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Enhanced tau neutrino appearance through invisible decay

Giulia Pagliaroli,[1,*] Natalia Di Marco,[2] and Massimo Mannarelli[2]

[1]*Gran Sasso Science Institute, viale Francesco Crispi, 7, 67100 L'Aquila (AQ), Italy*

[2]*INFN, Laboratori Nazionali del Gran Sasso, via G. Acitelli 22, 67100 Assergi (AQ), Italy*

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The decay of neutrino mass eigenstates leads to a change of the conversion and survival probability of neutrino flavor eigenstates. Exploiting the recent results released by the long-baseline OPERA experiment we perform the statistical investigation of the neutrino invisible decay hypothesis in the $\nu_\mu \to \nu_\tau$ appearance channel. We find that the neutrino decay provides an enhancement of the expected tau appearance signal with respect to the standard oscillation scenario for the long-baseline OPERA experiment. The increase of the $\nu_\mu \to \nu_\tau$ conversion probability by the decay of one of the mass eigenstates is due to a reduction of the "destructive interference" among the different massive neutrino components. Despite data showing a very mild preference for invisible decays with respect to the oscillations only hypothesis, we provide an upper limit for the neutrino decay lifetime in this channel of $\tau_3/m_3 \gtrsim 1.3 \times 10^{-13}$ s/eV at the 90% confidence level.

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I. INTRODUCTION

Nowadays, the three neutrino oscillation picture is established on a rather firm basis. Results from solar, reactor, atmospheric and accelerator experiments provide compelling evidence for the existence of in flight conversions between neutrinos of different flavors caused by nonzero neutrino masses and mixing angles [1].

Nevertheless, nonvanishing neutrino masses indicate the possibility that besides oscillating, neutrinos can decay. Historically, the neutrino decay scenario was the first mechanism proposed for explaining the solar neutrino problem [2,3]. At present, the possibility of neutrino decay is constrained by many experimental observations. The Standard Model neutrino decays both through radiative and nonradiative processes are well constrained by the high precision measurement of the cosmic microwave background [1,4]. Processes involving beyond Standard Model (BSM) physics as

$$\nu_i \to \nu + X, \tag{1}$$

are much less constrained. Here ν_i ($i = 1, 2, 3$) is a neutrino mass eigenstate with mass m_i, while ν and X are particles in the final state. Actually, ν can correspond to one or more neutrinos and X can correspond to one or more nonobservable particles, typically identified as scalar or pseudoscalar fields. The BSM decay in Eq. (1) can be classified as (i) *visible decay*, in which at least one neutrino in the final state is active; (ii) *invisible decay*, in which all ν and X are nonobservable particles. In this last case, the final state neutrino particles are identified as *sterile* neutrinos ν_s. Focusing on invisible decay, we expect that a beam of (relativistic) ν_i-neutrinos having lifetime, τ_i, is depleted due to the invisible neutrino decay by the factor

$$D_i(L, E) = \exp(-\alpha_i \times L/E), \tag{2}$$

where E is the neutrino energy, L is the distance between the source and the detector and

$$\alpha_i = \frac{m_i}{\tau_i} \tag{3}$$

is the decay parameter. It is evident that, for a given ratio L/E, the neutrino decay is only sensitive to decay parameter.

Limits on α_i have been derived by different neutrino sources. For electron antineutrinos, the most favorable combination is provided by the SN1987A ($L = 50$ kpc, $E \sim 20$ MeV): the observation of electron antineutrinos in Kamiokande-II [5] and IMB [6] yields the lower limit $\alpha_1 \sim \alpha_2 \lesssim 10^{-5}$ eV/s [7,8]. Other bounds are less stringent. As a leading example, the strongest model-independent limits on ν_2 nonradiative decays are obtained from solar neutrinos for which $E \sim 1$ MeV and $L = 1.5 \times 10^8$ km; in this case $\alpha_2 \lesssim 10^4$ eV/s [9,10]. For the visible decay modes, a stringent limit $\alpha_2 \lesssim 10^3$ eV/s is obtained by the nonobservation of solar $\bar{\nu}_e$ appearance in Kamland [11]. Independent and highly competitive limits can be also obtained by the observation of high-energy cosmic neutrinos as recently provided by the IceCube detector [12]. In this case due to the long baseline, the dependence on the lifetime parameters τ_i disappears and the main information for discriminating the presence of nonradiative neutrino decays is the observed flavor ratios of neutrinos [13]. The ν_3 lifetime can be bounded by atmospheric and long-baseline neutrino data obtaining [14]

