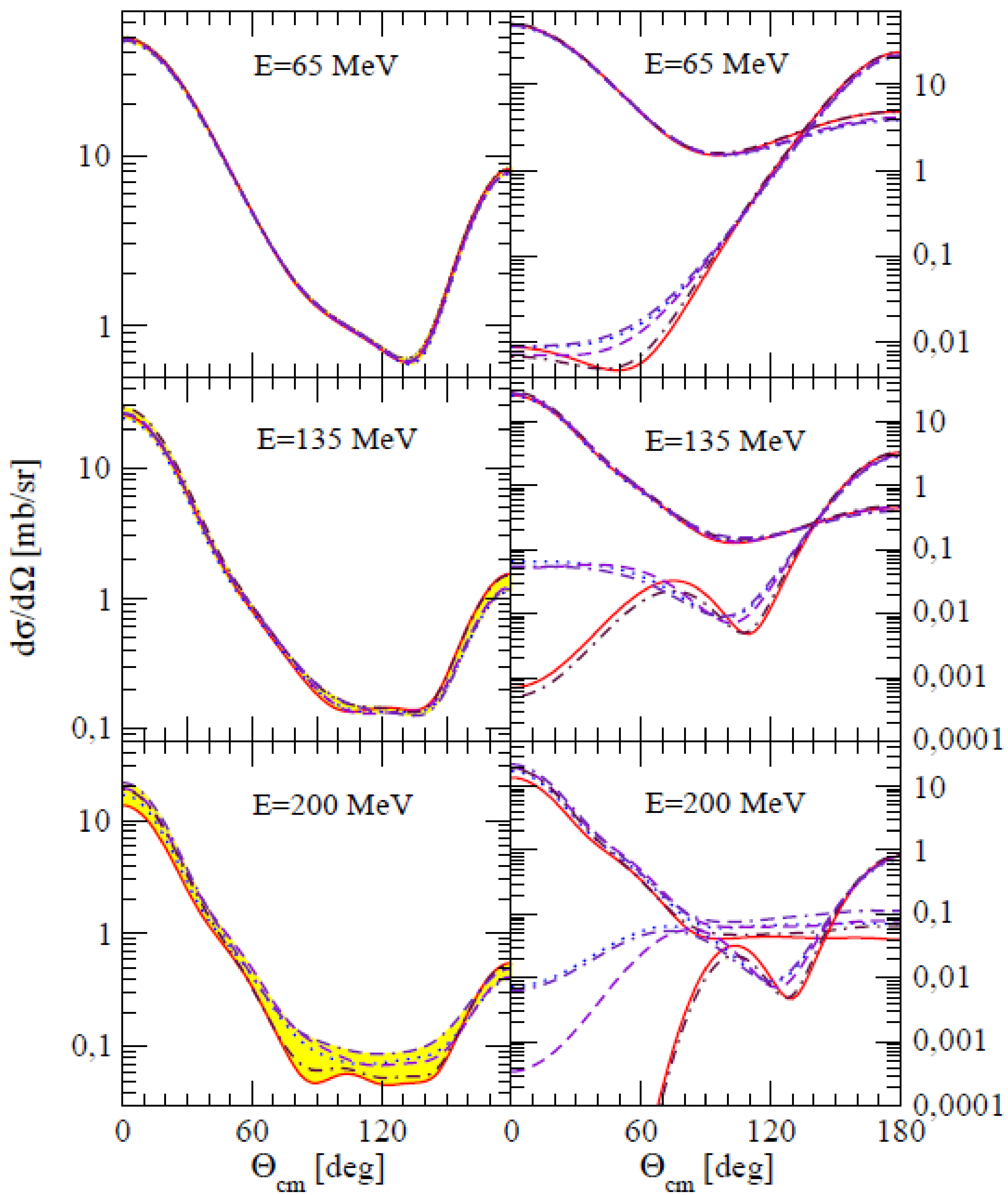


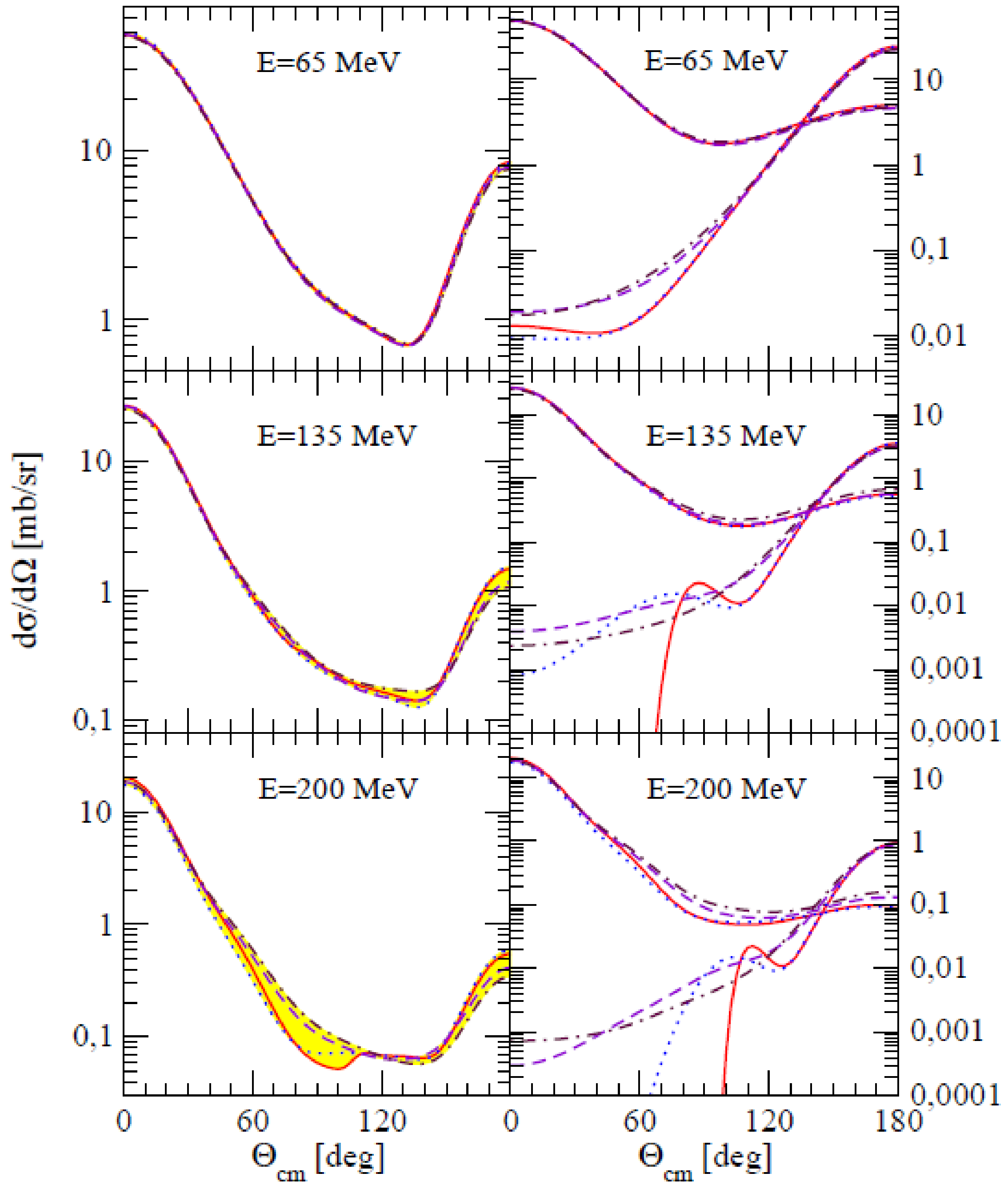
FIG. 10: (color online) The coordinate space deuteron wave function for different NN potentials. For explanation of lines see Fig.9.



N^{3}LO Bochum

$U = PT + PG_0^{-1}$

FIG. 12: (color online) The same as in Fig.11 but for the Bochum N^{3}LO NN potentials with different cut-off values of Table I. See Fig.11 for the description of lines and bands.



N^{3}LO Idaho

FIG. 13: (color online) The nd elastic scattering angular distributions at 65 MeV, 135 MeV and 200 MeV of incoming neutron lab. energy calculated with the Idaho N^{3}LO NN potentials for different cut-off values of Table II. In the left part the nd elastic scattering cross sections are shown. In the right part "cross sections" resulting only from the PT term in the elastic scattering transition amplitude are shown (lines peaked at forward angles) together with "cross sections" based on exchange-term PG_0^{-1} only (lines peaked at backward angles). Different lines correspond to different cut-off parameters from Table II: 414 - solid (red), 450 - dotted (blue), 500 - dashed (violet), 600 - dashed-dotted (maroon). In the left part light-shaded (yellow) band shows scatter of predictions for different cut-off values.

Nonlocal regularization Local regularization