Two-component flux explanation for the high energy neutrino events at IceCube

Chien-Yi Chen, P. S. Bhupal Dev, and Amarjit Soni

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A Possible Two-component Flux for the High Energy Neutrino Events at IceCube

Chien-Yi Chen,[1] P. S. Bhupal Dev,[2] and Amarjit Soni[1]

[1] *Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*

[2] *Consortium for Fundamental Physics, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*

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Understanding the spectral and flavor composition of the astrophysical neutrino flux responsible for the recently observed ultra-high energy events at IceCube is of great importance for both astrophysics and particle physics. We perform a statistical likelihood analysis to the 3-year IceCube data and derive the allowed range of the spectral index and flux normalization for various well-motivated physical flavor compositions at source. While most of the existing analyses so far assume the flavor composition of the neutrinos at an astrophysical source to be (1:2:0), it seems rather unnatural to assume only one type of source, once we recognize the possibility of at least two physical sources. Bearing this in mind, we entertain the possibility of a two-component source for the analysis of IceCube data. It appears that our two component hypothesis explains some key features of the data better than a single-component scenario, *i.e* it addresses the apparent energy gap between 400 TeV to about 1 PeV and easily accommodates the observed track to shower ratio. Given the extreme importance of the flavor composition for the correct interpretation of the underlying astrophysical processes as well as for the ramification for particle physics, this two-component flux should be tested as more data is accumulated.

I. INTRODUCTION

The recent observation of ultra-high energy (UHE) neutrino events at IceCube [1–3] in previously uncharted energy regime has commenced a new era in Neutrino Astrophysics. Following the initial two events around 1 PeV deposited energy [1], additional 26 events were found in the 30 - 400 TeV energy range [2] with the 2-year dataset. More recently, further 9 events were reported with the 3-year dataset [3], with one event at 2 PeV, the highest-energy neutrino interaction ever observed in Nature. Together, the observed total of 37 candidate events reject a purely atmospheric explanation at 5.7σ [3] and strongly suggest an extra-terrestrial origin. This provides a unique opportunity to *directly* probe the energetic physical processes occurring in dense astrophysical environments, which are otherwise inaccessible with traditional messengers like photons or charged particles in cosmic rays.

It is imperative for both astrophysics and particle physics to understand all possible aspects of the UHE neutrino events, and in particular, to extract information on the possible source(s) and the underlying spectral shape of the astrophysical neutrino flux (for reviews, see e.g. [4, 5]). Since no significant clustering is observed [3] and there is no evidence for point-like sources of astrophysical neutrinos [6], the current data suggests either many isotropically distributed point sources or some spatially extended sources. Moreover, most of the UHE neutrino events have arrival directions in high galactic latitudes [3], thereby suggesting a dominant extragalactic component [7], which could be attributed to various astrophysical sources.[1] Typical examples are cosmic-ray (CR) reservoirs like star-burst galaxies and galaxy clusters/groups [10], CR accelerators like active galactic nuclei (AGNs) [11, 12], gamma-ray bursts [13] and newborn pulsars [14], or even charmed meson decays in mildly relativistic jets of supernovae [15]. A cosmogenic source due to UHECR interactions with the CMB background [16] is now disfavored [17].

There are two conventional production sources of UHE neutrinos from interactions of UHECRs in a dense astrophysical system [18], namely, (i) hadro-nuclear production by inelastic pp or pn scattering in cosmic-ray reservoirs like starburst galaxies and galaxy clusters/groups, and (ii) photo-hadronic production by $p\gamma$ scattering in cosmic ray accelerators like GRBs and AGN. Both kinds of sources produce charged pions/kaons, whose subsequent decays are expected to give rise to astrophysical neutrinos. For charged pions produced by pp scattering, isospin invariance yields a roughly equal ratio of π^+, π^- and π^0 production, and the subsequent decay chain

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \quad \mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu) \quad (1)$$

leads to a flavor composition of $(\nu_e{:}\nu_\mu{:}\nu_\tau)_{\rm S}$=$(1{:}2{:}0)_{\rm S}$ at the source (S). Note that the kinematics of the decay chain is such that each neutrino in the decay chain carries off roughly equal energy [18]. After the neutrino oscillations are averaged over an astronomical distance scale, the final composition on Earth (E) becomes $(1{:}1{:}1)_{\rm E}$ [19]

[1] A sub-dominant galactic contribution, possibly associated with known local large diffuse TeV to PeV γ-ray sources at the galactic center [8] or the interstellar medium [9] cannot be ruled out yet.

for a tri-bi-maximal (TBM) neutrino mixing pattern [20]. The flux of neutrinos coming from *pp* collisions follows that of the progenitor protons, which is typically a power-law spectrum $\Phi \propto E^{-\gamma}$ with $\gamma \sim 2$ for a diffusive Fermi-shock acceleration mechanism, whereas the neutrino flux due to $p\gamma$ collisions has a strong Δ^+ resonance peak, and therefore, falls off at lower energies [18].

