Majorana vs. Dirac sterile neutrinos lighter than $M_W$ at the LHC

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Abstract. We propose to study the leptonic decays $W^\pm \rightarrow e^\pm e^\mp \mu^\mp \nu_\mu$ and $W^\pm \rightarrow \mu^\pm \mu^\mp e^\mp \nu_e$ at the LHC to discover sterile neutrinos with masses below $M_W$, and discriminate their Majorana or Dirac character. These decays are induced by a sterile neutrino $N$ that goes on mass shell in the intermediate state. We find that, even though the final (anti)-neutrino goes undetected and thus lepton number is unchecked, one can distinguish between the Majorana vs. Dirac character of the intermediate sterile neutrino by comparing the production of $e^\pm e^\mp \mu^\mp$ vs. $\mu^\pm \mu^\mp e^\mp$, provided the $N$-e and $N$-$\mu$ mixings are different enough. Alternatively, one can also distinguish the Majorana vs. Dirac character by studying the energy spectra of the opposite charge lepton, a method that works even if the $N$-e and $N$-$\mu$ mixings are equal.

Most explanations for the smallness of neutrino masses are based on seesaw models. These models predict additional heavy neutrinos, sterile in the Standard Model except for small mixings with the weak currents. Their masses, $m_N$, in most scenarios are of Majorana type and can lie anywhere from a few eV all the way to GUT scales. Search for Majorana masses are usually done in Neutrinoless Double Beta Decay experiments, but collider tests are also competitive for specific mass ranges.

At the LHC, $W \rightarrow \ell^+ \ell^- jj$ is appropriate for $m_N > M_W$, while leptonic modes such as $W^\pm \rightarrow e^\pm e^\mp \mu^\mp \nu$ and $W^\pm \rightarrow \mu^\pm \mu^\mp e^\mp \nu$ are preferred for $m_N < M_W$. However, the discrimination between Dirac vs. Majorana in these purely leptonic modes is a major challenge, because the conservation of lepton number cannot be tested directly, as the neutrino in the final state goes undetected. Indeed, if $N$ is Majorana, the mode $e^+ e^- \mu^- \nu$ is actually the sum of two exclusive modes: the lepton number violating (LVN) $W^+ \rightarrow e^+ e^- \mu^- \nu$, and the lepton number conserving (LNC) $W^+ \rightarrow e^+ e^- \mu^- \nu_e$ (Figs. 1 and 2 show the diagrams of these two processes). Instead, if $N$ is Dirac, only the LNC process occurs. These decays proceed through a heavy sterile neutrino $N$ in the intermediate state, resonantly enhanced if $m_N < M_W$.

Here we propose ways to tell whether the intermediate $N$ is Majorana or Dirac by observing the charged leptons $e^+ e^- \mu^-$ or $\mu^+ \mu^+ e^-$, while the final neutrino goes undetected.

Proposal 1: Compare the event rates of $e^+ e^- \mu^-$ with $\mu^+ \mu^+ e^-$ [1]. If $N$ is Majorana, the rates will be different provided the lepton mixings are different ($U_{Ne} \neq U_{N\mu}$). Instead, if $N$ is Dirac,
the rates will be the same regardless of the lepton mixings. This is due to the fact that the \( \text{LNV} \) and \( \text{LNC} \) rates differ only in their neutrino mixing factors, \( U_{Ne} \) and \( U_{N\mu} \) [1, 2]:

\[
\Gamma(e^+e^-\mu^-)_{\text{LNV}} \sim |U_{Ne}|^4, \quad \Gamma(e^+e^-\mu^-)_{\text{LNC}} \sim |U_{Ne}U_{N\mu}|^2, \\
\Gamma(\mu^{+}\mu^{-}e^{-})_{\text{LNV}} \sim |U_{N\mu}|^4, \quad \Gamma(\mu^{+}\mu^{-}e^{-})_{\text{LNC}} \sim |U_{Ne}U_{N\mu}|^2.
\]

Let us define the mixing disparity ratio: \( r_{\text{mix}} = |U_{Ne}|^2/|U_{N\mu}|^2 \). Then,

- If \( N \) is Dirac, only \( \text{LNC} \) occurs \( \Rightarrow N(e^+e^-\mu^-) = N(\mu^{+}\mu^{-}e^{-}) \) regardless of \( r_{\text{mix}} \).
- If \( N \) is Majorana, both \( \text{LNC} \) and \( \text{LNV} \) occur \( \Rightarrow N(e^+e^-\mu^-) > N(\mu^{+}\mu^{-}e^{-}) \) if \( r_{\text{mix}} > 1 \), and vice versa if \( r_{\text{mix}} < 1 \).

