EFT for Non-Standard neutrino Interactions

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October 12, 2018

Introduction

Lot of interest and efforts (experiment and theory) in Neutrino physics.

New Physics can generate new Non-Standard Interactions (NSI) between neutrino and matter through new mediators.

NSI are not a new idea [Wolfenstein '78]:

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

Oscillations exp can only access these.

Measurements of Elastic neutrino-nucleus scattering [Akimov et al.: 1708.01294] can probe different NSI. (see also K. Scholberg's talk from Tuesday)

Framework of NSI can be systematically described by an Effective Field Theory. [W. Altmannshofer, MT, J. Zupan: 1810.xxxx].

New Physics at some scale $\sim \Lambda$, typical energy at experiment $p \ll \Lambda \rightarrow$ organize the Lagrangian as a series in p/Λ.

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

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

- This Lagrangian gives a systematic expansion in p/Λ of the full theory;
- it predicts low energy phenomenology in terms of "few" parameters with (in principle) an arbitrary small theoretical uncertainy of $\mathcal{O}(p/\Lambda)^{n+1}$;
- Measurements of Wilson coefficients give info on NP scale Λ.

[Les Houches 2017 lectures, Pich: 1804.05664 and Manohar: 1804.05863]

NSI operator basis

3 - Flavors basis: $f = e, \mu, u, d, s$

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:

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

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

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

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

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

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

Oscillations

Matter effect on neutrino oscillations (MSW effect). Described by an effective potential due to neutrino interactions with electrons and nuclei (for non-relativistic, electrically neutral and unpolarized medium)

Vector interactions: $\bar{\nu}\gamma_\mu P_L \nu$ (in the $q \to 0$ limit)

$$\mathcal{V}_{\text{eff}}^{(-)}\Big|_{\text{NSI}} \simeq G_F n_f \left(1 + \varepsilon_{\alpha\beta}^{fV}\right) , \quad \mathcal{V}_{\text{eff}}^{(+)} \sim \mathcal{O}\left(\frac{m_\nu^2}{E_\nu}\right)$$

New interactions:

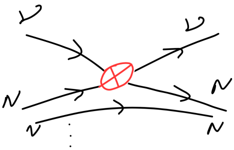
$$S: \bar{\nu} P_L \nu , \quad \bar{\nu}_\beta i\overleftrightarrow{\partial}_\mu P_L \nu_\alpha \quad \to \mathcal{V}_{eff}^S \propto \frac{m_\nu}{E_\nu} ,$$

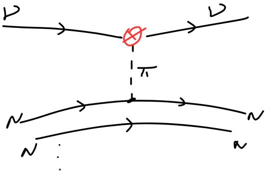
$$T: \bar{\nu}\sigma_{\mu\nu} P_L \nu , \; \partial_\mu(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha) \to \mathcal{V}_{eff}^T = 0 ,$$

N.B.: tensor operator can contribute in polarized mediums [Bergmann, Grossmann and Nardi: 9903517]

Elastic neutrino-nucleus scattering

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





At LO single nucleon interaction $\rightarrow$ hadronization described with form factors for single-nucleon currents [Bishara et al.: 1611.00368, 1707.06998]

$$\langle N'|\bar{q}\gamma^\mu q|N\rangle = \bar{u}'_N\left[F_1^{q/N}(q^2)\gamma^\mu + \frac{i}{2m_N}F_2^{q/N}(q^2)\sigma^{\mu\nu}q_\nu\right]u_N \,,$$

$$\langle N'|\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}|N\rangle = F^N_{\tilde{G}}(q^2)\,\bar{u}'_N i\gamma_5 u_N \,,$$

At small q^2

$$F_i(q^2) = F_i(0) + F_i'(0)q^2 + \ldots \,, \quad F^N_{\tilde{G}}(q^2) = \frac{q^2}{m_\pi^2 - q^2}a^N_{\tilde{G},\pi} + b^N_{\tilde{G}} + \cdots \,,$$

Complex structure of nuclei is described by nuclear response functions
[Fitzpatrick et al.: 1203.3542]

- *Spin-Independent*: $\sigma_{tot} \propto \sigma_N A^2 \to$ prefer high A materials for detectors (for CsI $A \simeq 130 \to 10^4$ enhancement);

  Induced by vector and scalar operators.

- *Spin-Dependent*: $\sigma_{tot} \propto \sigma_N S_A$ (nuclear spin $S_A \sim \mathcal{O}(1)$);

  Induced by axial, pseudoscalars and tensor operators.

