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Nonstandard interaction effects on astrophysical neutrino fluxes

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We investigate new physics effects in the production and detection of high-energy neutrinos at neutrino telescopes. Analyzing the flavor ratios ϕ_μ/ϕ_τ and $\phi_\mu/(\phi_\tau + \phi_e)$, we find that the standard model predictions for them can be sensibly altered by new physics effects in the case of pion sources. However, the experimental precision required to see the effects would be very difficult to obtain.

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I. INTRODUCTION

Neutrino oscillation physics has definitively entered the era of precision measurements of the fundamental neutrino parameters. Recent experiments such as Super-Kamiokande, SNO, KamLAND, K2K, and MINOS [1–6], have improved our knowledge of the neutrino mass squared differences (i.e., Δm^2_{31} and Δm^2_{21}) and some of the the leptonic mixing parameters (i.e., θ_{12}, θ_{23}). Whether θ_{13} is different from zero and CP violation is present in the leptonic sector of the standard model are questions that will be addressed by forthcoming experiments [7].

While there exist clear evidence that the $V - A$ structure of the weak interactions of the standard model correctly describes neutrino interactions with matter, there is still a possibility that some next-to-leading order mechanism affects the processes of neutrino production and detection. In general, this sort of physics beyond the standard model is described by a set of higher-dimensional nonrenormalizable operators suppressed by some high-energy scale (see, e.g., Refs. [8,9] and references therein). The precision measurements in the neutrino sector then open up the possibility to investigate such nonstandard interactions (NSI) at a quite accurate level.

Neutrino oscillations and NSI in terrestrial neutrino experiments have been studied extensively in the literature, using the neutrino factory project [10–20] and other different neutrino facilities (e.g., conventional neutrino beams, superbeams, and β beams) [21–27] to assess the impact of the NSI in neutrino physics.

Here, we adopt a different point of view,; we investigate the NSI in the neutrino sector using very high-energy neutrinos from astrophysical sources and the capability of neutrino telescopes to measure their fluxes on Earth [28–32]. We rely on the simplified assumption that the new physics effects arise in the production and detection processes but do not affect the neutrino propagation. We also assume that the lepton mixing matrix is the standard unitary matrix describing the couplings of the charged-lepton-neutrino-W vertices. Moreover, for the sake of illustration, we prefer to study the possible NSI signals for the three different sources (pion, muon-damped [MD], and neutron sources) separately, as the effects of new physics are quite different in these cases. The assumption of the source being the result of a single process is common in the literature (see, e.g., Refs. [33–37]). We use three source types to demonstrate the effects of NSI in the different scenarios. Clearly, an actual astrophysical source may not be so simple, but the source modelling is out of the scope of this paper. Since the sensitivity to the actual NSI parameters at a neutrino factory (see, e.g., Ref. [7] and references therein) would be much better than the ones obtainable from astrophysical sources, we instead focus on the impact of the NSI on the flavor fluxes rather than vice versa. However, we want to stress that even in the case where the NSI are known, it could be important to include their effect in deducing information about the source.

This work is organized as follows: In Sec. II, we will present analytic considerations for the NSI we study in the paper. In particular, we will first describe the detector effects in a unified way, since these are independent of the assumed neutrino source. We will then address the question of nonstandard physics in the production processes. In Sec. III, we will describe the statistical approach we use to study the sensitivity of neutrino telescopes to new physics effects and also present our numerical results. Finally, in Sec. IV, we will present a summary of the work as well as our conclusions.

II. NSI AT THE SOURCE AND DETECTOR

We consider NSI through effective four-fermion operators of the form

$$\mathcal{L}_{\text{B-NSI}} = -2\sqrt{2}G_F\cos(\theta_W)\varepsilon^{udP}_{\alpha\beta}[\bar{u}\gamma^\mu P d][\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta] + \text{H.c.} \tag{1}$$

for charged-current NSI with baryons, where θ_W is the Weinberg angle, $P = P_L$ or P_R, and

$$\mathcal{L}_{\ell\text{-NSI}} = -2\sqrt{2}G_F\varepsilon^{\alpha\beta P}_{\gamma\delta}[\bar{\ell}_\alpha\gamma^\mu P\ell_\beta][\bar{\nu}_\gamma\gamma_\mu P_L\nu_\delta] \tag{2}$$

