NSIs and their impact on the determination of neutrino parameters

Michele Maltoni

Instituto de Física Teórica UAM/CSIC

P2IO BSM-Nu first workshop

Online Virtual Seminar – February 12th, 2021

Instituto de Física Teórica UAM-CSIC

EXCELENCIA SEVERO OCHOA

UNIVERSIDAD AUTONOMA DE MADRID

CSIC Consejo Superior de Investigaciones Científicas

GOBIERNO DE ESPAÑA

MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

FEDER Fondo Europeo de Desarrollo Regional

"Una manera de hacer Europa"

Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}):
  - **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:

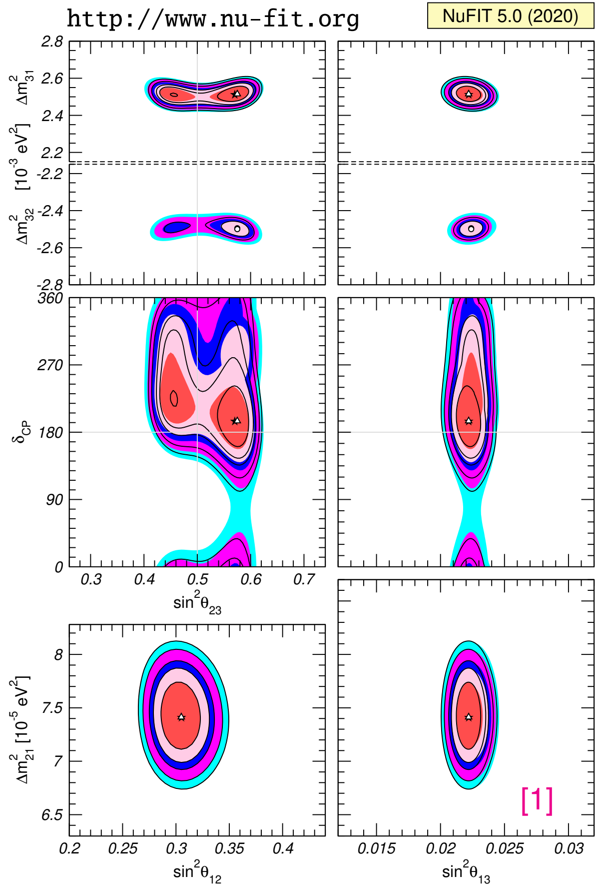
$$\theta_{12} = 33.44\,^{+0.78}_{-0.75}\,\binom{+2.42}{-2.17}, \qquad \Delta m^2_{21} = 7.42\,^{+0.21}_{-0.20}\,\binom{+0.62}{-0.60} \times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = \begin{cases} 49.0\,^{+1.1}_{-1.4}\,\binom{+2.8}{-9.4}, \\ 49.3\,^{+1.0}_{-1.2}\,\binom{+2.7}{-9.4}, \end{cases} \qquad \Delta m^2_{3\ell} = \begin{cases} +2.514\,^{+0.028}_{-0.027}\,\binom{+0.084}{-0.083} \times 10^{-3}\ \text{eV}^2, \\ -2.497\,^{+0.028}_{-0.028}\,\binom{+0.085}{-0.086} \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.57\,^{+0.13}_{-0.12}\,\binom{+0.40}{-0.37}, \qquad \delta_{\text{CP}} = 195\,^{+51}_{-25}\,\binom{+208}{-88};$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.631 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix}.$$



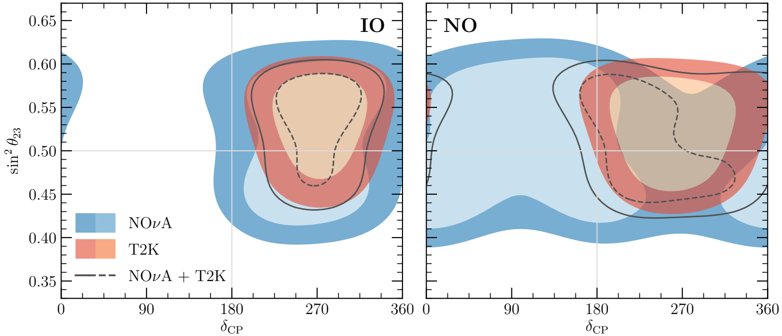
[1] I. Esteban *et al.*, JHEP **09** (2020) 178 [arXiv:2007.14792] & NuFIT 5.0 [http://www.nu-fit.org].

