Parity violation in radiative neutron capture on deuteron

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Chiral Dynamics 12,
Jefferson Lab
Aug 06-10,2012

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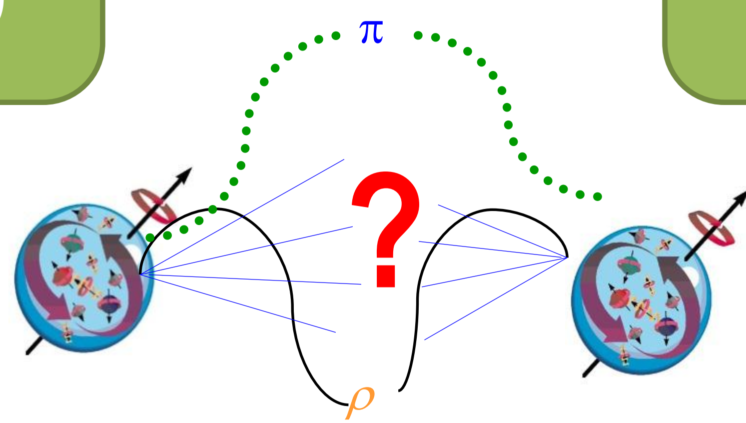
Introduction

- Direct application of standard model to (non-leptonic) hadronic parity violation is difficult.

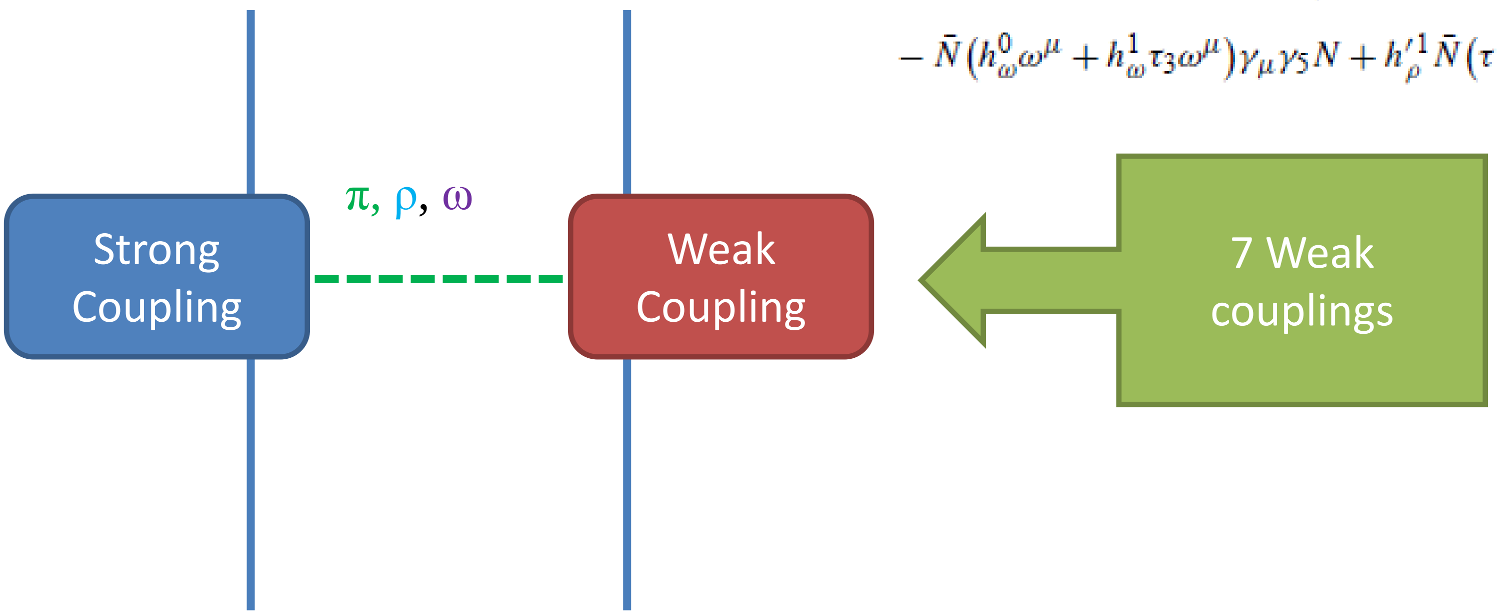
Standard Model (Quarks, Gluons, Weak bosons) → Hadronic Theory (Nucleons, Mesons)



DDH model

- Traditional approach : DDH (Desplanques, Donoghue, Holstein) model with meson exchange

$$
\begin{aligned}
\mathcal{H}_{\rm wk} = & \frac{h^1_{\pi NN}}{\sqrt{2}} \bar{N}(\tau \times \pi)_3 N \\
& - \bar{N}\left(h^0_\rho \tau \cdot \rho^\mu + h^1_\rho \rho^\mu_3 + \frac{h^2_\rho}{2\sqrt{6}}(3\tau_3\rho^\mu_3 - \tau \cdot \rho^\mu)\right)\gamma_\mu\gamma_5 N \\
& - \bar{N}(h^0_\omega \omega^\mu + h^1_\omega \tau_3 \omega^\mu)\gamma_\mu\gamma_5 N + h'^1_\rho \bar{N}(\tau \times \rho^\mu)_3 \frac{\sigma_{\mu\nu}k^\nu}{2m_N}\gamma_5 N .
\end{aligned}
$$



