This project is supported from the European Union's Horizon 2020 research and innovation program under grant agreement No 951754.

Long-Lived Particles at the FCC-ee

Juliette Alimena (CERN), on behalf of the FCC-ee LLP group

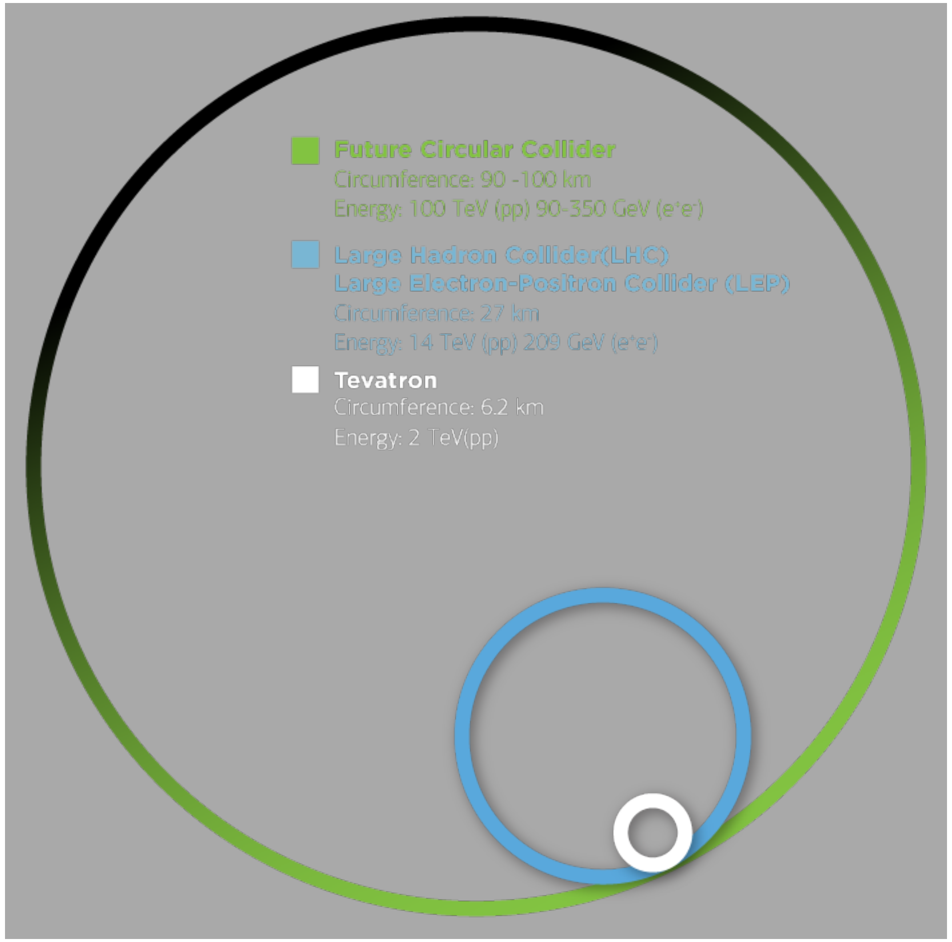
FCC Week, Campus des Cordeliers - Sorbonne Université

May 31, 2022

Future Circular Collider

Future Circular Collider (FCC) will have one 100 km tunnel, two stages:

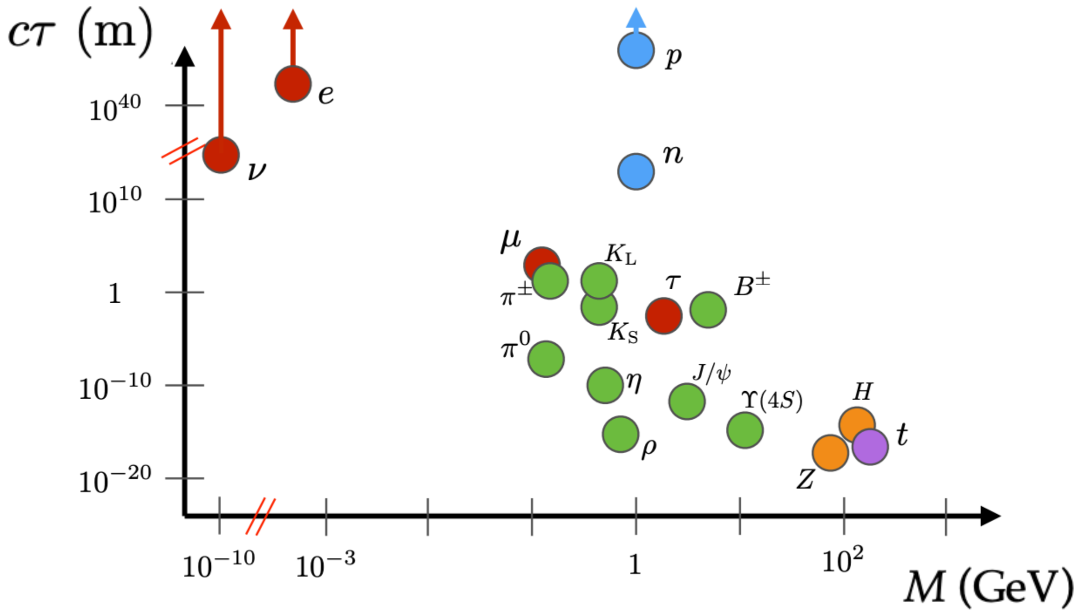
- Stage 1: FCC-ee (Z, W, H , tt) as Higgs EW and top factory at high luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options



The FCC is is a frontier Higgs, top, electroweak, and flavor factory where we can directly discover new physics ← **Enter LLPs!**

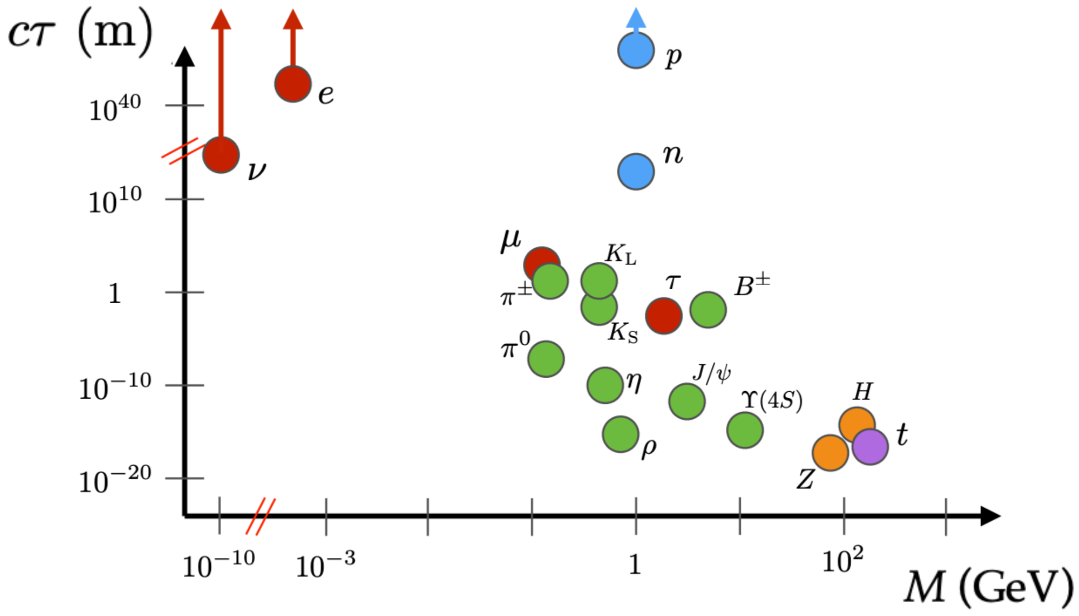
Long-Lived Particles (LLPs)

Standard model particles span a **wide range of lifetimes (τ)**



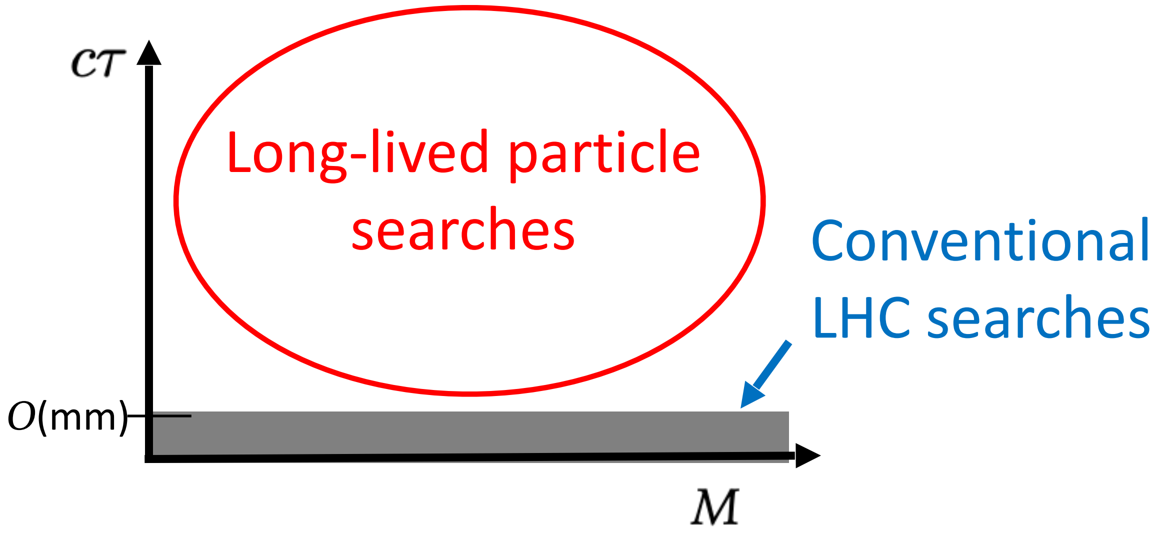
Long-Lived Particles (LLPs)

