Neutrino non-standard interactions (NSI)

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EXCELENCIA SEVERO OCHOA

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Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}): $\leadsto$ [Ternes]
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Bx;
  - **Atmospheric**: DeepCore;
  - **Reactor**: KamLAND + Dbl-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos + T2K + NOvA;

- best-fit point and 1σ (3σ) ranges:

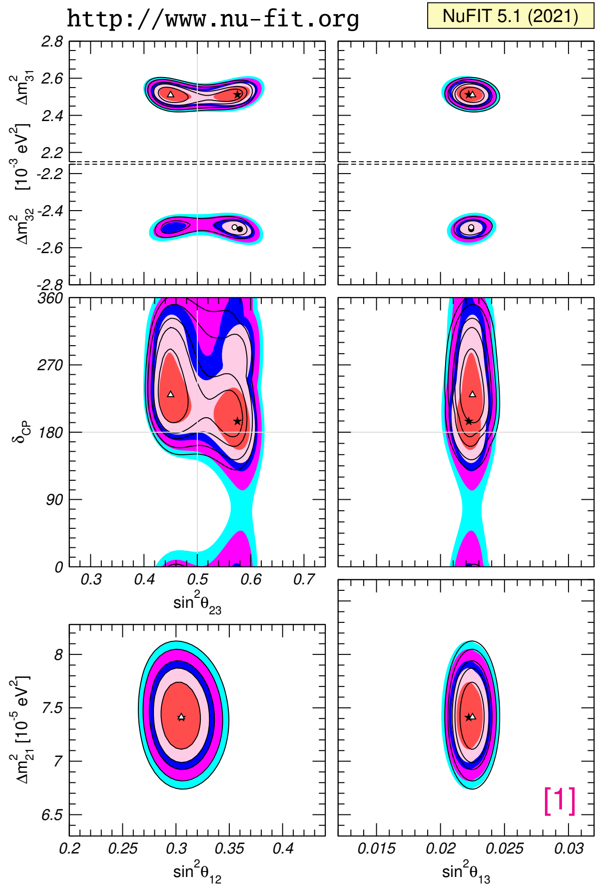
$$\theta_{12} = 33.44\,^{+0.77}_{-0.74}\,\left(^{+2.42}_{-2.17}\right), \qquad \Delta m^2_{21} = 7.42\,^{+0.21}_{-0.20}\,\left(^{+0.62}_{-0.60}\right) \times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = \begin{cases} 49.2\,^{+1.0}_{-1.3}\,\left(^{+2.8}_{-9.7}\right), \\ 49.5\,^{+1.0}_{-1.2}\,\left(^{+2.6}_{-9.7}\right), \end{cases} \qquad \Delta m^2_{3\ell} = \begin{cases} +2.515\,^{+0.028}_{-0.028}\,\left(^{+0.084}_{-0.084}\right) \times 10^{-3}\ \text{eV}^2, \\ -2.498\,^{+0.028}_{-0.029}\,\left(^{+0.085}_{-0.086}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.57\,^{+0.13}_{-0.12}\,\left(^{+0.40}_{-0.37}\right), \qquad \delta_{CP} = 194\,^{+52}_{-25}\,\left(^{+211}_{-89}\right);$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.232 \to 0.507 & 0.459 \to 0.694 & 0.629 \to 0.779 \\ 0.260 \to 0.526 & 0.470 \to 0.702 & 0.609 \to 0.763 \end{pmatrix}.$$



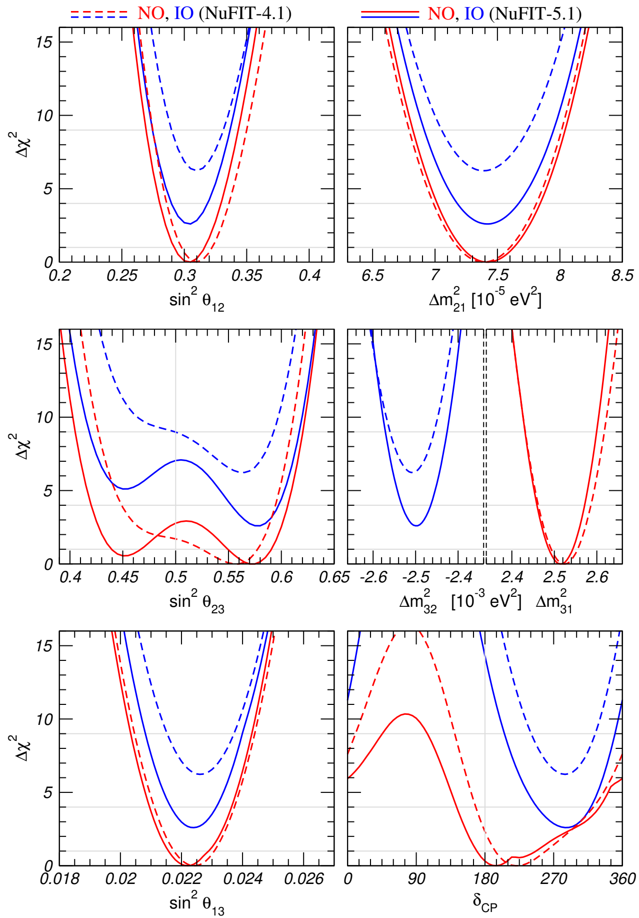
[1] I. Esteban *et al.*, JHEP **09** (2020) 178 [arXiv:2007.14792] & NuFIT 5.1 [http://www.nu-fit.org].