*giulia.pagliaroli@lngs.infn.it

$$\alpha_3 \lesssim 0.3 \times 10^{10} \text{ eV/s} \tag{4}$$

at 90% C.L., whereas the analysis using only long-baseline data provides less stringent limits [15,16] $\alpha_3 \lesssim 0.3 \div 0.5 \times 10^{12}$ eV/s at 90% C.L. In both cases, let us stress that the analysis regards how the α_3 decay parameter changes the $\nu_\mu \to \nu_\mu$ survival probability.

In the present manuscript, we exploit the recent results released by the long-baseline OPERA experiment [17] to perform the first investigation, to the best of our knowledge, of α_3 using the $\nu_\mu \to \nu_\tau$ appearance channel. The OPERA experiment [18,19], located at the Gran Sasso Underground Laboratory of INFN, is designed to investigate the ν_τ appearance channel on an event-by-event basis by using an artificial beam Cern Neutrino to Gran Sasso (CNGS) [20]] produced at CERN and mainly composed by ν_μ. We show that the presence of a decay channel increases the $\nu_\mu \to \nu_\tau$ conversion probability $P_{\mu\tau}$, for the OPERA values of L/E. This differs from the behavior in the typical L/E range values of Minos and T2K experiments, for which the neutrino decay leads to a decrease of $P_{\mu\tau}$. In the case of the OPERA experiment, the enhancement is produced by the following mechanism: due to the experimental setup, the "destructive interference" of different mass eigenstates occurs and the decay of one mass eigenstate can partially wash out this interference increasing the $P_{\mu\tau}$ with respect to the pure oscillations case. On the other hand, for the experimental setups of Minos and T2K, the decay of one mass eigenstate reduces the "constructive interference" of the different mass eigenstates decreasing $P_{\mu\tau}$ with respect to the standard oscillations case. This effect causes a very mild (less than 1σ) preference of the OPERA data [17] for the model where invisible decays is also included with respect to the oscillations only hypothesis. The upper limit value for α_3 that we obtain from this analysis is also weakened by this effect and is in agreement but not competitive with respect to the one already provided by the combined analysis of SK, Minos and T2K. The present paper is organized as follows. In Sec. II we discuss the ν_μ to ν_τ conversion probability given by the combination of flavor oscillations and the invisible decay of the ν_3 mass eigenstate. We provide a general analysis for any value of L/E, comparing the behavior of $P_{\mu\tau}$ for the OPERA experiment with that for the Minos and T2K experiments. In Sec. III we use the recent results on the number of observed ν_τ events reported by the OPERA collaboration in [17] to derive a best-fit value and the upper limit value for α_3. We draw our conclusions in Sec. IV.

II. COMBINING NEUTRINO OSCILLATION AND DECAY: THE MODEL

Let us assume that active neutrinos are subject to both standard mixing and invisible decays. Therefore, propagating neutrinos mix among flavor eigenstates in an oscillatory time-reversible manner and disappear due to time-irreversible decay. In this hypothesis, the mass eigenstates evolution is given by

$$|\nu_i(t)\rangle = |\nu_i(0)\rangle e^{-iE_i t - \frac{\Gamma_i}{2}t}, \tag{5}$$

where $E_i \simeq p + m_i^2/(2p)$ and $\Gamma_i = \alpha_i/E_i$. Clearly, massive neutrinos of any flavor can decay by invisible processes. In the two neutrino flavor approximation, which is adequate to describe long-baseline experiments, both ν_3 and ν_2 can decay. However, bearing in mind that the baseline of the OPERA experiment is $L_0 \simeq 730$ km, the mean neutrino energy is $E_0 \simeq 17$ GeV and the stringent limits on the value of α_2 found both with solar and SN data (see Sec. I), we can set $\alpha_2 = 0$ in our considerations. Note that this is implicitly assumed in the analysis reported in [14–16] where, in a two-flavor approximation, only ν_3 is allowed to decay through the process $\nu_3 \to \nu_s + X$ while ν_2 is considered stable.