Standard model particles span a **wide range of lifetimes (τ)**



We expect **new phenomena** to have a wide range of lifetimes as well

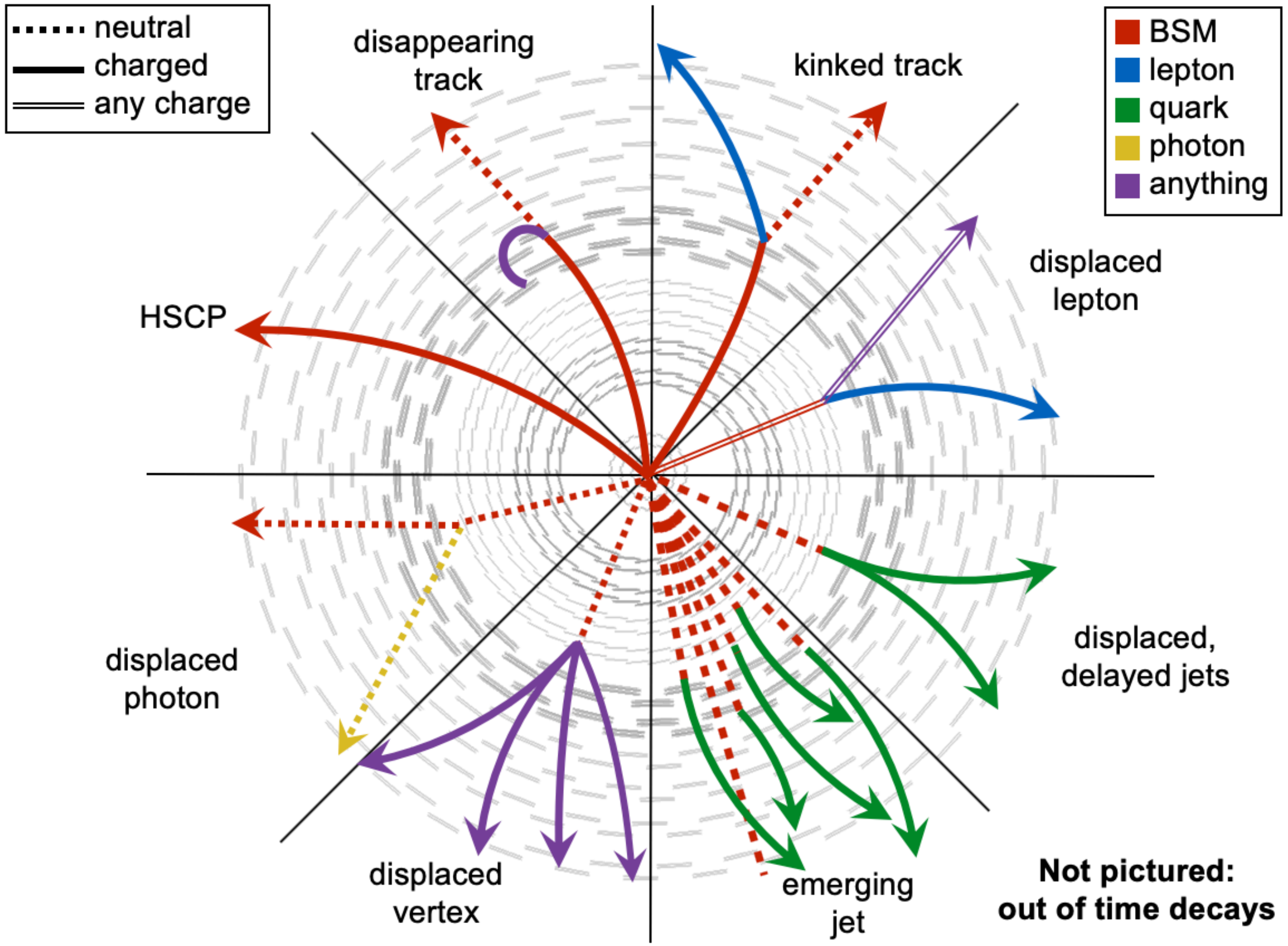
But **conventional searches** for new phenomena at the LHC are for **promptly** decaying particles



We also need to look for new particles with long lifetimes!

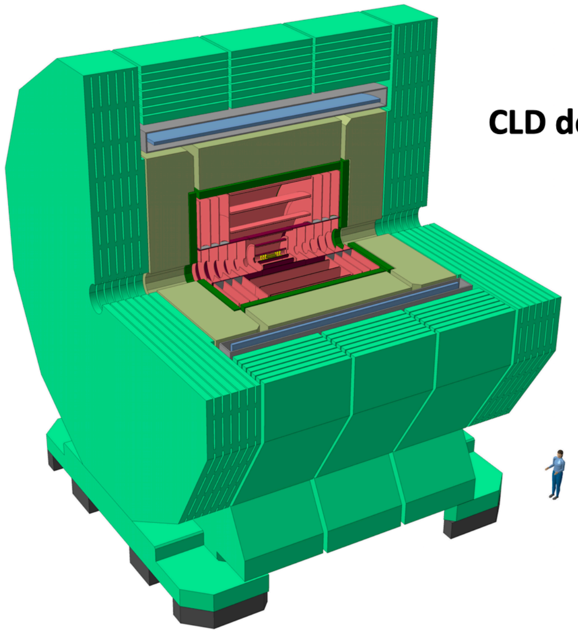
Long-Lived Particle Searches

- **Wide variety** of:
  - Charges
  - Final states
  - Decay locations
  - Lifetimes
- Design **signature-driven** searches
- Often interpret results with a **benchmark model**, but can expand **variety of scenarios**
- **Challenges of the LHC:** main detect triggers, offline reconstruction not designed for displaced particles



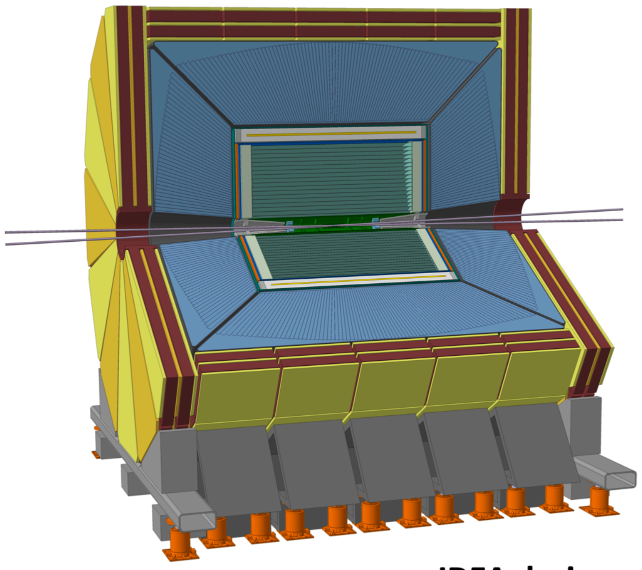
Big opportunity to do something different at the FCC!

Detectors at the FCC



CLD design

- **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 precision 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)



IDEA design

Past and Ongoing Work

- Snowmass LOI, white paper (arXiv:2203.05502)
- Several Masters student theses done or in progress:
  - Sissel Bay Nielsen (University of Copenhagen, 2017)
  - Rohini Sengupta (Uppsala University, 2021)
  - Lovisa Rygaard (Uppsala University, 2022)
  - Tanishq Sharma (University of Geneva, 2022)
- **Will discuss 3 long-lived physics cases, focusing on what is new since Feb FCC Physics Workshop:**
  1. Heavy Neutral Leptons (HNLs)
  2. Axion-like Particles (ALPs)
  3. Higgs bosons with exotic decays to LLPs

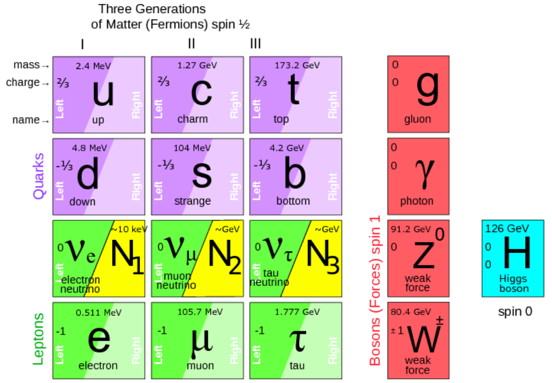
Analysis Overview

- **Analysis goals**
  - Perform an FCC case study with the "official" analysis tools and framework available for the FCC
    - FCCAnalysis, Delphes, latest IDEA card, centrally-produced samples, etc.
  - Try to be as realistic as possible
    - E.g. use high stats background samples

