

Double pulses and cascades above 2 PeV in IceCube

Andrea Palladino^{1,a}, Giulia Pagliaroli², Francesco L. Villante^{2,3}, Francesco Vissani^{1,2}

¹ Gran Sasso Science Institute, L'Aquila, Italy

² LNGS, L'Aquila, Italy

³ Università degli studi dell'Aquila, L'Aquila, Italy

Received: 26 October 2015 / Accepted: 11 January 2016 / Published online: 28 January 2016
© The Author(s) 2016. This article is published with open access at Springerlink.com

Abstract The IceCube collaboration has seen an unexpected population of high energy neutrinos compatible with an astrophysical origin. We consider two categories of events that can help to diagnose cosmic neutrinos: double pulse, which may allow us to clearly discriminate the cosmic component of ν_τ ; and cascades with deposited energy above 2 PeV, including events produced by $\bar{\nu}_e$ at the Glashow resonance, which can be used to investigate the neutrino production mechanisms. We show that one half of the double pulse signal is due to the neutrinos spectral region already probed by IceCube. By normalizing to HESE data, we find that 10 more years are required to obtain 90 % probability to observe a double pulse. The cascades above 2 PeV provide us a sensitive probe of the high energy tail of the neutrino spectrum and are potentially observable, but even in this case the dependence on type of the source is mild. In fact we find that pp or $p\gamma$ mechanisms give a difference in the number of cascades above 2 PeV of about 25 %, which can be discriminated at 2σ in ~ 50 years of data taking.

1 Introduction

In 4 years of data taking, IceCube has observed 32 High Energy Starting Events (HESE) with deposited energies between 60 TeV and 2 PeV [1–4]. 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.

In this work, we focus our attention on two specific classes of events, not yet observed, that can give us precious information on the extra terrestrial component of the neutrino flux: the so-called double pulse events, due to tau-neutrinos [5], and the cascades above 2 PeV, which include events due to electron antineutrinos interacting at the Glashow resonance.

The ν_τ are not expected to be produced in astrophysical sources (nor in the atmosphere) but they are predicted to be a non-negligible component of the cosmic neutrino flux due to flavor oscillations [6–13] and thus represent a distinctive signature of a cosmic population. At low energy, it is impossible to distinguish cascades produced by charged current (CC) interactions of ν_τ from those produced by CC interactions of ν_e and neutral current (NC) interactions of all neutrino flavors. The only way to tag ν_τ is to observe a double pulse in the detector [14–16], which is produced by the CC interaction of ν_τ , when τ is produced, followed by a second energy release, when the τ decays.¹ A very recent analyses from IceCube [5], dedicated to the search of these events with different topology with respect to tracks and cascades, reported a null result. We discuss the implications of this result and the perspective for future ν_τ detection.

The second class of events considered in this paper are cascades with deposited energy above 2 PeV; these events can be produced by deep inelastic scattering (DIS) of high energy ν_e and ν_τ and by $\bar{\nu}_e$ interacting with electrons through the Glashow resonance [17]. As already discussed in [11, 18–21], the rate of these events depends on the neutrino production mechanisms. In particular, since Glashow resonance is only possible for $\bar{\nu}_e$, a larger signal is expected if neutrinos are produced by pp collisions with respect to the case of $p\gamma$ interactions (see [22–24] for a review on the spectra of secondary particles produced in pp and $p\gamma$ interaction), being indeed the antineutrino fraction larger in the first case. The possibility to discriminate among the two mechanisms depends on the relative contributions of events produced by DIS and Glashow resonance. We perform a realistic calcula-

¹ We use the terminology double pulse, recently introduced by the IceCube collaboration [5], rather than with the traditional terminology double bang [14], in order to emphasize that we adopt the same experimental requirements of the IceCube collaboration. It is possible that, in future years, experimental cuts will be optimized further, with a possible increased number of events.

^a e-mail: andrea.palladino@gsi.infn.it

tion of these contributions. Differently from previous work on the subject [21], we discuss the role of leptonic channels in Glashow resonance that can be correctly evaluated only if the difference between the incoming neutrino energy and the energy deposited in the detector is taken into account.

The expected rates of both classes of events depend on the assumed neutrino energy distribution. Our nominal hypothesis is that the cosmic neutrino spectra are described by single power law that extends until 10 PeV. We consider the neutrino spectral index as a free parameter and we fix the normalization of fluxes by requiring that they produce the events observed by IceCube at low energies (i.e. below 2 PeV). We thus obtain the expected rates of double pulse and cascades above 2 PeV as a function of the slope of the neutrino spectrum. This permits us to discuss the relevance of the assumed neutrino energy distribution for future ν_τ detection, for the discrimination of pp or $p\gamma$ production mechanism and/or for the observation of high energy cutoff, automatically implementing the present information provided by IceCube at low energy.

The plan of the paper is as follows: in Sect. 2 we describe our assumptions on the cosmic neutrino flux, in Sect. 3 we calculate the expected number of double pulse events in IceCube and in Sect. 4 the expected number of cascades with deposited energy above 2 PeV. In Sect. 5 we made a comparison between our results and previous works on these subjects and finally, in Sect. 6, we draw our conclusions.

2 The cosmic neutrino flux

We assume that the total flux of cosmic neutrinos (and antineutrinos) has an isotropic distribution and that the spectrum can be described by a power law

$$\frac{d\phi_{\nu+\bar{\nu}}}{dE_\nu} = F(\alpha) \frac{1}{\text{PeV m}^2 \text{ year}} \left(\frac{E_\nu}{\text{PeV}} \right)^{-\alpha} \quad (1)$$

that extends till $E_{\text{cut}} = 10 \text{ PeV}$. Recalling that neutrinos take about 1/20 of the energy of the parent proton in cosmic ray interactions, this means that we are considering protons with energies up to 200 PeV in their sources. It is generally expected that, due to flavor oscillations, a cosmic neutrino population is characterized by a flavor content (1/3:1/3:1/3) independently on the specific production mechanism. In reality, a certain imprint of the neutrino production mechanism does remain, as it is discussed e.g. in [7,8,12]. The fluxes divided per flavors can be generally given as:

$$\begin{aligned} \frac{d\phi_{\nu_e+\bar{\nu}_e}}{dE_\nu} &= \left(\frac{1}{3} + \frac{2P_1}{3} \right) \frac{d\phi_{\nu+\bar{\nu}}}{dE_\nu} \\ \frac{d\phi_{\nu_\mu+\bar{\nu}_\mu}}{dE_\nu} &= \left(\frac{1}{3} - \frac{P_1}{3} + \frac{2P_2}{3} \right) \frac{d\phi_{\nu+\bar{\nu}}}{dE_\nu} \end{aligned}$$

$$\frac{d\phi_{\nu_\tau+\bar{\nu}_\tau}}{dE_\nu} = \left(\frac{1}{3} - \frac{P_1}{3} - \frac{2P_2}{3} \right) \frac{d\phi_{\nu+\bar{\nu}}}{dE_\nu} \quad (2)$$

where P_1 and P_2 are (small) parameters described in [11] that are determined by the neutrino flavor content at the source (i.e. before oscillations). In the following, we consider the case of neutrino produced by charged pion decays for which $P_1 = 0.000 \pm 0.029$, $P_2 = 0.010 \pm 0.007$; the errors are obtained by propagating uncertainties in neutrino oscillation parameters.

