What is the Flavor of the Cosmic Neutrinos Seen by IceCube?

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We analyze the high-energy neutrino events observed by IceCube, aiming to probe the initial flavor of cosmic neutrinos. We study the track-to-shower ratio of the subset with energy above 60 TeV, where the signal is expected to dominate, and show that different production mechanisms give rise to different predictions even accounting for the uncertainties due to neutrino oscillations. We include for the first time the passing muons observed by IceCube in the analysis. They corroborate the hypotheses that cosmic neutrinos have been seen and their flavor matches expectations derived from the neutrino oscillations.

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Introduction.—The search for high-energy starting events (HESE) in the IceCube detector provided the first evidence for a high-energy neutrino flux of extraterrestrial origin [1–3]. In three year of data taking [1], 37 events with deposited energies above 30 TeV were observed, relative to an expected background of 8.4 ± 4.2 cosmic-ray muon events and 6.6 ± 5.9 atmospheric neutrinos.

The scientific debate about the origin of these events is extremely lively. There is little doubt that cosmic neutrinos have been seen, but their origin is not understood. In order to proceed, the flavor composition has to be probed. The flavor discrimination is, in principle, possible by looking at the topology of the events. Most HESE have "shower" topology that includes neutral-current (NC) interactions of all neutrino flavors and charged-current (CC) interactions of ν_e and ν_τ, since the decay length of the τ lepton is too short to be resolved below ~1 PeV. On the other hand, events with "track" topology are produced by CC interactions of ν_μ. Thus, the crucial observable quantity is the ratio between track and shower events at high energy and it can be used to confirm the cosmic origin and/or to discriminate among different production scenarios. With this purpose, the authors of Refs. [4,5] recently discussed the observed track-to-shower ratio of the IceCube data with energy above 30 TeV. They conclude that these data exclude at 92% confidence level (C.L.) the hypothesis of cosmic neutrinos produced by hadronic interactions. They suggest misunderstanding of the background, misidentification of tracks, or exotic physics as possible explanations of their results. These studies have been influential, setting the case for a muon deficit problem in IceCube; see, e.g., Refs. [6,7].

In view of the importance of this issue, we perform an independent analysis adding our contribution to the discussion. We focus on the subset of events with deposited energy above 60 TeV, where the signal is expected to dominate. We show that different production mechanisms give rise to distinctive expectations of the track-to-shower ratio, even when the uncertainties due to neutrino oscillations are included. Additionally, the muon neutrinos passing through Earth confirm the existence of an astrophysical component and we include for the first time this information in the analysis. We find that the present data set is well compatible with the hypothesis that cosmic neutrinos have been seen, even if the limited statistics does not yet allow us to discriminate the initial flavor.

From neutrinos to HESE events.—Let us consider HESE events with deposited energies between 60 TeV and 3 PeV and starting inside IceCube which are likely to be dominated by the signal due to cosmic neutrinos. The expected number of events produced by an isotropic flux Φ_ℓ of neutrinos and antineutrinos with flavor ℓ is

$$N = 4\pi T \int dE \Phi_\ell(E) A_\ell(E), \tag{1}$$

where $\ell = e, \mu, \tau$ and T is the observation time. The effective areas $A_\ell(E)$ are provided by the IceCube Collaboration [3] and include the effects of neutrino cross sections, partial neutrino absorption in the earth, detector efficiency, and specific cuts of the HESE analysis.

In order to calculate the track-to-shower ratio, we separate the different contributions to the effective areas,

$$A_\mu(E) = A_\mu^T(E) + A_\mu^S(E), \tag{2}$$

where $A_\mu^T(E) \equiv p_T(E) A_\mu(E)$ is the effective area for ν_μ CC interactions that produce tracks in the detector, while $A_\mu^S(E) \equiv [1 - p_T(E)] A_\mu(E)$ is the effective area for NC interactions that are instead observed as showers. The parameter $p_T(E)$ is the probability that an *observed* event (i.e., passing all the cuts in the HESE analysis) produced by a muon neutrino with energy E is a track event. This quantity is given by

$$p_T(E) = \frac{\sigma_{\rm CC}(E) M_\mu^{\rm CC}(E)}{\sigma_{\rm NC}(E) M^{\rm NC}(E) + \sigma_{\rm CC}(E) M_\mu^{\rm CC}(E)},$$

where $\sigma_{\rm CC}(E)$ and $\sigma_{\rm NC}(E)$ are the cross section for CC and NC interactions of neutrinos [8] while $M_\mu^{\rm CC}(E)$ and $M^{\rm NC}(E)$ are the effective detector mass for CC and NC interactions of ν_μ [3]. The probability p_T is mildly dependent on energy and approximately equals 0.8.

