Global analysis of oscillation data in the presence of BSM neutrino properties

Michele Maltoni

Instituto de Física Teórica UAM/CSIC

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Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + BX(1–3);
  - **Atmospheric**: IC19 | IC24 + SK(1–5);
  - **Reactor**: KamLAND + SNOplus + DC + DB + Reno;
  - **Accelerator**: Minos + T2K + NOvA;
- best-fit point and 1σ (3σ) ranges:

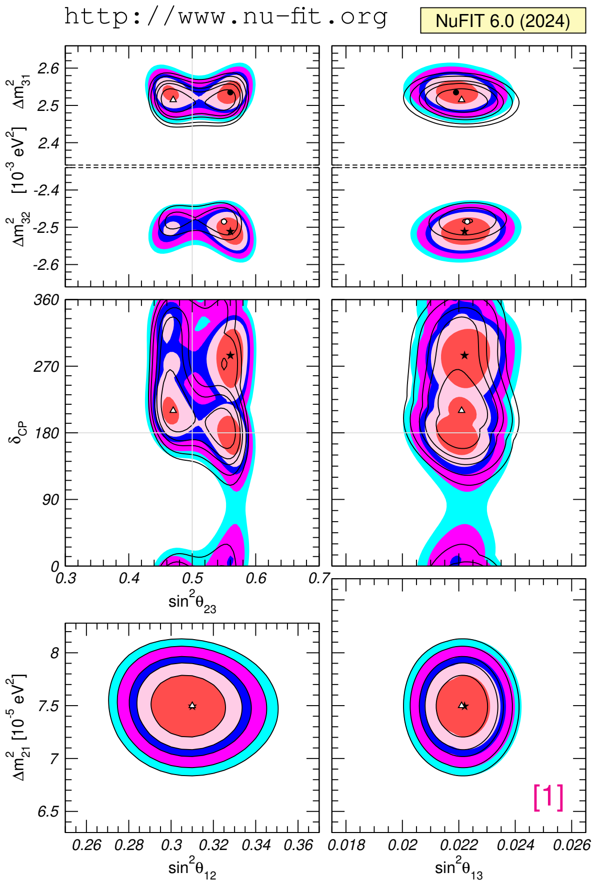
$$\theta_{12} = 33.68\,^{+0.73}_{-0.70}\,\left(^{+2.27}_{-2.05}\right), \qquad \Delta m^2_{21} = 7.49\,^{+0.19}_{-0.19}\,\left(^{+0.56}_{-0.57}\right)\times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = \begin{cases} 48.5\,^{+0.7}_{-0.9}\,\left(^{+2.0}_{-7.6}\right), \\ 48.6\,^{+0.7}_{-0.9}\,\left(^{+2.0}_{-7.2}\right), \end{cases} \qquad \Delta m^2_{31} = \begin{cases} +2.534\,^{+0.025}_{-0.023}\,\left(^{+0.072}_{-0.071}\right)\times 10^{-3}\ \text{eV}^2, \\ -2.510\,^{+0.024}_{-0.025}\,\left(^{+0.072}_{-0.073}\right)\times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.58\,^{+0.11}_{-0.13}\,\left(^{+0.33}_{-0.39}\right), \qquad \delta_{CP} = 285\,^{+25}_{-28}\,\left(^{+129}_{-182}\right);$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.842 & 0.519 \to 0.580 & 0.142 \to 0.155 \\ 0.248 \to 0.505 & 0.473 \to 0.682 & 0.649 \to 0.764 \\ 0.270 \to 0.521 & 0.483 \to 0.690 & 0.628 \to 0.746 \end{pmatrix}.$$



[1] I. Esteban *et al.*, arXiv:2410.05380 & NuFIT 6.0 [http://www.nu-fit.org].

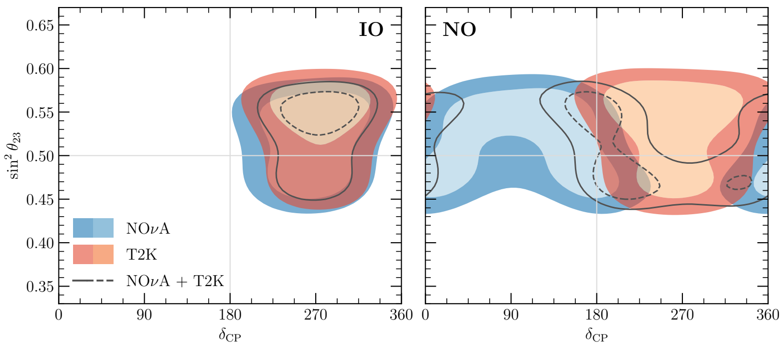
I. Non-standard neutrino-matter interactions

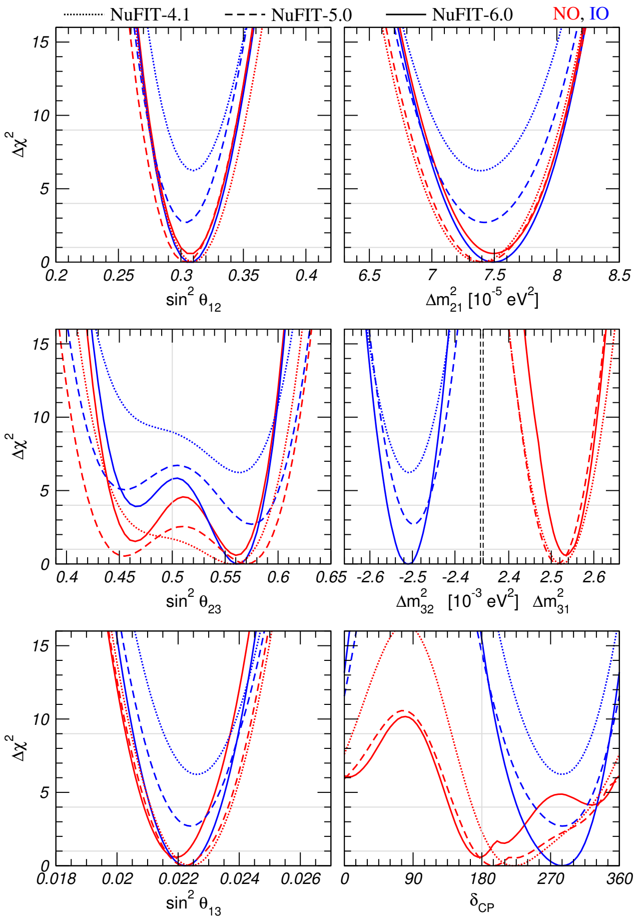
Open issues in 3ν oscillations

- **CP violation**: tension between T2K and NOvA for NO $\Rightarrow$ $\delta_{CP} \approx 180^\circ$ (NO) | $\delta_{CP} \approx 270^\circ$ (IO);
- **Mass ordering**: various hints in favor of NO, but the T2K/NOvA tension nullifies them;
- **θ_{23} octant**: no indication on whether θ_{23} deviates from maximal, and (if so) in which direction;

• future experiments expected to shed light;

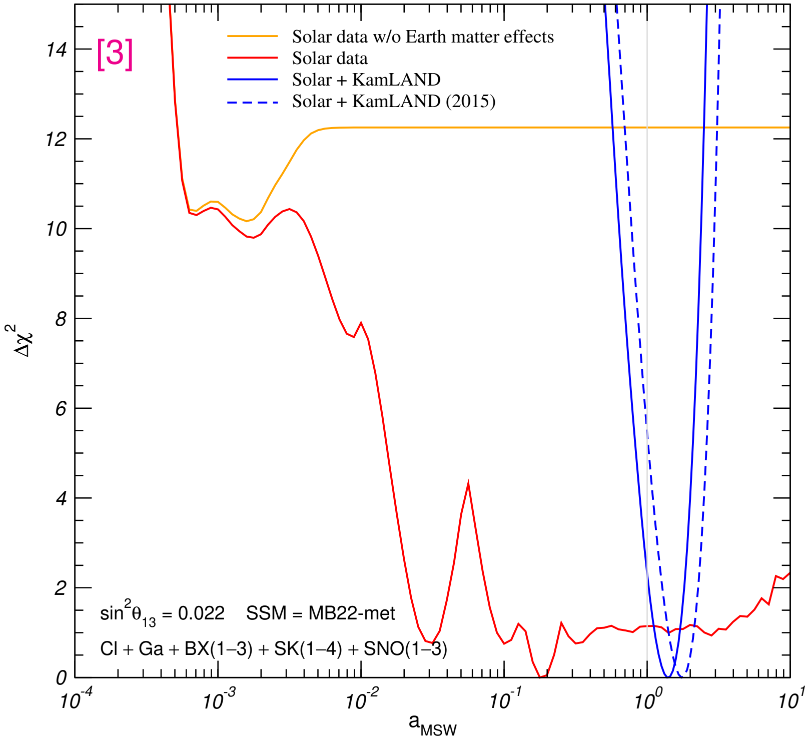
¿? can New Physics play a role in their task?





Non-standard neutrino interactions: a first example

- Ref. [2]: is solar MSW as expected?
- model: $V_e \to a_{\text{MSW}} V_e$ (a kind of NSI);
- Sun: lots of matter, yet no bound as:
  - P invariant if Δm^2 & L also scaled;
  - MSW regime insensitive to L;
- including Earth D/N effects set a scale for L, but a_{MSW} still unconstrained;
- KamLAND: almost no matter, thus no sensitivity to a_{MSW}, but fixes Δm^2;
- together: $0.67 < a_{\text{MSW}} < 2.32$ at 3σ;
- in brief:
  - **degeneracies** arise;
  - **synergies** solve them.



