Hints for Leptonic *CP* Violation or New Physics?

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One of the major open questions in the neutrino sector is the issue of leptonic *CP* violation. Current global oscillation data show a mild preference for a large, potentially maximal value for the Dirac *CP* phase in the neutrino mixing matrix. In this Letter, we point out that new physics in the form of neutral-current-like nonstandard interactions with real couplings would likely yield a similar conclusion even if *CP* in the neutrino sector were conserved. Therefore, the claim for a discovery of leptonic *CP* violation will require a robust ability to test new physics scenarios.

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In 2015, a Nobel prize for the discovery of the neutrino oscillation was given. The bulk of the existing data currently are very well described by the oscillation of three active neutrinos; see, for instance, Refs. [1,2]. There are potential indications for additional, sterile neutrinos, which at this stage are not conclusive [3] and we therefore will neglect for the remainder of this Letter. Lately, due to a tension between reactor and accelerator neutrino experiments, a preference for a value of the Dirac *CP* phase close to $-\pi/2$ was first reported in Ref. [4].

In the context of inflationary cosmology, the baryon asymmetry of the Universe has to be generated dynamically. This process known as baryogenesis requires several conditions (Sakharov conditions): baryon number violation, charge conjugation and charge conjugation times parity (*CP*) violation, and out of equilibrium dynamics. Within the standard model, this baryogenesis scenario cannot be accomplished, mainly because the amount of *CP* violation from the phase in the quark mixing matrix is not enough to explain the baryon asymmetry measured in big bang nucleosynthesis and the cosmic microwave background. Therefore, to explain the baryon asymmetry the standard model should be extended. Seesaw models provide an appealing mechanism for baryogenesis via leptogenesis. In this mechanism, a lepton asymmetry is dynamically generated and then partially converted into a baryon asymmetry.

Thus, the seesaw mechanism not only explains the smallness of the neutrino masses but also provides a framework for baryogenesis. To fulfill the second Sakharov condition, new sources of *CP* violation must be introduced, which in the seesaw models are achieved by the complex Yukawa couplings of the new fields. The resulting low-energy *CP* observables appear in the neutrino mixing matrix as three physical phases: two Majorana phases and one Dirac *CP*-violating phase. In general, there are more high-energy parameters than there are low-energy observables, and only once additional assumptions are used do predictive models of leptogenesis arise; for a review, see, for instance, Ref. [5]. Long-baseline neutrino oscillations are sensitive to the Dirac *CP*-violating phase, and thanks to the MINOS [6], T2K [7], and NOvA [8] measurements in the appearance channel, in combination with reactor neutrino experiments, currently there is a preferred value consistent with *CP* violation in the leptonic sector. This in itself would not constitute a proof of leptogenesis but certainly would make it more plausible.

Another, more general reason why leptonic *CP* violation is of interest is that the *CP* properties of the standard model are nontrivial: *CP* is violated to a large degree in quark mixing but unusually well conserved in the QCD sector. It is far from obvious why this should be the case, and the neutrino sector provides another *CP* observable.

The question of *CP* violation in the leptonic sector is *a priori*ty of the future neutrino program, and the main effort is dedicated to the DUNE experiment [9]. Apart from a number of experimental challenges and the need to understand neutrino-nucleus interactions, subleading effects of theoretical origin can also affect the determination of the Dirac *CP* phase. In this Letter, we focus on so-called nonstandard interactions (NSIs), which have been speculated about even before the discovery of neutrino oscillation [10–13]; for a recent review, see Ref. [14]. NSIs provide a model-independent, effective field theory framework to include new physics effects in the standard neutrino description; see, e.g., Ref. [15].

NSIs are parameterized by dimensionless couplings ε, which are measured relative to G_F. From neutrino data alone, large magnitudes for the dimensionless couplings $|\varepsilon_{e\tau}^{f=u,d}| \lesssim 0.14$ at 90% [16] are allowed, which for Earth matter densities translates into $|\varepsilon_{e\tau}| \sim \mathcal{O}(1)$. Generally, NSIs can provide new phases that can potentially be new sources of *CP* violation. In the context of flavor-changing NSIs in the source and the detection of neutrinos, a discussion of new sources of *CP* violation appeared in Ref. [17]. In the case of neutral current NSIs, a discussion of this issue appeared in Ref. [18]. In the context of NOvA, and motivated by large NSIs allowed by solar neutrino data, one example of the potential NSIs and standard oscillation confusion was analyzed at the probability level in Ref. [19].

