On the effect of NSI in the present determination of the mass ordering

Ivan Esteban,†‡ M. C. Gonzalez-Garcia,†‡§ and Michele Maltoni†

1Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain
2C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, NY 11794-3840, USA
3Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluís Companys 23, 08010 Barcelona, Spain
4Instituto de Física Teórica UAM/CSIC, Calle de Nicolás Cabrera 13-15, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain

In a recent work by Capozzi et al. [1], it is observed that the introduction of non-standard neutrino-matter interactions considerably relaxes the preference of T2K and NOνA for normal over inverted mass ordering observed in the standard three-neutrino scenario. Motivated by this, in this note we update our previous global fit to investigate whether such result still holds once the information of solar, atmospheric and reactor experiments is taken into account. We find that the non-standard parameters responsible for the improvement of the inverted ordering fit to T2K and NOνA data are not compatible with the other oscillation experiments, and that the preference for NO is restored.

I. INTRODUCTION

The unambiguous determination of the neutrino mass ordering is one of the primary goals of forthcoming long-baseline (LBL) neutrino experiments. The technical requirements needed to achieve it have been widely studied in the context of the standard three-neutrino oscillation framework, so that success is guaranteed as long as no “unexpected” physical phenomenon takes place. On the other hand, in the presence of New Physics the capability of a given experiment to resolve the neutrino mass ordering can be severely reduced. For example, in the context of non-standard neutrino-matter interactions (NSI) a new parameter degeneracy is present, which involves a change in the octant of the solar mixing angle (thus leading to the appearance of a new region characterized by \( \Theta_{12} \) in the second octant, the so-called LMA-Dark (LMA-D) solution [2]) as well as a change in the neutrino mass ordering (i.e., sign of \( \Delta m_{31}^2 \)) [3–5]. This “generalized mass ordering degeneracy” [6] cannot be resolved by Earth-based oscillation experiments alone, and therefore it undermines the capability of any LBL experiment to establish the neutrino mass ordering. The degeneracy is only approximate once experiments observing neutrinos which have traveled through matter with variable chemical composition, such as the Sun, are included into the fit. Still the LMA-D region, and hence the corresponding inversion in the mass ordering, remains a valid solution in the global analysis of oscillation data for a broad spectrum of NSI with quarks [6]. However, the appearance of the LMA-D/flip-ordering solution requires pretty large values of the NSI parameters, which lead to sizable effects on non-oscillation neutrino experiments such as COHERENT [7]. This means that the generalized mass-ordering degeneracy can be resolved (at least in principle) by combining data from both oscillation and scattering neutrino experiments [8].

Even if the LMA-D solution is ruled out, the introduction of NSI may still pose a threat to the sensitivity of LBL experiments by simply allowing for small but potentially dangerous deformations of the standard three-neutrino oscillations. In this case, the NSI parameters need not be particularly large, hence the possibility of disentangling them from genuine neutrino masses and mixing is not guaranteed. A detailed analysis of such situation using all the solar, atmospheric, reactor and accelerator neutrino data available at the end of 2018 was presented in Ref. [9]. In that work it was found that no further parameter degeneracy beyond the LMA-D generalized mass-ordering one is induced by NSI, and that the \( \sim 2\sigma \) preference for normal over inverted ordering observed in the standard three-neutrino scenario [10] is not affected by NSI as long as the LMA-D solution is neglected.

A similar analysis, updated with the data released in summer 2019 but limited to the T2K and NOνA accelerator experiments, was later presented in Ref. [11], leading however to different conclusions. The authors found that the current sensitivity to the mass ordering [11] is completely washed out once NSI are introduced in the fit, even without considering the LMA-D region. The authors ascribe the discrepancy between their result and those in Ref. [9] to the different data sets used in the two analyses, in particular for what concerns the T2K and NOνA results. Specifically, the slightly newer data used in Ref. [11] are found to significantly favor a non-zero value of \( |\epsilon_{e\tau}| \) when inverted ordering is considered, hence improving the quality of the corresponding fit and removing the tension with respect to normal ordering.