Using the $(1{:}1{:}1)_{\rm E}$ flavor composition and assuming a single-component $E^{-\gamma}$ flux over the entire energy range of interest, it was shown [21, 22] that the 2-year IceCube data was largely consistent with the expectations from the Standard Model (SM) neutrino-nucleon interactions. This provides a unique test of the SM involving the highest energy neutrinos ever observed in Nature and any statistically significant deviations in future might call for a non-standard explanation. In fact, several New Physics scenarios have been envisaged in this context, e.g. early-decay of a massive long-lived particle [23], decay [24] or annihilation [25] of a heavy Dark Matter, secret neutrino interactions involving a light mediator [26], lepto-quark resonance [27], decay of massive neutrinos to light ones over cosmological distances [28], mirror neutrinos [29], superluminal neutrinos [30], color-octet neutrinos [31], extra-dimensions [32] and TeV-scale gravity [33]. Even within the SM framework, various other possibilities have been considered, e.g. the Glashow resonance in $\bar{\nu}_e e^-$ [34] and $\nu_\ell \gamma$ scattering [35], and interactions of nuclei with matter [36]. If the data continues to be consistent with the SM predictions, one can put useful constraints on some of the exotic scenarios mentioned above [5], which are otherwise difficult to probe in low-energy laboratory experiments.

Nevertheless, it was pointed out in [22] that the $(1{:}1{:}1)_{\rm E}$ flux seems to give a mild deficit in the observed muon tracks at high energies, where the atmospheric background is anyway expected to be small. This was independently confirmed in a dedicated likelihood analysis [37]. Although the $(1{:}1{:}1)_{\rm E}$ flavor composition is still allowed at the 90% C.L. [38, 39] and a potential muon deficit could be attributed to experimental effects such as track mis-identification, it is worth scrutinizing other possible flavor ratios at source.

In this paper, we critically examine the possible physical flavor and spectral compositions of the UHE neutrino flux in light of the 3-year IceCube data. After confirming the mild 'muon deficit problem' with the standard $(1{:}2{:}0)_{\rm S}$ flux, we consider other well-motivated sources with $(1{:}0{:}0)_{\rm S}$, $(0{:}1{:}0)_{\rm S}$ and $(1{:}1{:}0)_{\rm S}$ flavor compositions and show that it is possible to mitigate the muon deficit problem, if it really exists, with the $(1{:}0{:}0)_{\rm S}$ flux, whereas the $(0{:}1{:}0)_{\rm S}$ and $(1{:}1{:}0)_{\rm S}$ fluxes further aggravate the problem. In any case, once one recognizes the existence of any of these additional sources along with the standard $(1{:}2{:}0)_{\rm S}$ source, it is rather *natural* to consider at least a *two-component* flux, instead of a single component over the entire energy range of interest. Moreover, we show that such a two-component flux could also offer a simple explanation of the apparent energy gap between 400 TeV–1 PeV, apart from addressing the muon deficit problem, all *within* the SM framework, i.e. without invoking any New Physics.

The plan of the paper is as follows: in Section II, we give the pertinent details of the calculation of event rate at IceCube, as used in our simulation. In Section III, we discuss various possible flavor compositions at source. In Section IV, we perform a Poisson likelihood analysis for different astrophysical flavor compositions and flux normalizations. In Section V, we analyze the two-component flux with various flavor compositions. Our conclusions are given in Section VI.

II. EVENT RATE

The expected number of neutrino-induced events at IceCube can be written as

$$N = T N_A \Omega \int_{E_{\rm min}}^{E_{\rm max}} dE_{\rm dep} \int_0^1 dy \; \Phi \, V_{\rm eff} \, A \, \frac{d\sigma}{dy}, \qquad (2)$$

where $E_{\rm dep}$ is the electromagnetic-equivalent deposited energy, which is *always* smaller than the incoming neutrino energy E_ν in the laboratory frame by a factor depending on E_ν and the type of interaction, T is the time of exposure, N_A is the Avogadro number, Ω is the solid angle of coverage, Φ is the incident neutrino flux, $V_{\rm eff}$ is the effective target volume of the detector, A is the attenuation factor for upgoing neutrinos traveling through the Earth material, σ is the neutrino-induced interaction cross section, and $y = (E_\nu - E_\ell)/E_\nu$, E_ℓ is the inelasticity parameter which is a measure of the energy carried by the outgoing lepton in the laboratory frame. The limits of the energy integration $E_{\rm min}$ and $E_{\rm max}$ give the bin size over which the expected number of events is being calculated.

The numerical values of the various parameters appearing in Eq. (2) as used in our analysis are computed using the procedure given below:

(i) $T = 988$ days for the IceCube data collected between 2010–2013 [3].

(ii) $N_A = 6.022 \times 10^{23}\,{\rm mol}^{-1}$, which is equal to 6.022×10^{23} cm^{-3} water equivalent for interactions with the ice nuclei. For interactions with electrons, N_A should be replaced with $(10/18)N_A$ for the number of electrons in one mole of H_2O.

