RECEIVED: November 13, 2020

REVISED: January 25, 2021

ACCEPTED: February 23, 2021

PUBLISHED: April 2, 2021

CP violation in rare lepton-number-violating W decays at the LHC

Fatemeh Najafi, Jacky Kumar and David London

Physique des Particules, Université de Montréal,

1375 Avenue Thérèse-Lavoie-Roux, Montréal, QC, Canada H2V 0B3, U.S.A.

E-mail: fatemeh.najafi@umontreal.ca, jacky.kumar@umontreal.ca,
london@lps.umontreal.ca

ABSTRACT: Some models of leptogenesis involve a quasi-degenerate pair of heavy neutrinos $N_{1,2}$ whose masses can be small, $O(\text{GeV})$. Such neutrinos can contribute to the rare lepton-number-violating (LNV) decay $W^\pm \rightarrow \ell_1^\pm \ell_2^\pm (q' \bar{q})^\mp$. If both N_1 and N_2 contribute, there can be a CP-violating rate difference between the LNV decay of a W^- and its CP-conjugate decay. In this paper, we examine the prospects for measuring such a CP asymmetry A_{CP} at the LHC. We assume a value for the heavy-light neutrino mixing parameter $|B_{\ell N}|^2 = 10^{-5}$, which is allowed by the present experimental constraints, and consider $5 \text{ GeV} \leq M_N \leq 80 \text{ GeV}$. We consider three versions of the LHC — HL-LHC, HE-LHC, FCC-hh — and show that small values of the CP asymmetry can be measured at 3σ , in the range $1\% \lesssim A_{\text{CP}} \lesssim 15\%$.

KEYWORDS: Beyond Standard Model, CP violation, Neutrino Physics

ARXIV EPRINT: [2011.03686](https://arxiv.org/abs/2011.03686)

Contents

1	Introduction	1
2	$W^- \rightarrow \ell_1^- \ell_2^- (f' \bar{f})^+$	2
2.1	Preamble	3
2.2	Decay amplitudes $\mathcal{M}_i^{--}$	4
2.3	$ \mathcal{M}_{\text{tot}}^{--} ^2$	6
2.4	CP violation	7
3	Experimental analysis	9
4	Summary & discussion	12

1 Introduction

The standard model (SM) has been extremely successful in explaining most of the data taken to date. Still, there are questions that remain unanswered. For example, in the SM, neutrinos are predicted to be massless. However, we now know that neutrinos do have masses, albeit very small. What is the origin of these neutrino masses? Furthermore, are neutrinos Dirac or Majorana particles? If the latter, lepton-number-violating (LNV) processes, such as neutrinoless double-beta ($0\nu\beta\beta$) decay, may be observable.

The most common method of generating neutrino masses uses the seesaw mechanism [1–3], in which three right-handed (sterile) neutrinos N_i are introduced. The diagonalization of the mass matrix leads to three ultralight neutrinos ($m_\nu \lesssim 1$ eV) and three heavy neutrinos, all of which are Majorana.

Another question is: what is the explanation for the baryon asymmetry of the universe? All we know is that out-of-equilibrium processes involving baryon-number violation and CP violation are required [4]. One idea that has been proposed to explain the baryon asymmetry is leptogenesis. Here the idea is that CP-violating LNV processes can produce an excess of leptons over antileptons. This lepton asymmetry is converted into a baryon asymmetry through sphaleron processes [5, 6].

A great deal of work has been done trying to combine these two ideas. One scenario that often arises is the appearance of a pair of heavy neutrinos, N_1 and N_2 , whose masses are nearly degenerate. With this quasi-degenerate pair, leptogenesis can be produced through CP-violating decays of the heavy neutrinos [7, 8], or via neutrino oscillations [9, 10].

One particularly intriguing aspect of this scenario is that the nearly-degenerate neutrinos can have masses as small as $O(\text{GeV})$ [11]. The possibility that there can be CP-violating LNV processes involving these light sterile neutrinos has led some authors to examine ways to see such effects in the decays of mesons [12–19] and τ leptons [20, 21]. Note that these

studies all use as motivation the neutrino minimal standard model (ν MSM) [22–25], which combines the seesaw mechanism and leptogenesis, and even provides a candidate for dark matter. However, it is argued in ref. [26] (see also refs. [27, 28]) that the size of CP violation in the ν MSM, while large enough to explain the baryon asymmetry of the universe, is too small to lead to a measurable effect at low energies. Still, CP-violating effects in other models may not be so small, which is the motivation for our work.

The idea of refs. [12–21] is as follows. The seesaw mechanism yields heavy-light neutrino mixing, which generates a W - ℓ - N coupling. This leads to decays such as $B^\pm \rightarrow D^0 \ell_1^\pm \ell_2^\pm \pi^\mp$ via $B^\pm \rightarrow D^0 W^{*\pm} (\rightarrow \ell_1^\pm N)$, with $N \rightarrow \ell_2^\pm W^{*\mp} (\rightarrow \pi^\mp)$ [17]. CP violation occurs because there are two heavy neutrinos, $N = N_1$ or N_2 , and these are nearly degenerate in mass. The interference of the two amplitudes leads to a difference in the rates of process and anti-process, which is a signal of CP violation.

The key point here is that the underlying LNV process is a W decay. In the above meson and τ decays, the W is virtual, but similar effects can be searched for in the decays of real W s at the LHC. To be specific, the $0\nu\beta\beta$ -like process is $W^- \rightarrow \ell_1^- \ell_2^- (q'\bar{q})^+$. This decay has been studied extensively, both theoretically [29–37] and experimentally [38–41, 43, 44], as a signal of LNV. In the present paper, we push this further and study CP violation in this decay.

We consider both the decay $W^- \rightarrow \ell_1^- \ell_2^- (q'\bar{q})^+$ and its CP-conjugate. In order to generate a CP-violating rate difference between the two processes, the two interfering amplitudes mediated by the nearly-degenerate N_1 and N_2 must have different CP-odd and CP-even phases. The CP-odd phase difference is due simply to different couplings of the two heavy neutrinos. As for the CP-even phase difference, this can be generated through propagator effects or heavy neutrino oscillations. (These mirror the two different ways of producing CP-violating LNV processes for leptogenesis.) We take both into account in our study of these decays at the LHC. We will show that, if the new-physics parameters are such that $W^- \rightarrow \ell_1^- \ell_2^- (q'\bar{q})^+$ is observable, a CP-violating rate asymmetry A_{CP} may be as well.

In section 2, we consider the decay $W^- \rightarrow \ell_1^- \ell_2^- (q'\bar{q})^+$. We work out the individual amplitudes $\mathcal{M}_i^-$, the square of the total amplitude, $|\mathcal{M}_1^- + \mathcal{M}_2^-|^2$, and the CP asymmetry A_{CP} . The experimental prospects for measuring A_{CP} are examined in section 3. We compute the expected number of events at the LHC and the corresponding minimal value of $|A_{\text{CP}}|$ measurable. We include the production of $W^\pm$ in pp collisions, and take into account the lifetime of the N_i and experimental efficiency. A summary & discussion are presented in section 4.

2 $W^- \rightarrow \ell_1^- \ell_2^- (f'\bar{f})^+$

As described in the Introduction, the seesaw mechanism produces three ultralight neutrinos, ν_j ($j = 1, 2, 3$), and three heavy neutrinos, N_i ($i = 1, 2, 3$). The flavour eigenstates ν_ℓ are expressed in terms of the mass eigenstates as follows:

$$\nu_\ell = \sum_{j=1}^3 B_{\ell j} \nu_j + \sum_{i=1}^3 B_{\ell N_i} N_i. \quad (2.1)$$

Here the parameters $B_{\ell N_i}$ describe the heavy-light neutrino mixing. These parameters are small, but nonzero. Because of this, there are W - ℓ - N_i couplings. We are particularly interested in the couplings that involve the nearly-degenerate heavy neutrinos N_1 and N_2 . They are

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \bar{\ell} \gamma^\mu P_L (B_{\ell N_1} N_1 + B_{\ell N_2} N_2) W_\mu + h.c. \quad (2.2)$$

These couplings generate the W decay $W^- \rightarrow \ell_1^- \bar{N}_i$. Using the fact that the N_i is Majorana ($N_i = \bar{N}_i$), the $\bar{N}_i$ can subsequently decay (as an N_i) to $\ell_2^- W^{*+} (\rightarrow f' \bar{f})$, where $f' \bar{f} = q' \bar{q}$ or $\ell_3^+ \nu_{\ell_3}$.

