Global constraints on non-standard neutrino interactions with quarks and electrons

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Non-standard neutrino interactions (NSI)

Generically these can be classified in charged-current (CC) NSI:

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

Very constraint from meson and muon decays (**We do not include them**)

and neutral-current (NC) NSI:

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

Where $P = P_L, P_R$. To make the analysis feasible and obtain relevant results we further simplify the (NC) NSI by considering:

$$\varepsilon_{\alpha\beta}^{f,P} \equiv \varepsilon_{\alpha\beta}\xi^f \chi^P \qquad \varepsilon_{\alpha\beta}^{f,P} \in \mathbb{R}, \text{CP conserving}$$

For the analysis will be also relevant to think in terms of vector and axial NSI.

$$\varepsilon_{\alpha\beta}^{f,V} \equiv \varepsilon_{\alpha\beta}^{f,L} + \varepsilon_{\alpha\beta}^{f,R} \quad \text{and} \quad \varepsilon_{\alpha\beta}^{f,A} \equiv \varepsilon_{\alpha\beta}^{f,L} - \varepsilon_{\alpha\beta}^{f,R} .$$

The NSI Lagrangian we consider in our analysis

Why are NSI analysis useful?

An NSI analysis provides a model independent way to provide constraints to a wide variety of models from which the NSI can arise

- Light mediators

K.S. Babu, et al [1705.01822] , Y. Farzan, et al [1505.06906]
Y. Farzan, et al [1607.07616], Y. Farzan, et al [1512.09147]
A. Greljo, et al [2203.13731], J. Heeck, et al [1812.04067]
Y. Farzan, et al [1912.09408], N. Bernal, et al [2211.15686]

- Radiative neutrino mass models involving new scalars

K.S. Babu, [1907.09498]

- Models with leptoquarks

M.B. Wise, [1404.4663]
A. Greljo, [2107.07518]

Experiments included in the Global fit

NSI

Propagation

(only vector NSI)

Detection cross sections

(Both vector and axial NSI)

- Elastic scattering with electrons (ES) (Vector)
- 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.

Light mediators

One of the most paradigmatic models that give rise to NSI are light mediators.

To put a concrete example, let us consider models with a vector mediator coupling to electrons and neutrinos.

$$\mathcal{L}_V = g_{Z'} Z'_\mu \left(q^e_{Z'} \bar{e}\gamma^\mu e + \sum_\alpha q^{\nu_\alpha}_{Z'} \bar{\nu}_{\alpha,L}\gamma^\mu \nu_{\alpha,L} \right) + \frac{1}{2} M^2_{Z'} Z'^\mu Z'_\mu,$$

Model	q^e	q^{ν_e}	q^{ν_μ}	q^{ν_τ}
Universal/leptonic scalar (or pseudoscalar)	1	1	1	1
$B-L$ vector	-1	-1	-1	-1
$L_e - L_\mu$ vector	1	1	-1	0
$L_e - L_\tau$ vector	1	1	0	-1

The oscillation data can be used to constraint very light mediators but for scattering the mass of the mediator must be larger than the momentum transfer (q) of the neutrinos interacting $M_{\rm med} \gtrsim q$

- Borexino scattering: $q \sim \mathcal{O}(500\ \mathrm{keV})$,
- SNO and SuperK: $q \sim \mathcal{O}(5-10\ \mathrm{MeV})$
- CEvNS: COHERENT $q \sim 30-50\ \mathrm{MeV}$ Dresden II $q \sim 5\ \mathrm{MeV}$

Neutrino Propagation and LMA-D solution

The neutrino propagation is governed by $H^\nu = H_{\rm vac} + H_{\rm mat}$ the transformation $H^\nu \to -(H^\nu)^*$ leaves the oscillation probabilities invariant

$$H_{\rm vac} = U_{\rm vac} D_{\rm vac} U_{\rm vac}^\dagger \quad \text{with} \quad D_{\rm vac} = \frac{1}{2E_\nu}\,\mathrm{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right).$$