Assuming that the flavor eigenstates are obtained by rotation with the standard mixing matrix,

$$\mathbf{U} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}, \tag{6}$$

and upon substituting $\Gamma_i = \delta_{i3}\alpha_i/E_i$ in Eq. (5), we find, in agreement with [16], the survival probability

$$P_{\mu\mu}(E, L, \alpha_3) = \left(\cos^2\theta_{23} + \sin^2\theta_{23} e^{-\frac{\alpha_3}{2E}L}\right)^2 - 4\cos^2\theta_{23}\sin^2\theta_{23} e^{-\frac{\alpha_3}{2E}L} \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right), \tag{7}$$

and the conversion probability

$$P_{\mu\tau}(E, L, \alpha_3) = \cos^2\theta_{23}\sin^2\theta_{23}\left(1 - e^{-\frac{\alpha_3}{2E}L}\right)^2 + 4\cos^2\theta_{23}\sin^2\theta_{23} e^{-\frac{\alpha_3}{2E}L} \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right), \tag{8}$$

where $\Delta m_{23}^2 = m_3^2 - m_2^2$ and we replaced $t \to L$. These probabilities depend on the combination of three different effects:

(1) The flavor eigenstates are superposition of the mass eigenstates, leading to the θ_{23} dependence.
(2) The mass eigenstates have different masses, leading to the Δm_{23}^2 dependence.
(3) The mass eigenstate ν_3 can decay, leading to the α_3 dependence.

An interesting aspect is that $P_{\mu\mu} + P_{\mu\tau} = 1 - \sin^2\theta_{23}(1 - e^{-\frac{2\alpha_3}{2E}L})$, meaning that the total number of neutrinos is not conserved if $\alpha_3 \neq 0$. Moreover, the conversion probability is nonzero even for $\Delta m^2_{32} \to 0$, corresponding to the pure decay case. First introduced by Barger in [21], the pure decay case is ruled out at more than 3σ by SK [22] atmospheric neutrino data and at 7σ by the Minos data analysis [23].

The plots in Fig. 1 represent the survival probability (top panel) and the conversion probability (bottom panel) as a function of L/E in the two-flavor approximation. In these plots we used $m^{\rm BF}_{23} = \Delta m^2_{23} = 2.44 \times 10^{-3}$ eV^2, $\theta^{\rm BF}_{23} = \sin(\theta_{23})^2 = 0.452$ corresponding to the best-fit values of the global analysis of [24]. The general effect of the neutrino decay is a damping of the standard oscillation amplitude. With increasing values of α_3, i.e., decreasing the neutrino lifetime, the damping effect is stronger. For very short decay times the neutrino oscillations are strongly suppressed even for low values of the ratio L/E. For very high values of L/E, or equivalently allowing the neutrino to propagate through very long distances at a fixed neutrino source energy, the neutrino conversion probability tends to the constant value $\cos^2\theta_{23}\sin^2\theta_{23}$. The pure decay case is shown in Fig. 1 with the green solid line for $\alpha_3 = 10^{11}$ eV/s.