- **Latest improvements** (since FCC Physics Workshop)
  - Increased background MC sample size
    - Due to now able to run the analysis in batch and store processed samples in common eos area - thanks!
  - We profit also from recent technical developments in FCCAnalyses
    - Much smoother analysis workflow

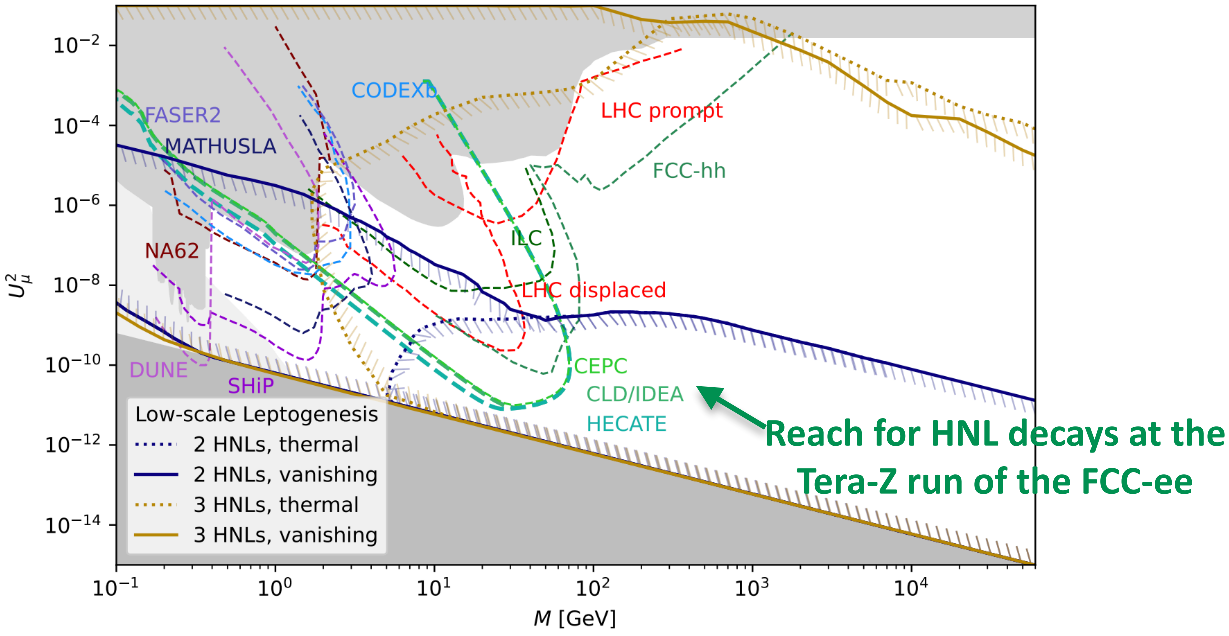
1st Physics Case: LL Heavy Neutral Leptons

- 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



- 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
- See Saw type I is simplest way we can probe HNLs at the FCC, but not only one
- Most studies only consider N1 to be light and long-lived, but not necessarily true: arXiv:1907.13034

arXiv:2203.05502

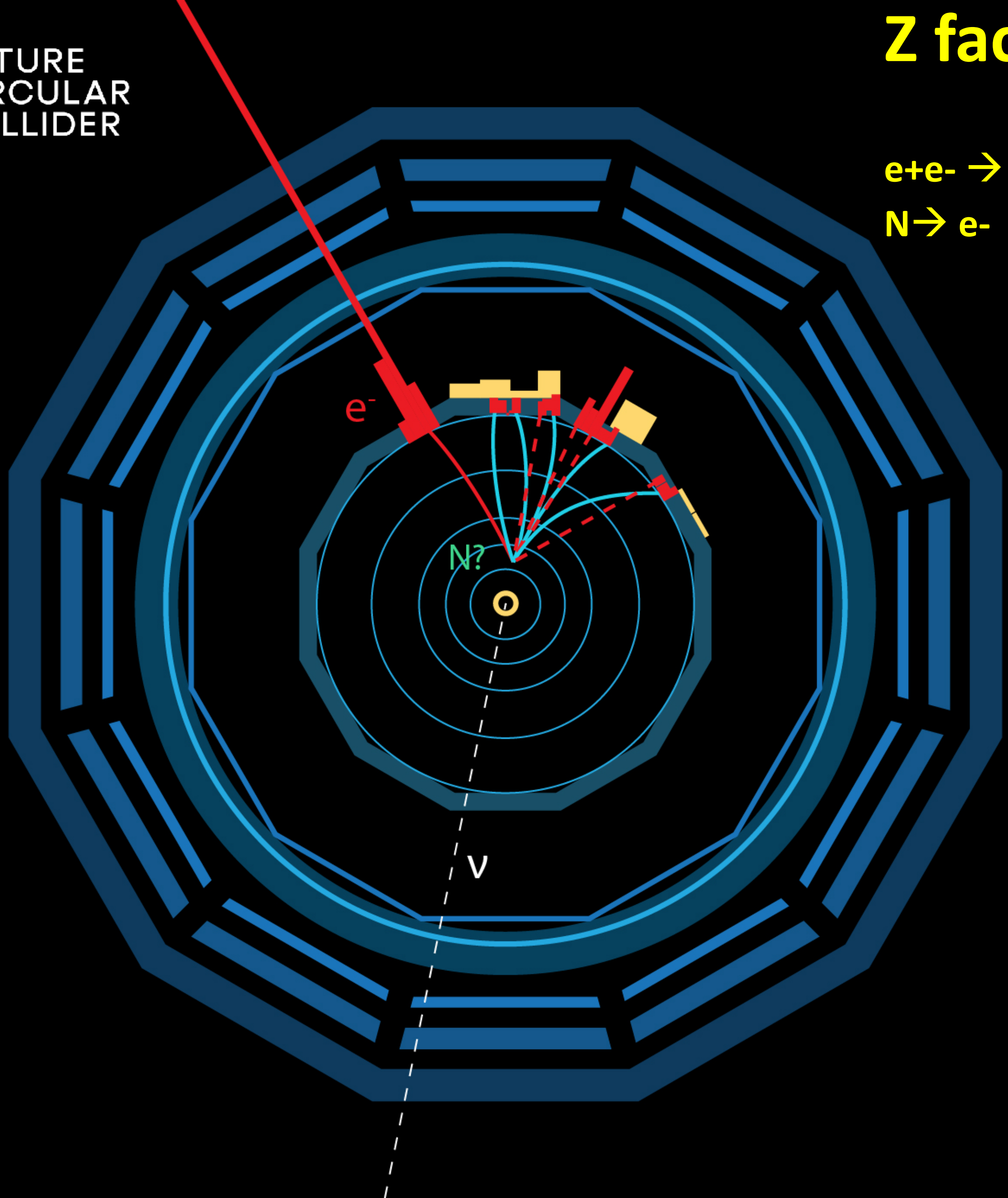


FUTURE CIRCULAR COLLIDER

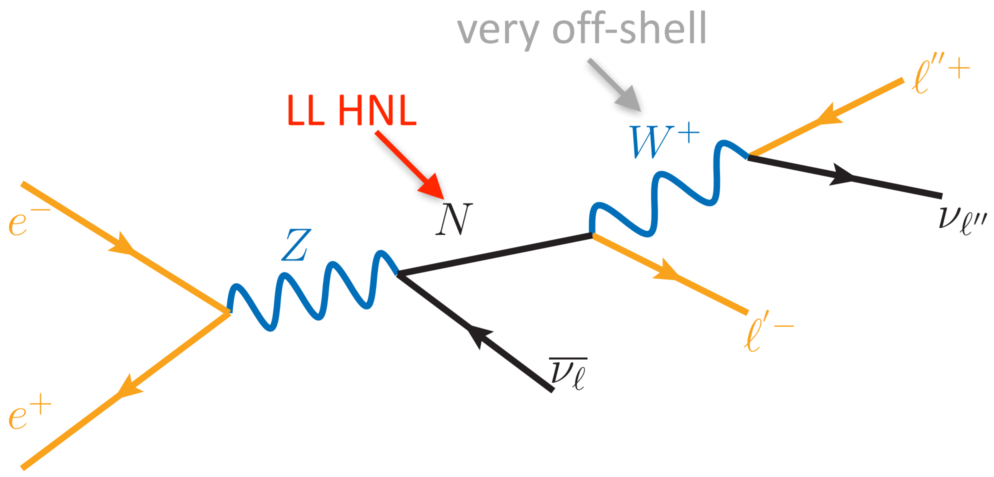
Z factory

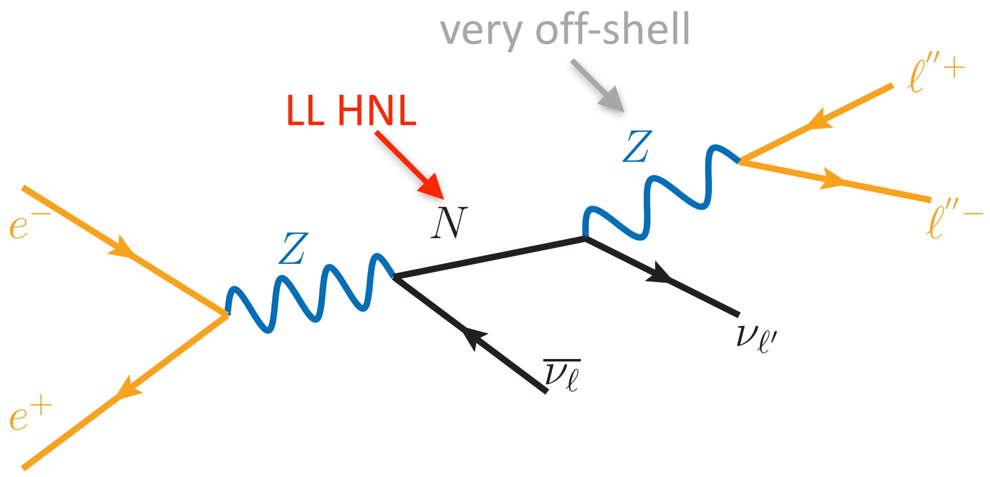
$e^+e^- \rightarrow Z \rightarrow \nu N$