Generalized mass-ordering degeneracy

$$H^\nu_{\rm vac} \to -(H^\nu_{\rm vac})^* \quad \Rightarrow \quad \begin{aligned} &\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21} = -\Delta m^2_{32},\\ &\theta_{12} \to \pi/2 - \theta_{12}\\ &\delta_{\rm CP} \to \pi - \delta_{\rm CP}\end{aligned}$$

Miranda,Tortola, Valle, 0406280
MCGG,Maltoni,Salvado 1103,4265
Coloma, Schwetz, 1604.05772
Farzan, 1505.06906

The solution with θ_{12} in the second octant is called LMA-D solution

$$H_{\rm mat} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1+\mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\ \mathcal{E}^*_{e\mu}(x) & \mathcal{E}_{\mu\mu}(x) & \mathcal{E}_{\mu\tau}(x) \\ \mathcal{E}^*_{e\tau}(x) & \mathcal{E}^*_{\mu\tau}(x) & \mathcal{E}_{\tau\tau}(x) \end{pmatrix} \qquad \mathcal{E}_{\alpha\beta}(x) = \sum_{f=e,u,d} \frac{N_f(x)}{N_e(x)} \varepsilon^{f,V}_{\alpha\beta}$$

$$H^\nu_{\rm mat} \to -(H^\nu_{\rm mat})^* \quad \Rightarrow \quad \begin{aligned} &[\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] - 2,\\ &[\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)]\\ &\mathcal{E}_{\alpha\beta}(x) \to -\mathcal{E}^*_{\alpha\beta}(x) \quad (\alpha \neq \beta),\end{aligned}$$

Atmospheric and long baseline neutrino oscillations

The neutron/proton ratio $Y_n(x)$ in earth can be taken to be constant to a very good approximation, that allow us to define the $\varepsilon_{\alpha\beta}^{\oplus}$

$$\varepsilon_{\alpha\beta}^{\oplus} = \left(\varepsilon_{\alpha\beta}^{e,V} + \varepsilon_{\alpha\beta}^{p,V}\right) + Y_n^{\oplus}\varepsilon_{\alpha\beta}^{n,V},$$

$$Y_n^{\oplus} = \frac{N_n^{\oplus}}{N_e^{\oplus}} \simeq 1.051$$ (Average in Earth)

These $\varepsilon_{\alpha\beta}^{\oplus}$ act as phenomenological parameters and control the deviation to SM propagation for atmospheric and LBL experiments

Solar neutrinos oscillations

For the study of propagation of solar and KamLAND neutrinos one can work in the one mass dominance approximation, $\Delta m^2_{31} \to \infty$. In this limit In this limit the neutrino evolution can be calculated in an effective 2 × 2 model described by the Hamiltonian:

$$H_{\text{eff}} = H^{\text{eff}}_{\text{vac}} + H^{\text{eff}}_{\text{mat}}$$

where

$$H^{\text{eff}}_{\text{vac}} = \frac{\Delta m^2_{21}}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} e^{i\delta_{\text{CP}}} \\ \sin 2\theta_{12} e^{-i\delta_{\text{CP}}} & \cos 2\theta_{12} \end{pmatrix},$$

$$H^{\text{eff}}_{\text{mat}} = \sqrt{2} G_F N_e(x) \left[\frac{c^2_{13}}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \left[\xi^e + \xi^p + Y_n(x)\xi^n\right] \left(\chi^L + \chi^R\right) \begin{pmatrix} -\varepsilon_D & \varepsilon_N \\ \varepsilon^*_N & \varepsilon_D \end{pmatrix} \right]$$

$$\begin{aligned} \varepsilon_D =& c_{13} s_{13} \operatorname{Re}\left(s_{23}\varepsilon_{e\mu} + c_{23}\varepsilon_{e\tau}\right) - \left(1 + s^2_{13}\right) c_{23} s_{23} \operatorname{Re}\left(\varepsilon_{\mu\tau}\right) \\ & - \frac{c^2_{13}}{2}\left(\varepsilon_{ee} - \varepsilon_{\mu\mu}\right) + \frac{s^2_{23} - s^2_{13} c^2_{23}}{2}\left(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}\right), \\ \varepsilon_N =& c_{13}\left(c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau}\right) + s_{13}\left[s^2_{23}\varepsilon_{\mu\tau} - c^2_{23}\varepsilon^*_{\mu\tau} + c_{23}s_{23}\left(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}\right)\right]. \end{aligned}$$

