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Long-Lived Particles at the FCC

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

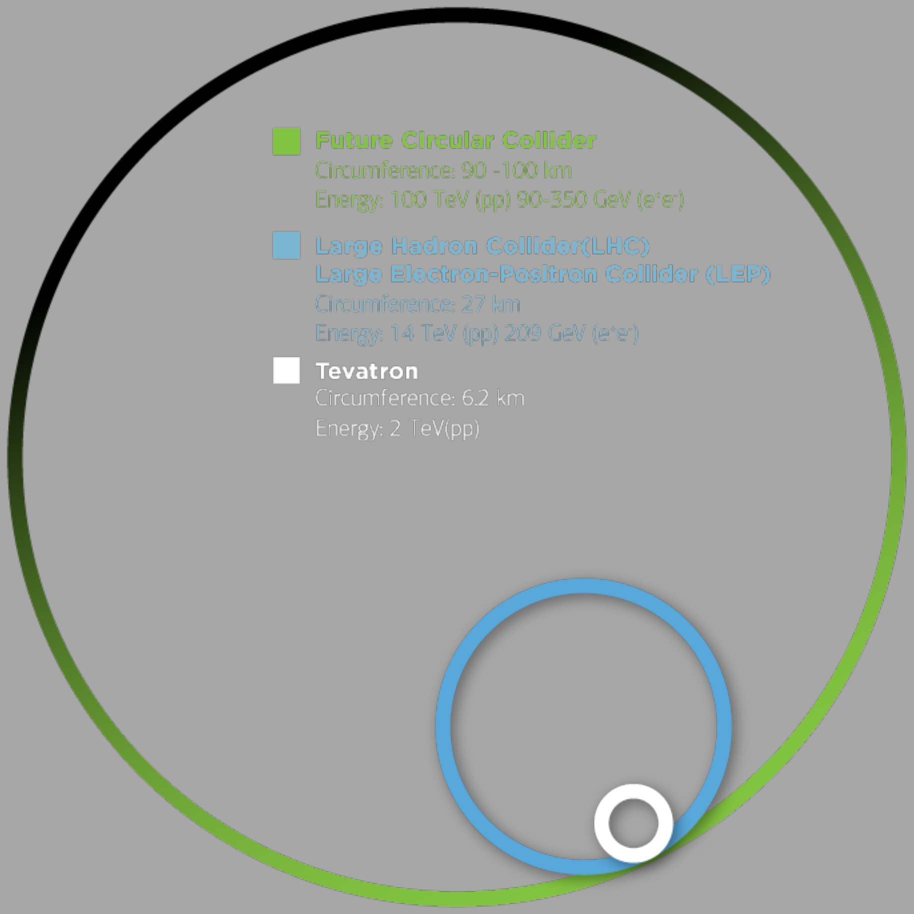
Mini-Workshop on BSM at ILC

March 2, 2022

Future Circular Collider

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

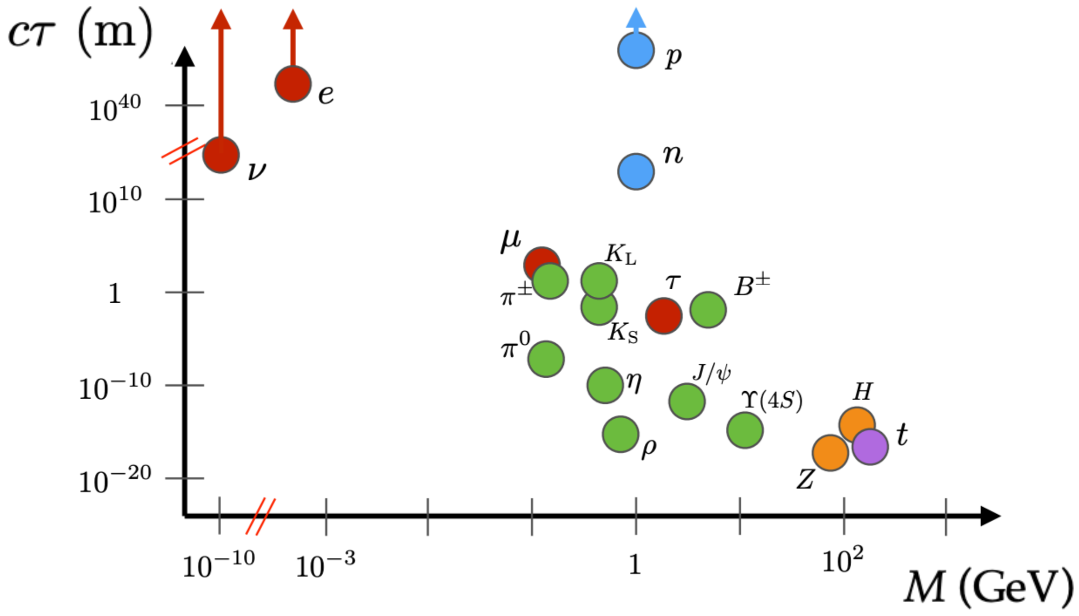
- Stage 1: FCC-ee (Z, W, H , tt) as Higgs EW and top factory at high luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options



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)

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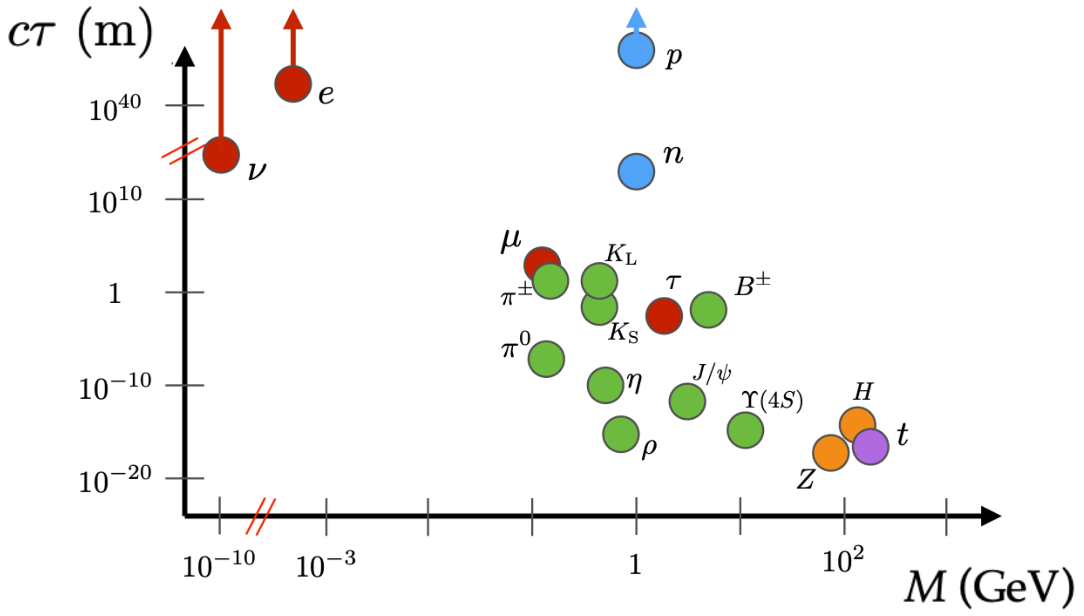
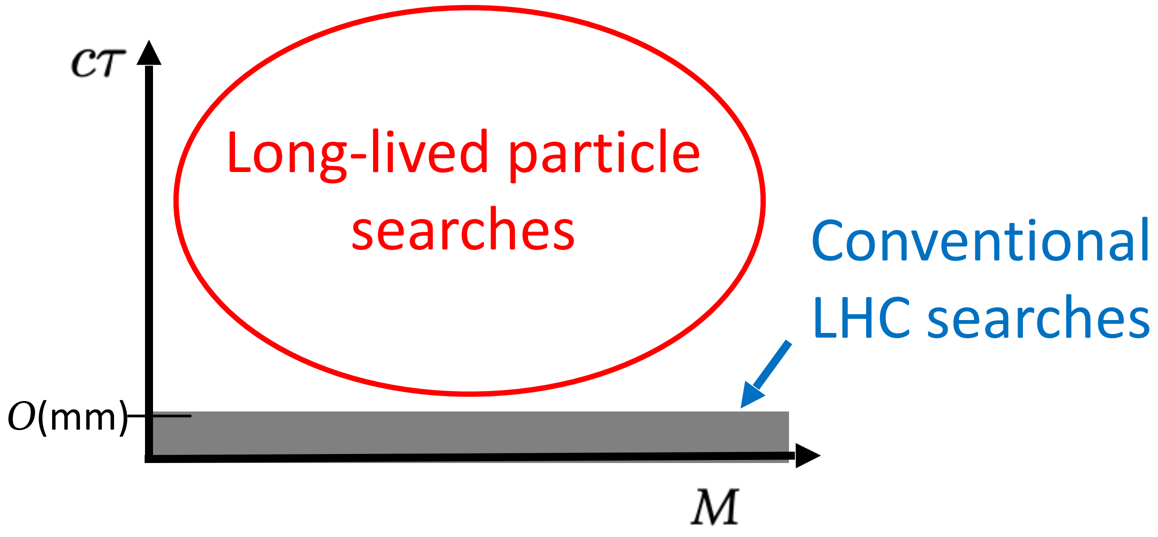


We expect **new phenomena** to have a wide range of lifetimes as well

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!

