The proton-proton weak capture reaction within chiral effective field theory

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The proton-proton weak capture: where do we stand

$$S(E) = S(0) + S'(0)\,E + \frac{1}{2}S''(0)\,E^2 + \cdots$$

- Gamow peak: $E \simeq 6$ keV in the Sun, $E \simeq 15$ keV in larger stars
- Latest review: SFII: E.G. Adelberger *et al.*, RMP **83**, 195 (2011)

$$\boxed{S(0) = \mathbf{4.01(1 \pm 0.009)} \times 10^{-23}\ \mathbf{MeV\ fm^2}}$$

(PMA[1], χEFT*[2] and $\not\pi$EFT[3] calculations)

$$\boxed{S'(0) = S(0)\ \mathbf{(11.2 \pm 0.1)\ MeV^{-1}}}$$

(only a PMA calculation)

$$\boxed{\textbf{No realistic calculation of } S''(0)}$$

[1] Schiavilla *et al.*, PRC **58**, 1263 (1998)
[2] Park *et al.*, PRC **67**, 055206 (2003)
[3] Chen *et al.*, PRC **67**, 025801 (2003)

Nuclear EW currents in χEFT

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

History

$\mathbf{j}^\gamma$

- Park *et al.* in heavy-baryon χPT (HBχPT) $\rightarrow$ since $\simeq$ 1995
- Pastore *et al.* in time-ordered perturbation theory (TOPT) $\rightarrow$ since 2009
- Kölling *et al.* with the unitary transform method $\rightarrow$ in parallel since 2009

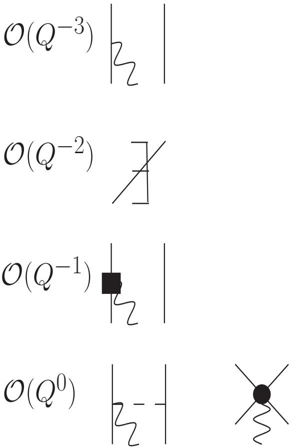
$\mathbf{j}^A$

- Park *et al.* in HBχPT $\rightarrow$ since $\simeq$ 2000
- Baroni *et al.* in TOPT $\rightarrow$ work in progress

To be remarked:

- Park *et al.* currents ready BEFORE the χEFT potentials $\Rightarrow$ "hybrid" χEFT
- Park *et al.*: **only available FULL set**

Power counting for $\mathbf{j}^A$



Note:

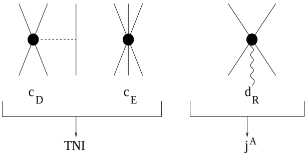
- $\mathcal{O}(Q^1)$: loop and two-pion-exchange contributions (not yet calculated)
- Park *et al.* only available model at $\mathcal{O}(Q^0)$ $\rightarrow$ one LEC - d_R

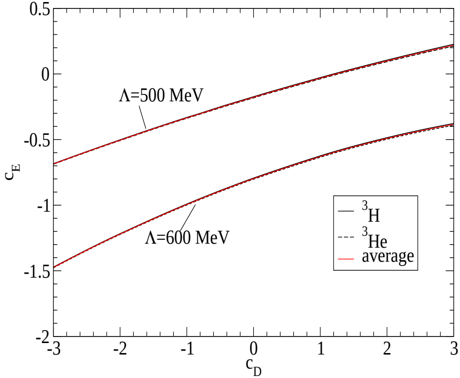
$$\boxed{d_R = \frac{M_N}{\Lambda_\chi g_A} c_D + \frac{1}{3} M_N (c_3 + 2c_4) + \frac{1}{6}}$$

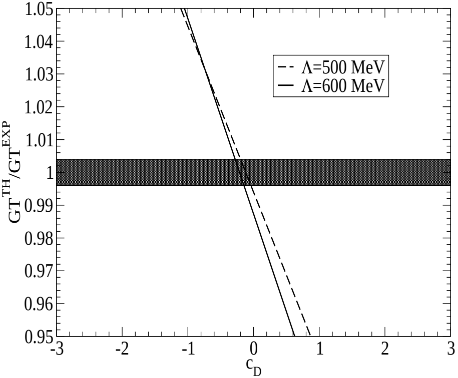
Gårdestig and Phillips, PRL **96**, 232301 (2006)