This leads to the (apparently) LNV W decay $W^- \rightarrow \ell_1^- \ell_2^- (f' \bar{f})^+$. But if $f' \bar{f} = \ell_3^+ \nu_{\ell_3}$, there is a complication. The $\bar{N}_i$ can also decay as an $\bar{N}_i$ to $\ell_3^+ W^{*-} (\rightarrow \ell_2^- \bar{\nu}_{\ell_2})$. This is a lepton-number-conserving (LNC) decay. But since neither the $\bar{\nu}_{\ell_2}$ nor the ν_{ℓ_3} is detected, this final state is indistinguishable from the one above. That is, there are effectively both LNV and LNC contributions to the same decay. Since we wish to focus on pure LNV decays, hereafter we consider only $f' \bar{f} = q' \bar{q}$.

Thus, we have the rare LNV W decay $W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$. This is the same decay that appears with a virtual W in the decays of mesons and τ leptons, studied in refs. [12–19] and [20, 21], respectively. In those papers, it was pointed out that the interference between the N_1 and N_2 contributions can lead to a CP-violating rate difference between process and anti-process. But if this effect is present in these processes, it should also be seen in rare LNV decays of a real W . In the present paper we study the prospects for measuring CP violation in such decays at the LHC.

2.1 Preamble

It is useful to make some preliminary remarks. For the decay $W^- \rightarrow F$, where F is the final state, the signal of CP violation will be a nonzero value of

$$A_{\text{CP}} = \frac{BR(W^- \rightarrow F) - BR(W^+ \rightarrow \bar{F})}{BR(W^- \rightarrow F) + BR(W^+ \rightarrow \bar{F})}. \quad (2.3)$$

Suppose this decay has two contributing amplitudes, A and B . The total amplitude is then

$$A_{\text{tot}} = A + B = |A| e^{i\phi_A} e^{i\delta_A} + |B| e^{i\phi_B} e^{i\delta_B}, \quad (2.4)$$

where $\phi_{A,B}$ and $\delta_{A,B}$ are CP-odd and CP-even phases, respectively. With this,

$$A_{\text{CP}} = \frac{2|A||B| \sin(\phi_A - \phi_B) \sin(\delta_A - \delta_B)}{|A|^2 + |B|^2 + 2|A||B| \cos(\phi_A - \phi_B) \cos(\delta_A - \delta_B)}. \quad (2.5)$$

The point is that, in order to produce a nonzero A_{CP} , the two interfering amplitudes must have different CP-odd and CP-even phases. In $W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$, the two amplitudes are $W^- \rightarrow \ell_1^- \bar{N}_{1,2}$, with $\bar{N}_{1,2}$ each subsequently decaying to $\ell_2^- (q' \bar{q})^+$. The two CP-odd phases are $\arg[B_{\ell_1 N_1} B_{\ell_2 N_1}]$ and $\arg[B_{\ell_1 N_2} B_{\ell_2 N_2}]$, which can clearly be different.

For the CP-even phases, things are a bit more complicated. The usual way such phases are generated is via gluon exchange (which is why they are often referred to as “strong phases”). However, since this decay involves the $W^\pm$, $\ell_i^\pm$ and N_i , which are all colourless, this is not possible. Instead, the CP-even phases can be generated in one of two ways. First, the propagator for the N_i is proportional to

$$\frac{1}{(p_N^2 - M_{N_i}^2) + iM_{N_i}\Gamma_{N_i}} = \frac{1}{\sqrt{(p_N^2 - M_{N_i}^2)^2 + M_{N_i}^2\Gamma_{N_i}^2}} e^{i\eta_i},$$

$$\text{with} \quad \tan \eta_i = \frac{-M_{N_i}\Gamma_{N_i}}{(p_N^2 - M_{N_i}^2)}. \quad (2.6)$$

Thus, η_i is the CP-even phase associated with the propagator. Since N_1 and N_2 do not have the same mass — they are nearly, but not exactly, degenerate — if one of the N_i is on shell ($p_N^2 = M_{N_i}^2$), the other is not. This creates a nonzero CP-even phase difference: the on-shell N_i has $\eta_i = -\pi/2$, while the CP-even phase of the other N_i obeys $|\eta_i| < \pi/2$. This leads to what is known as resonant CP violation.¹

A second way of generating a CP-even phase difference is through oscillations of the heavy neutrinos. As we will see below, the time evolution of a heavy N_i mass eigenstate involves e^{-iE_it} (in addition to the exponential decay factor). Since N_1 and N_2 do not have the same mass, their energies are different, leading to different e^{-iE_it} factors. This is another type of CP-even phase difference, and can also lead to CP violation.

Below we derive the amplitudes for $W^- \rightarrow \ell_1^- \bar{N}_i$, with each $\bar{N}_i$ subsequently decaying to $\ell_2^- (q'\bar{q})^+$, including both types of CP-even phases.

2.2 Decay amplitudes $\mathcal{M}_i^{--}$

Consider the diagram of figure 1, with $N_i = N_1$. If this were the only contribution, its amplitude could be written simply as the product of two amplitudes, one for $W^- \rightarrow \ell_1^- \bar{N}_i$, the other for $\bar{N}_i \rightarrow \ell_2^- (q'\bar{q})^+$. However, because there are contributions from N_1 and N_2 , and because N_1 and N_2 cannot be on shell simultaneously, we must include the heavy neutrino propagator.

Furthermore, although the neutrino is produced as $\bar{N}_i$, it actually decays as N_i , leading to the fermion-number-violating and LNV process $W^- \rightarrow \ell_1^- \ell_2^- (q'\bar{q})^+$. This implies that (i) conjugate fields will be involved in the amplitudes, and (ii) the amplitudes will be proportional to the neutrino mass.

We can now construct the amplitudes $\mathcal{M}_i^{--} \equiv \mathcal{M}(W^- \rightarrow \ell_1^- \bar{N}_i, N_i \rightarrow \ell_2^- W^{*+}(\rightarrow (q'\bar{q})^+)$. Writing $\mathcal{M}_i^{--} = \mathcal{M}_i^{\mu\nu} \epsilon_\mu j_\nu$, where ϵ_μ is the polarization of the initial W^- and

¹Note that it is important that the N_i be nearly degenerate. From eq. (2.5) we see that A_{CP} is sizeable only when the two contributing amplitudes are of similar size ($|A| \sim |B|$). But if the masses of N_1 and N_2 were very different, the size of their contributions to the decay would also be very different, leading to a small A_{CP} .

Figure 1. Diagram for $W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$ via an intermediate N_i . There is no arrow on the N_i line because it is a Majorana particle and the decay is fermion-number violating.

