

Searches for Heavy Neutral Leptons at FCC-ee in final states including a muon.

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ABSTRACT: The sensitivity of the CERN FCC-ee collider to the production of heavy neutral leptons (HNL) is investigated. The study focuses on a simplified model with a single low-mass HNL mixing with a muon, and addresses the fully leptonic and semileptonic decay modes of the HNL. Complete Monte Carlo analyses of signal and background based on a parametrised detector simulation are performed for the FCC-ee run at the Z -pole, resulting in an estimate of the intervals of the mixing parameter for which the FCC-ee will have a 95% CL sensitivity as a function of the HNL mass.

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1 Introduction

The next generation of proposed e^+e^- circular colliders, such as the CERN FCC-ee [1], will provide access to a broad range of physics studies.

The production of HNLs has been identified as one of the most promising new physics channels for FCC-ee at the Z pole in a seminal paper of 2014 [2]. Several different decay channels and lifetime scenarios will be accessible at the FCC, yielding severe requirements on the performance of the detectors, which must be quantified through detailed studies taking into account realistic performance figures for the foreseen detectors. Detailed discussions of previous experimental studies targeting FCC-ee are contained in [3, 4].

The present study aims to evaluate the sensitivity for the production of HNLs to the e^+e^- future collider, at the centre of mass energy $\sqrt{s} = 91.2$ GeV and with target integrated luminosity $L_{int} = 2.0 \times 10^8 \text{ pb}^{-1}$, distributed over three energy points around the Z peak corresponding to $6 \times 10^{12} e^+e^- \rightarrow Z$ interactions. A HNL mass region ranging from 5 GeV to 85 GeV is investigated.

We study the production of HNL in Z decay through mixing with light neutrinos. The HNLs decay to a virtual or real Z or W vector boson and, respectively a light neutrino or a lepton. The vector boson decays in turn to two fermions, as shown in the diagrams of Figure 1. We concentrate on a benchmark model with a single light HNL mixing only with muons, so the model is defined in terms of two parameters: the HNL mass (M_{N_1}) and

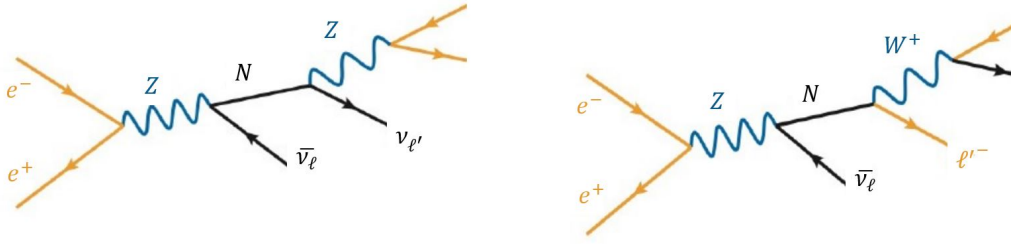


Figure 1: Diagrams for production and decay of a heavy neutral lepton in the decay of a Z boson.

the mixing parameter $U_{\mu N}$ with the active neutrino. Prompt and long-lived signatures are both possible, depending on the value of those parameters.

Two decay channels are considered:

- a fully leptonic final state $\mu^+\mu^-\nu$, which yields a very clean final state signature, and is produced both through the mediation of a charged and a neutral vector boson. The branching fraction is approximately 5% over the parameter range of interest.
- The semileptonic decay into $\mu jj'$, where j, j' are jets from $q\bar{q}'$ pairs coming from the charged vector boson coupling with HNL and the muon. This channel is the most copiously produced, with a total branching fraction of approximately 50% over the full HNL mass range of interest. Moreover, this channel, with a single neutrino in the final state, allows the complete reconstruction both of the mass of the HNL and of the energy of the recoiling neutrino from the Z decay, providing a very strong handle for the reduction of non-resonant background sources.

The present study complements and completes the results shown in the Snowmass reports [3, 4], which focused on long-lived signatures, and for which the results including consideration of experimental effects were limited to leptonic decays of the HNL. The experimental sensitivity of a future circular e^+e^- collider to the prompt HNL decay in $\mu jj'$ has been studied in a master thesis [5] and in two papers focused on the CEPC collider in China [6, 7]. We improve on the previous work by performing a full Monte Carlo study based on a parametrised simulation of the expected performance for the IDEA detector proposal [8]. Background studies rely on the centrally produced large background statistics for the FCC Physics-Experiment-Detector (PED) studies [9]. Both prompt and long-lived (LLP, long-lived particles) signatures are studied in an integrated environment, which offers the possibility of statistically combining the different channels studied.

The paper is organised as follows. We first describe the generation of signal and background followed by a description of detector simulation and event reconstruction, with special focus on the reconstruction of vertices in the inner detector and of hadronic jets. In the following two sections, the fully leptonic and semi-leptonic analyses are described separately, arriving at the definition of optimal signal regions. Based on these selections, the

covered area for each analysis in the model parameter space is assessed. Finally, the results of the different analyses are combined and compared to existing experimental limits.

2 The simulation setup

The discovery potential for Heavy Neutral Leptons with the IDEA detector [8] at FCC-ee is studied through a detailed Monte Carlo analysis. The generated events are passed through a parametrised simulation of the detector response, and physics objects for analysis are reconstructed from the output of the simulation. In the following, we provide some details on the event simulation procedure.

2.1 Model definition and signal generation

The model of interest is implemented in the `SM_HeavyN_LO` [10–12] package, and signal samples were generated with `MG5aMC@NLO` [13]. The masses of the heavy neutrinos N_2 and N_3 were set to 10 TeV, and all mixing terms were set to zero, except for the mixing $U_{\mu N}$ between the muon and the HNL (N_1) in the model. The associated production of a muon (anti)neutrino and the heavy neutrino N_1 was simulated at a centre-of-mass energy of 91.2 GeV, with the N_1 directly decayed into the final state of interest in the `MG5aMC@NLO` process card, so as to have the correct decay kinematics.

For the analysis addressing the semileptonic decay, a scan was performed on the mass of N_1 (M_{N_1}) between 5 and 85 GeV. For each mass a scan on $U_{\mu N}$ was performed in a range going from the minimal coupling yielding at least one event decaying within 2.5 meters of the centre of the detector for the full FCC-ee Z-pole statistics, to $U_{\mu N}^2 = 5 \times 10^{-4}$ which is excluded by existing experiments. A total of 10k events were generated for each sample.

For the fully leptonic case, a scan was performed over M_{N_1} between 10 and 50 GeV with a step of 5 GeV and for couplings $U_{\mu N}$ in the range from 10^{-2} to 5×10^{-6} . For each sample 2k events were generated.

The LHE files generated with `MG5aMC@NLO` were hadronised with `PYTHIA8` [14] and then fed into the `DELPHES` [15] fast simulation of the IDEA detector, based on the official data cards used for the "Winter2023" production of backgrounds [16].

For the backgrounds from Z decays, the official samples produced by the central software group for the FCC PED studies under the tag "Winter2023" were used [9]. The total available Monte Carlo statistics correspond to the production of approximately 3×10^9 $e^+e^- \rightarrow Z$ events.

The irreducible background from the four-fermion process

$$e^+e^- \rightarrow \mu\nu jj$$

was produced at LO with `MG5aMC@NLO`, including both the associated production of a real and a virtual W , and Z/γ production followed by the radiation of a virtual W off one of the decay legs of the Z . The only generation-level requirements were that leptons and jets were produced within a pseudorapidity of ± 5 and that the invariant mass of the two jets was in excess of 5 GeV. The cross-section for the process is 3.2 fb, and a sample of 500k events was

produced, corresponding to approximately the full expected statistics for the FCC-ee run at the Z pole. The events were then processed through the same `PYTHIA8-DELPHES` chain as the signal events.

2.2 The IDEA detector and its simulation

The IDEA detector concept is a proposal for a general-purpose detector for the FCC-ee. The design includes an inner detector composed of 5 Monolithic silicon pixel (MAPS) layers followed by a high-transparency and high-resolution drift chamber. Outside the inner detector is a dual-readout electromagnetic (EM) crystal calorimeter providing high-precision energy measurement of photons and electrons, followed by a superconducting solenoid producing a 2 T magnetic field. Outside the solenoid is located a dual-readout fibre calorimeter, providing, together with the EM calorimeter, high precision energy measurement of hadrons. The detector is completed by three μ -rwell layers for muon detection, embedded in the return yoke of the solenoid.