$$i\frac{\mathrm{d}}{\mathrm{d}x}\left(\begin{array}{c}\tilde{\nu}_1\\ \tilde{\nu}_2\end{array}\right)=\left(\begin{array}{cc}-\Delta_m(x) & -i\theta'_m(x)\\ i\theta'_m(x) & \Delta_m(x)\end{array}\right)\left(\begin{array}{c}\tilde{\nu}_1\\ \tilde{\nu}_2\end{array}\right)$$

$$\theta_m(x)\equiv\frac{1}{2}\arctan\left[H^{\mathrm{eff}}_{12}(x)/H^{\mathrm{eff}}_{22}(x)\right] \qquad \Delta_m(x)\equiv\sqrt{\left[H^{\mathrm{eff}}_{12}(x)\right]^2+\left[H^{\mathrm{eff}}_{22}(x)\right]^2}$$

In most of the literature to simplify the computation the so-called adiabatic approximation is assumed

$$\gamma^{-1}(x)\equiv\left|\frac{\theta'_m(x)}{\Delta_m(x)}\right|\ll 1$$

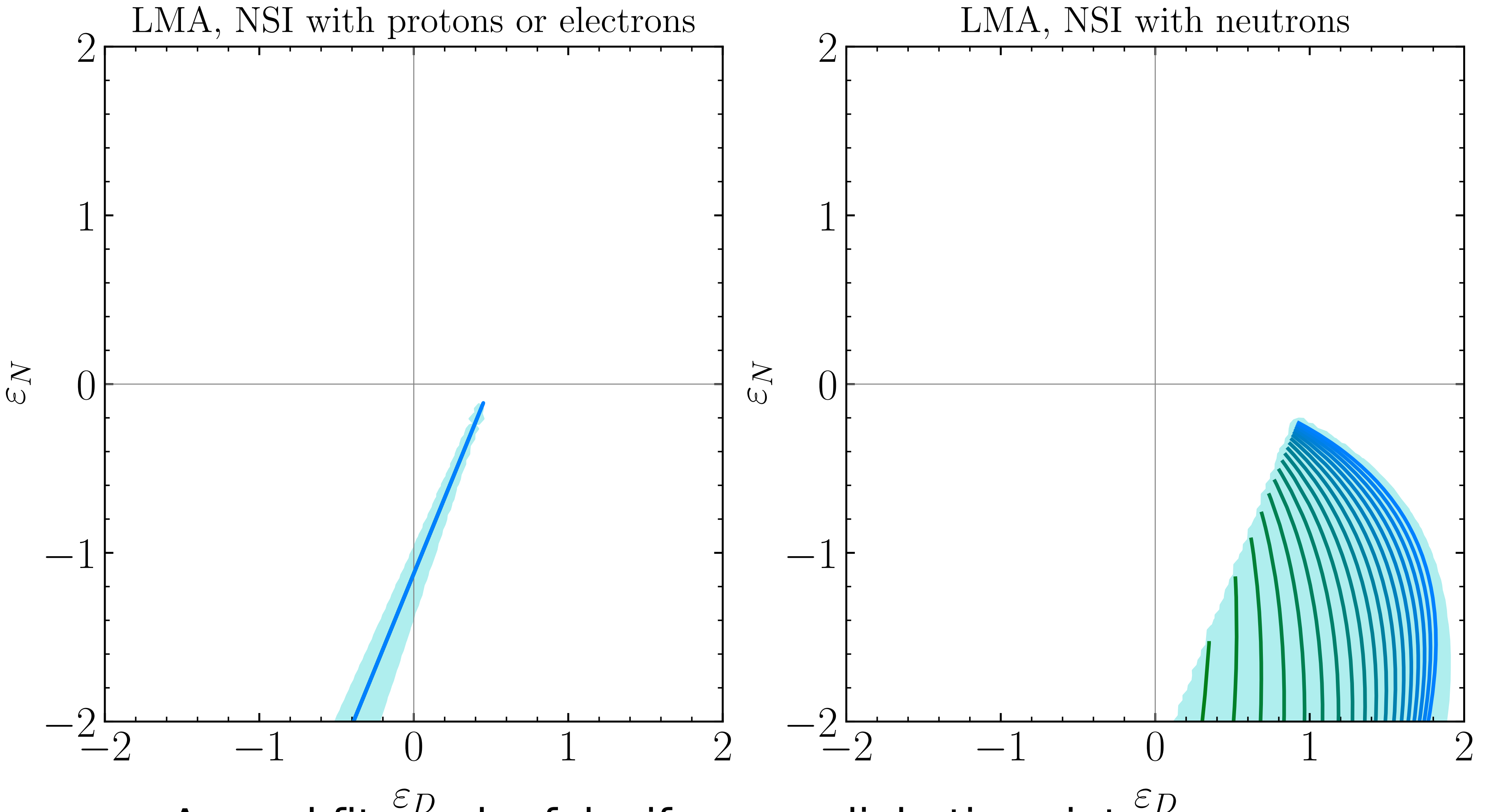
However in the presence of NSI, we can have the case in which $\Delta_m(x)\to 0$, this is realized when:

$$\left[\xi^e+\xi^p+Y_n(x)\xi^n\right]\left(\chi^L+\chi^R\right)\varepsilon_D\to-\frac{\Delta m^2_{12}\cos 2\theta_{12}}{4E_\nu V(x)}+\frac{c^2_{13}}{2}$$

$$\left[\xi^e+\xi^p+Y_n(x)\xi^n\right]\left(\chi^L+\chi^R\right)\varepsilon_N\to-\frac{\Delta m^2_{12}\sin 2\theta_{12}}{4E_\nu V(x)}$$

Results

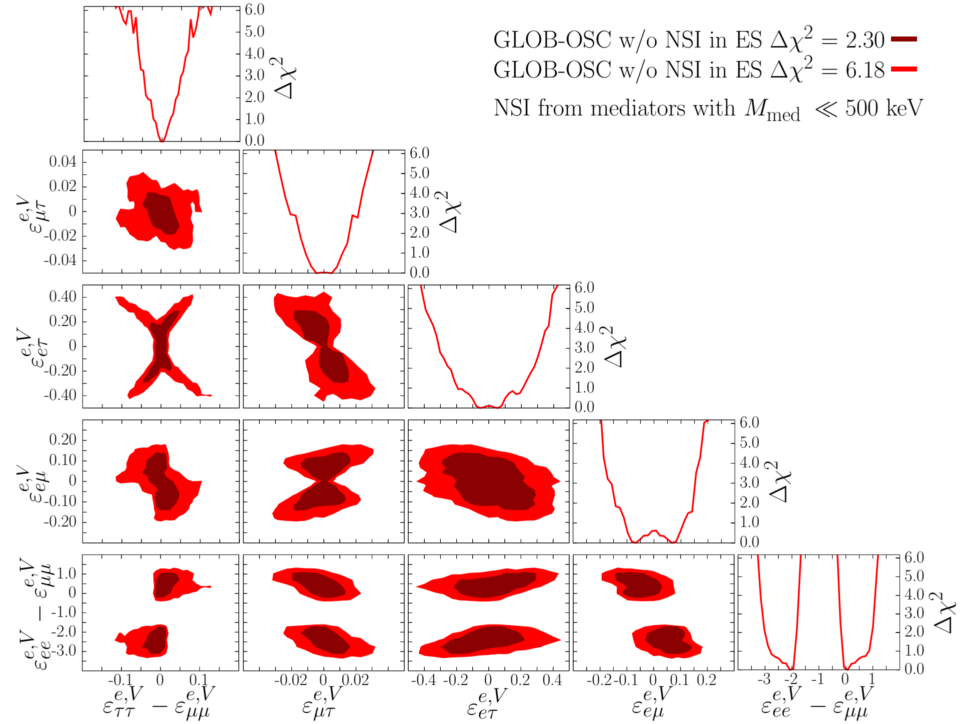
Results: Adiabaticity



- A good fit can be fake if we use the adiabatic approximation for non adiabatic points.
- If we throw away the non adiabatic points we recover the correct sensitivity regions.