(iii) $\Omega = 4\pi$ sr for an isotropic neutrino flux. For the upgoing events, i.e. those coming from the northern hemisphere at IceCube, we must include an attenuation factor due to scattering within the Earth, which is represented by an energydependent shadow factor [40]

$$A(E_\nu) \;=\; \frac{1}{2}\int_{-1}^{1} d(\cos\theta)\,\exp\left[-\frac{z(\theta)}{L_{\rm int}(E_\nu)}\right], \qquad (3)$$

where θ is the incident angle of the incoming neutrinos above nadir, $L_{\rm int}(E_\nu) = 1/\sigma(E_\nu)N_A$ is the interaction length, and $z(\theta)$ is the effective column depth for upgoing neutrinos (for downgoing events, $z(\theta) = 0$), which is obtained from the Earth density profile as given by the Preliminary Reference Earth Model [41]. The Earth attenuation effects become important at energies above ~ 100 TeV, making the Earth opaque to UHE neutrinos [40]. This is why all the PeV events observed so far at IceCube are downgoing events. For the upgoing τ-neutrinos, one should also include the regeneration effects inside the Earth [42], which lead to fast τ-decays producing secondary neutrinos of all flavors with lesser energy than the original incident one [43].[2]

(iv) $V_{\rm eff}(E_\nu) = M_{\rm eff}(E_\nu)/\rho_{\rm ice}$ is the effective target volume, where $\rho_{\rm ice} = 0.9167\ {\rm g\,cm^{-3}}$ is the density of natural ice and $M_{\rm eff}$ is the effective target mass which includes the background rejection cuts and event containment criteria [2]. $M_{\rm eff}$ depends on the incoming neutrino energy and attains its maximum value $M_{\rm eff}^{\rm max} \simeq 400$ Mton, corresponding to $V_{\rm eff}^{\rm max} \simeq 0.44\ {\rm km}^3$ water-equivalent, above 100 TeV for ν_e CC events, and above 1 PeV for other CC and NC events [2]. There is some flavor bias at low energies caused by the deposited energy threshold due to missing energy in escaping particles from ν_μ and ν_τ CC events as well as all flavor NC events, which decreases $M_{\rm eff}$ for these events as compared to the ν_e CC events.

(v) For the incoming neutrino flux, we first assume a single-component unbroken power-law spectrum:

$$\Phi(E_\nu) \;=\; \Phi_0\left(\frac{E_\nu}{E_0}\right)^{-\gamma}, \qquad (4)$$

where Φ_0 is the *total* $\nu+\bar\nu$ flux for all flavors at $E_0 = 100$ TeV in units of ${\rm GeV^{-1}cm^{-2}sr^{-1}s^{-1}}$ and γ is the spectral index.[3] The exact energy dependence might vary for different extra-terrestrial source evolution models [5], and hence, the spectral index γ is kept as a free parameter in our analysis.

(vi) $E_{\rm dep}$ as a function of E_ν is calculated using the procedure outlined in [22]; see also [38, 45, 46]. For the cascade events caused by ν_e, ν_τ charged-current (CC) and a sub-dominant all-flavor neutral current (NC) interactions, the underlying true neutrino energy can be reconstructed better than that for the track events caused by ν_μ CC interactions [47]. In the latter case, the true muon neutrino energy could be much higher than the deposited energy due to the through-going muons, thus allowing us to set only a *lower* limit on E_ν [45].

(vii) The (anti)neutrino-nucleon cross sections are calculated using the `NNPDF2.3` [48] parton distribution functions (PDFs) at next-to-next-to-leading order. With x-grids as low as 10^{-9} and Q^2 grids up to $10^8\ {\rm GeV}^2$, they have a relatively small error on the cross sections for the current energy range of interest [22]. For a more precise determination of the cross sections at high energies, one has to include the non-linear QCD effects [49] beyond the DGLAP formalism [50].

III. FLAVOR COMPOSITION

Given a flavor ratio $(f_e^0{:}f_\mu^0{:}f_\tau^0)_{\rm S}$ of $\nu+\bar\nu$ at source, the corresponding value $(f_e{:}f_\mu{:}f_\tau)_{\rm E}$ on Earth is given by

$$f_\ell \;=\; \sum_{\ell'=e,\mu,\tau}\sum_{i=1}^{3}|U_{\ell i}|^2|U_{\ell' i}|^2 f_{\ell'}^0 \;\equiv\; \sum_{\ell'} P_{\ell\ell'}f_{\ell'}^0\,, \quad (5)$$

where $U_{\ell i}$ are the elements of the PMNS mixing matrix and $P_{\ell\ell'}$ is the oscillation probability for $\nu_\ell \to \nu_{\ell'}$ in vacuum. Assuming a TBM mixing [20], which is a good approximation at this stage [51], the positive definite elements of P are given by

$$P \;=\; \frac{1}{18}\begin{pmatrix} 10 & 4 & 4\\ 4 & 7 & 7\\ 4 & 7 & 7\end{pmatrix}. \qquad (6)$$

Using this in Eq. (5), one can easily check that a $(1{:}2{:}0)_{\rm S}$ flavor composition at the source [cf. Eq. (1)] will lead to a $(1{:}1{:}1)_{\rm E}$ composition on Earth.[4] Here we make an interesting observation that for an observed $(1{:}1{:}1)_{\rm E}$ composition on Earth, the source composition may not be necessarily $(1{:}2{:}0)_{\rm E}$, as a flavor-universal source composition of $(1{:}1{:}1)_{\rm S}$ also leads to the same composition $(1{:}1{:}1)_{\rm E}$ on Earth.