The present analysis relies on the parametrised simulation in `DELPHES` of the inner detector for the estimate of the tracking and vertexing performance of IDEA, complemented by a parametrised simulation of the calorimeter response to reconstruct hadronic jets.

The `DELPHES` simulation software relies on a full description of the geometry of the IDEA vertex detector and drift chamber and accounts for the finite detector resolution and for the multiple scattering in each tracker layer. It turns charged particles emitted within the angular acceptance of the tracker into five-parameter tracks (the helix parameters that describe the trajectory of the particle, including the transverse and longitudinal impact parameters), and determines the full covariance matrix of these parameters. Vertices are reconstructed using these tracks as input, based on a simple χ^2 minimisation with constraints, producing 3D vertices with their χ^2 and covariance matrix. More details on the vertexing code used here can be found in [17].

The calorimeter response is simulated by smearing the energy of electrons and photons based on the expected resolution of the crystal EM calorimeter, parametrised as

$$\frac{\sigma(E)}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005 \oplus \frac{0.002}{E}.$$

The response for hadrons is parametrised as

$$\frac{\sigma(E)}{E} = \frac{0.3}{\sqrt{E}} \oplus 0.01 \oplus \frac{0.05}{E},$$

which is the expected response for the dual readout fiber calorimeter.

From the tracks and energy depositions in the calorimeter, particle flow objects (PFOs) are built. Reconstructed tracks are used for charged particles. For neutrals, the PFOs are vectors with magnitude equal to the calorimetric energy measurement, and direction corresponding to the segment connecting the centre of the detector with the centre of the face of the hit calorimeter cell, smeared by the size of the cell. Hadronic jets are reconstructed giving collections of particle flow objects in input to the `FASTJET` package [18].

3 Fully leptonic muon channel with $\mu^+\mu^-\nu\bar{\nu}$ final state

The decay of the HNL into $\mu\mu\nu_\mu$ can take place through the virtual exchange of an off-shell Z or a W boson, and it has a branching fraction of $\sim 5\%$ in the considered model. It is an experimentally clean channel with only two reconstructed muons in the detector and missing energy due to escaping neutrinos. The long-lived signature, which characterizes HNL decays in a significant portion of the parameter space, can be exploited to suppress the massive Standard Model background due to the decay of Z to muons, taus and heavy flavours and to the four fermion process $e^+e^- \rightarrow \mu\mu\nu\nu$.

3.1 Event processing and reconstruction

The signal and background events are generated and reconstructed using the DELPHES fast simulation as described in Section 2. A pre-selection is applied that requires two final-state muons with momentum larger than 3 GeV and nothing else in the detector. In addition, the two muon tracks are required to be fitted to a common vertex, and a cut on the χ^2 per degree of freedom, $\chi^2/\text{ndf} < 10$, is applied to ensure a reasonable fit quality. The distance between the reconstructed vertex and the interaction point (IP) is the crucial parameter used to separate signal from background.

Figures 2 and 3 show, for two generated points, the distribution of the transverse distance between the IP and the decay vertex at generator level (D_{xy}^{truth}), before and after the pre-selection requirements (left), together with the corresponding pre-selection efficiency (right). At a large distance from the interaction point, the lower mass point, characterized by a much longer decay-length, exhibits a clear drop in the efficiency due to the acceptance of the central tracking detector. Muons without a track in the central tracking detector are not considered in the present analysis.

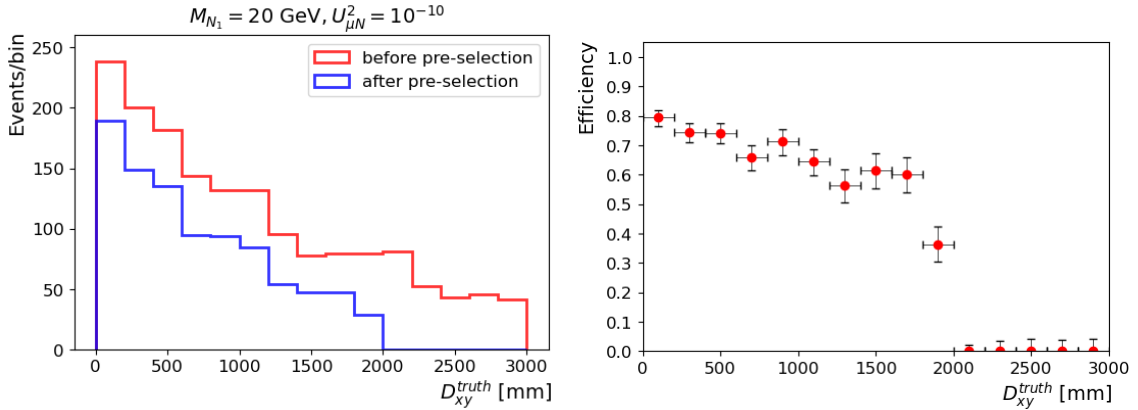


Figure 2: Distribution of the transverse distance between the IP and the decay vertex at the generator level before and after the pre-selection requirements for 2k signal events generated at $M_{N_1} = 20$ GeV and $U_{\mu N}^2 = 10^{-10}$ (left) and corresponding efficiency (right).

The cross-sections of the simulated background samples are several orders of magnitude larger than the signal in a large part of the parameter space, and the generated statistics

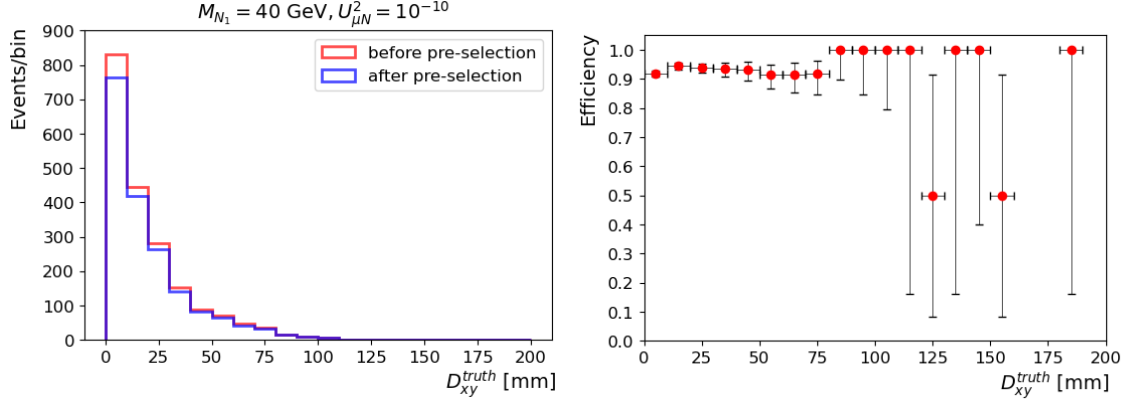


Figure 3: Distribution of the transverse distance between the IP and the decay vertex at the generator level before and after the pre-selection requirements for 2k signal events generated at $M_{N_1} = 40$ GeV and $U_{\mu N}^2 = 10^{-10}$ (left) and corresponding efficiency (right).

is not sufficient to populate the tails of the distributions which contribute to the possible background. The samples can hence only suggest reasonable selection requirements for signal to background separation taking into account the intrinsic limitations of the study.

The natural variable to consider for background rejection, taking advantage of the LLP topology of the signal, is the reconstructed transverse distance D_{xy} between the displaced vertex and the interaction point. Figure 4 shows the distributions of D_{xy} for $Z \rightarrow \mu\mu/\tau\tau$ and $Z \rightarrow bb/cc$, applying the pre-selection requirements and a further cuts $\cos(\alpha_{\mu\mu}) > -0.95$, where $\alpha_{\mu\mu}$ is the angle between the two reconstructed muon tracks at the decay vertex.

