Recent progresses in *ab-initio* studies of low-energy few-nucleon reactions of astrophysical interest

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Results obtained in collaboration with:

- The FBS Pisa Group
- The astrophysics colleagues of the Dep. (E. Tognelli, S. Degl'Innocenti, P. Prada Moroni)
- R. Schiavilla and collaborators
- G. Mangano (Napoli)

Outline

- *Ab-initio* methods for few-nucleon systems
  - (Standard) phenomenological approach (PhenAp)
  - Chiral effective field theory (χEFT)
- Tests
  - Electromagnetic structure of $A = 2, 3, 4$ nuclei
  - Muon capture on light nuclei
- Results
  - $p + p \to d + e^+ + \nu_e$
  - $p + d \to {}^3\mathrm{He} + \gamma$
- Outlook
  - The weak sector in χEFT
  - Recent (local) χEFT potential WITH Δ's

Theoretical framework: *ab-initio* studies

A-nucleon system ↔ Cross section σ [or *S*-factor $S(E)$]

Ingredients

- Realistic nuclear Hamiltonian
  $H = T + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk}$
- *Ab-initio* method to solve the *A*-body quantum problem (HH method for $A = 3$)
- Realistic nuclear electroweak currents j^{EW}

Nuclear Hamiltonian

- PhenAp → AV18/UIX
- χEFT → N3LO(Idaho)/N2LO(local form) – $\Lambda = 500, 600$ MeV

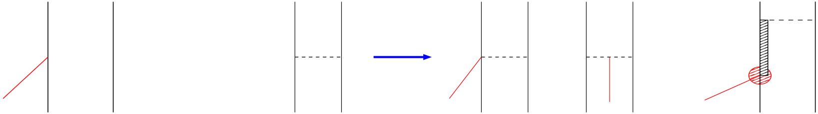
Electroweak currents in PhenAp

EW operators: $\rho^\gamma, \mathbf{j}^\gamma$; $\rho^{V/A}, \mathbf{j}^{V/A}$ but CVC $\Rightarrow \rho^V/\mathbf{j}^V \to \rho^\gamma/\mathbf{j}^\gamma$

- $\mathbf{j}^\gamma \to$ Current Conservation Relation (CCR) $\longrightarrow \mathbf{q}\cdot\mathbf{j}^\gamma \propto [\rho^\gamma, H]$

Realistic model

1b operators **2b operators**: Meson-exchange currents + $\mathbf{j}^{MD} \perp \mathbf{q}$

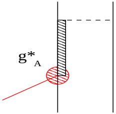


CCR with T at $\mathcal{O}(\frac{1}{m})$ | Interplay potential-current: MI | MD

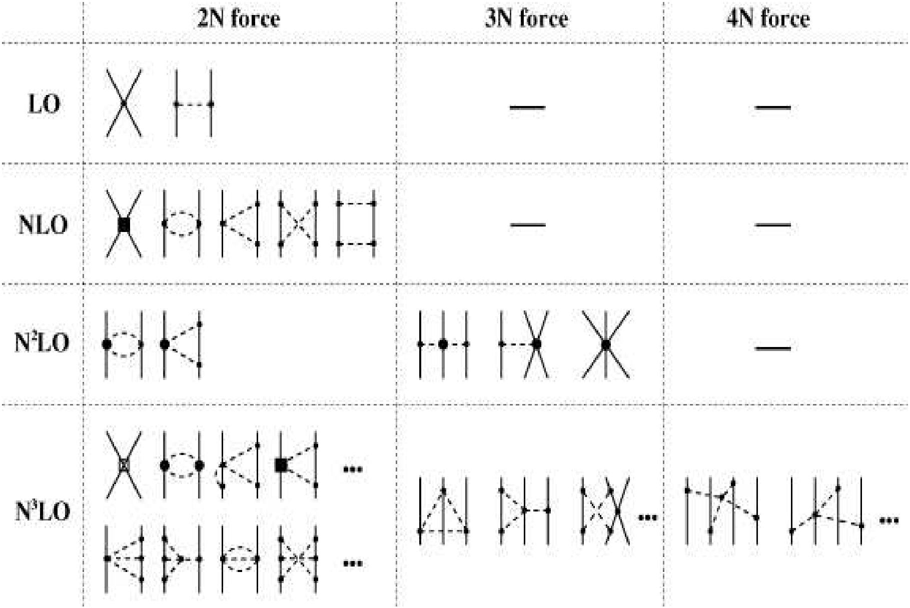
CCR "exact" with AV18/UIX [L.E. Marcucci *et al.*, PRC **72**, 014001 (2005)]

