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FUTURE CIRCULAR COLLIDER

Updated HNL studies with winter23 samples

Sarah Williams (University of Cambridge), building on work by
Daniel Beech and John Hayward

Introduction

- A lot of the work in this group in the past year(s) builds on studies from a Snowmass LOI, an LLP white paper was recently published in Front. Phys. 10:967881 (2022) which included case studies with the official FCC analysis tools.

- These initial studies motivate further optimization of experimental conditions and analysis techniques for LLP signatures.

Searches for long-lived particles at the future FCC-ee

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In 2022-23 and 2023-24 I had 2 masters students working on HNLs trying to extend the sensitivity studies for the $ee\nu$ channel using the Winter23 samples. This summer I have tried to write up the main conclusions and am eager to discuss how we could get them published.

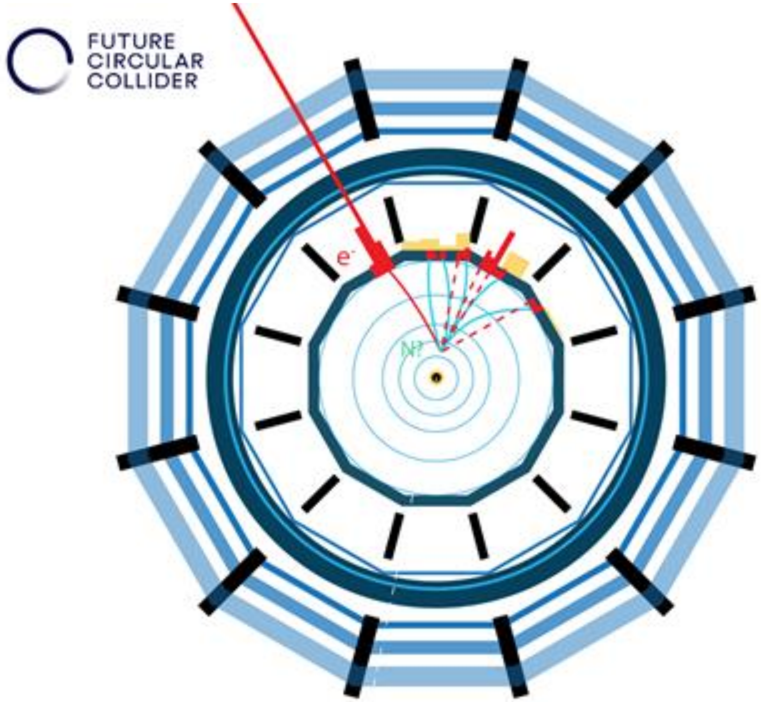
Heavy Neutral Leptons (HNL) at FCC-ee

Snowmass review: arXiv:2203.08039 Front. Phys. 10:967881 (2022)

- Right- handed (sterile) neutrinos could provide an explanation for neutrino masses, the baryon asymmetry in the universe and dark matter.

- For small mixing angles with their LH counterparts- long-lived.

- Obvious benchmark for LLP searches with displaced vertices.



$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\mathrm{dec}}} \left(\frac{M}{\mathrm{GeV}}\right)^{-6} \left(1 - (M/m_Z)^2\right) \mathrm{cm}.$$

c_{det}= 1 (majorana) or ½ (dirac)

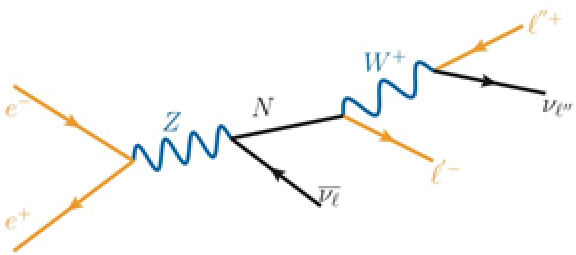
arXiv:2210.17110 i.e. LLPs when couplings and masses are small!

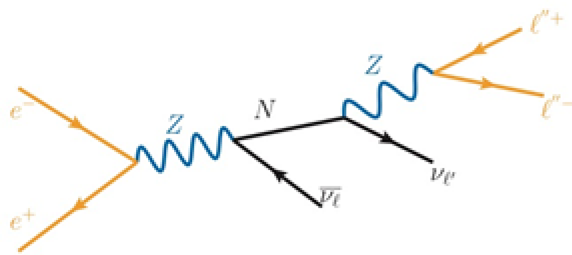
HNL searches at FCC-ee Tera-Z run

[Front. Phys. 10:967881 (2022)]

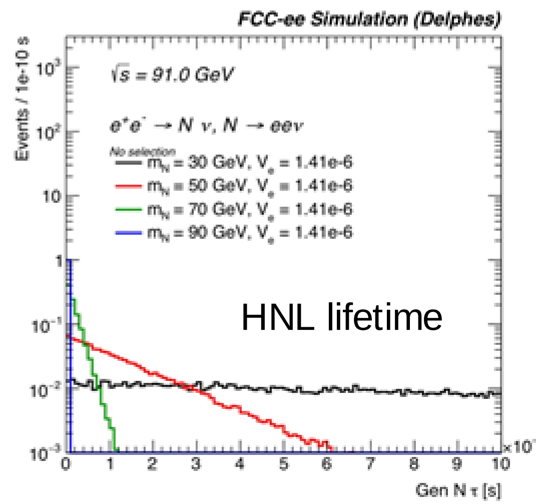
Searches for displaced HNL decays are most efficient at the Z-pole run (larger luminosity and cross-section from Z→Nν decays). Benefit from:

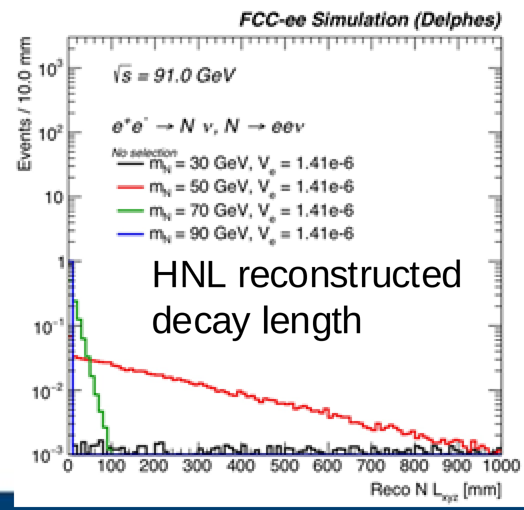
- Low SM backgrounds with displaced vertex.
- Small beam pipe radius.
- Clean experimental conditions.





