Nonleptonic weak interactions in NN and few nucleon systems

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Outline

Collaborators

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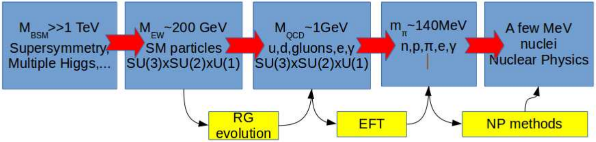
- L. Girlanda - *INFN & Universitá del Salento, Lecce (Italy)*
- R. Schiavilla - *ODU & Jefferson Lab. Newport News (USA)*

Fundamental symmetries in few-nucleon systems



Scales of energies

- $\gg$ 1 TeV: Physics Beyond Standard Model (BSM) (dof: ?)
- 200 GeV: Standard Model (SM) (all quarks, gluons, γ, leptons, Higgs, $W^\pm$, Z)
- 1 GeV: SM (u, d, s quarks, gluons, γ, $e^\pm$, $\mu^\pm$, νs)
- 100 MeV: Hadrons (p, n, π, γ, $e^\pm$, $\mu^\pm$, νs)
- 1-10 MeV: Nuclear Physics (d, ^{3}H, ^{4}He, ...)

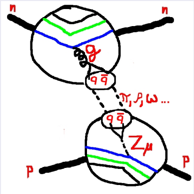
Interest

- Parity-violation (PV) $\rightarrow$ hadron weak interaction
- Time-reversal violation (TRV): θ-term, BSM physics
- Detection of dark-matter, dark photons, etc via nuclear interaction
- Relic neutrinos $\nu_e + {}^3\mathrm{H} \rightarrow e^- + {}^3\mathrm{He}$
- ...

Study of PV in few-nucleon systems

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}}\left[J^\dagger_{W\mu}J^\mu_W + J^\dagger_{Z\mu}J^\mu_Z\right]$$

$$J^\mu_W = \cos\theta_c \bar{d}\gamma^\mu(1-\gamma_5)u + \sin\theta_c \bar{s}\gamma^\mu(1-\gamma_5)u$$
$$J^\mu_Z = \bar{u}(A_u(\theta_W) - B_u(\theta_W)\gamma^5)u + \bar{d}(A_d(\theta_W) - B_d(\theta_W)\gamma^5)d$$



- Interest: quark-quark weak interaction
- $\Delta T = 1$ component: dominated by neutral currents see, for example, [Haxton & Holstein, 2013]
- Several discrepancies theory-experiment in hyperon non-leptonic decays $\Lambda \to p + \pi^-$, etc. [Ramsey-Musolf & Page, 2008]
- Example: $\Delta T = 3/2$ suppressed with respect to $\Delta T = 1/2$

Ingredients

- Parity conserving (PC) strong interaction
- PV interaction V_{PV}
- Few-nucleon wave functions $\Psi^{(\pm)}$
- Observables $\sim \langle \Psi^{(-)}|V_{PV}|\Psi^{(+)}\rangle$

Experiments in few-nucleon systems

- Longitudinal asymmetries $\vec{p}p$, $\vec{p}\,^4\mathrm{He}$, $\vec{n}\,^3\mathrm{He}$
- Neutron spin rotation $\vec{n}p$, $\vec{n}d$, $\vec{n}\,^4\mathrm{He}$
- Longitudinal asymmetries in EM capture $n + p \to \gamma + d$, $n + d \to \gamma + {}^3\mathrm{H}$
- γ polarization $\vec{n} + p \to \gamma d$

PC strong NN & 3N forces (1)

Meson exchange models

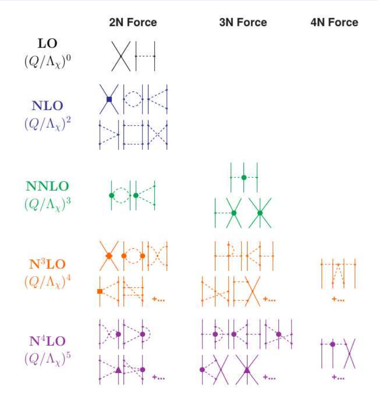
- Exchanges of π, ρ, ω, ... mesons
- Refined after many years: Argonne V18, CD-Bonn, ...
- Fit of NN experimental data with $\chi^2 \approx 1$
- 3NF: Fujita-Miyazawa ...
- No consistent NN & 3N forces, no systematic way to improve them
- No consistent way to introduce e.m. and weak interactions