How You Get LLPs

- Mechanisms to produce long-lived particles are the same ones as those that give us long-lived particles in the SM

- Three main ways:
  - Heavy (off-shell) mediator
  - Small couplings
  - Compressed spectra

e.g. $\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ ($c\tau_0 \sim 7.8$m)

small coupling

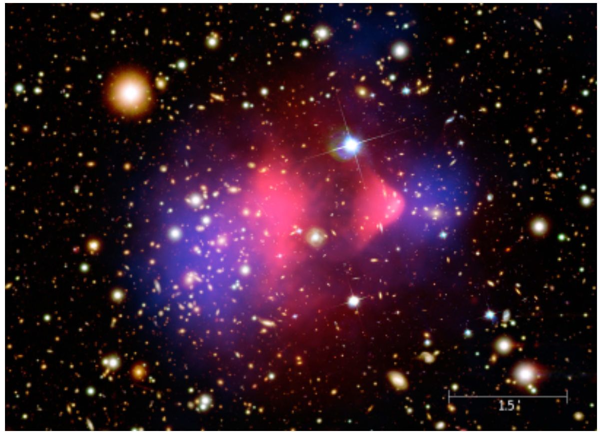
$$\frac{2\pi h}{\tau} = \frac{f_\pi^2}{256\pi m_\pi}\left[\frac{G_F^2}{M_W^2}\frac{m_\mu}{m_\pi}(m_\pi^2 - m_\mu^2)\right]^2$$

heavy mediator

compressed spectra

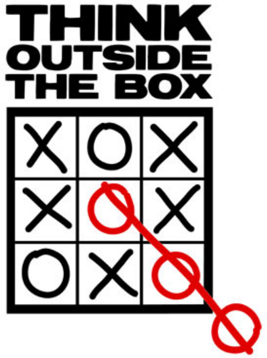
Why Search for New LLPs?

- **LLPs appear in many BSM scenarios**
  - Supersymmetry, heavy neutral leptons, dark photons, inelastic dark matter, and more!



- **Can provide a dark matter candidate**

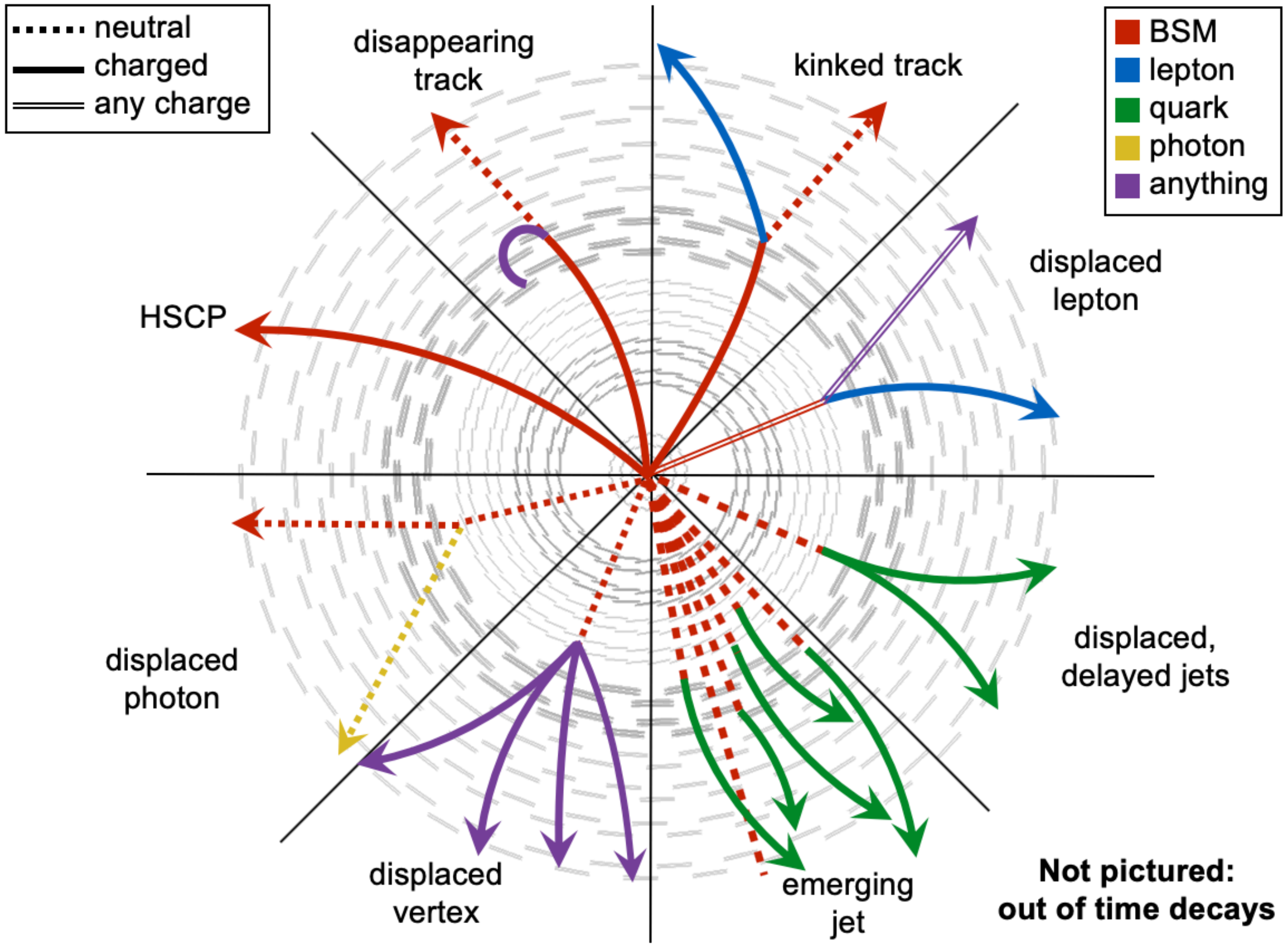
- **Why not?**
  - No sign of new phenomena at the LHC yet! → **Need to look everywhere**
  - A new massive, long-lived particle would be a clear sign of new phenomena



Great discovery potential!

Long-Lived Particle Searches

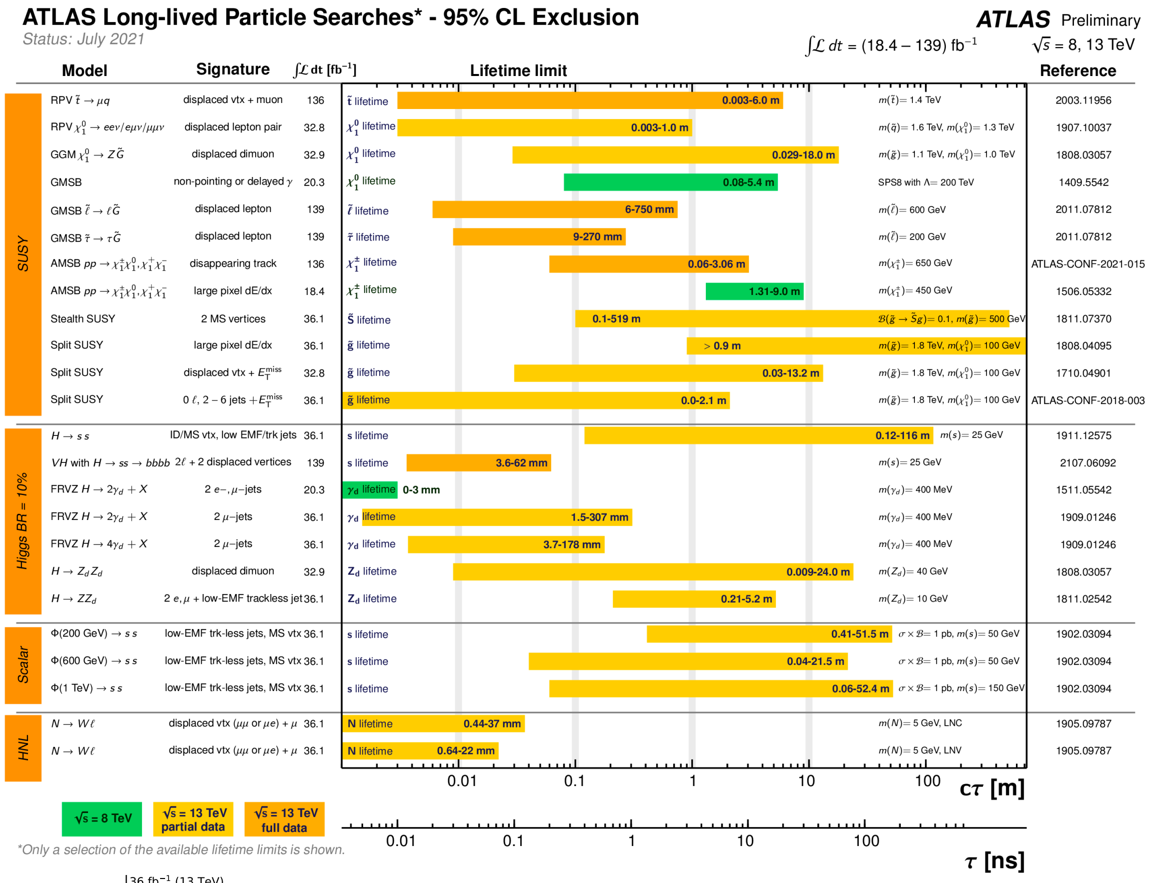
- **Wide variety** of:
  - Charges
  - Final states
  - Decay locations
  - Lifetimes
- Design **signature-driven** searches
- Often interpret results with a **benchmark model**, but can expand to a **variety of scenarios**
- **Challenges of the LHC:** detectors, triggers, offline reconstruction not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



