Improving the Global SMEFT Picture with Bounds on Neutrino NSI

Salvador Urrea

Based on arXiv:2411.00090

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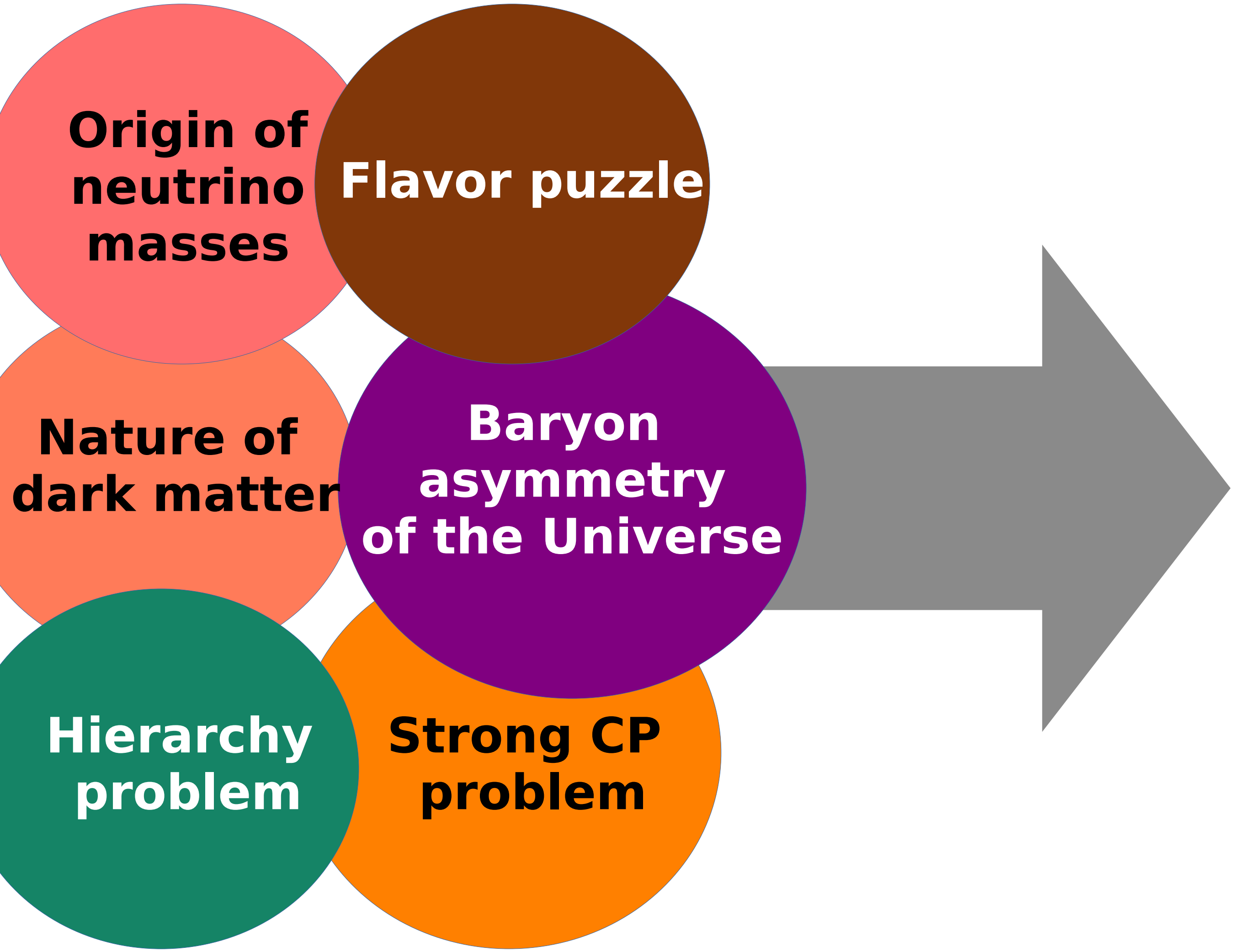
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