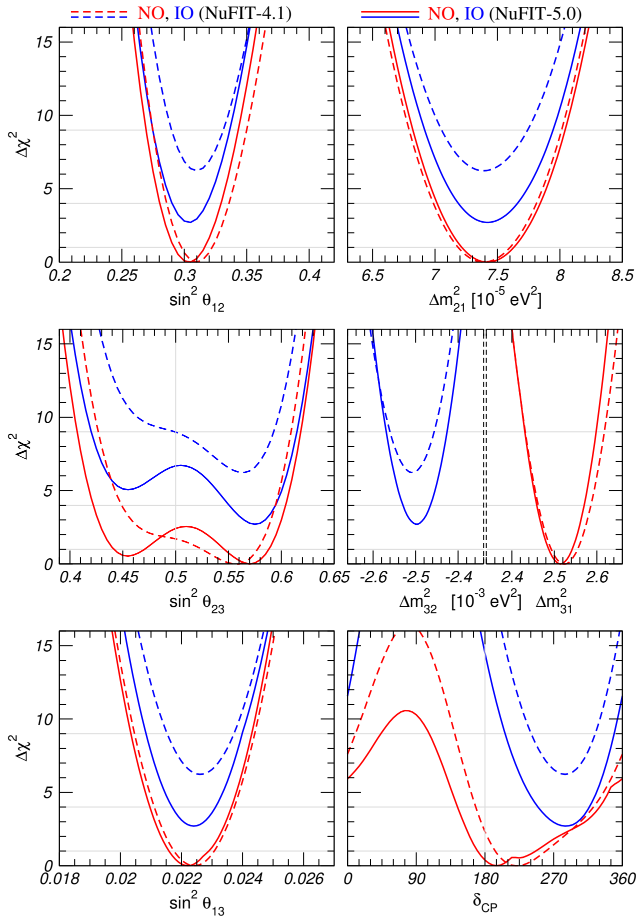
Open issues in 3ν oscillations

- **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:

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

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:

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

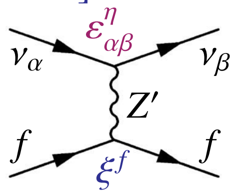
- ordinary matter composed by $\{e, u, d\}$ $\Rightarrow$ ν propagation sensitive to NSI with them;
- some experiments sensitive to $\nu - e$ elastic scattering $\Rightarrow$ NC-like NSI with e affect both propagation and interactions $\Rightarrow$ require dedicated treatment $\Rightarrow$ not considered here;
- 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 $\Rightarrow$ simplifications needed;
- here we assume that the ν flavor structure is **independent** of the charged fermion type:

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

- 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 $\Rightarrow$ 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]:

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

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

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

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

- notice that our definition of U_{vac} differ by the “usual” one by an overall rephasing, $U_{\text{vac}} = PUP^*$ with $P \equiv \text{diag}(e^{i\delta_{\text{CP}}}, 1, 1)$, 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: $H \to -H^*$ does not affect the neutrino probabilities;
- we have $H = H_{\text{vac}} \pm V_{\text{mat}}$. For vacuum, $H_{\text{vac}} \to -H_{\text{vac}}^*$ 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, $V_{\text{mat}} \to -V_{\text{mat}}^*$ requires: $\begin{cases} [\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] - 2\,, \\ [\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)]\,, \\ \mathcal{E}_{\alpha\beta}(x) \to -\mathcal{E}_{\alpha\beta}^*(x) \qquad (\alpha \neq \beta)\,, \end{cases}$
- since $V_{\text{mat}} = V_{\text{SM}} + V_{\text{NSI}}$ and V_{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):