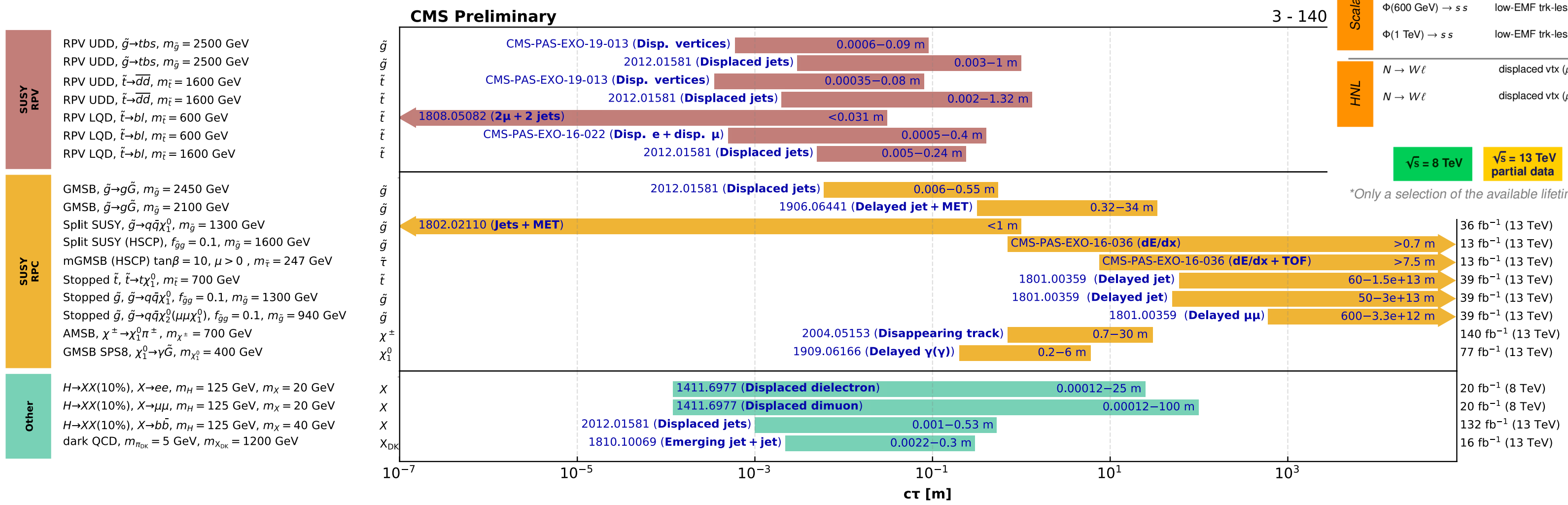
Big opportunity to do something different at the FCC!

Status of Searches

- A number of searches for LLPs have been performed at ATLAS, CMS, and LHCb
  - Also at the Tevatron, LEP…
- Still uncovered phase space! More to do! No discovery yet!



Overview of CMS long-lived particle searches

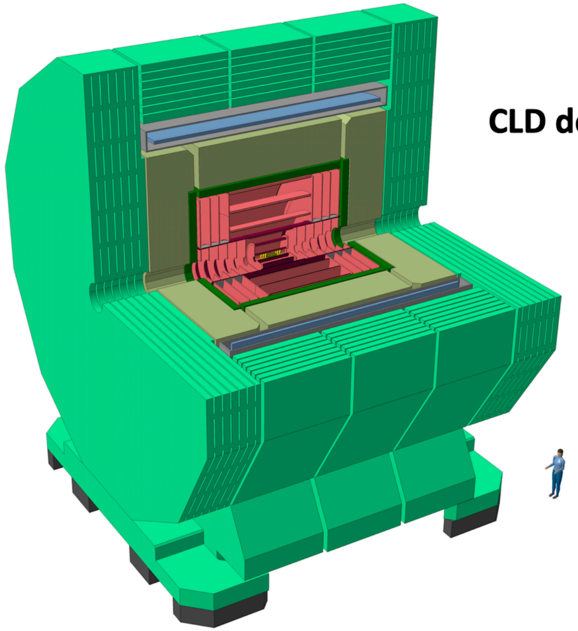


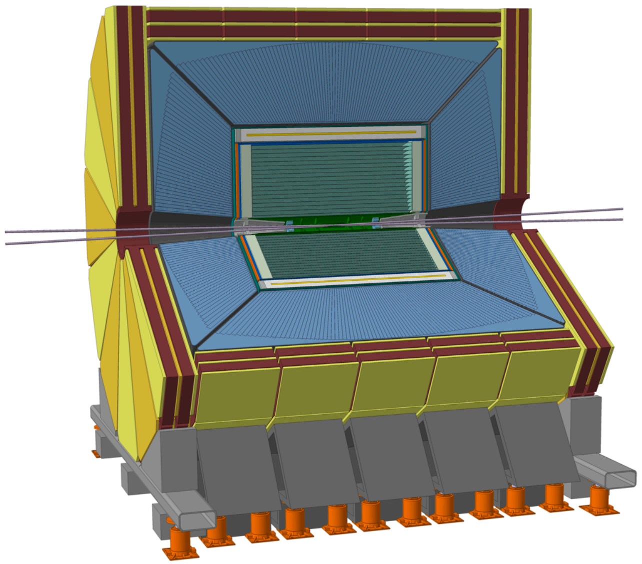
Moriond 2021

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Detectors at the FCC

- **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)


CLD design

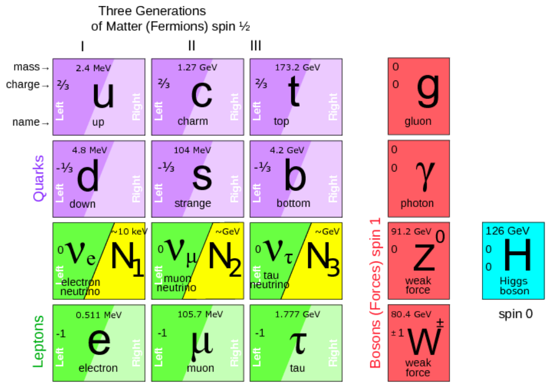

IDEA design

Ongoing Work

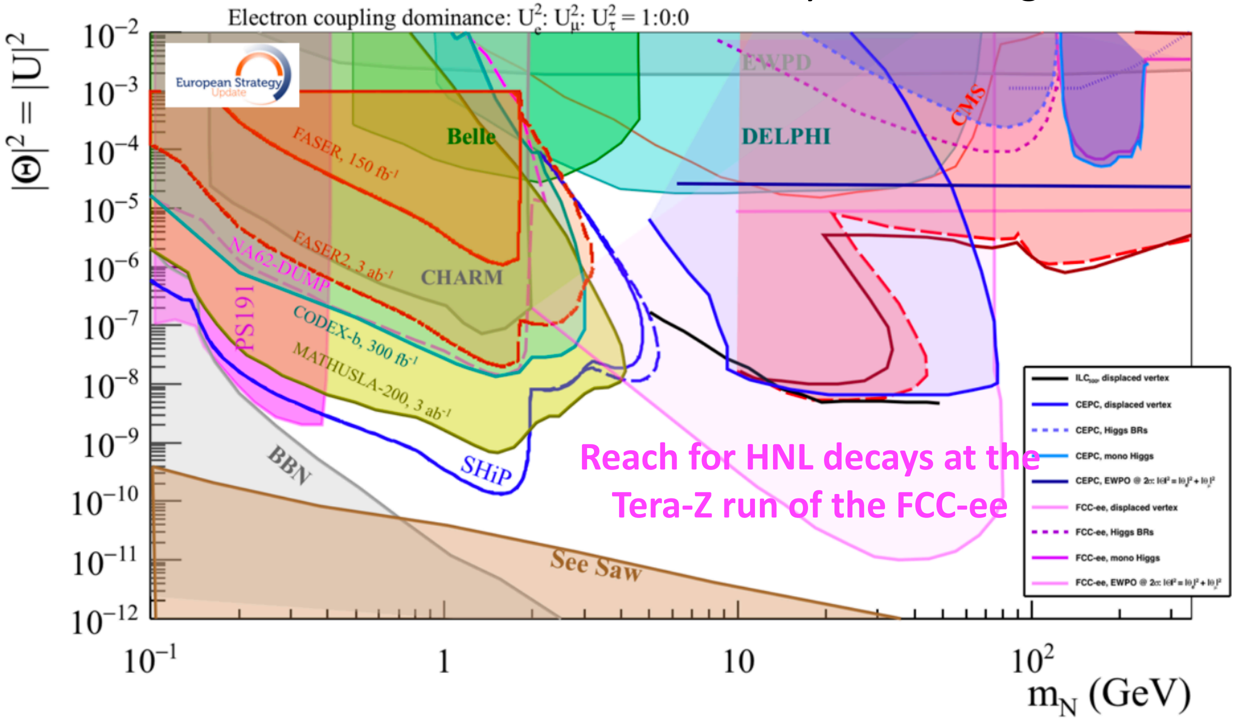
- Snowmass LOI, now preparing white paper
- Several Masters student theses done or in progress:
  - Sissel Bay Nielsen (University of Copenhagen, 2017)
  - Rohini Sengupta (Uppsala University, 2021)
  - Lovisa Rygaard (Uppsala University, 2022)
  - Tanishq Sharma (University of Geneva, 2022)
- **Will now discuss 3 long-lived benchmarks:**
  1. Heavy Neutral Leptons (HNLs)
  2. Axion-like Particles (ALPs)
  3. Higgs bosons with exotic decays to LLPs

