Sensitivity to Long-Lived Particles at the FCC-ee

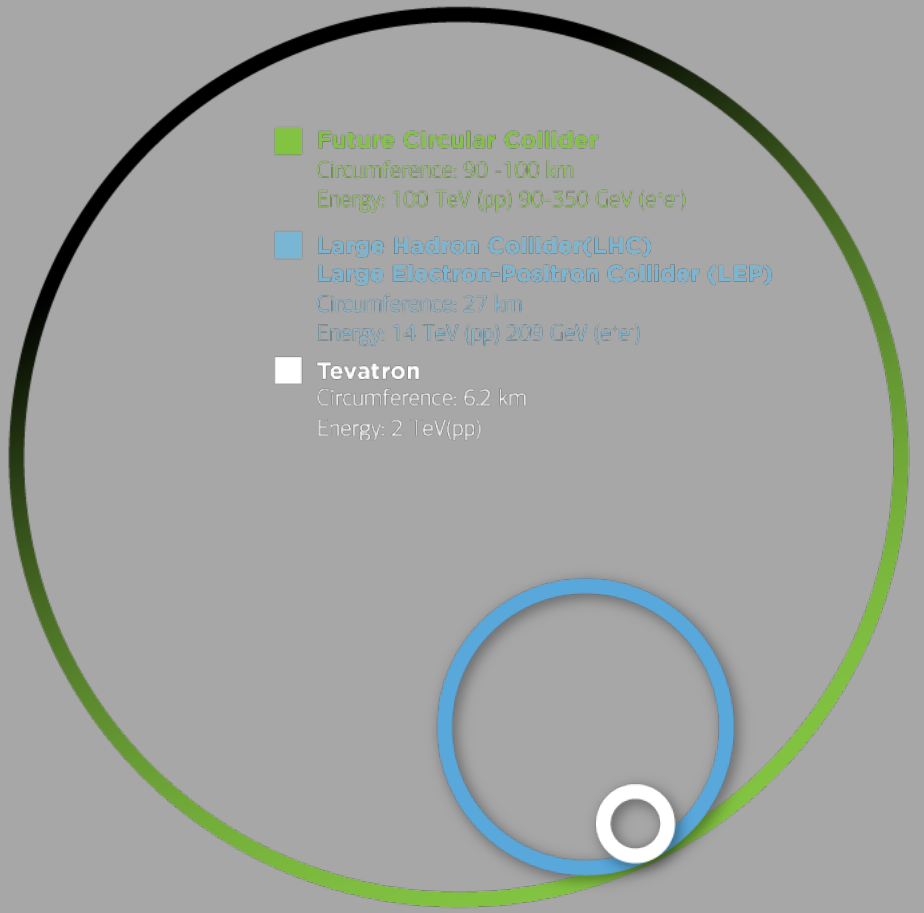
Juliette Alimena (CERN) on behalf of the LLPs at FCC-ee group

Snowmass EF09 BSM-General Meeting on LLPs

November 19, 2021

FCC-ee

- The FCC-ee is the electron-positron stage of the Future Circular Collider (FCC)
- Post-LHC circular collider program at CERN
    - Recommendation of the Update of the European Strategy for Particle Physics
- One 100 km tunnel, two stages:
    - Stage 1: FCC-ee (Z, W, H , tt) as 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

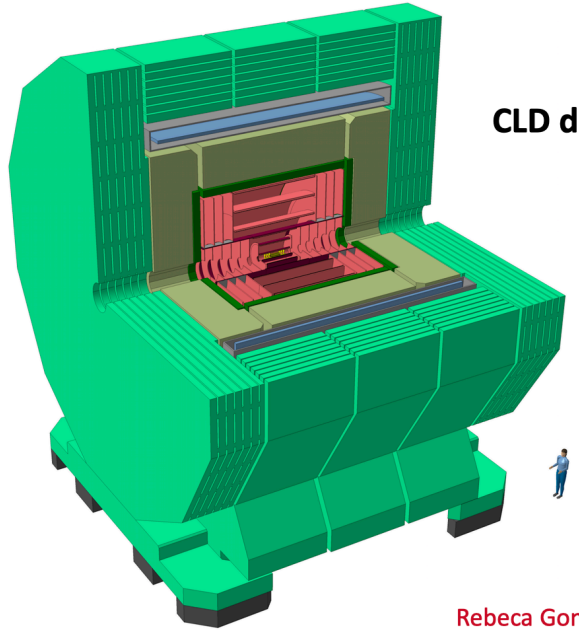


The FCC-ee is primarily a Higgs factory but will offer many other options to explore tops, flavor physics, precision physics and directly discover new physics

Enter LLPs!

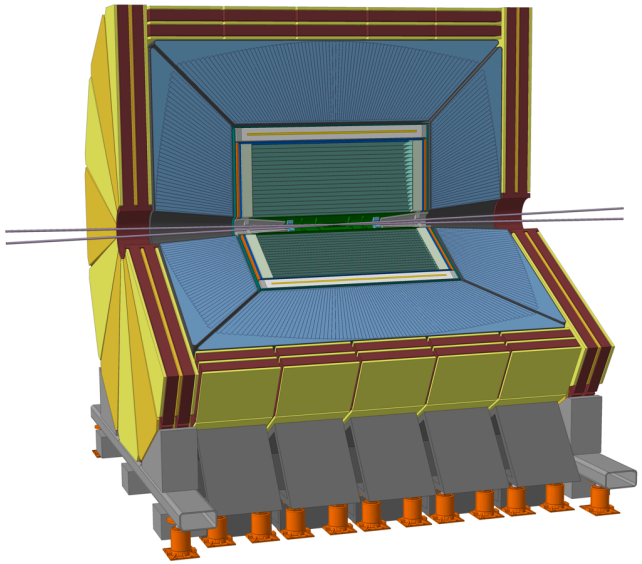
Detectors

- **Two detector concepts** used for integration, performance, and cost 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)
- Now ready to take a broader look at the physics potential and optimize detector designs for a complete physics program
- **Have the opportunity to design general-purpose detectors with LLPs in mind!**
  - Can prioritize e.g. displaced tracking and timing information
  - Can also prioritize LLPs in the online filtering and offline reconstruction
- FCC-ee new baseline is consistent with having 2 or 4 detectors
  - Opportunities for new, creative designs!
  - E.g. HECATE dedicated to long lifetimes (arXiv:2011.01005)