[2] Our estimates show that the regeneration effect on the total number of events in the energy range of interest is $\lesssim 5\%$.

[3] In the notation followed by our earlier analysis [22], $\Phi = CE^{-\gamma}$, where $C = (10^{10}\ {\rm GeV}^2)\Phi_0 E_0^{\gamma-2}$.

[4] Using the current 3σ values of the neutrino mixing parameters [60] instead of the TBM structure (6), we obtain $(0.9\text{-}1{:}1.1\text{-}1{:}1\text{-}0.9)_{\rm E}$ which can be safely assumed to be $(1{:}1{:}1)_{\rm E}$ for numerical purposes.

Apart from the standard $\pi^{\pm}$ production mode (1) giving rise to $(1:2:0)_S$ flavor composition of astrophysical neutrinos, there are a few other possibilities [52], leading to different flavor compositions as follows:

(i) If the charged pions are produced by $p\gamma$ scattering, the Δ^+ resonance gives rise to $\pi^+ + n$ and $\pi^0 + p$, in the ratio of 1:2. Since π^- (and hence μ^- and $\bar{\nu}_e$) production is suppressed in this case, we get the source flavor ratio $(1:1:0)_S$ for neutrinos and $(0:1:0)_S$ for anti-neutrinos. Using Eqs. (5) and (6), we get the corresponding earthly flavor ratios of $(14:11:11)_E$ and $(4:7:7)_E$ respectively. Note that $(1:1:0)_S \equiv (14:11:11)_E$ flavor ratio for both neutrinos and antineutrinos is also possible in prompt decays of charmed particles.

(ii) Since the rest-frame lifetime of muons, $\tau_\mu = 2.2 \times 10^{-6}$ s, is larger than that of charged pions, $\tau_{\pi^\pm} = 2.6 \times 10^{-8}$ s [60], it is possible that the muon in the decay chain of Eq. (1) loses energy in the source environment, e.g. due to synchrotron radiation in a strong magnetic field or by scattering in a dense astrophycal medium, before decaying [53, 54]. In this case, the flavor composition at source will be $(0:1:0)_S$ and the corresponding earthly composition will be $(4:7:7)_E$.

(iii) It is also possible to have a purely electron (anti)neutrino flux at source, i.e. with flavor ratio $(1:0:0)_S$, which will give rise to $(5:2:2)_E$ flux on Earth. This is possible e.g. when the source injects a nearly pure neutron flux [62, 63].

IV. LIKELIHOOD ANALYSIS

Using the parameter values given above, we use Eq. (2) to compute the expected number of events from the SM CC and NC interactions, assuming a single-component astrophysical power-law spectrum for the incoming neutrino flux. Together with the expected atmospheric background, we obtain the predictions for the SM signal+background events with mean values λ_i, where $i = 1, ..., 14$ denotes the number of the deposited energy bin between 15.8 TeV $< E_{\rm dep} <$ 10 PeV. For a given flavor composition, the observed count n_i in each bin i is compared to the SM prediction through a Poisson likelihood function

$$L = \prod_{\text{bins } i} \frac{e^{-\lambda_i}\lambda_i^{n_i}}{n_i!} \tag{7}$$

The best-fit values for the flux normalization Φ_0 and the spectral index γ will correspond to the maximum value of $L = L_{\rm max}$ in Eq. (7). The corresponding confidence level (CL) ranges can be obtained from a likelihood-ratio

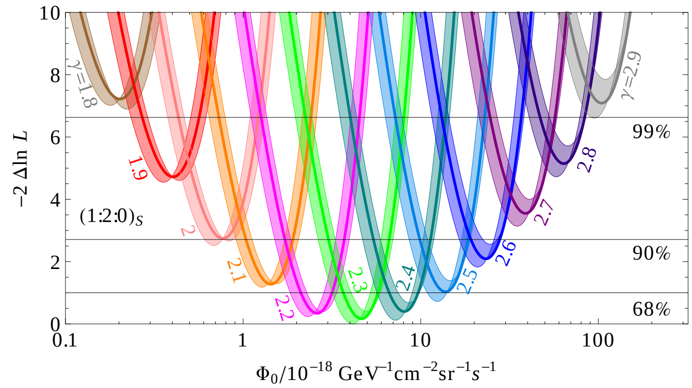

FIG. 1. The likelihood profile for the total astrophysical flux normalization Φ_0 with different values of the spectral index γ and with $(1:2:0)_S$ flavor composition. The shaded regions show the 90% CL PDF uncertainty.

