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Non-Standard Interactions with High-energy Atmospheric Neutrinos at IceCube

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Non-standard neutrino interactions affect the propagation of atmospheric neutrinos through the Earth. While most previous analyses have focused on relatively low-energy, $\mathscr{O}$(10 GeV), atmospheric neutrino data, we consider instead the one-year high-energy (> 100 GeV) through-going muon sample in IceCube to set limits on new interactions in the $\mu\tau$-sector. Taking into account several sources of systematic errors, we obtain the bound $-6.0\times10^{-3} < \varepsilon_{\mu\tau} < 5.4\times10^{-3}$ at 90% credible interval. We also provide a forecast of the future sensitivity to $\varepsilon_{\mu\tau}$ by simulating 10 years of high-energy neutrino data in IceCube, and we find that if it is close to its current limit, IceCube high-energy atmospheric neutrino data can determine its value at high confidence.

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1. Introduction

Neutrino oscillation experiments have established that neutrinos are massive, providing certain evidence for physics beyond the Standard Model (SM). The new physics scale is largely unknown, however if sufficiently low, the particles involved in neutrino mass generation could have an impact in neutrino oscillations. For instance, in the inverse seesaw scenario there could be sizable deviations from unitarity of the leptonic mixing matrix, and in radiative neutrino mass models new particles with mass at the TeV scale could induce non-standard interactions (NSI) of the neutrinos with leptons and/or quarks. The relative size of NSI with respect to standard neutrino oscillations depends on the neutrino energy: at low (< GeV) energies, the NSI terms are sub-dominant with respect to standard (vacuum) neutrino oscillations, at intermediate energies, $\mathscr{O}(1-10)$ GeV, NSI are comparable with the standard matter potential and vacuum oscillation terms, and at higher energies NSI effects may dominate, since the standard neutrino oscillation phase is inversely proportional to the neutrino energy. In the presence of NSI, oscillations are not suppressed with energy and they only depend on the baseline. As a consequence, atmospheric neutrinos provide an ideal tool to test NSI, as their spectrum covers a huge energy range ($\sim$ 1 GeV - 100 TeV) and they may travel distances across the Earth from tens to several thousands kilometers, depending on the zenith angle.

In this talk, after a brief review of NSI theory and phenomenology, we analyze the potential of the high energy ($>$ 100 GeV) atmospheric neutrino data at IceCube to set constraints on NSI in the $\nu_\mu - \nu_\tau$ sector (see [1] for further details of the analysis).

2. NSI: theory

For recent reviews about NSI, and a complete list of references (missing in this proceedings for lack of space), see, e.g., [2, 3, 4] and the talk by T. Ota in this conference [5], which contains a thorough update of phenomenology and model building of NSI, both for heavy and light mediators.

At energy scales well below the new physics generating the neutrino NSI, these can be parametrized via model-independent, effective four-fermion operators, which for the neutral current (NC) or matter case read [1].

$$\mathscr{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}\,G_F\,\varepsilon_{\alpha\beta}^{fP}\,(\bar{\nu}_\alpha\gamma_\rho L\nu_\beta)(\bar{f}\gamma^\rho Pf)\ , \tag{2.1}$$

where $\varepsilon_{\alpha\beta}^{fP}$ are the NC NSI parameters (by hermiticity $\varepsilon_{\alpha\beta}^{fP} = (\varepsilon_{\beta\alpha}^{fP})^*$), $P = \{L,R\}$ (with L and R the left and right chirality projectors) and f is any SM fermion.

If the contact interactions in eq. (2.1) are generated by mass dimension-six operators in $SU(2)\times U(1)_Y$ gauge invariant models of new physics at high energies, generically they appear with a charged lepton counter part with a coefficient of the same order. Charged lepton physics imposes tight constraints on these coefficients, rendering neutrino NSI unobservable. There are only two UV completions (at tree level) in which neutrino NC NSI can be induced by dimension six operators without the charged-lepton counterpart, and without fine-tuned ad-hoc cancellations: one

[1] Model-independent bounds on charged current (CC) NSI, that affect neutrino's production and detection, are generally one order of magnitude stronger than NC ones, which mainly modify neutrino propagation; thus we neglect CC NSI in the following.