The requirement on $\cos(\alpha_{\mu\mu})$ has a negligible impact on the signal efficiency and removes back-to-back topologies that could produce relatively large D_{xy} values due to poor vertex reconstruction. While Z decays to muons produce prompt muons, Z decays to taus or heavy quarks give rise to genuinely displaced vertices, arising from leptonic tau decays, semi-leptonic heavy-quark decays, and vector meson decays. However, as clearly shown in Figure 4, the background from heavy-quark production is strongly suppressed by the exclusive requirement of two final-state muons, while the τ -induced background exhibits a tail extending up to a few millimeters.

3.2 Final selection and signal sensitivity

The strategy adopted in this study involves the variable D_{xy} to separate signal from background, following a conservative approach and assuming negligible background after the final selection requirements listed below:

- 2 tracks reconstructed as muons with momentum > 3 GeV and nothing else in the detector;
- $\cos(\alpha_{\mu\mu}) > -0.95$;
- a reconstructed vertex with $D_{xy} > 10$ mm.

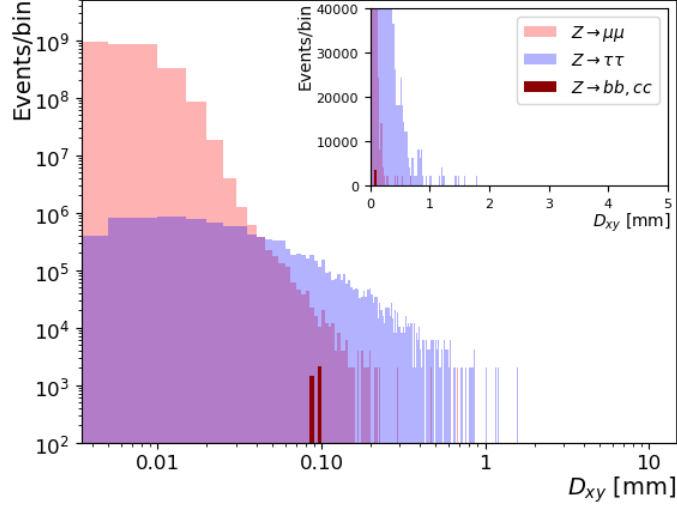


Figure 4: D_{xy} distribution for $Z \rightarrow \mu\mu$, $Z \rightarrow \tau\tau$ and $Z \rightarrow bb/cc$, applying pre-selection requirements and a cut on the angle between the two reconstructed muons to reject back-to-back topology as described in the text. The inset shows the same distribution in linear scale. The plot has been normalized to a luminosity corresponding to 6×10^{12} Z events.

An improved background simulation will allow for future optimization of the selection, leveraging additional kinematic variables and potentially relaxing the D_{xy} requirement to enhance the sensitivity in the parameter space, especially towards higher masses.

The signal efficiency for the selections described above is parameterized for each considered HNL mass as a function of $\log_{10}(c\tau)$, based on the generated grid of signal points. The results are presented in Figure 5, where the signal points in the parameter space are shown as blue dots. A very high efficiency, of order 80%, is obtained for the range of couplings for which the HNL mean decay length is comparable with the size of the inner detector. Since the adopted parametrisation has large fluctuations for low efficiency values, the efficiency is conservatively set to zero when its parametrised value falls below 10%.

The final sensitivity for the HNL signal has been estimated at 95% CL assuming no SM background survives the final selection. The number of expected signal events, N_{exp} , is normalised to the production of 6×10^{12} Z bosons. Assuming negligible background and no observed events, the 95% CL limits on the number of signal events is $N_{95} = 3$. Figure 6 shows 95% CL limit contours. The solid line represents the central limit, while the dashed lines correspond to relative shifts in signal efficiency by ± 0.05 , accounting for the uncertainty associated with the parametrization model. The threshold set at 0.1 for the signal efficiency induces a visible feature in the upper part of the exclusion curve, starting from the corner at high M_{N_1} and extending towards higher couplings.

Couplings down to $U_{\mu N}^2 \sim 10^{-10}$ for a range of N_1 masses between 20 and 35 GeV can be excluded by this analysis.

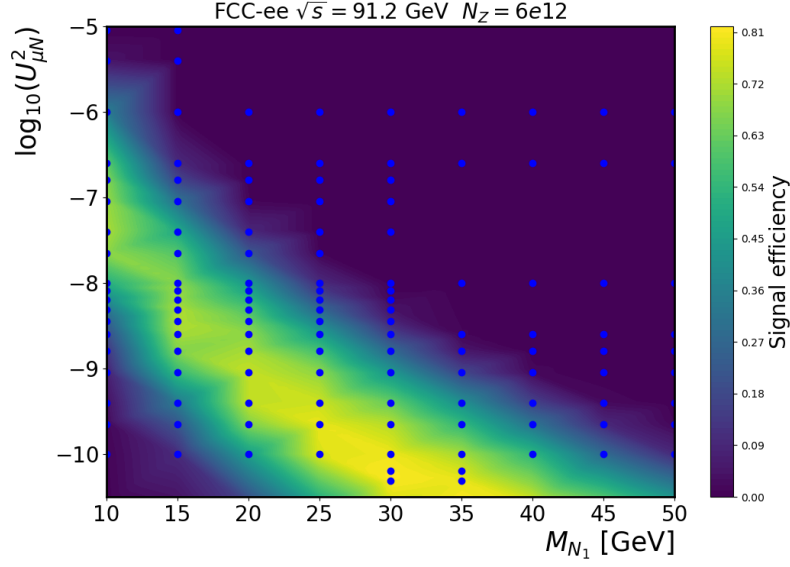


Figure 5: Signal efficiency in the considered parameter space. The generated points are shown as blue dots.

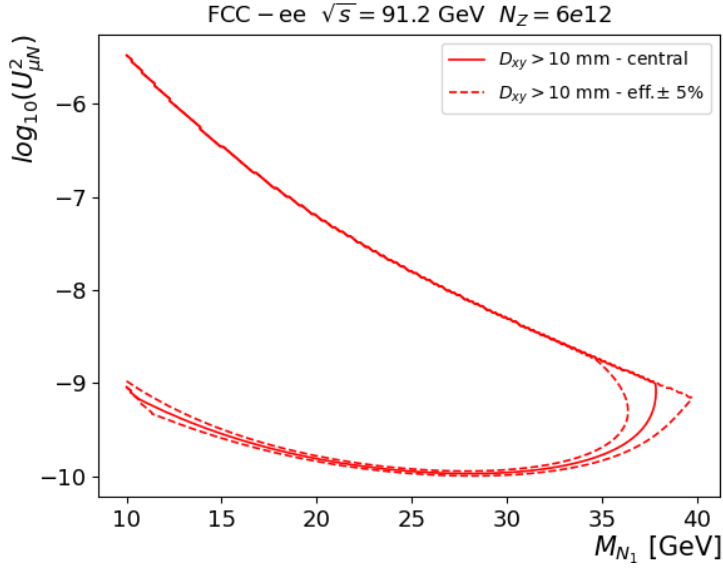


Figure 6: 95% CL exclusion limits in the parameter space. The solid line represents the central limit while the dashed lines correspond to shifts in the signal efficiency by ± 0.05 . The effect of the threshold set at 0.1 for the signal efficiency determines the behaviour of the upper part of the exclusion curve from the corner at high M_{N_1} towards higher couplings.

4 Semi-leptonic muon channel with $\mu\nu jj$ final state

The semi-leptonic decay $N_1 \rightarrow \mu jj$ proceeds through a virtual W , and has a branching fraction of $\sim 50\%$. Compared to all other HNL decays it has the advantage that it does not contain neutrinos, which allows for the full reconstruction of the decay and also of the neutrino recoiling against the HNL using the beam constraints. Due to this, it is an ideal channel for the study of prompt HNL production, which suffers from large SM backgrounds, which can be reduced with appropriate kinematic cuts. The main backgrounds originate from:

- hadronic decays of the Z boson with a non-isolated muon in the final state from the decay of a meson inside the hadronic jet;
- events where Z decays into τ pairs, which may contain a muon, jets, and a high missing momentum;
- the four-fermion process $e^+e^- \rightarrow \mu\nu qq'$ which is an irreducible background.

A long-lived analysis is also possible, exploiting the precise vertex reconstruction provided by the high track multiplicity of the jets and the high branching ratio.

