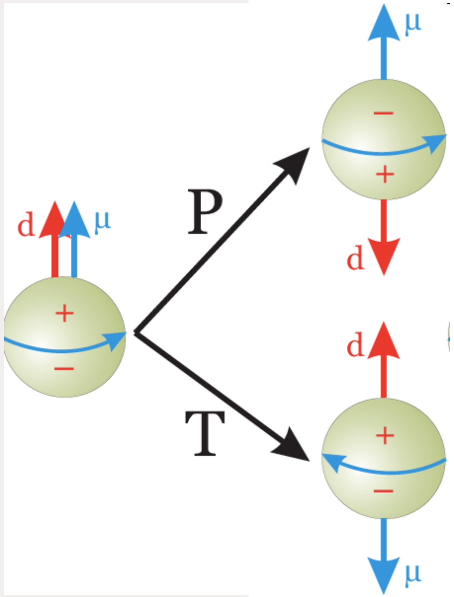
EM and weak observables in few-nucleon systems using hybrid EFT approach



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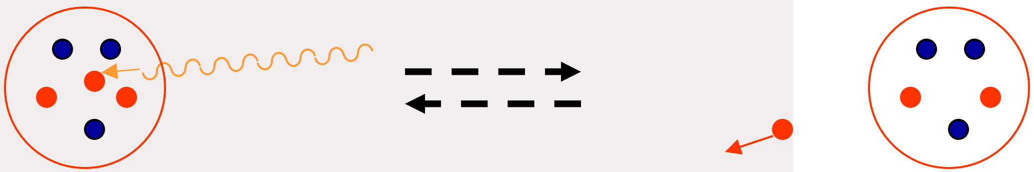
Guideline

- Description of the approach
- Results
  EM process in 2-4 body system
  PT violations in 3-body systems
- Conclusion

Approach



$$\mathcal{M} \sim \left\langle \Psi_f \right| \quad \vec{J}_\nu(\vec{q}) \quad \left| \Psi_i \right\rangle$$

Wavefunctions

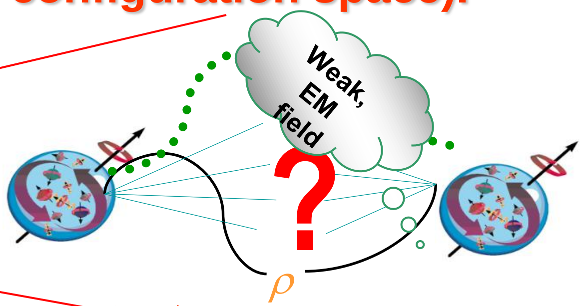
- Choose the accurate nuclear Hamiltonian: Paris, Nimegen II, Argonne Av18, CD Bonn, N3LO … with or w/o tri-nucleon interactions (Urbana, Tuscon-Melborne,…).
- Solve underlaying few-body QM problem to get $|\Psi_{i,f}>$

  (we employ Faddeev, Faddeev-Yakubovski equations in configuration space).

Electromagnetic current operators $J^\mu{}_{em}$

- Use gauge-invariance to deduce $J^\mu{}_{em}$ from the potential.
- cf) Gauge invariance restricts only longitudinal part
- Add various "model-dependant terms"

(Strong model dependence due to phenomenology of NN interaction)



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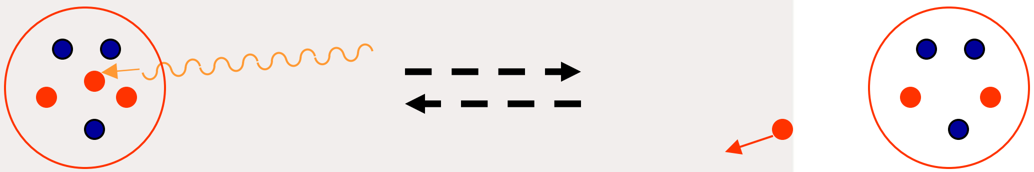

$$\mathcal{M} \sim \langle \Psi_f | \quad \vec{J}_\nu(\vec{q}) \quad | \Psi_i \rangle$$

✓ Wavefunctions

- Choose the accurate nuclear Hamiltonian: Paris, Nimegen II, Argonne Av18, CD Bon N3LO … with or w/o tri-nucleon interactions (Urbana, Tuscon-Melborne,…).
- Solve underlaying few-body QM problem to get $|\Psi_{i,f}\rangle$
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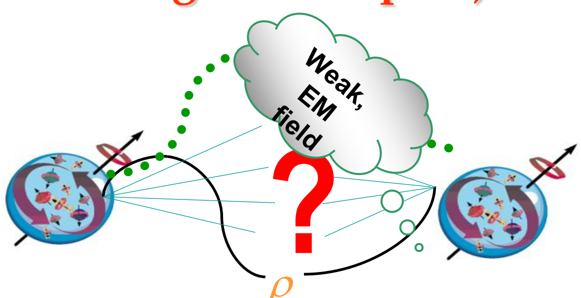
✓ Electromagnetic current operators $J^\mu{}_{em}$



- Perturbative using HBχEFT*
- How to fix coefficients of LECs?
  - Solve QCD (craziness !!)
  - Determine from other (known) observables => usual practice in EFTs, i.e., renormalization procedure

*P.F. Bedaque and U. van Kolck, **Ann. Rev. Nucl. Part. Sci. 52** (2002) 339*

HBχEFT* currents: counting scheme

- ✓ **Degrees of freedom: pions & nucleons**
  (ρ, ω, Δ, ⋯) + high energy part => appears as local operators of p′s and *N*′s.

- ✓ **Expansion parameter = Q/ Λχ**
  Q : typical momentum scale and/or m_π
  $\Lambda\chi$: $m_N \sim 4p\, f_p \sim$ **1 GeV .**
  $L = L_0 + L_1 + L_2 + \cdots$ **with** $L_n \sim (Q/\Lambda\chi)^n$

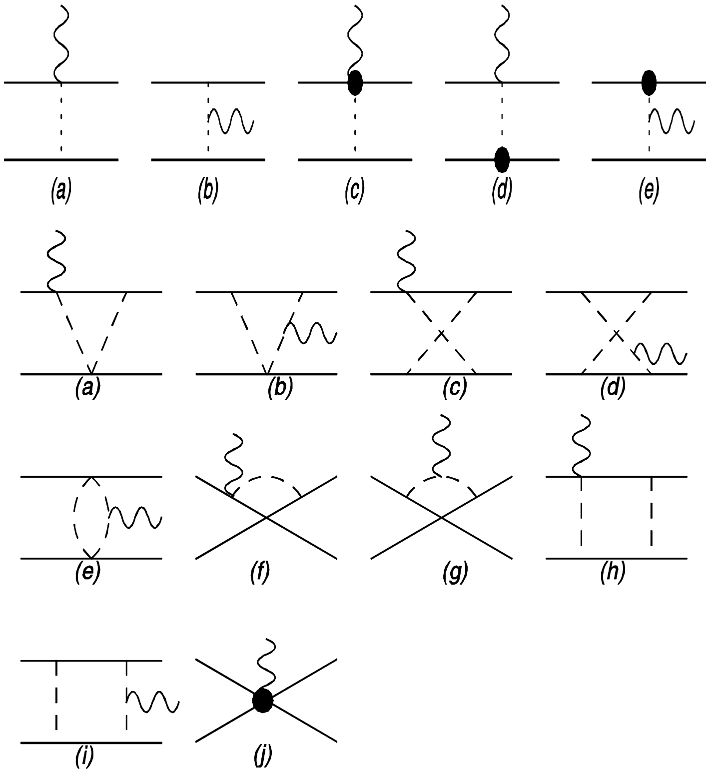
- ✓ **Weinberg's power counting rule for irreducible diagrams**

*S. Weinberg, **Phys. Lett. B 251** (1990) 288 ; **Nucl. Phys. B363** (1991) 3*

Covariant pert theory:

*T.-S. Park, D.-P. Min, and M. Rho, **Nucl. Phys. A596** (1996) 515*

- ✓ LO: <1-body>
- ✓ NLO: <1πE>
- ✓ N^3LO:
  - o 1L-correction to <1πE>
  - o <2πE>
  - o <contact terms>
  - o <1-body> RC



Consistent with time ordered pert. theory:

*Pastore et al., **PRC 80** (2009) 064002, Kölling et al., **PRC 80** (2009) 045502*