CNRS

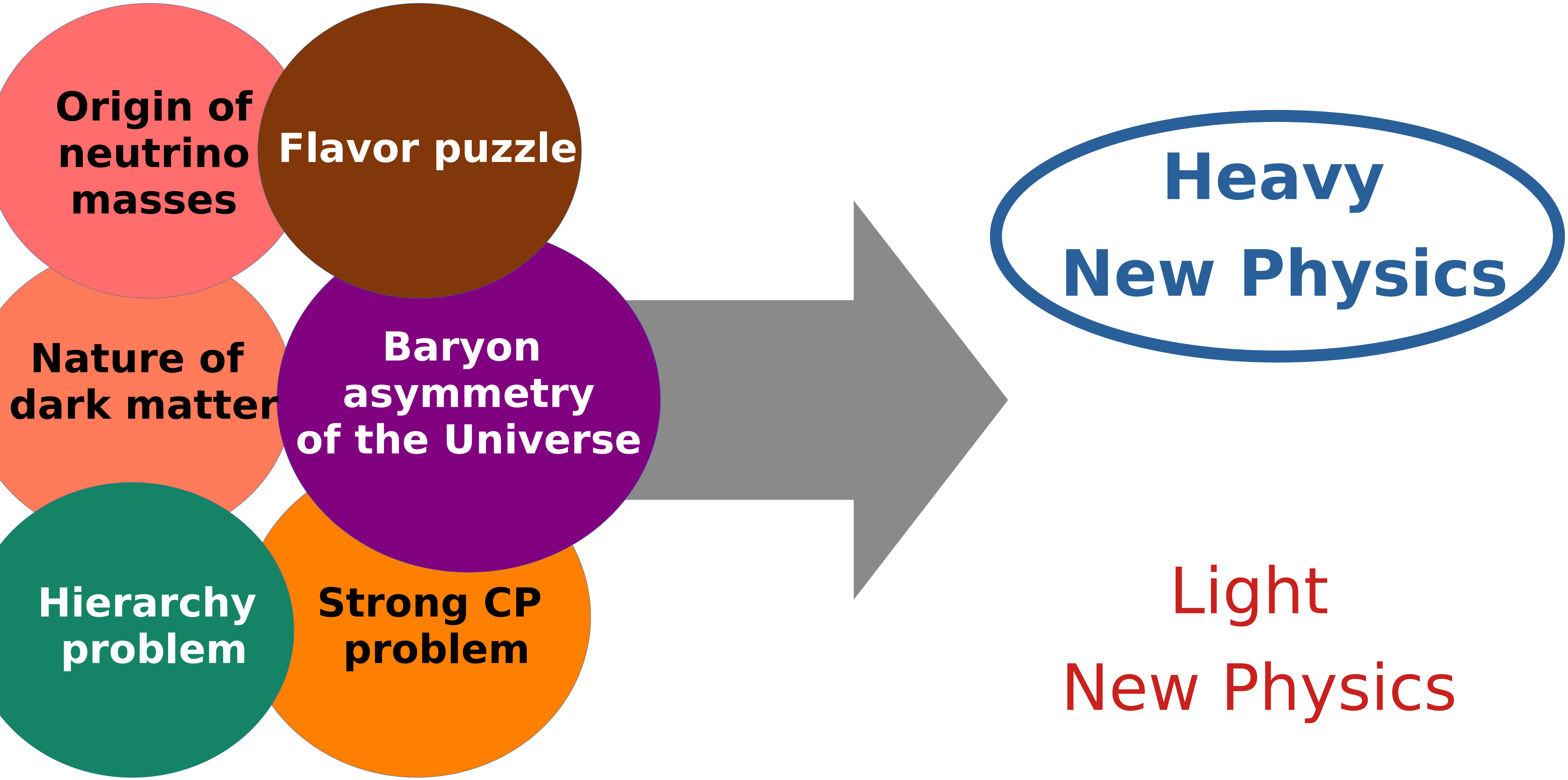
Call for new Physics



Heavy New Physics

Light New Physics

Call for new Physics



SMEFT

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots$$

$$\delta\mathcal{L}^{d} \equiv \sum_k \frac{c_k \mathcal{O}_k^{(d)}}{\Lambda^{d-4}}$$

Weinberg operator

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\frac{\kappa^{(5)}_{\alpha\beta}}{\Lambda}\left(\overline{l^C_{L\alpha}}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger l_{L\beta}\right) + \text{ h.c.}$$

Neutrino Masses

Weinberg, S. 1979

SMEFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots$$

$$\delta\mathcal{L}^{d} \equiv \sum_{k} \frac{c_k \mathcal{O}_k^{(d)}}{\Lambda^{d-4}}$$

A few examples

$$O_{lq}^{(1)} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{q}_L \gamma^\mu q_L\right)$$

$$O_{lq}^{(3)} = \left(\bar{l}_L \gamma_\mu \sigma^k l_L\right)\left(\bar{q}_L \gamma^\mu \sigma^k q_L\right)$$

$$O_{lu} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{u}_R \gamma^\mu u_R\right)$$

$$O_{ld} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{d}_R \gamma^\mu d_R\right)$$

$$O_{eq} = \left(\bar{e}_R \gamma_\mu e_R\right)\left(\bar{q}_L \gamma^\mu q_L\right)$$

SMEFT connection with NSI

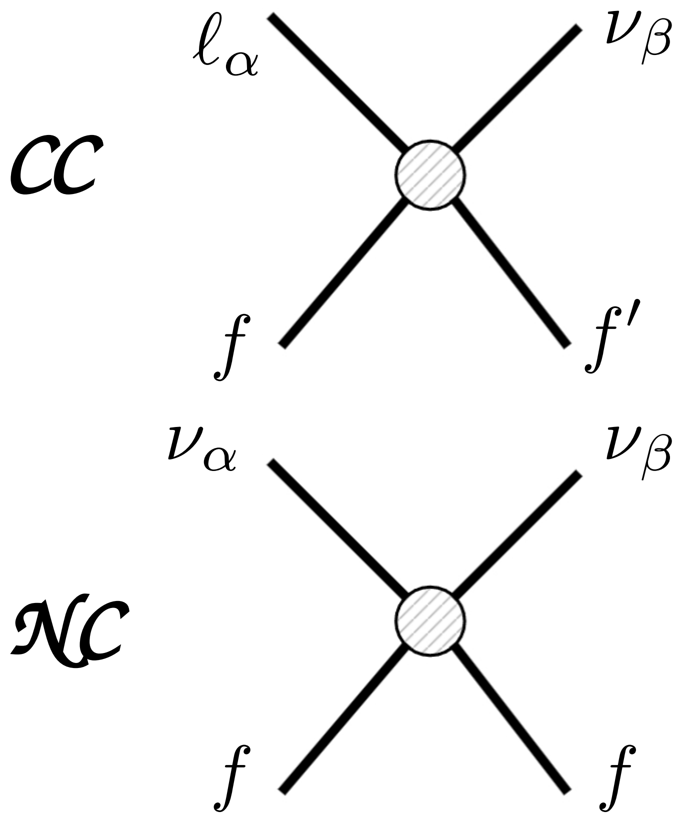
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots$$

$$\delta\mathcal{L}^{d} \equiv \sum_k \frac{c_k \mathcal{O}_k^{(d)}}{\Lambda^{d-4}}$$