DDH model

- Experimental Constraints on couplings show inconsistency

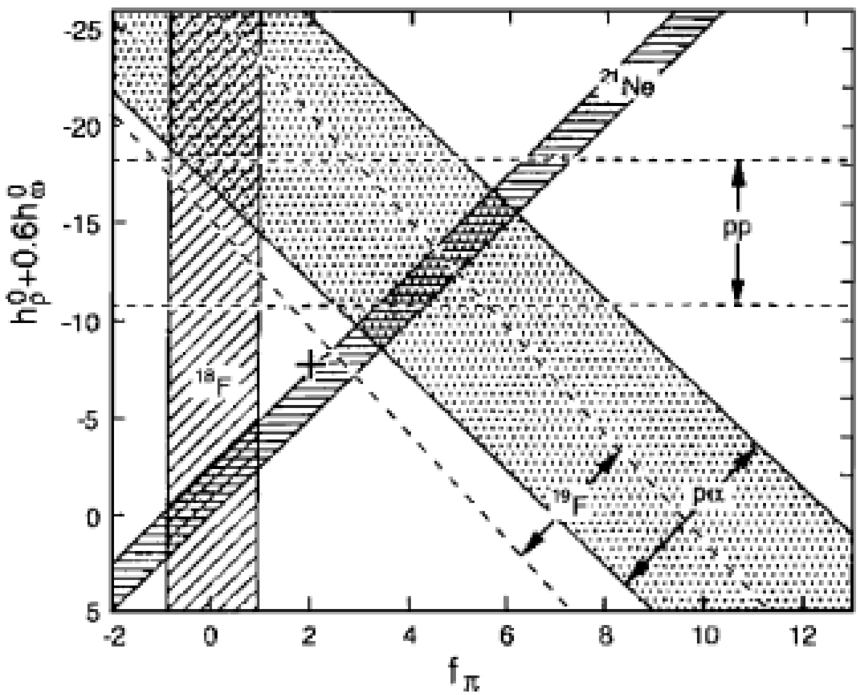


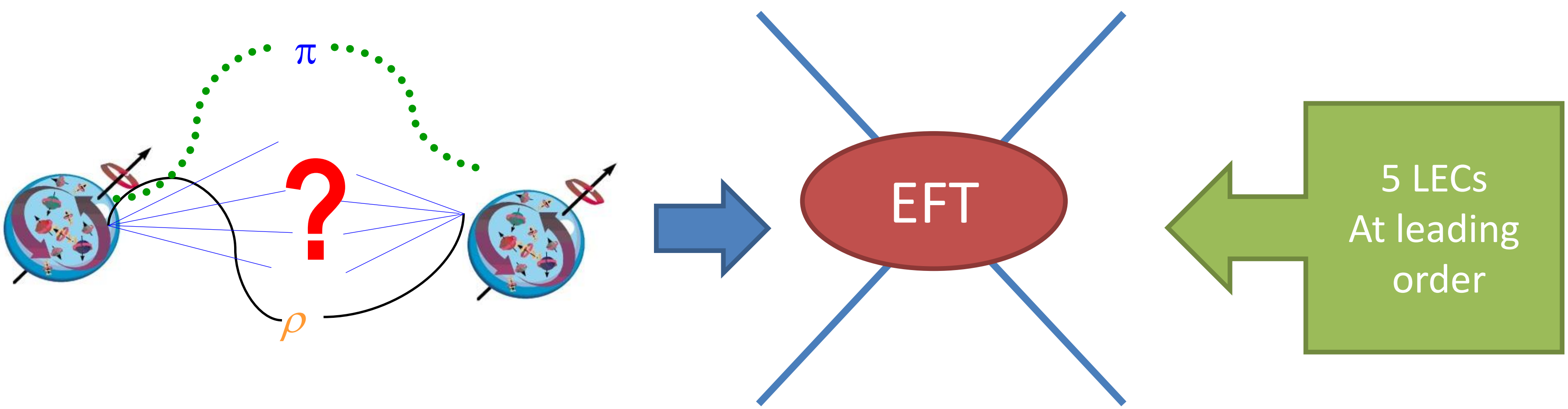
Fig. 2. Restrictions on weak parity-violating pion and isoscalar vector meson couplings (in units of 3.8×10^{-7}) which arise from various particle and nuclear experiments.

Holstein,
Eur.Phys.J.A 32,505
(2007)

Few body system
Would remove
nuclear uncertainty

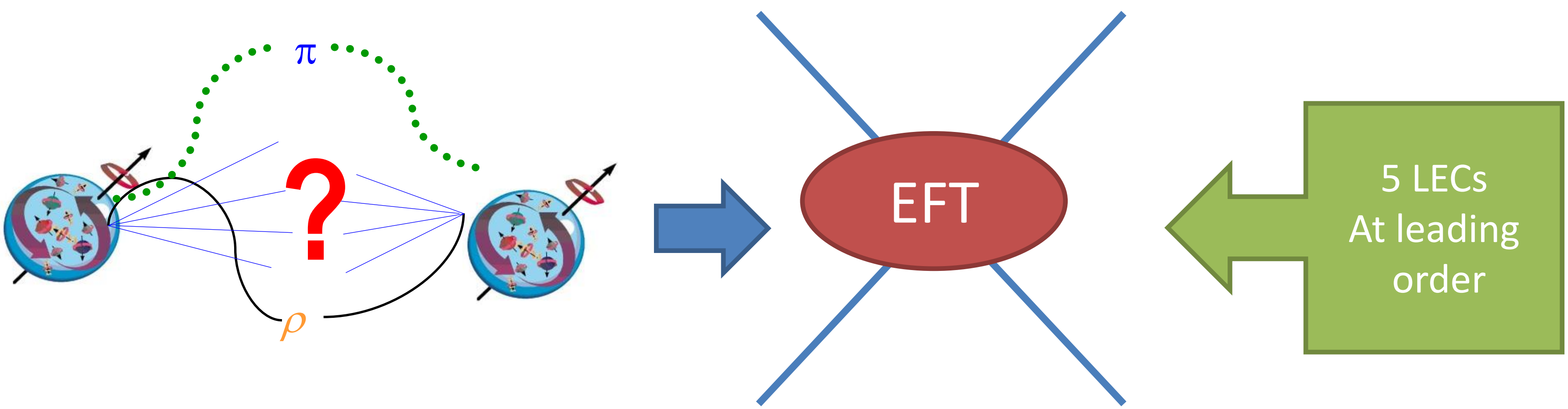
EFT approach

- At Low energy, short range details can not be seen.
- Hide all details into several Low energy Constants and keep symmetry.
- -> Effective Field Theory : Most General Low energy theory



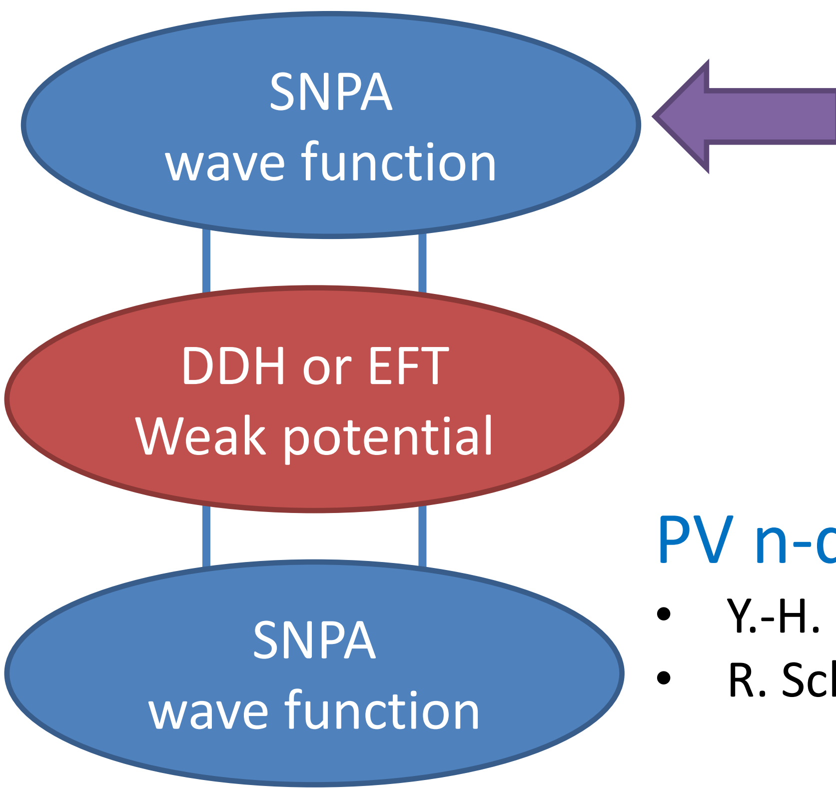
EFT approach

- Fixing all 5 LECs from two-body experiment
  is not feasible at this moment
  (n-p scattering, n-n scattering, n-p capture, …)
- Need 3-body systems. : n-d scattering ,n-d capture



Hybrid Method

- Introduce Weak Potential derived from EFT
- Standard Nuclear Physics Approach: Wave functions of nucleons from highly accurate potential models (AV18+UIX)
- DDH and EFT can be treated in the same formalism.



Model	$^2a_{nd}$ [fm]	B (^3H) [MeV]
Av18	1.266	7.623
Av18+UIX	0.598	8.483
Exp.	0.65(4)	8.482

PV n-d Scattering in hybrid method

- Y.-H. Song, et..al. Phys. Rev. C 83, 015501 (2011)
- R. Schiavilla, et.al. , Phys. Rev. C 78, 014002 (2008).

