Few-body results from χEFT

Laura E. Marcucci

University of Pisa

INFN-Pisa

SFB 1044-Workshop: Electromagnetic observables for low-energy nuclear physics

Results obtained in collaboration with:

- A. Kievsky and M. Viviani (INFN - Pisa)
- L. Girlanda (Univ. of Lecce)
- A. Gnech (GSSI - L'Aquila)
- R. Machleidt and F. Sammarruca (Univ. of Idaho)
- A. Baroni (USC)
- S. Pastore and M. Piarulli (WUSL)
- R. Schiavilla (ODU and JLab)
- S. Pieper and R.B. Wiringa (ANL)

Color code: blue: "Pisa group"; green: "Idaho group";
cyan: "JLab group"

Outline

- Q: Which nuclei? A: d, ^{3}H and ^{3}He (ideal "labs")
- Q: What are we investigating? A: Electromagnetic (EM) structure and NN momentum distributions
- Q: Within which framework? A: chiral EFT (χEFT)
  - Nuclear potential
    - N3LO V_{NN} (+ N2LO V_{3N}) of EM03[1]
    - LO–N4LO V_{NN} (+ N2LO V_{3N}) of EMN17[2]
    - N3LO V_{NN} (+ N2LO V_{3N}) of NV[3]
  - Electromagnetic currents

[1] D.R. Entem and R. Machleidt, PRC **68**, 041001 (2003)
[2] D.R. Entem, R. Machleidt, and Y. Nosyk, PRC **96**, 023004 (2017)

[3] M. Piarulli *et al.*, PRC **91**, 024003 (2015) & PRL **120**, 052503 (2018)

Nuclear interactions (latest non-local)

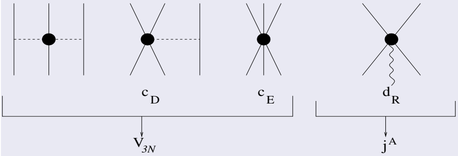
Two-nucleon interaction V_{NN} of EMN17

- from LO to N4LO with $\Lambda = 450, 500, 550$ MeV
- same power counting scheme and cutoff procedures at each order
- πN LECs from Roy-Steiner analysis[1]

[1] M. Hoferichter *et al.*, PRL **115**, 192301 (2015)

Three-nucleon interaction V_{3N}

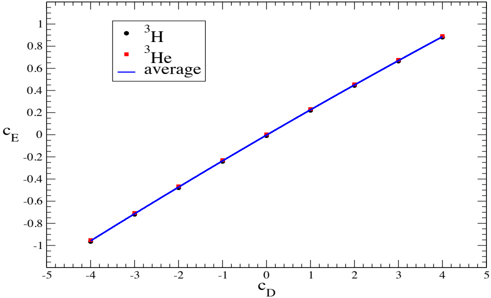
V_{3N} at N2LO: Fit c_D and c_E with $B(A=3)$ and GT ^{3}H β-decay



$$\boxed{d_R = -\frac{1}{4}\frac{M_N}{\Lambda_\chi\, g_A} c_D + \frac{1}{3} M_N (c_3 + 2\,c_4) + \frac{1}{6}}$$ [2]

Possibility to add the 2π-exchange V_{3N} at N3LO or N4LO just readjusting c_1, c_3, c_4 [3]

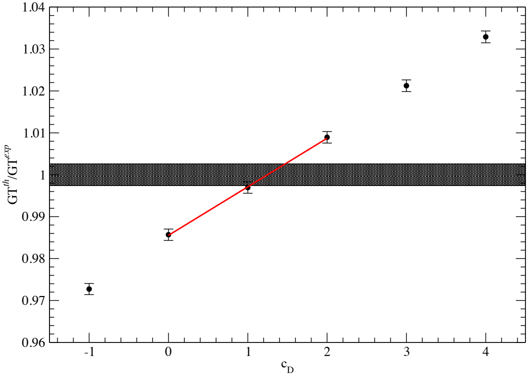
[2] R. Schiavilla, unpublished; L.E. Marcucci *et al.*, PRL **121**, 049901 (2018) (E)
[3] H. Krebs *et al.*, PRC **85**, 054006 (2012)