Operators affecting neutrinos oscillations

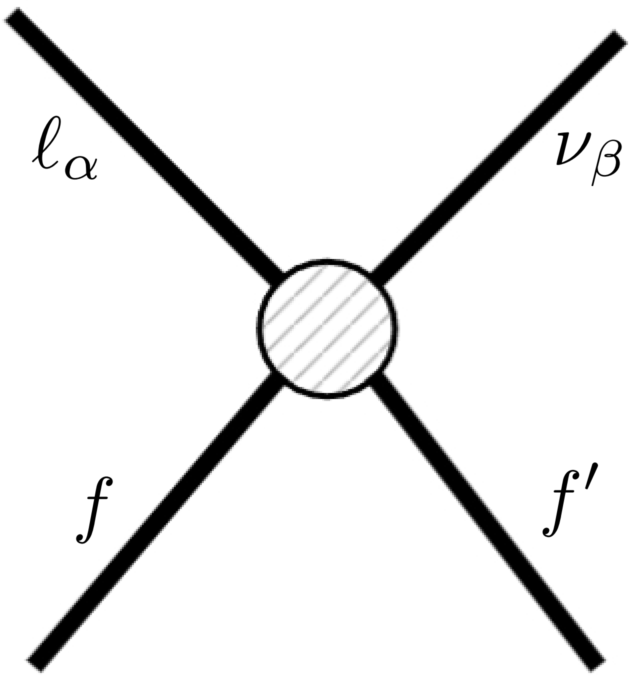
$$\delta\mathcal{L}^{d=6} = \text{NSI} + \ldots$$

- ν Production
- ν Propagation
- ν Detection



Charged current (CC) NSI

$$\mathcal{L}_{\rm NSI,CC} = -2\sqrt{2}G_F \sum_{f,f',\alpha,\beta} \varepsilon_{\alpha\beta}^{ff',P} \left(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta\right)\left(\bar{f}\gamma^\mu P f'\right) + \text{ h.c.}$$



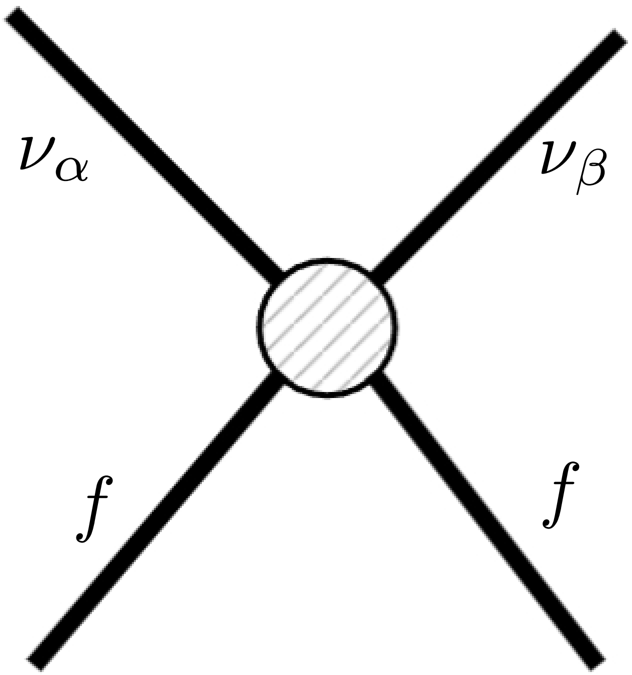
- Affect detection and production.
- **Strongly constrained** by other observables like meson and lepton decays.
- **Neglected in neutrino oscillation studies**

Biggio, Blennow, Fernández-Martínez 2019

Neutral current (NC) NSI

$$P = P_L, P_R$$

$$\mathcal{L}_{\mathrm{NSI,NC}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f}\gamma_\mu P f\right) .$$



$$\varepsilon^{f,V}_{\alpha\beta} \equiv \varepsilon^{f,L}_{\alpha\beta} + \varepsilon^{f,R}_{\alpha\beta}$$

Propagation
Detection

$$\varepsilon^{f,A}_{\alpha\beta} \equiv \varepsilon^{f,L}_{\alpha\beta} - \varepsilon^{f,R}_{\alpha\beta}$$

Detection

- Much more difficult to probe, **main bounds from oscillation data.**

Combination of global fits

Non-Osc. + CEvNS

Bresó-Pla, V., Falkowski, A., González-Alonso, M., & Monsálvez-Pozo, K. (2023). **EFT analysis of New Physics at COHERENT**. JHEP, 05, 074.

SMEFT

ν_μ, ν_e scattering on nuclei

β decays

π, K decays

μ, τ decays

$\cdots$
$\cdots$
$\cdots$

COHERENT CsI and LAr

Osc. + CEvNS

Coloma, P., Gonzalez-Garcia, M. C., Maltoni, M., Pinheiro, J. P., & Urrea, S. (2023). **Global constraints on non-standard neutrino interactions with quarks and electrons.** JHEP, 08, 032.

NC NSI

Solar

Atmospheric

Reactor

Accelerator

COHERENT CsI and LAr

Dresden II Ge

Lepton flavor conserving

Theoretical framework

NSI: Propagation

$$i\frac{d}{dx}\,|\nu_\alpha(x)>=H_{\alpha\beta}|\,\nu_\beta(x)>\,.$$

$$\mathrm{H}=\frac{1}{2E}U\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}U^\dagger+\sqrt{2}G_F N_e(x)\begin{pmatrix} 1+\mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\ \mathcal{E}_{e\mu}^*(x) & \mathcal{E}_{\mu\mu}(x) & \mathcal{E}_{\mu\tau}(x) \\ \mathcal{E}_{e\tau}^*(x) & \mathcal{E}_{\mu\tau}^*(x) & \mathcal{E}_{\tau\tau}(x) \end{pmatrix}$$

Vacuum Matter

$$\mathcal{E}_{\alpha\beta}(x)=\left(\varepsilon_{\alpha\beta}^{e,V}+\varepsilon_{\alpha\beta}^{p,V}\right)+Y_n(x)\varepsilon_{\alpha\beta}^{n,V} \quad \text{with} \quad Y_n(x)\equiv\frac{N_n(x)}{N_e(x)}$$