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for purely leptonic NSI (see [38–41] for a discussion on the limits on $\varepsilon_{\gamma\delta}^{\alpha\beta P}$). While the addition of the Hermitian conjugate in the case of NSI with baryons leads to operators of the form $[\bar{d}\gamma^\mu P u][\bar{\nu}_\beta \gamma_\mu P_L \ell_\alpha]$, the requirement of a Hermitian Lagrangian for the purely leptonic NSI implies $\varepsilon_{\gamma\delta}^{\alpha\beta P} = \varepsilon_{\delta\gamma}^{\beta\alpha P*}$. In what follows, we will assume effective parameters ε^{ud} and $\varepsilon^{\mu e}$, which in general are some combination of ε^{udL} and ε^{udR} as well as $\varepsilon^{\mu eL}$ and $\varepsilon^{\mu eR}$, respectively, (the actual combination depends on the processes in which the εs are involved). We will further assume that the coherence among the neutrino mass eigenstates that arrive at the Earth has been lost. Thus, we do not need to take any interference terms into account and may treat the source and detector processes separately.

A. Detector effects

Since the detector processes are essentially the same regardless of the source, we will start by considering these. In principle, the detection of astrophysical neutrinos is done through charged-current reactions of the form $\nu + X \to Y + \ell_\alpha$ and then identifying the neutrino flavor through identification of the outgoing charged lepton. Assuming that the neutrino arrives at the Earth in the mass eigenstate ν_i, the matrix element involved in computing the reaction rate is given by

$$\mathcal{M}_{i\alpha} = \mathcal{M}_0[(\mathbb{1} + \varepsilon^{ud})U]_{\alpha i}, \tag{3}$$

where $\mathcal{M}_0$ is the matrix element for the corresponding reaction if the incoming neutrino would have been of flavor α and there were no NSI, $\mathbb{1}$ is the 3×3 unit matrix, $\varepsilon^{ud} = (\varepsilon^{ud}_{\alpha\beta})$, and U is the leptonic mixing matrix. Thus, if the incoming ν_i flux is ϕ_i, then the measured flux of ν_α is given by

$$\phi_\alpha = \phi_i |[(\mathbb{1} + \varepsilon^{ud})U]_{\alpha i}|^2. \tag{4}$$

Naturally, the composition of the neutrino flux arriving at the Earth is not purely ν_i. Thus, in order to compute the actual flavor flux, we need to sum over all mass eigenstates and arrive at

$$\phi_\alpha = \sum_i \phi_i |[(\mathbb{1} + \varepsilon^{ud})U]_{\alpha i}|^2. \tag{5}$$

The actual fluxes ϕ_i are dependent on the source type and may also contain effects from the same NSI as those affecting the detector processes.

B. Hadronic sources

Let us first assume that the astrophysical neutrino source creates neutrinos through hadron decays only. Out of the usually considered scenarios, this category includes the MD pion sources (giving initial flavor ratios of $\phi_e{:}\phi_\mu{:}\phi_\tau = 0{:}1{:}0$ in the neutrino fluxes) as well as neutronlike (NL) sources (1:0:0). These sources produce neutrinos through processes where a meson or baryon decays into a charged lepton of a given flavor,[1] a neutrino and possibly other products. When a neutrino is produced together with a charged lepton of flavor β in a weak decay of a meson or a baryon, the probability of producing it in the neutrino mass eigenstate ν_i is given by

$$P_i = |U_{\beta i}|^2 \tag{6}$$

in the standard model. With the addition of NSI, there is also the possibility to produce the neutrino in a different flavor state and the corresponding probability changes according to

$$P_i \propto |[(\mathbb{1} + \varepsilon^{ud})U]_{\beta i}|^2. \tag{7}$$

In general, the full expression for P_i also contains a normalization factor, since $\mathbb{1} + \varepsilon^{ud}$ may not be unitary. However, this normalization factor is the same for all P_i and will be removed once we consider neutrino flux ratios. Since the meson/baryon decay gives the only neutrino contribution in this scenario, the ν_i flux will be given by

$$\phi_i = \phi_0 P_i, \tag{8}$$

where ϕ_0 is the total initial neutrino flux. By insertion into Eq. (5), the measured flux of ν_α at the detector is therefore given by

$$\phi_\alpha \propto \phi_0 \sum_i |[(\mathbb{1} + \varepsilon^{ud})U]_{\beta i}|^2 |[(\mathbb{1} + \varepsilon^{ud})U]_{\alpha i}|^2. \tag{9}$$

