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Exploring the νSMEFT with Missing Energy and Displaced Vertex Signatures at FCC-ee

Patrick D. Bolton,[a,*] **Frank F. Deppisch,**[b] **Suchita Kulkarni,**[c] **Chayan Majumdar**[b] **and Wenna Pei**[b,d]

[a] *Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia*
[b] *University College London, Gower Street, London WC1E 6BT, UK*
[c] *Institute of Physics, NAWI Graz, University of Graz, Universitätsplatz 5, A-8010 Graz, Austria*
[d] *Institute of Physics, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/A, H-1117 Budapest, Hungary*

E-mail: patrick.bolton@ijs.si, f.deppisch@ucl.ac.uk, suchita.kulkarni@uni-graz.at, c.majumdar@ucl.ac.uk, wenna.pei.20@ucl.ac.uk

We study the potential of FCC-ee to probe GeV-scale heavy neutral leptons (HNLs) in Standard Model extensions using the effective field theory (EFT) approach. Focusing on νSMEFT operators at dimension $d \leq 7$, we study their impact on HNL production and decay at an e^+e^- collider. For Majorana and Dirac HNLs, sensitivities to the active-sterile mixing and EFT Wilson coefficients are evaluated for monophoton searches and displaced vertex signatures at FCC-ee. Constraints on Wilson coefficients are translated into lower bounds on the new physics scale.

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*Speaker

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1. SMEFT Extended With Right-Handed Neutrinos

In extensions of the Standard Model (SM) explaining the neutrino masses and leptonic mixing implied by the neutrino oscillation data, right-handed (RH) neutrino fields N are natural ingredients. As a number of well-motivated models include N alongside other heavy fields, phenomenological studies of RH neutrinos can benefit from the effective field theory (EFT) approach. At low energies, the impact of heavy degrees of freedom can be described by a tower of higher-dimensional operators suppressed by powers of the high scale Λ. The dimension-d operators $Q_i^{(d)}$ are constructed from the light degrees of freedom and respect any unbroken gauge symmetries. For RH neutrinos, the so-called νSMEFT is often considered; a basis of $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant operators built from SM fields and N. The effective Lagrangian for this theory can be written as

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N} i \partial\!\!\!/ N - \left[\bar{L} Y_\nu N \tilde{H} + \frac{1}{2} \bar{N}^c M N + \text{h.c.} \right] + \sum_i C_i^{(d)} Q_i^{(d)} , \tag{1}$$

where $C_i^{(d)} = 1/\Lambda^{d-4}$ are Wilson coefficients (WCs) and $N = C\bar{N}^T$, with C the charge conjugation matrix. A complete basis of independent operators in the νSMEFT, taking into account redundancies from Fierz identities, integration by parts and equations of motion, can be found in Ref. [1]. In Eq. (1), the terms in the square brackets are the renormalisable Yukawa coupling and RH neutrino Majorana mass term, respectively. After electroweak symmetry breaking, these terms induce mixing between the left-handed (active) and RH (sterile) neutrino fields as

$$\begin{pmatrix} \nu \\ N^c \end{pmatrix} = P_L \begin{pmatrix} 1 & \Theta \\ -\Theta^\dagger & 1 \end{pmatrix} \begin{pmatrix} \nu' \\ N' \end{pmatrix} ; \quad \Theta_{\alpha i} \equiv V_{\alpha N_i} = \frac{v (Y_\nu)_{\alpha i}}{\sqrt{2} M_i} , \tag{2}$$

where we have assumed that Θ is small, suppressing $O(\Theta^2)$ terms (leading to non-unitarity effects in lepton mixing), and we have taken M to be diagonal without loss of generality. The mixing in Eq. (2) receives further modifications from the higher-dimensional operators in Eq. (1) which can be absorbed in the definitions of Y_ν and M. The resulting massive states are Majorana fermions ($N' = N'^c$) and the active-sterile mixing $V_{\alpha N_i}$ couples the heavy neutral leptons (HNLs) N'_i to the SM via the charged and neutral currents. The phenomenology of Majorana HNLs with non-zero active-sterile mixing is diverse, with constraints reviewed in Refs. [2–4].