For N→Wl decays, depending on the W decay final states include ll'$\nu\nu$ or lνjj





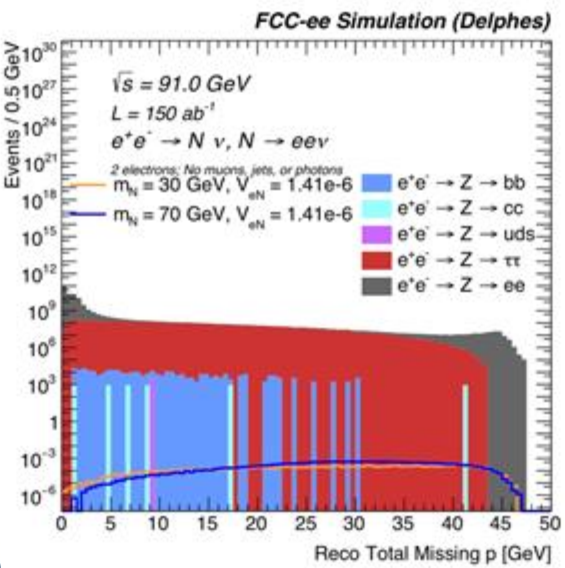
HNL sensitivity study: N→eeν

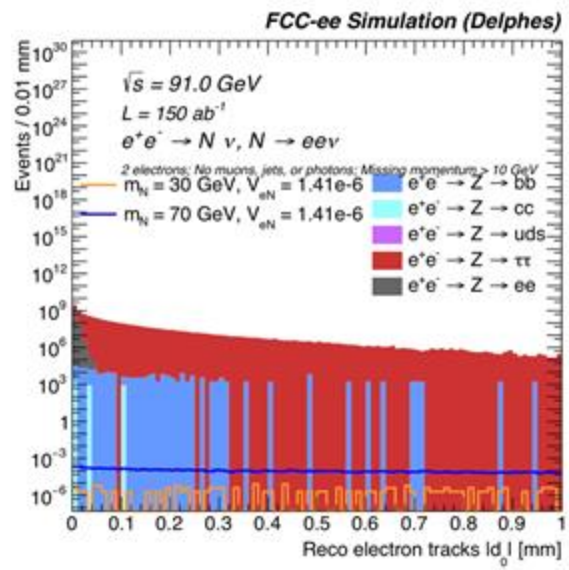
Front. Phys. 10:967881 (2022)

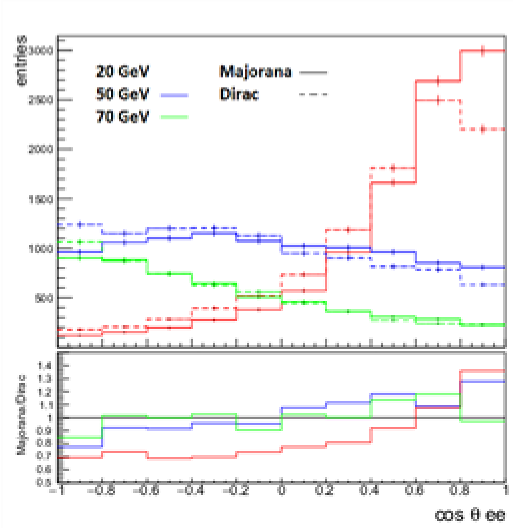
Initial study developed an event selection to reduce the backgrounds:

- 2 electrons with a veto on additional photons, jets, muons.
- p^{Miss}> 10 GeV to reduce the Z→ee background with instrumental missing momentum.
- Electron $|d_0|$>0.5 mm

Also studied angular distributions sensitive to majorana vs Dirac nature of HNLs…

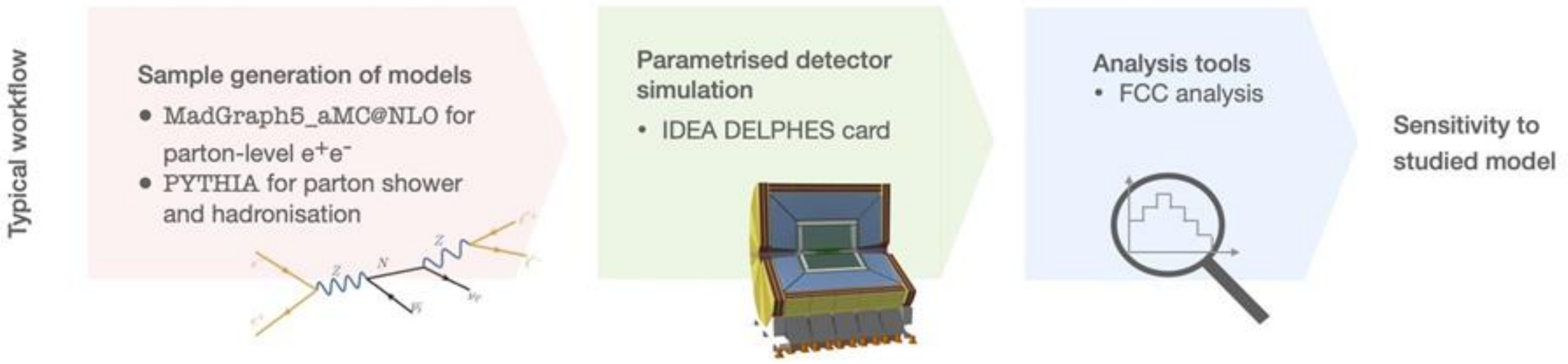






Summary of workflow

Most studies so far use Pythia+Delphes for backgrounds- would like to move to FullSim and be able to consider alternative generators.



- Use FCCAnalysis software to analyse centrally generated EDM4HEP files, though some signal files produced privately.
- Dedicated LLP tutorial prepared by Juliette Alimena enables full workflow.
- Note: when beginning this work encountered quite a few problems with 'scalability' of FCC software running over full production. These are now (as far as I know) broadly fixed but including filtering in "stage 1" speeds things up significantly.

Notes on spring21 vs winter23 studies

https://github.com/HEP-FCC/FCCeePhysicsPerformance/blob/master/General/README.md#common-event-samples

Common event samples

(Oldish) The "spring2021" Monte-Carlo samples (May 2021)

- some input on the MC production had been collected in early 2021 at this googledoc.
- Details of the spring2021 samples:
  - the production uses the EventProducer developed by C. Helsens.
  - release from 2021-04-30, uses Delphes 3.4.3pre10
  - configuration cards (delphes cards, Monte-Carlo cards): see the FCC-configs repository, branch **spring2021**.
- See here for information about the files made with IDEA
- The event files can be found in EOS /eos/experiment/fcc/ee/generation/DelphesEvents/spring2021
- a few files were produced, corresponding to IDEA with a 3T field, and to "IDEA" where the Drift Chamber was repaced by the CLD tracker

Known caveats in the "spring2021" samples:

- there is some inefficiency for electrons, due primarily to the overlap removal procedure, see Jean-Loup's talk and here
- the efficiency for very low momentum tracks is lower than what it should be, see Tristan's talk and here
- the jets that are on the EDM4Hep files, i.e. that were produced during the Delphes step, **should not be used**. See Jean-Loup's talk and here. The issue lies in the Delphes card that was used (some jets are suppressed in the overlap removal procedure). The solution is to **re-cluster the jets in FCCAnalyses, as explained below.**

=> Based on studies by John, and the example files on git- we did not perform this jet reclustering for the snowmass results- all results based on jet vetos are not reliable

Notes on spring21 vs winter23 studies

https://github.com/HEP-FCC/FCCeePhysicsPerformance/blob/master/General/README.md#common-event-samples

The "winter2023" Monte-Carlo samples (January 2023)