$j_\nu = \frac{g}{\sqrt{2}} \bar{q} \gamma_\nu P_L q'$ is the current of final-state particles to which W^{*+} decays, we have

$$\begin{aligned}
 \mathcal{M}_i^{\mu\nu} &= \bar{\ell}_1 \gamma^\mu P_L \left(\frac{g}{\sqrt{2}} B_{\ell_1 N_i} \right) N_i \times e^{-\Gamma_i t/2} e^{-iE_i t} \times \bar{\ell}_2 \gamma^\nu P_L \left(\frac{g}{\sqrt{2}} B_{\ell_2 N_i} \right) N_i \\
 &= \frac{g^2}{2} B_{\ell_1 N_i} B_{\ell_2 N_i} \bar{\ell}_1 \gamma^\mu P_L N_i \bar{N}_i^c \gamma^\nu P_R \ell_2^c \times e^{-\Gamma_i t/2} e^{-iE_i t} \\
 &\rightarrow \frac{g^2}{2} B_{\ell_1 N_i} B_{\ell_2 N_i} \bar{\ell}_1 \gamma^\mu P_L \frac{\not{p} + M_i}{p_N^2 - M_i^2 + i\Gamma_i M_i} \gamma^\nu P_R \ell_2^c \times e^{-\Gamma_i t/2} e^{-iE_i t} \\
 &= \frac{g^2}{2} B_{\ell_1 N_i} B_{\ell_2 N_i} \frac{M_i e^{-\Gamma_i t/2} e^{-iE_i t}}{p_N^2 - M_i^2 + i\Gamma_i M_i} L^{\mu\nu}, \tag{2.7}
 \end{aligned}$$

where $L^{\mu\nu} = \bar{\ell}_1 \gamma^\mu \gamma^\nu P_R \ell_2^c$. In the first line, the first term is the amplitude for $W^- \rightarrow \ell_1^- \bar{N}_i$, the second term is the time dependence of the N_i state, and the third term is the amplitude for $N_i \rightarrow \ell_2^- W^{*+}$. The $e^{-iE_i t}$ factor is due to the quantum-mechanical evolution of the N_i state; its energy E_i is evaluated in the rest frame of the decaying W . In the second line, we have taken the transpose of the third term, writing the current in terms of conjugate fields, $\psi^c = C \bar{\psi}^T$. And in the third line, we have replaced $N_i \bar{N}_i^c$ by the neutrino propagator.

Another contribution to this process comes from a diagram like that of figure 1, but with $\ell_1 \leftrightarrow \ell_2$. The amplitude for this diagram is the same as that above, but with (i) $p_N \rightarrow p'_N$ and (ii) $\bar{\ell}_1 \gamma^\mu \gamma^\nu P_R \ell_2^c \rightarrow \bar{\ell}_2 \gamma^\mu \gamma^\nu P_R \ell_1^c = -\bar{\ell}_1 \gamma^\nu \gamma^\mu P_R \ell_2^c$. Now, if $\ell_1 \neq \ell_2$, one simply adds the diagrams, while if $\ell_1 = \ell_2$, there is an additional minus sign. Thus, the amplitude for this second diagram is

$$\mathcal{M}'_i{}^{\mu\nu} = \pm \frac{\frac{g^2}{2} B_{\ell_1 N_i} B_{\ell_2 N_i} M_i e^{-\Gamma_i t/2} e^{-iE_i t}}{p_N'^2 - M_i^2 + i\Gamma_i M_i} L^{\mu\nu}, \tag{2.8}$$

and the total amplitude is $\mathcal{M}_i^{\mu\nu} + \mathcal{M}'_i{}^{\mu\nu}$. Now, the dominant contributions to these amplitudes come from (almost) on-shell N_i s. This means that, while both diagrams lead to $W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$, the final-state particles do not have the same momenta in the two cases. As a result, when the total amplitude is squared, $\mathcal{M}_i^{\mu\nu}$ and $\mathcal{M}'_i{}^{\mu\nu}$ will not interfere. Thus, we can consider only the $\mathcal{M}_i^{\mu\nu}$; the contribution from the $\mathcal{M}'_i{}^{\mu\nu}$ will be identical.

We can now compute $\mathcal{M}^{\mu\nu} = \mathcal{M}_1^{\mu\nu} + \mathcal{M}_2^{\mu\nu}$. Writing

$$B_{\ell_1 N_1} B_{\ell_2 N_1} = B_1 e^{i\phi_1}, \quad B_{\ell_1 N_2} B_{\ell_2 N_2} = B_2 e^{i\phi_2}, \quad (2.9)$$

we have

$$\mathcal{M}^{\mu\nu} = \frac{g^2}{2} \left(\frac{M_1 B_1 e^{i\phi_1} e^{-\Gamma_1 t/2} e^{-iE_1 t}}{p_N^2 - M_1^2 + i\Gamma_1 M_1} + \frac{M_2 B_2 e^{i\phi_2} e^{-\Gamma_2 t/2} e^{-iE_2 t}}{p_N^2 - M_2^2 + i\Gamma_2 M_2} \right) L^{\mu\nu}. \quad (2.10)$$

2.3 $|\mathcal{M}_{\text{tot}}^{--}|^2$

The complete amplitude is $\mathcal{M}_{\text{tot}}^{--} = \mathcal{M}^{\mu\nu} \epsilon_\mu j_\nu = (g^2/2) \mathcal{A}_{--}(t) L^{\mu\nu} \epsilon_\mu j_\nu$, where $\mathcal{A}_{--}(t)$ is the piece in parentheses in eq. (2.10). The next step is to compute $|\mathcal{M}_{\text{tot}}^{--}|^2$.

From the point of view of studying CP violation in the decay $W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$, the most important term in $\mathcal{M}_{\text{tot}}^{--}$ is $\mathcal{A}_{--}(t)$. It is instructive to compare this quantity with eq. (2.4) above. In the first term of $\mathcal{A}_{--}(t)$, we can identify the CP-odd phase (ϕ_1) and the CP-even phase associated with neutrino oscillations ($-E_1 t$). There is also a (different) CP-even phase η_i associated with the propagator [see eq. (2.6)]. The phases of the second term can be similarly identified.

Consider now $|\mathcal{A}_{--}(t)|^2$. We have

$$\begin{aligned} |\mathcal{A}_{--}(t)|^2 &= \frac{M_1^2 B_1^2 e^{-\Gamma_1 t}}{(p_N^2 - M_1^2)^2 + \Gamma_1^2 M_1^2} + \frac{M_2^2 B_2^2 e^{-\Gamma_2 t}}{(p_N^2 - M_2^2)^2 + \Gamma_2^2 M_2^2} \\ &\quad + 2\text{Re} \left(\frac{M_1 M_2 B_1 B_2 e^{-i\delta\phi} e^{-\Gamma_{\text{avg}} t} e^{-i\Delta E t}}{(p_N^2 - M_1^2 + i\Gamma_1 M_1)(p_N^2 - M_2^2 - i\Gamma_2 M_2)} \right), \end{aligned} \quad (2.11)$$

where

$$\Gamma_{\text{avg}} = \frac{1}{2}(\Gamma_1 + \Gamma_2), \quad \Delta E \equiv E_1 - E_2 = \frac{M_1^2 - M_2^2}{2M_W}, \quad \delta\phi \equiv \phi_2 - \phi_1. \quad (2.12)$$

There are two simplifications that can be made. First, in order to compute the rate for the decay, it will be necessary to integrate over the phase space of the final-state particles. Due to energy-momentum conservation, this will involve an integral over p_N . Since the N_i can go on shell, we can use the narrow-width approximation to replace

$$\frac{1}{(p_N^2 - M_i^2)^2 + \Gamma_i^2 M_i^2} \rightarrow \frac{\pi}{\Gamma_i M_i} \delta(p_N^2 - M_i^2). \quad (2.13)$$

Second, although it is important to take neutrino oscillations into account in considerations of CP violation, we do not focus on actually measuring such oscillations. (This is examined in refs. [45–47].) That is, we can integrate over time: $\int_0^\infty dt |\mathcal{A}_{--}(t)|^2 = |\mathcal{A}_{--}|^2$. Note that, in integrating to ∞ , we assume that the N_i are heavy enough that their lifetimes are sufficiently small that most N_i s decay in the detector. We will quantify this in the next section.