PV potential

- Consider three Parity Violating NN potential model
  - DDH model
  - Pionless EFT(EFT without explicit pion)
  - Pionful EFT(EFT with explicit pion)
- All PV Potential model can be written in compact way

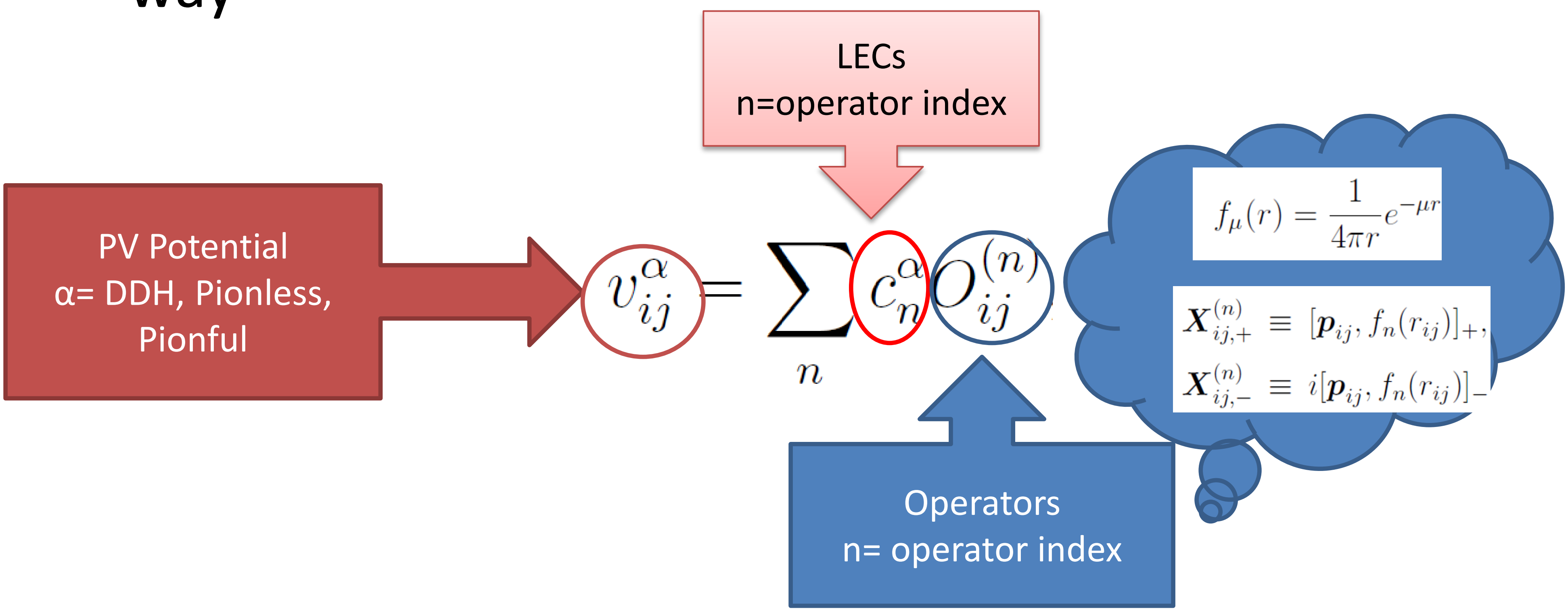
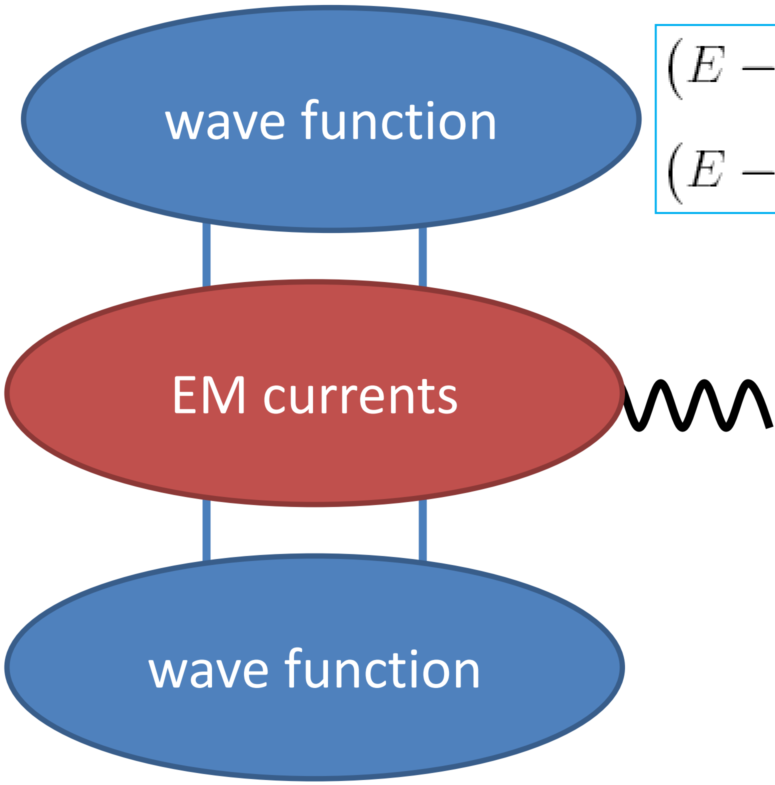


TABLE I: Parameters and operators of parity violating potentials. $g_A = 1.26$, $F_\pi = 92.4$ MeV. $\mathcal{T}_{ij} \equiv (3\tau_i^z\tau_j^z - \tau_i\cdot\tau_j)$. Scalar function $\tilde{L}_\Lambda(r) \equiv 3L_\Lambda(r) - H_\Lambda(r)$.