4.1 Event reconstruction

The final state of interest consists of two hadronic jets and a muon, all produced at a single vertex with a distance from the undetected interaction point corresponding to the flight path of the HNL in the tracking detector. Thus, the reconstruction of the event kinematics and signal/background separation rely on the jet reconstruction and vertexing capability of the IDEA detector. The relevant reconstruction algorithms are briefly discussed below.

The jets are reconstructed through a two-step procedure. They are first reconstructed with the inclusive Durham k_T algorithm with a 5 GeV cut on the merging scale using the FASTJET package. If the algorithm returns one or two jets, these are used for the analysis, and if a larger number of jets is produced, the exclusive k_T algorithm is run requesting exactly two jets.

This algorithm yields a reasonable match between the kinematics of the reconstructed jets and the originating partons for all the HNL masses considered. This is shown in Figures 7 and 8, where the energy distributions and the angular separation of the two jets are compared to the equivalent partonic quantities for two different values of the HNL mass, 20 and 50 GeV. As expected, for low HNL masses, when the two jets are collimated, the algorithm somewhat underestimates the jet-jet separation.

The initial step of vertex reconstruction builds a vertex (vx) out of all the reconstructed tracks in the events, as described in Section 2. The next step is the identification of a good ‘primary vertex’ (vxp) defined as follows. The vertexing algorithm iteratively removes tracks with the largest contribution to the vertex χ^2/ndf up to the point when the χ^2/ndf value is stable. The vertex thus reconstructed is taken as vxp . Two useful quality parameters for the event are χ_{vxp}^2/ndf , and the difference between the total number of tracks and those attached to the primary vertex, $\Delta N_{trk} \equiv N_{trk}^{vx} - N_{trk}^{vxp}$. The two -dimensional distributions

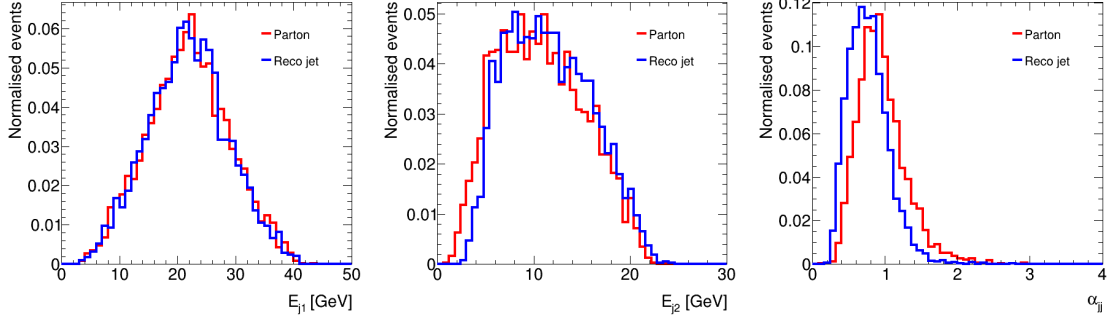


Figure 7: Energy and angular distributions of jets compared to those of the partons. Durham k_T algorithm, $M_{N_1} = 20$ GeV.

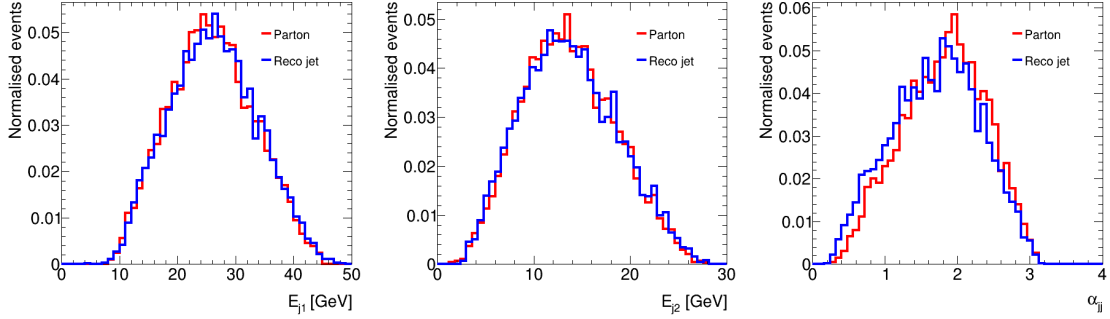


Figure 8: Energy and angular distributions of jets compared to those of the partons. Durham k_T algorithm, $M_{N_1} = 50$ GeV.

of ΔN_{trk} versus $\log_{10}(\chi_{vxp}^2/\text{ndf})$ for signal and $Z \rightarrow b\bar{b}$ events are shown in Figure 9. For the signal, there is a small population of badly reconstructed vertices at very high χ_{vxp}^2/ndf , and the good vertices have $\log_{10}(\chi_{vxp}^2/\text{ndf}) < 1$; ΔN_{trk} is much larger for $Z \rightarrow b\bar{b}$, corresponding to events where the two b -quarks have different decay paths before decaying, thus creating two or three separate vertices, if one considers the fragmentation tracks originating from the Z decay vertex. Selections on these variables, as well as on the position of the primary vertex, will be used in the following both for event cleaning purposes and for reducing the heavy-flavour background.

4.2 Preselection

The analysis starts with a filtering step, needed to bring the large background samples of Z decay down to a manageable size. The filter requirements are at least a reconstructed muon with energy greater than 3 GeV, missing energy larger than 5 GeV and at least three reconstructed tracks. The final state of interest is then selected by requiring only one reconstructed muon, at least one jet with energy in excess of 3 GeV, and vetoing reconstructed electrons. A good primary vertex inside the tracking detector is required, with $\log_{10}(\chi_{vxp}^2/\text{ndf}) < 1$, and $\Delta N_{trk} < 11$, which has approximately full efficiency for

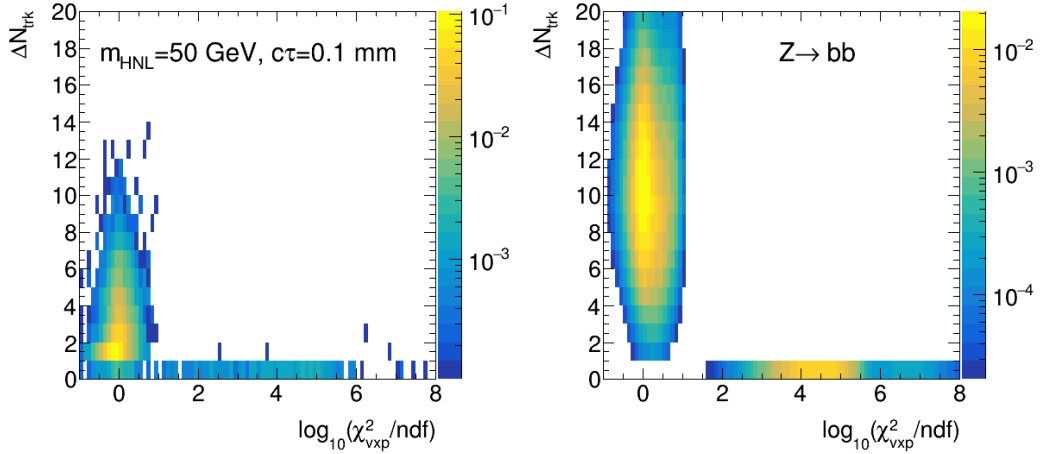


Figure 9: Correlation of the difference between the total number of reconstructed tracks in the event and the tracks attached to the primary vertex with the value of $\log_{10}(\chi^2_{vxp}/\text{ndf})$ for an example 50 GeV signal (Left) and $Z \rightarrow b\bar{b}$ (Right) after the selection cuts.

well-reconstructed signal events, as shown in Figure 9. The event is also required to be well contained in the detector, by imposing $|\cos \theta_m| < 0.98$ where θ_m is the angular distance of the missing energy vector from the beam direction. The muons in the Z backgrounds are predominantly produced alongside neutrinos in the decay of heavy quarks and taus, and are thus well aligned with the missing energy vector. An additional requirement $\cos(\alpha_{lm}) < 0.99$ is applied, where α_{lm} is the angle between the missing energy and the muon. This ensemble of requirements is called the preselection, and is applied to all events.