(slight difference in isospin dependence of the Sachs terms)

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EM currents: regularisation

- ✓ Wave functions
  - o Off-shell properties of available potentials very different => Model-dependence??
- ✓ $J_{CT} = C_{12}(\Lambda)\ (\tau\ \sigma)_{ij}\ \delta_\Lambda(r_{ij})$
  - o 3 LEC's related to hadronic coupling constants using resonance saturation arguments
  - o For a given w.f. and Λ, determine 2 remaining LECs to reproduce the experimental values of a selected set of observables that are sensitive on C_0 => **we choose MM of ^3H & ^3He**
- ✓ Model-dependence in short-range region:
  - o Can be visualized by a cutoff-dependence
  - o Difference in short-range physics is well described by local contact operators
  - o We expect that …
    - Values of LECs: Λ-dependent
    - Net matrix element: Λ-independent
- ✓ Model-dependence in long-range region:
  - o Long-range part of ME: governed by the effective-range parameters (ERPs) such as binding energy, scattering length, effective range etc
  - o In two-nucleon sector, practically no problem *(realistic potentials are fitted to reproduce 2N data)*
  - o In A ≥3, things are not quite trivial…

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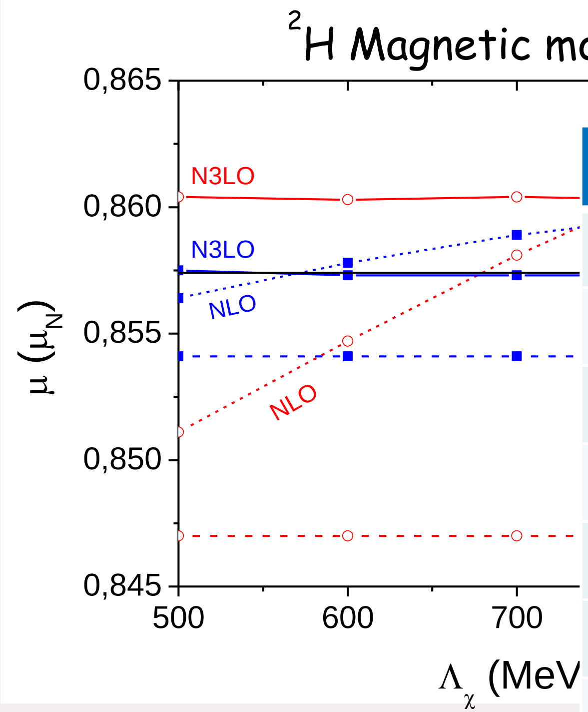

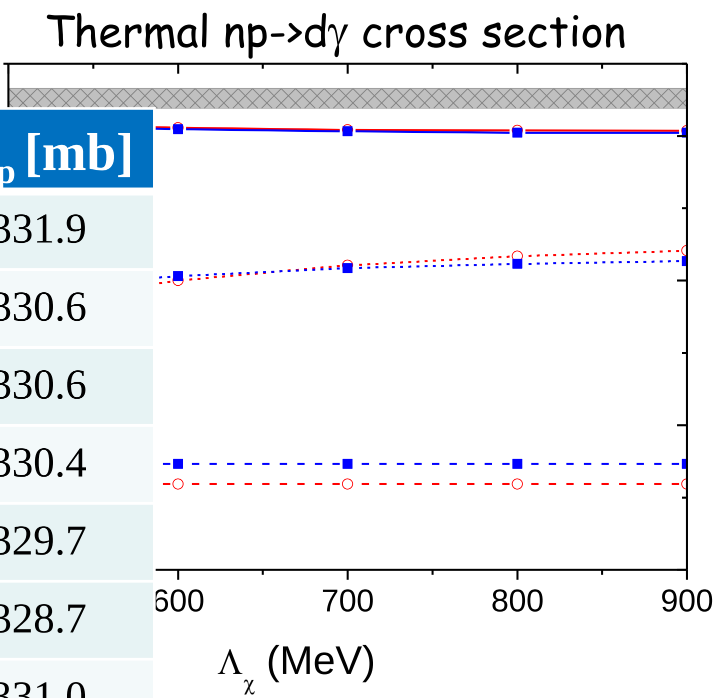

AV18+UIX

Model	$\mu(^2H)$	σ_{np} [mb]
Av18	0.858	331.9
Av18+UIX	0.860	330.6
INOY	0.859	330.6
I-N3LO	0.857	330.4
I-N3LO+UIX*	0.859	329.7
E1-N3LO	0.858	328.7
E4-N3LO	0.859	331.0
E5-N3LO	0.855	330.9
Exp.	0.8574	332.6(7)

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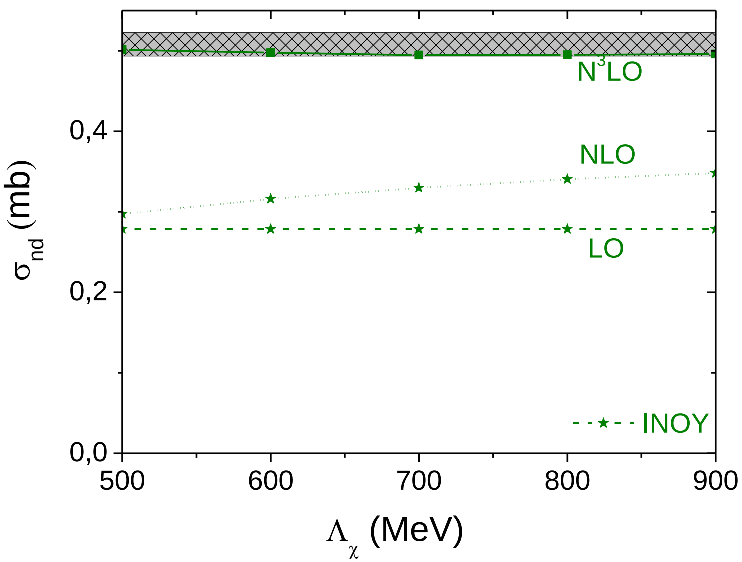
Thermal $n+{}^2H \to {}^3H+\gamma$ capture process

Model	σ_{nd} [mb]	-R_c	${}^2a_{nd}$ [fm]	B (^{3}H) [MeV]
Av18	0.680(3)	0.435	1.266	7.623
Av18+UIX	**0.478(3)**	0.458	**0.598**	**8.483**
INOY	**0.498(3)**	0.465	**0.551**	**8.483**
I-N3LO	0.626(2)	0.441	1.101	7.852
I-N3LO+UIX*	**0.477(2)**	0.468	**0.634**	**8.482**
E1-N3LO	0.688(4)	0.438	1.263	7.636
E4-N3LO	0.609(4)	0.448	1.024	7.930
E5-N3LO	0.879(8)	0.411	1.781	7.079
Exp.	**0.508(15)**	**0.420(30)**	**0.65(4)**	**8.482**



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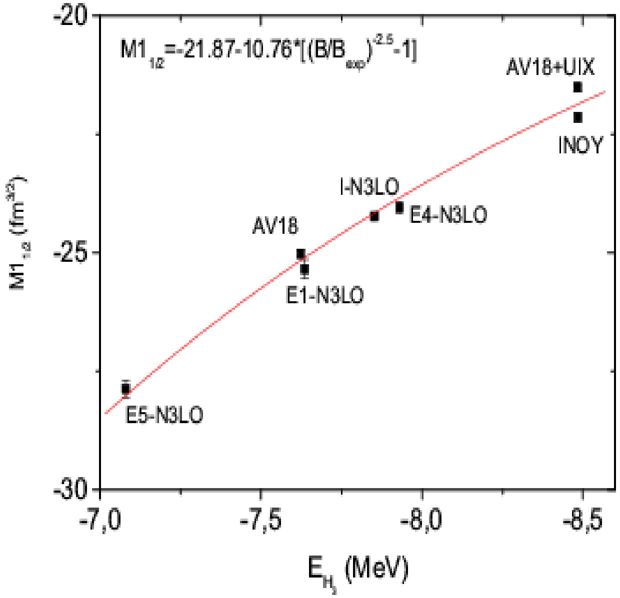
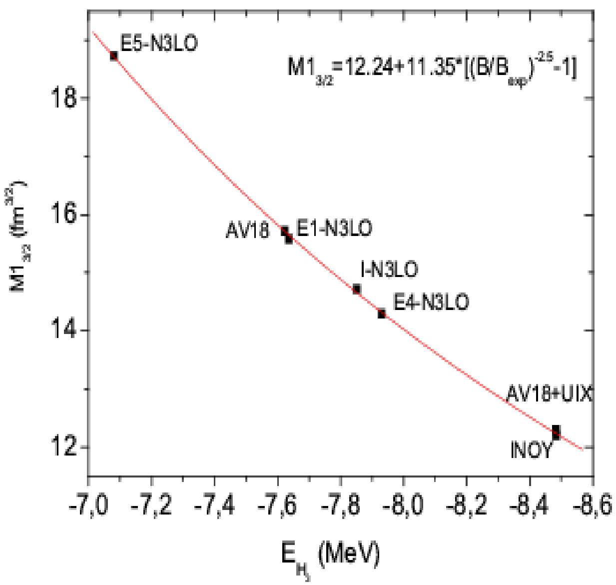
Thermal $n+{}^2H \to {}^3H+\gamma$ capture process