The number of showers N_S and tracks N_T in the IceCube detector can then be calculated according to

$$\begin{aligned} N_S &= 4\pi T \int_0^{\bar{E}} dE \{\Phi_e(E) A_e(E) + \Phi_\tau(E) A_\tau(E) \\ &\quad + \Phi_\mu(E)[1 - p_T] A_\mu(E)\}, \\ N_T &= 4\pi T \int_0^{\bar{E}} dE \Phi_\mu(E) p_T A_\mu(E). \end{aligned} \tag{3}$$

In the above relation, we neglected the small fraction of ν_τ CC events followed by taus decaying into muons, which can be potentially observed as tracks. Moreover, we introduced an upper integration limit at $\bar{E} = 3$ PeV, since the HESE analysis only includes events with deposited energy below 3 PeV. In principle, the effects of the threshold at $E_{\rm dep} = 3$ PeV should be implemented as a correction of the effective areas. Here, we assume that this can be mimicked by a sharp cut in the $A_\ell(E)$ at the neutrino energy $E = 3$ PeV.

We use the effective areas calculated by IceCube, thus implementing the correct relationship between the neutrino energy and the energy deposited in the detector. These areas are the critical ingredient to correctly predict the track-to-shower ratio. We tested the validity of our calculations by comparing the expected numbers of events with those shown in supplemental Table IV of Ref. [1]. For the best-fit astrophysical spectrum, we obtain $N_S = 14.8$ and $N_T = 3.6$ to be compared with $N_S = 14.4$ and $N_T = 3.8$. Also, we reproduce the fraction of tracks produced by π/K and prompt atmospheric neutrinos within 0.03.

Note that the threshold of $E_{\rm dep} = 60$ TeV adopted in this work and in IceCube fits [1,3] does not coincide with the charge cut adopted for HESE collection, corresponding to about 30 TeV, and that Ref. [3] does not state explicitly which threshold was included in effective area calculations. However, as far as the signal (not the background) is concerned, these points are of minor relevance, since events below 60 TeV account for only ~10% of the expected rate and they do not modify the track-to-shower ratio. We conclude that our approach is appropriate for the level of precision at which we aim in this analysis.

Description of cosmic neutrinos.—Cosmic neutrinos are certainly due to nonthermal processes. Thus, we expect that their fluxes averaged over the directions are approximated by a power-law distribution up to a maximum value that we assume to be larger than 3 PeV,

$$\Phi_\ell(E) = \frac{F_\ell \times 10^{-8}}{\text{cm}^2\,\text{s}\,\text{sr}\,\text{GeV}} \left(\frac{\text{GeV}}{E}\right)^\alpha, \tag{4}$$

where the factors F_ℓ are (non-negative) adimensional coefficients and α is the spectral index. We use the value $\alpha = 2$, expected on a theoretical basis, and find the following expressions for the number of shower and track events,

$$N_S = 8.4 F_e + 0.9 F_\mu + 6.3 F_\tau, \qquad N_T = 3.7 F_\mu. \tag{5}$$

The track-to-shower ratio is then

$$\frac{N_T}{N_S} = \frac{\xi_\mu}{2.3 - 2.0\xi_\mu - 0.6\xi_\tau}, \tag{6}$$

where we introduced the flavor fractions at Earth (i.e., in the detection point), defined as

$$\xi_\ell \equiv F_\ell / F_{\rm tot}, \tag{7}$$

with $F_{\rm tot} = F_e + F_\mu + F_\tau$, and we considered that $\xi_e = 1 - \xi_\mu - \xi_\tau$. The numerical coefficients of Eq. (6) depend mildly on the spectral index, as quantified later.