It is also interesting to consider the lepton number conserving ($\Delta L = 0$) limit of Eq. (1). To do this, it is convenient to introduce the SM gauge-singlet fermion field S and assign the lepton numbers $L(\nu) = L(N) = L(S) = +1$. For simplicity, we assume an equal number of N and S fields. In the $\Delta L = 0$ limit, the effective Lagrangian becomes

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N} i \partial\!\!\!/ N + \bar{S} i \partial\!\!\!/ S - \left[\bar{L} Y_\nu N \tilde{H} + \bar{S} M' N + \text{h.c.} \right] + \sum_i C_i^{(d)} Q_i^{(d)} , \tag{3}$$

where the sum is over $\Delta L = 0$ operators constructed from SM degrees of freedom plus N and S. Active-sterile mixing is again induced below the electroweak scale as in Eq. (2), with $N^c \to S$ and $M \to M'$, and $N = P_R N'$. The physical states are three massless Weyl fermions (ν') and massive Dirac fermions (N'). Clearly, modifications to this picture are required to generate the observed neutrino masses. For example, small $\Delta L = \pm 2$ terms can be added such as the $d = 5$ Weinberg operator or the Majorana mass $-\frac{1}{2}\mu\bar{S}S^c$. The heavy states are then expected to be pseudo-Dirac fermions, equivalent to two Majorana fermions with a small mass splitting. The phenomenology of (pseudo-)Dirac HNLs with active-sterile mixing is similar to the Majorana HNL case, except the (suppression) absence of lepton number violating ($\Delta L = \pm 2$) signatures [5–7].

2. HNL Phenomenology at FCC-ee

The proposed Future Circular e^+e^- Collider (FCC-ee) at CERN [8] will provide unprecedented sensitivity to HNLs in the GeV to a few 100 GeV mass range. Four centre of mass energies are in consideration; in order of decreasing baseline luminosity are the Z-pole ($\sqrt{s} = 91.2$ GeV), W^+W^- ($\sqrt{s} = 161$ GeV), Zh ($\sqrt{s} = 240$ GeV) and $t\bar{t}$ ($\sqrt{s} = 350/365$ GeV) runs. For non-zero active-sterile mixing, the relevant SM charged- and neutral-current interactions are

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\Big[(\bar{\nu}_e\gamma_\mu e) + V_{eN}^*(\bar{N}\gamma_\mu e)\Big]W^{+\mu} \\ -\frac{g}{c_w}g_L^\nu\sum_\alpha\left[\frac{1}{2}(\bar{\nu}_\alpha\gamma_\mu\nu_\alpha) + V_{\alpha N}(\bar{\nu}_\alpha\gamma_\mu N) + \frac{1}{2}|V_{\alpha N}|^2(\bar{N}\gamma_\mu N)\right]Z^\mu + \text{h.c.}\,, \tag{4}$$

with $g_L^\nu = \frac{1}{2}$, which enable the single ($e^+e^- \to \nu N$) and pair ($e^+e^- \to NN$) production (the latter suppressed by an additional power of $V_{\alpha N}$) of Majorana or Dirac HNLs via t-channel $W^\pm$ exchange and s-channel Z exchange. The second diagram significantly enhances the production cross section at the Z-pole. This was used by the four experiments at LEP-I to perform direct searches for HNLs; through the active-sterile mixing, the HNLs can decay (in order of decreasing branching fraction) via $N \to \ell jj$, $N \to \nu\ell\ell$, $N \to \nu jj$ and $N \to 3\nu$. The DELPHI collaboration set the most stringent limits [9] with searches for short-lived HNLs decaying to monojet and dijet final states and long-lived HNLs decaying to charged tracks in the outer detector. While short-lived HNL signatures can be improved upon at FCC-ee [10], the largest gain in sensitivity comes from displaced vertex (DV) signatures from long-lived HNLs [11–13], due to a significant reduction in the SM background.

The Z-pole electroweak precision observables (EWPOs) measured at LEP-I have also been used to indirectly constrain HNLs via non-unitary mixing effects [14]. Corrections of $\mathcal{O}(\Theta^2)$ enter the EWPO predictions depending on the input scheme used. The combined LEP fit [15], accounting for an updated Bhabha scattering cross section calculation, can be expressed as the number of light neutrinos $N_\nu = 2.9963 \pm 0.0074$ [16], corresponding to an invisible Z width of $\Gamma_{\text{inv}} = 500.7 \pm 1.5$ MeV. FCC-ee will be able to improve the precision to EWPOs at the Z-pole considerably [17]. However, the measured value of Γ_{inv} requires the Z peak cross section as input, limiting the sensitivity by luminosity uncertainties. A higher precision is expected from the radiative return process $e^+e^- \to Z\gamma$ at higher centre of mass energies [8].