"Pionless" EFT approach

- d.o.f: only nucleons, contact interactions
- $\mathcal{L} = \overline{C}_0 N N \overline{N} N + \dots$
- LO: no derivatives, NLO: two derivatives, etc.
- Direct solution for the transition amplitudes [Schindler & Springer, 2013]
- Minimum set of unknown parameters (Low-energy constants –LECs)
- They can be reduced (large N_c analysis, etc)
- Valid for energies $\ll m_\pi$

PC strong NN & 3N forces (2)

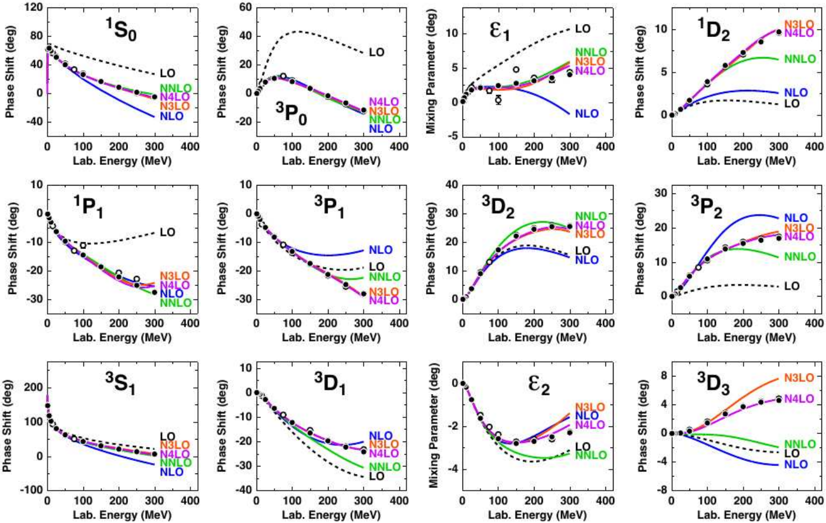
χEFT approach – based on the chiral symmetry approximately satisfied by QCD (u, d quarks)



- NN & 3N force in the "Weinberg naive counting"
- [Bernard, Kaiser, & Meissner (1995)], [Ordonéz, Ray, & van Kolck (1996)], [Epelbaum, Meissner, & Gloeckle (1998)], [. . .]
- N4LO: [Epelbaum, Krebs, & Meissner, 2015], [Machleidt *et al.*, 2017]
- "N2LO+" with Δ dof: [Piarulli, Kievsky, Marcucci, MV *et al.*, 2016]
- Coupling constants (LECs) fitted to NN and 3N database
- Chiral perturbation theory $\sim (Q/\Lambda_\chi)^\nu$

EFT approach: systematic inprovements, interaction of nucleons with external currents can be consistently taken into account

Comparison with NN data - convergence

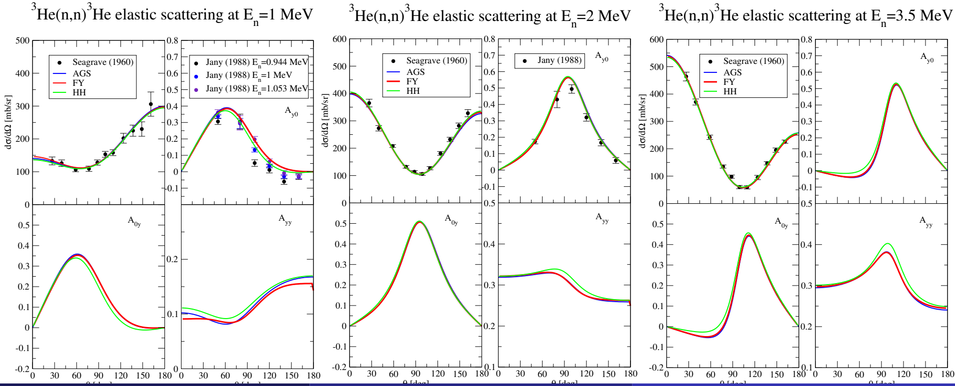


Calculation of few-nucleon wave functions

Numerical techniques to find bound and continuum states

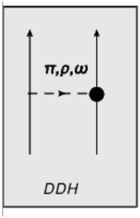
- Faddeev-Yakubovsky methods [Lazauskas & Carbonell, 2004], [Deltuva & Fonseca, 2007]
- Expansion on a basis: NCSM [Quaglioni, Navratil & Roth, 2010], Gaussians [Aoyama *et al.*, 2011], HH [Kievsky, MV, *et al.*, 2008]

