EFT for Non-Standard neutrino Interactions in Elastic Neutrino - Nucleus scattering

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based on 1812.02778 with W. Altmannshofer and J. Zupan

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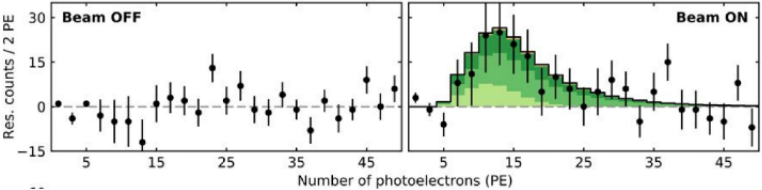
CEνNS

Coherent Elastic neutrino - nucleus Scattering (CEνNS).

Measured for the first time by COHERENT Collaboration in August 2017 with a detector composed by 14.6 kg of CsI. [Akimov et al.: 1708.01294]



This opens a new window in the search for Non-Standard Interactions (NSI)

New Physics can generate new NSI between neutrino and matter through new mediators [Wolfenstein '78]:

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

This includes all effective NSI operators at dimension 6, but in principle NP can generate a larger set of NSI.

Oscillations experiments can only access these dim 6 NSI.

Measurements of Elastic neutrino-nucleus scattering can probe different NSI.

We need a consistent theoretical framework to analyze these NSI from a low energy point of view.

Outline

- Build the complete set of operators up to dimension 7 describing NSI in CEνNS;
- Match the quark NSI basis with the nuclear basis;
- Perform a phenomenological analysis to get lower limit on the NP scale.

Systematic framework of NSI by an Effective Field Theory.
[W. Altmannshofer, MT, J. Zupan: 1812.02778.
See also: Farzan et al. 1802.05171; Billard et al. 1805.01798; Sierra et al. 1806.07424.].

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.

Measurements of Wilson coefficients give info on NP scale Λ up to coupling constants.

NSI complete operator basis

3 - Flavors basis ($\mu \sim 2$ GeV): $f = e, \mu, u, d, s$

Dimension five:

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

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Dimension seven:

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

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

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

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

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

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

Oscillations

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:

$$\begin{aligned} S: &\quad \bar{\nu} P_L \nu \,, & \bar{\nu}_\beta i\overleftrightarrow{\partial}_\mu P_L \nu_\alpha \,, & \quad \mathcal{V}_{eff}^S \propto \frac{m_\nu}{E_\nu} \,, \\ T: &\quad \bar{\nu}\sigma_{\mu\nu} P_L \nu \,, & \partial_\mu(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha) \,, & \quad \mathcal{V}_{eff}^T = 0 \,, \end{aligned}$$

To probe these we need to look at CEνNS (or DIS)

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) scattering elastically with non-relativistic nuclei in the detector.

$q \ll \Lambda_{\rm ChEFT} \sim \mathcal{O}(1~\rm GeV)$ effective ν interactions can be included in the chiral EFT framework.

Three steps:

1. quarks $\to$ nucleons (hadronization)

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2. nucleons $\to$ Non-Relativistic nucleons (ChPT and Heavy Baryon ChPT)
3. NR nucleons $\to$ nuclei (nuclear response functions)

Step 1

At LO in $q/\Lambda_{\rm ChEFT}$ single nucleon interaction $\to$ hadronization described with form factors for single-nucleon currents [Bishara et al.: 1611.00368, 1707.06998]

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

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

In general these new form factors are computed on Lattice.

At small q^2 expand form factors in a series.

$$F_i(q^2) = F_i(0) + F_i'(0)q^2 + \dots\,,$$

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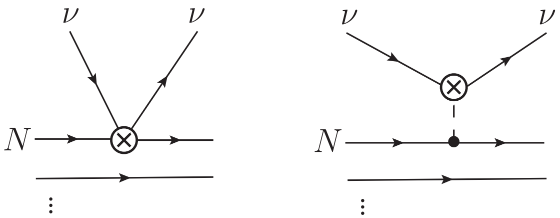