n	c_n^{DDH}	$f_n^{DDH}(r)$	$c_n^{\not\pi}$	$f_n^{\not\pi}(r)$	c_n^{π}	$f_n^{\pi}(r)$	$O_{ij}^{(n)}$
1	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$-\frac{\mu^2 C_6^{\not\pi}}{\Lambda_\chi^3}$	$f_\mu^{\not\pi}(r)$	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\Lambda^\pi(r)$	$(\tau_i\times\tau_j)^z(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,-}^{(1)}$
2	$-\frac{g_\rho}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i\cdot\tau_j)(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,+}^{(2)}$
3	$-\frac{g_\rho(1+\kappa_\rho)}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i\cdot\tau_j)(\boldsymbol{\sigma}_i\times\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,-}^{(3)}$
4	$-\frac{g_\rho}{2m_N}h_\rho^1$	$f_\rho(r)$	$\frac{\mu^2}{\Lambda_\chi^3}(C_2^{\not\pi}+C_4^{\not\pi})$	$f_\mu^{\not\pi}(r)$	$\frac{\Lambda^2}{\Lambda_\chi^3}(C_2^\pi+C_4^\pi)$	$f_\Lambda(r)$	$(\tau_i+\tau_j)^z(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,+}^{(4)}$
5	$-\frac{g_\rho(1+\kappa_\rho)}{2m_N}h_\rho^1$	$f_\rho(r)$	0	0	$\frac{2\sqrt{2}\pi g_A^3\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$L_\Lambda^\pi(r)$	$(\tau_i+\tau_j)^z(\boldsymbol{\sigma}_i\times\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,-}^{(5)}$
6	$-\frac{g_\rho}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	$-\frac{2\mu^2}{\Lambda_\chi^3}C_5^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$-\frac{2\Lambda^2}{\Lambda_\chi^3}C_5^\pi$	$f_\Lambda(r)$	$\mathcal{T}_{ij}(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,+}^{(6)}$
7	$-\frac{g_\rho(1+\kappa_\rho)}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	0	0	0	0	$\mathcal{T}_{ij}(\boldsymbol{\sigma}_i\times\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,-}^{(7)}$
8	$-\frac{g_\omega}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}C_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^3}C_1^\pi$	$f_\Lambda(r)$	$(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,+}^{(8)}$
9	$-\frac{g_\omega(1+\kappa_\omega)}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}\tilde{C}_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^3}\tilde{C}_1^\pi$	$f_\Lambda(r)$	$(\boldsymbol{\sigma}_i\times\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,-}^{(9)}$
10	$-\frac{g_\omega}{2m_N}h_\omega^1$	$f_\omega(r)$	0	0	0	0	$(\tau_i+\tau_j)^z(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,+}^{(10)}$
11	$-\frac{g_\omega(1+\kappa_\omega)}{2m_N}h_\omega^1$	$f_\omega(r)$	0	0	0	0	$(\tau_i+\tau_j)^z(\boldsymbol{\sigma}_i\times\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,-}^{(11)}$
12	$-\frac{g_\omega h_\omega^1-g_\rho h_\rho^1}{2m_N}$	$f_\rho(r)$	0	0	0	0	$(\tau_i-\tau_j)^z(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,+}^{(12)}$
13	$-\frac{g_\rho}{2m_N}h_\rho^{\prime 1}$	$f_\rho(r)$	0	0	$-\frac{\sqrt{2}\pi g_A\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$L_\Lambda^\pi(r)$	$(\tau_i\times\tau_j)^z(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,-}^{(13)}$
14	0	0	0	0	$\frac{2\Lambda^2}{\Lambda_\chi^3}C_6^\pi$	$f_\Lambda(r)$	$(\tau_i\times\tau_j)^z(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\cdot\boldsymbol{X}_{ij,-}^{(14)}$

Hybrid Method for n-d capture



wave function: Solution of Faddeev eq.

$$\left(E - H_0 - V_{ij}^{PC}\right)\psi_k^{+} = V_{ij}^{PC}(\psi_i^{+} + \psi_j^{+}),$$

$$\left(E - H_0 - V_{ij}^{PC}\right)\psi_k^{-} = V_{ij}^{PC}(\psi_i^{-} + \psi_j^{-}) + V_{ij}^{PV}(\psi_i^{+} + \psi_j^{+} + \psi_k^{+})$$

EM multipoles

$$X1_J \equiv \langle -\boldsymbol{q}, J_B || \hat{T}_1^X || J \rangle, \quad \text{with } X = (M, E),$$

$$M1_J = i\frac{\omega\mu_N}{\sqrt{6\pi}\sqrt{4\pi}}\widetilde{\mathcal{M}}_J, \quad E1_J = -i\frac{\omega}{\sqrt{6\pi}}\widetilde{\mathcal{E}}_J,$$

NLO Parity violating EM charge operator
Is not considered in this work

This is not a rigorous EFT calculation.
Model dependence have to be checked.

PV Observables

$$a_n^\gamma(E) = \frac{2}{3}\frac{\mathrm{Re}\left[\sqrt{2}(E1^*_{\frac{3}{2}}M1_{\frac{1}{2}} + E1^*_{\frac{1}{2}}M1_{\frac{3}{2}}) + \frac{5}{2}(E1^*_{\frac{3}{2}}M1_{\frac{3}{2}}) - (E1^{*,(+)}_{\frac{1}{2}}M1_{\frac{1}{2}})\right]}{|M1_{\frac{1}{2}}|^2 + |M1_{\frac{3}{2}}|^2},$$

$$P^\gamma(E) = \frac{2\mathrm{Re}\left[E1^*_{\frac{1}{2}}M1_{\frac{1}{2}} + E1^*_{\frac{3}{2}}M1_{\frac{3}{2}}\right]}{|M1_{\frac{1}{2}}|^2 + |M1_{\frac{3}{2}}|^2},$$

$$A_d^\gamma(E) = -\frac{\mathrm{Re}\left[-5E1^*_{\frac{3}{2}}M1_{\frac{3}{2}} - 4E1^*_{\frac{1}{2}}M1_{\frac{1}{2}} + \sqrt{2}E1^*_{\frac{3}{2}}M1_{\frac{1}{2}} + \sqrt{2}E1^*_{\frac{1}{2}}M1_{\frac{3}{2}}\right]}{2(|M1_{\frac{1}{2}}|^2 + |M1_{\frac{3}{2}}|^2)}.$$

$$\widetilde{\mathcal{E}}_J = \sum_n c_n \widetilde{\mathcal{E}}_J^{(n)};$$

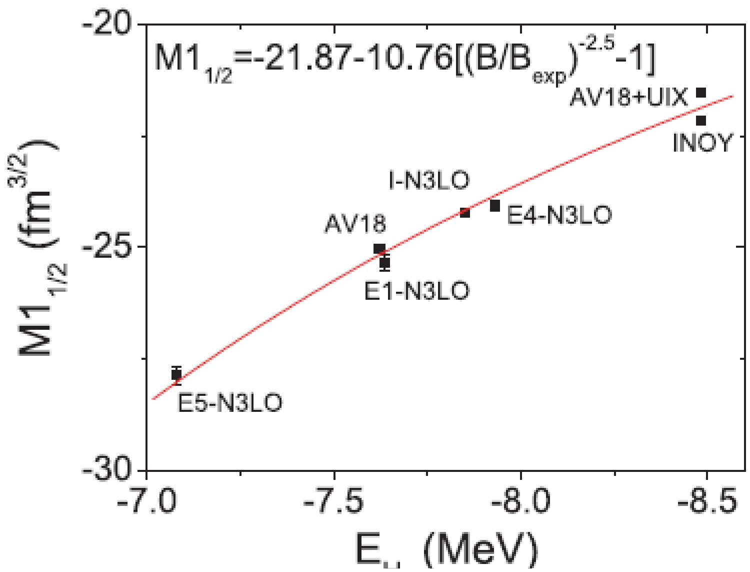
PV couplings (LECs)

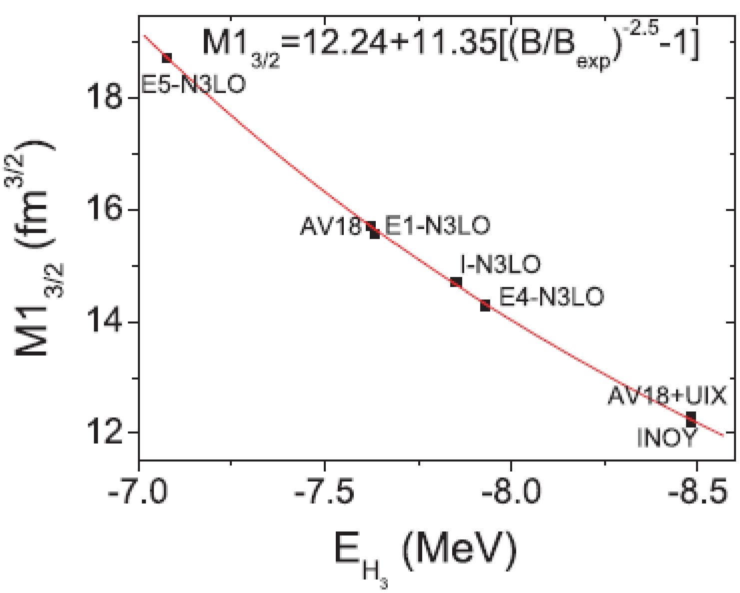
$$X = \sum \left(\frac{c_m}{\mu_N}\right) X^{(m)},$$

$$E1_J = \langle J_B || \frac{q}{\sqrt{6\pi}} \sum_i Q_i r_i || J \rangle = (-i) \sum_n \frac{\omega}{\sqrt{6\pi}} c_n \widetilde{\mathcal{E}}_J^{(n)};$$