Now consider the interference term. Using the narrow-width approximation, the product of propagators can be written

$$\frac{1}{(p_N^2 - M_1^2 + i\Gamma_1 M_1)(p_N^2 - M_2^2 - i\Gamma_2 M_2)} = \frac{\Gamma_1 M_1 \pi \delta(p_N^2 - M_2^2)}{(\Delta M^2)^2 + \Gamma_1^2 M_1^2} + \frac{\Gamma_2 M_2 \pi \delta(p_N^2 - M_1^2)}{(\Delta M^2)^2 + \Gamma_2^2 M_2^2} - \frac{i\Delta M^2 \pi \delta(p_N^2 - M_2^2)}{(\Delta M^2)^2 + \Gamma_1^2 M_1^2} - \frac{i\Delta M^2 \pi \delta(p_N^2 - M_1^2)}{(\Delta M^2)^2 + \Gamma_2^2 M_2^2}, \quad (2.14)$$

where $\Delta M^2 \equiv M_1^2 - M_2^2$. Note that the imaginary part is proportional to $\Delta M^2 = (M_1 - M_2)(M_1 + M_2) \equiv \Delta M(M_1 + M_2)$. Referring to eq. (2.6), we see that the CP-even phase difference $\eta_1 - \eta_2$ is proportional to ΔM .

Putting all the pieces together, we obtain

$$\begin{aligned} |\mathcal{A}_{--}|^2 &= \frac{\pi M_1 B_1^2}{\Gamma_1^2} \delta(p_N^2 - M_1^2) + \frac{\pi M_2 B_2^2}{\Gamma_2^2} \delta(p_N^2 - M_2^2) \\ &+ \frac{2M_1 M_2 B_1 B_2}{\Gamma_{\text{avg}}^2 + (\Delta E)^2} \left(\frac{\Gamma_1 M_1 \pi \delta(p_N^2 - M_2^2)}{(\Delta M^2)^2 + \Gamma_1^2 M_1^2} + \frac{\Gamma_2 M_2 \pi \delta(p_N^2 - M_1^2)}{(\Delta M^2)^2 + \Gamma_2^2 M_2^2} \right) (\cos(\delta\phi) \Gamma_{\text{avg}} - \Delta E \sin(\delta\phi)) \\ &+ \frac{2M_1 M_2 B_1 B_2}{\Gamma_{\text{avg}}^2 + (\Delta E)^2} \left(\frac{\Delta M^2 \pi \delta(p_N^2 - M_2^2)}{(\Delta M^2)^2 + \Gamma_1^2 M_1^2} + \frac{\Delta M^2 \pi \delta(p_N^2 - M_1^2)}{(\Delta M^2)^2 + \Gamma_2^2 M_2^2} \right) (\cos(\delta\phi) \Delta E + \sin(\delta\phi) \Gamma_{\text{avg}}). \end{aligned} \quad (2.15)$$

2.4 CP violation

The time-integrated square of the amplitude for $W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$ is therefore $|\mathcal{M}_{--}|^2 = (g^2/2)^2 |\mathcal{A}_{--}|^2 |L^{\mu\nu} \epsilon_\mu j_\nu|^2$. The CP asymmetry is defined as [see eq. (2.3)]

$$A_{\text{CP}} = \frac{\int d\rho (|\mathcal{M}_{--}|^2 - |\mathcal{M}_{++}|^2)}{\int d\rho (|\mathcal{M}_{--}|^2 + |\mathcal{M}_{++}|^2)} = \frac{\int d\rho (|\mathcal{A}_{--}|^2 - |\mathcal{A}_{++}|^2) |L^{\mu\nu} \epsilon_\mu j_\nu|^2}{\int d\rho (|\mathcal{A}_{--}|^2 + |\mathcal{A}_{++}|^2) |L^{\mu\nu} \epsilon_\mu j_\nu|^2}, \quad (2.16)$$

where $|\mathcal{A}_{++}|^2$ is obtained from $|\mathcal{A}_{--}|^2$ [eq. (2.15)] by changing the sign of the CP-odd phase, and $\int d\rho$ indicates integration over the phase space.

For the phase-space integration, the only pieces that depend on the integration variables are the delta function $\delta(p_N^2 - M_i^2)$ in eq. (2.15) and $|L^{\mu\nu} \epsilon_\mu j_\nu|^2$. The phase-space integrals are therefore

$$\mathcal{I}(M_i) = \int d\rho \pi \delta(p_N^2 - M_i^2) |L^{\mu\nu} \epsilon_\mu j_\nu|^2. \quad (2.17)$$

In ref. [14], it was shown that, since $M_1 \simeq M_2$, $\mathcal{I}(M_1) \simeq \mathcal{I}(M_2)$. Thus, to a very good approximation, these terms cancel in eq. (2.16), so that

$$A_{\text{CP}} = \frac{|\tilde{\mathcal{A}}_{--}|^2 - |\tilde{\mathcal{A}}_{++}|^2}{|\tilde{\mathcal{A}}_{--}|^2 + |\tilde{\mathcal{A}}_{++}|^2}, \quad (2.18)$$

where $\tilde{\mathcal{A}}_{--}$ ($\tilde{\mathcal{A}}_{++}$) is the same as $\mathcal{A}_{--}$ ($\mathcal{A}_{++}$), but with the $\pi \delta(p_N^2 - M_i^2)$ factors removed.

In the numerator we have

$$\begin{aligned}
 |\tilde{\mathcal{A}}_{--}|^2 - |\tilde{\mathcal{A}}_{++}|^2 = & \quad (2.19) \\
 & - \frac{2M_1M_2B_1B_2}{\Gamma_{\text{avg}}^2 + (\Delta E)^2} \left(\frac{\Gamma_1M_1}{(\Delta M^2)^2 + \Gamma_1^2M_1^2} + \frac{\Gamma_2M_2}{(\Delta M^2)^2 + \Gamma_2^2M_2^2} \right) (2\Delta E \sin(\delta\phi)) \\
 & + \frac{2M_1M_2B_1B_2}{\Gamma_{\text{avg}}^2 + (\Delta E)^2} \left(\frac{\Delta M^2}{(\Delta M^2)^2 + \Gamma_1^2M_1^2} + \frac{\Delta M^2}{(\Delta M^2)^2 + \Gamma_2^2M_2^2} \right) (2\sin(\delta\phi)\Gamma_{\text{avg}}).
 \end{aligned}$$

In eq. (2.5), we see that A_{CP} is proportional to $\sin(\phi_A - \phi_B) \sin(\delta_A - \delta_B)$, i.e., a nonzero A_{CP} requires that the two interfering amplitudes have different CP-odd and CP-even phases. This is also true in the present case. Above, both terms are proportional to $\sin(\delta\phi)$ ($\delta\phi$ is the CP-odd phase difference). In the first term, the CP-even phase arises due to neutrino oscillations: $\sin(\delta_A - \delta_B)$ is proportional to ΔE . And in the second term, the CP-even phase difference comes from the propagators [see eq. (2.14)]: it is proportional to ΔM . In the denominator,

$$\begin{aligned}
 |\tilde{\mathcal{A}}_{--}|^2 + |\tilde{\mathcal{A}}_{++}|^2 = & \quad (2.20) \\
 & \frac{2M_1B_1^2}{\Gamma_1^2} + \frac{2M_2B_2^2}{\Gamma_2^2} \\
 & + \frac{2M_1M_2B_1B_2}{\Gamma_{\text{avg}}^2 + (\Delta E)^2} \left(\frac{\Gamma_1M_1}{(\Delta M^2)^2 + \Gamma_1^2M_1^2} + \frac{\Gamma_2M_2}{(\Delta M^2)^2 + \Gamma_2^2M_2^2} \right) (2\cos(\delta\phi)\Gamma_{\text{avg}}) \\
 & - \frac{2M_1M_2B_1B_2}{\Gamma_{\text{avg}}^2 + (\Delta E)^2} \left(\frac{\Delta M^2}{(\Delta M^2)^2 + \Gamma_1^2M_1^2} + \frac{\Delta M^2}{(\Delta M^2)^2 + \Gamma_2^2M_2^2} \right) (2\cos(\delta\phi)\Delta E).
 \end{aligned}$$

We now make the (reasonable) approximations that $\Gamma_1 \simeq \Gamma_2 \equiv \Gamma$ and $M_1 \simeq M_2 \equiv M_N$ (but $\Delta M \neq 0$ and is $\ll M_N$). With the assumption that $B_1 = B_2$, A_{CP} takes a simple form:

$$A_{\text{CP}} = \frac{2(2y - x) \sin \delta\phi}{(1 + x^2)(1 + 4y^2) + 2(1 - 2xy) \cos \delta\phi}, \quad (2.21)$$

where

$$x \equiv \frac{\Delta E}{\Gamma}, \quad y \equiv \frac{\Delta M}{\Gamma}. \quad (2.22)$$

Once again comparing to eq. (2.5), we see that x and y each play the role of the CP-even phase-difference term $\sin(\delta_A - \delta_B)$. Now, x and y reflect CP-even phases arising from neutrino oscillations and the neutrino propagator, respectively. However, they are not, in fact, independent. From eq. (2.12), we have

$$\Delta E = \frac{M_1^2 - M_2^2}{2M_W} = \frac{2\Delta M M_N}{2M_W} \implies x = y \frac{M_N}{M_W}. \quad (2.23)$$

Thus, y is always present; x is generally subdominant, except for large values of M_N .