CLD design

Rebeca Gonzalez Suarez



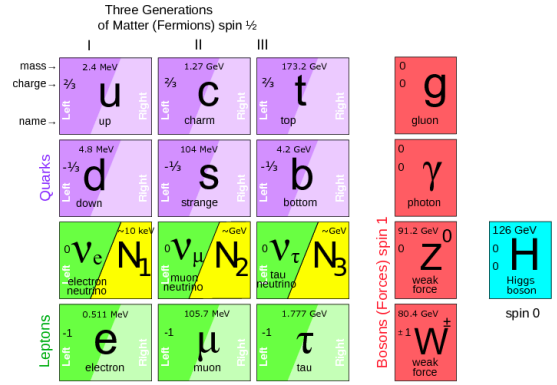
IDEA design

Goals

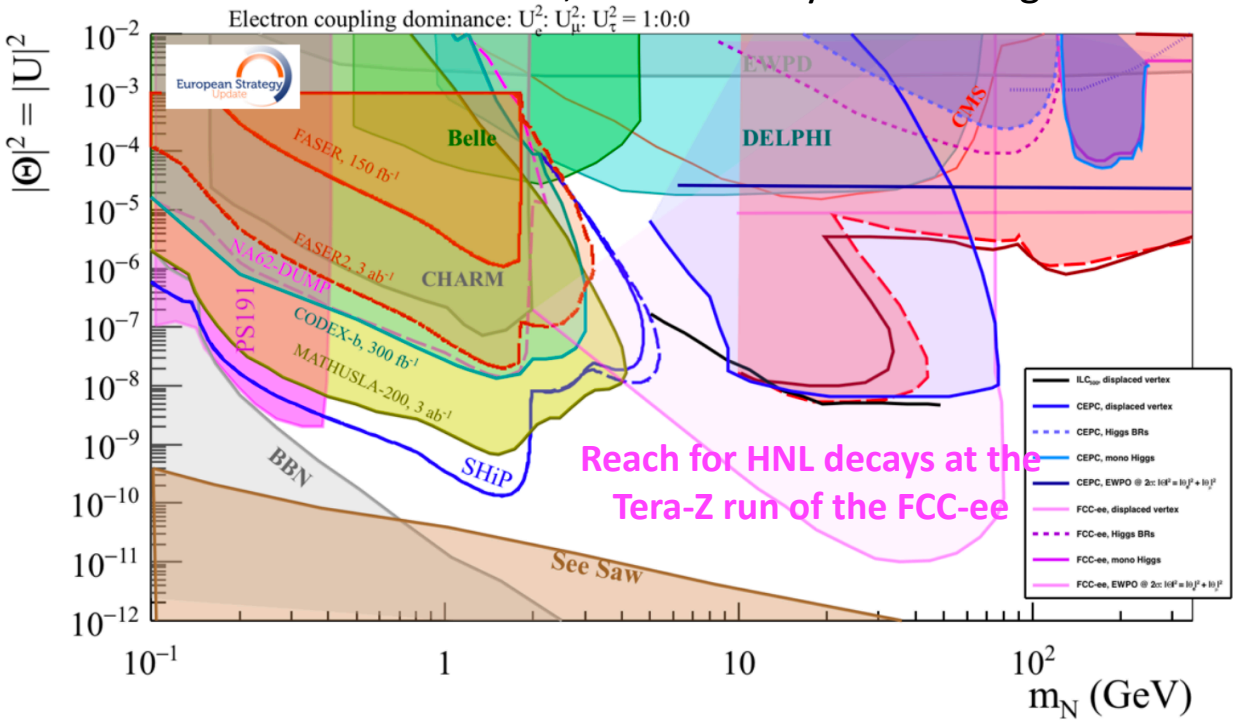
- **Theoretical discussion** and **experimental analysis** with **FCC software** for 3 long-lived benchmark models:
    1. Heavy Neutral Leptons (HNLs)
    2. Axion-like Particles (ALPs)
    3. Higgs bosons with exotic decays to LLPs
- Analysis includes:
    - Generate and run signals and backgrounds through FCC software (Delphes, key4hep)
    - Long-lived signal reconstruction efficiency, vertexing performance
    - Event selection
    - Estimate backgrounds from simulation
    - Limits/discovery plots
- Build on the work done for the LOI and Rohini Sengupta's Masters thesis
- Complete white paper in time for Snowmass

1st Benchmark: LL Heavy Neutral Leptons

- Right-handed, sterile neutrinos
- Dirac or Majorana fermions with sterile neutrino quantum numbers
- Heavy enough to not disrupt the simplest BBN bounds and/or unstable on cosmological timescales
- Could shed light some open questions of the SM:
  - Neutrino masses
  - Baryon asymmetry
  - Dark matter



