Discovering intermediate mass sterile neutrinos through $\tau^- \to \pi^- \mu^- e^+ \nu(\text{or } \bar{\nu})$ decay

C. S. Kim,[1,*] G. López Castro,[2,†] and Dibyakrupa Sahoo[1,‡]

[1]*Department of Physics and IPAP, Yonsei University, Seoul 120-749, Korea*
[2]*Departamento de Física, Centro de Investigación y de Estudios Avanzados, Apartado Postal 14-740, 07000 México Distrito Federal, México*

(Received 10 August 2017; published 13 October 2017)

Distinguishing the Dirac and Majorana nature of neutrinos remains one of the most important tasks in neutrino physics. By assuming that the $\tau^- \to \pi^- \mu^- e^+ \nu(\text{or } \bar{\nu})$ decay is resonantly enhanced by the exchange of an intermediate mass sterile neutrino N, we show that the energy spectrum of emitted pions and muons can be used to easily distinguish between the Dirac and Majorana nature of N. This method takes advantage of the fact that the flavor of light neutrinos is not identified in the tau decay under consideration. We find that it is particularly advantageous, because of no competing background events, to search for N in the mass range $m_e + m_\mu \leq m_N \leq m_\mu + m_\pi$, where m_X denotes the mass of particle $X \in \{e, \mu, \pi, N\}$.

DOI: 10.1103/PhysRevD.96.075016

I. INTRODUCTION

Lepton number is an absolutely conserved property of the standard model of particle physics. However, observations of flavor oscillations in neutrinos have revealed that neutrinos are massive as well as mixed with one another, opening the interesting possibility that lepton number violation (LNV) occurs. Being electrically neutral fermions, neutrinos can get their observed masses from the well-known Yukawa couplings (Dirac neutrinos) or from their self-conjugated fields (Majorana neutrinos); in other words, they can be different or identical to their own antiparticles, respectively. Another interesting consequence of massive neutrinos is that the occurrence of lepton-flavor violation (LFV) in decays of charged leptons is possible due to the mixing mechanism, although with unobservably suppressed rates. Their observation at proposed flavor factory experiments would indicate that mechanisms of LFV beyond the standard neutrino mixing are necessary.

Among the important implications that neutrinos turn out to be Majorana particles is that their masses originate beyond the Yukawa couplings via the Higgs mechanism. The presence of Majorana mass terms for neutrinos entail total lepton number nonconservation by two units ($\Delta L = 2$), which would manifest, for instance, in neutrinoless double-beta decays of nuclei, hadrons and leptons. So far, $\Delta L = 2$ violating processes have not been observed, leading to strong constrains on their mass and mixing parameters [1]. In recent years, many studies have been reported on the possibility of observing LNV by $\Delta L = 2$ units in decays of mesons [2] and tau leptons [3] mediated by the exchange of a heavy Majorana neutrino. The upper bounds on branching fractions obtained at flavor factories [4,5] have allowed us to set constraints on the square of mixing of light ordinary neutrinos and heavy sterile neutrinos ranging from $|V_{\ell N}|^2 = 10^{-8} \sim 10^{-2}$ (where $\ell \in \{e, \mu, \tau\}$) as the neutrino mass increases from a few hundred MeV to a few GeV.

The question of whether neutrinos are Dirac or Majorana particles remains one of the most important questions for particle physics experiments. The existence of heavy Majorana neutrinos would open the possibility to find mechanisms to explain the smallness of active neutrino masses, as well as the viability of theories to explain the baryon asymmetry or dark matter abundance in the Universe [6–8]. Different processes that may be sensitive to the effects of light or heavy Majorana neutrinos have been proposed and several experimental searches are underway. Beyond the standard searches of nuclear neutrinoless double-beta decay experiments, several studies have been suggested to distinguish between the Dirac and Majorana nature of neutrinos, among others, precise measurements of neutrino-electron scattering [9,10], the pseudo-Dalitz plot of sequential weak decay processes involving $\nu\bar{\nu}$ pair as final products [11], and the spectrum of charged leptons from decays of intermediate on-shell heavy neutrinos [12].

The Dirac-type neutrinos can mediate processes with LFV but not LNV. Conversely, Majorana neutrinos can intervene in processes with both LFV and LNV. In this paper, we use these properties of neutrinos to investigate how the study of $\tau^- \to \pi^- \mu^- e^+ \nu(\text{or } \bar{\nu})$ decays can help to disentangle the nature of the intermediate mass sterile neutrino mediating these decays. Since the flavor of the light active neutrino in the final state is not identified, it is not straightforward to distinguish scenarios with LFV ($\nu = \nu_{e,\tau}$) from those with LNV ($\bar{\nu} = \bar{\nu}_\mu$). Among the four channels possible in our case, the choice of a

*cskim@yonsei.ac.kr
†glopez@fis.cinvestav.mx
‡sahoodibya@yonsei.ac.kr

monoenergetic pion allows one to single out two specific contributions. We show how, in the context of these two chosen channels, the energy spectrum of the emitted muon can be useful to distinguish between the Majorana and Dirac nature of the intermediate mass sterile neutrino.