At this point two different analyses are developed, an analysis targeting ‘prompt’ decays of the HNL, and an analysis targeting long-lived decays. The separation of the two analyses is to some extent arbitrary. We use the variable D_{xy}^{vxp} for the separation, the radial distance of the primary vertex from the centre of the detector, and we define the separation point at $D_{xy}^{vxp} = 0.5$ mm. Two different strategies are adopted. For the prompt analysis a significant background will always be present, and a standard kinematic analysis optimising the significance of signal over background is performed. For the ‘long-lived’ analysis, after the $D_{xy}^{vxp} > 0.5$ mm cut there is a relatively small residual background, which can be fully removed by kinematic selections which retain most of the long-lived HNL signal.

4.3 Prompt analysis

The final state topology of signal events depends on the HNL mass. The angle between the two jets of the HNL decay decreases as the HNL mass decreases, as one can see by comparing the rightmost plot in Figures 7 and 8, and there is an increasing probability that the two jets are reconstructed as a single jet. Thus, for lower HNL mass the signal is more likely to display a one-jet signature, while at higher masses the two-jet signature dominates. The percentage of events with a single cluster ranges from $\sim 55\%$ for $M_{N_1} = 20$ GeV to $\sim 6\%$ for $M_{N_1} = 70$ GeV.

Two different analysis strategies are implemented for the 1-jet and the 2-jet cases, chosen to have a higher signal yield at low (high) M_{N_1} respectively.

The selection strategy is determined by the nature of the dominant Z decay background in the different HNL mass ranges. This can be seen in the left panel of Figure 10, where the distribution of the visible invariant mass M_{vis} built with the jet(s) and the muon is shown for three signal examples and for the stacked backgrounds after preselection. Both 1-jet and 2-jet events enter the distributions. The irreducible 4-fermion background is approximately independent of the mass and always subdominant. For $M_{N_1} < 30$ GeV $Z \rightarrow \tau\tau$ is dominant, whereas for $M_{N_1} > 30$ GeV all the Z decay channels contribute, dominated by the decays into b and c -quarks in the higher part of the mass range.

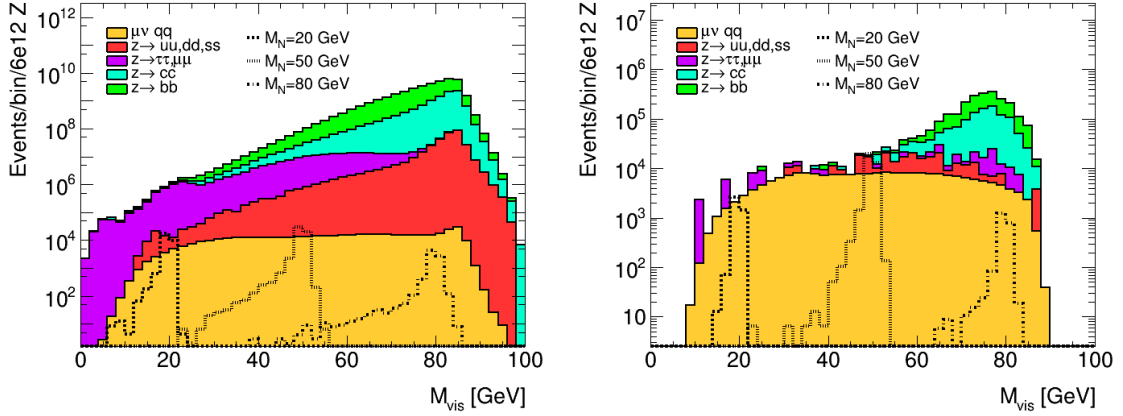


Figure 10: Distribution of the reconstructed visible mass for the backgrounds and three signal samples. Plot on the left: after preselection. Plot on the right: after kinematic selections as defined in Table 1. The events are normalised to the FCC-ee Z -pole run statistics.

For the Z decay into quarks the dominant topology includes two approximately back-to-back jets with a muon very near one of the jets, and the missing energy aligned with the lepton. The discriminant variables resulting from this observation are the cosines of the angular distances between the muon and each of the two jets, $\alpha_{j_1 l}$ and $\alpha_{j_2 l}$, shown in the upper row of Figure 11, and of the angle α_{lm} between the lepton and the missing momentum, shown in the lower left panel. For the two-jet case, the angular difference between jets, α_{jj} , is also a good discriminant, as shown in the lower right panel of the figure.

The presence in the event of two quarks with a long lifetime can be exploited by applying selections on ΔN_{trk} defined in the previous section, and on the transverse impact parameter of the muon with respect to the centre of the detector $D_{0,\mu}$. For the higher range of masses considered, ≥ 70 GeV, the requirement that $D_{0,\mu}$ be smaller than 8 times its resolution is fully efficient for signal and provides additional rejection of heavy flavour backgrounds.

For $Z \rightarrow \tau\tau$ the dominant topology is the case where on one leg the τ decays into a

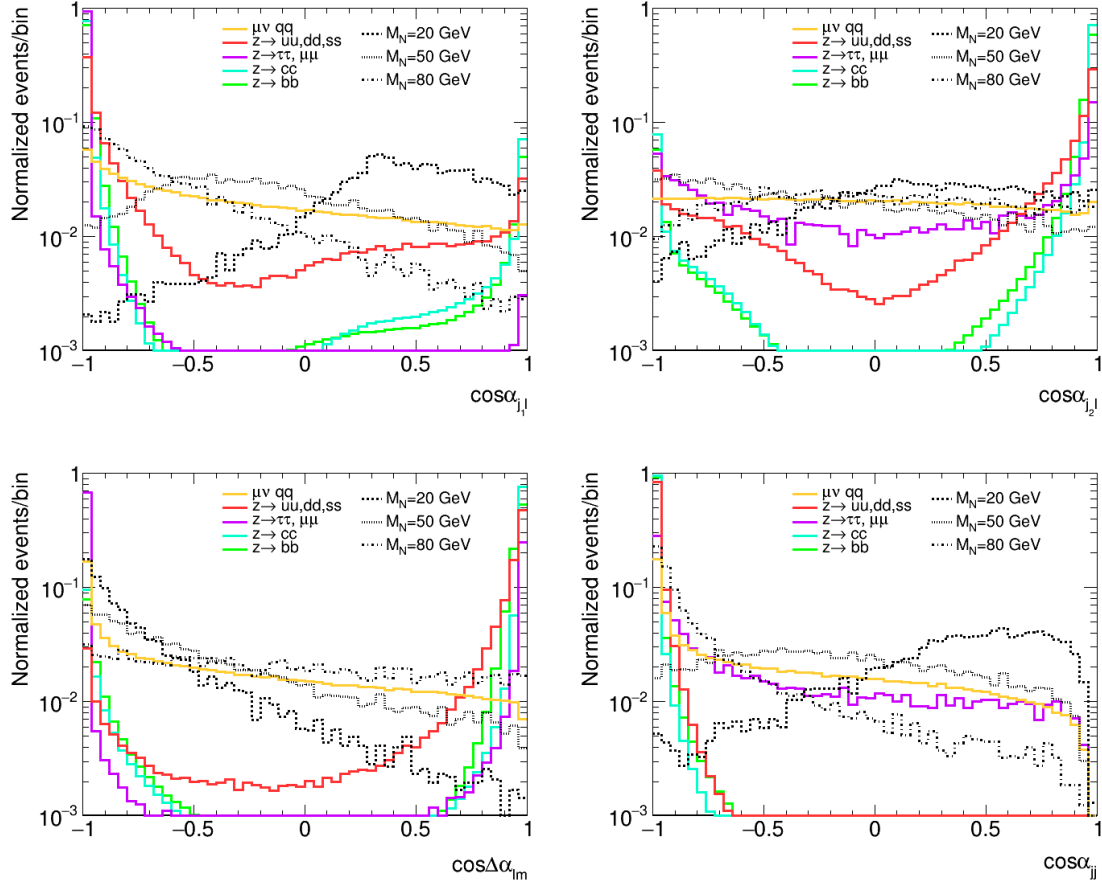


Figure 11: Normalized distributions of the angular discriminant variables discussed in the text for the backgrounds and three signal samples. The distributions are after preselection and for the prompt analysis. For the left column no selection is applied on the number of jets, the plots in the right column are for events with two reconstructed jets.

hadronic jet and neutrino, and on the other leg it decays into a muon and two neutrinos. The preferred topology would be a lepton back-to-back to a single jet, and a cut on the angle between them, α_{jl} , would strongly reduce this background. The signal has a single neutrino in the final state, and the invariant mass built from the visible particles and the missing energy (M_{tot}) is peaked at the Z mass. For the $Z \rightarrow \tau\tau$ with at least two neutrinos in the final state, M_{tot} has a large tail towards lower masses. This is also true for part of the heavy flavour decays, as shown in Figure 12.