$SU(2)$ singlet scalar with $Y = 1$ and non-canonical neutrino kinetic terms due to mixing with heavy SM singlet fermions which are integrated out. In this last case, after diagonalizing and normalizing the neutrino kinetic terms, a non-unitary lepton mixing matrix is generated that leads to NC NSI just for neutrinos. However, a detailed study of this class of scenarios shows that the constraints on the NC NSI turn out to be even stronger than the ones for operators which also produce interactions of four charged fermions at the same level: typically $\varepsilon_{\alpha\beta}^{fP} < \mathcal{O}(10^{-3})$, too small to be observable in current neutrino oscillation experiments. The only exception is the case of non-unitarity effects produced by mixing with sterile neutrinos in the keV range [6], which allows for NC NSI parameters of $\mathcal{O}(10^{-2})$.

In principle, gauge invariant operators of dimension eight or larger can generate the four fermion interactions of eq. (2.1) at tree level without any charged lepton counterpart, leading to sizable neutrino NC NSI. In practice, constructing ($SU(2) \times U(1)_Y$ gauge-invariant) UV completions that generate dimension 8 operators but no dimension 6 ones requires a considerable fine-tuning [7], although they cannot be completely excluded.

Recently, it has been considered the possibility of generating the NC NSI in models based on a new $U(1)'$ gauge interaction with a light gauge boson mass $\sim$ 10 MeV. Since for neutrino propagation only forward scattering is relevant, the effective coupling in eq. (2.1) can be used for neutrino oscillations at energies much higher than the mediator mass, while in scattering experiments such as NuTeV the effects are strongly suppressed, allowing to satisfy current bounds while having potentially sizable NC NSI [4].

3. Phenomenology of NSI

In the presence of NC NSI, neutrino propagation in matter is described by the effective Hamiltonian

$$H(E_\nu, x) = \frac{1}{2E_\nu} U M^2 U^\dagger + \mathrm{diag}(V_e, 0, 0) + \sum_f V_f\, \varepsilon^{fV} , \tag{3.1}$$

where U is the PMNS mixing matrix, $M^2 = \mathrm{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2)$, with $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ the neutrino mass square differences and $V_f(x) = \sqrt{2}\, G_F\, n_f(x)$, with $n_f(x)$ the number density of fermion f. NSI generate the last term of Eq. (3.1), where ε^{fV} is the matrix in lepton flavor space that contains the vector combination of the NSI chiral parameters, $\varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}^{fR} + \varepsilon_{\alpha\beta}^{fL}$. For antineutrinos, the matter potentials change sign, $V_f \to -V_f$, and $U \to U^*$. It is convenient to define effective NSI parameters for a given medium by normalizing the fermion number density, n_f, to the density of d-quarks, n_d,

$$\varepsilon_{\alpha\beta} \equiv \sum_f \frac{n_f}{n_d}\, \varepsilon_{\alpha\beta}^{fV} , \tag{3.2}$$

so that $\sum_f V_f \varepsilon^{fV} \equiv V_e\, r\, \varepsilon = V_d\, \varepsilon$, and $r = n_d/n_e$. For the Earth, $n_n \approx n_p$ and therefore, $r \approx 3$. Notice that oscillation experiments are only sensitive to the differences between the diagonal terms in the matter potential, e.g., $\varepsilon'_{\alpha\alpha} \equiv \varepsilon_{\alpha\alpha} - \varepsilon_{\mu\mu}$.

See [2, 3, 4] for current bounds on $\varepsilon_{\alpha\beta}^{fP}$ from neutrino oscillation and scattering data, which are rather weak for some of the NSI parameters. Remarkably, in addition to the standard LMA solution to solar neutrino data there is another solution called LMA-Dark which requires NSI with effective couplings $\varepsilon_{ee}^{qV} - \varepsilon_{\mu\mu}^{qV}$ as large as the SM ones, as well as a solar mixing angle in the second octant, and implies an ambiguity in the neutrino mass ordering [8, 9]. However it has been shown recently that the degeneracy between the two solutions can be lifted by a combined analysis of data from oscillation experiments with the neutrino scattering experiments CHARM and NuTeV, provided the neutrino NSI take place with down quarks, and the mediators are not much lighter than the electroweak scale [10]. For light mediators (but heavier than 50 MeV) a combined analysis of neutrino oscillation data and the number of events recently observed in the coherent neutrino-nucleus scattering experiment COHERENT has excluded the LMA-Dark solution at the 3σ level and has improved current bounds on flavour diagonal vector interactions of ν_τ by one order of magnitude (for NSI with up and down quarks) [11].