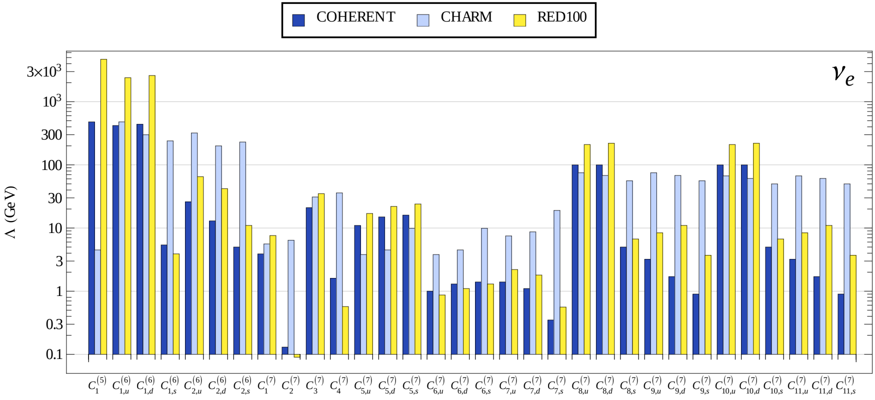
Differential cross section:

$$\frac{d\sigma}{dE_R}(E_\nu) \sim R_\nu W_N \,, \qquad R_\nu\left(\hat{\mathcal{C}}_i^{(d)}, E_\nu, q^2\right) \text{ neutrino kinematics}$$

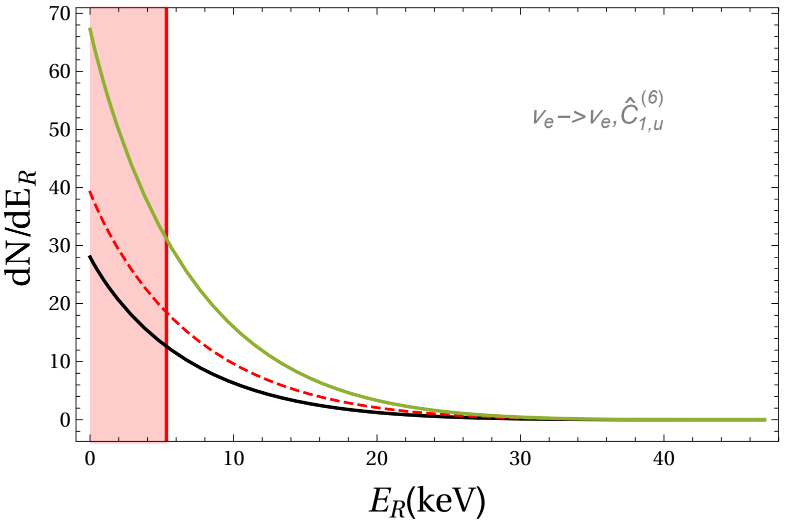
N.B.: form factors carry uncertainty that affect theoretical prediction.

Results (preliminary!)

Assume $\mathcal{C}_i^{(d)} = 1 \rightarrow$ put lower limit on Λ

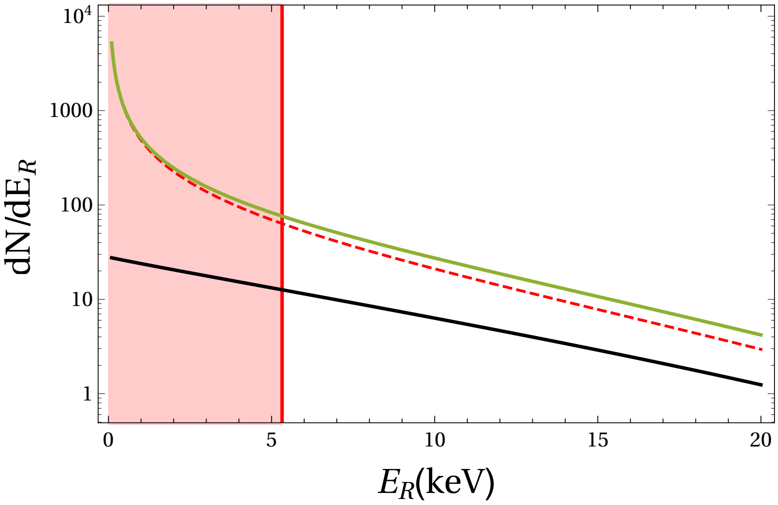


Reduce uncertainties, *e.g.* $\mathcal{Q}^{(6)}_{1,f} = (\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha)(\bar{f}\gamma^\mu f)\,.$



