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Majorana vs. Dirac sterile neutrinos at the LHC

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Abstract. We study leptonic decays $W^\pm \rightarrow e^\pm e^\pm \mu^\mp \nu$ and $W^\pm \rightarrow \mu^\pm \mu^\pm e^\mp \nu$ which would occur at the LHC if there exist sterile neutrinos with masses below M_W . We also study ways to discriminate their Majorana or Dirac character, a rather non trivial task, because lepton number conservation cannot be checked due to the missing neutrino in the final state. We find that it is indeed possible to discriminate between Majorana vs. Dirac sterile neutrinos by comparing the production of $e^\pm e^\pm \mu^\mp$ vs. $\mu^\pm \mu^\pm e^\mp$ if the N - e and N - μ mixings are sufficiently different. Alternatively, one could also distinguish the Majorana vs. Dirac character by studying the energy spectra of the opposite charge lepton, a method that works even for equal N - e and N - μ mixings.

1. Introduction

The origin of the small neutrino masses and their Dirac or Majorana character is a currently outstanding problem, since these are naturally zero in the Standard Model. Most explanations for the small neutrino masses are based on *seesaw* models [1]. These models predict additional heavy neutrinos, sterile in the Standard Model except for small mixings with the weak currents. The heavy neutrinos masses, m_N , in most scenarios should be of Majorana type and, depending on the model, they could lie anywhere from a few eV all the way to GUT scales. It is thus very important to explore the existence of these extra particles, and to resolve their mass character and scale, as they will shed light onto physics beyond the Standard Model.

Search for Majorana masses are usually done in *Neutrinoless Double Beta Decay* experiments [2]. Nevertheless, collider tests are also competitive for specific mass ranges. At the LHC, $W \rightarrow \ell^+ \ell^+ jj$ is appropriate for $m_N > M_W$ [3, 4], while leptonic modes such as $W^\pm \rightarrow e^\pm e^\pm \mu^\mp \nu$ and $W^\pm \rightarrow \mu^\pm \mu^\pm e^\mp \nu$ are preferred for $m_N < M_W$ [5]. However, here the discrimination of Dirac vs. Majorana is a major challenge, because the final neutrino, which may or may not balance Lepton Number, escapes detection [6, 7].

Indeed, the mode e.g. $W^+ \rightarrow e^+ e^+ \mu^- \nu$ is actually a sum of two exclusive modes:

- (i) $W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu$: a Lepton Number violating process (LNV),
- (ii) $W^+ \rightarrow e^+ e^+ \mu^- \nu_e$: a Lepton Number conserving process (LNC).

These decays are forbidden in the Standard Model. They proceed only if there exist heavy sterile neutrinos, which would appear as intermediate states in these processes. These rates are very small, but they get resonantly enhanced if $m_N < M_W$ as N goes on its mass shell.



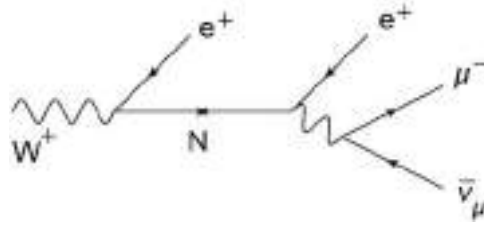


Figure 1. LNV process mediated by a sterile neutrino N (Majorana N only).

The amplitude for the LNV decay $W^+ \rightarrow e^+e^+\mu^-\bar{\nu}_\mu$ is depicted in the Feynman diagram of Fig. 1. Only a Majorana N can induce this process, since it violates lepton number. However, since the final neutrino $\bar{\nu}_\mu$ will escape detection in an experiment, it is not possible to directly verify this violation of lepton number.

The spectrum of the opposite charge lepton (i.e. the muon), in the N rest frame, is:

$$\Gamma(W^+ \rightarrow e^+e^+\mu^-\bar{\nu}_\mu) = \frac{G_F^3 M_W^3 m_N^5}{12\sqrt{2} \pi^4} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right) \times \frac{|U_{Ne}|^4}{\Gamma_N} \int_0^{1/2} d\epsilon_\mu (\epsilon_\mu^2 - 2\epsilon_\mu^3). \quad (1)$$

where $\epsilon_\mu \equiv E_\mu/m_N$ is the normalized muon energy.

