



This is the accepted manuscript made available via CHORUS. The article has been published as:

## COHERENT enlightenment of the neutrino dark side

Pilar Coloma, M. C. Gonzalez-Garcia, Michele Maltoni, and Thomas Schwetz

Phys. Rev. D **96**, 115007 — Published 11 December 2017

DOI: [10.1103/PhysRevD.96.115007](https://doi.org/10.1103/PhysRevD.96.115007)

# A COHERENT enlightenment of the neutrino Dark Side

Pilar Coloma,<sup>1,\*</sup> M. C. Gonzalez-Garcia,<sup>2,3,4,†</sup> Michele Maltoni,<sup>5,‡</sup> and Thomas Schwetz<sup>6,§</sup>

<sup>1</sup>*Theory Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*

<sup>2</sup>*C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794-3840, USA*

<sup>3</sup>*Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos,*

*Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain*

<sup>4</sup>*Institució Catalana de Recerca i Estudis Avançats (ICREA),*

*Pg. Lluís Companys 23, 08010 Barcelona, Spain.*

<sup>5</sup>*Instituto de Física Teórica UAM/CSIC, Calle de Nicolás Cabrera 13-15,*

*Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*

<sup>6</sup>*Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany*

In the presence of non-standard neutrino interactions (NSI), oscillation data are affected by a degeneracy which allows the solar mixing angle to be in the second octant (*aka* the dark side) and implies a sign flip of the atmospheric mass-squared difference. This leads to an ambiguity in the determination of the ordering of neutrino masses, one of the main goals of the current and future experimental neutrino program. We show that the recent observation of coherent neutrino–nucleus scattering by the COHERENT experiment, in combination with global oscillation data, excludes the NSI degeneracy at the  $3.1\sigma$  ( $3.6\sigma$ ) CL for NSI with up (down) quarks.

## I. INTRODUCTION

The standard three-flavour oscillation scenario is supported by a large amount of data from neutrino oscillation experiments. The determination of oscillation parameters (see, *e.g.*, Ref. [1]) is very robust, and for a broad range of new physics scenarios only small perturbations of the standard oscillation picture are allowed by data. There is, however, an exception to this statement: in the presence of non-standard neutrino interactions (NSI) [2–4] a degeneracy exists in oscillation data, leading to a qualitative change of the lepton mixing pattern. This was first observed in the context of solar neutrinos, where for suitable NSI the data can be explained by a mixing angle  $\theta_{12}$  in the second octant, the so-called LMA-Dark (LMA-D) [5] solution. This is in sharp contrast to the established standard MSW solution [2, 6], which requires a mixing angle  $\theta_{12}$  in the first octant.

The origin of the LMA-D solution is a degeneracy in oscillation probabilities due to a symmetry of the Hamiltonian describing neutrino evolution in the presence of NSI [7–10]. This degeneracy involves not only the octant of  $\theta_{12}$  but also a change in sign of the larger neutrino mass-squared difference,  $\Delta m_{31}^2$ , which is used to parameterize the type of neutrino mass ordering (normal versus inverted). Hence, the LMA-D degeneracy makes it impossible to determine the neutrino mass ordering by oscillation experiments [10], and therefore jeopardizes one of the main goals of the upcoming neutrino oscillation program. As discussed in Refs. [5, 10–12], non-oscillation data (such as that from neutrino scattering experiments)

is needed to break this degeneracy.

Recently, coherent neutrino–nucleus scattering [13] has been observed for the first time by the COHERENT experiment [14], using neutrinos produced at the Spallation Neutron Source (SNS) in Oak Ridge National Laboratory. The potential of neutrino–nucleus scattering for constraining NSI has been studied, *e.g.*, in Refs. [11, 15–19]. The observed interaction rate at COHERENT is in good agreement with the Standard Model (SM) prediction. In this work we show that this result excludes the LMA-D solution at  $3.1\sigma$  ( $3.6\sigma$ ) CL for NSI with up (down) quarks when combined with oscillation data.