Gazit *et al.*, PRL **103**, 102502 (2009)

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





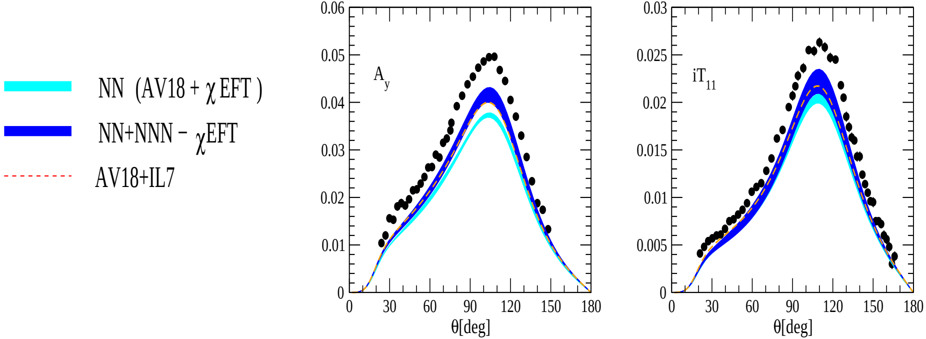


$\Rightarrow \{c_D; c_E\}_{\mathrm{MAX}}$ and $\{c_D; c_E\}_{\mathrm{MIN}}$

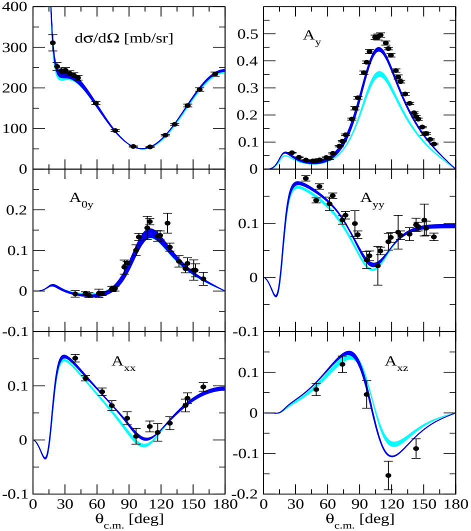
Model	Λ [MeV]	c_D	c_E	B(^{4}He) [MeV]	$^2a_{nd}$ [fm]
N3LO/N2LO*	500	1.0	−0.029	28.36	0.675
N3LO/N2LO	500	−0.12	−0.196	28.49	0.666
N3LO/N2LO	600	−0.26	−0.846	28.64	0.696
Exp.				28.30	0.645(10)

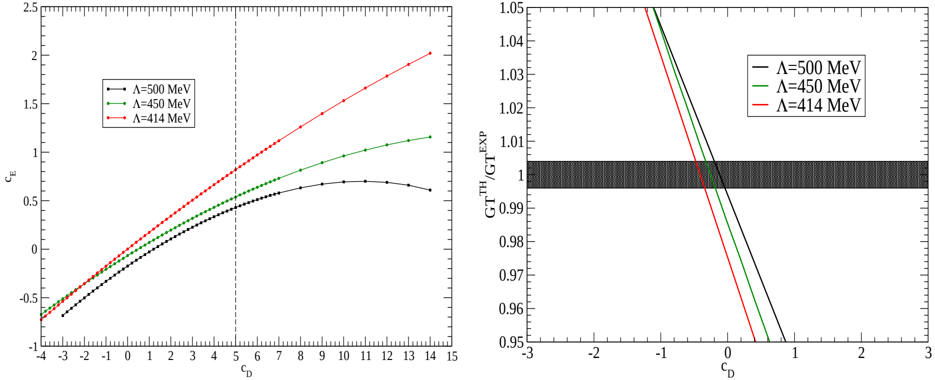
Marcucci *et al.*, PRL **108**, 052502 (2012); Viviani *et al.*, PRL **111**, 172302 (2013)