NSI: Propagation

$$i\frac{d}{dx}\,|\nu_\alpha(x)>= H_{\alpha\beta}|\,\nu_\beta(x)>\,.$$

$$\mathrm{H}=\frac{1}{2E}U\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}U^\dagger+\sqrt{2}G_F N_e(x)\begin{pmatrix} 1+\mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\ \mathcal{E}_{e\mu}^*(x) & \mathcal{E}_{\mu\mu}(x) & \mathcal{E}_{\mu\tau}(x) \\ \mathcal{E}_{e\tau}^*(x) & \mathcal{E}_{\mu\tau}^*(x) & \mathcal{E}_{\tau\tau}(x) \end{pmatrix}$$

Vacuum — Matter

$$\mathcal{E}_{\alpha\beta}(x) = \left(\varepsilon_{\alpha\beta}^{e,V} + \varepsilon_{\alpha\beta}^{p,V}\right) + Y_n(x)\varepsilon_{\alpha\beta}^{n,V} \quad \text{with} \quad Y_n(x) \equiv \frac{N_n(x)}{N_e(x)}$$

A global phase in the Hamiltonian does not modify propagation and propagation is only sensitive to

$$\Delta m_{21}^2 \quad \Delta m_{32}^2 \quad \mathcal{E}_{ee}-\mathcal{E}_{\mu\mu}$$

$$\mathcal{E}_{\tau\tau}-\mathcal{E}_{\mu\mu} \quad \mathcal{E}_{\alpha\beta}\ \alpha\neq\beta$$

NSI: Propagation

$$i\frac{d}{dx}\,|\nu_\alpha(x)>= H_{\alpha\beta}|\,\nu_\beta(x)>\,.$$

$$\text{H}=\frac{1}{2E}U\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}U^\dagger+\sqrt{2}G_F N_e(x)\begin{pmatrix} 1+\mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\ \mathcal{E}^*_{e\mu}(x) & \mathcal{E}_{\mu\mu}(x) & \mathcal{E}_{\mu\tau}(x) \\ \mathcal{E}^*_{e\tau}(x) & \mathcal{E}^*_{\mu\tau}(x) & \mathcal{E}_{\tau\tau}(x) \end{pmatrix}$$

Vacuum **Matter**

$$\mathcal{E}_{\alpha\beta}(x)=\left(\varepsilon^{e,V}_{\alpha\beta}+\varepsilon^{p,V}_{\alpha\beta}\right)+Y_n(x)\varepsilon^{n,V}_{\alpha\beta} \quad \text{with} \quad Y_n(x)\equiv\frac{N_n(x)}{N_e(x)}$$

A global phase in the Hamiltonian does not modify propagation and propagation is only sensitive to

$$\Delta m^2_{21} \quad \Delta m^2_{32} \quad \mathcal{E}_{ee}-\mathcal{E}_{\mu\mu}$$
$$\mathcal{E}_{\tau\tau}-\mathcal{E}_{\mu\mu} \quad \mathcal{E}_{\alpha\beta}\ \alpha\neq\beta$$

Atmospheric and LBL

$$\varepsilon^{\oplus}_{\alpha\beta}=\left(\varepsilon^{e,V}_{\alpha\beta}+\varepsilon^{p,V}_{\alpha\beta}\right)+Y^{\oplus}_n\varepsilon^{n,V}_{\alpha\beta}\,, \qquad Y^{\oplus}_n=\frac{N^{\oplus}_n}{N^{\oplus}_e}\simeq 1.051$$

(Average in Earth)

NSI: NC detection

Elastic ν scattering with electrons

$$\mathrm{ES} \longrightarrow g(\varepsilon^{e,R}_{\alpha\alpha}, \varepsilon^{e,L}_{\alpha\alpha})$$

NC on deutirum

$$\mathrm{SNO} \longrightarrow h(\sum_{\alpha} \varepsilon^{u,A}_{\alpha\alpha} - \varepsilon^{d,A}_{\alpha\alpha})$$

CEvNS

$$\mathrm{CE}\nu\mathrm{NS} \longrightarrow f(\varepsilon^{d,V}_{\alpha\alpha}, \varepsilon^{u,V}_{\alpha\alpha})$$

$$\alpha = e, \mu$$

Matching

$$\mathcal{L}_{\mathrm{SMEFT}} \Longrightarrow \mathcal{L}_{\mathrm{WEFT}} \supset \mathcal{L}_{\mathrm{NSI}}$$

Integrate out the heavy SM fields like the W,Z... employing EOM

Matching

$$\mathcal{L}_{\text{SMEFT}} \Longrightarrow \mathcal{L}_{\text{WEFT}} \supset \mathcal{L}_{\text{NSI}}$$

$$\varepsilon^{e,V}_{\alpha\alpha} = O(\text{Well constraint by Non-Osc}), \qquad \varepsilon^{e,A}_{\alpha\alpha} = O(\text{Well constraint by Non-Osc}),$$

$$\varepsilon^{u,V}_{\alpha\alpha} = \frac{1}{2}\left(\left[c^{(1)}_{\ell q}\right]_{\alpha\alpha 11} + \left[c^{(3)}_{\ell q}\right]_{\alpha\alpha 11} + \left[c_{\ell u}\right]_{\alpha\alpha 11}\right) + O(\text{Well constraint by Non-Osc}),$$

$$\varepsilon^{d,V}_{\alpha\alpha} = -\frac{1}{2}\left(\left[c^{(1)}_{\ell q}\right]_{\alpha\alpha 11} - \left[c^{(3)}_{\ell q}\right]_{\alpha\alpha 11} + \left[c_{\ell d}\right]_{\alpha\alpha 11}\right) + O(\text{Well constraint by Non-Osc}),$$

$$\varepsilon^{u,A}_{\alpha\alpha} = -\frac{1}{2}\left(\left[c^{(1)}_{\ell q}\right]_{\alpha\alpha 11} + \left[c^{(3)}_{\ell q}\right]_{\alpha\alpha 11} - \left[c_{\ell u}\right]_{\alpha\alpha 11}\right) + O(\text{Well constraint by Non-Osc}),$$