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

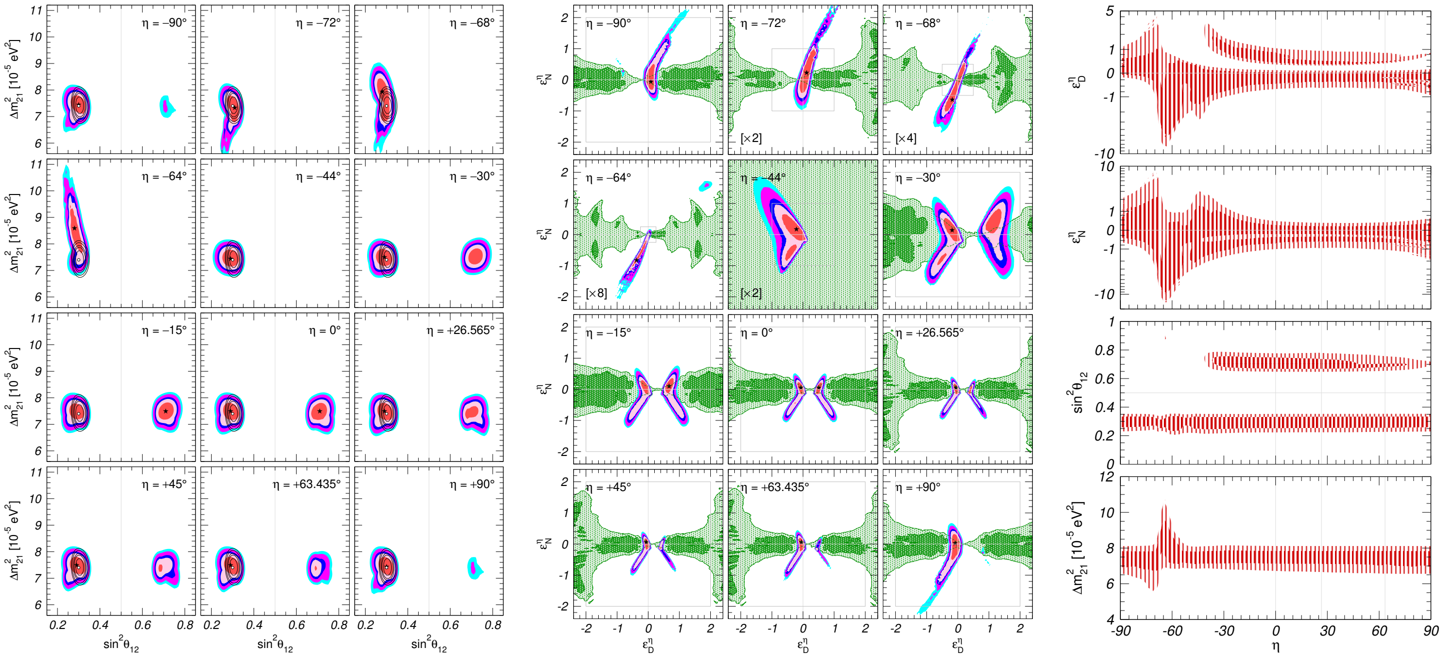
$$H^{\text{eff}}_{\text{mat}} \equiv \sqrt{2}\,G_F N_e(r)\left[\begin{pmatrix}c_{13}^2 & 0 \\ 0 & 0\end{pmatrix} + \sqrt{5}\,[\cos\eta + Y_n(x)\sin\eta]\begin{pmatrix}-\varepsilon_D^\eta & \varepsilon_N^\eta \\ \varepsilon_N^{\eta\star} & \varepsilon_D^\eta\end{pmatrix}\right],$$

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

- 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 ⇒ new LMA-D solution with $\theta_{12} > 45°$ [6];
- $\eta = 0$ ⇒ NSI terms proportional to $N_p(x) \equiv N_e(x)$ ⇒ 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:

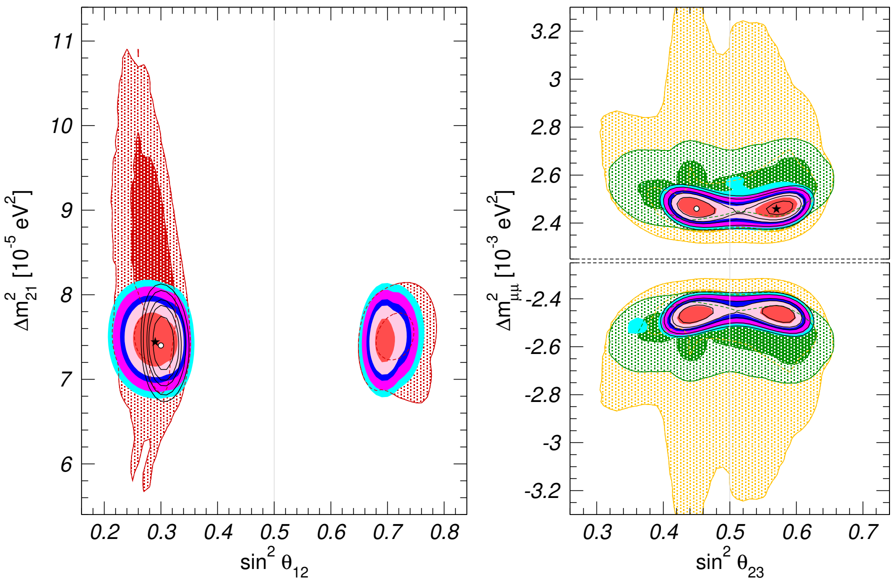
$$\begin{aligned}
\varepsilon_{ee}^\oplus - \varepsilon_{\mu\mu}^\oplus &= \quad \varepsilon_\oplus (\cos^2\varphi_{12} - \sin^2\varphi_{12}) \cos^2\varphi_{13} - 1\,,\\
\varepsilon_{\tau\tau}^\oplus - \varepsilon_{\mu\mu}^\oplus &= \quad \varepsilon_\oplus (\sin^2\varphi_{13} - \sin^2\varphi_{12}\cos^2\varphi_{13})\,,\\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

- 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

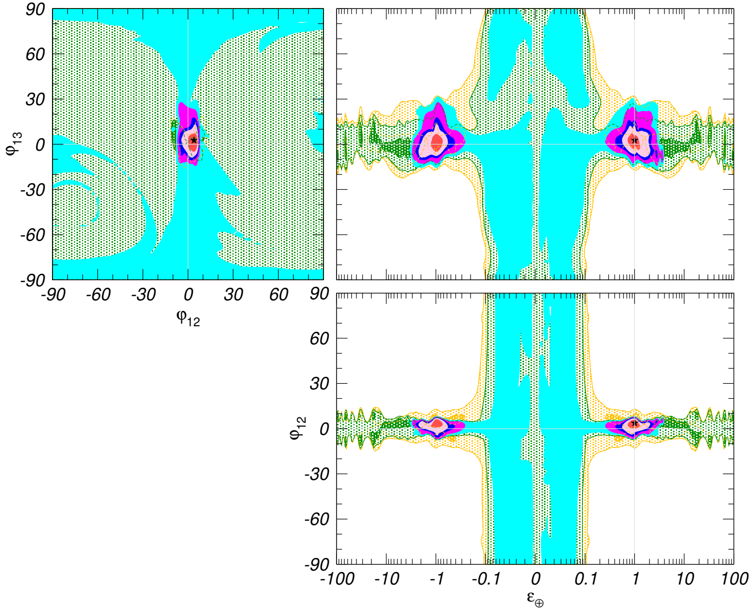
- Once marginalized over η, analysis of solar + KamLAND data shows strong deterioration of the precision on Δm^2_{21} and θ_{12}, as well as the appearance of the LMA-D solution [6];
- a similar worsening appears in ATM + LBL-dis + LBL-app + IceCUBE + MBL-rea analysis;
- synergies between solar and atmospheric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