- release from 2022-12-23, uses Delphes 3.5.1pre05
- configuration cards (delphes cards, Monte-Carlo cards): see the FCC-configs repository, branch **winter2023**.
- Main changes compared to spring2021 - see details here
  - Updated IDEA geometry in the Delphes card:
    - smaller radius beam-pipe (R = 1 cm)
    - ECAL crystal calorimeter hence much better ECAL resolution. Note that while the crystals are a seriously considered option, this is not yet the baseline of IDEA.
  - Electrons and Muons are stored prior to any isolation requirement => (1)
  - Track uncertainties are now reliable also for very displaced tracks
  - fixed issues with electron inefficiencies and inefficiencies for low pT tracks. Overlap removal left to the user. => (2)
  - Updated machine parameters (hence beam energy spread and size of the luminous region)
  - Whizard samples now have a non-zero event vertex
  - Jets that are on the files correspond to the ee_genkt algorithm, with p = -1 (i.e. antikT like), radius = 1.5, PTmin = 1 GeV. These jets may not be suited to all analyses, and as before, the best is to **re-cluster the jets in FCCAnalyses, as explained below.** => (3)
  - Electron resolution: slightly degraded compared to muon resolution (by 20%), to account approximatively for the brems.
  - Generator cards: Particles are decayed only if the decay vertex is within a cylindrical volume, corresponding to the volume of the tracker.
  - The magnetic field is stored on the files (branch "magFieldBz")
  - For the tracks, the dNdx can be accessed in the "EFlowTrack_2" collection.
- List of samples produced is here. More samples, esp. at 91 GeV, will be produced.
- The event files can be found in EOS /eos/experiment/fcc/ee/generation/DelphesEvents/winter2023

Notes on spring21 vs winter23 studies

1. No isolation requirement in winter23 vs spring21=> likely to effect the Z=> qq samples. Have not considered further (yet) in these studies.
2. Fixed electron efficiency means we could gain signal acceptance. Can emulate overlap removal in key4hep through removing the leptons from the list of reconstructed particles considered in the jet reclustering => done.
3. Whilst jet clustering fixed, the default jet collection considers not helpful for our studies => have generally reclustered with inclusive antikt to mimic what we thought we were doing for the spring21 studies.

Overview of updated studies

- All results presented today is written up here: https://www.overleaf.com/read/pcvchdvjbsbg#fdc827 => comments/questions welcome.

- This includes:
  - Comparison of spring21 vs winter23 samples in terms of background rejection for cuts in $ee\nu$ channel.
  - Impact of placing requirements on reconstructed secondary vertices.
  - An attempt at an updated sensitivity plot (to be discussed and extended?)
  - Discussion of future work?

Statistics in spring21 vs winter23

Spring21

Process	Raw events in ref [3]	Cross-section in ref [3] [pb]	Sample luminosity [ab^{-1}]
Z→ ee	10,000,000	1,462	0.01
Z→ $\mu\mu$	10,000,000	1,462	0.01
Z→ $\tau\tau$	10,000,000	1,477	0.01
Z→ qq (q=u,d,s)	1,000,000,000	18,617	0.05
Z→ cc	1,000,000,000	5,215	0.19
Z→ bb	1,000,000,000	6,645	0.15

Winter23

Process	Raw events	Ratio to raw events in ref [3]	Cross-section [pb]
Z→ ee	100,000,000	10	1,462
Z→ $\mu\mu$	100,000,000	10	1,462
Z→ $\tau\tau$	100,000,000	10	1,477
Z→ qq (q=u,d)	497,658,654	— —	11,871
Z→ ss	499,842,440	— —	5,215
Z→ cc	499,786,495	5.00	5,215
Z→ bb	438,738,637	4.39	6,645

=> Despite improvements, we are still heavily limited by MC statistics with the winter23 samples- need to note this as a big caveat when quoting prospects for background-free searches.

Spring21 event selections

$Z \to$	Total	Exactly 2 electrons	Vetoes	$\not{p} > 10$ GeV	Electron $\lvert d_0 \rvert > 0.5$ mm	Rejection factor
ee	2.19 ± 10^{11}	1.85×10^{11} $\pm 6.19 \times 10^{7}$ (0.798)	1.53×10^{11} $\pm 5.8 \times 10^{7}$ (0.698)	7.07×10^{8} $\pm 3.94 \times 10^{6}$ (0.003)	$\leq 3.94 \times 10^{-6}$ (< 0.001)	55,659.90
$\tau\tau$	2.22×10^{11}	5.49×10^{9} $\pm 1.10 \times 10^{7}$ (0.025)	5.10×10^{9} $\pm 1.06 \times 10^{7}$ (0.023)	2.52×10^{9} $\pm 7.47 \times 10^{6}$ (0.011)	6.64×10^{4} $\pm 3.84 \times 10^{4}$ (< 0.001)	3,336,596.39
uds	2.79×10^{12}	2.30×10^{7} $\pm 2.54 \times 10^{5}$ (< 0.001)	2.79×10^{3} $\pm 2.79 \times 10^{3}$	$\lesssim 2.79 \times 10^{3}$	$\lesssim 2.79 \times 10^{3}$	1,000,913,978.49
cc	7.82×10^{11}	1.69×10^{7} $\pm 1.21 \times 10^{5}$ (< 0.001)	5.22×10^{3} $\pm 2.13 \times 10^{3}$	1.74×10^{3} $\pm 1.23 \times 10^{3}$	$\lesssim 1.23 \times 10^{3}$	635,975,609.76
bb	9.97×10^{11}	5.64×10^{8} $\pm 9.85 \times 10^{5}$ (< 0.001)	3.25×10^{5} $\pm 2.36 \times 10^{4}$	1.22×10^{5} $\pm 1.45 \times 10^{4}$	1.72×10^{3} $\pm 1.72 \times 10^{3}$	579,505,813.95
$m_N, \lvert V_{eN} \rvert$						
$10,\ 2 \times 10^{-4}$	2534	1006 ± 7 (0.397)	996 ± 7 (0.395)	951 ± 7 (0.375)	907 ± 7 (0.358)	2.79
$20,\ 9 \times 10^{-5}$	458	313 ± 2 (0.683)	308 ± 2 (0.672)	293 ± 2 (0.640)	230 ± 1 (0.502)	1.99
$20,\ 3 \times 10^{-5}$	51	34.7 ± 0.2 (0.680)	34.2 ± 0.2 (0.671)	32.6 ± 0.2 (0.639)	31.2 ± 0.2 (0.612)	1.63
$30,\ 1 \times 10^{-5}$	5.01	3.85 ± 0.02 (0.768)	3.76 ± 0.02 (0.750)	3.54 ± 0.02 (0.707)	3.39 ± 0.02 (0.677)	1.48
$50,\ 6 \times 10^{-6}$	1.23	0.99 ± 0.01 (0.805)	0.96 ± 0.01 (0.780)	0.92 ± 0.01 (0.748)	0.729 ± 0.004 (0.593)	1.69

- Significant background rejection was taken as supporting evidence that we could perform background-free searches at FCC-ee.
- Benchmark point with $m_N = 50$ GeV and $|V_{eN}| = 6 \times 10^{-6}$ which gave ~ 1 event taken as illustrative of the maximum sensitivity to HNLs that could be achieved.