C. Non-muon-damped pion sources

We now consider the situation where the source is producing neutrinos both through an initial decay of a charged pion and through the subsequent decay of the resulting charged muon. The complete decay chain is then

$$\begin{array}{lll} \pi^+ \to & \mu^+ & + \nu_\alpha \\ & \downarrow & \\ & e^+ & + \nu_\beta + \bar{\nu}_\gamma \end{array}, \tag{10}$$

as well as the corresponding CP-conjugate reaction for π^-. With only standard model interactions, $\alpha = \gamma = \mu$ and $\beta = e$; the produced flavor ratio is then approximately 1:2:0.

Mathematically, the decay of the pion can be described in the same way as in the previous section, with the exception that we now need to know the normalization factor for P_i, since we will add the contributions from the pion and muon decays and need to be consistent while doing so. The normalization factor N_μ is simply given by the fact that the total probability of the pion decay should be equal to one, i.e.,

[1]In the case of pion decay, there is a small contamination of decays into electrons, which is suppressed by m_e^2/m_μ^2.

$$\sum_i P_i = \frac{1}{N_\mu}\sum_i |[(\mathbb{1} + \varepsilon^{ud})U]_{\mu i}|^2 = 1 \Rightarrow N_\mu = [(\mathbb{1} + \varepsilon^{ud})(\mathbb{1} + \varepsilon^{ud\dagger})]_{\mu\mu} \quad (11)$$

(essentially, this is the factor by which the decay rate of the pion would change due to the NSI).

The muon decay is a little more involved, since the final state involves two neutrinos, where one of these is not observed. In the literature, this problem is usually solved by considering only NSI of the form $[\bar{e}\gamma^\rho P_L \mu]\times[\bar{\nu}_\alpha \gamma_\rho P_L \nu_e]$. With this simplification, the situation is completely analogous to the case of the pion decay, simply because we know the flavor of the outgoing $\bar{\nu}$ (in the case of μ^+ decay). With general NSI however, we need to consider the full matrix element for the decay $\mu^+ \to e^+\bar{\nu}_i\nu_j$, which is given by

$$\mathcal{M}_{ij} = \mathcal{M}_0[U^\dagger(\mathcal{J}^{\mu e} + \varepsilon^{\mu e})U]_{ji}, \quad (12)$$

where $\mathcal{M}_0$ is the matrix element when neutrinos do not mix and only standard model interactions are considered, $\mathcal{J}^{\mu e}_{\alpha\beta} = \delta_{e\alpha}\delta_{\mu\beta}$, and $\varepsilon^{\mu e} = (\varepsilon^{\mu e}_{\alpha\beta})$ is a matrix containing the strengths of the NSI. In order to obtain the probability for a neutrino from this type of decay to be in the mass eigenstate ν_i, we need to consider the fact that we do not measure the antineutrino from the same decay. Thus, the probability will be given by an incoherent sum over the antineutrino mass eigenstates as

$$P_i^{\mu^+} \propto \sum_j |\mathcal{M}_{ij}|^2 \propto [U^\dagger(\mathcal{J}^{\mu e} + \varepsilon^{\mu e})^\dagger(\mathcal{J}^{\mu e} + \varepsilon^{\mu e})U]_{ii}. \quad (13)$$

Again, this needs to be normalized and the normalization factor is given by

$$N^{\mu^+} = \mathrm{Tr}[(\mathcal{J}^{\mu e} + \varepsilon^{\mu e})^\dagger(\mathcal{J}^{\mu e} + \varepsilon^{\mu e})]. \quad (14)$$