Benchmark test of 4N scattering calculations
N3LO500 potential – ^{3}He$(n,n)^3$He elastic scattering



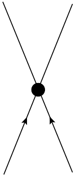
PV NN interaction (1)

Meson exchange potentials
DDH [Desplanques, Donoghue, & Holstein, 1980]



DDH has 7 unknown parameters h_π^1, h_ρ^0, h_ρ^1, h_ρ^2, h_ω^0, h_ω^1, $h_\rho'^1$ (≈ 0)

Pionless EFT potential
[Schindler & Springer, 2013],[Haxton & Holstein, 2013]
[Haxton, Gadner & Holstein (GHH), 2017]



5 parameters at LO [Girlanda 2008]

PV NN interaction (2)

[Haxton, Gadner & Holstein (GHH), 2017]

$$
\begin{aligned}
V_{CT}^{PV}(\mathbf{r}) \;=\;& \Lambda_0^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{i}\frac{\boldsymbol{\nabla}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
+\;& \Lambda_0^{{}^3S_1-{}^1P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)-\frac{1}{i}\frac{\boldsymbol{\nabla}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
+\;& \Lambda_1^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1\,z}+\tau_{2\,z})\right)\\
+\;& \Lambda_1^{{}^3S_1-{}^3P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1\,z}-\tau_{2\,z})\right)\\
+\;& \Lambda_2^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}}{2m_N}\frac{\delta^3(\mathbf{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right)
\end{aligned}
$$

PV NN interaction (3)

Large N_c analysis

- [Schindler, Springer, & Vanasse, 2016]

$$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1} + \frac{1}{4}\Lambda_0^{^1S_0-^3P_0} \sim N_c$$

$$\Lambda_2^{^1S_0-^3P_0} \sim N_c,$$

$$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1} - \frac{3}{4}\Lambda_0^{^1S_0-^3P_0} \sim 1/N_c$$

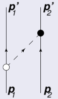
$$\Lambda_1^{^1S_0-^3P_0} \sim \sin^2\theta_W$$

$$\Lambda_1^{^3S_1-^3P_1} \sim \sin^2\theta_W$$

Lattice calculations

- $h_\pi^1 = 1 \times 10^{-7}$ [Wasem, 2012]
- calculation of $\Lambda_2^{^1S_0-^3P_0}$ in progress [Tiburzi, 2012], [Kurth *et al.*, 2016], [Berkowitz, next talk]

$\sim Q^{-1}$ Leading order (LO)



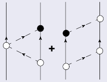
One Pion Exchange

$$V_{PV}^{(-1)}(\mathrm{OPE}) = \frac{g_A h_\pi^1}{2\sqrt{2} f_\pi} (\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)_z \frac{i\boldsymbol{k}\cdot(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)}{\omega_k^2}$$

$$\boldsymbol{k} = \boldsymbol{p}_1' - \boldsymbol{p}_1 = \boldsymbol{p}_2 - \boldsymbol{p}_2' \quad \omega_k = \sqrt{m_\pi^2 + k^2} \quad g_A = 1.267 \quad f_\pi = 92.4\ \mathrm{MeV} \quad \Lambda_\chi = 4\pi f_\pi$$

$\sim Q$ next-to-leading order (NLO)

Contact Terms
5 LECs C_i, $i = 1, \ldots, 5$



Two Pion Exchange (TPE) diagrams depending on h_π^1

- 5 LECS

- [Zhu *et al.*, 2005], [Hyun *et al.*, 2008], [De Vries *et al.*, 2014]
- [MV *et al.*, (2014)] (independent PV Lagrangian terms allowed at order Q^2)
- Regularization at large k with a cutoff $F_\Lambda(k) = \exp\left(-(k/\Lambda)^4\right)$
- Test: convergence with the orders – independence on Λ