[2] G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo, Phys. Lett. B **583** (2004) 149 [hep-ph/0309100].
[3] M. Maltoni, A. Yu. Smirnov, Eur. Phys. J. A **52** (2016) 87 [arXiv:1507.05287]

Non-standard neutrino interactions: general formalism

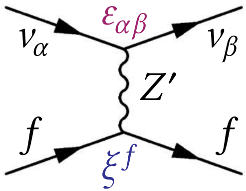
- Let us extend the SM by a NC-like **non-standard** neutrino-matter term:

$$\mathscr{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2} G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{fP} \, [\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta][\bar{f} \gamma^\mu P f] \, ;$$

where $P \in \{P_L, P_R\}$ and $f \in \{e, u, d\}$ is a fermion present in ordinary matter;

- however, most general parameter space too large to handle $\Rightarrow$ simplifications needed;
- here we assume that the ν flavor structure is **independent** of the charged fermion type:

$$\varepsilon_{\alpha\beta}^{fP} \equiv \varepsilon_{\alpha\beta} \, \xi^f \chi^P \,, \quad \Rightarrow \quad \mathscr{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2} G_F \Bigg[\sum_{\alpha,\beta} \varepsilon_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) \Bigg] \Bigg[\sum_{fP} \xi^f \chi^P (\bar{f} \gamma_\mu P f) \Bigg] \, ;$$



- quarks always confined inside nucleons $\Rightarrow$ introduce effective couplings:

$$\xi^p = 2\xi^u + \xi^d \,, \qquad \xi^n = 2\xi^d + 2\xi^u \, ;$$

- length of $\vec{\xi} \equiv (\xi^e, \xi^p, \xi^n)$ degenerate with $|\varepsilon_{\alpha\beta}| \Rightarrow$ fix $|\vec{\xi}| = \sqrt{5} \Rightarrow$ half-sphere;
- strenght of various effects (matter potential, scattering, ...) controlled by mediator mass $m_{Z'}$ [4].

[4] Y. Farzan, Phys. Lett. B **748** (2015) 311 [arXiv:1505.06906].

Non-standard neutrino interactions: propagation effects

- Typical oscillation length $\gg$ km $\Rightarrow$ contact-interaction regime for $m_{Z'} \gg 10^{-11}$ eV;
- most neutrino detection occur through CC interactions $\Rightarrow$ unaffected by our NC-like NSI;
- some experiments sensitive to elastic scattering $\Rightarrow$ affected by NC-like NSI with e, but effects suppressed for $m_{Z'} \ll \mathcal{O}(500\text{ keV})$ [Borexino] or $m_{Z'} \ll \mathcal{O}(5\text{--}10\text{ MeV})$ [SK, SNO];
- hence, for a large range of $m_{Z'}$, our NC-like NSI only manifest themselves in ν propagation;
- matter potential sensitive to vector couplings $\Rightarrow$ only $\chi^V \equiv \chi^L + \chi^R$ combination relevant;
- NSI effects controlled by fermion $N_f(\vec{x})$, but matter neutrality implies $N_e(\vec{x}) = N_p(\vec{x})$, hence:

$$V_{\text{NSI}} \propto \sum_f N_f(\vec{x})\, \varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}\, \chi^V \sum_f N_f(\vec{x})\, \xi^f = \varepsilon_{\alpha\beta}\, \chi^V \left[N_{e=p}(\vec{x}) \left(\xi^e + \xi^p \right) + N_n(\vec{x})\, \xi^n \right];$$

- only the direction in the $(\xi^e + \xi^p,\ \xi^n)$ plane probed by ν oscillations $\Rightarrow$ define an angle η':

$$\xi^e + \xi^p \equiv \sqrt{5}\, \mathcal{N} \cos\eta',\quad \xi^n \equiv \sqrt{5}\, \mathcal{N} \sin\eta',\quad \varepsilon'_{\alpha\beta} \equiv \mathcal{N}\, \varepsilon_{\alpha\beta} \text{ with } \mathcal{N} \equiv \left| (\xi^e + \xi^p,\ \xi^n) \right| \big/ \left| \vec{\xi} \right|;$$

- special cases: $\eta' = \pm 90^\circ$ (n), $\eta' = 0$ $(p+e)$, $\eta' \approx 26.6^\circ$ (u), $\eta' \approx 63.4^\circ$ (d).

Non-standard interactions and 3ν oscillations

- Equation of motion: **6** (vac) + **8** (NSI-ν) + **1** (NSI-f) = **15** parameters [5]:

$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^\dagger \pm V_{\text{mat}}; \qquad D_{\text{vac}} = \frac{1}{2E_\nu}\,\mathbf{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right);$$

$$U_{\text{vac}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12}\,e^{i\delta_{\text{CP}}} & 0 \\ -s_{12}\,e^{-i\delta_{\text{CP}}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix},$$

$$\mathcal{E}_{\alpha\beta}(\vec{x}) \equiv \sum_f \frac{N_f(\vec{x})}{N_e(\vec{x})}\,\varepsilon^{fV}_{\alpha\beta} = \sqrt{5}\,\varepsilon'_{\alpha\beta}\,\chi^V \left[\cos\eta' + Y_n(\vec{x})\sin\eta'\right], \qquad Y_n(\vec{x}) \equiv \frac{N_n(\vec{x})}{N_e(\vec{x})},$$

$$V_{\text{mat}} \equiv V_{\text{SM}} + V_{\text{NSI}} = \sqrt{2}G_F N_e(\vec{x}) \begin{pmatrix} 1 + \mathcal{E}_{ee}(\vec{x}) & \mathcal{E}_{e\mu}(\vec{x}) & \mathcal{E}_{e\tau}(\vec{x}) \\ \mathcal{E}^\star_{e\mu}(\vec{x}) & \mathcal{E}_{\mu\mu}(\vec{x}) & \mathcal{E}_{\mu\tau}(\vec{x}) \\ \mathcal{E}^\star_{e\tau}(\vec{x}) & \mathcal{E}^\star_{\mu\tau}(\vec{x}) & \mathcal{E}_{\tau\tau}(\vec{x}) \end{pmatrix};$$

- notice that our definition of U_{vac} differ by the "usual" one by an overall rephasing, $U_{\text{vac}} = \Phi \cdot U \cdot \Phi^\star$ with $\Phi \equiv \mathbf{diag}\left(e^{i\delta_{\text{CP}}}, 1, 1\right)$, which is irrelevant in the standard case of no-NSI.

[5] I. Esteban *et al.*, JHEP **08** (2018) 180 [arXiv:1805.04530].

The generalized mass ordering degeneracy

- General symmetry: $\boldsymbol{H} \to -\boldsymbol{H}^\star$ does not affect the neutrino probabilities;
- we have $\boldsymbol{H} = \boldsymbol{H}_{\text{vac}} \pm \boldsymbol{V}_{\text{mat}}$. For vacuum, $\boldsymbol{H}_{\text{vac}} \to -\boldsymbol{H}^\star_{\text{vac}}$ occurs if: $\begin{cases} \Delta m^2_{31} \to -\Delta m^2_{32}\,, \\ \theta_{12} \to \pi/2 - \theta_{12}\,, \\ \delta_{\text{CP}} \to \pi - \delta_{\text{CP}}\,, \end{cases}$
- notice how this transformation links together mass ordering and solar octant [6, 7, 8];
- for matter, $\boldsymbol{V}_{\text{mat}} \to -\boldsymbol{V}^\star_{\text{mat}}$ requires: $\begin{cases} \left[\mathcal{E}_{ee}(\vec{x}) - \mathcal{E}_{\mu\mu}(\vec{x})\right] \to -\left[\mathcal{E}_{ee}(\vec{x}) - \mathcal{E}_{\mu\mu}(\vec{x})\right] - 2\,, \\ \left[\mathcal{E}_{\tau\tau}(\vec{x}) - \mathcal{E}_{\mu\mu}(\vec{x})\right] \to -\left[\mathcal{E}_{\tau\tau}(\vec{x}) - \mathcal{E}_{\mu\mu}(\vec{x})\right]\,, \\ \mathcal{E}_{\alpha\beta}(\vec{x}) \to -\mathcal{E}^\star_{\alpha\beta}(\vec{x}) \qquad (\alpha \neq \beta)\,, \end{cases}$
- since $\boldsymbol{V}_{\text{mat}} = \boldsymbol{V}_{\text{SM}} + \boldsymbol{V}_{\text{NSI}}$ and $\boldsymbol{V}_{\text{SM}}$ is fixed, this symmetry requires NSI;
- in general, $\mathcal{E}_{\alpha\beta}(\vec{x})$ varies along trajectory $\Rightarrow$ symmetry only approximate, **unless**:
  - NSI proportional to electric charge ($\eta' = 0$), so same matter profile for SM and NSI;
  - neutron/proton ratio $Y_n(\vec{x})$ is constant, and same for all the neutrino trajectories.

[6] M.C. Gonzalez-Garcia, M. Maltoni, JHEP **09** (2013) 152 [arXiv:1307.3092]
[7] P. Bakhti, Y. Farzan, JHEP **07** (2014) 064 [arXiv:1403.0744].
[8] P. Coloma, T. Schwetz, Phys. Rev. D **94** (2016) 055005 [arXiv:1604.05772].

