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Distinguishing Dirac and Majorana Heavy Neutrinos at Lepton Colliders

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We discuss the potential to observe lepton number violation in displaced vertex searches for heavy neutral leptons at future lepton colliders. Even though a direct detection of lepton number violation is impossible for the dominant production channel because lepton number is carried away by an unobservable neutrino, there are several signatures of lepton number violation that can be searched for. They include the angular distribution and spectrum of decay products as well as the heavy neutral lepton lifetime. We comment on the perspectives to observe lepton number violation in realistic neutrino mass models and argue that the dichotomy of Dirac vs Majorana heavy neutral leptons is in general not sufficient to effectively capture their phenomenology, but these extreme cases nevertheless represent well-defined benchmarks for experimental searches. Finally, we present accurate analytic estimates for the number of events and sensitivity regions during the Z-pole run for both Majorana and Dirac heavy neutral leptons.

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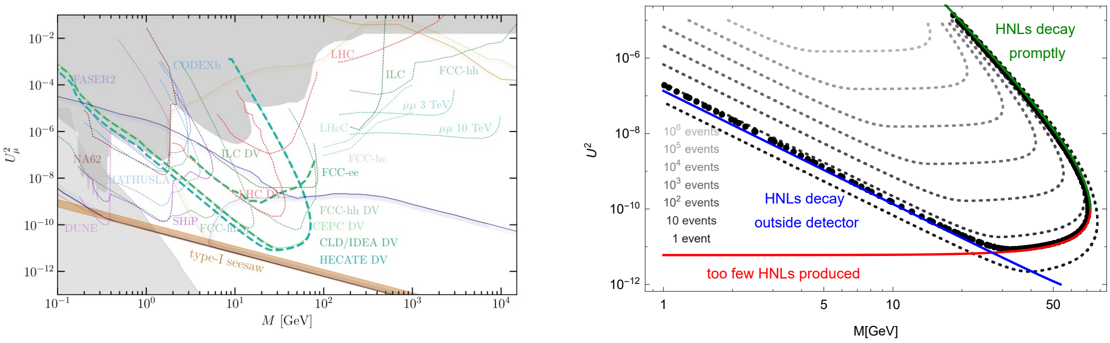

Figure 1: *Left:* Allowed HNL parameter region (white) compared to the sensitivities of various experiments, in particular displaced vertex searches at FCC-ee and CEPC, details given in [1]. *Right:* Simulated 4-event curves from [1] (black dots) compared to the analytic estimates (2) (gray dotted), (3) (red and green) and (4) (blue) for $U^2 = U_\mu^2$, $c_{\rm prod} = c_{\rm dec} = 1$, $N_{\rm obs} = 4$, $N_{\rm IP} = 2$, $N_Z = 2.5 \times 10^{12}$, $l_0 = 400\mu$m, $d_{\rm cyl} = 10$m, $l_{\rm cyl} = 8.6$m, $\epsilon_{\alpha\beta} = 1$.

Motivation Neutrinos are the sole fermions in the Standard Model (SM) of particle physics that could be their own antiparticles, in which case the would be the only known elementary Majorana fermions, and their masses would break the global $U(1)_{B-L}$ symmetry of the SM. An immediate consequence would be the existence of processes that violate the total lepton number L. However, due to the smallness of the light neutrino masses m_i the rate for lepton number violating (LNV) processes in neutrino experiments would be parametrically suppressed. At the same time it is clear that any explanation of the light neutrino masses requires an extension of the SM field content, and LNV may occur at an observable rate in processes involving new particles. This in particular can include heavy neutral leptons (HNLs) N_i[1] that couple to the Z- and W-bosons and the Higgs bosons h via the SM weak interaction with an amplitude suppressed by the mixing angles $\theta_{\alpha i}$ (with $\alpha = e, \mu, \tau$ and $i = 1 \ldots n$),