In turn, the integrated rate for this process is:

$$Br(W^+ \rightarrow e^+e^+\mu^-\bar{\nu}_\mu) \approx 4.8 \times 10^{-3} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right) \frac{|U_{Ne}|^4}{\sum_{\ell=e,\mu,\tau} |U_{N\ell}|^2}. \quad (2)$$

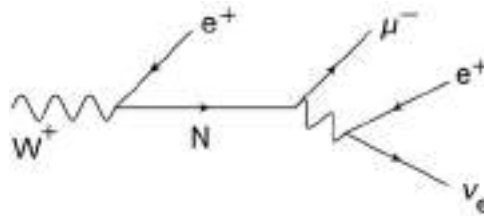


Figure 2. LNC process mediated by a sterile neutrino N (Dirac or Majorana N).

On the other hand, the LNC decay $W^+ \rightarrow e^+e^+\mu^-\nu_e$ is depicted in Fig. 2. This process conserves lepton number, and thus can be induced by a sterile neutrino of either Majorana or Dirac character. However, again such conservation cannot be directly verified in an experiment due to the neutrino ν_e in the final state, which would escape detection.

The spectrum of the opposite charge lepton in this process, measured in the N rest frame, is:

$$\Gamma(W^+ \rightarrow e^+e^+\mu^-\nu_e) = \frac{G_F^3 M_W^3 m_N}{12\sqrt{2} \pi^4} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right) \times \frac{|U_{Ne} U_{N\mu}|^2}{\Gamma_N} \int_0^{1/2} d\epsilon_\mu \left(\frac{1}{2}\epsilon_\mu^2 - \frac{2}{3}\epsilon_\mu^3\right), \quad (3)$$

where again $\epsilon_\mu \equiv E_\mu/m_N$ is the normalized muon energy. It is clear that this spectrum differs from that of the LNV process, given in Eq. (1). The two spectra are shown in Fig. 3 (left).

Even when the spectra are different, the integrated rate for the LNC and LNV processes are identical, except for the lepton mixing elements which appear as a global factor:

$$Br(W^+ \rightarrow e^+e^+\mu^-\nu_e) \approx 4.8 \times 10^{-3} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 + \frac{m_N^2}{2M_W^2}\right) \frac{|U_{Ne}U_{N\mu}|^2}{\sum_{\ell=e,\mu,\tau} |U_{N\ell}|^2}. \quad (4)$$

Not knowing a priori the values of these mixing elements, the two rates are, apparently, also undistinguishable in an experiment. Therefore some clever way must be devised to distinguish the Majorana vs. Dirac character of the intermediate neutrino, should these decay modes of W happen to be observed.

2. Analysis of the Spectra

The actual event rate of $e^+e^+\mu^-\nu$ at the LHC will depend on whether N is a Dirac or a Majorana neutrino. If N is a Dirac neutrino, it will be the LNC rate only, $\Gamma(e^+e^+\mu^-)_{LNC}$, while if N is a Majorana neutrino, it will be the sum of the LNC + LNV rates, $\Gamma(e^+e^+\mu^-)_{LNC} + \Gamma(e^+e^+\mu^-)_{LNV}$.

Our problem is then how to distinguish at the LHC a Majorana from a Dirac N (how to distinguish LNV from LNC), given that the two rates are the same, except for the mixing elements –so far unknown.

One way to discriminate between the Dirac and Majorana character of the sterile neutrino N is to analyze the spectrum of the opposite charge lepton, i.e. μ^- in the case of $(e^+e^+\mu^-)$, or e^- in the case of $(\mu^+\mu^+e^-)$ [1].