Off-diagonal NSI $\varepsilon_{e\tau}^{qV} \sim \mathscr{O}(0.1)$ is also slightly favoured, due to mild tension between the Δm^2_{12} determination by solar neutrino data and KamLAND within the standard neutrino oscillation scenario; such NSI can be tested by atmospheric neutrinos at Hyper-Kamiokande (talk by O. Yasuda in this conference and [12]).

Notice that many atmospheric neutrino's NSI analysis restrict to the $\nu_\mu - \nu_\tau$ sector, however allowing for all non-vanishing $\varepsilon_{\alpha\beta}$ in the $\nu_e - \nu_\tau$ sector leads to a matter potential that mimics vacuum oscillations $\nu_\mu \to \nu_{\tau'}$ with the same E_ν dependence, but modified mixing and mass differences, along the parabola $\varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$ [13]. As a consequence, $\mathscr{O}(1)$ values of $\varepsilon_{\tau\tau}, \varepsilon_{e\tau}$ are possible in this region. We disregard this somehow fine-tuned possibility and consider only the effect of $\nu_\mu - \nu_\tau$ NSI in the high energy atmospheric neutrino sample at IceCube.

4. NSI with HE Atmospheric Neutrinos at IceCube

The standard evolution Hamiltonian for neutrinos in a medium includes the coherent forward scattering on fermions of the type f, $\nu_\alpha + f \to \nu_\beta + f$, given by the matter interaction potential in Eq. (3.1), which affects neutrino oscillations. Since the neutrino-nucleon cross section increases with energy, for neutrinos with energies above ~TeV both oscillation and attenuation effects occur simultaneously when they travel across the Earth, and the evolution equations should include them (ν_τ regeneration can be safely neglected). Therefore, we have used the density matrix formalism to describe the neutrino propagation though the Earth, including SM NC and CC inelastic scattering. We have solved numerically the full three-neutrino evolution equation by employing the publicly available libraries SQuIDS and ν-SQuIDS. In Fig. 1 we show the effect of attenuation and NSI for both, neutrinos and antineutrinos. Notice that al low energies, the effect of NSI and attenuation is different for neutrinos and antineutrinos, while at high energies both ratios coincide (right panel).

In order to understand this behaviour, it is illustrative to study analytically the oscillation probabilities for two neutrinos in the approximation of constant matter density and neglecting inelastic scattering. When vacuum and matter NSI terms are of the same order of magnitude ($\Delta m^2_{31}/2E_\nu \sim V_{\rm NSI}$, with $V_{\rm NSI} = V_d\sqrt{4\varepsilon^2_{\mu\tau} + \varepsilon'^2}$), the transition probability after propagating a distance L reads

$$P(\nu_\mu \to \nu_\tau) \simeq \left(\sin 2\theta_{23}\,\frac{\Delta m^2_{31}}{2E_\nu} + 2V_d\,\varepsilon_{\mu\tau}\right)^2 \left(\frac{L}{2}\right)^2 , \qquad (4.1)$$

while the NSI matter term has opposite sign for antineutrinos. However in the high-energy limit the matter NSI term dominates over vacuum oscillations, and for $V_{\rm NSI}/L \ll 1$ the two-neutrino

