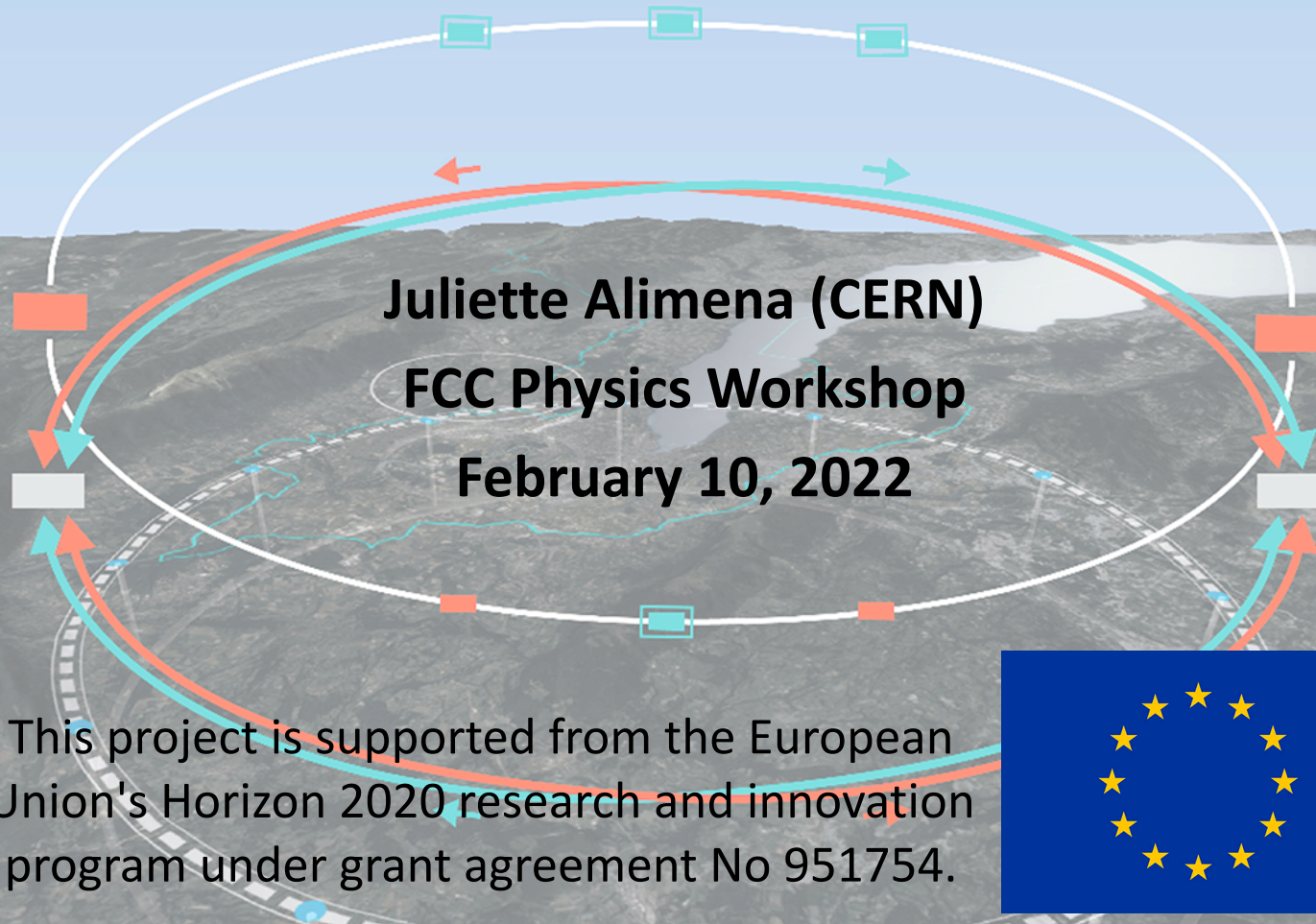


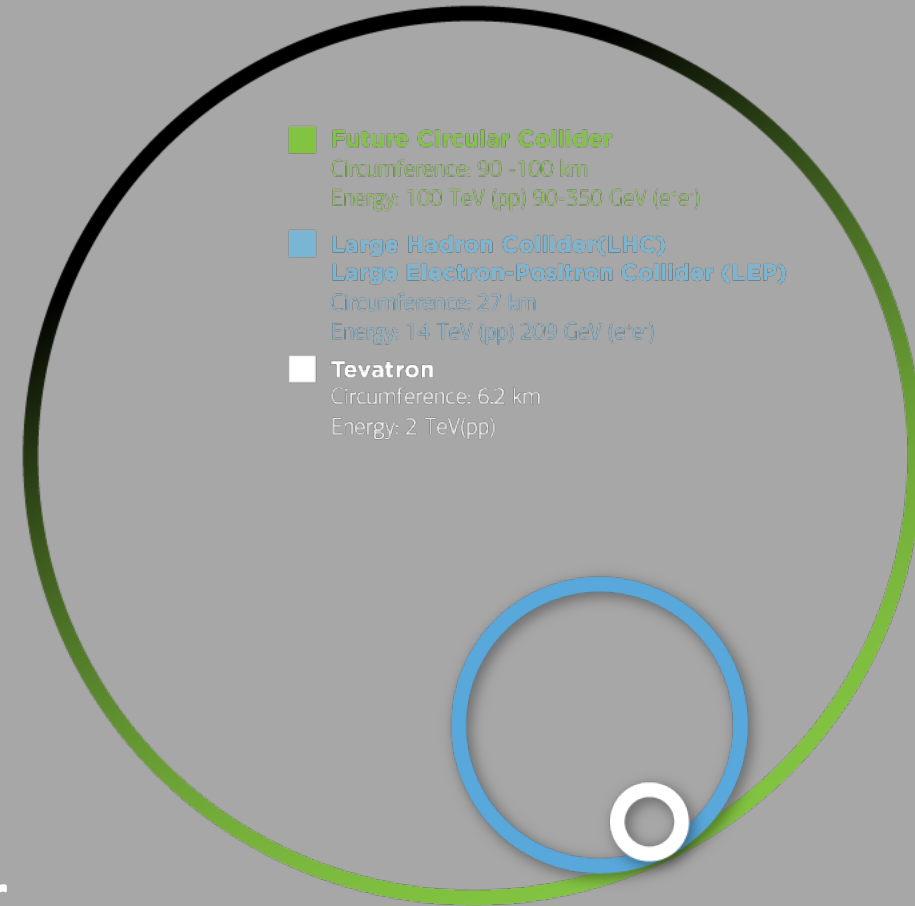
Long-Lived Particles at the FCC



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



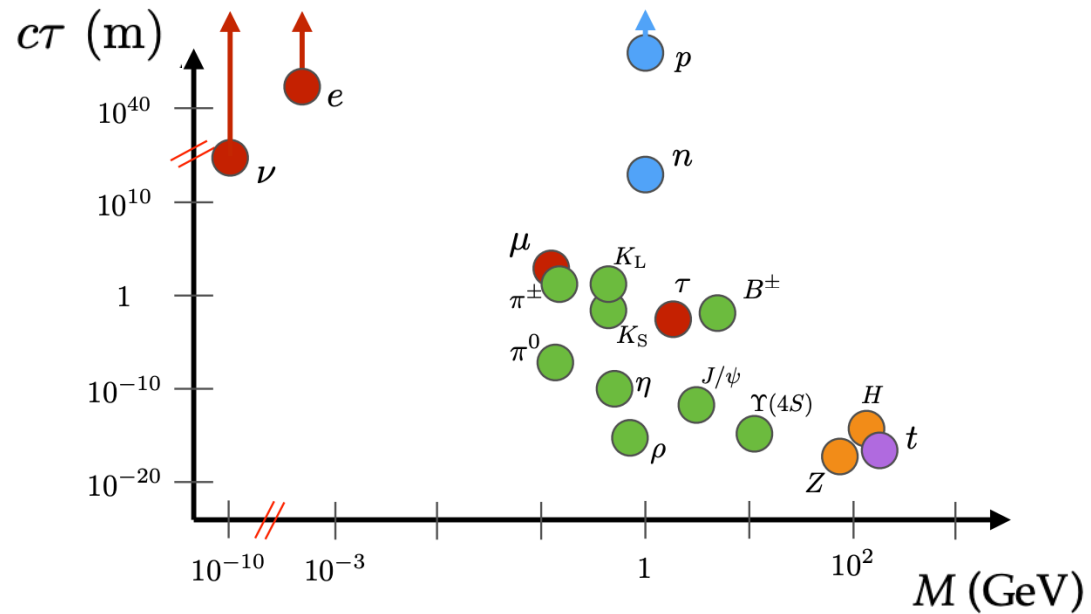
The FCC is a frontier Higgs, top, electroweak, and flavor factory where we can **directly discover new physics**

Enter LLPs!