This paper is organized as follows: In Sec. II we compute the partial decay width of $\tau^- \to \pi^-\mu^-e^+\nu(\text{or }\bar{\nu})$ decays assuming it to be facilitated by an on-shell intermediate mass sterile neutrino. Here we discuss how by choosing monoenergetic pions we can pick out the Feynman diagrams relevant to our methodology. Then in Sec. III we discuss about the muon energy spectrum and show how it helps in distinguishing between the Dirac and Majorana possibilities for the intermediate mass neutrino. In Sec. IV we compare our chosen modes with $\tau^- \to \mu^-\pi^+\pi^-$ which has been already searched for experimentally. Here we note that there exists a mass range for N in which we have no contamination from background events. Finally, we conclude in Sec. V, reiterating the salient features of our methodology.

II. PARTIAL DECAY WIDTH OF THE $\tau^- \to \pi^-\mu^-e^+\nu(\text{or }\bar{\nu})$ DECAYS

Let us consider the $\tau^- \to \pi^-\mu^-e^+\nu(\text{or }\bar{\nu})$ decay,[1] which we will assume to be mediated by the exchange of a single on-shell (intermediate mass) sterile neutrino N; see Fig. 1. This decay violates lepton flavor irrespective of the specific flavor identity of the neutrino (or antineutrino) in the final state. If in the final state we have a muon antineutrino ($\bar{\nu}_\mu$), the decay under consideration is a LNV process and must be mediated by an intermediate mass Majorana neutrino N as shown in Figs. 1(b) and 1(c); otherwise, the intermediate neutrino N can be either Dirac or Majorana. Since, the flavor of the neutrino (or antineutrino) in our final state can not be determined, it is not straightforward to distinguish the Dirac and Majorana cases. Nevertheless, this flavor ambiguity forces us to find some observables that can be used to distinguish between the Dirac and Majorana neutrinos.

It is interesting to observe that the contributions in Figs. 1(a) and 1(b) can be differentiated from those in Figs. 1(c) and 1(d) by looking at the pion kinematics.[2] Owing to the on-shell nature of the intermediate mass neutrino N, the pion energy spectrum (in the rest frame of the tau lepton) is monoenergetic for Figs. 1(a) and 1(b) and has a continuous energy distribution for Figs. 1(c) and 1(d).

[1]The analogous $\tau^- \to \pi^-\mu^+e^-\nu(\text{or }\bar{\nu})$ decay follows a similar discussion under the exchange of $\mu \leftrightarrow e$ flavor labels.

[2]Of course, if the lifetime of N is large enough, those set of diagrams are also differentiated by the pion (muon) identification at the primary (secondary) or secondary (primary) vertices, respectively. Our analysis assumes no finite propagation of the intermediate mass neutrino with the displaced vertices.

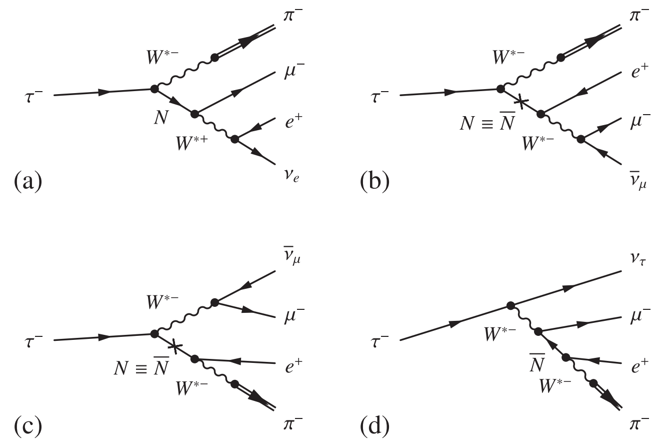

FIG. 1. Feynman diagrams contributions to $\tau^- \to \pi^-\mu^-e^+\nu(\text{or}\bar{\nu})$, mediated by an intermediate mass sterile neutrino N (the crossed lines correspond to a Majorana particle). The light active neutrino (or antineutrino) of flavor $\ell \in \{e, \mu, \tau\}$ allowed in each case is denoted by ν_ℓ (or $\bar{\nu}_\ell$). Diagrams (a) and (d) correspond to LFV processes while (b) and (c) correspond to both LFV and LNV processes.

Conversely, the muon spectrum is continuous in all cases. In the following we will focus on the case of a monoenergetic pion emission and show how measurements of the branching ratio and muon energy spectrum in this case allow us to distinguish between the effects of Dirac and Majorana neutrinos.

Thus, let us consider only the Feynman diagrams shown in Figs. 1(a) and 1(b). For given a mass m_N of the sterile neutrino N, the distinctive feature of Figs. 1(a) and 1(b) is the monoenergetic pion with energy $E_\pi = (m_\tau^2 + m_\pi^2 - m_N^2)/2m_\tau$. The intermediate mass Majorana neutrino can be produced on shell for mass values in the range $m_e + m_\mu \leq m_N \leq m_\tau - m_\pi$, i.e., $\approx 0.1061\ \text{GeV} \leq m_N \leq 1.6372\ \text{GeV}$. Using the narrow-width approximation for N, the partial decay width of tau decay in our case is given by

$$\Gamma(\tau^- \to \pi^-\mu^-e^+\nu) = \Gamma(\tau^- \to \pi^-N)\frac{\Gamma(N \to \mu^-e^+\nu(\text{or }\bar{\nu}))}{\Gamma_N}, \tag{1}$$

where Γ_N is the full width of the sterile neutrino, and the partial decay widths appearing in Eq. (1) are given, respectively, by

TABLE I. Upper bounds on the mixings of sterile neutrinos with light active neutrinos [14] and total decay width of the sterile neutrino for two reference values of m_N.