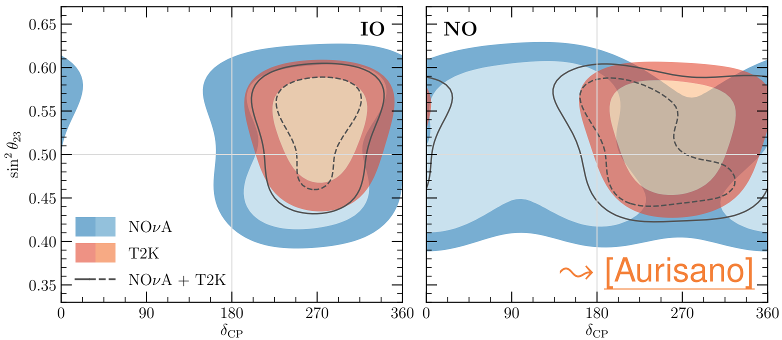
Open issues in 3ν oscillations

- **CP violation**: tension on δ_{CP} between T2K and NOvA for the case of normal ordering (NO);
- **Mass ordering**: due to such tension, long-standing hints in favor of NO is now reduced;
- **θ_{23} octant**: still no clue on deviation of θ_{23} 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: formalism

- Effective low-energy Lagrangian for **standard** neutrino interactions with matter:

$$\mathcal{L}_{\text{SM}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{f,\beta} \Big([\bar{\nu}_\beta \gamma_\mu L \ell_\beta][\bar{f}\gamma^\mu L f'] + \text{h.c.} \Big) - 2\sqrt{2}G_F \sum_{f,P,\beta} g_P^f [\bar{\nu}_\beta \gamma_\mu L \nu_\beta][\bar{f}\gamma^\mu P f]$$

where $P \in \{P_L, P_R\}$, (f, f') form an SU(2) doublet, and g_P^f is the Z coupling to fermion f:

$$g_L^\nu = \frac{1}{2}\,, \qquad g_L^\ell = \sin^2\theta_W - \frac{1}{2}\,, \qquad g_L^u = -\frac{2}{3}\sin^2\theta_W + \frac{1}{2}\,, \qquad g_L^d = \frac{1}{3}\sin^2\theta_W - \frac{1}{2}\,,$$

$$g_R^\nu = 0\,, \qquad g_R^\ell = \sin^2\theta_W\,, \qquad g_R^u = -\frac{2}{3}\sin^2\theta_W\,, \qquad g_R^d = \frac{1}{3}\sin^2\theta_W\,;$$

- here we consider NC-like **non-standard** neutrino-matter described by:

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

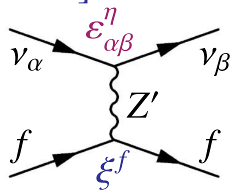
- ordinary matter composed by $\{e, u, d\}$ $\Rightarrow$ ν propagation sensitive to NSI with them;
- some experiments sensitive to $\nu - e$ elastic scattering $\Rightarrow$ NC-like NSI with e affect both propagation and interactions $\Rightarrow$ require dedicated treatment $\Rightarrow$ ignored for now;
- conversely, NC-like NSI's with quarks do **not** affect processes such as lepton appearance, which involve quarks through CC interactions $\Rightarrow$ only ν propagation affected.