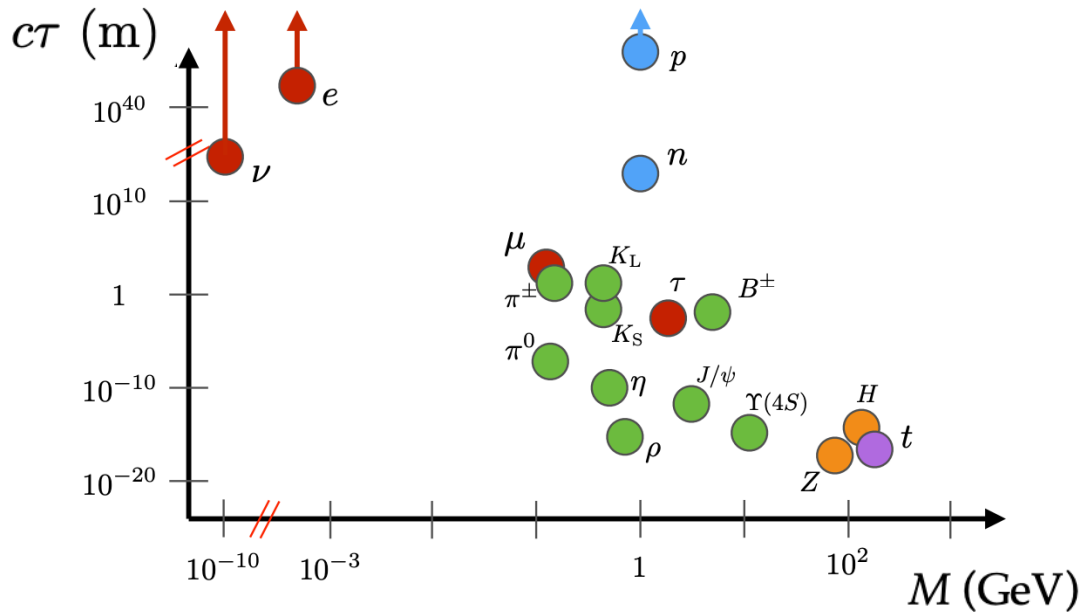
Long-Lived Particles (LLPs)

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



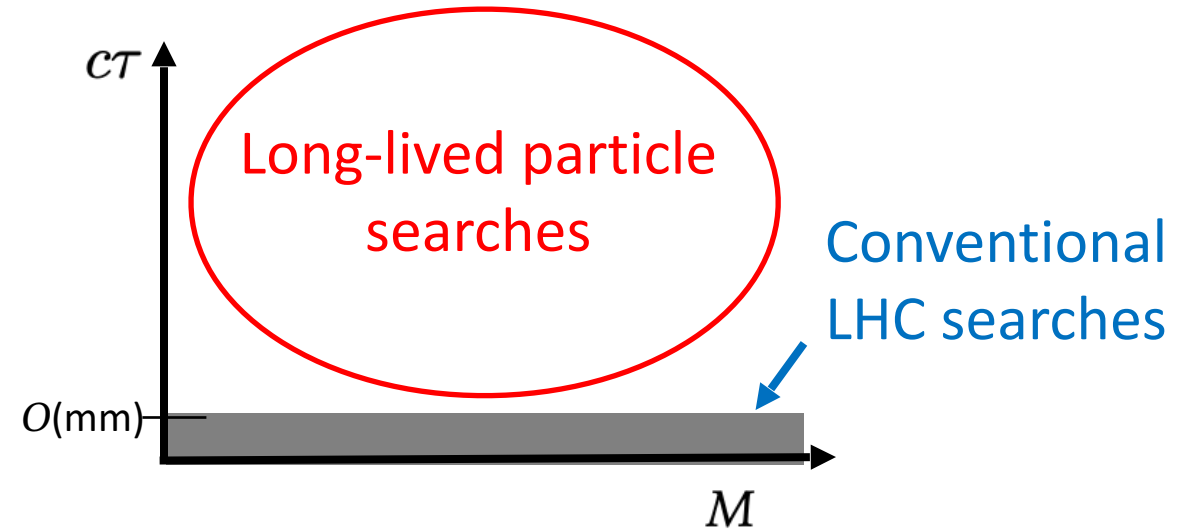
Long-Lived Particles (LLPs)

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!

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

small coupling

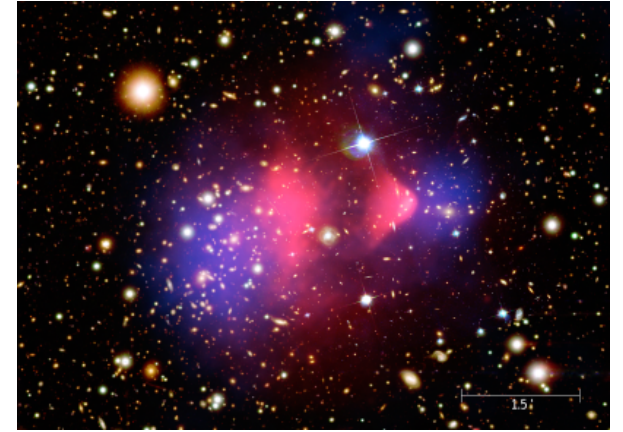
$$\frac{2\pi h}{\tau} = \frac{f_\pi^2}{256\pi m_\pi} \left[\frac{G_F^2 m_\mu}{M_W^2 m_\pi} (m_\pi^2 - m_\mu^2) \right]^2$$

heavy mediator

compressed spectra

Why Search for New LLPs?

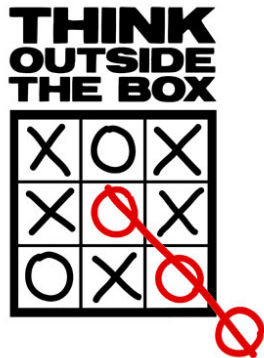
- **LLPs appear in many BSM scenarios**
 - Supersymmetry, heavy neutral leptons, dark photons, inelastic dark matter, and more!



- **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!

What's a New LLP?

- From an experimentalist's point of view, it's a particle beyond the standard model that:
 - decays a reconstructable distance from the primary collision
 - or
 - is quasi-stable on the scale of the detector

What's a New LLP?

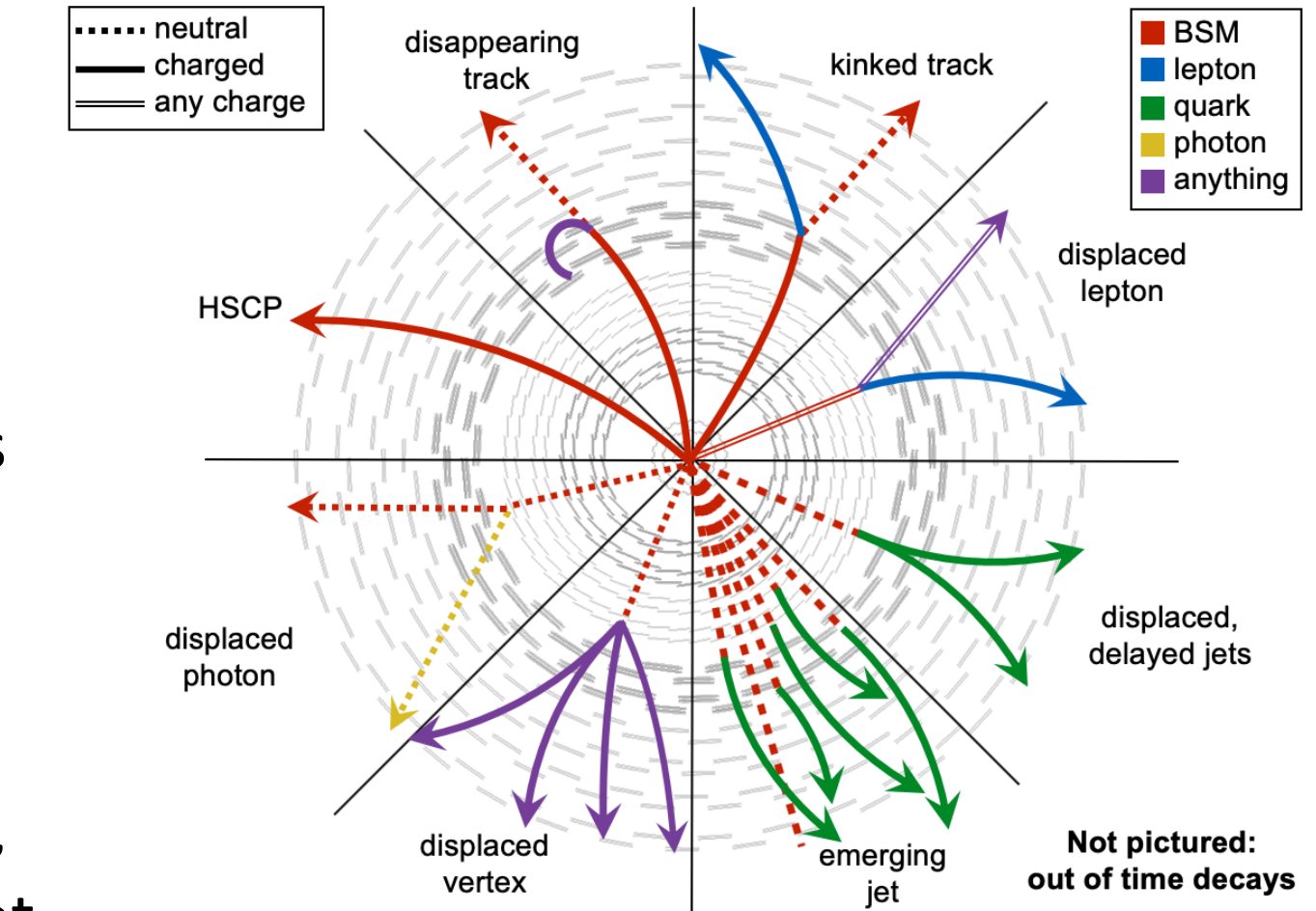
- From an experimentalist's point of view, it's a particle beyond the standard model that:
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- They can:
 - be **charged**, neutral or have **color**
 - be **light** or **heavy**
 - travel **fast** or **slow**
 - decay to anything

What's a New LLP?

