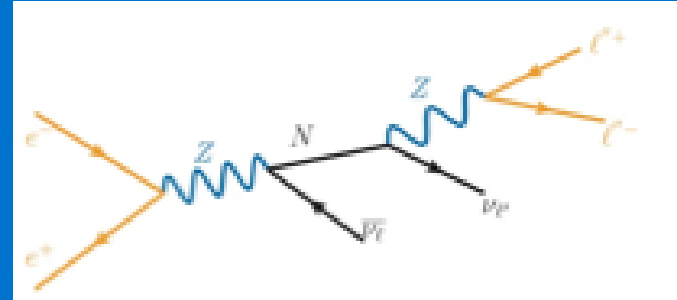
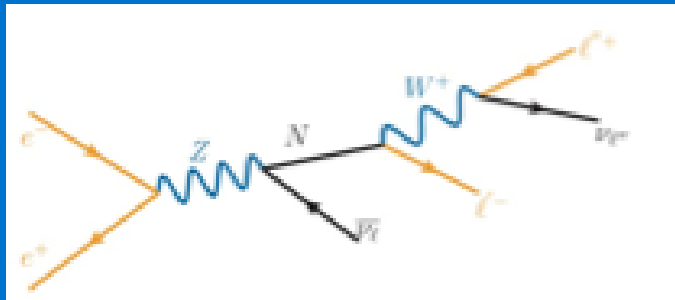


HNL studies in $ee\nu$ channel



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

Frontiers in particle physics

This diagram could do with an update (what about the quantum frontier?)

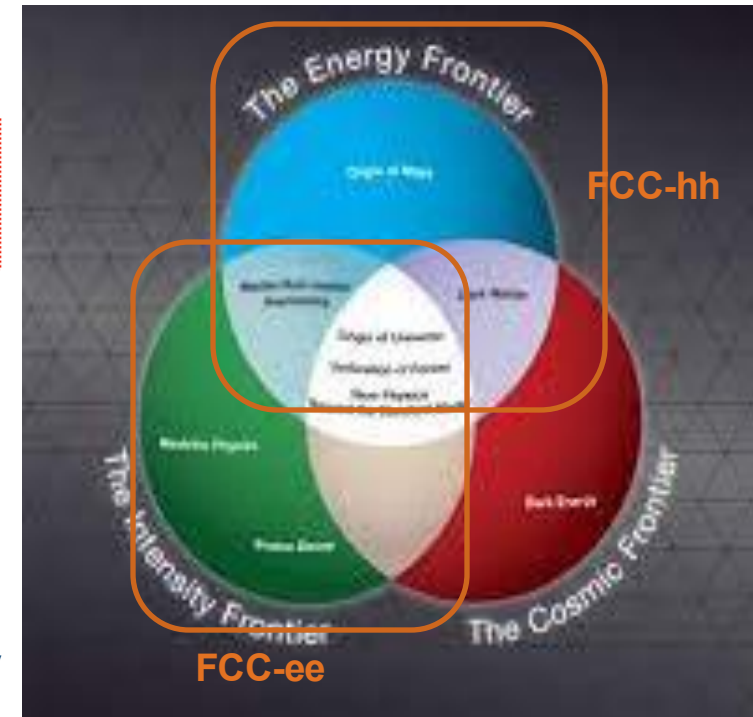
- Pushing the intensity and energy frontiers represent two complementary routes for probing new physics.

What's a discovery in particle physics

S. Gori

- Detecting for the first time a new fundamental process
- Discovering new particles (indirectly or directly)

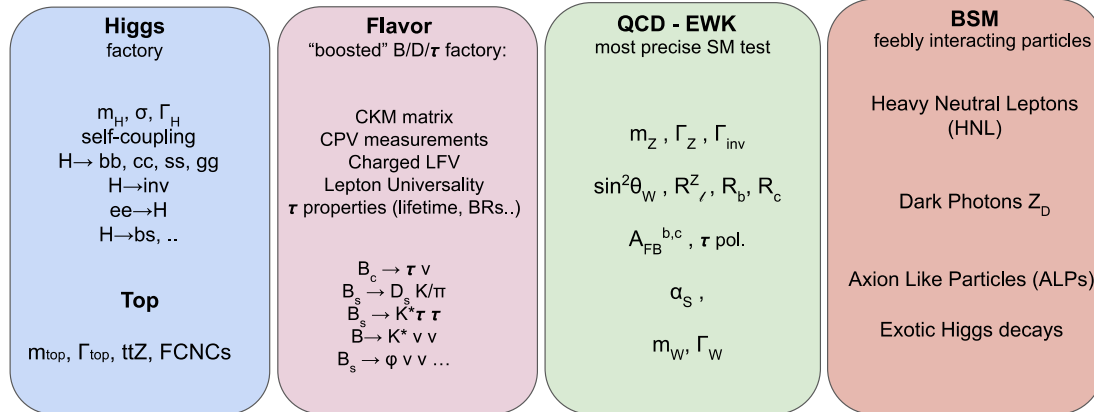
- Whilst the 'focus' of e^+e^- machines is precision (intensity frontier) - FCC-ee could meet all definitions of discovery.
 - Possible evidence for electron/strange yukawa?
 - Direct discovery of $\sim$ low-mass (very) weakly coupled BSM.
 - Indirect discoveries up to ~ 50 -100 TeV.