N4LO ($\Lambda = 450$ MeV)

model I (V_{3N} at N2LO);

model II (V_{3N} with TPE at N#LO)

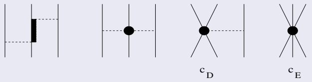


Nuclear interactions (NV potential)

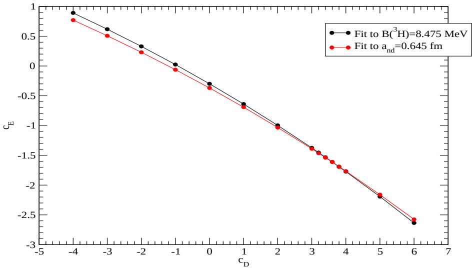
N3LO V_{NN}

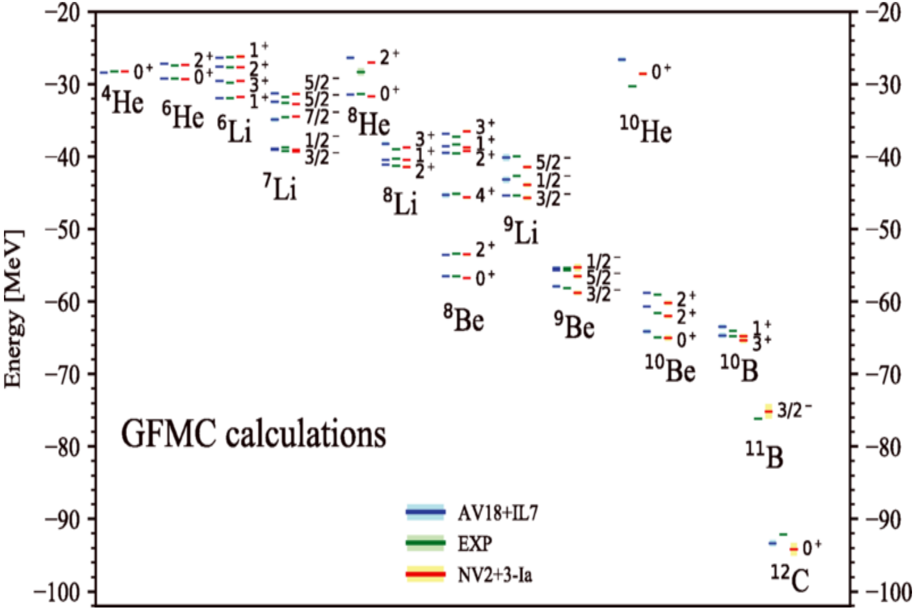
- Explicit Δ's in 2π-exchange up to N3LO
- minimally non-local/coordinate space: Gaussian cutoffs $(R_S, R_L) = (0.8, 1.2)$ fm (model I)
- fit the 2013 Granada database
  - up to $E_{lab} = 125$ MeV ($\sim$ 2700 data) with χ^2/datum ≤ 1.1 (model a)
  - up to $E_{lab} = 200$ MeV ($\sim$ 3500 data) with χ^2/datum ≤ 1.4 (model b)

Three-nucleon interaction V_{3N}



V_{3N} at N2LO: Fit c_D and c_E to $B(A = 3)$ and a_{nd} (NVIa and NVIb)

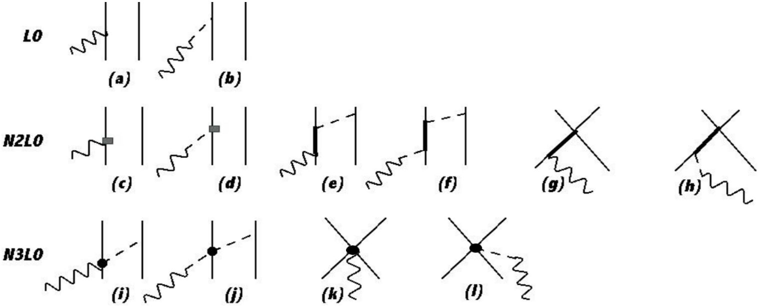




M. Piarulli *et al.*, PRL **120**, 052503 (2018)

The NVIa* and NVIb* potentials

To avoid correlation between $B(A=3)$ and a_{nd} $\rightarrow$ $B(A=3)$ and GT ^{3}H β-decay $\Rightarrow j_A(q)$



