



On the flavor composition of the high-energy neutrinos in IceCube

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Abstract

The IceCube experiment has recently released 3 years of data of the first ever detected high-energy ($\gtrsim 30$ TeV) neutrinos, which are consistent with an extraterrestrial origin. In this talk, we compute the compatibility of the observed track-to-shower ratio with possible combinations of neutrino flavors with relative proportion $(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$. Although this observation is naively favored for the canonical $(1 : 1 : 1)_\oplus$ at Earth, once we consider the IceCube expectations for the atmospheric muon and neutrino backgrounds, this flavor combination presents some tension with data. We find that, for an astrophysical neutrino E_ν^{-2} energy spectrum, $(1 : 1 : 1)_\oplus$ at Earth is currently disfavored at 92% C.L. We discuss the trend of this result by comparing the results with the 2-year and 3-year data. We obtain the best-fit for $(1 : 0 : 0)_\oplus$ at Earth, which cannot be achieved from any flavor ratio at sources with averaged oscillations during propagation. Although it is not statistically significant at present, if confirmed, this result would suggest either a misunderstanding of the expected background events, or a misidentification of tracks as showers, or even more compellingly, some exotic physics which deviates from the standard scenario.

Keywords: high-energy neutrinos, IceCube, flavor ratios

1. Introduction

The first evidence for a high-energy neutrino flux of extraterrestrial origin was obtained with a 2-year search in the IceCube neutrino detector, from May 2010 to May 2012 [1, 2]. In this period, 28 veto-passing events were recorded (7 tracks and 21 showers) with deposited energies between ~ 30 TeV and ~ 1 PeV. The atmospheric neutrino and muon background is expected to be $10.6_{-3.6}^{+5.0}$ events [2]. This rate, and also the observed spectrum, is inconsistent with this background alone, with a significance of 4.1σ . Recently, an extra year of data was released, with 2 extra tracks and 7 extra showers in the ~ 30 TeV to 2 PeV range, which increases the significance of their extraterrestrial origin at

the 5.7σ level [3]. The identification of the sources of this incoming neutrino flux requires disentangling the background from the signal, with the study of the energy distribution of the observed events, their correlation with photons and/or protons, their arrival direction and their flavor composition. A first detailed discussion on the flavor composition of these high-energy neutrinos was carried out in Ref. [4]. In this talk, we highlight the main results presented there and extend further the discussion with the 3-year results.

For the 2-year (3-year) data, IceCube expects to see 8.6 (12.1) tracks from the background [2, 3], whereas only 7 (9) tracks have been observed above ~ 30 TeV in deposited energy. This would imply that the astrophysical component overwhelmingly produces showers inside the detector. However, as a result of (photo)hadronic interactions, astrophysical neutrinos are commonly modeled as the decay products of pions,

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kaons and secondary muons, and the expectation for the neutrino flavor ratio at the source¹ is $(\alpha_{e,S} : \alpha_{\mu,S} : \alpha_{\tau,S}) = (1 : 2 : 0)_S$. However, these neutrinos travel over cosmic distances, so oscillations are averaged and this ratio becomes $(\alpha_{e,\oplus} : \alpha_{\mu,\oplus} : \alpha_{\tau,\oplus}) = (1 : 1 : 1)_\oplus$ at Earth [5], which leads to a non-negligible component of astrophysical tracks. However, the comparison between the expected background and the observed events indicates that there cannot be a significant number of astrophysical tracks, so a departure from the canonical expectation is present (see Ref. [6], however). Deviations of the neutrino flavor ratios from this canonical expectation have been discussed in the literature, as the default diagnostic of standard effects (including meson energy losses or muon polarization [7, 8, 9, 10, 11, 12]), neutron decays [13], deviations from tribimaximal mixing [14, 15, 16, 10, 11, 17, 18, 19, 20, 21], neutrino matter effects in the source [22] and other more exotic scenarios [14, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34].