The normalization of the flux $F(\alpha)$ is obtained by requiring that the number of events, due to cosmic neutrinos, reproduces the results obtained by IceCube at low energies (i.e. between 60 Tev and 2 PeV). In 3 years of data taking, IceCube has observed $N_{\text{tot}} = 20$ events against an expected background of $N_B = 2.8$ events from atmospheric muons and neutrinos.² We require that the number of events from astrophysical neutrinos, calculated as:

$$N = T \int_2^{20 \text{ PeV}} dE_\nu \sum_{\ell=e,\mu,\tau} A_\ell(E_\nu) \frac{d\phi_{\nu_\ell+\bar{\nu}_\ell}}{dE_\nu} \quad (3)$$

where T is the observation time and $A_\ell(E_\nu)$ are the *effective areas* for the various neutrino flavors ℓ given in [1], is equal to $N = N_{\text{tot}} - N_B$. We introduced an upper integration limit to mimic the effect of the IceCube observation threshold at 2 PeV.

By following the above procedure, we obtain the flux normalization:

$$F(\alpha) = 0.12 \cdot [0.95 - 0.9(\alpha - 2)] \quad (4)$$

Note that the coefficient $F(\alpha)$ determines the flux of cosmic neutrinos at 1 PeV. In the power law assumption, see Eq. (1), this quantity is relatively well constrained, being equal to ~ 0.11 for $\alpha = 2$ and ~ 0.05 for $\alpha = 2.6$.

3 Tau neutrinos and double pulse events

As stated in the Sect. 1, one of the goals of this work is to discuss the detection of the ν_τ component of the high energy (HE) neutrino flux providing the proof of existence of a cosmic population. We are interested to investigate the dependence of the expected number of double pulse events from the energy distribution of cosmic neutrinos and from the IceCube observation time.

² We assume that the prompt atmospheric neutrinos give negligible contributions, as it is required by the arrival angles distributions of IceCube events [2]. Anyway it will be important to measure also this component of atmospheric neutrinos in the future. We normalize the neutrino spectrum by using the three year IceCube results because the complete information for this data set is provided in Supplementary Table IV of [2] allowing us to crosscheck and validate our conclusions.

In order to perform this calculation we need the effective area for double pulse events, A_{τ}^{2P} , recently published by the IceCube collaboration [5]. Following the IceCube prescription, the expected number of double pulse events in the observation time T is

$$N_{2P}(\alpha) = T \times \int^{E_{cut}} dE_{\nu} A_{\tau}^{2P}(E_{\nu}) \frac{d\phi_{\nu_{\tau} + \bar{\nu}_{\tau}}}{dE_{\nu}} \quad (5)$$

where the differential flux of the ν_{τ} component, $\frac{d\phi_{\nu_{\tau} + \bar{\nu}_{\tau}}}{dE_{\nu}}$ is normalized to reproduce the HESE events observed by IceCube (see previous section).

In order to discuss the dependence of N_{2P} from the spectral index α , it is useful to give an analytical description of the IceCube effective area. Considering that double pulse events are a *subset* of the events caused by CC tau neutrino interactions, we describe the effective area by

$$A_{\tau}^{2P}(E_{\nu}) = \epsilon_{2P} \times \eta_{CC} \times A_{\tau}(E_{\nu}) \times P_{2P}(E_{\nu}, L_{min}) \quad (6)$$

where $A_{\tau}(E_{\nu}) \approx 13.4 \text{ m}^2 (E_{\nu}/\text{PeV})^{0.455}$ is the effective area for ν_{τ} calculated in [1], the factor $\eta_{CC} = (1 + \sigma_{NC}/\sigma_{CC})^{-1} \approx 0.7$ gives the fraction of ν_{τ} interactions that are due to CC processes and the constant $\epsilon_{2P} < 1$ describes the effect of geometrical and quality cuts implemented by IceCube for the search of these events. The function $P_{2P}(E_{\nu}, L_{min})$ describes the probability that a neutrino with energy E_{ν} produces a tau traveling more than L_{min} before it decays, where L_{min} is the minimum distance to give rise to an observable double pulse in the detector. We expect that L_{min} is of the order of tens of meters,³ that is the typical distance between the DOMs [5].

The taus produced in CC-DIS have an average energy equal to

$$E_{\tau} = (1 - \langle y \rangle) E_{\nu} \simeq \frac{3}{4} E_{\nu} \quad (7)$$

where $\langle y \rangle$ is the mean inelasticity which is nearly constant in the energy range that we are considering [25]. If we neglect τ energy dispersion and assume the one-to-one relationship between E_{τ} and E_{ν} expressed by Eq. (7), the probability $P_{2P}(E_{\nu}, L_{min})$ is given by

$$P_{2P}(E_{\nu}, L_{min}) = \exp \left[- \frac{E_{min}(L_{min})}{E_{\nu}} \right] \quad (8)$$

where E_{min} represents the minimum neutrino energy which is necessary to produce a tau with decay length larger than L_{min} . This can be calculated as:

³ One can implement a condition for containment replacing $P_{2P}(E_{\nu}, L_{min}) \rightarrow P_{2P}(E_{\nu}, L_{min}) - P_{2P}(E_{\nu}, L_{max})$ with $L_{max} \sim 0.5$ km; we checked that the changes are not conspicuous in the range of energies of interest.

$$E_{min} = \frac{L_{min}}{c t_{\tau}} \times \frac{m_{\tau} c^2}{1 - \langle y \rangle} = 3.3 \text{ PeV} \left(\frac{L_{min}}{120 \text{ m}} \right) \quad (9)$$

with $m_{\tau} c^2 = 1.777 \text{ GeV}$ and $t_{\tau} = 0.29 \cdot 10^{-12} \text{ s}$.

Using the expression in Eq. (6), we find that the effective area of IceCube, in the energy region from 0.1 to 10 PeV, is reasonably well described setting

$$\epsilon_{2P} = 0.25 \quad \text{and} \quad E_{min} = 0.5 \text{ PeV} \quad (10)$$

that corresponds to $L_{min} = 18 \text{ m}$. In other words the following parameterized expression for the effective area can be used:

$$A_{\tau}^{2P} = \bar{A}_{2P} \times \left(\frac{E_{\nu}}{\text{PeV}} \right)^{\beta} \exp \left(- \frac{E_{min}}{E_{\nu}} \right) \quad \text{with} \quad (11)$$

$$\times \left\{ \begin{array}{l} \bar{A}_{2P} = 2.33 \text{ m}^2 \\ \beta = 0.455 \\ E_{min} = 0.5 \text{ PeV} \end{array} \right\},$$

as showed in Fig. 1 for a direct comparison of the IceCube effective area.

Using the previous expression it is possible to obtain an accurate analytical formula for the expected number of double pulse events

$$N_{2P}(\alpha) = \frac{F(\alpha)}{3} \times \frac{\bar{A}_{2P}}{\text{m}^2} \times \frac{T}{\text{yr}} \times \left(\frac{E_{min}}{\text{PeV}} \right)^{\beta - \alpha + 1} \Gamma \left(\alpha - \beta - 1, \frac{E_{min}}{E_{cut}} \right) \quad (12)$$

where Γ is the incomplete gamma function and the normalization of $\nu_{\tau} + \bar{\nu}_{\tau}$ flux is assumed to be $F(\alpha)/3$, as is expected for neutrinos produced by charged pions decays with few % uncertainty due to errors in the neutrino oscillation param-

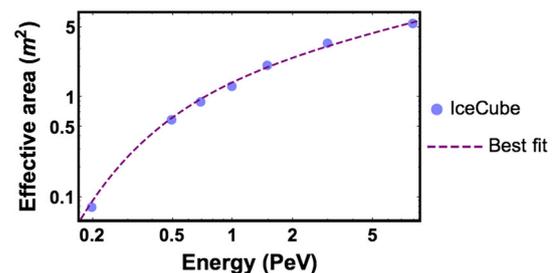


Fig. 1 Effective areas of double pulse. The *points* are the values given by IceCube [5] while the *line* is the parameterization described in the text

ters (see previous section for details). To check our result, we compare with IceCube calculations in [5] finding agreement at the level of few percents.