- Ignore pion-pole terms [(b), (d), (f), (h), (j), (l)]
- diagrams (g) and (h) vanish; diagram (e) $\rightarrow c_3^\Delta; c_4^\Delta$ (similar to $c_3; c_4$ of diagram (i))
- CTs in (i) and (k)

$$\mathbf{j}_{5,a}^{N3LO}(\mathbf{q}; CT) = z_0\, \mathrm{e}^{i\mathbf{q}\cdot R_{ij}} \frac{\mathrm{e}^{-(r_{ij}/R_S)^2}}{\pi^{3/2}} (\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j)_a (\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)$$

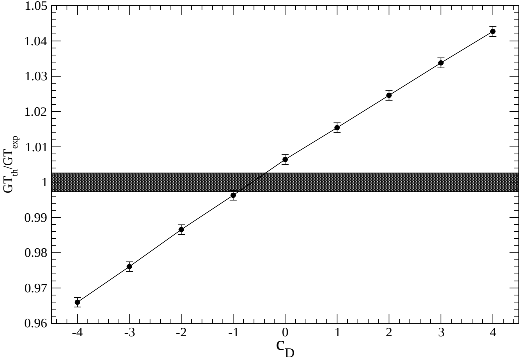
$$z_0 = \frac{g_A}{2}\frac{m_\pi^2}{f_\pi^2}\frac{1}{(m_\pi R_S)^3}\left[-\frac{m_\pi}{4 g_A \Lambda_\chi} c_D + \frac{m_\pi}{3}(c_3 + 2c_4 + c_3^\Delta + 2c_4^\Delta) + \frac{m_\pi}{6m}\right]$$

$$\text{but} \quad c_3^\Delta + 2c_4^\Delta = -\frac{h_A^2}{9 m_{\Delta N}} + 2\frac{h_A^2}{18 m_{\Delta N}} = 0 \quad \text{with } h_A \equiv g_A^*$$

	NVIa	NVIb
c_D	3.666	–2.061
c_E	–1.638	–0.982
GT	0.9885	0.9730

	NVIa*	NVIb*
c_D	–0.635	–4.71
c_E	–0.09	0.55

$$GT^{exp} = 0.9511 \pm 0.0013$$



"Obvious comment"

- d_R/z_0 ($\Rightarrow c_D$) from muon capture on deuteron (MuSun experiment)
- In V_{3N} only c_E to be fixed with $B(A = 3)$

$\rightarrow$ GT in ^{3}H β-decay and muon capture on ^{3}He become predictions

$\Rightarrow$ more stringent test for χEFT using the weak sector

More are the data, the better it is!

Muon capture on deuteron and ^{3}He

- $\mu^- + d \to n + n + \nu_\mu$ (MuSun at PSI with 1.5 % accuracy)
- $\mu^- + {}^3\mathrm{He} \to {}^3\mathrm{H} + \nu_\mu$ [$\Gamma({}^3\mathrm{He})^{Exp} = (1496 \pm 4)$ s^{-1}]
- $\mu^- + {}^3\mathrm{He} \to n + d + \nu_\mu$ (poor data)
- $\mu^- + {}^3\mathrm{He} \to n + n + p + \nu_\mu$ (poor data)

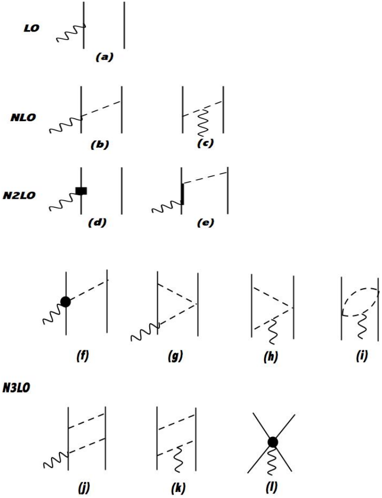
	$^1S_0$	$^3P_0$	$^3P_1$	$^3P_2$	$^1D_2$	$^3F_2$	$\Gamma(^2\mathrm{H})$	$\Gamma(^3\mathrm{He})$
IA(500)	238.8	21.1	44.0	72.4	4.5	0.9	381.7	1355
IA(600)	238.7	20.9	43.8	72.0	4.5	0.9	380.8	1351
FULL(500)	253.7±0.9	20.3	47.0	72.0	4.5	0.9	398.4±0.9	1488±10
FULL(600)	253.3±1.0	20.1	46.7	71.6	4.5	0.9	397.1±1.0	1495±9