Elastic $p-d$ scattering $E_{lab} = 3$ MeV



Elastic p—^{3}He scattering $E_p = 5.54$ MeV





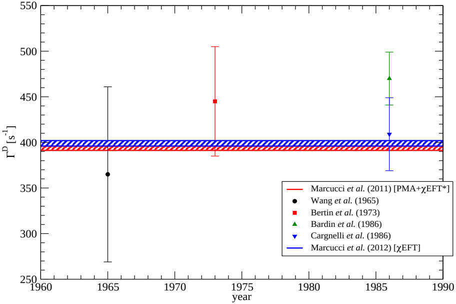
see L. Coraggio's talk

Results: muon capture on $A = 2, 3$ nuclei

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

$$\boldsymbol{\Gamma^D = 399(3)\ \mathrm{s}^{-1}\ \&\ \Gamma_0 = 1494(21)\ \mathrm{s}^{-1}}$$

$$\text{vs. } \Gamma^D(\mathrm{exp}) \cdots \quad \& \ \Gamma_0(\mathrm{exp}) = 1496(4)\ \mathrm{s}^{-1}$$



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

The *pp* reaction

$S(E)$
in χEFT and PMA

- Energy range 2 keV – 100 keV
- PMA [AV18] or χEFT [N3LO] + FULL EM interaction
- *pp* $L \leq 1$ partial waves: ${}^1S_0$ + all P-waves

$S(0) - {}^1S_0$
(in 10^{-23} MeV fm^2)

	$V_{nucl} + V_{Coul}$	$V_{nucl} + V_{EM}$
PMA-IA	3.99	3.96
PMA-FULL	4.03	4.00
χEFT(500)-IA	3.96	3.94
χEFT(500)-FULL	4.03	4.01
χEFT(600)-IA	3.94	3.93
χEFT(600)-FULL	4.01	4.01

- agreement with $S^{\mathrm{SFII}}(0) = 4.01(1 \pm 0.009)$
- V_{EM}-V_{Coul} $\rightarrow$ $\leq$1 % effect
- agreement PMA-χEFT
- very small cutoff dependence ($\leq$1 %)

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

Cumulative contributions to $S(0)$

	${}^1S_0$	$\cdots + {}^3P_0$	$\cdots + {}^3P_1$	$\cdots + {}^3P_2$
PMA	4.000(3)	4.003(3)	4.015(3)	4.033(3)
χEFT(500)	4.008(5)	4.011(5)	4.020(5)	4.030(5)
χEFT(600)	4.007(5)	4.010(5)	4.019(5)	4.029(5)

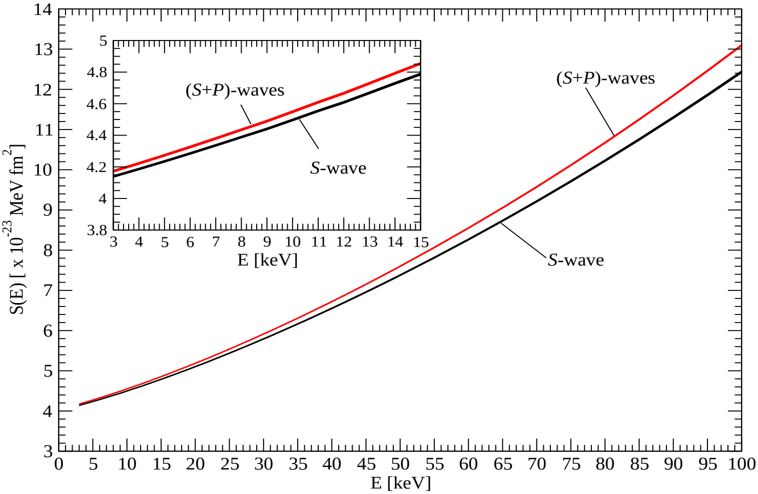
- P-waves contribution to $S(0) \simeq 1$ %
- theoretical uncertainty very small

$$\boxed{S(0)=\mathbf{4.03(1 \pm 0.006)} \times 10^{-23}\ \mathbf{MeV\ fm^2}}$$

vs.