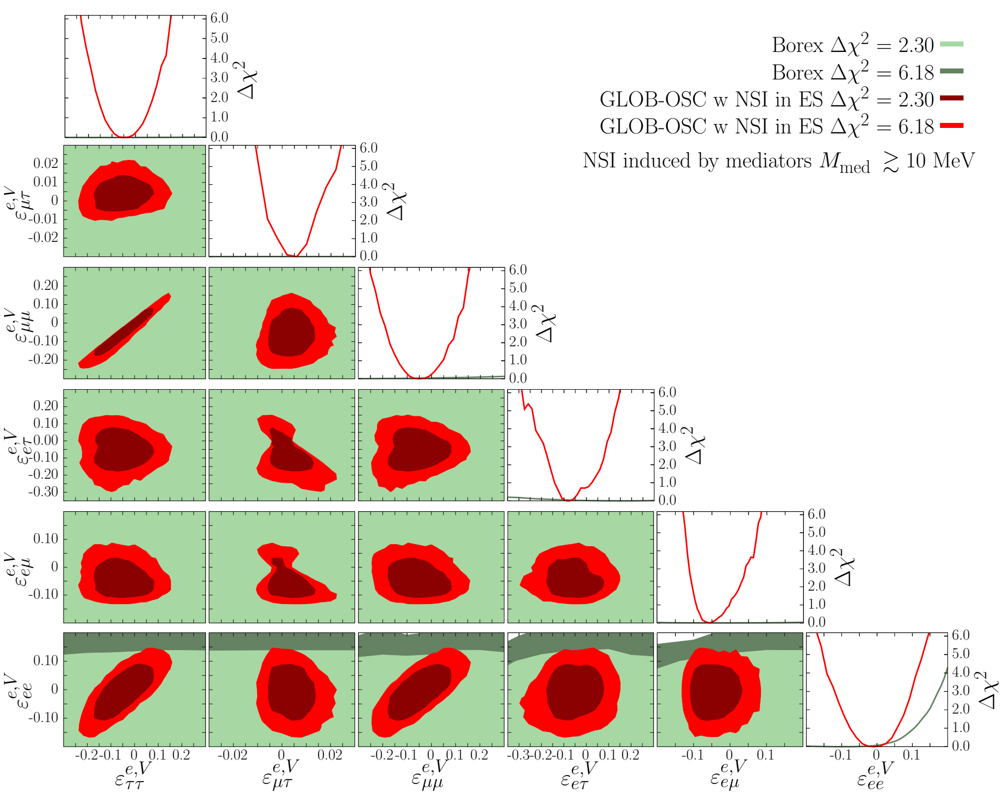
Results: vector NSI with electrons in propagation and ES