$$\sigma = \frac{2}{9}\frac{\alpha}{(v_{rel}/c)}\left(\frac{\hbar c}{2mc^2}\right)^2\left(\frac{q}{\hbar c}\right)^3\sum_{J_i}\sum_{J=1}^{J_i+\frac{1}{2}}\left\|\widetilde{\mathcal{E}}_J^{J_i(\frac{1}{2})}\right\|^2+\left\|\widetilde{\mathcal{M}}_J^{J_i(\frac{1}{2})}\right\|^2$$

$L_{nd}=0$; $J_{nd}=1/2$ & $3/2$





$$\phi_2(B_3) = -21.87 - 10.76\left[(B_3/B_3^{\exp})^{-2.5}-1\right], \quad \phi_4(B_3) = 12.24 + 11.35\left[(B_3/B_3^{\exp})^{-2.5}-1\right].$$

$R_c=0.462 \pm 0.003$; $\sigma_{nd}=0.49\pm 0.008$ mb

Exp: $R_c=0.420 \pm 0.03$; $\sigma_{nd}=0.508\pm 0.015$ mb

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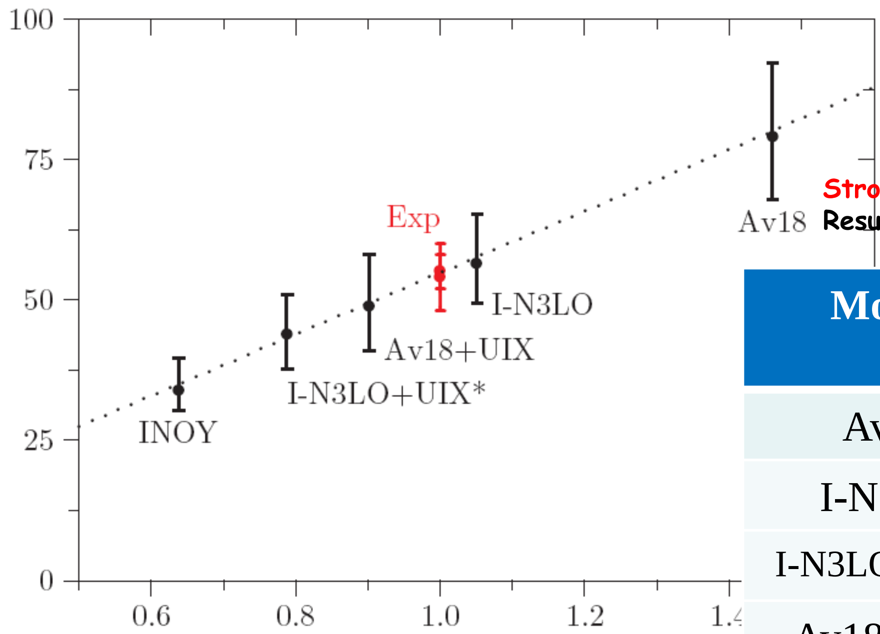
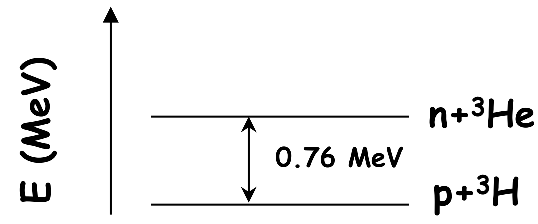
EM currents: results

Thermal $n+{}^3He \to {}^4He+\gamma$ capture process $L_{n3He}=0;\ J_{n3He}=1$



$\zeta/\zeta_{\exp},\ \zeta \equiv [q\,(a_{nHe3}/r_{He4})^2]^{-2.75}$

$=c(P_D)^{2/3}q^{-5}+0.42$



Strong cut-off dependence!
Result of 1B & 2B compensations

Model	σ_{n3He} [μb]	${}^3a_{n3He}$ [fm]	B(^{4}He) [MeV]
Av18	80(12.2)	3.43-0.0082i	24.23
I-N3LO	57.3(7.9)	3.56-0.007i	25.36
I-N3LO+UIX*	44.4(6.7)	3.44-0.0055i	28.12
Av18+UIX	49.4(8.5)	3.23-0.0054i	28.47
INOY	**34.4(4.5)**	3.26-0.0058i	29.08
Exp.	**55(3); 54(6)**	**3.28(5)-0.001(2)i**	**28.3**

In agreement: L. Girlanda, A. Kievsky et al., Phys. Rev. Lett. ***105****, 232502 (2010)*

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Weak process $V^{weak} << V^{strong}$

$\langle O^{weak} \rangle << \langle O^{strong} \rangle$

Need to find independent signature and enhancement

- EDM heavy nuclei
- Coherent neutron scattering

Two possible observables for scattering of the "slow" polarized neutrons:

$$\Delta\sigma = \frac{4\pi}{p}\,\mathrm{Im}(f_+ - f_-)$$

Difference in cross section parallel-antiparallel to some axis

$$\frac{d\phi}{dz} = -\frac{2\pi N}{p}\,\mathrm{Re}(f_+ - f_-)$$

Neutron spin rotation angle with respect to this axis (experiments at NIST & SNS)

Other possible observables:

Photon asymmetry $X(\vec{N},\gamma)Y$ and circular polarization $X(N,\vec{\gamma})Y$

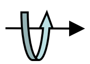
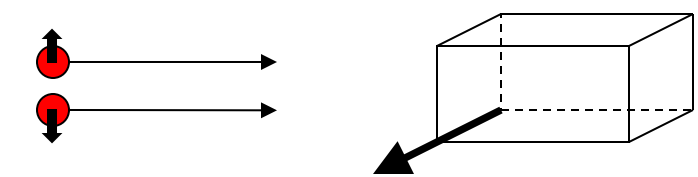
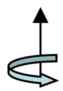
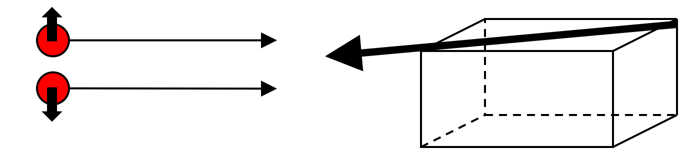
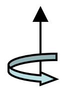
Photon helicity dependence $X(\vec{\gamma},N)Y$

2-body NN case studied in *R. Schiavilla et al.,Phys.Rev.* ***C70*** *(2004) 044007*

Two possible observables for scattering of polarized neutron:

$$\Delta\sigma = \frac{4\pi}{p}\,\mathrm{Im}(f_+ - f_-)$$ Difference in cross section parallel-antiparallel to some axis

$$\frac{d\phi}{dz} = -\frac{2\pi N}{p}\,\mathrm{Re}(f_+ - f_-)$$ Neutron spin rotation angle around this axis

	Correlation		n spin rotatio n axis
$T\not P$	$\vec{\sigma}_n \cdot \hat{p}_n$		
$\not T\not P$	$\vec{\sigma}_n \cdot \left[\hat{p}_n \times \vec{I}\right]$		
$\not T P$	$\vec{\sigma}_n \cdot \left[\hat{p}_n \times \vec{I}\right]\left(\hat{p}_n \cdot \vec{I}\right)$		