L.E. Marcucci *et al.*, PRL **108**, 052502 (2012); PRL **121**, 049901 (2018) (E)

see also B. Acharya *et al.*, arXiv:1806.09481: $\Gamma(^2\mathrm{H}) - {}^1S_0 = (252.8 \pm 4.6 \pm 3.9)$ s^{-1}

Room for more "fun":

- Apply χEFT to breakup $A = 3$ channels
- Connection to neutrino scattering and more (see Golak's contribution)
- Study muon capture on ^{4}He



- $\mathbf{j}_{\Delta}^{\rm N2LO}(\mathbf{q})$ in panel (e) absent in $\not\Delta$-EFT
- not included the Δ intermediate states at N3LO
- $\mathbf{j}_{\rm OPE}^{\rm N3LO}(\mathbf{q}) \rightarrow d_2^S$
- $\mathbf{j}_{\rm MIN}^{\rm N3LO}(\mathbf{q}) \rightarrow$ from πN scattering
- $\mathbf{j}_{\rm NM}^{\rm N3LO}(\mathbf{q}) \rightarrow d_1^S\,;\, d_1^V$

To be noticed: in $\not\Delta$-EFT

$$\mathbf{j}_{\rm OPE}^{\rm N3LO}(\mathbf{q}) \propto \frac{\boldsymbol{\sigma}_j \cdot \mathbf{k}_j}{(m_\pi^2 + \mathbf{k}_j^2)}\, \mathbf{q} \times \left[(d_2^S \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j + d_2^V \tau_j^z)\mathbf{k}_j + d_3^V (\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j)^z \boldsymbol{\sigma}_i \times \mathbf{k}_j \right]$$

$d_2^V\,;\, d_3^V \rightarrow$ saturated with Δ-current of panel (e)

Electromagnetic current (II)

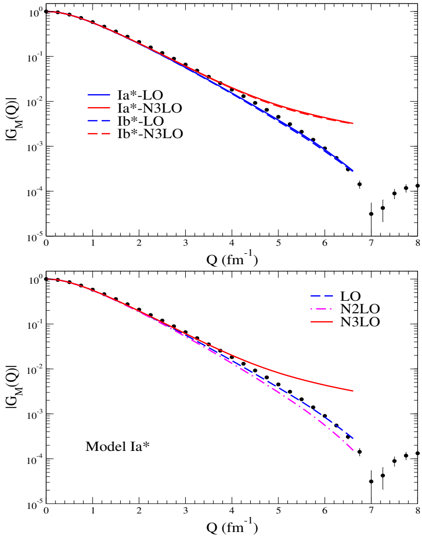
Fitting the LECs with NVIa* and NVIb*

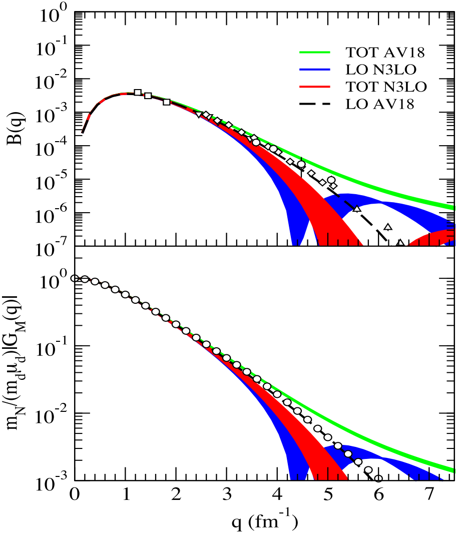
- d_1^S and d_2^S $\rightarrow \mu_d$ and $\mu_S(A=3)$
- d_1^V $\rightarrow \mu_V(A=3)$

Fitting the LECs with N3LO of EM03 ($\not\Delta$-EFT)

- d_1^S and d_2^S $\rightarrow \mu_d$ and $\mu_S(A=3)$
- (SET III) d_1^V $\rightarrow \mu_V(A=3)$
- d_2^V and d_3^V Δ-resonance saturation picture