GLOB-OSC w/o NSI in ES



- LMA-D solution allowed

GLOB-OSC w NSI in ES



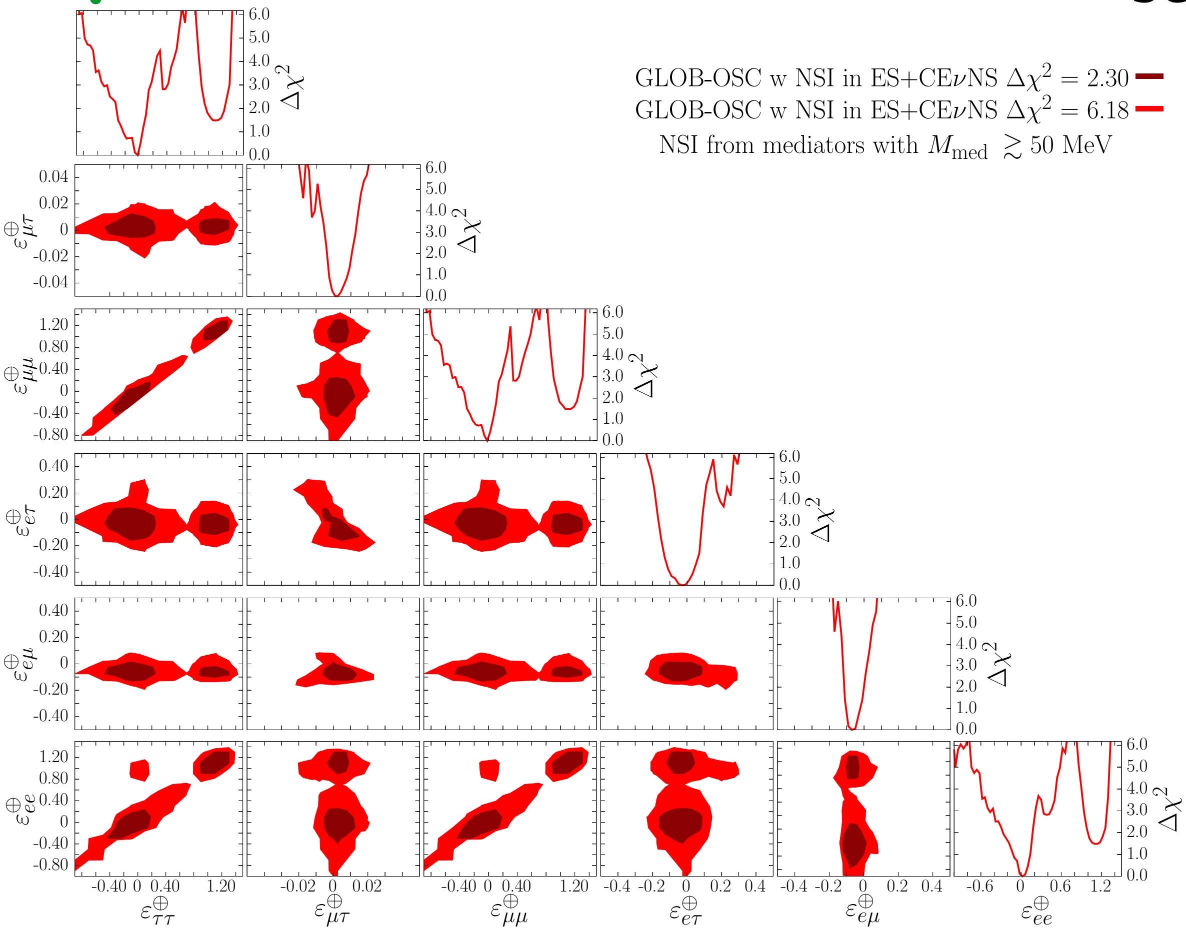
- Borexino+SNO+SK break the LMA-D degeneracy through ES.
- The limits improve 4-200 times over our results of Borexino phase II data only (Arxiv:2204.03011)

Results: General NSI with e, p and n in propagation and scattering

$$\varepsilon^{\oplus}_{\alpha\beta} = \left(\varepsilon^{e,V}_{\alpha\beta} + \varepsilon^{p,V}_{\alpha\beta}\right) + Y^{\oplus}_{n}\varepsilon^{n,V}_{\alpha\beta}\,,$$

- Includes both **electron and quarks NSI**
- **Important bounds** to be considered in **LBL experiments** sensitivity studies