At the energies under consideration, below a few PeV, there are two main event topologies in IceCube: muon tracks, associated with a propagating muon, and electromagnetic or hadronic showers. Here, we assess the probability of observing the track-to-shower ratio seen by the IceCube neutrino telescope as a function of the astrophysical neutrino flavor composition, and we consider the full range $(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$ at the detector. Following Ref. [4], we first outline the calculation of the muon track and shower event rates in IceCube, after which we describe our statistical approach. Then, we present and discuss our results for the 2-year and 3-year data, summarized in Figs. 1 and 2. We show that, with the 2-year (3-year) data and after accounting for the expected backgrounds, the canonical combination $(1 : 1 : 1)_\oplus$ is disfavored at the 81% (92%) confidence level (C.L.) for an E_ν^{-2} spectrum. We stress that the new 3-year data follow a similar proportion of tracks and showers, so the observation does not seem to be an statistical fluctuation, as shown in Fig. 3.

2. Neutrino events in IceCube

At these energies, the IceCube events consist of two type of event topologies: muon tracks and showers. In both cases, we consider the deposited energy to be equal to the sum of the energies of all the showers in the event

¹We use the subscript “S” to denote the flavor composition at the location of the astrophysical sources, before any propagation effect takes place, whereas “ \oplus ” represents the composition at Earth. In the analysis presented here, we do not place any restrictions on the flavor ratios at Earth.

and whenever a muon is produced, we neglect the small amount of energy deposited along the muon track. We also neglect the small suppression of the light yield in hadronic showers due to the presence of more neutral particles [35]. We do not take into account the error in the determination of the deposited energy and we use the effective detector masses for each flavor and type of interaction as a function of the neutrino energy, instead of the detector mass as a function of the deposited energy², which is the quantity which is actually measured. Although these approximations are not appropriate when performing a spectral analysis, they introduce very small errors in an analysis with a single and wide energy bin like the one we consider here. Overall, we have checked that all these approximations have little impact on our results.

Showers are induced by both ν_e and ν_τ charge current (CC) interactions, as well as by neutral current (NC) interactions of neutrinos of all three flavors. The total number of showers (sh) produced by NC interactions for any neutrino (and analogously antineutrino) flavor i reads

$$N_{\nu_i}^{\text{sh,NC}} = T N_A \int_{E_{\min}}^{\infty} dE_\nu M^{\text{NC}}(E_\nu) \text{Att}_{\nu_i}(E_\nu) \frac{d\phi_{\nu_i}(E_\nu)}{dE_\nu} \times \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma^{\text{NC}}(E_\nu, y)}{dy}, \quad (1)$$

where $E_{\nu,y} = (E_\nu - E'_\nu)$ is the shower energy and E'_ν is the energy of the outgoing neutrino, with $y_{\min} = E_{\min}/E_\nu$ and $y_{\max} = \min\{1, E_{\max}/E_\nu\}$. The minimum (maximum) deposited energy in this analysis is $E_{\min} = 30$ TeV ($E_{\max} = 2$ PeV). The differential NC cross section is $d\sigma^{\text{NC}}/dy$, T is the observation time, M^{NC} is the energy-dependent effective detector mass for NC interactions, $N_A = 6.022 \times 10^{23} \text{g}^{-1}$, Att_{ν_i} is the attenuation/regeneration factor due to the absorption and regeneration of ν_i when traversing the Earth and $d\phi_{\nu_i}/dE_\nu$ is the ν_i flux.