Selected results: the deuteron magnetic form factors

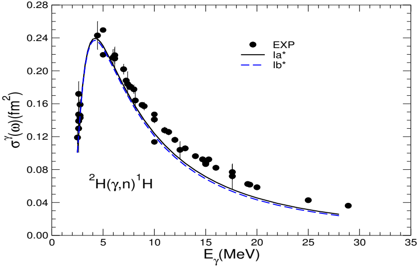


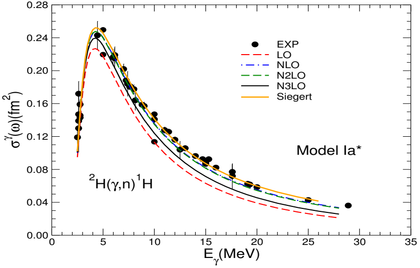


M. Piarulli *et al.*, PRC **87**, 014006 (2013)

$\rightarrow$ "old" N3LO of EM03

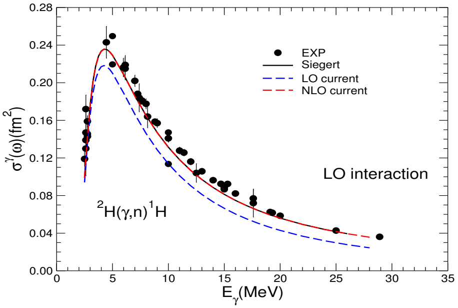
Selected results: the deuteron photodisintegration





$$\boxed{\mathbf{q}\cdot\mathbf{j}^{\rm NLO} = [v_{ij}^{\rm LO}, \rho(\mathbf{q})] \quad \text{for} \;\; q \to 0}$$

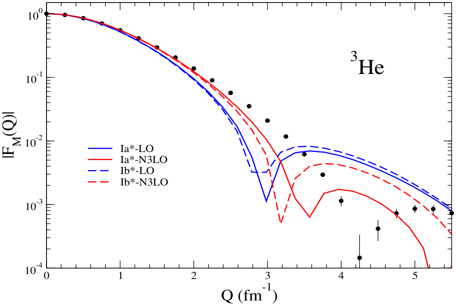
$v_{ij}^{\rm LO} \to$ OPE + CT (C_S and C_T LECs) fitted to B_d and NN data up to 125 MeV

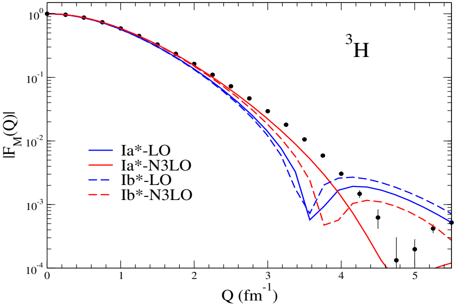


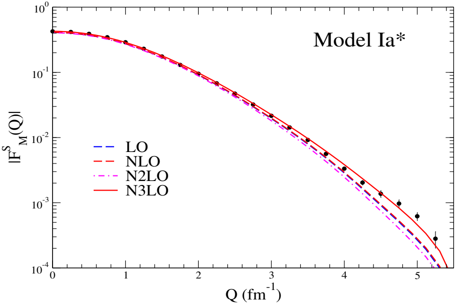
CCR with $v_{ij}^{\rm N3LO} \to \mathbf{j}^{\rm N5LO}(\mathbf{q})$!!

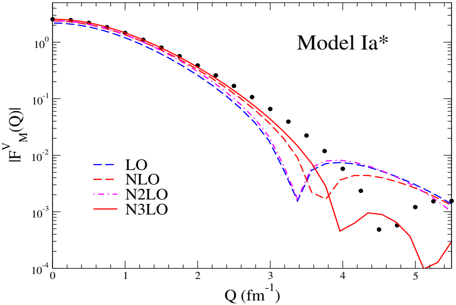
But in this case how many LECs?!