Non-standard neutrino interactions: formalism

- Conventionally, only NSI with either u or d quarks have been considered;
- still, both cases can appear simultaneously, and produce consequences (*e.g.*, cancellations) which invalidate the u-only or d-only bounds;
- however, most general parameter space too large to handle ⇒ simplifications needed;
- here we assume that the ν flavor structure is **independent** of the charged fermion type:

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

- since neutrino **propagation** is only sensitive to the vector couplings:



$$\varepsilon_{\alpha\beta}^{f} \equiv \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR} = \varepsilon_{\alpha\beta}^{\eta}\,\xi^{f} \quad \text{with} \quad \xi^f = \xi^{fL} + \xi^{fR};$$

- only the direction in the (ξ^u, ξ^d) plane is non-trivial for ν oscillations ⇒ define an angle η:

$$\xi^u = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta)\,, \qquad \xi^d = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta)\,;$$

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

Non-standard interactions and 3ν oscillations

- Equation of motion: **6** (vac) + **8** (NSI-ν) + **1** (NSI-q) = **15** parameters [2]:

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

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

$$\mathcal{E}_{\alpha\beta}(x) \equiv \sum_f \frac{N_f(x)}{N_e(x)}\,\varepsilon^f_{\alpha\beta} = \sqrt{5}\,\varepsilon^\eta_{\alpha\beta}\,[\cos\eta + Y_n(x)\sin\eta]\,, \qquad Y_n(x) \equiv \frac{N_n(x)}{N_e(x)}\,,$$

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

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

[2] 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 [3, 4, 5];
- for matter, $\boldsymbol{V}_{\text{mat}} \to -\boldsymbol{V}^\star_{\text{mat}}$ requires: $\begin{cases} [\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] - 2\,, \\ [\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)]\,, \\ \mathcal{E}_{\alpha\beta}(x) \to -\mathcal{E}^\star_{\alpha\beta}(x) \qquad (\alpha \neq \beta)\,, \end{cases}$
- 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, $\mathcal{E}_{\alpha\beta}(x)$ 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 $Y_n(x)$ is constant, and same for all the neutrino trajectories.

[3] M.C. Gonzalez-Garcia, M. Maltoni, JHEP **09** (2013) 152 [arXiv:1307.3092]
[4] P. Bakhti, Y. Farzan, JHEP **07** (2014) 064 [arXiv:1403.0744].
[5] 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):

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

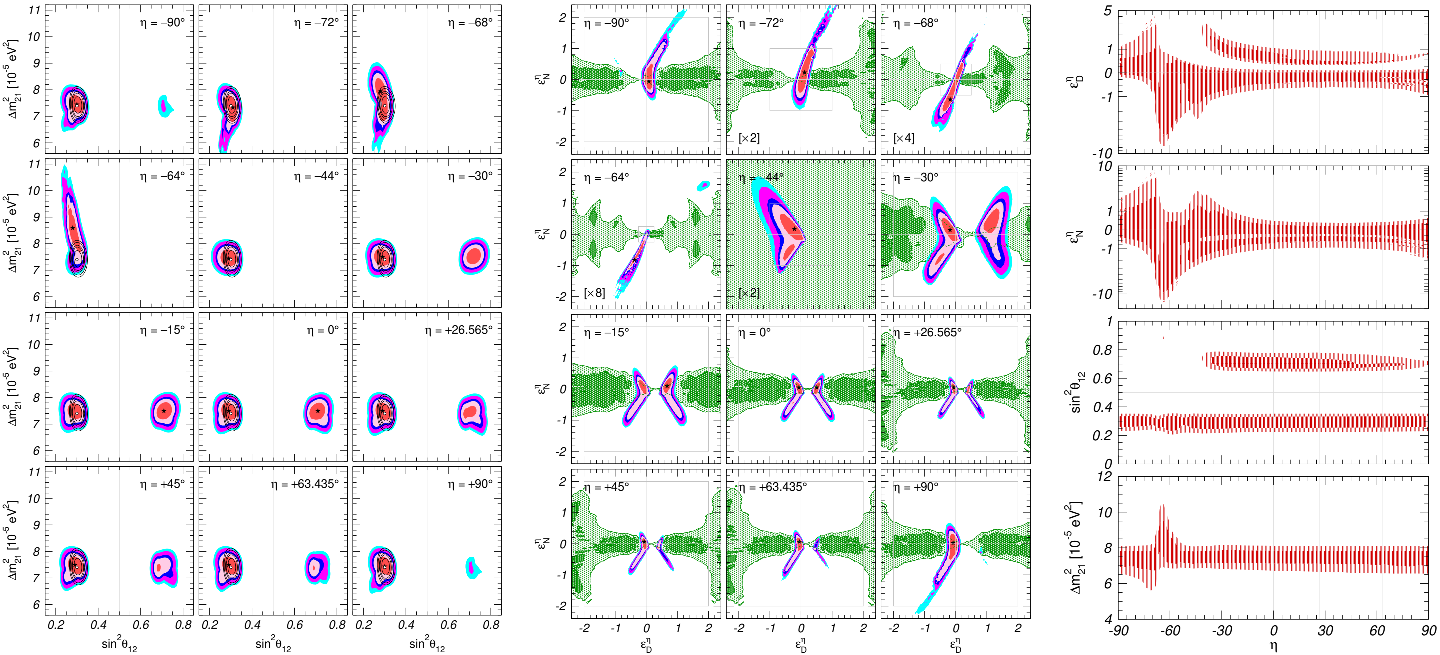
$$\boldsymbol{H}^{\text{eff}}_{\text{mat}} \equiv \sqrt{2}\, G_F N_e(r)\left[\begin{pmatrix}c_{13}^2 & 0\\ 0 & 0\end{pmatrix} + \sqrt{5}\,[\cos\eta + Y_n(x)\sin\eta]\begin{pmatrix}-\varepsilon_D^\eta & \varepsilon_N^\eta\\ \varepsilon_N^{\eta\star} & \varepsilon_D^\eta\end{pmatrix}\right],$$