The above expression allows us to investigate the dependences of the expected number of double pulse events on the spectral index α and on the high energy cutoff E_{cut} of the neutrino spectrum. In particular, it permits us to show that our knowledge of the neutrino spectrum is already sufficient to make significant predictions.

The number of double pulse events expected in 4 years of data taking is 0.66, 0.53, 0.41, 0.31 for $\alpha = 2.0, 2.2, 2.4$ and 2.6, so it is not surprising that IceCube have not seen double pulse events so far. Our calculations are done by adopting the nominal cutoff energy $E_{\text{cut}} = 10$ PeV. However, the predicted values are not strongly dependent on the assumed high energy cutoff. For $\alpha = 2.0$, the counting rate varies indeed by only $\sim 25\%$ when the cutoff energy is varied within the decade $E_{\text{cut}} = 5\text{--}50$ PeV. For larger values of α , the dependence of $N_{2p}(\alpha)$ on E_{cut} is considerably weaker.

The dependence of $N_{2p}(\alpha)$ on the spectral index mainly arises from the normalization $F(\alpha)$ of the cosmic neutrino flux at 1 PeV, see Eq. (1). The residual dependence on α is relatively weak and affects the final results at the few % level when $\alpha = 2.0\text{--}2.6$. A good approximation for the predicted number of double pulses is thus given by

$$N_{2p}(\alpha) \approx 1.45 \times \frac{T}{\text{year}} \times F(\alpha) \tag{13}$$

We recall that the normalization $F(\alpha)$ is constrained within a factor of 2 for $2.0 \leq \alpha \leq 2.6$. As remarked in [5], the optimal neutrino energy window to see the double pulse events is between 0.1 and 10 PeV. It is important to remark the consequence of this fact: assuming cosmic origin, a large fraction of the double pulse events are generated by a parent neutrino spectrum which is already observed by IceCube; conversely, a lack of observation would have dramatic implications, either on the origin of these events or on the nature of neutrino oscillations. This can be better appreciated from Fig. 7, where we show with a yellow line the integrand dN_{2p}/dE_ν of Eq. (5) calculated for $\alpha = 2.3$. The function dN_{2p}/dE_ν is peaked around 0.5 PeV and approximately one half of the double pulse signal is due to neutrinos with initial energy below 2 PeV, i.e. to the energy region already probed by HESE observations in IceCube.

Finally, we show in Fig. 2 the probability to observe at least one double pulse as a function of spectral index and number of years.

To observe a double pulse in IceCube with a probability greater than 90 % we must wait about 10 years in the most favorable case ($\alpha = 2$), about 15 years in the case $\alpha = 2.3$ and much more if the spectral index is close to $\alpha = 2.6$.

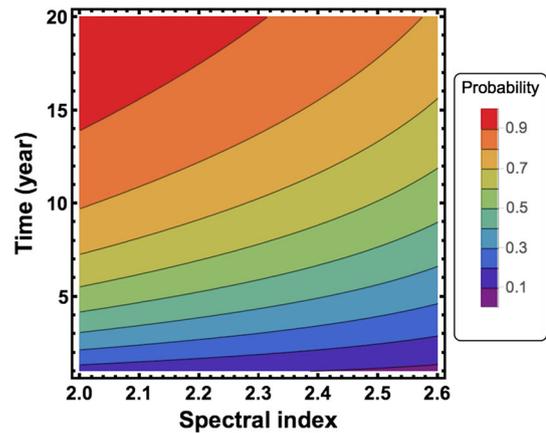


Fig. 2 Probability to observe at least one double pulse event as a function of spectral index and number of years

4 Cascades events above 2 PeV

In this section we estimate the number of cascade events with deposited energy above 2 PeV in IceCube. Two types of cascade events are described: those from deep inelastic scattering (DIS) and those produced by the Glashow resonance [17].

4.1 Cascades from DIS

Cascades from DIS are mostly given by CC interactions of ν_e and ν_τ with a negligible contribution from NC interactions of neutrinos of all flavors, as discussed in the following. The expected number of cascades from DIS, with deposited energy above 2 PeV, is given by

$$N_{\text{DIS}}(\alpha) = \eta_{\text{CC}} T \int dE_\nu \left[\frac{d\phi_{\nu_e + \bar{\nu}_e}}{dE_\nu} A_e^{\text{DIS}}(E_\nu) P_e(E_\nu, E_{\text{th}}) + \frac{d\phi_{\nu_\tau + \bar{\nu}_\tau}}{dE_\nu} A_\tau^{\text{DIS}}(E_\nu) P_\tau(E_\nu, E_{\text{th}}) \right] \tag{14}$$

where

- A_e^{DIS} and A_τ^{DIS} are the effective area for DIS of ν_e and ν_τ , which are calculated in Sect. 4.3;
- the factor η_{CC} is given in the previous section;
- the function $P_\ell(E_\nu, E_{\text{th}})$ represents the probability that a CC-DIS event produced by neutrino ν_ℓ of energy E_ν has a visible energy above $E_{\text{th}} = 2$ PeV.

In CC interactions of ν_e an electromagnetic cascade is produced and the incoming neutrino energy is entirely deposited in the detector, i.e. $E_{\text{dep}} = E_\nu$. By using the direct relationship between E_{dep} and E_ν we can write the probability to observe an event with $E_{\text{dep}} \geq E_{\text{th}}$ as:

$$P_e(E_\nu, E_{th}) = \frac{1}{2} \left[1 + \text{Erf} \left(\frac{E_\nu - E_{th}}{\sqrt{2} E_\nu \delta} \right) \right] \quad (15)$$

where ‘Erf’ indicates the error function, $\delta = 12\%$ and we assumed that the energy resolution for the deposited energy is described by a Gaussian with a variance $\Delta E_{dep} = \delta \cdot E_{dep}$ [2].

In CC interactions of ν_τ , a small fraction of the incoming neutrino energy is carried away by the invisible outgoing neutrinos produced in τ decay. If we neglect the energy dispersion of outgoing neutrinos, we can take this into account by writing $E_{dep} = \eta_{\nu_\tau} E_\nu$, where $\eta_{\nu_\tau} = 0.8$ is the average energy fraction deposited in the detector by hadrons and charged leptons (see [7]). With this assumption the probability $P_\tau(E_\nu, E_{th})$ is obtained from Eq. (15) by replacing $E_\nu \rightarrow \eta_{\nu_\tau} E_\nu$. In the above estimate, we neglect that the 17.4% of taus decays into muon producing track events and this corresponds to overestimating the total number of cascades due to ν_e and ν_τ by 7% at most.

