# Long-Lived Particles at the FCC-ee

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# What is the FCC-ee?

**Electron-positron stage of the Future Circular Collider (FCC) integrated program**

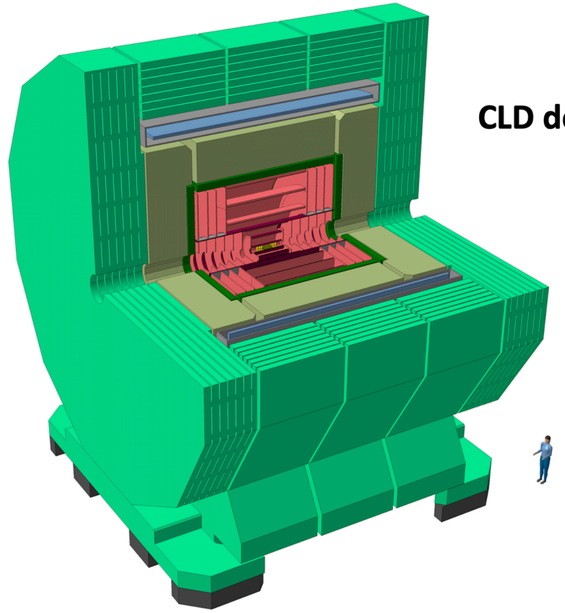
- The FCC will have one tunnel of 100 Km of circumference, two stages:
  - **Stage 1:** FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at high luminosities
  - **Stage 2:** FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options


**The FCC is a frontier Higgs, top, electroweak and flavour factory where we can directly discover new physics**

**Enters LLPs!**

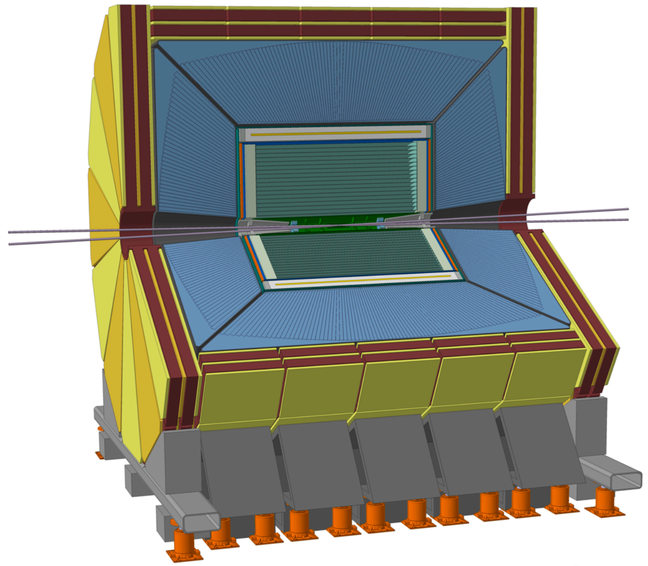
# Detectors at the FCC-ee

- **Two detector concepts** used for integration estimates:
  - **CLD design**: adapted for the FCC-ee by the CERN Linear Collider Detector group
  - **IDEA design**: specifically designed for the FCC-ee (and CEPC)



CLD design

- **Have the opportunity to design general-purpose detectors with LLPs in mind!**
  - Opportunities for new, creative designs!
  - E.g. HECATE dedicated to long lifetimes (arXiv:2011.01005)



IDEA design

# Ongoing work

- Snowmass white paper 2021 arXiv:2203.05502

  **Searches for Long-Lived Particles at the Future FCC-ee**

  J. Alimena, P. Azzi, M. Bauer, A. Blondel, M. Drewes, R. Gonzalez Suarez, J. Klaric, S. Kulkarni, O. Mikulenko, M. Neubert, M. Ovchynnikov, C. Rizzi, R. Ruiz, L. Rygaard, A. Sfyrla, T. Sharma, A. Thamm, C. B. Verhaaren

- 3 long-lived physics cases:
  - Heavy Neutral Leptons (HNLs)
  - Axion-Like Particles (ALPs)
  - Higgs bosons with exotic decays to LLPs
- My master's thesis: Simulations of long-lived Heavy Neutral Leptons at the FCC-ee

