Flavor Composition of the High-Energy Neutrino Events in IceCube

Olga Mena,* Sergio Palomares-Ruiz,† and Aaron C. Vincent‡
Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València, Apartado de Correos 22085, E-46071 Valencia, Spain
(Received 7 May 2014; revised manuscript received 27 June 2014; published 28 August 2014)

The IceCube experiment has recently reported the observation of 28 high-energy (> 30 TeV) neutrino events, separated into 21 showers and 7 muon tracks, consistent with an extraterrestrial origin. In this Letter, we compute the compatibility of such an observation with possible combinations of neutrino flavors with relative proportion $(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$. Although the 7:21 track-to-shower ratio is naively favored for the canonical $(1:1:1)_\oplus$ at Earth, this is not true once the atmospheric muon and neutrino backgrounds are properly accounted for. We find that, for an astrophysical neutrino E^{-2} energy spectrum, $(1:1:1)_\oplus$ at Earth is disfavored at 81% C.L. If this proportion does not change, 6 more years of data would be needed to exclude $(1:1:1)_\oplus$ at Earth at 3σ C.L. Indeed, with the recently released 3-yr data, that flavor composition is excluded at 92% C.L. The best fit is obtained for $(1:0:0)_\oplus$ at Earth, which cannot be achieved from any flavor ratio at sources with averaged oscillations during propagation. 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.

DOI: 10.1103/PhysRevLett.113.091103 PACS numbers: 95.85.Ry, 14.60.Pq, 29.40.Ka, 95.55.Vj

Introduction.—An all-sky search by the IceCube Collaboration has recently revealed the detection of 28 veto-passing events (7 tracks and 21 showers) between 30 TeV and 1.2 PeV, over a 662-day period, from May 2010 to May 2012 [1]. This rate is inconsistent with atmospheric neutrinos and muons alone, with a significance of 4.1σ, pointing to a major extraterrestrial component. Identifying the sources of such a neutrino flux requires dedicated analyses of the observed events, which include the study of their energy distribution, their correlation with photons and/or protons, their arrival direction, and their flavor composition. In this Letter, we perform, for the first time, the study of the flavor composition of the 28 observed events.

The atmospheric neutrino and muon background is expected to be $10.6^{+5.0}_{-3.6}$ events, of which 8.6 are expected to be tracks [1]. With only 7 observed tracks, this implies that the extraterrestrial component overwhelmingly produces showers inside the detector. However, this largely departs from the canonical expectation (see Ref. [2], though). Astrophysical neutrinos are commonly modeled as the decay products of pions, kaons, and secondary muons produced by (photo)hadronic interactions. As a result, the expectation for the neutrino flavor ratio at the source is $(\alpha_{e,S} : \alpha_{\mu,S} : \alpha_{\tau,S}) = (1:2:0)_S$. (We use the subscript $\oplus$ to denote the flavor composition as observed by the detector at Earth, whereas S represents the composition at the location of the astrophysical sources before any propagation effect takes place.) Decoherence occurs after propagating over astronomical distances, meaning that oscillations are averaged and this ratio becomes $(\alpha_{e,\oplus} : \alpha_{\mu,\oplus} : \alpha_{\tau,\oplus}) = (1:1:1)_\oplus$ at Earth [3]. This is given explicitly by the measured structure of the neutrino mixing matrix [4–6] and leads to a non-negligible component of astrophysically sourced tracks. 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 [7–12]), neutron decays [13], deviations from tribimaximal mixing [10,11,14–20], neutrino matter effects in the source [21], and other more exotic scenarios [14,22–31].

Below a few PeV, neutrino flavor ratios can be inferred from two event topologies: muon tracks, associated with the Čerenkov light of a propagating muon, and electromagnetic or hadronic showers. In this Letter, we assess the probability of observing the track-to-shower ratio seen by the IceCube neutrino telescope as a function of the signal neutrino composition. We consider two parameter spaces: first the full range $(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$ at the detector and second the restricted range allowed after averaging oscillations during propagation from astrophysical sources. 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, summarized in Figs. 1 and 2. We show that, after accounting for the expected backgrounds, the canonical scheme $(1:1:1)_\oplus$ is excluded at the 81% confidence level (C.L.) for an E^{-2} spectrum. Finally, we note that the new 3-yr data follow a similar proportion of tracks and showers [32], which increases the level of exclusion of the canonical scheme to the 92% C.L.

Neutrino events in IceCube.—The 28 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.