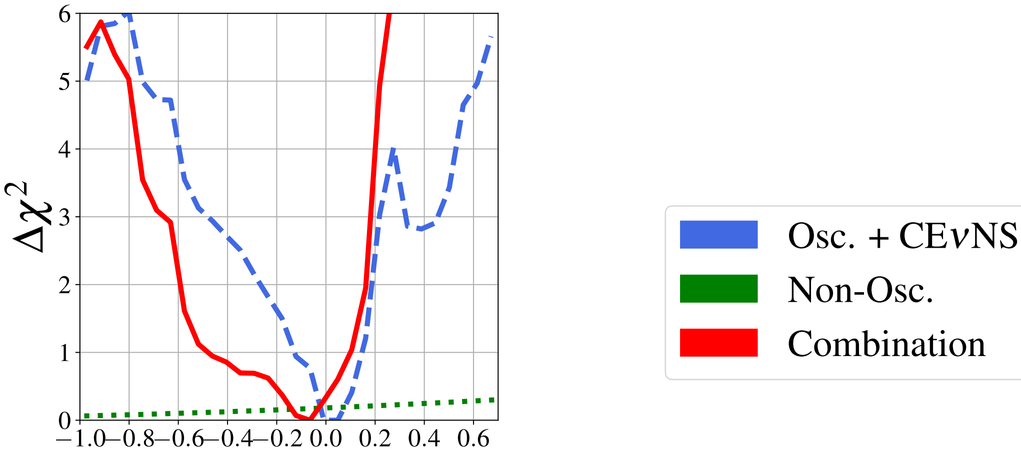
$$\varepsilon^{d,A}_{\alpha\alpha} = -\frac{1}{2}\left(\left[c^{(1)}_{\ell q}\right]_{\alpha\alpha 11} - \left[c^{(3)}_{\ell q}\right]_{\alpha\alpha 11} - \left[c_{\ell d}\right]_{\alpha\alpha 11}\right) + O(\text{Well constraint by Non-Osc}).$$

$$O_{lu} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{u}_R \gamma^\mu u_R\right) \qquad O^{(1)}_{lq} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{q}_L \gamma^\mu q_L\right)$$

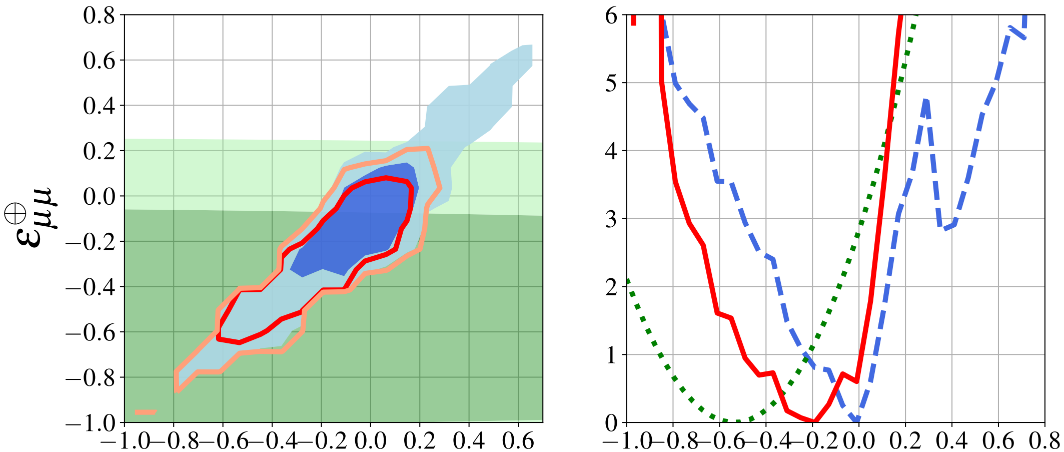
$$O_{ld} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{d}_R \gamma^\mu d_R\right) \qquad O^{(3)}_{lq} = \left(\bar{l}_L \gamma_\mu \sigma^k l_L\right)\left(\bar{q}_L \gamma^\mu \sigma^k q_L\right)$$

