

Zee-Burst: A New Probe of Neutrino Nonstandard Interactions at IceCubeK. S. Babu¹, P. S. Bhupal Dev², Sudip Jana¹, and Yicong Sui²¹*Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078, USA*²*Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri 63130, USA*

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We propose a new way to probe nonstandard interactions (NSI) of neutrinos with matter using the ultrahigh energy (UHE) neutrino data at current and future neutrino telescopes. We consider the Zee model of radiative neutrino mass generation as a prototype, which allows two charged scalars—one $SU(2)_L$ doublet and one singlet, both being leptophilic, to be as light as 100 GeV, thereby inducing potentially observable NSI with electrons. We show that these light charged Zee scalars could give rise to a Glashow-like resonance feature in the UHE neutrino event spectrum at the IceCube neutrino observatory and its high-energy upgrade IceCube-Gen2, which can probe a sizable fraction of the allowed NSI parameter space.

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Introduction.—The observation of ultrahigh energy (UHE) neutrinos at the IceCube neutrino observatory [1–6] has commenced a new era in neutrino astrophysics. Understanding all aspects of these UHE neutrino events, including their sources, energy flux, flavor composition, propagation, and detection, is of paramount importance to both astrophysics and particle physics communities [7,8]. A simple, single-component unbroken power-law flux $\Phi(E_\nu) = \Phi_0(E_\nu/100 \text{ TeV})^{-\gamma}$ gives a reasonably good fit to the high-energy starting event (HESE) component of the IceCube data, with the latest best-fit values of $\Phi_0 = (6.45_{-0.46}^{+1.46}) \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and $\gamma = 2.89_{-0.19}^{+0.20}$ at 1σ significance [9]. Any anomalous features in the observed event spectrum could potentially be used as a probe of fundamental physics. One such anomalous feature could be in the form of a new resonance. The purpose of this Letter is to show that such a new resonance can arise naturally in the popular Zee model of radiative neutrino masses [10,11], which contains two charged scalars. We refer to this Zee-scalar resonance as the “Zee-burst.”

Within the SM, the only resonance IceCube is sensitive to is the Glashow resonance [12], where electron antineutrinos hitting the target electrons in ice could produce an on-shell W boson: $\bar{\nu}_e e^- \rightarrow W^- \rightarrow \text{anything}$. The energy of the incoming neutrino required to make this resonance happen is fixed at $E_\nu = m_W^2/2m_e = 6.3 \text{ PeV}$. One candidate Glashow event was identified in a partially contained PeV event (PEPE) search with deposited energy of

$5.9 \pm 0.18 \text{ PeV}$ [5,13], but has not been included in the event spectrum yet [6]. The nonobservation of Glashow events might be still consistent with the SM expectations within the error bars, given the uncertainty in the source type (pp versus $p\gamma$), as well as $(\nu_e, \nu_\mu, \nu_\tau)$ flavor composition (1:2:0 vs 0:1:0) [14–18]. On the other hand, the possibility of observing a Z -boson resonance (Z burst) at IceCube due to UHE antineutrinos interacting with nonrelativistic relic neutrinos [19] is bleak, as the required incoming neutrino energy in this case turns out to be $E_\nu = m_Z^2/2m_\nu \gtrsim 10^{23} \text{ eV}$, well beyond the Greisen-Zatsepin-Kuzmin cutoff energy of $\sim 5 \times 10^{19} \text{ eV}$ for the UHE cosmic rays [20,21]—the most likely progenitors of the UHE neutrinos (for related discussion, see Ref. [22]). An interesting alternative is the existence of secret neutrino interactions with a light (MeV scale) Z' [23–26] or light neutrinophilic neutral scalar [27–29], in which case the resonance could again fall in the multi-TeV to PeV range which will be accessible at IceCube. Heavy (TeV-scale) resonances induced by neutrino-nucleon interactions mediated by exotic charged particles, such as leptoquarks [30–33], or squarks in R -parity violating supersymmetry [34–37], have also been discussed. In this Letter, we propose the possibility of *light* charged scalar resonances at IceCube, which are intimately related to neutrino mass generation [10], as well as observable nonstandard interactions (NSI) [38] (for a recent update, see Ref. [39]).