## II. NSI FORMALISM AND THE LMA-D DEGENERACY

We consider the presence of neutral-current (NC) NSI in the form of dimension-six four-fermion operators, following the notation of Ref. [8]. Since we are interested in the contribution of the NSI to the effective potential of neutrinos in matter, we will only consider vector interactions in the form

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{f,V}(\bar{\nu}_{\alpha L}\gamma^\mu\nu_{\beta L})(\bar{f}\gamma_\mu f), \quad (1)$$

where,  $\alpha, \beta = e, \mu, \tau$ , and  $f$  denotes a SM fermion. The parameter  $\epsilon_{\alpha\beta}^{f,V}$  parametrizes the strength of the new interaction relative to the Fermi constant  $G_F$ , and hermiticity requires that  $\epsilon_{\alpha\beta}^{f,V} = (\epsilon_{\beta\alpha}^{f,V})^*$ . In gauge invariant models of new physics at high energies, NSI parameters are expected to be subject to tight constraints from charged lepton observables [20, 21], leading to no visible effect in oscillations. However, more recently it has been argued that viable gauge models with light mediators (*i.e.*, below the electro-weak scale) may lead to observable effects in oscillations without entering in conflict with other bounds [22–24] (see also Ref. [25] for a

\*Electronic address: [pcoloma@fnal.gov](mailto:pcoloma@fnal.gov)

†Electronic address: [maria.gonzalez-garcia@stonybrook.edu](mailto:maria.gonzalez-garcia@stonybrook.edu)

‡Electronic address: [michele.maltoni@csic.es](mailto:michele.maltoni@csic.es)

§Electronic address: [schwetz@kit.edu](mailto:schwetz@kit.edu)

discussion). In particular, for light mediators, bounds from high-energy neutrino scattering experiments such as CHARM [26] and NuTeV [27] do not apply. In this framework, prior to the COHERENT results, the only direct bounds on NC-NSI with quarks arise from their effect on neutrino oscillations when propagating in matter (for bounds in the heavy mediator case see [11]). In the following we will assume that the mediator responsible for the NSI has a mass larger than about 10 MeV, and hence the contact interaction approximation adopted in Eq. (1) applies for COHERENT.

The operators in Eq. (1) will contribute to the effective matter potential in the Hamiltonian describing the evolution of the neutrino flavour state:

$$H_{\text{mat}} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}, \quad (2)$$

$$\epsilon_{\alpha\beta}(x) = \sum_{f=e,u,d} Y_f(x) \epsilon_{\alpha\beta}^{f,V}, \quad (3)$$

with  $Y_f(x) \equiv N_f(x)/N_e(x)$ ,  $N_f(x)$  being the density of fermion  $f$  along the neutrino path. Therefore, the effective NSI parameters entering oscillations,  $\epsilon_{\alpha\beta}$ , may depend on  $x$  and will be generally different for neutrinos crossing the Earth or the solar medium. The “1” in the  $ee$  entry in Eq. (2) corresponds to the standard matter potential [2, 6]. In this work we consider the cases of NSI with either up ( $f = u$ ) or down ( $f = d$ ) quarks. Note that oscillation experiments are only sensitive to differences between the diagonal terms in the matter potential (for instance,  $\epsilon_{ee} - \epsilon_{\mu\mu}$  and  $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ ).

In general, neutrino evolution is invariant if the relevant Hamiltonian is transformed as  $H \rightarrow -H^*$ . This is a consequence of the CPT symmetry, see [7, 8] for a discussion in the context of NSI. In vacuum this transformation can be realized by changing the oscillation parameters as

$$\begin{aligned} \Delta m_{31}^2 &\rightarrow -\Delta m_{31}^2 + \Delta m_{21}^2 = -\Delta m_{32}^2, \\ \sin \theta_{12} &\leftrightarrow \cos \theta_{12}, \\ \delta &\rightarrow \pi - \delta, \end{aligned} \quad (4)$$

where  $\delta$  is the leptonic Dirac CP phase, and we are using here the parameterization conventions from Ref. [10]. The symmetry is broken by the standard matter effect, which allows a determination of the octant of  $\theta_{12}$  and (in principle) of the sign of  $\Delta m_{31}^2$ . However, in the presence of NSI, the symmetry can be restored if in addition to the transformation Eq. (4), NSI parameters are transformed as [8–10]

$$\begin{aligned} (\epsilon_{ee} - \epsilon_{\mu\mu}) &\rightarrow -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2, \\ (\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) &\rightarrow -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu}), \\ \epsilon_{\alpha\beta} &\rightarrow -\epsilon_{\alpha\beta}^* \quad (\alpha \neq \beta). \end{aligned} \quad (5)$$