In NC interactions only a small fraction of the initial neutrino energy is deposited in the detector: on average $E_{dep} = \frac{1}{4} E_\nu$. Therefore only neutrinos of relatively high energy give a contribution to the signal; with the threshold of 2 PeV we need neutrinos with energy around $E_\nu = 8$ PeV. We estimated that the contribution of NC to the total number of events above 2 PeV is equal to few % when $\alpha = 2$ and decreases with the increasing of the spectral index. For this reason we neglected it in the calculation.

4.2 Cascades from Glashow resonance

The CC interaction process $\bar{\nu}_e + e^-$, mediated by an intermediate W boson, has a resonant character at:

$$E_G = \frac{M_W^2}{2m_e} = 6.32 \text{ PeV} \quad (16)$$

The cross section at $E \simeq E_G$ is about 2 order of magnitude larger than that of DIS and provides the dominant contribution to the $\bar{\nu}_e$ interaction rate at few PeVs.

The properties of events produced by Glashow resonance depend on the final state of the interaction process, i.e. on the W^- decay mode. We thus consider separately the different contributions to the total events number $N_G(\alpha)$, with deposited energy above 2 PeV, obtaining:

$$N_G(\alpha) = T \int dE_\nu \frac{d\phi_{\nu_e + \bar{\nu}_e}}{dE_\nu} A_e^G(E_\nu) \frac{\xi_{\bar{\nu}_e}}{\xi_{\nu_e}} \left[B_H P_H(E_\nu, E_{th}) + \sum_{\ell=e,\tau} B_{\nu\ell} P_{\nu\ell}(E_\nu, E_{th}) \right] \quad (17)$$

where

Table 1 Branching ratio of W^- decay

	Branching ratio (%)
$\Gamma(\ell \nu) / \Gamma_{total}$	10.86 ± 0.09
$\Gamma(\text{hadrons}) / \Gamma_{total}$	67.41 ± 0.27

- $A_e^G(E_\nu)$ is the effective area for Glashow resonance which is calculated in Sect. 4.3;
- the parameter $\xi_{\bar{\nu}_e}$ is the fraction of $\bar{\nu}_e$ in the electron neutrino + antineutrino flux. We take as reference the value $\tilde{\xi}_{\bar{\nu}_e} = 1/2$, which is used by IceCube in effective areas calculations [1];
- the factors B_H and $B_{\nu\ell}$ are the branching ratios of $W^- \rightarrow \text{hadrons}$ and $W^- \rightarrow \bar{\nu}_\ell + \ell$ with $\ell = e, \tau$, respectively, which are given in Table 1. Note that we do not include the contribution from $W^- \rightarrow \bar{\nu}_\mu + \mu$ because muons produce tracks (not cascades) in the detector;
- the functions $P_H(E_\nu, E_{th})$ and $P_{\nu\ell}(E_\nu, E_{th})$ represent the probability that an event produced by $\bar{\nu}_e$ of energy E_ν through hadronic or leptonic decay modes has a deposited energy above $E_{th} = 2$ PeV.

When W^- decays in hadrons, a hadronic shower is produced and all the energy of the incoming $\bar{\nu}_e$ is deposited in the detector, i.e. $E_{dep} = E_\nu$. The function $P_H(E_\nu, E_{th})$ is thus given by Eq. (15) and it is essentially $P_H(E_\nu, E_{th}) \simeq 1$, as we can understand by considering that $E_G \gg E_{th}$.

In leptonic decays, a large part of the incoming neutrino energy E_ν is carried away by the invisible outgoing neutrinos. The charged lepton has a continuous spectrum of energy that for any leptonic species is given by

$$\frac{dP}{dE} = \frac{3}{E_\nu} \left(1 - \frac{E}{E_\nu} \right)^2 \theta(E_\nu - E) \quad (18)$$

and it is shown by the yellow line in Fig. 3. We see that processes in which the lepton takes a small fraction of the neutrino energy are favored. When $W^- \rightarrow \bar{\nu}_e + e$, the electron deposits all its energy into the detector as an electromagnetic cascade. Neglecting energy resolution effects, we evaluate:

$$P_{\nu e}(E_\nu, E_{th}) = \int_{E_{th}} dE (dP/dE) = (1 - E_{th}/E_\nu)^3 \quad (19)$$

When $W^- \rightarrow \bar{\nu}_\tau + \tau$, the tau deposits a fraction $x_\tau = 73\%$ of its total energy as electromagnetic and hadronic cascade; the function $P_{\nu\tau}(E_\nu, E_{th})$ can be obtained from Eq. (19) by replacing $E_\nu \rightarrow x_\tau E_\nu$. Note that the factor x_τ is different from the parameter η_{ν_τ} , defined in Sect. 4.1, which gives the average fraction of incoming neutrino energy in ν_τ CC interactions which is deposited in the detector. The two

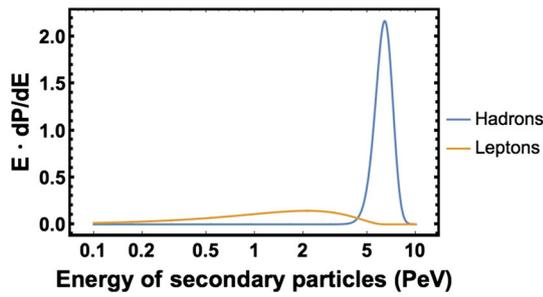


Fig. 3 Energy spectra of secondary charged particles produced at the Glashow resonance. For the hadronic component, the energy resolution of the detector is taken into account. The integrals of fluxes equate the branching ratio of Table 1, about 2/3 for hadronic channel and about 1/3 for all leptonic channels

quantities are related by $\eta_{\nu\tau} = (1 - \langle y \rangle)x_\tau + \langle y \rangle$, where $\langle y \rangle \simeq 1/4$ is the mean inelasticity in ν_τ CC interactions.

Note that the finite width of the charged lepton energy distributions reduces the relative contribution of leptonic modes to cascades produced by Glashow resonance above a certain threshold. For $E_\nu = E_G$ and $E_{th} = 2$ PeV, we obtain $P_{\nu e} = 0.32$ and $P_{\nu\tau} = 0.18$ showing that, due to threshold effects, the contribution to the event rate of leptonic modes is reduced by $\sim 75\%$. By taking into account the branching ratios of the different channels, this implies that hadronic modes account for 90 % of the total signal produced by Glashow resonance.

4.3 The effective areas for DIS and for the Glashow resonance

In order to calculate the number of cascades produced above 2 PeV by DIS and Glashow resonance, we need to determine the effective areas $A_e^{DIS}(E_\nu)$, $A_\tau^{DIS}(E_\nu)$ and $A_e^G(E_\nu)$ defined in Eqs. (14) and (17). The simplest way is to consider that, at high energy, the DIS cross section is essentially independent on the neutrino flavor. Thus, we expect:

$$A_e^{DIS}(E_\nu) = A_\tau^{DIS}(E_\nu) = A_\tau(E_\nu) \tag{20}$$

where we considered that ν_τ only interact through DIS and we implicitly assumed that detection efficiencies of ν_e and ν_τ are equal above ~ 1 PeV. The effective area for Glashow resonance can then be calculated by subtraction, obtaining:

$$A_e^G(E_\nu) = A_e(E_\nu) - A_\tau(E_\nu). \tag{21}$$

Both the total effective areas $A_e(E_\nu)$ and $A_\tau(E_\nu)$ have been calculated by IceCube and are given in [1].