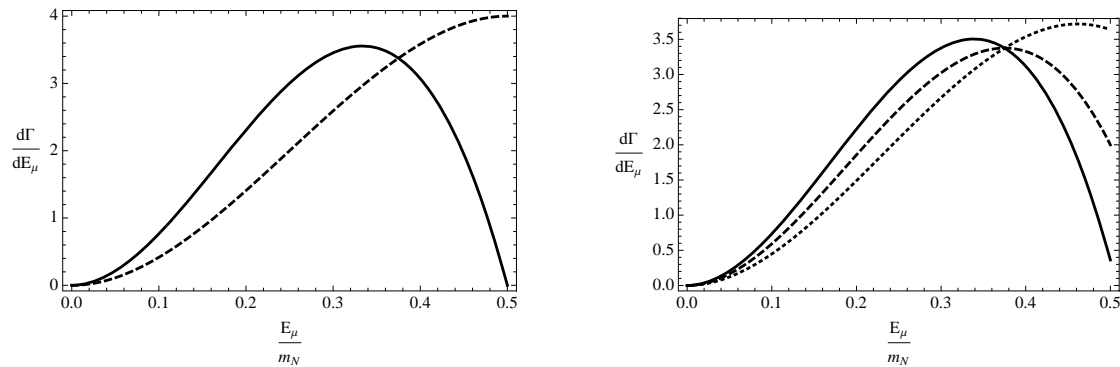


Figure 3. Muon energy spectra in the N rest frame, $(1/\Gamma)d\Gamma(e^+e^+\mu^-)/dE_\mu$ in the N . Left: Solid line: LNV (see Eq. 1); dashed line: LNC (see Eq. 3). Right: LNV+LNC for 3 mixing ratios $r_{\text{mix}} \equiv |U_{Ne}|^2/|U_{N\mu}|^2$: $r_{\text{mix}} = 10$ (solid), $r_{\text{mix}} = 1$ (dashed) and $r_{\text{mix}} = 1/10$ (dotted). For exchanged flavor $(\mu^+\mu^+e^-)$, the spectra correspond to the inverse of r_{mix} .

For a Dirac N , the spectrum will be that of the LNC process (fig. 3 left, dashed line), while for a Majorana N , the spectrum will be the sum of the LNC and LNV spectra, shown in fig. 3 right; the shape of this spectrum depends on the disparity ratio of mixings:

$$r_{\text{mix}} \equiv |U_{Ne}|^2/|U_{N\mu}|^2,$$

which defines whether the LNC or the LNV part dominates. For $r_{\text{mix}} \gtrsim 1$, the spectrum of $\Gamma(e^+e^+\mu^-)$ for a Majorana N vs. a Dirac N differ enough for the two cases to be discriminated.

For $r_{\text{mix}} \ll 1$ the spectrum of $\Gamma(e^+e^+\mu^-)$ for a Majorana N is indistinguishable from that of a Dirac N , in which case one should use the exchanged flavour mode $\Gamma(\mu^+\mu^+e^-)$, where the Majorana and Dirac spectra differ the most. Currently we are doing simulations for the reconstruction of these spectra at the LHC, a work that is still in progress.

Nevertheless, it is already clear that the discrimination of spectra in such rare decays is uncertain, as it will require a rather sizable sample of events.

3. Analysis of the Rates

Another way to discriminate between the Majorana vs. Dirac character if the sterile neutrino that induces the trilepton modes is to compare the rates with exchanged flavors, namely $\Gamma(e^+e^+\mu^-)$ and $\Gamma(\mu^+\mu^+e^-)$ [2]. From Eq. (4), one can see that the LNC rates are identical:

$$\Gamma(e^+e^+\mu^-)_{LNC} = \Gamma(\mu^+\mu^+e^-)_{LNC} \sim |U_{Ne}U_{N\mu}|^2, \quad (5)$$

while the LNV rates, Eq. (2), differ depending on the mixing –or more precisely on the disparity ratio r_{mix} :

$$\Gamma(e^+e^+\mu^-)_{LNV} \sim |U_{Ne}|^4, \quad \Gamma(\mu^+\mu^+e^-)_{LNV} \sim |U_{N\mu}|^4. \quad (6)$$