Eq. (4) shows that this degeneracy implies a change in the octant of  $\theta_{12}$  (as manifest in the LMA-D fit to solar

neutrino data [5]) as well as a change in the neutrino mass ordering, *i.e.*, the sign of  $\Delta m_{31}^2$ . For that reason it has been called “generalized mass ordering degeneracy” in Ref. [10].

The  $\epsilon_{\alpha\beta}$  in Eq. (5) are defined in Eq. (3) and depend on the density and composition of the medium. It is easy to see that, if NSI simultaneously affect both up and down quarks with a coupling proportionally to their charge,  $\epsilon_{\alpha\beta}^{u,V} = -2\epsilon_{\alpha\beta}^{d,V}$ , the dependence on  $x$  cancels out for neutral matter and the degeneracy is mathematically exact. In this work, however, we consider only NSI with either up or down quarks and hence the degeneracy will be approximate, mostly due to the non-trivial neutron density along the neutrino path inside the Sun [8].

### III. GLOBAL FIT TO OSCILLATION DATA

For oscillation constraints on NSI parameters and the detailed description of methodology and data included we refer to the comprehensive global fit in the framework of 3-flavour oscillations plus NSI with up and down quarks performed in Ref. [8]. In principle the analysis depends on six oscillations parameters plus eight NSI parameters per  $f$  target, of which five are real and three are phases. To keep the fit manageable in Ref. [8] only real NSI were considered and  $\Delta m_{21}^2$  effects were neglected in the analysis of atmospheric and long-baseline experiments. This renders the analysis independent of the CP phase in the leptonic mixing matrix. For further details see Ref. [8]. For completeness we show the results of this fit as dashed lines in Fig. 1. Two different sets of solutions are shown: dashed blue lines corresponding to the LMA solution, and dashed red lines corresponding to the LMA-D solution, which implies a flipped mass spectrum and  $\theta_{12}$  in the second octant according to Eq. (4).

### IV. COHERENT RESULTS

The COHERENT collaboration has recently reported the observation of coherent neutrino–nucleus scattering at  $6.7\sigma$  [14]. The experiment uses neutrinos produced from pion decay at rest, and a 14.6 kg CsI[Na] detector. Here we describe our implementation of their constraints on NSI parameters, following closely Ref. [14].

At the SNS, the neutrino flux consists of a monochromatic  $\nu_\mu$  line coming from  $\pi^+ \rightarrow \mu^+ \nu_\mu$ , plus a continuous spectrum of  $\bar{\nu}_\mu$  and  $\nu_e$  from the subsequent  $\mu^+$  decay. Hence the total number of coherent scattering events will receive contributions from the three flux components,  $\nu_\mu$ ,  $\bar{\nu}_\mu$  and  $\nu_e$ . We extract the relative contribution  $f_\alpha$  of each flavour to the total number of events from the shaded histograms of Fig. S11 in the supplementary material of Ref. [14] as  $f_{\nu_e} = 0.31$ ,  $f_{\nu_\mu} = 0.19$ ,  $f_{\bar{\nu}_\mu} = 0.50$ . Coherent elastic neutrino–nucleus interactions take place with a momentum transfer  $Q^2 \simeq 2ME_r$ , where  $E_r$  is the recoil energy of the nucleus and  $M$  is its