m_N (in GeV)	$\lvert V_{eN}\rvert^2$	$\lvert V_{\mu N}\rvert^2$	$\lvert V_{\tau N}\rvert^2$	Γ_N (in GeV)
0.25	10^{-8}	10^{-7}	10^{-4}	8.97×10^{-21}
1.0	10^{-7}	10^{-7}	10^{-2}	9.14×10^{-16}

TABLE II. Upper bounds on the partial decay widths for production and decay of the intermediate mass sterile neutrino N, and the branching fraction for the $\tau^- \to \pi^-\mu^-e^+\nu$ (or $\bar{\nu}$) decay.

m_N (in GeV)	$\Gamma(\tau^- \to \pi^- N)$ (in GeV)	$\Gamma(N \to \mu^- e^+\nu(\text{or } \bar{\nu}))$ (in GeV)	Branching Fraction for $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$
0.25	4.86×10^{-17}	$6.14 \times 10^{-25}(1 + \frac{\alpha}{10})$	$1.47 \times 10^{-9}(1 + \frac{\alpha}{10})$
1	1.61×10^{-15}	$2.10 \times 10^{-21}(1 + \alpha)$	$1.63 \times 10^{-9}(1 + \alpha)$

$$\Gamma(\tau^- \to \pi^- N) = \frac{G_F^2 f_\pi^2 m_\tau^3 |V_{ud}|^2}{8\pi} |V_{\tau N}|^2 \sqrt{\lambda(1, r_N, r_\pi)} [(1 - r_N)^2 - r_\pi(1 + r_N)], \tag{2}$$

$$\Gamma(N \to \mu^- e^+ \nu(\text{or } \bar{\nu})) = \Gamma(N \to \mu^- e^+ \nu_e) + \Gamma(N \to \mu^- e^+ \bar{\nu}_\mu) = \frac{G_F^2 m_N^5 |V_{\mu N}|^2}{192\pi^3} (1 - 8r_\mu + 8r_\mu^3 - r_\mu^4 - 12 r_\mu^2 \ln r_\mu)(1 + \alpha R_{e\mu}), \tag{3}$$

$$= \begin{cases} \frac{G_F^2 m_N^5 |V_{\mu N}|^2}{192\pi^3} (1 - 8r_\mu + 8r_\mu^3 - r_\mu^4 - 12 r_\mu^2 \ln r_\mu), & (\text{if } N \text{ is a Dirac neutrino}, \alpha = 0) \\ \frac{G_F^2 m_N^5 |V_{\mu N}|^2}{192\pi^3} (1 - 8r_\mu + 8r_\mu^3 - r_\mu^4 - 12 r_\mu^2 \ln r_\mu)(1 + R_{e\mu}). & (\text{if } N \text{ is a Majorana neutrino}, \alpha = 1) \end{cases} \tag{4}$$

where $f_\pi = 130.2$ MeV [13], $r_{N,\pi} = m_{N,\pi}^2/m_\tau^2$, $r_\mu = m_\mu^2/m_N^2$, with $|V_{\ell N}|^2$ denoting the mixing of the active neutrino of flavor $\ell = e, \mu, \tau$ with the sterile neutrino N. In the above expressions, α is a parameter that allows us to distinguish the sterile intermediate Dirac ($\alpha = 0$) and Majorana ($\alpha = 1$) neutrinos,[3] $R_{e\mu} = |V_{eN}|^2/|V_{\mu N}|^2$, and $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + yz + zx)$ is the Källén function. It is easy to check that Eq. (2) gives the usual expression for the decay width of $\tau^- \to \pi^- \nu_\tau$ when one takes $r_N \to 0$ and $|V_{\tau N}|^2 \to 1$. Similarly, when $\alpha = 0$ and $|V_{\ell N}|^2 = 1$ (the case of Dirac neutrino) Eq. (4) becomes identical to the well-known rate of muon decay in the crossed channel.

In order to provide an estimate of the $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$ branching fraction we need an input for the total width Γ_N. From the sum over all the exclusive decay channels that open below m_N [14] we get the following expressions for the total decay width of N for two typical values of the neutrino mass:

$$\Gamma_N \approx \frac{G_F^2 m_N^5}{96\pi^3} (15|V_{eN}|^2 + 8|V_{\mu N}|^2 + 2|V_{\tau N}|^2), \qquad \begin{pmatrix} \text{for} \\ m_N = 0.25 \text{ GeV} \end{pmatrix} \tag{5}$$

$$\Gamma_N \approx \frac{G_F^2 m_N^5}{96\pi^3} (7|V_{eN}|^2 + 7|V_{\mu N}|^2 + 2|V_{\tau N}|^2). \qquad \begin{pmatrix} \text{for} \\ m_N = 1 \text{ GeV} \end{pmatrix} \tag{6}$$

Using the upper bounds for the mixing elements $|V_{\ell N}|^2$ that were reported in Ref. [14], we evaluate the decay width Γ_N of the intermediate mass neutrino. The results are given in Table I.

Finally, the branching fraction for the $\tau^- \to \pi^-\mu^-e^+\nu(\text{or} \bar{\nu})$ decay can be obtained by dividing Eq. (1) by the measured width of the τ lepton [13]. The estimated upper limits for the partial widths involved Eqs. (2) and (4) and are shown in Table II for the two values of m_N, and the branching fraction for the $\tau^- \to \pi^-\mu^-e^+\nu(\text{or} \bar{\nu})$ decay is shown in the last column.