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 - be **light** or **heavy**
 - travel **fast** or **slow**
 - decay to anything
- They often require **dedicated searches**

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

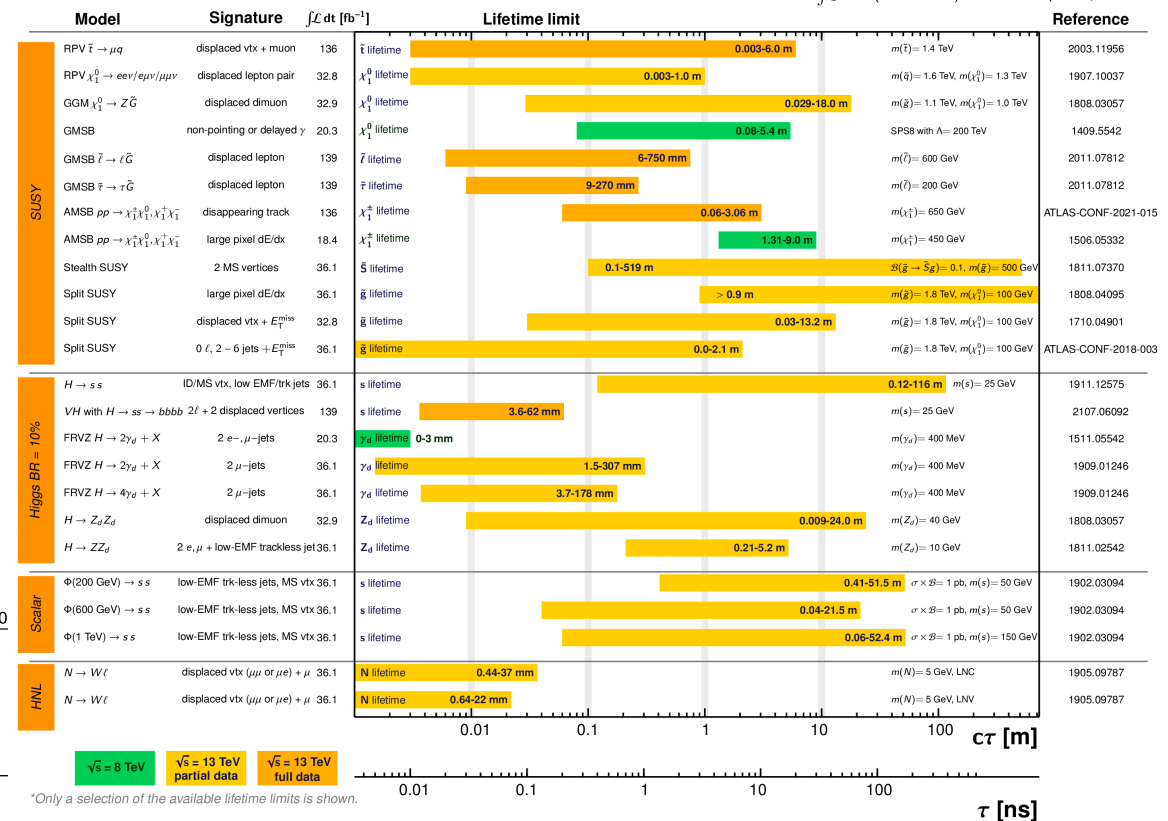
- A number of searches for LLPs have been performed at ATLAS, CMS, and LHCb
- Also at the Tevatron, LEP...
- Still uncovered phase space! More to do!
- No discovery yet!

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

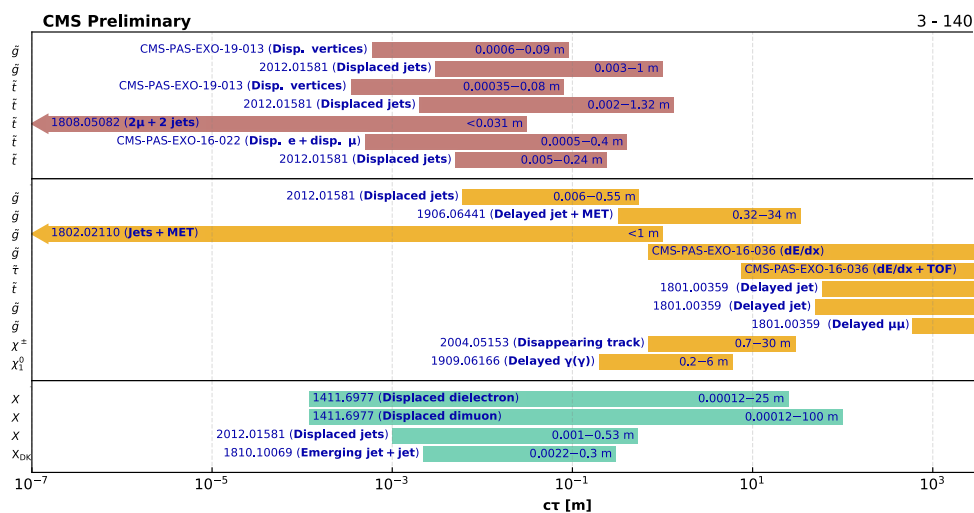
Status: July 2021

ATLAS Preliminary

$\int \mathcal{L} dt = (18.4 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$



Overview of CMS long-lived particle searches

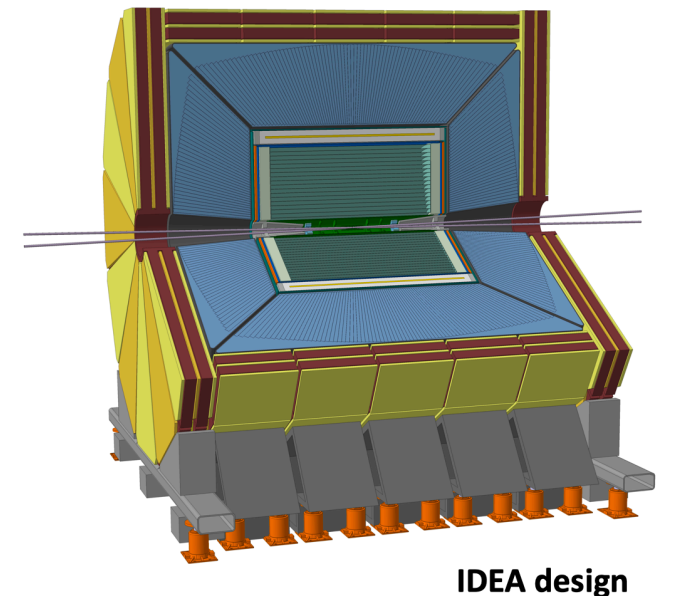
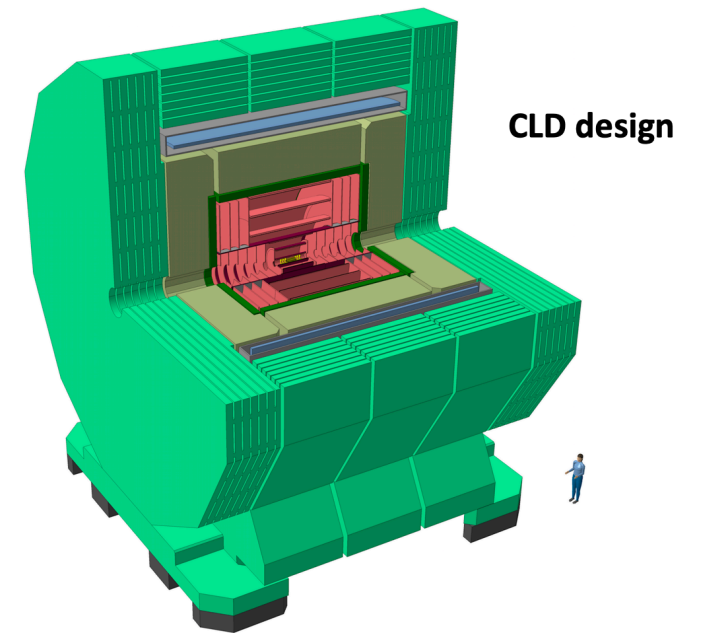


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Moriond 2021

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](https://arxiv.org/abs/2011.01005))



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) - **new results** since FCC week 2021
 2. Axion-like Particles (ALPs) - **new results** since FCC week 2021
 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
- See [Richard's talk](#) tomorrow

Three Generations of Matter (Fermions) spin 1/2

	I	II	III	
mass	2.4 MeV	1.27 GeV	173.2 GeV	0
charge	2/3	2/3	2/3	0
name	u up	c charm	t top	g gluon
Quarks	d down	s strange	b bottom	γ photon
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z weak force
Leptons	e electron	μ muon	τ tau	W weak force
				H Higgs boson