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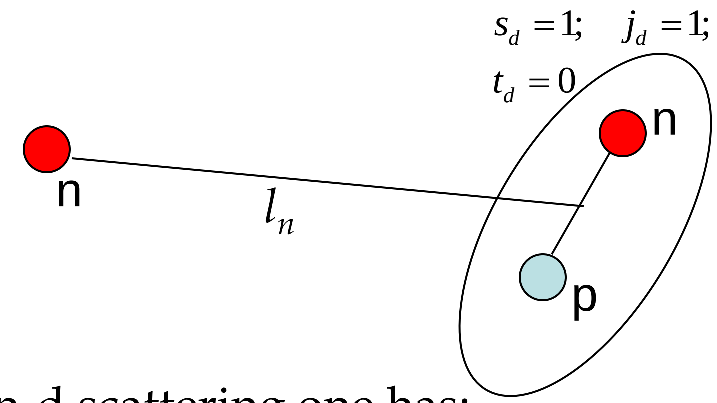
3-body Observables

- Partial wave decomposition

$$F_{ij}(\vec{x}_{ij},\vec{y}_{ij}) = \sum_{\alpha} \frac{f_\alpha(x_{ij},y_{ij})}{x_{ij}y_{ij}} \left| \left[\left(l_x s_x \right)_{j_x} s_k \right]_S l_y \right\rangle_{JM} \otimes \left| \left(t_i t_j \right)_{t_x} t_k \right\rangle_{TT_Z}$$

- R-matrix defined by l_n and $(j_d s_n)_S$ quantum numbers (S=1/2 or 3/2) at low p_n

$$R^{J}_{l'_n S', l_n S} \sim p_n^{1+l_n+l'_n} + i p_n^{2+l_n+l'_n}$$



- For n-d scattering one has:

$$s_{i,j,k} = \frac{1}{2}; \quad t_{i,j,k} = \frac{1}{2}; \quad T_z = -\frac{1}{2} \quad T \approx \frac{1}{2}$$

$$s_d = 1; \quad j_d = 1; \quad t_d = 0$$

For low energy neutrons only transitions with smallest l_n values must be considered

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3-body Observables

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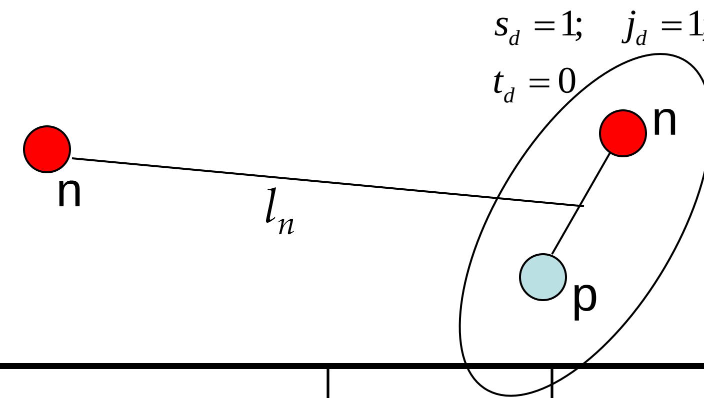

	Correlation	$\frac{1}{N}\frac{d\phi}{dz} = \frac{\pi}{p_n^2}\times$	$\frac{1}{N}\frac{d\phi}{dz}\sim$	$\Delta\sigma\sim$
$T\not{P}$	$\vec{\sigma}_n \cdot \hat{p}_n$	$\frac{4}{9}\mathrm{Im}\left[R^{\frac12}_{0\frac12,1\frac12} - 2\sqrt{2}R^{\frac12}_{0\frac12,1\frac32} + 4R^{\frac32}_{0\frac32,1\frac12} - 2\sqrt{5}R^{\frac32}_{0\frac32,1\frac32}\right]$	1	p_n
$\not{T}\not{P}$	$\vec{\sigma}_n \cdot \left[\hat{p}_n \times \vec{I}\right]$	$-\mathrm{Re}\left[\sqrt{2}R^{\frac12}_{0\frac12,1\frac32} + 2R^{\frac32}_{0\frac32,1\frac12}\right]$	1	p_n
$\not{T}P$	$\vec{\sigma}_n \cdot \left[\hat{p}_n \times \vec{I}\right]\left(\hat{p}_n \cdot \vec{I}\right)$	$\frac{1}{2}\mathrm{Re}\left[\sqrt{2}R^{\frac12}_{0\frac12,2\frac32} + \sqrt{2}R^{\frac12}_{1\frac12,1\frac32} + 2R^{\frac32}_{0\frac32,2\frac12} - \frac{1}{\sqrt{5}}R^{\frac32}_{1\frac12,1\frac32}\right]$	p_n	p_n^2

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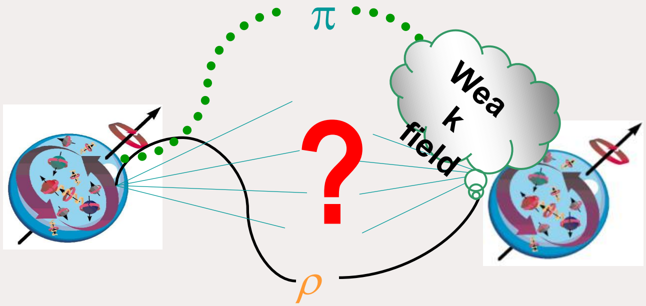
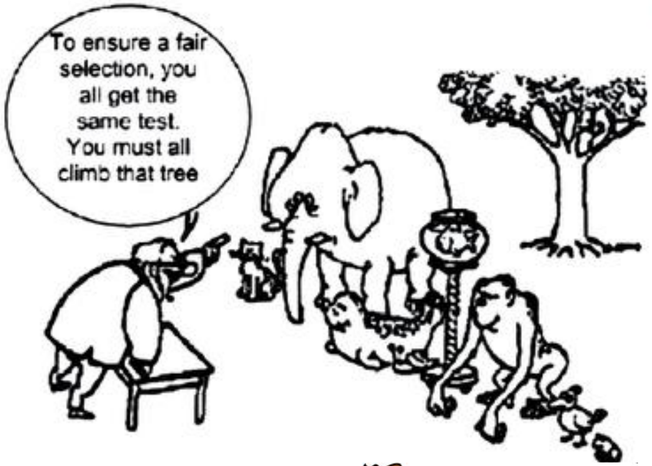


Guideline

- Writedown the most general Lagrangian
- Derive from it potential
- Retain most important terms



Models

- Meson-exchange theory - select the most pertinant meson-exchange diagrams for π,ρ, ω..

  DDH (*B. Desplanques et al.:, Ann. Phys. (N.Y.)* ***124*** *(1980) 449*)
- Pionless EFT - select the most pertinant Lagrangian terms (lowest momenta), fit low energy constants (LECs) *S.-L. Zhu, et al.:, Nucl. Phys.* ***A748****, 435 (2005), L. Girlanda, Phys. Rev.* ***C 77****, 067001 (2008).*
- ‘Pionfull’ EFT – retain lightest mesons + pionless EFT procedure

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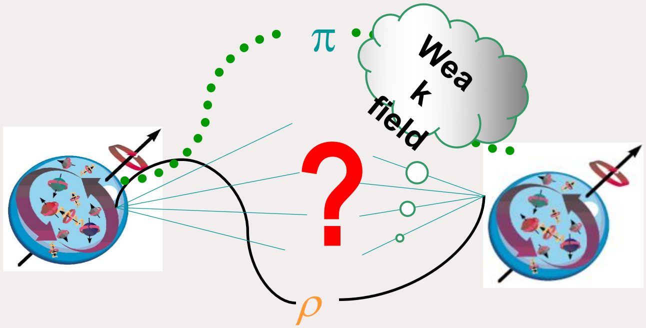
Parity violation