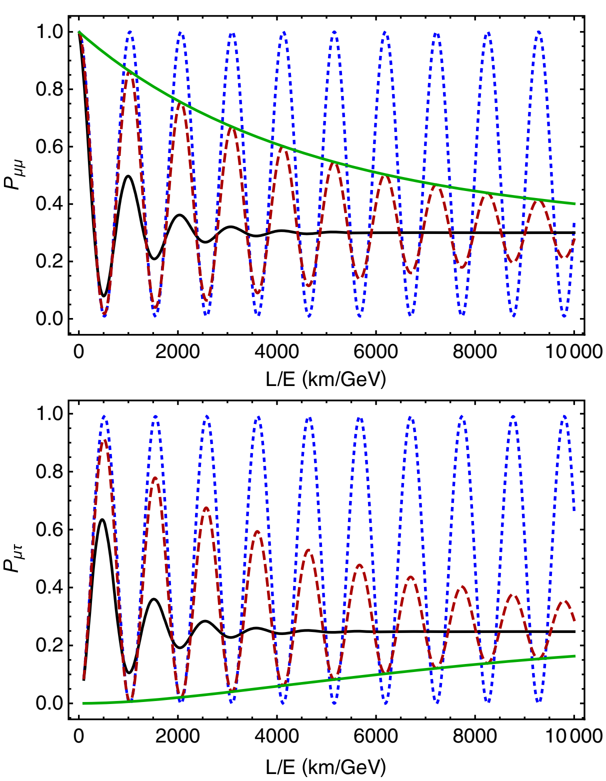

FIG. 1. Survival probability (top panel) and conversion probability (bottom panel), as a function of the ratio L/E in the two-flavor approximation. The dotted blue lines correspond to the oscillation-only scenario. The red dashed lines refer to the oscillation plus decay hypothesis for $\alpha_3 = 10^{11}$ eV/s. The black solid lines correspond to the oscillation plus decay hypothesis for $\alpha_3 = 10^{13}$ eV/s. The green solid lines represent the pure decay case with $\alpha_3 = 10^{11}$ eV/s.

As discussed in Sec. I, the analysis of disappearance data of atmospheric and long baseline experiments led to the limits on the value of α_3 reported in Eq. (4). The same parameter can be studied with the appearance data of the long baseline OPERA experiment. Figure 2 shows a zoom of the conversion probability $P_{\mu\tau}$ in the region of L/E relevant for OPERA, Minos and T2K. The dotted blue line corresponds to the oscillation-only scenario, the red dashed line refers to the oscillation plus decay hypothesis for $\alpha_3 = 10^{11}$ eV/s while the black solid line refers to the oscillation plus decay hypothesis for $\alpha_3 = 10^{13}$ eV/s. Arrows in the figure indicate the characteristic ratio $\hat{R} = L_0/E_0$ for the different long-baseline experiments, where L_0 is the baseline and E_0 is the average neutrino beam energy. In particular, $\hat{R}_{\rm OPERA} \simeq 730/17$ km/GeV, $\hat{R}_{\rm Minos} \simeq 730/3$ km/GeV and $\hat{R}_{\rm T2K} \simeq 295/2.6$ km/GeV. These ratios determine the phase of the transition probability $P_{\mu\tau}$ of Eq. (8). When the decay is turned off, i.e., $\alpha_3 = 0$, Eq. (8) reduces only to the last term due to the interference between the massive components. For the value $\hat{R}_{\rm OPERA}$ a situation of destructive interference occurs giving the very small value $P_{\mu\tau} \simeq 0.02$. On the other hand, for $\alpha_3 \to \infty$, Eq. (8) reduces only to the constant term $\cos^2\theta_{23}\sin^2\theta_{23}$ and $P_{\mu\tau} \simeq 0.25$ (with $\theta^{\rm BF}_{23}$). As a consequence, the OPERA experiment is the only one characterized by an enhancement of the conversion probability when the decay mechanism is turned on with respect to the oscillation-only hypothesis. The opposite situation happens in the case of Minos and T2K, for which the conversion probability decreases for nonvanishing α_3 with respect to the oscillation-only hypothesis. Clearly, an increase of the

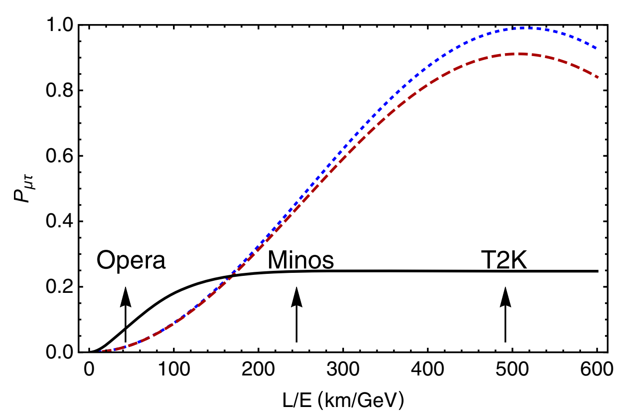

FIG. 2. Conversion probability in the region of L/E investigated by OPERA, Minos and T2K experiments. The dotted blue line corresponds to the oscillation-only scenario. The red dashed line refers to the oscillation plus decay hypothesis for $\alpha_3 = 10^{11}$ eV/s. The black solid line refers to the oscillation plus decay hypothesis for $\alpha_3 = 10^{13}$ eV/s. The arrows indicate the characteristic L/E of OPERA, Minos, and T2K.

conversion probability leads to an increase of the number of expected ν_τ events in OPERA. We will discuss this issue in the next section.