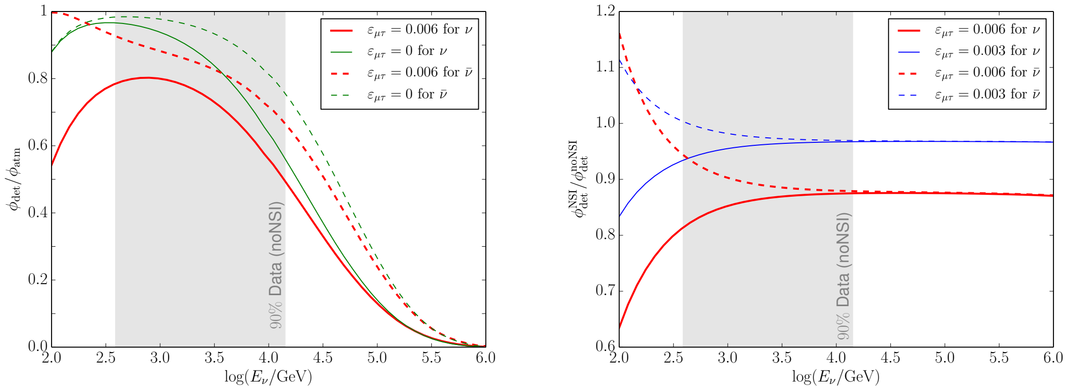

Figure 1: *Left panel:* Comparison of the ratios of propagated to unpropagated atmospheric ν_μ (solid lines) and $\bar{\nu}_\mu$ (dashed lines) fluxes for $\varepsilon_{\mu\tau} = 0.006$ (thick red lines) and $\varepsilon_{\mu\tau} = 0$ (thin green lines). *Right panel:* Comparison of the ratios of atmospheric ν_μ and $\bar{\nu}_\mu$ fluxes at the detector (after propagation) with NSI to those without NSI, for two values of $\varepsilon_{\mu\tau}$. In both panels, $\cos\theta_z = -1$ and $\varepsilon' = 0$. The gray area corresponds to the energy interval that produced 90% of the events in the entire sample considered here in the absence of NSI effects.

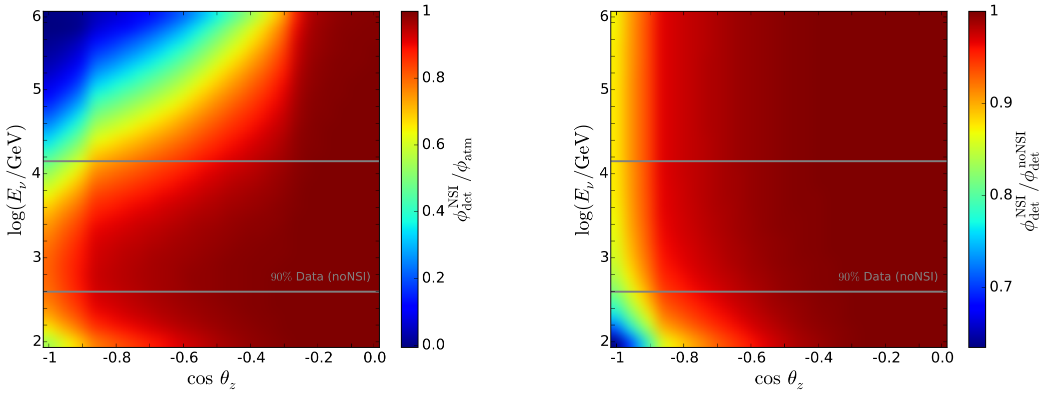

Figure 2: *Left panel:* Ratio of propagated to unpropagated atmospheric ν_μ fluxes as a function of the neutrino energy and the zenith angle. *Right panel:* Ratio of atmospheric ν_μ fluxes at the detector (after propagation) with NSI to those without NSI. In both panels the NSI off-diagonal parameter $\varepsilon_{\mu\tau} = 0.006$ and the diagonal parameter to be $\varepsilon' = 0$. The two gray lines bound the energy interval in which 90% of the events in the entire sample (assuming no NSI) are produced.

transition probability is approximately given by

$$P(\nu_\mu \to \nu_\tau) \simeq \left(\sin^2 2\xi\right) \phi_{\rm mat}^2 = (\varepsilon_{\mu\tau} V_d L)^2 \,, \tag{4.2}$$

which is proportional to $\varepsilon_{\mu\tau}^2$ and becomes independent of ε'. As a consequence, the high-energy IceCube atmospheric neutrino data cannot significantly constrain the diagonal NSI parameter ε', so in our analysis we use a prior on ε' based on SK limits [14], which were obtained from data at lower energies: $|\varepsilon'| = |\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}| < 0.049$ at 90% confidence level (C.L.). From these results, we set the 1σ C.L. prior on ε' to $\sigma_{\varepsilon'} = 0.040$.

In our analysis we consider the one-year upgoing muon sample [15], referred to as IC86 (IceCube 86-string configuration), which contains 20145 muons, and we use the public IceCube Monte Carlo[2] that models the detector realistically and allows us to relate physical quantities, as the neutrino energy and direction, to observables, as the reconstructed muon energy and zenith angle.

