Low energy electroweak interaction processes in A=2, 3 nuclei in pionless EFT

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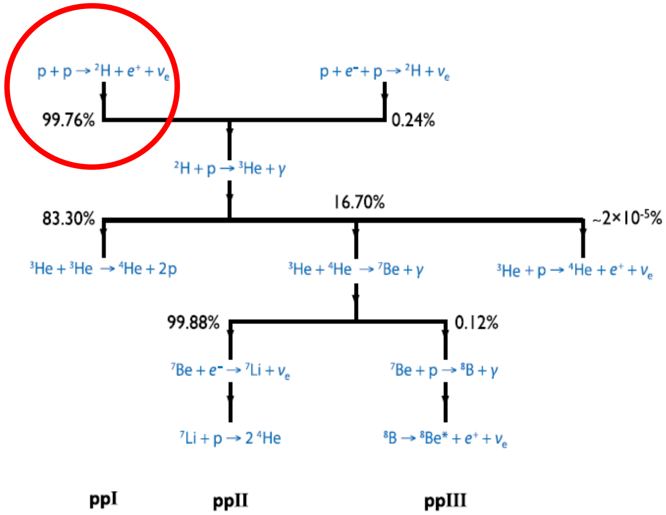
pp Fusion

- Low energy electroweak interactions in light nuclear systems (d, ^{3}H, ^{3}He) take part in many scenarios such as Big Bang nucleosynthesis and evolution of the Sun
- The energy generated in the Sun comes from an exothermic set of reactions, *pp* chain:

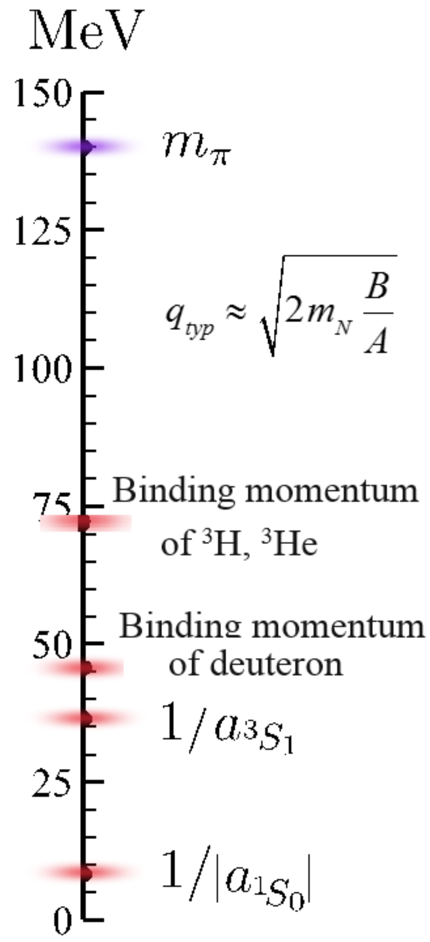
$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_\mathrm{e}.$$



- The leading reaction (~99%) is *pp* fusion: $p + p \rightarrow d + e^+ + \nu_\mathrm{e}$
- This reaction is the slowest reaction in the whole chain ($\tau \sim 109$ years) and therefore it determines the Sun's lifetime.
- Measurement of its cross section is impossible, so it must be calculated from the fundamental theory of physics.

Effective Field Theory

- The fundamental theory is Quantum Chromo-Dynamics (QCD), non-perturbative in the low energy regime.
- Simple theory for describing a few-nucleon system at low energies exists - Effective Field Theory.
- For low energies ($q < \Lambda_{cut} = m_\pi$), pion can be integrate out and only nucleons are left as effective degrees of freedom.
- **QCD → EFT($\cancel{\pi}$)**
- $\mathcal{L}_{\text{effective}} = \underbrace{\mathcal{O}(1)}_{LO} + \underbrace{\mathcal{O}\left(\frac{q}{\Lambda_{cut}}, \frac{r}{a}\right)}_{NLO} + \cdots +$
- Calculation of $\langle\mu_{^3\mathrm{H}}\rangle$, $\langle\mu_{^3\mathrm{He}}\rangle$ in EFT($\cancel{\pi}$) as well as a prediction for pp fusion rate.



