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On the high-energy cosmic neutrinos seen by IceCube

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Abstract. We analyze the subset of high energy neutrino events observed by IceCube above 60 TeV, combined with the information provided by passing muons, aiming to probe the flavor of cosmic neutrinos. First, we compare the observed track-to-shower ratio with the predictions for a cosmic neutrino population, taking into account the different production mechanisms and the uncertainties due to neutrino oscillations. Our results corroborate the hypotheses that cosmic neutrinos have been seen. In addition, we show that the possibility of neutrinos decay is disfavored at about 2σ level of significance for both the normal and inverted neutrino mass hierarchy.

1. Introduction
The search for High Energy Starting Events (HESE) in IceCube detector provided the first evidence for a high-energy neutrino flux of extraterrestrial origin [1, 2, 3, 4, 5]. 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 yet understood. Based on our previous works Palladino et al. [6] and Pagliaroli et al. [7], we summarize our results concerning the flavor ratio of cosmic neutrinos and the possibility to use the information provided by the high-energy (HE) neutrinos observed by IceCube to constrain non-radiative neutrino decays.

2. The flavor ratio of HE cosmic neutrinos
Cosmic neutrinos are surely due to non-thermal processes. Thus we expect that their fluxes averaged over the directions, are approximated by a power law distribution of the kind

$$\Phi_\ell(E) = \frac{F_\ell \cdot 10^{-18}}{\text{cm}^2 \text{s sr GeV}} \cdot \left(\frac{100 \text{ TeV}}{E}\right)^{\alpha},$$

where the factors $F_\ell$ are (non-negative) adimensional coefficients and $\alpha$ is the spectral index. Different production mechanisms can generate a different blend of neutrinos and antineutrinos that can be expressed in term of a given flavor fractions at the source defined as:

$$\xi_\ell^0 \equiv \frac{F_\ell^0}{F_{\text{tot}}},$$

where the index 0 indicates that these quantities are defined at the source before oscillations and $F_{\text{tot}} = F_e + F_\mu + F_\tau$. 

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In the following we investigate four specific assumptions for the flavor composition at the source \((\xi^0 : \xi^0 : \xi^0)\) which are related to specific production mechanisms. We consider

i) \((1/3 : 2/3 : 0)\) for \(\pi\) decay (yellow);

ii) \((1/2 : 1/2 : 0)\) for charmed mesons decay (blue);

iii) \((1 : 0 : 0)\) for \(\beta\) decay of neutrons (green);

iv) \((0 : 1 : 0)\) for \(\pi\) decay with damped muons (red),

where we made reference to the color code used in Fig. 1. The blend of neutrinos is modified during propagation by neutrinos oscillations and a different flavor composition will arrive to the Earth \([8]\). Following Eq.(2), we can define the flavor fractions at Earth (i.e., in the detection point), as:

\[
\xi_\ell \equiv \frac{F_\ell}{F_{tot}}.
\]

For neutrinos travelling over cosmic distances the oscillation probabilities \(P_{\ell\ell'}\) are energy independent and 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. By using this prescription the expected flavor ratios at Earth are within the ranges \((\xi_e : \xi_\mu : \xi_\tau) \sim (0.24 - 0.55 : 0.24 - 0.40 : 0.21 - 0.35)\) due to the different production mechanisms (the oscillation parameters are fixed to their best-fit values \([9]\)).

3. Expected Track-to-Shower Ratio

The HESE events observed by IceCube encompass two different topologies: ‘shower’ topology (also known as cascade), that includes neutral current (NC) interactions of all neutrino flavors and charged current (CC) interactions of \(\nu_e\) and \(\nu_\tau\); ‘track’ topology produced by CC interactions of \(\nu_\mu\). Thus the track-to-shower ratio is the observable quantity that is most directly related to the flavor ratios at Earth discussed in the previous section. We can calculate the number of showers \(N_S\) and tracks \(N_T\) in the IceCube detector produced by an isotropic flux \(\Phi_\ell\) of neutrinos and antineutrinos of flavor \(\ell\) following \([6]\). The number of showers and tracks is obtained as:

\[
N_S = T \left\{ F_e c_e + F_\tau c_\tau + F_\mu c_\mu (1 - p_T) \right\}
\]

\[
N_T = T F_\mu c_\mu p_T ,
\]