It is, however, important to understand the main properties of $A_e^{DIS}(E_\nu)$ and $A_e^G(E_\nu)$ on physical basis. We expect that

$$A_\ell^{DIS}(E_\nu) = \epsilon(E_\nu)[N_n \times \sigma_{DIS}(E_\nu) \times (1 + h(E_\nu))/2] \quad \text{where } \ell = e, \tau \tag{22}$$

where $N_n = \frac{\rho V}{m_N} = 5.5 \times 10^{38}$ is the number of nucleons in 1 km^3 of ice with density of 0.92 g/cm^3 , $\sigma_{DIS}(E_\nu) = 0.89(E_\nu/\text{PeV})^{0.45} \times 10^{-33} \text{ cm}^2$ is the total DIS (CC+NC) cross section [25] and we considered negligible the difference between the cross section of ν and $\bar{\nu}$ that is less than 5 % for neutrino energy above 1 PeV (see [25]). Let us remark that both CC and NC cross sections must be included to reproduce the IceCube effective areas above 1 PeV, because the effective areas given in [1] have been calculated with a low energy threshold around 30 TeV that does not cut events produced by NC interactions of PeV neutrinos, even if the deposited energy is about 1/4 of the incoming neutrino energy. The factor $h(E_\nu)$ describes neutrino absorption in the Earth, modeled using PREM [26] and averaged over the angle of arrival of neutrinos.⁴ The parameter $\epsilon(E_\nu)$ gives the IceCube effective volume with respect to an ideal 1 km^3 detector and includes the effects of space, time and energy cuts in the HESE analysis. By comparing the effective areas calculated by IceCube [1], $A_\tau(E_\nu)$, with our estimate, $A_\tau^{DIS}(E_\nu)$, we determine the unknown efficiency $\epsilon(E_\nu)$. The efficiency can be described by

$$\epsilon(E_\nu) = 0.40 \left(\frac{E_\nu}{\text{PeV}} \right)^{0.075} \tag{23}$$

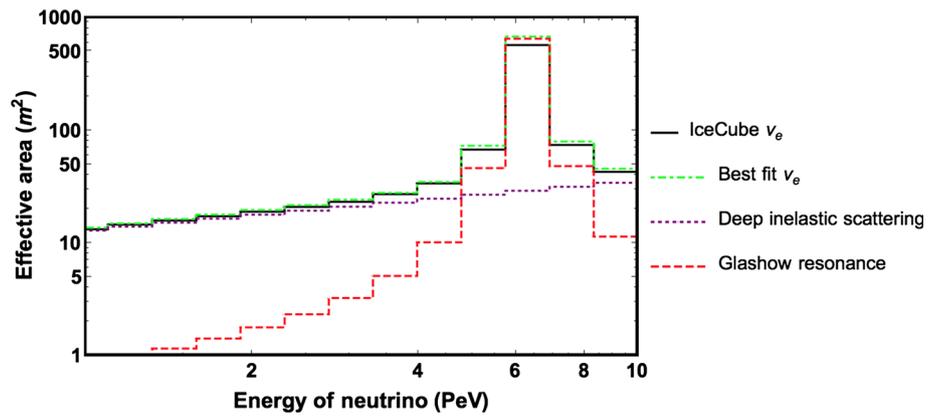
for neutrino energies $1 \text{ PeV} \leq E_\nu \leq 10 \text{ PeV}$. We see that it is nearly constant, varying by $\sim 15\%$ when E_ν varies by one decade. Using this efficiency it is possible to obtain the effective area for the Glashow resonance, as follows:

$$A_e^G(E_\nu) = \epsilon(E_\nu) \left[\frac{1}{2} \times \frac{1}{2} \times N_e \times \sigma_G(E_\nu) \right] \tag{24}$$

where $\sigma_G(E_\nu)$ is the total $\bar{\nu}_e + e$ cross section and $N_e = 10/18 \times N_n = 3.1 \times 10^{38}$ is the total number of electrons in 1 km^3 of ice. The first factor 1/2 takes into account that only $\bar{\nu}_e$ interact through the Glashow resonance and that IceCube calculations are obtained by considering an antineutrino fraction $\xi_{\bar{\nu}_e} = 1/2$ [1]. The second factor 1/2 is obtained by assuming complete absorption of antineutrinos crossing the Earth, only for the Glashow resonance piece of the ν_e effective area. In order to verify the adequacy of our interpretation, we compare in Fig. 4 the IceCube effective area, $A_e(E_\nu)$, with the sum of the two contributions $A_e^G(E_\nu) + A_e^{DIS}(E_\nu)$. We

⁴ For energies $E_\nu = 10, 100, 1000$ and $10,000$ TeV we find that $h = 0.91, 0.66, 0.37$ and 0.18 , respectively.

Fig. 4 Effective areas of ν_e at high energies. The effective area given by IceCube (continuous line) is reproduced within 10 % on average (15 % in the worst bin) by the sum of a contribution due to DIS (dotted line) and the contribution of Glashow resonance (dashed line), discussed in Sect. 4



are able to reproduce $A_e(E_\nu)$ within 10 % accuracy, showing that the main physical ingredients are correctly understood and implemented. The small difference between our parametrization and IceCube calculation near the Glashow resonance could be due to a slightly lower efficiency of IceCube to detect muons and tau produced by leptonic channels of the W^- boson.

4.4 Results

By using the previous considerations we can obtain the expected number of cascades above $E_{\text{dep}} = 2$ PeV as a function of the spectral index α of the incoming neutrino flux. The number of events from Glashow resonance is given to a good approximation by the analytical expression:

$$N_G(\alpha) \approx 4.75 \times \frac{T}{\text{year}} \times \frac{\xi_{\bar{\nu}_e}}{\xi_{\nu_e}} \times F(\alpha) \times \left(\frac{E_G}{\text{PeV}}\right)^{2-\alpha} \quad (25)$$

where T is the exposure time and the factor $F(\alpha)$ is the flux normalization discussed in Eq. (4). The reference value $\xi_{\bar{\nu}_e} = 1/2$ is discussed after Eq. (17). The number of events from DIS can be fitted with the same functional form as:

$$N_{\text{DIS}}(\alpha) \approx 4.14 \times \frac{T}{\text{years}} \times \left(\frac{E_{\text{DIS}}}{\text{PeV}}\right)^{2-\alpha} \times F(\alpha) \quad (26)$$

where the parameter $E_{\text{DIS}} = 4.05$ PeV. We notice that both Glashow resonance and DIS events depend on α more strongly than double pulse events, as can be seen comparing with Eq. (13).

The total number of cascades with energy above 2 PeV depends from the production mechanism. The relevant parameter is the $\bar{\nu}_e$ fraction $\xi_{\bar{\nu}_e}$, which determines $N_G(\alpha)$ and thus fix the relative contribution of events from Glashow resonance and DIS [19–21]. In the case of pp interactions, about an equal number of neutrinos and antineutrinos are produced at the source, with flavor ratios (1:2:0). On the other hand, if the production mechanism is $p\gamma$ and we consider the

simplest scenario, only π^+ are produced and there are not $\bar{\nu}_e$ at the source. Taking into account neutrinos oscillations and their uncertainties the fraction of $\bar{\nu}_e$ arriving at Earth with respect to the total electronic flux is given by

$$\xi_{\bar{\nu}_e} = \begin{cases} \frac{1}{2} + P_1 = 0.500 \pm 0.029 & \text{if } pp \text{ source} \\ \frac{1 - 3P_0}{3} + P_1 = 0.224 \pm 0.029 & \text{if } p\gamma \text{ source} \end{cases}$$

where $\xi_{\bar{\nu}_e}$ as a function of P_i is obtained in [11]. This extreme scenario maximizes the difference between the signals from pp and $p\gamma$ sources; when we take into account the possibility that some amount of $\bar{\nu}_e$ is also created by $p\gamma$ interactions at the source, the differences diminish. The contamination with $\bar{\nu}_e$ at the source is for $p\gamma$ depending on the target photon spectrum, typically around 20-50 % with respect to the flux of ν_e , in the energy range between 1 TeV and 1 PeV (see Fig. 13 of [27] and [28], in which the contaminations of $\bar{\nu}_e$ in $p\gamma$ interactions are discussed in detail). In our extreme scenario the two mechanisms give separate predictions for $\xi_{\bar{\nu}_e}$ even if uncertainties on oscillation parameters are included.