Using the same notation, the total number of CC ν_e (and analogously $\bar{\nu}_e$) induced showers can be written as

$$N_{\nu_e}^{\text{sh,CC}} = T N_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_e}^{\text{CC}}(E_\nu) \text{Att}_{\nu_e}(E_\nu) \frac{d\phi_{\nu_e}(E_\nu)}{dE_\nu} \times \int_0^1 dy \frac{d\sigma_{\nu_e}^{\text{CC}}(E_\nu, y)}{dy} \times \Theta(E_{\max} - E_\nu). \quad (2)$$

For ν_τ (and analogously for $\bar{\nu}_\tau$), the total number of shower events induced by CC interactions with an

²Whereas the effective masses as a function of the neutrino energy were published in Ref. [2], the effective mass as a function of the deposited energy is not publicly available.

hadronic tau decay mode is given by [36]

$$N_{\nu_\tau}^{\text{sh,CC-had}} = T N_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_\tau}^{\text{CC}}(E_\nu) \text{Att}_{\nu_\tau}(E_\nu) \frac{d\phi_{\nu_\tau}(E_\nu)}{dE_\nu} \\ \times \int_0^1 dy \frac{d\sigma_{\nu_\tau}^{\text{CC}}(E_\nu, y)}{dy} \int_0^1 dz \frac{dn(\tau \rightarrow \text{had})}{dz} \\ \times \Theta(E_\nu(y + (1-y)(1-z)) - E_{\min}) \\ \times \Theta(E_{\max} - E_\nu(y + (1-y)(1-z))), \quad (3)$$

where the total hadronic shower energy is the sum of the hadronic energy from the broken nucleon, $E_\nu y$, and the hadronic energy from the tau decay, $E_\nu(1-y)(1-z)$, where $z = E'_\nu/E_\tau$, with E'_ν the energy of the neutrino from the decay. The spectrum of the daughter neutrino in hadronic τ decays is $dn(\tau \rightarrow \text{had})/dz$.

The number of showers produced by the electronic decay of the tau lepton, $N_{\nu_\tau}^{\text{sh,CC-em}}$, is written in an analogous way [36],

$$N_{\nu_\tau}^{\text{sh,CC-em}} = T N_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_\tau}^{\text{CC}}(E_\nu) \text{Att}_{\nu_\tau}(E_\nu) \frac{d\phi_{\nu_\tau}(E_\nu)}{dE_\nu} \\ \times \int_0^1 dy \frac{d\sigma_{\nu_\tau}^{\text{CC}}(E_\nu, y)}{dy} \int_0^1 dz_e \frac{dn(\tau \rightarrow e)}{dz_e} \\ \times \Theta(E_\nu(y + (1-y)z_e) - E_{\min}) \\ \times \Theta(E_{\max} - E_\nu(y + (1-y)z_e)), \quad (4)$$

where the electron distribution from tau decays is $dn(\tau \rightarrow e)/dz_e$, with $z_e = E_e/E_\tau$, and E_e is the electron energy. The total number of showers produced by ν_τ CC interactions (and equivalently by $\bar{\nu}_\tau$), $N_{\nu_\tau}^{\text{sh,CC}}$, is the sum of the purely hadronic and hadronic/electromagnetic showers.

Tracks are induced by muons from ν_μ and ν_τ CC interactions. The energy deposited in the detector comes dominantly from the hadronic shower, so we consider the muon track as a tag for this type of events. Thus, the total number of contained-vertex track-like (tr) events from ν_μ (and analogously from $\bar{\nu}_\mu$) is

$$N_{\nu_\mu}^{\text{tr}} = T N_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_\mu}^{\text{CC}}(E_\nu) \text{Att}_{\nu_\mu}(E_\nu) \frac{d\phi_{\nu_\mu}(E_\nu)}{dE_\nu} \\ \times \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma_{\nu_\mu}^{\text{CC}}(E_\nu, y)}{dy}. \quad (5)$$

The total number of muon tracks produced by CC ν_τ (and $\bar{\nu}_\tau$) interactions, $N_{\nu_\tau}^{\text{tr}}$, followed by tau decays ($\tau \rightarrow \nu_\tau \nu_\mu \mu$), is given by

$$N_{\nu_\tau}^{\text{tr}} = T N_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_\tau}^{\text{CC}}(E_\nu) \text{Att}_{\nu_\tau}(E_\nu) \frac{d\phi_{\nu_\tau}(E_\nu)}{dE_\nu} \\ \times \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma_{\nu_\tau}^{\text{CC}}(E_\nu, y)}{dy} Br(\tau \rightarrow \mu), \quad (6)$$

where $Br(\tau \rightarrow \mu)$ is the branching ratio of tau decays into muons.