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

$$N_{\nu_i}^{\mathrm{sh,NC}} = TN_A \int_{E_{\min}}^{\infty} dE_\nu M^{\mathrm{NC}}(E_\nu) Att_{\nu_i}(E_\nu)\phi_\nu(E_\nu) \times \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma^{\mathrm{NC}}(E_\nu, y)}{dy}, \quad (1)$$

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 $d\sigma^{\mathrm{NC}}/dy$, $T = 662$ days. M^{NC} is the energy-dependent effective detector mass for NC interactions, $N_A = 6.022 \times 10^{23}\ \mathrm{g}^{-1}$. Att_{ν_i} is the attenuation factor due to the absorption and regeneration of ν_i when traversing the Earth and ϕ_ν is the neutrino flux.

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

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

For ν_τ (and analogously for $\bar{\nu}_\tau$), the total number of shower events induced by CC interactions with an hadronic tau decay mode is given by [33]

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

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 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/dz.

The number of showers produced by the electronic decay of the tau lepton, $N^{\mathrm{sh,CC\text{-}em}}$, is written in a similar way, but the differential distribution is instead the leptonic distribution with $z = E_e/E_\tau$ and the Θ functions in Eq. (3) are replaced by $\Theta(E_\nu(y + (1-y)z) - E_{\min}) \times \Theta(E_{\max} - E_\nu(y + (1-y)z))$ [33]. The total number of showers produced by ν_τ CC interactions (and equivalently by $\bar{\nu}_\tau$), $N_{\nu_\tau}^{\mathrm{sh,CC}}$, 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 the total number of contained-vertex tracklike (tr) events from ν_μ (and analogously from $\bar{\nu}_\mu$) is

$$N_{\nu_\mu}^{\mathrm{tr}} = TN_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_\mu}^{\mathrm{CC}}(E_\nu) Att_{\nu_\mu}(E_\nu)\phi_\nu(E_\nu) \times \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma_{\nu_\mu}^{\mathrm{CC}}(E_\nu, y)}{dy}. \quad (4)$$

In addition, muon tracks produced by CC ν_τ (and $\bar{\nu}_\tau$) interactions, $N_{\nu_\tau}^{\mathrm{tr}}$, followed by tau decays ($\tau \to \nu_\tau \nu_\mu \mu$), also contribute to the track rate. To account for these events, the branching ratio of tau decays into muons is included in an equation analogous to Eq. (4).

For the neutrino and antineutrino differential cross sections, we use the NUSIGMA neutrino-nucleon scattering Monte Carlo code [34], which uses the CTEQ6 parton distribution functions [35,36]. We use the IceCube effective masses $M_{\nu_i}^{\mathrm{CC}}$ and M^{NC} [1]. The attenuation factors have been computed for each flavor and for neutrinos and antineutrinos independently, following Refs. [37–39]. For simplicity and because typically it only amounts to a small correction [40], we have not considered the secondary ν_μ flux produced by ν_τ interactions [41]. The attenuation factor in the above equations is the average attenuation 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, $E_\nu^{-\gamma}$, for the three neutrino and antineutrino flavors. Although a detailed analysis using all of the spectral information is described elsewhere, we note that $\gamma \sim 2$ is the value favored by IceCube data [1].

Statistical analysis.—We denote the fractions of electron, muon, and tau neutrinos produced in astrophysical sources as $\{\alpha_{i,S}\}$. After propagation, averaged neutrino oscillations cause the flavor ratio at Earth to be $\{\alpha_{j,\oplus}\} = \sum_{k,i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_{i,S}\}$, where U is the neutrino mixing matrix for which we use the latest νfit results [6]. 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, $(1{:}1{:}1)_\oplus$.

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

$$N_{\mathrm{a}}(\{\alpha_{i,\oplus}\}) = \alpha_{e,\oplus}\left(N_{\nu_e}^{\mathrm{sh,CC}} + N_{\nu_e}^{\mathrm{sh,NC}}\right) + \alpha_{\mu,\oplus}\left(N_{\nu_\mu}^{\mathrm{tr}} + N_{\nu_\mu}^{\mathrm{sh,NC}}\right) + \alpha_{\tau,\oplus}\left(N_{\nu_\tau}^{\mathrm{tr}} + N_{\nu_\tau}^{\mathrm{sh,CC}} + N_{\nu_\tau}^{\mathrm{sh,NC}}\right), \quad (5)$$

where we implicitly assume the sum of neutrino and antineutrino events. The proportion of these events which is expected to produce muon tracks is

$$p_{\mathrm{a}}^{\mathrm{tr}}(\{\alpha_{i,\oplus}\}) = \frac{1}{N_{\mathrm{a}}(\{\alpha_{i,\oplus}\})}(\alpha_{\mu,\oplus} N_{\nu_\mu}^{\mathrm{tr}} + \alpha_{\tau,\oplus} N_{\nu_\tau}^{\mathrm{tr}}), \quad (6)$$