The total number of cascades above 2 PeV after 4 years is shown in Fig. 5, where we can see the different contri-

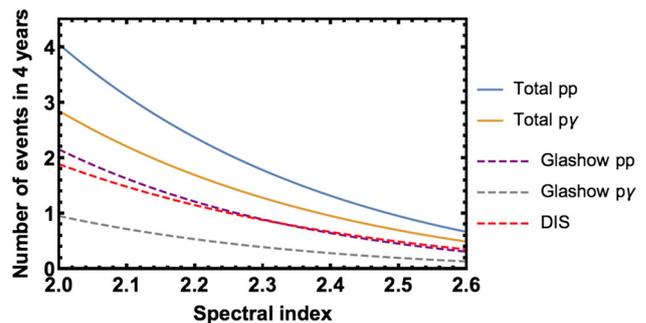


Fig. 5 Number of expected cascade events with deposited energy above 2 PeV with an exposure time of 4 years as a function of the neutrino flux spectral index. We show the total number of events for the two different production mechanisms. For the Glashow resonance we have chosen the best fit values of $\xi_{\bar{\nu}_e}$, both for pp and $p\gamma$ mechanisms

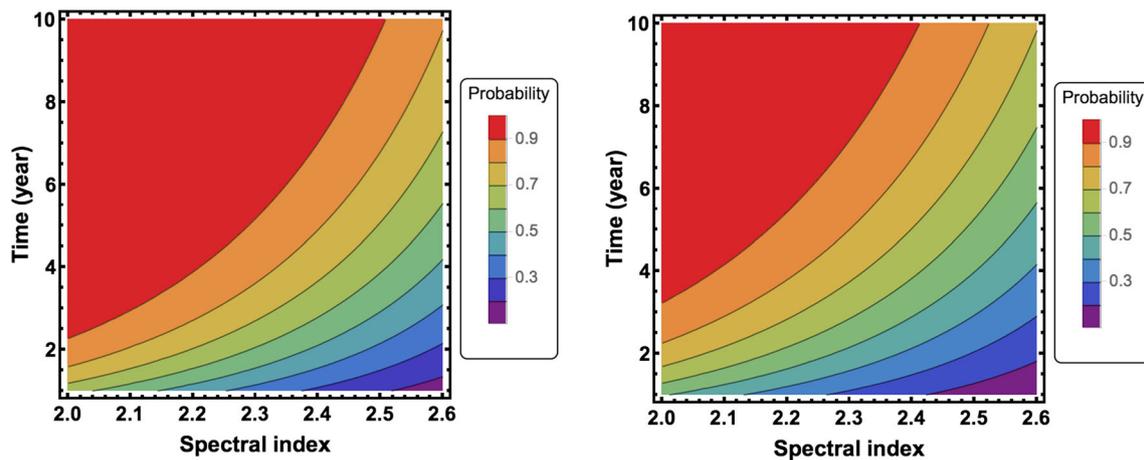


Fig. 6 Probability to observe at least one cascade above 2 PeV as a function of spectral index and number of years of exposure. On the *left panel* pp interaction at the source, on the *right panel* $p\gamma$ interaction at the source

butions of DIS and Glashow resonance. In the assumption of pp interactions at the source, we obtain 4.0, 2.4, 1.3, 0.7 events expected in 4 years with $\alpha = 2.0, 2.2, 2.4$ and 2.6, respectively. These numbers are reduced by $\simeq 25\%$ for $p\gamma$ interactions. In Fig. 6 we show the probability to observe at least one event as a function of the assumed spectral index and of the observation time. The non-observation of cascades above 2 PeV is in tension with the hypothesis of a hard neutrino spectrum. An example, for pp mechanism, $\alpha < 2.2$ is excluded at 90% CL.

It is evident from the above results that, unless the neutrino spectral index is fixed, we cannot discriminate between different neutrino production mechanisms. In fact, the indetermination of the event rate due to our incomplete knowledge of the neutrino spectrum, is comparable with the differences generated by the various production mechanisms. It is interesting to note that, also for a fixed value of the spectral index, the number of expected events is so small that an exposure of tens of years is required. For example, focusing on events around 6.32 PeV, where the background due to DIS is negligible, and with $\alpha = 2.3$, we need more than 50 years to obtain some constraint of a 2σ discrimination between pp and $p\gamma$ interaction at the source. Of course this time increases if some $\bar{\nu}_e$ are produced at the source also by the $p\gamma$ mechanism, reducing the differences between pp and $p\gamma$ interaction. For these reasons, we think that nowadays every conclusion about the mechanism of production is just a speculation and only a detector with a bigger exposure can clarify the situation in the future.

Previous results are obtained by assuming an unbroken power law for the neutrino flux in the energy region below 10 PeV. The presence of an energy cutoff below E_G drastically decreases the number of events due to the Glashow resonance, whereas reduces the DIS events of only about 20%. In the opposite case in which the energy cutoff is

much greater than 10 PeV the number of Glashow events is not affected, whereas the number of DIS events increases of about 30–40%.

To determine our ability to distinguish between an unbroken power law with $\alpha = 2.3$ from a power law with cutoff below E_G we used Poissonian statistics $P(n, \mu) = \frac{e^{-\mu} \mu^n}{n!}$. The absence of events due to the Glashow resonance around 6.32 PeV with an energy resolution of 10% in the deposited energy, is to date compatible with both the spectral shapes. To have a hint at 2σ of a cutoff, we need to wait 15 years for pp interaction at the source. Indeed this corresponds to $\mu = 3$ expected events, that means a probability $P(0, 3) = e^{-3}$ less than 5% to see no events. Of course the required number of years is less than 15 years for $\alpha < 2.3$ and greater for $\alpha > 2.3$ and it doubles in the case of $p\gamma$ mechanism of production.

5 Discussion

To summarize we report in Table 2 the number of IceCube expected events for 1 year of exposure and for the different channels discussed in this work. Moreover, we report in the last two columns the ratios between the number of cascades above 2 PeV and double pulse events. The ratios of the last two columns decreases with α , because Glashow resonance and deep inelastic scattering are more affected by a change of the slope with respect to the number of double pulse events, as we can see in Eqs. (13), (25), and (26).