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



FCC will probe space not constrained by astrophysics or cosmology,

complementary to accelerator and neutrino prospects

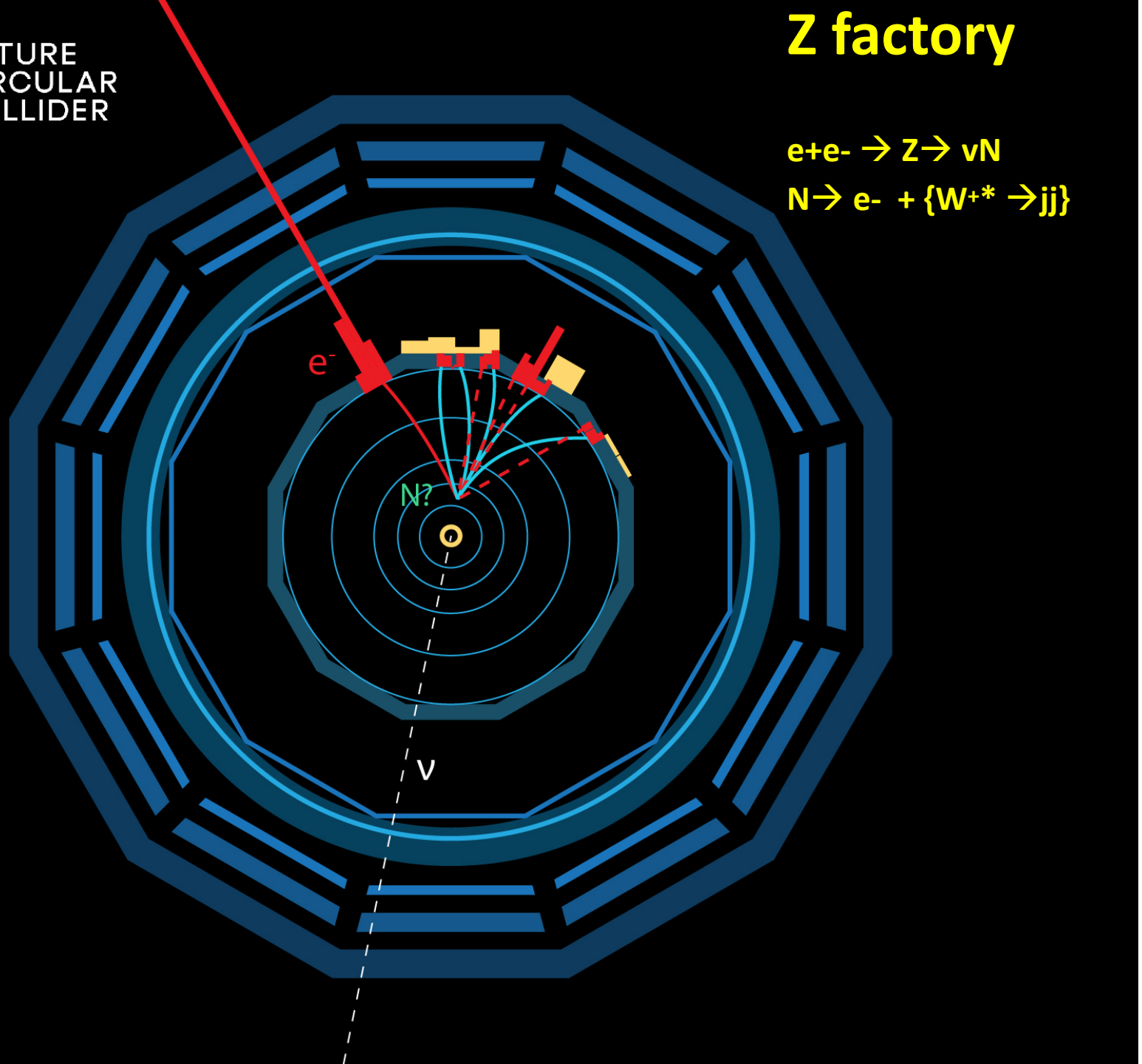
HNLs at the FCC-ee are right in the parameter region that is good for baryogenesis! arXiv:2106.16226