test, by constructing a test statistic

$$-2\Delta \ln L = -2(\ln L - \ln L_{\rm max}) , \tag{8}$$

where the 68%, 90% and 99% CL limits correspond to the values of $-2\ln L = 1$, 2.71 and 6.63 respectively [60] for our case with one degree of freedom. This is shown in Figure 1 for the $(1:2:0)_S$ flavor composition. Here the individual $L_{\rm max}$ was computed by only varying the spectral index and flux normalization for a given flavor composition. We find that the best-fit spectral index is $\gamma \sim 2.3$ and the best-fit normalization is $\Phi_0 \sim 5 \times 10^{-18}$ GeV^{-1}cm^{-2}sr^{-1}s^{-1}. Note that the flux normalization values shown here are consistent with the observational upper bounds on the UHECR and diffuse neutrino fluxes [57], as well as with the sub-PeV gamma-ray flux limits $E_\gamma^2\Phi_\gamma \lesssim 10^{-8}$ GeVcm^{-2}sr^{-1}s^{-1} [5]. This might indicate a relation between the sources of the UHE neutrinos and UHECRs [4]. However, our best-fit spectral index is slightly higher than that predicted by a typical Waxman-Bahcall flux, which is proportional to E^{-2} [58].[5]

Using the above procedure, we can similarly compute the likelihood profiles for other flavor compositions mentioned at the end of Section II, which look similar to that shown in Figure 1, and hence, are not shown here. We find that for all the cases, the best-fit spectral index is $\gamma = 2.3$ and the best-fit flux normalization is of the same order as in the $(1:2:0)_S$ case, though the exact value depends on the flavor composition. This is shown in Figure 2. Here the overall maximum likelihood was computed by comparing all the corresponding local maxima $L_{\rm max}$ for each flavor composition. As we can see from this plot, all the physical flavor compositions are

[5] This is largely consistent with other recent analyses of the IceCube data; see e.g. [38, 39, 59, 68].

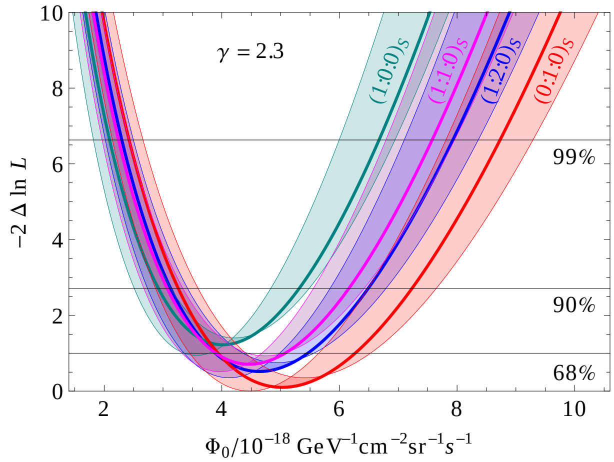

FIG. 2. The likelihood profile for the total astrophysical flux normalization Φ_0 with different flavor compositions and with the spectral index $\gamma = 2.3$. The shaded regions show the 90% CL PDF uncertainty.

currently consistent with the IceCube data within 90% CL, although the $(0{:}1{:}0)_{\rm S}$ flux has the maximum likelihood to explain the current data. This is consistent with the recent IceCube analysis on flavor composition [39].

In Figure 3, we show the deposited energy spectra for a single component flux (4) with $(1{:}1{:}1)_{\rm E}$ flavor composition and an unbroken $E^{-\gamma}$ spectrum for some typical values of the spectral index γ . The expected background of $6.6^{+5.9}_{-1.6}$ atmospheric neutrinos and 8.4 ± 4.2 CR muons is shown by the black shaded region, which includes the systematic and statistical uncertainties as well as the 90% CL charm limit [3]. Our SM signal+background prediction is shown by the green solid line and the associated green shaded region includes the PDF uncertainty in the cross section (cf. Figure 3). The mild enhancement of events around 6 PeV is due to the Glashow resonance caused by $\bar{\nu}_e e^-$ interactions [66].

A closer look at the signal events for $(1{:}2{:}0)_{\rm S}$ reveals a potential 'muon deficit' problem, as illustrated in Table I. Here we have shown the expected number of signal events for the best-fit scenario with $\gamma = 2.3$ and $(1{:}2{:}0)_{\rm S}$ composition in various categories. Including the contribution from the expected atmospheric background [3] due to CR muons and atmospheric muon neutrinos from π/K and charmed meson decays, we compare our best-fit predictions with the observed data for integrated number of events between 60 TeV $< E_{\rm dep} <$ 3 PeV. It is clear that the $(1{:}2{:}0)_{\rm S}$ flavor composition predicts higher number of muon tracks than that observed in this energy range. This deficit becomes more severe if we consider the fact that out of the 4 candidate events above 60 TeV, one event has an apparent first interaction near the detector boundary, which is consistent with the expected muon background [3].

For comparison, we also show in Table I the corresponding predictions for number of events with other physical flavor compositions. It is clear that the muon deficit problem becomes worse for $(1{:}1{:}0)_{\rm S}$ and $(0{:}1{:}0)_{\rm S}$, whereas $(1{:}0{:}0)_{\rm S}$ significantly improves the situation, as expected.