The corresponding argumentation for the outgoing antineutrino results in

$$\bar{P}_j^{\mu^+} \propto \sum_i |\mathcal{M}_{ij}|^2 \propto [U^\dagger(\mathcal{J}^{\mu e} + \varepsilon^{\mu e})(\mathcal{J}^{\mu e} + \varepsilon^{\mu e})^\dagger U]_{jj}, \quad (15)$$

with the same normalization constant $\bar{N}^{\mu^+} = N^{\mu^+}$. Repeating the same derivation for μ^- decay, we arrive at $P_i^{\mu^-} = \bar{P}_i^{\mu^+}$ and $\bar{P}_j^{\mu^-} = P_j^{\mu^+}$. Thus, assuming equal numbers of positive and negative pions decaying, the flux of neutrino mass eigenstate ν_i (or antineutrino mass eigenstate $\bar{\nu}_i$) is given by

$$\phi_i = \phi_0(P_i + P_i^{\mu^+} + \bar{P}_i^{\mu^+}), \quad (16)$$

where ϕ_0 is the initial flux of ν_e in the case of standard model interactions only.

III. EXPERIMENTAL IMPLICATIONS

For experimental reasons, it is customary to consider the flavor flux ratios

$$R_{e\mu} = \frac{\phi_e}{\phi_\mu}, \qquad R_{\mu\tau} = \frac{\phi_\mu}{\phi_\tau}, \quad \text{and} \quad R = \frac{\phi_\mu}{\phi_e + \phi_\tau} \quad (17)$$

(note that these are not independent). With the flavor fluxes computed as in Sec. II, we want to know how NSI at the source and detector can affect the results of these measurements. In order to do this, we will examine how well a value of any of the Rs can be accommodated when considering standard model interactions only, as well as when allowing for NSI. To quantify this, we perform a Markov chain Monte Carlo (MCMC) sampling of the currently allowed parameters spaces for three different setups:

(1) All of the NSI parameters set to zero, i.e., the standard setup.
(2) All parameters free, with the priors on the εs according to the most stringent bounds from Ref. [42].
(3) All parameters free, with the prior on the real part of $\varepsilon^{ud}_{\tau\tau}$ loosened to that of he imaginary part.

The motivation for setup 3 is that the most stringent bound on $\varepsilon^{ud}_{\tau\tau}$ stems from the comparison of rate of tau decay into pions with the rate of pion decay into muons, which means that the bound is on the axial vector combination $\varepsilon^{udR}_{\tau\tau} - \varepsilon^{udL}_{\tau\tau}$. However, while the axial structure is also present at the production (assuming production through pion decays into muons), it is not the preferred structure at detection through inverse beta decay. We therefore assume a prior which is the least stringent one among the ε^{ud} simply in order to get some insight to what the effects may be. The other bounds range between $\mathcal{O}(10^{-5})$ and $\mathcal{O}(0.1)$. The actual MCMC sampling was performed using the MONTECUBES plugin [43] for the GLOBES software [44,45] (without any experimental initialization in order to simply sample the priors).

It should be noted that most of the bounds on the εs have been set assuming only one ε at a time and no correlations between first and second order terms in ε. However, what is bound is really a particular function of the εs, forming a sphere in the ε parameter space. If one allows for correlations along this sphere (essentially fine-tuning the linear term of the ε interfering with the standard model with the quadratic contributions), then we are left with a situation where essentially any flavor combination is allowed with the exception of some more direct bounds from negative neutrino oscillation searches.

In the MCMC samplings, we adopt the standard parametrization of the neutrino mixing matrix (see Refs. [46–50]), assuming also a tribimaximal structure [51] for it. We assume Gaussian priors on the standard mixing parameters of the same size as the errors in Ref. [52]. In Table I, we give the corresponding values for these parameters.

TABLE I. Summary of the best fit values and 3σ errors used in our numerical computation for the standard neutrino oscillation parameters.

Parameter	Best fit	3σ error
θ_{12}	35.3°	5°
θ_{13}	0	12.5°
θ_{23}	45°	10°
δ	Free ($[0, 2\pi]$)	

Finally, we compute the predicted flavor flux ratios for each set of sampled parameters and use Bayesian inference to obtain the predictions of the models.