$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}_i\theta^*_{\alpha i}\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}_i\theta^*_{\alpha i}\gamma^\mu \nu_{L\alpha}Z_\mu - \frac{M_i}{v\sqrt{2}}\theta_{\alpha i}h\overline{\nu_L}_\alpha N_i + \text{h.c.}, \tag{1}$$

with m_Z, m_W the weak gauge boson masses and v the Higgs vev. The N_i can be Dirac or Majorana fermions. For $M_i < m_Z$ they can be produced copiously during the Z-mass run of future lepton colliders [10] such as FCC-ee [11] or CEPC [12], cf. Fig. 1, making it possible to not only discover them but also study their properties in sufficient detail to probe their role in neutrino mass generation and leptogenesis [13]. An important question in this context is whether the LNV in N_i-decays can be observed. This is hampered by two main obstacles, both of which can be overcome, I) LNV can be detected most directly when the final state of a process can be fully reconstructed, such as $W^\pm \to \ell^\pm_\alpha N \to \ell^\pm_\alpha \ell^\pm_\alpha W^\mp_*$. However, at lepton colliders N_i with $M_i < m_Z$ are dominantly produced in the decays of Z-bosons along with an unobservable neutrino or antineutrino, making it

[1]In addtion to possible connections to neutrino masses, HNLs can potentially play an important role in other areas of particle physics and cosmology [6], such as leptogenesis [7] as an explanation for the observed matter-antimatter asymmetry of the observable universe [4] (including low scale scenarios [8] that can be tested [3]), or as Dark Matter candidates [9].

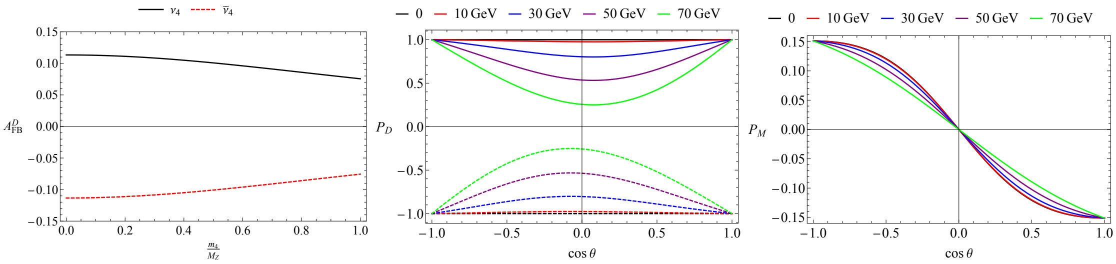

Figure 2: *Left panel:* Forward-backward asymmetry as a function of M/m_Z. *Middle, right panel:* Polarisations of Dirac (P_D) and Majorana (P_M) HNLs as a function of the HNL-electron angle. From [15].

impossible to reconstruct the final state and determine its total L. II) In models that employ the type-I seesaw mechanism [5], the light neutrino masses parametrically scale as $m_i \sim \theta^2 M_i$ while the HNL production cross section scales as $\sigma_N \sim \theta^2$, cf. (2), so that one may expect σ_N to be parametrically suppressed by $\sim m_i/M_i$. This is not the case if the m_i are protected by an approximate global $U(1)_{B-\bar{L}}$ symmetry, with $\bar{L}$ a generalised lepton-number under which the HNLs are charged [14]. The symmetry would lead to systematic cancellations in the neutrino mass matrix that keep the m_i small while allowing for (almost) arbitrarily large $U^2_{\alpha i} = |\theta_{\alpha i}|^2$. The approximate $\bar{L}$-conservation would, however, also suppress all LNV processes parametrically. One may expect that the ratio of L-violating to L-conserving N_i-decays scales as $R_{ll} \sim U_i^{-2} m_i/M_i$ with $U_i^2 = \sum_\alpha U^2_{\alpha i}$ and is practically unobservable even if the N_i are fundamentally Majorana particles.