Matter potential for solar and KamLAND neutrinos

- One mass dominance ($\Delta m^2_{31} \to \infty$) $\Rightarrow$ $P_{ee} = c_{13}^4 P_\text{eff} + s_{13}^4$ with the probability P_eff determined by an effective 2ν model (as in the SM):

$$i\frac{d\vec{\nu}}{dt} = \left[\boldsymbol{H}^\text{eff}_\text{vac} + \boldsymbol{H}^\text{eff}_\text{mat}\right]\vec{\nu}, \qquad \vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}, \qquad \boldsymbol{H}^\text{eff}_\text{vac} \equiv \frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12}\, e^{i\delta_\text{CP}} \\ \sin 2\theta_{12}\, e^{-i\delta_\text{CP}} & \cos 2\theta_{12}\end{pmatrix},$$

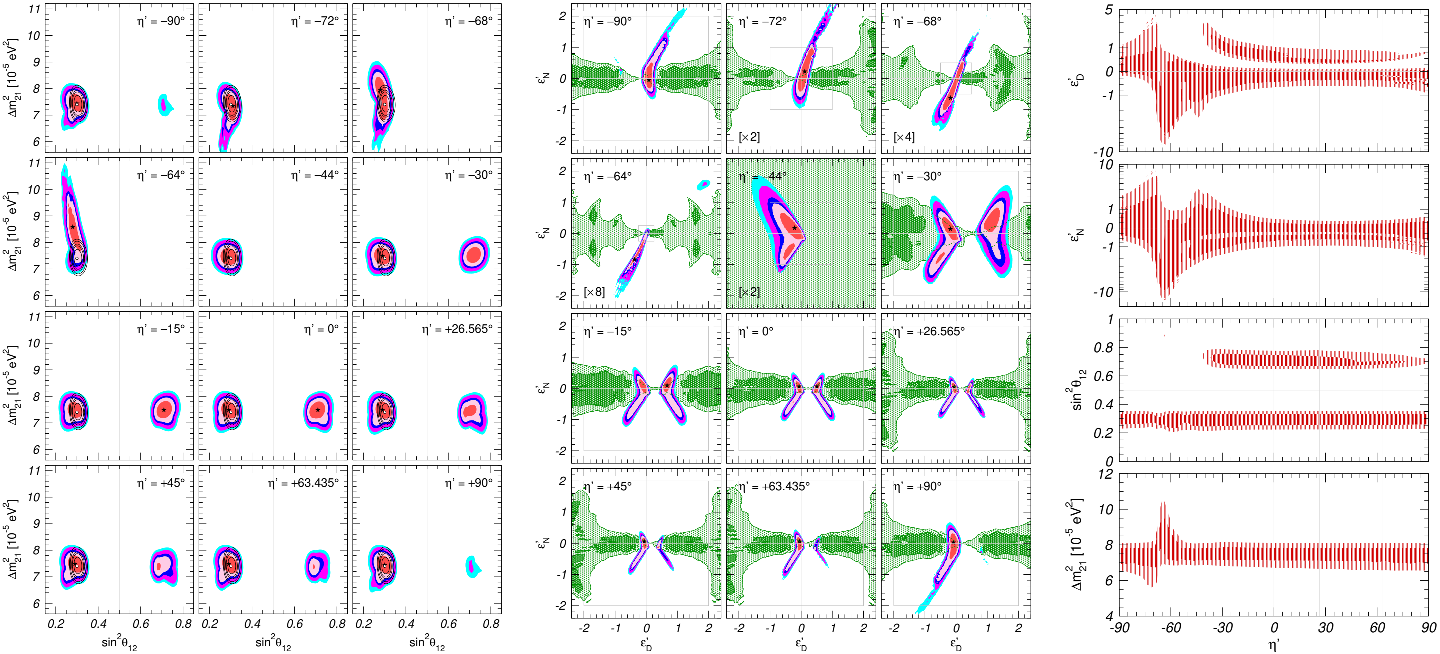
$$\boldsymbol{H}^\text{eff}_\text{mat} \equiv \sqrt{2}\, G_F N_e(\vec{x}) \left[\begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0\end{pmatrix} + \sqrt{5}\,\chi^V \left[\cos\eta' + Y_n(\vec{x})\sin\eta'\right]\begin{pmatrix}-\varepsilon'_D & \varepsilon'_N \\ \varepsilon'^{\star}_N & \varepsilon'_D\end{pmatrix}\right],$$

$$\begin{cases} \varepsilon'_D = c_{13}s_{13}\,\text{Re}\big(s_{23}\,\varepsilon'_{e\mu} + c_{23}\,\varepsilon'_{e\tau}\big) - \big(1 + s_{13}^2\big)c_{23}s_{23}\,\text{Re}\big(\varepsilon'_{\mu\tau}\big) \\ \qquad\quad - c_{13}^2\big(\varepsilon'_{ee} - \varepsilon'_{\mu\mu}\big)/2 + \big(s_{23}^2 - s_{13}^2 c_{23}^2\big)\big(\varepsilon'_{\tau\tau} - \varepsilon'_{\mu\mu}\big)/2, \\ \varepsilon'_N = c_{13}\big(c_{23}\,\varepsilon'_{e\mu} - s_{23}\,\varepsilon'_{e\tau}\big) + s_{13}\left[s_{23}^2\,\varepsilon'_{\mu\tau} - c_{23}^2\,\varepsilon'^{\star}_{\mu\tau} + c_{23}s_{23}\big(\varepsilon'_{\tau\tau} - \varepsilon'_{\mu\mu}\big)\right]; \end{cases}$$

- solar data can be perfectly fitted by NSI only $\Rightarrow$ solar LMA solution **is unstable** with respect to the introduction of NSI;
- KamLAND **requires** Δm^2_{21} but only weakly sensitive to NSI $\Rightarrow$ it **determines** Δm^2_{21};
- in the solar core $Y_n(\vec{x}) \in [1/6, 1/2]$ $\Rightarrow$ approximate cancellation of NSI for $\eta' \in [-80^\circ, -63^\circ]$.

Oscillation results for solar and KamLAND neutrinos

- Generalized mass-ordering degeneracy ⇒ new LMA-D solution with $\theta_{12} > 45^\circ$ [9];
- $\eta' = 0 \Rightarrow$ NSI terms proportional to $N_p(\vec{x}) \equiv N_e(\vec{x}) \Rightarrow$ the degeneracy becomes exact.



[9] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].

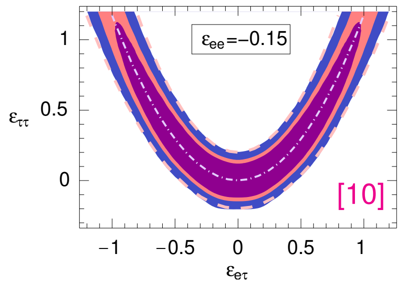
Matter potential for atmospheric and long-baseline neutrinos

- In Earth matter: $Y_n(\vec{x}) \to Y_n^\oplus \approx 1.051 \Rightarrow \mathcal{E}_{\alpha\beta}(\vec{x}) \to \varepsilon^\oplus_{\alpha\beta}$ becomes an effective parameter:

$$\varepsilon^\oplus_{\alpha\beta} \equiv \sqrt{5}\left[\cos\eta' + Y_n^\oplus \sin\eta'\right] \varepsilon'_{\alpha\beta} \,,$$

- the bounds on $\varepsilon^\oplus_{\alpha\beta}$ are independent of the fermion couplings (*i.e.*, of η');
- for $\eta' = \arctan(-1/Y_n^\oplus) \approx -43.6^\circ$ ATM+LBL data imply **no** bound on $\varepsilon'_{\alpha\beta}$;
- the NSI parameter space is too big to be properly studied $\Rightarrow$ simplification needed;
- bounds on $\varepsilon^\oplus_{\alpha\beta}$ are weakest when $V_{\text{mat}} \propto \delta_{e\alpha}\delta_{e\beta} + \varepsilon^\oplus_{\alpha\beta}$ has two degenerate eigenvalues [10] $\Rightarrow$ focus on such case $\Rightarrow$ introduce parameters ($\varepsilon_\oplus$, φ_{12}, φ_{13}, α_1, α_2) and define:

$$\begin{aligned}
\varepsilon^\oplus_{ee} - \varepsilon^\oplus_{\mu\mu} &= \varepsilon_\oplus \left(\cos^2\varphi_{12} - \sin^2\varphi_{12}\right)\cos^2\varphi_{13} - 1 \,, \\
\varepsilon^\oplus_{\tau\tau} - \varepsilon^\oplus_{\mu\mu} &= \varepsilon_\oplus \left(\sin^2\varphi_{13} - \sin^2\varphi_{12}\cos^2\varphi_{13}\right), \\
\varepsilon^\oplus_{e\mu} &= -\varepsilon_\oplus \cos\varphi_{12}\sin\varphi_{12}\cos^2\varphi_{13}\, e^{i(\alpha_1-\alpha_2)} \,, \\
\varepsilon^\oplus_{e\tau} &= -\varepsilon_\oplus \cos\varphi_{12}\cos\varphi_{13}\sin\varphi_{13}\, e^{i(2\alpha_1+\alpha_2)} \,, \\
\varepsilon^\oplus_{\mu\tau} &= \varepsilon_\oplus \sin\varphi_{12}\cos\varphi_{13}\sin\varphi_{13}\, e^{i(\alpha_1+2\alpha_2)} \,.
\end{aligned}$$