FCC-ee physics landscape

Schematics from [slides](#) by M. Selvaggi at FCC week

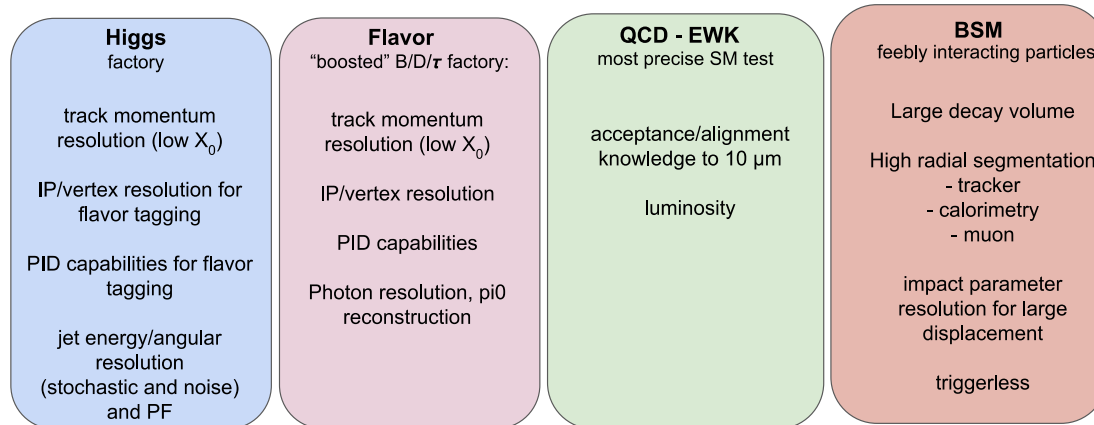
FCC-ee Physics landscape



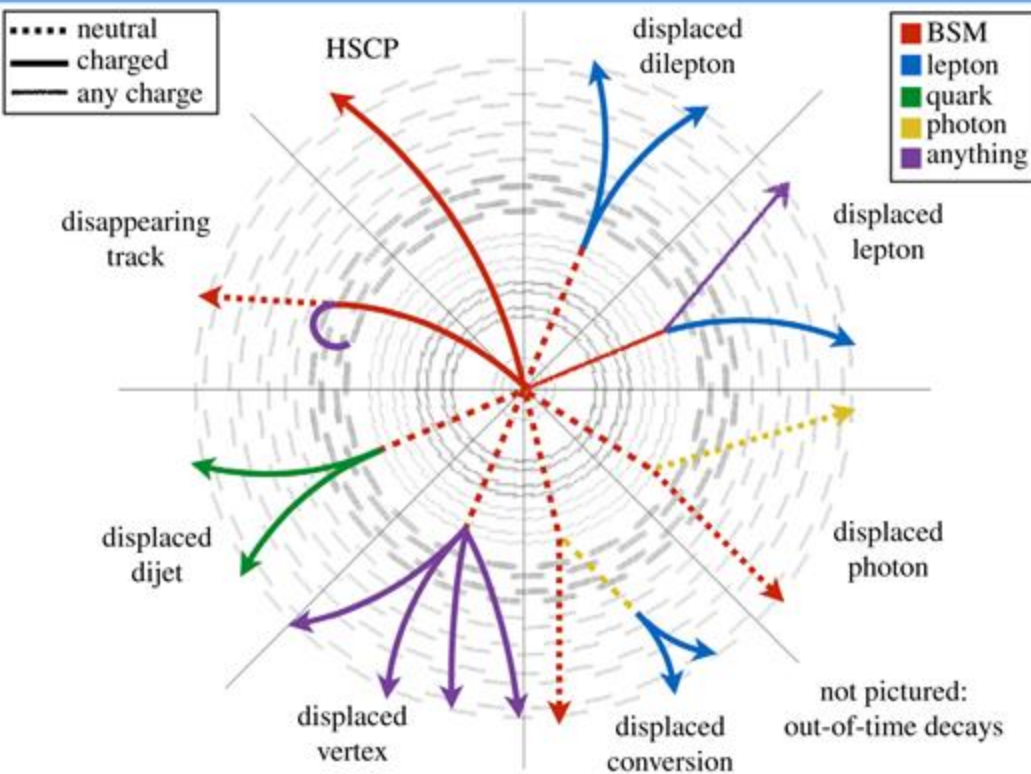
⇒ Broad landscape of physics opportunities!

