Nonstandard interactions

Timo J. Kärkkäinen

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University of Silesia, Katowice, Poland (starting 1.8.2026)
Helsinki Institute of Physics, Helsinki, Finland

Contents

- Formalism of Non-Standard Interactions
- Connection to Neutrino Oscillation
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In the context of neutrino physics, there are three important effective operators:

$$\mathcal{O}_W = \frac{C_W}{\Lambda}(\overline{L^c} \cdot H)(H \cdot L)$$
$$\mathcal{O}_{\text{NSI}} = \frac{C_{\text{NSI}}}{\Lambda^2}(\overline{L}\gamma^\mu P_L L)(\overline{f}\gamma_\mu P_C f)$$
$$\mathcal{O}_{\text{mix}} = \frac{C_{\text{mix}}}{\Lambda^2}(\overline{L} \cdot H) i\not{\partial}(H^\dagger \cdot L)$$

Non-Standard Interactions (NSI)

Wolfenstein 1978, Valle 1987, Roulet 1991, Guzzo, Masiero, Petcov 1991, Grossmann 1995...

New physics responsible for neutrino masses and mixing may change the effects of matter on propagating neutrinos, and also neutrino production at the source and detection process at detector: NSI. (Similar effects from ν decay, beam decoherence etc.)

NSI is V$\pm$A type, but other operators with S, T and P can be considered. In low energy regime, the NSI operators are

$$\mathcal{L}^{\mathrm{CC}}_{\mathrm{NSI}} = -2\sqrt{2}G_F\varepsilon^{ff',C}_{\alpha\beta}(\overline{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})(\overline{f}\gamma^\mu P_C f'),$$
$$\mathcal{L}^{\mathrm{NC}}_{\mathrm{NSI}} = -2\sqrt{2}G_F\varepsilon^{f,C}_{\alpha\beta}(\overline{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})(\overline{f}\gamma^\mu P_C f), \quad C = L, R.$$

$|\varepsilon|$ describes the strength of the NSI with respect to Fermi interaction. As $G_F \sim 1/M_W^2$,

$$|\varepsilon| \sim \left(\frac{M_W}{\Lambda}\right)^2,$$

where Λ is the scale of new physics assuming the high-energy theory has natural couplings. If $|\varepsilon| \sim 0.01$, the new physics scale $\Lambda \sim \mathcal{O}(1)$ TeV.

Hamiltonian related to standard interactions (SI) is given by

$$H_{\rm SI} = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} + \sqrt{2} G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

Neutrino oscillations are sensitive to MSW potential, which is distorted via NSI:

$$H = H_{\rm SI} + H_{\rm NSI}$$

$$H_{\rm NSI} = \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix} \xmapsto{\text{ph. rot.}} \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon^m_{ee} - \varepsilon^m_{\mu\mu} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & 0 & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} - \varepsilon^m_{\mu\mu} \end{pmatrix}$$

NSI introduces eight extra free parameters to global fit. (Two from real diagonal entries, and six from complex off-diagonals.)

Bounds on NSI from neutrino oscillation

Biggio, Blennow, Fernandez-Martinez 2009, Ohlsson 2012, Miranda, Nunokawa 2015, Dev et al. 2019...

The NSI parameters $\varepsilon^m_{\alpha\beta}$ in Hamiltonian H_{NSI} are constructed from the NSI parameters $\varepsilon^{f,C}_{\alpha\beta}$ Lagrangian $\mathcal{L}^{\mathrm{NC}}_{\mathrm{NSI}}$ as follows:

$$\varepsilon^m_{\alpha\beta} = \sum_{\substack{f=e,u,d \\ C=L,R}} \varepsilon^{f,C}_{\alpha\beta}$$

$$\varepsilon^m_{\alpha\beta} = \begin{cases} \varepsilon^e_{\alpha\beta} + 2\varepsilon^u_{\alpha\beta} + \varepsilon^d_{\alpha\beta} + \dfrac{N_n}{N_e}(\varepsilon^u_{\alpha\beta} + 2\varepsilon^d_{\alpha\beta}) \text{ for Earth-like matter,} \\ \varepsilon^e_{\alpha\beta} + 2\varepsilon^u_{\alpha\beta} + \varepsilon^d_{\alpha\beta} \text{ for solar-like matter} \end{cases}$$

