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Long-Lived Particles at the FCC-ee

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

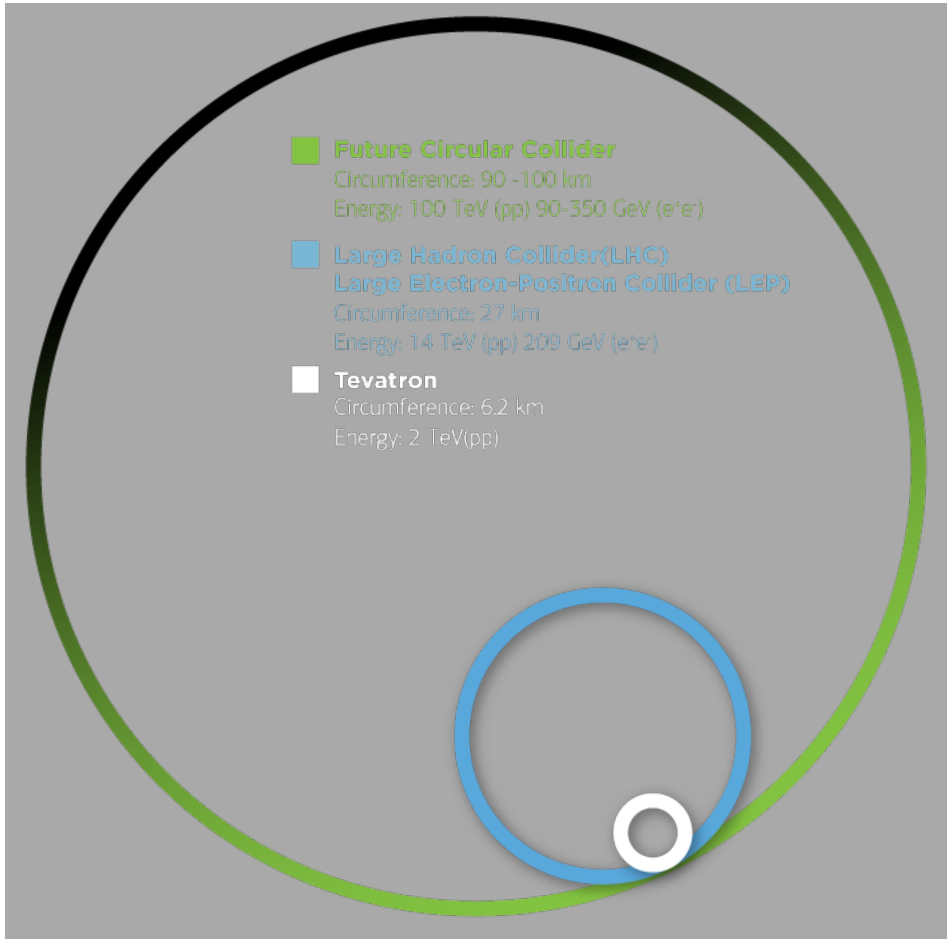
FCC Phenomenology Workshop

July 5, 2023

Future Circular Collider

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

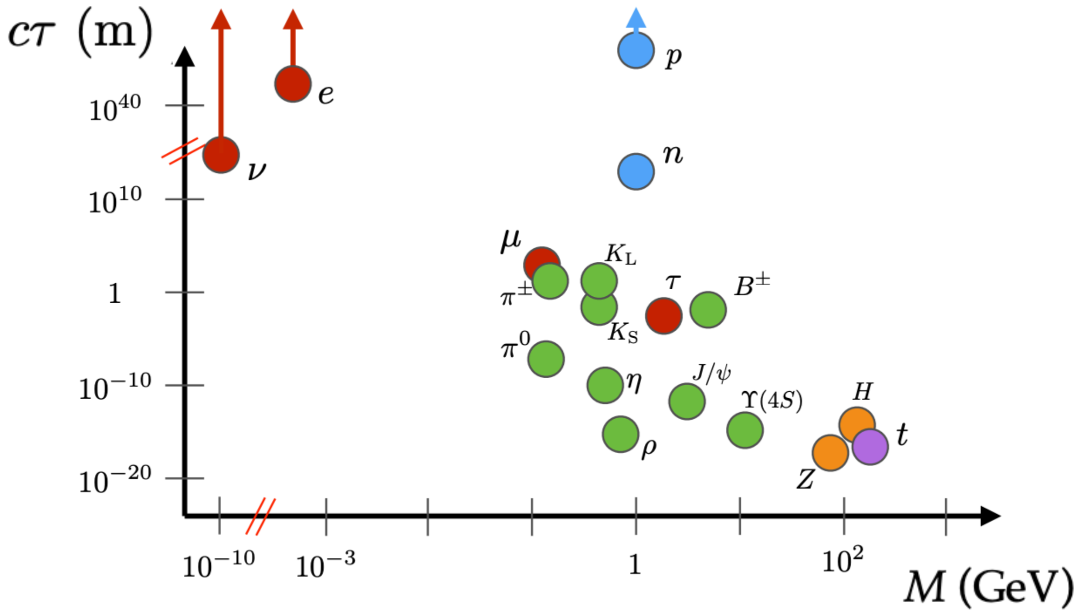
- Stage 1: FCC-ee (Z, W, H , tt) as Higgs EW and top factory at high luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options



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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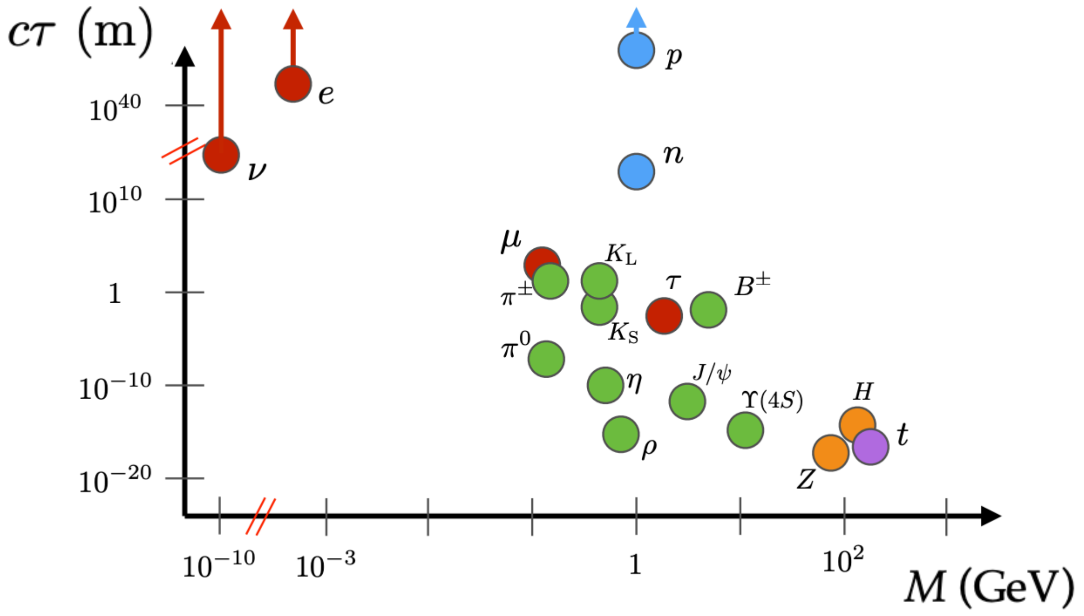
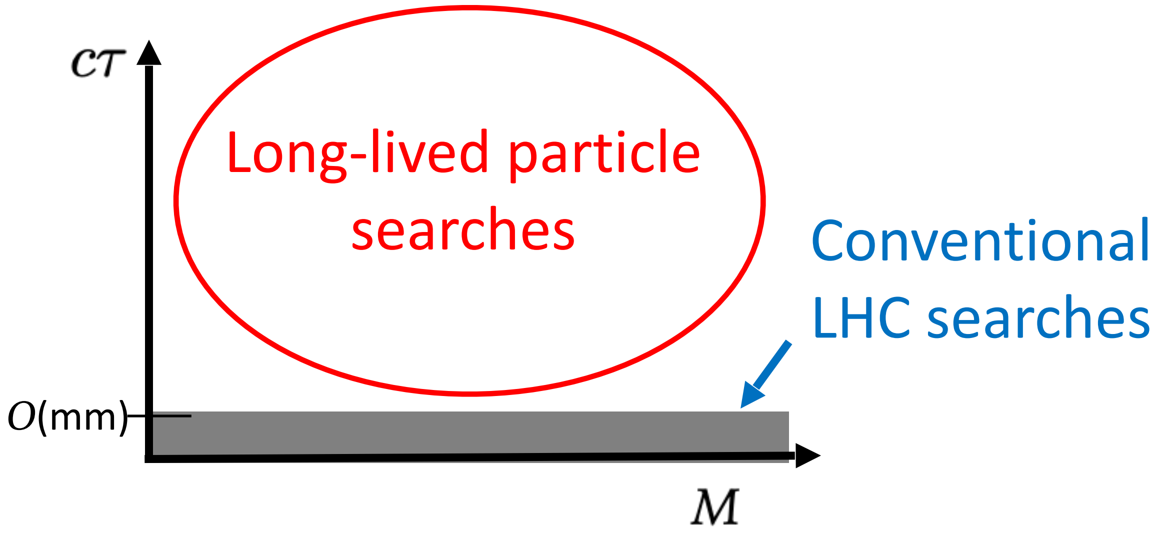


We expect **new phenomena** to have a wide range of lifetimes as well

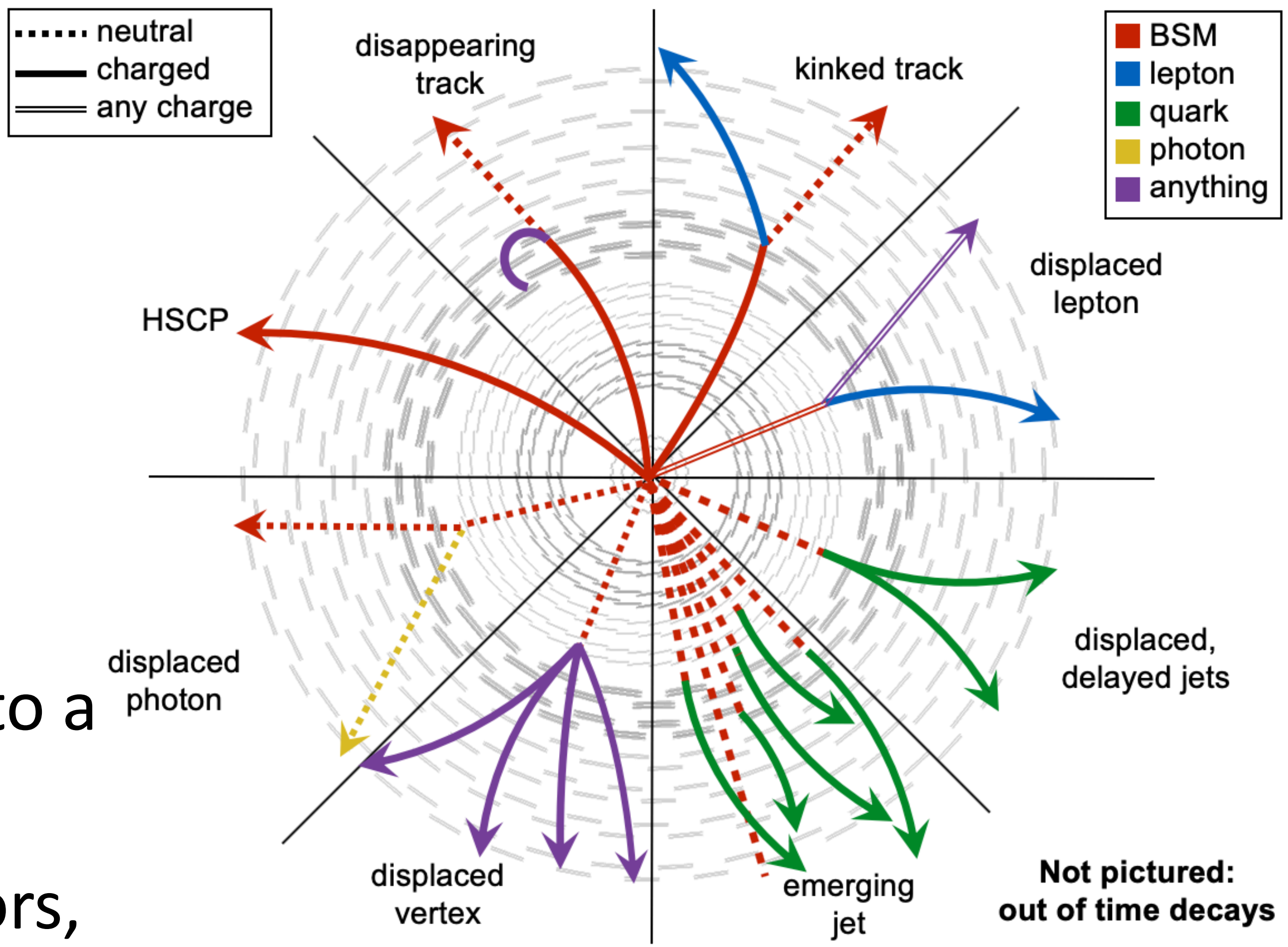
But **conventional searches** for new phenomena at the LHC are for **promptly** decaying particles