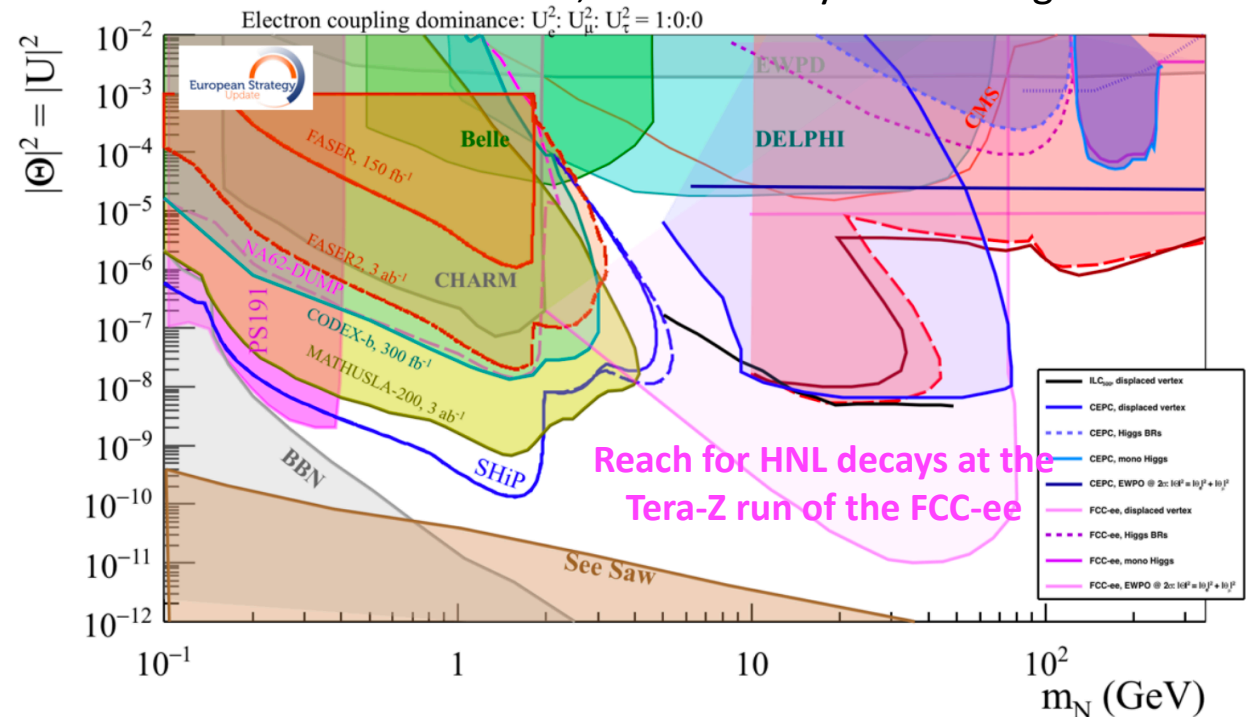
Bosons (Forces) spin 1

spin 0

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](https://arxiv.org/abs/2106.16226)