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



Simulating HNLs





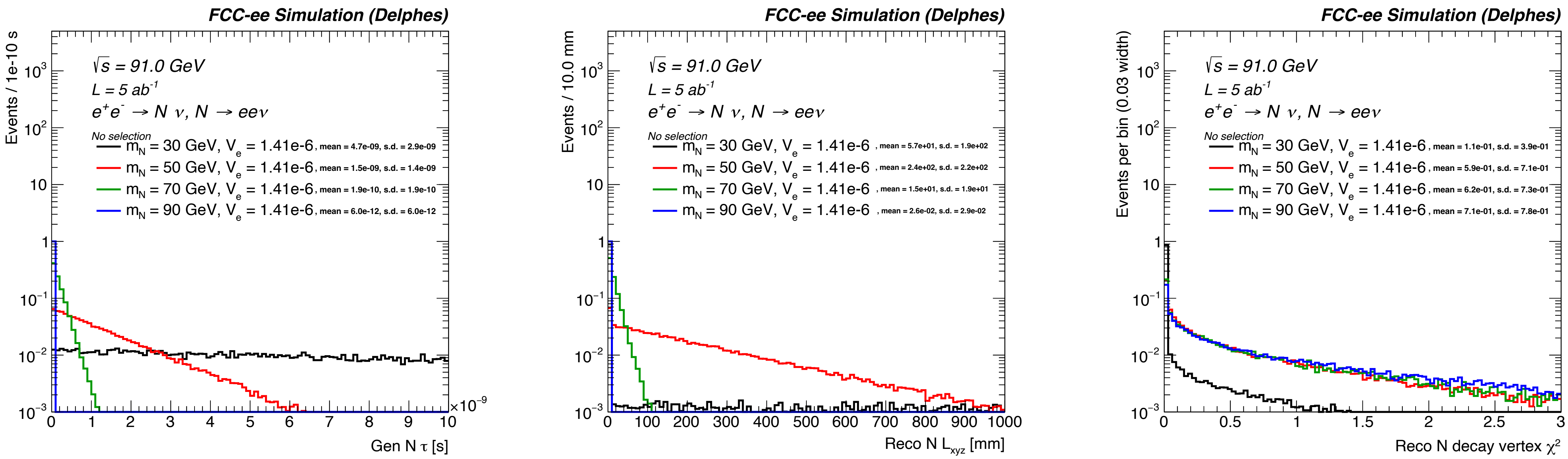
- Generated Majorana and Dirac HNLs with the SM_HeavyN_CKM_AllMasses_LO and SM_HeavyN_Dirac_CKM_Masses_LO models (arXiv:1411.7305, arXiv:1602.06957)
- Started with the $ee\nu$ final state (suggested as early as 1984(!) by S. Petcov)
- FCC-ee, $\sqrt{s} = 91\ \text{GeV}$
- Generated in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card
- Experimental signature of LL HNLs: displaced vertex

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

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

Get long-lived HNLs when coupling and mass are small

HNL Lifetime and Decay Vertex

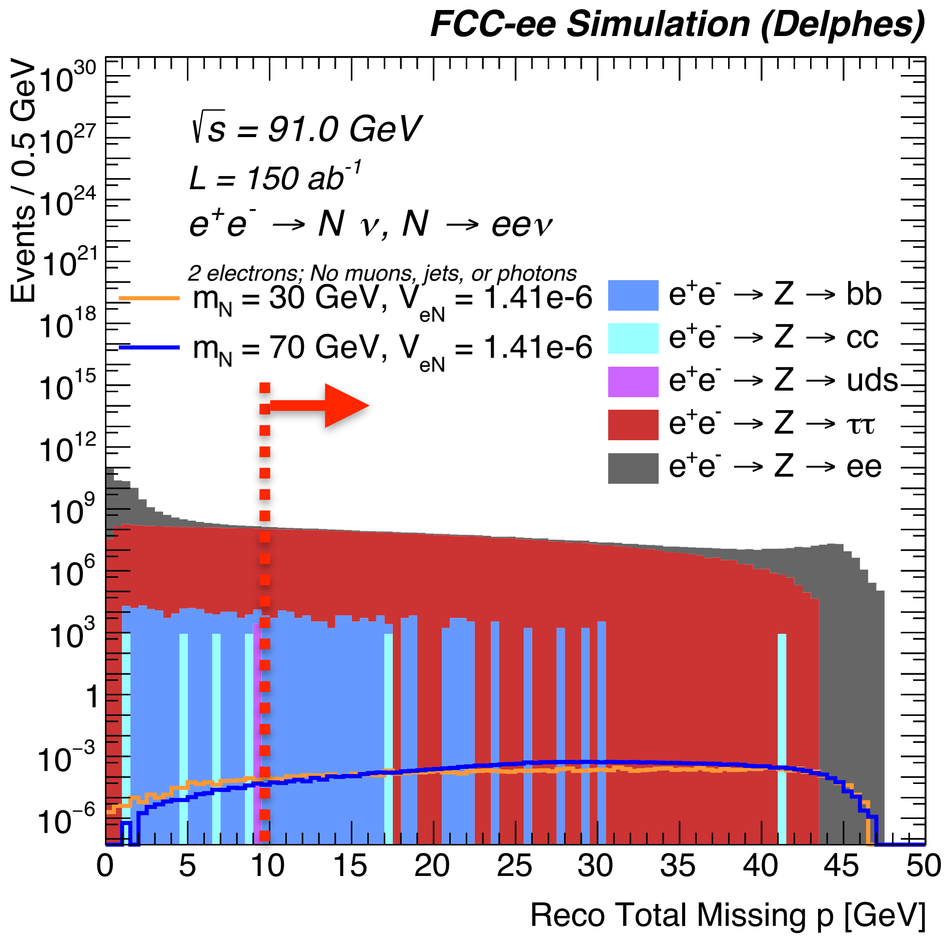


- Confirmed HNL signal kinematics behave as expected, at gen and reco level
- For example, for **m = 50 GeV, Ve = 1.41e-6**, the mean of the generated lifetime is 1.5E-9 s —> 45 cm, which is what we expected
  - On the other hand, **m = 90 GeV, Ve = 1.41e-6** is pretty prompt
- Reco L_{xyz} (3D decay length) and vertex χ^2 distributions are also understood
  - **m = 30 GeV, Ve = 1.41e-6** is fairly displaced, so less isolated electrons are reconstructed

