EFT for Non-Standard neutrino Interactions

Michele Tammaro

University of Cincinnati

May 7, 2018

Neutrino sector of SM is an open field for research:

- coherent neutrino scattering;
- flavor oscillations;
- mass problem and right-handed neutrino;

Many experiments are probing (or going to) the low energy regime.

Very low energy phenomenology can be systematically described by an Effective Field Theory. [W. Altmannshofer, MT, J. Zupan: 1805.xxxx]

NSI mediated by New Physics at a scale $\sim \Lambda$, experiments at energy scale $E \ll \Lambda$.

Factorization of scales: short distance physics in Wilson coefficients $\mathcal{C}_i^{(d)}$, long distance in particle operators $\mathcal{O}_i^{(d)}$.

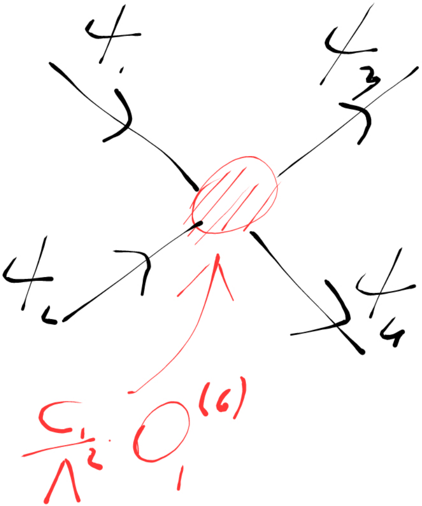
Lagrangian compsed by all possible operators and expanded in a series of E/Λ, *i.e.* operator mass dimensionality:

$$\mathcal{L}_{eff} = \sum_{i,d} \frac{\mathcal{C}_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

The ”full theory” (at Λ scale) is unknown $\rightarrow$ fit Wilson coefficients to experiments.

- This Lagrangian predicts low energy phenomenology in terms of ”few” parameters;
- Measurements of Wilson coefficients give info on NP scale Λ.

Example: Fermi theory of weak interactions



$$\mathcal{L}_{Fermi} \supset \frac{\mathcal{C}_1}{\Lambda^2}\mathcal{O}_1^{(6)}$$

$$\mathcal{O}_1^{(6)} = \left(\bar{\psi}_1\psi_2\right)_{V-A}\left(\bar{\psi}_3\psi_4\right)_{V-A}$$

From experiments (e.g. muon lifetime)

$$\frac{\mathcal{C}_1}{\Lambda^2} \propto 1.6 \times 10^{-5}\mathrm{GeV}^{-2}(\simeq G_F)$$

- Xsec of all weak processes can be predicted from $\mathcal{L}_{Fermi}$ and are $\propto G_F^2$;
- "NP" scale $\Lambda \propto G_F^{-2} \sim m_W$.

The basis:

Dimension five:

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha) F_{\mu\nu}\,,$$

Dimension six:

$$\mathcal{Q}_{1,f}^{(6)} = (\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha)(\bar{f}\gamma^\mu f), \qquad \mathcal{Q}_{2,f}^{(6)} = (\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha)(\bar{f}\gamma^\mu \gamma_5 f)\,,$$

Dimension seven:

$$\mathcal{Q}_1^{(7)} = \frac{\alpha}{12\pi}(\bar{\nu}_\beta P_L \nu_\alpha) F^{\mu\nu} F_{\mu\nu}, \qquad \mathcal{Q}_2^{(7)} = \frac{\alpha}{8\pi}(\bar{\nu}_\beta P_L \nu_\alpha) F^{a\mu\nu} \widetilde{F}_{\mu\nu},$$

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{12\pi}(\bar{\nu}_\beta P_L \nu_\alpha) G^{a\mu\nu} G^a_{\mu\nu}, \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\nu}_\beta P_L \nu_\alpha) G^{a\mu\nu} \widetilde{G}^a_{\mu\nu}\,,$$

$$\mathcal{Q}_{5,f}^{(7)} = m_f(\bar{\nu}_\beta P_L \nu_\alpha)(\bar{f} f)\,, \qquad \mathcal{Q}_{6,f}^{(7)} = m_f(\bar{\nu}_\beta P_L \nu_\alpha)(\bar{f} i\gamma_5 f)\,,$$

$$\mathcal{Q}_{7,f}^{(7)} = m_f(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha)(\bar{f}\sigma_{\mu\nu} f)\,, \qquad \mathcal{Q}_{8,f}^{(7)} = (\bar{\nu}_\beta i\overleftrightarrow{\partial}_\mu P_L \nu_\alpha)(\bar{f}\gamma^\mu f)\,,$$

$$\mathcal{Q}_{9,f}^{(7)} = (\bar{\nu}_\beta i\overleftrightarrow{\partial}_\mu P_L \nu_\alpha)(\bar{f}\gamma^\mu \gamma_5 f)\,, \qquad \mathcal{Q}_{10,f}^{(7)} = \partial_\mu(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha)(\bar{f}\gamma_\nu f)\,,$$

$$\mathcal{Q}_{11,f}^{(7)} = \partial_\mu(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha)(\bar{f}\gamma_\nu \gamma_5 f)\,.$$

Non-Standard Interactions (NSI) [Wolfenstein '78]:

$$\mathcal{L}_{NSI} = \frac{G_F}{\sqrt{2}} \sum_q \left(\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha\right) \left(\varepsilon^{qV}_{\alpha\beta} \bar{q}\gamma^\mu q + \varepsilon^{qA}_{\alpha\beta} \bar{q}\gamma^\mu \gamma_5 q\right)$$

The effect of this NSI can be probed by measuring matter effect on neutrino oscillations. These are described by an effective potential due to neutrino interactions with electrons and nuclei.