⇒ Significant effort to study impact of detector concepts across range of physics areas, with lots still to do in the coming years (opportunities for engagement)

FCC-ee Detector requirements



BSM case study: LLPs



LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

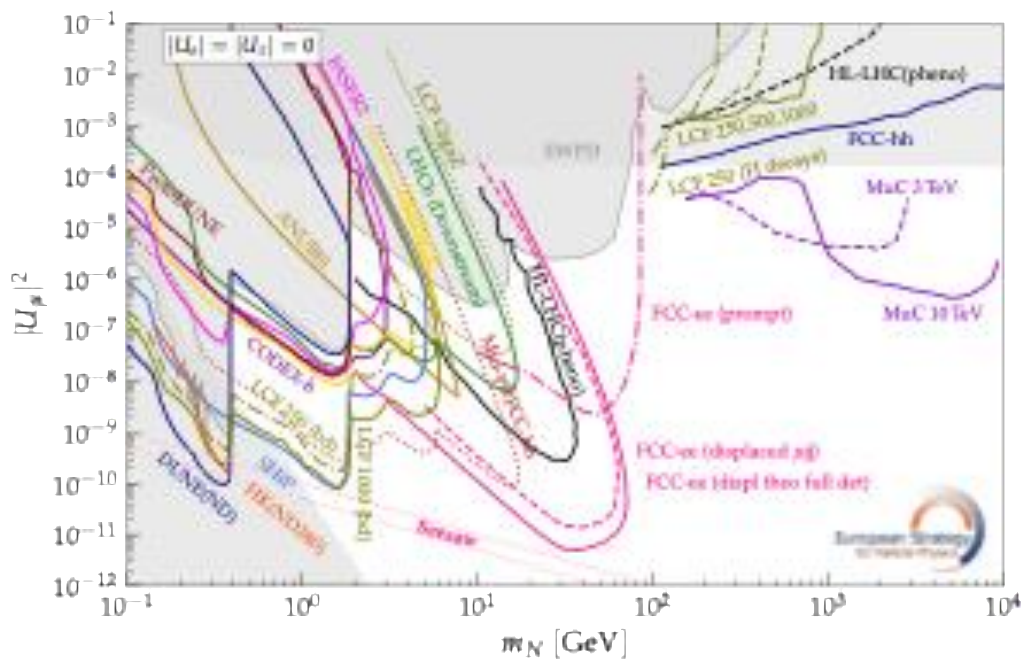
- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- ALPs
- Dark sector models

The range of unconventional signatures and rich phenomenology means that understanding the impact of detector design/performance on the sensitivity of future experiments is key!

LLPs @ FCC-ee

High luminosities at Z-pole and ZH threshold offer unique sensitivity to LLPs coupling to Z or Higgs.

- No trigger requirements.
- Excellent vertex reconstruction and impact parameter resolution can target low LLP lifetimes (this can drive hardware choices).
- **Projections often assume background-free searches** (we should check these assumptions).



ESPPU briefing plot for HNLs mixing with muon neutrinos.

Heavy Neutral Leptons (HNL) at FCC-ee

Snowmass review: [arXiv:2203.08039](https://arxiv.org/abs/2203.08039)