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

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:** main detectors, triggers, offline reconstruction not designed for displaced particles



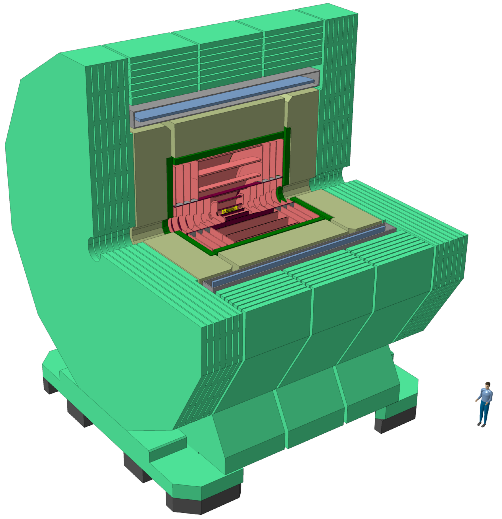
Big opportunity to do something different at the FCC!

Detectors at the FCC-ee

A few detector concepts being used for integration, performance, and cost estimates:

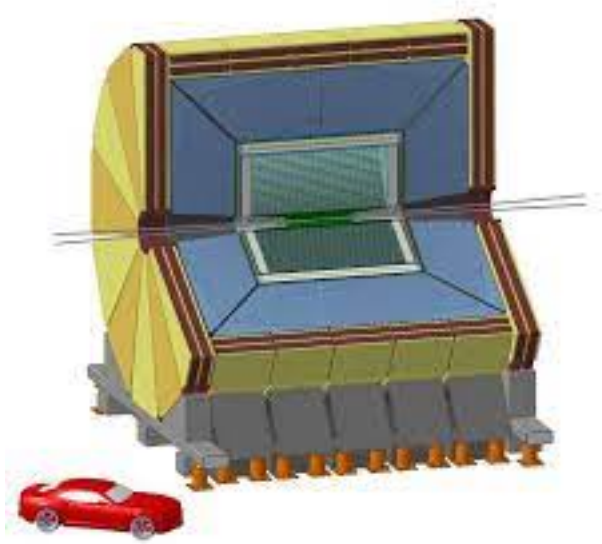
CLIC-like Detector (CLD)

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



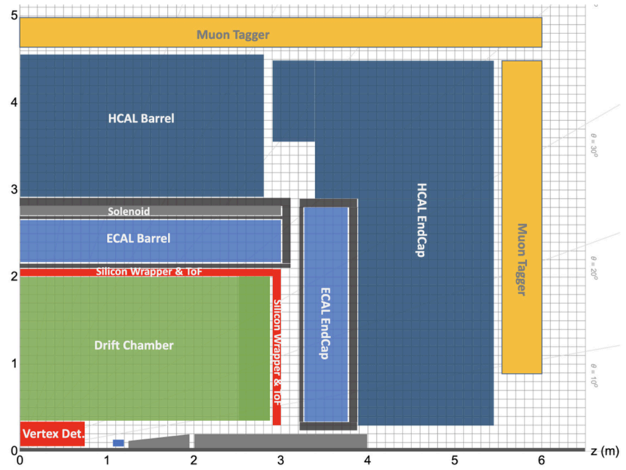
Innovative Detector for an Electron-Positron Accelerator (IDEA)

- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter (solenoid inside)



Noble Liquid

- High-granularity noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Newest proposal



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

Past and Ongoing Work

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)
- Magdalena Vande Voorde (Uppsala University, 2023)
- Daniel Beech (University of Cambridge, 2023)
- Dimitri Moulin (University of Geneva, 2023)
  - *defending thesis today!*

Snowmass:

- LOI
- White paper (Front. Phys. 10:967881 (2022) / arXiv:2203.05502)

Searches for long-lived particles at the future FCC-ee

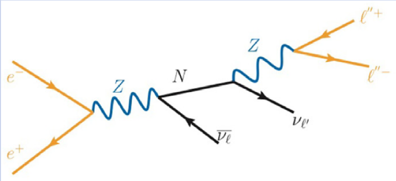
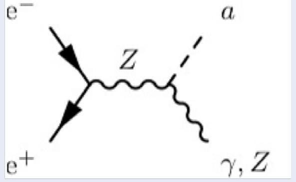
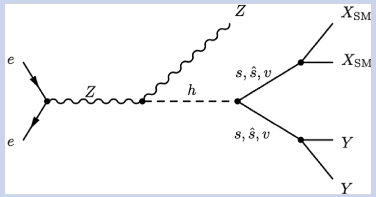
C. B. Verhaaren[1], J. Alimena[2]*, M. Bauer[3], P. Azzi[4], R. Ruiz[5], M. Neubert[6,7], O. Mikulenko[8], M. Ovchynnikov[8], M. Drewes[9], J. Klaric[9], A. Blondel[10], C. Rizzi[10], A. Sfyrla[10], T. Sharma[10], S. Kulkarni[11], A. Thamm[12], A. Blondel[13], R. Gonzalez Suarez[14] and L. Rygaard[14]

LLP group focusing on 3 physics cases:

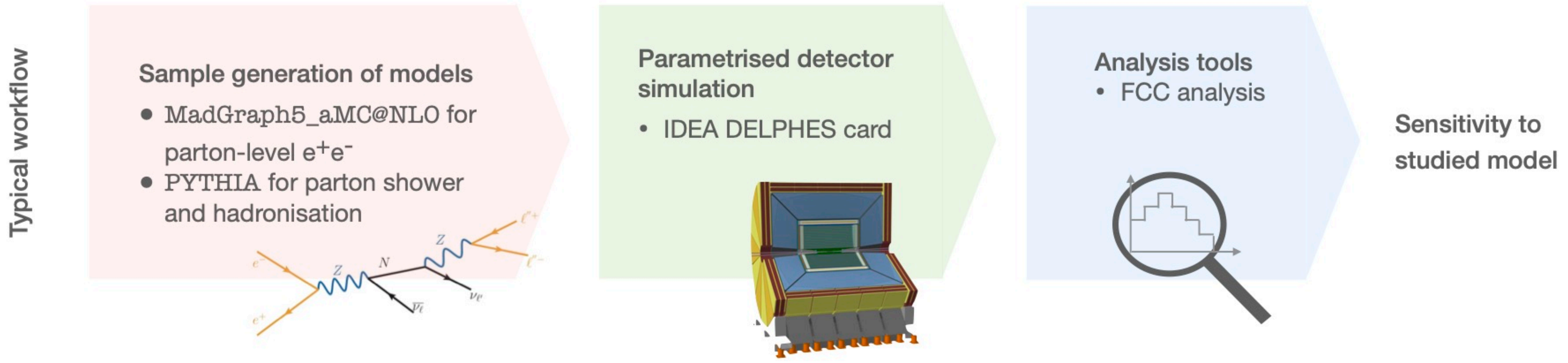
1. Heavy Neutral Leptons (HNLs)
2. Axion-like Particles (ALPs)
3. Higgs bosons with exotic decays to LLPs

I'll present the latest activities of several LLP FCC analyses

Overview of Analyses

Physics scenario	FCC-ee signature	Studies for snowmass	Ongoing work
Heavy neutral leptons (HNLs)	Displaced vertices 	Generator validation and reco-level analysis for $ee\nu\nu$. First look at Dirac vs Majorana HNLs	• Update $ee\nu\nu$ studies with winter23 samples. • Dirac vs Majorana in $e\nu$jj channel • First look at $\mu\mu\nu\nu$ channel
Axion-like particles (ALPs)	Displaced photon/ lepton pair 	Generator-level validation for a→γγ at Z-pole run	*No studies continuing at the moment* ***-> Opportunities to get involved!***
Exotic Higgs decays	e.g. 	Theory discussion and motivation for studies at ZH-pole	• Reco-level analysis (inc. vertexing) for h→ss→bbbb

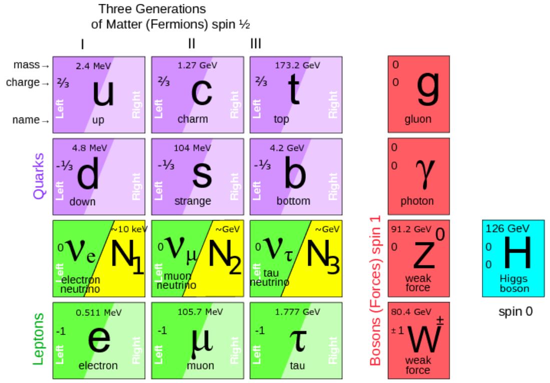
Workflow



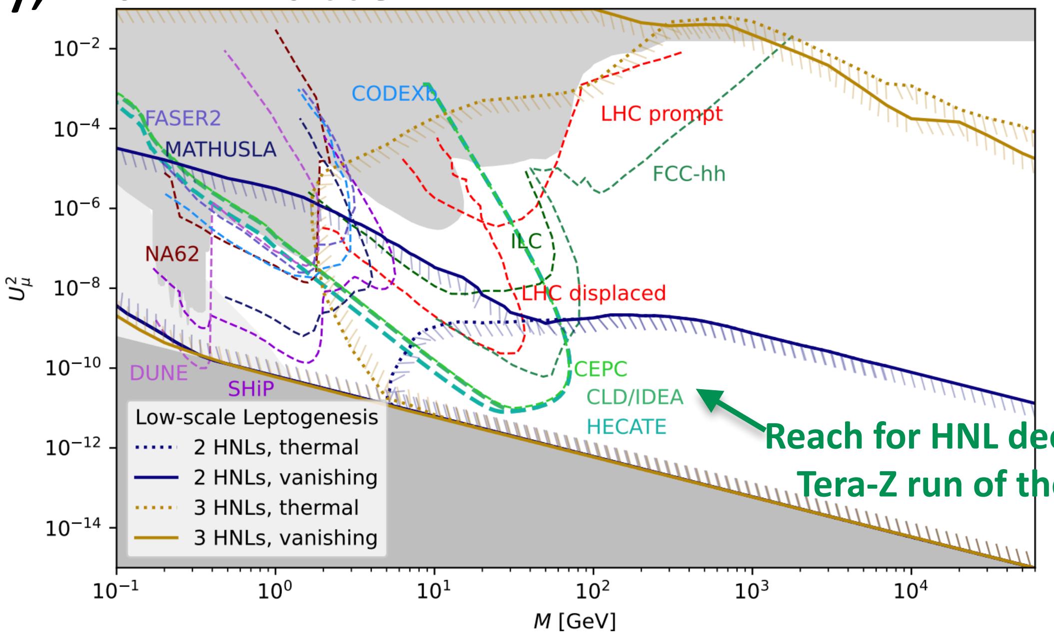
- Perform an FCC case studies with the **"official" analysis tools and framework** available for the FCC
  - **Use FCCAnalysis software** to analyze centrally-produced **EDM4HEP** samples with the **IDEA** detector in **Delphes**, although some signal samples produced privately
  - Dedicated tutorial available for LLP studies
- Try to be as realistic as possible, with **high stats background samples**