- $\mathbf{j}^A \to$ no CCR $\Rightarrow$ **MD**

Largest contribution to $\mathbf{j}^A$(MD) from



g_A^* fit to observable: GT_{Exp} of tritium β-decay



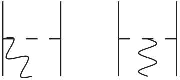
Similar power counting for the EW currents

Electroweak currents in χEFT: power counting for $\mathbf{j}^\gamma$

$\mathcal{O}(Q^{-2})$

$$\mathbf{j}^{(-2)} \propto [e_N(1)(\mathbf{p}_1' + \mathbf{p}_1) + i\mu_N(1)\sigma_1 \times \mathbf{q}] \times \delta(\mathbf{p}_2' - \mathbf{p}_2) + 1 \leftrightarrow 2$$

$\mathcal{O}(Q^{-1})$

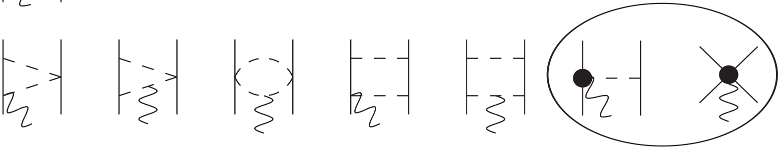


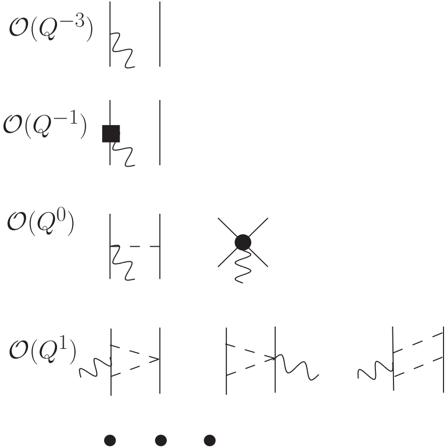
"standard" one – pion – exchange

$\mathcal{O}(Q^{0})$

■ = relativistic corrections

$\mathcal{O}(Q^{1})$



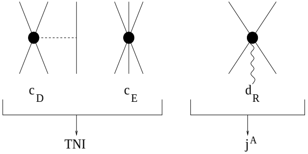


Note:

- $\mathcal{O}(Q^1)$: two-pion-exchange
  A. Baroni *et al.*, PRC **93**, 015501 (2016)
- Park *et al.* up to $\mathcal{O}(Q^0)$
  $\rightarrow$ one LEC - d_R

$$d_R = \frac{M_N}{\Lambda_\chi g_A} c_D + \frac{1}{3} M_N (c_3 + 2c_4) + \frac{1}{6}$$

- fit c_D and c_E (in TNI at N2LO) to $B(A=3)$ and GT_{Exp}



Electroweak currents: latest development

PhenAp

A new 1b term $\rightarrow$ relativistic correction (RC) $\mathcal{O}(1/m^3)$.
L. Girlanda *et al.*, PRL **105**, 232502 (2010): significant (few %) contribution to $n + d \rightarrow {}^3\text{H} + \gamma$.