For the neutrino and antineutrino differential cross sections we use the nusigma neutrino-nucleon scattering MonteCarlo code [37], which uses the CTEQ6 parton distribution functions [38, 39]. We use the IceCube effective masses $M_{\nu_\tau}^{\text{CC}}$ and M^{NC} [2]. The attenuation/regeneration factors have been computed for each flavor and for neutrinos and antineutrinos independently following Refs. [40, 41, 42]. We have not included the small correction [43] due to the secondary ν_μ and ν_e flux produced by ν_τ interactions [44]. The attenuation/regeneration factor in the above equations is the average factor for the whole sky, and thus it only depends on the incoming neutrino energy. We assume the astrophysical neutrino flux to be given by the same power law and the same normalizations, $E_\nu^{-\gamma}$, for the three neutrino and antineutrino flavors. Throughout this letter, we consider $\gamma = 2$ as our default value, which is in good agreement with the data [2, 3].

3. Statistical analysis

The fractions of electron, muon and tau neutrinos produced in astrophysical sources are denoted as $\{\alpha_{i,S}\}$. After propagation, averaged neutrino oscillations cause the flavor ratio at Earth to be $\{\alpha_{i,\oplus}\} = \sum_{k,i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_{i,S}\}$, where U is the neutrino mixing matrix for which we use the latest *fit* results [45] (see also Refs. [46, 47]). For $\{\alpha_{i,S}\} = (1 : 2 : 0)_S$, this yields a flavor ratio at Earth of $(1.04 : 0.99 : 0.97)_\oplus$, very close to the tribimaximal expectation, $(1 : 1 : 1)_\oplus$.

For a given combination $\{\alpha_{i,\oplus}\}$, the total number of events produced by astrophysical neutrinos is

$$N_a(\{\alpha_{i,\oplus}\}) = \alpha_{e,\oplus} (N_{\nu_e}^{\text{sh,CC}} + N_{\nu_e}^{\text{sh,NC}}) \\ + \alpha_{\mu,\oplus} (N_{\nu_\mu}^{\text{tr}} + N_{\nu_\mu}^{\text{sh,NC}}) \\ + \alpha_{\tau,\oplus} (N_{\nu_\tau}^{\text{tr}} + N_{\nu_\tau}^{\text{sh,CC}} + N_{\nu_\tau}^{\text{sh,NC}}), \quad (7)$$

where we implicitly assume the sum of neutrino and antineutrino events. The proportion of muon tracks³ is

$$p_a^{\text{tr}}(\{\alpha_{i,\oplus}\}) = \frac{1}{N_a(\{\alpha_{i,\oplus}\})} (\alpha_{\mu,\oplus} N_{\nu_\mu}^{\text{tr}} + \alpha_{\tau,\oplus} N_{\nu_\tau}^{\text{tr}}), \quad (8)$$

and conversely for showers, $p_a^{\text{sh}}(\{\alpha_{i,\oplus}\}) \equiv 1 - p_a^{\text{tr}}(\{\alpha_{i,\oplus}\})$.

For the 2-year (3-year) data, the IceCube collaboration estimated the background of atmospheric muons

³We have checked that the fraction of tracks and showers predicted by the IceCube collaboration for different astrophysical spectra [3] agrees with our expectations for the $(1 : 1 : 1)_\oplus$ flavor ratio.