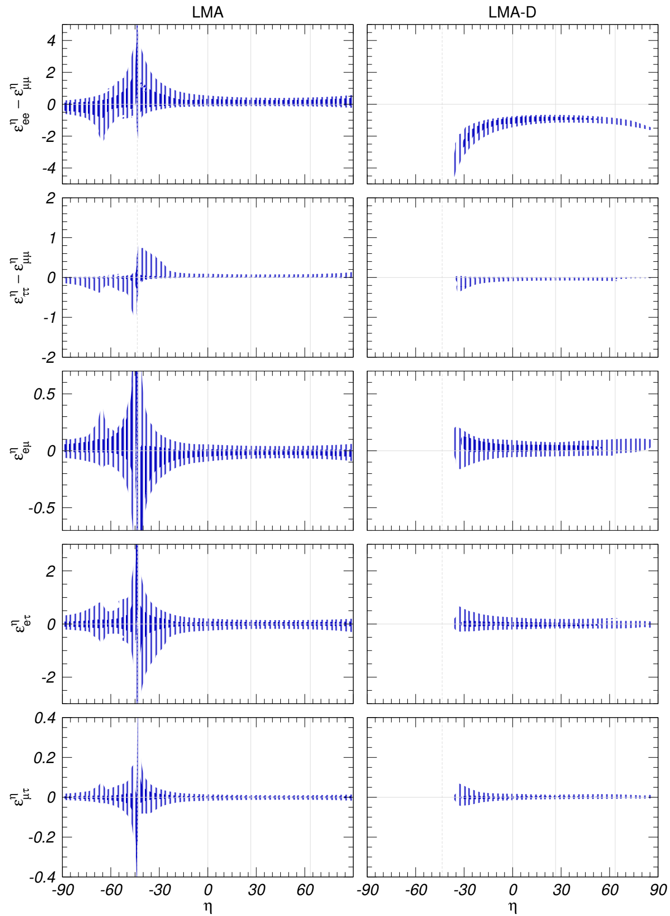


[6] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].