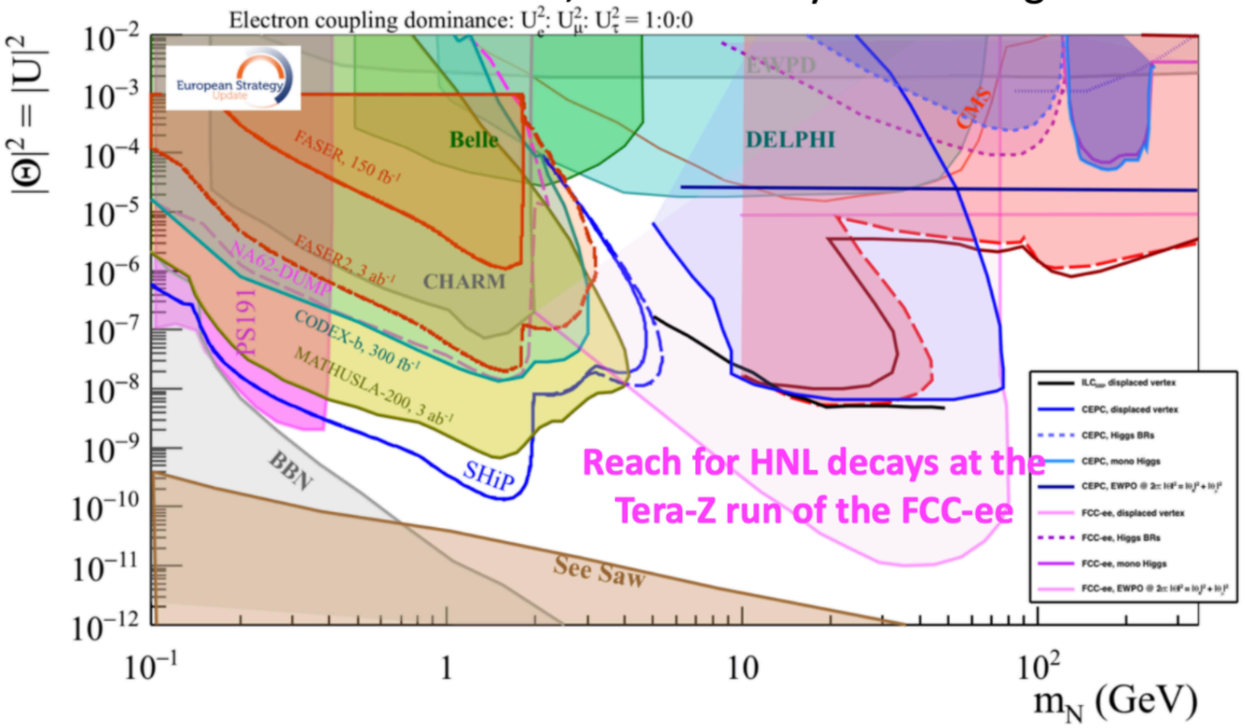
# Heavy Neutral Leptons at the FCC-ee

- Right-handed/sterile/heavy neutrinos
- Could shed light on some open questions of the SM:
  - Neutrino masses
  - Baryon Asymmetry
  - Dark Matter

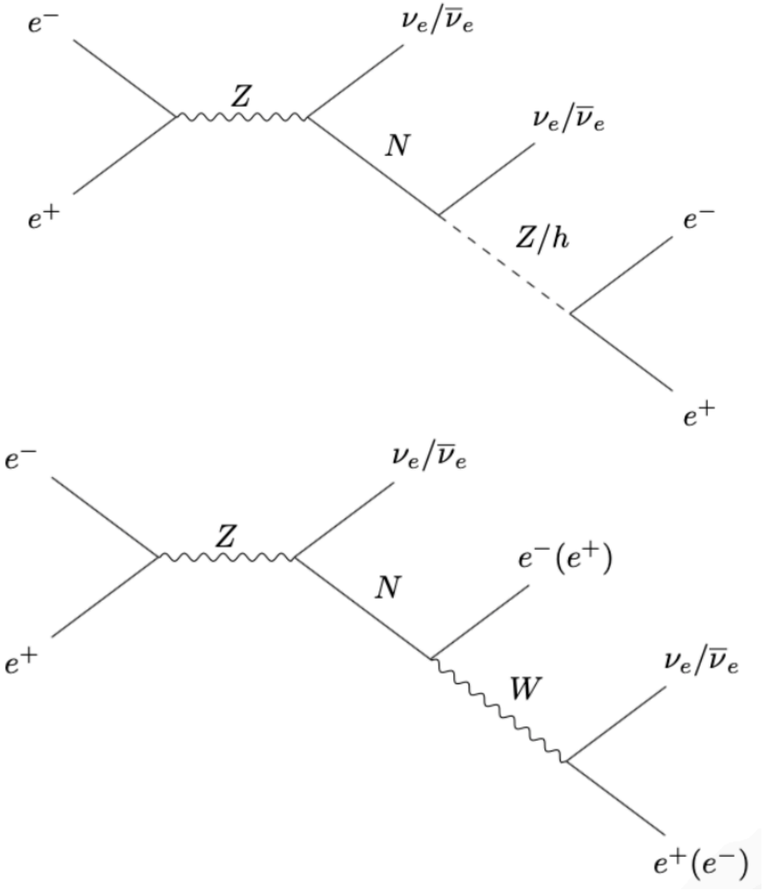
- FCC will probe space not constrained by astrophysics or cosmology, complementary to accelerator and neutrino prospects

- HNLs at the FCC-ee are right in the parameter region that is good for baryogenesis! arXiv:2106.16226

90% CL exclusion limits for a HNL mixed with the electron neutrino, from the Physics Briefing Book



# Simulating HNLs




- FCC-ee Z pole run, $\sqrt{s} = 91$ GeV, $\mathscr{L}^{-1} = 150$ ab$^{-1}$
- In this analysis: $N \to ee\nu_e$

- Generated in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card
- Generating Majorana and Dirac HNLs using
  - SM_HeavyN_CKM_AllMasses_LO and
  - SM_HeavyN_Dirac_CKM_Masses_LO models