We conclude that, with current bounds on the mixing elements $|V_{\ell N}|^2$, the effects the branching fraction of the tau decay under consideration may be more sensitive to the effects of Majorana neutrinos for larger values of heavy neutrino mass. Those branching fractions lie at the edge of Belle II capabilities, which is expected to produce about $\mathcal{O}(10^{10})$ tau lepton pairs in the full data set [15]. Conversely, from an experimental upper limit on the $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$ decay at future flavor factories, one can constrain the parameter space $(|V_{\ell N}|^2, m_N)$ under the assumption that the exchanged sterile neutrino is a Dirac or Majorana particle.

III. MUON ENERGY SPECTRUM IN THE $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$ DECAYS

From Eq. (4) it is clear that the decay rate for $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$ (more precisely, the decay rate of the

[3] Note that a Majorana neutrino ($\alpha = 1$) with $R_{e\mu} \to 0$ can not be distinguished here from a Dirac neutrino ($\alpha = 0$). However, if we instead consider the decay $\tau^- \to \pi^-\mu^+e^-\nu(\text{or } \bar{\nu})$ and look at the pion and muon energy distributions as discussed in this paper, the above problem does not appear.

intermediate mass neutrino N) is the same for both Dirac and Majorana cases up to an overall normalization factor that depends on the nature of the exchanged neutrino. Therefore, in order to distinguish between the Majorana and Dirac cases, we have to look at another observable like the muon energy spectrum.

The normalized muon energy distribution for the decay $N \to \mu^- e^+ \nu(\text{or } \bar{\nu})$ in the rest frame of N is given by

$$\frac{1}{\Gamma(N\to\mu^-e^+\nu(\text{or }\bar{\nu}))}\frac{d\Gamma(N\to\mu^-e^+\nu(\text{or }\bar{\nu}))}{dE_\mu} = \frac{96 m_N^3(-\frac{1}{3} m_N m_\mu^2 + (\frac{1}{2}+\alpha R_{e\mu})(m_N^2+m_\mu^2)E_\mu - (\frac{2}{3}+2\alpha R_{e\mu})m_N E_\mu^2)\sqrt{E_\mu^2-m_\mu^2}}{((m_N^4-m_\mu^4)(m_N^4+m_\mu^4-8m_\mu^2m_N^2)-24m_\mu^4m_N^4\log(\frac{m_\mu}{m_N}))(1+\alpha R_{e\mu})}. \tag{7}$$

The muon energy distributions for $m_N = 0.25$ and 1 GeV and for various values of $R_{e\mu}$ are shown in Fig. 2. It is clear from these plots that the shape of the muon spectrum can help to differentiate between the contributions of the intermediate mass Dirac and Majorana neutrinos. A peak of the muon energy spectrum at the end of the maximum

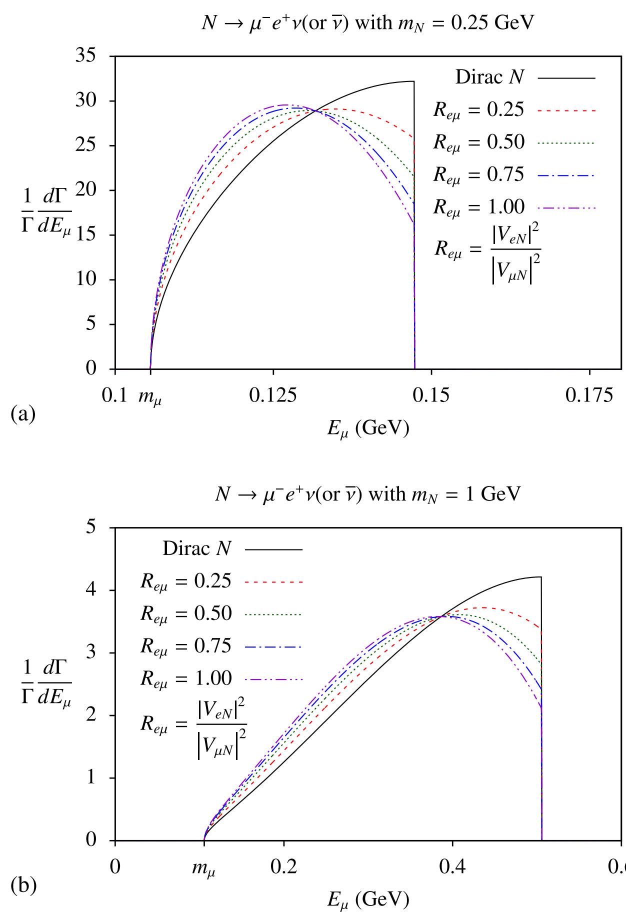

FIG. 2. Normalized muon energy distribution for the decay $N \to \mu^- e^+ \nu(\text{or } \bar{\nu})$ where the flavor of the final neutrino (or antineutrino) is unknown. The upper (lower) plot corresponds to $m_N = 0.25$ GeV ($m_N = 1$ GeV). The solid curves correspond to the case with Dirac neutrino ($\alpha = 0$), while the other curves correspond to the case with Majorana neutrino ($\alpha = 1$) for different choices of $R_{e\mu}$. It should again be noted that if the Majorana neutrino N has vanishingly small mixing with electron-type neutrino, i.e., $R_{e\mu} \to 0$, then such a neutrino cannot be distinguished from the Dirac neutrino case using the plots shown here. Nevertheless, this special case can be easily addressed if we consider the $\tau^- \to \pi^- \mu^+ e^- \nu(\text{or } \bar{\nu})$ decays and follow our methodology of looking at the pion and muon energies as discussed in the main text. All experimental values were taken from PDG 2016 [13].