Based on these considerations, selection criteria based on the variables described above were applied to the events, where the cuts were optimised to achieve the best significance for the two topologies considered. The values of the selections are given in detail in Table 1.

The incremental efficiencies for the signal, and the number of predicted background events surviving the different analysis stages are shown in Tables 2 and 3 respectively.

Preselection				
Filter	$N_\mu > 0, N_{tracks} \geq 3, E_m > 5 \text{ GeV}$			
Final state	$N_\mu = 1, N_{ele} = 0, N_{jets} > 0$			
Vertexing	$D_{xy}^{vxp} < 2 \text{ m}, z_{vxp} < 2 \text{ m}, \log_{10}(\chi_{vxp}^2/\text{ndf}) < 1, \Delta N_{trk} < 11$			
Kinematics	$ \cos \theta_m < 0.98, \cos \alpha_{lm} < 0.99$			
Kinematic selections				
Variable	Prompt		LLP	
$D_{xy}^{vxp} \text{ [mm]}$	< 0.5		> 0.5	
N_{jets}	1	2	> 0	
$M_{N_1} \text{ [GeV]}$	-		≤ 30	> 30
$M_{tot} \text{ [GeV]}$	> 85		> 85	
$ \cos \theta_m $	< 0.95		< 0.98	
$\cos \alpha_{jj}$	-	> -0.8	-	$> -0.98 \text{ (2j)}$
$\cos \alpha_{lm}$	< 0.5	< 0.8	-	< 0.9
$\cos \alpha_{j_1 l}$	$\in [-0.5, 0.96]$	$\in [-0.8, 0.98]$	> -0.5	$\in [-0.99, 0.99]$
$\cos \alpha_{j_2 l}$	-	$\in [-0.8, 0.98]$	-	$\in [-0.99, 0.99] \text{ (2j)}$
ΔN_{trk}	< 5		-	< 5
$D_{0,\mu}$	$> 8\sigma \text{ (} M_{N_1} > 70 \text{ GeV)}$		-	
Mass selection				
$E_{miss} \text{ [GeV]}$	$\in E_\nu \pm 2 \times 10\% \sqrt{E_\nu}$		> 38	> 20
$M_{vis} \text{ [GeV]}$	$\in M_{N_1} \pm 2 \times 10\% \sqrt{M_{N_1}}$		< 35	-

Table 1: Selection criteria for the different branches of the $HNL \rightarrow \mu jj$ analysis

Signal efficiencies					
M_{N_1} [GeV]	Filter	Preselection	Kinematic selection	Mass selection	Total
10	0.77	0.62	0.57	0.92	0.25
20	0.88	0.77	0.57	0.87	0.33
30	0.94	0.84	0.65	0.89	0.45
40	0.96	0.88	0.67	0.89	0.50
50	0.97	0.89	0.63	0.87	0.47
60	0.97	0.90	0.55	0.87	0.42
65	0.97	0.91	0.50	0.85	0.38
70	0.97	0.91	0.45	0.85	0.34
80	0.91	0.90	0.28	0.81	0.18
85	0.40	0.91	0.09	0.75	0.03

Table 2: Incremental efficiencies of the different stages of the event selection as a function of M_{N_1} for prompt signal.

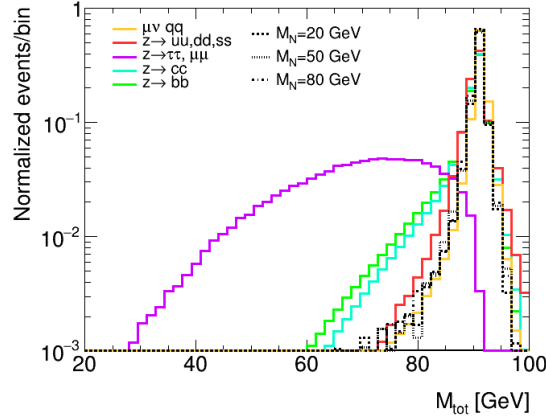


Figure 12: Normalized distribution of the total reconstructed mass of the event for the backgrounds and three signal samples. The distribution are after preselection and for the prompt analysis.

Sample	Produced	Preselection $D_{xy}^{vxp} < 0.5 \text{ mm}$	Selection $D_{xy}^{vxp} < 0.5 \text{ mm}$
$Z \rightarrow b\bar{b}$	9.36e+11	2.98e+10	5.57e+05
$Z \rightarrow c\bar{c}$	6.96e+11	1.08e+10	4.76e+05
$Z \rightarrow s\bar{s}$	9.36e+11	1.43e+08	7.68e+04
$Z \rightarrow u\bar{u}, d\bar{d}$	1.60e+12	2.32e+08	2.29e+04
$Z \rightarrow \mu^+\mu^-$	2.20e+11	1.21e+06	6.59e+03
$Z \rightarrow \tau^+\tau^-$	2.20e+11	1.38e+08	4.46e+05
$\mu\nu qq'$	6.56e+05	4.91e+05	2.21e+05

Table 3: Background events passing each stage of the selection normalised to the expected statistics of the FCC-ee Z -pole run

After these cuts a significant amount of backgrounds is still present, especially at high HNL masses, as shown in the right panel of Figure 10. Additional rejection can be achieved by considering a grid of test values for M_{N_1} . For each HNL test mass M_{N_1} , the M_{vis} variable has a peak around M_{N_1} , as shown in Figure 10. Similarly for a given value of M_{N_1} and e^+e^- collisions at the Z -pole the energy of the neutrino recoiling against the HNL, $E_\nu(M_{N_1})$, has a fixed value of:

$$E_\nu(M_{N_1}) = \frac{M_Z^2 - M_{N_1}^2}{2 M_Z}. \quad (4.1)$$

The correlation between the two variables for the background is shown in the left panel of Figure 13.

The resolution on M_{vis} obtained with the DELPHES simulation is shown in the right panel of Figure 13 for a signal with $M_{N_1} = 50 \text{ GeV}$. The distribution is not gaussian, as the jets are reconstructed in DELPHES with an idealised version of the particle flow algorithm which does not account for uncertainties on the amount of calorimetric energy associated with a

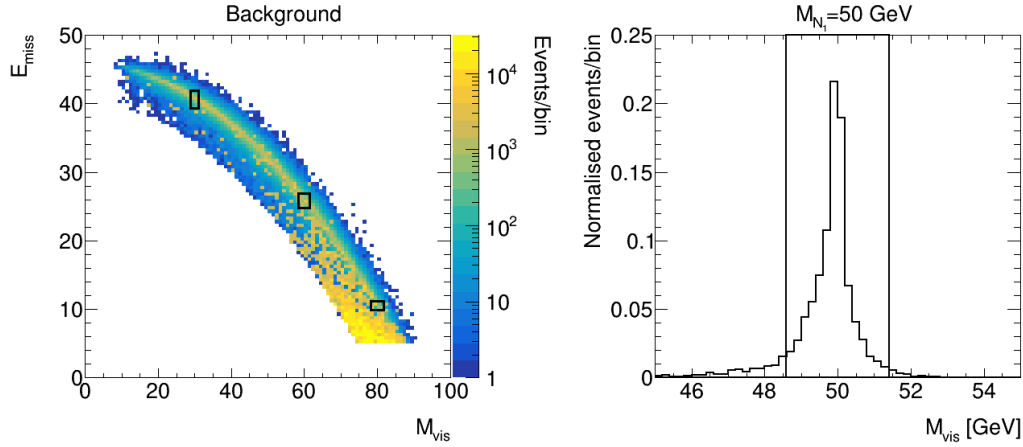


Figure 13: Left: Distribution of E_{miss} versus M_{vis} for the backgrounds after selection cuts. The black rectangles show the effect of the mass selection for three values of the HNL test mass: 30, 60 and 80 GeV. Right: Distribution of the reconstructed visible mass for a signal point at $M_{N_1} = 50$ GeV.

track. It is found that about 90% of the signal is contained within a mass window centred around the nominal visible mass with a width scaling approximately as $2 \times 10\% \times \sqrt{M/\text{GeV}}$. A window in the (M_{vis}, E_{miss}) plane defined as:

$$M_{vis} \in M_{N_1} \pm 2 \times 10\% \sqrt{M_{N_1}/\text{GeV}}$$

$$E_{miss} \in E_\nu(M_{N_1}) \pm 2 \times 10\% \sqrt{E_\nu/\text{GeV}},$$

shown in the left side of Figure 13 for three values of M_{N_1} , contains between 80 and 90% of the signal, except for the highest values of M_{N_1} , and selects only a small fraction of the background.