Strong Hamiltonian independence, due to dominance of $J^{\pi}=3/2^{+}$ channel

TABLE I: Parameters and operators of parity violating potentials. πNN coupling $g_{\pi NN}$ can be represented by g_A by using Goldberger-Treiman relation, $g_\pi = g_A m_N/F_\pi$ with $F_\pi = 92.4$ 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	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$\frac{2\mu^2}{\Lambda_\chi^2}C_6^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$(\tau_i\times\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,-}^{(1)}$
2	$-\frac{g_\rho}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i\cdot\tau_j)(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(2)}$
3	$-\frac{g_\rho(1+\kappa_\rho)}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i\cdot\tau_j)(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(3)}$
4	$-\frac{g_\rho}{2m_N}h_\rho^1$	$f_\rho(r)$	$\frac{\mu^2}{\Lambda_\chi^2}(C_2^{\not\pi}+C_4^{\not\pi})$	$f_\mu^{\not\pi}(r)$	$\frac{\Lambda^2}{\Lambda_\chi^2}(C_2^{\pi}+C_4^{\pi})$	$f_\Lambda(r)$	$(\tau_i+\tau_j)^z(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(4)}$
5	$-\frac{g_\rho(1+\kappa_\rho)}{2m_N}h_\rho^1$	$f_\rho(r)$	0	0	$\frac{2\sqrt{2}\pi g_A^2\Lambda^2}{\Lambda_\chi^2}h_\pi^1$	$L_\Lambda(r)$	$(\tau_i+\tau_j)^z(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(5)}$
6	$-\frac{g_\rho}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	$-\frac{2\mu^2}{\Lambda_\chi^2}C_5^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$-\frac{2\Lambda^2}{\Lambda_\chi^2}C_5^{\pi}$	$f_\Lambda(r)$	$\mathcal{T}_{ij}(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(6)}$
7	$-\frac{g_\rho(1+\kappa_\rho)}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	0	0	0	0	$\mathcal{T}_{ij}(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(7)}$
8	$-\frac{g_\omega}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^2}C_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^2}C_1^{\pi}$	$f_\Lambda(r)$	$(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(8)}$
		$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^2}\tilde{C}_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^2}\tilde{C}_1^{\pi}$	$f_\Lambda(r)$	$(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(9)}$
		$f_\omega(r)$	0	0	0	0	$(\tau_i+\tau_j)^z(\sigma_i-\sigma_j)\cdot X_{ij,+}^{(10)}$
		$f_\omega(r)$	0	0	0	0	$(\tau_i+\tau_j)^z(\sigma_i\times\sigma_j)\cdot X_{ij,-}^{(11)}$
		$f_\rho(r)$	0	0	0	0	$(\tau_i-\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,+}^{(12)}$
		$f_\rho(r)$	0	0	$-\frac{\sqrt{2}\pi g_A\Lambda^2}{\Lambda_\chi^2}h_\pi^1$	$L_\Lambda(r)$	$(\tau_i\times\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,-}^{(13)}$
		0	0	0	$\frac{2\Lambda^2}{\Lambda_\chi^2}C_6^{\pi}$	$f_\Lambda(r)$	$(\tau_i\times\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,-}^{(14)}$
		0	0	0	$\frac{\sqrt{2}\pi g_A^2\Lambda^2}{\Lambda_\chi^2}h_\pi^1$	$\tilde{L}_\Lambda(r)$	$(\tau_i\times\tau_j)^z(\sigma_i+\sigma_j)\cdot X_{ij,-}^{(15)}$

TABLE VI: Coefficients I_n^π for AV18 and AV18+UIX strong potentials, and πEFT-I and πEFT-II parameter sets for parity violating potentials. $I_{2,3,6,7,10,11,12}^\pi = 0$.

n	πEFT-I/AV18	πEFT-I/AV18+UIX	πEFT-II/AV18	πEFT-II/AV18+UIX
1	$0.616\times10^{+02}$	$0.600\times10^{+02}$	$0.616\times10^{+02}$	$0.600\times10^{+02}$
4	$0.152\times10^{+01}$	$0.142\times10^{+01}$	$0.549\times10^{+00}$	$0.488\times10^{+00}$
5	$0.435\times10^{+01}$	$0.185\times10^{+01}$	$0.123\times10^{+01}$	0.664×10^{-01}
8	$-0.184\times10^{+01}$	$-0.179\times10^{+01}$	$-0.782\times10^{+00}$	$-0.748\times10^{+00}$
9	$-0.820\times10^{+00}$	$-0.730\times10^{+00}$	$-0.340\times10^{+00}$	$-0.288\times10^{+00}$
13	$0.226\times10^{+02}$	$0.218\times10^{+02}$	$0.970\times10^{+01}$	$0.936\times10^{+01}$
14	$0.339\times10^{+01}$	$0.333\times10^{+01}$	$0.177\times10^{+01}$	$0.174\times10^{+01}$
15	$0.654\times10^{+02}$	$0.631\times10^{+02}$	$0.273\times10^{+02}$	$0.264\times10^{+02}$

tributing mesons

40), $I^G(J^{\pi C}) = 1^-(0^{-+})$ // 1

70), $I^G(J^{\pi C}) = 1^+(1^{--})$ // 2-7

82), $I^G(J^{\pi C}) = 0^-(1^{--})$ // 8-13

In agreement with *R. Schiavilla et al., Phys.Rev.C78:014002,2008; Erratum-ibid.C83:029902,2011*

Compares well with Pionless EFT results: **Eur.Phys.J. A48 (2012) 7, Phys.Rev. C86 (2012) 014001**

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Parity violation

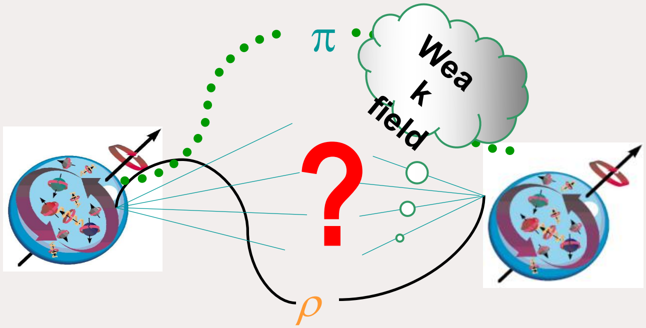

TABLE X: DDH PV coupling constants in units of 10^{-7}. Strong couplings are $\frac{g_\pi^2}{4\pi} = 13.9$, $\frac{g_\rho^2}{4\pi} = 0.84$, $\frac{g_\omega^2}{4\pi} = 20$, $\kappa_\rho = 3.7$, and $\kappa_\omega = 0$, h'_ρ contribution is neglected. 4-paramter fir and 3-parameter fit uses the same h^1_ρ and h^1_ω with DDH 'best'.

DDH Coupling	DDH 'best'	4-parameter fit[25]	3-parameter fit[25]
h^1_π	+4.56	−0.456	−0.5
h^0_ρ	−11.4	−43.3	−33
h^2_ρ	−9.5	37.1	41
h^0_ω	−1.9	13.7	0
h^1_ρ	−0.19	−0.19	−0.19
h^1_ω	−1.14	−1.14	−1.14

TABLE XI: Neutron spin rotation in 10^{-7} rad-cm^{-1} for the case of DDH-II potential with AV18+UIX strong potential for a liquid deuteron density $N = 0.4 \times 10^{23}$ atoms per cm^3.

	DDH 'best'	4-parameter fit[25]	3-parameter fit[25]
1	$0.108 \times 10^{+00}$	-0.108×10^{-01}	-0.118×10^{-01}
2	0.386×10^{-02}	0.147×10^{-01}	0.112×10^{-01}
3	-0.317×10^{-01}	$-0.120 \times 10^{+00}$	-0.918×10^{-01}
4	0.349×10^{-04}	0.349×10^{-04}	0.349×10^{-04}
5	0.150×10^{-03}	0.150×10^{-03}	0.150×10^{-03}
8	-0.423×10^{-02}	0.305×10^{-01}	$0.000 \times 10^{+00}$
9	-0.202×10^{-02}	0.146×10^{-01}	$0.000 \times 10^{+00}$
10	0.967×10^{-03}	0.967×10^{-03}	0.967×10^{-03}
11	0.113×10^{-02}	0.113×10^{-02}	0.113×10^{-02}
12	0.102×10^{-02}	0.102×10^{-02}	0.102×10^{-02}
total	0.768×10^{-01}	-0.682×10^{-01}	-0.891×10^{-01}

J. D. Bowman, http://www.int.washington.edu/talks/WorkShops/int_07_1/.

np case: (0.46 -0.74)10^{-8} rad cm^{-1} (R. Schiavilla et al.,Phys.Rev.* ***C70*** *(2004) 044007)*

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Parity violating n+d capture

Observables: polarization of the emitted photon (P_γ)
photon assymetry in relation to neutron (a_n)
& deutron (A_d)

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

Model	DDH best values			Four-parameter fits		
	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

Important model-dependence!!!

TABLE X. Two-body parity-violating observables for potential models with DDH best parameter values and Bowman's four-parameter fits.