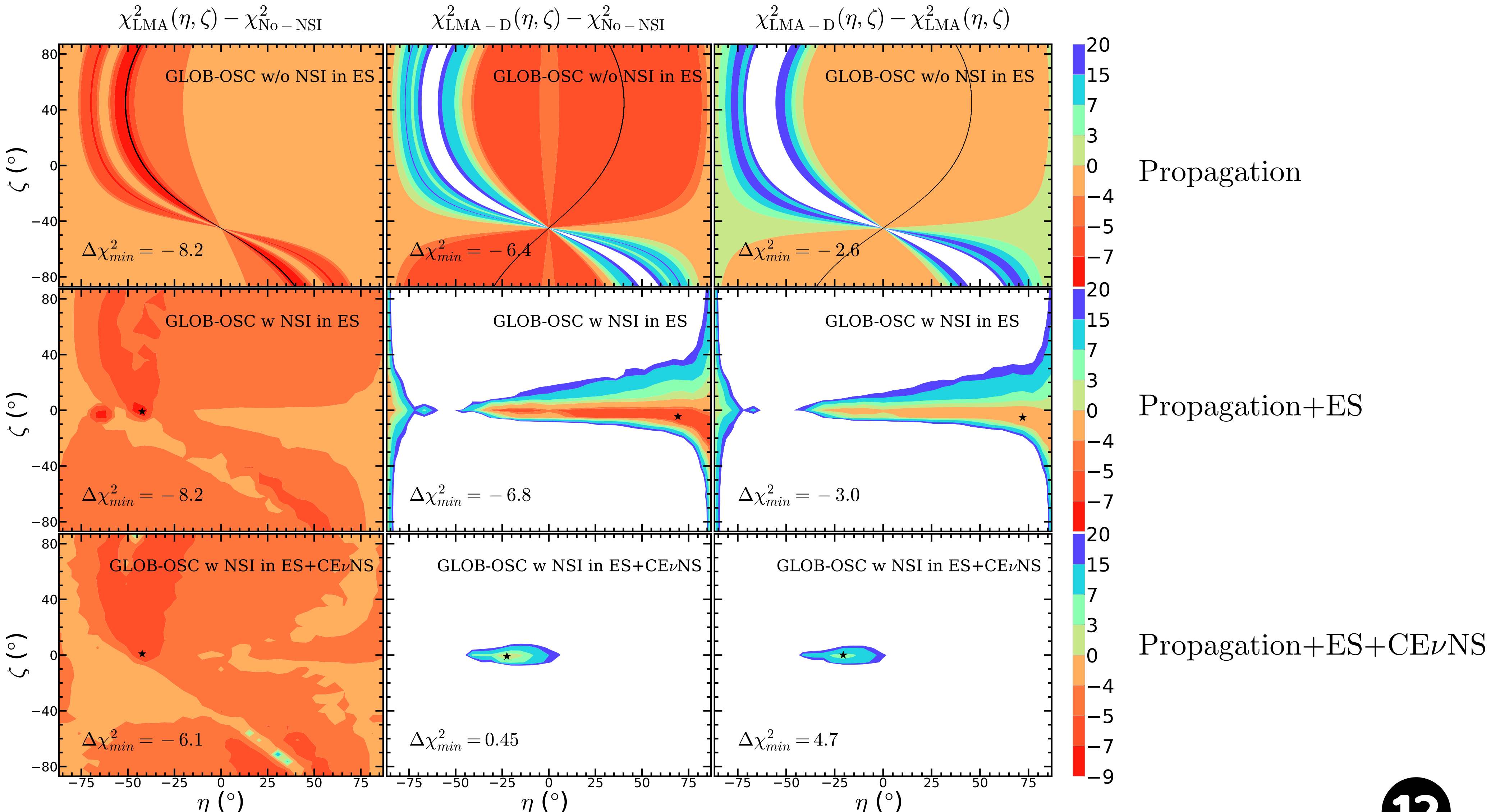
GLOB-OSC w NSI in ES-CEvNS: quarks+electrons



	Ranges at 99% CL marginalized
	GLOB-OSC w NSI in ES + CE ν NS
$\varepsilon^{\oplus}_{ee}$	$[-0.23, +0.25] \oplus [+0.81, +1.3]$
$\varepsilon^{\oplus}_{\mu\mu}$	$[-0.29, +0.20] \oplus [+0.83, +1.4]$
$\varepsilon^{\oplus}_{\tau\tau}$	$[-0.29, +0.20] \oplus [+0.83, +1.4]$
$\varepsilon^{\oplus}_{e\mu}$	$[-0.18, +0.08]$
$\varepsilon^{\oplus}_{e\tau}$	$[-0.25, +0.33]$
$\varepsilon^{\oplus}_{\mu\tau}$	$[-0.020, +0.021]$

Results: LMA-D solution general status

$$\xi^e = \sqrt{5}\cos\eta\sin\zeta, \quad \xi^p = \sqrt{5}\cos\eta\cos\zeta, \quad \xi^n = \sqrt{5}\sin\eta$$