In view of this recent development, in this note we update our former analysis [9] to account for the newer T2K and NOνA data included in Ref. [11]. We perform first an analysis including only \( \epsilon_{e\tau} \) so to directly address the impact of this parameter on the ordering determination once the information from all experiments is taken into account. Second we update our global analyses includ-
ing all NSI couplings with the new LBL data samples as well as the timing and energy information from the COHERENT experiment as detailed in Ref. [8]. In Sec. III we describe the results of our analysis and in Sec. IIII we draw our conclusions.

II. DISCUSSION

We are going to consider NSI affecting neutral-current processes relevant to neutrino propagation in matter. The coefficients accompanying the relevant operators are usually parametrized in the form:

\[
\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{f,\alpha,\beta} \varepsilon_{\alpha\beta}^f (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\tilde{f} \gamma_\mu f),
\]

where \( G_F \) is the Fermi constant, \( \alpha \) and \( \beta \) are flavor indices, and \( f \) is a SM charged fermion. In this notation, \( \varepsilon_{\alpha\beta}^f \) parametrizes the strength of the vector part of the new interactions (which are the ones entering the neutrino matter potential) with respect to the Fermi constant, \( \varepsilon_{\alpha\beta}^f \sim O(G_X/G_F) \). In this framework, the evolution of the neutrino and antineutrino flavor state during propagation is governed by the Hamiltonian:

\[
H^0 = H_{\text{vac}} + H_{\text{mat}} \quad \text{and} \quad H^0 = (H_{\text{vac}} - H_{\text{mat}})^*,
\]

where \( H_{\text{vac}} \) is the vacuum part which in the flavor basis \( (\nu_e, \nu_\mu, \nu_\tau) \) reads

\[
H_{\text{vac}} = \frac{1}{2E_\nu} U_{\text{vac}} \cdot \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U_{\text{vac}}^\dagger.
\]

Here \( U_{\text{vac}} \) denotes the three-lepton mixing matrix in vacuum [12–14] which we parametrize following the conventions of Ref. [5].

If all possible operators in Eq. 1 are added to the SM Lagrangian, the matter part \( H_{\text{mat}} \) is a function of the number densities \( N_f(x) \) of the fermions \( f \) in the matter along the trajectory:

\[
H_{\text{mat}} = \sqrt{2}G_F N_e(x) \begin{pmatrix}
1 + \mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\
\mathcal{E}_{e\mu}^*(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\
\mathcal{E}_{e\tau}(x) & \mathcal{E}_{e\tau}(x) & \mathcal{E}_{e\tau}(x)
\end{pmatrix}
\]

where the “+1” term in the \( ee \) entry accounts for the standard contribution, and

\[
\mathcal{E}_{\alpha\beta}(x) = \sum_{f=u,d} \frac{N_f(x)}{N_e(x)} \varepsilon_{\alpha\beta}^f(x) = \varepsilon_{\alpha\beta}^{en} + 2\varepsilon_{\alpha\beta}^{en} + \varepsilon_{\alpha\beta}^{en} + Y_n(x) \left( 2\varepsilon_{\alpha\beta}^{en} + \varepsilon_{\alpha\beta}^{en} \right)
\]

describes the non-standard part. \( Y_n(x) \equiv N_n(x)/N_e(x) \) is the composition-dependent neutron abundance and we have used that matter neutrality implies \( N_e(x) = N_p(x) \). For experiments where neutrinos travel in the Earth matter, like LBL experiments, one can safely set \( Y_n(x) \) to a fixed value \( Y_n^\odot \) which is not very different from one. Within this approximation, the analysis of atmospheric and LBL neutrinos holds for any combination of NSI with up and down quarks as well as electrons, and it can be performed in terms of the effective NSI couplings \( \varepsilon_{\alpha\beta}^{\odot} \), given by Eq. 5 with a constant \( Y_n^\odot \), which play the role of phenomenological parameters.