Measurements of PV observables

Longitudinal pp asymmetry

E_p (MeV)	$A_L(\vec{p}p)$	(θ_1, θ_2)	Lab. (year)
13.6	$(-0.97 \pm 0.20) \times 10^{-7}$	$(20^\circ, 78^\circ)$	Bonn Germany (1991)
45	$(-1.53 \pm 0.21) \times 10^{-7}$	$(23^\circ, 52^\circ)$	PSI Switzerland (1987)
221	$(+0.84 \pm 0.34) \times 10^{-7}$	$(5^\circ, 90^\circ)$	TRIUMF Canada (2003)

The two data at lower energies are not independent $A_L \sim \sqrt{E_p}$
In pionless EFT it is not allowed to use the TRIUMF datum at $E_P = 221$ MeV

Npdgamma expt.: γ asymmetry in $\vec{n} + p \to d + \gamma$

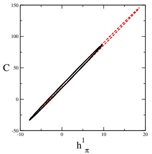
A_γ^{np}	Lab. (year)
$(-3.0 \pm 1.4) \times 10^{-8}$	SNS, USA (2018)

Mostly sensitive to h_π^1

$h_\pi^1 = (2.6 \pm 1.2) \times 10^{-8}$ [Blyth *et al.*, 2018], [talk by Barrón-Palos]

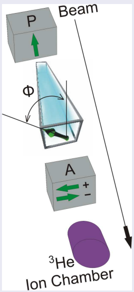
$$A_L^{pp}(E) = a_0^{(pp)}(E)\, h_\pi^1 + a_1^{(pp)}(E)\, C$$

$$C = C_1 + C_2 + 2\,(C_4 + C_5)$$



units 10^{-7}
$C \approx 10 \times 10^{-7}$

Neutron spin rotation (1)



- Forward amplitude depends on the helicity
- $f(0) = f_{PC}(0) + f_{PV}(0)\boldsymbol{\sigma} \cdot \boldsymbol{k}$
- $f_{PV}(0)$ induced by the PV NN interaction

transversely-polarized neutrons corkscrew due to the NN weak interaction

$$|\hat{+y}\rangle_{z=0} = \frac{1}{\sqrt{2}}\Big[|+\hat{z}\rangle + |-\hat{z}\rangle\Big] \qquad |\hat{y}\rangle_{z=L} = \frac{1}{\sqrt{2}}\Big[e^{-i(\varphi_{PC}+\varphi_{PV})}|+\hat{z}\rangle + e^{-i(\varphi_{PC}-\varphi_{PV})}|-\hat{z}\rangle\Big]$$

After the target, the neutron spin has rotated by an angle φ
(independent of incident neutron energy)

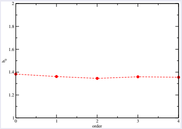
$$\varphi = \varphi_{+} - \varphi_{-} = 2\varphi_{PV} = 4\pi L\rho f_{PV}(0)$$

Neutron spin rotation (2)

$$\frac{d\varphi}{dz} = h_\pi^1 b_0 + C_1 b_1 + C_2 b_2 + C_3 b_3 + C_4 b_4 + C_5 b_5$$

$\vec{n}$-p scattering – coeff. $b_0^{(np)}$					
PV/PC→	LO	NLO	N2LO	N3LO	N4LO
LO	1.2235	1.2247	1.2168	1.2215	1.2267
NLO	1.3829	1.3614	1.3453	1.3593	1.3553

Units: rad/m



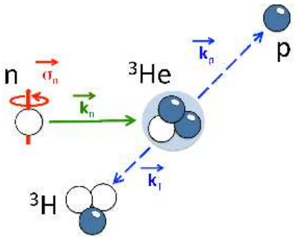
Dependence on the cutoff parameter Λ

$\vec{n}$-p scattering						
Λ [MeV]	$b_0^{(np)}$	$b_1^{(np)}$	$b_2^{(np)}$	$b_3^{(np)}$	$b_4^{(np)}$	$b_5^{(np)}$
500	1.360	0.2440	0.1739	0.1054	0.0000	−0.9058
600	1.2639	0.2354	0.1584	0.0848	0.0000	−0.8646
$\vec{n}$-d scattering						
Λ [MeV]	$b_0^{(nd)}$	$b_1^{(nd)}$	$b_2^{(nd)}$	$b_3^{(nd)}$	$b_4^{(nd)}$	$b_5^{(nd)}$
500	2.17913	−0.01046	−0.15997	0.19117	0.06367	0.00032
600	2.22165	−0.00684	−0.18226	0.18232	0.06750	0.00030