Results

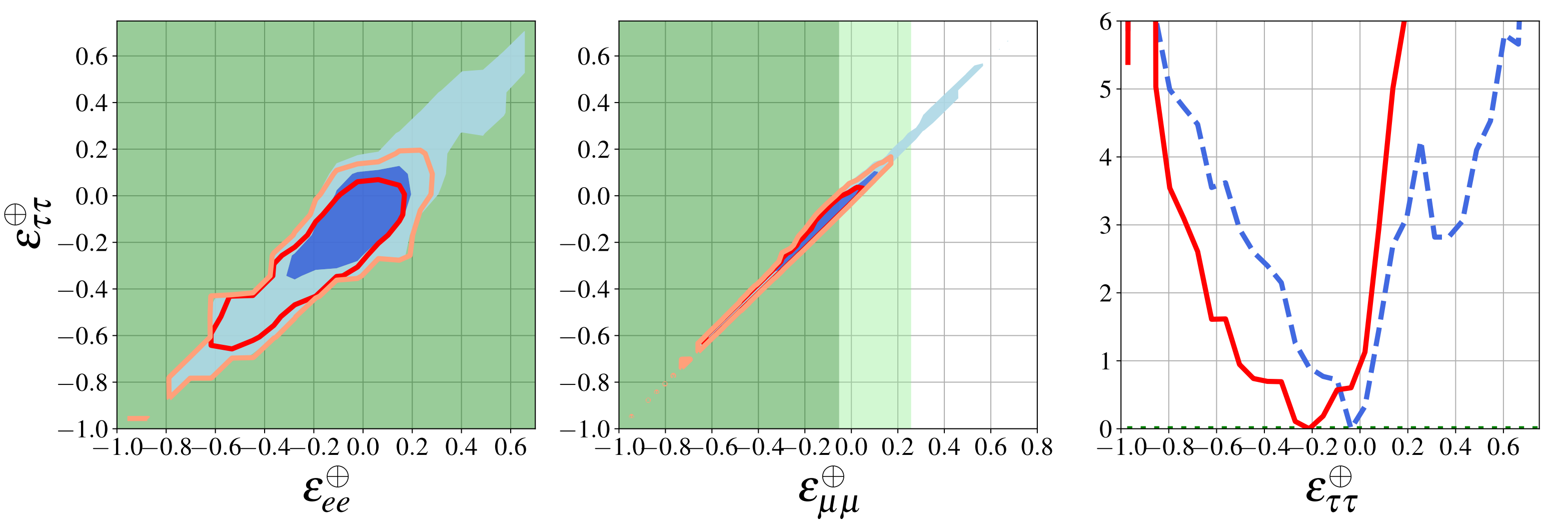
SMEFT impact on neutrino NSIs



NSI	95% C.L. bound	
	Osc. + CEνNS	Non-Osc. + Osc. + CEνNS
$\varepsilon^{\oplus}_{ee}$	(-0.58, 0.50)	(-0.75, 0.16)
$\varepsilon^{\oplus}_{\mu\mu}$	(-0.61, 0.47)	(-0.79, 0.11)
$\varepsilon^{\oplus}_{\tau\tau}$	(-0.62, 0.43)	(-0.80, 0.08)
$\varepsilon^{\oplus}_{ee} - \varepsilon^{\oplus}_{\mu\mu}$	(-0.14, 0.27)	(-0.14, 0.27)
$\varepsilon^{\oplus}_{\tau\tau} - \varepsilon^{\oplus}_{\mu\mu}$	(-0.014, 0.025)	(-0.014, 0.025)



- Neutrino propagation depends only on the differences of NSI.
- Improvements in the second family propagate to the other families.



Neutrino data impact on SMEFT

$$[\hat{c}_{eq}]_{ee11} := [c_{eq}]_{ee11} + \left[c_{\ell q}^{(1)}\right]_{ee11}$$

Operators	1σ interval	
	Non-Osc.	Non-Osc. + Osc. + CEνNS
$[\hat{c}_{eq}]_{ee11}$	0.76 ± 1.80	0.07 ± 0.30
$[c_{\ell u}]_{\mu\mu 11}$	0.110 ± 0.091	0.058 ± 0.076
$[c_{\ell d}]_{\mu\mu 11}$	0.19 ± 0.27	0.11 ± 0.25
$[\hat{c}_{\ell q}^{(1)}]_{\tau\tau 11}$	Unconstrained	0.07 ± 0.19
$[\hat{c}_{\ell u}]_{\tau\tau 11}$	Unconstrained	-0.04 ± 0.54

CEvNS

New bounded SMEFT combinations

$$\varepsilon_{\tau\tau}^{\oplus} \longrightarrow \left[\hat{c}_{\ell q}^{(1)}\right]_{\tau\tau 11} = \left[c_{\ell q}^{(1)}\right]_{\tau\tau 11} + \frac{2+Y_n^{\oplus}}{3\left(1+Y_n^{\oplus}\right)}[c_{\ell u}]_{\tau\tau 11} + \frac{1+2Y_n^{\oplus}}{3\left(1+Y_n^{\oplus}\right)}[c_{\ell d}]_{\tau\tau 11}$$

$$\text{SNO} \longrightarrow [\hat{c}_{\ell u}]_{\tau\tau 11} = [c_{\ell u}]_{\tau\tau 11} - [c_{\ell d}]_{\tau\tau 11}\,.$$

1 flat direction

$$[c_{\ell u}]_{\tau\tau 11} = [c_{\ell d}]_{\tau\tau 11} = -\left[c_{\ell q}^{(1)}\right]_{\tau\tau 11}$$

Conclusions

- **SMEFT and NSI are a good way to parametrize new physics in a model-independent way.**

- **Current neutrino data can provide useful complementary information to constrain SMEFT.**

Back-up

Lagrangians

$$\mathcal{L}_{\mathrm{NC-NSI}} \supset -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{f,X} \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right) \left(\bar{f}\gamma^\mu P_X f\right),$$

$$\begin{aligned}\mathcal{L}_{\mathrm{CC-NSI}} \supset & -2\sqrt{2}G_F \Big\{ \varepsilon_{\alpha\beta}^{\mu e X} \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right) \left(\bar{\mu}\gamma^\mu P_X e\right) + \varepsilon_{\alpha\beta}^{udL} \left(\bar{e}_\alpha \gamma_\mu P_L \nu_\beta\right) \left(\bar{u}\gamma^\mu P_L d\right) \\ & + \varepsilon_{\alpha\beta}^{udR} \left(\bar{e}_\alpha \gamma_\mu P_L \nu_\beta\right) \left(\bar{u}\gamma^\mu P_R d\right) + \frac{1}{2}\varepsilon_{\alpha\beta}^{udS} \left(\bar{e}_\alpha P_L \nu_\beta\right) \left(\bar{u} d\right) \\ & + \frac{1}{2}\varepsilon_{\alpha\beta}^{udP} \left(\bar{e}_\alpha P_L \nu_\beta\right) \left(\bar{u}\gamma_5 d\right) + \varepsilon_{\alpha\beta}^{udT} \left(\bar{e}_\alpha \sigma_{\mu\nu} P_L \nu_\beta\right) \left(\bar{u}\sigma^{\mu\nu} P_L d\right) \Big\} + h.c.\end{aligned}$$