As a prototypical example, we take the Zee model [10]—one of the most popular radiative neutrino mass models, which contains an $SU(2)_L$ -singlet charged scalar η^\pm and an $SU(2)_L$ -doublet scalar H_2 , in addition to the SM-like Higgs doublet H_1 . The original version of the Zee model [10] is fully consistent with neutrino oscillation data [40] (for explicit neutrino mass fits, see Ref. [11]), although the Wolfenstein version of the model [41], which assumes a Z_2

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symmetry, thus making the diagonal entries of the neutrino mass matrix vanishing, is excluded by oscillation data [42,43]. Furthermore, it was pointed out in Ref. [11] that both the singlet and doublet charged scalar components can be as light as ~ 100 GeV, while satisfying all existing theoretical and experimental constraints in both charged and neutral scalar sectors. More interestingly, such light charged scalars can lead to sizable diagonal NSI of neutrinos with electrons, with the maximum allowed values of the NSI parameters $(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (8\%, 3.8\%, 43\%)$. We show here that the possibility of having a resonance feature with these light charged Zee scalars (Zee burst) provides a new probe of NSI at high-energy IceCube, complementary to the low-energy neutrino oscillation and scattering experiments.

Light charged scalars in the Zee model.—In the Higgs basis [44], only the neutral component of H_1 gets a vacuum expectation value $\langle H_1^0 \rangle = v \simeq 246.2$ GeV, while H_2 is parametrized as $H_2 = [H_2^+, (H_2^0 + iA^0)/\sqrt{2}]$. The charged scalars $\{H_2^+, \eta^+\}$ mix in the physical basis to give rise to the physical charged scalar mass eigenstates

$$\begin{aligned} h^+ &= \cos\varphi\eta^+ + \sin\varphi H_2^+, \\ H^+ &= -\sin\varphi\eta^+ + \cos\varphi H_2^+, \end{aligned} \quad (1)$$

with the mixing angle φ given by

$$\sin 2\varphi = \frac{-\sqrt{2}v\mu}{m_{H^+}^2 - m_{h^+}^2}, \quad (2)$$

where μ is the dimensionful coefficient of the cubic term $\mu H_1^i H_2^j \epsilon_{ij} \eta^-$ in the scalar potential, with $\{i, j\}$ being the $SU(2)_L$ indices and ϵ_{ij} being the $SU(2)_L$ antisymmetric tensor.

The leptonic Yukawa couplings are given by the Lagrangian

$$\begin{aligned} -\mathcal{L}_Y \supset & f_{\alpha\beta} L_\alpha^i L_\beta^j \epsilon_{ij} \eta^+ + \tilde{Y}_{\alpha\beta} \tilde{H}_1^i L_\alpha^j \ell_\beta^c \epsilon_{ij} \\ & + Y_{\alpha\beta} \tilde{H}_2^i L_\alpha^j \ell_\beta^c \epsilon_{ij} + \text{H.c.}, \end{aligned} \quad (3)$$

where $\{\alpha, \beta\}$ are flavor indices, ℓ^c denotes the left-handed antilepton fields, and $\tilde{H}_a = i\tau_2 H_a^*$ ($a = 1, 2$) with τ_2 being the second Pauli matrix. The neutrino mass is generated at the one-loop level and is given by

$$M_\nu = \kappa(fM_\ell Y + Y^T M_\ell f^T), \quad (4)$$

where $M_\ell = \tilde{Y}v/\sqrt{2}$ is the charged lepton mass matrix and κ is a one-loop factor given by

$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log\left(\frac{m_{h^+}^2}{m_{H^+}^2}\right). \quad (5)$$

According to Eq. (4), the product of the Yukawa couplings f and Y is constrained by the neutrino oscillation data, which allow for only one of these couplings to be of order one. We will adopt the choice $Y \sim \mathcal{O}(1)$ and $f \ll 1$, which maximizes the neutrino NSI in the model [11].