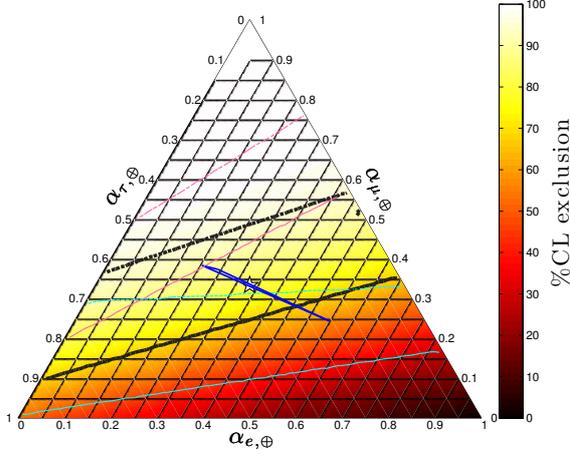


Figure 1: Ternary plot of the exclusion C.L. for all possible flavor combinations ($\alpha_{e,\oplus} : \alpha_{\mu,\oplus} : \alpha_{\tau,\oplus}$) as seen at Earth, given the 7 tracks and 21 showers observed at IceCube after 2 years. The lower right corner corresponds to 100% electron neutrinos, the upper corner is 100% muon neutrinos, and the lower left corner to 100% tau neutrinos. The central sliver in blue corresponds to the possible flavor combinations for astrophysical neutrinos, after oscillations have been averaged during propagation. The best-fit is the darkest point, $(1 : 0 : 0)_{\oplus}$. The white star corresponds to $(1 : 1 : 1)_{\oplus}$, which is expected from a $(1 : 2 : 0)_S$ combination at the source. The color scale indicates the exclusion C.L. given an E_{ν}^{-2} spectrum of incoming neutrinos. Solid (dashed) lines show 68% C.L. (95% C.L.) contours, cyan for E_{ν}^{-1} , thick black for E_{ν}^{-2} and pink for E_{ν}^{-3} spectra. From Ref. [4].

and neutrinos to be $b_{\mu} = 6 \pm 3.4$ ($b_{\mu} = 8.4 \pm 4.2$) and $b_{\nu} = 4.6_{-1.2}^{+3.7}$ ($b_{\nu} = 6.6_{-1.6}^{+5.9}$), respectively [2, 3]. In the results presented below, we take the background events to be Poisson-distributed, but we do not include the quoted systematic errors. We note that even if we consider the lower end of the 1σ intervals, only about two tracks would be allowed to be of astrophysical origin, in both the 2-year and the 3-year data samples. Let us notice that, even in that case, the number of expected astrophysical showers would be much larger than that of tracks, a factor of about 10 larger. We have checked that this does not change the best-fit value, but it just slightly reduces the significance of our results. Additionally, neutrinos from atmospheric charmed meson decays could represent a few extra background events. Given the uncertainty in this prediction (see, e.g., Ref. [48]), we consider this case separately and use a benchmark component [48]. For the fraction of background showers and tracks in the 30 TeV – 2 PeV energy range, we use the numbers quoted by the IceCube collaboration: tracks account for 69% of the conventional atmospheric neutrino event rate, 19% of the prompt atmospheric neutrino event rate and 90% of the

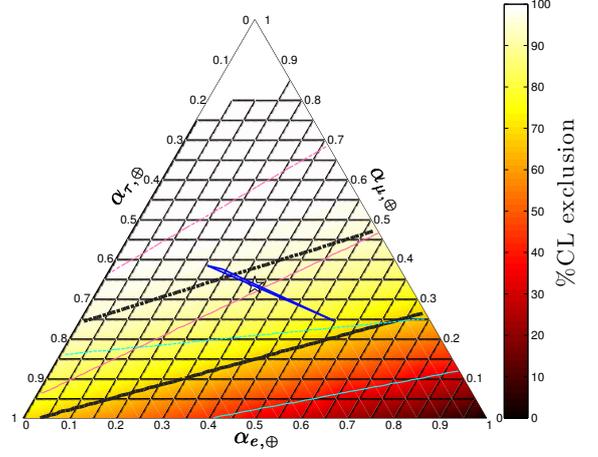


Figure 2: Same as Fig. 1, but given the 9 tracks and 28 showers observed at IceCube after 3 years. The best-fit is still $(1 : 0 : 0)_{\oplus}$, and the canonical flavor ratio $(1 : 1 : 1)_{\oplus}$ is disfavored at a slightly higher C.L.

events induced by atmospheric muons [3]. We have also checked that the uncertainties in the ratio of tracks to showers from atmospheric neutrinos, as computed with different initial fluxes, do not change our results in a significant way. For instance, using the high-energy atmospheric neutrino fluxes of Refs. [49, 50, 51], the fraction of tracks induced by the conventional flux is $\sim 50\%$. This would only weaken our conclusions by changing the C.L. contours by a few percent.