Models	a_n^γ		P_γ	
	DDH best value	Four-parameter fit	DDH best value	Four-parameter 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}

Some model dependance already visible for np (short range physics Pγ dominated by ω & ρ mesons

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Parity violating n+d capture

$\varepsilon_{3/2}$ amplitude for nd

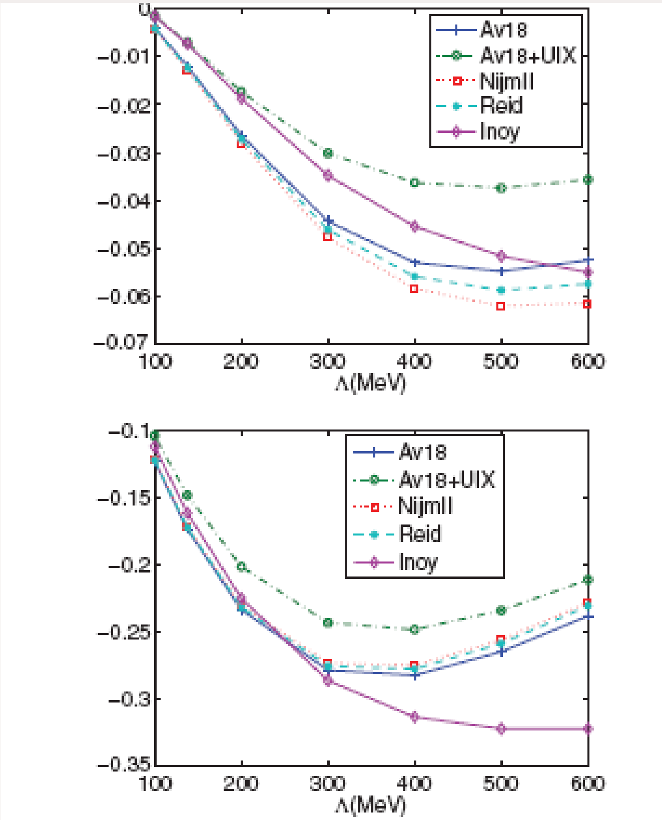

FIG. 1. (Color online) Cutoff and strong model dependencies of the amplitudes for $\not{\pi}$EFT-I calculated with AV18, AV18 + UIX, Nijmegen-II, INOY, and Reid strong potentials. The first graph shows $\Lambda^2\tilde{\mathcal{E}}_{\frac{3}{2}(+)}$ for operator 1 and the second graph shows $\Lambda^2\tilde{\mathcal{E}}_{\frac{3}{2}(+)}$ for operator 9 in units of fm$^{-\frac{1}{2}}$. The multiplier Λ^2 is used to absorb the artificial cutoff dependence of c_n coefficients.

ε_1 amplitude for np

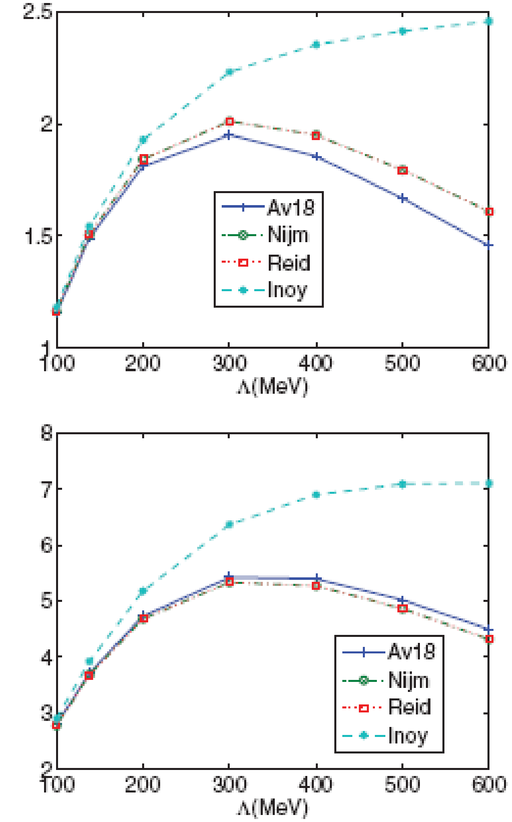

FIG. 3. (Color online) Cutoff and strong model dependencies of amplitudes for $\not{\pi}$EFT-I with various strong potential models. The first graph shows $\Lambda^2\tilde{\mathcal{E}}_{1,(+)}$ of operator 1 and the second graph shows $\Lambda^2\tilde{\mathcal{E}}_{0,(-)}$ of operator 9 in units of fm$^{-\frac{1}{2}}$. The multiplier Λ^2 is used to absorb the artificial cutoff dependence of c_n coefficients.

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P&T violation

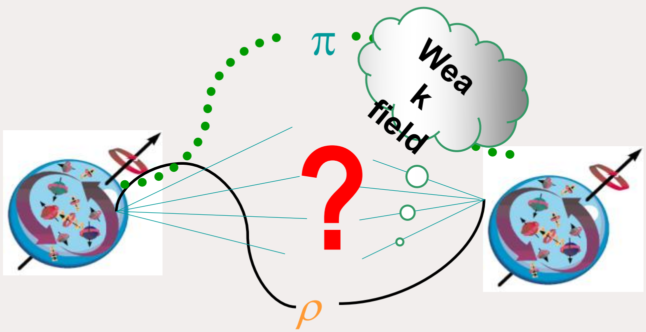

TABLE I. A typical matrix elements of TRIV potential, $\mathrm{Re}\frac{\langle (l'_y j'_y), J | V_n^{T\not P} | (l_y j_y), J\rangle}{\tilde{C}_{np}}$, in jj-coupling scheme with $AV18+UIX$ strong potential at zero energy limit. Imaginary part of potential matrix element is zero at zero energy limit. Scalar functions are chosen as $\frac{m_\pi^2}{4\pi}Y_1(m_\pi r)$ for operators $1-5$, $\frac{m_\pi^2}{4\pi}Y_0(m_\pi r)$ for operators $6-16$. $O_{3,8,12}=0$ because of isospin selection rules. All data are in fm^2.

n	$\langle 1\frac{1}{2}\vert v^{1/2}\vert 0\frac{1}{2}\rangle/p$	$\langle 1\frac{3}{2}\vert v^{1/2}\vert 0\frac{1}{2}\rangle/p$	$\langle 1\frac{1}{2}\vert v^{3/2}\vert 0\frac{1}{2}\rangle/p$	$\langle 1\frac{3}{2}\vert v^{3/2}\vert 0\frac{1}{2}\rangle/p$
1	0.590×10^{-01}	-0.787×10^{-01}	0.151×10^{-01}	0.177×10^{-01}
2	$0.627\times10^{+00}$	-0.863×10^{-01}	$-0.144\times10^{+00}$	$-0.167\times10^{+00}$
4	$-0.268\times10^{+00}$	$0.107\times10^{+00}$	0.330×10^{-01}	0.379×10^{-01}
5	$0.321\times10^{+00}$	$-0.267\times10^{+00}$	$-0.199\times10^{+00}$	-0.691×10^{-01}
6	0.719×10^{-01}	-0.104×10^{-01}	-0.115×10^{-01}	-0.141×10^{-01}
7	-0.206×10^{-01}	0.520×10^{-02}	0.337×10^{-01}	0.384×10^{-01}
9	-0.650×10^{-01}	0.865×10^{-02}	0.238×10^{-03}	0.134×10^{-02}
10	0.106×10^{-01}	-0.932×10^{-03}	0.658×10^{-03}	0.622×10^{-03}
11	0.171×10^{-01}	-0.548×10^{-03}	-0.237×10^{-02}	-0.273×10^{-02}
13	-0.163×10^{-01}	0.111×10^{-02}	0.131×10^{-03}	0.288×10^{-03}
14	0.649×10^{-02}	-0.628×10^{-02}	-0.876×10^{-02}	-0.250×10^{-03}
15	0.338×10^{-01}	-0.230×10^{-01}	-0.293×10^{-01}	-0.198×10^{-02}
16	0.128×10^{-01}	-0.816×10^{-02}	-0.119×10^{-01}	-0.335×10^{-03}

$$H_{stat}^{T\not P} = g_1(r)\boldsymbol{\sigma}_-\cdot\hat{r} + g_2(r)\tau_1\cdot\tau_2\boldsymbol{\sigma}_-\cdot\hat{r} + g_3(r)T_{12}^z\boldsymbol{\sigma}_-\cdot\hat{r}$$
$$+ g_4(r)\tau_+\boldsymbol{\sigma}_-\cdot\hat{r} + g_5(r)\tau_-\boldsymbol{\sigma}_+\cdot\hat{r}$$