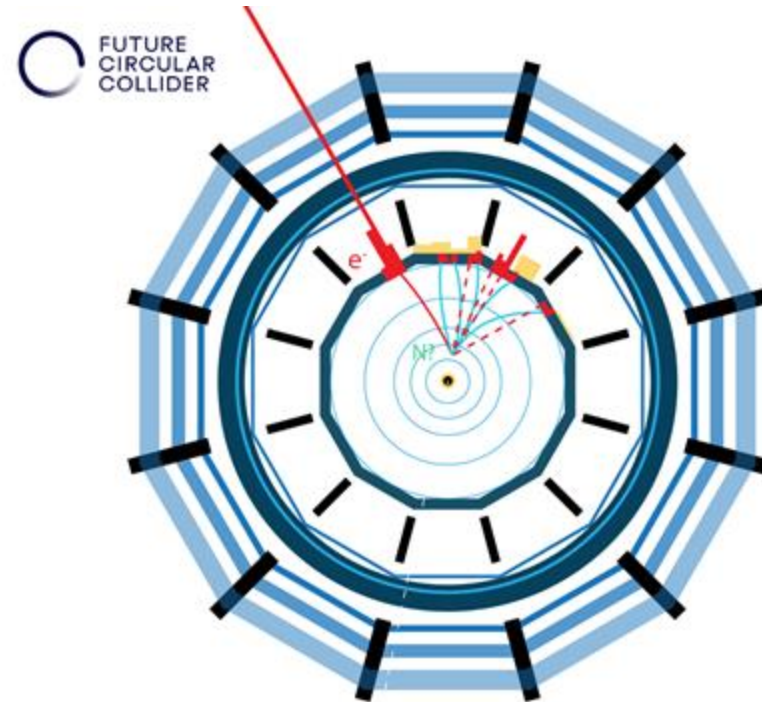
[Front. Phys. 10:967881 \(2022\)](https://arxiv.org/abs/2203.08039)

- 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.

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

[arXiv:2210.17110](https://arxiv.org/abs/2210.17110)

i.e. LLPs when couplings and masses are small!



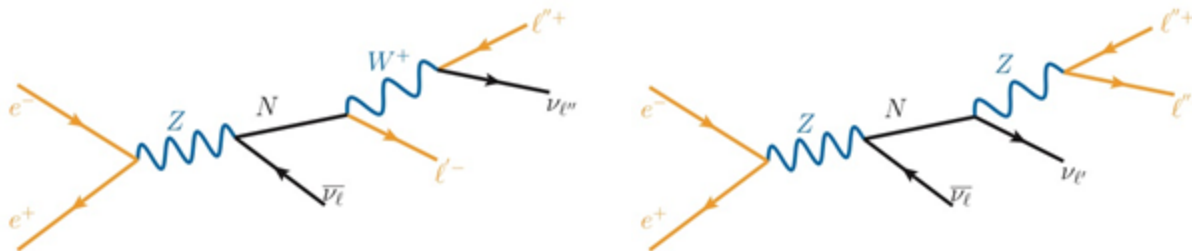
$c_{\text{det}} = 1$ (majorana) or $\frac{1}{2}$ (dirac)

HNL searches at FCC-ee Tera-Z run

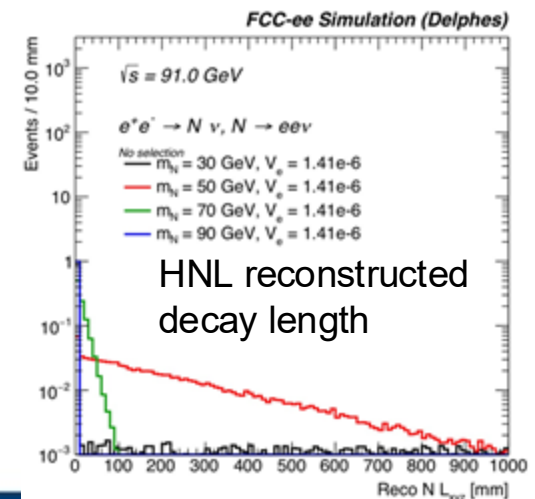
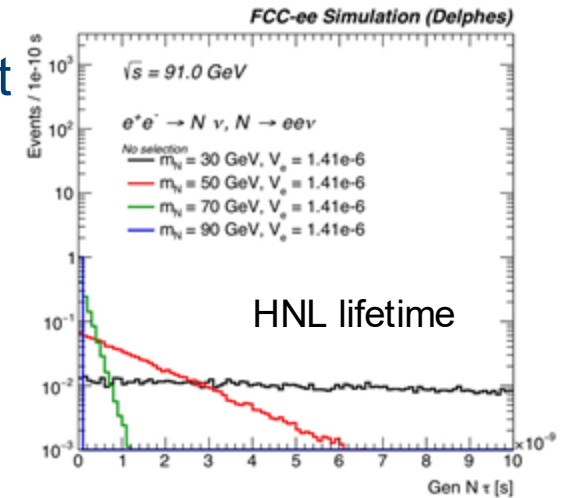
[Front. Phys. 10:967881 \(2022\)](#)

Searches for displaced HNL decays are most efficient at the Z-pole run (larger luminosity and cross-section from $Z \rightarrow N\nu$ decays). Benefit from:

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

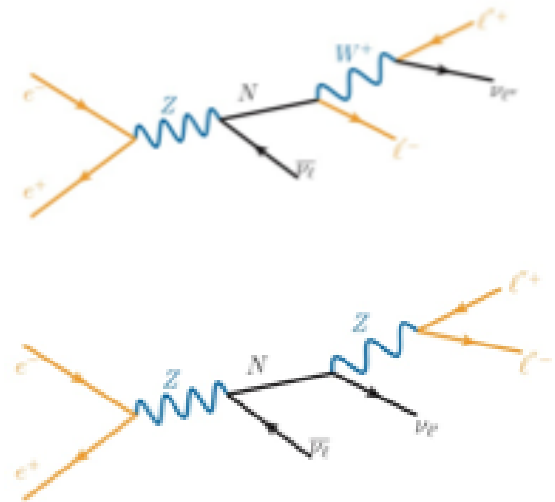


For $N \rightarrow Wl$ decays, depending on the W decay final states include $l'l'\nu\nu$ or $l\nu jj$



HNLs decaying to electron pairs and neutrinos

- Consider scenario where HNLs only have non-zero mixing with ν_e
 - Focus on long-lived scenario and extend work performed for snowmass ([Front. Phys. 10:967881 \(2022\)](#))
- Goals:
 - Study updated (winter23) signal and background samples using IDEA detector.
 - Calculate sensitivity for a background-free search requiring exactly one SV

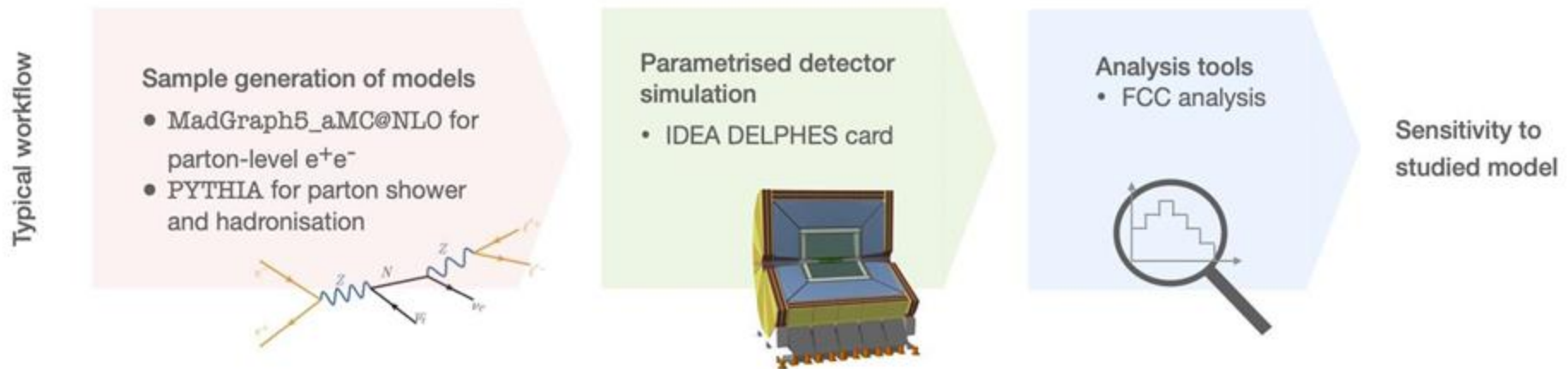


Disclaimer: some of the time on the project got diverted to studying differences between the background samples and technical work towards skimmed MC samples, but this talk will mainly highlight the physics results!

FCC analysis software

<https://key4hep.github.io/key4hep-doc/>

- Integrated in the Key4Hep ecosystem which also provides a common EDM for future collider studies.
- Central MC samples produced (in EDM4HEP format) to facilitate physics/detector studies.
- FCC Analysis software developed to analyse EDM4HEP files and support sensitivity/detector development studies.