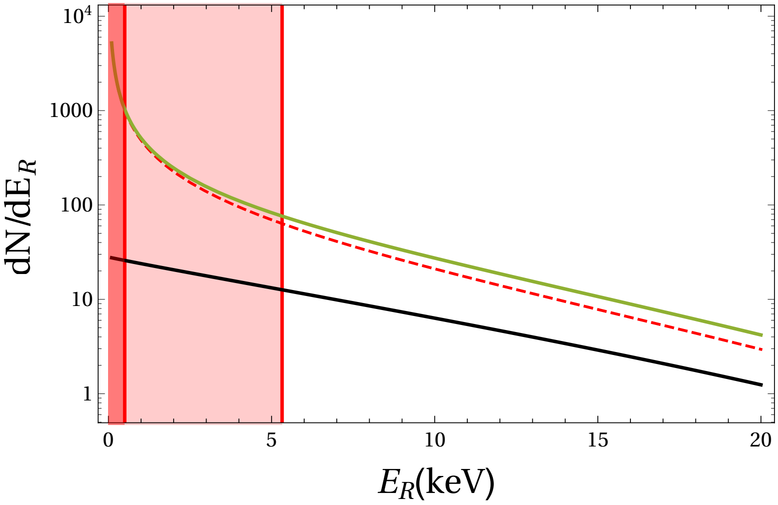
$$R_\nu \propto 4E_\nu^2 - \vec{q}^{\,2} \qquad \hat{\mathcal{C}}^{(6)}_{1,u} \sim \frac{10^{-6}}{\mathrm{GeV}^2} \to \Lambda \sim 400\mathrm{GeV}\,.$$

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



$$R_\nu \propto 1/\vec{q}^2 \qquad \hat{\mathcal{C}}_1^{(5)} \sim \frac{10^{-3}}{\text{GeV}} \to \Lambda \sim 1\text{TeV} \,.$$

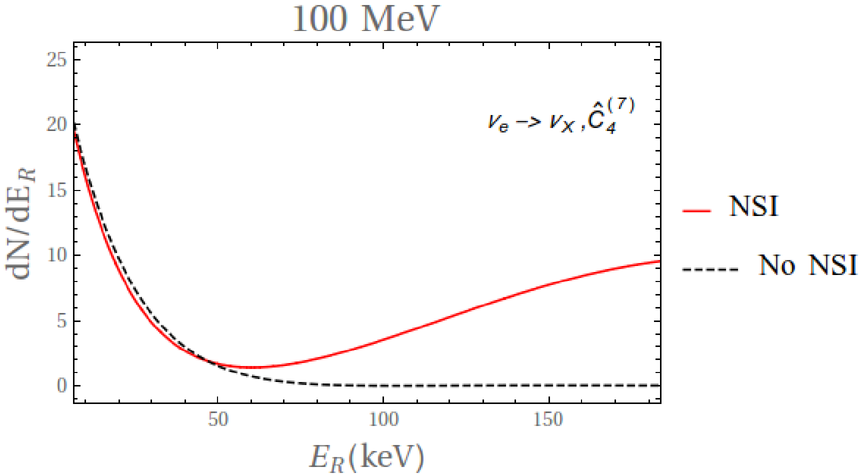
Lower threshold, *e.g.* $\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha) F_{\mu\nu}$.



$$R_\nu \propto 1/\vec{q}^{\,2} \qquad \hat{\mathcal{C}}_1^{(5)} \sim \frac{10^{-3}}{\text{GeV}} \to \Lambda \sim 1\text{TeV} \, .$$

Higher energy, *e.g.*

$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\nu}_\beta P_L \nu_\alpha) G^{a\mu\nu}\widetilde{G}^a_{\mu\nu} \quad \text{or} \quad \mathcal{Q}_{6,f}^{(7)} = m_f(\bar{\nu}_\beta P_L \nu_\alpha)(\bar{f} i\gamma_5 f)$$



$$R_\nu \propto \vec{q}^{\,4} \qquad \hat{\mathcal{C}}_4^{(7)} \sim \frac{10^{-1}}{\text{GeV}^3} \to \Lambda \sim 2\text{GeV}\,.$$

Conclusions

- Elastic neutrino - nucleus scattering provides a possible probe of NSI not accesible to oscillation;
- Need to reduce theoretical and experimental uncertainties;
- Probe different q^2 dependence by lower threshold and higher energy;
- Inelastic scattering;
- Various projects for experiment upgrades... wait for new data.

Thanks!