Hybrid Method for n-d capture

- M1 amplitudes from Hybrid method





EM currents operator from EFT up to two-pion exchange order

Y.-H. Song , R. Lazauskas, and T.-S. Park, PHYS. REV. C **79**, 064002 (2009)

Correlation between M1 amplitudes
And 3H binding energy

$$\widetilde{\mathcal{M}}_{\frac{1}{2}} = +21.87 + 10.76[(B_{model}/B_{exp})^{-2.5} - 1]\ \mathrm{fm}^{\frac{3}{2}}$$

$$\widetilde{\mathcal{M}}_{\frac{3}{2}} = -12.24 - 11.35[(B_{model}/B_{exp})^{-2.5} - 1]\ \mathrm{fm}^{\frac{3}{2}}$$

$$\sigma = 0.49(1)mb$$

Results

- DDH potential case

TABLE III: Parity violating amplitudes $\widetilde{\mathcal{E}}_{J,(P)}$ in $\text{fm}^{\frac{3}{2}}$ units, where (P) stands for the parity of the scattering wave, calculated with AV18+UIX strong and DDH-II weak potentials.

n	$\widetilde{\mathcal{E}}_{\frac{1}{2},(+)}$	$\widetilde{\mathcal{E}}_{\frac{1}{2},(-)}$	$\widetilde{\mathcal{E}}_{\frac{3}{2},(+)}$	$\widetilde{\mathcal{E}}_{\frac{3}{2},(-)}$
1	-3.37×10^{-1}	-3.75×10^{-2}	-1.44×10^{-2}	-2.97×10^{-1}
2	-2.64×10^{-3}	-1.52×10^{-2}	-5.37×10^{-3}	-2.52×10^{-2}
3	-9.72×10^{-3}	3.12×10^{-2}	-1.35×10^{-2}	1.31×10^{-2}
4	1.03×10^{-2}	-1.32×10^{-2}	1.47×10^{-2}	-2.87×10^{-3}
5	1.26×10^{-2}	-1.56×10^{-2}	1.75×10^{-2}	-3.79×10^{-3}
6	-2.03×10^{-3}	-8.85×10^{-3}	-1.85×10^{-3}	1.51×10^{-3}
7	-2.42×10^{-3}	-9.62×10^{-3}	-2.45×10^{-3}	1.94×10^{-3}
8	-7.37×10^{-3}	2.43×10^{-2}	-1.08×10^{-2}	9.51×10^{-3}
9	-7.10×10^{-3}	1.24×10^{-2}	-1.05×10^{-2}	-2.14×10^{-3}
10	9.79×10^{-3}	-1.25×10^{-2}	1.39×10^{-2}	-2.71×10^{-3}
11	1.20×10^{-2}	-1.48×10^{-2}	1.67×10^{-2}	-3.61×10^{-3}
12	-2.75×10^{-3}	9.29×10^{-3}	-4.10×10^{-4}	-9.10×10^{-3}
13	-3.05×10^{-3}	1.84×10^{-2}	-1.96×10^{-3}	-1.53×10^{-2}

Results

- DDH potential case(AV18+UIX, DDH)

$$
\begin{aligned}
a_n &= 0.42h_\pi^1 - 0.17h_\rho^0 + 0.085h_\rho^1 + 0.008h_\rho^2 - 0.238h_\omega^0 + 0.086h_\omega^1 - 0.010h_\rho'^1 = 4.11\times 10^{-7} \\
P_\gamma &= -1.05h_\pi^1 + 0.19h_\rho^0 - 0.096h_\rho^1 - 0.018h_\rho^2 + 0.28h_\omega^0 - 0.046h_\omega^1 + 0.023h_\rho'^1 = -7.31\times 10^{-7} \\
A_d^\gamma &= -1.51h_\pi^1 + 0.17h_\rho^0 - 0.083h_\rho^1 - 0.024h_\rho^2 + 0.024h_\omega^0 + 0.013h_\omega^1 + 0.032h_\rho'^1 = -9.05\times 10^{-7}.
\end{aligned}
$$

TABLE IV: The DDH PV coupling constants in units of 10^{-7} (h'_ρ contribution is neglected). Strong interactions parameters are $\frac{g_\pi^2}{4\pi} = 13.9$, $\frac{g_\rho^2}{4\pi} = 0.84$, $\frac{g_\omega^2}{4\pi} = 20$, $\kappa_\rho = 3.7$, and $\kappa_\omega = 0$.

DDH Coupling	DDH 'best'	4-parameter fit[?]
h_π^1	$+4.56$	-0.456
h_ρ^0	-11.4	-43.3
h_ρ^2	-9.5	37.1
h_ω^0	-1.9	13.7
h_ρ^1	-0.19	-0.19
h_ω^1	-1.14	-1.14

Results

- DDH potential case

TABLE V: Parity violating observables for different potential models with the DDH-best parameter values and Bowman's 4-parameter fits in 10^{-7} units.

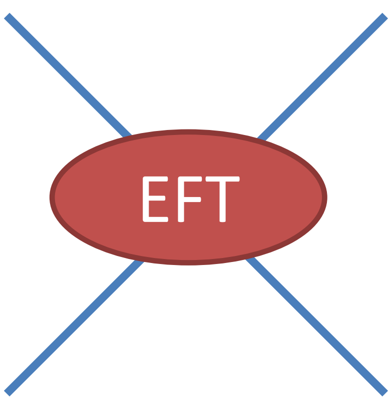
	DDH-best values			4-parameter fits		
models	a_n	P_γ	A_d	a_n	P_γ	A_d
AV18+UIX/DDH-I	3.30	−6.38	−8.23	1.97	−2.16	−1.81
AV18/DDH-II	4.61	−8.30	−10.3	4.60	−5.18	−4.46
AV18+UIX/DDH-II	4.11	−7.30	−9.04	4.14	−4.71	−4.09
Reid/DDH-II	4.74	−8.45	−10.4	4.70	−5.25	−4.46
NijmII/DDH-II	4.71	−8.45	−10.5	4.76	−5.26	−4.41
INOY/DDH-II	9.24	−12.9	−13.8	17.5	−17.9	−13.5

Results

- Pionless EFT case

TABLE VIII: Parity violating observables for AV18+UIX strong potential for $\not\pi EFT$-I at $\mu = 138$ MeV. The results are in fm^{-2} units.

n	$\frac{c_n}{\mu_N \mu^2}$	$\mu^2 a_n^{(n)}$	$\mu^2 P_\gamma^{(n)}$	$\mu^2 A_d^{(n)}$
1	$\frac{4m_N}{\Lambda_\chi^3} C_6^{\not\pi}$	2.17×10^{-2}	-5.52×10^{-2}	-7.93×10^{-2}
4	$\frac{2m_N}{\Lambda_\chi^3} (C_2^{\not\pi} + C_4^{\not\pi})$	-7.94×10^{-2}	6.55×10^{-2}	3.16×10^{-2}
6	$-\frac{2}{\Lambda_\chi^3} C_r^{\not\pi}$	-2.81×10^{-2}	5.96×10^{-2}	8.01×10^{-2}
8	$-\frac{4m_N}{\Lambda_\chi^3} C_1^{\not\pi}$	1.04×10^{-1}	-1.03×10^{-1}	-7.58×10^{-2}
9	$\frac{4m_N}{\Lambda_\chi^3} \tilde{C}_1^{\not\pi}$	3.81×10^{-2}	-4.29×10^{-2}	-3.67×10^{-2}