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

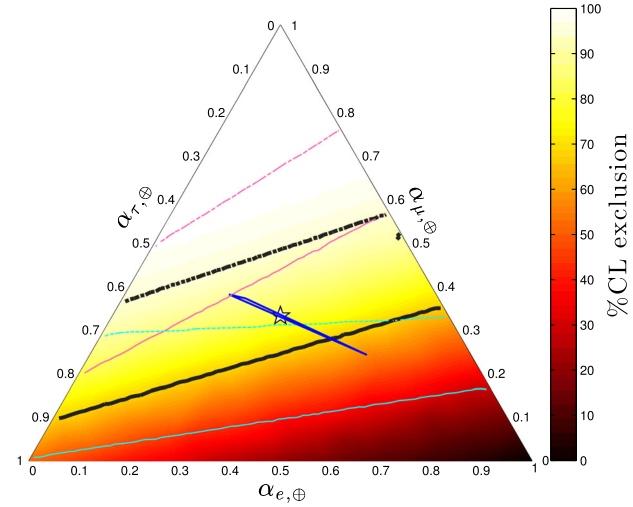

FIG. 1 (color online). Ternary plot of the exclusion C.L. for all possible flavor combinations $(\alpha_{e,\oplus}:\alpha_{\mu,\oplus}:\alpha_{\tau,\oplus})$ as seen at Earth, given the 7 tracks and 21 showers observed at IceCube. The lower right corner corresponds to 100% electron neutrinos, the upper corner to 100% muon neutrinos, and the lower left corner to 100% tau neutrinos. The central sliver outlined 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^{-2} spectrum of incoming neutrinos. Solid (dashed) lines show 68% C.L. (95% C.L.) contours, cyan for E^{-1}, thick black for E^{-2}, and pink for E^{-3} spectra.

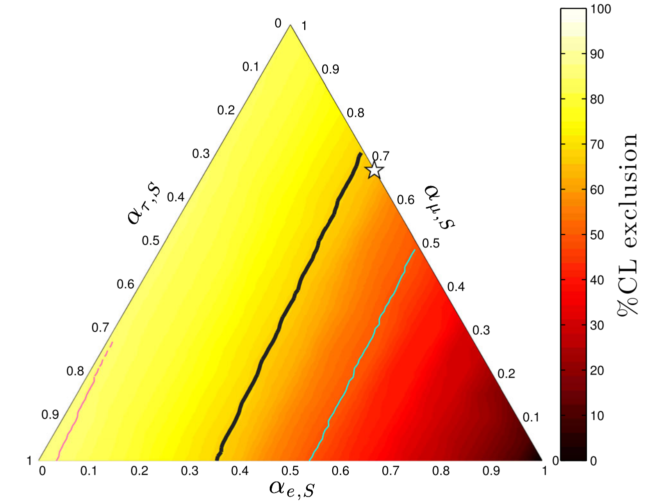

FIG. 2 (color online). Same as Fig. 1, but for $\{\alpha_{i,S}\}$ at the source and assuming the signal neutrinos are astrophysical and oscillation probabilities are in the averaged regime. That is, the parameter space is restricted to the blue sliver shown in Fig. 1. The best fit is the darkest point, $(1:0:0)_S$. The white star corresponds to the $(1:2:0)_S$ flavor combination. Standard flavor compositions lie within a narrow band along the right side of the triangle. Note that all combinations are allowed at 95% C.L. for the three spectra, and even at 68% C.L. for E^{-3}.

For the background, we consider $b_\mu = 6$ atmospheric muons and $b_\nu = 4.6$ atmospheric neutrinos [1]. We take the background events to be Poisson distributed and only consider statistical errors. We note that the lower systematic error quoted by the IceCube Collaboration on the total number of expected background events is 3.6, which is comparable to the statistical error for 10.6 events. This could reduce the significance of the exclusion limits we present below, whereas the upper value of the systematic error would pull the analysis toward a worse fit for $(1:1:1)_\oplus$, thus not affecting our results significantly. Additionally, neutrinos from atmospheric charmed meson decays could, in the benchmark model, represent 1.5 extra background events. Given the uncertainty in this prediction (see, e.g., Ref. [42]), we consider this case separately. 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 events induced by atmospheric muons [32]. 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. [43–45], the fraction of tracks induced by the conventional flux is ~50%. This would only weaken our conclusions by decreasing the exclusion C.L. by a few percent.