1st Physics Case: Heavy Neutral Leptons

- Dirac or Majorana sterile neutrinos with very small mixing with active neutrinos
- Heavy enough to not disrupt the simplest BBN bounds and/or unstable on cosmological timescales
- Could provide answers to some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter



arXiv:2203.05502



Reach for HNL decays at the Tera-Z run of the FCC-ee

- FCC will probe space not constrained by astrophysics or cosmology, complementary to fixed target, neutrino, and 0vbb prospects
- HNLs at the FCC-ee are right in the parameter region that is good for baryogenesis! arXiv:2106.16226

LL HNLs

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

c_{dec} = 1 (Majorana) or 1/2 (Dirac)

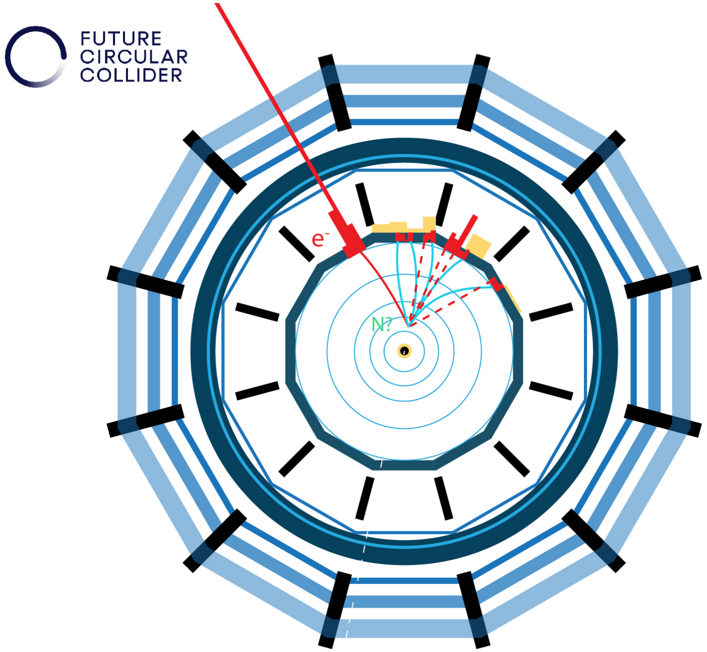
[arXiv:2210.17110]

Get long-lived HNLs when coupling and mass are small

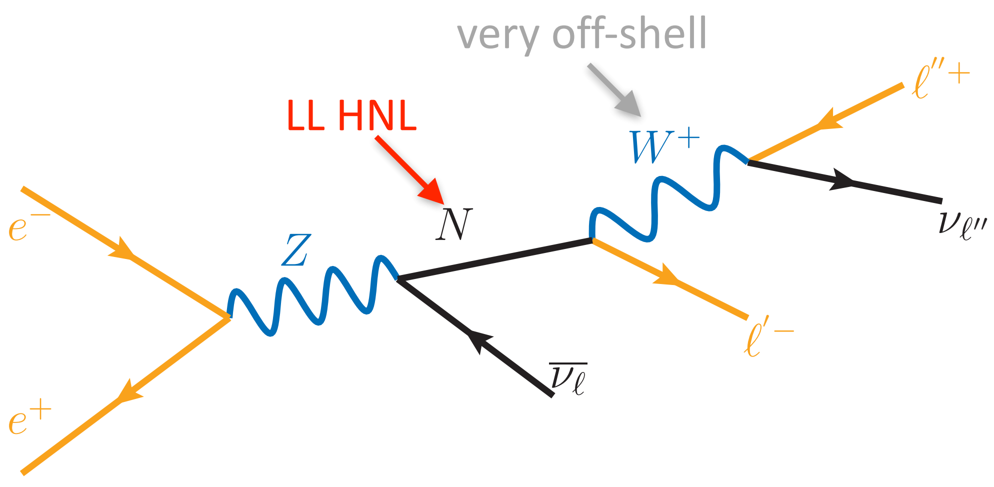
Experimental signature of LL HNLs: displaced vertex

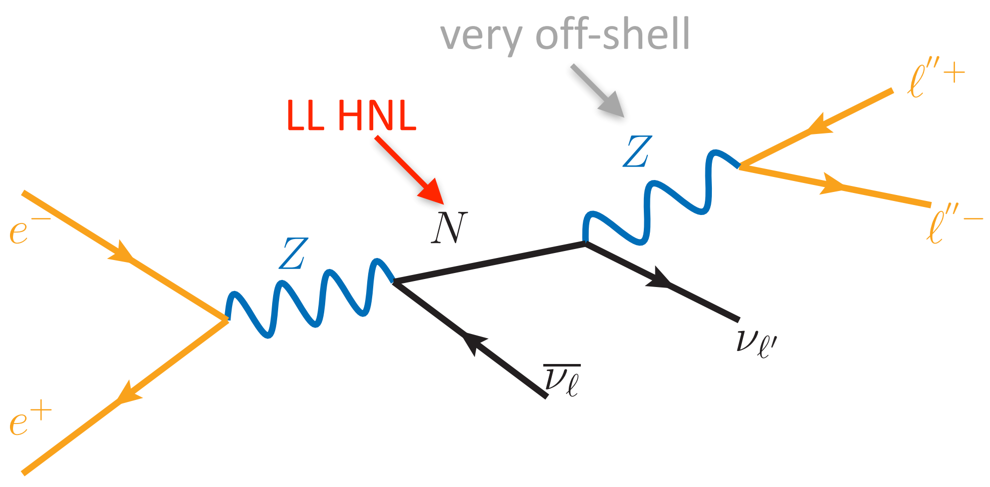
e+e- → Z→ vN

N→ e- + {W^{+*} →jj}

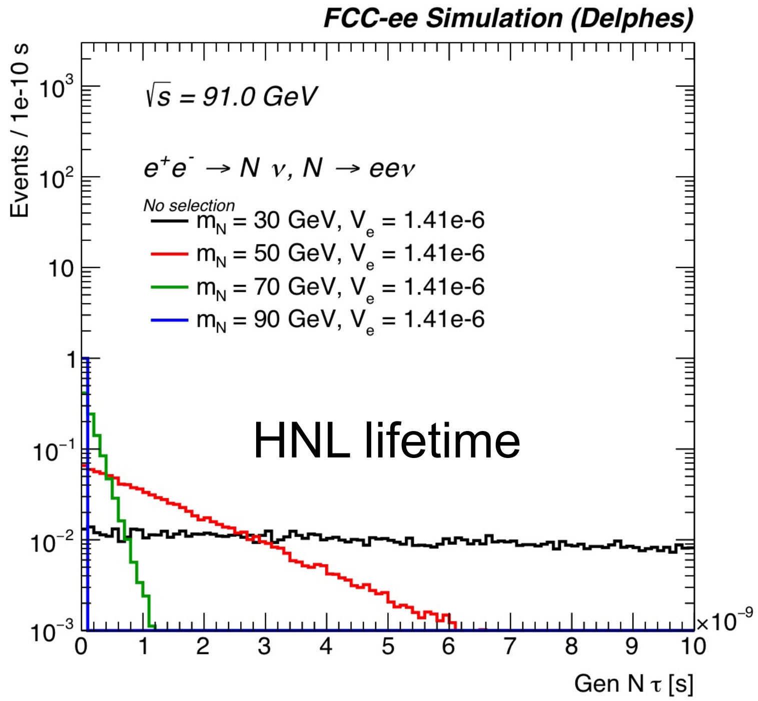


$N \rightarrow ll\nu$ Generation





- 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)
- FCC-ee, $\sqrt{s} = 91\ \text{GeV}$
- Generated in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card

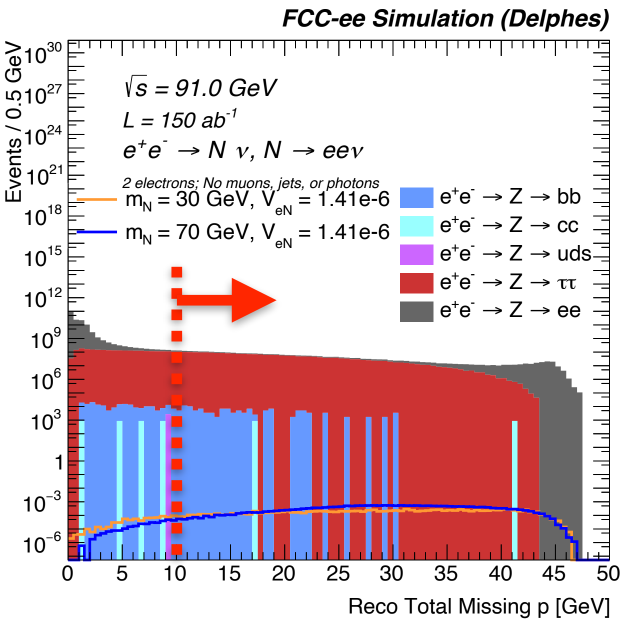


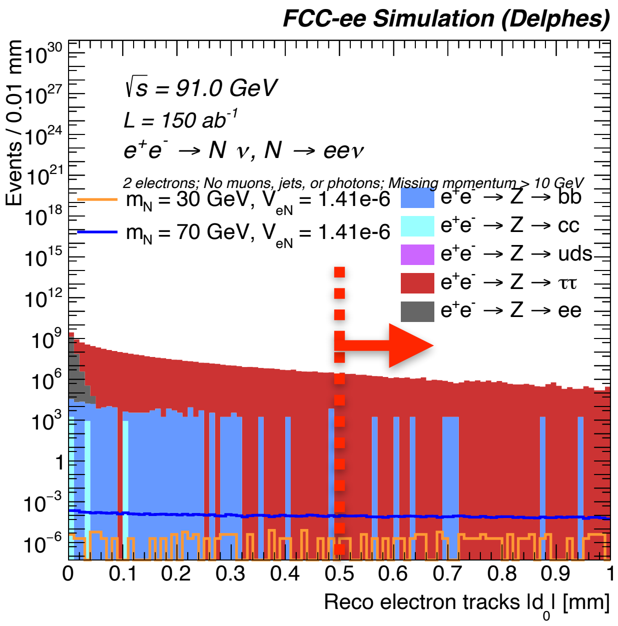
Lovisa Rygaard

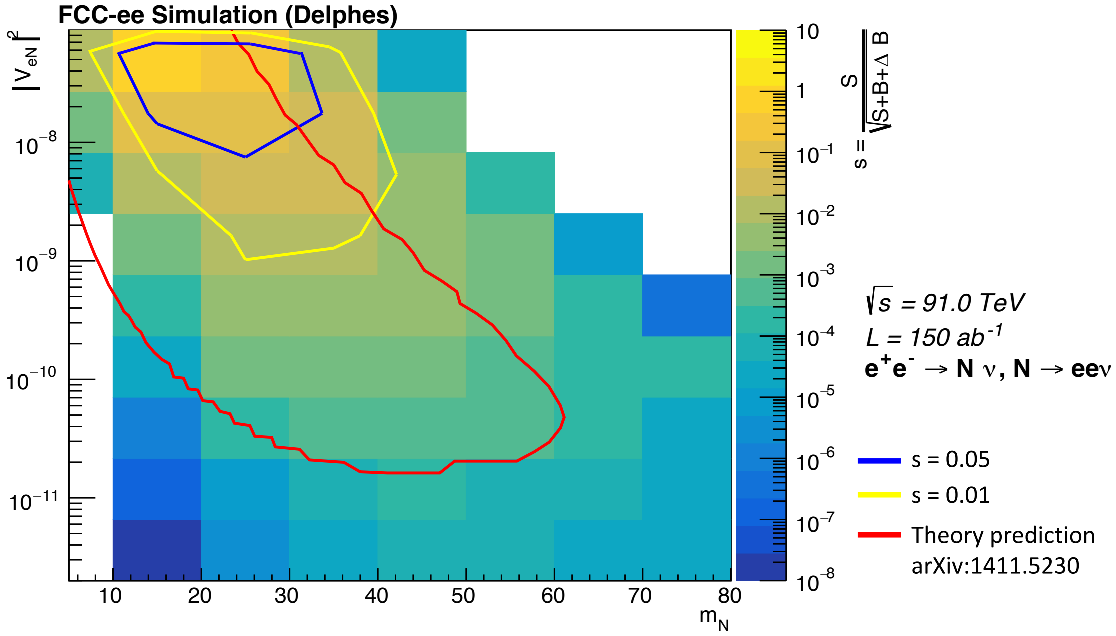
$N \to ee\nu$: Snowmass Results

- Used centrally-produced **"spring2021" background samples**
- **Main selections:**
  - Exactly 2 electrons, veto on additional photons, muons, and jets
  - Missing energy > 10 GeV (reduce Z->ee background with fake missing momentum)
  - Electron $|d_0|$ > 0.5 mm (remove most of the rest of SM background)