For the IceCube phenomenology, we are specifically interested in the light charged scalar scenario. This is confronted with several theoretical and experimental constraints, such as charge breaking minima, electroweak precision tests, charged lepton flavor violation (cLFV), collider constraints from LEP and LHC, lepton universality tests, and monophoton constraints. It was shown [11] that both h^+ and H^+ charged scalars can be as light as 100 GeV, while satisfying all these constraints. The main constraints for light charged scalars come from direct searches at LEP, which are applicable as long as $Y_{\alpha e} \neq 0$ for any flavor α . More stringent limits from lepton universality tests in W decays [45] will apply if $Y_{ee} \neq 0$, restricting the charged scalar masses to above 130 GeV [11]. In what follows, we will consider the scenario where $Y_{\tau e} \neq 0$ and $Y_{\alpha\tau} \neq 0$ for $\alpha = e$ or μ , which satisfies all constraints for $m_{h^+} = 100$ GeV, and at the same time, allows for the largest NSI effect.

Signature at IceCube.—Expanding the last term in Eq. (3), we get

$$\mathcal{L}_Y \supset Y_{\alpha\beta}(h^- \sin\varphi + H^- \cos\varphi)\nu_\alpha \ell_\beta^c + \text{H.c.} \quad (6)$$

For $\beta = e$, this will induce neutrino-electron interactions mediated by the charged scalars h^- and H^- . For $E_\nu = m_{h^-(H^-)}^2/2m_e$, this will lead to an $h^-(H^-)$ resonance (Zee-burst) at IceCube. There is no interference with the SM Glashow process (even for $\alpha = e$), because the Zee burst involves only right-handed electrons. Thus, depending on the mass spectrum of h^- and H^- , we would expect either one or two additional resonance peaks in the IceCube energy spectrum. We will consider two benchmark scenarios: (i) $m_{h^-} \approx m_{H^-}$, so that the two peaks are indistinguishable, i.e., contribute to the same energy bin, and (ii) $\Delta m_h \equiv m_{H^-} - m_{h^-} = 30$ GeV, so that the two peaks are distinguishable (i.e., their dominant contributions fall in different energy bins).

To estimate the modification to the event spectrum, we compute the number of events in a given energy bin i as

$$N_i = T \int d\Omega \int_{E_i^{\min}}^{E_i^{\max}} dE \sum_\alpha \Phi_{\nu_\alpha}(E) A_{\nu_\alpha}(E, \Omega). \quad (7)$$

Here, T is the exposure time for which we use $T_0 = 2653$ day, corresponding to 7.5 yr of live data taking at IceCube [6]; Ω is the solid angle of coverage and we integrate over the whole sky; E is the electromagnetic-equivalent deposited energy which is an approximately linear function of the incoming neutrino energy [46]; the limits of the energy integration E_i^{\min} and E_i^{\max} give the size of the i th deposited energy bin over which the expected number of events is

being calculated; $\Phi_{\nu_\alpha}(E)$ is the differential astrophysical neutrino + antineutrino flux for flavor α , for which we use a simple, single-component unbroken power law, isotropic flux $\Phi(E_\nu) = \Phi_0(E_\nu/E_0)^{-\gamma}$ with the IceCube best-fit values of $\Phi_0 = 6.45 \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and $\gamma = 2.89$ [9]; and A_{ν_α} is the effective area per energy per solid angle for the neutrino flavor ν_α , which includes the effective neutrino-matter cross section, number density of target nucleons or electrons and acceptance rates for the shower and track events. In the presence of new interactions as in Eq. (6), only the neutrino-electron cross section gets modified, which in turn affects the effective area. For the SM interactions only, we use the publicly available flavor-dependent effective area integrated over solid angle from Ref. [5] (for 2078 day of IceCube data), along with a 67% increase in the acceptance (for 2653 day of data) [47]. In the presence of non-SM interactions as in Eq. (6), we rescale the effective area accordingly by taking the ratio of the cross sections, assuming that the acceptance remains the same.