In order to clarify what is the relevant energy region of the parental neutrino flux giving a contribution to expected events discussed in this work, we show in Fig. 7 the integrands dN/dE_ν of Eqs. (5)–(14)–(17) multiplied by an extra factor E_ν for the three channels analyzed in this paper for a spectral index $\alpha = 2.3$. It is interesting to remark that also ν_τ of about 0.5 PeV can give rise to a “double pulse” event, because there

Table 2 Expected number of events per year for the different classes of events by using the best fit value of $\xi_{\bar{\nu}_e}$ and $(\nu_e : \nu_\mu : \nu_\tau) = (1/3:1/3:1/3)$ at the Earth. N_{DIS} and N_G refer to showers with deposited energy above 2 PeV, N_{2P} refers to double pulses without threshold

α	N_{2P}	N_{DIS}	N_G^{PP}	N_G^{PY}	$(N_G^{PP} + N_{DIS})/N_{2P}$	$(N_G^{PY} + N_{DIS})/N_{2P}$
2	0.165	0.473	0.539	0.239	6.116	4.306
2.2	0.132	0.288	0.304	0.135	4.504	3.220
2.4	0.103	0.168	0.162	0.072	3.192	2.319
2.6	0.078	0.089	0.079	0.035	2.182	1.613

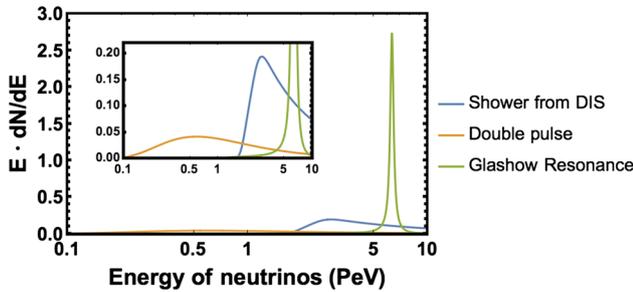


Fig. 7 $E \frac{dN}{dE}$ for the three types of processes analyzed in the paper, under the hypothesis $\alpha = 2.3$ in the neutrino spectra

is a compensation between the flux power law decrease and the probability to not decay that increases exponentially with the energy.

The difference between pp and $p\gamma$ interaction at the source is already discussed in other work. We compare here with some of them, which are important and well known, namely [19, 21, 29, 30]. We point out the reasons why our analysis is different and show that, although results could seem to be incompatible, there are no contradictions. Our analysis of the events with deposited energy above 2 PeV shows that the rate in the case of $p\gamma$ interaction at the source is about 75 % of the rate given by pp interaction. In fact, the difference is due to events produced by Glashow resonance, but in this region of energy, the rate of DIS events is large and this reduces the difference between the two types of mechanism. This is not in contradiction with Ref. [21], in which the ratio between resonant and non resonant event above 2 PeV, is about one half. In that analysis, in fact, *the energy of incoming neutrino and not the deposited energy into the detector* is considered. When the deposited energy is considered instead, the neutral current interaction of all type of neutrinos and the charged current interaction of ν_μ give a negligible contribution to cascade above 2 PeV: this explain the difference between the results of the two papers. Our analysis uses the deposited energy, since this is observable, and it is not simple (or possible) to reconstruct the energy of incoming neutrinos. That explain also the difference with respect to [31].

The comparison with [19] concerns another important remark. Even in this work, the difference between pp and $p\gamma$ interaction at the source is discussed and their conclu-

sion is that the number of Glashow events, in the case of pp mechanism, is about six times greater than what expected in the case of $p\gamma$ mechanism. Again, this statement is not in contradiction with our statement, because *they compare models with the same flux of protons at the source* whereas we take into account the observed flux of neutrinos at the Earth. In other words, we ask ourselves what is the fraction of electron antineutrinos with respect to the *observed* total flux of neutrinos and, as a consequence, only the difference due to neutrinos oscillations is relevant for these considerations. The oscillations produce a difference of about a factor of 2 between the two mechanisms of production, and the additional difference found by [19] is due to the different fraction of energy that neutrinos receive in the pp and $p\gamma$ production mechanism.

The last remark concerns a hypothesis proposed in [29, 30], where it was suggested that the events observed above PeV could be due to Glashow resonance. If this was true, were caused by leptonic decay, since the energy resolution is incompatible with a visible energy being 6.32 PeV. Now, the ratio between hadronic and leptonic branching ratios is, $\Gamma(\text{hadr})/3\Gamma(l\nu) \simeq 2$ and the same neutrino flux leads to leptonic and hadronic decays. To date there are three events with energy below 2 PeV, so in the above assumption, we expect to have also six hadronic events. The probability to observe none is given by the Poissonian PDF, $P(0) = e^{-6}$, which is disfavored at 3σ .

6 Conclusion

In this paper we have considered two categories of very high energy events in IceCube that can help to diagnose cosmic neutrinos: the double pulse events, which may allow us to clearly discriminate the cosmic component of ν_τ ; the cascades with deposited energy above 2 PeV, including events produced by $\bar{\nu}_e$ at the Glashow resonance, which can be used to investigate the cosmic neutrino production mechanisms.

As stated in the Introduction, we estimated the rate of these high energy events with the important constraint provided by the data already observed by IceCube, i.e. we used the data collected in the low-energy region below 2 PeV to normalize our calculations. In this way, we obtained the expected rates

of high energy events as a function of the neutrino spectral index α , which we varied in the range $\alpha = (2-2.6)$.

We found that the non-observation of double pulse events does not contradict the hypothesis of a cosmic neutrino population. This conclusion is only marginally dependent on the assumed cosmic neutrino spectrum. In fact, we have shown that:

- (i) One half of the expected signal is due to neutrinos with energy below $E_\nu = 2$ PeV, i.e. *from a spectral region that is already observed in the HESE data* (see Fig. 7 and discussion in the Sect. 3)
- (ii) In the most favorable case, with spectral index $\alpha = 2$ we need to wait about 10 more years to observe a double pulse with a probability greater than 90 %.

Concerning the cascades with deposited energy above 2 PeV, we have shown that:

- (i) Due to the difference between the energy deposited in the detector and the energy of the interacting neutrino, the contribution of leptonic channels to Glashow resonance events is suppressed by 75 %. This implies that hadronic modes account for 90 % of the total signal produced by Glashow resonance above 2 PeV;
- (ii) This class of events can be used to probe the high energy tail of the cosmic neutrino spectrum. The absence of cascades above 2 PeV disfavors a neutrino spectral index $\alpha = 2$ (with a cutoff $E_{\text{cut}} \geq 10$ PeV) at about 2σ considering that three events are expected in the worst scenario ($p\gamma$ interaction). An unbroken power law with $\alpha = 2.6$ is instead still compatible at 1σ with the present results. The absence of events close to the Glashow resonance energy $E_G = 6.32$ PeV is not problematic under this hypothesis, since only 0.4 events are expected due to Glashow resonance after 4 years (see Table 2);
- (iii) the difference between the event rates produced by pp or $p\gamma$ neutrino production mechanisms is not large enough to distinguish among the two options, even if we assume that the parent neutrino spectrum is known. An observation time $T \sim 50$ years would be required to obtain a 2σ discrimination, if the neutrino spectral index is $\alpha = 2.3$.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP³.