- Preliminary sensitivity shown with $\frac{S}{\sqrt{S+B+\Delta B}}$
- **This analysis:** $N \to ee\nu$
  - Contours show where FOM = 0.01 and 0.05
- Theory prediction from arXiv:1411.5230
  - Includes all HNL decay modes, not only electrons







Tanishq Sharma

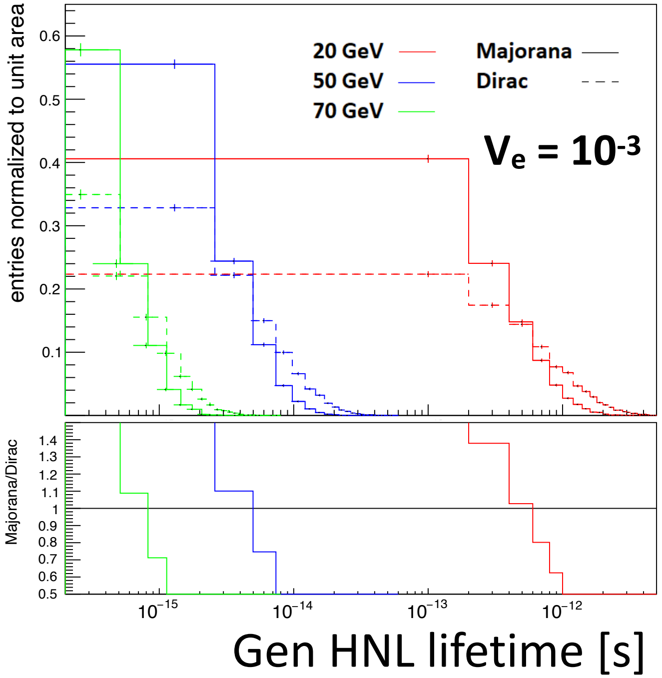
$N \to ee\nu$: Dirac vs Majorana

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

Variables that can distinguish between Majorana and Dirac HNLs:

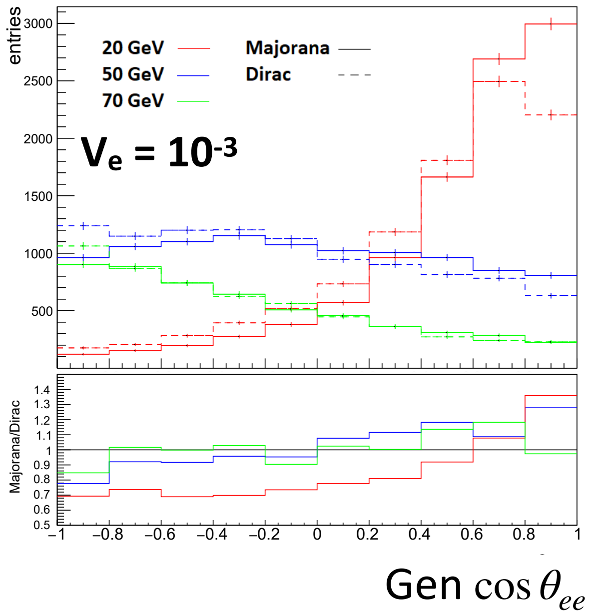
HNL Lifetime

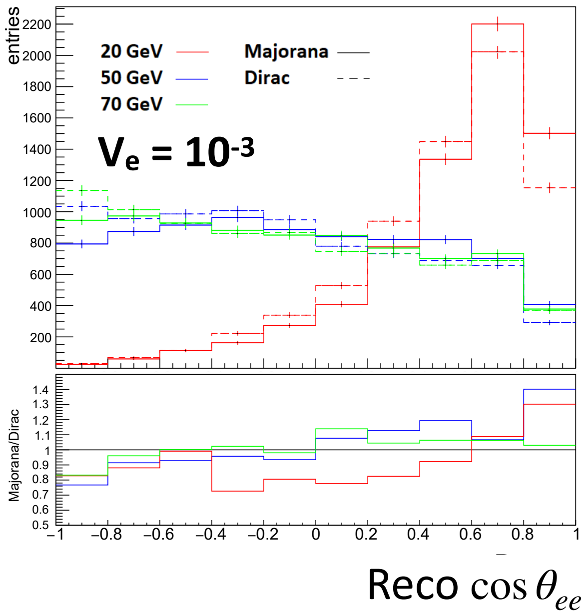
(model-dependent)



$\cos\theta_{ee}$

(opening angle between final state electron/positron)

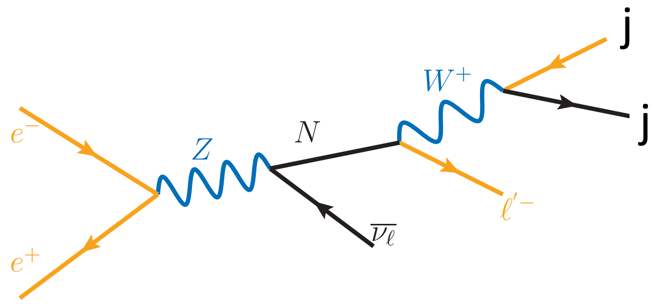




Next: improve reconstruction, find more discriminating variables

Nicolo Valle, Giacomo Polesello

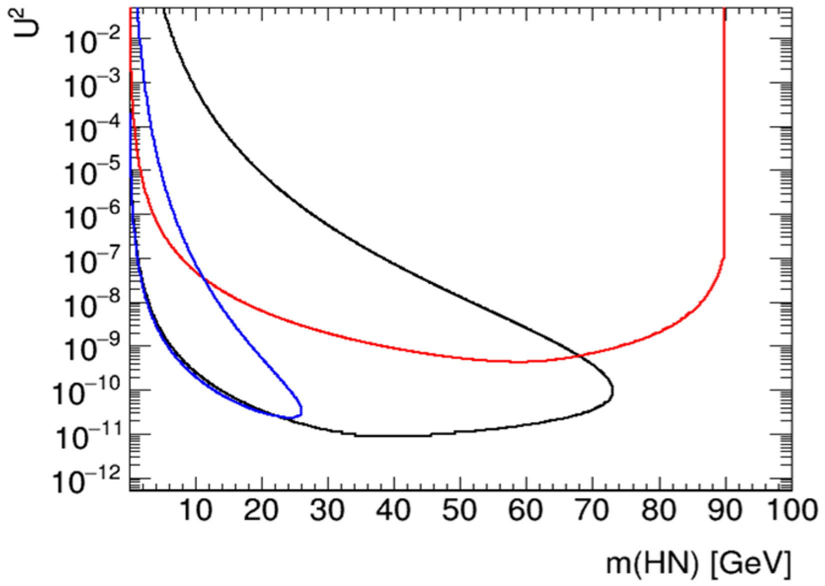
$N \to \mu jj$: Ongoing Studies



- High branching fraction: ~50%
- Target HNL masses from 5 to 85 GeV, with scan over couplings
- Performing two subanalyses:
  - **Prompt analysis** for **high HNL mass (> 50 GeV)**
    - Studied jet energy resolution and prompt vertex performance
    - Detailed analysis largely complete
    - See more in Nicolo's talk at FCC week
  - **Long-lived analysis** for **low HNL mass**
    - Bkg suppressed by displaced vertex
    - Will study vertex and timing performance requirements
    - Will focus on this analysis on the next slide

100 evts prompt decay (red)
4 events long-lived (black: decay $0.04 < \lambda < 150$ cm)
4 evtnts long-lived (blue: decay $200 < \lambda < 450$ cm)

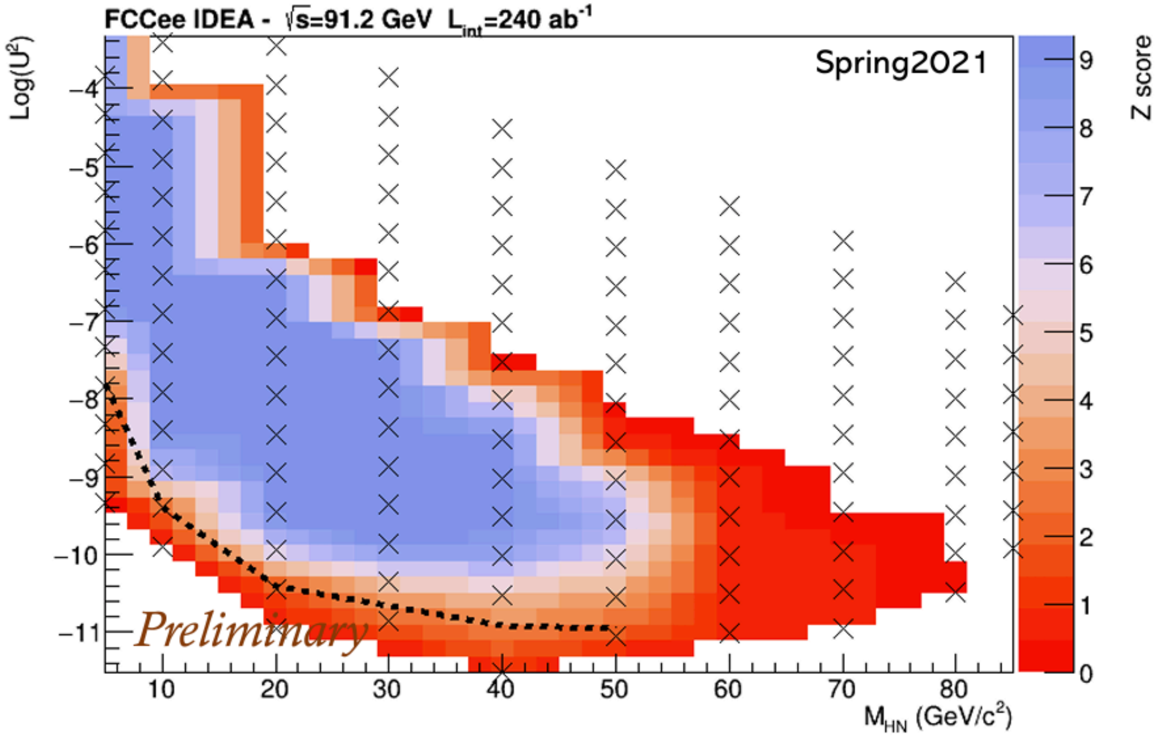
Based on arXiv:2210.17110



$N \to \mu jj$: LL Analysis

Nicolo Valle, Giacomo Polesello

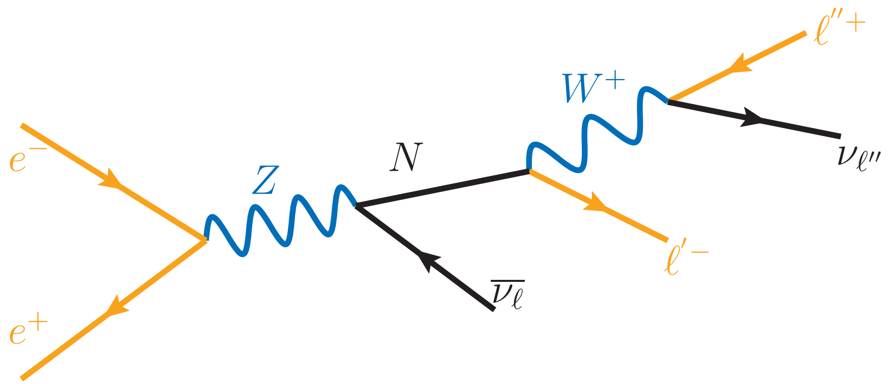
- Kinematic selections kept the same as the prompt analysis:
  - 1 muon with p > 3 GeV
  - >= 3 tracks
  - E_{miss} > 5 GeV
- Additionally, suppress prompt backgrounds by requiring muon $|d_0|$> 1 mm
- Preliminary results for LLP analysis at $\sqrt{s} = 91\ \text{GeV}$, assuming 240 ab^{-1}
- Investigating further selection requirements using vertex fitter