Electroweak interaction in EFT($\not\pi$)

	EM	Weak
1-body LEC	κ_n, κ_p	g_A
1-body operator	$\sigma, \sigma\tau^0$	$\tau^{+,-}, \sigma\tau^{+,-},$
2-body operator	$L_1 s^\dagger d, L_2 d^\dagger d$	$L_{1A} s^\dagger d$
$A = 2, q \approx 0$ obs.	$\sigma_{np}, \langle \mu_d \rangle$	Λ_{pp}
$A = 3, q \approx 0$ obs.	$\langle \mu_{3H} \rangle, \langle \mu_{3He} \rangle$	^{3}H β decay

- There are four well measured EM obs. and two unknown 2-body LECs
- A successful prediction of EM in EFT($\not\pi$) will indicate its ability to predict Λ_{pp}.
- For the first time we use $A = 3$ EM obs. to fix L_1, L_2 and to predict $A = 2$ obs.
- Same the weak interaction: use ^{3}H β decay to predict Λ_{pp}.

Numerical Results

EM:

	$\langle\mu_{^3\mathrm{H}}\rangle$	$\langle\mu_{^3\mathrm{He}}\rangle$	σ_{np}	$\langle\mu_d\rangle$
LO	3.088	−2.45	298.2	0.8798
LO, Z_d	3.1	-2.4	298.2	0.8798
Full NLO	2.980	-2.127	338.8	0.8592
Full NLO, Z_d	2.93	−2.150	347.8	0.8547
Δ Z_d	2%	1%	3%	1%
Exp data	2.9789	−2.12762	334.2 ± 0.5	0.8574
Δ Exp	≲ 1%	≲ 1%	≲ 4%	≲ 0.3%

LECs was calibrated from A=2

LECs was calibrated from A=3

$$Z_d = \underbrace{1}_{\mathrm{LO}} + \underbrace{\gamma_t\rho_t}_{\mathrm{NLO}} + \underbrace{(\gamma_t\rho_t)^2}_{\mathrm{N^2LO}}$$

$$Z_d = \underbrace{1}_{\mathrm{LO}} + \underbrace{Z_d - 1}_{\mathrm{NLO}} + \underbrace{0}_{\mathrm{N^2LO}} + \ldots$$

Weak:

We compare to Marcucci et al, pure Coulomb χEFT S-calculation, with the same ^{3}H decay rate & g_A values and the same $\langle F\rangle$ value.

$S_{pp}^{\chi EFT}(^3\mathrm{S}_1, \text{pure Coulomb})$	$4.02 \pm 0.01 \cdot 10^{-23}\mathrm{MeV} \cdot fm^2$
$S_{pp}^{EFT(\cancel{\pi})}(0)$	$3.90 \cdot 10^{-23}\mathrm{MeV} \cdot fm^2$
$S_{pp}^{EFT(\cancel{\pi})}(0), Z_d$	$4.16 \cdot 10^{-23}\mathrm{MeV} \cdot fm^2$

H. D and D. Gazit. In preparation, . H-W. Grießhamme 2004 , L.E. Marcucci et al 2013

Summery

- EFT($\not\pi$) consistently predict $A = 2,3$ EM $q \approx 0$ observables up to NLO with $\mathcal{O}(1\%)$ accuaracy
- We determine the pp fusion rate with reliable uncertainty estimate.
- Our prediction:

$S_{pp}^{EFT(\not\pi)}(0)_{g_A=1.2695}$	$4.02 \pm_{theo(range)} 0.14 \pm_{g_A(1\sigma)} 0.07 \pm_{^3\mathrm{H}(1\sigma)} 0.04 \cdot 10^{-23}\mathrm{MeV} \cdot fm^2$
$S_{pp}^{EFT(\not\pi)}(0)_{g_A=1.275}$	$4.16 \pm_{theo(range)} 0.14 \pm_{g_A(1\sigma)} 0.07 \pm_{^3\mathrm{H}(1\sigma)} 0.04 \cdot 10^{-23}\mathrm{MeV} \cdot fm^2$

- Better determination of g_A and ^{3}H half-life are needed to reduce the error-bar.
- N^{2}LO can reduce the theoretical uncertainty significantly, to less then 1%.