A. Muon-damped pion sources

In order to appreciate the effects of the new physics on the flux ratios of Eq. (17), it is useful to recall the standard model expectations for these quantities. Putting $\varepsilon^{ud} = 0$ and $\beta = \mu$ in Eq. (9), we get the following expressions for the flavor fluxes:

$$\phi_e = \phi_0 \sum_i |U_{\mu i}|^2 |U_{ei}|^2, \qquad \phi_\mu = \phi_0 \sum_i |U_{\mu i}|^4, \qquad \phi_\tau = \phi_0 \sum_i |U_{\mu i}|^2 |U_{\tau i}|^2. \tag{18}$$

In the limit of exact tribimaximal mixing ($\theta_{13} = 0$, $\sin^2\theta_{12} = 1/3$, and $\sin^2\theta_{23} = 1/2$ [51]), we obtain

$$R_{e\mu} = \tfrac{4}{7}, \qquad R_{\mu\tau} = 1, \quad \text{and} \quad R = \tfrac{7}{11}. \tag{19}$$

Before concluding that deviations from these values are signals of new physics, we should carefully take the role of the uncertainties of the standard parameters into account [53]. In particular, the distributions of the flavor flux ratios in the standard setup 1 are shown in Fig. 1. It can be clearly seen that the largest spread due to the uncertainties on the mixing angles θ_{12}, θ_{23} and on the product $\theta_{13}\cos\delta$ (see also Eq. (4) in Ref. [54]) is obtained for $R_{e\mu}$. The fact that most decays will result in neutrinos of the mass eigenstate with the largest ν_μ content protects $R_{\mu\tau}$ from becoming much smaller than 1, an effect that can also be seen in the ratio R, which cannot be much smaller than $1/2$. The pile-up of the distributions close to these values are the results of θ_{23} being close to maximal, which results in only a higher order dependence on the deviation from maximal mixing. It is then possible that new physics effects would be much more visible in the ratios containing τ neutrinos and, for this reason, we will investigate the effects of the ε parameters in the $R_{\mu\tau} - R$ plane.

The correlation between $R_{\mu\tau}$ and R can be analyzed using the posterior MCMC distributions for these flavor flux ratios. Thus, in Fig. 2, we show the prediction of the 90% most likely values of the ratios in all of our three setups. Before discussing the figure, it should be noted that, in all our figures, the small wiggles in the curves are the result of our MCMC approach and are not physically relevant. As for the effects of the NSI, we can see that with the nominal bounds of setup 2, the changes in the predicted flavor flux ratios are smaller (although they are of more or less the same size for the lower left region in the plot) than the uncertainty due to the spread of the standard neutrino oscillation parameters. In any case, the change is mostly in $R_{\mu\tau}$ ratio, which would require the identification of taus at a neutrino telescope, while the ratio R, essentially sensitive to the relative muon track versus shower frequencies, is basically unaffected by the new physics. The large change happens in setup 3, where the allowance of a large $\varepsilon^{ud}_{\tau\tau}$ results in a different tau interaction probability. Since the tau flux is involved in both of the ratios, significant

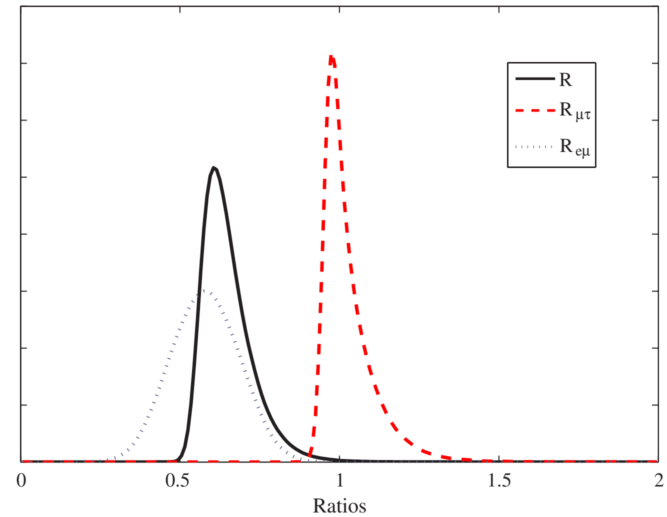

FIG. 1 (color online). Posterior distributions of the flux ratios R, $R_{\mu\tau}$, and $R_{e\mu}$, as computed in the standard model for a muon-damped pion source.