FUTURE CIRCULAR COLLIDER

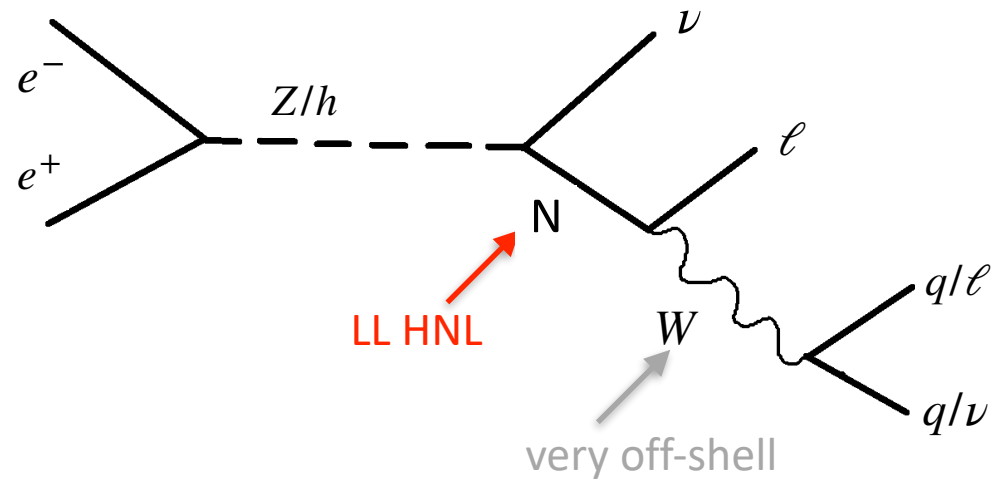
Z factory

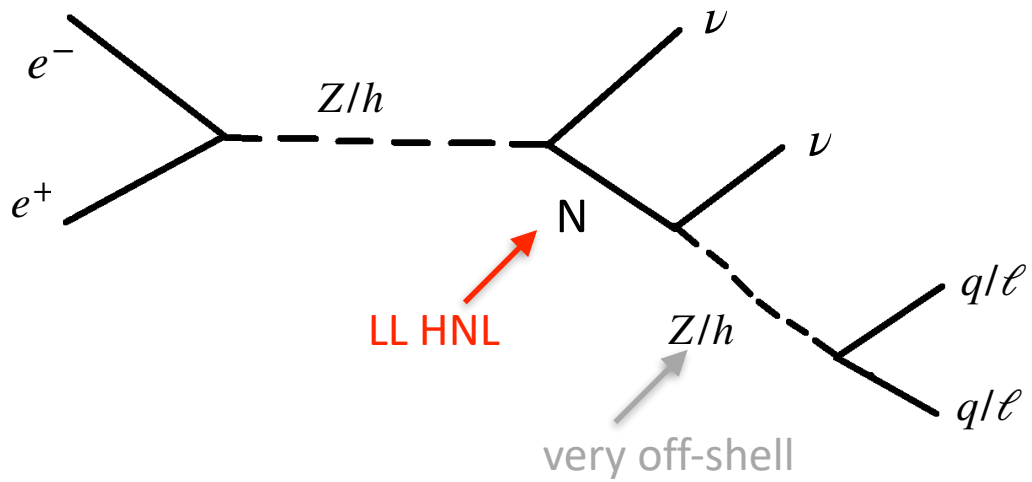
$e^+e^- \rightarrow Z \rightarrow \nu N$

$N \rightarrow e^- + \{W^{+*} \rightarrow jj\}$



Simulating HNLs





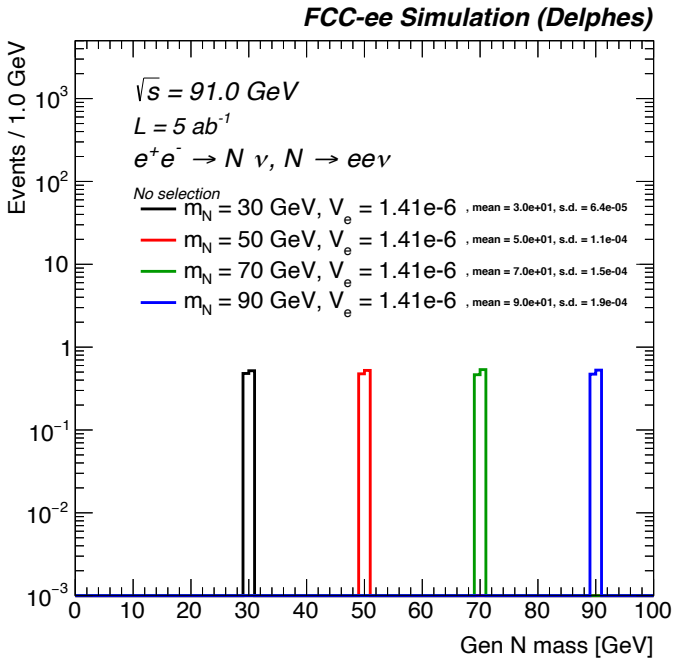
- Generated Majorana and Dirac HNLs with the SM_HeavyN_CKM_AllMasses_LO and SM_HeavyN_Dirac_CKM_Masses_LO models (arXiv:411.7305, arXiv:1602.06957)
- Started with the $ee\nu$ final state (first suggested in 1984(!) by S. Petcov)
- Generated in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card
- $\sqrt{s} = 91\ \mathrm{GeV}$
- Experimental signature of LL HNLs: displaced vertex

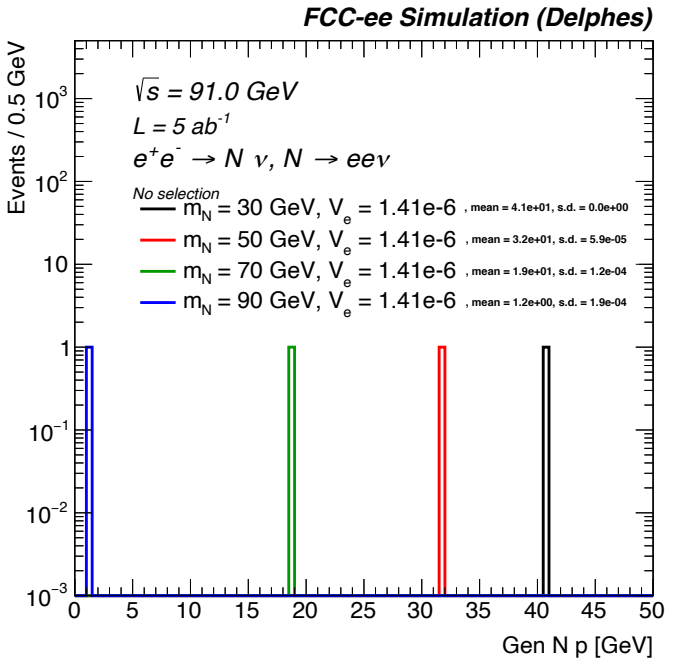
$$L \sim 0.025\mathrm{m}\left(\frac{10^{-6}}{V_l}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_N}\right)^5$$

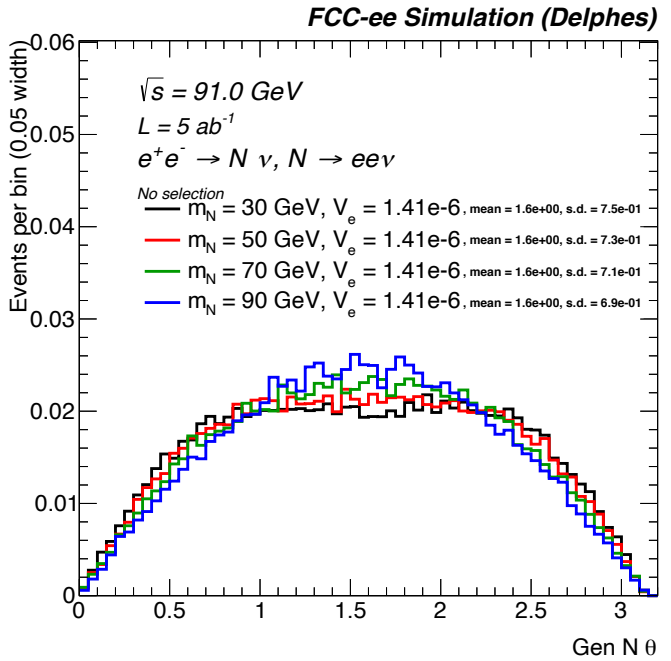
[Valid when $m_N \lesssim 100\ \mathrm{GeV}$, arXiv:1905.11889]