$$\begin{cases}\varepsilon_D^\eta = c_{13}s_{13}\,\text{Re}\,(s_{23}\,\varepsilon_{e\mu}^\eta + c_{23}\,\varepsilon_{e\tau}^\eta) - (1+s_{13}^2)c_{23}s_{23}\,\text{Re}(\varepsilon_{\mu\tau}^\eta)\\ \qquad - c_{13}^2(\varepsilon_{ee}^\eta - \varepsilon_{\mu\mu}^\eta)/2 + (s_{23}^2 - s_{13}^2 c_{23}^2)(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta)/2\,,\\ \varepsilon_N^\eta = c_{13}(c_{23}\,\varepsilon_{e\mu}^\eta - s_{23}\,\varepsilon_{e\tau}^\eta) + s_{13}\left[s_{23}^2\,\varepsilon_{\mu\tau}^\eta - c_{23}^2\,\varepsilon_{\mu\tau}^{\eta\star} + c_{23}s_{23}(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta)\right];\end{cases}$$

- 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 $Y_n(x) \in [1/6, 1/2]$ $\Rightarrow$ approximate cancellation of NSI for $\eta \in [-80^\circ, -63^\circ]$.

Oscillation results for solar and KamLAND neutrinos

- Generalized mass-ordering degeneracy $\Rightarrow$ new LMA-D solution with $\theta_{12} > 45°$ [6];
- $\eta = 0 \Rightarrow$ NSI terms proportional to $N_p(x) \equiv N_e(x) \Rightarrow$ the degeneracy becomes exact.



[6] 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: $Y_n(x) \to Y_n^\oplus \approx 1.051 \Rightarrow \mathcal{E}_{\alpha\beta}(x) \to \varepsilon_{\alpha\beta}^\oplus$ becomes an effective parameter:

$$\varepsilon_{\alpha\beta}^\oplus \equiv \sqrt{5}\,[\cos\eta + Y_n^\oplus \sin\eta]\,\varepsilon_{\alpha\beta}^\eta\,,$$

- the bounds on $\varepsilon_{\alpha\beta}^\oplus$ are independent of the quark couplings (*i.e.*, of η);
- for $\eta = \arctan(-1/Y_n^\oplus) \approx -43.6^\circ$ ATM+LBL data imply **no** bound on $\varepsilon_{\alpha\beta}^\eta$;
- the NSI parameter space is too big to be properly studied $\Rightarrow$ simplification needed;
- bounds on $\varepsilon_{\alpha\beta}^\oplus$ are weakest when $V_{\text{mat}} \propto \delta_{e\alpha}\delta_{e\beta} + \varepsilon_{\alpha\beta}^\oplus$ has two degenerate eigenvalues [7] $\Rightarrow$ focus on such case $\Rightarrow$ introduce parameters ($\varepsilon_\oplus$, φ_{12}, φ_{13}, α_1, α_2) and define:

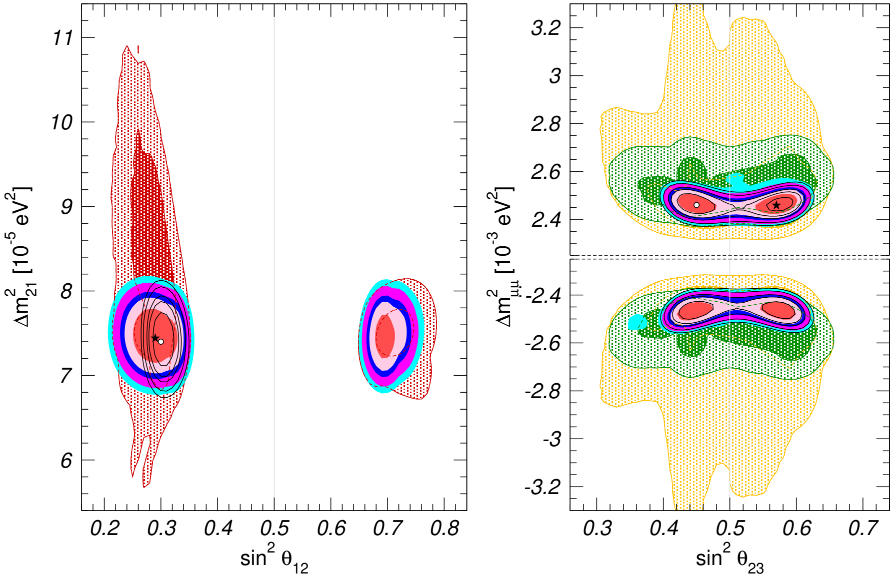
$$\begin{aligned}
\varepsilon_{ee}^\oplus - \varepsilon_{\mu\mu}^\oplus &= \quad \varepsilon_\oplus\,(\cos^2\varphi_{12} - \sin^2\varphi_{12})\cos^2\varphi_{13} - 1\,,\\
\varepsilon_{\tau\tau}^\oplus - \varepsilon_{\mu\mu}^\oplus &= \quad \varepsilon_\oplus\,(\sin^2\varphi_{13} - \sin^2\varphi_{12}\cos^2\varphi_{13})\,,\\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

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

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

Impact of NSI on the oscillation parameters

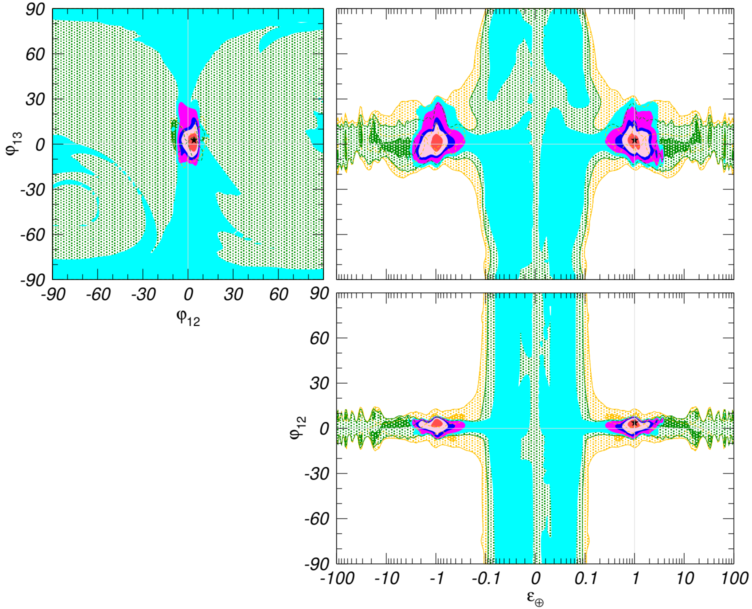
- Once marginalized over η, analysis of solar + KamLAND data shows strong deterioration of the precision on Δm^2_{21} and θ_{12}, as well as the appearance of the LMA-D solution [6];
- a similar worsening appears in ATM + LBL-dis + LBL-app + IceCUBE + MBL-rea analysis;
- synergies between solar and atmospheric 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.

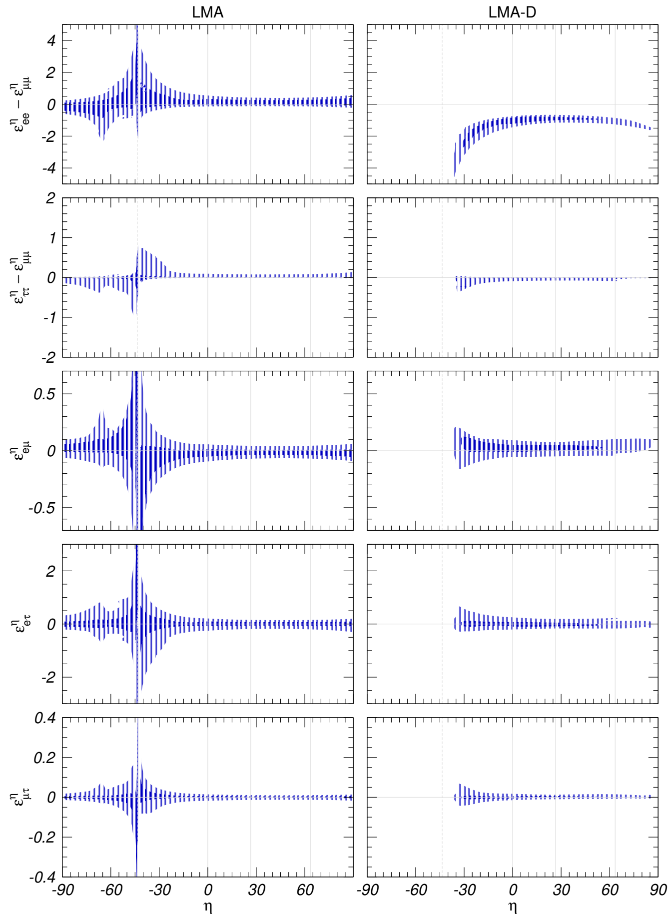


[6] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].