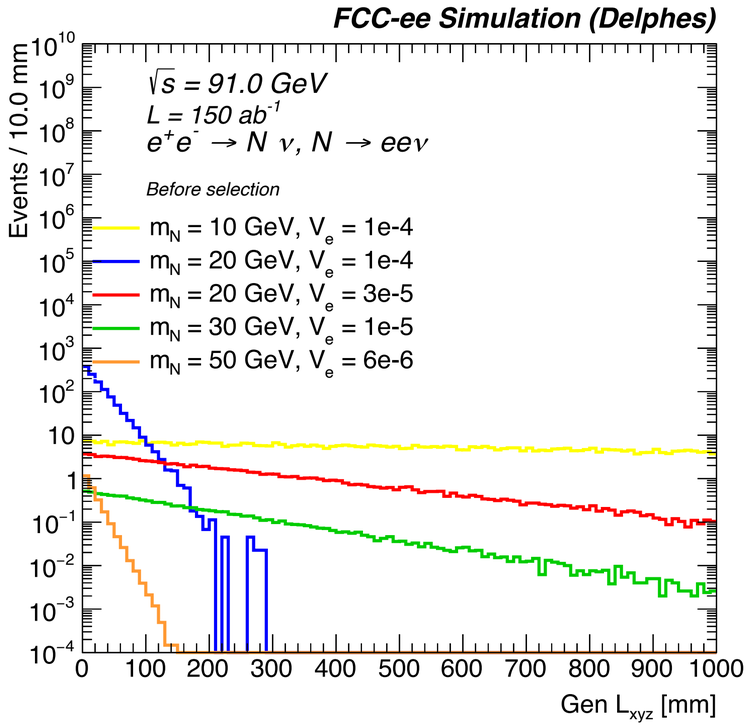
  (arXiv:1411.7305, arXiv:1602.06957)
- Analysis in the FCC framework

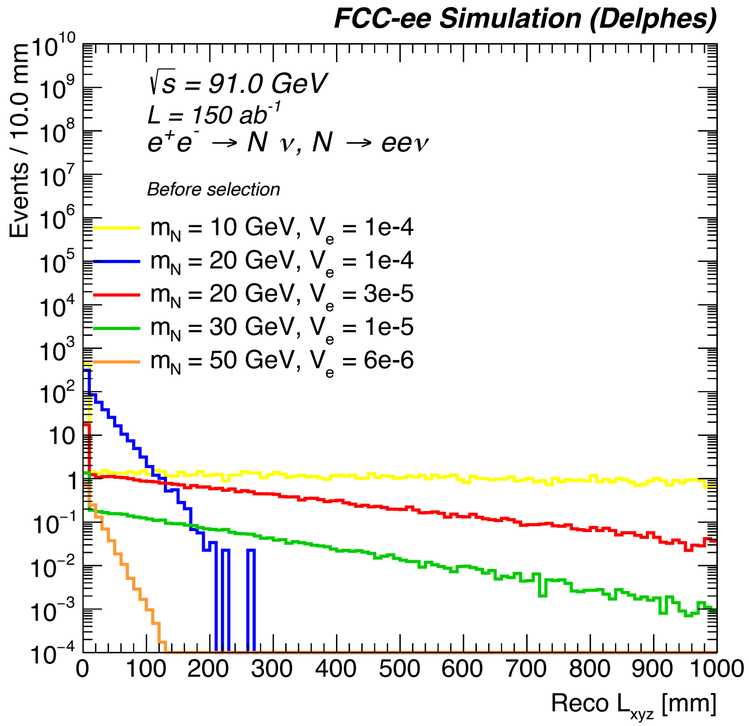
- Long-lived HNLs for small mass and coupling:

  For $m_N \lesssim$ ~ 100 GeV (arXiv:1905.11889)

$$L \sim 0.025\text{m} \left(\frac{10^{-6}}{V_{lN}}\right)^2 \left(\frac{100\ \text{GeV}}{m_N}\right)^5$$