$$S(0)^{\rm SFII}=4.01(1 \pm 0.009) \times 10^{-23}\ \mathrm{MeV\ fm^2}$$

Energy dependence of $S(E)$



Polynomial fit of $S(E)$

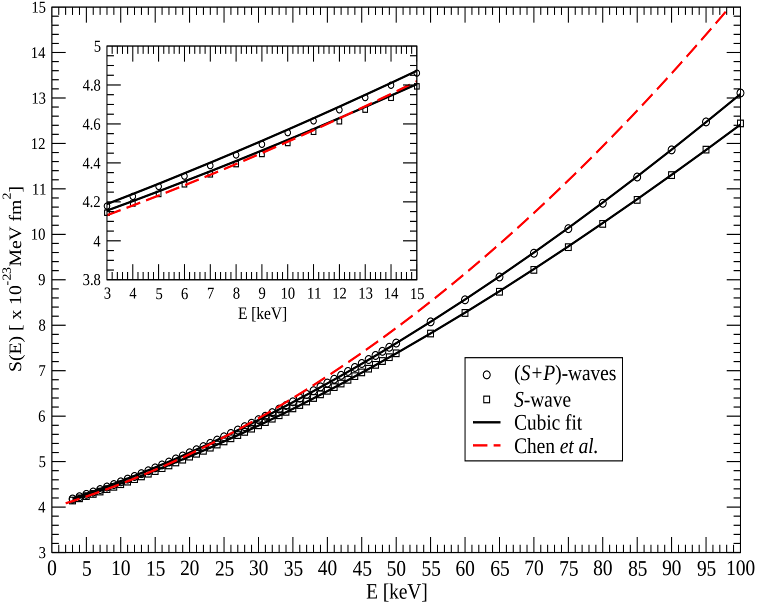
$$\text{Fit 1} \quad \rightarrow \quad S(E) = S(0) + S'(0)\,E + \frac{1}{2}S''(0)\,E^2$$

$$\text{Fit 2} \quad \rightarrow \quad S(E) = S(0) + S'(0)\,E + \frac{1}{2}S''(0)\,E^2 + \frac{1}{6}S'''(0)\,E^3$$

	$S'(0)/S(0)$ [MeV^{-1}]	$S''(0)/S(0)$ [MeV^{-2}]	$S'''(0)/S(0)$ [MeV^{-3}]	$\chi^2 = \sum_i (1 - f_i^{fit}/f_i^{calc})^2$
$S+P$ - Fit 1	12.59(1)	199.3(1)		8.8×10^{-4}
$S+P$ - Fit 2	11.94(1)	248.8(2)	–1183(8)	1.9×10^{-4}
$^1S_0$ - Fit 1	12.23(1)	178.4(3)		1.2×10^{-3}
$^1S_0$ - Fit 2	11.42(1)	239.6(5)	–1464(5)	1.9×10^{-4}
$^1S_0$ - $\not\pi$EFT[1]	11.3(1)	170(2)		3.4×10^{-1}

$S'(0)/S(0)^{\mathrm{SFII}} = (11.2 \pm 0.1)$ MeV^{-1}

[1] Chen *et al.*, PLB **720**, 385 (2013)



(S+P)-waves
S-wave
Cubic fit
Chen et al.
S(E) [x 10^-23 MeV fm^2]
E [keV]

Outlook

Near future

- $p + d \rightarrow {}^3\mathrm{He} + \gamma$
- $p + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$
- $\mu^- + {}^3\mathrm{He} \rightarrow n + d + \nu_\mu$

Less near future

- $A = 3$ full breakup $\rightarrow$ other reactions ($\mu^- + {}^3\mathrm{He} \rightarrow n + n + p + \nu_\mu$)
- Other $A = 4$ reactions
- $A > 4$ systems