Selected results: the $A = 3$ form factors (I)

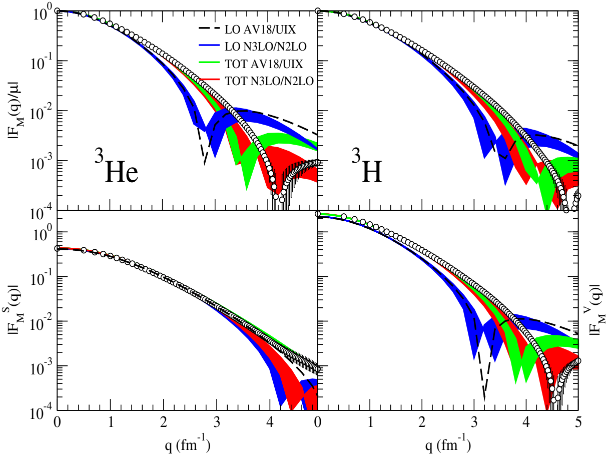








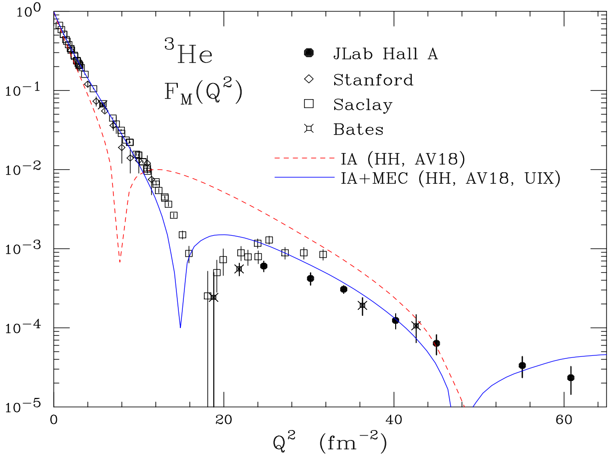
Selected results: the $A = 3$ form factors (II)



Piarulli *et al.*, PRC **87**, 014006 (2013) $\rightarrow$ "old" N3LO of EM03

Discrepancy also within phenomenological approach: Isn't this also a puzzle?

Saclay vs. JLab data



A. Camsonne *et al.*, PRL **119**, 162501 (2017)

Static properties for $A = 2, 3$ nuclei

	PhenApp (AV18)	χEFT (N3LO - EM03)	Exp.
$r_c(d)$ [fm]	2.119	2.126(4)	2.130(10)
$Q(d)$ [fm^2]	0.280	0.2836(16)	0.2859(3)
$r_c(^3\mathrm{He})$ [fm]	1.928	1.962(4)	1.973(14)
$r_m(^3\mathrm{He})$ [fm]	1.909	1.920(7)	1.976(47)
$r_c(^4\mathrm{He})$ [fm]	1.639	1.663(11)	1.681(4)

L.E. Marcucci *et al.*, JPG **43**, 023002 (2016)

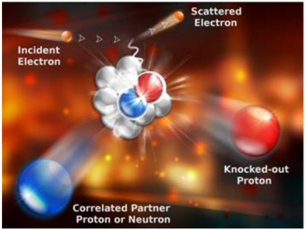
^{3}He momentum distributions

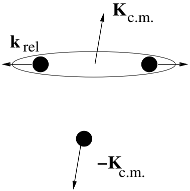
Two-nucleon momentum distributions

$$n^{np}(k_{rel}, K_{c.m.}) = \int d\hat{\mathbf{k}}_{rel} \int d\hat{\mathbf{K}}_{c.m.} \Psi^\dagger(\mathbf{k}_{rel}, \mathbf{K}_{c.m.}) P_{np} \Psi(\mathbf{k}_{rel}, \mathbf{K}_{c.m.})$$

$$n^{np}(k_{rel}, K_{c.m.} = 0) \rightarrow \text{back} - \text{to} - \text{back (BB)}$$