The likelihood of observing N_{tr} tracks and N_{sh} showers, for a given combination $\{\alpha_{i,\oplus}\}$ and a total number of astrophysical neutrinos N_a , is

$$\begin{aligned} \mathcal{L}(\{\alpha_{i,\oplus}\}, N_a | N_{\text{tr}}, N_{\text{sh}}) = & e^{-(p_a^{\text{tr}} N_a + p_{\mu}^{\text{tr}} b_{\mu} + p_{\nu}^{\text{tr}} b_{\nu})} \frac{(p_a^{\text{tr}} N_a + p_{\mu}^{\text{tr}} b_{\mu} + p_{\nu}^{\text{tr}} b_{\nu})^{N_{\text{tr}}}}{N_{\text{tr}}!} \\ & \times e^{-(p_a^{\text{sh}} N_a + p_{\mu}^{\text{sh}} b_{\mu} + p_{\nu}^{\text{sh}} b_{\nu})} \frac{(p_a^{\text{sh}} N_a + p_{\mu}^{\text{sh}} b_{\mu} + p_{\nu}^{\text{sh}} b_{\nu})^{N_{\text{sh}}}}{N_{\text{sh}}!}, \end{aligned} \quad (9)$$

where $p_{\nu}^{\text{tr}} = 0.69$ ($p_{\nu}^{\text{sh}} = 1 - p_{\nu}^{\text{tr}}$) is the fraction of tracks (showers) in the atmospheric neutrino background and $p_{\mu}^{\text{tr}} = 0.9$ ($p_{\mu}^{\text{sh}} = 1 - p_{\mu}^{\text{tr}}$) is the fraction of tracks (showers) in the atmospheric muon background [3]. Since the total number of events produced by astrophysical neutrinos is not of interest in this analysis, N_a can be treated as a nuisance parameter and can be set to the value $N_a^{\text{max}}(\{\alpha_{i,\oplus}\})$ which maximizes $\mathcal{L}(\{\alpha_{i,\oplus}\}, N_a | N_{\text{tr}}, N_{\text{sh}})$ for $\{\alpha_{i,\oplus}\}$, yielding $\mathcal{L}_{\text{p}}(\{\alpha_{i,\oplus}\} | N_{\text{tr}}, N_{\text{sh}}) \equiv \mathcal{L}(\{\alpha_{i,\oplus}\}, N_a^{\text{max}}(\{\alpha_{i,\oplus}\}) | N_{\text{tr}}, N_{\text{sh}})$.

We define the log-likelihood ratio

$$\lambda(N_{\text{tr}}, N_{\text{sh}} | \{\alpha_{i,\oplus}\}) = -2 \ln \left(\frac{\mathcal{L}_{\text{p}}(\{\alpha_{i,\oplus}\} | N_{\text{tr}}, N_{\text{sh}})}{\mathcal{L}_{\text{p}}(\{\alpha_{i,\oplus}\}_{\text{max}} | N_{\text{tr}}, N_{\text{sh}})} \right), \quad (10)$$