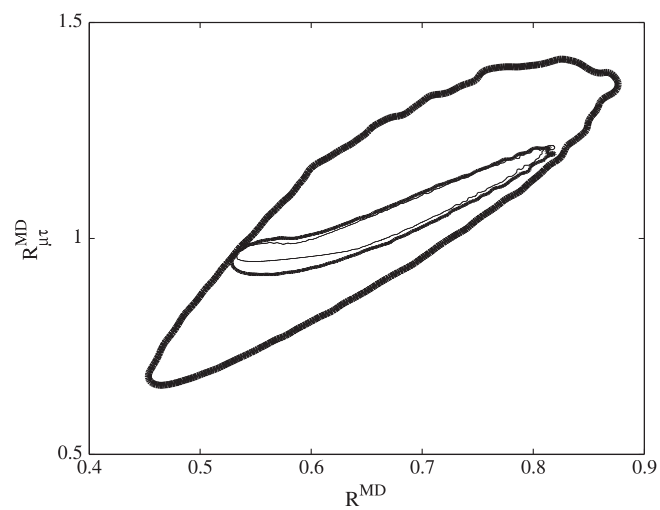

FIG. 2. The 90% likelihood regions for the flavor flux ratios of a muon-damped pion source in our setups 1 (thin), 2 (medium), and 3 (thick).

deviations from setup 1 can be obtained in either, although the $R_{\mu\tau}$ is still more affected due to the fact that the loss or gain in taus can be compared only to the tau flux as opposed to the sum of the tau and electron fluxes. In fact, the largest deviations from the standard setup could be visible at neutrino telescopes with a resolution to the flavor flux ratio R of about 15%. In order to put this number into context, it is necessary to briefly review the expected uncertainties in the flavor flux ratio. Clearly, the statistical uncertainty depends on the number of events collected. Since the flux of high-energy astrophysical neutrinos has not yet been measured, the number of expected events is essentially unknown. For a neutrino flux at the Waxman-Bahcall bound [55], the expected uncertainty in R after 1 yr of data taking at IceCube is about 20% [56]. A study of the expected uncertainty given the number of events rather than the actual flux [57] (see, in particular, Table I of this reference), but including also some systematics such as background normalization, results in numbers ranging from complete uncertainty in the worst cases to an uncertainty of the order 5% in the best cases studied (these are assuming negligible backgrounds and 500 muon tracks).

B. Neutronlike sources

In the case when the source of the astrophysical neutrino flux is NL (i.e., essentially a beta decay), then the considerations corresponding to those made for the muon-damped pion sources result in the flavor flux ratios

$$R_{e\mu} = \tfrac{5}{2}, \qquad R_{\mu\tau} = 1, \quad \text{and} \quad R = \tfrac{2}{7} \qquad (20)$$

in the case of tribimaximal mixing. Figure 3 shows the predictions of the 90% most likely results in the $R_{\mu\tau} - R$ plane for a neutronlike source for our different setups. In this scenario, we can see that the spreads of the flavor flux ratios are already quite large in the standard setup. This is mainly related to the neutrino production. The difference to the muon-damped pion source is mainly that the mixing angle involved (θ_{12}) is not close to maximal, which means that even small deviations from the central value can have a significant effect. Since the extensions of the allowed regions when introducing NSI are more or less of the same size as in the muon-damped scenario, the relative impact is much smaller in this scenario and are clearly not measurable.

C. Non-muon-damped pion sources

As discussed in Sec. II, when a pion source is not muon-damped, there will essentially be two different sources of neutrinos—the pion decay and the subsequent decay of the muon. Since the NSI involved in the two different processes do not depend upon the same εs, the effective parameter space is increased quite dramatically, even compared to the previously considered NSI scenarios. For this type of source, the prediction of tribimaximal lepton mixing is given by

$$R_{e\mu} = 1, \qquad R_{\mu\tau} = 1, \quad \text{and} \quad R = \tfrac{1}{2}, \qquad (21)$$

simply due to the fact that the flavor fluxes are predicted to be equal.