χEFT

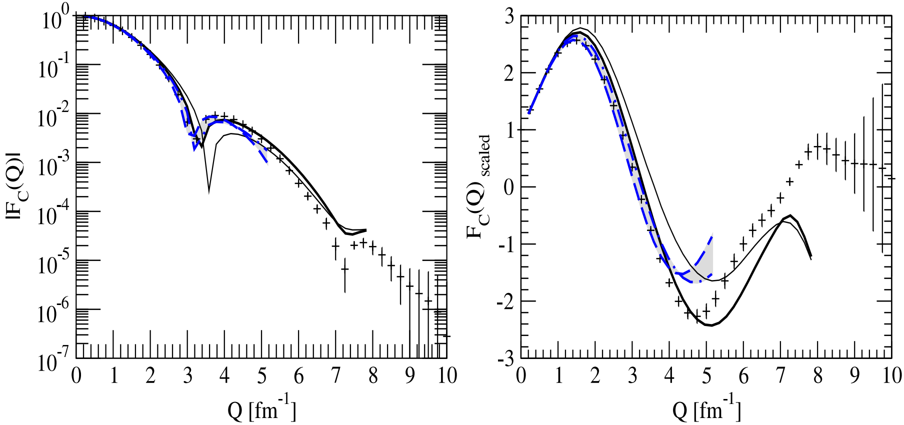
Main results in the weak sector up to $\mathcal{O}(Q^0)$ (Park *et al.*). Preliminary results also including the $\mathcal{O}(Q^1)$ contributions.

Electromagnetic structure of $A = 2, 3, 4$ nuclei

	PhenAp	χEFT	Exp.
$r_c(d)$ [fm]	**2.119**	**2.126 ± 0.004**	2.130 ± 0.010
$\mu(d)$ [n.m.]	0.847	0.8574	0.8574
$Q(d)$ [fm^2]	**0.280**	**0.2836 ± 0.0016**	0.2859 ± 0.0003
$r_c(^3\mathrm{He})$ [fm]	**1.928**	**1.962 ± 0.004**	1.973 ± 0.014
$r_m(^3\mathrm{He})$ [fm]	1.909	1.920 ±0.007	1.976 ±0.047
$\mu(^3\mathrm{H})$ [n.m.]	2.953	2.979	2.979
$\mu(^3\mathrm{He})$ [n.m.]	–2.125	–2.128	–2.128
$r_c(^4\mathrm{He})$ [fm]	**1.639**	**1.663 ± 0.011**	1.681 ± 0.004

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

$A = 4$ form factor

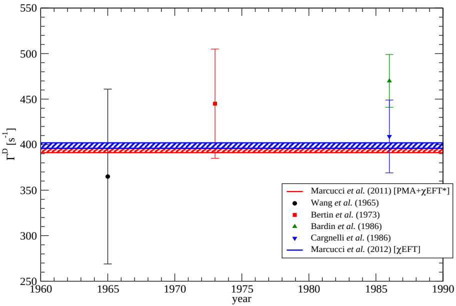


Scaling function: $F_C(Q)_{\rm scaled} = F_c(Q)/[F_0 \exp(-Q/k)]$, with $F_0 = 1$ & $k = 0.760488$ fm^{-1}

Muon capture on $A = 2, 3$ nuclei

- $\mu^- + d \rightarrow n + n + \nu_\mu \longrightarrow$ capture rate in the doublet hyperfine state Γ^D
- $\mu^- + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \nu_\mu \longrightarrow$ total capture rate Γ_0

$\mu^- + d \rightarrow n + n + \nu_\mu$



$\mu^- + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \nu_\mu$

Γ_0(PhenAp)=1495(11) s^{-1}

vs. $\Gamma_0(\chi$EFT)=1494(21) s^{-1}

vs. Γ_0(Exp)=1496(4) s^{-1}

L.E. Marcucci *et al.*, PRC **83**, 014002 (2011)

L.E. Marcucci *et al.*, PRL **108**, 052502 (2012)