As suggested in [22], one possible way to address the muon deficit problem is by invoking some exotic lepton flavor violating interactions, which could also be linked with the longstanding muon $(g-2)$ anomaly [60]. It was shown [70] that a light leptophilic Z' explaining the muon $(g-2)$ anomaly could also explain the apparent energy gap between 400 TeV and 1 PeV in the IceCube spectrum as due to resonant scattering of UHE neutrinos with the cosmic relic neutrino background. In the following section, we propose an alternative explanation of the gap within the SM framework.

V. A TWO-COMPONENT SOLUTION

As stated earlier, once we identify the existence of more than one flavor compositions, it seems rather natural to consider a multi-component flux for the astrophysical neutrinos. Here we should clarify that multiple flavor components do not necessarily require multiple sources, since it is possible to have significant parameter spread even in a single source class. For example, the energy at which muons of astrophysical origin start to lose energy before decaying strongly depends on the source parameters such as the magnetic field strength. For a given source class, such parameters could have a broad distribution, thus leading to a diffuse neutrino flux with more than one flavor composition.

For illustration, we entertain the simplest multi-component possibility, i.e. a two-component flux:

$$\Phi(E_\nu) \;=\; \Phi_1 \left(\frac{E_\nu}{E_0}\right)^{-\gamma_1} e^{-E_\nu/E_1} + \Phi_2 \left(\frac{E_\nu}{E_0}\right)^{-\gamma_2}, \quad (9)$$

with five hitherto unknown parameters, i.e. $\Phi_{1,2}, \gamma_{1,2}$ and a cut-off scale E_1. Note that in the single-component case, there is no need for a cut-off [22, 68], as long as $\gamma \gtrsim 2$.[6] However, if the apparent gap in the deposited energy spectrum between 400 TeV and 1 PeV persists, the single-component solution will be disfavored, as illustrated in Figure 3. A two-component flux (9) can easily explain such a gap, if $E_1 \lesssim 1$ PeV for the first component and the second component becomes dominant beyond E_1. The cut-off energy E_1 may arise due to interactions of UHECRs en route to Earth or due to a natural acceleration endpoint [5]. Similarly, a low-energy cut-off

[6] For $\gamma \lesssim 2$, a cut-off is required to avoid the Fermi-LAT constraint on diffuse γ-ray flux [5].

	Background	$(1{:}2{:}0)_S$ [or $(1{:}1{:}1)_E$]	$(1{:}1{:}0)_S$ [or $(14{:}11{:}11)_E$]	$(0{:}1{:}0)_S$ [or $(4{:}7{:}7)_E$]	$(1{:}0{:}0)_S$ [or $(5{:}2{:}2)_E$]	Two-comp [$(1{:}0{:}0)_S$+$(1{:}2{:}0)_S$]	IceCube
Total	$2.8+ < 5.3$	14.5	14.4	14.8	14.2	13.7	20
Up	$1.5+ < 3.7$	5.5	5.4	5.6	5.2	5.0	5
Down	$1.2+ < 1.6$	9.0	9.0	9.1	9.0	8.7	15
Track	$\sim 2.1+ < 1.0$	4.4	3.9	5.6	2.6	2.8	4
Shower	$\sim 0.7+ < 4.2$	10.1	10.5	9.2	11.6	10.9	16

TABLE I. SM predictions for the number of events between 60 TeV $< E_{\rm dep} <$ 3 PeV in 988 days for the best-fit single-component solutions as well as for a two-component solution. The atmospheric background due to CR muons and muon neutrinos from π/K and charmed meson decays, and the IceCube observed events are taken from [3].

for the second component could be due to its production mechanism, e.g. from a $p\gamma$ collision which has a sharp Δ-resonance.[7]

Similarly, the potential muon deficit problem can be adressed by taking the first component of the two-component flux to be $(1{:}0{:}0)_S$. We should clarify that although the $(1{:}0{:}0)_S$ is not favored by the current data over the other possible flavor compositions as a *single*-component flux, mainly because of the lack of enough events in the Glashow resonance bin, it is still perfectly acceptable as the low-energy part of a two-component flux. Moreover, it is easier to satisfy the Fermi-LAT bound on diffuse gamma-ray flux [69] for a $(1{:}0{:}0)_S$ source in the low-energy regime [63].

Assuming the first component to be $(1{:}0{:}0)_S$ for reasons stated above, we perform a likelihood analysis for the two-component case, similar to that presented in Section IV for the single-component case, with different choices of flavor compositions for the second component and different spectral indices (γ_1, γ_2) in Eq. (9). We keep the cut-off scale fixed at $E_1 = 1$ PeV. Our results are shown in Figure 4, where we show the relative likelihood for each case. It is clear that the best-fit is obtained for $(\gamma_1, \gamma_2) = (2.4-2.5, 2.4-2.7)$ and for the second component flavor composition $(0{:}1{:}0)_S$. However, the other cases shown in Figure 4 are all currently allowed within 90% CL, if we consider the UHE neutrino events only above 60 TeV. This is consistent with the fact that, for the single-component case, $(0{:}1{:}0)_S$ gives the best-fit solution, while all the other cases are still within the 90% CL interval (cf. Figure 2) for $\gamma = 2.3-2.7$.