In Fig. 4, we show the 90% likelihood regions of all our setups. In this scenario, the fluxes are predicted to be $\phi_e{:}\phi_\mu{:}\phi_\tau \propto 1{:}1{:}1$ at tribimaximal mixing and, as can be seen from the figure, this prediction is very robust to changes in the standard parameters. Thus, already the effects of the more constrained NSI of setup 2 significantly broadens the regions of the 90% likelihood regions for the flavor flux ratios. However, since the absolute broadening is still quite small, it is most likely out of reach for any neutrino telescope. Again, this changes significantly when

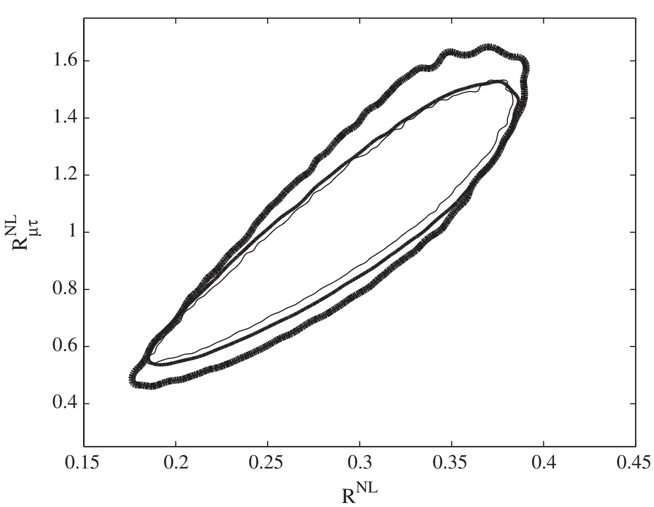

FIG. 3. The 90% likelihood regions for the flavor flux ratios of a neutronlike source in our setups 1 (thin), 2 (medium), and 3 (thick).

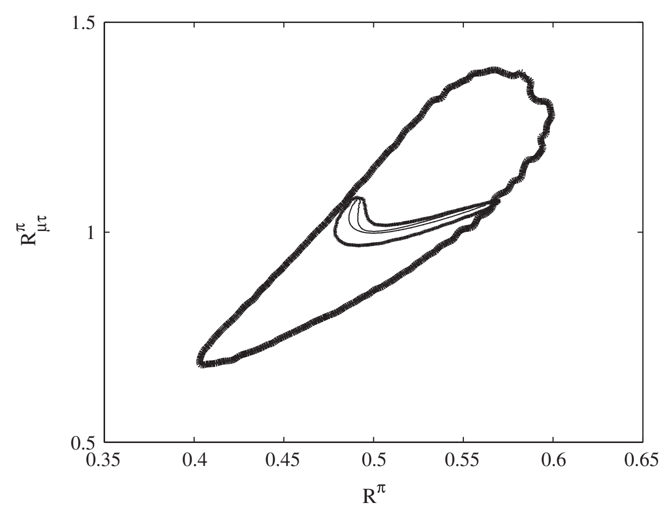

FIG. 4. The 90% likelihood regions for the flavor flux rations of a pion (π) source in our setups 1 (thin), 2 (medium), and 3 (thick).

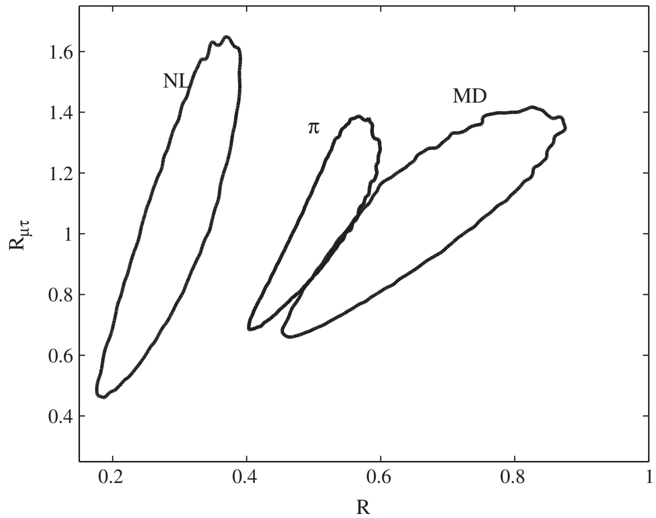

FIG. 5. The 90% likelihood regions in the $R - R_{\mu\tau}$ plane in setup 3 for the sources we have discussed.

allowing the large values of $\varepsilon^{ud}_{\tau\tau}$. The values of $R \simeq 0.4$ could be distinguished from the allowed standard region with a resolution in R, which is just slightly better than 20%. According to [57], this precision could be reached assuming $\mathcal{O}(250)$ muon tracks, even including some sources of systematic uncertainties and backgrounds.