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



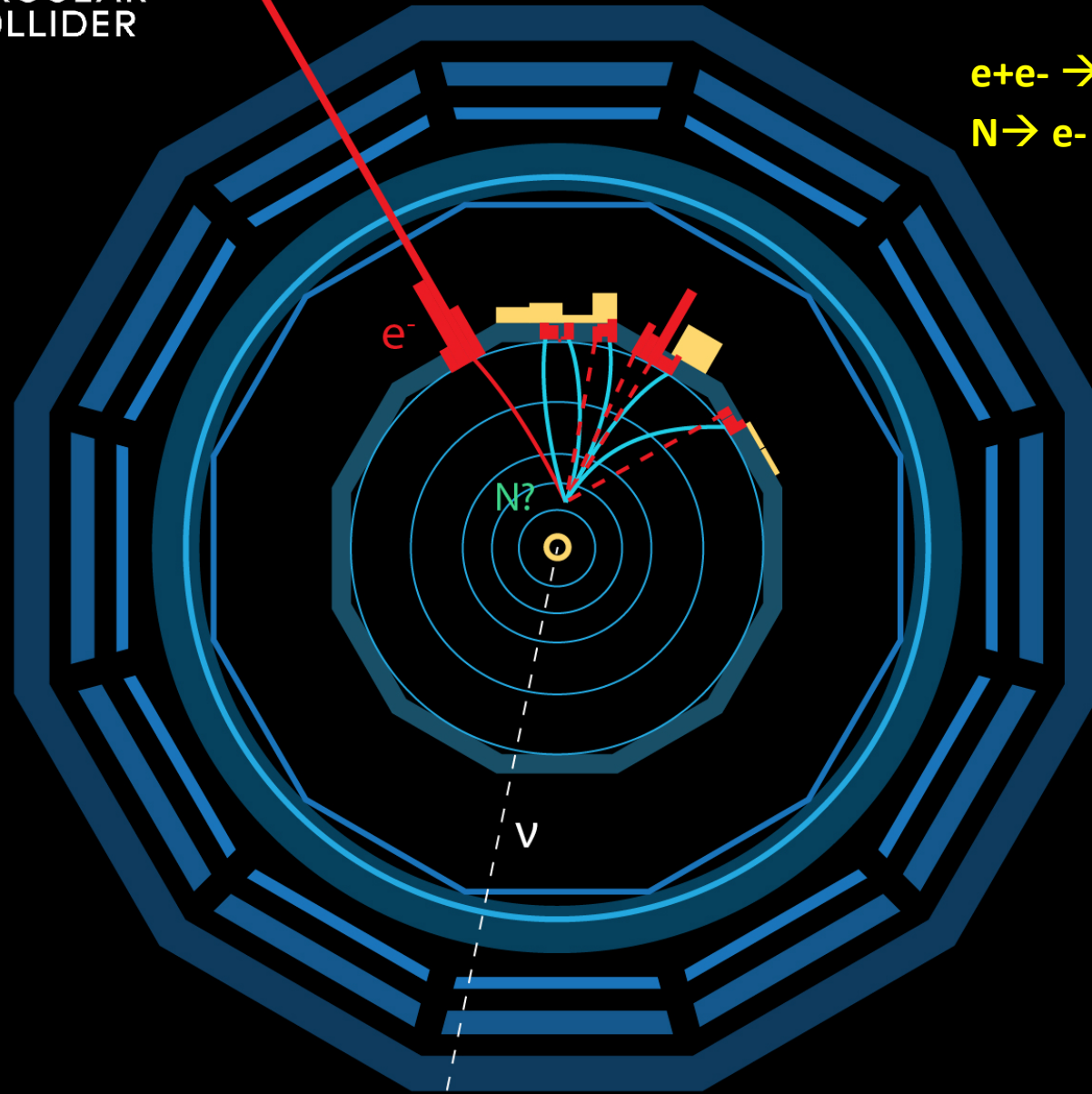


FUTURE
CIRCULAR
COLLIDER

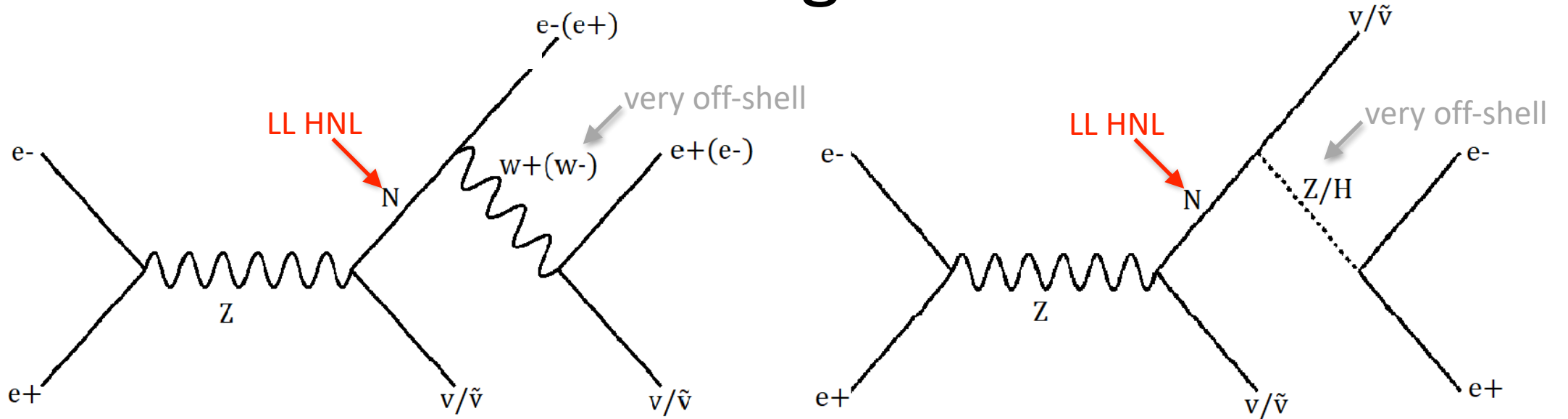
Z factory

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

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



Simulating HNLs



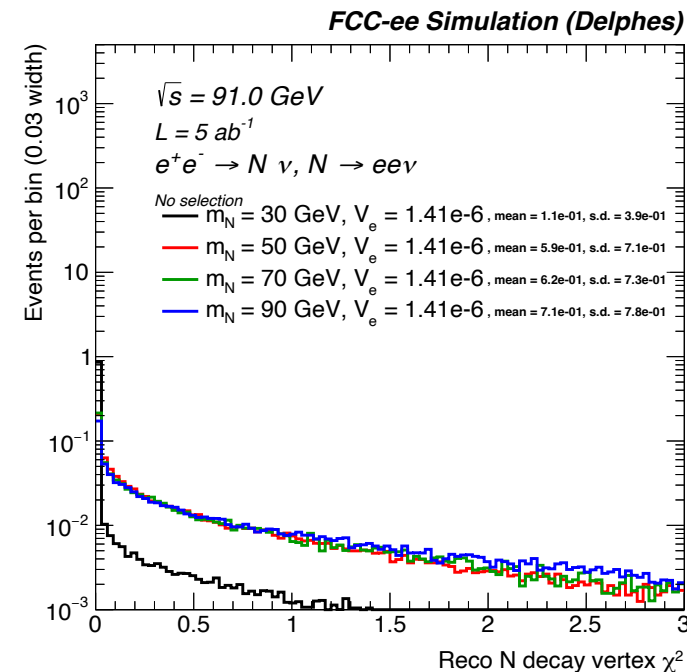
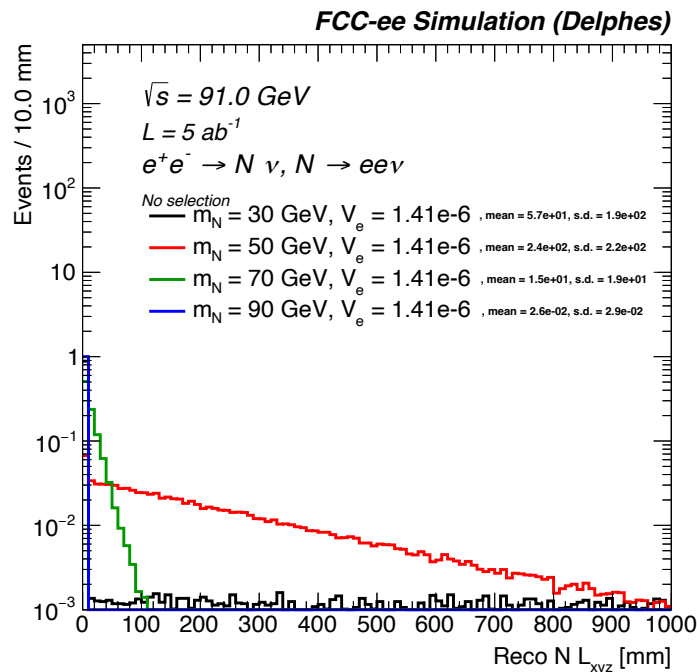
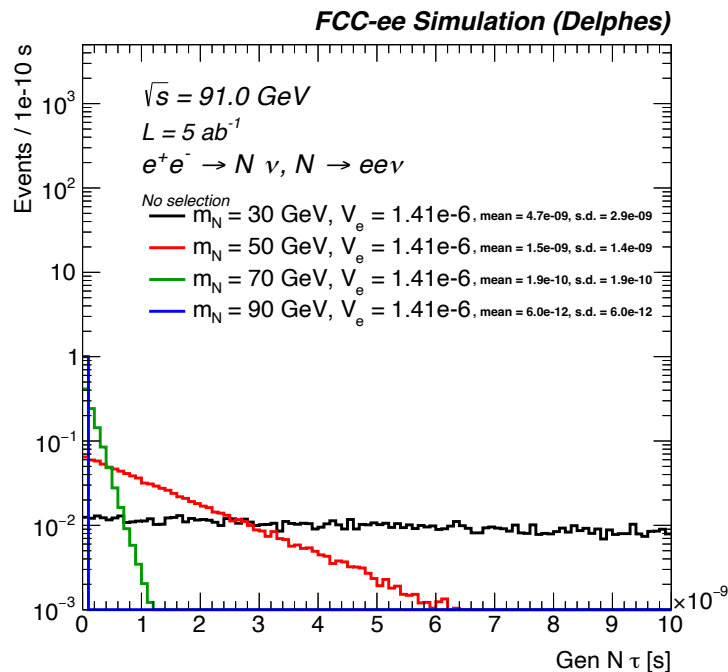
- Generated Majorana and Dirac HNLs with the SM_HeavyN_CKM_AllMasses_LO and SM_HeavyN_Dirac_CKM_Masses_LO models ([arXiv:1411.7305](https://arxiv.org/abs/1411.7305), [arXiv:1602.06957](https://arxiv.org/abs/1602.06957))
- Started with the $ee\nu$ final state (suggested as early as 1984(!) by [S. Petcov](#))
- 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

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

[Valid when $m_N \lesssim 100$ GeV, [arXiv:1905.11889](https://arxiv.org/abs/1905.11889)]

Get long-lived HNLs when coupling and mass are small

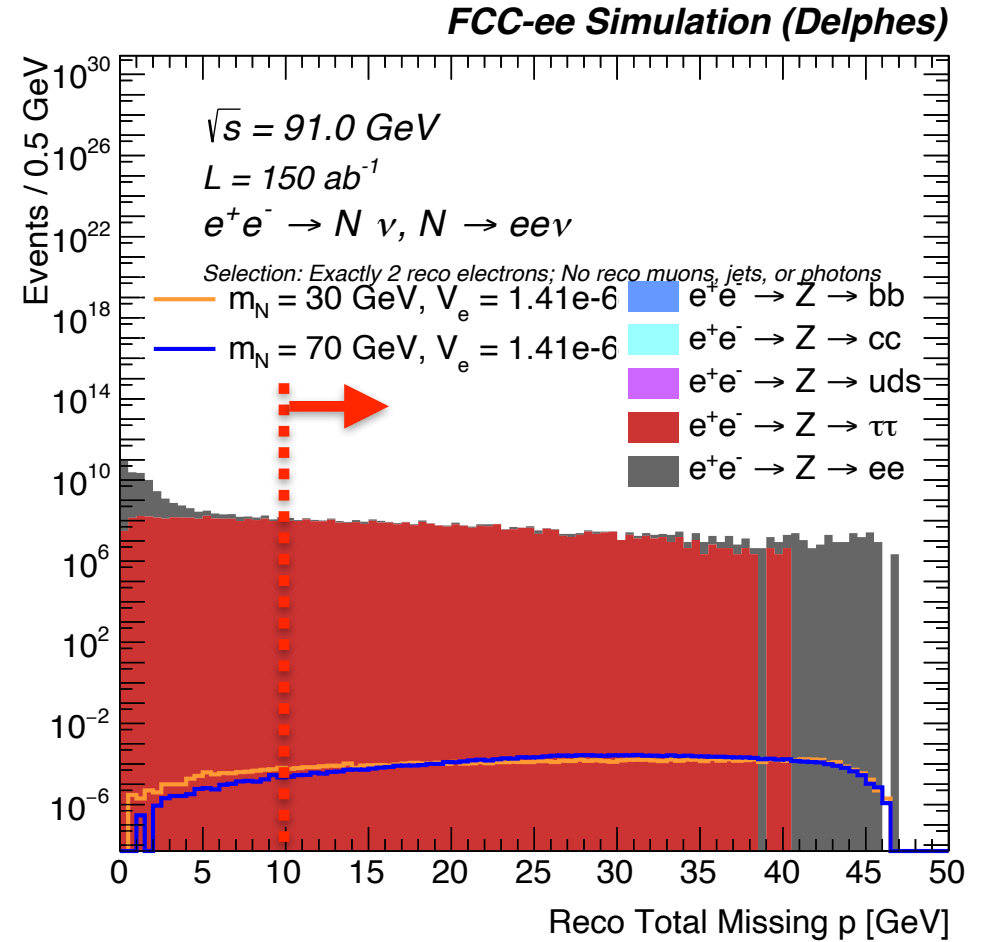
HNL Lifetime and Decay Vertex



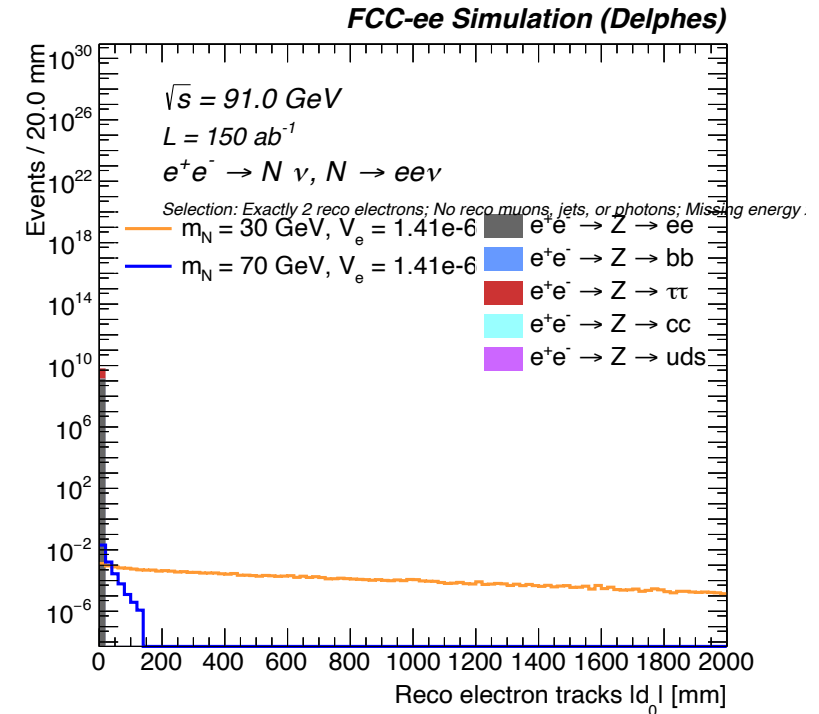
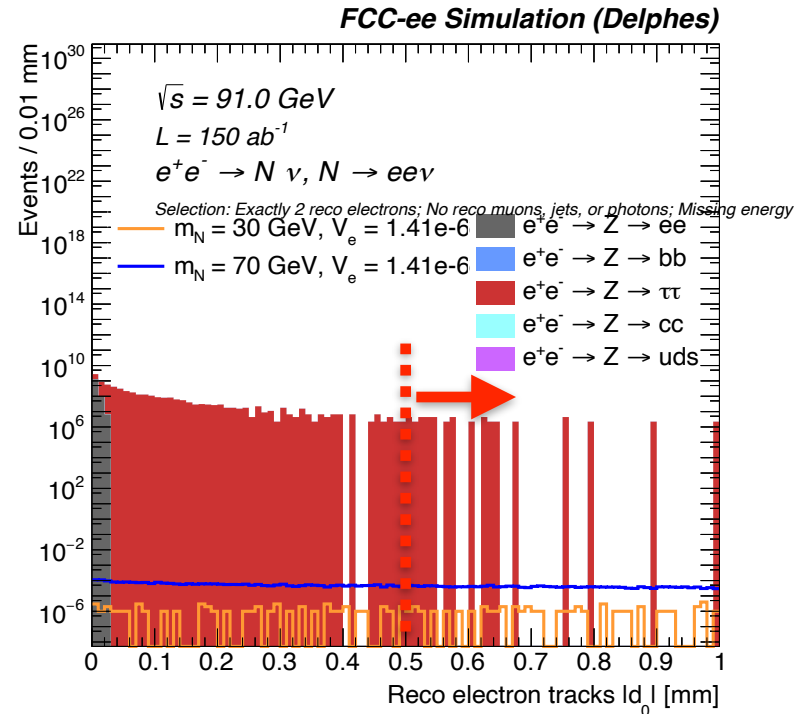
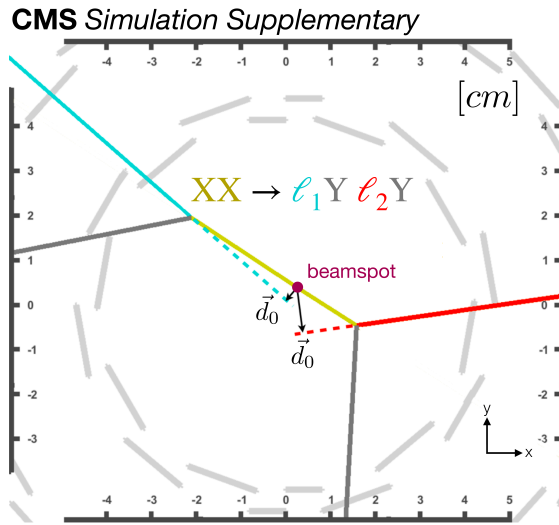
- Confirmed HNL signal kinematics behave as expected, at gen and reco level
- For example, for $m = 50 \text{ GeV}, V_e = 1.41e-6$, the mean of the generated lifetime is $1.5E-9 \text{ s} \rightarrow 45 \text{ cm}$, which is what we expected
 - On the other hand, $m = 90 \text{ GeV}, V_e = 1.41e-6$ is pretty prompt
- Reco L_{xyz} (3D decay length) and vertex χ^2 distributions are also understood
 - $m = 30 \text{ GeV}, V_e = 1.41e-6$ 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 IDEEA 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})
- $|d_0| > 0.5 \text{ mm}$ removes the vast majority of the SM background