# HNL Decay Length



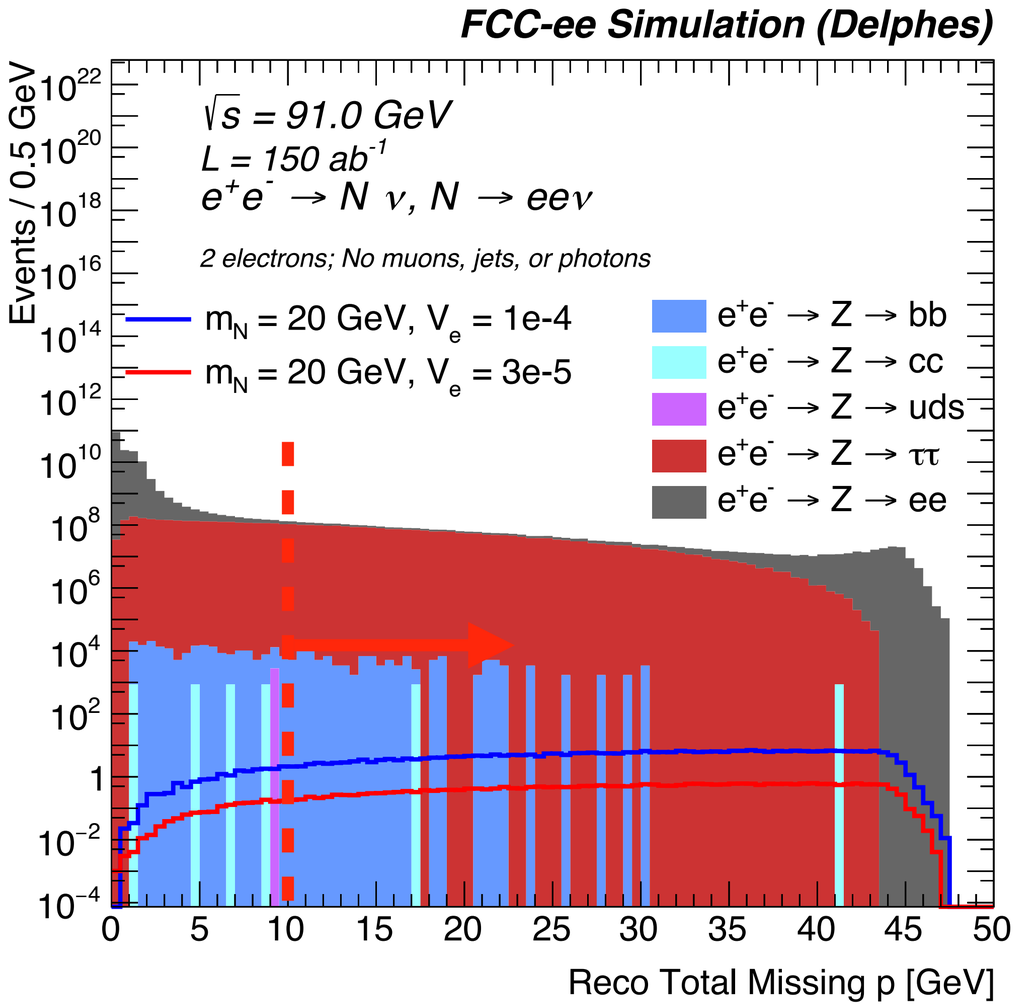

- Confirmed HNL signal kinematics behave as expected, at gen and reco level
  - For Ve = 1e-4: decay length longer for **m = 10 GeV** than **m = 20 GeV**
  - For m = 20: decay length longer for **Ve = 3e-5** than **Ve = 1e-4**

- The HNLs with longer decay lengths give less number of reconstructed events

# Signal vs Background

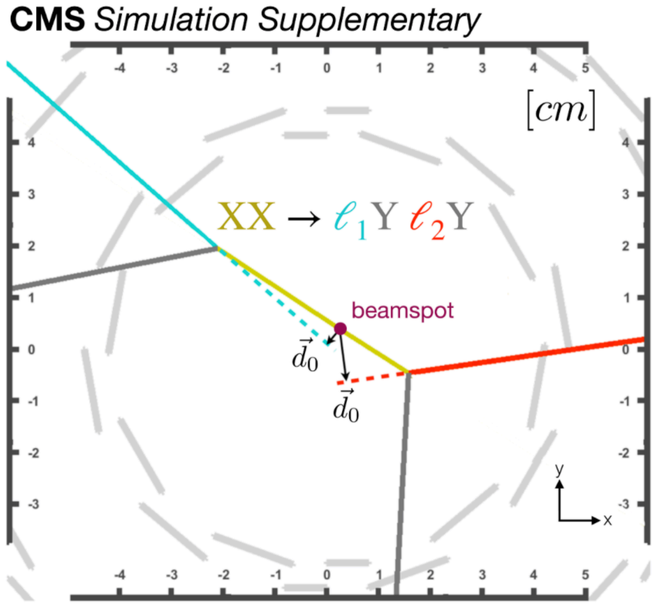
## Missing energy

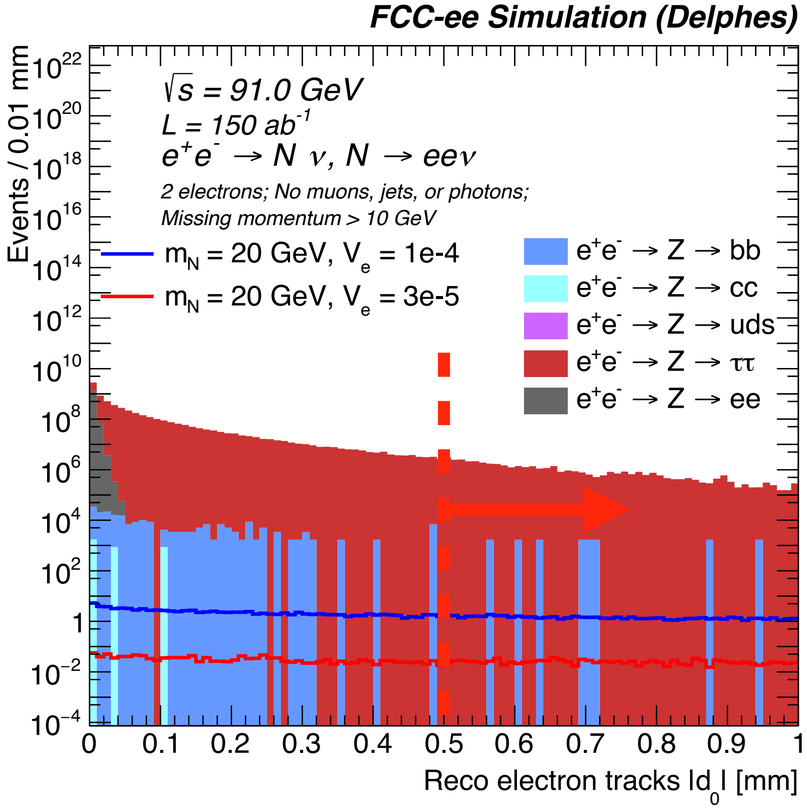
- Centrally produced background samples with the IDEA detector at $\sqrt{s} = 91$ GeV
- We can look at total missing energy at e+e- colliders!
- Require total missing momenta $\not{p} > 10$ GeV