Update background studies- jet reclustering

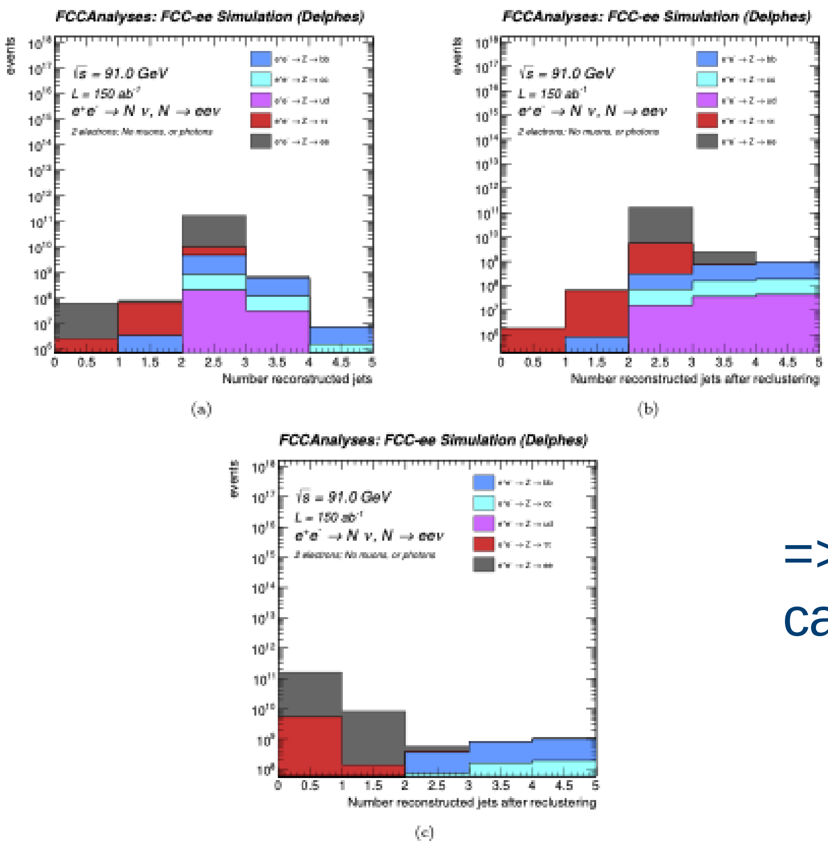


Figure 2: Jet multiplicity distributions for (a) the default jet collection stored in the Delphes samples (generalised k_T with $p = -1$ and a minimum p_T cut of 1 GeV), (b) jets reclustered using the anti-k_T algorithm with a minimum p_T cut of 1 GeV and (c) jets reclustered with the anti-k_T algorithm as in (b) but with all reconstructed leptons (electrons and muons) removed from the reclustering.

=> All results presented use this third category of reclustered jets!

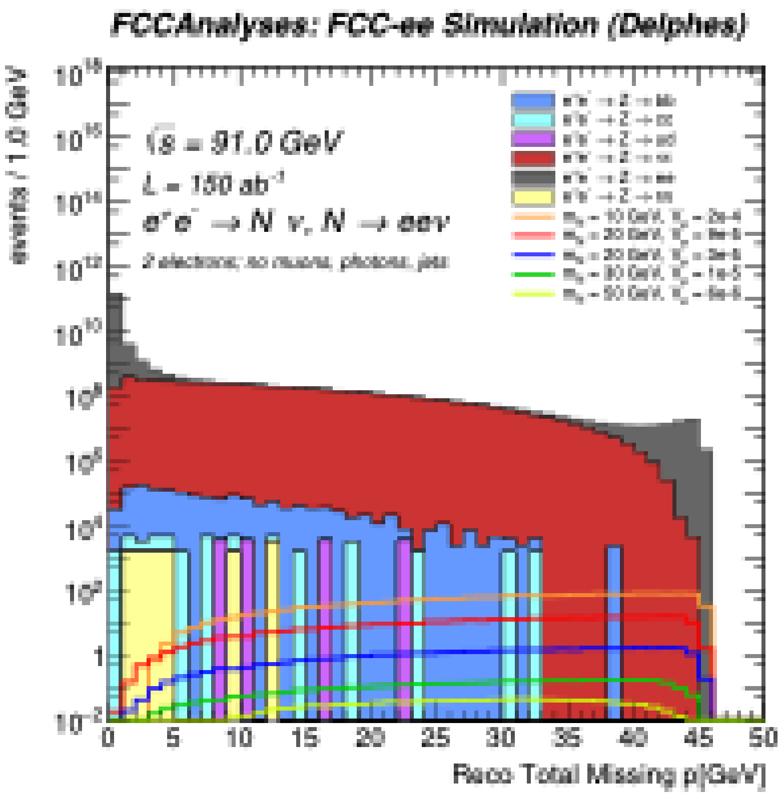
Updated selections, including displaced vertex requirement

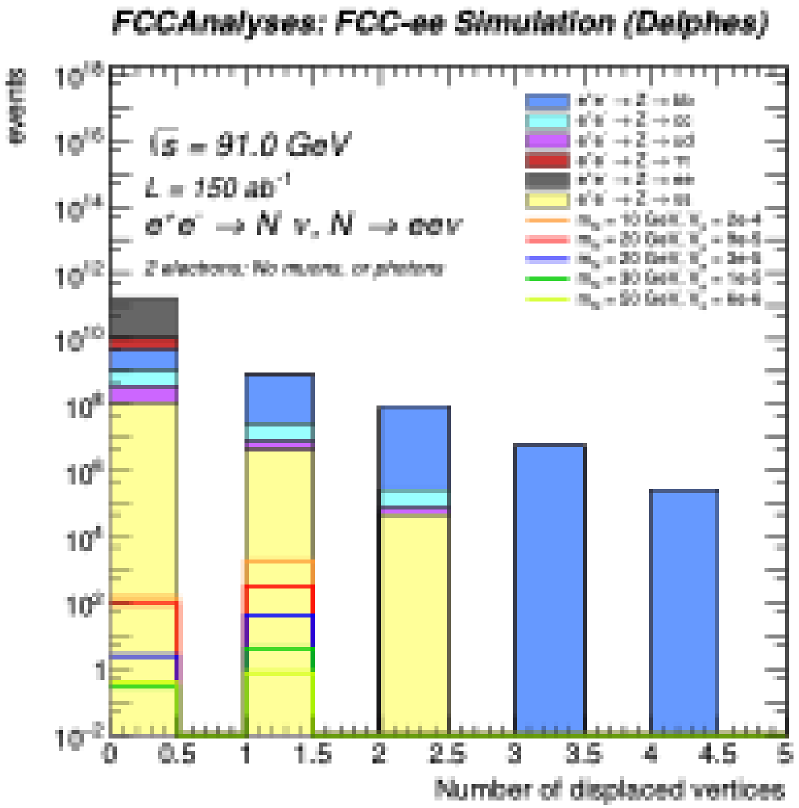
$Z \rightarrow$	2 electrons	Veto photons and muons	Veto jets	Vetoes and $\not{p} > 10$GeV	Vetoes and 1 DV
ee	1.62e+11 ± 8.83e+08	1.62e+11 ± 1.89e+07	1.54e+11 ± 1.84e+07 (0.702)	3.21e+08 ± 8.39e+05	≤ 8.39e+05
$\tau\tau$	5.39e+09 ± 1.63e+08	5.39e+09 ± 3.46e+06	5.22e+09 ± 3.40e+06 (0.023)	2.57e+09 ± 2.39e+06	4.43e+03 ± 3.13e+03
bb	4.27e+09 ± 1.48e+08	4.27e+09 ± 3.11e+06	1.40e+06 ± 5.65e+04 (< 0.001)	4.29e+05 ± 3.12e+04	2.27e+03 ± 2.27e+03
cc	7.39e+08 ± 4.25e+07	7.39e+08 ± 1.08e+06	3.29e+04 ± 7.17e+03 (< 0.001)	1.10e+04 ± 4.14e+03	≤ 4.14e+03
ud	2.28e+08 ± 5.40e+07	2.28e+08 ± 9.03e+05	1.43e+04 ± 7.16e+03 (< 0.001)	1.07e+04 ± 6.20e+03	≤ 6.20e+03
ss	1.19e+08 ± 1.70e+07	1.19e+08 ± 4.31e+05	1.10e+04 ± 4.14e+03 (< 0.001)	3.13e+03 ± 2.21e+03	≤ 2.21e+03
m_N, $\lvert V_{eN} \rvert$					
10, 2×10^{-4}	2.04e+03 ± 2.29e+00	2.04e+03 ± 1.02e+01	2.04e+03 ± 1.02e+01 (0.805)	1.98e+03 ± 1.00e+01	1.89e+03 ± 9.77e+00
20, 9×10^{-5}	4.04e+02 ± 1.84e-01	4.04e+02 ± 1.92e+00	4.04e+02 ± 1.92e+00 (0.882)	3.87e+02 ± 1.88e+00	3.11e+02 ± 1.69e+00
20, 3×10^{-5}	4.44e+01 ± 6.77e-03	4.44e+01 ± 2.12e-01	4.43e+01 ± 2.12e-01 (0.869)	4.25e+01 ± 2.08e-01	4.18e+01 ± 2.06e-01
30, 1×10^{-5}	4.62e+00 ± 2.15e-04	4.62e+00 ± 2.15e-02	4.62e+00 ± 2.15e-02 (0.922)	4.37e+00 ± 2.09e-02	4.33e+00 ± 2.08e-02
50, 6×10^{-6}	1.17e+00 ± 2.67e-05	1.17e+00 ± 5.38e-03	1.17e+00 ± 5.38e-03 (0.952)	1.13e+00 ± 5.28e-03	7.89e-01 ± 4.41e-03