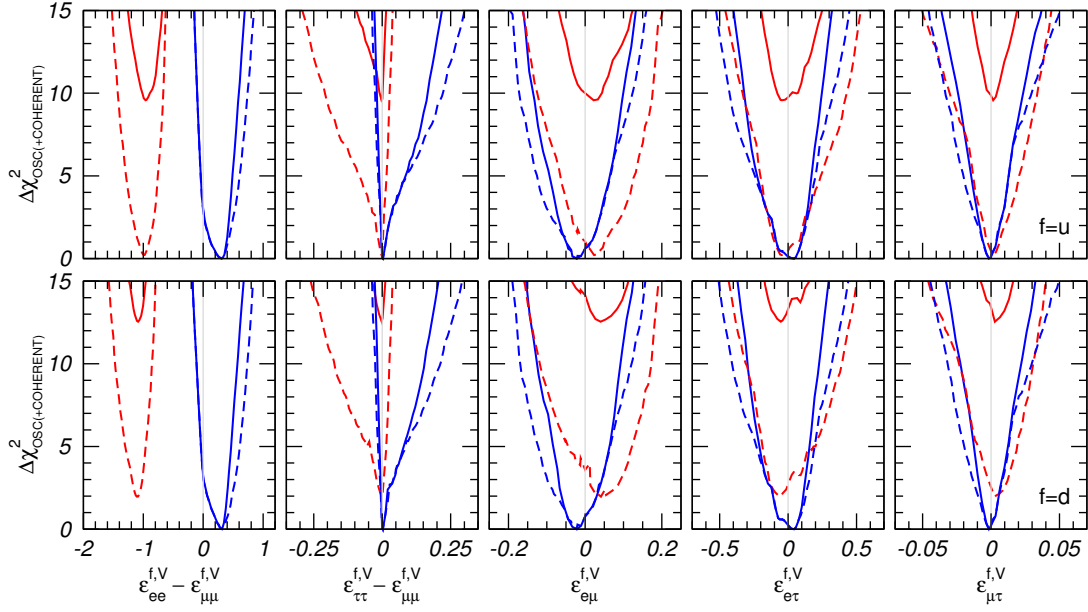


FIG. 1:  $\Delta\chi^2$  as a function of NSI parameters  $\epsilon_{\alpha\beta}^{f,V}$ , for a global fit to oscillation experiments (dashed curves) and for a fit to oscillations and COHERENT data (solid curves). Blue lines correspond to the LMA solution ( $\theta_{12} < \pi/4$ ), while the red lines correspond to the LMA-D solution ( $\theta_{12} > \pi/4$ ). We minimize the  $\chi^2$  with respect to all oscillations parameters and all un-displayed NSI parameters in each panel.

mass. Thus, for the COHERENT experiment the contact interaction approximation is valid for interactions with mediator masses above 10 MeV [11]. Within this approximation, for neutrinos of flavor  $\alpha$  interacting with a nucleus with total zero spin, for which both the sum of proton spins and of neutron spins is also zero, the interaction rate is sensitive to the following combination of SM and NSI vector couplings (see, *e.g.*, Ref. [15]):

$$Q_{w\alpha}^2 \propto [Z(g_p^V + 2\epsilon_{\alpha\alpha}^{u,V} + \epsilon_{\alpha\alpha}^{d,V}) + N(g_n^V + \epsilon_{\alpha\alpha}^{u,V} + 2\epsilon_{\alpha\alpha}^{d,V})]^2 + \sum_{\beta \neq \alpha} [Z(2\epsilon_{\alpha\beta}^{u,V} + \epsilon_{\alpha\beta}^{d,V}) + N(\epsilon_{\alpha\beta}^{u,V} + 2\epsilon_{\alpha\beta}^{d,V})]^2. \quad (6)$$

Here,  $N$  and  $Z$  are the number of neutrons and protons in the target nucleus (we take into account the contributions from both, Cs and I), and  $g_p^V = 1/2 - 2\sin^2\theta_W$ ,  $g_n^V = -1/2$  are the SM couplings of the  $Z$  boson to protons and neutrons, respectively,  $\theta_W$  being the weak mixing angle. The predicted number of signal events  $N_{\text{NSI}}$ , for a given set of NSI parameters  $\epsilon$ , can be expressed as:

$$N_{\text{NSI}}(\epsilon) = \gamma [f_e Q_{we}^2(\epsilon) + (f_{\nu_\mu} + f_{\bar{\nu}_\mu}) Q_{w\mu}^2(\epsilon)], \quad (7)$$

where  $\gamma$  is an overall normalization constant which depends on the exposure, detector efficiencies, etc. We then construct a chi-squared function  $\chi_{\text{COH}}^2$  using just the total number of events, according to the expression given in the supplementary material of Ref. [14]. We consider  $N_{\text{meas}} = 142$  observed events and take into account the statistical errors of the signal and the subtracted background, as well as systematic errors of the signal (28%)