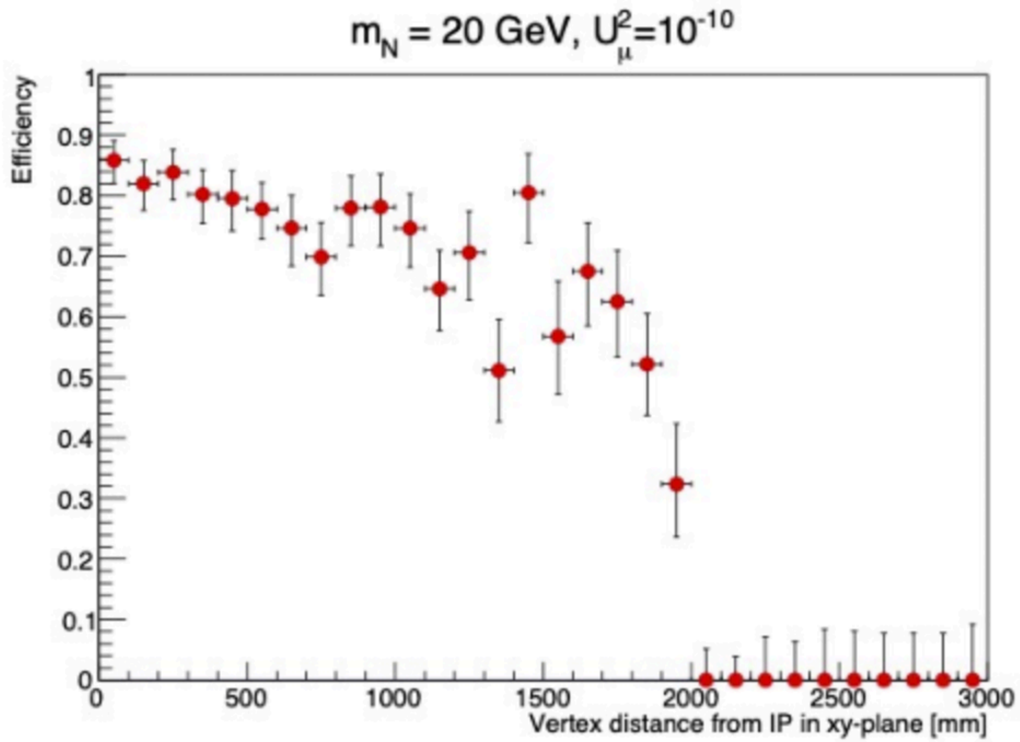


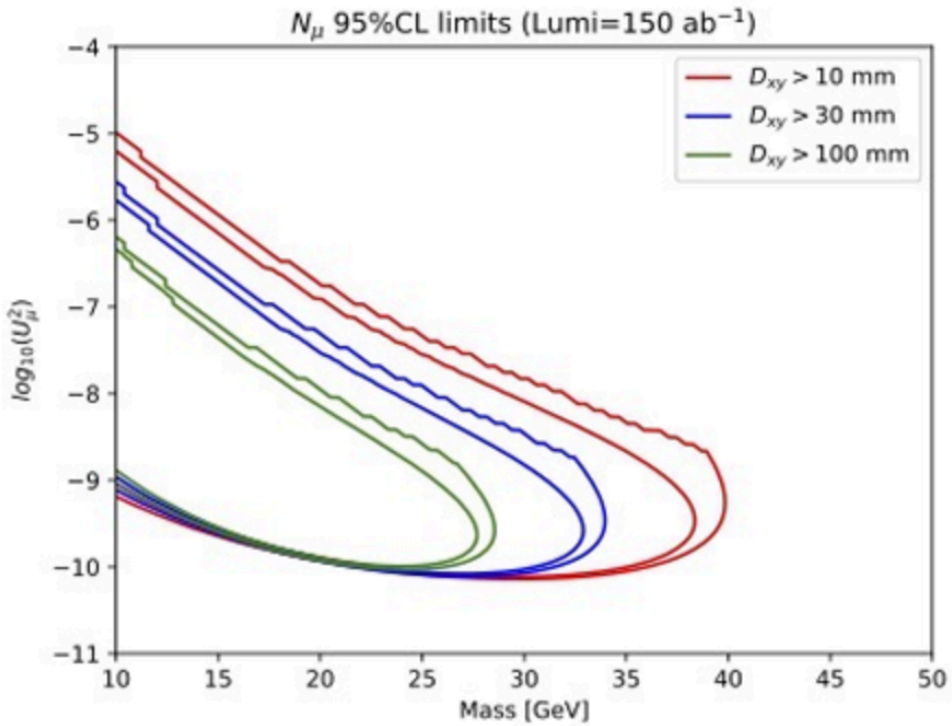
Lorenzo Bellagamba

$N \to \mu\mu\nu$: Ongoing Studies

- Early studies of sensitivity with N→$\mu\mu\nu$ channel looking for DV + missing energy
- Optimizing search based on the distance from the 2-muon decay vertex to the IP
- DV reconstruction efficiency a promising area for further improvements



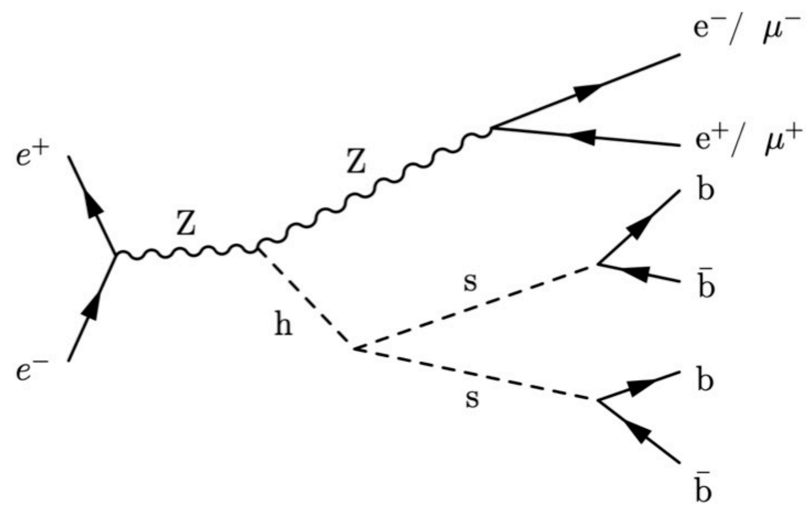


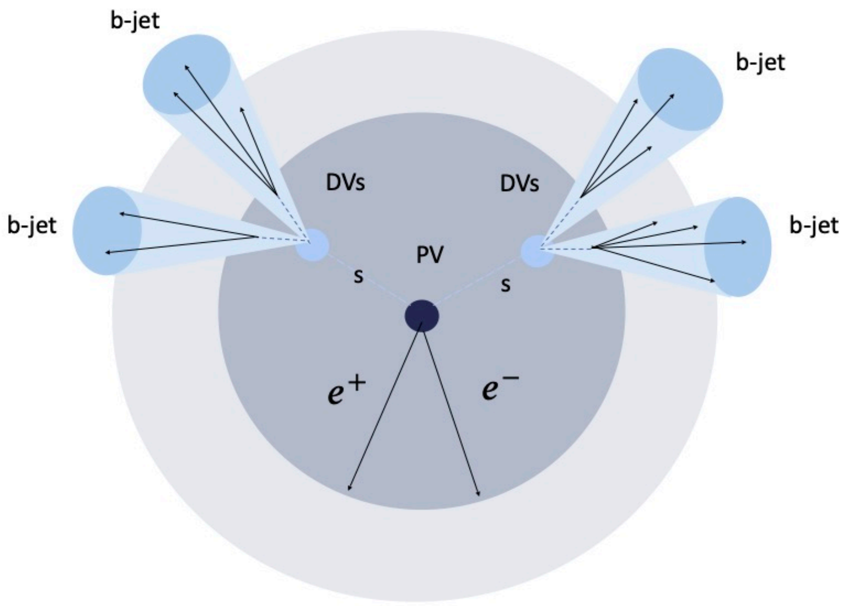


Magdalena Vande Voorde, Giulia Ripellino

Another Physics Case: Exotic Higgs Decays to LLPs

- Higgs bosons could undergo **exotic decays** to e.g. **scalars that could be long-lived**
- New scalar could be a **portal between the SM and a dark sector** (arXiv:1312.4992, arXiv:1412.0018)
- Higgs boson (h) and the scalar (s) mix with a mixing angle sin θ
- **For sufficiently small mixing, the scalar can be long-lived**
  - cτ ~ meters if θ < 1e-6
- Probe **h→ss→bbbb** in events with **2 displaced vertices** and **Z boson reconstructed from ee or mumu pair**

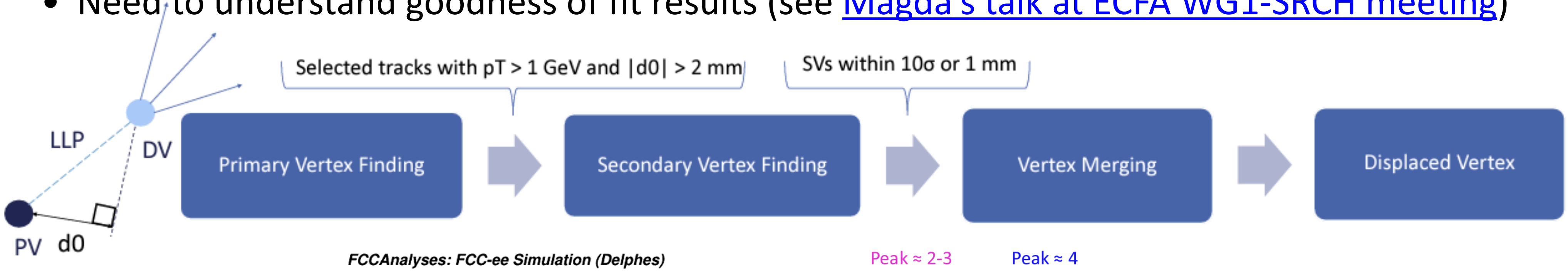


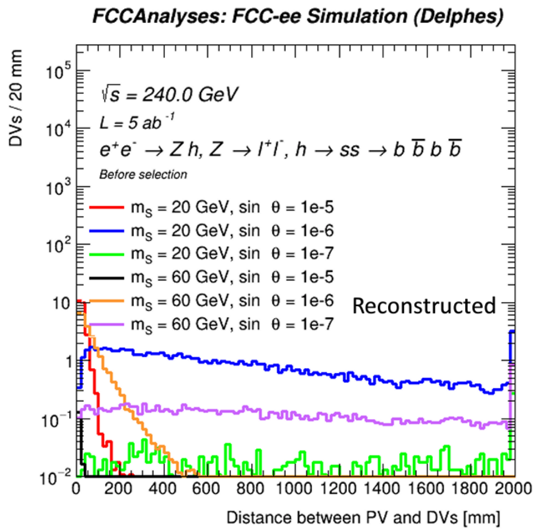


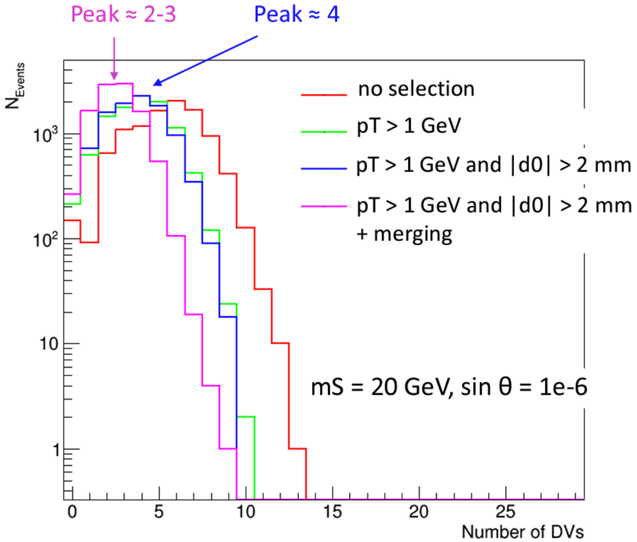
Magdalena Vande Voorde, Giulia Ripellino