Table 4: Event yields, normalised to $150ab^{-1}$ for background and signal processes for event selection criteria taken from the snowmass study, but extended to consider the presence of displaced vertices. For comparison, the efficiency of the requirement of 2 electrons and a veto on photons, muons and jets is provided in brackets.

- Higher rejection of hadronic backgrounds due to fixed jet reclustering.
- Improved signal acceptance probably due to recovery in electron efficiency at low pT (see backup).
- The DV requirement removes ~ all backgrounds- hard to study additional variables at this stage.

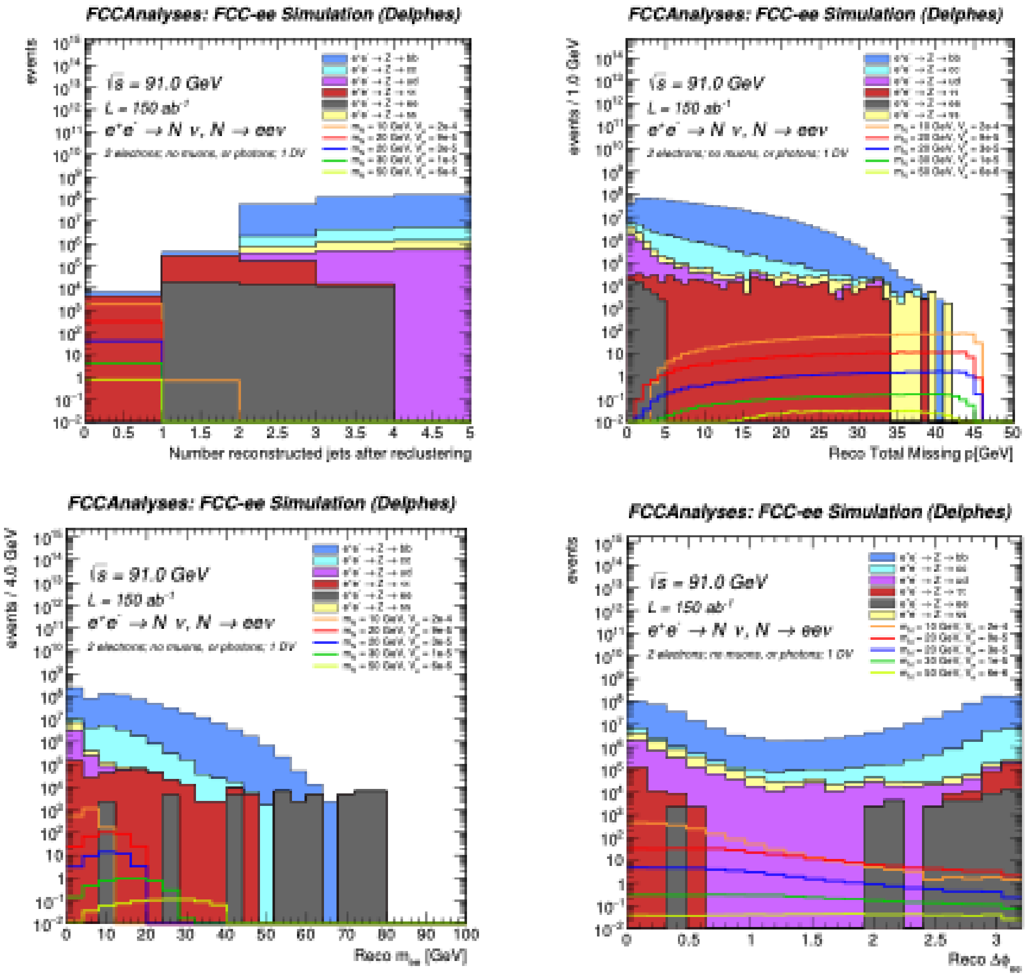
Distributions at jet veto level





DV requirement will remove ~ all Z=> ee, perhaps missing momentum cut no longer required or should at least be reoptimized?