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 $\varepsilon^\eta_{\alpha\beta}$.





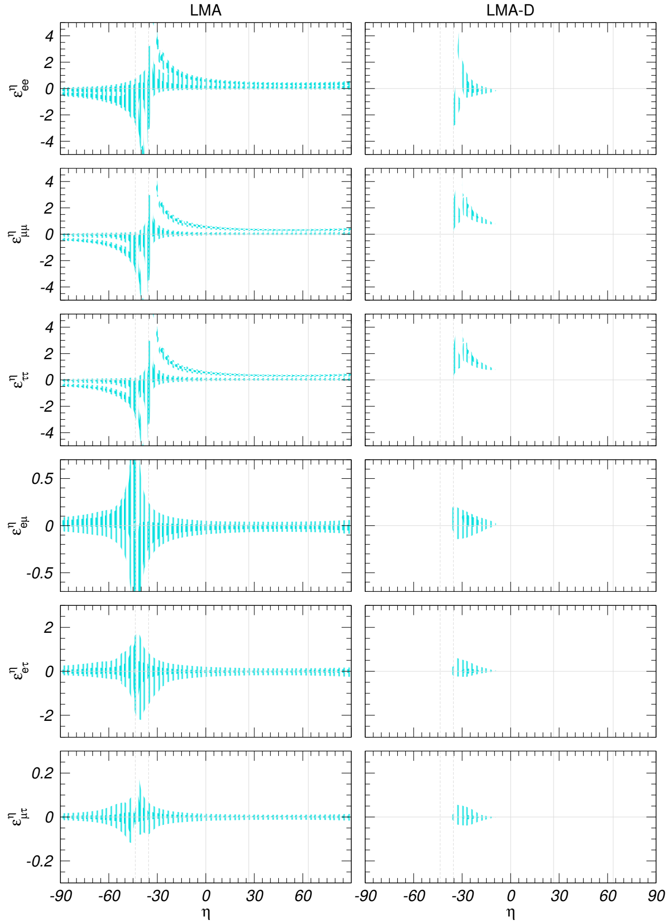
The COHERENT experiment

- Observation of coherent neutrino-nucleus scattering [8] allows to put bounds on NSI through the effective charges ($Y_n^{\text{coh}} \approx 1.407$):

$$Q_\alpha^2 \propto [(g_p^V + Y_n^{\text{coh}} g_n^V) + \varepsilon_{\alpha\alpha}^{\text{coh}}]^2 + \sum_{\beta\neq\alpha} (\varepsilon_{\alpha\beta}^{\text{coh}})^2$$

with $\varepsilon_{\alpha\beta}^{\text{coh}} = \sqrt{5}\,[\cos\eta + Y_n^{\text{coh}} \sin\eta]\,\varepsilon_{\alpha\beta}^\eta$;

- for $\eta = \arctan(-1/Y_n^{\text{coh}}) \approx -35.4°$ no bound on $\varepsilon_{\alpha\beta}^\eta$ is implied;
- separate bounds on diagonal $\varepsilon_{\alpha\alpha}^\eta$ couplings can be placed.



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

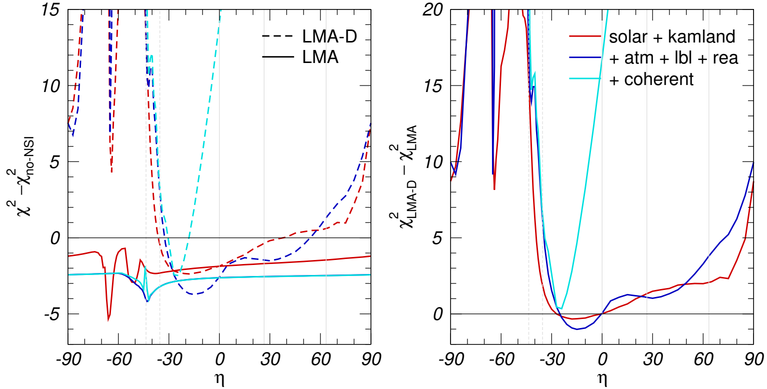
[9] P. Coloma, I. Esteban *et al.*, JHEP **02** (2020) 023 [arXiv:1911.09109].