III. ANALYSIS OF THE OPERA $\nu_\mu \to \nu_\tau$ APPEARANCE RESULTS

The OPERA collaboration recently reported the observation of the fifth candidate ν_τ event found in the analysis of an enlarged data sample. The total numbers of expected events were 2.64 ± 0.53 and 0.25 ± 0.05 for signal and background respectively, obtained by assuming $\Delta m^2_{23} = 2.44 \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) = 1$. This result provides a 5.1σ evidence for the presence of $\nu_\mu \to \nu_\tau$ oscillations in the three neutrino flavors framework [17]. In the neutrino decay plus oscillation hypothesis, the number of expected ν_τ events can be obtained combining the oscillation probability in Eq. (8) with the beam and detector characteristics as follows:

$$N^{th}_{\nu_\tau}(\alpha_3) = \epsilon n_{\text{p.o.t}} N_{Pb} \int dE \Phi_\mu(E) \sigma_{\nu_\tau}(E) P_{\mu\tau}(E, L_0, \alpha_3), \tag{9}$$

where $\Phi_\mu(E)$ is the CNGS ν_μ flux [25], $n_{\text{p.o.t}} = 17.97 \times 10^{19}$ is the total number of delivered protons on target (p.o.t.) in five years of data taking (from 2008 to 2012) [17], $\sigma_{\nu_\tau}(E)$ is the ν_τ CC cross section [26], $\text{N}_{Pb} = N_A \times M$ is the number of nucleon contained in the 1.2 kton of OPERA lead target [19]. Finally, the factor ϵ is the overall experimental ν_τ detection efficiency.

In order to estimate the efficiency factor ϵ, we consider the oscillation-only hypothesis, i.e., $\alpha_3 = 0$, with $\Delta m^2_{23} = 2.44 \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) = 1$. Using Eq. (9) and setting the efficiency to 1, the number of expected ν_τ events is ~43.5. Comparing this value with the one quoted by the OPERA collaboration 2.64, we assume $\epsilon = 2.64/43.5 \simeq 6\%$.

The dependence of $N^{th}_{\nu_\tau}$ on α_3 is reported in Fig. 3 with a solid black line; the dotted red line represents the observed number of events in OPERA. The number of expected ν_τ events $N^{th}_{\nu_\tau}$ increases as a function of the parameter α_3 and saturates to about 67 events when the decay is complete, i.e., $\alpha_3 \to \infty$.

The best-fit value for the decay parameter α_3 can be estimated by maximizing the Poisson likelihood functions,

$$\mathcal{L}(\alpha_3) \propto \lambda^n \times e^{-\lambda}, \tag{10}$$

where $\lambda = N^{th}_{\nu_\tau}(\alpha_3) + b$, n are the observed events, $b = 0.25$ are the background events quoted by the OPERA collaboration. The normalized likelihood function is reported in Fig. 3 in arbitrary units with a dashed blue line. In this case the oscillation parameters $\sin^2\theta_{23}$ and

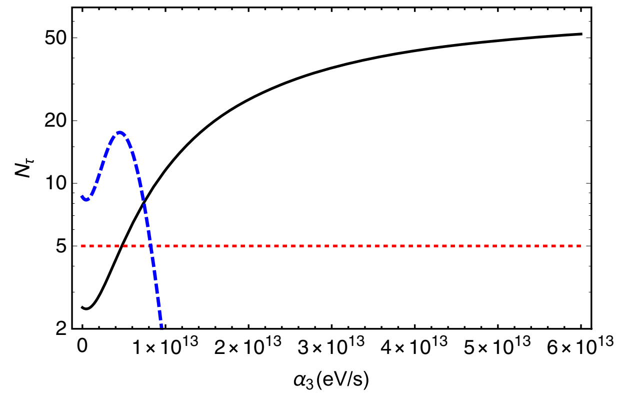

FIG. 3. Expected number of ν_τ events (solid black line) from Eq. (9) as a function of the decay parameter α_3 and for m^{BF}_{23}, θ^{BF}_{23} [24]. The blue dashed line shows, in arbitrary units, the normalized likelihood function. The dotted red line is the number of observed ν_τ events in OPERA.