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





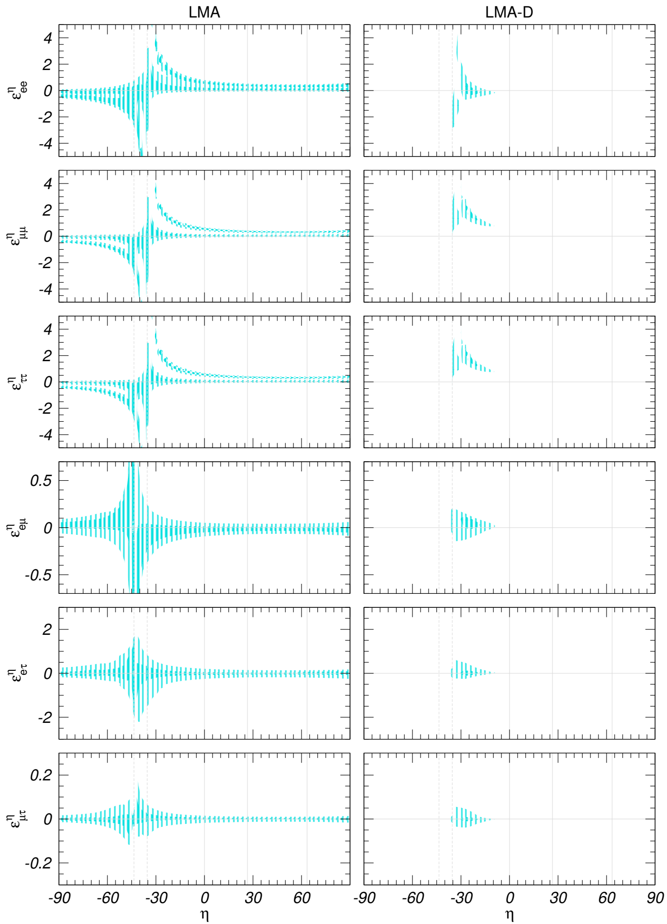
The COHERENT experiment

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

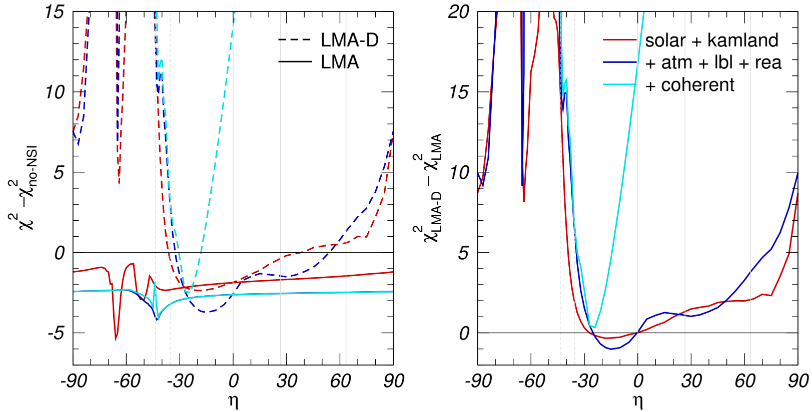


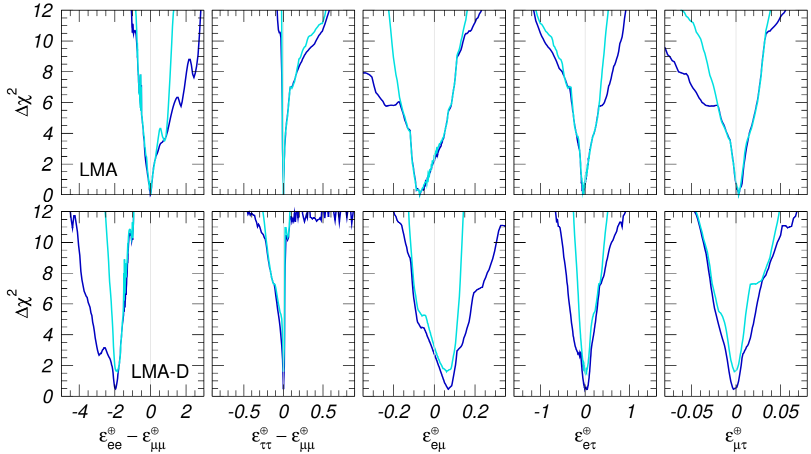
[8] D. Akimov *et al.* [COHERENT], Science **357** (2017) 1123 [arXiv:1708.01294].
[9] P. Coloma, I. Esteban *et al.*, JHEP **02** (2020) 023 [arXiv:1911.09109].

General NSI bounds

- Inclusion of COHERENT data rules out LMA-D for NSI with u, d, or p, but **not** in the general case;
- unlike oscillation data, COHERENT is sensitive to $\varepsilon^\eta_{ee} + \varepsilon^\eta_{\mu\mu} + \varepsilon^\eta_{\tau\tau}$;
- general 2σ bounds [9]:

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

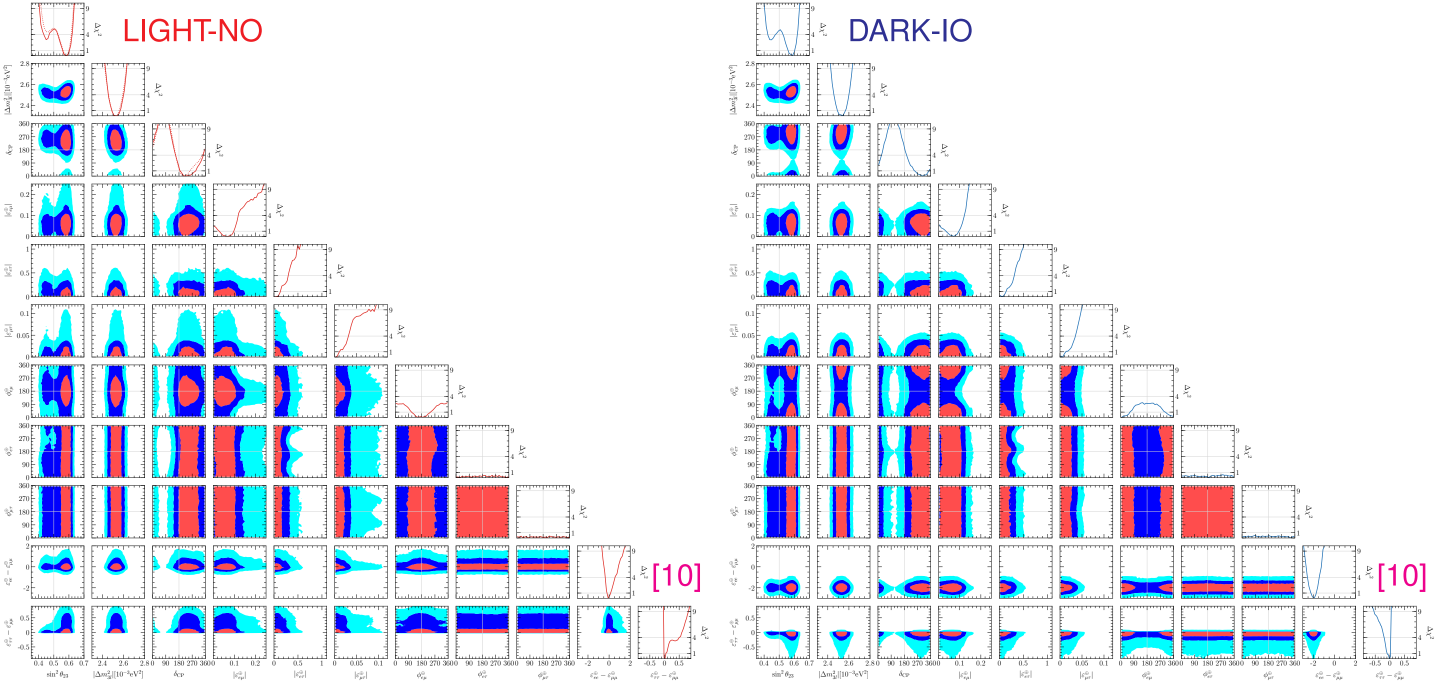




[9] P. Coloma, I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, JHEP **02** (2020) 023 [arXiv:1911.09109].

CP violation in the presence of NSI

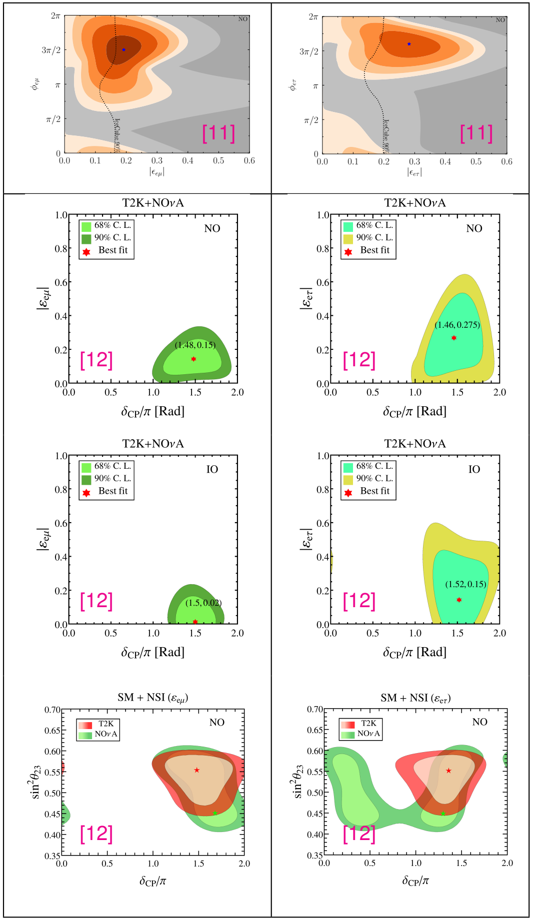
- NSI introduce three additional phases $\phi^{\oplus}_{\alpha\beta}$, associated to the non-diagonal elements $\varepsilon^{\oplus}_{\alpha\beta}$.



[10] I. Esteban *et al.*, JHEP **06** (2019) 055 [arXiv:1905.05203].

Impact of NSI on T2K and NOvA

- It has been noted [11, 12] that tension between T2K and NOvA in the determination of δ_{CP} for Normal Ordering can be alleviated by NSI;
- both papers suggest two alternative mechanisms: $|\varepsilon_{e\mu}^{\oplus}| \sim 0.15$ and $|\varepsilon_{e\tau}^{\oplus}| \sim 0.3$, yielding similar improvements ($\Delta\chi^2_{e\mu} \sim 4.5$ and $\Delta\chi^2_{e\tau} \sim 3.7$) w.r.t. SM for NO;
- no significant NSI contribution is found for IO;
- both mechanisms favor maximal CP violation ($\delta_{CP} \sim 270°$) in the presence of NSI;
- by alleviating the T2K–NOvA tension, the worsening of NO w.r.t. IO does **not** take place.