Exotic Higgs Decays: Displaced Vertex Reconstruction

- Studied options of **DV reconstruction implemented in the FCCAnalyses framework** with extra constraints and functions inspired by [ATLAS DV reconstruction]
    - **SV finder** from **LCFI+ algorithm** ([arXiv:1506.08371])
    - Added **vertex merging** to reconstruct the scalar DVs
        - Need to understand goodness of fit results (see [Magda's talk at ECFA WG1-SRCH meeting])







Magdalena Vande Voorde, Giulia Ripellino

Exotic Higgs Decays: Sensitivity

Selection:

Type	Parameter	Value
Track Selection	Min p_T	1 GeV
	Min $\|d_0\|$	2 mm
Vertex Reconstruction	V^0 rejection	True
	Max χ^2	9
	Max M_{inv}	40 GeV
	Max χ^2 added track	5
	Vertex merging	False
Vertex Selection	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV

	Selection
Pre-selection	$\geq$ 2 oppositely charged electrons or muons
Z boson tag	$70 < m_{ll} < 110$ GeV
Multiplicity of DVs	n_DVs ≥ 2

Sensitivity:

- Backgrounds:

	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
WW	8.22e+07 $\pm$ 7.45e+06	2.11e+06 $\pm$ 4.16e+04	4.68e+05 $\pm$ 1.96e+04	0 ($\leq$ 1.96e+04)
ZZ	6.79e+06 $\pm$ 1.77e+05	8.91e+05 $\pm$ 7.78e+03	5.85e+05 $\pm$ 6.31e+03	0 ($\leq$ 6.31e+03)
ZH	1.01e+06 $\pm$ 1.01e+04	5.97e+04 $\pm$ 7.76e+02	4.75e+04 $\pm$ 6.93e+02	0 ($\leq$ 6.93e+02)

- Signals:

m_s, sin θ	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
20 GeV, 1e-5	44.3 $\pm$ 0.0295	29.8 $\pm$ 0.363	28.9 $\pm$ 0.358	3.55 $\pm$ 0.125
20 GeV, 1e-6	44.3 $\pm$ 0.0295	30.4 $\pm$ 0.367	29.7 $\pm$ 0.363	22.4 $\pm$ 0.315
20 GeV, 1e-7	44.3 $\pm$ 0.0295	36.3 $\pm$ 0.401	35.6 $\pm$ 0.397	0.531 $\pm$ 0.0485
60 GeV, 1e-5	13.1 $\pm$ 0.00474	8.38 $\pm$ 0.105	8.12 $\pm$ 0.103	0 ($\leq$ 0.103)
60 GeV, 1e-6	13.1 $\pm$ 0.00474	8.34 $\pm$ 0.104	8.09 $\pm$ 0.103	6.43 $\pm$ 0.0917
60 GeV, 1e-7	13.1 $\pm$ 0.00474	9.69 $\pm$ 0.113	9.45 $\pm$ 0.111	4.10 $\pm$ 0.0732

All but 2 signal points could be excluded at 95% CL

See more in Magda’s talk at ECFA WG1-SRCH meeting

Dedicated LLP Detectors at Future Facilities?

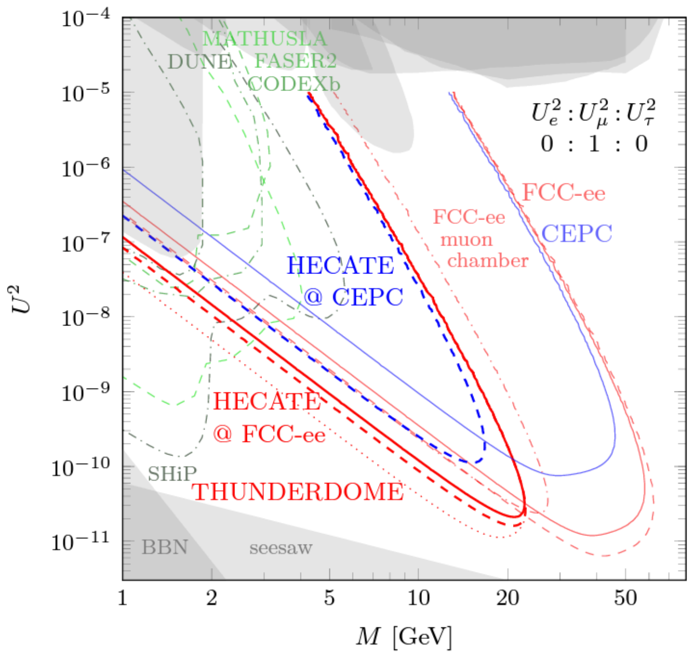
- FCC-ee baseline is consistent with having 2 or 4 detectors
- Opportunities for new, creative designs!

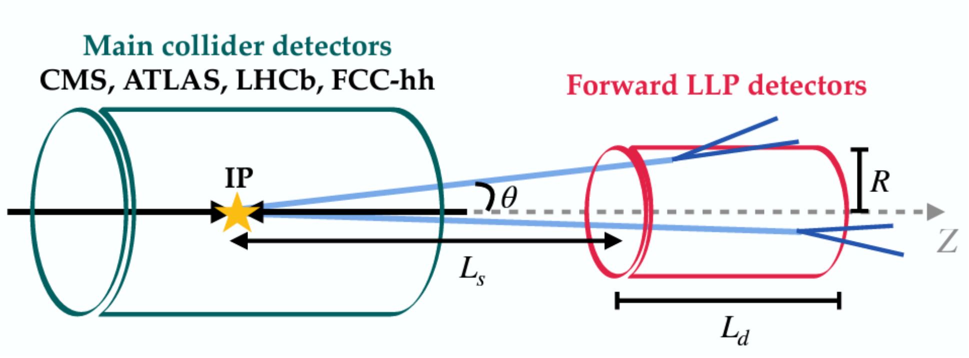
Lepton collider ideas:

- **HECATE** ([EPJC 81 (2021) 546](#) / [arXiv:2011.01005](#))
  - Instrument cavern walls with scintillators or RPCs
- **Study at ILC** ([PRD 107 (2023) 076022](#) / [arXiv:2202.11714](#))
  - Conclude that ILD still does better for LL ALPs

Hadron collider ideas:

- **DELIGHT** ([PRD 106 (2022) 095018](#) / [arXiv:2111.02437](#))
  - Transverse detector
- **FORESEE** ([PRD 104 (2021) 035012](#) / [arXiv:2105.07077](#))
  - Numerical package to simulate sensitivity of far-forward detectors
- **FOREHUNT** ([arXiv:2306.11803](#))
  - Forward detector
  - See next slide





FOREHUNT

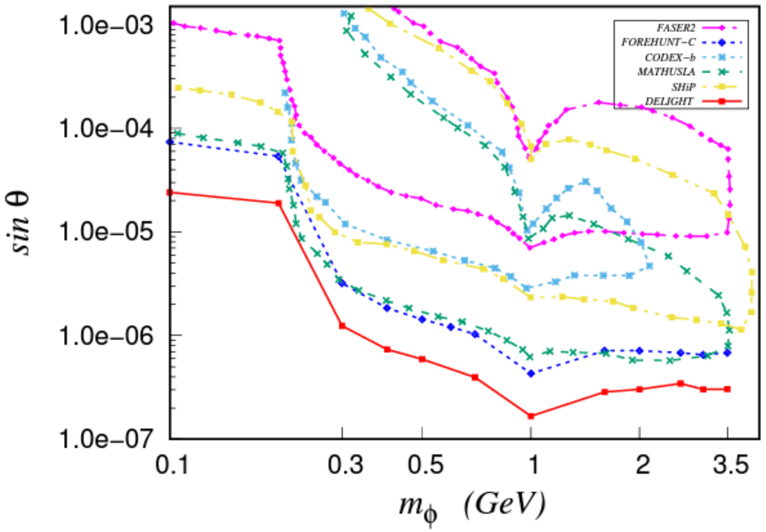
arXiv:2306.11803

- Brand new proposal (June 20, 2023)
- Place **dedicated LLP detector** in the **forward region** at the **FCC-hh**
- **Target LLPs from B-meson decays**

- Assume main FCC-hh detector at $z \in$ [-25, 25] m and sufficient shielding
- **Put FOREHUNT at at least 50 m in z**
- Option: put FOREHUNT-C slightly off z-axis
  - 1 m off z-axis: acceptance drops by factor of 2
  - 5 m off z-axis: acceptance falls drastically

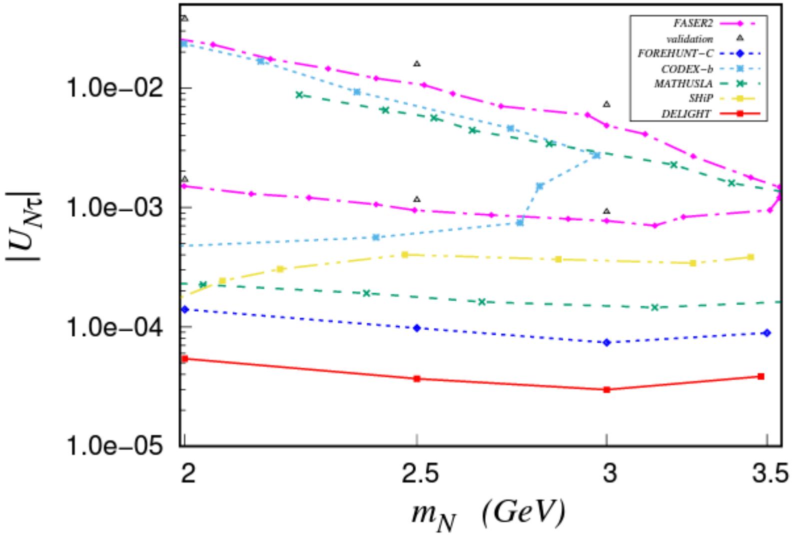
Dark Higgs scalar:

$$B^{\pm} \to K^{\pm}\phi$$



HNLs:

$$B^0 \to D^{\pm}\tau^{\mp}N_\tau\,,$$
$$B^{\pm} \to D^0\tau^{\pm}N_\tau\,,$$
$$B^{\pm} \to \tau^{\pm}N_\tau\,.$$