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & - & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}, \quad |\varepsilon^{\odot}_{\alpha\beta}| < \begin{pmatrix} 2.5 & 0.21 & 17 \\ 0.21 & - & 0.21 \\ 1.7 & 0.21 & 9.0 \end{pmatrix}$$

The diagonal ($\alpha = \beta$) terms are real, but off-diagonal terms can be complex and interfere with the standard CP phase δ of neutrino oscillations.

Entering the precision era of neutrino oscillation physics

Sub-leading contributions and effects must be taken into account for precision studies. Next-generation oscillation experiments can determine oscillation probabilities at sub-percent level.

- Misinterpretation of mass ordering via $\varepsilon_{e\tau}$ interference [Capozzi, Chatterjee, Palazzo, PRL 124 (2020) 11]
- One-loop corrections to Mikheyev-Smirnov-Wolfenstein potential [Huang, Ohlsson, Vihonen, Zhou, PRD 112 (2025) 11]
- Interference of NSI on resolving octant degeneracy.
- NOνA-T2K -tension can be explained via NSI or neutrino decoherence.

NSI originating from theories beyond the SM

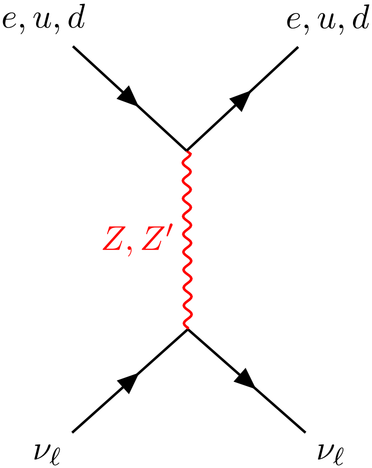
$SU(2)_L$ leptoquark	$\varepsilon^{u}_{\alpha\beta} = -\dfrac{\lambda_\alpha \lambda^*_\beta}{4\sqrt{2} G_F M_S^2}$
Triplet Higgs model	$\varepsilon^{e}_{\alpha\beta} = -\dfrac{M_\Delta^2}{2\sqrt{2} G_F v^4 \lambda^2_{\Delta\phi\phi}} (m_\nu)_{e\beta} (m_\nu^\dagger)_{\alpha e}$
Zee model	$\varepsilon^{e}_{\alpha\beta} = \dfrac{Y_{\alpha e} Y^*_{\beta e}}{4\sqrt{2} G_F} \left(\dfrac{\sin^2\phi}{M^2_{h^+}} + \dfrac{\cos^2\phi}{M^2_{H^+}} \right)$

- These assume new physics scale Λ is large. What if BSM is hiding in the low-energy, small-coupling region?
- Small couplings present in SM, why not in BSM? (Electron Yukawa $\sim 3 \times 10^{-6}$.)
- Example: superweak extension.

$$\varepsilon^{m}_{\alpha\beta} = -\frac{v^2}{8M^2_{Z'}} \frac{N_n}{N_e} \left(g'_y \cos\theta_Z - \frac{g_L \sin\theta_Z}{\cos\theta_W} \right) \left((g'_y - g'_z) \cos\theta_Z - \frac{g_L \sin\theta_Z}{\cos\theta_W} \right)$$

Light and heavy mediator NSI

[Coloma, Denton, González-García, Maltoni, Schwetz, JHEP 04 (2017) 116]



The coupling g^2 times the propagator of NSI mediator (mass M) is generically given by

$$\frac{g^2}{q^2 - M^2}, \quad \text{where } q \text{ is the momentum transfer.}$$

- If the mediator is heavy, the NSI effects are proportional to $-g^2/M^2$.
- If the mediator is light, the NSI effects are proportional to g^2/q^2
- If we probe NSI via neutrino oscillations, the neutrino propagation in matter is affected by MSW potential arising from *forward coherent scattering*, where $q^2 = 0$ regardless of mediator mass.