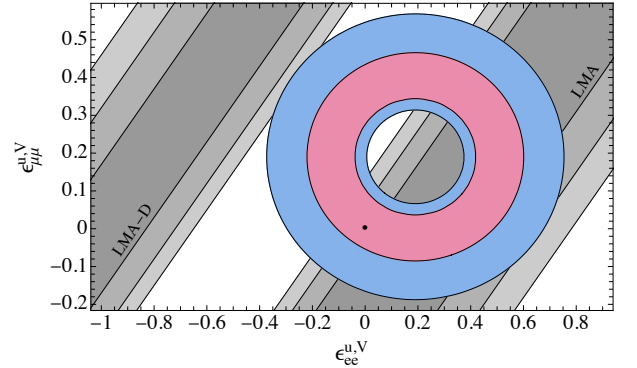


FIG. 2: Allowed regions in the plane of  $\epsilon_{ee}^{u,V}$  and  $\epsilon_{\mu\mu}^{u,V}$  from the COHERENT experiment shown together with the allowed regions from the global oscillation analysis. Diagonal shaded bands correspond to the LMA and LMA-D regions as indicated, at  $1\sigma$ ,  $2\sigma$ ,  $3\sigma$  (2 dof). The COHERENT regions are shown at  $1\sigma$  and  $2\sigma$  only because the  $3\sigma$  region extends beyond the boundaries of the figure.

and beam-on background (25%). The normalization constant  $\gamma$  (which is not given in Ref. [14]) is determined by requiring the  $\chi^2$  to be zero at the best-fit point quoted in Ref. [14] (*i.e.*,  $\epsilon_{ee}^{u,V} = -0.57$ ,  $\epsilon_{ee}^{d,V} = 0.59$ , all other  $\epsilon_{\alpha\beta}^{f,V} = 0$ ).<sup>1</sup>

To illustrate the impact of COHERENT on the LMA-

<sup>1</sup> Let us note that, with this procedure, our constraints on  $\epsilon_{ee}^{u,V}$

D solution, we show in Fig. 2 the chi-squared for oscillations and for the COHERENT experiment separately, projected onto the  $\epsilon_{ee}^{f,V}$  vs  $\epsilon_{\mu\mu}^{f,V}$  plane. In this example, we have restricted to flavour diagonal NSI with  $f = u$  quarks. Oscillation data only constraints the difference  $\epsilon_{ee}^{f,V} - \epsilon_{\mu\mu}^{f,V}$  and therefore two separate bands in this plane are allowed by the data: one corresponding to the LMA, and a second one for the LMA-D solution. Conversely, the COHERENT experiment constrains the combination given in Eq. (6) and therefore its results project onto an ellipse in this plane.

## V. RESULTS

Our final results for the combined fit of oscillations and COHERENT data are given in Fig. 1, where we show as full lines the total  $\Delta\chi^2 = \Delta(\chi_{\text{OSC}}^2 + \chi_{\text{COH}}^2)$  as a function of the NSI parameters  $\epsilon_{\alpha\beta}^{f,V}$ , for  $f = u$  (upper panels) and  $f = d$  (lower panels) after marginalization over the undisplayed oscillation and NSI parameters in each panel. While the LMA-D solution is perfectly compatible with oscillation data alone we find that, once COHERENT data is included in the fit, it is disfavored with respect to LMA with  $\Delta\chi^2 \geq 9.6$  (12.6) for  $f = u$  ( $f = d$ ), which corresponds to  $3.1\sigma$  ( $3.6\sigma$ ) for 1 dof.