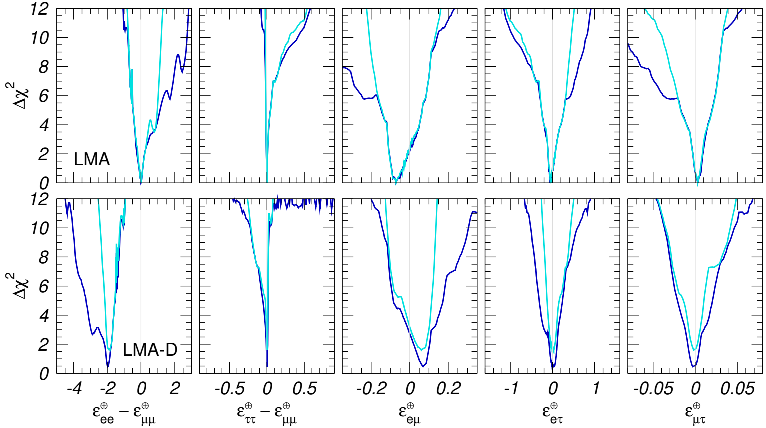
General NSI bounds

- 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 [9]:

OSCILLATIONS			+ COHERENT (t+E Duke)	
	LMA	LMA $\oplus$ LMA-D		LMA = LMA $\oplus$ 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 $\Delta\chi^2 \sim 4$ [10].





[9] P. Coloma, I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, JHEP **02** (2020) 023 [arXiv:1911.09109].
[10] M. Chaves and T. Schwetz, JHEP **05** (2021), 042 [arXiv:2102.11981].

Non-standard interactions with electrons: formalism

- Let's focus here on solar neutrinos. In the presence of NC-like NSI with e, elastic scattering is modified $\Rightarrow$ detection process (*e.g.*, in SK, SNO, Borexino) is affected;

- in the SM, ν interactions (both CC and NC) are diagonal in the flavor basis. Hence:

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

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

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

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

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

- 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 $N_{\text{ev}} \propto \text{Tr}\left[\rho^{(e)}\, \sigma^{\text{NSI}}\right]$ must be used;
- the cross-section matrix σ^{NSI} is the integral over T_e of the following expression:

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

- where f_+, f_-, $f_\pm$ are loop functions, $y \equiv T_e/E_\nu$, and C_L, C_R are 3×3 hermitian matrices:

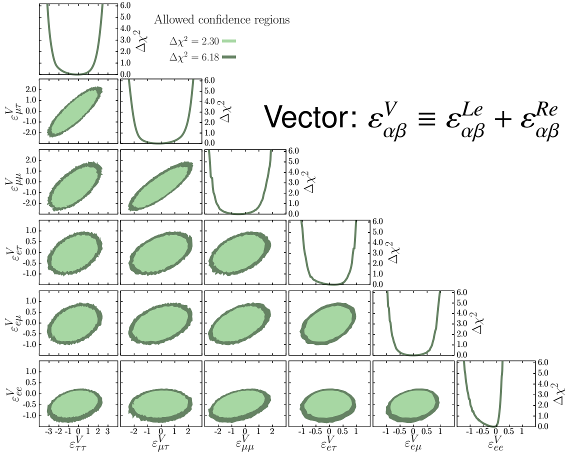
$$\begin{cases} C^L_{\alpha\beta} \equiv c_{L\beta}\,\delta_{\alpha\beta} + \varepsilon^{Le}_{\alpha\beta} \\ C^R_{\alpha\beta} \equiv c_{L\beta}\,\delta_{\alpha\beta} + \varepsilon^{Re}_{\alpha\beta} \end{cases} \quad \text{with} \quad \begin{cases} c_{L\tau} = c_{L\mu} = g^\ell_L \quad \text{and} \quad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

- when the NSI terms $\varepsilon^{Le}_{\alpha\beta}$ and $\varepsilon^{Re}_{\alpha\beta}$ are set to zero, the matrix $d\sigma^{\text{NSI}}/dT_e$ becomes diagonal and the SM expressions are recovered;
- the cross section for antineutrinos can be obtained by interchanging $C_L \leftrightarrow C_R^\star$;
- NSI effects on neutrino propagation are the same as in the previous section (for $\eta = 0$) and are accounted by the density matrix $\rho^{(e)}$.