Furthermore, we note that x and y have the same sign, and that $|x| < |y|$. Thus, $|2y - x| \leq |2y|$. That is, as $|x|$ increases, A_{CP} decreases. We therefore expect to see smaller CP-violating effects for larger values of M_N . The reason this occurs is as follows. Above, we said that x and y each play the role of $\sin(\delta_A - \delta_B)$. However, in this system, their contributions have the opposite sign, hence the factor $2y - x$ in eq. (2.21).

Figure 2. Value of A_{CP} as a function of y , for $\delta\phi = \pi/2$ and for various values of M_N . For negative values of y , $A_{\text{CP}} \rightarrow -A_{\text{CP}}$.

In order to get an estimate of the potential size of A_{CP} , we set $\delta\phi = \pi/2$. In figure 2, we show A_{CP} as a function of y , for various values of M_N . We see that large values (≥ 0.9) of $|A_{\text{CP}}|$ can be produced for light M_N . The maximal values of $|A_{\text{CP}}|$ are found when $y \simeq \pm \frac{1}{2}$, with $|A_{\text{CP}}|$ decreasing for larger values of $|y|$. As expected, the size of $|A_{\text{CP}}|$ decreases as M_N increases, with $|A_{\text{CP}}|_{\text{max}} < 0.6$ for larger values of M_N .

3 Experimental analysis

In this section, we explore the prospects for measuring A_{CP} at the LHC. We consider three versions of the LHC: (i) the high-luminosity LHC (HL-LHC, $\sqrt{s} = 14$ TeV, peak $\mathcal{L}_{\text{int}} = 3 \text{ ab}^{-1}$), (ii) the high-energy LHC (HE-LHC, $\sqrt{s} = 27$ TeV, peak $\mathcal{L}_{\text{int}} = 15 \text{ ab}^{-1}$) [48], (iii) the future circular collider² (FCC-hh, $\sqrt{s} = 100$ TeV, peak $\mathcal{L}_{\text{int}} = 30 \text{ ab}^{-1}$) [49]. We implement the model in `FeynRules` [34, 51] and use `MadGraph` [52] to generate events.

The CP asymmetry of eq. (2.18) involves the branching ratios of the decay $W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$ and its CP-conjugate decay, $W^+ \rightarrow \ell_1^+ \ell_2^+ (q \bar{q}')^-$. Another way of describing A_{CP} is: given an equal number of initial W^- and W^+ bosons,

$$A_{\text{CP}} = \frac{N_{--} - N_{++}}{N_{--} + N_{++}}, \quad (3.1)$$

where N_{--} and N_{++} are the number of observed events of $W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$ and $W^+ \rightarrow \ell_1^+ \ell_2^+ (q \bar{q}')^-$, respectively.

But there is a problem: these decays are not measured directly at the LHC. Instead, one has pp collisions, so that the processes are $\bar{u}_i d_j \rightarrow W^- \rightarrow \ell_1^- \ell_2^- (q' \bar{q})^+$ and $\bar{d}_j u_i \rightarrow W^+ \rightarrow \ell_1^+ \ell_2^+ (q \bar{q}')^-$, where u_i and d_j represent up-type and down-type quarks, respectively.

²The Future e^+e^- Circular Collider, FCC-ee (TLEP) [50], would also be a promising place to make this measurement.

Since protons do not contain equal amounts of $\bar{u}_i d_j$ and $\bar{d}_j u_i$ pairs, the number of W^- and W^+ bosons produced will not be the same, and this must be taken into account in the definition of the CP asymmetry.

This is done by changing eq. (3.1) to

$$A_{\text{CP}} = \frac{N_{--}^{pp}/\sigma^- - N_{++}^{pp}/\sigma^+}{N_{--}^{pp}/\sigma^- + N_{++}^{pp}/\sigma^+} = \frac{R_W N_{--}^{pp} - N_{++}^{pp}}{R_W N_{--}^{pp} + N_{++}^{pp}}, \quad (3.2)$$

where N_{--}^{pp} and N_{++}^{pp} are the number of observed events of $pp \rightarrow XW^-(\rightarrow \ell_1^- \ell_2^-(q'\bar{q})^+)$ and $pp \rightarrow XW^+(\rightarrow \ell_1^+ \ell_2^+(\bar{q}'q)^-)$, respectively, and $R_W = \sigma^+/\sigma^-$, with

$$\sigma^+ = \sigma(pp \rightarrow W^+ X), \quad \sigma^- = \sigma(pp \rightarrow W^- X). \quad (3.3)$$

Experimentally, it is found that $R_W = 1.295 \pm 0.003 \text{ (stat)} \pm 0.010 \text{ (syst)}$ at $\sqrt{s} = 13 \text{ TeV}$ [53]. Presumably, R_W can be measured with equally good precision (if not better) at higher energies, so it is clear how to obtain a CP-violating observable from the experimental measurements.³

Now, given a CP asymmetry A_{CP} , the number of events ($N_{\text{events}} = N_{--}^{pp} + N_{++}^{pp}$) required to show that it is nonzero at $n\sigma$ is

$$N_{\text{events}} = \frac{n^2}{A_{\text{CP}}^2 \epsilon}, \quad (3.4)$$

where ϵ is the experimental efficiency. This can be turned around to answer the question: given a certain total number of events N_{events} , what is the smallest value of $|A_{\text{CP}}|$ that can be measured at $n\sigma$?

There are two ingredients to establishing N_{events} . The first is the cross section for $pp \rightarrow XW^\mp$, multiplied by the branching ratio for $W^\mp \rightarrow \ell_1^\mp \bar{N}_i(N_i)$, and further multiplied by the branching ratio for the decay of $\bar{N}_i(N_i)$ to the final state of interest. The branching ratio for $W^\mp \rightarrow \ell_1^\mp \bar{N}_i(N_i)$ depends on the value of the heavy-light mixing parameter $|B_{\ell_1 N_1}|^2$. Constraints on this quantity can be obtained from experimental searches for the same $0\nu\beta\beta$ -like process we consider here. A summary of these constraints can be found in ref. [55]. For $5 \text{ GeV} \lesssim M_N \lesssim 50 \text{ GeV}$, $|B_{\ell N}|^2 \lesssim 10^{-5}$ ($\ell = e, \mu, \tau$), but the constraint is weaker for larger values of M_N . In our analysis, to be conservative, we take $|B_{\ell N}|^2 = 10^{-5}$ for all values of M_N .

We now use **MadGraph** to calculate the cross sections for $pp \rightarrow X\ell_1^\mp \bar{N}$, with $\bar{N} \rightarrow \ell_2^-(q'\bar{q})^+$ and $pp \rightarrow X\ell_1^+ N$, with $N \rightarrow \ell_2^+(\bar{q}'q)^-$. The results are shown in table 1. In the table, we consider $M_N = 5 \text{ GeV}$ and 50 GeV . For other neutrino masses that obey $M_N \ll M_W$, such as $M_N = 1 \text{ GeV}$ or 10 GeV , the numbers do not differ much from those for $M_N = 5 \text{ GeV}$.