Observables sensitive to LNV Collider studies are often performed in a *phenomenological type I seesaw model*, defined by (1) with only one HNL species ($n = 1$) of mass M. This is not a realistic model of neutrino mass, but it can effectively capture many phenomenological aspects with only five parameters $(M, \theta_e, \theta_\mu, \theta_\tau, R_{ll})$, where $R_{ll} = 0$ for Dirac-N and $R_{ll} = 1$ for Majorana-N. If all HNLs decay inside the detector the total number of events with $n = 1$ is the same for the Dirac and Majorana cases, but there are at least three ways in which Dirac and Majorana HNLs can be distinguished at FCC-ee. 1) In the Dirac case a N ($\bar{N}$) is always produced along with a $\bar{\nu}$ (ν). The chiral nature of the weak interaction and angular momentum conservation imply that ν and $\bar{\nu}$ are emitted with different angular distributions for a given Z-polarisation. Due to the parity-violation of the weak SM interaction the Z-bosons at lepton colliders are polarised at the level of $P_Z \simeq 15\%$ even if the $e^\pm$ beams are not, hence the angular distributions of the N and $\bar{N}$ are different [15]. Since Dirac N ($\bar{N}$) can only decay into leptons (antileptons), this introduces differences in the angular distribution of leptons and antileptons. This can be observed in the form of a forward-backward asymmetry $\simeq P_Z \frac{3}{4}/(1 - (M/m_Z)^2/2) \sim 10\%$, cf. Fig. 2. For Majorana HNLs there is no forward-backward asymmetry because they can decay into leptons and antileptons. 2) For the Dirac case, the N and $\bar{N}$ individually are highly polarised because N ($\bar{N}$) can only have been produced along with $\bar{\nu}$ (ν), whose helicity is fixed in the massless limit. Since N can only decay into leptonic final states ($\bar{N}$ into antileptonic ones), the parent particle of leptons and antileptons tend to have opposite polarisation. The decay rates are polarisation-dependent [2], leading to different spectra for leptons and antileptons [15]. For Majorana HNL there is no difference between N and $\bar{N}$; their polarisaion is of order (and proportional to) P_Z, and they can decay into either leptons and antileptons. This difference in the lepton spectra is observable. 3) For long-lived HNLs counting the number of

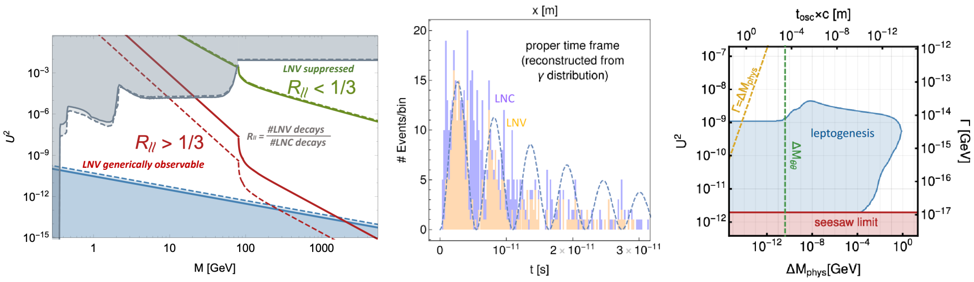

Figure 3: Left to right: Parameter region where R_{ll} is suppressed or not [18], reconstructed HNL oscillation time at LHCb [21] (will be easier at FCC-ee because of the smaller boost), compared to the oscillation time expected from leptogenesis [13].

events as a function of displacement provides an additional probe that is independent of P_Z. While the number $N_{\text{HNL}\alpha}$ of HNLs produced in Z-decays along with a lepton or antilepton of flavour α is the same for Dirac and Majorana HNLs, their decay rate Γ_N differs by a factor two, leading to a twice larger decay length in the detector $\lambda_N = \beta\gamma/\Gamma_N$, with $\beta\gamma = \mathrm{p}_N/M$ and p_N the HNL three-momentum. Hence, the number of decays into lepton flavour β with a displacement between l_0 and l_1 is sensitive to c_{dec}. It is given by (with $0 \le \epsilon_{\alpha\beta} \le 1$ an overall efficiency factor)

$$N_{\text{obs}} \simeq \mathrm{u}_\beta^2 N_{\text{HNL}\alpha} \left[\exp(-l_0/\lambda_N) - \exp(-l_1/\lambda_N)\right] \epsilon_{\alpha\beta} \tag{2}$$