Effect of neutrino oscillations.—For neutrinos traveling over cosmic distances, the simplest regime (the Gribov-Pontecorvo regime [9]) applies and the oscillation probabilities $P_{\ell\ell'}$ are energy independent. The flavor fractions at Earth are thus given by

$$\xi_\ell = \sum_{\ell'} P_{\ell\ell'} \xi^0_{\ell'} \quad \text{with} \quad P_{\ell\ell'} = \sum_{i=1,3} |U^2_{\ell i} U^2_{\ell' i}|,$$

where U is the neutrino mixing matrix and ξ^0_ℓ are the flavor fractions at the source given by

$$\xi^0_\ell \equiv F^0_\ell / F_{\rm tot}, \tag{8}$$

where F^0_ℓ indicates the adimensional flux normalizations before oscillations—see Eqs. (4) and (7). It is generally expected, see, e.g., Refs. [10–14], that a cosmic population is characterized by a flavor content $(\xi_e : \xi_\mu : \xi_\tau) \sim (1/3 : 1/3 : 1/3)$ independently of the specific production mechanism. In this case, the track-to-shower ratio in IceCube is

$$\frac{N_T}{N_S} = 0.24, \tag{9}$$

as can be calculated from Eq. (5). If we consider a spectral index $\alpha \neq 2$, this prediction is only marginally affected, and is approximately $N_T/N_S = 0.24 + 0.08(2 - \alpha)$.

The equipartition of neutrino flavors at Earth is, however, only an approximation that is no longer adequate after IceCube data: A certain imprint of the neutrino production mechanism does remain. It is important to exploit the track-to-shower ratio observed by IceCube to discriminate the neutrino origin. To explore this possibility on realistic grounds, it is necessary to quantify the relevance of uncertainties in oscillation parameters for the predictions of N_T/N_S. We note that the probabilities $P_{\ell\ell'}$ have a nonlinear dependence on the neutrino oscillation parameters and, as a consequence, the errors in θ_{12}, θ_{13}, θ_{23}, and δ cannot be propagated linearly. Moreover, the allowed regions for θ_{23} and δ parameters have complicated structures that cannot be correctly described by assuming Gaussian dispersions with the quoted 1σ errors. We overcame these difficulties by constructing likelihood distributions of $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, and δ from the $\Delta\chi^2$ profiles given by Ref. [15]. Namely, we assume that the probability distributions of each parameter are provided by $\mathcal{L} = \exp(-\Delta\chi^2/2)$. Then, we combine the various likelihood functions assuming negligible correlations and we determine the probability distributions of N_T/N_S by Monte Carlo extraction of the oscillation parameters. Our approach automatically implements the unitarity of the neutrino mixing matrix (and the nonlinear dependence of the $P_{\ell\ell'}$ on oscillation parameters) and takes into account non-Gaussian parameter distributions.

We consider four specific assumptions for the flavor composition at the source $(\xi_e^0 : \xi_\mu^0 : \xi_\tau^0)$ which are relevant for the interpretation of observational data because they are related to specific production mechanisms. We consider (where color references are to colors used in Fig. 1) (i) (1/3 : 2/3 : 0) for π decay (yellow), (ii) (1/2 : 1/2 : 0) for charmed mesons decay (blue), (iii) (1 : 0 : 0) for β decay of neutrons (green), and (iv) (0 : 1 : 0) for π decay with damped muons (red).

Figure 1 summarizes our results. The left-hand panel is obtained by using the distribution of the oscillation parameters corresponding to the assumption of normal hierarchy, while the right-hand panel corresponds to the case of inverse hierarchy. We see that N_T/N_S distributions are well separated when different neutrino production mechanisms are considered. This means that a precise determination of N_T/N_S could provide hints on the neutrino origin, even with the present knowledge of neutrino mixing parameters. From the neutrino physics point of view, large contributions to N_T/N_S dispersions are provided by the δ and θ_{23} parameters. Finally, our results indicate that the flavor composition of cosmic neutrinos cannot be used to learn about neutrinos, unless the neutrino production mechanism is independently identified.

For the purposes of our discussion, it is finally important to note that the track-to-shower ratio has a limited range of possible values, if neutrinos have cosmic origin. If we take the best-fit oscillation parameters and assume a spectral index $\alpha = 2$, we obtain

$$0.15 < \frac{N_T}{N_S} < 0.30 \quad \text{(expected from cosmic origin)}. \qquad (10)$$

The minimal value, obtained for neutron decay (i.e., $\xi_\mu^0 = \xi_\tau^0 = 0$ and $\xi_e^0 = 1$) matters for the claims of a possible muon deficit problem in IceCube. If we vary the spectral index, this interval shifts by $\sim\mp 10\%$. The oscillation parameters slightly affect these expectations; e.g., for the lowest (highest) value of $\sin^2\theta_{23} = 0.385$ (0.644) [15], the interval of Eq. (10) narrows to [0.16,0.27] (widens to [0.09,0.43]).