In the SM, neutrinos interact with nucleons via charged- and neutral-current processes. In the energy range of interest, the corresponding deep inelastic scattering cross sections can be approximated by [48]

$$\sigma_{\nu(\bar{\nu})N}^{\text{CC}} \approx 3\sigma_{\nu(\bar{\nu})N}^{\text{NC}} \simeq 2.7 \times 10^{-36} \text{ cm}^2 \left(\frac{E_\nu}{\text{GeV}}\right)^{0.4}. \quad (8)$$

In addition, there are subdominant antineutrino-electron interactions, except in the energy range of 4.6–7.6 PeV, when the $\bar{\nu}_e - e^-$ interaction becomes important due to the Glashow resonance [12]. In the vicinity of the resonance, the dominant piece of the cross section can be expressed by a Breit-Wigner distribution as [49]:

$$\sigma_{\text{Glashow}}(s) = 24\pi\Gamma_W^2 \text{BR}(W^- \rightarrow \bar{\nu}_e e^-) \text{BR}(W^- \rightarrow \text{had}) \times \frac{s/m_W^2}{(s - m_W^2)^2 + (m_W\Gamma_W)^2}, \quad (9)$$

where $s = 2m_e E_\nu$ and Γ_W is the total width of the W boson with $\text{BR}(W^- \rightarrow \bar{\nu}_e e^-) = 10.7\%$ and $\text{BR}(W^- \rightarrow \text{had}) = 67.4\%$ [50]. At resonance, Eq. (9) gives $\sigma_{\text{Glashow}}(E_\nu = 6.3 \text{ PeV}) = 3.4 \times 10^{-31} \text{ cm}^2$, about 240 times larger than $\sigma_{\nu(\bar{\nu})N}^{\text{CC}}(E_\nu = 6.3 \text{ PeV}) \approx 1.4 \times 10^{-33} \text{ cm}^2$. However, due to the narrowness of the resonance and the $E_\nu^{-\gamma}$ nature of the astrophysical neutrino flux, the ratio of the reconstructed events between the resonance-induced $\bar{\nu}_e - e^-$ and nonresonant $\nu(\bar{\nu}) - N$ interactions is not so pronounced in the event spectrum, as shown by the red-shaded histograms in Fig. 1. For instance, for $E_\nu > 4 \text{ PeV}$, $N_{\text{Res}}/N_{\text{non-Res}} \sim 2.05$ giving a total of about 0.3 events in the Glashow bin for the IceCube best-fit flux. Also shown in Fig. 1 (gray shaded) are the total expected atmospheric background (from atmospheric muons and neutrinos, as well as the charm

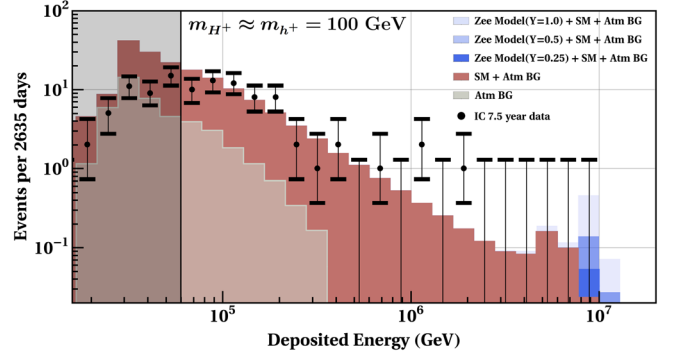


FIG. 1. Reconstructed event spectra for the expected atmospheric background (gray), SM best fit with a single-component astrophysical flux (red) and the Zee model with $m_{h^+} \approx m_{h^-} = 100 \text{ GeV}$, $\varphi = \pi/4$, and $Y_{\tau e} = 1, 0.5, 0.25$ (light, medium, and dark blue, respectively), all compared with the 7.5-yr IceCube data. The data points below 60 TeV (inside the vertical black-shaded band) are not included in the IceCube HESE analysis we are using here.

contribution) and the 7.5 yr IceCube data [9]. The vertical line at 60 TeV denotes the low-energy cutoff for the HESE analysis, i.e., the bins below this energy are not considered in the fitting process.