The proton-proton weak capture reaction

$S(E)$ in χEFT and PhenAp

- Energy range 2 keV – 100 keV
- PhenAp or χEFT + FULL EM interaction
- pp $L \leq 1$ partial waves: $^1S_0$ + all P-waves

$S(0)$ cumulative contributions (in 10^{-23} MeV fm^2)

	$^1S_0$	$\cdots + {}^3P_0$	$\cdots + {}^3P_1$	$\cdots + {}^3P_2$
PhenAp	4.000(3)	4.003(3)	4.015(3)	4.033(3)
χEFT	4.008(6)	4.011(6)	4.020(6)	4.030(6)

$$S(0) = (\mathbf{4.030 \pm 0.006}) \times 10^{-23}\ \textbf{MeV fm}^2$$

vs.

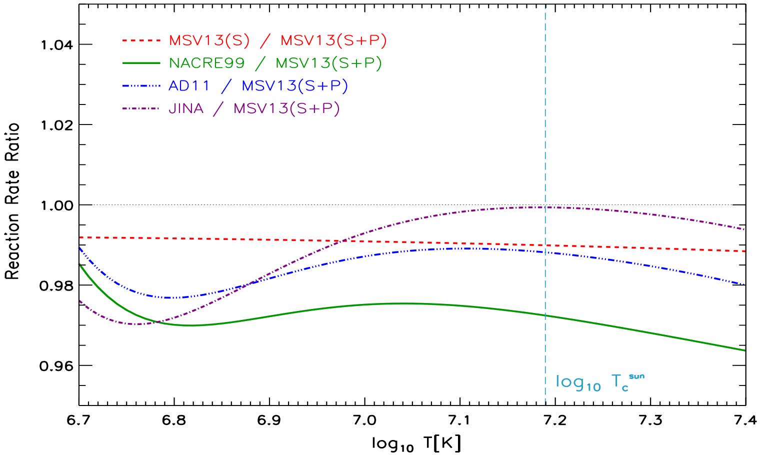
$$S(0)^{\rm SFII} = (4.01 \pm 0.04) \times 10^{-23}\ \text{MeV fm}^2$$

SFII: E.G. Adelberger *et al.*, RMP **83**, 195 (2011)

L.E. Marcucci *et al.*, PRL **110**, 192503 (2013)

Effects on

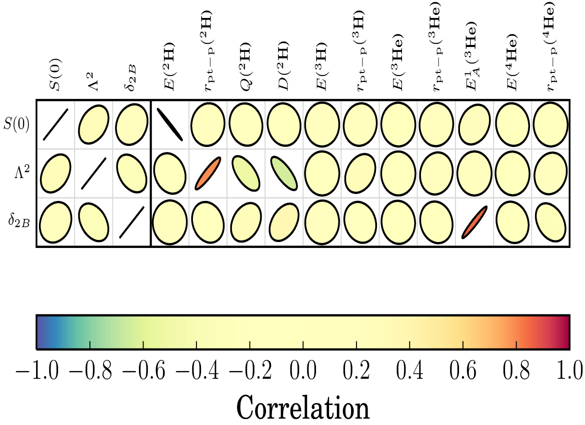
- age of mid and old stellar clusters (1-12 Gyr)
- standard solar model predictions