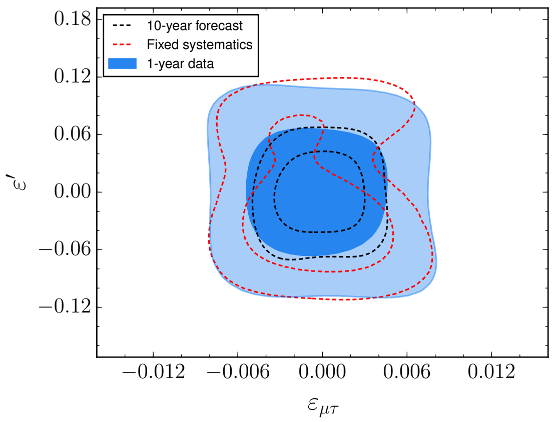

Figure 3: Comparison of the 68% and 95% credible contours in the $\varepsilon_{\mu\tau} - \varepsilon'$ plane for our default analysis (filled blue regions) with those obtained when all nuisance parameters are fixed at their default values (red closed curves). Black closed curves show the result expected in the case of no NSI after 10 years of data taking.

To evaluate the impact of possible systematic uncertainties, we have included the following nuisance parameters: normalization of the atmospheric neutrino flux, N, pion-to-kaon ratio in the atmospheric neutrino flux, π/K, spectral index of the atmospheric neutrino spectrum, $\Delta\gamma$, uncertainties in the efficiency of the digital optical modules of the detector, $\mathrm{DOM_{eff}}$ and current uncertainties in Δm^2_{31} and θ_{23}. In addition, we have considered several combinations of primary cosmic-ray flux and hadronic interaction models, being our default choice the Honda-Gaisser model and Gaisser-Hillas H3a correction (HG-GH-H3a) for the primary cosmic-ray flux and the QGSJET-II-4 hadronic model.

We have obtained that the current limits on the off-diagonal NSI parameter $\varepsilon_{\mu\tau}$ are robust with respect to all the continuous nuisance parameters we consider, being the main source of systematic uncertainties the choice of the combination of primary cosmic-ray and hadronic interaction models. For our default combination of models, we find

$$-6.0\times 10^{-3} < \varepsilon_{\mu\tau} < 5.4\times 10^{-3}\,, \qquad \text{90\% credible interval (C.I.),} \tag{4.3}$$

and similar results from all the other possible combinations. Our bound is comparable to the one obtained in ref. [16], from a combined fit of $\varepsilon_{\mu\tau}$ and ε' using 79-string IceCube configuration and DeepCore data, although they do not include nuisance parameters in their analysis: $-6.1\times 10^{-3} < \varepsilon_{\mu\tau} < 5.6\times 10^{-3}$ at 90% C.L. (after marginalizing with respect to ε'), and is slightly more stringent than the bound derived by the IceCube Collaboration using only DeepCore atmospheric neutrinos of lower energies [17]: $-6.7\times 10^{-3} < \varepsilon_{\mu\tau} < 8.1\times 10^{-3}$ at 90% C.L. (with $\varepsilon' = 0$).