Selection

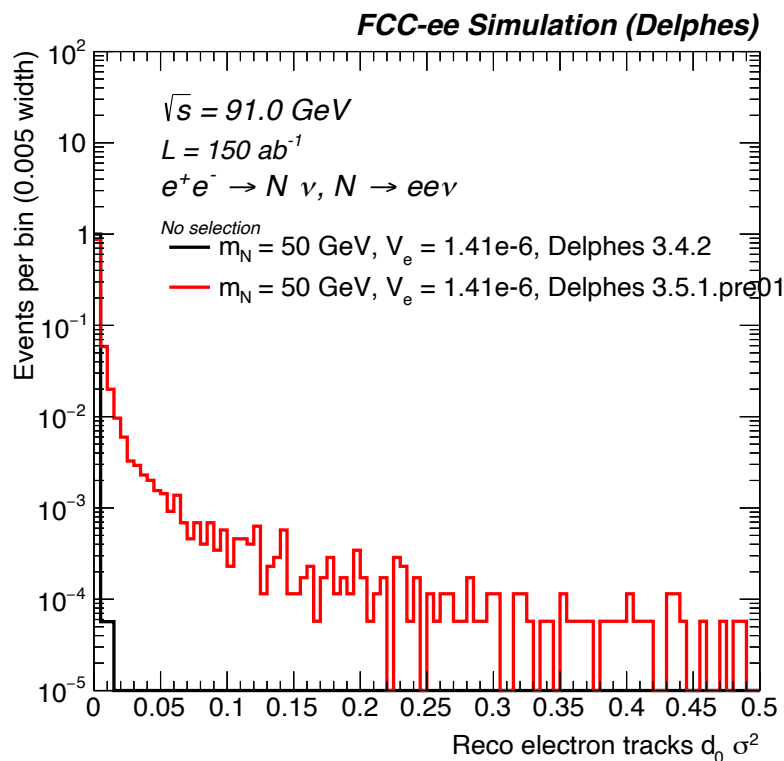
- First attempt at an event selection
- Table shows the expected number of events at 150 ab^{-1} , cumulative after each cut (on reco variables)
- Caveat: here just used 100k (50k) raw/unscaled events for background (signal)
- Most discriminating variables: missing energy and $|d_0|$
- Next steps:
 - 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 $V_e = 1.41\text{e-}6$	m = 70 GeV $V_e = 1.41\text{e-}6$
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 \text{ 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

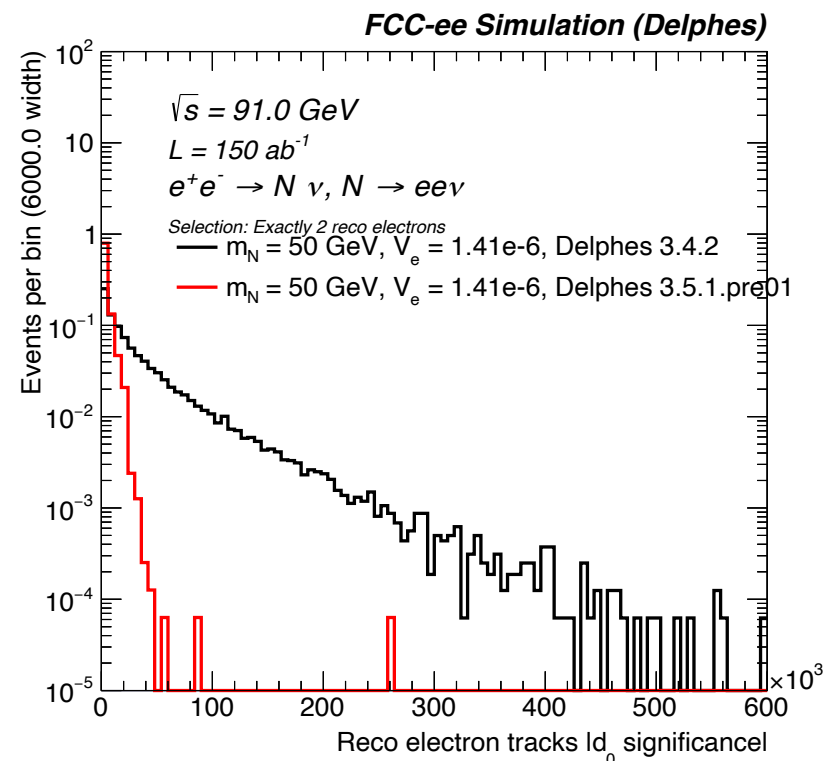
Bonus: Displaced Track Parameters Uncertainty

- Newest version of delphes gives the proper uncertainties for the parameters of displaced tracks
- Makes a significant difference in long-lived HNL sample:

d_0 uncertainty

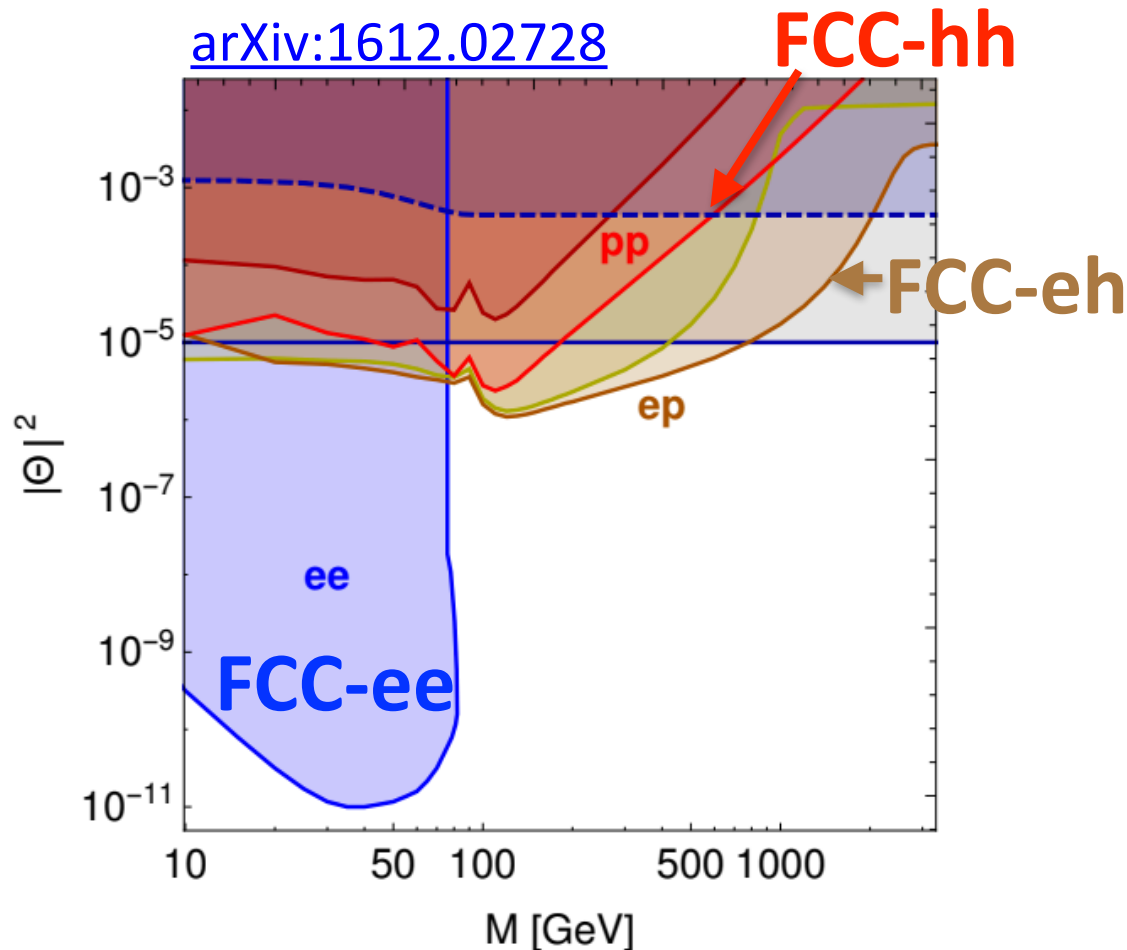


$|\mathbf{d}_0 \text{ significance}| = |\mathbf{d}_0/\sigma|$



What about FCC-hh and FCC-eh?