In order to better address the sensitivity loss to the ordering found in Ref. [1], we start by performing our analysis in the same scenario studied there: oscillations of three massive neutrinos in the presence of a single NSI effective complex parameter \( \varepsilon_{e\tau}^{\odot} \). The results are presented in Fig. 1, where we plot the \( \Delta \chi^2 \) from the combined analysis of different sets of oscillation data as a function of \( \delta_{CP} \) (above) and \( |\varepsilon_{e\tau}^{\odot}| \) (below) after marginalizing over the undisplayed parameters. In each panel we plot the curves obtained marginalizing separately in NO (red) and IO (blue). For the sake of comparison in the upper panels we also plot the corresponding \( \Delta \chi^2(\delta_{CP}) \) from the 3ν oscillation analysis with the SM matter potential (labeled “NuFIT” in the figure).

In the left panels of Fig. 1 we present the results of the analysis including only the updated results of T2K and NOνA. In this analysis \( \Delta m^2_{31} \) and \( \theta_{12} \) are fixed to their best fit value determined by solar and KamLAND data, and a bias for \( \theta_{13} \) is included to account for the constraints from the medium-baseline (MBL) reactor experiments Double-CHOOZ [16], Daya-Bay [17] and RENO [18]. The curves shown here can be directly compared with the corresponding ones in the left panels of Fig. 3 in Ref. [1], with which we find a good agreement. In particular we note the \( \sim 2.1\sigma \) preference for NO from the analysis of T2K and NOνA without NSI, clearly visible from the dotted curves, is completely washed out once \( \varepsilon_{e\tau}^{\odot} \) NSI are introduced, as shown by the solid lines. Also from the lower-left panel we find that the best fit in IO corresponds to a non-zero value of \( \varepsilon_{e\tau}^{\odot} \sim 0.4 \) (well in agreement with Ref. [1]) which is preferred over the SM null value by more than 2\( \sigma \).

The other panels in Fig. 1 quantify how this result is affected by the inclusion of additional data samples. In the center-left panels the information from the MINOS LBL experiment is included. This leads to a slight improvement of IO with respect to NO in the standard 3ν scenario, but the main conclusion about the total wash-out of the preference for NO in the presence of \( \varepsilon_{e\tau}^{\odot} \) still holds and the corresponding projections over \( |\varepsilon_{e\tau}^{\odot}| \) are barely changed.

In the center-right panels we also add the information on \( \Delta m^2_{31} \) from the MBL reactor experiments [16–18], so

\footnote{The PREM model [15] fixes \( Y_n = 1.012 \) in the mantle and \( Y_n = 1.137 \) in the core, so that for atmospheric and LBL neutrino experiments one can set it to an average value \( Y_n^\odot = 1.051 \) all over the Earth.}
that we no longer assume a bias on $\theta_{13}$ but instead we combine the full data from LBL accelerator and MBL reactor experiments. First of all, we note that the inclusion of the $\Delta m^2_{31}$ information from MBL reactors adds to the preference for NO in the standard $3\nu$ oscillation scenario. This is due to the well known fact that the precise determination of the oscillation frequencies in $\nu_\mu$ disappearance at LBL experiments and $\nu_e$ disappearance in reactor experiments yields information on the sign of $\Delta m^2_{31}$. With the present MBL data it adds substantially to the preference for NO which in the $3\nu$ oscillation scenario is favored at the $\sim 2.5\sigma$ level. But more importantly, given the short baselines of these reactor experiments which renders them practically insensitive to matter effects, this extra preference for NO cannot be washed out by the inclusion of NSI. Hence from the center-right panels we see that NO is favored over IO at the $\sim 1.4\sigma$ level even in the presence of $\varepsilon_{e\tau}$. Consistently the shape of the dependence of the $\chi^2$ on $|\varepsilon_{e\tau}^0|$ for IO does not change by the inclusion of the MBL data, although its minimum value is shifted.

Finally, in the rightmost panels of Fig. 1, we add the information from all other experiments and perform a global analysis where the the LBL and MBL results are explicitly combined with the data from solar neutrino experiments, IceCube and its sub-detector DeepCore, and Super-Kamiokande (SK) atmospheric data (see Ref. [31] for the details on the analysis and the references to the data included). As seen in the figure, once the results from all experiments are combined, the preference of NO at the $2\sigma$ level is recovered even in the presence of the $\varepsilon_{e\tau}$ NSI. From the lower-right panel we see that the analysis in IO still favors a non-zero (though smaller) $|\varepsilon_{e\tau}^0| \sim 0.25$ though its significance is reduced to $\Delta \chi^2 \sim 2.5$. Indeed the curve shows a second almost degenerate minima at smaller $|\varepsilon_{e\tau}^0| \sim 0.1$ as a consequence of the tension of the larger value favored by T2K+NOνA and the zero value favored by the rest of the experiments.