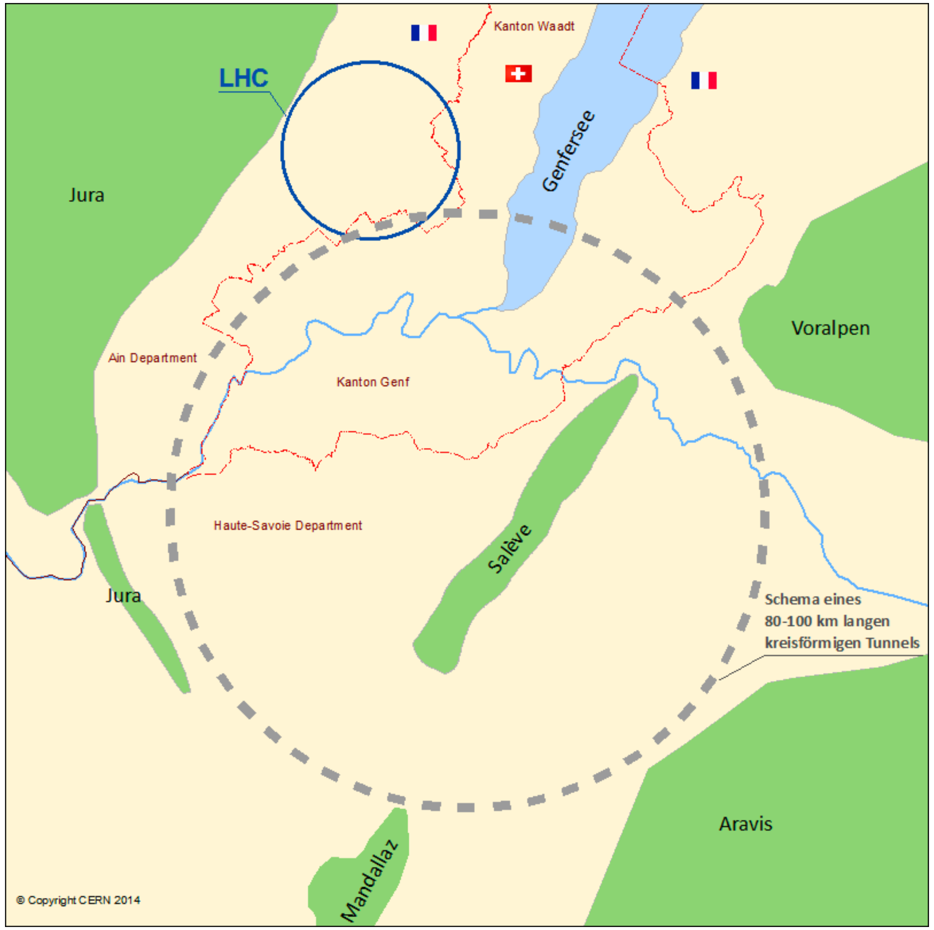


Detector Configuration @100 TeV	Radius (R)	Length (L_d)	Position (Z)
FOREHUNT-A	1 m	10 m	50 m
FOREHUNT-B	2 m	20 m	50 m
FOREHUNT-C	5 m	50 m	50 m
FOREHUNT-D	2 m	20 m	75 m
FOREHUNT-E	5 m	50 m	75 m
FOREHUNT-F	5 m	50 m	100 m

Thanks!

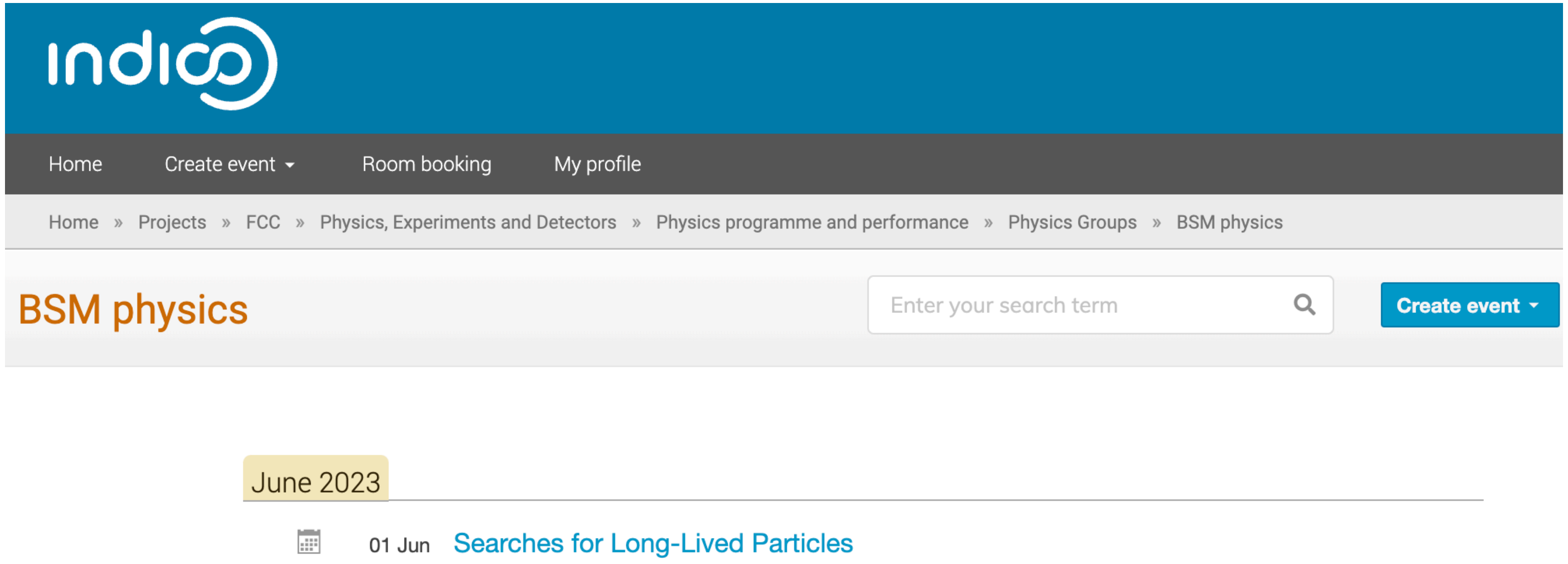
… to all who provided input for this talk

- Anna Sfyrla (University of Geneva)
- Daniel Beech (University of Cambridge)
- Dimitri Moulin (University of Geneva)
- Giacomo Polesello (INFN)
- Giulia Ripellino (Uppsala University)
- Juliette Alimena (DESY)
- Lorenzo Bellagamba (INFN)
- Magdalena Vande Vorde (KTH)
- Nicolo Valle (INFN)
- Pantelis Kontaxakis (University of Geneva)
- Rebeca Gonzalez Suarez (Uppsala University)
- Sarah Williams (University of Cambridge)
- Suchita Kulkarni (University of Graz)



LLPs at FCC-ee group

- Informal group with:
  - Meetings: https://indico.cern.ch/category/5664/
  - Mailing lists:
    - LLP-FCCee-informal@cern.ch
    - FCC-PED-PhysicsGroup-BSM@cern.ch —> meetings announced here
- **We welcome new people, join us!**

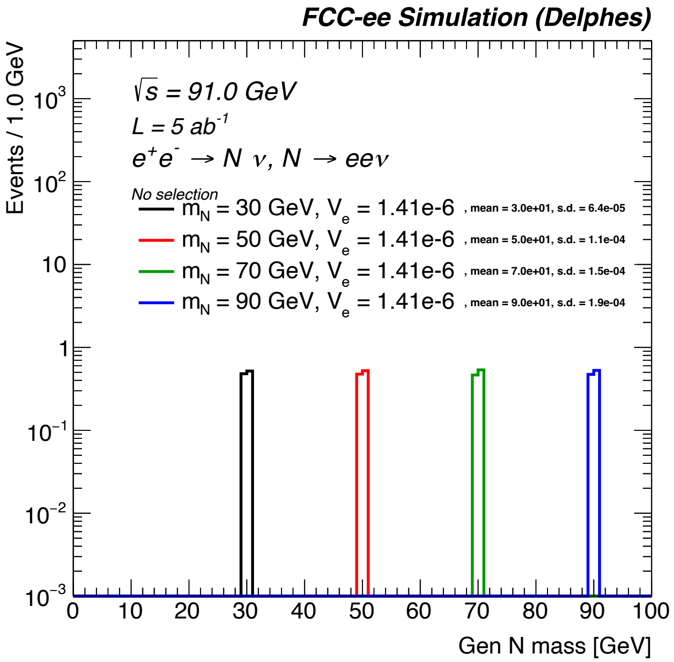


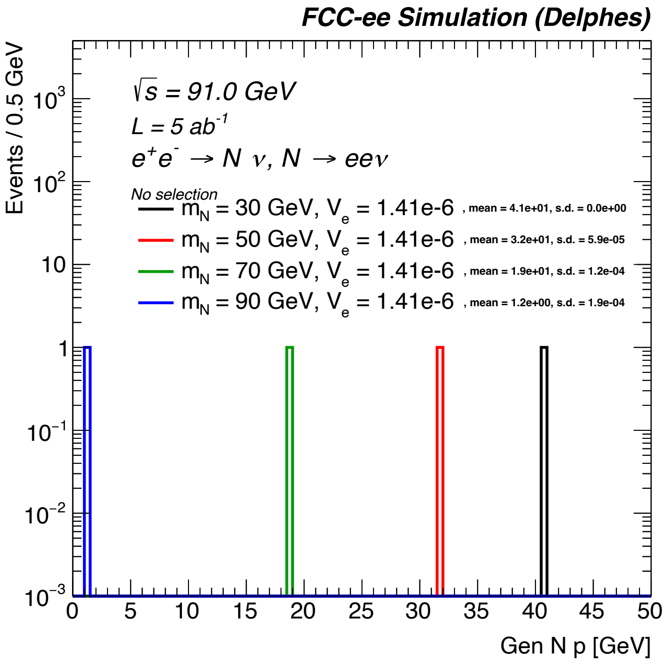
Summary

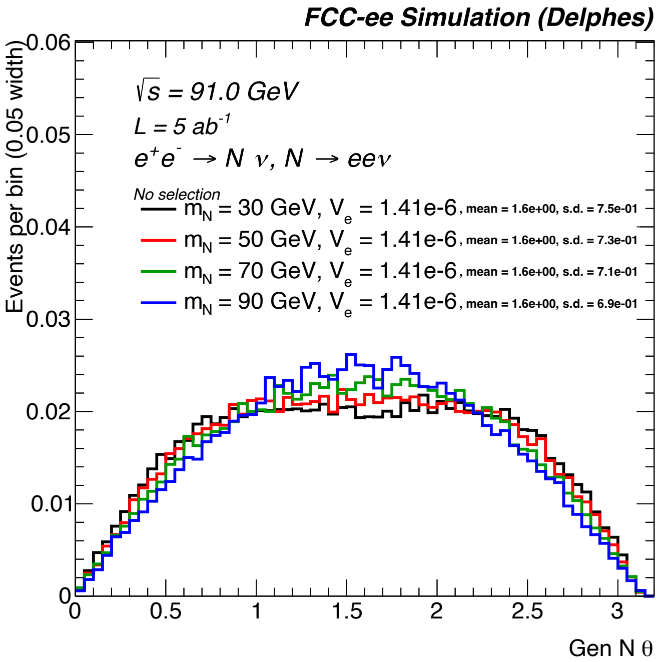
- The FCC will have the ability to uniquely probe LLP areas of phase space, and discovery potential!
- Many interesting signals: Heavy Neutral Leptons, hidden sectors, axion-like particles, exotic Higgs decays, and more
- We now have the opportunity to design detectors and algorithms with LLPs in mind
- Also to consider: dedicated LLP detectors at the FCC
- Plenty of phase space to explore at the FCC! Let’s make sure we don’t miss new physics!