Step 2

NR nucleons currents $1/m_N$ expansion [Jenkins et al. : 91]

d=0

$$\mathcal{O}^{(0)}_{1,p} = (\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha)(v^\mu \bar{p}_v p_v), \qquad \mathcal{O}^{(0)}_{2,p} = (\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha)(\bar{p}_v S^\mu_N p_v)\,,$$
$$\mathcal{O}^{(0)}_{3,p} = (\bar{\nu}_\beta P_L \nu_\alpha)(\bar{p}_v p_v)\,, \qquad \mathcal{O}^{(0)}_{4,p} = (\bar{\nu}_\beta \sigma_{\mu\nu} P_L \nu_\alpha)(\bar{p}_v \sigma^{\mu\nu}_\perp p_v)\,,$$

d=1

$$\mathcal{O}^{(1)}_{1,p} = (\bar{\nu}_\beta P_L \nu_\alpha)\left(\bar{p}_v \frac{iq\cdot S_N}{m_N} p_v\right), \qquad \mathcal{O}^{(1)}_{2,p} = (\bar{\nu}_\beta P_L \nu_\alpha)\left(\bar{p}_v \frac{p_{12}\cdot S_N}{m_N} p_v\right),$$

d=2

$$\mathcal{O}^{(2)}_{1,p} = \frac{iq_\mu p_{12,\nu}}{m_N^2}(\bar{\nu} P_L \nu)(\bar{p}_v \sigma^{\mu\nu}_\perp p_v)\,,$$

Matching 3F - NR basis

$$c^{(0)}_{3,p} = F^p_G \hat{\mathcal{C}}^{(7)}_3 + \sum_q \left(F^{q/p}_S \hat{\mathcal{C}}^{(7)}_{5,q} + Q_q \frac{e^2}{8\pi^2}\frac{2\bar{E}_\nu}{q^2} F^{q/p}_1 \hat{\mathcal{C}}^{(5)}_1\right),$$

Different NSI can match into the same operator in the nuclear basis.

Step 3

Nuclei structure described by nuclear response functions W_N .
[Fitzpatrick et al.: 1203.3542]

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Differential cross section:

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

Theory uncertainty

Expected number of events per neutrino flavor:

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

Uncertainties from nuclear response function (10%) + quenching (25% at COHERENT) + neutrino flux (10%) $\Rightarrow$ Total theory uncertainty: $\sigma_\alpha = 28\%$

Nucleon form factors introduce additional uncertainty! [Bishara et al.: 1707.06998]

opers.	F_i	σ_{F_i}	σ_α
$\hat{\mathcal{C}}_1^{(5)}, \hat{\mathcal{C}}_{1,u/d}^{(6)}, \hat{\mathcal{C}}_{8,u/d;10,u/d}^{(7)}$	$F_1^{u,d/N}(0)$	0%	0.28
$\hat{\mathcal{C}}_{1,s}^{(6)}, \hat{\mathcal{C}}_{8,s;10,s}^{(7)}$	$F_1^{s/N\prime}(0)$	50%	0.57
$\hat{\mathcal{C}}_{2,u/d}^{(6)}, \hat{\mathcal{C}}_{9,u/d;11,u/d}^{(7)}$	$F_A^{u,d/N}(0)$	$3-7\%$	0.34
$\hat{\mathcal{C}}_{2,s}^{(6)}, \hat{\mathcal{C}}_{9,s;11,s}^{(7)}$	$F_A^{s/N}(0)$	16%	0.37
$\hat{\mathcal{C}}_{5,u/d}^{(7)}$	$F_S^{u,d/N}(0)$	$28-31\%$	0.40
$\hat{\mathcal{C}}_{5,s}^{(7)}$	$F_S^{s/N}(0)$	18%	0.33

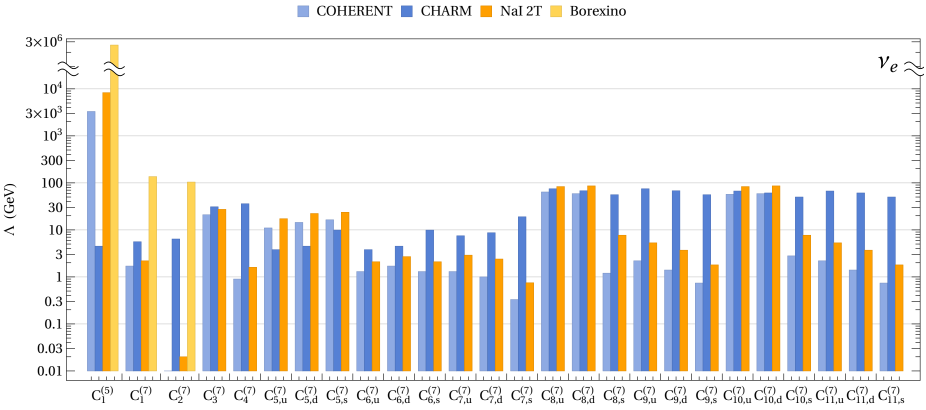
Table continued...