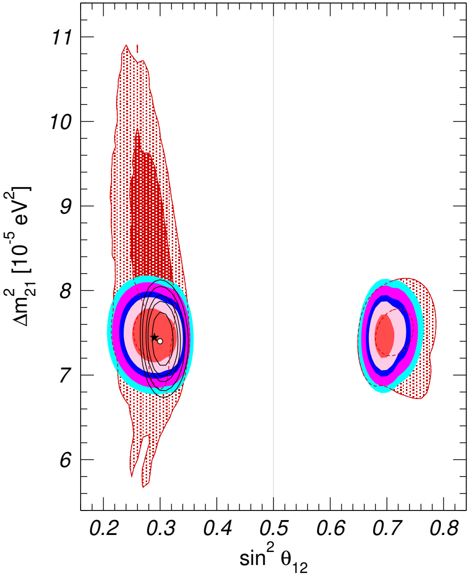


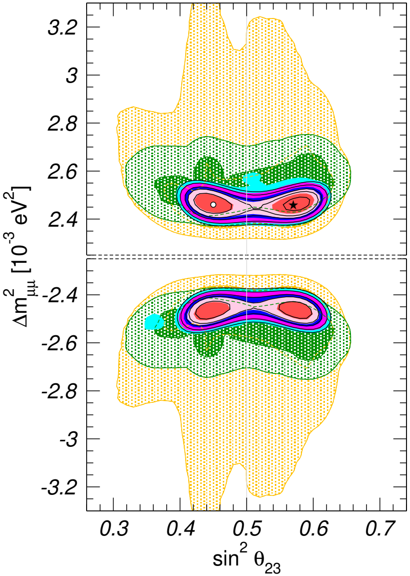
- for definiteness we also assume on CP conservation and set $\delta_{\text{CP}} = \alpha_1 = \alpha_2 = 0$.

[10] A. Friedland, C. Lunardini, M. Maltoni, Phys. Rev. D **70** (2004) 111301 [hep-ph/0408264].

Impact of NSI on the oscillation parameters

- Once marginalized over η', analysis of solar + KamLAND data shows strong deterioration of the precision on Δm^2_{21} and θ_{12}, as well as the appearance of the LMA-D solution [9];
- a similar worsening appears in ATM + LBL-dis + LBL-app + IceCUBE + MBL-rea analysis;
- synergies between solar and atmospheric sectors allow to recover the SM accuracy on most parameters (except θ_{12});
- notice that the LMA-D solution persists also in the global fit;
- high-energy atmos. IceCUBE data have no sensitivity to oscillations ($P_{\mu\mu} \propto 1/E^2$), hence they contribute little.

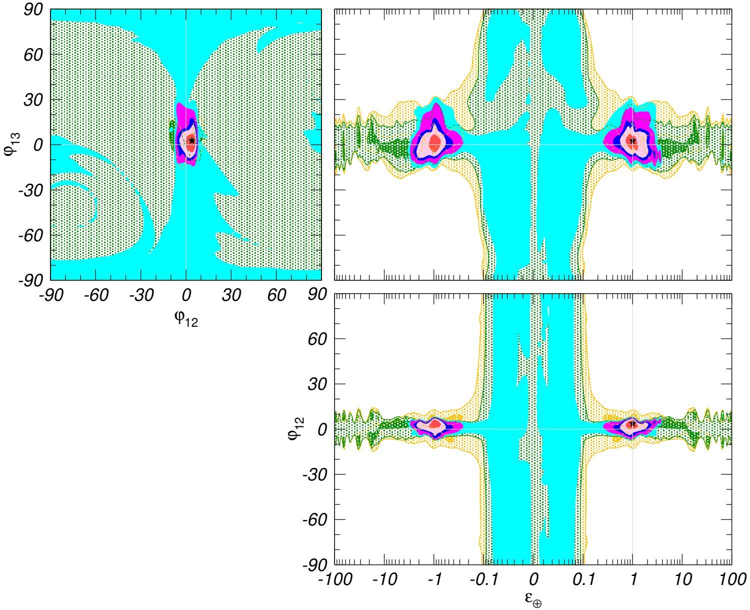


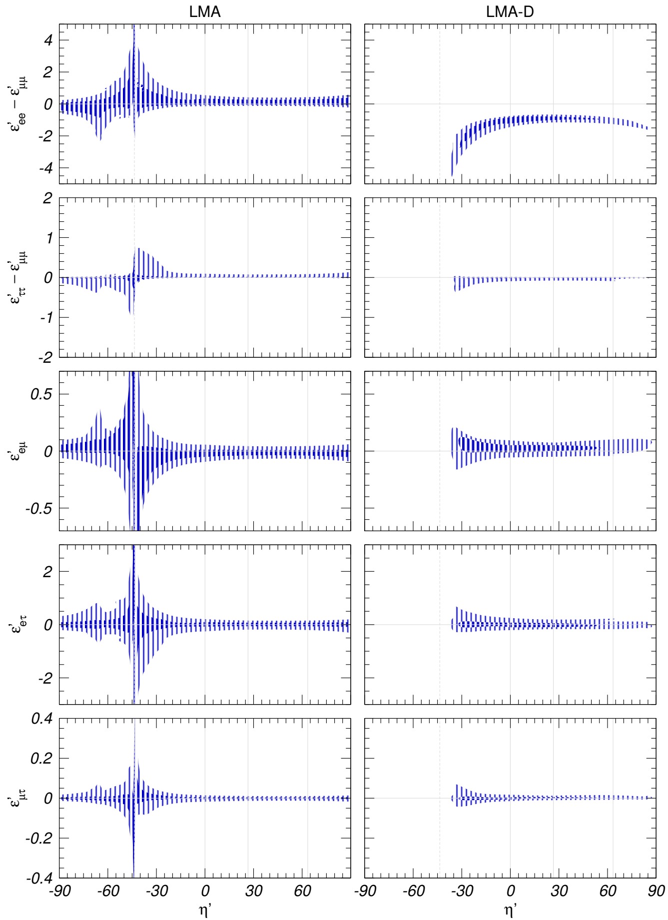


[9] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].

Determination of NSI parameters

- Reduced ($\varepsilon_\oplus$, φ_{12}, φ_{13}) parameter space can be constrained by joint solar+KamLAND and ATM+LBL analysis;
- bounds can then be recast in term of $\varepsilon'_{\alpha\beta}$.





Non-standard interactions with electrons: formalism

- Let's focus on solar ν and assume $m_{Z'} \gtrsim \mathcal{O}(\text{MeV})$. In the presence of NC-like NSI with e, elastic scattering is modified $\Rightarrow$ detection process (SK, SNO, Borexino) is affected;
- in the SM, ν interactions (both CC and NC) are diagonal in the flavor basis. Hence:

$$N_{\text{ev}} \propto \sum_\beta P_{e\beta}\, \sigma_\beta^{\text{SM}} \quad \text{with} \quad P_{e\beta} \equiv |S_{\beta e}|^2 \quad (\nu_e \to \nu_\beta \text{ transition probabilities})$$

- this expression is only valid in the flavor basis. Unitary rotation $\boldsymbol{U} \Rightarrow$ arbitrary basis:

$$S_{\beta e} = \sum_i U_{\beta i}\, S_{ie} \quad \Rightarrow \quad P_{e\beta} = \sum_{ij} U_{\beta i}\, \rho_{ij}^{(e)}\, U_{j\beta}^\dagger \quad \text{with} \quad \rho_{ij}^{(e)} \equiv S_{ie}\, S_{ej}^\dagger = \left[\boldsymbol{S}\, \boldsymbol{\Pi}^{(e)}\, \boldsymbol{S}^\dagger\right]_{ij}$$

- where $\boldsymbol{\rho}^{(e)}$ is the ν density matrix at the detector (for a ν_e at the source). Substituting:

$$N_{\text{ev}} \propto \sum_{ij} \rho_{ij}^{(e)} \sum_\beta U_{j\beta}^\dagger\, \sigma_\beta^{\text{SM}}\, U_{\beta i} = \boxed{\text{Tr}\left[\boldsymbol{\rho}^{(e)}\, \boldsymbol{\sigma}^{\text{SM}}\right]} \quad \text{with} \quad \sigma_{ji}^{\text{SM}} \equiv \left[\boldsymbol{U}^\dagger \mathbf{diag}\left\{\sigma_\beta^{\text{SM}}\right\} \boldsymbol{U}\right]_{ji};$$

- here $\boldsymbol{\sigma}^{\text{SM}}$ is a matrix in flavor space, containing enough information to describe the ES interaction of *any* neutrino state without the need to explicitly project it onto the interaction eigenstates: such projection is now implicitly encoded into $\boldsymbol{\sigma}^{\text{SM}}$.