In summary, we conclude that the non-standard parameters responsible for the improvement of the inverted ordering fit to T2K and NOνA data, as observed in Ref. [1] and reproduced in our own analysis shown in the left panel of Fig. 1, are not compatible with the other oscillation experiments, and that the preference for NO is restored once the data from those experiments is included in the analysis.

We next move to study the effect of the updated LBL samples on the conclusions of our analysis in Ref. [9]
about the LMA-D degeneracy. To this aim we perform an analysis including all the NSI parameters, not just $\varepsilon_{\tau\tau}$. The results are shown in Fig. 2 which can be directly compared with Fig. 3 of Ref. 9. In this figure we plot the one-dimensional $\chi^2(\delta_{CP})$ function obtained from $\chi^2_{\text{GLOB}}$ after marginalizing over the ten undisplayed parameters. In the left, central and right panels we focus on the GLOBAL analysis including T2K, NO$\nu$A, and T2K+NO$\nu$A respectively – so the data samples included in the analysis corresponding to the right panels of Figs. 1 and 2 are the same. In each panel we plot the curves obtained marginalizing separately in NO (red) and IO (blue) and within the LIGHT (full lines) and DARK (dashed lines) solutions. For the sake of comparison we also plot the corresponding $\chi^2(\delta_{CP})$ from the 3$\nu$ oscillation analysis with the SM matter potential (dotted lines labeled “NuFIT”). In the lower panels we also include the timing and energy information from the COHERENT experiment as detailed in Ref. 8. Compared to Fig. 3 of Ref. 9, we find that, even though there are minor quantitative differences (especially in the central panel), the main conclusions with respect to the status of the LMA-D ordering degeneracy remain unchanged. In particular in the global analysis (right panel of Fig. 2) the DARK-IO solution is still allowed below 2$\sigma$, but it has become slightly more disfavored and it is now at $\Delta\chi^2 \sim 3$ (in Ref. 9 it was $\Delta\chi^2 \sim 2$) with respect to the best fit LIGHT-NO.

We finish by noticing that comparing the results for the LIGHT solutions in the global analysis in the upper-right panel of Figs. 2 with those of the corresponding 3$\nu + \varepsilon_{\tau\tau}$ in the upper-right panel of Fig. 1 we see that enlarging the number of NSI couplings included in the analysis increases the preference for NO. This may seem counter-intuitive. The reason is that allowing non-vanishing $\varepsilon_{\tau\mu}$ results in an improvement of the fit in both NO and IO with respect to the standard 3$\nu$ fit, a result also pointed out in Ref. 1. In the global analysis, the improvement is slightly more significant for NO, hence the increase of the preference for NO in this case. We also see that the minima of the blue full and dotted lines in the lower right panel lay at the same $\Delta\chi^2$. In other words, once the updated constraints from COHERENT are included we find the same preference for NO for LIGHT solutions than in the standard 3$\nu$ oscillation scenario.

III. CONCLUSIONS

In this note we have updated our former analysis 9 by including the newer T2K and NO$\nu$A data. We have found that:

- when only the LBL accelerator data from T2K and NO$\nu$A are considered, the introduction of a non
vanishing NSI $\varepsilon_{e\tau}$ considerably relaxes the preference for normal over inverted ordering found in the standard three-neutrino oscillation scenario, in line with what was pointed out in Ref. [1];

- on the other hand, once the information from other oscillation experiments (solar, atmospheric, reactor as well as MINOS experiments) is taken into account the large $|\varepsilon_{e\tau}|$ values responsible for the improvement of the fit in the IO become disfavored, thus restoring the preference for NO observed in the standard scenario.

- the status of the LMA-D degeneracy is only mildly affected by the inclusion of the updated LBL data and COHERENT timing and energy information.

In summary, the updated results of the global analysis reconfirm the conclusions of Ref. [9].