Data analysis: General considerations.—In the energy window 60 TeV $< E_{\rm dep} <$ 3 PeV, 20 events have been observed, consisting of 16 shower and 4 track events, against an expected background of ~3 events from atmospheric muons and neutrinos. By performing a likelihood fit, an isotropic astrophysical component with E^{-2} spectrum and flavor composition (1/3 : 1/3 : 1/3), as expected due to neutrino flavor oscillations (see, e.g., Refs. [11–13]), is extracted at 5.7σ confidence level [1]. Namely, the best-fit astrophysical neutrino flux is given by $E^2\Phi_\ell(E) = (0.95 \pm 0.3) \times 10^{-8}\ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$, where the index $\ell = e, \mu, \tau$ refers to the neutrino flavor.

New data and analyses confirm the evidence for a cosmic-neutrino population. Recently, a new technique was developed that permits one to isolate events starting

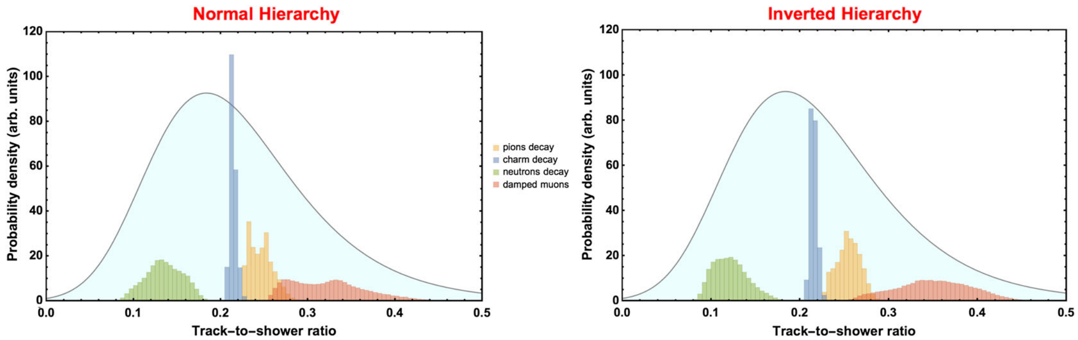

FIG. 1 (color online). Expected track-to-shower ratio of cosmic neutrinos for the four production mechanisms described in the text. The distributions show the effect of uncertainties in the neutrino oscillation parameters. The left-hand (right-hand) panel is obtained for normal (inverse) hierarchy. The shaded region is the likelihood corresponding to Eq. (12).

in the IceCube detector down to ∼1 TeV and to observe astrophysical neutrinos (in the southern sky) with energies as low as 10 TeV [2]. Even more interesting, an independent analysis of the spectrum of muon neutrinos passing through Earth has confirmed the existence of an astrophysical component. Analyzing the same period of the HESE analysis, an excess of high-energy muon tracks is observed, which was fitted by assuming an astrophysical muon neutrino flux equal to $E^2\Phi_\mu(E) = (1.01 \pm 0.35) \times 10^{-8}\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$ [16,17].

Track-to-shower ratio.—The set of events observed by IceCube in three years of data taking between 60 TeV and 3 PeV consists of a total number of $n_T = 4$ tracks and $n_S = 16$ showers. These include, on average, $b_T = 2.1$ and $b_S = 0.7$ background events expected from atmospheric neutrinos (1.7 tracks and 0.7 showers) and muons (0.4 tracks and no showers) [1]. In the above estimates, we assume that the prompt atmospheric neutrinos give negligible contributions, as is required by the spectral and arrival angle distributions of IceCube events. The number of tracks N_T and showers N_S that have to be ascribed to cosmic sources can be estimated from the Poisson likelihood functions: $\mathcal{L}(N_i) \propto \lambda_i^{n_i} e^{-\lambda_i}$, where $\lambda_i = N_i + b_i$ and the index $i = T, S$ is used to refer to track and shower events. By using the above data, we obtain $N_T = 3.1 \pm 2.1$ and $N_S = 16.3 \pm 4.1$. Marginalizing over the total number of events, we reconstruct the track-to-shower ratio of a cosmic neutrino obtaining