D. Comparison of scenarios

An important aspect in the study of astrophysical neutrino fluxes is what we could learn about the source from studying the flavor composition of the flux (i.e., what type of source that is providing the flux). Thus, in Fig. 5, we show the 90% likelihood regions for all of the source types discussed above for the worst-case scenario of setup 3. As can be seen in this figure, even in this worst-case scenario, the pion sources could be relatively well separated from the neutronlike sources simply by a relatively precise measurement of R. It may be slightly more difficult to tell the muon damped from the non-muon-damped pion source and clearly there may also be sources where the muon damping is present but not complete, so that only a fraction of the muons are stopped before decaying. Furthermore, the ratio $R_{\mu\tau}$ is practically useless for this type of consideration due to θ_{23} being close to maximal. Essentially, it is the flux of electron neutrinos relative to the other neutrino flavors that changes from source to source. This also means that the source determination is more or less unaffected by the introduction of NSI, which could mainly alter the tau flux.

IV. SUMMARY AND CONCLUSIONS

In this paper we analyzed the impact of new physics effects in the production and detection of astrophysical neutrinos. Detection processes were considered independent of the source producing neutrinos and the possible new physics effects were parametrized in terms of the matrix $\varepsilon^{ud}_{\alpha\beta}$, which alters the charged-current reaction $\nu + X \rightarrow Y + \ell_\alpha$ involving leptons and hadrons. The same matrix also intervenes in the production of neutrinos from muon-damped pion sources (in which neutrinos coming from subsequent muon decays do not contribute to the measurable neutrino flux on Earth) and from neutronlike sources. If muon decays also play a role in the production of neutrinos (as in the case of the "standard" pion sources), then a new set of parameters $\varepsilon^{\mu e}_{\alpha\beta}$ should be introduced to take the purely leptonic process into account. Since the fluxes of astrophysical neutrinos can be measured at neutrino telescopes, we have considered the experimentally accessible flux ratios $R_{\mu\tau} = \phi_\mu/\phi_\tau$ and $R = \phi_\mu/(\phi_e + \phi_\tau)$, in order to investigate the effects of the new parameters. This was done through Markov chain Monte Carlo sampling of the parameter space in order to see what flavor flux ratios could be allowed in different setups. For the priors, we assumed tribimaximal mixing as central values for the standard neutrino oscillation parameters. Making this analysis in the standard model first and then including the NSI gave us insight of how new physics can affect the possible ranges of these observables. Our results can be summarized in the simplified scenario, where only one source at a time is responsible for the neutrino flux on Earth. In particular, for muon-damped sources, we found that with NSI, the measured flux may be slightly altered when considering our setup 2 with the more optimistic bound on $\varepsilon^{ud}_{\tau\tau}$. For the more pessimistic bound in setup 3, this alteration can be even larger. However, in either case it would be extremely difficult to measure the flavor flux ratios with enough precision to distinguish the NSI scenarios from the standard one.

For neutronlike sources the extension of the allowed regions when allowing for NSI effects are small in comparison to the uncertainties introduced already by the standard parameters. Thus, in this scenario, the effect of NSI are small in comparison to both the expected experimental resolution as well as the effect of uncertainties in the standard parameters. This scenario is therefore the scenario that is least sensitive to NSI. In contrast, the non-muon-damped pion source is the case where the uncertainties in the standard parameters have the least impact on the flavor flux ratios. Therefore, this type of source is the one most susceptible to NSI effects.

Finally, we have seen that the introduction of NSI does not significantly alter the prospects of determining the source type from the flavor flux ratios. This is due to the NSI mainly affecting the measured tau flux, while the determination of the source type is more dependent on the measured flux of electron neutrinos.

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