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



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 precision SM measurements (not discussed)

FCC-hh

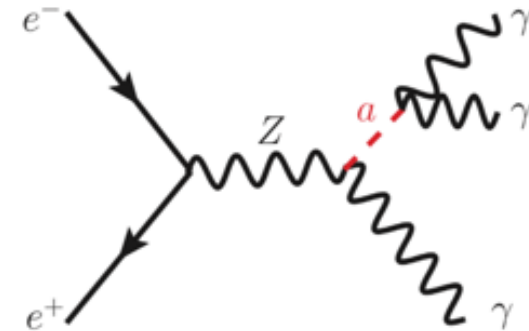
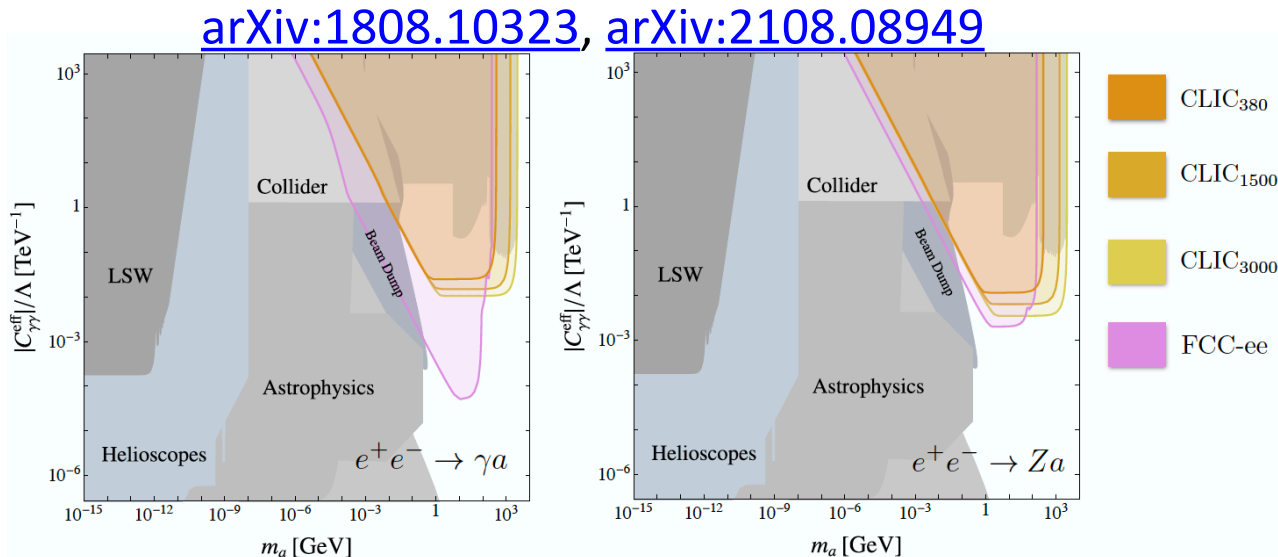
- Direct search for single HNL production in W/Z decays
- Can explore LNV and LFV
- Can test HNLs with masses up to ~ 2 TeV

FCC-eh

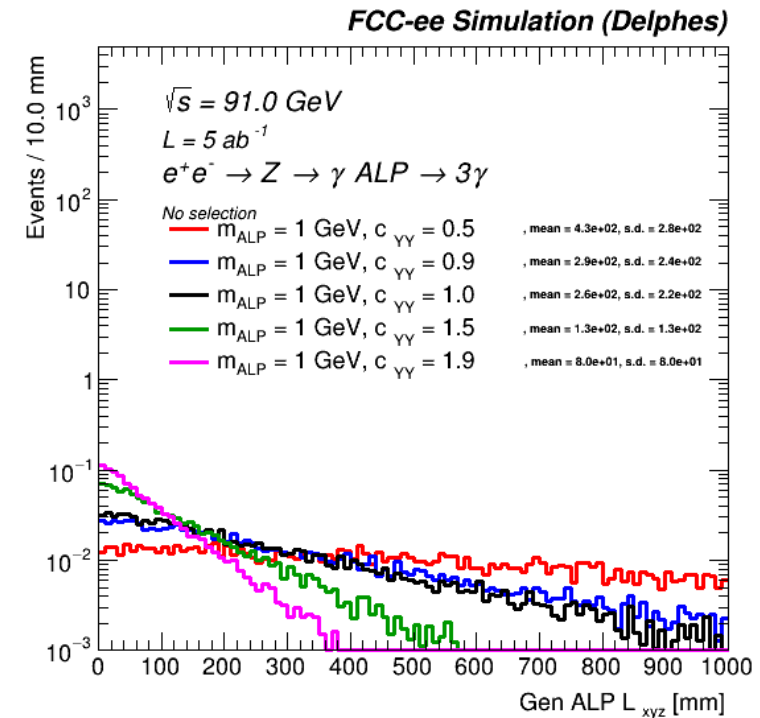
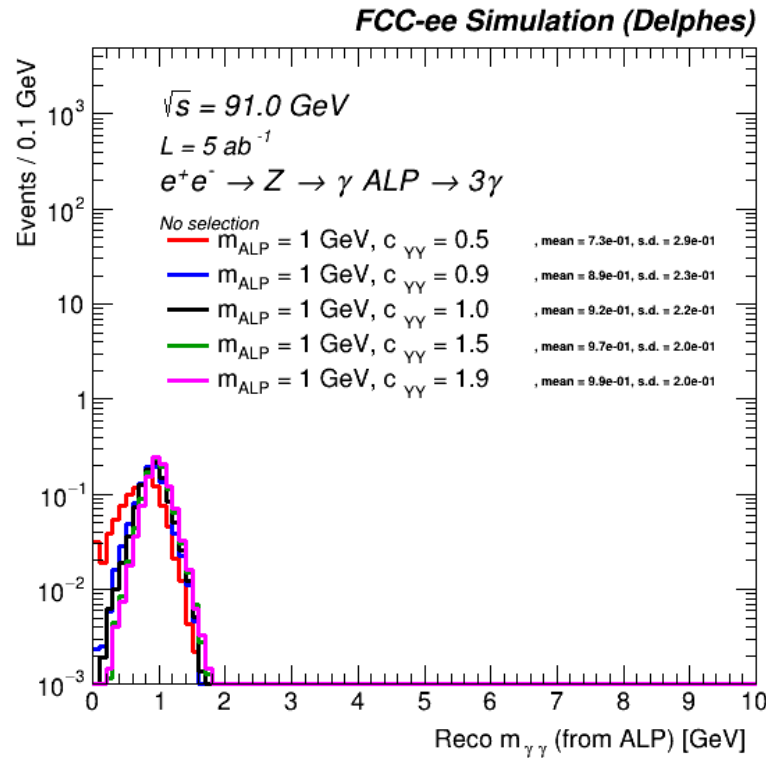
- Can extend the reach of the FCC-hh up to ~ 2.7 TeV in mass
- Best reach above W mass
- Sensitive to LFV and LNV signatures

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, $\sqrt{s} = 91$ GeV**
 ([arXiv:1808.10323](https://arxiv.org/abs/1808.10323))



Variables to Explore

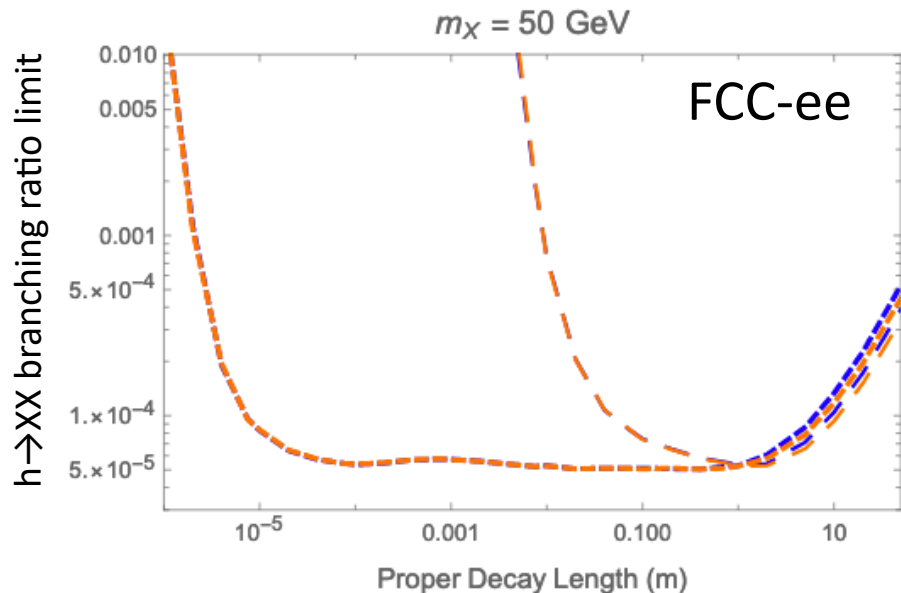


- Started with 1 GeV ALP mass, vary the coupling
- ALP mass confirmed with the reco invariant mass from the 2 photons coming from the ALP
- ALP decay length will also be a nice discriminating variable