$$\frac{N_T}{N_S} = 0.11^{+0.23}_{-0.05} \quad \text{(HESE only)}, \tag{11}$$

where the error was obtained by integrating out symmetrically $(1 - \mathrm{C.L.})/2$ on both sides of the N_T/N_S distribution using a confidence level of 68.3%. The above result can be compared with the range given in Eq. (10) and shows that IceCube results do not contradict the assumption of a cosmic-neutrino population. Due to the small number of tracks, the determination of the ratio N_T/N_S has a large error, that does not permit to derive any conclusion on the initial flavor of cosmic neutrinos. Fortunately, completely equivalent and independent information can be obtained by the recently released IceCube data on passing muons [16]. About 12 events with visible energy above 60 TeV have been observed which cannot be explained by atmospheric neutrinos and muons. In the assumption of a E^{-2} neutrino spectrum, this corresponds to a flux normalization $F_\mu = 1.01 \pm 0.35$ that can be translated into a number of tracks from cosmic neutrinos by using Eq. (5). We obtain $N_T = 3.7 \pm 1.3$, which is perfectly compatible with the value $N_T = 3.1 \pm 2.1$ obtained from the HESE analysis, but is affected by a factor ∼2 smaller error. We also include this information in our analysis by constructing a combined likelihood, given by the product of the two Poisson likelihoods for N_T and N_S and the Gaussian likelihood for F_μ. We then extract the bound,

$$\frac{N_T}{N_S} = 0.18^{+0.13}_{-0.05} \quad \text{(all data)}, \tag{12}$$

by taking into account the equivalence between F_μ and N_T expressed by Eq. (5) and marginalizing with respect to the total number of events. The likelihood distribution for the track-to-shower ratio of cosmic neutrinos is shown by the shaded region in Fig. 1.

Discussion and summary.—Figure 1 shows clearly that (i) there is no tension between the present observational results and the assumption of a cosmic-neutrino population, which is the central observational value in the middle of the expected region, and (ii) there is no clear preference for a specific neutrino production mechanism, which is the observational error comparable to the difference between the various predictions.

Our results are substantially different from those obtained by Refs. [4,5]. This is partly due to the inclusion of the data on passing muons [16], and partly to the fact that Refs. [4,5] include in their analysis the HESE IceCube data between 30 and 60 TeV. Following IceCube, we do not consider this region which is background dominated and much less valuable to extract the signal.

Below 60 TeV, IceCube observes 16 events, consisting of 4 tracks and 12 showers [1]. The sum of tracks and showers agrees with the expectations, but there is a deficit of track events (the uncertainty on the background muon rate is, however, 50%) and an excess of shower events. The analysis of the data below 60 TeV of Refs. [4,5] assumes a background of $N_S \sim 3$; thus, most of the 12 showers should be cosmic neutrinos. This implies that $N_S > 50$ shower events are expected above 60 TeV [1], which disagrees with the observations. In short, the spectral distribution of the events, not discussed in Ref. [4], makes this position untenable.

One possible explanation of the track deficit and shower excess at low energy is that few ν_μ CC interactions were erroneously identified as showers since the muon track was missed (e.g., for events occurring close to the boundary of the fiducial volume). It is important to remark that our results, expressed by Eq. (12), are stable with respect to a possible track misidentification systematical error. Indeed, above 60 TeV, the number of expected showers is much larger than the rate of ν_μ CC interactions (and thus the erroneously identified events have a small relative importance on N_S). Moreover, N_T is well estimated by passing muon data [16], which are free from track misidentification systematics.

To summarize, the HESE events observed by IceCube above 60 TeV are consistent with the hypothesis that cosmic neutrinos have been seen. The same is true for passing muon events [16]. The flux of the cosmic muon neutrinos can be determined reasonably well. The analysis of the present data gives a track-to-shower ratio, Eq. (12), that agrees with that expected for a cosmic population, Eq. (10). The initial neutrino flavor cannot yet be probed: indeed, all production mechanisms are allowed.

Note added.—Recently, two works appeared [18,19] that contribute to assess the claims made in Ref. [4]. In this respect, their conclusions compare well with ours. Both papers discuss the spectral distribution of the events. None of these works analyze the effect of the uncertainty on the oscillation parameters.

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