Here $\mathrm{u}_\alpha^2 = U_\alpha^2/U^2$ and $N_{\text{HNL}\alpha} \simeq 2\mathrm{u}_\alpha^2 U^2 \mathrm{c}_{\text{prod}} N_Z N_{\text{IP}} \mathrm{B}_\alpha \Pi$ [16, 17] where $\mathrm{B}_\alpha = \mathrm{BR}(Z \to \nu_\alpha \bar{\nu}_\alpha) = \frac{1}{5}\frac{1}{3}$, $\Pi = (2\mathrm{p}_N/m_Z)^2 \left(1 + (M/m_Z)^2/2\right)$, $\mathrm{p}_N = \frac{m_Z}{2}\left(1 - (M/m_Z)^2\right)$, N_{IP} and N_Z the number of interaction points and number of Z-bosons produced at each of them, and c_{prod} a numerical coefficient that is the same for Dirac or Majorana HNL ($\mathrm{c}_{\text{prod}} = 1$) if $n = 1$. The decay rate is $\Gamma_N \simeq a\mathrm{c}_{\text{dec}} U^2 M^5 G_F^2/(96\pi^3)$ with $a \simeq 12$ for $M < m_Z$ [16], with and $\mathrm{c}_{\text{dec}} = 1$ ($\mathrm{c}_{\text{dec}} = 1/2$) for Majorana (Dirac), and $\lambda_N \simeq 1.6/(U^2\mathrm{c}_{\text{dec}}) \times (M/\text{GeV})^{-6}(1 - (M/m_Z)^2)$cm.

Probing realistic neutrino mass models and leptogenesis Realistic neutrino mass models typically require more than one HNL flavour. In the type-I seesaw n must equal or exceed the number of non-zero m_i. In technically natural low-scale realisations that can be probed at colliders the m_i are protected by a symmetry, cf issue II). If the symmetry is exact, the HNLs have to be organised in pairs with $M_i = M_j$ and $\theta_{\alpha i} = i\theta_{\alpha j}$ that form Dirac spinors [22] with distinctively different N and $\bar{N}$; this would imply $m_i = 0$ and $R_{ll} = 0$. Naively one would expect that the tiny symmetry breaking due to the $m_i \neq 0$ can only lead to an unobservably small R_{ll}, cf. issue II). However, even a small splitting ΔM between the physical HNL masses induced by the symmetry breaking can give rise to $\bar{L}$-violating oscillations between the N-like and $\bar{N}$-like states inside the detector (cf. [20, 23] and references therein). If the HNL decay length λ_N exceeds the oscillation length, LNV processes are unsuppressed. Since $\Delta M \ll M_i$ for the approximate symmetry to protect the m_i, ΔM may be smaller than the experimental mass resolution δM_{exp}, resulting in a single resonance that is effectively characterised by a non-integer $R_{ll} = \Delta M^2/(2\Gamma_N^2 + \Delta M^2)$ [19]. Figure 3 shows what values of R_{ll} one can expect as a function of M and U^2 [18], indicating that LNV would be observable in long-lived HNL searches at lepton colliders. For $\Delta M/\Gamma_N \sim$ a few it may further be possible to resolve the HNL oscillations by observing R_{ll} as a function of the displacement [21]. In summary, the phenomology of realistic seesaw models is much richer than that of the widely-used phenomenological model (1) with $n = 1$. Many aspects can effectively still be captured in this model by adjusting R_{ll}, $\mathrm{c}_{\mathrm{dec}}$, $\mathrm{c}_{\mathrm{prod}}$ to non-integer values, and if one considers R_{ll} as a function of the displacement.[2] The extreme cases $R_{ll} = 1$ and $R_{ll} = 0$ are realised in the lower left and upper right corner of the leftmost panel in figure 3, respectively. They represent well-defined benchmarks [24] that can easily be implemented in event generators, but it is important to keep in mind that nature is likely to be more complex.

Practical feasibility and number of events Discovering HNLs only requires a handful of events, but studying their properties with the methods 1)-3) (or others) will require reliable statistics. In displaced vertex searches the number of events can vary by many orders of magnitude across the sensitivity region. For the Z-pole run at FCC-ee or CEPC we can reliably estimate the total number of observed HNL decays inside a cylindrical detector of length l_{cyl} and diameter d_{cyl} by identifying l_0 in (2) with the smallest displacement for which the assumption of vanishing backgrounds can be justified and setting $l_1 = \frac{1}{2}(3/2)^{1/3} d_{\mathrm{cyl}}^{2/3} l_{\mathrm{cyl}}^{1/3}$ (so that a sphere of radius l_1 has the same volume as the cylinder), cf. Fig. 1. In the limit of an infinitely large detector we can estimate the maximal mixing U^2_{max} and the minimal mixing U^2_{min} for which one can see N_{obs} events by solving (2) with $l_1 \to \infty$ for U^2,