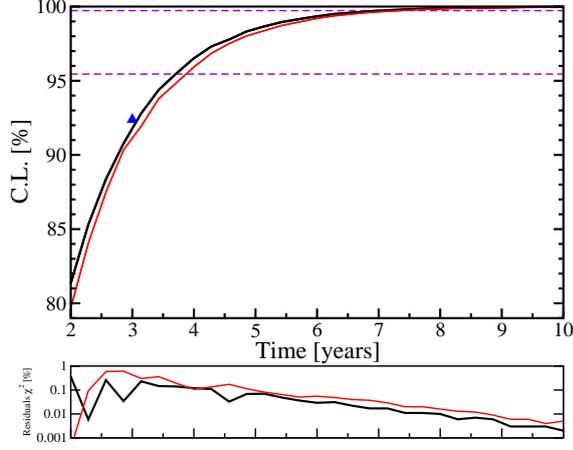


Figure 3: *Top panel:* Evolution of the C.L. of exclusion of the canonical flavor ratio $(1 : 1 : 1)_\oplus$ for an E_ν^{-2} spectrum, computed by using the 2-year data and the background expectation and extrapolating them in time. The black (red) line represents the case without the (with the benchmark) prompt atmospheric neutrino background. The blue triangle indicates the actual result with the 3-year data. The two dashed lines represent the 2σ and 3σ C.L. *Bottom panel:* Residuals with respect to a χ^2 distribution with two degrees of freedom, showing that indeed the actual distribution of the test statistic λ is very close to a χ^2 distribution.

where $\{\alpha_{i,\oplus}\}_{\max}$ is the combination of neutrino flavors that maximizes the likelihood of observing N_{tr} tracks and N_{sh} showers. The p-value for a given combination $\{\alpha_{i,\oplus}\}$ is

$$p(\{\alpha_{i,\oplus}\}) = \sum_{N_{\text{tr}}, N_{\text{sh}}} P(N_{\text{tr}}, N_{\text{sh}} | \{\alpha_{i,\oplus}\}), \quad (11)$$

where $P(N_{\text{tr}}, N_{\text{sh}} | \{\alpha_{i,\oplus}\}) \equiv \mathcal{L}_p(\{N_{\text{tr}}, N_{\text{sh}}\} | \{\alpha_{i,\oplus}\})$ is the probability of observing N_{tr} tracks and N_{sh} showers given the flavor ratio $\{\alpha_{i,\oplus}\}$ and $N_{\text{a}}^{\max}(\{\alpha_{i,\oplus}\})$, and the sum runs over all combinations of N_{tr} and N_{sh} which satisfy $\lambda(N_{\text{tr}}, N_{\text{sh}} | \{\alpha_{i,\oplus}\}) > \lambda(N_{\text{tr}} = 7, N_{\text{sh}} = 21 | \{\alpha_{i,\oplus}\})$. Although we use the exact definition of the p-value, Eq. (11), we note that the test statistic λ asymptotically approaches a χ^2 distribution with two degrees of freedom (see the bottom panel in Fig. 3). The p-value can easily be translated into an exclusion C.L.: $\text{C.L.}(\{\alpha_{i,\oplus}\}) = 1 - p(\{\alpha_{i,\oplus}\})$.

4. Results

Using Eq. (11), we compute the exclusion limits for all combinations of $\{\alpha_{i,\oplus}\}$, without any restrictions on the flavor ratios at Earth. We show the results for the 2-year data in Fig. 1 and in Tab. 1 we quantitatively state how disfavored the canonical flavor ratio $(1 : 1 : 1)_\oplus$

$d\phi_\nu/dE_\nu \propto$	E_ν^{-1}	E_ν^{-2}	E_ν^{-3}
π/K	96%	81%	52%
$\pi/K + \text{charm}$	95%	80%	53%
π/K (3-yr data)	99%	92%	70%

Table 1: C.L. limits for the $(1 : 1 : 1)_\oplus$ flavor ratio observed at Earth. The three columns represent three possible assumptions for the index of the power-law energy spectrum of the astrophysical neutrinos. “ π/K ” includes the conventional atmospheric muon and neutrino background and “ $\pi/K + \text{charm}$ ” additionally includes the benchmark flux of “prompt” neutrinos from the decay of charmed mesons in the atmosphere. The two upper rows refer to the 2-year data [2] and the last one to the 3-year data [3].