opers.	F_i	σ_{F_i}	σ_α
$\hat{\mathcal{C}}_3^{(7)}$	$F_G^N(0)$	2%	0.28
$\hat{\mathcal{C}}_4^{(7)}$	$F_{\tilde{G}}^N(q)$	20%	0.39
$\hat{\mathcal{C}}_{7,u}^{(7)}$	$F_{T,0}^{u/N}(0)$	2%	0.34
$\hat{\mathcal{C}}_{7,d}^{(7)}$	$F_{T,0}^{d/N}(0)$	4%	0.34
$\hat{\mathcal{C}}_{7,s}^{(7)}$	$F_{T,0}^{s/N}(0)$	270%	2.7
$\hat{\mathcal{C}}_{6,q}^{(7)}$	$a_{P,(\pi/\eta)}^{q/N}$	$4-11\%$	0.35

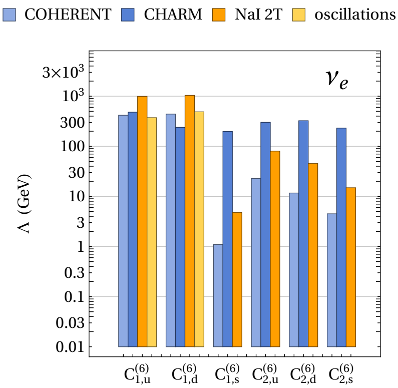
An improvement from Lattice calculations is necessary to provide better predictions.

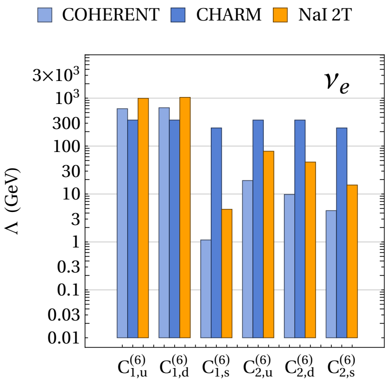
Results at COHERENT

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



Bounds on dim 7 operators are weak, "light" NP is not excluded [Pospelov et al.: 1311.5764, Bertuzzo et al. : 1808.02500]

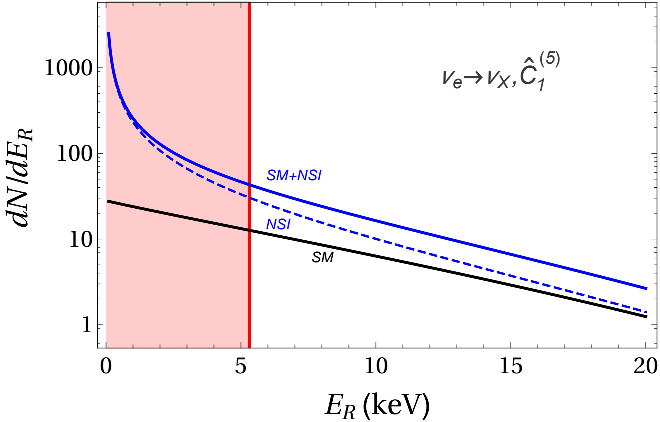




Bounds of $\mathcal{O}(300)$ GeV for SI $C^{(6)}_{1,u(d)}$, much weaker for $C^{(6)}_{1,s}$ and $C^{(6)}_{2,q}$.

Kinematic factor

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha) F_{\mu\nu}\,, \quad R_\nu \propto 1/\vec{q}^2 \qquad \hat{\mathcal{C}}_1^{(5)} \sim \frac{10^{-3}}{\text{GeV}} \to \Lambda \sim 1\text{TeV}\,.$$