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

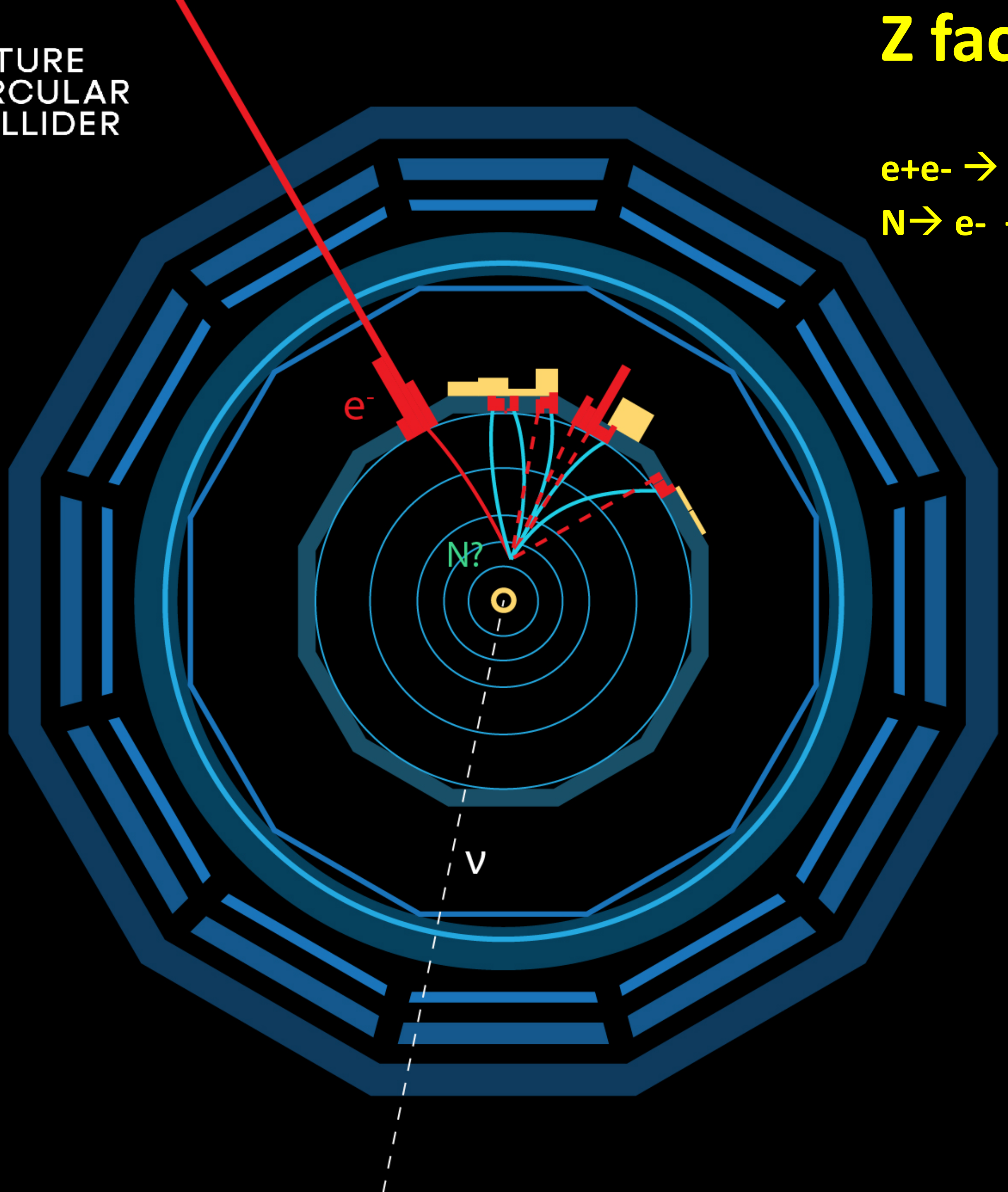
HNLs at the FCC-ee are right in the parameter region that is good for baryogenesis! arXiv:2106.16226

FUTURE CIRCULAR COLLIDER

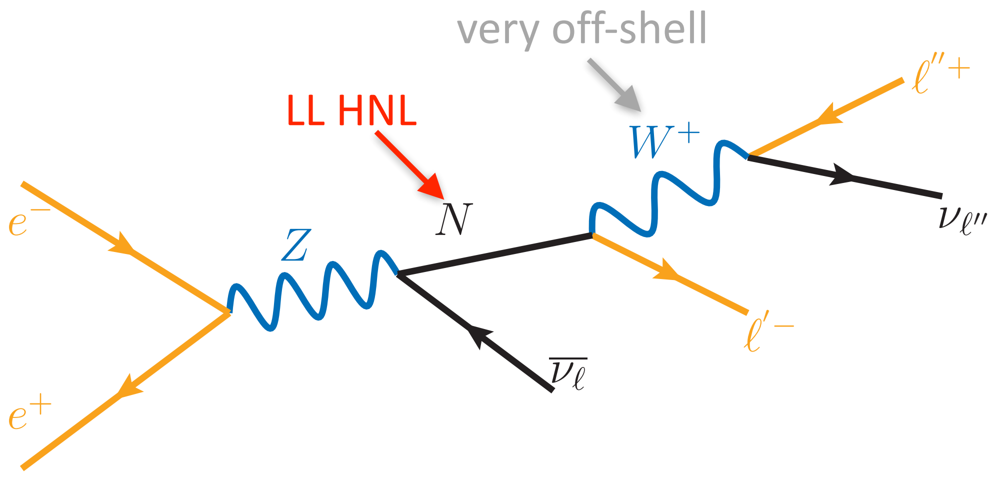
Z factory

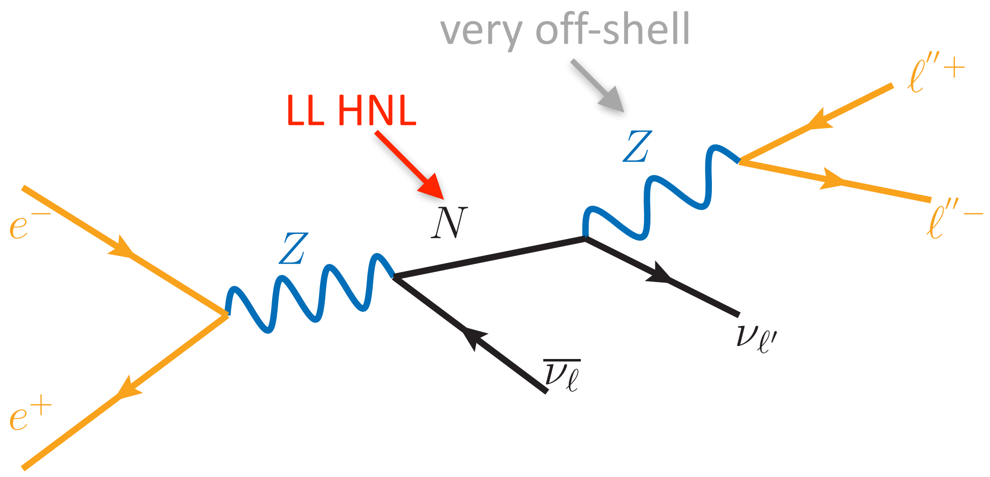
e+e- → Z→ vN

N→ e- + {W+* →jj}



Simulating HNLs





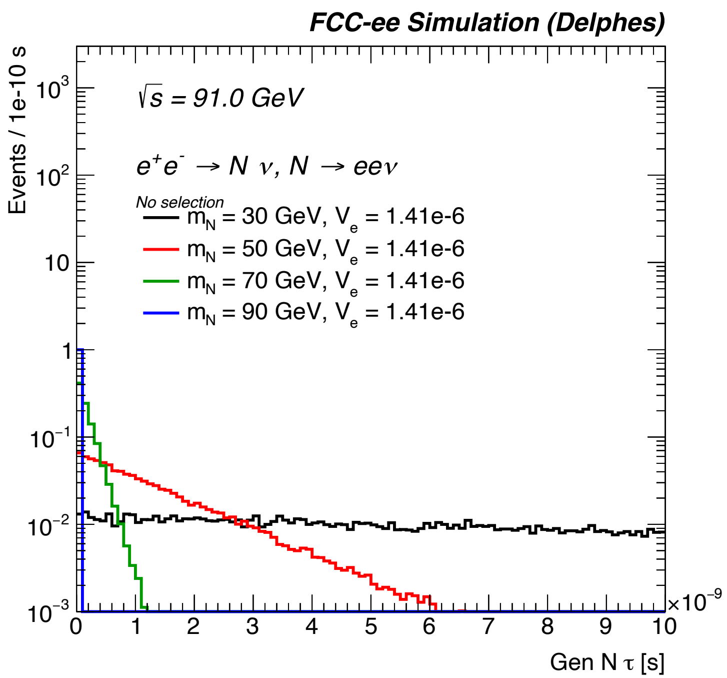
- Generated Majorana and Dirac HNLs with the SM_HeavyN_CKM_AllMasses_LO and SM_HeavyN_Dirac_CKM_Masses_LO models (arXiv:1411.7305, arXiv:1602.06957)
- Started with the $ee\nu$ final state (suggested as early as 1984(!) by S. Petcov)
- FCC-ee, $\sqrt{s} = 91$ GeV
- Generated in Madgraph5 v3.2.0 + Pythia8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