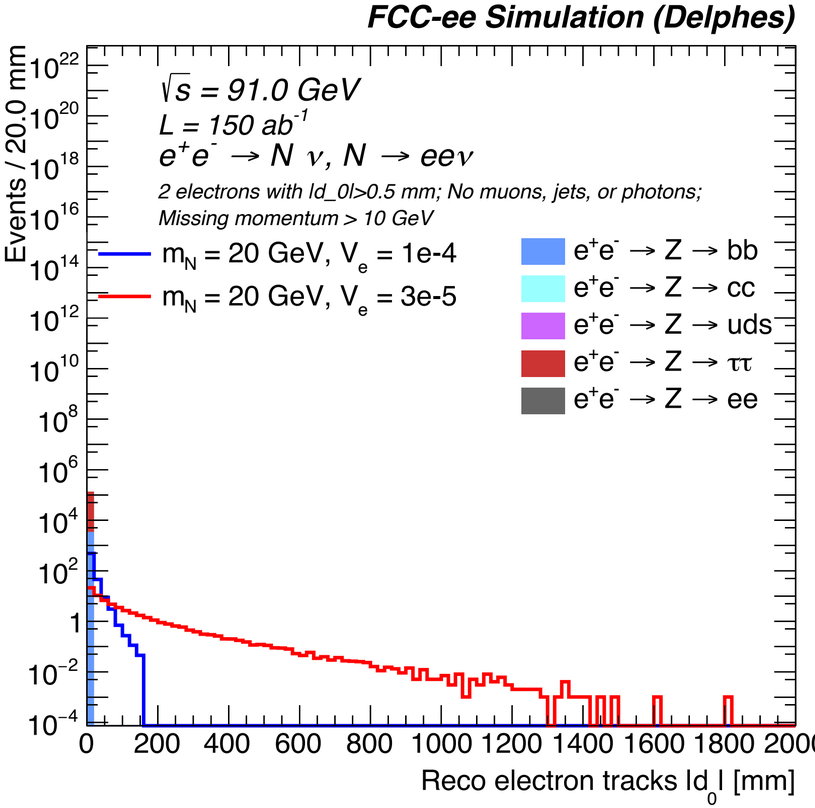


# Signal vs Background

## Transverse impact parameter $d_0$ of the electron tracks




- Starting with transverse impact parameter ($d_0$ or $d_{xy}$) but can move to 3D impact parameter ($d_{xyz}$)
- Require with $|d_0| > 0.5$ mm

# Event Selection

- First attempt at event selection
- Tables show the cumulative expected number of events after each selection left to right (on reco variables) for 150 $ab^{-1}$
- Most explored discriminating variables: total missing momenta $\not{p}$ and traverse impact parameter $d_0$
- Vetoes on muons, photons and jets

**Signal**

| | Before selection | Exactly 2 reco e | Vetoes | $\not{p} > 10$ GeV | $\lvert d_0 \rvert > 0.5$ mm |
|---|---|---|---|---|---|
| $m_N = 10$ GeV, $\lvert V_{eN} \rvert = 2e\text{-}4$ | $2534 \pm 11$ | $1006 \pm 7$ | $996 \pm 7$ | $951 \pm 7$ | $907 \pm 7$ |
| $m_N = 20$ GeV, $\lvert V_{eN} \rvert = 9e\text{-}5$ | $458 \pm 2$ | $313 \pm 2$ | $308 \pm 2$ | $293 \pm 2$ | $230 \pm 1$ |
| $m_N = 20$ GeV, $\lvert V_{eN} \rvert = 3e\text{-}5$ | $51.0 \pm 0.2$ | $34.7 \pm 0.2$ | $34.2 \pm 0.2$ | $32.6 \pm 0.2$ | $31.2 \pm 0.2$ |
| $m_N = 30$ GeV, $\lvert V_{eN} \rvert = 1e\text{-}5$ | $5.01 \pm 0.02$ | $3.85 \pm 0.02$ | $3.76 \pm 0.02$ | $3.54 \pm 0.02$ | $3.39 \pm 0.02$ |
| $m_N = 50$ GeV, $\lvert V_{eN} \rvert = 6e\text{-}6$ | $1.23 \pm 0.01$ | $0.99 \pm 0.01$ | $0.96 \pm 0.01$ | $0.92 \pm 0.01$ | $0.729 \pm 0.004$ |

# Event Selection

- First attempt at event selection
- Tables show the cumulative expected number of events after each selection left to right (on reco variables) for 150 $ab^{-1}$
- Most explored discriminating variables: total missing momenta $\not{p}$ and traverse impact parameter $d_0$
- Vetoes on muons, photons and jets
- Here: backgrounds with $10^7$-$10^9$ raw events
  - Next: simulate larger background samples to reduce the uncertainties