Now in the presence of light charged scalars, we expect a new resonance for $\bar{\nu}_\alpha e^- \rightarrow X^- \rightarrow \text{anything}$ (where $X^- = h^-, H^-$ for the Zee model) with a cross section similar to Eq (9):

$$\sigma_{\text{Zee}}(s) = 8\pi\Gamma_X^2 \text{BR}(X^- \rightarrow \bar{\nu}_\alpha e^-) \text{BR}(X^- \rightarrow \text{all}) \times \frac{s/m_X^2}{(s - m_X^2)^2 + (m_X\Gamma_X)^2}, \quad (10)$$

where $\Gamma_X = \sum_{\alpha\beta} |Y_{\alpha\beta}|^2 \sin^2 \varphi m_X / 16\pi$ is the total decay width of X . The factor of 1/3, compared to Eq. (9), is due to the difference in the degrees of polarization between scalar and vector bosons.

In Fig. 1, we consider a benchmark case with $m_{h^-} \approx m_{H^-} = 100 \text{ GeV}$, so that the two new resonances due to h^- and H^- coincide, and thus, maximize the effect in the bin containing the resonance energy $E_\nu = m_{h^-}^2 / 2m_e$, as shown by the light, medium, and dark blue shaded histograms corresponding to three illustrative values of $Y_{\tau e} = 1, 0.5, 0.25$, respectively. The excess events due to this new resonance mostly populate the energy bins between 7.6–12.9 PeV, distinguishable from those dominated by the Glashow resonance bin (4.6–7.6 PeV), and the effect is more pronounced for larger Yukawa couplings, as expected from Eq. (10). Here we have taken the maximal mixing $\varphi = \pi/4$ and $\text{BR}(h^- \rightarrow \bar{\nu}_\tau e) = 60\%$, $\text{BR}(h^- \rightarrow \bar{\nu}_\beta \tau) = 40\%$ (with $\beta = e$ or μ) for a fixed $Y_{\tau e}$ given above and accordingly chosen $Y_{\beta\tau}$, while all other Yukawa couplings $Y_{\alpha\beta}$ are taken to be much smaller than 1 to satisfy the cLFV constraints [11]. Note that as we increase the mass

difference $\Delta m_h \equiv m_{H^-} - m_{h^-}$, the two peaks start populating different bins, but because of the falling power-law flux, the effect is more pronounced in the smallest resonance energy bin. Also note that we cannot make Δm_h exactly zero, otherwise the neutrino mass vanishes [cf. Eq. (5)].

From Fig. 1, it is clear that for a given charged scalar mass m_{h^-} , the Yukawa coupling $Y_{\tau e}$ cannot be made arbitrarily large without spoiling the best fit to the observed IceCube HESE data. We can use this fact to derive new IceCube constraints in the $m_{h^-} - Y_{\tau e}$ plane, as shown in Fig. 2 by the thick black contours. The curve labeled ‘‘IC 1T₀’’ represents the parameter set which would give rise to one event when summed over the last three bins considered by IceCube best-fit ($4.6 < E_\nu / \text{PeV} < 10$) with the current exposure $T_0 = 2653$ day [9], and the other curves are with increased exposures of $2T_0$, $4T_0$, $10T_0$, and $50T_0$, respectively, keeping the other parameters in Eq. (7) the same. The left panel is for $m_{h^+} \approx m_{H^+}$ and the right panel is for $m_{H^+} - m_{h^+} = 30$ GeV. This explains the appearance of one ‘‘dip’’ in the left panel (corresponding to one resonance for h^- and H^- combined) and two ‘‘dips’’ in the right panel (corresponding to two distinct resonances for h^- and H^-).