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + \ldots,$$

$$\mathcal{L}_{d=6} = \sum_i \frac{c_i}{v^2}\mathcal{O}_i$$

Lagrangians

$$
\begin{aligned}
\mathcal{L} \supset\; & eA^\mu \sum_{f=u,d,e} Q_f \left(\bar{f}_I \bar{\sigma}_\mu f_I + f_I^c \sigma_\mu \bar{f}_I^c\right) \\
& + \frac{g_L}{\sqrt{2}} \left[W^{\mu +} \bar{\nu}_I \bar{\sigma}_\mu \left(\delta_{IJ} + \left[\delta g_L^{We}\right]_{IJ}\right) e_J + W^{\mu +} \bar{u}_I \bar{\sigma}_\mu \left(V_{IJ} + \left[\delta g_L^{Wq}\right]_{IJ}\right) d_J + \text{ h.c. } \right] \\
& + \frac{g_L}{\sqrt{2}} \left[W^{\mu +} u_I^c \sigma_\mu \left[\delta g_R^{Wq}\right]_{IJ} \bar{d}_J^c + \text{ h.c. } \right] \\
& + \sqrt{g_L^2 + g_Y^2} Z^\mu \sum_{f=u,d,e,\nu} \bar{f}_I \bar{\sigma}_\mu \left(\left(T_3^f - s_\theta^2 Q_f \right) \delta_{IJ} + \left[\delta g_L^{Zf}\right]_{IJ} \right) f_J \\
& + \sqrt{g_L^2 + g_Y^2} Z^\mu \sum_{f=ude} f_I^c \sigma_\mu \left(-s_\theta^2 Q_f \delta_{IJ} + \left[\delta g_R^{Zf}\right]_{IJ} \right) \bar{f}_J^c
\end{aligned}
$$

Operators SMEFT

Chirality conserving $(I,J=1,2,3)$	Chirality violating $(I,J=1,2,3)$
$[O_{\ell q}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(\bar q_J \bar\sigma^\mu q_J)$	$[O_{\ell equ}]_{IIJJ} = (\bar\ell_I^j \bar e_I^c)\epsilon_{jk}(\bar q_J^k \bar u_J^c)$
$[O^{(3)}_{\ell q}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \sigma^i \ell_I)(\bar q_J \bar\sigma^\mu \sigma^i q_J)$	$[O^{(3)}_{\ell equ}]_{IIJJ} = (\bar\ell_I^j \bar\sigma_{\mu\nu} \bar e_I^c)\epsilon_{jk}(\bar q_J^k \bar\sigma_{\mu\nu} \bar u_J^c)$
$[O_{\ell u}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(u_J^c \sigma^\mu \bar u_J^c)$	$[O_{\ell edq}]_{IIJJ} = (\bar\ell_I^j \bar e_I^c)(d_J^c q_J^j)$
$[O_{\ell d}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(d_J^c \sigma^\mu \bar d_J^c)$	
$[O_{eq}]_{IIJJ} = (e_I^c \sigma_\mu \bar e_I^c)(\bar q_J \bar\sigma^\mu q_J)$	
$[O_{eu}]_{IIJJ} = (e_I^c \sigma_\mu \bar e_I^c)(u_J^c \sigma^\mu \bar u_J^c)$	
$[O_{ed}]_{IIJJ} = (e_I^c \sigma_\mu \bar e_I^c)(d_J^c \sigma^\mu \bar d_J^c)$	

One flavor $(I=1,2,3)$	Two flavors $(I<J=1,2,3)$
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar\ell_I \bar\sigma_\mu \ell_I)(\bar\ell_I \bar\sigma^\mu \ell_I)$	$[O_{\ell\ell}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(\bar\ell_J \bar\sigma^\mu \ell_J)$
	$[O_{\ell\ell}]_{IJJI} = (\bar\ell_I \bar\sigma_\mu \ell_J)(\bar\ell_J \bar\sigma^\mu \ell_I)$
$[O_{\ell e}]_{IIII} = (\bar\ell_I \bar\sigma_\mu \ell_I)(e_I^c \sigma^\mu \bar e_I^c)$	$[O_{\ell e}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(e_J^c \sigma^\mu \bar e_J^c)$
	$[O_{\ell e}]_{JJII} = (\bar\ell_J \bar\sigma_\mu \ell_J)(e_I^c \sigma^\mu \bar e_I^c)$
	$[O_{\ell e}]_{IJJI} = (\bar\ell_I \bar\sigma_\mu \ell_J)(e_J^c \sigma^\mu \bar e_I^c)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e_I^c \sigma_\mu \bar e_I^c)(e_I^c \sigma^\mu \bar e_I^c)$	$[O_{ee}]_{IIJJ} = (e_I^c \sigma_\mu \bar e_I^c)(e_J^c \sigma^\mu \bar e_J^c)$

Full NC Matching

$$\varepsilon^{e,V}_{\alpha\alpha} = \delta_{e\alpha}\left(\delta g_L^{We} - \delta g_L^{W\mu} + \frac{1}{2}[c_{\ell\ell}]_{e\mu\mu e}\right) - (1-4s_{\rm w}^2)\delta g_L^{Z\nu_\alpha} + \delta g_L^{Ze} + \delta g_R^{Ze} - \frac{1}{2}\Big([c_{\ell\ell}]_{ee\alpha\alpha} + [c_{\ell e}]_{\alpha\alpha ee}\Big)\,,$$

$$\varepsilon^{u,V}_{\alpha\alpha} = \delta g_L^{Zu} + \delta g_R^{Zu} + \left(1-\frac{8}{3}s_{\rm w}^2\right)\delta g^{Z\nu_\alpha} - \frac{1}{2}\left([c_{\ell q}^{(1)}]_{\alpha\alpha 11} + [c_{\ell q}^{(3)}]_{\alpha\alpha 11} + [c_{\ell u}]_{\alpha\alpha 11}\right)\,,$$

$$\varepsilon^{d,V}_{\alpha\alpha} = \delta g_L^{Zd} + \delta g_R^{Zd} - \left(1-\frac{4}{3}s_{\rm w}^2\right)\delta g^{Z\nu_\alpha} - \frac{1}{2}\left([c_{\ell q}^{(1)}]_{\alpha\alpha 11} - [c_{\ell q}^{(3)}]_{\alpha\alpha 11} + [c_{\ell d}]_{\alpha\alpha 11}\right)\,,$$

$$\varepsilon^{u,A}_{\alpha\alpha} = \delta g_L^{Zu} - \delta g_R^{Zu} + \delta g^{Z\nu_\alpha} - \frac{1}{2}\left([c_{\ell q}^{(1)}]_{\alpha\alpha 11} + [c_{\ell q}^{(3)}]_{\alpha\alpha 11} - [c_{\ell u}]_{\alpha\alpha 11}\right)\,,$$

$$\varepsilon^{d,A}_{\alpha\alpha} = \delta g_L^{Zd} - \delta g_R^{Zd} - \delta g^{Z\nu_\alpha} - \frac{1}{2}\left([c_{\ell q}^{(1)}]_{\alpha\alpha 11} - [c_{\ell q}^{(3)}]_{\alpha\alpha 11} - [c_{\ell d}]_{\alpha\alpha 11}\right)\,,$$