We also present in table 1 the expected number of events, based on the cross section and integrated luminosity of the machine. However, that is not necessarily the final answer. The second ingredient is to look at the N lifetime and see what percentage of the

³In ref. [54], it is argued that a more promising way to search for $W^- \rightarrow \ell_1^- \ell_2^-(q'\bar{q})^+$ is to use W^-s coming from the decay of a $\bar{t}$. If this is true, then if such a decay is observed, one can measure CP violation in these decays using the above formalism. And since top quarks mainly arise through $t\bar{t}$ production, there are equal numbers of W^- and W^+ bosons, so that an adjustment using R_W is not required.

Machine	σ (fb): $\ell_1^- \ell_2^- jj$		$\mathcal{N}_{\text{events}} (\times 10^{-3})$	
	$M_N = 5$ GeV	$M_N = 50$ GeV	$M_N = 5$ GeV	$M_N = 50$ GeV
HL-LHC	51.7	22.3	155.1	66.9
HE-LHC	98.1	42.0	1471.5	630
FCC-hh	323.8	136.7	9714	4101
Machine	σ (fb): $\ell_1^+ \ell_2^+ jj$		$\mathcal{N}_{\text{events}} (\times 10^{-3})$	
	$M_N = 5$ GeV	$M_N = 50$ GeV	$M_N = 5$ GeV	$M_N = 50$ GeV
HL-LHC	80.0	31.9	240	95.7
HE-LHC	131.0	52.8	1965	792
FCC-hh	358.2	147.6	10746	4428

Table 1. Predicted cross sections and number of events for $pp \rightarrow X \ell_1^- \ell_2^- (q' \bar{q})^+$ and $pp \rightarrow X \ell_1^+ \ell_2^+ (\bar{q}' q)^-$. Neutrino masses $M_N = 5$ and 50 GeV are considered. Results are given for the HL-LHC ($\sqrt{s} = 14$ TeV, peak $\mathcal{L}_{\text{int}} = 3$ ab $^{-1}$), HE-LHC ($\sqrt{s} = 27$ TeV, peak $\mathcal{L}_{\text{int}} = 15$ ab $^{-1}$), and FCC-hh ($\sqrt{s} = 100$ TeV, peak $\mathcal{L}_{\text{int}} = 30$ ab $^{-1}$).

heavy neutrinos produced in the W decays actually decay in the detector. To obtain the number of *measurable* events, one must multiply the expected number of produced events by this percentage.

For a given value of M_N , it is straightforward to find the neutrino lifetime, and to convert this into a distance traveled. However, the question of how many neutrinos actually decay in the detector depends on the size of the detector, and this depends on the particular experiment. As an example, we note that, in its search for $W^- \rightarrow \ell_1^- \ell_2^- (f' \bar{f})^+$, the CMS Collaboration considered this question [41]. They found that, for $M_N = 10$ GeV, there was essentially no reduction factor, i.e., the percentage of neutrinos decaying in the detector was close to 100%. However, for $M_N = 5$ GeV, the reduction factor was 0.1, while for $M_N = 1$ GeV, it was 10^{-3} . Thus, the efficiency of a given experiment for observing this decay, and measuring A_{CP} , depends on this reduction factor.

For a given value of M_N , one can determine the reduction factor, and hence the total number of measurable events $\mathcal{N}_{\text{events}}$. In order to turn this into a prediction for the smallest value of $|A_{\text{CP}}|$ that can be measured at $n\sigma$, the experimental efficiency must be included. In refs. [40, 42], the CMS Collaboration searched for heavy Majorana neutrinos at the $\sqrt{s} = 8$ TeV LHC using the final state $\ell_1^- \ell_2^- jj$. Including backgrounds, detector efficiency, etc., their overall efficiency was $\sim 1\%$.

Using an overall efficiency of 1%, in table 2 we present the minimum values of A_{CP} measurable at 3σ at the HL-LHC, HE-LHC and FCC-hh. The results are shown for $M_N = 5$ GeV (with a reduction factor of 0.1), $M_N = 10$ GeV (with no reduction factor), and $M_N = 50$ GeV (with no reduction factor).

From this table, we see that, as the LHC increases in energy and integrated luminosity, smaller and smaller values of A_{CP} are measurable. The most promising results are for $M_N = 10$ GeV, but in all cases reasonably small values of A_{CP} can be probed.

Minimum A_{CP} measurable at 3σ			
Machine	$M_N = 5 \text{ GeV}$	$M_N = 10 \text{ GeV}$	$M_N = 50 \text{ GeV}$
HL-LHC	15.0%	4.8%	7.4%
HE-LHC	5.1%	1.6%	2.5%
FCC-hh	2.1%	0.7%	1.0%

Table 2. Minimum value of A_{CP} measurable at 3σ at the HL-LHC ($\sqrt{s} = 14 \text{ TeV}$, peak $\mathcal{L}_{\text{int}} = 3 \text{ ab}^{-1}$), HE-LHC ($\sqrt{s} = 27 \text{ TeV}$, peak $\mathcal{L}_{\text{int}} = 15 \text{ ab}^{-1}$), and FCC-hh ($\sqrt{s} = 100 \text{ TeV}$, peak $\mathcal{L}_{\text{int}} = 30 \text{ ab}^{-1}$). Results are given for $M_N = 5 \text{ GeV}$ (reduction factor = 0.1), $M_N = 10 \text{ GeV}$ (no reduction factor), and $M_N = 50 \text{ GeV}$ (no reduction factor).

4 Summary & discussion

Two subjects whose explanation requires physics beyond the SM are neutrino masses and the baryon asymmetry of the universe. The standard method for generating tiny neutrino masses is the seesaw mechanism, in which one introduces three right-handed neutrinos N_i . As for the baryon asymmetry, leptogenesis is often used: CP-violating, lepton-number-violating processes produce a lepton asymmetry, and this is converted into a baryon asymmetry through sphaleron processes. Models that combine these two ideas often involve a quasi-degenerate pair of heavy neutrinos N_1 and N_2 ; leptogenesis arises through the CP-violating decays of these heavy neutrinos.

Here, an intriguing aspect is that the masses of $N_{1,2}$ can be small, $O(\text{GeV})$. This has led to suggestions to look for CP-violating LNV effects in decays of light mesons or τ leptons. These processes all involve the exchange of a virtual W . However, one can also consider CP-violating LNV decays of real W s at the LHC. Indeed, searches for LNV at the LHC use the decay $W^\pm \rightarrow \ell_1^\pm \ell_2^\pm (q'\bar{q})^\mp$. In this paper, we have examined the prospects for measuring CP violation in such decays at the LHC.

The point is that the decay $W^\pm \rightarrow \ell_1^\pm \ell_2^\pm (q'\bar{q})^\mp$ arises via $W^\pm \rightarrow \ell_1^\pm N_i$, with $N_i \rightarrow \ell_2^\pm W^{*\mp} (\rightarrow q'\bar{q})^\mp$. Here, the W - ℓ - N_i couplings are generated due to the heavy-light neutrino mixing of the seesaw mechanism. CP violation occurs due to the interference of the N_1 and N_2 contributions.

A signal of CP violation would be the measurement of a nonzero difference in the rates of the decay $W^- \rightarrow \ell_1^- \ell_2^- (q'\bar{q})^+$ and its CP-conjugate. This type of CP asymmetry requires that the two interfering amplitudes have both CP-odd and CP-even phase differences. The CP-odd phase difference is due to different W - ℓ - N_1 and W - ℓ - N_2 couplings. A CP-even phase difference can be generated in two ways, via propagator effects or oscillations of the heavy neutrino. Both are taken into account in our study.