References

1. M.G. Aartsen et al., [IceCube Collaboration], Evidence for high-energy extraterrestrial neutrinos at the IceCube detector. *Science* **342**, 1242856 (2013). [arXiv:1311.5238](https://arxiv.org/abs/1311.5238) [astro-ph.HE]
2. M.G. Aartsen et al., [IceCube Collaboration], Observation of high-energy astrophysical neutrinos in three years of IceCube data. *Phys. Rev. Lett.* **113**, 101101 (2014). [arXiv:1405.5303](https://arxiv.org/abs/1405.5303) [astro-ph.HE]
3. M.G. Aartsen et al., [IceCube Collaboration], A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube. *Astrophys. J.* **809**(1), 98 (2015). [arXiv:1507.03991](https://arxiv.org/abs/1507.03991) [astro-ph.HE]
4. Olga Botner slides, <https://events.icecube.wisc.edu/conferenceDisplay.py?confId=68>
5. M.G. Aartsen et al., [IceCube Collaboration], Search for astrophysical tau neutrinos in three years of IceCube data. [arXiv:1509.06212v1](https://arxiv.org/abs/1509.06212v1) [astro-ph.HE]
6. J.F. Beacom et al., Measuring flavor ratios of high-energy astrophysical neutrinos. *Phys. Rev. D* **68**, 093005 (2003) (E-ibid. *D* **72**, 019901, 2005)
7. F. Vissani, G. Pagliaroli, F.L. Villante, The fraction of muon tracks in cosmic neutrinos. *JCAP* **1309**, 017 (2013). [arXiv:1306.0211](https://arxiv.org/abs/1306.0211) [astro-ph.HE]
8. A. Palladino, G. Pagliaroli, F.L. Villante, F. Vissani, What is the flavor of the cosmic neutrinos seen by IceCube? *Phys. Rev. Lett.* **114**(17), 171101 (2015). [arXiv:1502.02923](https://arxiv.org/abs/1502.02923) [astro-ph.HE]
9. M.G. Aartsen et al., [IceCube Collaboration], Flavor ratio of astrophysical neutrinos above 35 TeV in IceCube. *Phys. Rev. Lett.* **114**(17), 171102 (2015). [arXiv:1502.03376](https://arxiv.org/abs/1502.03376) [astro-ph.HE]
10. A.C. Vincent, S.P. Ruiz, O. Mena, The flavour composition of the high-energy IceCube neutrinos. [arXiv:1505.03355](https://arxiv.org/abs/1505.03355) [astro-ph.HE]
11. A. Palladino, F. Vissani, The natural parameterization of cosmic neutrino oscillations. *Eur. Phys. J. C* **75**, 433 (2015). [arXiv:1504.05238](https://arxiv.org/abs/1504.05238) [hep-ph]
12. M. Bustamante, J.F. Beacom, W. Winter, Theoretically palatable flavor combinations of astrophysical neutrinos. [arXiv:1506.02645](https://arxiv.org/abs/1506.02645) [astro-ph.HE]
13. G. Pagliaroli, A. Palladino, F. Vissani, F.L. Villante, Testing neutrino decay scenarios with IceCube data. [arXiv:1506.02624](https://arxiv.org/abs/1506.02624) [hep-ph]
14. J.G. Learned, S. Pakvasa, Detecting tau-neutrino oscillations at PeV energies. *Astropart. Phys.* **3**, 267 (1995). [arXiv:hep-ph/9405296](https://arxiv.org/abs/hep-ph/9405296), [arXiv:hep-ph/9408296](https://arxiv.org/abs/hep-ph/9408296)
15. D.F. Cowen, [IceCube Collaboration], Tau neutrinos in IceCube. *J. Phys. Conf. Ser.* **60**, 227 (2007)
16. R. Abbasi et al., [IceCube Collaboration], A search for UHE tau neutrinos with IceCube. *Phys. Rev. D* **86**, 022005 (2012). [arXiv:1202.4564](https://arxiv.org/abs/1202.4564) [astro-ph.HE]
17. S.L. Glashow, Resonant scattering of antineutrinos. *Phys. Rev.* **118**, 316 (1960)
18. V.S. Berezinsky, A.Z. Gazizov, Cosmic neutrinos and possibility to search for W bosons having 30-GeV-100-GeV masses in underwater experiments. *JETP Lett.* **25**, 254 (1977) (*Pisma. Zh. Eksp. Teor. Fiz.* **25**, 276 (1977))
19. L.A. Anchordoqui, H. Goldberg, F. Halzen, T.J. Weiler, Neutrinos as a diagnostic of high energy astrophysical processes. *Phys. Lett. B* **621**, 18 (2005). [arXiv:hep-ph/0410003](https://arxiv.org/abs/hep-ph/0410003)
20. A. Bhattacharya, R. Gandhi, W. Rodejohann, A. Watanabe, The Glashow resonance at IceCube: signatures, event rates and pp vs. $p\gamma$ interactions. *JCAP* **1110**, 017 (2011). [arXiv:1108.3163](https://arxiv.org/abs/1108.3163) [astro-ph.HE]
21. V. Barger, L. Fu, J.G. Learned, D. Marfatia, S. Pakvasa, T.J. Weiler, Glashow resonance as a window into cosmic neutrino sources. *Phys. Rev. D* **90**, 121301 (2014). [arXiv:1407.3255](https://arxiv.org/abs/1407.3255) [astro-ph.HE]

22. S.R. Kelner, F.A. Aharonian, V.V. Bugayov, Energy spectra of gamma-rays, electrons and neutrinos produced at proton-proton interactions in the very high energy regime. *Phys. Rev. D* **74**, 034018 (2006) (erratum-ibid. *D* **79**, 039901, 2009)
23. S.R. Kelner, F.A. Aharonian, Energy spectra of gamma-rays, electrons and neutrinos produced at interactions of relativistic protons with low energy radiation. *Phys. Rev. D* **78**, 034013 (2008) (erratum-ibid. *D* **82**, 099901, 2010)
24. F.L. Villante, F. Vissani, How precisely neutrino emission from supernova remnants can be constrained by gamma ray observations? *Phys. Rev. D* **78**, 103007 (2008). [arXiv:0807.4151](https://arxiv.org/abs/0807.4151) [astro-ph]
25. R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic, Neutrino interactions at ultrahigh-energies. *Phys. Rev. D* **58**, 093009 (1998). [arXiv:hep-ph/9807264](https://arxiv.org/abs/hep-ph/9807264)
26. A.M. Dziewonski, D.L. Anderson, Preliminary reference earth model. *Phys. Earth Planet. Interiors* **25**, 297 (1981)
27. S. Hummer, M. Ruger, F. Spanier, W. Winter, Simplified models for photohadronic interactions in cosmic accelerators. *Astrophys. J.* **721**, 630 (2010). [arXiv:1002.1310](https://arxiv.org/abs/1002.1310) [astro-ph.HE]
28. S. Hummer, M. Maltoni, W. Winter, C. Yaguna, Energy dependent neutrino flavor ratios from cosmic accelerators on the Hillas plot. *Astropart. Phys.* **34**, 205 (2010). [arXiv:1007.0006](https://arxiv.org/abs/1007.0006) [astro-ph.HE]
29. A. Bhattacharya, R. Gandhi, W. Rodejohann, A. Watanabe, On the interpretation of IceCube cascade events in terms of the Glashow resonance. [arXiv:1209.2422](https://arxiv.org/abs/1209.2422) [hep-ph]
30. V. Barger, J. Learned, S. Pakvasa, IceCube PeV cascade events initiated by electron-antineutrinos at Glashow resonance. *Phys. Rev. D* **87**(3), 037302 (2013). [arXiv:1207.4571](https://arxiv.org/abs/1207.4571) [astro-ph.HE]
31. L. Yacobi, D. Guetta, E. Behar, Implication of the non-detection of neutrinos above 2PeV. [arXiv:1510.01244](https://arxiv.org/abs/1510.01244) [astro-ph.HE]