Distributions with 1DV, and muon and photon veto



- ~ all signal in 0-jet bin.
- Signal peaks at higher missing momentum, but harder to motivate cut based on Z=> ee shape.
- Additional kinematic distributions presented that could be used to further suppress backgrounds or to characterize signal

DV reconstruction choices

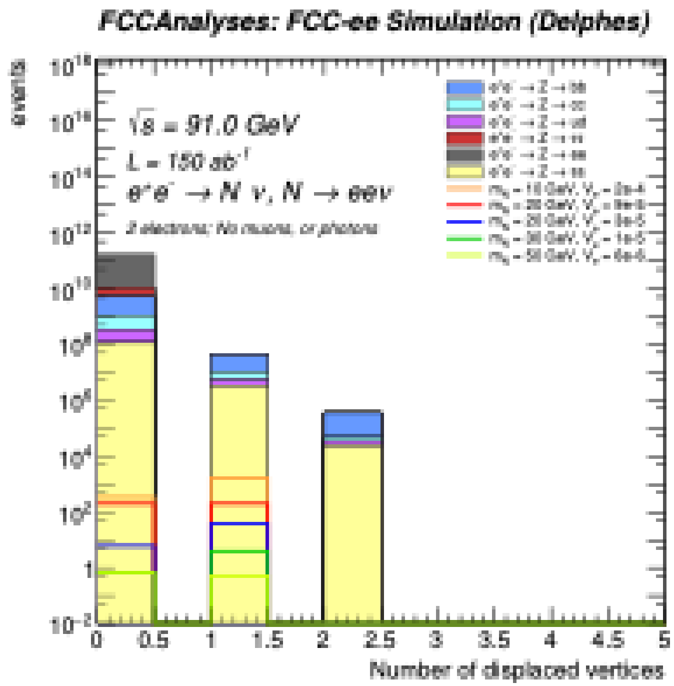


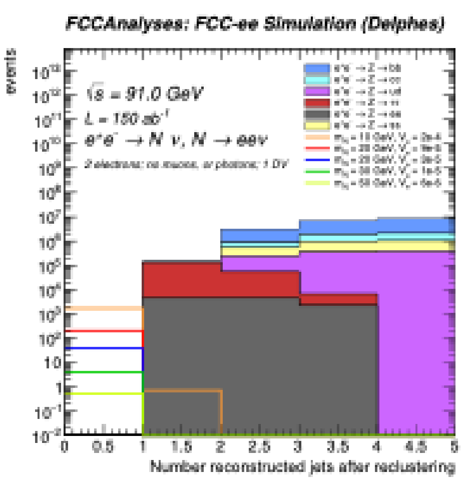
Figure 11: Distribution of the number of reconstructed secondary vertices (reconstructed with a track p_T cut of 1 GeV and a minimum $|d_0|$ requirement of 2 mm) , normalised to 150 ab^{-1}, for representative HNL benchmark points and the main Z-pole background processes. All events are required to have exactly two electrons, and no additional muons or photons.

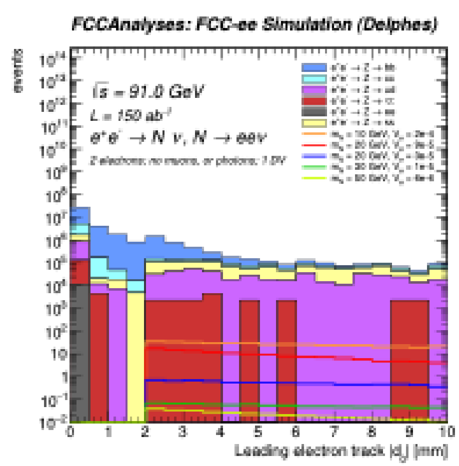
=> Looked at increasing the d0 cut for tracks entering SV reconstruction.

Results with tighter DV selection

$Z \rightarrow$	2 electrons	Veto photons and muons	Veto photons and muons; 1 DV	Veto photons, muons, jets; 1 DV
ee	1.62e+11 ± 8.83e+08	1.62e+11 ± 1.89e+07	1.10e+04 ± 4.90e+03	≤ 4.90e+03
$\tau\tau$	5.39e+09 ± 1.63e+08	5.39e+09 ± 3.46e+06	1.77e+05 ± 1.98e+04	≤ 1.98e+04
bb	4.27e+09 ± 1.48e+08	4.27e+09 ± 3.11e+06	3.08e+07 ± 2.65e+05	≤ 2.65e+05
cc	7.39e+08 ± 4.25e+07	7.39e+08 ± 1.08e+06	4.77e+06 ± 8.64e+04	≤ 8.64e+04
ud	2.28e+08 ± 5.40e+07	2.28e+08 ± 9.03e+05	2.10e+06 ± 8.67e+04	≤ 8.67e+04
ss	1.19e+08 ± 1.70e+07	1.19e+08 ± 4.31e+05	3.28e+06 ± 7.17e+04	≤ 7.17e+04

Table 5: Event yields, normalised to $150ab^{-1}$ for Z-pole background processes for a baseline di-electron event selection involving vetoes on muons, photons and jets and requiring exactly 1 reconstructed secondary vertex (reconstructed with a track p_T cut of 1 GeV and a minimum $|d_0|$ requirement of 2 mm). The inequalities in the final column indicate that all MC events are removed by the full selection.





=> Significantly higher background rejection. Would be nice to optimize further on larger background samples.