Units: rad/m

$n - d$ spin rotation with AV18+DDH [Song, Lazauskas, & Gukov, 2010]
comparison ok!

Longitudinal asymmetry in $\vec{n} + {}^3\mathrm{He} \to p + {}^3\mathrm{H}$



Interest

- $A_z(\theta) = a_z \cos\theta$
- Recently measured at ORNL

Studies already published

- [MV *et al.*, PRC **82**, 044001 (2010)] AV18/UIX + DDH PV pot.
- [MV *et al.*, PRC **89**, 064004 (2014)] N3LO/N2LO + NLO χEFT PV pot.
- A. Gnech, Master Thesis (2016)] N2LO χEFT PV pot.

Contributing waves

- initial state ($n - {}^3\mathrm{He}$) $q \approx 0$: ${}^1S_0$, ${}^3S_1$
- final state ($p - {}^3\mathrm{H}$) $q = 0.165$ fm^{-1}:
  - $J = 0$: ${}^1S_0$, ${}^3P_0$
  - $J = 1$: ${}^3S_1 - {}^3D_1$, ${}^1P_1 - {}^3P_1$

Neglecting ${}^3D_1$, we have to compute the matrix elements $T^{(nh,pt),J}_{LS,L'S'}$

PC	
${}^1S_0 \to {}^1S_0$	$T^{(nh,pt),0}_{00,00}$
${}^3S_1 \to {}^3S_1$	$T^{(nh,pt),1}_{01,01}$

PV	
${}^1S_0 \to {}^3P_0$	$T^{(nh,pt),0}_{00,11}$
${}^3S_1 \to {}^1P_1$	$T^{(nh,pt),1}_{01,10}$
${}^3S_1 \to {}^3P_1$	$T^{(nh,pt),1}_{01,11}$

- PC T-matrix elements + Ψ^J_{LS}: using the KVP+HH method, starting from a NN+3N interaction model (neglecting the PV potential)
- PV T-matrix elements: $T^{(nh,pt),J}_{0J,1S} = \langle \mathcal{T}\Psi^{J-}_{1S} | V_{PV} | \Psi^{J+}_{0J} \rangle$ (Monte Carlo code by R. Schiavilla)

Results for $A_L(n - {}^3\mathrm{He})$

$$a_z = h_\pi^1 a_0 + C_1 a_1 + C_2 a_2 + C_3 a_3 + C_4 a_4 + C_5 a_5$$

Λ	a_0	a_1	a_2	a_3	a_4	a_5
500	-0.1444	0.0061	0.0226	-0.0199	-0.0174	-0.0005
600	-0.1293	0.0081	0.0320	-0.0161	-0.0156	-0.0001

Preliminary result of the N3he Coll. $a_z = (1.2 \pm 1.0) \times 10^{-8}$ [see talks by Fry & Crawford]

Assuming $h_\pi^1 = 2.6 \times 10^{-7}$, $C_i \sim 10 \times 10^{-7}$
$a_z < 0$ unless $C_2 > 20 \times 10^{-7}$

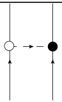
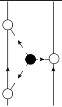
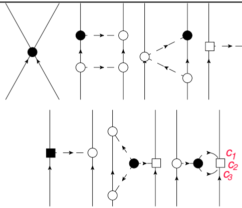
Using the pionless potential by GHH + Large N_c

$$a_z = a_+ \Lambda_0^+ + a_2 \Lambda_2^{{}^1S_0 - {}^3P_0}$$

	a_+	a_2
	$+8.5 \times 10^{-4}$	3.1×10^{-5}

$a_2 \ll a_+$; from the *pp* asymmetry $\Lambda_0^+ \approx 500 \to a_z = 4 \times 10^{-8}$ too large