Constraints to NSI

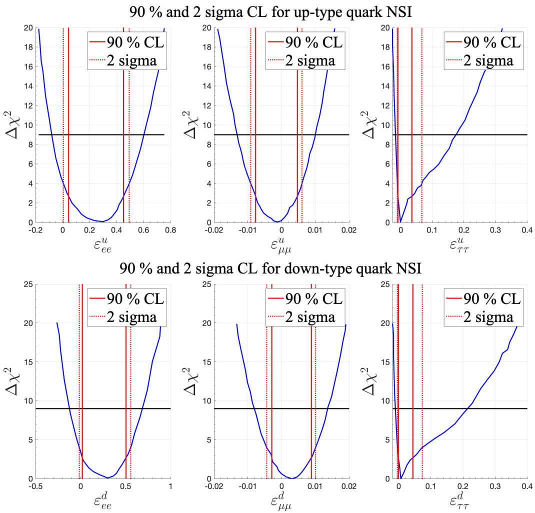
- First stage: high-energy theory enforces texture for NSI matrix.

	$\begin{pmatrix} \varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \end{pmatrix}$ $\mu - \tau$ symmetry	$\begin{pmatrix} \varepsilon_e & 0 & 0 \\ 0 & \varepsilon_\mu & 0 \\ 0 & 0 & \varepsilon_\tau \end{pmatrix}$ Flavour-conserving	$\begin{pmatrix} \varepsilon & 0 & 0 \\ 0 & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{pmatrix}$ Flavour-universal
CLFV decays	✓	No	No
ν oscillation	✓	✓	No
CEνNS	✓	✓	✓
ν scattering	maybe	maybe	maybe

- Second stage: existing limits on NSI constrain the parameters of the high-energy theory.

Global bounds: NSI with heavy mediators

[Kärkkäinen, Trócsányi, Phys.Rev.D **107** (2023) 11, arXiv: 2301.06621

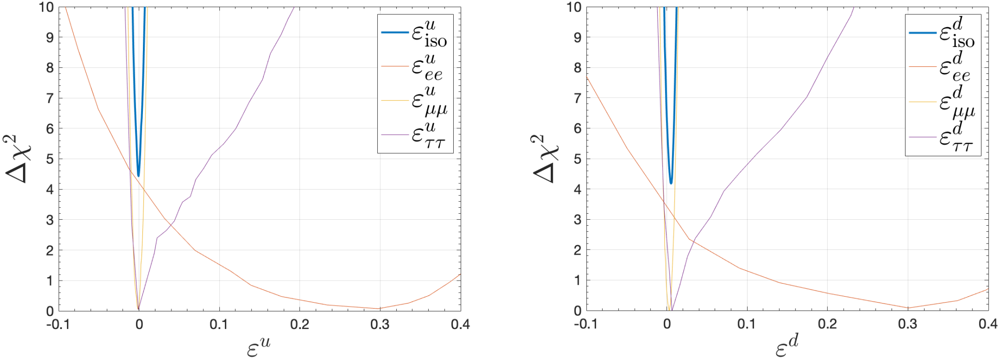


How well the the existing bounds are consistent with theories exhibiting flavour-universal NSI?

$$\boxed{\varepsilon^m_{ee} \stackrel{?}{=} \varepsilon^m_{\mu\mu} \stackrel{?}{=} \varepsilon^m_{\tau\tau}}$$

We test the hypothesis by combining the individual $\Delta\chi^2$ distributions.

Flavour-universal NSI with heavy mediators in tension



Mediators with $M > \mathcal{O}(10)$ GeV and quark-flavour universal couplings are excluded at 2σ. $\varepsilon^{u,d} = \mathcal{O}(10^{-3})$ is within 3σ CI.