where \(T\) is the observation time and the coefficients

\[
c_\ell = \frac{4\pi \cdot 10^{-18}}{\text{cm}^2 \text{s sr GeV}} \int dE \left( \frac{100 \text{ TeV}}{E} \right)^\alpha A_\ell(E)
\]

are determined by the detector effective areas \(A_\ell(E)\) \([3]\) and the energy dependence of the fluxes. The factor \(p_T \simeq 0.8\) in Eq.(4) represents the probability that a muon neutrino interacting in IceCube produces a track event, thus \(c_\mu (1 - p_T)\) is the contribution of muon neutrinos to showers due to neutral current interactions. This probability is derived in \([6]\) and is mildly dependent on energy.

Note that we use the effective areas calculated by IceCube, thus implementing the correct relationship between the neutrino energy and the energy deposited in the detector. We can test the validity of our calculations by comparing the expected numbers of events with those shown in Suppl. Tab. IV of \([1]\). As an example, for the best fit astrophysical spectrum with \(\alpha = 2\) we obtain \(N_S = 14.8\) and \(N_T = 3.6\) to be compared with \(N_S = 14.4\) and \(N_T = 3.8\).
The track-to-shower ratio can be obtained as a function of the neutrino flavor ratios at Earth as:

\[ \frac{N_T}{N_S} = \frac{\xi_\mu}{A + B \xi_\mu + C \xi_\tau}, \]  

(6)

where the numerical coefficients are approximately given by:

\[ A = \frac{c_e}{p_T \cdot c_\mu} \approx 2.27 + 1.12(\alpha - 2) + 0.46(\alpha - 2)^2 \]

\[ B = \frac{1 - p_T}{p_T} - A \approx 0.25 - A \]

\[ C = \frac{c_\tau - c_e}{p_T \cdot c_\mu} \approx -0.58 - 0.77(\alpha - 2) - 0.39(\alpha - 2)^2 \]

(7)

and the spectral index is within the range \(2.0 \leq \alpha \leq 2.6\).

An important contribution to the track-to-shower ratio theoretical uncertainty is provided by errors in neutrino oscillations parameters. To correctly account for these uncertainties, we construct likelihood distributions of \(\sin^2 \theta_{12}, \sin^2 \theta_{13}, \sin^2 \theta_{23}\) and \(\delta\) from the \(\Delta \chi^2\) profiles given by [9]. Namely, we assume that the probability distributions of each parameter are provided by \(L = \exp(-\Delta \chi^2/2)\). Then, we combine the various likelihood functions assuming negligible correlations and we determine the probability distributions of \(N_T/N_S\) by Montecarlo extraction of the oscillation parameters. The resulting Probability Density (PD) distributions are reported in Fig.(1) with a color code showing the different production mechanisms described in the previous section.

**Figure 1.** 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 (resp. right) panel is obtained for normal (resp. inverse) hierarchy. The shaded region is the likelihood corresponding to Eq. (8).

**4. Observed Track-to-Shower Ratio in IceCube**

The predicted Track-to-Shower ratio for a cosmic population of high-energy neutrinos can be compared with the Track-to-Shower ratio observed by IceCube in the HESE data-set. This set of events collected by IceCube in three years of data-taking 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]. The number of tracks \(N_T\) and showers \(N_S\) which have to be ascribed to cosmic sources can be estimated from the Poisson likelihood functions: \(L(N_i) \propto \lambda_i^{N_i} \times e^{-\lambda_i}\) 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 \(N_S = 16.3 \pm 4.1\). A completely equivalent information
can be obtained by the recently published IceCube data on passing muons [4] that provided an independent evidence for a $\nu_\mu$ flux of astrophysical origin. In Ref.[4], the passing muon data are fitted allowing the spectral index of the cosmic muon neutrino flux $\Phi_\mu (E_\nu)$ to vary, leading to a best-fit value of $\alpha = 2.2$ and a normalization $F_\mu = 1.7 \pm 0.7$, see eq. (1). For $\alpha = 2$ the corresponding flux normalization becomes $F_\mu = 1.01 \pm 0.35$ that can be translated into a number of tracks from cosmic neutrinos by using eq. (4). We included also this information in our analysis by constructing a combined likelihood, given by the product of the 2 Poisson likelihoods for $N_T$ and $N_S$ and of the Gaussian likelihood for $F_\mu$. We then extract the bound:

$$\frac{N_T}{N_S} = 0.18^{+0.13}_{-0.05} \quad [\text{all data}] \quad (8)$$

by taking into account the equivalence between $F_\mu$ and $N_T$ expressed by eq. (4) 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 showing that the IceCube data provide a best-fit track-to-shower ratio in the middle of the expected region for a cosmic population. The observational error is comparable to the difference between the various predictions and does not allow to discriminate the production mechanism.