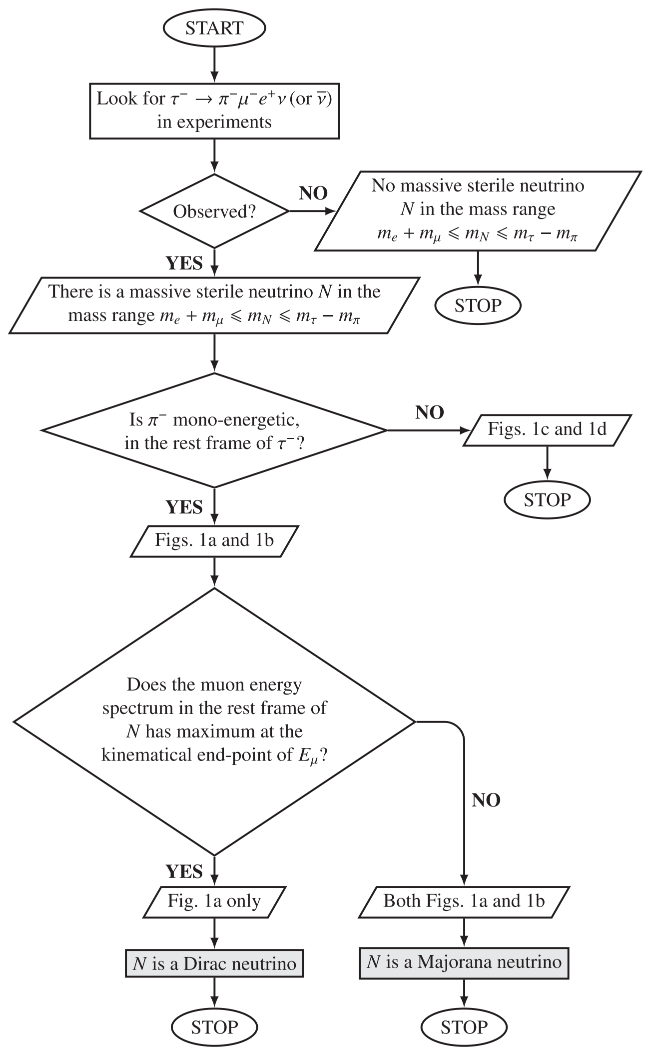

FIG. 3. The flow chart for disentangling the Dirac and Majorana nature of the exchanged intermediate mass neutrino N in the decay $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$. This flowchart must be read in conjunction with Fig. 1.

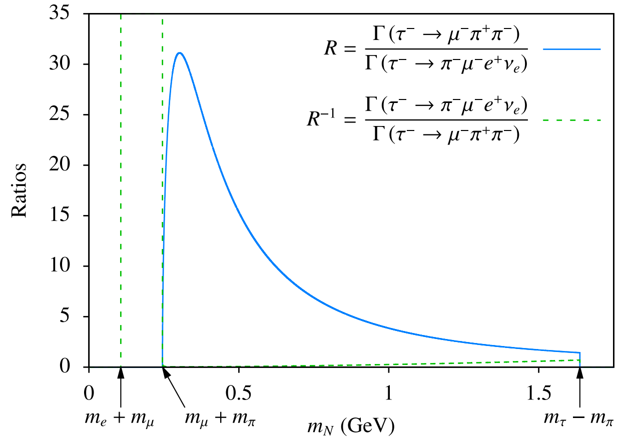

FIG. 4. Comparison between the decay rates of $\tau^- \to \mu^-\pi^+\pi^-$ and $\tau^- \to \pi^-\mu^-e^+\nu_e$ assuming that both are mediated by an intermediate mass on-shell sterile neutrino of mass m_N, with $m_\mu + m_\pi \leq m_N \leq m_\tau - m_\pi$. Here we have also used the narrow-width approximation for N. In the mass range $m_e + m_\mu \leq m_N \leq m_\mu + m_\pi$ the $\tau^- \to \pi^-\mu^-e^+\nu_e$ is allowed, but $\tau^- \to \mu^-\pi^+\pi^-$ is not. Therefore, in this mass range there are no background events for the decay mode $\tau^- \to \pi^-\mu^-e^+\nu_e$. The dashed line in the mass region $m_e + m_\mu \leq m_N \leq m_\mu + m_\pi$ rises to infinity.

allowed muon energy would signal that the intermediate mass neutrino is a Dirac particle. Conversely, a peaked spectrum towards lower energies (i.e. away from the kinematic end-point of E_μ) would indicate its Majorana nature.