Vector interactions: $\bar{\nu}\gamma_\mu P_L \nu$

$$\mathcal{V}_{eff} \simeq \sqrt{2} G_F n_e \tag{1}$$

New interactions: $\bar{\nu} P_L \nu$, $\bar{\nu}\sigma_{\mu\nu} P_L \nu$

$$\mathcal{V}_{eff} \propto m_\nu \tag{2}$$

Heavily suppressed by neutrino mass!

Coherent neutrino-nucleus scattering

Very low-energy neutrinos ($E_\nu \sim q \sim \mathcal{O}(10)$ MeV) $\rightarrow$ coherent interaction with non-relativistic nuclei in the detector.

Spin-dependent interactions might be small, but spin-independent interactions are enhanced by a factor of A^2.

COHERENT Collaboration measured CνNS in August 2017 with a detector composed by 14.6 kg of CsI. [Akimov et al.: 1708.01294]

Neutrino produced by $\pi^+ \rightarrow \nu_\mu + \mu^+$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$.

Expected number of events per neutrino flavor:

$$N_\alpha = n_N \int dE_R dE_\nu \phi_\alpha(E_\nu) \frac{d\sigma}{dE_R}(E_\nu)$$

Deep Inelastic Scattering

Scattering on partons (quarks, gluons, photons) with $q \sim \mathcal{O}(10)$ GeV.

CHARM experiment: 78 plates of marble ($CaCO_3$) $\rightarrow$ isoscalar target ($Z = N$). Neutrinos from 400 GeV proton beam dump. [Dorenbosch et al. '86]

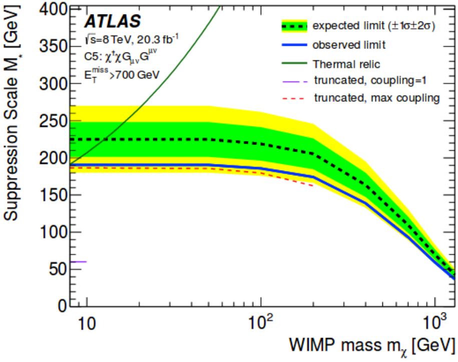
$$R_e = \frac{\sigma^{NC}_{\nu_e} + \sigma^{NC}_{\bar{\nu}_e}}{\sigma^{CC}_{\nu_e} + \sigma^{CC}_{\bar{\nu}_e}} = 0.406 \pm 0.140\,, \qquad R_\mu = 0.340 \pm 0.005\,.$$

Compare results with prediction:

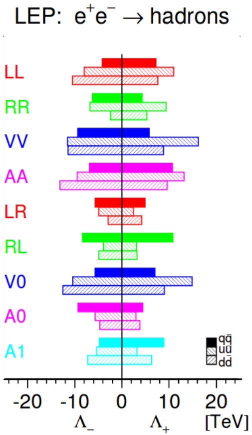
$$R_e = R_e^{\mathrm{SM}} + R_e^{\mathrm{NSI}}$$

Is EFT still valid? Freedom in parameter space is reduced from the assumption of EFT validity at high q.

Other constraints



Monojet (+ missing energy) at LHC



Fermion contact interactions at LEP (or Tevatron)

Results (preliminary!)

Lower bounds on Λ (in GeV)			
$\mathcal{C}_{i,q}^{(d)}$	COHERENT	CHARM	OTHERS
$\mathcal{C}_1^{(5)}$	14	2.1	—
$\mathcal{C}_1^{(7)}$	—	3	47.7
$\mathcal{C}_2^{(7)}$	—	3.4	47.7
$\mathcal{C}_3^{(7)}$	22.3	51	190
$\mathcal{C}_4^{(7)}$	2	56.2	217
$\mathcal{C}_{5,u}^{(7)}$	13.8	4.7	5
$\mathcal{C}_{5,d}^{(7)}$	17.8	5.6	6.4
$\mathcal{C}_{5,s}^{(7)}$	19	12.5	17.4
$\mathcal{C}_{7,u}^{(7)}$	1.5	9.3	16.5
$\mathcal{C}_{7,d}^{(7)}$	1.2	10.9	21.1
$\mathcal{C}_{7,s}^{(7)}$	0.4	24.5	57.1

Summary and Conclusions

- EFT provides a complete and model-independent framework for low energy neutrino phenomenology ("a foamboard for people to cook up models");
- New scalar/tensor interactions in the neutrino sector are poorly contrained with oscillation experiments;
- Deviations from SM predictions of coherent scattering will signal the presence of NSI;
- Future neutrino cross sections measurements will improve these bounds;
- With more data a more general numerical analysis of EFT contributions is required (in progress for a different project).