After mass selection, for each point in the generated signal grid the numbers of signal and background events are calculated normalised to the expected statistics of the FCC-ee Z -pole run. The statistical significance z for each point is calculated based on the prescription in [19] and is shown in Figure 14. The line corresponding to $z = 2$, the 95% CL exclusion for the signal was calculated by interpolating through the generated points, which are shown as blue dots in the plot.

4.4 Long lived analysis

As discussed above, long-lived signal regions are defined by the requirement $D_{xy}^{vxp} > 0.5$ mm. This selection removes the irreducible 4-fermion background. The signal has a significant long-lived cross-section for $M_{N_1} < 70$ GeV, a region in which $Z \rightarrow \tau\tau$ is the dominant background, and the contribution from the decay of Z into heavy quarks is strongly reduced. Therefore, as for the fully leptonic decays, we define a selection which reduces the backgrounds to zero, while maximising signal efficiency, and we define the 95% sensitivity area as the area where at least three signal events survive the selections for the expected integrated luminosity of the Z -pole run of the FCC-ee.

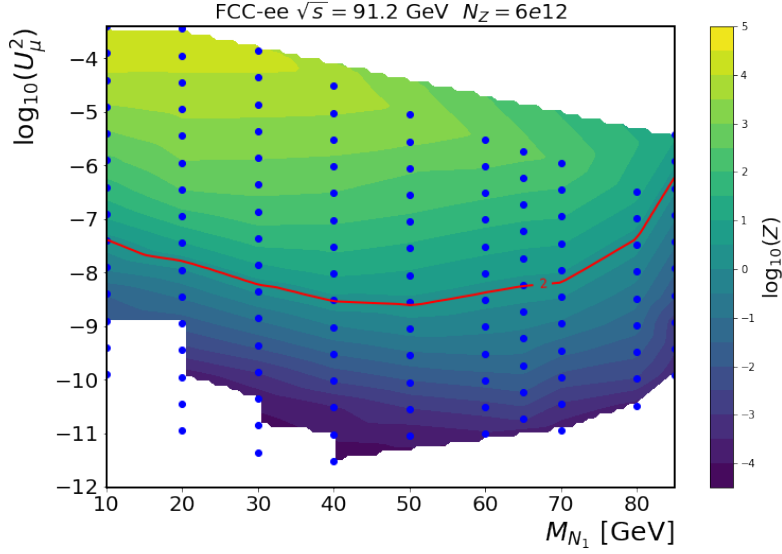


Figure 14: Map of the sensitivity z of the prompt analysis $M_{N_1} - \log_{10}(U_{\mu N}^2)$ plane. The generated points are shown as blue dots, and the line corresponding to $z = 2$ is shown in red.

A selection on $M_{tot} > 85$ GeV, ensuring that no neutrino is produced, strongly reduces $Z \rightarrow \tau\tau$. A veto on the topology where the muon and the leading jet are approximately back to back, and in the two-jet case where the jets are back to back, together with the request that $E_{miss} > 38$ GeV fully eliminate the background for values of the HNL test mass smaller than or equal to 30 GeV.

For higher HNL test masses, in the range 30-65 GeV, the additional contributions from heavy quarks demand more complex selection criteria, based on the same angular variables as for the prompt analysis. These criteria are shown in Table 1, and reduce the background to zero, while retaining high signal efficiency. The values of the selection efficiencies in the $M_{N_1} - \log_{10}(U_{\mu N}^2)$ plane are shown in Figure 15. On the left panel the total selection efficiency is displayed, incorporating both the request of a well-reconstructed vertex and the kinematic selection criteria; on the right panel we show the incremental efficiency of the kinematic selections. The latter is very high, between 75% and almost 100%, and for lower masses the experimental efficiency is completely dominated by the requirement that the decay occurs in the volume of the tracking detector and is reconstructed by the tracker.

As explained in Section 2, for the Z decay backgrounds only $\sim 3 \times 10^9$ Monte Carlo events were generated, well short of the expected statistics at the FCC-ee Z -pole run. In order to have some confidence that the zero-event condition can be reached, the number of Z decay events after selections as a function of D_{xy}^{vp} was fitted with an exponential for both signal regions defined above. It was found that for a cut $D_{xy}^{vp} > 0.1$ mm the extrapolated curve yields a prediction of less than one event in both cases, thus ensuring

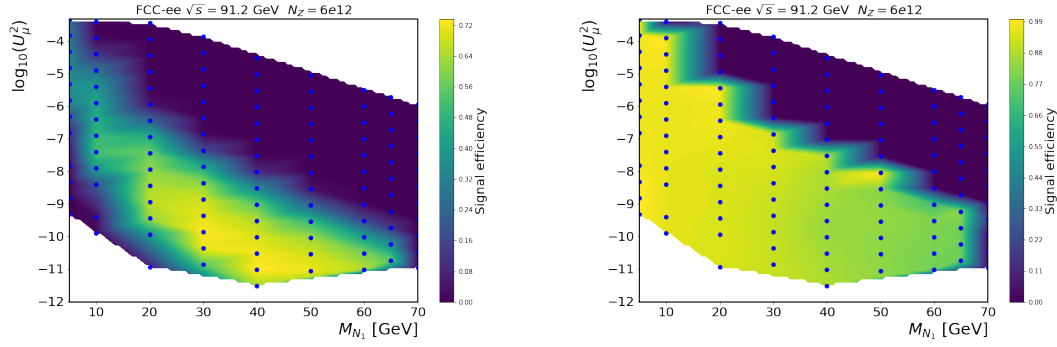


Figure 15: Efficiency of the long-lived selections in the $M_{N_1} - \log_{10}(U_{\mu N}^2)$ plane. On the left: total selection efficiency; on the right: efficiency of the kinematic cuts with respect to the events with a reconstructed vertex in the inner tracker. The generated points are shown as blue dots.

that no background from well-reconstructed events is left over. In addition, no Z Monte Carlo events would pass the selection $D_{xy}^{vxp} > 0.2$ mm, and the reach curve was calculated for $D_{xy}^{vxp} > 1, 5$ and 10 mm, in addition to the nominal $D_{xy}^{vxp} > 0.5$ mm selection, to evaluate how much tighter cuts on the HNL decay length would affect the experimental reach.

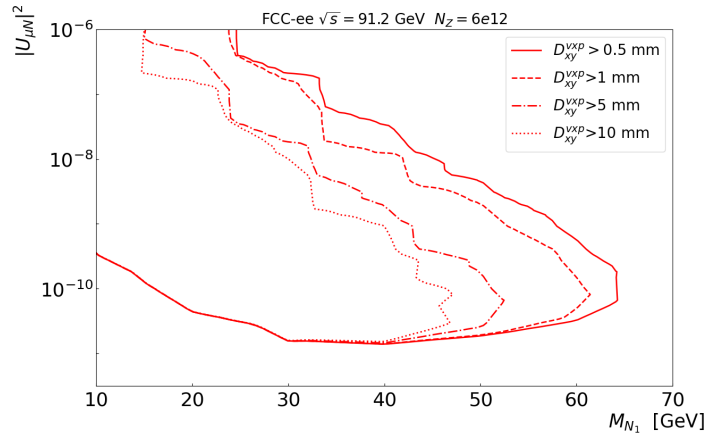


Figure 16: Curves bounding the areas where three events survive the long-lived selections in the $M_{N_1} - \log_{10}(U_{\mu N}^2)$ plane for four values of the threshold on the transverse position of the reconstructed decay vertex D_{xy}^{vxp} .