$$U^2_{\mathrm{min}} = \frac{W_0\,(XY)}{X} \simeq Y \quad , \quad U^2_{\mathrm{max}} = \frac{W_{-1}\,(XY)}{X} \simeq \frac{\log\,(-XY)}{X} \tag{3}$$

where $X = -l_0/(U^2_\beta \lambda_N) = -(a G_F^2 l_0 M^6 \mathrm{c}_{\mathrm{dec}})/(96 \mathrm{p}_N \pi^3)$ and $Y = \frac{U^2 N_{\mathrm{obs}}/\mathrm{u}^2_\beta}{\epsilon_{\alpha\beta} N_{\mathrm{HNL}\alpha}} = \frac{N_{\mathrm{obs}}/(\mathrm{u}^2_\alpha \mathrm{u}^2_\beta)}{2\epsilon_{\alpha\beta} \mathrm{B}_\alpha \mathrm{c}_{\mathrm{prod}} N_{\mathrm{IP}} \Pi N_Z}$, with W_s the s-branch of the Lambert W-function. For $U^2 > U^2_{\mathrm{max}}$ for assumption of background-freedom is not justified. For $U^2 < U^2_{\mathrm{min}}$ less than N_{obs} HNLs are produced in the first place, so even an infinitely large ideal detector could not see enough decays. Both limits strongly depend on M. The finite detector size comes into play for very long-lived HNLs, for which one can expand the exponential in (2) and find (neglecting l_0)

$$U^2_{\mathrm{min}} = \frac{2^{1/6} 3^{1/3} 8 \pi^{3/2} (\mathrm{p}_N Y)^{1/2}}{(a \mathrm{c}_{\mathrm{dec}})^{1/2} G_F M^3 d_{\mathrm{cyl}}^{1/3} l_{\mathrm{cyl}}^{1/6}} \simeq \sqrt{\frac{N_{\mathrm{obs}}}{\mathrm{u}^2_\alpha \mathrm{u}^2_\beta}} \frac{57}{G_F M^3} \sqrt{\mathrm{p}_N} d_{\mathrm{cyl}}^{-1/3} l_{\mathrm{cyl}}^{-1/6} \left(\epsilon_{\alpha\beta} N_Z N_{\mathrm{IP}} \mathrm{c}_{\mathrm{dec}} \mathrm{c}_{\mathrm{prod}} \Pi\right)^{-1/2} \tag{4}$$

The dependence of (4) on l_{cyl} and d_{cyl} quantifies the sensitivity gain with additional detectors [25]. The smallest mixing that can be probed is given by the maximum of U^2_{min} in (3) and and (4); one can estimate the point where they cross at $M \simeq 2.75 \left(Y G_F^2 \mathrm{c}_{\mathrm{dec}} d_{\mathrm{cyl}}^{2/3} l_{\mathrm{cyl}}^{1/3}/\mathrm{p}_N\right)^{-1/6}$ Since $N_{\mathrm{HNL}\alpha} \propto U^2$ one can potentially see over a million events at FCC-ee or CEPC, cf. Fig. 1. This does not only make the methods 1)-3) to search for LNV feasible, but also allows for further measurements of the HNL properties, including measurements of R_{ll} and of the u^2_α. The sensitivity gain that can

[2] Limiting cases for $n = 2$ with $\theta_{\alpha i} = i\theta_{\alpha j}$ can effectively be captured by (2), (3), (4) with the following replacements:

mass spectrum	$\mathrm{c}_{\mathrm{prod}}$	$\mathrm{c}_{\mathrm{dec}}$	R_{ll}	appearance
$\Delta M > \delta M_{\mathrm{exp}} \gg \Gamma_N$	1	1	1	two Majorana HNLs with mixing U^2 each
$\delta M_{\mathrm{exp}} > \Delta M \gg \Gamma_N$	2	1	1	one HNL, mixing $2U^2$, lifetime as Dirac, R_{ll} as Majorana
$\delta M_{\mathrm{exp}} > \Gamma_N \gg \Delta M$	2	1	0	one Dirac HNL with mixing $2U^2$

be achieved with additional detectors [25] can be estimated with (4). This shows the potential of lepton collider to test neutrino mass models and leptogenesis [13].

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