E. Tognelli *et al.*, PLB **742**, 189 (2015)

Neutrino fluxes relative differences

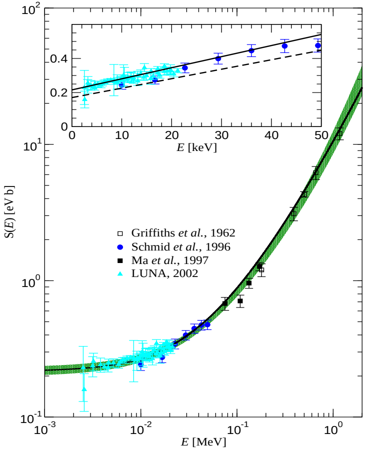
	MSV13(S+P) reference	MSV13(S)	NACRE99	AD11	JINA
		relative differences			
T_c [10^7 K]	1.54794	$-1‰$	$-3‰$	$-2‰$	$-1‰$
Φ^{ν}_{pp} [10^{10}]	6.020	$1‰$	$2‰$	$2‰$	$1‰$
Φ^{ν}_{pep} [10^8]	1.446	$-2‰$	$-6‰$	$-2‰$	$-1‰$
Φ^{ν}_{hep} [10^3]	8.584	$-1‰$	$-3‰$	$< 1‰$	$2‰$
Φ^{ν}_{Be-7} [10^9]	4.503	**−1%**	**−3%**	**−1%**	$-9‰$
Φ^{ν}_{B-8} [10^6]	3.694	**−3%**	**−7%**	**−4%**	**−2%**
Φ^{ν}_{N-13} [10^8]	2.417	**−2%**	**−6%**	**−3%**	**−1%**
Φ^{ν}_{O-15} [10^8]	1.811	**−3%**	**−8%**	**−4%**	**−2%**
Φ^{ν}_{F-17} [10^6]	3.373	**−3%**	**−8%**	**−4%**	**−2%**

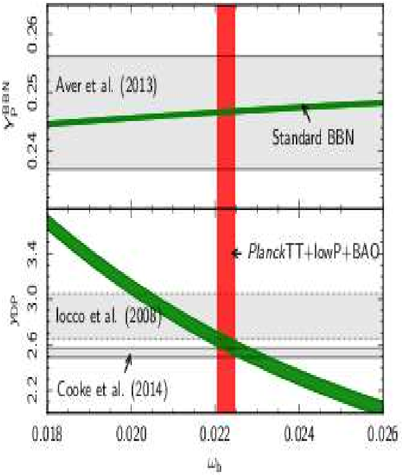


$$S_{\rm cor}(0) = (4.047^{+0.024}_{-0.032}) \times 10^{-23} \text{ MeV fm}^2$$

B. Acharya *et al.*, arXiv:1693.01593

The $p + d \rightarrow {}^3\mathrm{He} + \gamma$ reaction





SFII: E.G. Adelberger *et al.*, RMP **83**, 195 (2011)

Planck Collab., arXiv:1501.01589 (2015)

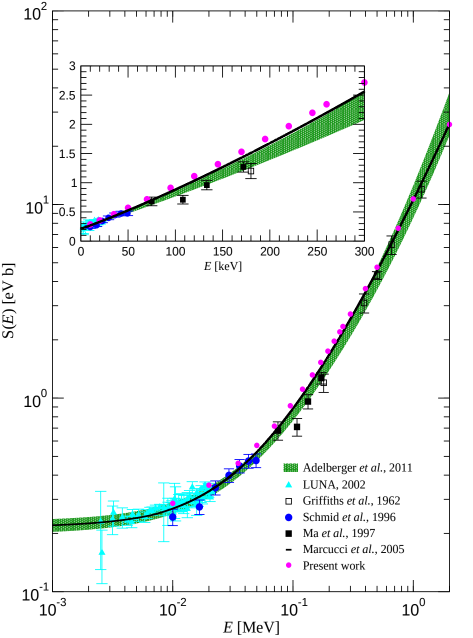
Latest news on the $p + d \rightarrow {}^3\mathrm{He} + \gamma$ reaction

- New ongoing measurement by the **LUNA Collab.** at LNGS in the energy range of interest for BBN
- "New" calculation in PhenAP:
  1. test of the nuclear scattering wave functions by calculating $\langle H \rangle = \langle \Psi^{LSJ} | H | \Psi^{LSJ} \rangle$ in a box with $R_{box} = 70$ fm
  2. inclusion of the 1b RC term
- Preliminary calculation in χEFT