Lovisa Rygaard

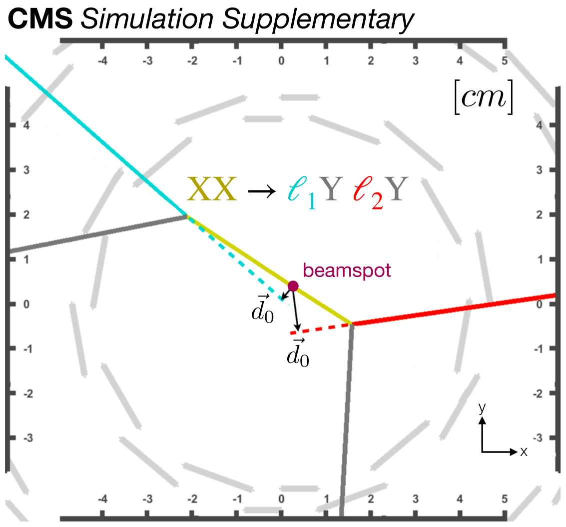
S vs B: Missing Energy

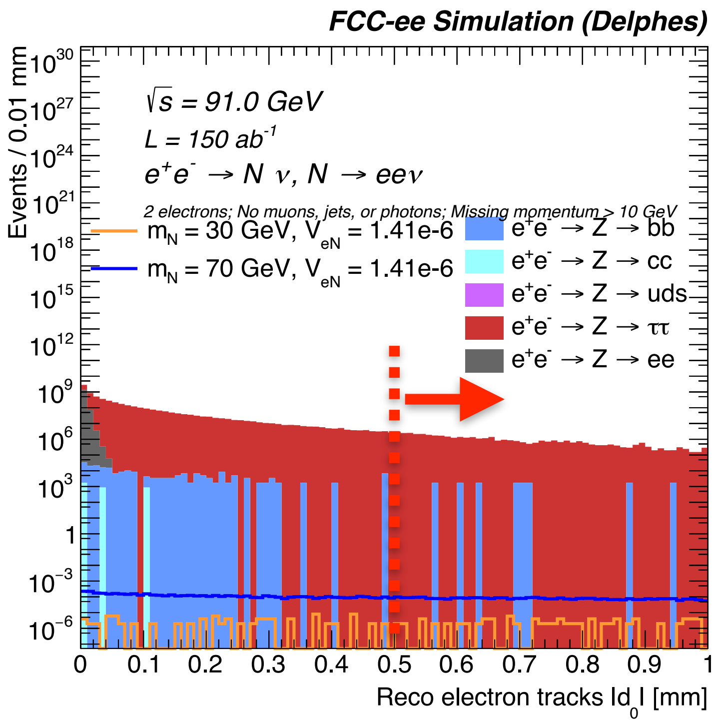
- Then added centrally-produced "spring2021" background samples with the IDEA detector, at 91 GeV CME
- Recent update: more background statistics
- Can look at the total missing energy at an e+e- collider!
- Require missing energy > 10 GeV

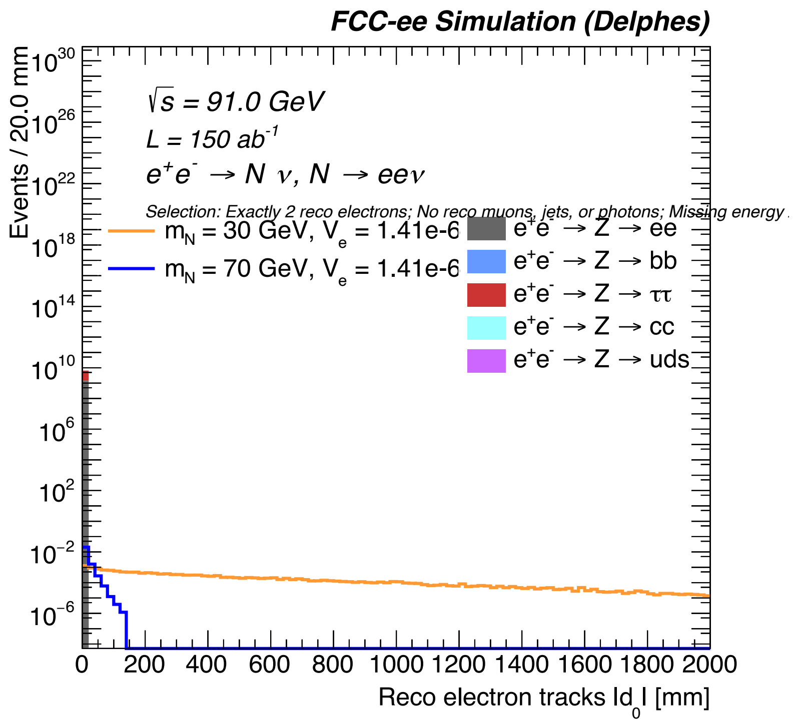


Lovisa Rygaard

S vs B: Impact Parameter







Note the x-axis ranges

- Another good discriminating variable is the impact parameter
- Recent update: more background statistics
- Started by looking at transverse impact parameter (d_0 or d_{xy}), but will move to the 3D impact parameter (d_{xyz})
- $|d_0| > 0.5$ mm removes the vast majority of the SM background

Selection

- Preliminary event selection
- Tables show the expected number of events at 150 ab^{-1}, cumulative after each cut (on reco variables)
- Here used 10^7—10^9 ($5*10^4$) raw/unscaled events for background (signal)
    - Will need to generate larger samples for some background
- Most discriminating variables explored so far: missing energy and $|d_0|$

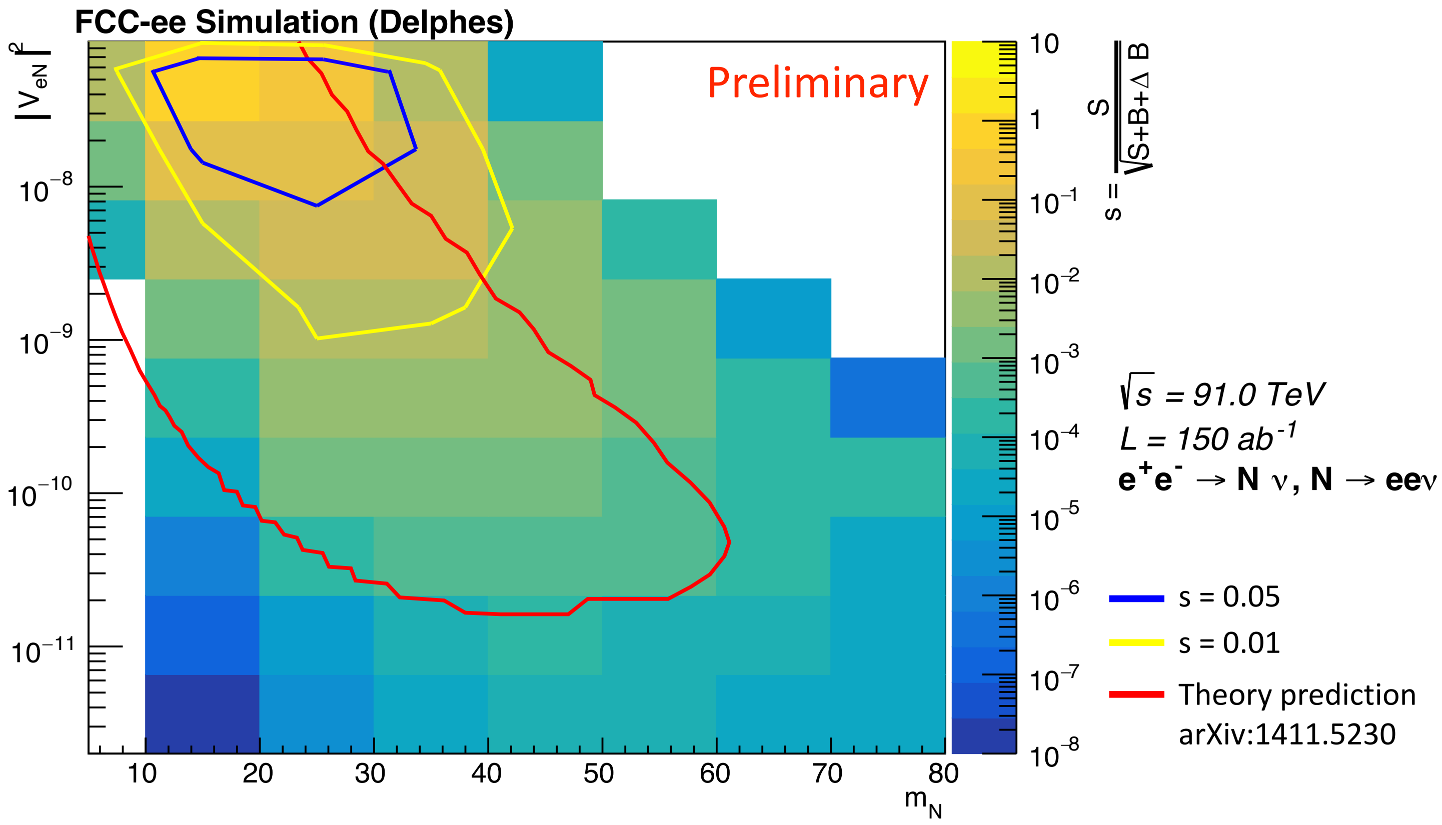
	Before selection	Exactly 2 reco e	Veto photons, muons, and jets	$\not{p} > 10$ GeV	$\|d_0\| > 0.5$ mm
$Z \to ee$	$2.19 \times 10^{11} \pm 6.94 \times 10^7$	$1.75 \times 10^{11} \pm 6.19 \times 10^7$	$1.53 \times 10^{11} \pm 5.80 \times 10^7$	$7.07 \times 10^8 \pm 3.94 \times 10^6$	$\leq 3.94 \times 10^6$
$Z \to bb$	$9.97 \times 10^{11} \pm 4.14 \times 10^7$	$5.64 \times 10^8 \pm 9.85 \times 10^5$	$3.25 \times 10^5 \pm 2.36 \times 10^4$	$1.22 \times 10^5 \pm 1.45 \times 10^4$	$1.72 \times 10^3 \pm 1.72 \times 10^3$
$Z \to \tau\tau$	$2.21 \times 10^{11} \pm 7.00 \times 10^7$	$5.49 \times 10^9 \pm 1.10 \times 10^7$	$5.10 \times 10^9 \pm 1.06 \times 10^7$	$2.52 \times 10^9 \pm 7.47 \times 10^6$	$6.64 \times 10^4 \pm 3.84 \times 10^4$
$Z \to cc$	$7.82 \times 10^{11} \pm 2.61 \times 10^7$	$1.69 \times 10^7 \pm 1.21 \times 10^5$	$5.22 \times 10^3 \pm 2.13 \times 10^3$	$1.74 \times 10^3 \pm 1.23 \times 10^3$	$\leq 1.23 \times 10^3$
$Z \to uds$	$2.79 \times 10^{12} \pm 8.83 \times 10^7$	$2.30 \times 10^7 \pm 2.54 \times 10^5$	$2.79 \times 10^3 \pm 2.79 \times 10^3$	$\leq 2.79 \times 10^3$	$\leq 2.79 \times 10^3$

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

Lovisa Rygaard

Sensitivity

New!