Neutrino-electron cross-section in the presence of NSI

- In the presence of flavor-changing NSI, the SM flavor basis no longer coincides with the interaction eigenstates. Hence, the general formula $N_{\text{ev}} \propto \text{Tr}\left[\boldsymbol{\rho}^{(e)}\,\boldsymbol{\sigma}^{\text{NSI}}\right]$ must be used;
- the cross-section matrix $\boldsymbol{\sigma}^{\text{NSI}}$ is the integral over T_e of the following expression:

$$\frac{\mathrm{d}\boldsymbol{\sigma}^{\text{NSI}}}{\mathrm{d}T_e}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left\{\boldsymbol{C}_L^2\left[1+\frac{\alpha}{\pi}f_-(y)\right]+\boldsymbol{C}_R^2\,(1-y)^2\left[1+\frac{\alpha}{\pi}f_+(y)\right]-\left\{\boldsymbol{C}_L,\boldsymbol{C}_R\right\}\frac{m_e y}{2E_\nu}\left[1+\frac{\alpha}{\pi}f_\pm(y)\right]\right\}$$

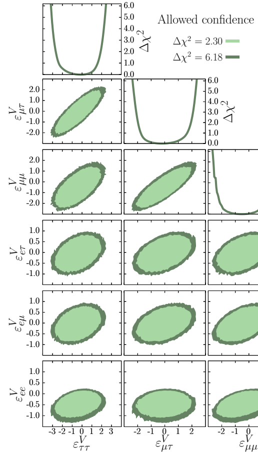
where f_+, f_-, $f_\pm$ are loop functions, $y \equiv T_e/E_\nu$, and $\boldsymbol{C}_L$, $\boldsymbol{C}_R$ are 3×3 hermitian matrices:

$$\begin{cases} C^L_{\alpha\beta} \equiv c_{L\beta}\,\delta_{\alpha\beta} + \varepsilon^{eL}_{\alpha\beta} \\ C^R_{\alpha\beta} \equiv c_{L\beta}\,\delta_{\alpha\beta} + \varepsilon^{Re}_{\alpha\beta} \end{cases} \quad \text{with} \quad \begin{cases} c_{L\tau} = c_{L\mu} = g_L^\ell \quad \text{and} \quad c_{Le} = g_L^\ell + 1\,, \\ c_{R\tau} = c_{R\mu} = c_{Re} = g_R^\ell \quad \text{(at tree level)}\,; \end{cases}$$

- when the NSI terms $\varepsilon^{eL}_{\alpha\beta}$ and $\varepsilon^{eR}_{\alpha\beta}$ are set to zero, the matrix $\mathrm{d}\boldsymbol{\sigma}^{\text{NSI}}/\mathrm{d}T_e$ becomes diagonal and the SM expressions are recovered;
- the cross section for antineutrinos can be obtained by interchanging $\boldsymbol{C}_L \leftrightarrow \boldsymbol{C}_R^\star$;
- NSI effects on neutrino propagation are the same as in the previous section (with $\eta' = 0$ for $\xi^p = \xi^n = 0$) and are accounted by the density matrix $\boldsymbol{\rho}^{(e)}$.

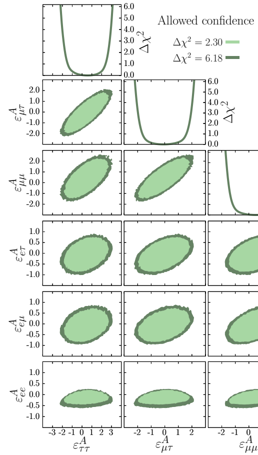
Bounds on NSI-e from Borexino

- $m_{Z'} \gtrsim \mathcal{O}(500\text{ keV}) \Rightarrow$ Borexino sensitive to NSI-e;
- Ref. [11]:
  - only diagonal NSI considered;
  - only 1 or 2 NSI varied at-a-time;
- in [12] we studied the general case. We found:
  - degeneracies strongly weakens the bounds;
  - yet a definite $\mathcal{O}(1)$ bound is always found.



Vector: $\varepsilon^{eV}_{\alpha\beta} \equiv \varepsilon^{eL}_{\alpha\beta} + \varepsilon^{eR}_{\alpha\beta}$

	Allowed regions at 90% CL ($\Delta\chi^2 = 2.71$)			
	Vector		Axial Vector	
	1 Parameter	Marginalized	1 Parameter	Marginalized
ε_{ee}	$[-0.09, +0.14]$	$[-1.05, +0.17]$	$[-0.05, +0.10]$	$[-0.38, +0.24]$
$\varepsilon_{\mu\mu}$	$[-0.51, +0.35]$	$[-2.38, +1.54]$	$[-0.29, +0.19] \oplus [+0.68, +1.45]$	$[-1.47, +2.37]$
$\varepsilon_{\tau\tau}$	$[-0.66, +0.52]$	$[-2.85, +2.04]$	$[-0.40, +0.36] \oplus [+0.69, +1.44]$	$[-1.82, +2.81]$
$\varepsilon_{e\mu}$	$[-0.34, +0.61]$	$[-0.83, +0.84]$	$[-0.30, +0.43]$	$[-0.79, +0.76]$
$\varepsilon_{e\tau}$	$[-0.48, +0.47]$	$[-0.90, +0.85]$	$[-0.40, +0.38]$	$[-0.81, +0.78]$
$\varepsilon_{\mu\tau}$	$[-0.25, +0.36]$	$[-2.07, +2.06]$	$[-1.10, -0.75] \oplus [-0.13, +0.22]$	$[-1.95, +1.91]$



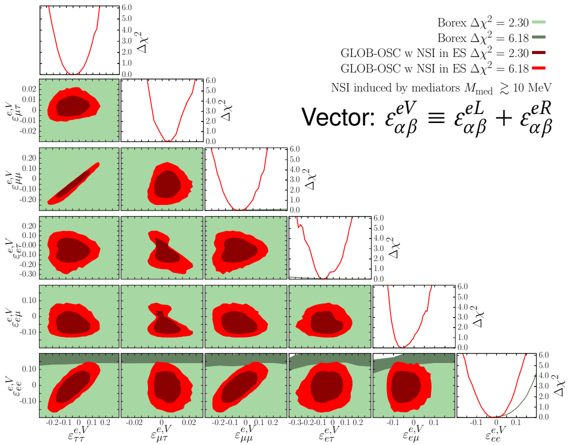
Axial: $\varepsilon^{eA}_{\alpha\beta} \equiv \varepsilon^{eL}_{\alpha\beta} - \varepsilon^{eR}_{\alpha\beta}$

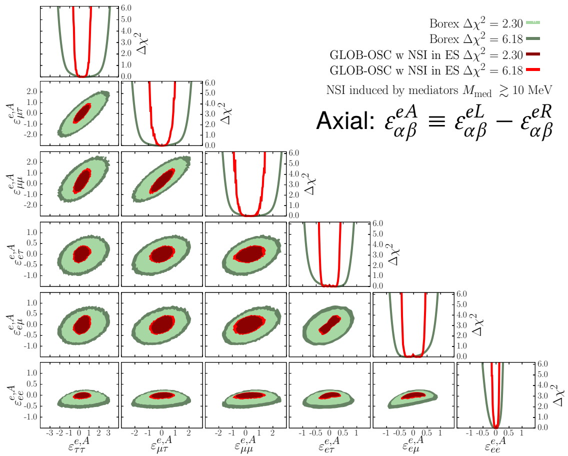
[11] Borexino coll., JHEP **02** (2020) 038 [arXiv:1905.03512]
[12] Coloma *et al.*, JHEP **07** (2022) 138 [arXiv:2204.03011]

Bounds on NSI-e from global data

- $m_{Z'} \gtrsim \mathcal{O}(10\ \text{MeV}) \Rightarrow$ SK & SNO sensitive to NSI-e:
  - SK measures ES events with high statistics;
  - SNO determines the ^{8}B flux accurately via NC;
- bounds from Borexino alone greatly enhanced [13];
- limits dominated by NSI contributions to the ES cross-section, which allow to derive separate bounds on diagonal $\varepsilon^{eV}_{\alpha\alpha}$ and $\varepsilon^{eA}_{\alpha\alpha}$ couplings.

	Allowed ranges at 90% CL (marginalized)			
	Vector ($X = V$)		Axial-vector ($X = A$)	
	Borexino	GLOB-OSC w NSI in ES	Borexino	GLOB-OSC w NSI in ES
$\varepsilon^{e,X}_{ee}$	$[-1.1, +0.17]$	$[-0.13, +0.10]$	$[-0.38, +0.24]$	$[-0.13, +0.11]$
$\varepsilon^{e,X}_{\mu\mu}$	$[-2.4, +1.5]$	$[-0.20, +0.10]$	$[-1.5, +2.4]$	$[-0.70, +1.2]$
$\varepsilon^{e,X}_{\tau\tau}$	$[-2.8, +2.1]$	$[-0.17, +0.093]$	$[-1.8, +2.8]$	$[-0.53, +1.0]$
$\varepsilon^{e,X}_{e\mu}$	$[-0.83, +0.84]$	$[-0.097, +0.011]$	$[-0.79, +0.76]$	$[-0.41, +0.40]$
$\varepsilon^{e,X}_{e\tau}$	$[-0.90, +0.85]$	$[-0.18, +0.080]$	$[-0.81, +0.78]$	$[-0.36, +0.36]$
$\varepsilon^{e,X}_{\mu\tau}$	$[-2.1, +2.1]$	$[-0.0063, +0.016]$	$[-1.9, +1.9]$	$[-0.79, +0.81]$





[13] Coloma *et al.*, JHEP **08** (2023) 032 [arXiv:2305.07698]