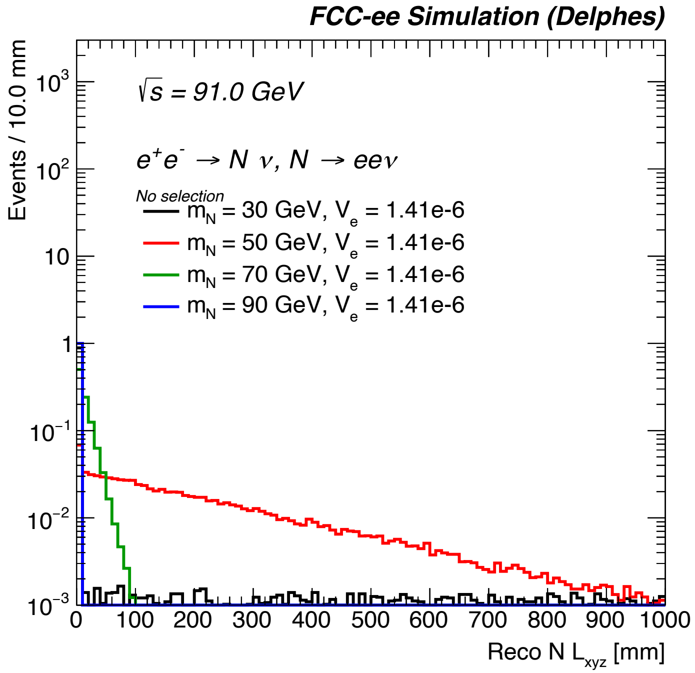
$$L \sim 0.025\text{m}\left(\frac{10^{-6}}{V_l}\right)^2\left(\frac{100\text{ GeV}}{m_N}\right)^5$$

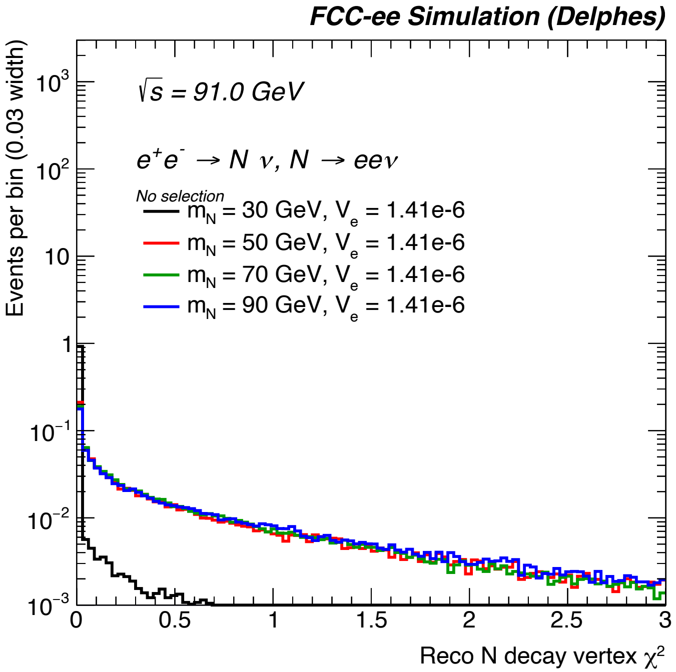
[Valid when $m_N \lesssim 100$ GeV, arXiv:1905.11889]

Get long-lived HNLs when coupling and mass are small

HNL Lifetime and Decay Vertex



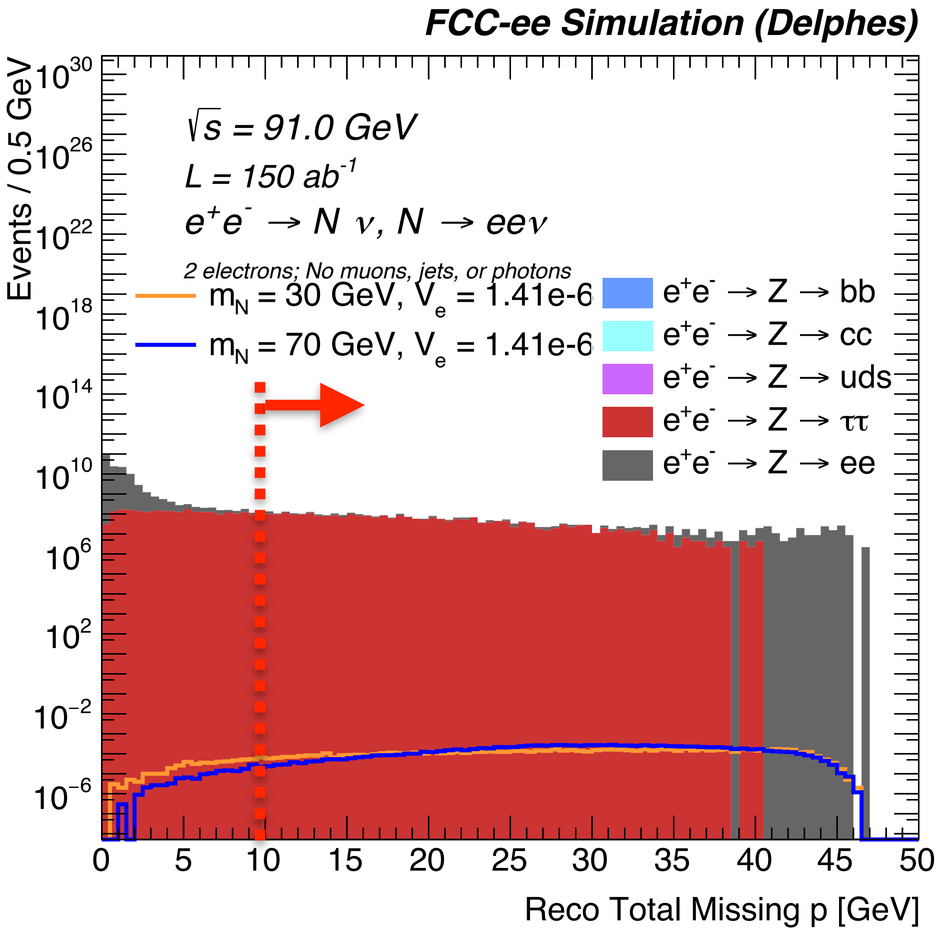




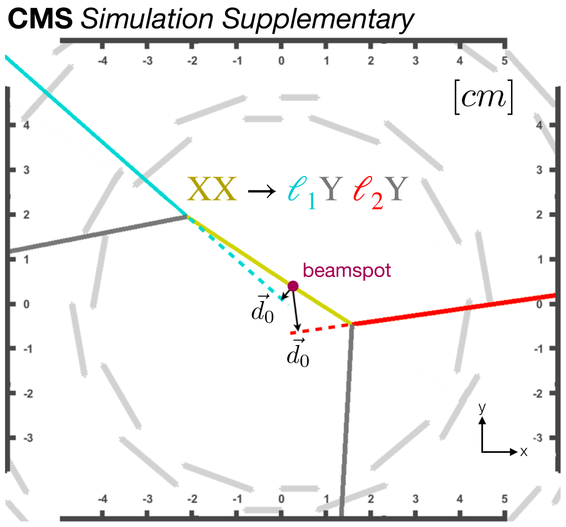
- Confirmed HNL signal kinematics behave as expected, at gen and reco level
- For example, for **m = 50 GeV, Ve = 1.41e-6**, the mean of the generated lifetime is 1.5E-9 s —> 45 cm, which is what we expected
  - On the other hand, **m = 90 GeV, Ve = 1.41e-6** is pretty prompt
- Reco L_{xyz} (3D decay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