PhenAp results

E [keV]	ΔS_{WF} [%]	$\Delta \mathbf{j}^{(RC)}$ [%]
35	1.1	+1.3
70	0.4	+2.1
95	0.3	+2.3
120	0.8	+2.4
145	0.4	+2.5
170	0.4	+2.6
195	0.4	+2.6
220	0.5	+2.8
245	0.4	+2.7

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

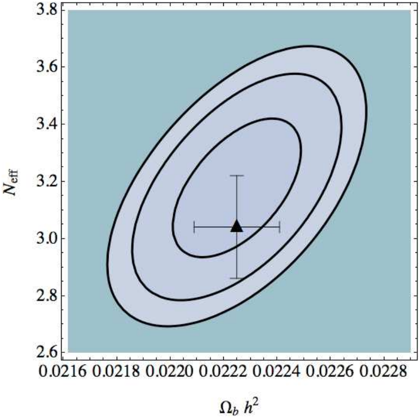


Implications for Big Bang Nucleosynthesis

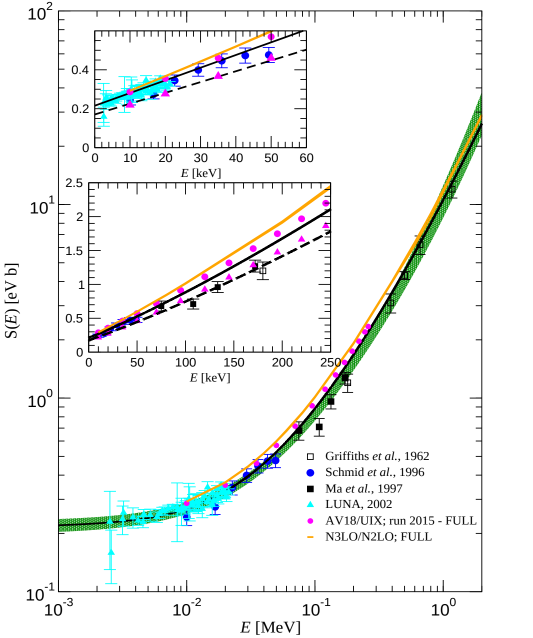
- $S(E) \rightarrow$ primordial ^{2}H abundance
- ^{2}H/H abundance as function of $\Omega_b h^2$ and N_{eff}
- Likelihood function to get the best fit on $\Omega_b h^2$ and N_{eff}

$^2\mathrm{H/H}|_{TH} = (2.49 \pm 0.03 \pm 0.03) \times 10^{-5}$
$\Omega_b h^2$ $\rightarrow$Planck 2015 & standard N_{eff}
vs.
$^2\mathrm{H/H}|_{Exp}$=$(2.53 \pm 0.04) \times 10^{-5}$

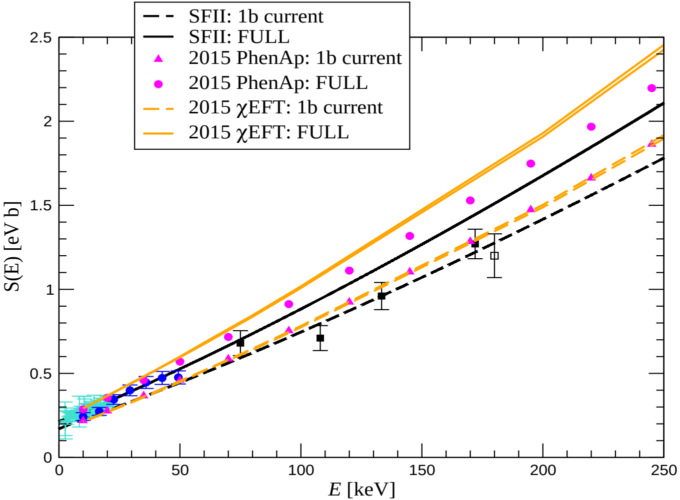
L.E. Marcucci *et al.*, PRL **116**, 102501 (2016)