- $$\text{FOM} = \frac{S}{\sqrt{S + B + \Delta B}}$$
- **This analysis:** $N \rightarrow ee\nu$
  - Contours show where FOM = 0.01 and 0.05
- Theory prediction from arXiv:1411.5230
  - Includes all HNL decay modes, not only electrons
- Next step: add more decay modes, particularly $N \rightarrow ejj$

Tanishq Sharma

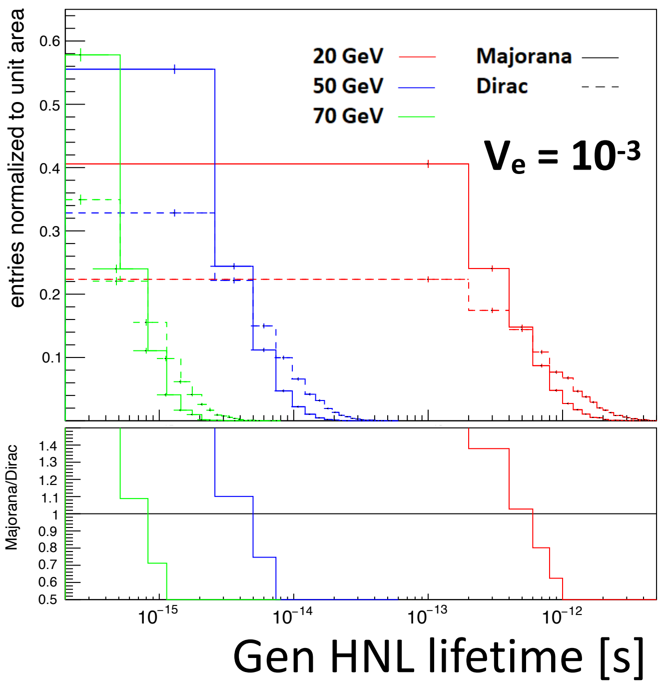
Bonus: Dirac vs Majorana HNLs

Dirac (LNC) and Majorana (LNC+LNV) HNLs produce different kinematic distributions: arXiv:2105.06576

Variables that can distinguish between Majorana and Dirac HNLs:

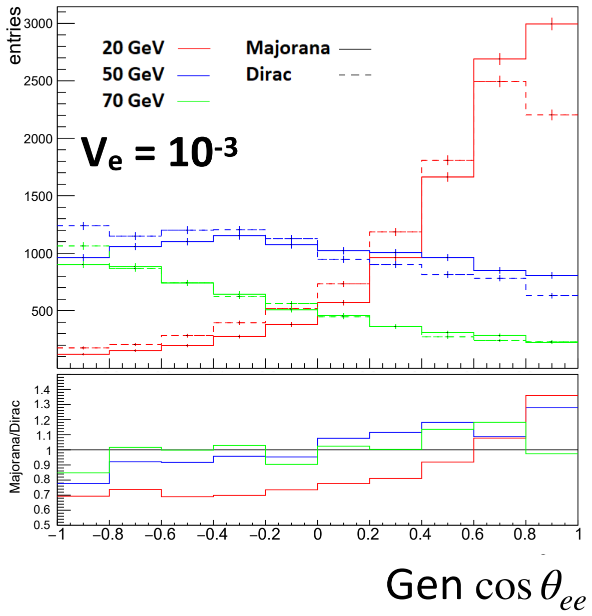
HNL Lifetime

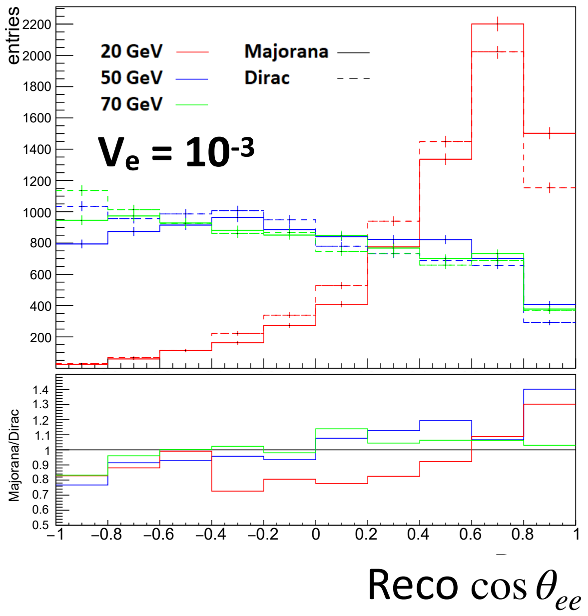
(model-dependent)



$\cos\theta_{ee}$

(opening angle between final state electron/positron)



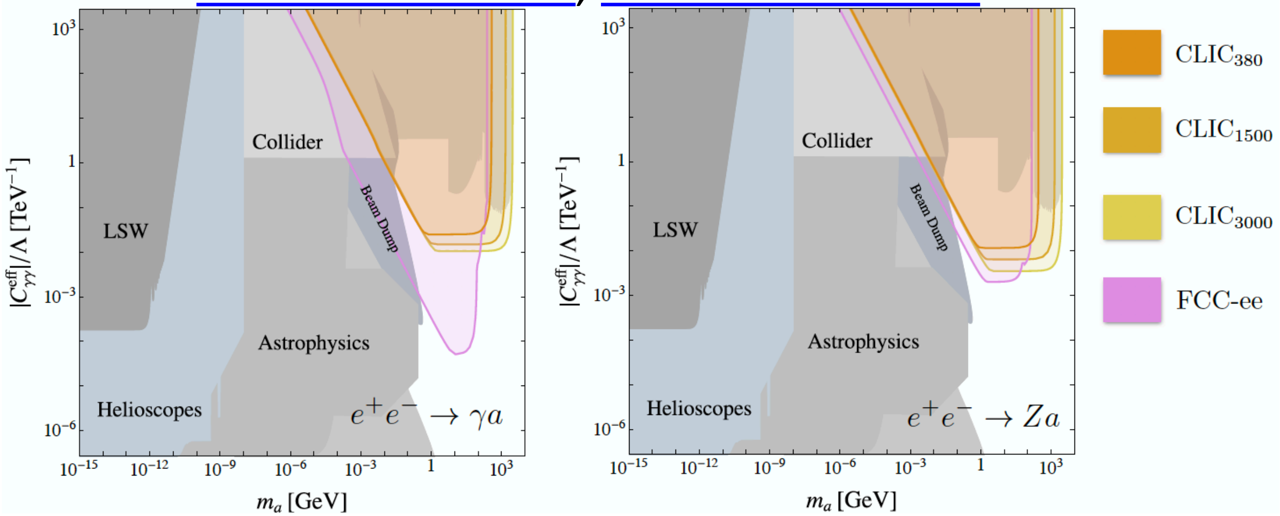


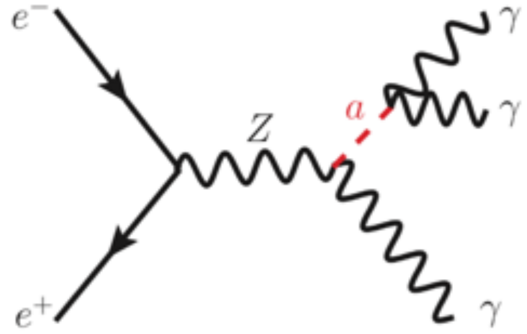
Next: improve reconstruction, find more discriminating variables