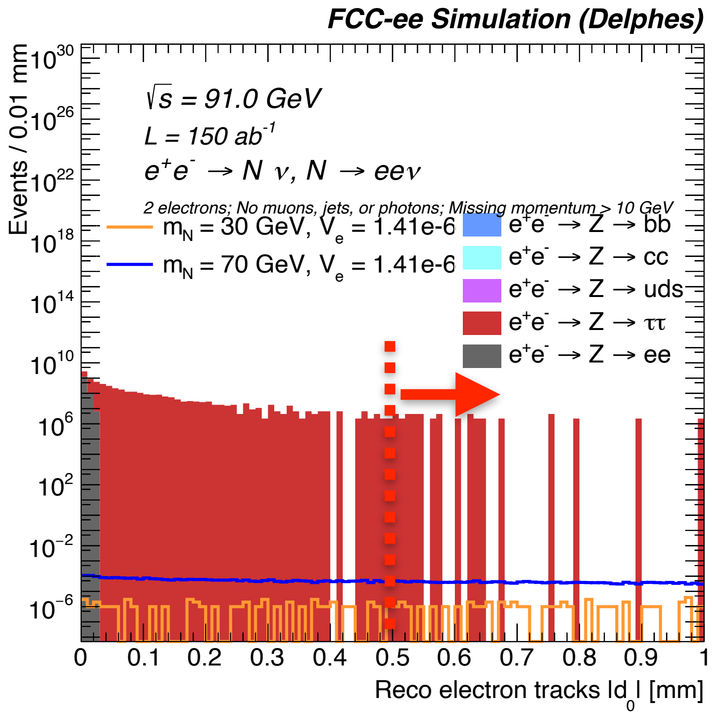
S vs B: Missing Energy

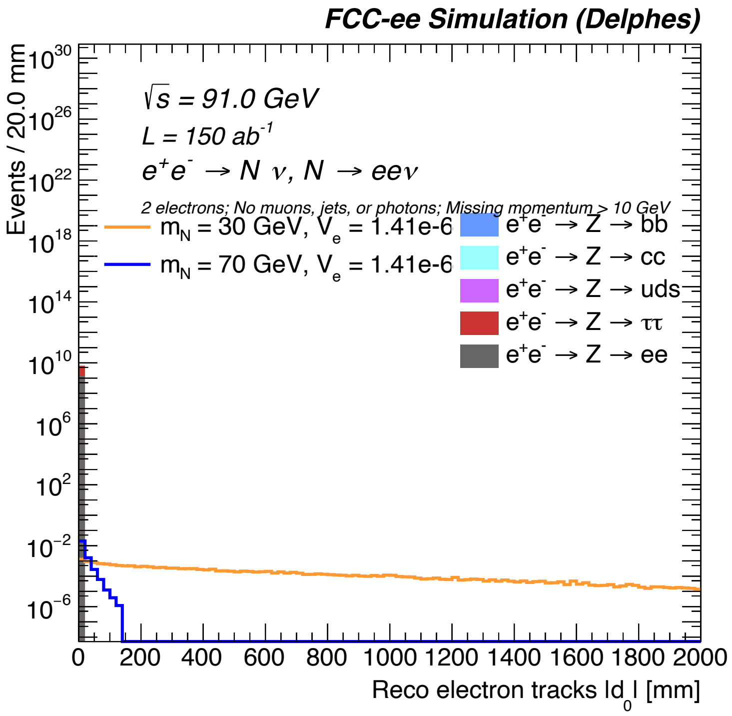
- Then added centrally-produced "spring2021" background samples with the IDEA detector, at 91 GeV CME
- Can look at the total missing energy at an e+e- collider!
- Considering missing energy > 10 GeV cut



S vs B: Impact Parameter







Note the x-axis ranges

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

Selection

- First attempt at an event selection
- Table shows the expected number of events at 150 ab^{-1}, cumulative after each cut (on reco variables)
- Caveat: here just used 100k (50k) raw/unscaled events for background (signal)
- Most discriminating variables: missing energy and $|d_0|$
- Next steps:
  - Run over more events
  - Explore other variables

Cumulative number of expected events at 150 ab^{-1}	Backgrounds						HNL Signals	
	Z->ee	Z->tautau	Z->bb	Z->cc	Z->uds	Total Background	m = 30 GeV V_e = 1.41e-6	m = 70 GeV V_e = 1.41e-6
All generated events	2.19E+11	2.21E+11	9.97E+11	7.82E+11	2.79E+12	5.01E+12	4.98E-02	1.47E-02
Exactly 2 electrons	1.74E+11	5.52E+09	4.69E+08	4.69E+07	2.79E+07	1.80E+11	9.55E-03	1.18E-02
No photons, jets, or muons	1.53E+11	5.11E+09	0.00E+00	0.00E+00	0.00E+00	1.58E+11	9.22E-03	1.13E-02
Missing energy > 10 GeV	6.86E+08	2.58E+09	0.00E+00	0.00E+00	0.00E+00	3.27E+09	8.69E-03	1.12E-02
Both electrons with $|d_0|$>0.5 mm	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	**8.65E-03**	**9.00E-03**

Tanishq Sharma

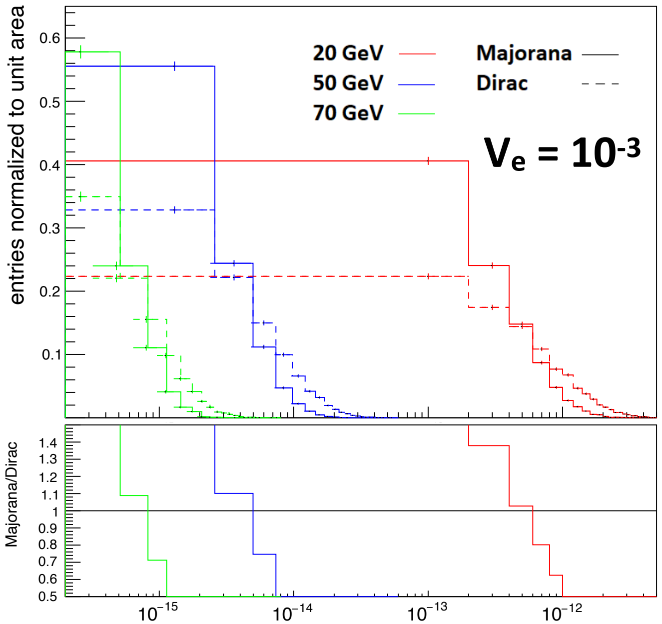
Dirac vs Majorana HNLs

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

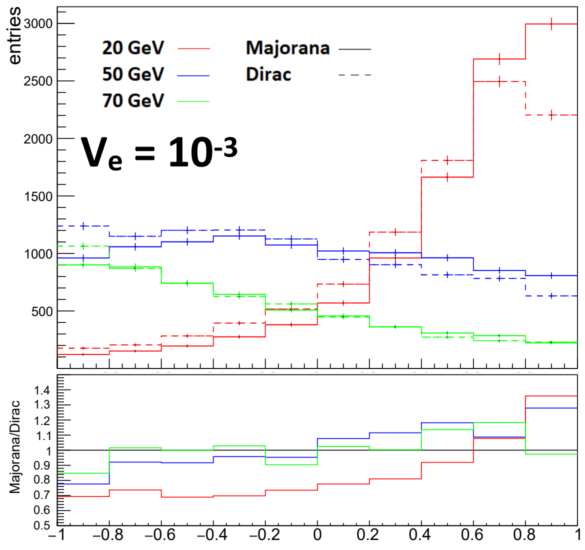
(model-dependent)



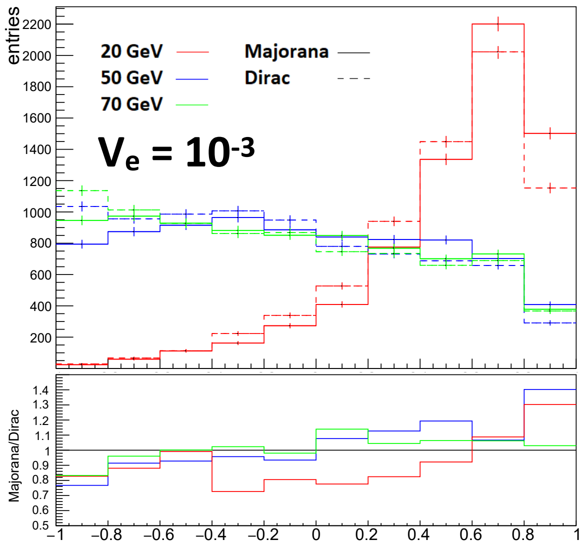
Gen HNL lifetime [s]

$\cos\theta_{ee}$

(opening angle between final state electron/positron)