Backup

Generated HNL Kinematics

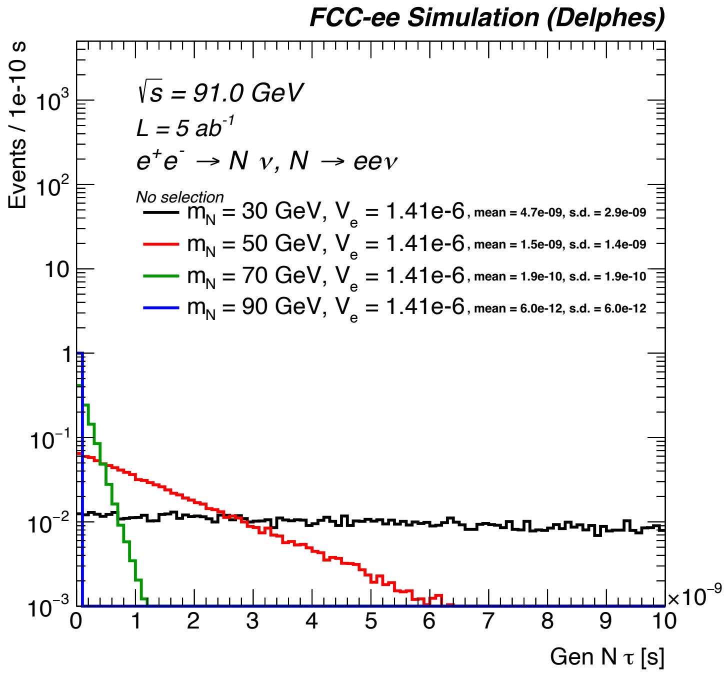


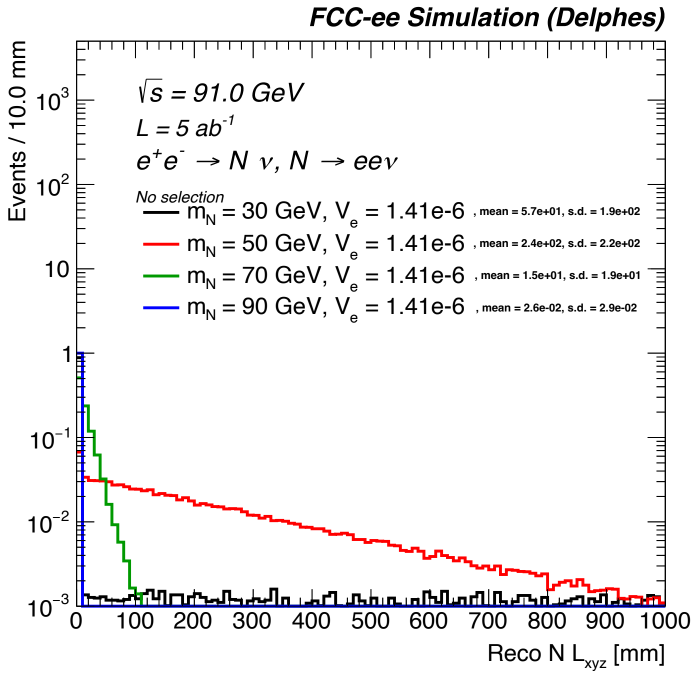


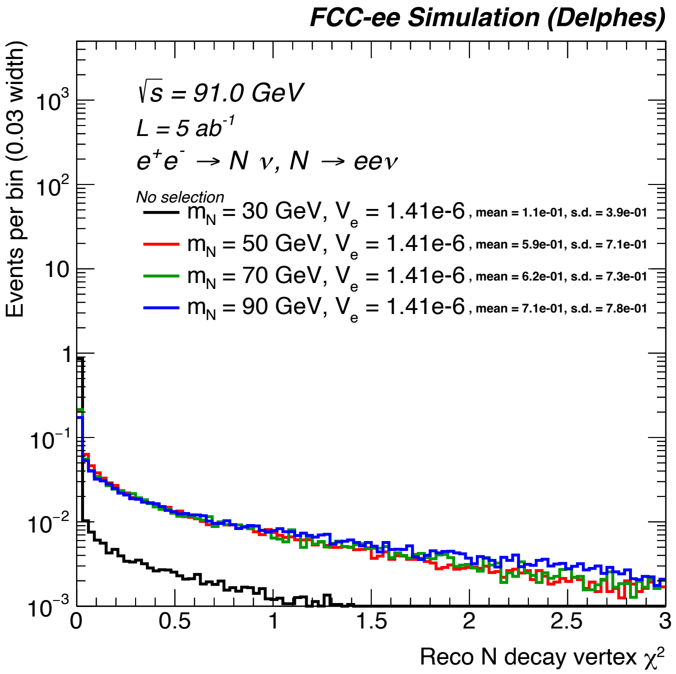


- At the FCC-ee, should look at total momentum, θ, and total missing energy!
- Generator-level distributions look as expected
  - Momentum decreases as HNL mass increases
  - Slightly more central events as HNL mass increases

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

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 $|d_0|$

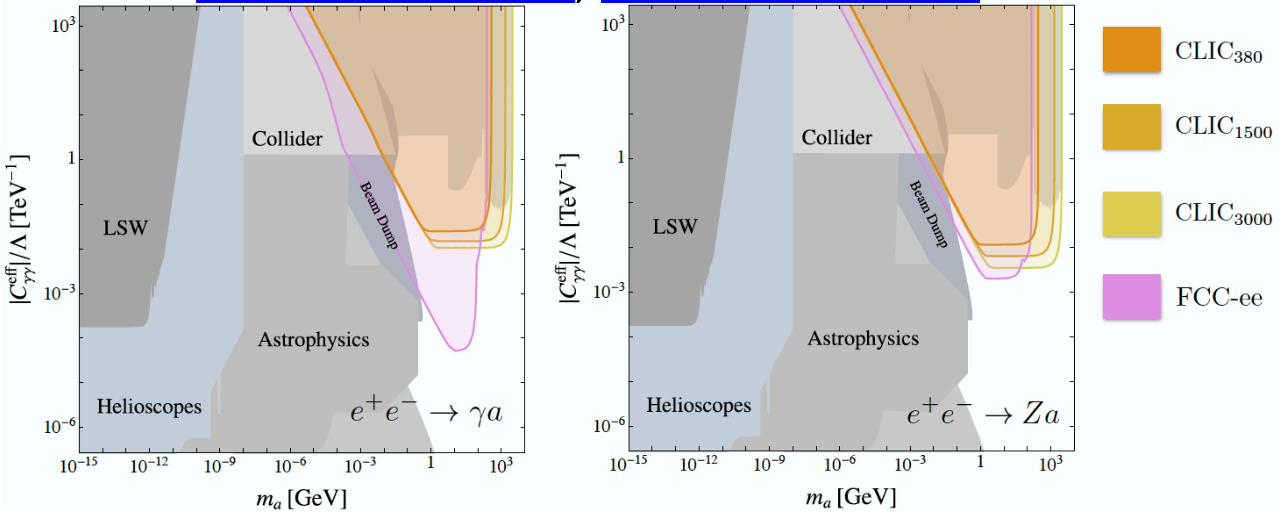
	Before selection	Exactly 2 reco e	Veto photons, muons, and jets	$\not{p} > 10$ GeV	$\lvert d_0 \rvert > 0.5$ mm
$Z \to ee$	$2.19 \times 10^{11} \pm 6.94 \times 10^7$	$1.75 \times 10^{11} \pm 6.19 \times 10^7$	$1.53 \times 10^{11} \pm 5.80 \times 10^7$	$7.07 \times 10^8 \pm 3.94 \times 10^6$	$\leq 3.94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

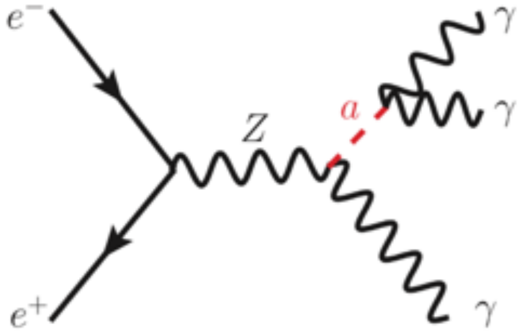
	Before selection	Exactly 2 reco e	Vetoes	$\not{p} > 10$ GeV	$\lvert d_0 \rvert > 0.5$ mm
$m_N = 10$ GeV, $\lvert V_{eN} \rvert = 2 \times 10^{-4}$	2534 ± 11	1006 ± 7	996 ± 7	951 ± 7	907 ± 7
$m_N = 20$ GeV, $\lvert V_{eN} \rvert = 9 \times 10^{-5}$	458 ± 2	313 ± 2	308 ± 2	293 ± 2	230 ± 1
$m_N = 20$ GeV,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

2nd Physics Case: LL Axion-Like Particles

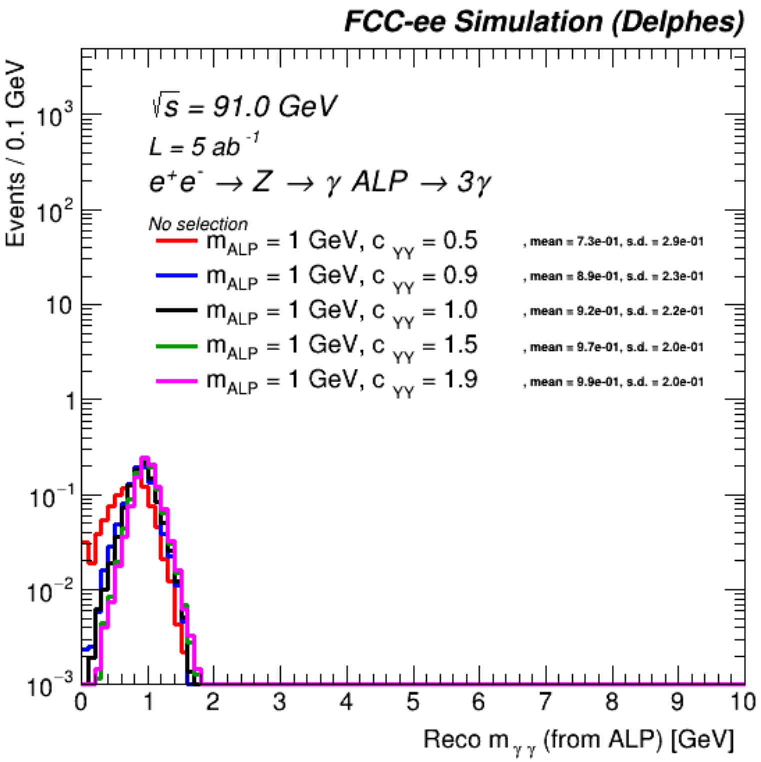
- Axion-like Particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries in BSM scenarios
- Very weakly coupled to the dark sector
- Get long-lived ALPs when couplings and mass are small
- At the FCC-ee:
  - Orders of magnitude of parameter space accessible
  - Especially 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)**

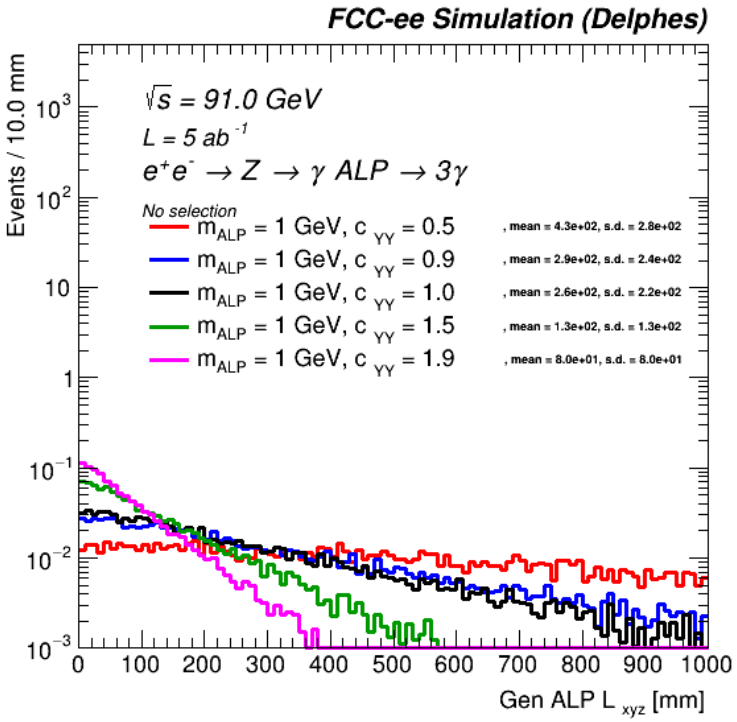
arXiv:1808.10323, arXiv:2108.08949





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!**