Get long-lived HNLs when coupling and mass are small

Generated HNL Kinematics

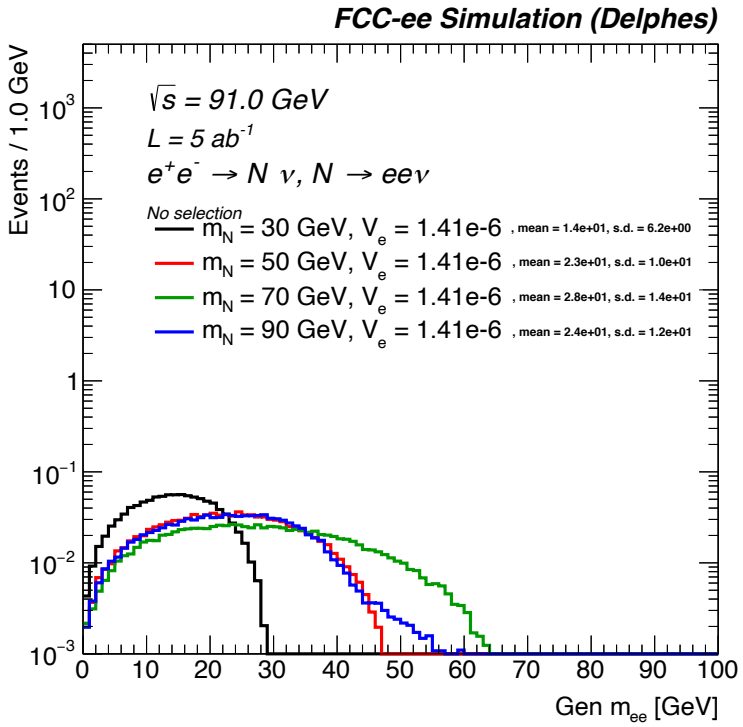


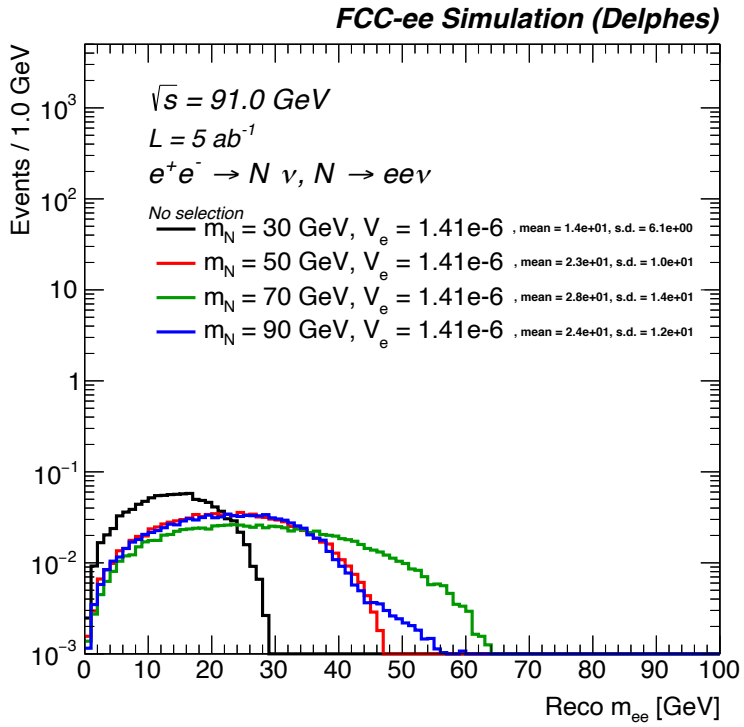




- At the FCC-ee, should look at total momentum, θ, and total missing energy!
- Generator-level distributions look as expected
  - Momentum decreases as HNL mass increases
  - Slightly more central events as HNL mass increases