2nd Physics Case: LL Axion-Like Particles

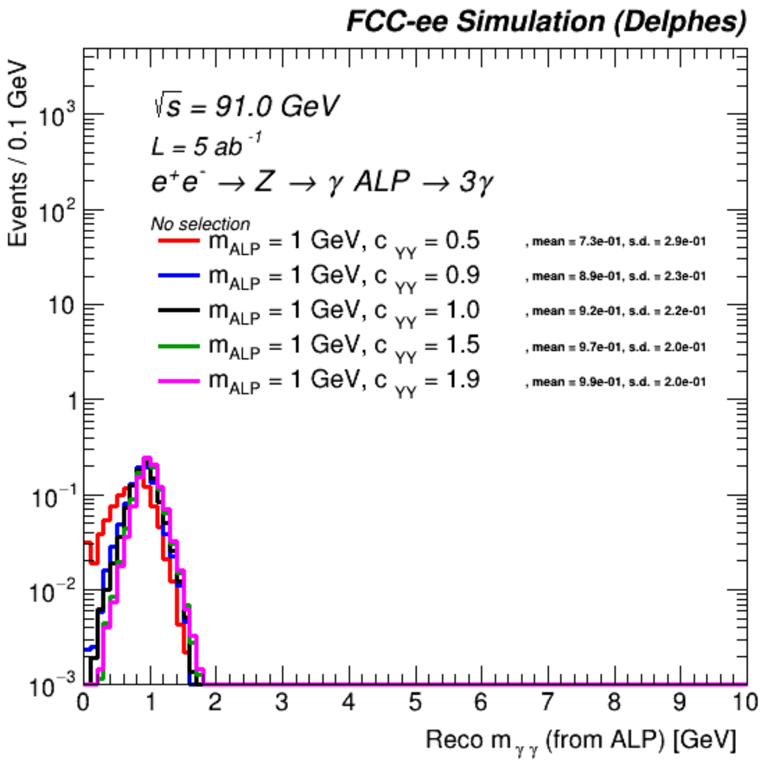
- Axion-like Particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries in BSM scenarios
- Very weakly coupled to the dark sector
- Get long-lived ALPs when couplings and mass are small
- At the FCC-ee:
  - Orders of magnitude of parameter space accessible
  - Especially sensitive to final states with at least 1 photon
- **Privately generated ALPs in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card,** $\sqrt{s} = 91\ \text{GeV}$ **(arXiv:1808.10323)**

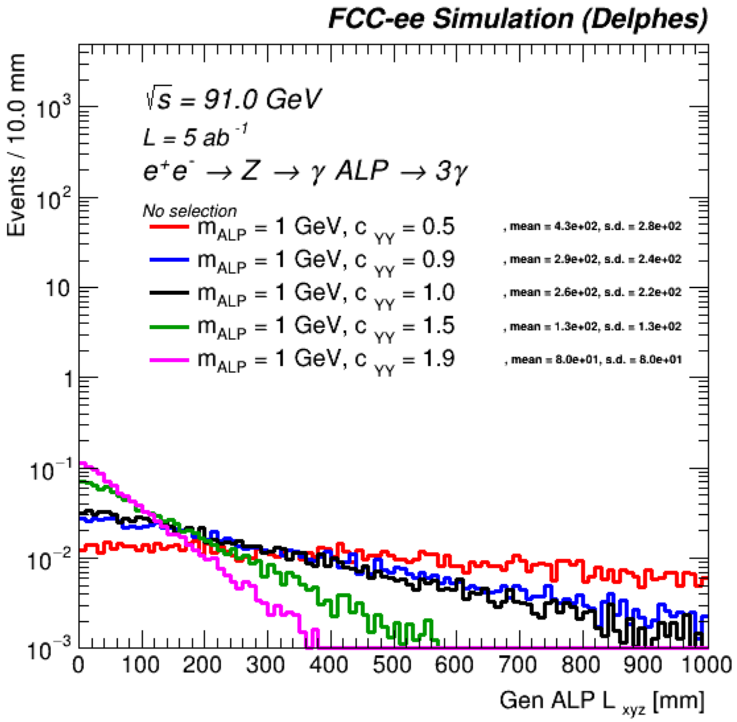
arXiv:1808.10323, arXiv:2108.08949





Variables to Explore



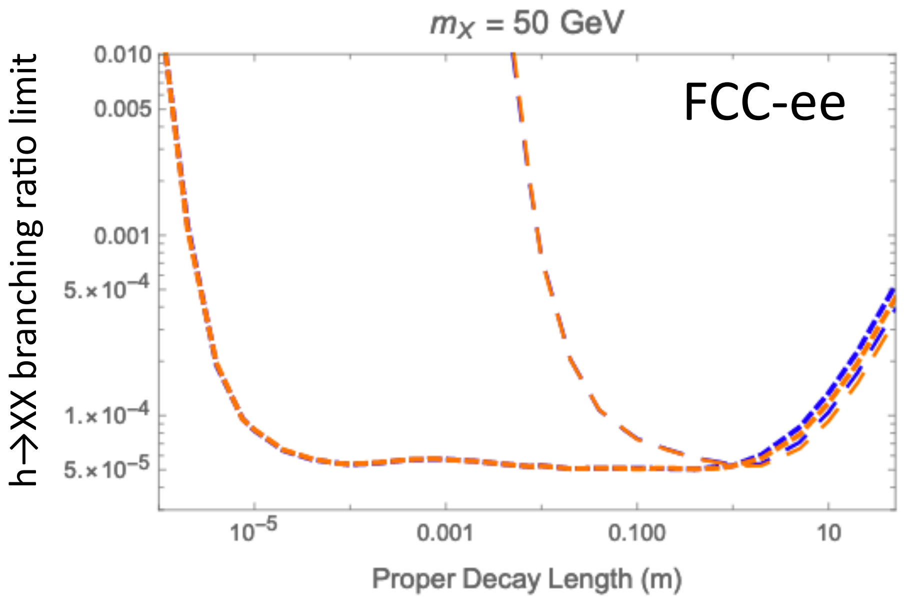


- Started with simulating 1 GeV ALP mass, vary the coupling
- ALP mass confirmed with the reco invariant mass from the 2 photons coming from the ALP
- ALP decay length will also be a nice discriminating variable
- **Ready for more personpower to step in and complete an analysis, guidance available!**

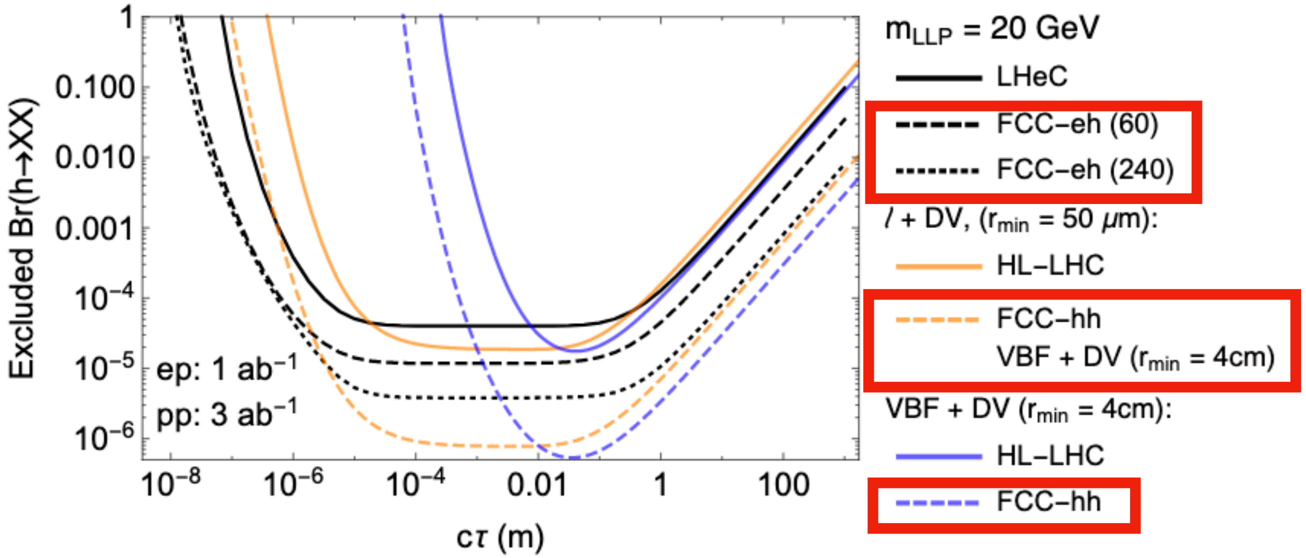
3rd Benchmark: Exotic Higgs decays to LLPs

- 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)
- **Another call for personpower**: can generate with e.g. this model in Madgraph, then incorporate into FCC framework

arXiv:1812.05588



arXiv:1712.07135



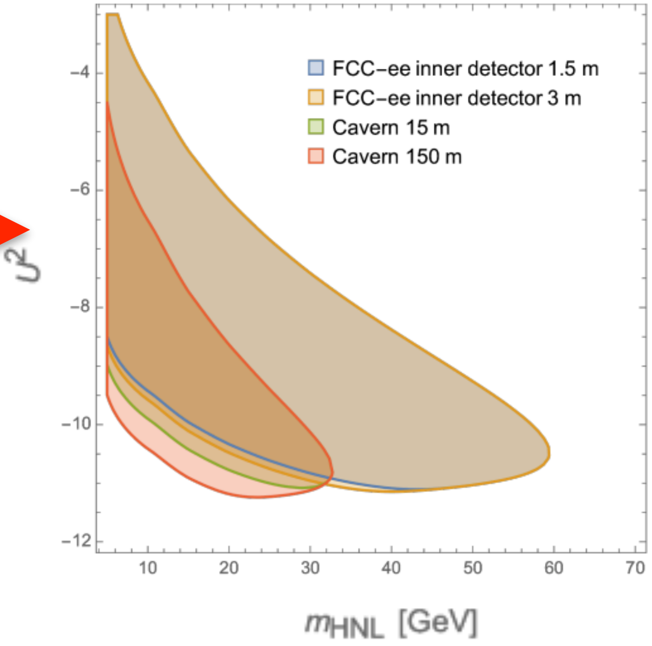
Other Topics to Explore at the FCC

- How well we can distinguish a long-lived HNL/ALP/exotic Higgs decay from SM backgrounds
  - For leptonic decays? For hadronic decays? For decays to photons?