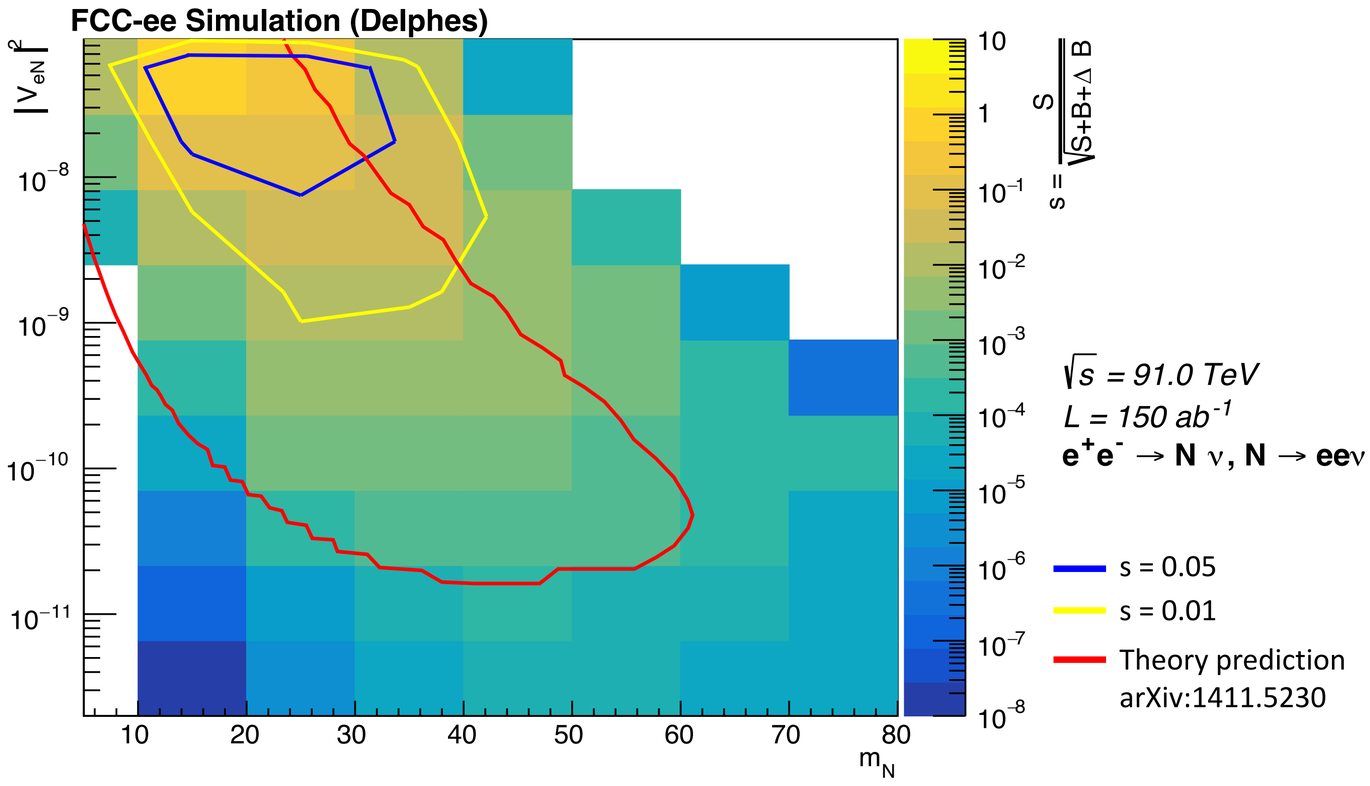
## Background

| | Before selection | Exactly 2 reco e | Vetoes | $\not{p} > 10$ GeV | $\lvert d_0 \rvert > 0.5$ mm |
|---|---|---|---|---|---|
| $Z \to \tau\tau$ | $2.21 \times 10^{11} \pm 7.00 \times 10^{7}$ | $5.49 \times 10^{9} \pm 1.10 \times 10^{7}$ | $5.10 \times 10^{9} \pm 1.06 \times 10^{7}$ | $2.52 \times 10^{9} \pm 7.47 \times 10^{6}$ | $6.64 \times 10^{4} \pm 3.84 \times 10^{4}$ |
| $Z \to ee$ | $2.19 \times 10^{11} \pm 6.94 \times 10^{7}$ | $1.75 \times 10^{11} \pm 6.19 \times 10^{7}$ | $1.53 \times 10^{11} \pm 5.80 \times 10^{7}$ | $7.07 \times 10^{8} \pm 3.94 \times 10^{6}$ | $\leq 3.94 \times 10^{6}$ |
| $Z \to bb$ | $9.97 \times 10^{11} \pm 4.14 \times 10^{7}$ | $5.64 \times 10^{8} \pm 9.85 \times 10^{5}$ | $3.25 \times 10^{5} \pm 2.36 \times 10^{4}$ | $1.22 \times 10^{5} \pm 1.45 \times 10^{4}$ | $1.72 \times 10^{3} \pm 1.72 \times 10^{3}$ |
| $Z \to cc$ | $7.82 \times 10^{11} \pm 2.61 \times 10^{7}$ | $1.69 \times 10^{7} \pm 1.21 \times 10^{5}$ | $5.22 \times 10^{3} \pm 2.13 \times 10^{3}$ | $1.74 \times 10^{3} \pm 1.23 \times 10^{3}$ | $\leq 1.23 \times 10^{3}$ |
| $Z \to uds$ | $2.79 \times 10^{12} \pm 8.83 \times 10^{7}$ | $2.30 \times 10^{7} \pm 2.54 \times 10^{5}$ | $2.79 \times 10^{3} \pm 2.79 \times 10^{3}$ | $\leq 2.79 \times 10^{3}$ | $\leq 2.79 \times 10^{3}$ |
| Total backgrounds | $5.01 \times 10^{12} \pm 1.41 \times 10^{8}$ | $1.81 \times 10^{11} \pm 6.29 \times 10^{7}$ | $1.58 \times 10^{11} \pm 5.90 \times 10^{7}$ | $3.23 \times 10^{9} \pm 8.45 \times 10^{6}$ | $6.81 \times 10^{4} \pm 3.94 \times 10^{6}$ |