Rough sensitivity projection

m_N [GeV], $\|V_{eN}\|$	$c\tau_N$ [cm] ($C_0 = 1$)	Cross-section [pb]	Expected events	2 electrons	Veto photons and muons	1 DV	Veto jets and 1 DV
10, 1×10^{-4}	52.0833	4.221×10^{-5}	633.19	3.64e+02 ± 2.42e-01	3.64e+02 ± 2.15e+00	3.10e+02 ± 1.98e+00	**3.10e+02 ± 1.98e+00**
10, 1×10^{-5}	5208.3333	4.221×10^{-8}	6.33	6.89e-02 ± 3.32e-05	6.89e-02 ± 2.95e-03	5.90e-02 ± 2.73e-03	5.89e-02 ± 2.73e-03
10, 1×10^{-6}	520833.3333	4.221×10^{-10}	0.06	5.19e-02 ± 2.89e-07	5.19e-02 ± 2.56e-04	≤ 2.56e-04	≤ 2.56e-04
20, 1×10^{-4}	1.6276	3.763×10^{-5}	564.42	4.99e+02 ± 2.52e-01	4.99e+02 ± 2.37e+00	2.26e+02 ± 1.60e+00	**2.26e+02 ± 1.60e+00**
20, 1×10^{-5}	162.7604	3.764×10^{-8}	5.65	2.81e+00 ± 1.89e-04	2.81e+00 ± 1.78e-02	2.52e+00 ± 1.69e-02	**2.51e+00 ± 1.68e-02**
20, 1×10^{-6}	16276.0417	3.765×10^{-10}	0.06	4.33e-04 ± 2.35e-08	4.33e-04 ± 2.21e-05	3.80e-04 ± 2.07e-05	3.78e-04 ± 2.07e-05
30, 1×10^{-4}	0.2143	3.341×10^{-5}	501.12	4.68e+02 ± 2.17e-01	4.68e+02 ± 2.17e+00	1.31e+01 ± 3.62e-01	**1.31e+01 ± 3.62e-01**
30, 1×10^{-5}	21.4335	3.341×10^{-8}	5.01	4.62e+00 ± 2.15e-04	4.62e+00 ± 2.15e-02	3.95e+00 ± 1.99e-02	**3.95e+00 ± 1.99e-02**
30, 1×10^{-6}	2143.3471	3.341×10^{-10}	0.05	4.74e-03 ± 6.90e-08	4.74e-03 ± 6.89e-05	4.28e-03 ± 6.55e-05	4.27e-03 ± 6.54e-05
40, 1×10^{-4}	0.0509	2.855×10^{-5}	428.24	4.06e+02 ± 1.73e-01	4.06e+02 ± 1.86e+00	≤ 1.86e+00	≤ 1.86e+00
40, 1×10^{-5}	5.0863	2.855×10^{-8}	4.28	4.05e+00 ± 1.72e-04	4.05e+00 ± 1.86e-02	2.40e+00 ± 1.43e-02	**2.40e+00 ± 1.43e-02**
40, 1×10^{-6}	508.6263	2.855×10^{-10}	0.04	2.02e-02 ± 1.22e-07	2.02e-02 ± 1.31e-04	1.82e-02 ± 1.25e-04	1.82e-02 ± 1.25e-04
50, 1×10^{-4}	0.0167	2.282×10^{-5}	342.34	3.26e+02 ± 1.24e-01	3.26e+02 ± 1.49e+00	≤ 1.49e+00	≤ 1.49e+00
50, 1×10^{-5}	1.6667	2.282×10^{-8}	3.42	3.26e+00 ± 1.24e-04	3.26e+00 ± 1.49e-02	7.24e-01 ± 7.04e-03	**7.24e-01 ± 7.04e-03**
50, 1×10^{-6}	166.6667	2.282×10^{-10}	0.03	3.03e-02 ± 1.19e-07	3.03e-02 ± 1.44e-04	2.45e-02 ± 1.30e-04	2.45e-02 ± 1.29e-04
60, 1×10^{-4}	0.0067	1.643×10^{-5}	246.45	2.35e+02 ± 7.55e-02	2.35e+02 ± 1.08e+00	≤ 1.08e+00	≤ 1.08e+00
60, 1×10^{-5}	0.6698	1.643×10^{-8}	2.46	2.35e+00 ± 7.56e-05	2.35e+00 ± 1.08e-02	4.51e-02 ± 1.49e-03	4.51e-02 ± 1.49e-03
60, 1×10^{-6}	66.9796	1.643×10^{-10}	0.02	2.33e-02 ± 7.52e-08	2.33e-02 ± 1.07e-04	1.36e-02 ± 8.20e-05	1.36e-02 ± 8.20e-05
70, 1×10^{-4}	0.0031	9.898×10^{-7}	148.47	1.42e+02 ± 3.53e-02	1.42e+02 ± 6.48e-01	≤ 6.48e-01	≤ 6.48e-01
70, 1×10^{-5}	0.3099	9.898×10^{-9}	1.48	1.42e+00 ± 3.53e-05	1.42e+00 ± 6.48e-03	≤ 6.48e-03	≤ 6.48e-03
70, 1×10^{-6}	30.9891	9.898×10^{-11}	0.01	1.41e-02 ± 3.53e-08	1.41e-02 ± 6.48e-05	4.89e-03 ± 3.81e-05	4.89e-03 ± 3.81e-05
80, 1×10^{-4}	0.0016	2.353×10^{-6}	353.00	3.23e+02 ± 1.27e-01	3.23e+02 ± 1.51e+00	≤ 1.51e+00	≤ 1.51e+00
80, 1×10^{-5}	0.1589	2.353×10^{-8}	3.53	3.23e+00 ± 1.27e-04	3.23e+00 ± 1.51e-02	7.06e-05 ± 7.06e-05	7.06e-05 ± 7.06e-05
80, 1×10^{-6}	15.8946	2.353×10^{-10}	0.04	3.23e-02 ± 1.27e-07	3.23e-02 ± 1.51e-04	9.57e-03 ± 8.22e-05	9.57e-03 ± 8.22e-05
90, 1×10^{-4}	0.0009	8.797×10^{-9}	1.32	1.26e+00 ± 2.96e-05	1.26e+00 ± 5.77e-03	≤ 5.77e-03	≤ 5.77e-03
90, 1×10^{-5}	0.0882	8.797×10^{-11}	0.01	1.26e-02 ± 2.96e-08	1.26e-02 ± 5.77e-05	≤ 5.77e-05	≤ 5.77e-05
90, 1×10^{-6}	8.8204	8.797×10^{-13}	< 0.01	1.26e-04 ± 2.96e-11	1.26e-04 ± 5.77e-07	≤ 5.77e-07	≤ 5.77e-07

Table 6: Event yields, normalised to $150ab^{-1}$ for HNL signal points for a baseline di-electron event selection involving vetoes on muons, photons and jets and requiring exactly 1 reconstructed secondary vertex (reconstructed with a track p_T cut of 1 GeV and a minimum $|d_0|$ requirement of 2 mm). In the final column, the numbers marked in bold illustrate scenarios where this selection would yield at least O(1) signal events, and thus could be discovered at FCC-ee assuming a background-free search.

Rough sensitivity projection

m_N [GeV], $\lvert V_{eN}\rvert$	$c\tau_N$ [cm] ($C_0 = 1$)	Cross-section [pb]	Expected events	2 electrons	Veto photons and muons	1 DV	Veto jets and 1 DV
10, 1×10^{-4}	52.0833	4.221×10^{-6}	633.19	3.64e+02 ± 2.42e-01	3.64e+02 ± 2.15e+00	3.10e+02 ± 1.98e+00	**3.10e+02 ± 1.98e+00**
10, 1×10^{-5}	5208.3333	4.221×10^{-8}	6.33	6.89e-02 ± 3.32e-05	6.89e-02 ± 2.95e-03	5.90e-02 ± 2.73e-03	5.89e-02 ± 2.73e-03
10, 1×10^{-6}	520833.3333	4.221×10^{-10}	0.06	5.19e-02 ± 2.89e-07	5.19e-02 ± 2.56e-04	≤ 2.56e-04	≤ 2.56e-04
20, 1×10^{-4}	1.6276	3.763×10^{-6}	564.42	4.99e+02 ± 2.52e-01	4.99e+02 ± 2.37e+00	2.26e+02 ± 1.60e+00	**2.26e+02 ± 1.60e+00**
20, 1×10^{-5}	162.7604	3.764×10^{-8}	5.65	2.81e+00 ± 1.89e-04	2.81e+00 ± 1.78e-02	2.52e+00 ± 1.69e-02	**2.51e+00 ± 1.68e-02**
20, 1×10^{-6}	16276.0417	3.765×10^{-10}	0.06	4.33e-04 ± 2.35e-08	4.33e-04 ± 2.21e-05	3.80e-04 ± 2.07e-05	3.78e-04 ± 2.07e-05
30, 1×10^{-4}	0.2143	3.341×10^{-6}	501.12	4.68e+02 ± 2.17e-01	4.68e+02 ± 2.17e+00	1.31e+01 ± 3.62e-01	**1.31e+01 ± 3.62e-01**
30, 1×10^{-5}	21.4335	3.341×10^{-8}	5.01	4.62e+00 ± 2.15e-04	4.62e+00 ± 2.15e-02	3.95e+00 ± 1.99e-02	**3.95e+00 ± 1.99e-02**
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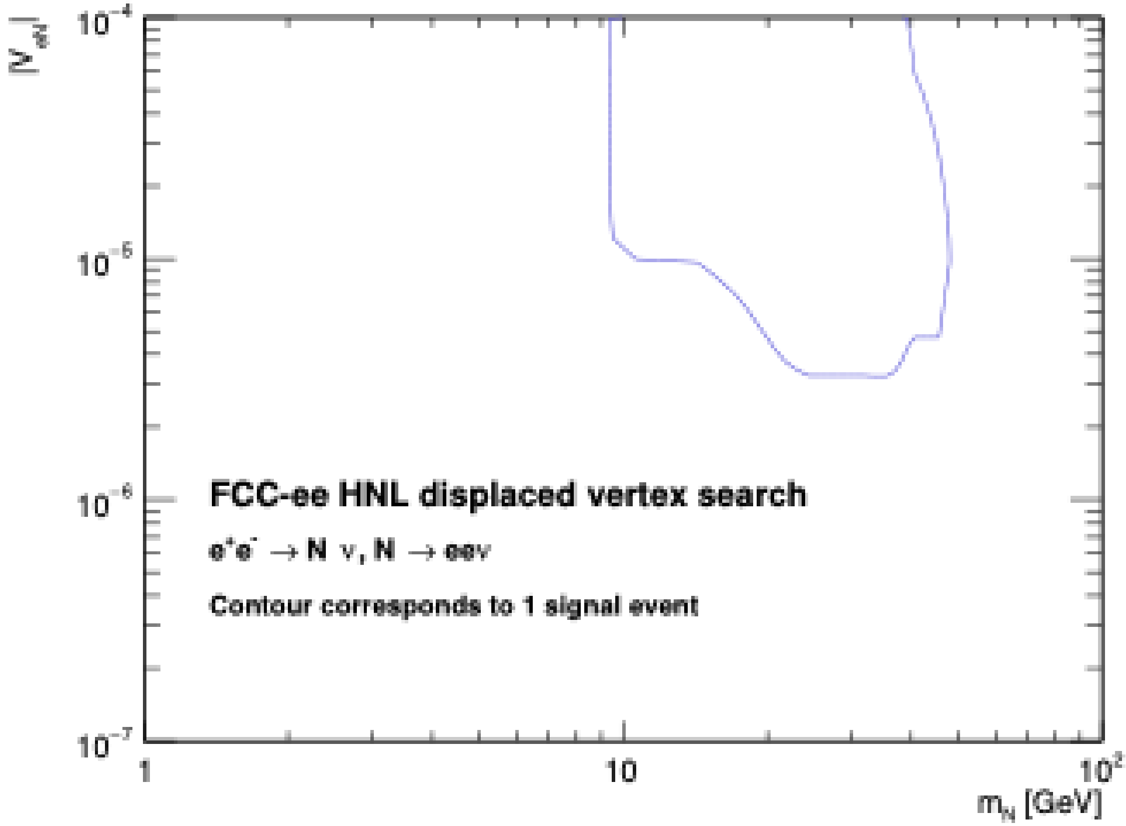
Rough sensitivity projection