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

$$\mathcal{L}(\{\alpha_{i,\oplus}\}, N_{\rm a}|N_{\rm tr}, N_{\rm sh}) = e^{-(p_{\rm a}^{\rm tr}N_{\rm a}+p_\mu^{\rm tr}b_\mu+p_\nu^{\rm tr}b_\nu)}\frac{(p_{\rm a}^{\rm tr}N_{\rm a}+p_\mu^{\rm tr}b_\mu+p_\nu^{\rm tr}b_\nu)^{N_{\rm tr}}}{N_{\rm tr}!} \times e^{-(p_{\rm a}^{\rm sh}N_{\rm a}+p_\mu^{\rm sh}b_\mu+p_\nu^{\rm sh}b_\nu)}\frac{(p_{\rm a}^{\rm sh}N_{\rm a}+p_\mu^{\rm sh}b_\mu+p_\nu^{\rm sh}b_\nu)^{N_{\rm sh}}}{N_{\rm sh}!}, \tag{7}$$

where $p_\nu^{\rm tr} = 0.69$ ($p_\nu^{\rm sh} = 1 - p_\nu^{\rm tr}$) is the fraction of tracks (showers) in the atmospheric neutrino background and $p_\mu^{\rm tr} = 0.9$ ($p_\mu^{\rm sh} = 1 - p_\mu^{\rm tr}$) is the fraction of tracks (showers) in the atmospheric muon background [32]. Since the total number of events produced by astrophysical neutrinos is not of interest in this analysis, $N_{\rm a}$ can be treated as a nuisance parameter and can be set to the value $N_{\rm a}^{\rm max}(\{\alpha_{i,\oplus}\})$, which maximizes $\mathcal{L}(\{\alpha_{i,\oplus}\}, N_{\rm a}|N_{\rm tr}, N_{\rm sh})$ for $\{\alpha_{i,\oplus}\}$, yielding $\mathcal{L}_{\rm p}(\{\alpha_{i,\oplus}\}|N_{\rm tr}, N_{\rm sh}) \equiv \mathcal{L}(\{\alpha_{i,\oplus}\}, N_{\rm a}^{\rm max}(\{\alpha_{i,\oplus}\})|N_{\rm tr}, N_{\rm sh})$.

We construct the log-likelihood ratio

$$\lambda(N_{\rm tr}, N_{\rm sh}|\{\alpha_{i,\oplus}\}) = -2\ln\left(\frac{\mathcal{L}_{\rm p}(\{\alpha_{i,\oplus}\}|N_{\rm tr}, N_{\rm sh})}{\mathcal{L}_{\rm p}(\{\alpha_{i,\oplus}\}_{\rm max}|N_{\rm tr}, N_{\rm sh})}\right), \tag{8}$$

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

$$p(\{\alpha_{i,\oplus}\}) = \sum_{N_{\rm tr},N_{\rm sh}} P(N_{\rm tr}, N_{\rm sh}|\{\alpha_{i,\oplus}\}), \quad (9)$$

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

Results.—Using Eq. (9), 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 of Eq. (9) in Fig. 1 and provide several exclusions limits for $(1:1:1)_\oplus$ at Earth in Table I. The color scale shows the exclusion C.L. assuming an E^{-2} astrophysical spectrum for all three flavors, which describes well data in the 30 TeV–2 PeV energy range [1]. Lines show the 68% and 95% C.L. limits, which we illustrate for three different spectra. The $(1:1:1)_\oplus$ scenario is excluded at 81% C.L. for an E^{-2} spectrum. Harder spectra are more constrained, since a larger flux of ν_μs and ν_τs at high energies necessarily 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.

We now turn to the following question: what happens if we impose the restriction that the observed nonatmospheric neutrinos are extraterrestrial, such that oscillations are averaged during propagation? In this case, they must be contained within the blue sliver of Fig. 1, and the event topology data become less constraining, at the expense of an overall worse fit. This is shown in Fig. 2, where one can see that $(1:2:0)_S$ for the E^{-2} spectrum is disfavored at 65% C.L. with respect to the best fit, $(1:0:0)_S$, which could be explained, for instance, by neutron decay sources [13]. However, we note that a large fraction of Fig. 2 is disfavored at 1σ CL or more with respect to the best fit in Fig. 1. Different exclusion limits for this case are also presented in Table I.

Beyond the conventional π/K atmospheric neutrino background, the effect of an atmospheric charm component is shown in Table I, where we see that the changes are not significant.