[2]https://icecube.wisc.edu/science/data/IC86-sterile-neutrino

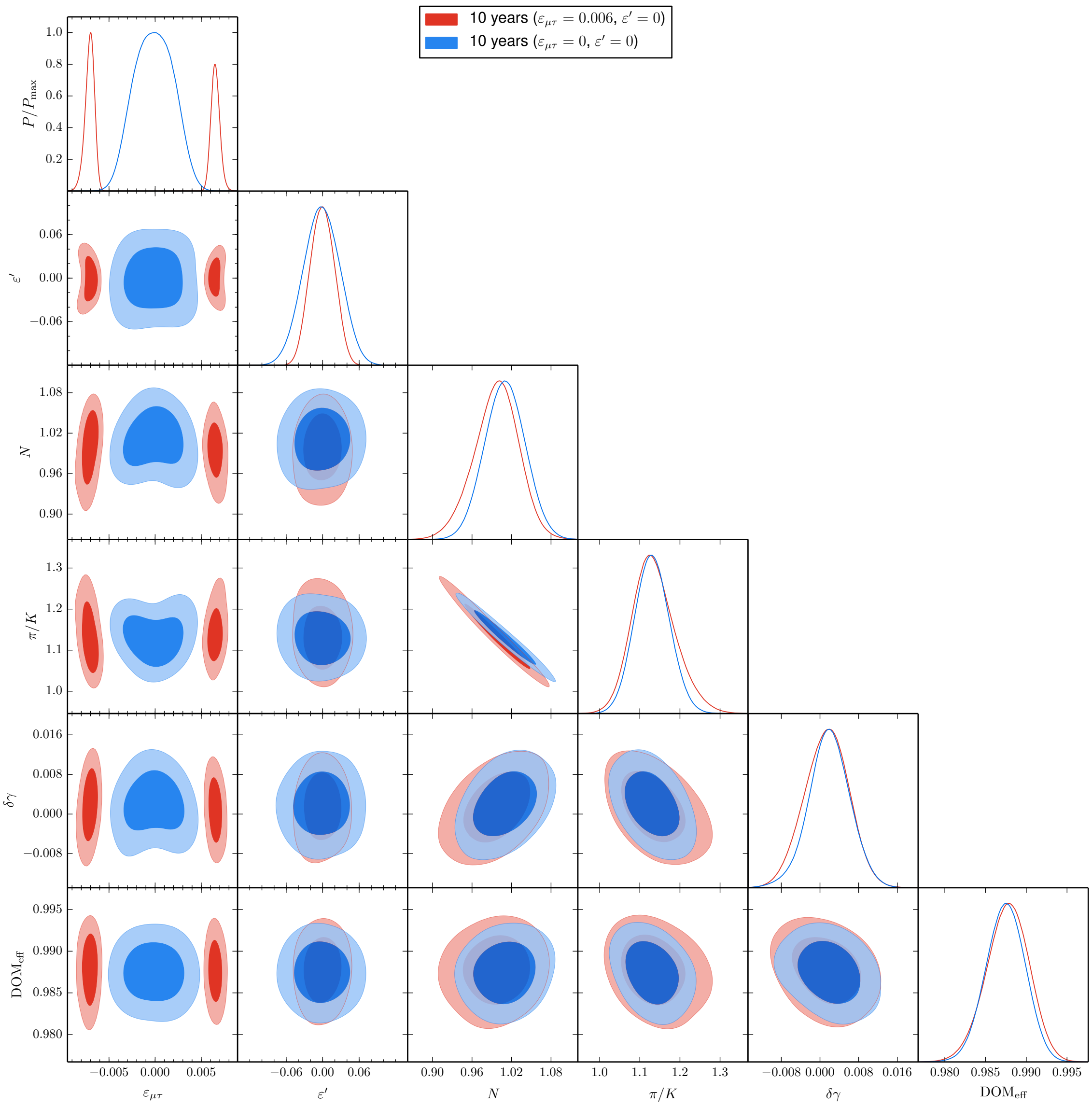

Figure 4: Posterior (68% and 95%) probability contours for two 10-year forecasts of high-energy atmospheric neutrino data in IceCube. Blue contours correspond to data generated without NSI and red contours to data including NSI with $\varepsilon_{\mu\tau} = 0.006$ and $\varepsilon' = 0$. On the right, we show the one-dimensional probability distribution of the parameter on the bottom. The atmospheric neutrino parameters Δm^2_{31} and θ_{23} are fixed to their current best fit values.

We have also performed a forecast of the future sensitivity to NSI by simulating 10 years of high-energy neutrino data in IceCube, for our default combination of primary cosmic-ray and hadronic interaction models (HG-GH-H3a + QGSJET-II-4), using the same priors on all nuisance parameters, except Δm^2_{31} and θ_{23} which we fix to their best fit values. We have simulated two sets of data: one assuming that NSI are not realized in Nature and a second one with $\varepsilon_{\mu\tau} = 0.006$, allowed by current data with 90% probability. Then, we find that after 10 years the constrain will improve to $-3.3\times10^{-3} < \varepsilon_{\mu\tau} < 3.0\times10^{-3}$ at 90% C.I. in the case without NSI, while if large NSI near current limits do exist, IceCube high-energy atmospheric neutrino data can establish its presence at high confidence (see Fig. 4).

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