Neutrino-nucleus cross-section in the presence of NSI

- At $m_{Z'} \gtrsim \mathcal{O}(50\text{ MeV})$, coherent neutrino-nucleus scattering becomes senstive to NSI;
- the cross-section matrix $\boldsymbol{\sigma}^{\text{coh}}$ is the integral over the recoil energy of the nucleus E_R of:

$$\frac{d\boldsymbol{\sigma}^{\text{coh}}}{dE_R}(E_\nu, E_R) = \frac{G_F^2}{2\pi}\,\mathcal{Q}^2\,F^2(2m_A E_R)\,m_A\left(2 - \frac{m_A E_R}{E_\nu^2}\right)$$

where m_A is the nucleus' mass, $F(q^2)$ its nuclear form factor, and $\mathcal{Q}$ an hermitian matrix:

$$\mathcal{Q}_{\alpha\beta} = Z\left(g_V^p\,\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{pV}\right) + N\left(g_V^n\,\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{nV}\right);$$

- here g_V^p and g_V^n are the SM vector couplings to protons and neutrons. We can rewrite:

$$\mathcal{Q}_{\alpha\beta} = Z\left[(g_p^V + Y_n^{\text{coh}}\,g_n^V)\,\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{\text{coh}}\right] \quad \text{with} \quad \varepsilon_{\alpha\beta}^{\text{coh}} \equiv \varepsilon_{\alpha\beta}^{pV} + Y_n^{\text{coh}}\,\varepsilon_{\alpha\beta}^{nV} \quad \text{and} \quad Y_n^{\text{coh}} \equiv N/Z\,;$$

- notice that only vector couplings matter, as for oscillations. Assuming factorization:

$$\varepsilon_{\alpha\beta}^{\text{coh}} = \varepsilon_{\alpha\beta}\,\chi^V\left(\xi^p + Y_n^{\text{coh}}\,\xi^n\right) = \sqrt{5}\,\varepsilon''_{\alpha\beta}\,\chi^V\left[\cos\eta'' + Y_n^{\text{coh}}\sin\eta''\right]$$

were we have used that only the direction η'' in the $(\xi^p,\ \xi^n)$ plane is probed by coherent:

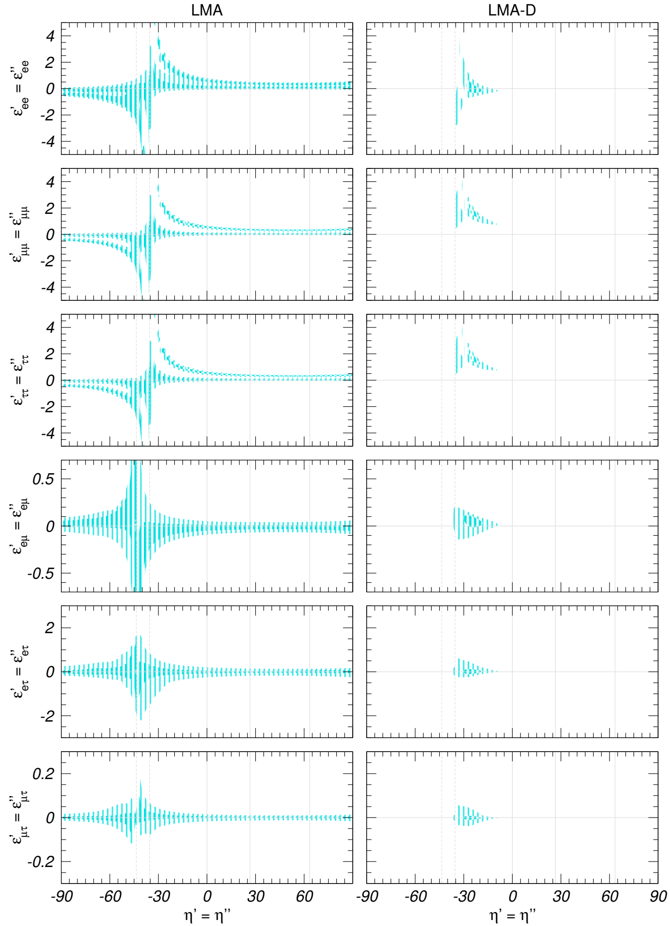
$$\xi^p \equiv \sqrt{5}\,\mathcal{N}\cos\eta''\,,\quad \xi^n \equiv \sqrt{5}\,\mathcal{N}\sin\eta''\,,\quad \varepsilon''_{\alpha\beta} \equiv \mathcal{N}\,\varepsilon_{\alpha\beta} \quad \text{with} \quad \mathcal{N} \equiv \left|(\xi^p,\ \xi^n)\right| \big/ \left|\vec{\xi}\right|.$$

The COHERENT experiment

- Observation of coherent neutrino-nucleus scattering [14] allows to put bounds on vector NSI:

$$\varepsilon^{\text{coh}}_{\alpha\beta} = \sqrt{5}\, \varepsilon''_{\alpha\beta}\, \chi^V \left[\cos\eta'' + Y^{\text{coh}}_n \sin\eta''\right];$$

- $Y^{\text{coh}}_n \approx 1.407 \Rightarrow$ no bound on $\varepsilon''_{\alpha\beta}$ is implied for $\eta'' = \arctan(-1/Y^{\text{coh}}_n) \approx -35.4^\circ$;
- combination: { oscillation effects $\to \eta'$, coherent scattering $\to \eta''$, elastic scattering $\to \xi^e$;
- NSI with quarks $\Rightarrow \xi^e = 0 \Rightarrow \eta' = \eta''$;
- separate bounds on diagonal $\varepsilon_{\alpha\alpha}$ ($= \varepsilon'_{\alpha\alpha} = \varepsilon''_{\alpha\alpha}$) couplings can be placed.



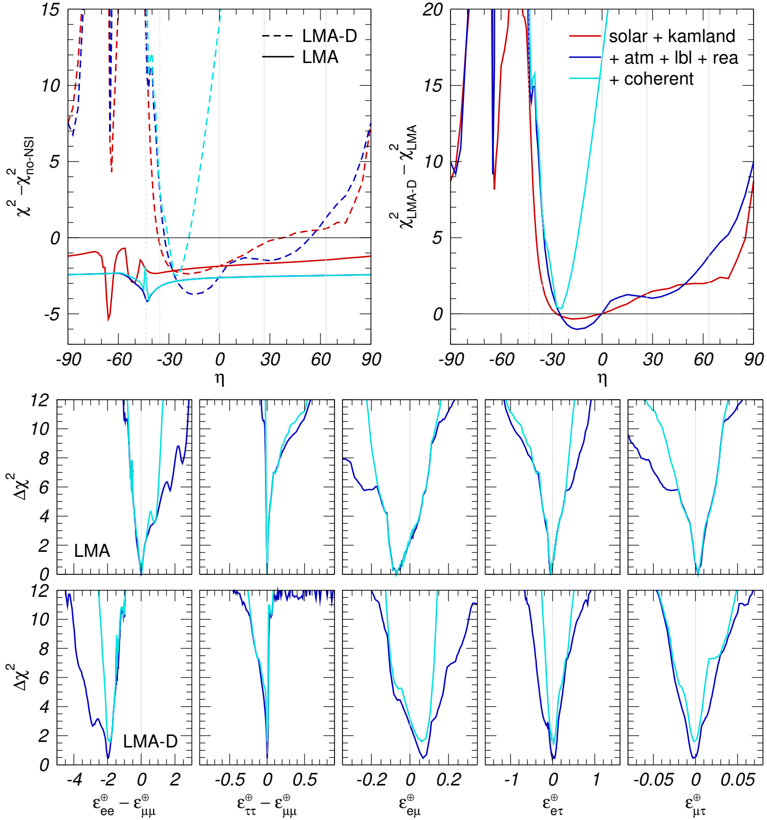
[14] D. Akimov *et al.* [COHERENT], Science **357** (2017) 1123 [arXiv:1708.01294]

Bounds on NSI with quarks

- Inclusion of COHERENT data rules out LMA-D for NSI with u, d, or p, but **not** in the general case;
- our general 2σ bounds [15]:

OSCILLATIONS			+ COHERENT (t+E Duke)	
	LMA	LMA ⊕ LMA-D		LMA = LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$	$\oplus[-1.042, -0.743]$	ε^u_{ee}	$[-0.031, +0.476]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.016, +0.018]$	$\varepsilon^u_{\mu\mu}$	$[-0.029, +0.068] \oplus [+0.309, +0.415]$
			$\varepsilon^u_{\tau\tau}$	$[-0.029, +0.068] \oplus [+0.309, +0.414]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$	$[-0.050, +0.059]$	$\varepsilon^u_{e\mu}$	$[-0.048, +0.020]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$	$[-0.111, +0.098]$	$\varepsilon^u_{e\tau}$	$[-0.077, +0.095]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$	$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.084, +0.326]$	$\oplus[-1.081, -1.026]$	ε^d_{ee}	$[-0.034, +0.426]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.001, +0.018]$	$\varepsilon^d_{\mu\mu}$	$[-0.027, +0.063] \oplus [+0.275, +0.371]$
			$\varepsilon^d_{\tau\tau}$	$[-0.027, +0.067] \oplus [+0.274, +0.372]$
$\varepsilon^d_{e\mu}$	$[-0.051, +0.020]$	$[-0.051, +0.038]$	$\varepsilon^d_{e\mu}$	$[-0.050, +0.020]$
$\varepsilon^d_{e\tau}$	$[-0.077, +0.098]$	$[-0.077, -0.098]$	$\varepsilon^d_{e\tau}$	$[-0.076, +0.097]$
$\varepsilon^d_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$	$\varepsilon^d_{\mu\tau}$	$[-0.006, +0.007]$
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	$[-0.190, +0.927]$	$\oplus[-2.927, -1.814]$	ε^p_{ee}	$[-0.086, +0.884] \oplus [+1.083, +1.605]$
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	$[-0.001, +0.053]$	$[-0.052, +0.053]$	$\varepsilon^p_{\mu\mu}$	$[-0.097, +0.220] \oplus [+1.063, +1.410]$
			$\varepsilon^p_{\tau\tau}$	$[-0.098, +0.221] \oplus [+1.063, +1.408]$
$\varepsilon^p_{e\mu}$	$[-0.145, +0.058]$	$[-0.145, +0.145]$	$\varepsilon^p_{e\mu}$	$[-0.124, +0.058]$
$\varepsilon^p_{e\tau}$	$[-0.238, +0.292]$	$[-0.292, +0.292]$	$\varepsilon^p_{e\tau}$	$[-0.239, +0.244]$
$\varepsilon^p_{\mu\tau}$	$[-0.019, +0.021]$	$[-0.021, +0.021]$	$\varepsilon^p_{\mu\tau}$	$[-0.013, +0.021]$