More terms from EFT:

$$^{T\not P}_{non-static} = \left(g_6(r) + g_7(r)\tau_1\cdot\tau_2 + g_8(r)T_{12}^z + g_9(r)\tau_+\right)\boldsymbol{\sigma}_\times\cdot\frac{\bar{p}}{m_N}$$
$$+\left(g_{10}(r) + g_{11}(r)\tau_1\cdot\tau_2 + g_{12}(r)T_{12}^z + g_{13}(r)\tau_+\right)$$
$$\times\left(\hat{r}\cdot\boldsymbol{\sigma}_\times\hat{r}\cdot\frac{\bar{p}}{m_N} - \frac{1}{3}\boldsymbol{\sigma}_\times\cdot\frac{\bar{p}}{m_N}\right)$$
$$+g_{14}(r)\tau_-\left(\hat{r}\cdot\boldsymbol{\sigma}_1\hat{r}\cdot(\boldsymbol{\sigma}_2\times\frac{\bar{p}}{m_N}) + \hat{r}\cdot\boldsymbol{\sigma}_2\hat{r}\cdot(\boldsymbol{\sigma}_1\times \ldots\right.$$
$$+g_{15}(r)(\tau_1\times\tau_2)^z\boldsymbol{\sigma}_+\cdot\frac{\bar{p}}{m_N}$$
$$+g_{16}(r)(\tau_1\times\tau_2)^z\left(\hat{r}\cdot\boldsymbol{\sigma}_+\hat{r}\cdot\frac{\bar{p}}{m_N} - \frac{1}{3}\boldsymbol{\sigma}_+\cdot\frac{\bar{p}}{m_N}\right),$$

If we retain only pions:

$$\frac{\phi^{T\not P}}{\phi^{\not P}} \simeq (1.2)\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.12)\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right),$$
$$\frac{\Delta\sigma^{T\not P}}{\Delta\sigma^{\not P}} \simeq (-0.47)\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26)\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right).$$

From EDM measurements $g/h<10^{-3}$

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P&T violation (EDMs)

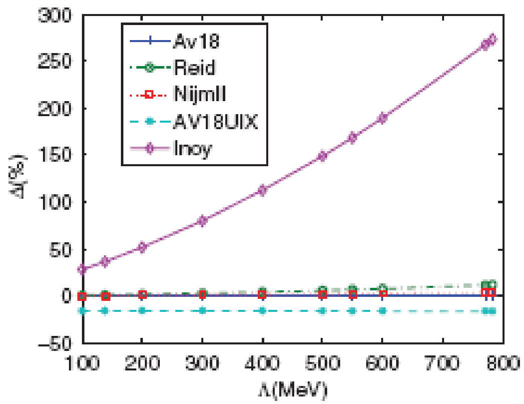
TABLE II. Contribution of the different TRIV operators in Eq. (5) to the expectation value of $\frac{2}{\sqrt{6}}\langle\Psi||\hat{D}^{pol}_{TP}||\Psi_{TP}\rangle$. Calculations have been performed for several different strong potentials and for the ^{3}He (^{3}H) nucleus; values are given in 10^{-3} $e$fm units.

Operator	Λ	AV18	Reid93	NijmII	AV18UIX	INOY
1	m_π	−5.32(5.28)	−5.37(5.33)	−5.31(5.28)	−4.46(4.42)	−7.24(7.23)
	m_η	−0.571(0.572)	−0.608(0.609)	−0.584(0.585)	−0.478(0.477)	−1.53(1.54)
	m_ρ	−0.233(0.234)	−0.26(0.261)	−0.241(0.242)	−0.195(0.195)	−0.857(0.862)
	m_ω	−0.223(0.224)	−0.249(0.25)	−0.231(0.232)	−0.187(0.186)	−0.833(0.838)
2	m_π	5.9(−5.89)	6.08(−6.07)	6.12(−6.11)	5.5(−5.48)	10.3(−10.2)
	m_η	0.673(−0.681)	0.803(−0.81)	0.771(−0.777)	0.629(−0.635)	2.72(−2.73)
	m_ρ	0.292(−0.296)	0.387(−0.391)	0.351(−0.354)	0.27(−0.273)	1.6(−1.6)
	m_ω	0.281(−0.284)	0.374(−0.378)	0.337(−0.341)	0.259(−0.262)	1.56(−1.56)
3	m_π	6.76(−7.02)	6.78(−7.01)	6.76(−6.98)	6.66(−6.89)	7.46(−7.72)
	m_η	0.775(−0.814)	0.773(−0.804)	0.762(−0.794)	0.784(−0.819)	1.25(−1.31)
	m_ρ	0.304(−0.32)	0.3(−0.312)	0.295(−0.307)	0.308(−0.322)	0.645(−0.674)
	m_ω	0.29(−0.305)	0.285(−0.297)	0.281(−0.293)	0.294(−0.307)	0.625(−0.653)
4	m_π	2.17(2.42)	2.2(2.41)	2.25(2.46)	2.81(3.03)	2.27(2.48)
	m_η	0.286(0.319)	0.291(0.317)	0.296(0.322)	0.372(0.403)	0.397(0.436)
	m_ρ	0.112(0.125)	0.114(0.125)	0.116(0.127)	0.146(0.159)	0.202(0.223)
	m_ω	0.107(0.12)	0.109(0.119)	0.111(0.121)	0.139(0.152)	0.196(0.216)
5	m_π	19.4(19.6)	19.6(19.8)	20(20.2)	18.3(18.5)	19.5(19.6)
	m_η	2.43(2.47)	2.59(2.63)	2.75(2.8)	2.32(2.35)	3.5(3.56)
	m_ρ	0.985(1.01)	1.09(1.11)	1.2(1.22)	0.937(0.953)	1.92(1.95)
	m_ω	0.942(0.961)	1.04(1.06)	1.15(1.17)	0.896(0.911)	1.86(1.9)

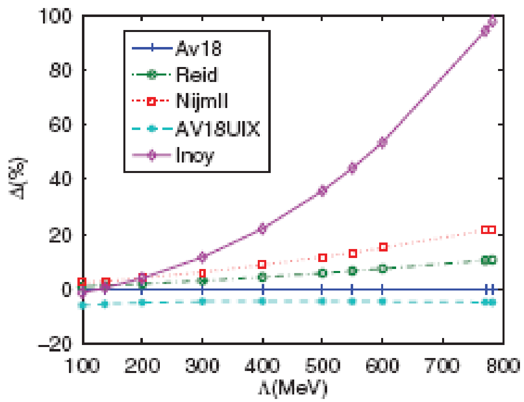
Discrepency with results of: *I. Stetcu, C.-P. Liu et al., Phys. Lett. B* ***665****, 168 (2008)!!*

Important model-dependence, already at π–level!!!

P&T violation (EDMs)



(a) Δ for operator 1



(b) Δ for operator 5

FIG. 2. (Color online) The relative deviations of the $d^{pol}_{^3\mathrm{He}}$ value from the one obtained for the AV18 potential, $\Delta \equiv \frac{d^{pol} - d^{pol}(AV18)}{d^{pol}(AV18)} \times 100$. Results are presented for the operators 1 (a) and 5 (b) and as a function of the cutoff parameter.

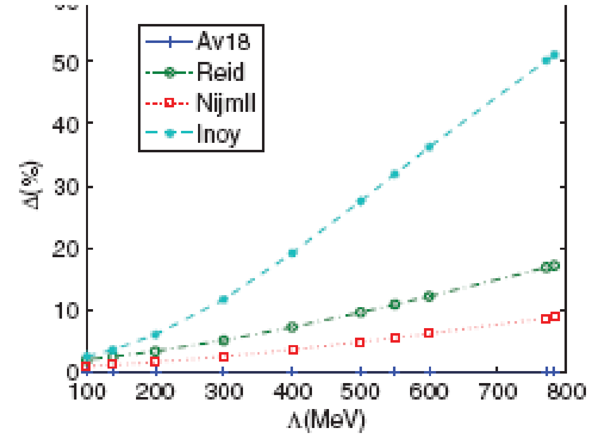


FIG. 1. (Color online) The relative deviations of the d^{pol}_{d} value from the one obtained for AV18 potential, $\Delta \equiv \frac{d^{pol} - d^{pol}(AV18)}{d^{pol}(AV18)} \times 100$. Results are presented as a function of the cutoff parameter.