# Sensitivity

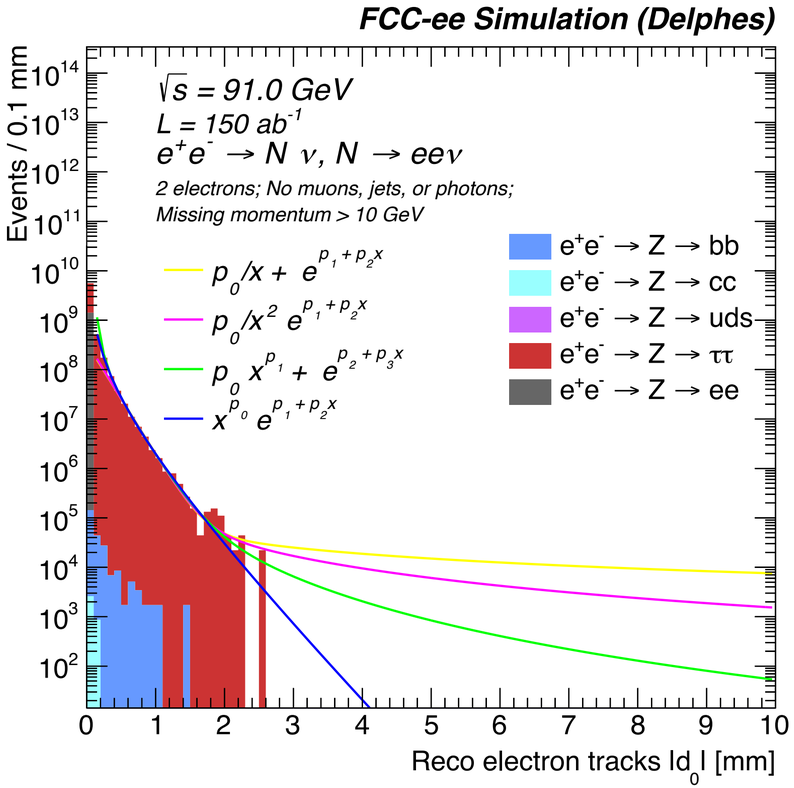
- Choice of merit: $s = \frac{S}{\sqrt{S + B + \Delta B}}$
- Contours:
  - s = 0.05 and s = 0.01
- Compared to **Theory prediction**
  - from arXiv:1411.5230
  - Prediction includes all HNL decay modes, not only electrons
  - In this analysis: $N \rightarrow ee\nu_e$

Preliminary



# Next steps

- Limited by background statistics
  - Production of larger/dedicated samples
  - Background fits
- Investigate additional variables and optimised selections
- Add remaining decay modes
- Explore different detector configurations




**Thank you for listening!**

# Backup slides

# Backup: HNL simulations

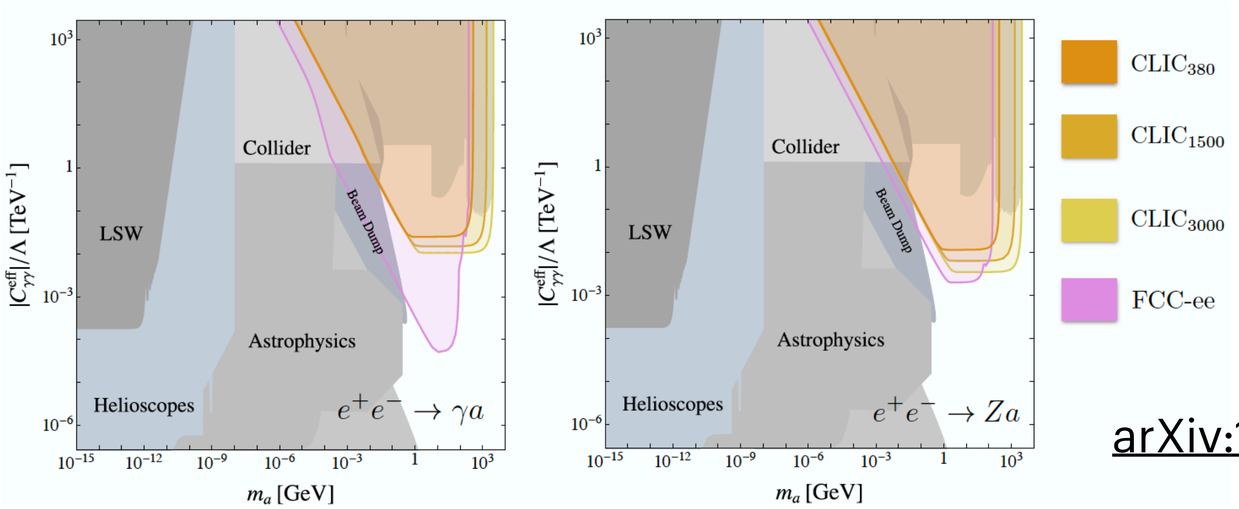
- Total number of raw events generated for all background and signal simulations

| Process | $Z \to ee$ | $Z \to \tau\tau$ | $Z \to bb$ | $Z \to cc$ | $Z \to uds$ | HNL signals |
|---|---|---|---|---|---|---|
| Number of events | $10^7$ | $10^7$ | $5.8 \times 10^8$ | $10^9$ | $10^9$ | $5 \times 10^4$ |