Our analysis has two pieces, theory predictions and experimental prospects. On the theory side, we have computed the expression for the CP-violating rate asymmetry A_{CP} [eqs. (2.21) and (2.22)]. We consider neutrino masses in the range $5 \text{ GeV} \leq M_N \leq 80 \text{ GeV}$. (The LHC has poor sensitivity to smaller masses.) For various values of the neutrino mass, we compute the potential size of A_{CP} . For low masses, e.g., $5 \text{ GeV} \leq M_N \leq 20 \text{ GeV}$, we find that (i) the contribution of neutrino oscillations to the CP-even phase is much suppressed

compared to that from propagator effects, and (ii) A_{CP} can be large, $\gtrsim 0.9$. For large masses, e.g., $M_N \geq 60 \text{ GeV}$, the contribution of neutrino oscillations to the CP-even phase becomes important, but has the effect of reducing the CP asymmetry, $A_{\text{CP}} \leq 0.6$.

On the experimental side, we want to determine the smallest value of A_{CP} that can be measured at 3σ at the LHC. This depends on the number of observed events, and we use **MadGraph** to find this for three versions of the LHC: (i) the high-luminosity LHC (HL-LHC, $\sqrt{s} = 14 \text{ TeV}$), (ii) the high-energy LHC (HE-LHC, $\sqrt{s} = 27 \text{ TeV}$), (iii) the future circular collider (FCC-hh, $\sqrt{s} = 100 \text{ TeV}$). We assume an experimental efficiency of 1% [40, 42]. The one input required is the size of the heavy-light neutrino mixing parameter $|B_{\ell_1 N_1}|^2$. Taking into account the present experimental constraints, in our analysis we take $|B_{\ell_1 N_1}|^2 = 10^{-5}$.

We find that, while the minimum value of A_{CP} measurable at the LHC depends on the neutrino mass M_N , smaller and smaller values of A_{CP} can be measured as the LHC increases in energy and integrated luminosity. The most promising result is for the FCC-hh with $M_N = 10 \text{ GeV}$, where $A_{\text{CP}} = O(1\%)$ is measurable. But even for the worst case, the HL-LHC with $M_N = 5 \text{ GeV}$, a reasonably small value of $A_{\text{CP}} = O(10\%)$ can be measured.

The point to take away from all of this is the following. The simple observation of the LNV decay $W^\pm \rightarrow \ell_1^\pm \ell_2^\pm (q' \bar{q})^\mp$ would itself be very exciting. But the next step would then be to try to understand the underlying new physics. If a CP asymmetry in this decay were measured, it would tell us that (at least) two amplitudes contribute to the decay, with different CP-odd and CP-even phases, and would hint at a possible connection with leptogenesis models.

Acknowledgments

This work was financially supported by NSERC of Canada.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] M. Gell-Mann, P. Ramond and R. Slansky, *Complex Spinors and Unified Theories*, *Conf. Proc. C* **790927** (1979) 315 [[arXiv:1306.4669](https://arxiv.org/abs/1306.4669)] [[INSPIRE](#)].
- [2] T. Yanagida, *Horizontal gauge symmetry and masses of neutrinos*, in *Proceedings: Workshop on the Unified Theories and the Baryon Number in the Universe*, O. Sawada and A. Sugamoto, eds., Natl. Lab. High Energy Phys., Tsukuba, Japan (1979).
- [3] R.N. Mohapatra and G. Senjanović, *Neutrino Mass and Spontaneous Parity Nonconservation*, *Phys. Rev. Lett.* **44** (1980) 912 [[INSPIRE](#)].
- [4] A.D. Sakharov, *Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe*, *Sov. Phys. Usp.* **34** (1991) 392 [[INSPIRE](#)].
- [5] G. 't Hooft, *Symmetry Breaking Through Bell-Jackiw Anomalies*, *Phys. Rev. Lett.* **37** (1976) 8 [[INSPIRE](#)].

- [6] G. 't Hooft, *Computation of the Quantum Effects Due to a Four-Dimensional Pseudoparticle*, *Phys. Rev. D* **14** (1976) 3432 [Erratum *ibid.* **18** (1978) 2199] [[INSPIRE](#)].
- [7] A. Pilaftsis, *CP violation and baryogenesis due to heavy Majorana neutrinos*, *Phys. Rev. D* **56** (1997) 5431 [[hep-ph/9707235](#)] [[INSPIRE](#)].
- [8] A. Pilaftsis and T.E.J. Underwood, *Resonant leptogenesis*, *Nucl. Phys. B* **692** (2004) 303 [[hep-ph/0309342](#)] [[INSPIRE](#)].
- [9] E.K. Akhmedov, V.A. Rubakov and A.Y. Smirnov, *Baryogenesis via neutrino oscillations*, *Phys. Rev. Lett.* **81** (1998) 1359 [[hep-ph/9803255](#)] [[INSPIRE](#)].
- [10] L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, *Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos*, *Phys. Rev. D* **87** (2013) 093006 [[arXiv:1208.4607](#)] [[INSPIRE](#)].
- [11] L. Canetti, M. Drewes and B. Garbrecht, *Probing leptogenesis with GeV-scale sterile neutrinos at LHCb and Belle II*, *Phys. Rev. D* **90** (2014) 125005 [[arXiv:1404.7114](#)] [[INSPIRE](#)].
- [12] G. Cvetič, C.S. Kim and J. Zamora-Saá, *CP violations in $\pi^\pm$ Meson Decay*, *J. Phys. G* **41** (2014) 075004 [[arXiv:1311.7554](#)] [[INSPIRE](#)].
- [13] G. Cvetič, 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** (2014) 093012 [[arXiv:1403.2555](#)] [[INSPIRE](#)].
- [14] C.O. Dib, M. Campos and C.S. Kim, *CP Violation with Majorana neutrinos in K Meson Decays*, *JHEP* **02** (2015) 108 [[arXiv:1403.8009](#)] [[INSPIRE](#)].
- [15] G. Cvetič, C. Dib, C.S. Kim and J. Zamora-Saa, *Probing the Majorana neutrinos and their CP-violation in decays of charged scalar mesons π, K, D, D_s, B, B_c* , *Symmetry* **7** (2015) 726 [[arXiv:1503.01358](#)] [[INSPIRE](#)].
- [16] G. Cvetič, C.S. Kim, R. Kogerler and J. Zamora-Saa, *Oscillation of heavy sterile neutrino in decay of $B \rightarrow \mu e \pi$* , *Phys. Rev. D* **92** (2015) 013015 [[arXiv:1505.04749](#)] [[INSPIRE](#)].
- [17] G. Cvetič, C.S. Kim, S. Mendizabal and J. Zamora-Saa, *Exploring CP-violation, via heavy neutrino oscillations, in rare B meson decays at Belle II*, *Eur. Phys. J. C* **80** (2020) 1052 [[arXiv:2007.04115](#)] [[INSPIRE](#)].
- [18] R.M. Godbole, S.P. Maharathy, S. Mandal, M. Mitra and N. Sinha, *Interference Effect in LNV and LNC Meson Decays for Left Right Symmetric Model*, [arXiv:2008.05467](#) [[INSPIRE](#)].
- [19] J. Zhang, T. Wang, G. Li, Y. Jiang and G.-L. Wang, *Study of two quasidegenerate heavy sterile neutrinos in rare meson decays*, *Phys. Rev. D* **103** (2021) 035015 [[arXiv:2010.13286](#)] [[INSPIRE](#)].
- [20] J. Zamora-Saa, *Resonant CP violation in rare $\tau^\pm$ decays*, *JHEP* **05** (2017) 110 [[arXiv:1612.07656](#)] [[INSPIRE](#)].
- [21] S. Tapia and J. Zamora-Saá, *Exploring CP-Violating heavy neutrino oscillations in rare tau decays at Belle II*, *Nucl. Phys. B* **952** (2020) 114936 [[arXiv:1906.09470](#)] [[INSPIRE](#)].
- [22] T. Appelquist and R. Shrock, *Neutrino masses in theories with dynamical electroweak symmetry breaking*, *Phys. Lett. B* **548** (2002) 204 [[hep-ph/0204141](#)] [[INSPIRE](#)].
- [23] T. Appelquist and R. Shrock, *Dynamical symmetry breaking of extended gauge symmetries*, *Phys. Rev. Lett.* **90** (2003) 201801 [[hep-ph/0301108](#)] [[INSPIRE](#)].