is. The color scale shows the exclusion C.L. assuming an E_ν^{-2} astrophysical spectrum with the same normalization for all three flavors, which describes well the data in the 30 TeV – 2 PeV energy range [2]. Lines show the 68% and 95% C.L. limits, which we illustrate for three different spectra. For the 2-year data, the $(1 : 1 : 1)_\oplus$ scenario is disfavored at 81% C.L. for an E_ν^{-2} spectrum. Harder spectra are more constrained, since a larger flux of ν_μ 's and ν_τ 's at high energies leads to the production of more muons. We note that the best-fit point is $(1 : 0 : 0)_\oplus$, which cannot be obtained from any flavor ratio at sources assuming averaged oscillations during propagation.

Beyond the conventional π/K atmospheric neutrino background, the effect of an atmospheric charm component is also shown in Tab. 1, where we see that the changes are not important.

The results for the 3-year data are depicted in Fig. 2, where we use the same convention for colors and lines as in Fig. 1. In this case, the $(1 : 1 : 1)_\oplus$ scenario is disfavored at 92% C.L. for an E_ν^{-2} spectrum. Aside from not being yet statistically very significant, we note that the 3-year data follows the trend we would expect if the 2-year results were not a statistical fluctuation. This is quantitatively shown in Fig. 3, where we compute the evolution of the C.L. for $(1 : 1 : 1)_\oplus$ by scaling up in time the astrophysical and background events of the 2-year data (with and without the prompt atmospheric background). The blue triangle represents the result with the 3-year data without including the prompt atmospheric background, which is very close to the extrapolation from the 2-year data.

5. Summary and discussion

Although the statistical power of the high-energy events seen at IceCube remains low, the fact that the observed number of tracks is smaller than the expectation from the atmospheric muon and neutrino backgrounds

allows us to place moderate constraints on the flavor ratios of the astrophysical neutrinos. If these are assumed to have an unbroken E_ν^{-2} energy spectrum and they are allowed to have any flavor combination, the $(1 : 1 : 1)_\oplus$ ratio at Earth is disfavored at 81% C.L. (92% C.L.) with the 2-year (3-year) data. For other spectra, the limits are presented in Tab. 1.

Let us also note that for the best-fit for the power-law index of the astrophysical spectrum quoted by IceCube using the events above 60 TeV (deposited energy), $E_\nu^{-2.3}$ [3], $(1 : 1 : 1)_\oplus$ at Earth is disfavored at 86% C.L. with the 3-year data. It is compelling to note that significant limits are potentially at hand. Indeed, in the 3-year data [3], the proportion of tracks and showers is similar to that in the 2-year data. If the ratio of 1 track per 3 showers above 30 TeV holds for future observations, $(1 : 1 : 1)_\oplus$ could be disfavored at 3σ C.L. for an E_ν^{-2} spectrum after a total of 8 years, as shown in Fig. 3. If this trend continues, we are faced with several potential implications: (a) the atmospheric background has been overestimated; (b) some tracks have been misidentified as showers; (c) the main mechanism of astrophysical neutrino production is *not* purely hadronic interactions; (d) no flavor combination at the source provides a good fit to the data and hence, the observed flavor ratios are due to some non-standard physics which favors a dominant $\nu_e + \bar{\nu}_e$ composition at Earth, for instance as in some scenarios of neutrino decay [23, 24, 31, 32], *CPT* violation [25], pseudo-Dirac neutrinos [27, 28, 32] or sterile neutrino altered dispersion relations due to shortcuts in an extra dimension [33]; or (e) the neutrino cross sections are different from the standard expectation at high energies, as in some models of TeV gravity [34].

The first very high-energy events detected by IceCube have opened the door to the era of neutrino astronomy. Even with such a small sample, the event topology could provide compelling information on the production, propagation and detection of neutrinos at high energies. Nevertheless, these searches are statistically limited. Therefore, a future high-energy extension of the IceCube detector and the planned KM3NeT telescope [52] could be crucial in order to have the potential to firmly establish the origin and composition of these neutrinos.

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