The Lagrangian in Eq. (4) is not the only way HNLs may couple to the SM. As discussed in Sec. 1, heavy degrees of freedom could be present that, when integrated out of the theory, result in effective interactions of HNLs. In particular, we are interested in the $d \leq 7$ νSMEFT operators which can be probed at FCC-ee. In Tab. 1 of Ref. [18], we display the relevant $d \leq 7$ operators arising from the addition of N and permitting lepton number violation (corresponding to the Majorana HNL scenario). In Tab. 2 of Ref. [18], we instead show the interesting operators with S and lepton number conservation enforced (Dirac HNL scenario).

In the Majorana HNL scenario (N only and $\Delta L = \pm 2$ allowed), the operators of type $\psi^2 H^2 D^2$ and $\psi^2 H^3 D^2$ generate the effective $W^\pm$ and Z interactions below the electroweak scale,

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\Big[W_N^L(\bar{\mathcal{N}}\gamma_\mu e) + W_N^R(\bar{\mathcal{N}}^c\gamma_\mu e)\Big]W^{+\mu} - \frac{g}{2c_w}Z_N^L(\bar{\mathcal{N}}\gamma_\mu\mathcal{N})Z^\mu + \text{h.c.}\,, \tag{5}$$

with $\mathcal{N} = (\nu\ N^c)^T$, while the operators of type ψ^4 and $\psi^4 H$ generate effective vector, scalar and tensor four-fermion operators,

$$\mathcal{L} \supset \frac{1}{2}C_{Ne}^{V,LX}(\bar{\mathcal{N}}\gamma_\mu\mathcal{N})(\bar{e}\gamma^\mu P_X e) + \frac{1}{2}C_{Ne}^{S,LX}(\bar{\mathcal{N}}^c\mathcal{N})(\bar{e}P_X e) + \frac{1}{2}C_{Ne}^{T,LL}(\bar{\mathcal{N}}^c\sigma_{\mu\nu}\mathcal{N})(\bar{e}\sigma^{\mu\nu}P_L e) + \text{h.c.}\,. \tag{6}$$

The interactions induced by the νSMEFT are of similar form in the Dirac HNL scenario ($N + S$ and $\Delta L = \pm 2$ forbidden) and are given explicitly in Ref. [18]. The tree-level matching relations between the νSMEFT and broken phase WCs is provided in App. A. Similar to Eq. (4), the effective HNL interactions induce the single and pair production via $e^+e^- \to \nu N/NN$. However, the pair production can now play an important role, while the HNLs decay differently with respect to the $|V_{\alpha N}| \neq 0$ scenario. The decay modes depend on both the non-zero WCs and the number and mass splittings of HNLs. If, for example, only diagonal couplings are present between HNLs (and the active-sterile mixing is negligible), they can be produced but not decay in a collider. This opens the possibility to probe the WCs via alternative signatures, such as monophoton (mono-γ) plus missing energy ($\not{E}$), i.e. $e^+e^- \to NN\gamma$. Constraints on the WCs of $d = 6$ operators from mono-γ plus missing energy $\not{E}$ at LEP has already been considered in Refs. [4, 19]. In this analysis, we consider the improvement in the sensitivity from mono-γ plus $\not{E}$ at FCC-ee, also including $d = 7$ operators. Keeping in mind that the HNLs may also decay in the EFT scenarios, we also examine the sensitivity of DV signatures, which have also been studied in Ref. [20] for $d = 6$ operators.

3. Analysis

For simplicity, we assume that there are two Majorana or Dirac HNLs N_1 and N_2 with negligible active-sterile mixing ($Y_\nu \approx 0$). We take only one diagonal (involving only N_2) or off-diagonal (N_1 and N_2) WC to be non-zero at a time. For the mono-γ plus $\not{E}$ analysis, we consider the Z-pole and Zh centre of mass energies and luminosities. In `MadGraph5_aMC@NLO`, we simulate the signal (S) $e^+e^- \to N_iN_j\gamma$ and the SM background (B) $e^+e^- \to \nu\bar{\nu}\gamma$ and apply cuts on the outgoing photon energy E_γ and angle θ_γ, informed by the event distributions, to maximise S/B. In both the Majorana and Dirac cases, these are $|\cos\theta_\gamma| < 0.4$, $|\cos\theta_\gamma| > 0.8$ ($\sqrt{s} = 91.2$ GeV) and $|\cos\theta_\gamma| < 0.95$ and $E_\gamma > 40$ GeV ($\sqrt{s} = 240$ GeV). After cuts, we find the upper bound at 90% CL on each WC as the value giving $S/\sqrt{B} > 1.28$. For the diagonal WCs, we obtain the limits shown in Fig. 7 of Ref. [18]. However, for the off-diagonal WCs, we further take into account that the HNL decays, therefore spoiling the mono-γ plus $\not{E}$ signal. The probability of the HNL decaying inside the detector is

$$\mathcal{P}_{\text{in}} = \int db\, f(\sqrt{s}, m_N, b)\left[e^{-L_1/b\tau_N} - e^{-L_2/b\tau_N}\right], \tag{7}$$

where $b \equiv \beta\gamma$ is the boost factor of the HNL with the probability distribution $f(\sqrt{s}, m_N, b)$ and $\tau_N = 1/\Gamma_N$ is the proper lifetime of the HNL via the non-zero WC. On an event-by-event basis we