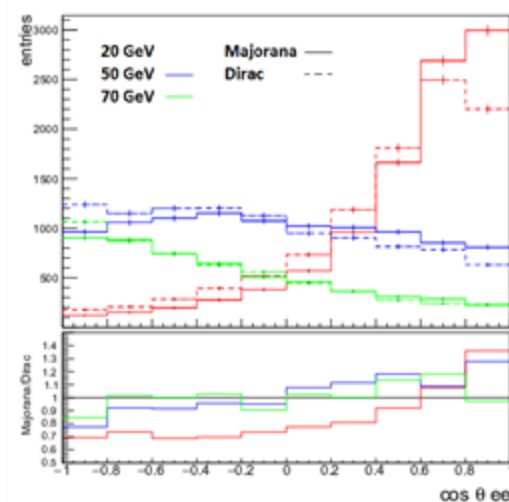
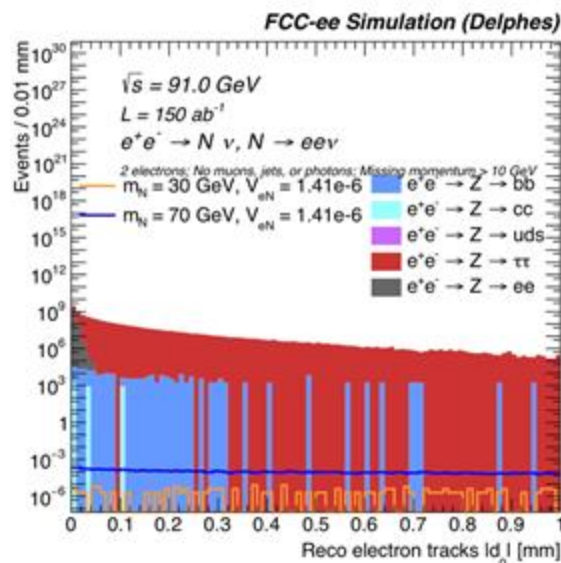
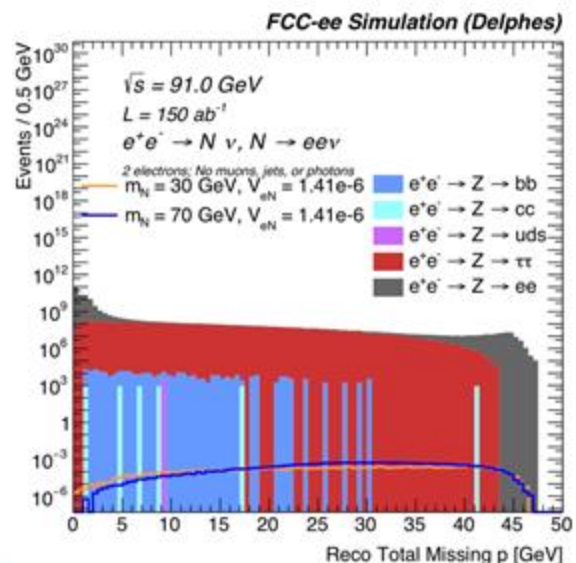


Previous Snowmass studies for HNLs

[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.
 - $p^{\text{Miss}} > 10$ GeV to reduce the $Z \rightarrow ee$ 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 our studies

- Previous study provided distributions and event selection tables motivating cuts to reduce the backgrounds.
- Signal yields were shown but no sensitivity projections provided due to limited MC statistics.
- This study aimed to perform sensitivity studies using new (improved) background samples (with higher statistics) and exploring additional variables.
- This included studying jet reconstruction algorithms and SV reconstruction in key4hep.
- Realistically, studies still limited by MC statistics- and some effort throughout these studies was diverted to investigating skimmed MC samples in key4hep.

Process	Raw events	Ratio to raw events in ref [4]	Cross-section [pb]
$Z \rightarrow ee$	100,000,000	10	1,462
$Z \rightarrow \mu\mu$	100,000,000	10	1,462
$Z \rightarrow \tau\tau$	100,000,000	10	1,477
$Z \rightarrow qq$ ($q=u,d$)	497,658,654	—	11,871
$Z \rightarrow ss$	499,842,440	—	5,216
$Z \rightarrow cc$	499,786,495	5.00	5,216
$Z \rightarrow bb$	438,738,637	4.39	6,646

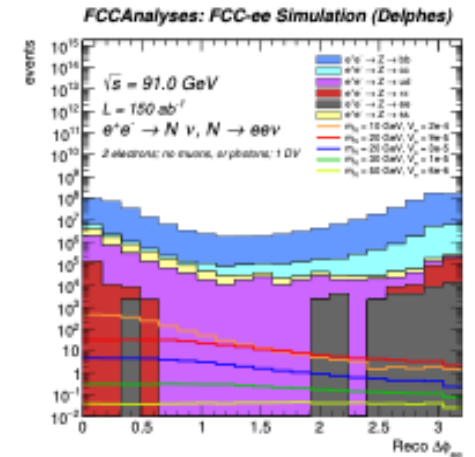
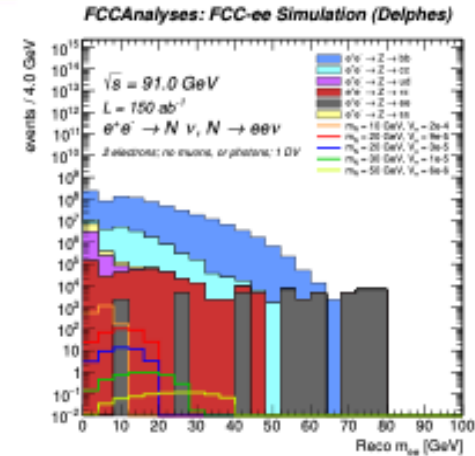
Headline results