In Figure 16 we show the lines bounding the area with at least three detected events after selections in the $M_{N_1} - \log_{10}(U_{\mu N}^2)$ plane corresponding to the 95% CL experimental sensitivity. The results are given for the four different requirements on D_{xy}^{vxp} given above. The extension of the sensitivity region towards low values of $U_{\mu N}^2$ is little affected by an increase in the threshold set on D_{xy}^{vxp} . The main effect would be a reduction of the accessible

mass range towards high mass values. The loss in coverage towards higher $U_{\mu N}^2$ values would be compensated by a corresponding increase of the coverage of the prompt analysis.

5 Combined results and conclusions

We have studied the experimental reach of the FCC-ee Z -pole run to the production of an HNL in a simplified benchmark model with a single experimentally accessible HNL mixing only with muons.

Two different decay channels for the HNL were addressed, a semileptonic one into a muon and two jets, and a fully leptonic one into a $\mu^+\mu^-$ pair and a neutrino. For the first case two analyses were performed, one addressing the ‘prompt’ decay of the HNL, and one addressing long-lived HNLs decaying after a measurable flight path in the detector; for the second channel only the long-lived signature was studied. The 95% CL coverages of the analyses in the $M_{N_1} - U_{\mu N}^2$ plane were obtained based on an analysis of simulated events. It is found that the long-lived analyses, thanks to the large Z statistics allow very low values of the mixing to be reached, down to $U_{\mu N}^2 \sim 10^{-11}$ for M_{N_1} between 5 and ~ 65 GeV. The ‘prompt’ analysis has larger backgrounds, but it is useful for covering higher values of $U_{\mu N}^2$ and M_{N_1} up to 85 GeV.

The statistical combination of the two LLP channels was performed by summing the number of expected signal events after the selections described above for each of the two channels on a grid in the $M_{N_1} - U_{\mu N}^2$ plane. The 95% sensitivity region was calculated by interpolation as the area in which at least three signal events survive the selection, and is shown as a dashed dotted line in the left panel of Figure 17, whereas the semileptonic channel is shown as a full line, and the fully leptonic one as a dashed line. The combined

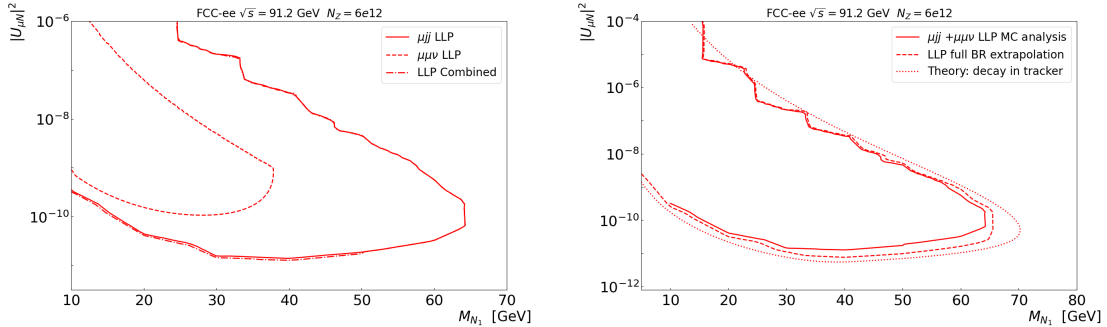


Figure 17: Sensitivity limits at 95% confidence level in the $M_{N_1} - U_{\mu N}^2$ plane for the LLP analyses described in the text and for their statistical combination. Left panel: combination of the semileptonic and leptonic LLP analyses. Right panel: comparison of the coverage of the combined LLP analyses (full line) with the extrapolation to the full visible branching fraction of the HNL (dashed line), and with the line corresponding to three events with decay in the tracker (dotted line).

analysis covers yields a gain of $\sim 10\%$ in terms of covered values of $U_{\mu N}^2$ with respect to

the semileptonic analysis alone, corresponding to the ratio of the branching fractions of the two considered channels. The present study is based on two Monte Carlo analyses that cover between 55 and 60% of the visible HNL branching fractions. Channels which were not studied are dominated by the decay of the HNL into a neutrino and two jets via a virtual Z , and fully leptonic decays with a muon, a neutrino and an electron or a tau, via a virtual W . Under the assumption that the analysis efficiency will be the same as for the channels explicitly studied, the parameter space coverage for the combined analysis of all visible HNL decay channels can be calculated. The results are shown in the right panel of Figure 17, where the combined results of the two analyses of this paper are compared to the extrapolated reach for the complete visible decay channels and to the theoretical calculation of the line corresponding to three events decaying in the IDEA inner tracker based on the formulas of [20]. With the analysis of all decay channels, mixing values as small as approximately 70% of the theoretical limit could be covered.

The results of the present study are compared with the existing experimental limits and with the expected limits for several proposed beam dump experiments in Figure 18. The theoretical curve corresponding to three HNL decaying within the volume of a detector with 4.5 m diameter and 11 m length is also shown. Thanks to the high Z statistics, these analyses could cover couplings down to $U_{\mu N}^2 \sim 10^{-11}$ for the kinematically accessible range of HNL masses.

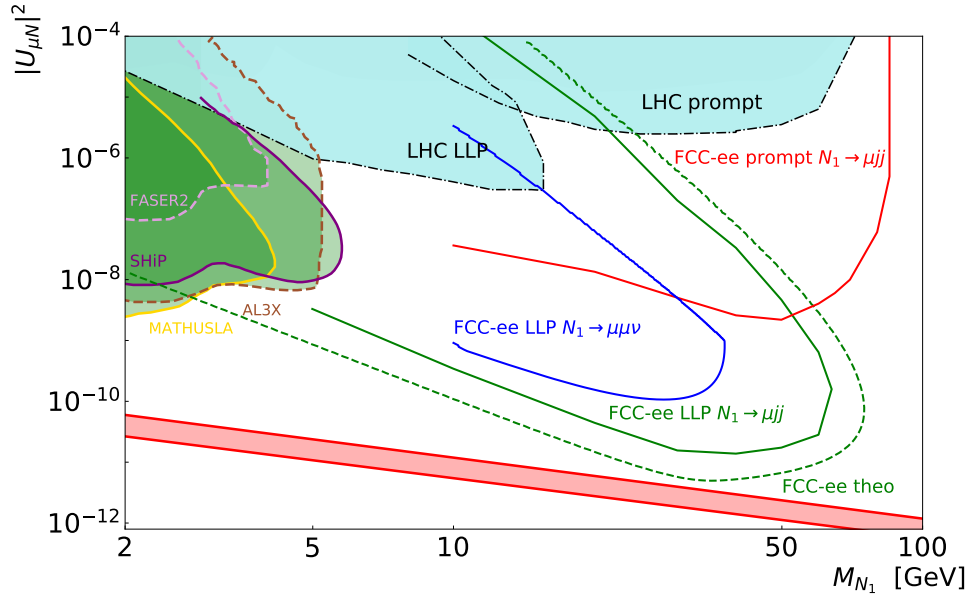


Figure 18: Discovery potential in the $M_{N_1} - U_{\mu N}^2$ plane. The FCC-ee potential shown as a red (green) line for the prompt (long-lived) semileptonic analyses described in the text. The blue line shows the reach of the leptonic decay $N_1 \rightarrow \mu^+ \mu^- \nu$. The dashed green line bounds the area where, out of 6×10^{12} Z bosons, three events with visible HNL decays inside the full IDEA detector are produced (based on the analytical formulas in [20]). The existing limits from LHC searches are given as turquoise areas. The expected discovery potential of projected experimental searches based on long baseline experiments is shown as green areas and is taken from the website accompanying [21], where all the original work is cited.

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