- Obvious note: there's probably a better script for this (let me know if you have one?).
- Relatively easy to add additional points to this curve which should make extrapolation easier.

Status of MC filtering studies

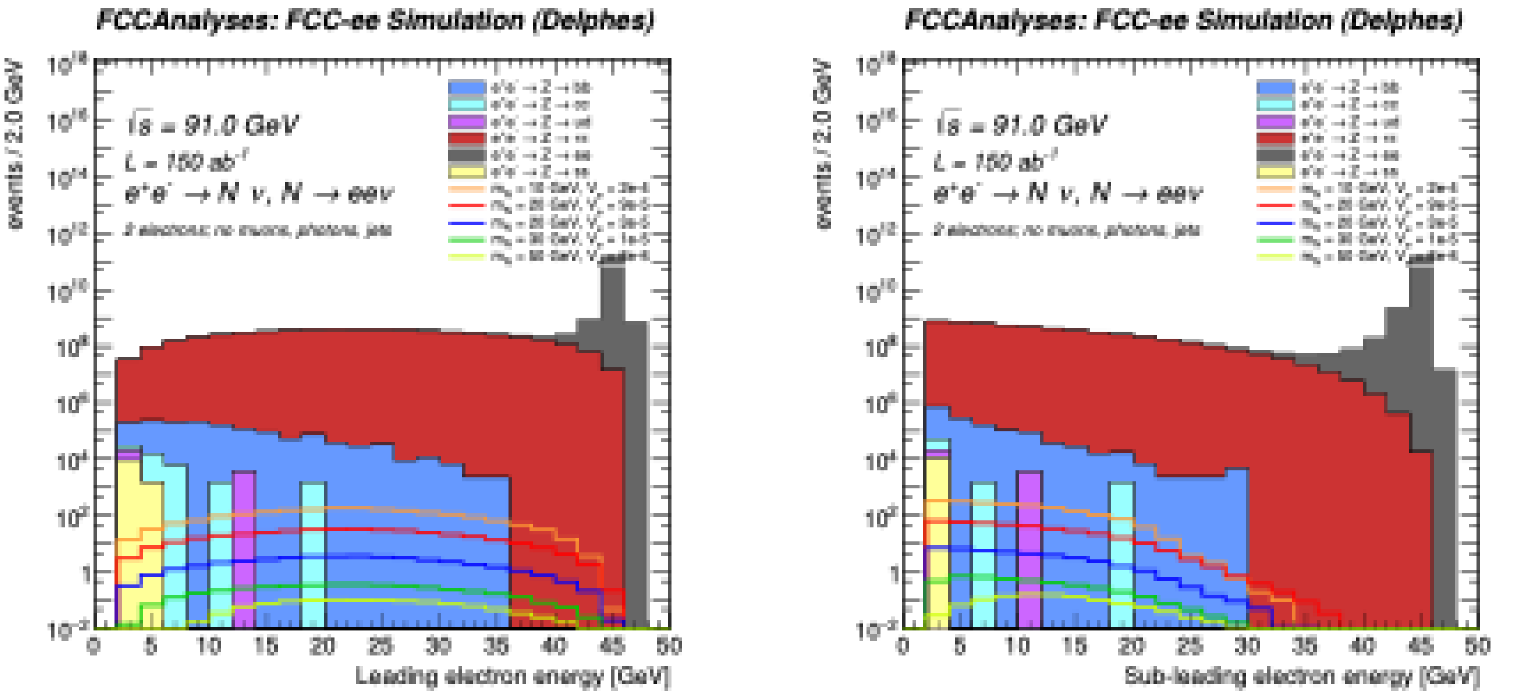
In order to get adequate MC statistics at the Z-pole run for LLP studies- need filtered MC samples!

- John made significant progress (helped by Juraj- thanks) implementing MC filtering in key4hep using Gaudi Filtering algorithms.
- However- due to updates in key4hep/backward compatibility problems it will be very difficult to compare filtered samples to winter23 samples.
- Hoping to pick this work up in the coming months, but would like to discuss possibilities for publishing the work presented today first.

Conclusion and next steps

- Have tried to document updated studies on HNL production in the $ee\nu$ channel at FCC-ee that I would like to see published in the coming months.
- Since a lot of the 'lessons/messages' require acknowledging some limitations of previous (and current) work, welcome input on how to proceed.
- Thanks for listening- happy to take comments/questions ☺

Backup- electron energy distributions



(a) (b)

Figure 3: (a) leading electron energy and (b) sub-leading electron energy distributions normalised to 150 ab^{-1}, for representative HNL benchmark points and the main Z-pole background processes. All events are required to have exactly two electrons, and no additional muons, jets or photons.