Towards Detector Requirements

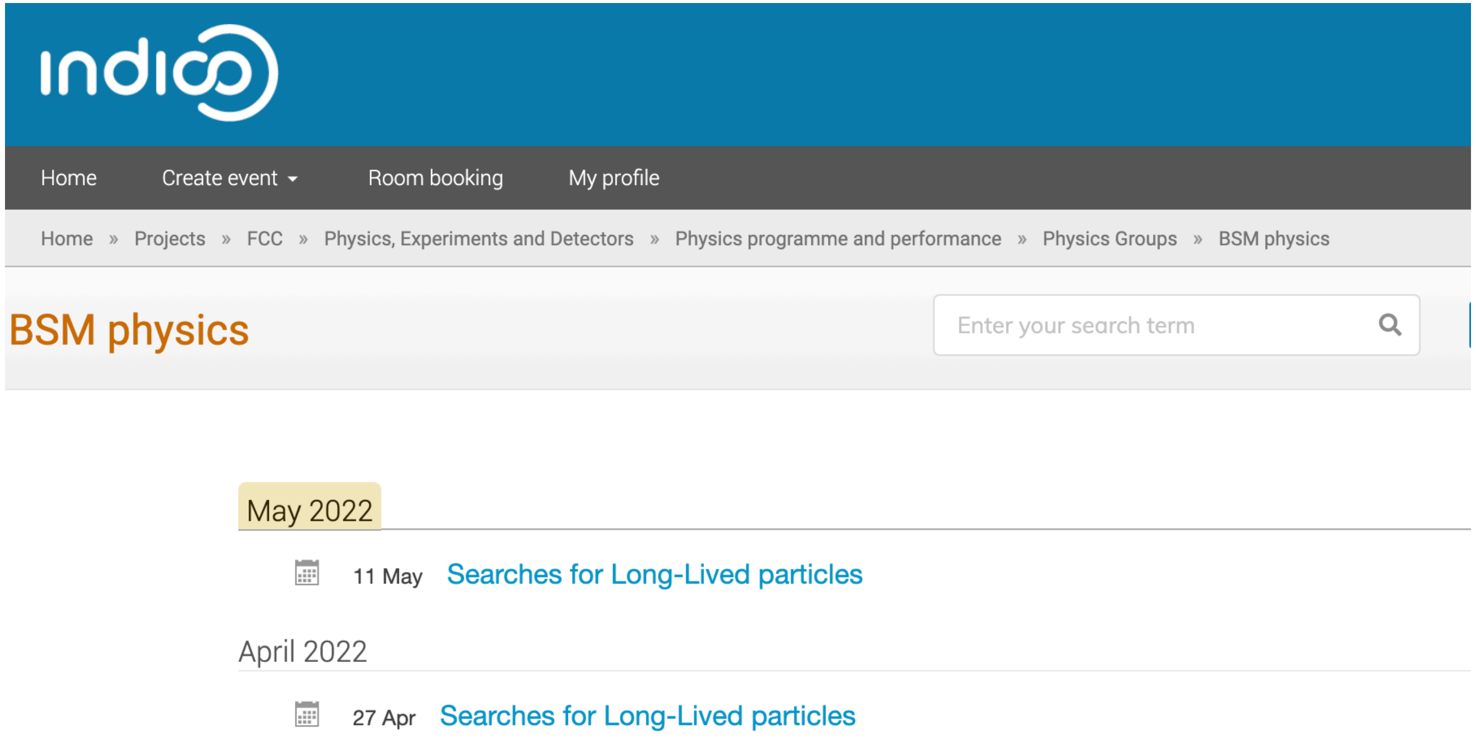
- Vertexing performance of the FCC prototype detectors
- Time-of-flight performance
- Different detector configurations: can we probe a larger/different theory landscape?
  - Bigger tracker? More layers?
- Majorana vs Dirac HNLs
- Not an exhaustive list!

Preliminary study (arXiv:2106.15459) shows the sensitivity of HNLs to different inner detector and cavern sizes



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!

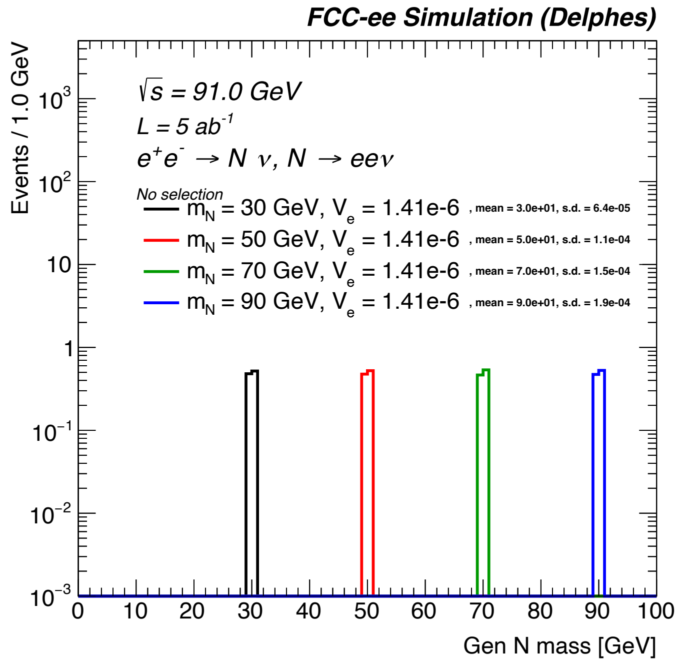


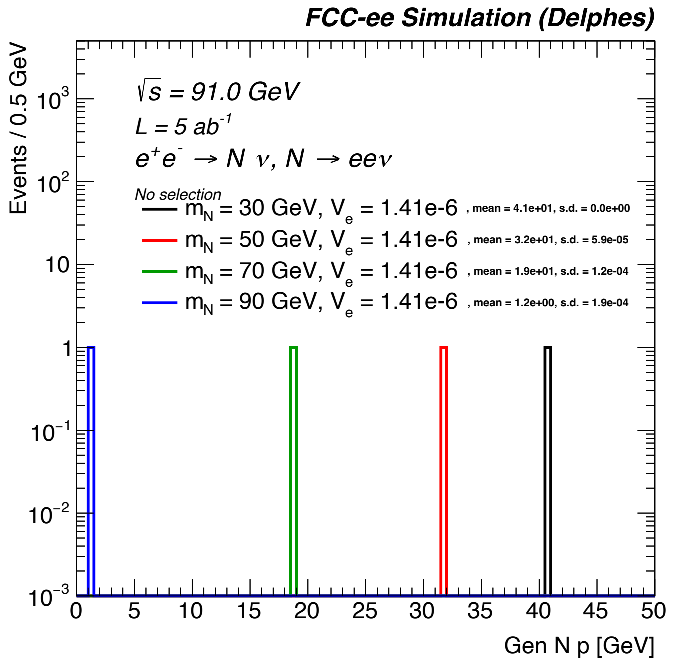
Summary

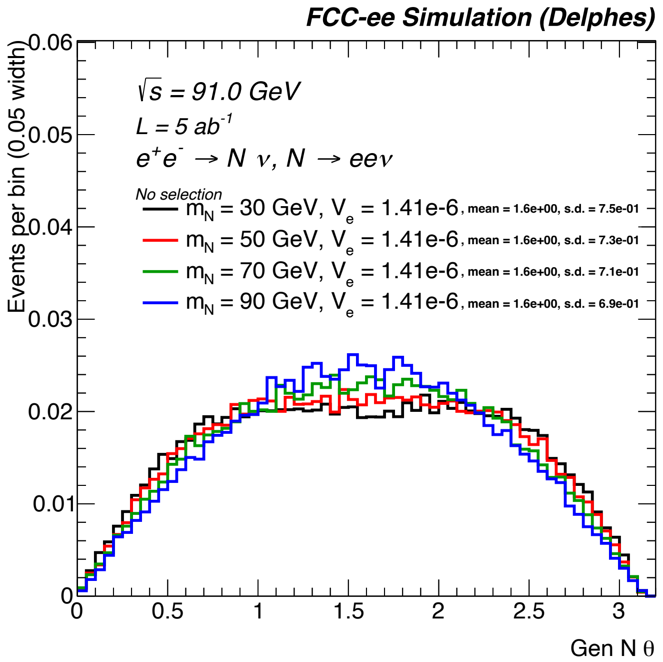
- To discover new phenomena, should look where no one else has looked before
- One way to do this: long-lived particles!
- The FCC will have the ability to uniquely probe LLP areas of phase space, and discovery potential!
- Many interesting signals: Heavy Neutral Leptons, hidden sectors, axion-like particles, exotic Higgs decays, and more
- Showed some brand new results
- We now have the opportunity to design detectors and algorithms with LLPs in mind
- A lot can be learned from Delphes
- See Rebeca's and Suchita's talks for more!
- Also see the ongoing LLP11 workshop
- Plenty of phase space to explore at the FCC! Let's make sure we don't miss new physics!

Backup

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