When oscillation parameters are marginalized within the “standard” LMA region the global analysis slightly favors non-vanishing diagonal NSI. The reason for this lies in the  $2\sigma$  tension between the determination of  $\Delta m_{21}^2$  from KamLAND and solar neutrino experiments (see, for example, Ref. [1] for the latest status on this issue).

In order to stress the effect of COHERENT in the fit with respect to the constraints already provided by oscillation data, the results for the diagonal NSI parameters are shown in Fig. 1 for the differences  $\epsilon_{ee}^{f,V} - \epsilon_{\mu\mu}^{f,V}$  and  $\epsilon_{\tau\tau}^{f,V} - \epsilon_{\mu\mu}^{f,V}$ , to which oscillations are sensitive. Notice, however, that the inclusion of COHERENT data allows to set independent bounds on all  $\epsilon_{\alpha\beta}^{f,V}$ , since COHERENT depends on a different combination of  $\epsilon_{ee}^{f,V}$  and  $\epsilon_{\mu\mu}^{f,V}$ . We show the projection of the marginalized  $\Delta\chi^2$  for each flavour diagonal NSI in Fig. 3. As can be seen, the combined fit of COHERENT and oscillation data is capable of constraining the individual flavour diagonal NSI up to  $\Delta\chi^2 \sim 12$ . Beyond that level oscillation data dominate and only the two differences relevant for oscillations are effectively bounded, which leads to the flattening of the marginalized  $\Delta\chi^2$  as a function of the individual diagonal NSI.

The 90% CL allowed ranges for the NSI parameters from our global analysis are given in Tab. I. The addition

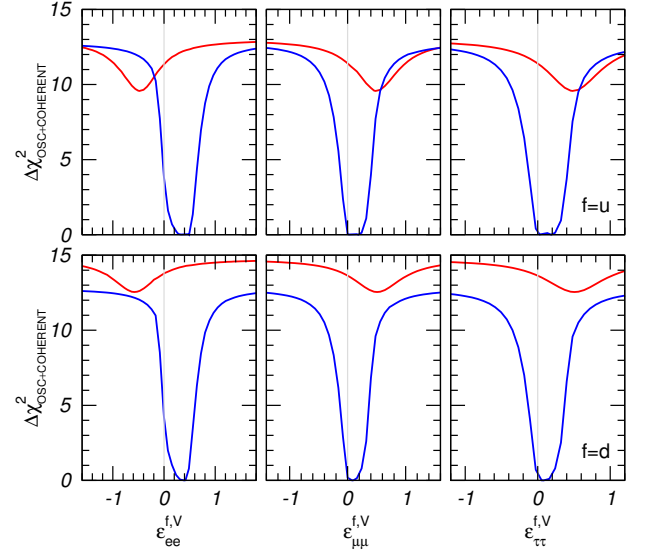


FIG. 3: Bounds on the flavour diagonal NSI parameters from the global fit to oscillation plus COHERENT data. Blue lines correspond to the LMA solution ( $\theta_{12} < \pi/4$ ), while the red lines correspond to the LMA-D solution ( $\theta_{12} > \pi/4$ ).

	$f = u$	$f = d$
$\epsilon_{ee}^{f,V}$	[0.028, 0.60]	[0.030, 0.55]
$\epsilon_{\mu\mu}^{f,V}$	[-0.088, 0.37]	[-0.075, 0.33]
$\epsilon_{\tau\tau}^{f,V}$	[-0.090, 0.38]	[-0.075, 0.33]
$\epsilon_{e\mu}^{f,V}$	[-0.073, 0.044]	[-0.07, 0.04]
$\epsilon_{e\tau}^{f,V}$	[-0.15, 0.13]	[-0.13, 0.12]
$\epsilon_{\mu\tau}^{f,V}$	[-0.01, 0.009]	[-0.009, 0.008]

TABLE I: Allowed ranges at 90% CL for the NSI parameters  $\epsilon_{\alpha\beta}^{f,V}$  for  $f = u, d$ , as obtained from a global fit to oscillation and COHERENT data. The results for each NSI parameter are obtained after marginalizing over all oscillation and the other NSI parameters.