- Argon data add further $\Delta\chi^2 \sim 4$ [16].



[15] P. Coloma, I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, JHEP **02** (2020) 023 [arXiv:1911.09109].

[16] M. Chaves and T. Schwetz, JHEP **05** (2021), 042 [arXiv:2102.11981].

Vector NSI in the general case

- Direction of $(\xi^e, \xi^u, \xi^d) \leftrightarrow$ half-sphere $|\vec{\xi}| = \sqrt{5}$;
- choose *two* angles (η, ζ) and define:

$$\varepsilon_{\alpha\beta}^{fV} \equiv \varepsilon_{\alpha\beta}\, \xi^f \chi^V \quad \text{with} \begin{cases} \xi^e = \sqrt{5}\cos\eta\sin\zeta\,, \\ \xi^p = \sqrt{5}\cos\eta\cos\zeta\,, \\ \xi^n = \sqrt{5}\sin\eta\,; \end{cases}$$

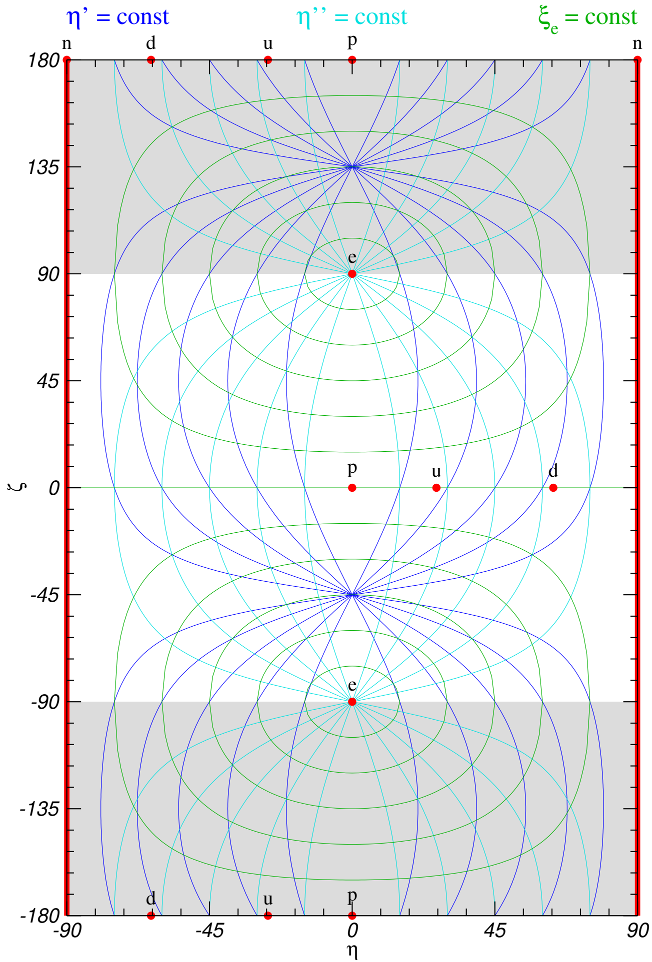
- each type of "effect" is constant on given lines:

oscillations: $\tan\eta' = \tan\eta \,/\, (\cos\zeta + \sin\zeta)\,,$

coherent sc.: $\tan\eta'' = \tan\eta \,/\, \cos\zeta\,,$

elastic sc.: $\xi^e \,/\, |\vec{\xi}| = \cos\eta\sin\zeta\,;$

- combining different sets breaks degeneracy;
- special case: $\zeta = 0 \Rightarrow \xi^e = 0 \Rightarrow \eta' = \eta'' = \eta$.



[13] Coloma *et al.*, JHEP [arXiv:2305.07698]

Bounds on vector NSI

- Determination of oscillation parameters remain stable under NSI (except θ_{12});
- ES effects disfavor region at large ξ^e (roughly $|\zeta| \gtrsim 45^\circ$) but have little impact on rejection of LMA-D;
- inclusion of coherent scattering data rules out LMA-D (except in a small region).

Allowed ranges at 90% CL / 99% CL marginalized

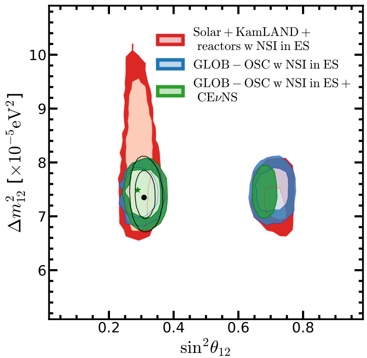
GLOB-OSC w/o NSI in ES

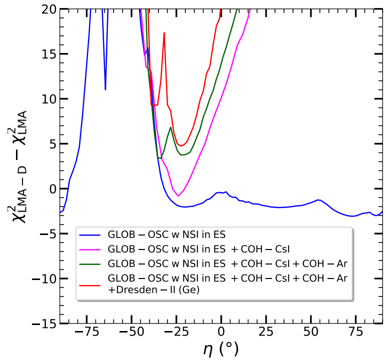
	90% CL / 99% CL
$\varepsilon_{ee}^{\oplus} - \varepsilon_{\mu\mu}^{\oplus}$	$[-3.1, -2.8] \oplus [-2.1, -1.88] \oplus [-0.15, +0.17]$ $[-4.8, -1.6] \oplus [-0.40, +2.6]$
$^{\oplus}_{\tau\tau} - \varepsilon_{\mu\mu}^{\oplus}$	$[-0.0215, +0.0122]$ $[-0.075, +0.080]$
$^{\oplus}_{e\mu}$	$[-0.11, -0.021] \oplus [+0.045, +0.135]$ $[-0.32, +0.40]$
$^{\oplus}_{\mu\tau}$	$[-0.22, +0.088]$ $[-0.49, +0.45]$
$^{\oplus}_{\mu\tau}$	$[-0.0063, +0.013]$ $[-0.043, +0.039]$

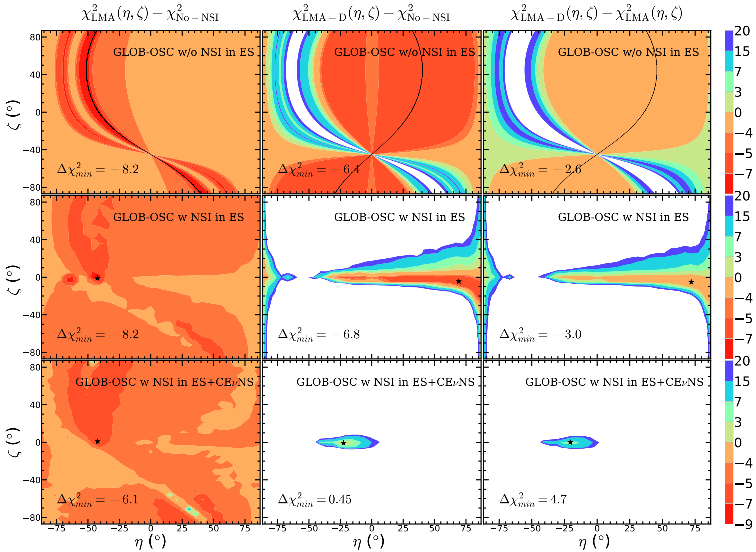
GLOB-OSC w NSI in ES + CEνNS

	90% CL / 99% CL
$^{\oplus}_{ee}$	$[-0.19, +0.20] \oplus [+0.95, +1.3]$ $[-0.23, +0.25] \oplus [+0.81, +1.3]$
$^{\oplus}_{\mu\mu}$	$[-0.43, +0.14] \oplus [+0.91, +1.3]$ $[-0.29, +0.20] \oplus [+0.83, +1.4]$
$^{\oplus}_{\tau\tau}$	$[-0.43, +0.14] \oplus [+0.91, +1.3]$ $[-0.29, +0.20] \oplus [+0.83, +1.4]$
$^{\oplus}_{e\mu}$	$[-0.12, +0.011]$ $[-0.18, +0.08]$
$^{\oplus}_{e\tau}$	$[-0.16, +0.083]$ $[-0.25, +0.33]$
$^{\oplus}_{\mu\tau}$	$[-0.0047, +0.012]$ $[-0.020, +0.021]$