While the LNC rates are always equal, the LNV rates are equal only if $|U_{Ne}|^2 = |U_{N\mu}|^2$. With the fact that a Dirac sterile neutrino will produce the LNC process only, while a Majorana neutrino will produce both the LNC and LNV processes, one can compare the production of $e^+e^+\mu^-$ and $\mu^+\mu^+e^-$ (or their charge conjugates) induced by a Dirac or a Majorana sterile neutrino. Table 1 shows the comparison, where the rate of $W^+ \rightarrow e^+e^+\mu^-\nu$ in the Dirac case is chosen as the reference value, by which the rates of other cases are normalized: for a Dirac sterile neutrino the production rates of $e^+e^+\mu^-$ and $\mu^+\mu^+e^-$ should be equal, while for the Majorana case they will differ, depending r_{mix} .

For $r > 1$, the number of events $N(e^+e^+\mu^-)$ should be larger than $N(\mu^+\mu^+e^-)$ and, viceversa, if $r < 1$ then $N(\mu^+\mu^+e^-)$ will be more abundant than $N(e^+e^+\mu^-)$. Similar comparison also exists in the corresponding charge-conjugated processes.

	Dirac	Majorana
$e^+e^+\mu^-$	1	$1 + r_{\text{mix}}$
$\mu^+\mu^+e^-$	1	$1 + 1/r_{\text{mix}}$

Table 1. Relative factors in the branching ratios of $W^+ \rightarrow e^+e^+\mu^-\nu$ and $W^+ \rightarrow \mu^+\mu^+e^-\nu$ for either a Dirac or Majorana sterile neutrino scenario, where ν represents a standard neutrino or anti-neutrino. The same applies for the respective charge conjugate modes.

Consequently, if $r_{\text{mix}} = 1$, we will not be able to discriminate between Dirac or Majorana, because the number of $(e^+e^+\mu^-)$ and $(\mu^+\mu^+e^-)$ events will be the same in either case. However, for $r_{\text{mix}} \neq 1$ the discrimination will be possible. Our question is then how far from unity must r_{mix} be in order to discriminate Majorana from Dirac at the LHC.

To answer this question, we generate events in a Majorana neutrino scenario and test whether one can significantly discriminate the Majorana from a Dirac case. The analysis is done for several mixings, and two mass benchmarks: $m_N = 20$ GeV and $m_N = 50$ GeV.

In our simulation analysis, we first use FeynRules [8] to extend the SM, and then we generate simulated events with MadGraph 5 [9] using PYTHIA 6 [10] for the parton showers and DELPHES 3 [11] for detector simulations. The main backgrounds considered are (i) WZ production with $W \rightarrow \text{leptonic}$ and $Z \rightarrow \tau^+\tau^-$ and $\tau \rightarrow \text{leptonic}$, and (ii) fake leptons from jets in processes $\gamma^*/Z+\text{jets}$ or $t\bar{t}$.

We test for different cuts and find that the best cuts that reduce background are: (i) $p_T > 10$ GeV and $|\eta| < 2.5$ for leptons, (ii) $p_T > 20$ GeV and $|\eta| < 5.0$ for jets; (iii) $M_T(3\ell + \cancel{p}_T) < 90$ GeV; (iv) $\cancel{p}_T < 40$ GeV, no b -jets and $\sum p_T^{jet} < 50$ GeV.

The results are shown in Fig. 4. Here we show the plane s vs. r , where s is the average mixing factor that sets the magnitude of the rates (i.e. the average number of events), while $r = r_{\text{mix}}$ is the mixing ratio. In this plane we show the contour lines for several confidence levels with which one can exclude the Dirac scenario from a Majorana case. As s gets larger, more events are produced and the exclusion becomes possible even for r_{mix} very close to unity. For both m_N benchmark scenarios, at least a 3σ exclusion level can be reached for mixing disparities r_{mix} as mild as e.g. $r_{\text{mix}} \lesssim 0.7$ (or $1/r_{\text{mix}} \lesssim 0.7$), provided the average mixing s is sufficiently large ($s \gtrsim 5$). For smaller s (smaller mixings), meaning fewer events, r_{mix} must be larger to reach the same level of discrimination; in the same way, as r_{mix} approaches 1, larger values of s are required as it becomes more and more difficult to exclude the Dirac case.