Light mediator NSI escapes high-energy constraints

- High-energy neutrino scattering experiments such as CHARM and NuTeV *are insensitive to light NSI mediators!* ($\langle q^2 \rangle \sim 20$ GeV^2 kills the NSI)
- Neutrino oscillations can only probe nondiagonal NSI and differences of diagonal NSI parameters due to phase freedom.

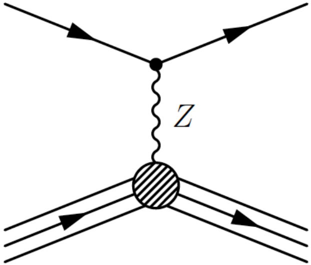
$$H_{\text{NSI}} = \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix} \xrightarrow{\text{ph. rot.}} \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon^m_{ee} - \varepsilon^m_{\mu\mu} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & 0 & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} - \varepsilon^m_{\mu\mu} \end{pmatrix}$$

- Only way to measure diagonal NSI elements themselves is via *Coherent elastic neutrino-nucleon scattering* (CEνNS). F_N and F_Z are nuclear form factors.

$$\frac{d\sigma(\nu_\alpha N \to \nu_\alpha N)}{dT}(E, T)\bigg|_{\text{SM, tree}} = \frac{G_F^2 M}{\pi} \left(1 - \frac{M_N T}{2E^2}\right) \left[g_p Z F_Z(|\mathbf{q}|^2) + g_n N F_N(|\mathbf{q}|^2)\right]^2$$

$g_n \ll g_p$, making the neutron term dominant. Above the sub-leading contribution from neutrino charge radius is suppressed. [Cadeddu et al., PRD 102 (2020) 1]

CEνNS with nonstandard interactions



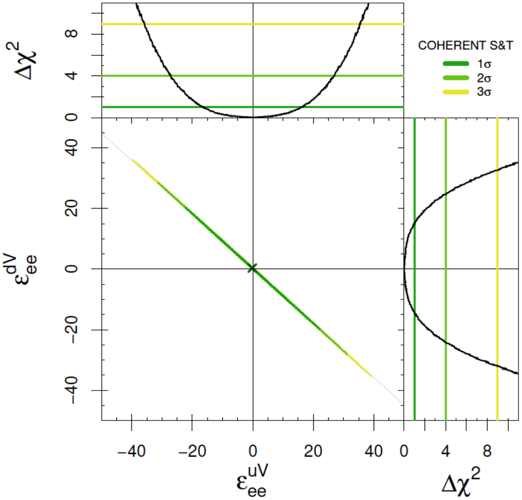
- CEνNS proposed in 1974 [Freedman, PRD 9 (1974) 1389].
- First observed in 2017 [COHERENT collab., Science 357 (2017) 6356, PRL 126 (2021) 1].
- Nuclear recoil kinetic energy $T \lesssim 10$ keV made the detection notoriously difficult.
- **Only way to to measure diagonal light-mediator NSI!** (Assuming $T^2 \ll M^2$, so no ultralight!)

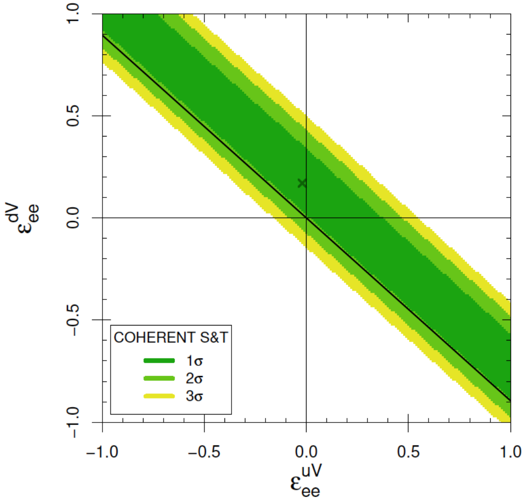
$$\left.\frac{d\sigma}{dT}\right|_{\text{NSI}} = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E^2}\right)\left\{\left[(g_p + 2\varepsilon^u_{ee} + \varepsilon^d_{\alpha\alpha}) Z F_Z(|\mathbf{q}|^2) + (g_n + \varepsilon^u_{\alpha\alpha} + 2\varepsilon^d_{\alpha\alpha}) N F_N(|\mathbf{q}|^2)\right]^2 + \sum_{\beta\neq\alpha}\left|(2\varepsilon^u_{\alpha\beta} + \varepsilon^d_{\alpha\beta}) Z F_Z(|\mathbf{q}|^2) + (\varepsilon^u_{\alpha\beta} + 2\varepsilon^d_{\alpha\beta}) N F_N(|\mathbf{q}^2|)\right|^2\right\},$$