IV. COMPARISON WITH $\tau^- \to \mu^-\pi^+\pi^-$ MODE, AND DISCUSSION ON SOME POSSIBLE NEW PHYSICS CONTRIBUTIONS

Figure 3 summarizes the procedure that needs to be followed to establish the nature of the intermediate mass sterile neutrino exchanged in $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$ decays (here, the flavor of the final light neutrino or antineutrino is unknown) with anticipation that this three-prong decay is observed at future colliders, such as Belle II. In this context it is important to note that the lepton-flavor violating decay $\tau^- \to \mu^-\pi^+\pi^-$ can also contribute to our decay channels via the sequential decay $\pi^+ \to e^+\nu_e$. Such lepton-flavor violating decays have already been searched for in experiments [16,17]. To make a quantitative comparison between the decay modes $\tau^- \to \mu^-\pi^+\pi^-$ and $\tau^- \to \pi^-\mu^-e^+\nu_e$ we define the ratio, $R = \Gamma(\tau^- \to \mu^-\pi^+\pi^-)/\Gamma(\tau^- \to \pi^-\mu^-e^+\nu_e)$. Assuming that both the decay modes are facilitated by the exchange of an intermediate mass neutrino and applying the narrow-width approximation for it, we get the result as shown in Fig. 4. Note that in both the decay modes, we consider the π^- to be monoenergetic in the rest frame of τ^-. From Fig. 4 it is very clear that for lower values of m_N the $\tau^- \to \mu^-\pi^+\pi^-$ has much larger branching ratio than $\tau^- \to \pi^-\mu^-e^+\nu_e$. In the region $m_e + m_\mu \leq m_N \leq m_\mu + m_\pi$ there

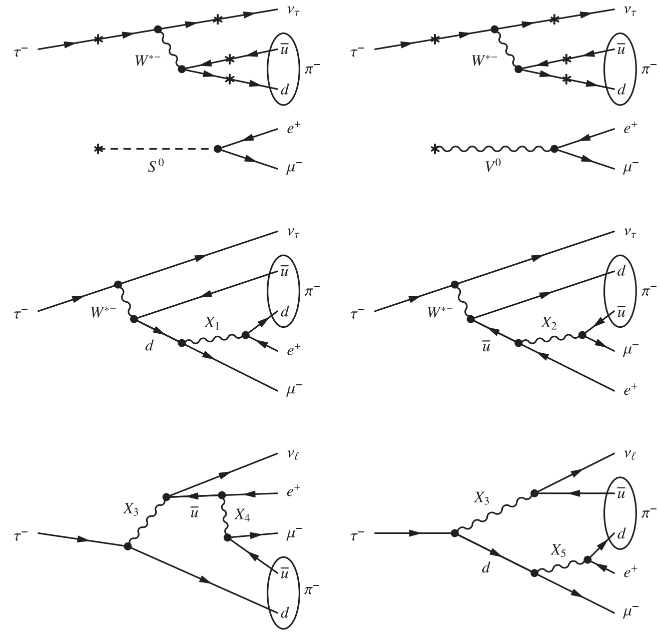

FIG. 5. Some generic new physics contributions to $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$ other than the intermediate mass sterile neutrino N. The new physics contributions can arise from some scalars (S^0) or vectors (V^0) or leptoquarks (X_i, with $i = 1, \ldots, 5$). Here the asterisk ($*$) denotes the four possibilities of connecting the S^0 and V^0 lines to the four fermion lines of the accompanying diagram.

is no contribution from the $\tau^- \to \mu^-\pi^+\pi^-$ mode due to phase space considerations; however, $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$ can still give contributions as long as $m_N > m_e + m_\mu$ (see the dashed line in Fig. 4 which goes to infinity in the mass region $m_e + m_\mu \leq m_N \leq m_\mu + m_\pi$). Because of a lack of any background events in the mass range $m_e + m_\mu \leq m_N < m_\mu + m_\pi$, it is the experimentally clean region to study the decay mode $\tau^- \to \pi^-\mu^-e^+\nu_e$. It is thus expected that observing the decay modes $\tau^- \to \pi^-\mu^-e^+\nu(\text{or } \bar{\nu})$ ought to be feasible with future colliders and following the flowchart of Fig. 3 it would be possible to decipher the nature of the heavy intermediate on-shell sterile neutrino.

Note that there can be some other generic new physics contributions, other than the intermediate mass sterile neutrinos, to our decay mode $\tau^- \to \pi^-\mu^-e^+\nu$ (or $\bar{\nu}$). Some such possibilities are shown in Fig. 5. As is clear from Fig. 5 there can be some lepton-flavor violating new physics via some scalar (S^0) or vector (V^0) particle (e.g., lepton-flavor violating modes of Higgs, or Z, or some Z'), as well as some leptoquark (X_i, with $i = 1, \ldots, 5$) contributions. It must be noted that in all these new physics possibilities, the pion is *not* monoenergetic. Hence, following the flowchart of Fig. 3, we can avoid these new physics possibilities completely. Furthermore, the lepton-flavor violating modes of Higgs, Z, as well as those of Z' are severely constrained by experimental data. The leptoquarks

$X_1, \ldots, X_5$ in Figs. 5 also facilitate lepton-flavor violation, and must therefore be severely constrained by $\mu \to e\gamma$ searches. Thus, other new physics possibilities for $\tau^- \to \pi^-\mu^-e^+\nu$ (or $\bar{\nu}$) decay are not only very constrained by existing data, but their presence, if any, does not affect our analysis as they are easily discarded by considering monoenergetic pions as emphasized in our methodology here.

V. CONCLUSION

From the four possible contributions to the decay $\tau^- \to \pi^-\mu^-e^+\nu$(or $\bar{\nu}$) as shown in Fig. 1, choosing a monoenergetic π^- in the rest frame of τ^- should allow us to isolate two of them [Figs. 1(a) and 1(b)]. The spectrum of muons produced from the decay of the intermediate mass neutrino N in Figs. 1(a) and 1(b), would indicate that a peak observed in the muon energy spectrum below its kinematic endpoint corresponds to an intermediate mass Majorana neutrino. Thus, by a clever analysis of the pion and muon energy spectra, we can easily distinguish between the Dirac and Majorana possibilities for the intermediate on-shell sterile neutrino.