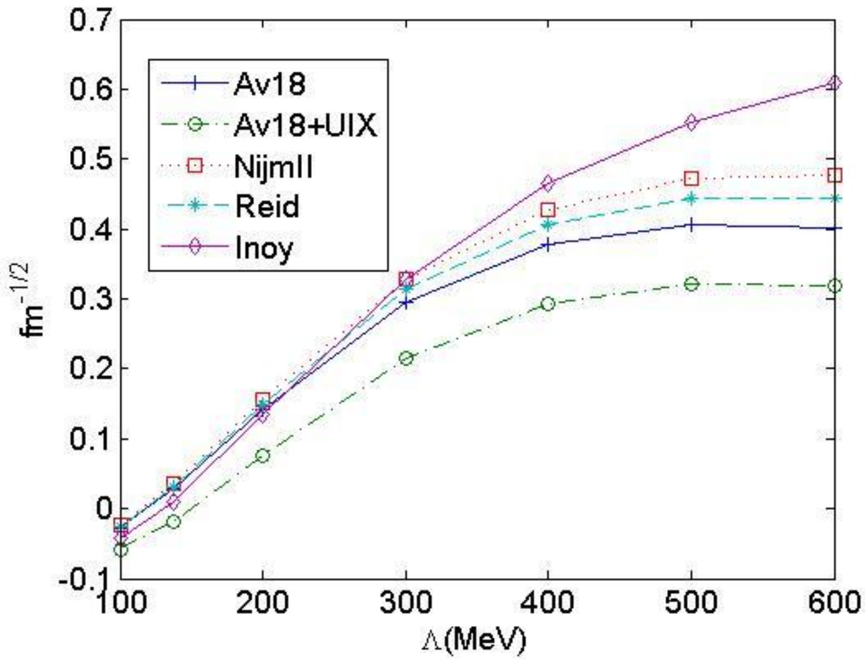


5 LECs
At leading order

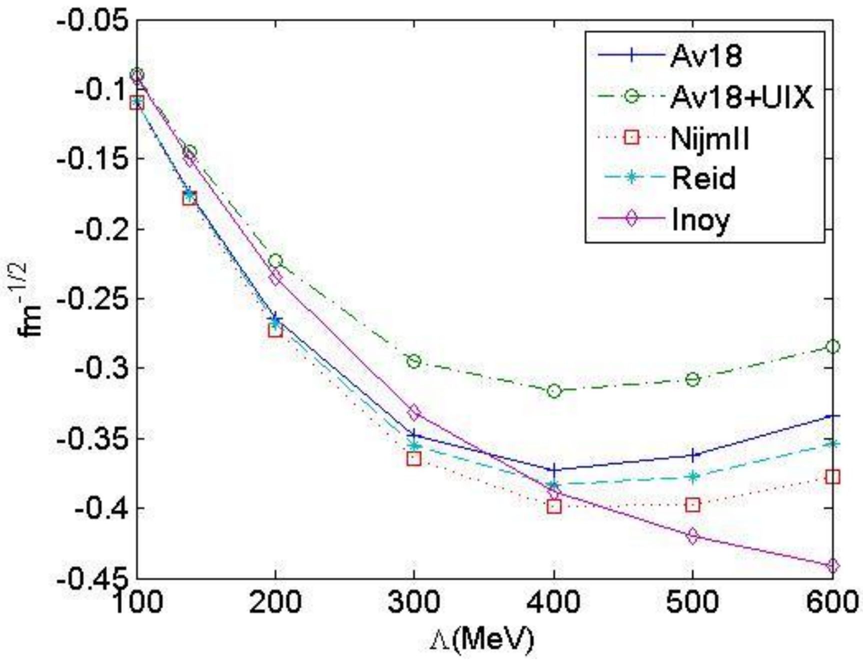
$$f_\mu(r) = \frac{1}{4\pi r} e^{-\mu r} \Leftrightarrow \frac{1}{\Lambda^2} \delta_\Lambda(r)$$

Results: cutoff and model

- DDH and Pionless EFT



J=1/2 , PV scattering wave, op1

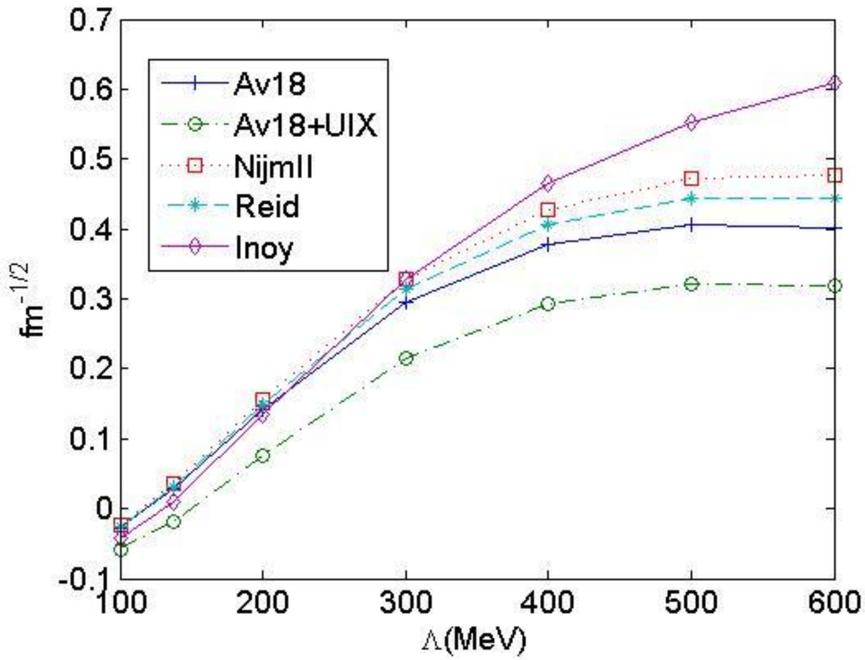


J=3/2, PV scattering wave,op9

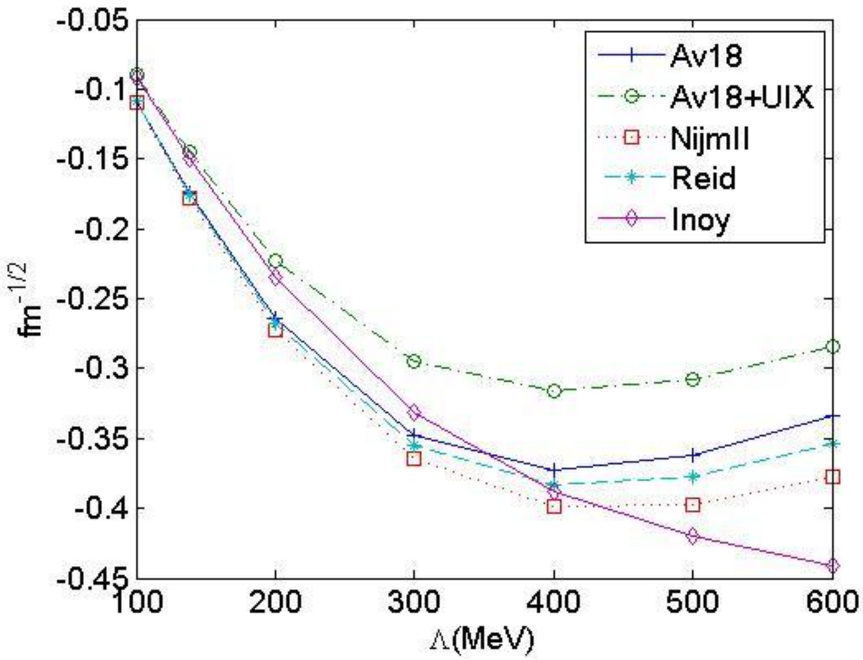
- Amplitudes are sensitive to cutoff and model
- Large model dependence in heavy meson DDH potential
- Three body potential is important.