Gen $\cos\theta_{ee}$



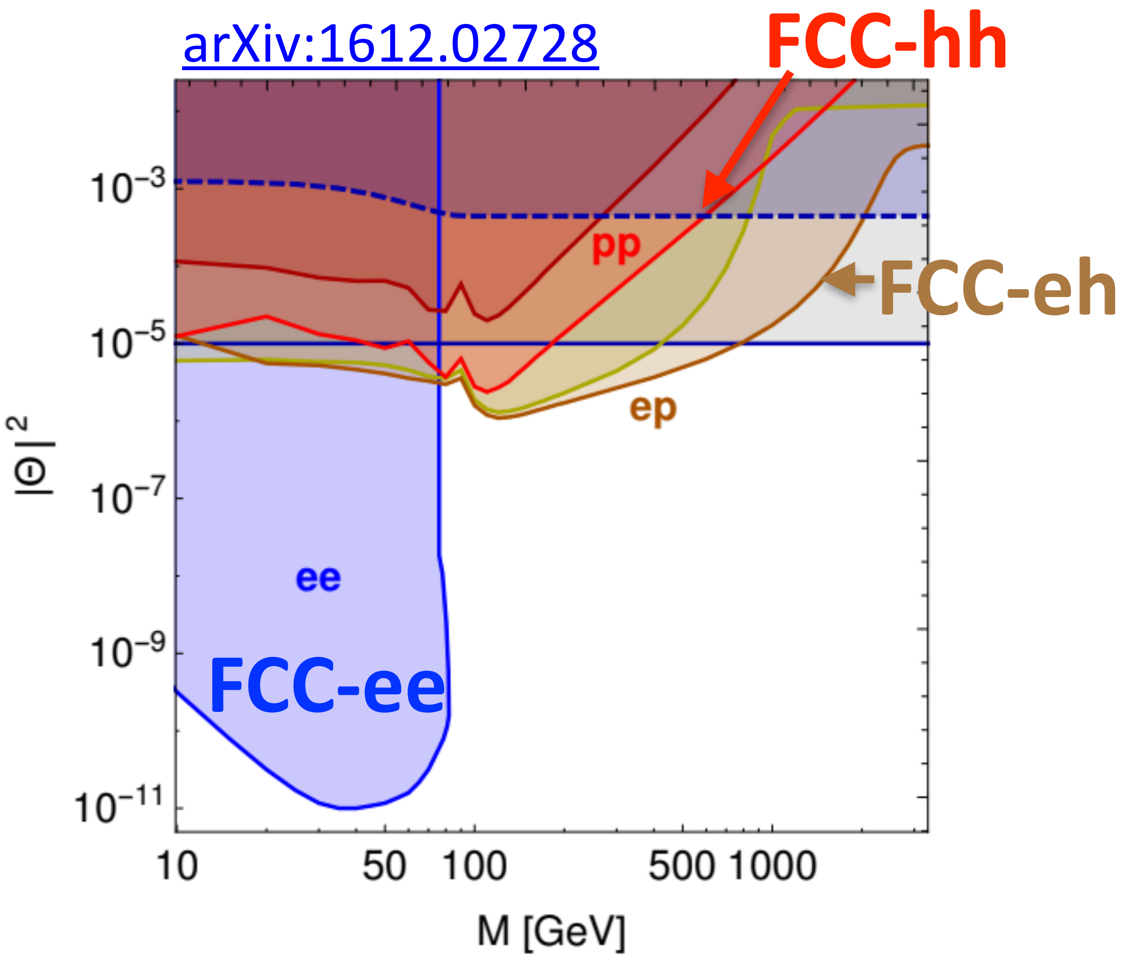
Reco $\cos\theta_{ee}$

Next: improve reconstruction, find more discriminating variables

What about FCC-hh and FCC-eh?

- **The three different stages of the FCC are complementary**
- Provides a unique potential to discover HNLs

arXiv:1612.02728



FCC-ee

- Direct search for single HNL production in W/Z decays
  - Sensitive to couplings down to 10^{-11} for M < W mass
- Indirect constraints from from precision SM measurements (not discussed)

FCC-hh

- Direct search for single HNL production in W/Z decays
- Can explore LNV and LFV
- Can test HNLs with masses up to ~2 TeV

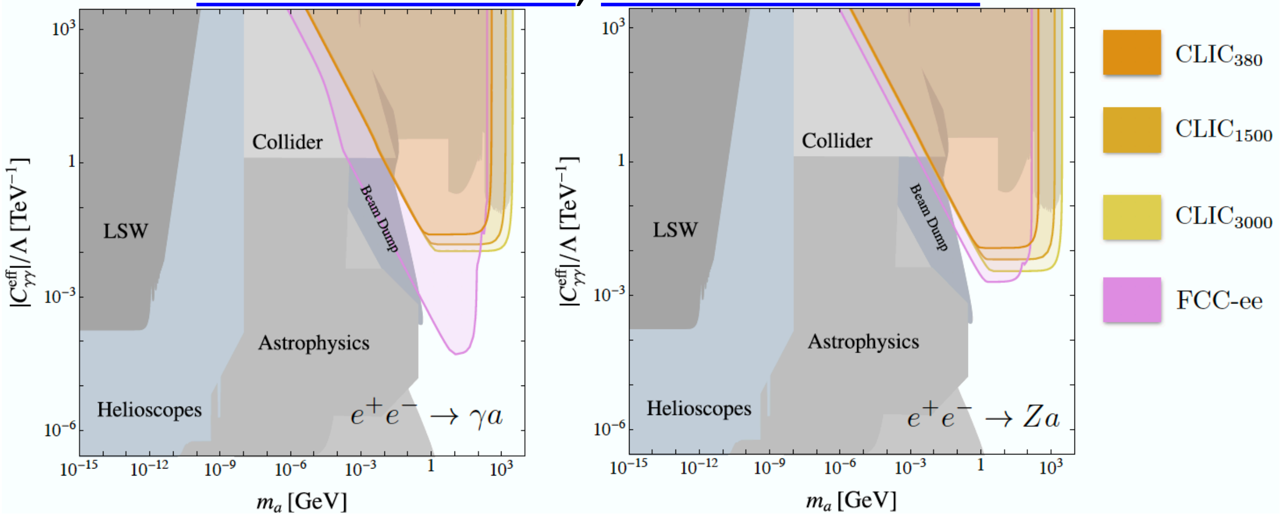
FCC-eh

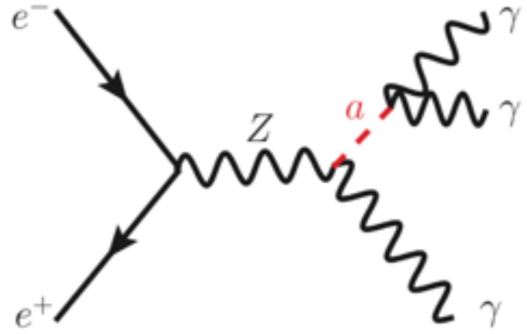
- Can extend the reach of the FCC-hh up to ~2.7 TeV in mass
- Best reach above W mass
- Sensitive to LFV and LNV signatures

2nd Benchmark: LL Axion-Like Particles

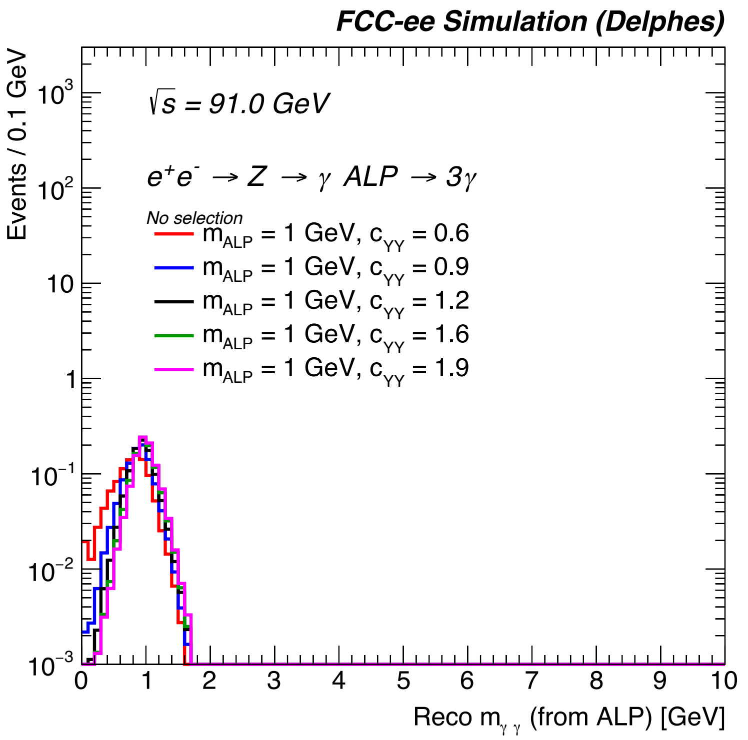
- Axion-like Particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries in BSM scenarios
- Very weakly coupled to the dark sector
- Get long-lived ALPs when couplings and mass are small
- At the FCC-ee:
    - Orders of magnitude of parameter space accessible
    - Especially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