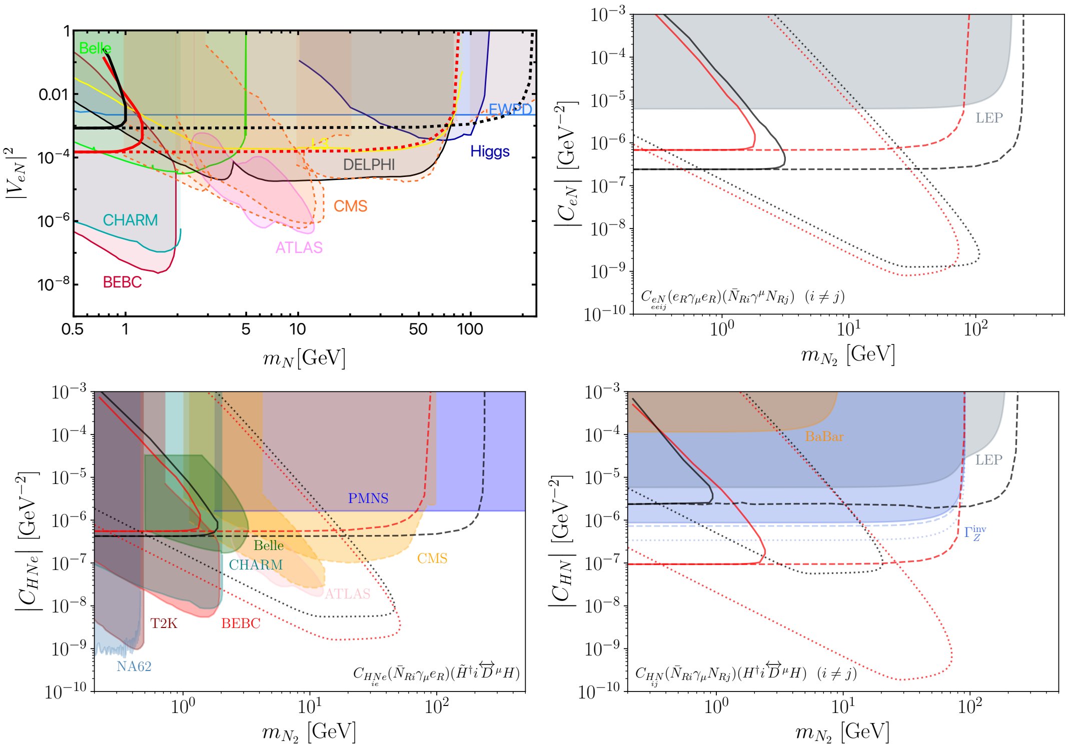

Figure 1: FCC-ee sensitivities to the active-sterile mixing V_{eN} (top left) and $d = 6$ νSMEFT operator coefficients C_{eN} (top right), C_{HNe} (bottom left) and C_{HN} (bottom right), in the Dirac HNL scenario (for a HNL pair with large mass splitting, $\delta = 1$), compared to existing constraints.

compute $\mathcal{P}_{\rm in}$ with the boost fixed to the fixed Monte Carlo value and approximate the total geometric acceptance by averaging over the total simulated data set. This is performed for three benchmark mass splittings between the HNL pair: $\delta \equiv (m_{N_2} - m_{N_1})/m_{N_2} = 0.01, 0.1$ and 1. The resulting excluded regions are shown in Figs. 8 and 9 of Ref. [18]. In Ref. [18], we also perform the mono-γ plus $\not{E}$ sensitivity analysis for the active-sterile mixing.

For the constraints from the DV signature, we consider the final state $N_2 \to \nu e^+e^-/N_1 e^+e^-$. Assuming that a cut can be placed on the electron-track transverse impact parameter [11], we assume a background-free signal. We then require that the total number of DV signal events, found as $S = \sigma \times \mathrm{BR} \times \mathcal{P}_{\rm in} \times \epsilon_k$ (where $\epsilon_k \approx 1$ is an efficiency factor from the requirement $p_T^e > 0.7$ GeV) is greater than 3. This puts a bound at 90% CL on the off-diagonal coefficients, shown in Figs. 10 and 11 of Ref. [18].