Δm^2_{23} are fixed to their best-fit values provided by the global analysis of oscillation data [24]. The corresponding $\Delta\chi^2$ function is reported in Fig. 4 with a dashed blue line. We find that OPERA data show a 1σ preference for the oscillations plus decay model with respect to the oscillation-only hypothesis. Indeed the minimum for the χ^2 is characterized by $\alpha^{\text{BF}}_3 \simeq 4.4 \times 10^{12}$ eV/s. To understand the role of the other oscillation parameters we include $\sin^2\theta_{23}$ and Δm^2_{23} as free parameters of the likelihood function. By maximizing the new Poisson likelihood function we find $\alpha^{\text{BF}}_3 \simeq 3.8 \times 10^{12}$ eV/s, $(\sin^2\theta_{23})^{BF} = 0.458$ and $(\Delta m^2_{23})^{BF} = 2.42 \times 10^{-3}$ eV^2. In Fig. 4 we show with a black solid line the $\Delta\chi^2$ function obtained by marginalizing with respect to the other two oscillation parameters, i.e., allowing them to fluctuate inside their 3σ ranges of uncertainty [1]. The preference for a value of α_3 different

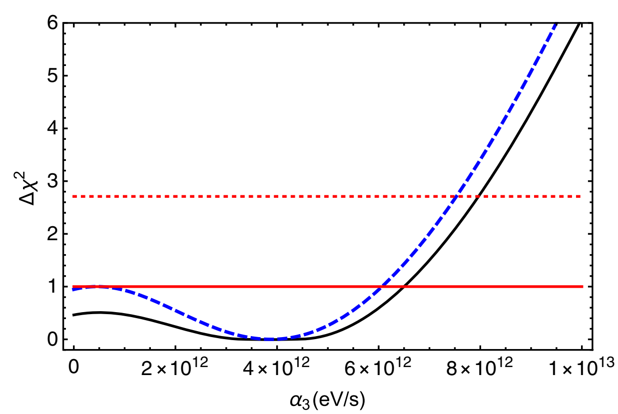

FIG. 4. Value of $\Delta\chi^2$ as a function of α_3 considering the other two oscillation parameters fixed to their best-fit values, i.e., m^{BF}_{23}, θ^{BF}_{23} (blue dashed line) and when the likelihood is marginalized with respect to these two (black solid line). The horizontal lines correspond to the 1σ (solid red line) and 90% confidence level (dotted red line).

from zero is stable, however $\alpha_3 = 0$ is now excluded only at $\Delta\chi^2 = 0.5$. Using this $\Delta\chi^2$, we can finally set our upper limit at 90% confidence level for the neutrino decay lifetime of $\alpha_3 \lesssim 7.7 \times 10^{12}$ eV/s, or $\tau_3/m_3 \gtrsim 1.3 \times 10^{-13}$ s/eV.

IV. CONCLUSIONS

Motivated by the recently released OPERA results in the ν_τ appearance channel we have performed an analysis of the conversion probability in the presence of neutrino invisible decays. Remarkably, neutrino decay enhances the conversion probability for the OPERA experimental setup, indeed data show a mild preference for a decay constant different to zero. We have demonstrated that for the ratio L/E characteristic of the OPERA experiment the oscillations plus decay model can provide an enhancement of the conversion probability $P_{\mu\tau}$ with respect to the oscillation-only hypothesis. This enhancement results in a corresponding increase of the expected number of ν_τ CC interactions that better fits the observed number of events (let us remind that the probability of observing five or more candidates with an expectation of 2.64 signal plus 0.25 background events is 17% from Poisson statistics [17]). Due to the small statistics, the best-fit value we have found for α_3 has less than 1σ significance. Unfortunately this effect weakened the upper limit at 90% confidence level for the neutrino decay lifetime which is not competitive with respect to the one already provided by the combined analysis of SK, Minos and T2K, see Eq. (4). However, this analysis provides the first upper limit for the neutrino decay lifetime of α_3 by using the ν_τ appearance channel. This channel can provide complementary information and could be interesting to strengthen this analysis by including the larger data sets of the SK detector in this channel [27].

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