Direct bounds derived from the neutrino sector are typically of the order of 0.1–1 in units of G_F; that is, new physics contributions of about the same size as the leading standard model (SM) contribution are still allowed. On the other hand, any model where these new interactions are introduced above the electroweak symmetry breaking scale has to address the fact that invariance under the weak $SU(2)$ group will create a charged lepton counterpart of any neutrino-only operator. Given that the electroweak scale is not very far from the scale at which typical neutrino experiments are conducted, breaking of the electroweak symmetry does not erase the correspondence between neutral and charged lepton operators; at best, factors of a few are gained. The charged lepton bounds involving the first and second families are very stringent. In Ref. [20], a systematic analysis of dimension-6 and -8 operators is performed, and it is found that for dimension-8 operators it is possible to arrange for cancellations, provided a suitable particle content is chosen, such that large NSIs in the neutrino sector can be realized without creating sizable effects in the charged lepton sector. This requires fine-tuning, and no actual models have been put forward. It is worth noting that, even without fine-tuning, third family NSIs in the τ sector can be potentially large of the order of $0.1G_F$ (see, e.g., [21]), since the corresponding charged lepton bounds themselves are very weak.

The situation is quite different if we consider models where a NSI is generated *below* the scale of electroweak symmetry breaking, since by construction there will be no correspondence between neutral and charged lepton operators. An early example of a low-scale neutrino mass model (without NSIs) is given in Ref. [22], where the breaking of a discrete gauge symmetry at a scale as low as a few keV is responsible for small Dirac neutrino masses. It would be straightforward to augment this model by additional flavor-changing neutral currents to create large NSIs. The general idea is to invoke new light degrees of freedom which preferentially couple to neutrinos and/or dark matter particles, e.g. [23–25]. These models tend to introduce new self-interactions in the dark matter sector and need to observe the relevant astrophysical bounds from structure formation. Also, in some of these models there are connections to the sterile neutrino sector, which in turn can help to accommodate sterile neutrinos in cosmology [26]. Thus, we see that there is ample room from both an experimental and a theoretical perspective for relatively large NSIs. The resulting degeneracies between new physics and oscillation physics recently have been studied in Ref. [27] in a more general setting. Here, we will study specifically the impact neutral-current-like NSIs can have on the analysis of Daya Bay, T2K, and NOvA data sets and point out that the current hint for maximal CP violation may, in fact, be caused by *CP-conserving* new physics.

The standard neutrino oscillations in vacuum are described by the Hamiltonian:

$$H_0 = \frac{1}{2E}[U\mathrm{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2)U^\dagger], \quad (1)$$

where U is the lepton mixing matrix parameterized by three mixing angles θ_{ij} and a CP-violating phase δ_{CP}. Δm_{k1}^2 in Eq. (1) denotes the two known mass square differences and E the neutrino energy.

Since we will consider long-baseline neutrino oscillations, the neutrino forward scattering interactions in matter can be effectively parameterized in the presence of NSIs by the following Hamiltonian:

$$H_{\mathrm{int}} = V\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} \quad (2)$$

with $V = \sqrt{2}G_F N_e$, where G_F is the Fermi constant and N_e is the electron density on Earth. Notice that the Hamiltonian in Eq. (2) has eight new physical parameters in addition to the standard oscillation ones. However, only a few of them are present in any specific oscillation channel. In the particular case of the (anti)neutrino appearance channel, only the two NSI complex parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$, and the real ε_{ee} NSI coupling, play a role [28]. Instead of an exhaustive analysis to quantify the interplay of all the NSI parameters with the SM ones, we will consider $\varepsilon_{ee} = |\varepsilon_{e\mu}| = 0$ and $\varepsilon_{e\tau} \equiv |\varepsilon|\exp(i\phi)$, which is enough for our discussion. Throughout this Letter, our results will correspond only to the normal ordering for the neutrino spectrum.

We have implemented a GLoBES [29,30] simulation of a 295-km-baseline neutrino beam experiment with the characteristics of T2K but scaling its exposure by a factor of 5 relative to the current data [7]. In addition, we have also implemented a simulation of NOvA running 3 years in neutrino mode plus 3 years in antineutrino mode [31]. The set of oscillation parameters used along this work corresponds to the best fit values in Ref. [1] except for the reactor mixing angle that was fixed to the Daya Bay best fit value in Ref. [32].

The interplay of the Dirac CP phase and the NSI parameters in each of the two considered facilities is shown in the birate plots of Fig. 1. For the chosen values of the NSI parameters, and considering the errors in both NSI and SM rates, an overlap in the SM point $\delta_{CP} = -\pi/2$ is clearly shown in both panels for T2K and NOvA. However, notice that in the case of the T2K rates (left panel) there is a tension between the considered NSI cases and the SM point $\delta_{CP} = -\pi/2$. Thus, in combination with NOvA the "confusion" will be significant for the NSI case with $\delta_{CP} = \pi$.