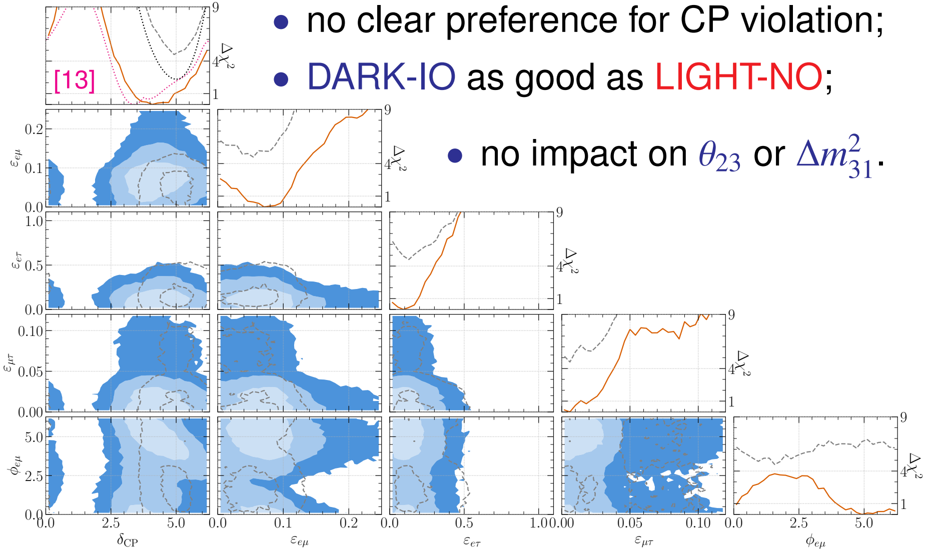


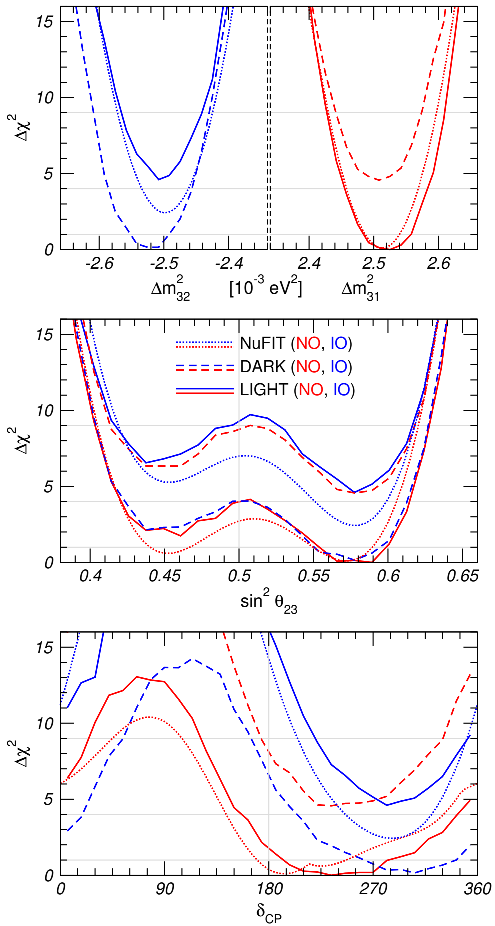
[11] P.B. Denton, J. Gehrlein, R. Pestes, Phys. Rev. Lett. **126** (2021) 051801 [arXiv:2008.01110].

[12] S.S. Chatterjee, A. Palazzo, Phys. Rev. Lett. **126** (2021) 051802 [arXiv:2008.04161].

Impact of NSI on oscillation parameters

- Global fits of **all** neutrino data indicate that:
  - $\varepsilon_{e\mu}^{\oplus}$ mechanism OK, but with smaller $|\varepsilon_{e\mu}^{\oplus}| \simeq 0.08$;
  - $\varepsilon_{e\tau}^{\oplus}$ mechanism severely constrained;
- preference of NO over IO increases by $\Delta\chi^2 \sim 2.3$;
  - no clear preference for CP violation;
  - DARK-IO as good as LIGHT-NO;
  - no impact on θ_{23} or Δm^2_{31}.





[13] I. Esteban, private communication.

- 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. However, once all the data are combined **together** the precision achieved in the 3ν scenario is recovered, except for θ_{12} where a new region (LMA-D) appears;
- a degeneracy between LMA-D and the neutrino mass ordering appears, which cannot be resolved by oscillation data alone. Combination with scattering experiments (*e.g.*, COHERENT) is essential.