5. Results for Decaying Neutrinos

Following the previous procedure we extend the analysis of high energy neutrinos data provided by IceCube to constrain the hypothesis of neutrinos decay [7]. Indeed, non-radiative decay processes of the kind $\nu_i \rightarrow \nu_j + X$ can be tested using HE cosmic neutrinos. Here $\nu_i$ and $\nu_j$ indicate neutrino (or antineutrino) mass eigenstates with masses $m_i \geq m_j$ while $X$ represents one (or more) invisible particle in the final state. In particular, in the assumption that only one stable state exists, the flavor ratios at Earth of decaying neutrinos are only determined by the neutrino mixing matrix and are not dependent on the neutrinos production mechanism. If we assume normal mass hierarchy, the stable eigenstate is necessarily $\nu_1$ since $m_1 < m_2 < m_3$ and the expected flavor ratios at Earth are $[|U_{e1}|^2 : |U_{\mu1}|^2 : |U_{\tau1}|^2] \sim (0.68 : 0.21 : 0.11)$. For inverted mass hierarchy, the lightest and stable state is $\nu_3$ and the final flavor ratios are expected to be $[|U_{e3}|^2 : |U_{\mu3}|^2 : |U_{\tau3}|^2] \sim (0.02 : 0.57 : 0.41)$. In this context of the neutrino decay scenarios and fixing the spectral index $\alpha = 2$, Eq.(6) becomes:

$$\frac{N_T}{N_S} = \frac{|U_{\mu j}|^2}{2.3 - 2.0 |U_{\mu j}|^2 - 0.6 |U_{\tau j}|^2} \quad (9)$$

where the index $j$ indicates the stable mass eigenstate. For normal mass hierarchy, the stable state is $\nu_1$ and substituting the best-fit values of the oscillation parameters, we obtain $(N_T/N_S)_{NH} = 0.12$. For inverted mass hierarchy, the stable state is $\nu_3$ and the track-to-shower ratio becomes $(N_T/N_S)_{IH} = 0.62$. Accounting for the errors in neutrino oscillations parameters the track-to-shower ratios fluctuate inside their Probability Density distributions as showed in Fig.(2) with a color code blue (resp. red) for normal (resp. inverted) mass hierarchy. These distributions are obtained by assuming the spectral index $\alpha = 2.2$ which, as discussed above, represents the best-fit value for the astrophysical component in the IceCube passing muons data [4].

Despite the large fluctuations, the predicted track-to-shower ratios for normal and inverted hierarchy are well separated, indicating that the two cases can be discriminated by a sufficiently accurate experimental determination of $N_T/N_S$. The normalized likelihood distribution corresponding to HESE data-set discussed in the previous section is reported with a solid black line in Fig.(2). By repeating the analysis with the preliminary 4 years data [13], under the
Figure 2. The expected track-to-shower ratio for decaying cosmic neutrinos in the assumption of normal (blue) and inverse (red) mass hierarchy. The distributions show the effect of uncertainties in the neutrino oscillation parameters. The black lines are the normalized likelihood functions for the track-to-shower ratio obtained by combining the 3 years HESE events (solid) or 4 years HESE events (dashed) with the IceCube passing muon data.

hypothesis that the background is proportional to the exposure time, we obtain the likelihood function described by the dashed line in Fig. (2) and we find the range:

\[
\frac{N_T}{N_S}^{\text{exp}} = 0.24^{+0.13}_{-0.07} \quad [1460 \text{ days}]
\]

which is compatible with the value found by analyzing the three year dataset. Summarizing our results, neutrino decay is excluded at about 2σ for both normal and inverted mass hierarchies. In the normal mass hierarchy scenario, this result represents at the present the most sensitive bound on neutrino lifetimes.

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