The question is then, how far from unity \( r_{\text{mix}} \) must be in order to discriminate Majorana from Dirac with these trilepton processes at the LHC. To answer this question we simulate events in a Majorana neutrino scenario and test whether one can significantly discriminate it from a Dirac case (where the \( e^+e^-\mu^- \) and \( \mu^{+}\mu^{-}e^{-} \) rates are equal). We do this analysis for several mixings, and choose two mass benchmarks: \( m_N = 20 \text{ GeV} \) and \( m_N = 50 \text{ GeV} \).

We use FeynRules [3] to extend the Standard Model and simulate events with MadGraph-5 [4], using PYTHIA-6 [5] for the parton showers and Delphes-3 [6] for the detector. The 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 \( t\bar{t} \). To reduce the background we impose the cuts: (i) \( p_T > 10 \text{ GeV} \) and \( |\eta| < 2.5 \) for leptons, (ii) \( p_T > 20 \text{ GeV} \) and \( |\eta| < 5.0 \) for jets; (iii) \( M_T(3\ell+\not{p}_T) < 90 \text{ GeV} \); (iv) \( \not{p}_T < 40 \text{ GeV} \), no \( b \)-jets and \( \sum_{j\ell} p_T < 50 \text{ GeV} \).
The results are shown in Fig. 3 for both benchmark scenarios. We find that a 3σ exclusion level can be reached for disparities $r_{\text{mix}}$ as mild as e.g. $r_{\text{mix}} \lesssim 0.7$ (or $1/r_{\text{mix}} \lesssim 0.7$), provided the average mixing $s$ – which determines the absolute rates – (see Fig. 3) is sufficiently large ($s \gtrsim 5$). For smaller $s$ (meaning fewer events), $r_{\text{mix}}$ must be larger in order to reach the same level of discrimination; in the same way, as $r_{\text{mix}}$ approaches 1, larger values of $s$ are required as it becomes more and more difficult to exclude the Dirac case.

**Proposal 2:** Analyse the spectrum of the opposite charge lepton, e.g. the $\mu^-$ in $\Gamma(e^+e^-\mu^-)$ [2]. If $r_{\text{mix}}$ is close to unity, the previous method cannot discriminate so well. In such case we can use this spectrum because it differs in the LNV and LNC processes. Denoting $\epsilon_\mu = E_\mu/m_N$ the muon energy in the $N$ rest frame, the spectra are given by:

$$\Gamma(W^+ \to e^+e^-\mu^-)_{\text{(LNV)}} \sim \frac{|U_{Ne}|^4}{U^2} \int_0^{1/2} d\epsilon_\mu \left( \epsilon_\mu^2 - 2 \epsilon_\mu^3 \right),$$

$$\Gamma(W^+ \to e^+e^-\mu^-)_{\text{(LNC)}} \sim \frac{|U_{Ne}U_{N\mu}|^2}{U^2} \int_0^{1/2} d\epsilon_\mu \left( \frac{1}{2} \epsilon_\mu^2 - \frac{2}{3} \epsilon_\mu^3 \right).$$

![Figure 4](image_url)

**Figure 4.** Muon energy spectra for $(e^+e^-\mu^-)$ in the $N$ rest frame. Left: LNV (solid) and LNC (dashed). Right: LNV+LNC for $r_{\text{mix}} = 10$ (solid), 1 (dashed) and 1/10 (dotted). For $(\mu^+\mu^-e^-)$ the spectra correspond to the inverse of $r_{\text{mix}}$.

For a Dirac $N$, the spectrum will always be LNC only (Fig. 3 left, dashed line). Instead, for a Majorana $N$, the spectrum will be LNC+LNV, shown in Fig. 3 right, which depends on $r_{\text{mix}}$. For $r_{\text{mix}} \ll 1$ the spectrum of $\Gamma(e^+e^-\mu^-)$ is indistinguishable from a Dirac case, in which case one should use the exchanged flavour mode $\Gamma(\mu^+\mu^-e^-)$. Simulations for the reconstruction of these spectra at the LHC are in progress.

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