ACKNOWLEDGMENTS

The work of C. S. K. was supported by the NRF grant funded by the Korean government of the MEST (No. 2016R1D1A1A02936965). G. L. C. is grateful to Conacyt for financial support under Projects No. 236394, No. 250628 (Ciencia Básica), and No. 296 (Fronteras de la Ciencia). C. S. K and D. S. would like to thank CINVESTAV, Mexico, where some initial part of this work was done, for hospitality.

Note added.—A related idea to the one presented in this paper was reported in Ref. [18]. Our work differs in several ways. First, contrary to us, Ref. [18] considers the decay $\tau^+ \to \pi^-e^+e^+\nu$, where the τ lepton and π meson have opposite charges (or same-sign charged leptons in the final state) which requires that two separate vertices are detected to avoid the exchange of identical fermions. Second, the authors of Ref. [18] compute the pion instead of the muon spectrum. This procedure, however, will not allow us to distinguish the nature of the exchanged neutrino since the pion spectra for Dirac and Majorana cases differ only in normalization but not in shape.

[1] W. Rodejohann, Neutrinoless double Beta decay and particle physics, Int. J. Mod. Phys. E **20**, 1833 (2011).

[2] C. Dib, V. Gribanov, S. Kovalenko, and I. Schmidt, K meson neutrinoless double muon decay as a probe of neutrino masses and mixings, Phys. Lett. B **493**, 82 (2000); C. Dib, V. Gribanov, S. Kovalenko, and I. Schmidt, Lepton number violating processes and Majorana neutrinos, Part. Nucl. Lett. **106**, 42 (2001); D. Delepine, G. Lopez Castro, and N. Quintero, Lepton number violation in top quark and neutral B meson decays, Phys. Rev. D **84**, 096011 (2011); Erratum: Lepton number violation in top quark and neutral B meson decays, Phys. Rev. D **86**, 079905(E) (2012)]; G. Lopez Castro and N. Quintero, Bounding resonant Majorana neutrinos from four-body B and D decays, Phys. Rev. D **87**, 077901 (2013); D. Milanes, N. Quintero, and C. E. Vera, Sensitivity to Majorana neutrinos in $\Delta L = 2$ decays of B_c meson at LHCb, Phys. Rev. D **93**, 094026 (2016); H. Yuan, T. Wang, G. L. Wang, W. L. Ju, and J. M. Zhang, Lepton-number violating four-body decays of heavy mesons, J. High Energy Phys. 08 (2013) 066; G. Cvetic, C. Dib, S. K. Kang, and C. S. Kim, Probing Majorana neutrinos in rare K and D, D_s, B, B_c meson decays, Phys. Rev. D **82**, 053010 (2010); G. Cvetic, C. Dib, and C. S. Kim, Probing Majorana neutrinos in rare $\pi^+ \to e^+e^+\mu^-\nu$ decays, J. High Energy Phys. 06 (2012) 149; C. Dib and C. S. Kim, Remarks on the lifetime of sterile neutrinos and the effect on detection of rare meson decays $M^+ \to M' - \ell^+\ell^+$, Phys. Rev. D **89**, 077301 (2014); G. Cvetic, C. S. Kim, Y. J. Kwon, and Y. M. Yook, Decay of $B^\pm \to \tau^\pm +$ missing momentum and direct measurement of the mixing parameter $U_{\tau N}$, Phys. Rev. D **93**, 013003 (2016); G. Cvetic and C. S. Kim, Rare decays of B mesons via on-shell sterile neutrinos, Phys. Rev. D **94**, 053001 (2016); Erratum: Rare decays of B mesons via on-shell sterile neutrinos, Phys. Rev. D **95**, 039901(E) (2017); G. Cvetic, F. Halzen, C. S. Kim, and S. Oh, Anomalies in (semi)-leptonic B decays $B^\pm \to \tau^\pm\nu$, $B^\pm \to D\tau^\pm\nu$, and $B^\pm \to D^*\tau^\pm\nu$, and possible resolution with sterile neutrino, arXiv:1702.04335; G. Cvetic and C. S. Kim, Sensitivity limits on heavy-light mixing $|U_{\mu N}|^2$ from lepton number violating B meson decays, Phys. Rev. D **96**, 035025 (2017); S. Mandal and N. Sinha, Favored B_c decay modes to search for a Majorana neutrino, Phys. Rev. D **94**, 033001 (2016); B. Shuve and M. E. Peskin, Revision of the LHCb limit on Majorana neutrinos, Phys. Rev. D **94**, 113007 (2016); C. O. Dib, C. S. Kim, and K. Wang, Search for heavy sterile neutrinos in trileptons at the LHC, Chin. Phys. C **41**, 103103 (2017); C. O. Dib, C. S. Kim, and K. Wang, Signatures of Dirac and Majorana sterile neutrinos in trilepton events at the LHC, Phys. Rev. D **95**, 115020 (2017).

[3] C. Dib, J. C. Helo, M. Hirsch, S. Kovalenko, and I. Schmidt, Heavy sterile neutrinos in tau decays and the MiniBooNE anomaly, Phys. Rev. D **85**, 011301 (2012); G. L. Castro and N. Quintero, Lepton number violating four-body tau lepton decays, Phys. Rev. D **85**, 076006 (2012); Erratum: Lepton number violating four-body tau lepton decays, Phys. Rev. D **86**, 079904(E) (2012); D. Gomez Dumm and P. Roig, Dispersive analysis of $\tau^- \to \pi^-\pi^0\nu_\tau$ Belle data, Nucl.