[13] Coloma *et al.*, JHEP [arXiv:2305.07698]







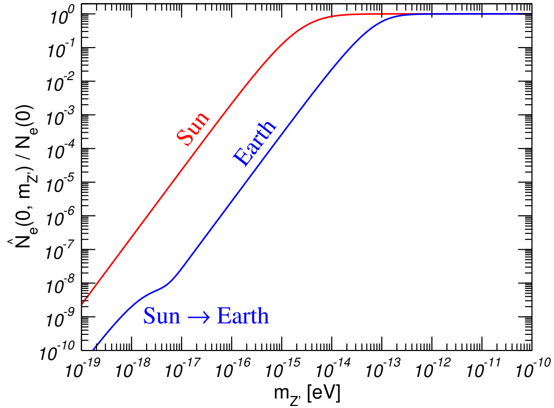
NSI potential for very light mediators

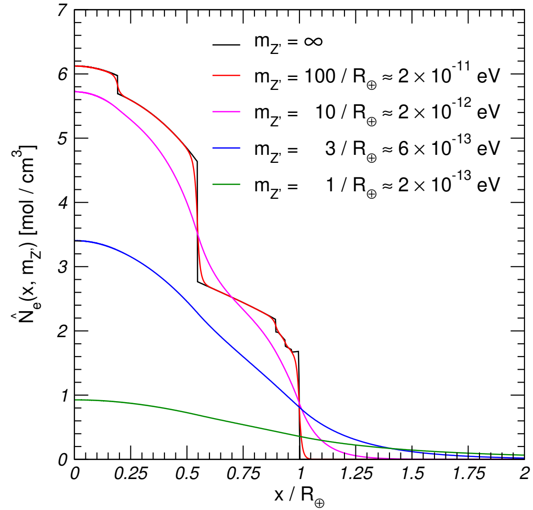
- Neutrino feels matter in a range $1/m_{Z'}$ around them;
- very light $m_{Z'}$ ⇒ replace $N_f(\vec{x}) \to \hat{N}_f(\vec{x},\, m_{Z'})$:

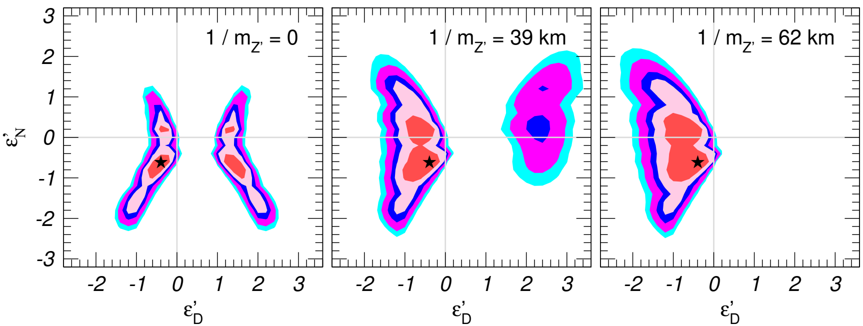
$$\hat{N}_f(\vec{x},\, m_{Z'}) \equiv \frac{m_{Z'}^2}{4\pi} \int N_f(\vec{\rho})\, \frac{e^{-m_{Z'}|\vec{\rho}-\vec{x}|}}{|\vec{\rho}-\vec{x}|}\, d^3\vec{\rho}\,;$$

- $$\frac{m_{Z'}}{N'_f/N_f} \begin{cases} \gg 1 : \hat{N}_f(\vec{x},\, m_{Z'}) \to N_f(\vec{x}) \ \text{(contact)}; \\ \sim 1 : \text{matter smeared as } 1/m_{Z'} \leftrightarrow \lambda_{\text{osc}}; \\ \ll 1 : \text{matter potential scales as } m_{Z'}^2; \end{cases}$$

★ LMA-D can only arise in the contact regime.







Bounds on long-range leptonic forces

- Let's consider the following lagrangian:

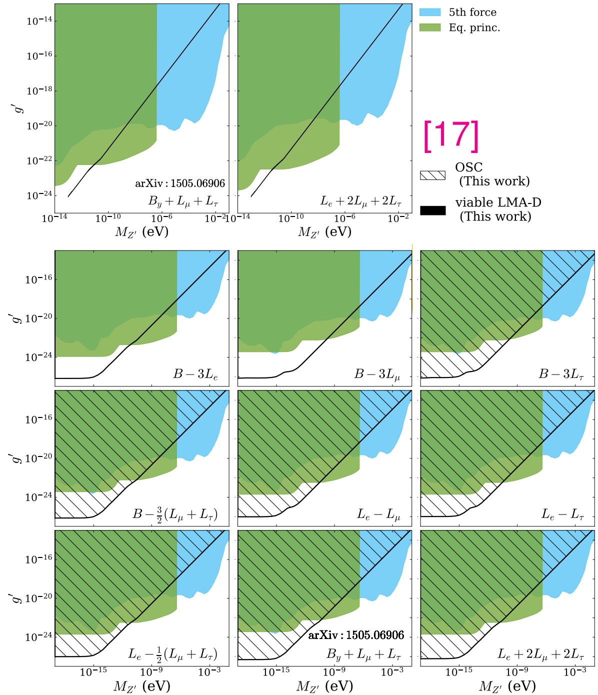
$$\mathscr{L}_{Z'}^{\text{matter}} = -g'\left(a_u\,\bar{u}\,\gamma^\alpha u + a_d\,\bar{d}\,\gamma^\alpha d + a_e\,\bar{e}\,\gamma^\alpha e + b_e\,\bar{\nu}_e\,\gamma^\alpha P_L \nu_e + b_\mu\,\bar{\nu}_\mu\,\gamma^\alpha P_L \nu_\mu + b_\tau\,\bar{\nu}_\tau\,\gamma^\alpha P_L \nu_\tau\right) Z'_\alpha\,;$$

- induced potential: $V_{\text{NSI}} \propto \sum_f \hat{N}_f(\vec{x},\, m_{Z'})\, \varepsilon_{\alpha\beta}^{fV}$ with

$$\varepsilon_{\alpha\beta}^{fV} = \frac{1}{2\sqrt{2}G_F}\,\frac{g'^2}{m_{Z'}^2}\, b_\alpha\,\delta_{\alpha\beta}\, a_f\,\chi^V$$

  matches the general $\varepsilon_{\alpha\beta}\,\xi^f\,\chi^V$ structure of our fits;

- hence, we can derive bounds:
  - contact regime: exact (from previous results);
  - long-range forces: approximate (using scaling);
- here we show limits in the light-mediator region;
- oscillation data allow to improve existing bounds.



Model	a_u	a_d	a_e	b_e	b_μ	b_τ	$(\Delta\chi^2_{\text{LRI}})_{\text{min}}$	$g' \leq$ bound
$B - 3L_e$	$\frac{1}{3}$	$\frac{1}{3}$	-3	-3	0	0	-1.4	6.6×10^{-27}
$B - 3L_\mu$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	-3	0	-1.1	7.0×10^{-27}
$B - 3L_\tau$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	0	-3	-1.8	7.3×10^{-27}
$B - \frac{3}{2}(L_\mu + L_\tau)$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	$-\frac{3}{2}$	$-\frac{3}{2}$	-1.2	7.2×10^{-27}
$L_e - L_\mu$	0	0	1	1	-1	0	-1.3	9.7×10^{-27}
$L_e - L_\tau$	0	0	1	1	0	-1	-1.7	1.0×10^{-26}
$L_e - \frac{1}{2}(L_\mu + L_\tau)$	0	0	1	1	$-\frac{1}{2}$	$-\frac{1}{2}$	-1.4	9.8×10^{-27}
$B_y + L_\mu + L_\tau$ Ref. [22]	$\frac{1}{3}$	$\frac{1}{3}$	0	0	1	1	0	4.9×10^{-27}
$L_e + 2L_\mu + 2L_\tau$	0	0	1	1	2	2	0	6.0×10^{-27}

[17] P. Coloma *et al.*, JHEP [arXiv:2009.14220].

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis. The three-neutrino scenario is nowadays well proven and **robust**;
- however, the possibility of physics beyond the 3ν paradigm remains open. Here we have focused on NC-like non-standard neutrino-matter interactions;
- we have extended previous studies by considering NSI with an arbitrary ratio of couplings to the constituents of ordinary matter (parametrized by coefficients ξ^e, ξ^u, ξ^d) and a lepton-flavor structure independent of the fermion type (parametrized by a matrix $\varepsilon_{\alpha\beta}$);
- we have found that NSI can spoil the precise determination of the oscillation parameters offered by **specific** class of experiments, but the 3ν precision is recovered once all the data are combined **together** – except for θ_{12} where a new region (LMA-D) appears;
- for $m_{Z'} \gtrsim \mathcal{O}(10\ \text{MeV})$ NSI with electrons also affect ES interactions in solar data. Interference between oscillation and scattering effects requires careful treatment;
- the degeneracy between LMA-D and the ν mass ordering cannot be resolved by oscillation data alone. Combination with scattering experiments (*e.g.*, COHERENT) is essential, but requires a sufficiently large mediator mass $m_{Z'} \gtrsim \mathcal{O}(50\ \text{MeV})$.