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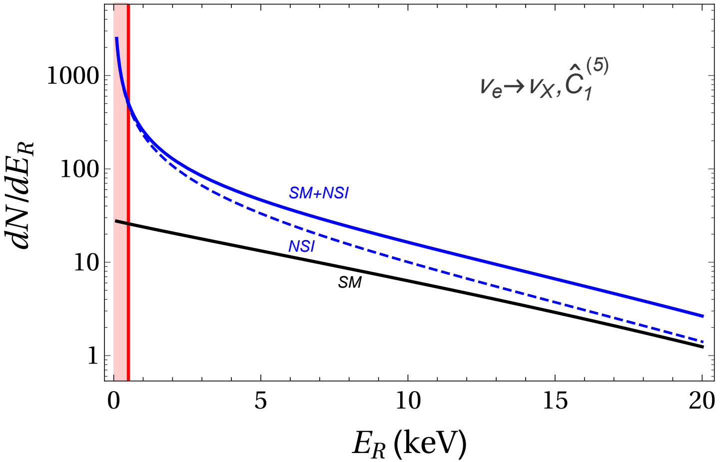
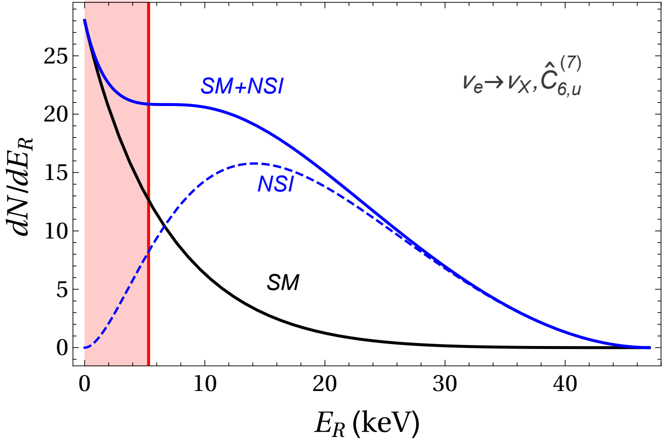
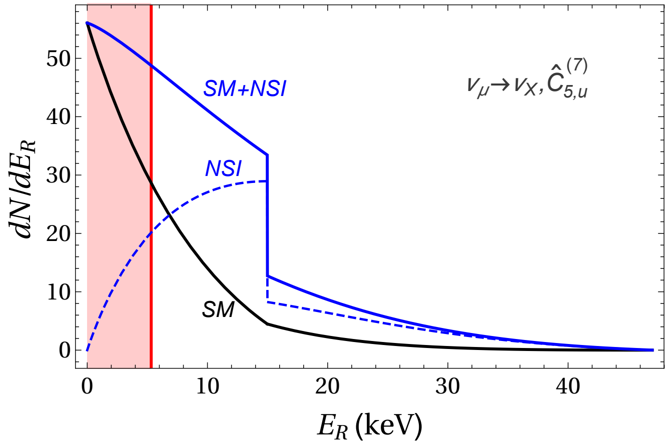


$$\mathcal{Q}_{6,f}^{(7)} = m_f(\bar{\nu}_\beta P_L \nu_\alpha)(\bar{f} i\gamma_5 f)\,, \quad R_\nu \propto \vec{q}^{\,4}\,, \quad \hat{\mathcal{C}}_{6,u}^{(7)} \sim \frac{10^{-1}}{\mathrm{GeV}^3} \to \Lambda \sim 2\mathrm{GeV}\,.$$



$$\mathcal{Q}^{(7)}_{5,f} = m_f(\bar{\nu}_\beta P_L \nu_\alpha)(\bar{f} f)\,, \quad R_\nu \propto \vec{q}^{\,2}\,, \quad \hat{\mathcal{C}}^{(7)}_{5,u} \sim \frac{5\cdot 10^{-4}}{\mathrm{GeV}^3} \to \Lambda \sim 12\mathrm{GeV}\,.$$



Future experiments

A large number of experiments are being planned/built

	T_{th} (keV)	Base (m)	Target	M (kg)	Source
NaI 2T COH	13	28	NaI	2000	SPD
Ge COH	5	22	Ge	10	SPD
LAr COH	20	29	Ar	22	SPD
RED100	0.5	19	Xe	100	3 GW
MINER	0.01	1	^{72}Ge+^{28}Si	30	1 MW
CONNIE	0.028	30	Si	1	3.8 GW
RICOCHET	$0.05 - 0.1$	< 10	Ge/Zn	10	8.54 GW
NU-CLEUS	0.02	< 10	$CaWO_4$,Al_2O_3	0.001	8.54 GW
νGEN	0.350	10	Ge	4×0.4	3 GW
CONUS	< 0.3	17	Ge	4	3.9 GW
TEXONO	$0.15 - 0.2$	28	Ge	1	2×2.9 GW

Reactor experiments fluxes $\sim 2 \times 10^{20} \bar{\nu}_e / s / \mathrm{GW}$ with max energy ~ 8 MeV.

Conclusions

- Elastic neutrino - nucleus scattering provides a possible probe of NSI not accesible to neutrino oscillation experiments;
- CEνNS can be systematically described by an EFT expansion;
- We provide the basis up to dimension 7 operators and the lower limits on NP scale;
- A large number of experiments will look at CEνNS in the near future!

Thanks!