Results: cutoff and model

- DDH and Pionless EFT: same scalar function



J=1/2

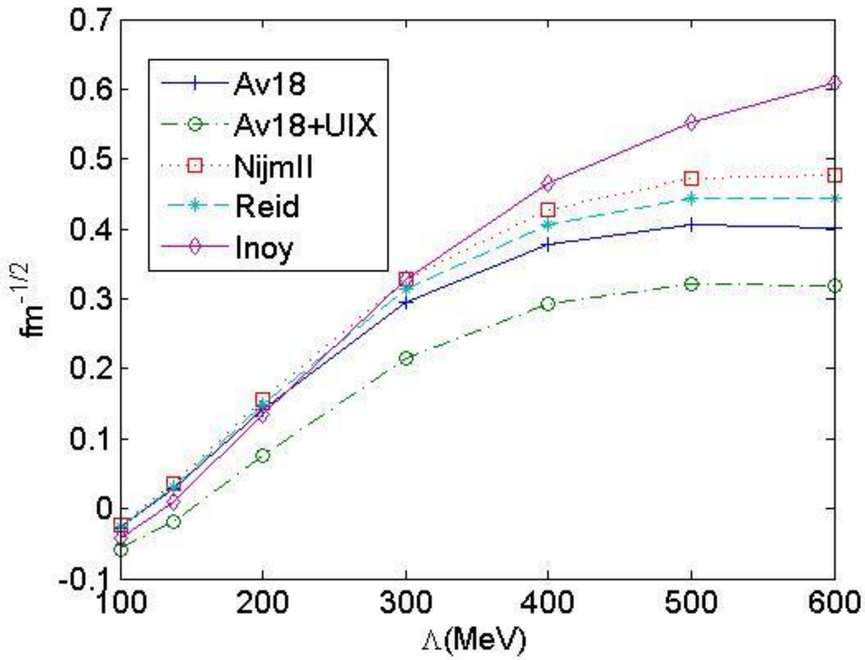


J=3/2

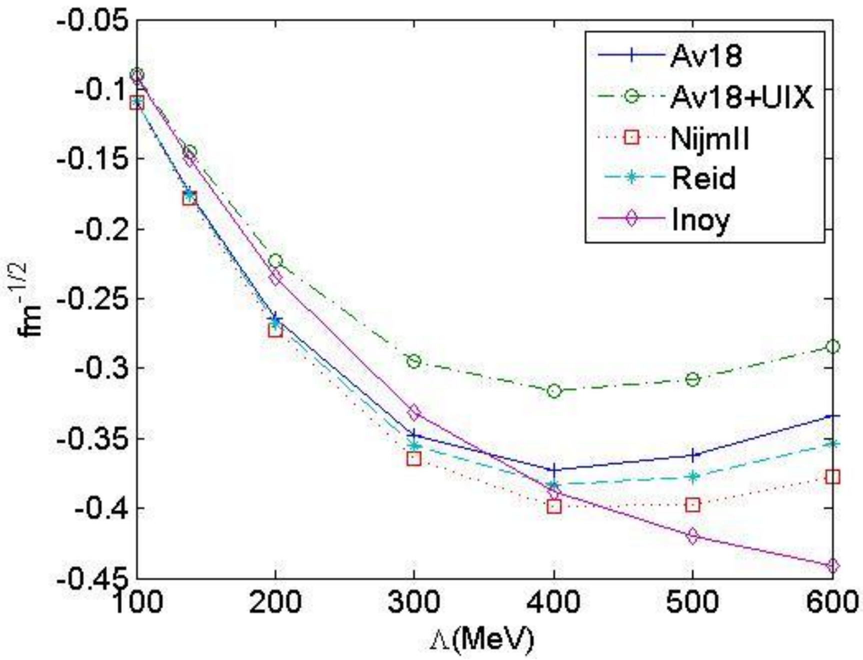
- Model/Cut off dependence of observable in EFT have to be considered after renormalization.
- Cutoff dependence in physical range can be absorbed to the LECs.
- Model dependence at short distance can be absorbed to the LECs.
- However, long distance model dependence can be a problem.

Results: cutoff and model

- DDH and Pionless EFT: same scalar function



J=1/2

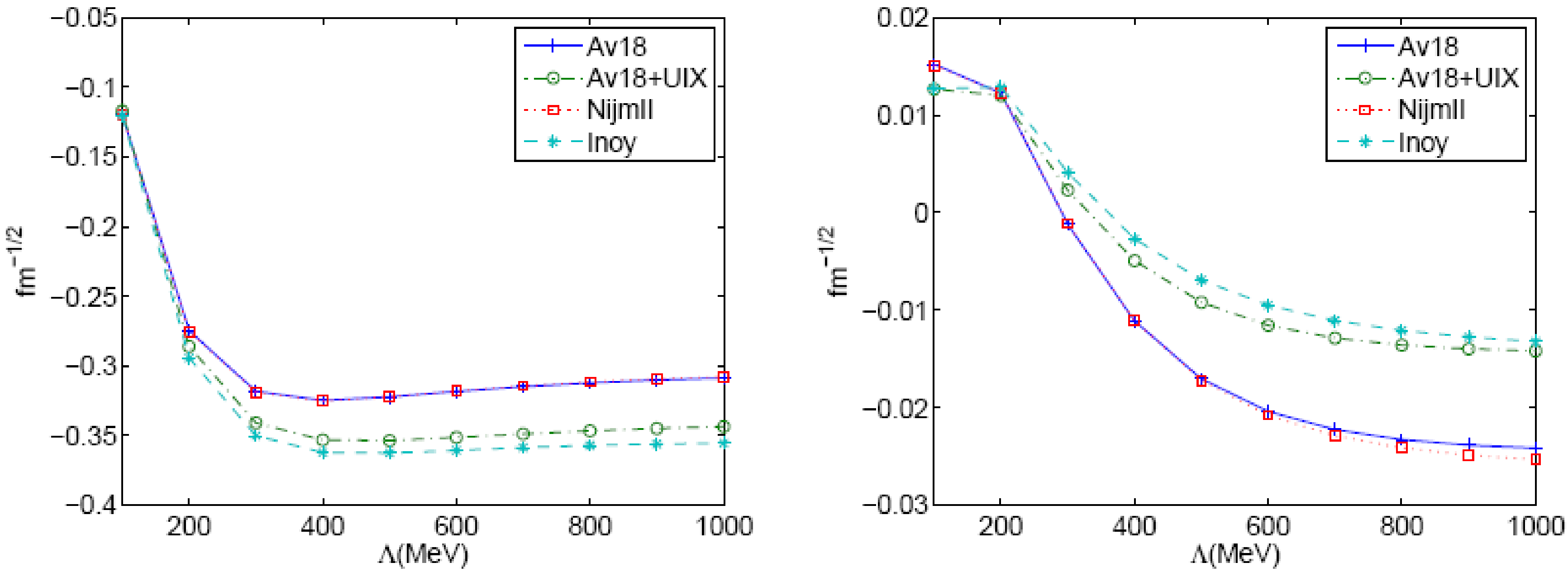


J=3/2

- At this moment, full analysis is not possible.
- Small model dependence at low cutoff is consistent with basic principle of EFT.
- => Model independence in the hybrid method.