- (Subject to background statistics) background-free search could be performed by vetoing jets, muons and electrons and placing requirement of 1 displaced secondary vertex.

$Z \rightarrow$	2 electrons	Veto photons and muons	Veto photons and muons; 1 DV	Veto photons, muons, jets; 1 DV
ee	$2.22\text{e}+11 \pm 1.41\text{e}+09$	$2.22\text{e}+11 \pm 2.58\text{e}+07$	$1.50\text{e}+04 \pm 6.70\text{e}+03$	$\leq 6.70\text{e}+03$
$\tau\tau$	$7.37\text{e}+09 \pm 2.60\text{e}+08$	$7.37\text{e}+09 \pm 4.72\text{e}+06$	$2.42\text{e}+05 \pm 2.71\text{e}+04$	$\leq 2.71\text{e}+04$
$b\bar{b}$	$5.83\text{e}+09 \pm 2.37\text{e}+08$	$5.83\text{e}+09 \pm 4.25\text{e}+06$	$4.21\text{e}+07 \pm 3.62\text{e}+05$	$\leq 3.62\text{e}+05$
$c\bar{c}$	$1.01\text{e}+09 \pm 6.80\text{e}+07$	$1.01\text{e}+09 \pm 1.47\text{e}+06$	$6.52\text{e}+06 \pm 1.18\text{e}+05$	$\leq 1.18\text{e}+05$
$u\bar{u}$	$3.12\text{e}+08 \pm 8.63\text{e}+07$	$3.12\text{e}+08 \pm 1.23\text{e}+06$	$2.87\text{e}+06 \pm 1.18\text{e}+05$	$\leq 1.18\text{e}+05$
$s\bar{s}$	$1.62\text{e}+08 \pm 2.72\text{e}+07$	$1.62\text{e}+08 \pm 5.89\text{e}+05$	$4.49\text{e}+06 \pm 9.80\text{e}+04$	$\leq 9.80\text{e}+04$

Table 5: Event yields, normalised to 205ab^{-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.

- Larger background samples would enable further optimization using additional variables (some included in the FCC note <https://repository.cern/records/v5bst-9ak09>).



Sensitivity

For final sensitivity plot, normalize to the luminosity listed here:

<https://fcc-ped.web.cern.ch/content/machine-parameters>

i.e. 205 ab⁻¹ at and around the Z pole (40 ab⁻¹ at 87.9 GeV, 40 ab⁻¹ at 94.3 GeV, 125 ab⁻¹ at 91.2 GeV, for a total of about 6.10¹² Z)

- Background-free search could be performed by vetoing jets, muons and electrons and placing requirement of 1 displaced secondary vertex (reconstructed with tracks with $|d_0| > 2\text{mm}$).

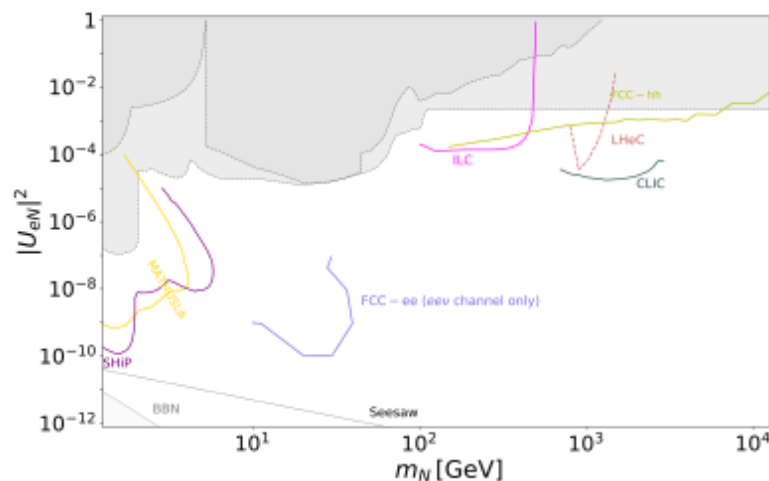
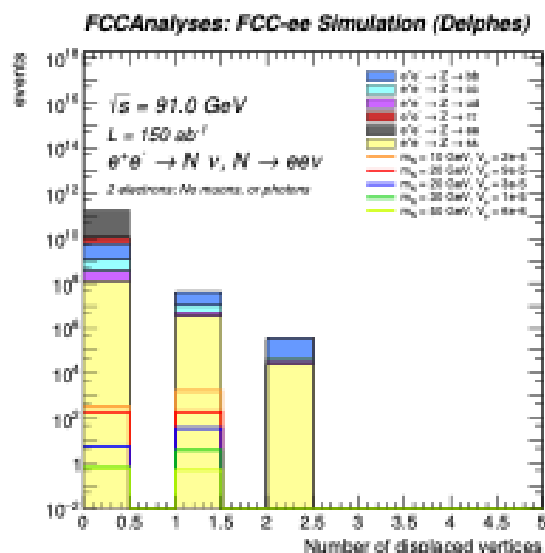