By assuming CP-conserving values, in the presence of NSIs, the freedom in $|\varepsilon|$ and ϕ can be used to "mimic" the

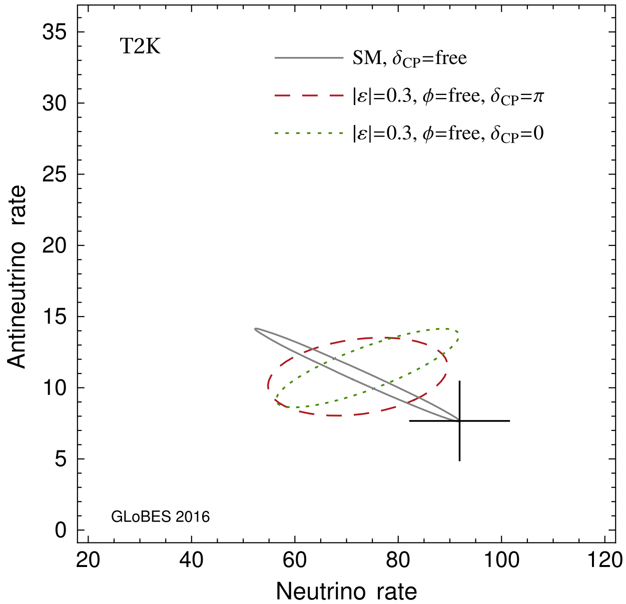

FIG. 1. Birate plots. The full line curve corresponds to the SM for all Dirac *CP* phase values. The dashed and dotted curves correspond to a fixed NSI magnitude $|\varepsilon| = 0.3$ and for all NSI phase ϕ values shown but for different values of the standard *CP* phase. The cross for the SM point $\delta_{CP} = -\pi/2$ shows the statistical uncertainty. The left (right) panel corresponds to our implementation of the T2K (NOvA) experiment. All parameters not shown in the plot were fixed to their best fit values; see the text for details.

SM point $\delta_{CP} = -\pi/2$. Basically, the value of $|\varepsilon|$ sets the opening of the NSI ellipse, while the phase ϕ can be tuned to coincide with the SM and NSI intersection point. Notice that, for T2K (left panel), a larger value for $|\varepsilon|$ is needed to exactly pick the SM point $\delta_{CP} = -\pi/2$, while for NOvA (right panel), a smaller ε would instead be required. This is mainly due to the different baseline of both experiments, since the sensitivity to the NSIs depends on the SM and NSI interference of vacuum and matter oscillations [see Eq. (33) of Ref. [28]]. Thus, a combination of experiments with different baselines limits the parameter tuning we are discussing, which in the future may allow us to disentangle these effects if both high-statistic data sets from DUNE and T2HK are available [33–35]. However, our philosophy here