Experimental program (JLab)





large k_{rel} and small $K_{c.m.}$ compared to k_F $\Rightarrow$ SRCs

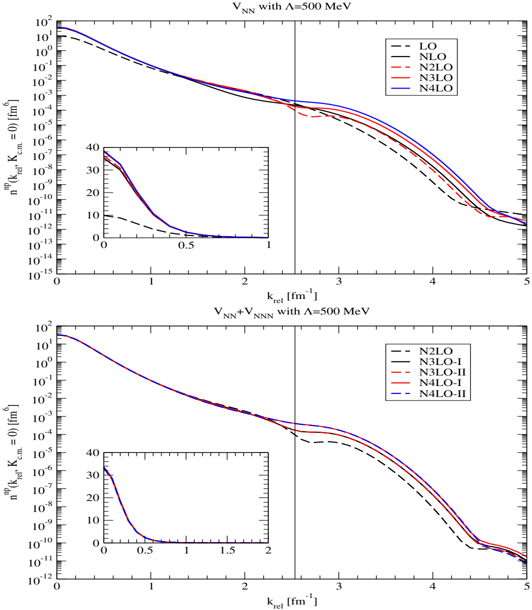
EMN17 potentials

See also:

- D. Lonardoni *et al.*, arXiv:1804.08027
- R. Weiss *et al.*, arXiv:1807.08677, 1806.10217, PLB **785**, 304 (2018); PLB **780**, 211 (2018) ...

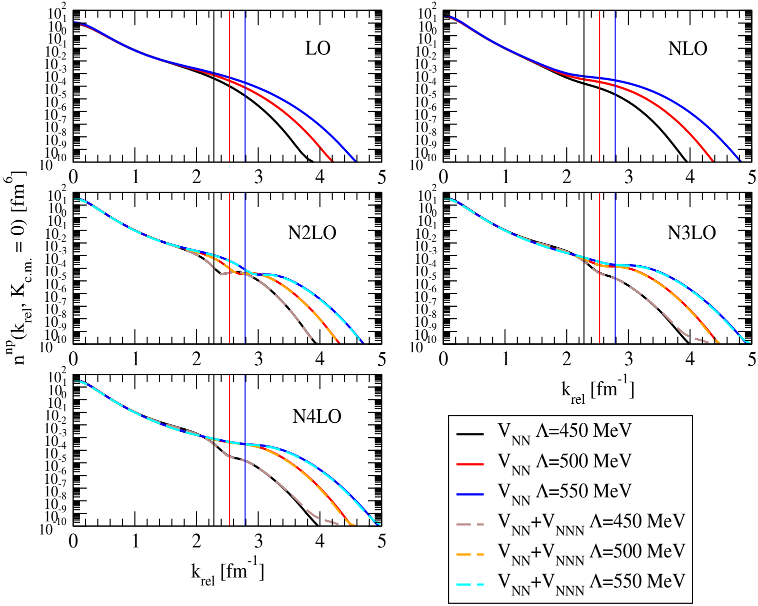
L.E. Marcucci *et al.*, arXiv:1809.01849

Order-by-order convergence ($\Lambda = 500$ MeV as an example)



- asymptotic w.f. at LO $\neq$ NLO, N2LO ...
- I-results (V_{3N} at N2LO) $\sim$ II-results (V_{3N} with TPE at N#LO) $\Rightarrow$ V_{3N} small
- N3LO $\neq$ N4LO for $k_{rel} \geq 2.2$ fm^{-1}

Λ-dependence



SRCs – BB ($N_{np}^{SRC,BB}$)

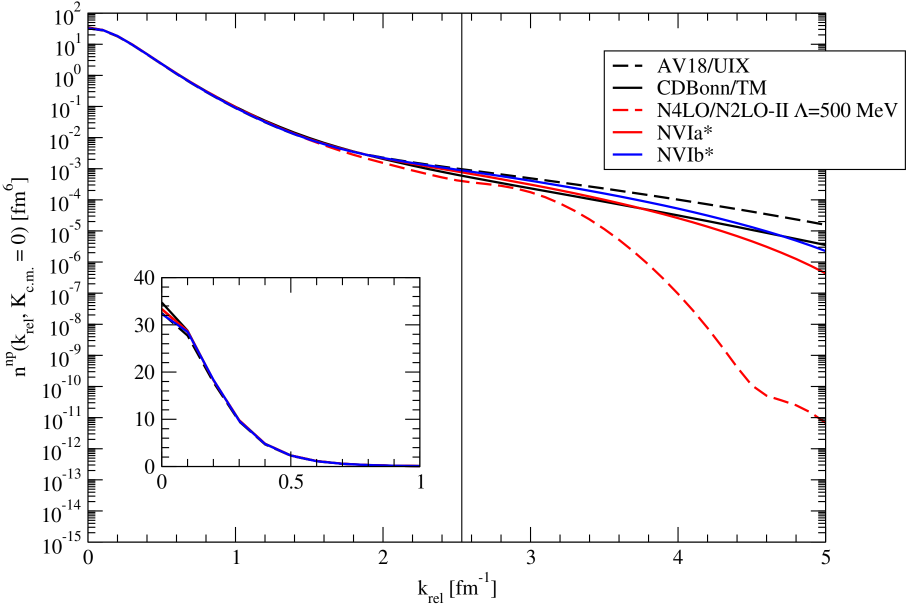
$$N_{np}^{SRC,BB} = 4\pi \int_{k_{rel}^-}^{\infty} n^{np}(k_{rel}, K_{c.m.} = 0) k_{rel}^2 \, dk_{rel} \quad \text{with } k_{rel}^- = 1.5\,\mathrm{fm}^{-1}$$