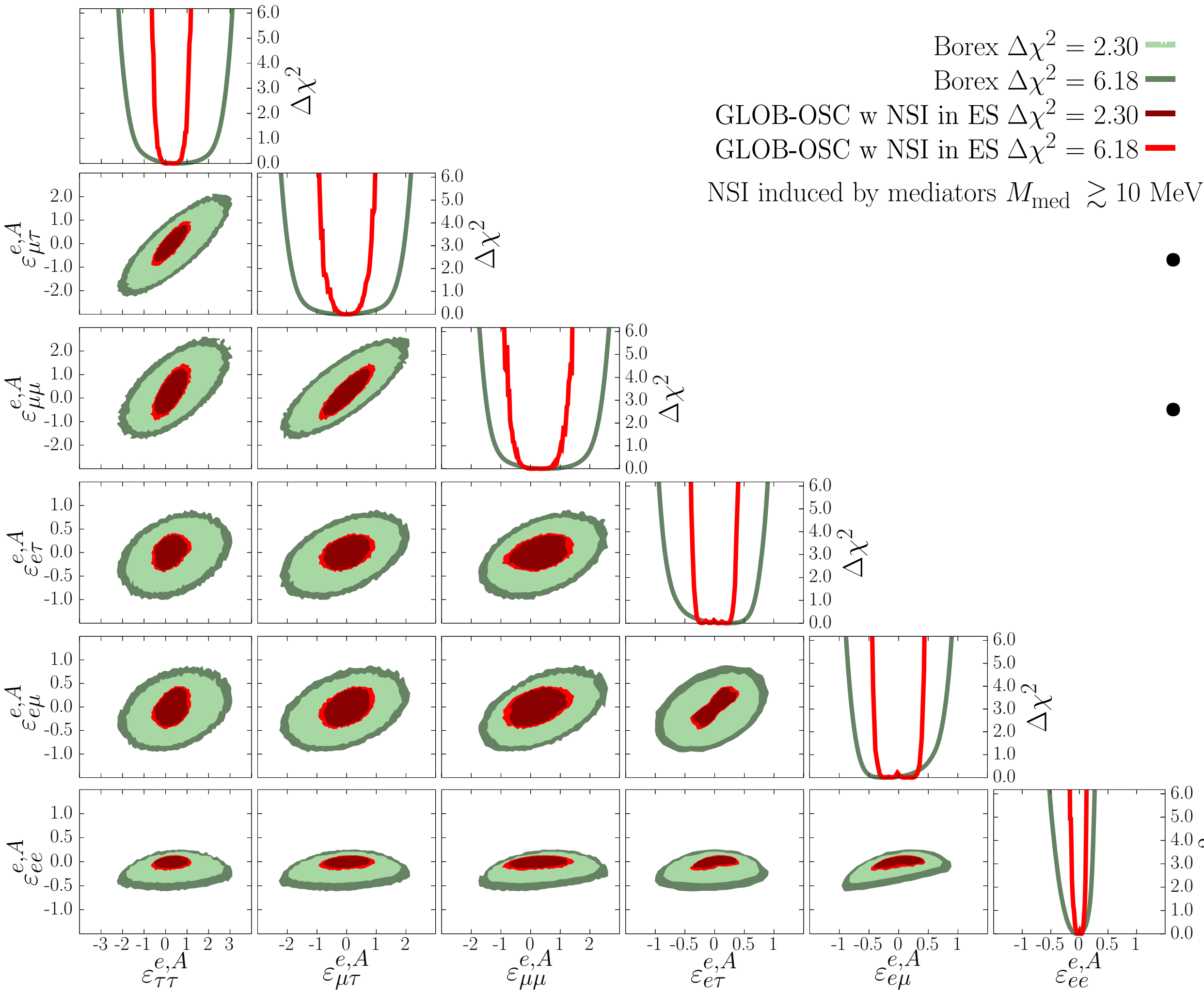


Thank you

Back-up

Results: axial NSI with electrons in ES

GLOB-OSC w NSI in ES



- Axial NSI do not contribute to propagation effects
- The limits improve around 2-3 times over our results of Borexino phase II data only (Arxiv:2204.03011)

Results: More on the LMA-D solution