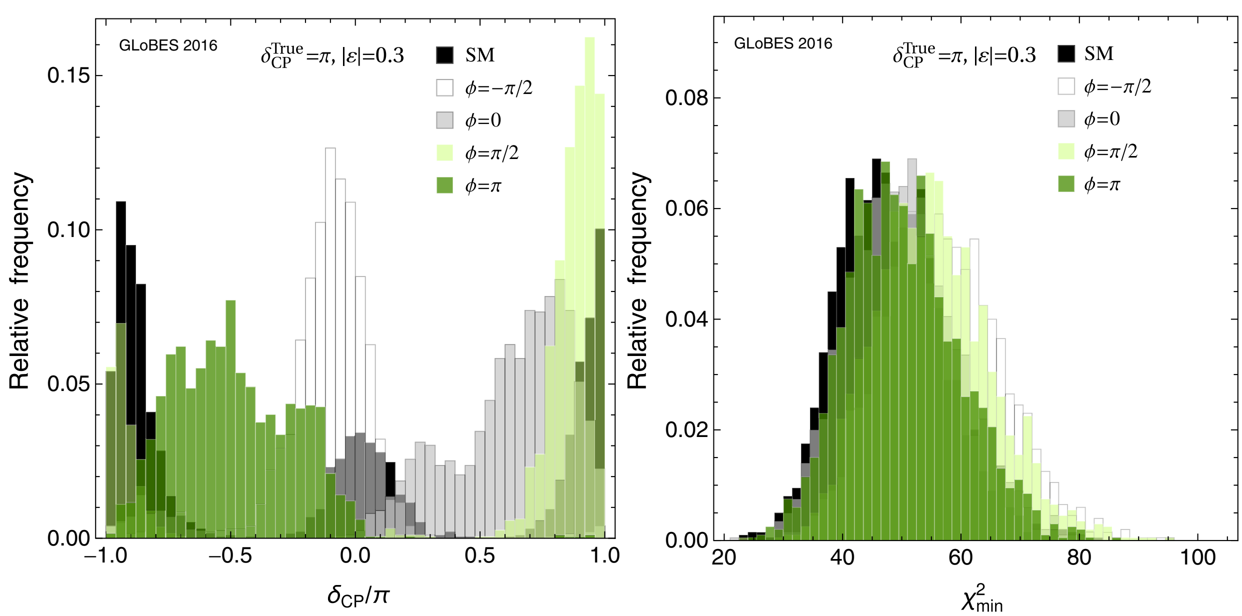

FIG. 2. Results assuming $\delta_{CP}^{True} = \pi$. In the left panel, the Dirac *CP* phase best fit distributions for SM and NSI interactions are shown. The NSI magnitude was fixed to the value $|\varepsilon| = 0.3$ for the different NSI phase ϕ values showed in the plot. In the right panel appears the minimum χ^2 distributions from the fit to the SM Dirac *CP* phase for each of the SM and NSI cases showed in the left panel. All not shown parameters were marginalized over; see the text for details of the analysis.

is quite different: Given a particular set of NSI parameters (allowed by current bounds), we want to quantify the level of confusion if the currently preferred value for the δ_{CP} turned out to be correct.

To quantify the sensitivity to the SM Dirac CP phase in the presence of NSIs, we have adopted the usual χ^2 analysis where $n_i = n_i(\vec{\lambda}^{\rm true}, \varepsilon^{\rm true})$ and $\mu_i = \mu_i(\vec{\lambda})$ correspond to the simulated and test events, respectively. The set of standard oscillation parameters, mixing angles, Dirac CP phase, and the solar and atmospheric splittings, are represented by $\vec{\lambda}$. To test SM oscillations rates μ_i against the ones with NSIs, we implemented random statistical fluctuations (Poisson distributed) on the "true" rates n_i. Gaussian priors for all the standard oscillation parameters but δ_{CP} were included in the analysis.

Our main result is presented in Fig. 2. The distribution of the Dirac CP phase best fit values for SM and NSI interactions are shown in the left panel. In all cases, $\delta_{CP}^{\rm true} = \pi$. In the case of the SM, the δ_{CP} has values distributed around CP-conserving values including zero, but it is mainly distributed around $\delta_{CP} = \pm\pi$ as expected. When NSIs are considered, two general features appear: In the case of complex NSIs, $\phi = -\pi/2$ and $\phi = \pi/2$, δ_{CP} is distributed with a higher probability with respect to the SM case around values that are close to zero and π, respectively; and the distributions are very peaked around their mean value. However, when $\phi = 0$ (real NSIs), the distribution of δ_{CP} is broader and extends for half of the parameter space in the positive region. In this case, the mean value is located near $\delta_{CP} = \pi$ with a probability closer to the one of the SM case. In the remaining case of real NSIs $\phi = \pi$, also the distribution is broader but the main feature is that its mean value is centered at $\delta_{CP} = -\pi/2$ almost with the same probability as the SM case. In both cases with real NSIs, there is a non-negligible probability to find δ_{CP}-violating values even though $\delta_{CP}^{\rm True}$ has been assumed to be CP conserving. This result is remarkable, in particular, when $\phi = \pi$, in the light of the current preference for the Dirac CP phase value.

The corresponding distributions of the χ^2 minima, for each case of the left-hand panel, are shown in the right-hand panel in Fig. 2. Because of the random statistical fluctuations, the $\chi^2_{\rm min}$ for the SM case is centered at $\chi^2 \simeq 40$, corresponding to the number of bins minus the number of fitted parameters. However, the main feature is that all the NSI χ^2 distributions are centered within ~7 units from the SM central value with almost the same probability. In the main case of $\phi = \pi$ both SM and NSI, the χ^2 distributions are even closer; they almost completely overlap each other. This result shows that existing experiments *cannot* distinguish these two cases.

In summary, we have studied the robustness of the recent hint for maximal leptonic CP violation in the presence of neutral-current-like NSIs. We simulate many iterations of the same experiments, T2K and NOvA, and perform a fit to the resulting data, both for a purely three-flavor oscillation and in the presence of NSIs. We find that, even if CP is fully conserved by the NSIs and standard oscillations, a preference for the best fit value of the leptonic CP phase $\delta_{CP} \simeq -\pi/2$ is shown. Thus, the current hint for maximal leptonic CP violation can be due to either maximal leptonic CP violation or CP conservation in the presence of new physics. The χ^2 distributions in both cases are nearly identical, highlighting the need for new experiments like DUNE and T2HK to resolve this confusion.

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