Figure 14: Comparison of the 3-event contour for the selection outlined in this study assuming a background-free search with signal yields normalised to 6×10^{12} Z bosons, compared to a selection of collider (and other) constraints compiled through the work of Ref. [14], as a function of the HNL mass and the electron-neutrino coupling, for the signal points displayed in Table 6

Purple line shows 3-event contour- maximal sensitivity would involve combining channels!

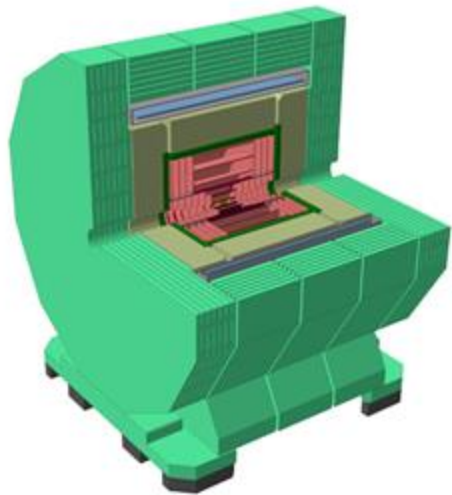
Conclusion and outlook

- I have summarized studies performed in Cambridge on the FCC-ee sensitivity to HNLs.
- There is a very active community studying LLPs with lots still to do (including studying impact of detector configurations).
- There will be a BSM round-table at CERN on 16th January to discuss plans moving forwards
<https://indico.cern.ch/event/1610585/>
- Thanks for listening- I am happy to take questions!

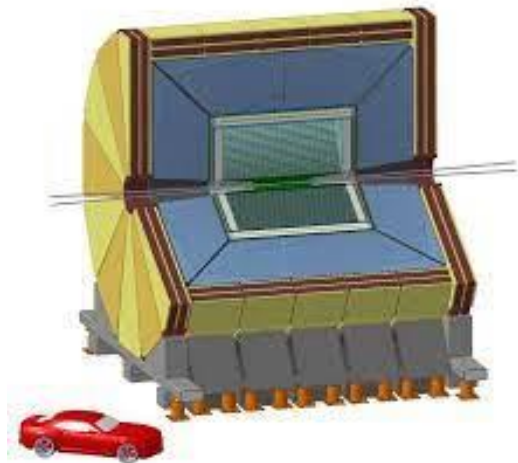


Detector concepts for FCC-ee

CLD (“CLIC-like Detector”)

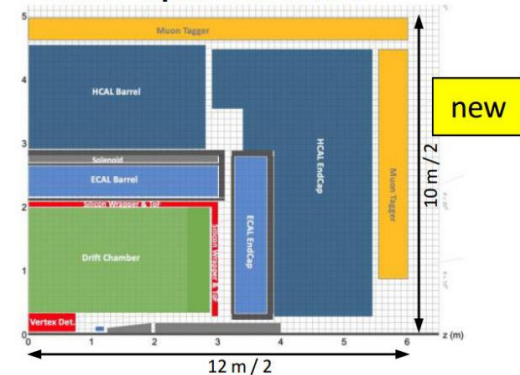


IDEA (“Innovative Detector for Electron-positron Accelerator”)



“Allegra”

Noble Liquid ECAL based



Full silicon vertex-detector+ tracker
3D high-granularity calorimeter
Solenoid outside calorimeter

Silicon vertex detector
Short-drift chamber tracker.
Dual-readout calorimeter

New proposal using liquid
LAr calorimeter!

Easy to study impact of detector design on physics sensitivity through FCC software framework!