Results: cutoff and model

- Pionful EFT



(a) $\Lambda^2 \widetilde{\mathcal{E}}_{\frac{1}{2},(+)}$ for op1

(b) $\Lambda^2 \widetilde{\mathcal{E}}_{\frac{3}{2},(+)}$ for op1

$$\{L_\Lambda(r), H_\Lambda(r), f_\Lambda(r), f_\Lambda^\pi(r)\} = \frac{1}{\Lambda^2}\int \frac{d^3q}{(2\pi)^3} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}} S_\Lambda(q)\{L(q), H(q), 1, \frac{\Lambda^2}{\boldsymbol{q}^2 + m_\pi^2}\}$$

Most of model dependence comes from short range part of wave functions

Results: revisit np capture

Two body n-p capture is easier to understand

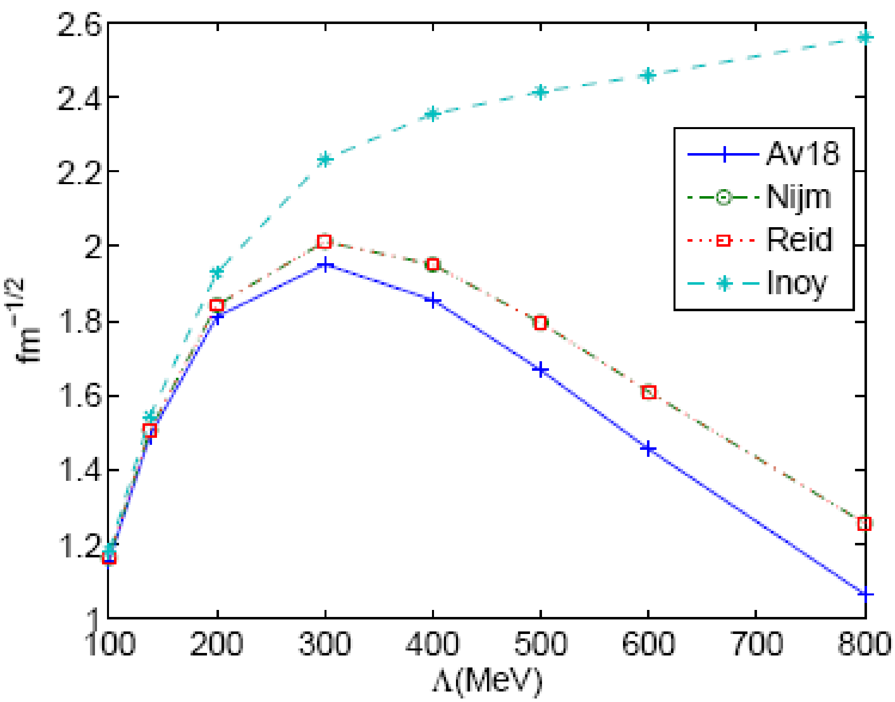
TABLE XIII: Two-body Parity violating observables for potential models with DDH-best parameter values and Bowman's 4-parameter fits.

models	a_n^γ		P_γ	
	DDH-best	4-para. fit	DDH-best	4-para. fit
AV18 +DDH-I	5.25×10^{-8}	-4.91×10^{-9}	6.94×10^{-9}	4.76×10^{-9}
AV18 +DDH-II	5.29×10^{-8}	-4.81×10^{-9}	1.76×10^{-8}	3.01×10^{-8}
NijmII+DDH-II	5.37×10^{-8}	-4.99×10^{-9}	2.61×10^{-8}	6.41×10^{-8}
Reid+DDH-II	5.33×10^{-8}	-4.85×10^{-9}	2.65×10^{-8}	4.68×10^{-8}
INOY+DDH-II	5.60×10^{-8}	-3.94×10^{-9}	2.55×10^{-7}	9.68×10^{-7}

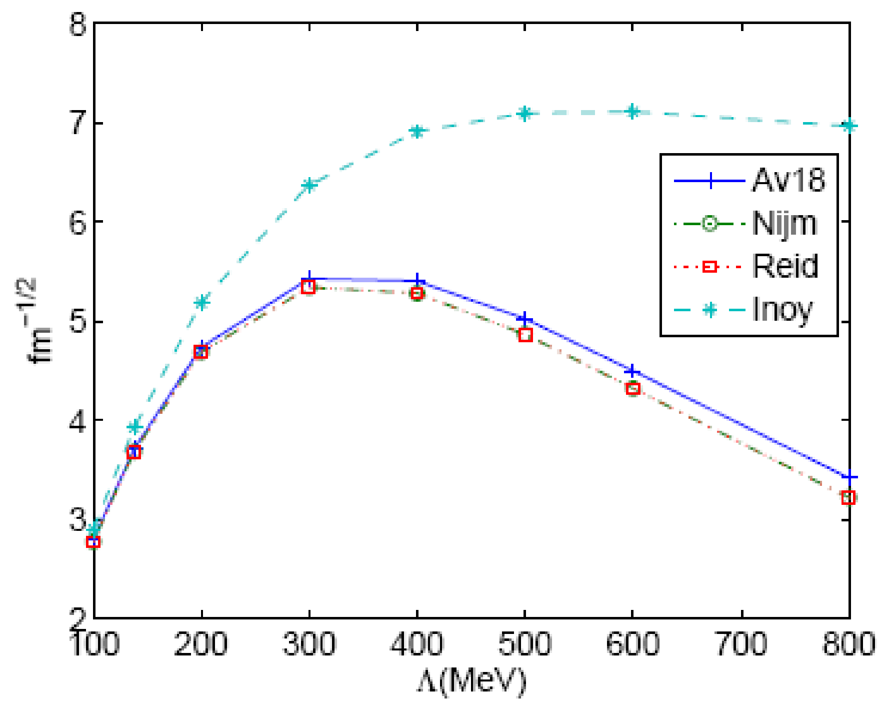
a is dominated by one-pion exchange.
P is dominated by rho,omega meson exchange.

Results: revisit np capture

Two body n-p capture is easier to understand



(a) $\mu^2 \widetilde{\mathcal{E}}_{1,(+)}$ of operator 1



(b) $\mu^2 \widetilde{\mathcal{E}}_{0,(-)}$ of operator 9

Conclusion

- The relation between parity violating observables in neutron-deuteron capture and Low Energy Constants in parity violating nucleon-nucleon potential is calculated.
- Amplitudes of each LECs contributes at the same order of magnitudes.
- Amplitudes are sensitive to the short range details(potential model, cutoffs, type of weak potential)

- Theoretical prediction of observables are limited because of unknown couplings.
- Full analysis of model and cutoff dependence requires renormalization of LECs.
- Other type of scalar functions are tried and get similar overall behavior.
- Importance of consistent calculations in DDH potential.(Importance of 3-body potential.)

  if no pion dominance in the observable.
- EFT approach can give model independent results in the hybrid method.

Acknowledgement :

This work was supported by Department of Energy Grant No. DE-FG02-09ER41621.