To illustrate the effect of the two-component flux on the event distribution, as compared to the single component flux shown in Figure 3, we change the low-energy part of the flavor composition to $(1{:}0{:}0)_S$, but keeping the high-energy part same as in Figure 3, i.e. $(1{:}2{:}0)_S$. We keep the cut-off scale fixed at $E_1 = 1$ PeV and use the best-fit solution for this flavor composition from Figure 4, i.e. $(\gamma_1, \gamma_2) = (2.4, 2.5)$, with the corresponding best-fit normalizations $(\Phi_1, \Phi_2) = (6.4, 32.2) \times 10^{-18}$ GeV^{-1}cm^{-2}sr^{-1}s^{-1}. The resulting number of events for this scenario are given in the penultimate column of Table I, which clearly shows that the muon deficit can be easily addressed in this scenario. The energy spectrum for this two-component solution is shown in Figure 5 along with the 90% CL PDF uncertainty (green shaded band). The best-fit $(1{:}2{:}0)_S$ single-component solution is also shown for comparison. We see that the two-component flux better explains the energy gap just below 1 PeV. With more data in future, the two-component flux can in principle be distinguished from a single-component flux. In particular, any further information on the number of events in the Glashow resonance bin will be crucial to pin down the flavor composition in the higher-energy bins. In the two-component example considered above, the $(1{:}2{:}0)_S$ flux in the higher energy range predicts less number of electron neutrino events in the Glashow resonance bin, and therefore, is preferred by the current data over a $(1{:}0{:}0)_S$ flux. In addition, a more accurate measurement of the energy spectrum can distinguish our two-component hypothesis from other possible explanations of the gap, e.g. due to secret neutrino interactions [26, 70] or due to the line-of-sight interactions of CRs emitted by blazars with background photons [11].

VI. CONCLUSION

Understanding all aspects of the IceCube UHE neutrino events is extremely important for both astrophysics and particle physics. We critically examine the single-component hypothesis with the standard $(1{:}2{:}0)_S$ astrophysical neutrino flux from pion/kaon decays. Identifying the existence of other well-motivated physical flavor compositions, we argue that it is natural to have a multi-component flux rather than a single-component one. We further show that a simple two-component flux could ex-

[7] In general, it is possible to back up such a two-component flux (9) by solid astrophysical scenarios; a detailed discussion of this will be postponed to a future work. Another possibility for the two-component flux is that one of the components (preferably the lower one) could have astrophysical origin, while the other one has some exotic origin, such as a decaying DM scenario [24].