of COHERENT data allows to derive competitive constraints on each of the diagonal parameters separately. This is especially relevant for  $\epsilon_{\tau\tau}^{f,V}$  for which the new bound  $-0.09 < \epsilon_{\tau\tau}^{u,V} < 0.38$  ( $-0.075 < \epsilon_{\tau\tau}^{d,V} < 0.33$ ) at 90% CL represents the first direct bound on NC vector interactions of  $\nu_\tau$  assuming light mediators and is an order of magnitude stronger than previous indirect (loop induced) limits [28]. We also see that for  $\epsilon_{ee}^{f,V}$  the 90% CL range does not include zero. As explained above this “non-standard” result is driven by the  $2\sigma$  tension in the determination of  $\Delta m_{21}^2$  from KamLAND and in solar neutrino experiments, and is still consistent with COHERENT results within present precision.

and  $\epsilon_{ee}^{d,V}$  turn out slightly weaker than the result in Ref. [14] (our 90% CL interval is about 20% larger). Hence our results can be regarded as conservative.



## VI. CONCLUSIONS

In this work, we have combined the recently reported measurement of neutrino–nucleus coherent scattering by the COHERENT collaboration with data from neutrino oscillation experiments, in order to constrain neutrino NSI affecting NC interactions with quarks. We find that the addition of COHERENT to the global fit from oscillation data excludes the LMA-D solution at  $3.1\sigma$  ( $3.6\sigma$ ) CL for NSI with up (down) quarks due to the exchange of a new mediator with a mass above 10 MeV. In addition, the combination of oscillation and COHERENT data allows to derive competitive constraints on all diagonal NSI parameters individually.

## Acknowledgments

This work is supported by USA-NSF grant PHY-1620628, by EU Networks FP10 ITN ELUSIVES

(H2020-MSCA-ITN-2015-674896) and INVISIBLES-PLUS (H2020-MSCA-RISE-2015-690575), by MINECO grants FPA2016-76005-C2-1-P, FPA2012-31880 and MINECO/FEDER-UE grants FPA2015-65929-P and FPA2016-78645-P, by Maria de Maetzu program grant MDM-2014-0367 of ICCUB, by the “Severo Ochoa” program grant SEV-2016-0597 of IFT. This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. The publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