Phys. B, Proc. Suppl. **253–255**, 12 (2014); J. Zamora-Saa, Resonant CP violation in rare $\tau^{\pm}$ decays, J. High Energy Phys. 05 (2017) 110; G. Cvetic, C. Dib, C. S. Kim, and J. D. Kim, Lepton flavor violation in tau decays, Phys. Rev. D **66**, 034008 (2002); Erratum: Lepton flavor violation in tau decays, Phys. Rev. D **68**, 059901(E) (2003).

[4] J. P. Lees *et al.* (*BABAR* Collaboration), Search for lepton-number violating processes in $B^+ \to h^- l^+ l^+$ decays, Phys. Rev. D **85**, 071103 (2012); Search for lepton-number violating $B^+ \to X^- \ell^+ \ell'^+$ decays, Phys. Rev. D **89**, 011102 (2014); O. Seon *et al.* (BELLE Collaboration), Search for Lepton-number-violating $B^+ \to D^- l^+ l'^+$ decays, Phys. Rev. D **84**, 071106 (2011); R. Aaij *et al.* (LHCb Collaboration), Searches for Majorana neutrinos in B^- decays, Phys. Rev. D **85**, 112004 (2012); R. Aaij *et al.* (LHCb Collaboration), Search for Majorana Neutrinos in $B^- \to \pi^+ \mu^- \mu^-$ Decays, Phys. Rev. Lett. **112**, 131802 (2014); J. Harrison (LHCb and *BABAR* and Belle Collaborations), Recent results on searches for heavy Majorana neutrinos, Nucl. Part. Phys. Proc. **260**, 143 (2015).

[5] Y. Miyazaki *et al.* (Belle Collaboration), Search for lepton-flavor-violating and lepton-number-violating $\tau \to \ell h h'$ decay modes, Phys. Lett. B **719**, 346 (2013); Search for lepton flavor and lepton number violating tau decays into a lepton and two charged mesons, Phys. Lett. B **682**, 355 (2010); B. Aubert *et al.* (*BABAR*, Collaboration), Search for Lepton-Flavor and Lepton-Number Violation in the Decay $\tau^- \to \ell^{\mp} h^{\pm} h'^-$, Phys. Rev. Lett. **95**, 191801 (2005).

[6] M. Drewes and B. Garbrecht, Combining experimental and cosmological constraints on heavy neutrinos, Nucl. Phys. **B921**, 250 (2017).

[7] L. Canetti, M. Drewes, and B. Garbrecht, Probing leptogenesis with GeV-scale sterile neutrinos at LHCb and Belle II, Phys. Rev. D **90**, 125005 (2014).

[8] T. Asaka, S. Blanchet, and M. Shaposhnikov, The νMSM, dark matter and neutrino masses, Phys. Lett. B **631**, 151 (2005); T. Asaka and M. Shaposhnikov, The νMSM, dark matter and baryon asymmetry of the universe, Phys. Lett. B **620**, 17 (2005); L. Canetti, M. Drewes, T. Frossard, and M. Shaposhnikov, Dark matter, baryogenesis and neutrino oscillations from right-handed neutrinos, Phys. Rev. D **87**, 093006 (2013).

[9] B. Kayser and R. E. Shrock, Distinguishing between Dirac and Majorana neutrinos in neutral current reactions, Phys. Lett. **112B**, 137 (1982).

[10] J. Barranco, D. Delepine, V. Gonzalez-Macias, C. Lujan-Peschard, and M. Napsuciale, Scattering processes could distinguish Majorana from Dirac neutrinos, Phys. Lett. B **739**, 343 (2014); W. Rodejohann, X. J. Xu, and C. E. Yaguna, Distinguishing between Dirac and Majorana neutrinos in the presence of general interactions, J. High Energy Phys. 05 (2017) 024.

[11] C. S. Kim and D. Sahoo, Deciphering the Majorana nature of neutrino via "effective", Dalitz plot method, arXiv:1612.00607.

[12] G. Cvetic, C. Dib, C. S. Kim, and J. Zamora-Saá, Probing the Majorana neutrinos and their CP violation in decays of charged scalar mesons π, K, D, D_s, B, B_c, Symmetry, High Energy Phys.**7**, 726 (2015).

[13] C. Patrignani *et al.* (Particle Data Group), Review of Particle Physics, Chin. Phys. C **40**, 100001 (2016).

[14] G. Cvetic, C. S. Kim, and J. Zamora-Saá, CP violation in lepton number violating semihadronic decays of K, D, D_s, B, B_c, Phys. Rev. D **89**, 093012 (2014).

[15] K. Inami (Belle II Collaboration), Lepton-flavor-violating τ decay prospects at SuperKEKB/Belle II, *Proc. Sci.*, ICHEP2016 (2016) 574.

[16] B. Aubert *et al.* (*BABAR* Collaboration), Search for Lepton-Flavor and Lepton-Number Violation in the Decay $\tau^- \to \ell^{\mp} h^{\pm} h'^-$, Phys. Rev. Lett. **95**, 191801 (2005).

[17] Y. Miyazaki *et al.* (Belle Collaboration), Search for lepton-flavor-violating and lepton-number-violating $\tau \to \ell h h'$ decay modes, Phys. Lett. B **719**, 346 (2013).

[18] H. Yuan, Y. Jiang, T. h. Wang, Q. Li, and G. L. Wang, Lepton number violating four-body tau decay, arXiv: 1702.04555.