Probing NSI.—The same Yukawa interactions in Eq. (6) lead to neutrino NSI with electrons, given by [11]

$$\epsilon_{\alpha\beta} = \frac{Y_{ae} Y_{\beta e}^*}{4\sqrt{2}G_F} \left(\frac{\sin^2 \varphi}{m_{h^+}^2} + \frac{\cos^2 \varphi}{m_{H^+}^2} \right), \quad (11)$$

where G_F is the Fermi coupling constant. In Fig. 2, we show the predictions for $\epsilon_{\tau\tau}$ by thin black dotted contours.

Here again we have taken the maximal mixing case with $\varphi = \pi/4$ to get the largest possible NSI. The shaded regions are all excluded: blue shaded by direct LEP searches [51,52] and lepton universality (LU) tests in tau decays [50]; green shaded by LEP dilepton searches [45,53]; purple shaded (dashed) by LEP monophoton searches off (on) Z pole [54,55]; red shaded by BOREXINO [56], orange shaded by global fit to neutrino oscillation plus COHERENT data [57], and brown shaded by IceCube atmospheric neutrino data [58,59]. For more details on these exclusion regions, see Ref. [11]. Note that the atmospheric neutrino data only constrain $|\epsilon_{\tau\tau} - \epsilon_{\mu\mu}| < 9.3\%$ [58,59], which in the Zee model is equivalent to a bound on $\epsilon_{\tau\tau}$ itself, because both $\epsilon_{\tau\tau}$ and $\epsilon_{\mu\mu}$ cannot be large simultaneously due to stringent cLFV constraints. One can do similar analysis for other $\epsilon_{\alpha\beta}$, which are however restricted to be less than a few % [11], and hence, are not so promising for IceCube.

We should comment here that the LEP dilepton constraints [45] shown in Fig. 2 (green shaded region) are equally applicable to the extra neutral CP -even and -odd scalars (H, A) present in the Zee model, since they could modify the $e^+e^- \rightarrow \ell_\alpha^+ \ell_\alpha^-$ cross section via t -channel mediation through the Yukawa couplings Y_{ae} . Moreover, these neutral scalars are required to be quasidegenerate with the doublet charged scalar H^+ in order to satisfy the electroweak T -parameter constraint [11].

From Fig. 2, we see that the existing constraints on NSI are stronger than the current sensitivity of high-energy IceCube data. However, the (non)observation of a resonance-like