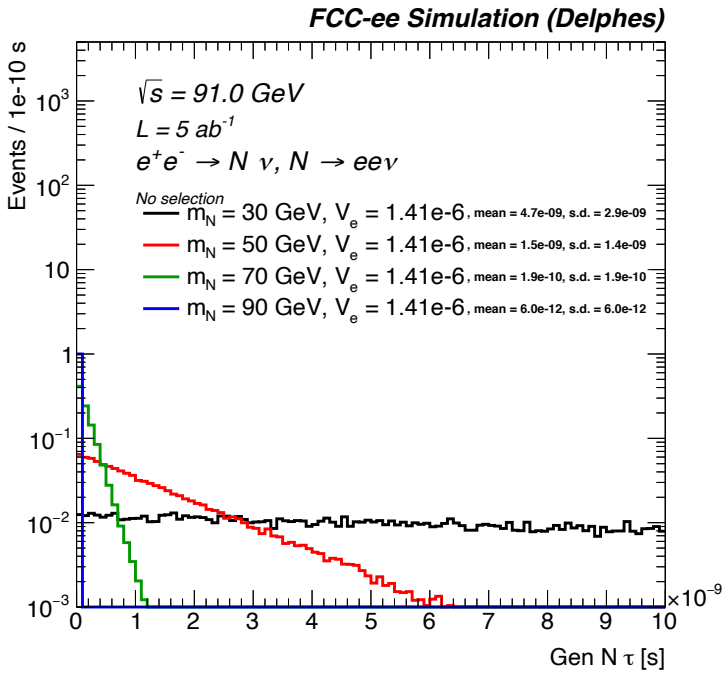
ee Invariant Mass

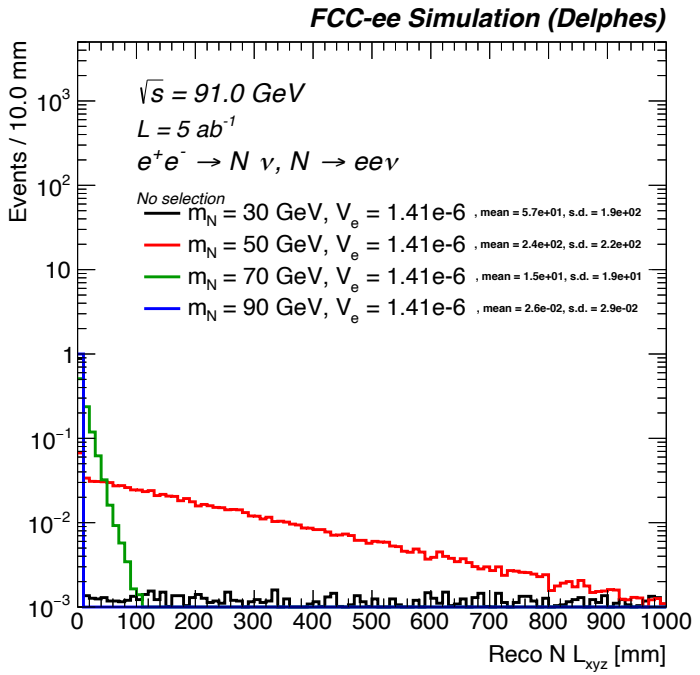


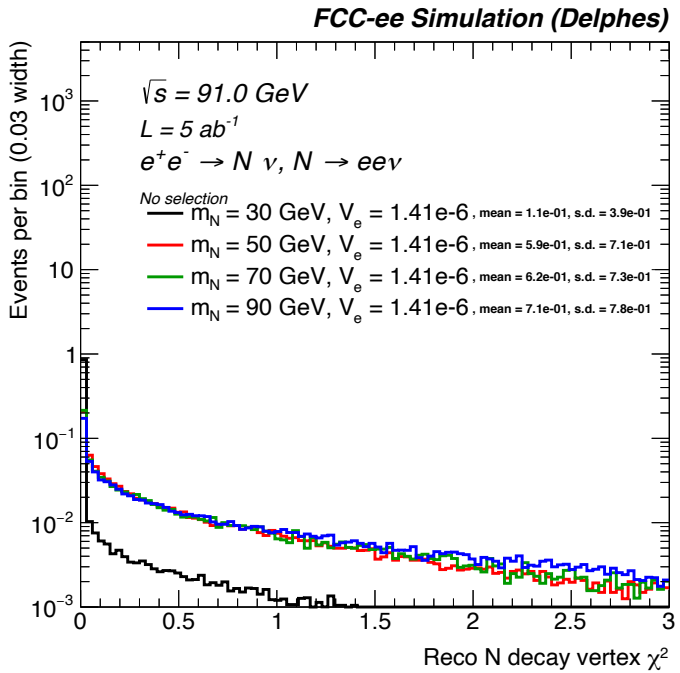


- Invariant mass from final state electrons and positrons makes sense, at gen and reco level
- Less energy available to electrons for 90 GeV mass than 70 GeV, so the mean of the 90 GeV invariant mass distribution is smaller than for 70 GeV
- Good agreement between gen and reco distributions

HNL Lifetime and Decay Vertex







- Generated proper lifetime looks as expected
  - For example, for 50 GeV mass, the mean lifetime is 1.5E-9 s —> 45 cm, which is what we expected
  - m = 90 GeV is pretty prompt
- Reco L_{xyz} and vertex χ^2 are also reasonable

m_{HNL} = 50 GeV

V_e = 0.1

Tanishq Sharma

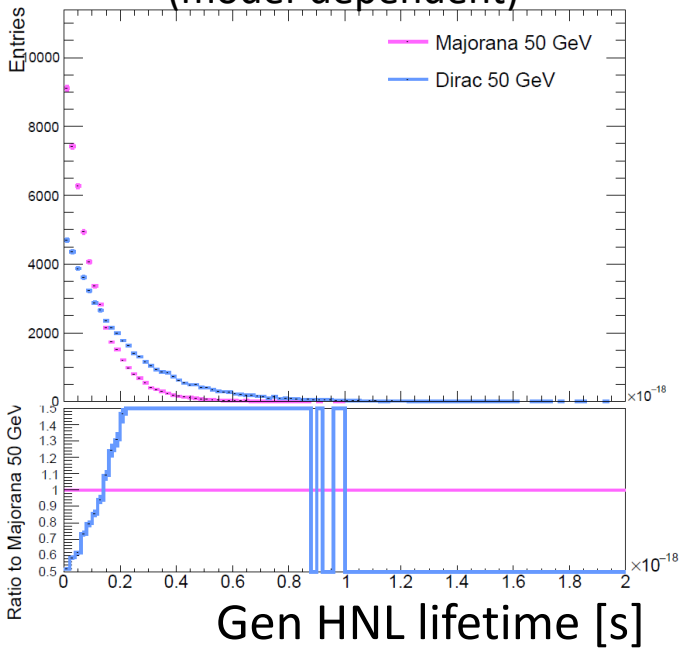
Majorana vs Dirac

Majorana and Dirac HNLs produce different kinematic distributions: arXiv:2105.06576

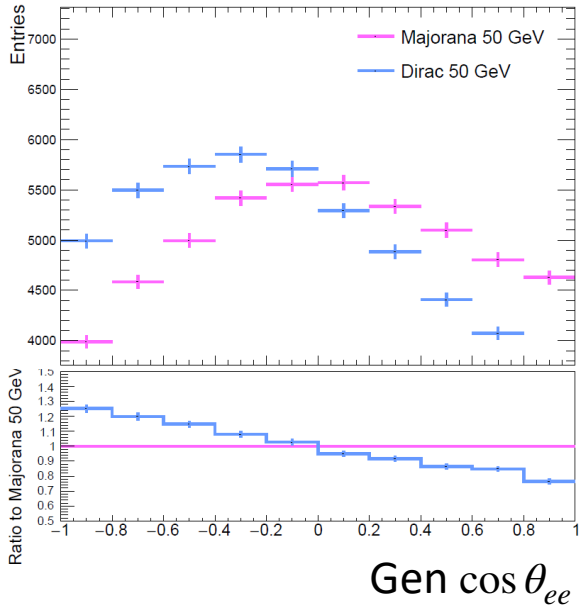
Variables that can distinguish between Majorana and Dirac HNLs:

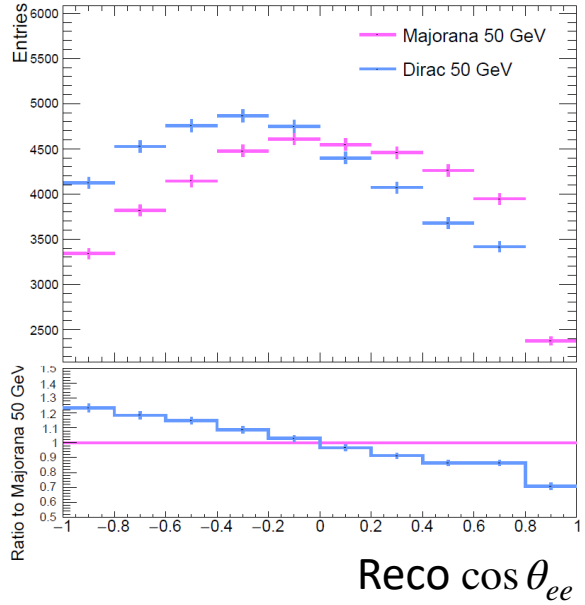
HNL Lifetime

(model-dependent)



$\cos\theta_{ee}$



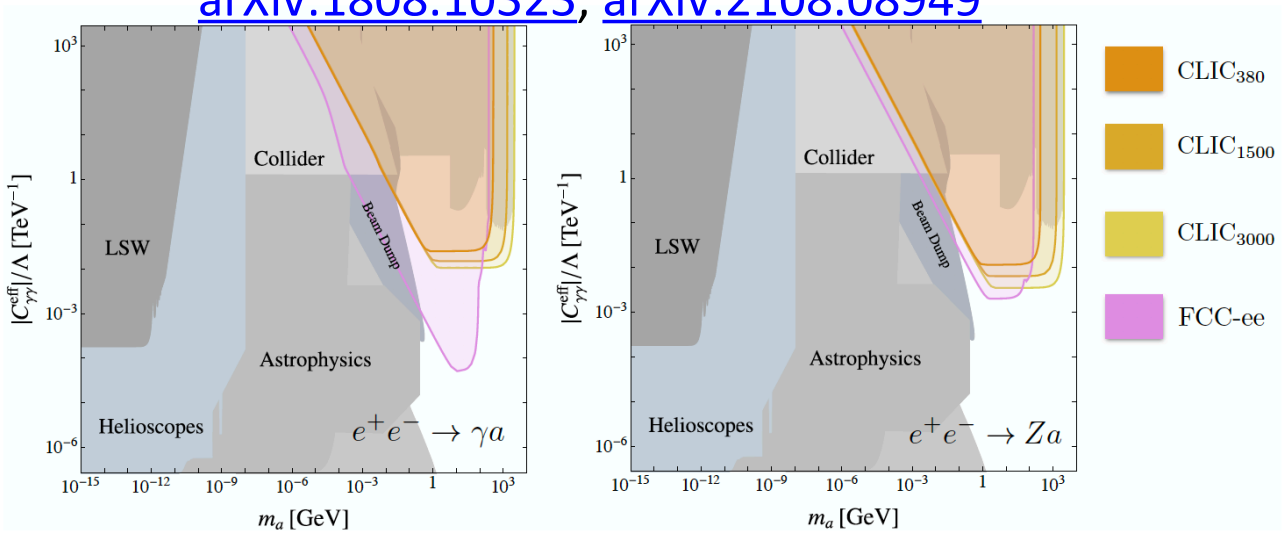


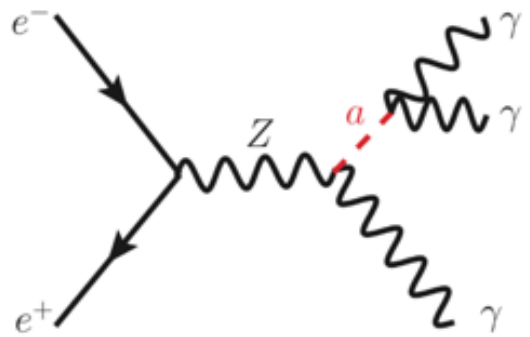
Next: improve reconstruction, find more discriminating variables

2nd Benchmark: LL Axion-Like Particles

- Axion-like Particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries in BSM scenarios
- Very weakly coupled to the dark sector
- Get long-lived ALPs when couplings and mass are small
- At the FCC-ee:
  - Orders of magnitude of parameter space accessible
  - Especially sensitive to final states with at least 1 photon
- **Status:** implemented and tested baseline ALP configuration in FCC framework, starting to generate in Madgraph

[arXiv:1808.10323](), [arXiv:2108.08949]()