PRELIMINARY RESULTS
in χEFT

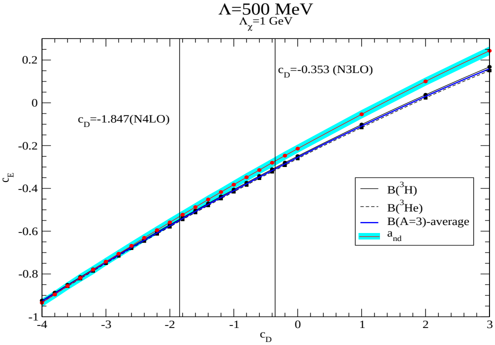


PRELIMINARY RESULTS in χEFT: zoom for $E = 0 - 250$ keV



Outlook: the weak sector in χEFT (I)

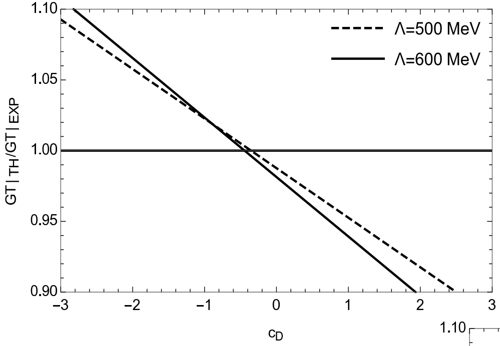
- Weak current up to $\mathcal{O}(Q^1)$ + N3LO(Idaho)/N2LO (local form)
- Fit c_D using $B(A=3)$ and GT_{Exp} (PRELIMINARY – $\Lambda = 500$ MeV)



Fit of GT_{Exp} up to $\mathcal{O}(Q^1)$
$\Rightarrow c_D = -1.847$ & $c_E = -0.548$
$a_{nd} = 0.654$ fm

Fit of GT_{Exp} up to $\mathcal{O}(Q^0)$
$\Rightarrow c_D = -0.353$ & $c_E = -0.305$
$a_{nd} = 0.665$ fm

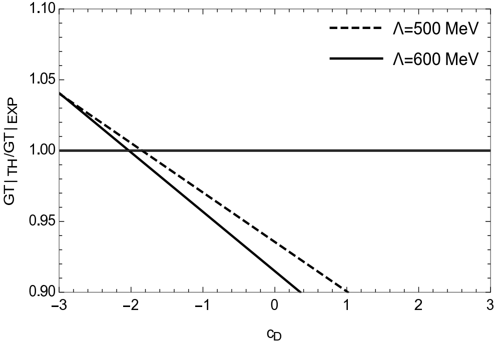
$a_{nd}^{Exp} = 0.645 \pm 0.010$ fm



1.10
1.05
1.00
0.95
0.90
GT|TH/GT|EXP
−3
−2
−1
0
1
2
3
cD
Λ=500 MeV
Λ=600 MeV

N2LO

N3LO



1.10
1.05
1.00
0.95
0.90
GT|TH/GT|EXP
−3
−2
−1
0
1
2
3
cD
Λ=500 MeV
Λ=600 MeV

Outlook: the weak sector in χEFT (II)

Using the χEFT weak current up to $\mathcal{O}(Q^1)$

- μ-capture on deuteron and $^3\mathrm{He}$
- $p + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$ – the *hep* reaction
- ν-scattering on light nuclei $(A = 2 - 4)$
- $\cdots$

Outlook: a new χEFT potential with Δ's

M. Piarulli *et al.*, PRC **91**, 024003 (2015)

- χEFT with Δ's in two-pion exchange up to $\mathcal{O}(Q^3)$ (N3LO)
- minimally non-local / coordinate space (operatorial structure $\sim$ AV18)
- fit to the 2013 Granada database with χ^2/datum ~ 1.3

Steps to be done:

- consistent TNI – work in progress
- fitting procedure of $c_D - c_E$
- EW currents with the same cutoff functions

Consistent χEFT framework

$\Rightarrow$ from few- to less few-nucleon systems