TRV potential with chiral EFT

Order	Chiral Power	TRV diagrams
LO	Q^{-1}	
NLO	Q^{0}	
N2LO	Q^{1}	

white=PC, black=TRV
dots=LO vertex, square=NLO vertex
First complete derivation of N2LO order

TRV spin rotation (1)

$$f(0) = f_0 + f_M\sigma_x + f_P\sigma_z + f_T\sigma_y$$

$\Rightarrow$ spin rotation term around the y-axis

$$\psi_{out} = e^{ip_n(z-d)} e^{i\frac{2\pi N d}{p_n} f_T\sigma_y} |\chi\rangle$$

The rotation around the y-axis is linearly dependent on TRV LECs

$$\frac{\mathrm{d}\phi_y}{\mathrm{d}z} = \bar{g}_0 d_0 + \bar{g}_1 d_1 + \bar{\Delta} d_2 + \bar{C}_1 d_3 + \bar{C}_2 d_4 + \bar{C}_3 d_5$$

Λ_F (MeV)	d_0	d_1	d_2	d_3	d_4	d_5
450	4.274	0	0	-0.126	-0.089	0
500	4.390	0	0	-0.128	-0.088	0
600	4.455	0	0	-0.118	-0.079	0

The coefficients d_i are in units of rad/m

- PC potential [Entem & Machleidt, 2011]
- No contribution from the LECs $\bar{g}_1$, $\bar{\Delta}$ and $\bar{C}_3$.

TRV spin rotation (2)

Using the estimates of the LECs in term of $\bar{\theta}$ [J. Bsaisou *et al.*, 2015]

$$
\begin{aligned}
\bar{\Delta}^{\theta} &= (0.37 \pm 0.09) \cdot 10^{-3} \bar{\theta} \\
\bar{g}_0{}^{\theta} &= (0.0155 \pm 0.0019) \bar{\theta} \\
\bar{g}_1{}^{\theta} &= (0.0034 \pm 0.0011) \bar{\theta} \\
\bar{C}^{\theta}_{1,2,3} &\simeq (3 \cdot 10^{-2}) \bar{\theta}
\end{aligned}
$$

Λ_F(MeV)	$\mathrm{d}\phi_y/\mathrm{d}z$(rad/m)
450	$(6.62 \pm 0.81) \cdot 10^{-2}\,\bar{\theta}$
500	$(6.80 \pm 0.83) \cdot 10^{-2}\,\bar{\theta}$
600	$(6.91 \pm 0.85) \cdot 10^{-2}\,\bar{\theta}$

- Only $\bar{g}_1^{\theta}$ contribution ($\bar{C}_1^{\theta}$, $\bar{C}_2^{\theta}$ not considered)
- The estimated value of $\bar{\theta} \lesssim 10^{-10}$ so we expect $\mathrm{d}\phi_y/\mathrm{d}z \lesssim 10^{-11}$ rad/m
- Any signal that $\mathrm{d}\phi_y/\mathrm{d}z \gtrsim 10^{-11}$ rad/m $\Rightarrow$ BSM effects

Conclusions

Study of PV observables

- $n-p$, $n-d$ spin rotations
- Longitudinal asymmetry in $n+{}^3\mathrm{He} \to p+{}^3\mathrm{H}$ scattering difficul to explain

Future work

- Aim: take a better control of uncertainties coming from the nuclear dynamics
- $\vec{n}\alpha$ spin rotation
- Extension to PV radiative capture ($n-p \to d-\gamma$, $n-d \to {}^3\mathrm{H}-\gamma$)
- Extension to time-reversal violation: EDMs & $\vec{n}A$ spin rotation along the y direction [Kabir, 1982], [Gudkov, 1992]
  - $\vec{n}p$: $d\phi_y/dz \approx (-6.0 \times \bar{\theta})$ rad m$^{-1} \lesssim 10^{-11}$ Rad m^{-1} $\Rightarrow$ too small ...
  - but it may be enhanced in medium heavy nuclei [Gudkov, 1992]
  - beyond standard model contributions? see, for example, [Mereghetti & van Kolck, 2015], [Bsaisou *et al.* , 2015]

Thank you!