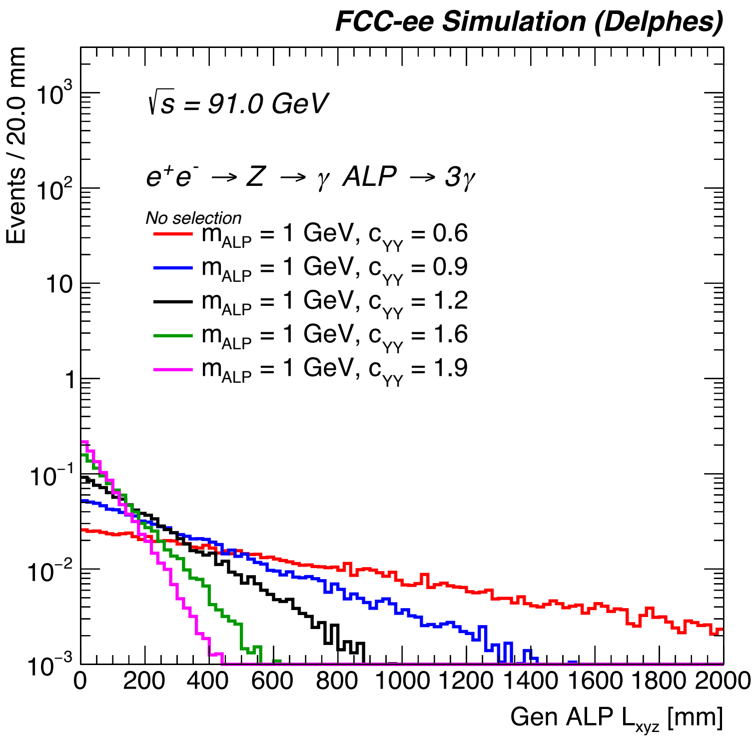
arXiv:1808.10323, arXiv:2108.08949





Variables to Explore



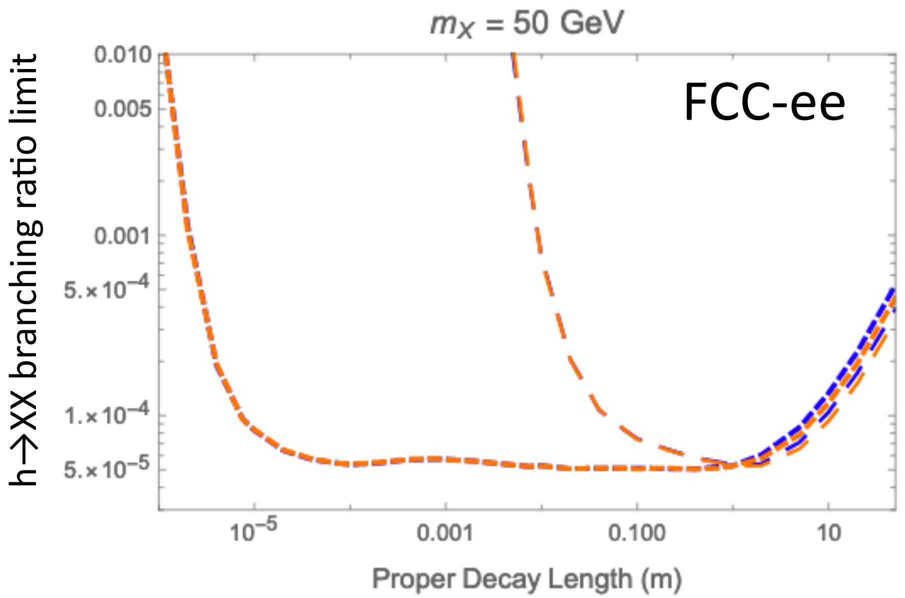


- Started with 1 GeV ALP mass, vary the coupling
- ALP mass confirmed with the reco invariant mass from the 2 photons coming from the ALP
- ALP decay length will also be a nice discriminating variable

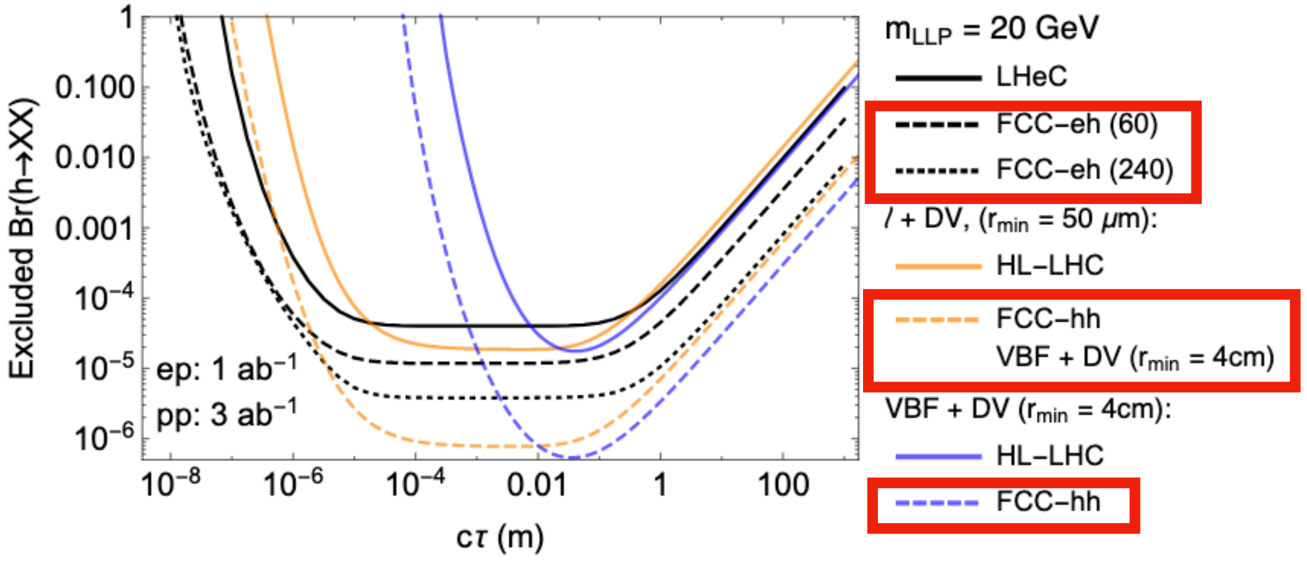
3rd Benchmark: Exotic Higgs decays to LLPs

- 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)
- Can do with e.g. this model in Madgraph

arXiv:1812.05588



arXiv:1712.07135



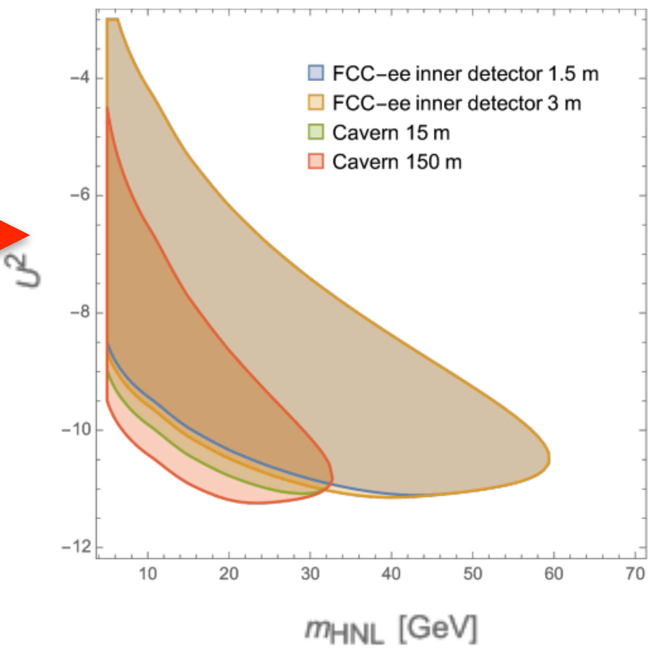
Other Topics to Explore at the FCC

- 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

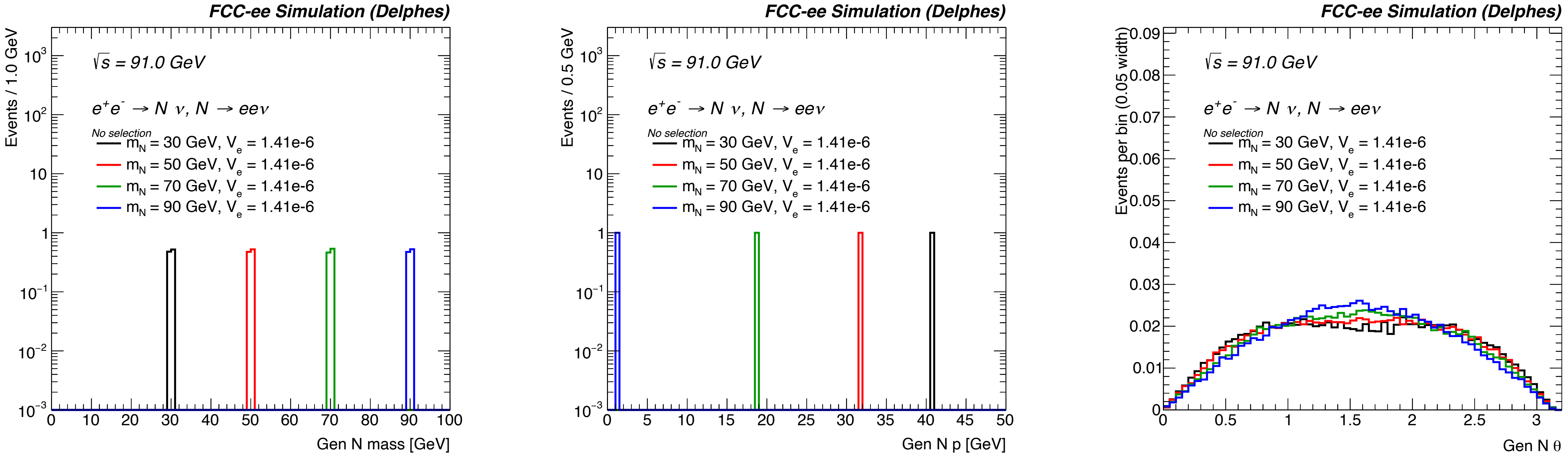
- Informal group with:
  - Meetings: https://indico.cern.ch/category/5664/
  - Mailing list: <LLP-FCCee-informal@cern.ch>
- We welcome new people, join us!

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
- Shown 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
- 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