In SM at low Q^2, the neutron contribution dominates.

COHERENT results

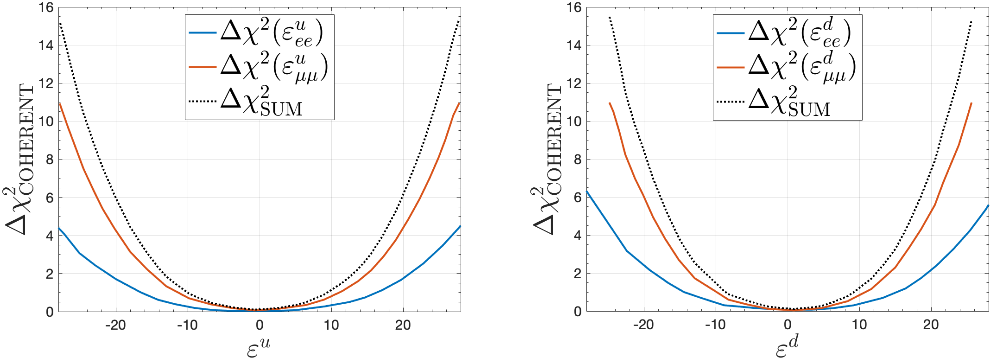
[Giunti, PRD 101 (3) (2020) 035039]





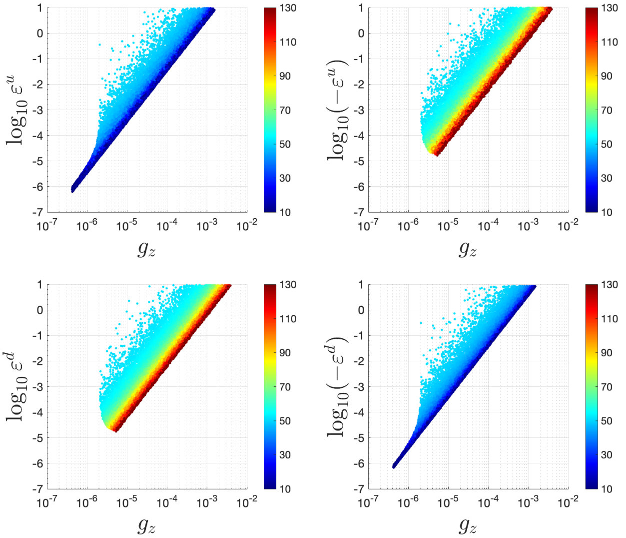
Flavour-universal NSI with light mediators is consistent with COHERENT

[Kärkkäinen, Trócsányi, Phys.Rev.D **107** (2023) 11, arXiv: 2301.06621



Within 2σ CI, $\varepsilon^u \in [-17, 17]$ and $\varepsilon^d \in [-15, 16]$.

Bounds on gauged $U(1)_z$ ("superweak") extension



A simple BSM containing a Z' boson on MeV scale (colour scale in figures), with gauge coupling g_z.

Sign of NSI parameter flips at $M_{Z'} \approx 51$ MeV.

Conclusions

- Nonstandard interactions provide an interface between high-energy theory parameters and low-energy observables via neutrino oscillations and CEνNS for light mediators.
- Heavy mediator flavour-universal NSI is in significant tension with experimental data.
- Light mediator NSI is insensitive to high-energy neutrino scattering experiments.
- A lot of *terra incognita* at low-energy flavour-universal processes.