- [24] T. Asaka, S. Blanchet and M. Shaposhnikov, *The nuMSM, dark matter and neutrino masses*, *Phys. Lett. B* **631** (2005) 151 [[hep-ph/0503065](#)] [[INSPIRE](#)].
- [25] T. Asaka and M. Shaposhnikov, *The ν MSM, dark matter and baryon asymmetry of the universe*, *Phys. Lett. B* **620** (2005) 17 [[hep-ph/0505013](#)] [[INSPIRE](#)].
- [26] M. Drewes, B. Garbrecht, D. Gueter and J. Klaric, *Testing the low scale seesaw and leptogenesis*, *JHEP* **08** (2017) 018 [[arXiv:1609.09069](#)] [[INSPIRE](#)].
- [27] J.A. Casas and A. Ibarra, *Oscillating neutrinos and $\mu \rightarrow e, \gamma$* , *Nucl. Phys. B* **618** (2001) 171 [[hep-ph/0103065](#)] [[INSPIRE](#)].
- [28] J. Kersten and A.Y. Smirnov, *Right-Handed Neutrinos at CERN LHC and the Mechanism of Neutrino Mass Generation*, *Phys. Rev. D* **76** (2007) 073005 [[arXiv:0705.3221](#)] [[INSPIRE](#)].
- [29] A. Datta, M. Guchait and A. Pilaftsis, *Probing lepton number violation via Majorana neutrinos at hadron supercolliders*, *Phys. Rev. D* **50** (1994) 3195 [[hep-ph/9311257](#)] [[INSPIRE](#)].
- [30] A. Ali, A.V. Borisov and N.B. Zamorin, *Majorana neutrinos and same sign dilepton production at LHC and in rare meson decays*, *Eur. Phys. J. C* **21** (2001) 123 [[hep-ph/0104123](#)] [[INSPIRE](#)].
- [31] T. Han and B. Zhang, *Signatures for Majorana neutrinos at hadron colliders*, *Phys. Rev. Lett.* **97** (2006) 171804 [[hep-ph/0604064](#)] [[INSPIRE](#)].
- [32] C.-Y. Chen, P.S.B. Dev and R.N. Mohapatra, *Probing Heavy-Light Neutrino Mixing in Left-Right Seesaw Models at the LHC*, *Phys. Rev. D* **88** (2013) 033014 [[arXiv:1306.2342](#)] [[INSPIRE](#)].
- [33] E. Izaguirre and B. Shuve, *Multilepton and Lepton Jet Probes of Sub-Weak-Scale Right-Handed Neutrinos*, *Phys. Rev. D* **91** (2015) 093010 [[arXiv:1504.02470](#)] [[INSPIRE](#)].
- [34] C. Degrande, O. Mattelaer, R. Ruiz and J. Turner, *Fully-Automated Precision Predictions for Heavy Neutrino Production Mechanisms at Hadron Colliders*, *Phys. Rev. D* **94** (2016) 053002 [[arXiv:1602.06957](#)] [[INSPIRE](#)].
- [35] A. Das, P. Konar and S. Majhi, *Production of Heavy neutrino in next-to-leading order QCD at the LHC and beyond*, *JHEP* **06** (2016) 019 [[arXiv:1604.00608](#)] [[INSPIRE](#)].
- [36] A. Das and N. Okada, *Bounds on heavy Majorana neutrinos in type-I seesaw and implications for collider searches*, *Phys. Lett. B* **774** (2017) 32 [[arXiv:1702.04668](#)] [[INSPIRE](#)].
- [37] P. Hernández, J. Jones-Pérez and O. Suarez-Navarro, *Majorana vs Pseudo-Dirac Neutrinos at the ILC*, *Eur. Phys. J. C* **79** (2019) 220 [[arXiv:1810.07210](#)] [[INSPIRE](#)].
- [38] DELPHI collaboration, *Search for neutral heavy leptons produced in Z decays*, *Z. Phys. C* **74** (1997) 57 [Erratum *ibid.* **75** (1997) 580] [[INSPIRE](#)].
- [39] L3 collaboration, *Search for heavy isosinglet neutrino in e^+e^- annihilation at LEP*, *Phys. Lett. B* **517** (2001) 67 [[hep-ex/0107014](#)] [[INSPIRE](#)].
- [40] CMS collaboration, *Search for heavy Majorana neutrinos in $\mu^\pm\mu^\pm + \text{jets}$ events in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett. B* **748** (2015) 144 [[arXiv:1501.05566](#)] [[INSPIRE](#)].
- [41] CMS collaboration, *Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. Lett.* **120** (2018) 221801 [[arXiv:1802.02965](#)] [[INSPIRE](#)].

- [42] CMS collaboration, *Search for heavy Majorana neutrinos in $e^\pm e^\pm + \text{jets}$ and $e^\pm \mu^\pm + \text{jets}$ events in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$* , *JHEP* **04** (2016) 169 [[arXiv:1603.02248](#)] [[INSPIRE](#)].
- [43] ATLAS collaboration, *Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector*, *JHEP* **10** (2019) 265 [[arXiv:1905.09787](#)] [[INSPIRE](#)].
- [44] LHCb collaboration, *Search for heavy neutral leptons in $W^+ \rightarrow \mu^+ \mu^\pm \text{jet}$ decays*, *Eur. Phys. J. C* **81** (2021) 248 [[arXiv:2011.05263](#)] [[INSPIRE](#)].
- [45] S. Antusch, E. Cazzato and O. Fischer, *Resolvable heavy neutrino-antineutrino oscillations at colliders*, *Mod. Phys. Lett. A* **34** (2019) 1950061 [[arXiv:1709.03797](#)] [[INSPIRE](#)].
- [46] G. Cvetič, A. Das and J. Zamora-Saá, *Probing heavy neutrino oscillations in rare W boson decays*, *J. Phys. G* **46** (2019) 075002 [[arXiv:1805.00070](#)] [[INSPIRE](#)].
- [47] G. Cvetič, A. Das, S. Tapia and J. Zamora-Saá, *Measuring the heavy neutrino oscillations in rare W boson decays at the Large Hadron Collider*, *J. Phys. G* **47** (2020) 015001 [[arXiv:1905.03097](#)] [[INSPIRE](#)].
- [48] F. Zimmermann, *HE-LHC Overview, Parameters and Challenges*, *ICFA Beam Dyn. Newslett.* **72** (2017) 138.
- [49] T. Golling, *Future Circular Collider Study (FCC)*, https://indico.cern.ch/event/389531/contributions/929678/attachments/1149541/1649500/FCC_Golling_LHCP_Sep042015.pdf.
- [50] FCC-EE STUDY TEAM collaboration, *Search for Heavy Right Handed Neutrinos at the FCC-ee*, *Nucl. Part. Phys. Proc.* **273–275** (2016) 1883 [[arXiv:1411.5230](#)] [[INSPIRE](#)].
- [51] A. Alloul, N.D. Christensen, C. Degrande, C. Duhr and B. Fuks, *FeynRules 2.0 — A complete toolbox for tree-level phenomenology*, *Comput. Phys. Commun.* **185** (2014) 2250 [[arXiv:1310.1921](#)] [[INSPIRE](#)].
- [52] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [53] ATLAS collaboration, *Measurement of $W^\pm$ and Z -boson production cross sections in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector*, *Phys. Lett. B* **759** (2016) 601 [[arXiv:1603.09222](#)] [[INSPIRE](#)].
- [54] N. Liu, Z.-G. Si, L. Wu, H. Zhou and B. Zhu, *Top quark as a probe of heavy Majorana neutrino at the LHC and future colliders*, *Phys. Rev. D* **101** (2020) 071701 [[arXiv:1910.00749](#)] [[INSPIRE](#)].
- [55] F.F. Deppisch, P.S. Bhupal Dev and A. Pilaftsis, *Neutrinos and Collider Physics*, *New J. Phys.* **17** (2015) 075019 [[arXiv:1502.06541](#)] [[INSPIRE](#)].