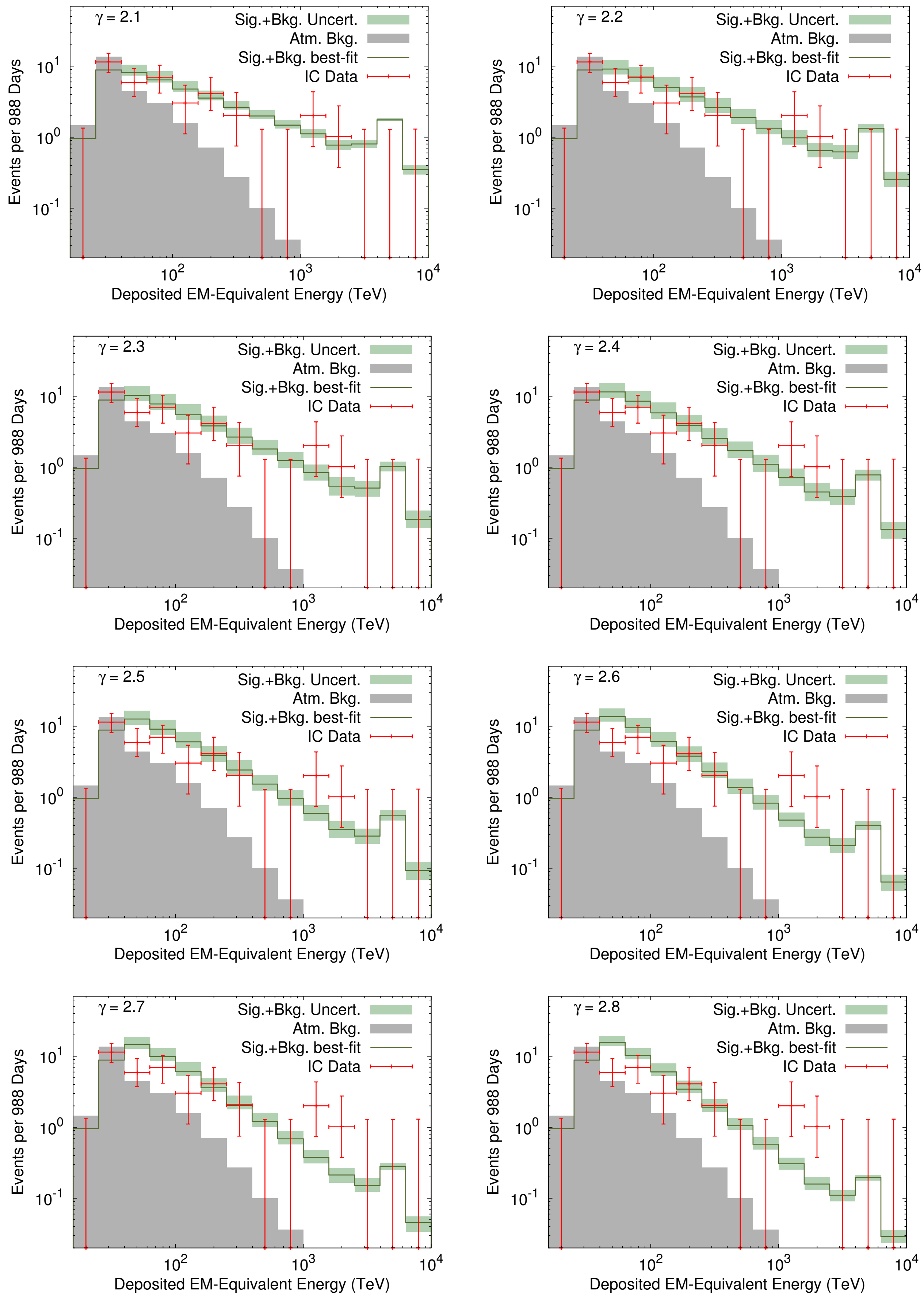

FIG. 3. The SM signal+background events for an $E^{-\gamma}$ flux with $(1{:}1{:}1)_{\rm E}$ flavor composition, along with their 3σ uncertainties (green shaded), for the IceCube deposited energy bins between 16 TeV - 10 PeV. The IceCube data points (with error bars) and the atmospheric background (black shaded) were taken from [3].

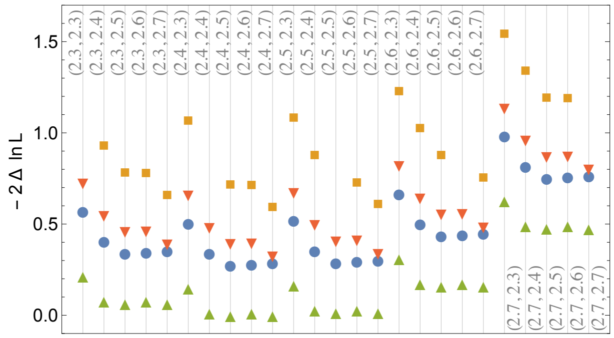

FIG. 4. A likelihood analysis for the two component flux for different flavor compositions, the first component being $(1{:}0{:}0)_S$ and the second being $(1{:}2{:}0)_S$ (circles), $(1{:}0{:}0)_S$ (squares), $(0{:}1{:}0)_S$ (triangle up) and $(1{:}1{:}0)_S$ (triangle down). The x-axis corresponds to the variation of the spectral indices (γ_1, γ_2), as indicated in the figure.

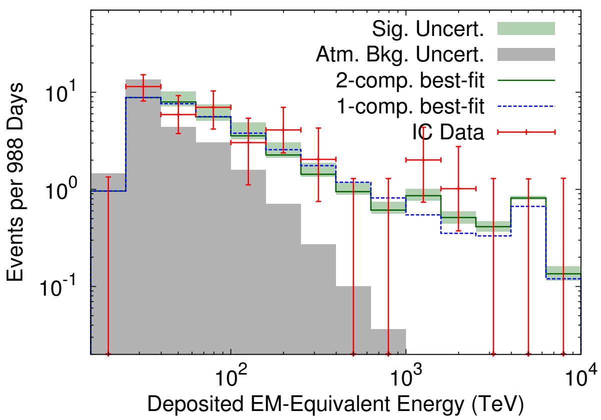

FIG. 5. The SM signal+background events for a two-component flux (solid line with 90% CL PDF uncertainty band) with $(1{:}0{:}0)_S$ as the low-energy component and $(1{:}2{:}0)_S$ as the high-energy component. We also show the best-fit single-component $(1{:}2{:}0)_S$ flux for comparison. The IceCube data points (with error bars) and the atmospheric background (black shaded) were taken from [3].

plain all the key features of the data *within* the SM framework, which are otherwise difficult to understand with a single-component flux. In particular, if the apparent energy gap between 400 TeV and 1 PeV deposited energy bins becomes statistically significant, our two-component hypothesis might provide a simple explanation for this observation, with important consequences for the identification of the underlying astrophysical sources. Given that so much is unknown about the dynamics of the UHE neutrino sources and that a precise knowledge of their flavor composition is crucial for a reliable understanding of the underlying astrophysical processes as well as for the particle physics interpretation, it is desirable to determine the flavor composition from experiment, as more data is collected at current and future large-volume neutrino detectors. Finally, we hope that the future experimental analyses will seriously consider the possibility of such a two-component flux.

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NOTE ADDED

After this work was finalized, we became aware of the preliminary 4-year IceCube dataset [71], in which the apparent energy gap between 400 TeV - 1 PeV still seems to be present, as the only new event recorded in this range is a muon track, which is most likely to have originated from a neutrino with much higher incoming energy. We look forward to the formal publication of the new dataset with more information on the events as well as on the atmospheric background, to be able to update our spectral and flavor analysis accordingly in a future work.

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