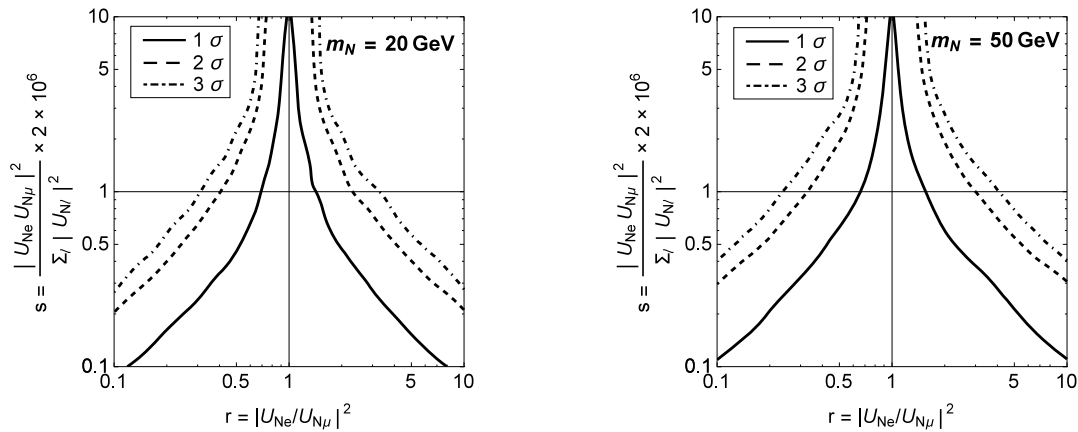


Figure 4. Confidence levels for excluding the Dirac case given a Majorana scenario, for two benchmarks: $m_N = 20$ GeV (left) and 50 GeV (right).

4. Conclusions

We studied the question of determining the Dirac vs. Majorana character of sterile neutrino with mass below M_W at the LHC. Because of such a low mass for the neutrino, in the conventional $\ell^+\ell^+jj$ search for Majorana sterile neutrinos at the LHC the jets are not energetic enough to pass the necessary detector cuts. Therefore, we focus on the alternative tri-lepton search channels. To avoid SM backgrounds we require no opposite-sign same-flavor lepton pairs in the final state. Although this tri-lepton search is ideal for such a low mass sterile neutrino search, the Dirac vs. Majorana discrimination becomes a non trivial task due to the missing neutrino (or antineutrino) in the final state.

We find two ways to distinguish between Dirac and Majorana in these tripleton events. One way is to analyse the energy spectrum of the opposite charge lepton. This is a robust method but has the difficulty of requiring a large sample of events, a rather difficult goal in such rare processes. Another way is to compare the rates of the two flavor configurations $e^\pm e^\pm \mu^\mp$ and $\mu^\pm \mu^\pm e^\mp$. Here the discrimination will be possible provided the mixing elements of the sterile neutrino N with electrons and muons are different enough. We find that one is able to exclude the Dirac sterile neutrino case by simply counting and then comparing the numbers of events in the $e^+e^+\mu^-$ and $\mu^+\mu^+e^-$ channels (or the corresponding charge-conjugated ones). We perform a careful collider simulation for this scenario. We have characterized the average size of the

mixings by the parameter $s = 2 \cdot 10^6 \times |U_{Ne}U_{N\mu}|^2 / (|U_{Ne}|^2 + |U_{N\mu}|^2)$, and the disparity between the mixings by the parameter $r = |U_{Ne}/U_{N\mu}|^2$. We find that, in the 14 TeV pp collisions at the LHC with an integrated luminosity of 3000 fb^{-1} , at least a 3σ level of exclusion of the Dirac case with respect to the Majorana case can be achieved, depending on the size and disparity of the two relevant mixing parameters. For example, such level of discrimination is achieved for $s \gtrsim 5$ and $r \lesssim 0.7$ (or $1/r \lesssim 0.7$). For smaller values of s the number of events will be smaller as well, and therefore this level of discrimination can be reached only for larger values of the disparity ratio r_{mix} .

Acknowledgments

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