	$\Lambda = 450$ MeV	$\Lambda = 500$ MeV	$\Lambda = 550$ MeV
LO	0.094	0.120	0.144
NLO	0.047	0.066	0.096
N2LO	0.087	0.118	0.141
N2LO/N2LO	0.086	0.114	0.135
N3LO	0.131	0.112	0.122
N3LO/N2LO-II	0.121	0.107	0.117
N4LO	0.125	0.119	0.129
N4LO/N2LO-II	0.116	0.113	0.123

CDBonn/TM $\Rightarrow$ 0.157 (no V_{3N}: 0.171)

AV18/UIX $\Rightarrow$ 0.210 (no V_{3N}: 0.241) $\Rightarrow$ Significant model-dependence

Preliminary results with NV potentials (I)



Preliminary results with NV potentials (II)

SRCs – BB ($N_{np}^{SRC,BB}$)

AV18/UIX	0.210
CDBonn/TM	0.157
N4LO/N2LO-II $\Lambda = 500$ MeV	0.113
NVIa*	0.167
NVIb*	0.185

$\Rightarrow$ again large model-dependence

Summary and outlook

Summary

- Few-body systems: "ideal" labs to study nuclear interactions and currents
- EM structure of $A \leq 3$ within "local" χEFT framework ($\rightarrow$ MC approach)
- Two-nucleon momentum distributions of ^{3}He in χEFT
  - Small V_{3N} contributions
  - Reasonable order-by-order convergence
  - Significant model-dependence

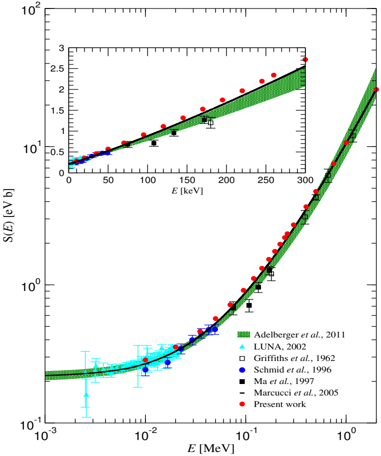
Outlook

- Other EM observables within the "local" χEFT framework: radiative captures (np, nd, pd^* ...), $A = 3, 4$ electro-disintegration
- Systematic study of $A \leq 4$ momentum-distributions, pp/np probabilities, spectral function $S_N(\mathbf{k}, E)$ ...
- Move to $A > 4$ (work in progress: $A = 6$ nuclei almost there)

The *pd* radiative capture

$$p + d \to {}^3\mathrm{He} + \gamma$$

- Relevant for Big Bang Nucleosynthesis ($E_{c.m.} \sim 100 - 300$ keV)



$^2\mathrm{H/H}|_{TH} = (2.46 \pm 0.03 \pm 0.03) \times 10^{-5}$

$\Omega_b h^2 \to$ Planck 2015 & standard N_{eff}

vs.

$^2\mathrm{H/H}|_{Exp} = (2.53 \pm 0.04) \times 10^{-5}$

L.E. Marcucci *et al.*, PRL **116**, 102501 (2016)

- Dark photon? $p + d \to {}^3\mathrm{He} + e^+ + e^-$

  $[p + d \to {}^3\mathrm{He} + \gamma^*$ and $\gamma^* \to e^+ + e^-]$