4. Results and Conclusions

The upper bounds from the mono-γ plus $\not{E}$ and DV signatures at FCC-ee on the WCs below the electroweak scale can be translated to bounds on the $d \leq 7$ νSMEFT WCs using the tree-level matching relations. These can then be converted to a lower bound on the scale of new physics Λ using $C_i^{(6)} = 1/\Lambda^2$ and $C_i^{(7)} = 1/\Lambda^3$. In Fig. 1, we show the upper bounds on the active-sterile mixing $|V_{eN}|$ and $d = 6$ νSMEFT WCs C_{eN}, C_{HNe} and C_{HN} in the Dirac HNL scenario. For the

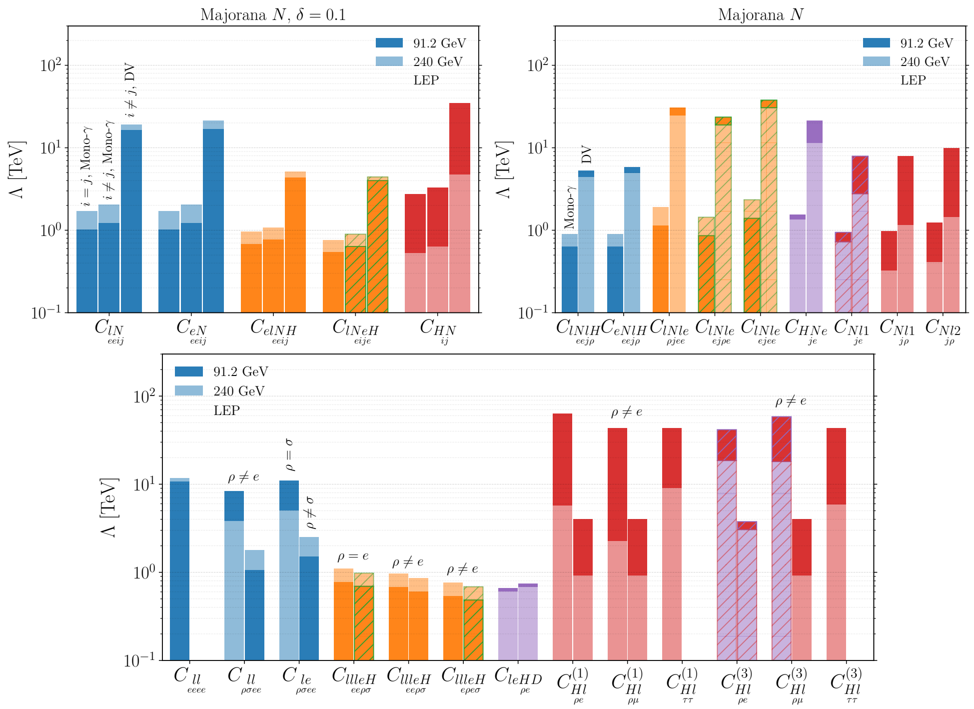

Figure 2: Scale of new physics Λ probed by the mono-γ plus $\not{E}$ and DV signatures at FCC-ee for the $d \leq 7$ νSMEFT operators in the Majorana HNL scenario.

EFT scenarios, we assume $m_{N_1} = 0$. The mono-γ plus $\not{E}$ (solid) and DV search (dotted) sensitivities are shown for $\sqrt{s} = 91.2$ GeV (red) and $\sqrt{s} = 240$ GeV (black). We compare to existing constraints on the active-sterile mixing and WCs, including bounds from the invisible Z width.

In Fig. 2, we show the values of Λ probed by the mono-γ plus $\not{E}$ and DV searches for all of the considered $d \leq 7$ operators in the Majorana HNL scenario. We also recast bounds onto the SMEFT operators contributing to the process $e^+e^- \to \nu\bar{\nu}\gamma$. In some cases, FCC-ee can probe Λ up to tens of TeV. However, we note that in some cases, more stringent bounds come from charged lepton flavour violating (cLFV) processes [21] (e.g. for off-diagonal C_{ll} and C_{le}) and neutrinoless double beta decay [22] (for the $\Delta L = \pm 2$ WCs C_{leHD} and C_{Nl1}). To conclude, this work highlights the potential of FCC-ee to probe a wide range of extensions leading to operators in the (ν)SMEFT at low energies. We have performed a detailed study of $d \leq 7$ operators that can be probed by mono-γ plus $\not{E}$ and DV signatures in different HNL scenarios. Our work complements previous studies on νSMEFT constraints at e^+e^- colliders [4, 19, 20, 23–26].

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