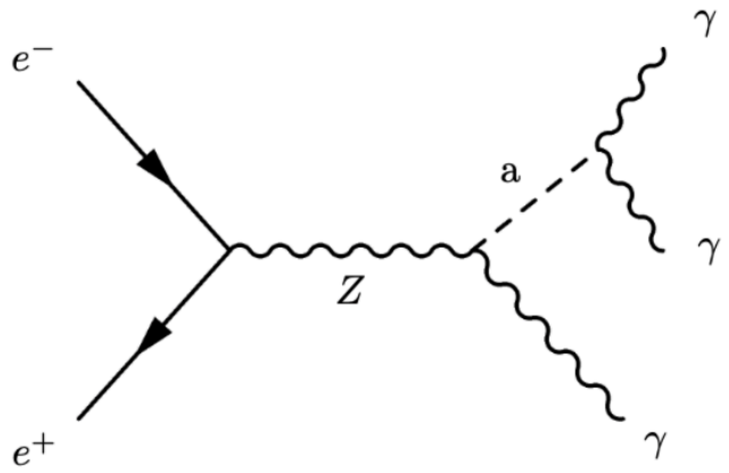
# Backup: ALPs at the FCC-ee

## Axion-Like Particles

- Pseudo Nambu-Goldstone bosons
- Very weakly coupled to the dark sector
- Small ALP couplings and mass give a considerably displaced vertex
- At the FCC-ee:
  - Orders of magnitude of parameter space accessible
  - Especially sensitive to final states with at least one photon



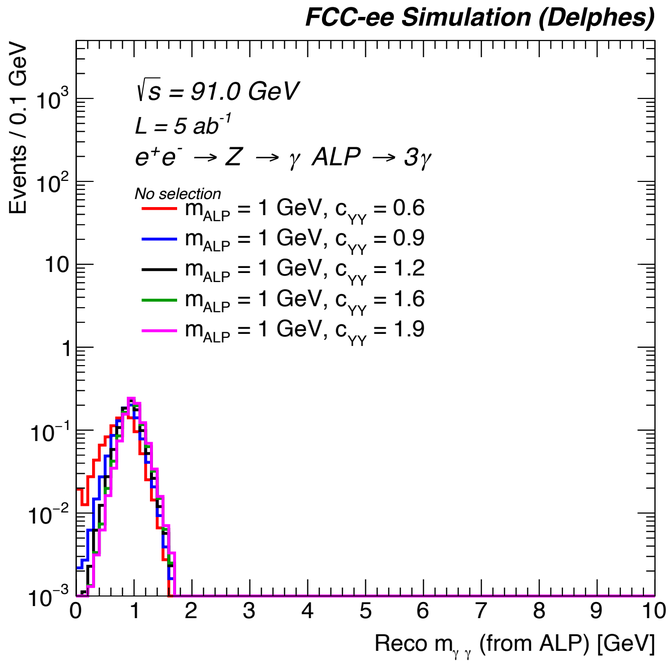

arXiv:1808.10323

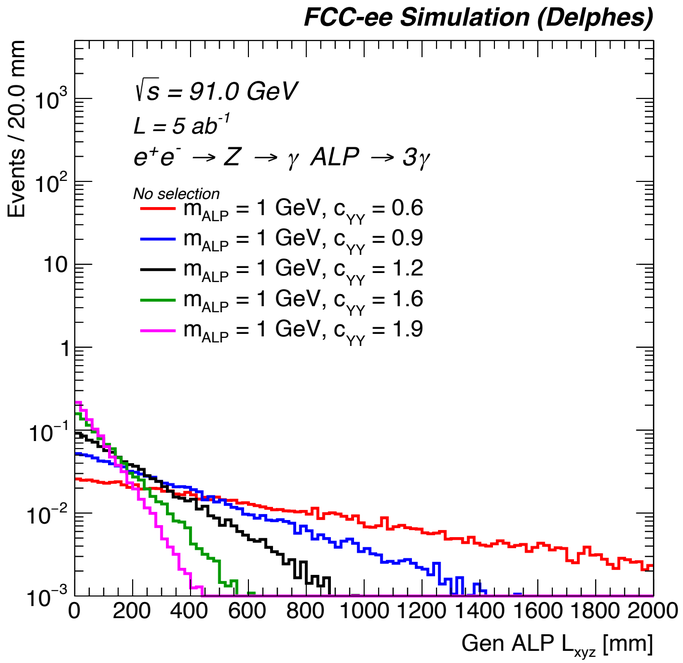


# Backup: ALPs at the FCC-ee

## Axion-Like Particles

- Very first implementation in the FCC framework!
- Generated ALPs in  Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card, $\sqrt{s} = 91$ GeV
- 1 GeV mass, with varying the coupling $C_{\gamma\gamma}$




- ALP mass confirmed with the reco invariant mass from the 2 photons coming from the ALP
- ALP decay length will also be a nice discriminating variable

# Backup: Sensitivity

- **Theory prediction** specifics:
  - from arXiv:1411.5230
  - Prediction includes all HNL decay modes, not only electrons
  - $10^{12}$ Z bosons
  - Decay length between 10-100cm

Preliminary