- 
- [1] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler and T. Schwetz, *Updated fit to three neutrino mixing: exploring the accelerator-reactor complementarity*, *JHEP* **01** (2017) 087, [[1611.01514](#)].
  - [2] L. Wolfenstein, *Neutrino Oscillations in Matter*, *Phys. Rev.* **D17** (1978) 2369–2374.
  - [3] J. W. F. Valle, *Resonant Oscillations of Massless Neutrinos in Matter*, *Phys. Lett.* **B199** (1987) 432–436.
  - [4] M. M. Guzzo, A. Masiero and S. T. Petcov, *On the MSW effect with massless neutrinos and no mixing in the vacuum*, *Phys. Lett.* **B260** (1991) 154–160.
  - [5] O. G. Miranda, M. A. Tortola and J. W. F. Valle, *Are solar neutrino oscillations robust?*, *JHEP* **10** (2006) 008, [[hep-ph/0406280](#)].
  - [6] S. P. Mikheev and A. Y. Smirnov, *Resonance enhancement of oscillations in matter and solar neutrino spectroscopy*, *Sov. J. Nucl. Phys.* **42** (1985) 913–917.
  - [7] M. C. Gonzalez-Garcia, M. Maltoni and J. Salvado, *Testing matter effects in propagation of atmospheric and long-baseline neutrinos*, *JHEP* **05** (2011) 075, [[1103.4365](#)].
  - [8] M. C. Gonzalez-Garcia and M. Maltoni, *Determination of matter potential from global analysis of neutrino oscillation data*, *JHEP* **09** (2013) 152, [[1307.3092](#)].
  - [9] P. Bakhti and Y. Farzan, *Shedding light on LMA-Dark solar neutrino solution by medium baseline reactor experiments: JUNO and RENO-50*, *JHEP* **07** (2014) 064, [[1403.0744](#)].
  - [10] P. Coloma and T. Schwetz, *Generalized mass ordering degeneracy in neutrino oscillation experiments*, *Phys. Rev.* **D94** (2016) 055005, [[1604.05772](#)].
  - [11] P. Coloma, P. B. Denton, M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, *Curtailling the Dark Side in Non-Standard Neutrino Interactions*, *JHEP* **04** (2017) 116, [[1701.04828](#)].
  - [12] F. J. Escrihuela, O. G. Miranda, M. A. Tortola and J. W. F. Valle, *Constraining nonstandard neutrino-quark interactions with solar, reactor and accelerator data*, *Phys. Rev.* **D80** (2009) 105009, [[0907.2630](#)].
  - [13] D. Z. Freedman, *Coherent neutrino nucleus scattering as a probe of the weak neutral current*, *Phys. Rev.* **D9** (1974) 1389–1392.
  - [14] D. Akimov et al., *Observation of Coherent Elastic Neutrino-Nucleus Scattering*, *Science* (2017) , [[1708.01294](#)].
  - [15] J. Barranco, O. G. Miranda and T. I. Rashba, *Probing New Physics with Coherent Neutrino Scattering Off Nuclei*, *JHEP* **12** (2005) 021, [[hep-ph/0508299](#)].
  - [16] K. Scholberg, *Prospects for measuring coherent neutrino-nucleus elastic scattering at a stopped-pion neutrino source*, *Phys. Rev.* **D73** (2006) 033005, [[hep-ex/0511042](#)].
  - [17] B. Dutta, R. Mahapatra, L. E. Strigari and J. W. Walker, *Sensitivity to Z-prime and nonstandard neutrino interactions from ultralow threshold neutrino-nucleus coherent scattering*, *Phys. Rev.* **D93** (2016) 013015, [[1508.07981](#)].
  - [18] M. Lindner, W. Rodejohann and X.-J. Xu, *Coherent Neutrino-Nucleus Scattering and new Neutrino Interactions*, **1612.04150**.
  - [19] I. M. Shoemaker, *COHERENT search strategy for beyond standard model neutrino interactions*, *Phys. Rev.* **D95** (2017) 115028, [[1703.05774](#)].
  - [20] M. B. Gavela, D. Hernandez, T. Ota and W. Winter, *Large gauge invariant non-standard neutrino interactions*, *Phys. Rev.* **D79** (2009) 013007, [[0809.3451](#)].
  - [21] S. Antusch, J. P. Baumann and E. Fernandez-Martinez, *Non-Standard Neutrino Interactions with Matter from Physics Beyond the Standard Model*, *Nucl. Phys.* **B810** (2009) 369–388, [[0807.1003](#)].
  - [22] Y. Farzan, *A model for large non-standard interactions*

- of neutrinos leading to the LMA-Dark solution, *Phys. Lett.* **B748** (2015) 311–315, [[1505.06906](#)].
- [23] Y. Farzan and I. M. Shoemaker, *Lepton Flavor Violating Non-Standard Interactions via Light Mediators*, *JHEP* **07** (2016) 033, [[1512.09147](#)].
- [24] K. S. Babu, A. Friedland, P. A. N. Machado and I. Mocioiu, *Flavor Gauge Models Below the Fermi Scale*, [[1705.01822](#)].
- [25] O. G. Miranda and H. Nunokawa, *Non standard neutrino interactions: current status and future prospects*, *New J. Phys.* **17** (2015) 095002, [[1505.06254](#)].
- [26] CHARM collaboration, J. Dorenbosch et al., *Experimental Verification of the Universality of  $\nu_e$  and  $\nu_\mu$  Coupling to the Neutral Weak Current*, *Phys. Lett.* **B180** (1986) 303–307.
- [27] NuTeV collaboration, G. P. Zeller et al., *A Precise determination of electroweak parameters in neutrino nucleon scattering*, *Phys. Rev. Lett.* **88** (2002) 091802, [[hep-ex/0110059](#)].
- [28] S. Davidson, C. Pena-Garay, N. Rius and A. Santamaria, *Present and future bounds on nonstandard neutrino interactions*, *JHEP* **03** (2003) 011, [[hep-ph/0302093](#)].