ACKNOWLEDGMENTS

This work was supported by the MINECO grant FPA2016-76005-C2-1-P, by the MINECO FEDER/UE grants FPA2016-78645-P, by USA-NSF grants PHY-1620628, by EU Network FP10 ITN ELUSIVES (H2020-MSCA-ITN-2015-674896), by the “Severo Ochoa” program grant SEV-2016-0597 of IFT and by AGAUR (Generalitat de Catalunya) grant 2017-SGR-929. IE acknowledges support from the FPU program fellowship FPU15/0369.

[1] F. Capozzi, S. S. Chatterjee, and A. Palazzo, Neutrino mass ordering obscured by non-standard interactions, Phys. Rev. Lett. 124, 111801 (2020) [arXiv:1908.06992] [hep-ph].
[2] O. G. Miranda, M. A. Tortola, and J. W. F. Valle, Are solar neutrino oscillations robust?, JHEP 10, 008 [arXiv:hep-ph/0406280] [hep-ph].
[3] M. C. Gonzalez-Garcia and M. Maltoni, Determination of matter potential from global analysis of neutrino oscillation data, JHEP 09, 152 [arXiv:1307.3092] [hep-ph].
[4] P. Bakhti and Y. Farzan, Shedding light on LMA-Dark solar neutrino solution by medium baseline reactor experiments: JUNO and RENO-50, JHEP 07, 064 [arXiv:1403.0744] [hep-ph].
[5] P. Coloma and T. Schwetz, Generalized mass ordering degeneracy in neutrino oscillation experiments, Phys. Rev. D94, 055005 (2016) [arXiv:1604.05772] [hep-ph].
[6] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, and J. Salvado, Updated Constraints on Non-Standard Interactions from Global Analysis of Oscillation Data, JHEP 08, 180 [arXiv:1805.04530] [hep-ph].
[7] D. Akimov et al. (COHERENT), Observation of Coherent Elastic Neutrino-Nucleus Scattering, Science 357, 1123 (2017) [arXiv:1708.01294] [nucl-ex].
[8] P. Coloma, I. Esteban, M. Gonzalez-Garcia, and M. Maltoni, Improved global fit to Non-Standard neutrino Interactions using COHERENT energy and timing data, JHEP 02, 023 [arXiv:1911.09109] [hep-ph].
[9] I. Esteban, M. C. Gonzalez-Garcia, and M. Maltoni, On the Determination of Leptonic CP Violation and Neutrino Mass Ordering in Presence of Non-Standard Interactions: Present Status, JHEP 06, 055 [arXiv:1905.05203] [hep-ph].
[10] I. Esteban, M. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, and T. Schwetz, Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of $\theta_{23}$, $\delta_{CP}$, and the mass ordering, JHEP 01, 106 [arXiv:1811.05487] [hep-ph].
[11] I. Esteban, M. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, and T. Schwetz, NuFit 4.1 (2019), http://www.nu-fit.org.
[12] B. Pontecorvo, Neutrino Experiments and the Problem of Conservation of Leptonic Charge, Sov. Phys. JETP 26, 984 (1968), [Zh. Eksp. Teor. Fiz.53,1717(1967)].
[13] Z. Maki, M. Nakagawa, and S. Sakata, Remarks on the unified model of elementary particles, Prog. Theor. Phys. 28, 870 (1962).
[14] M. Kobayashi and T. Maskawa, CP Violation in the Renormalizable Theory of Weak Interaction, Prog. Theor. Phys. 49, 652 (1973).
[15] A. Dziewonski and D. Anderson, Preliminary reference earth model, Phys.Earth Planet.Interiors 25, 297 (1981).
[16] A. Cabrera Serra, Double Chooz Improved Multi-Detector Measurements, talk given at the CERN EP colloquium, CERN, Switzerland, September 20, 2016.
[17] F. P. An et al. (Daya Bay), Measurement of electron antineutrino oscillation based on 1230 days of operation of the Daya Bay experiment, Phys. Rev. D95, 072006 (2017) [arXiv:1610.04802] [hep-ex].
[18] H. Seo, New Results from RENO, talk given at the EPS Conference on High Energy Physics, Venice, Italy, July 5–12, 2017.