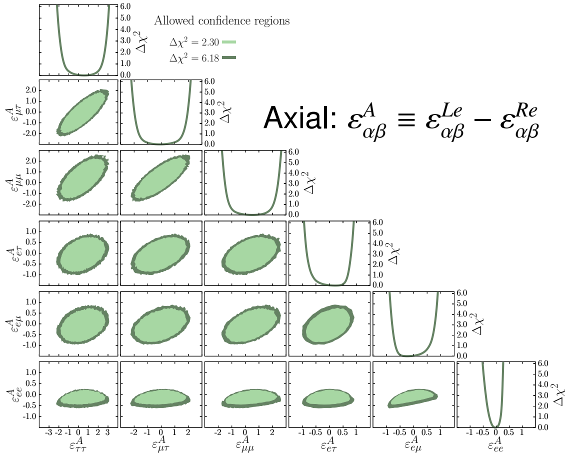
Bounds on NSI-e from Borexino II

- Ref. [11]: analysis of NSI-e with Borexino. Caveats:
  - only diagonal NSI considered;
  - only 1 or 2 NSI parameters 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.

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



Vector: $\varepsilon^V_{\alpha\beta} \equiv \varepsilon^{Le}_{\alpha\beta} + \varepsilon^{Re}_{\alpha\beta}$

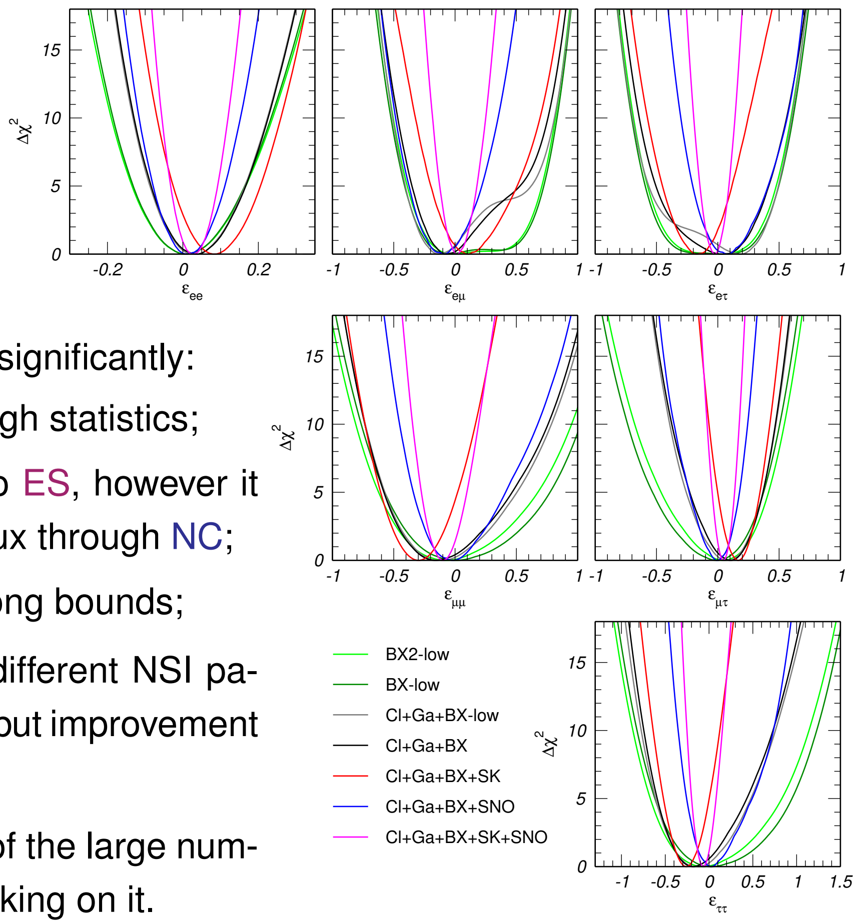


Axial: $\varepsilon^A_{\alpha\beta} \equiv \varepsilon^{Le}_{\alpha\beta} - \varepsilon^{Re}_{\alpha\beta}$

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

NSI-e from all solar data

- Caveat: in this slide we vary only 1 NSI parameter at-a-time;
- other low-E data such as BX1 and Cl+Ga have little impact;
- however, SK and SNO contribute significantly:
  - SK measures ES events with high statistics;
  - SNO is only weakly sensitive to ES, however it accurately determines the $^8\mathrm{B}$ flux through NC;
  - SK+SNO combination yield strong bounds;
- of course, degeneracies among different NSI parameters will weaken the bounds, but improvement over BX2-only data still expected;
- global analysis is tough because of the large number of parameters, but we are working on it.



- 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 up and down quarks (parametrized by an angle η) and a lepton-flavor structure independent of the quark type (parametrized by a matrix $\varepsilon^{\eta}_{\alpha\beta}$);
- 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;
- a 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;
- NSI with electrons also affect ES interactions in solar data. Interference between oscillation and scattering effects requires careful treatment. A global fit is under way.