Discussion.—Although the statistical power of the high-energy events seen at IceCube remains low, the 8.6 tracks expected from the atmospheric muon and neutrino backgrounds allow us to place moderate constraints on the flavor ratios of the nonbackground neutrinos. If these are assumed to have an E^{-2} energy spectrum and allowed to take any combination, the $(1:1:1)_\oplus$ ratio at Earth is excluded at 81% C.L. If they are constrained to be astrophysically sourced and oscillation probabilities are averaged during the propagation to Earth, this exclusion is reduced to 65% C.L. This is simply due to the reduction of the parameter space, so the likelihood varies by smaller amounts with respect to the full $\{\alpha_{i,\oplus}\}$ space, leading to a smaller constraining power for the same sample size.

It is compelling to note that significant limits are potentially at hand. Indeed, the new 3-yr IceCube data [32] indicate the detection of 9 extra events, of which only 2 are tracks. Hence, the proportion of tracks and showers after 3 years is similar to that in the 2-yr data. With an expected background of 8.4 ± 4.2 atmospheric muons and $6.6^{+5.9}_{-1.6}$ atmospheric neutrinos, this implies that, for an E^{-2} spectrum, $(1:1:1)_\oplus$ at Earth [$(1:2:0)_S$ at source] is excluded at 92% C.L. (77% C.L.). For other spectra, 3-yr exclusion limits are presented in Table I. With the new data, the best fit at source, $(1:0:0)_S$, is excluded with respect to the best fit at Earth, $(1:0:0)_\oplus$, at 75% C.L. for an E^{-2} spectrum. Let us also note that for the best-fit spectrum quoted by IceCube, $E^{-2.3}$ [32], $(1:1:1)_\oplus$ at Earth [$(1:2:0)_S$ at source] is excluded at 86% C.L. (70% C.L.). If the ratio of 1 track per 3 showers holds for future observations, $(1:1:1)_\oplus$ could be excluded at 3σ C.L. for an E^{-2} spectrum after a total of 8 years. If this trend continues, we are faced with several potential implications: (a) the main mechanism of astrophysical neutrino production is *not* purely hadronic interactions, and indeed, the best fit at source is $(1:0:0)_S$ indicating an origin in neutron, rather than meson, decay; (b) no flavor combination at the source provides a good fit to the data, and hence, the observed flavor ratios are due to some nonstandard effect which favors a dominant ν_e composition at Earth, for instance as in some scenarios of neutrino decay, *CPT* violation, or pseudo-Dirac neutrinos [22–24,30,31]; (c) the atmospheric background has been overestimated; or (d) some tracks have been misidentified as showers.

TABLE I. Exclusion limits for the $(1:1:1)_\oplus$ flavor ratio observed at Earth [for the $(1:2:0)_S$ flavor ratio at the source and assuming averaged oscillations]. The three columns represent three possible assumptions for the spectrum of the astrophysical neutrinos as a function of their energy. "π/K" includes the conventional atmospheric muon and neutrino background, and "π/K + 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-yr data [1] and the last one to the recently released 3-yr data [32].

$d\phi/dE_\nu \propto$	E_ν^{-1}	E_ν^{-2}	E_ν^{-3}
π/K	96% (78%)	81% (65%)	52% (36%)
π/K + charm	95% (76%)	80% (63%)	53% (37%)
π/K (3-yr data)	99% (87%)	92% (77%)	70% (52%)

The 28 IceCube events have opened the door to the era of neutrino astronomy. Even with such a small sample, the event topology provides compelling information on the production, propagation, and detection of neutrinos at high energies. Future data have the potential to firmly establish the origin and composition of these neutrinos.

We thank Claudio Kopper and Nathan Whitehorn for clarifying details about the IceCube data and for providing us with the effective masses and Sergei Sinegovsky for providing us with tabulated high-energy atmospheric neutrino fluxes. We also thank Glen Cowan and Miguel Nebot for enlightening discussions on statistics and Pilar Hernández, Carlos Peña-Garay, Tom Weiler, and Walter Winter for useful comments. O. M. is supported by the Consolider Ingenio project CSD2007–00060, by PROMETEO/2009/116, by the Spanish Grant No. FPA2011–29678 of the MINECO. S. P. R. is supported by a Ramón y Cajal contract and by the Spanish MINECO under Grant No. FPA2011-23596. A. C. V. is supported by FQRNT and European Contract No. FP7-PEOPLE-2011-ITN. The authors are also partially supported by PITN-GA-2011-289442-INVISIBLES. S. P. R. is also partially supported by the Portuguese FCT through the Projects No. CERN/FP/123580/2011, No. PTDC/FIS-NUC/0548/2012, and No. CFTP-FCT Unit 777 (PEst-OE/FIS/UI0777/2013), which are partially funded through POCTI (FEDER).

*omena@ific.uv.es
†sergiopr@ific.uv.es
‡vincent@ific.uv.es

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