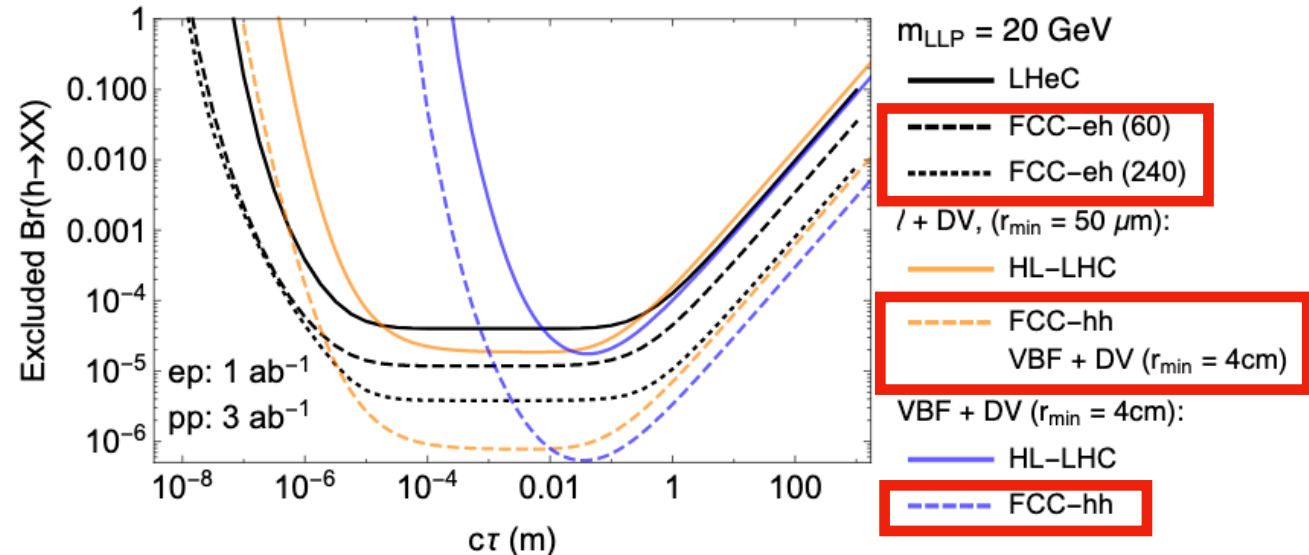
3rd Benchmark: Exotic Higgs decays to LLPs

- 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

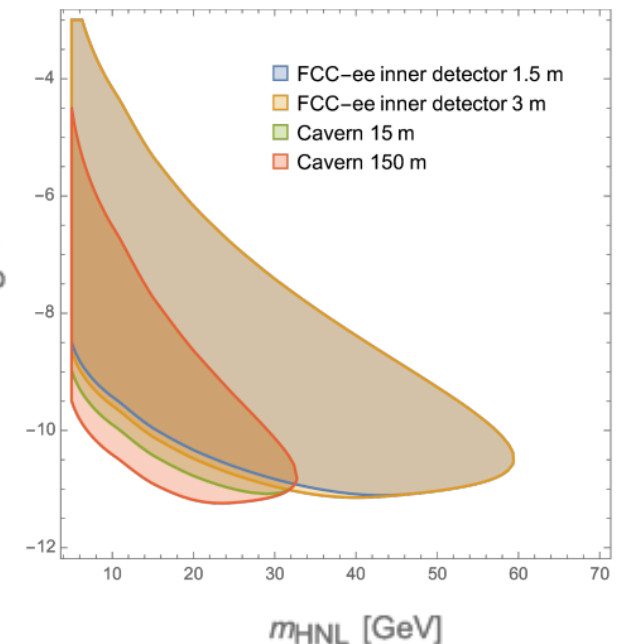


Other Topics to Explore at the FCC

- 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? 
 U^2
 - Bigger tracker? More layers?
 - Majorana vs Dirac HNLs (see [Richard's talk](#) tomorrow)
 - Not an exhaustive list!

Preliminary study ([arXiv:2106.15459](https://arxiv.org/abs/2106.15459)) shows the sensitivity of HNLs to different inner detector and cavern sizes



LLPs at FCC-ee group

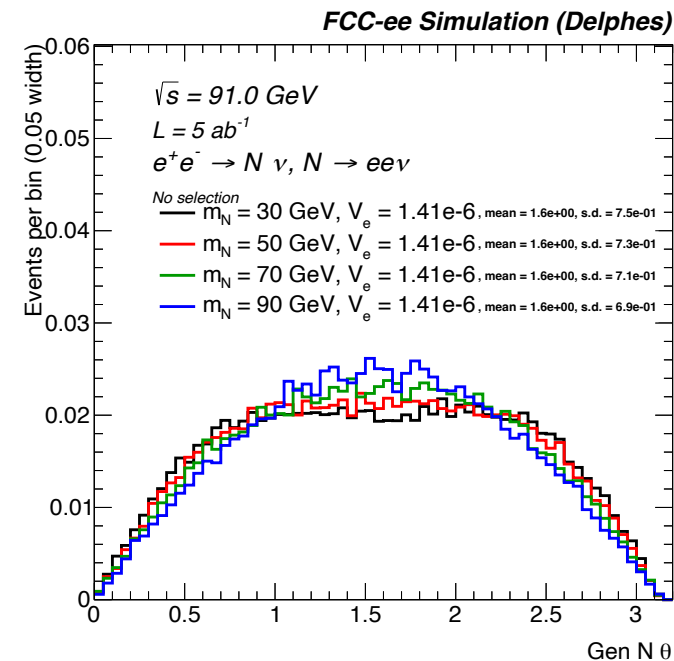
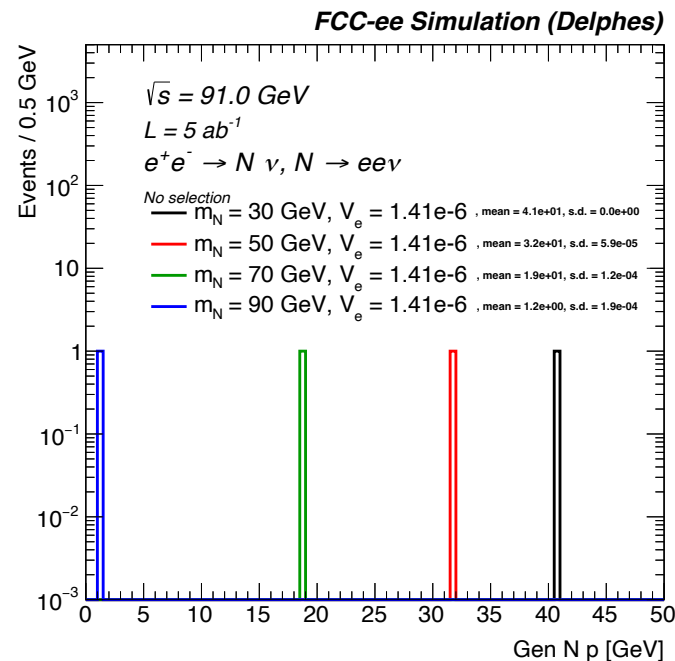
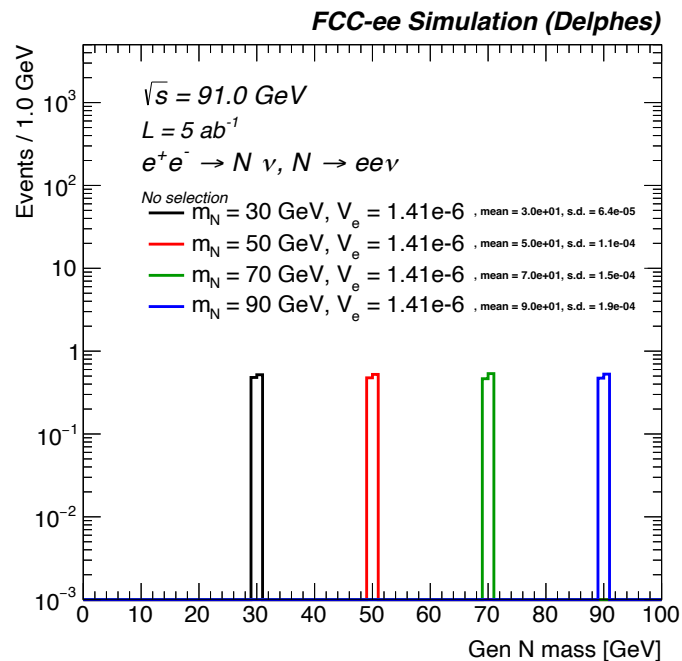
- Informal group with:
 - Meetings: <https://indico.cern.ch/category/5664/>
 - Mailing list: <LLP-FCCee-informal@cern.ch>
- We welcome new people, join us!

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
- Also see [Rebeca's talk](#) from the previous FCC week
- 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