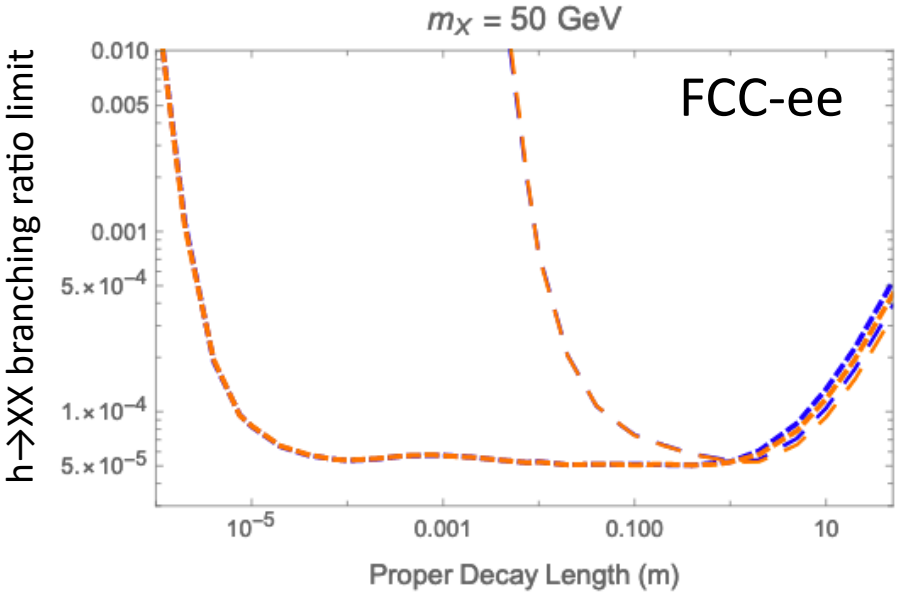




3rd Benchmark: Exotic Higgs decays to LLPs

- Higgs bosons could undergo exotic decays to e.g. scalars that could be long-lived
- Exotic Higgs decays to LLPs could be explored at future colliders
  - Twin Higgs models with displaced exotic Higgs boson decays, Hidden Valley models with Higgs bosons decaying to neutral LLPs (arXiv:1812.05588)
  - LLPs from Higgsinos or exotic Higgs decays (arXiv:1712.07135)
- **Status:** to do! Can do with e.g. this model in Madgraph

arXiv:1812.05588



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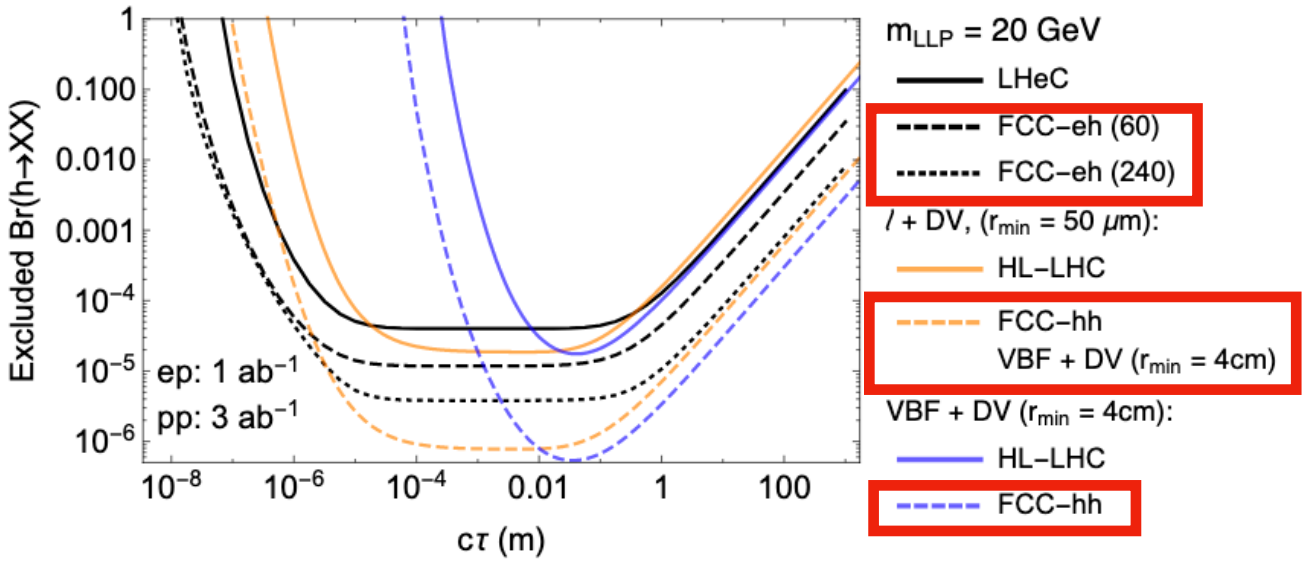

Some Physics Questions
That We Can Probe

- How well can we distinguish a long-lived HNL/ALP/exotic Higgs decay from SM backgrounds?
  - For leptonic decays? For hadronic decays? For decays to photons?
- What is the vertexing performance of the FCC-ee prototype detectors?
- Can we use time-of-flight (once ported to key4hep) as a discriminating variable at the FCC-ee?
- How does modifying the detector configuration allow us to probe a larger/different theory landscape?
  - Bigger tracker? More layers?
- At the FCC-ee, can we distinguish between Majorana and Dirac HNLs?
- Not an exhaustive list!

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A reach goal?

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Some Technical Developments

- The FCC and FCC-ee software is in a somewhat early stage
  - We can contribute here as well!
  - We are one of very few ongoing direct BSM searches at the FCC-ee

<u>Developments:</u>

- Simulated samples: eventually to be centrally produced
  - Signal + background
- key4hep developments, e.g:
  - Truth matching
- Try out the FCC-ee full simulation
- Analysis framework developments on ROOT DataFrame

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LLPs at FCC-ee group

- Informal group with:
  - Meetings: https://indico.cern.ch/category/5664/
  - Mailing list: <LLP-FCCee-informal@cern.ch>
- We welcome new people, join us!

Summary

- Exploring the sensitivity of the FCC-ee to long-lived particles in time for Snowmass
- Understanding HNL simulation
  - Long-lived HNLs with displaced vertex reconstructed
  - Can distinguish between Majorana and Dirac HNLs
- Started to implement simulation of ALPs
- Next major step: simulate backgrounds
- We have synergies with many other Snowmass groups looking for LLPs, particularly HNLs, groups interested in the FCC, etc: will keep the communication lines open!
- Several masters students starting now on some of the open tasks
- Lots to explore, largely independent tasks: room for others to come on board!