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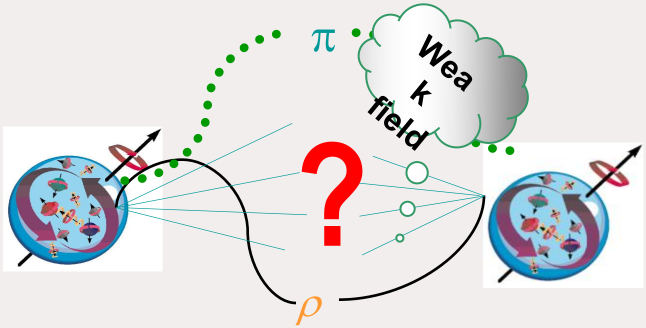
TVPC case



Contributing mesons

- Pion exchange does not contribute *(M. Simonius, Phys. Lett.,* ***B58****, 147 (1975))*
- ρ(770), $I^G(J^{\pi C}) = 1^+(1^{--})$
- h1(1170), $I^G(J^{\pi C}) = 0^-(1^{+-})$

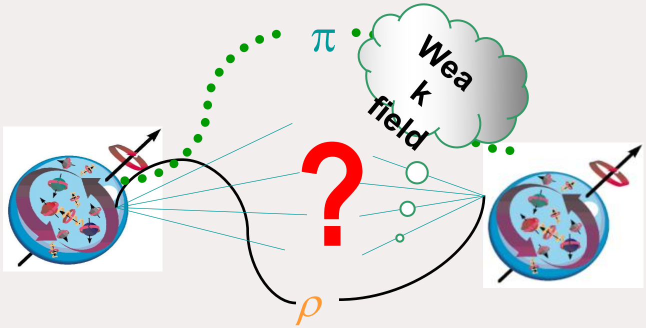
$$
\begin{aligned}
H^{\not{T}\not{P}} = & \left(g_1(r) + g_2(r)\tau_1\cdot\tau_2 + g_3(r)T_{12}^z + g_4(r)\tau_+\right)\hat{r}\cdot\frac{\bar{p}}{m_N} \\
& + \left(g_5(r) + g_6(r)\tau_1\cdot\tau_2 + g_7(r)T_{12}^z + g_8(r)\tau_+\right)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\hat{r}\cdot\frac{\bar{p}}{m_N} \\
& + \left(g_9(r) + g_{10}(r)\tau_1\cdot\tau_2 + g_{11}(r)T_{12}^z + g_{12}(r)\tau_+\right) \\
& \quad \times\left(\hat{r}\cdot\boldsymbol{\sigma}_1\frac{\bar{p}}{m_N}\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_2\frac{\bar{p}}{m_N}\cdot\boldsymbol{\sigma}_1 - \frac{2}{3}\hat{r}\cdot\frac{\bar{p}}{m_N}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right) \\
& + \left(g_{13}(r) + g_{14}(r)\tau_1\cdot\tau_2 + g_{15}(r)T_{12}^z + g_{16}(r)\tau_+\right) \\
& \quad \times\left(\hat{r}\cdot\boldsymbol{\sigma}_1\hat{r}\cdot\boldsymbol{\sigma}_2\hat{r}\cdot\frac{\bar{p}}{m_N} - \frac{1}{5}\left(\hat{r}\cdot\frac{\bar{p}}{m_N}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_1\frac{\bar{p}}{m_N}\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_2\frac{\bar{p}}{m_N}\cdot\boldsymbol{\sigma}_1\right)\right) \\
& + g_{17}(r)\tau_-\hat{r}\cdot\left(\boldsymbol{\sigma}_\times\times\frac{\bar{p}}{m_N}\right) + g_{18}(r)\tau_\times^z\hat{r}\cdot\left(\boldsymbol{\sigma}_-\times\frac{\bar{p}}{m_N}\right), \qquad (7)
\end{aligned}
$$

$$\sigma_\oplus = \sigma_1 \oplus \sigma_2$$

$$\Delta\sigma^{\not{T}\not{P}} = 10^{-6}[g_h\bar{g}_h(-1.09) + g_\rho\bar{g}_\rho(4.20\cdot 10^{-3})]\ \mathrm{b},$$

$$\frac{1}{N}\frac{d\phi^{\not{T}\not{P}}}{dz} = -10^{-3}[g_h\bar{g}_h(1.24) - g_\rho\bar{g}_\rho(5.81\cdot 10^{-3})]\ \mathrm{rad\ fm}^2.$$

Comparison



According to EFT, one gets following estimates at E_{cm}=100 keV:

$$\frac{1}{m_N C_n^{\not P}} \frac{\Delta f^{\not P}(\mu = m_\pi)}{p} = [(-1.93 \cdots 2.42) + i(-0.22 \cdots 0.67)]\ fm^2,$$

$$\frac{1}{m_N C_n^{\not T \not P}} \frac{\Delta f^{\not T \not P}(\mu = m_\pi)}{p} = [(-1.63 \cdots 0.66) + i(-0.063 \cdots 0.22)]\ fm^2,$$

$$\frac{1}{m_N C_n^{\not T P}} \frac{\Delta f^{\not T P}(\mu = m_\pi)}{p} = [(-0.01 \cdots 0.03) + i(-0.0013 \cdots 0.0004)]\ fm^2.$$

$\Delta\phi$ $\Delta\sigma$

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Conclusion

- Efficiency of χEFT demonstrated for EM few-body reactions
- Extensive analysis of P & T violating processes has been performed for low energy n-d scattering
- This reaction might be explored in order to improve our knowledge of $\not{P}$ & $\not{T}$ coupling constants
- Strong model dependence of matrix elements, it is still believed EFT can handle it

TO DO

- Higher energies, p-d case
- Heavier system as ^{3}He(n,p)^{3}H, studied at SNS

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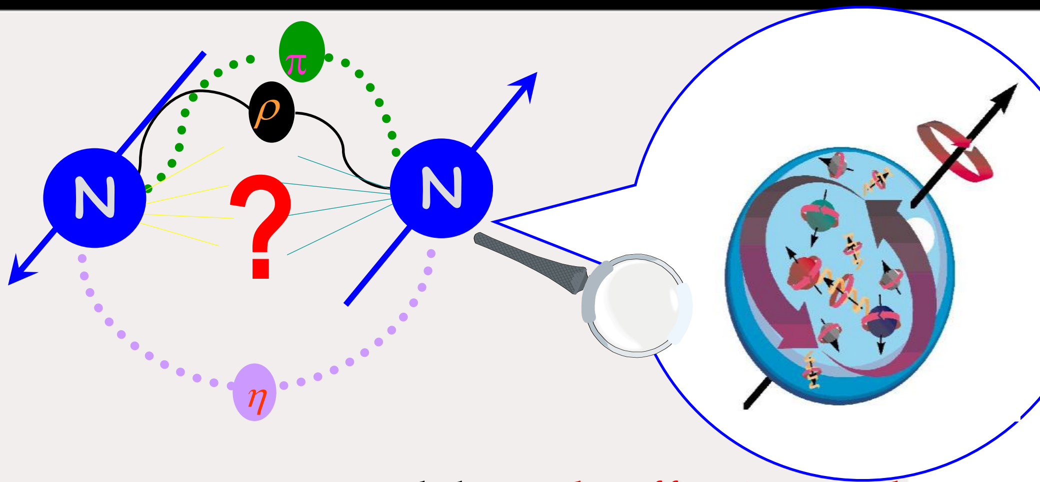

Model	$^2a_{nd}$ [fm]	B (^{3}H) [MeV]
Av18	1.266	7.623
Av18+UIX	0.598	8.483
Exp.	0.65(4)	8.482

- *NN* interaction models ***only effective tools!***
- Exact description is possible only fully taking into account *N* structure underlaying theory (*QCD*) but…

Our choice

Argonne **AV18** pot. (*Wiringa et al., Phys. Rev.* ***C 51*** *(1995) 38*) fitted to reproduce available np & pp data $\chi^2_{data} \approx 1.01$ (n~40 free parameters...)

Supplemented with **UIX** 3N-force (*B.S. Pudliner et al., Phys. Rev. Lett.* ***74*** *(1995) 4396*) fitted in order to improve description of ^{3}H and ^{4}He binding energies. But also improves n-d scattering observables at low energy.

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