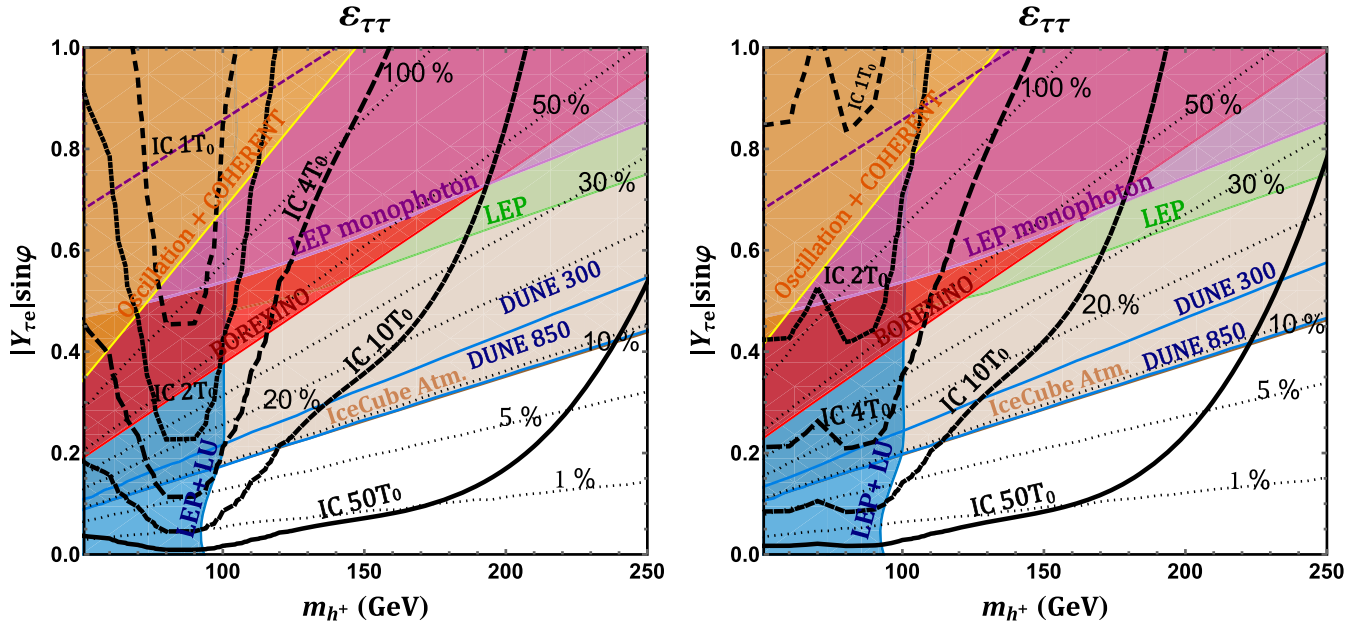


FIG. 2. IceCube sensitivity (corresponding to one expected event in the resonance energy bins combined) for the parameter space relevant for $\epsilon_{\tau\tau}$ are shown by thick black curves, for different exposure times (in terms of the current exposure $T_0 = 2653$ day). The left panel is for $m_{h^+} \approx m_{H^+}$ and the right panel is for $m_{H^+} - m_{h^+} = 30$ GeV. The predictions for $\epsilon_{\tau\tau}$ are shown by the thin dotted contours. The shaded regions are excluded; see text for details.

feature in the future IceCube HESE data could provide a complementary probe of the allowed NSI parameter space, which can even supersede the future DUNE sensitivities (shown by the upper and lower blue solid lines for 300 and 850 kt MWyr exposures, respectively [60]). We note here that an exposure of $10T_0$ does not necessarily require 75 yr of IceCube running, as a number of factors could improve the conservative projected IceCube limits shown here in a nonlinear fashion. For instance, the future data in all the bins may not scale proportionately to the current data and may turn out to be in better agreement with the SM prediction, thus restricting even further any room for new physics contribution. Similarly, the energy-dependent acceptance rate might improve in the future (as it did by 67% from 2–7 yr of data [47]), thereby increasing the effective area, and hence, the “effective” exposure time defined here at a rate faster than linear. Finally, the proposed IceCube-Gen2 with 10 km³ detector volume [61] could increase the total effective exposure by about an order of magnitude. At the very least, combining IceCube data with the future KM3NeT data [62] could increase the effective exposure by a factor of 2.

Before concluding, we remark that for heavier charged scalars, the resonance energy will be shifted to higher values at which IceCube will become less sensitive, given an isotropic power-law spectrum. However, if there exist powerful transient sources of UHE neutrinos, then IceCube, as well as current and next-generation radio-Cherenkov neutrino detectors, such as ARA [63], ARIANNA [64], ANITA [65], GNO [66], and RNO [67], could be sensitive to electrophilic charged scalars up to a TeV or so (corresponding to the resonance energy of EeV), as might occur, e.g., in the left-right symmetric model [68]. The possibility of a larger flux at higher energies, together with better energy resolution of the IceCube detectors, might help distinguishing the degenerate versus nondegenerate charged-scalar mass spectrum by exploiting the “dip” features in Fig. 2.

Conclusion.—We have proposed a new way to probe light charged scalars using a Glashow-like resonance feature in the ultrahigh energy neutrino data at IceCube and its future extensions. The same interactions that lead to the new signature at IceCube also give rise to observable nonstandard interactions of neutrinos with matter, so that the UHE neutrinos provide a complementary probe of NSI. Taking the popular Zee model of radiative neutrino mass as a prototypical example, we have provided an explicit realization of this idea.

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