Experiments included in the Global fit

NSI

Propagation

(only vector NSI)

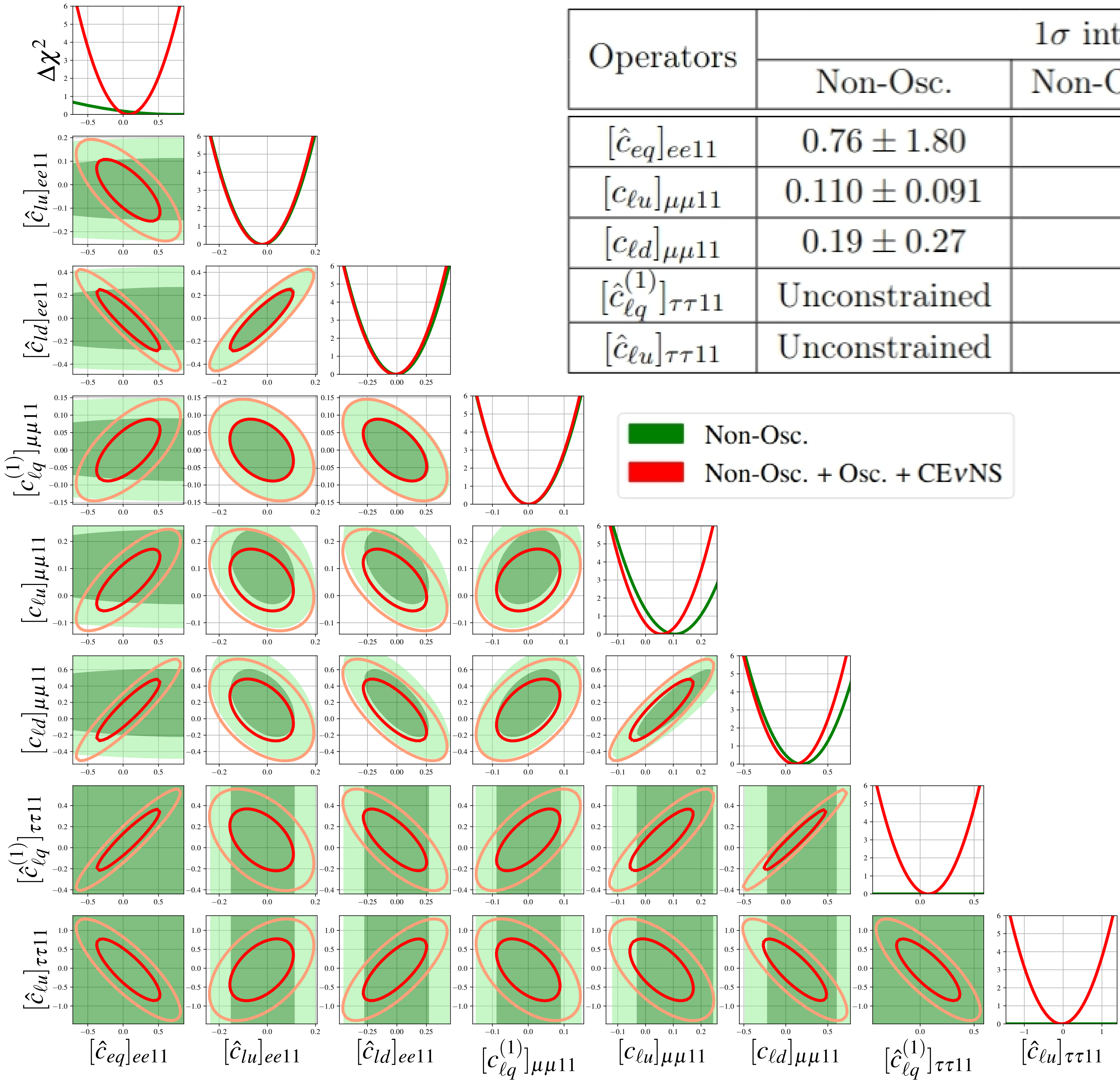
Detection cross sections

(Both vector and axial NSI)

- Elastic scattering with electrons (ES)
- NC on deuterium (Axial)
- CEvNS(Vector)

Our analysis includes data from:

- **Solar:** (Chlorine, Gallex/GNO, SAGE, SNO, SK[1-4], the first two phases of Borexino);
- **Atmospheric:** (SK[1-4], Deepcore, IceCUBE)
- **Reactor**: (KamLAND, Double-Chooz, Daya-Bay, RENO)
- **Accelerator:** (Minos, T2K, NovA)
- **CEvNS**: Dresden II, both the Ar target and the CsI target configurations of COHERENT.



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$[\hat{c}_{eq}]_{ee11}$	0.76 ± 1.80	0.07 ± 0.30
$[c_{\ell u}]_{\mu\mu 11}$	0.110 ± 0.091	0.058 ± 0.076
$[c_{\ell d}]_{\mu\mu 11}$	0.19 ± 0.27	0.11 ± 0.25
$[\hat{c}^{(1)}_{\ell q}]_{\tau\tau 11}$	Unconstrained	0.07 ± 0.19
$[\hat{c}_{\ell u}]_{\tau\tau 11}$	Unconstrained	-0.04 ± 0.54