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

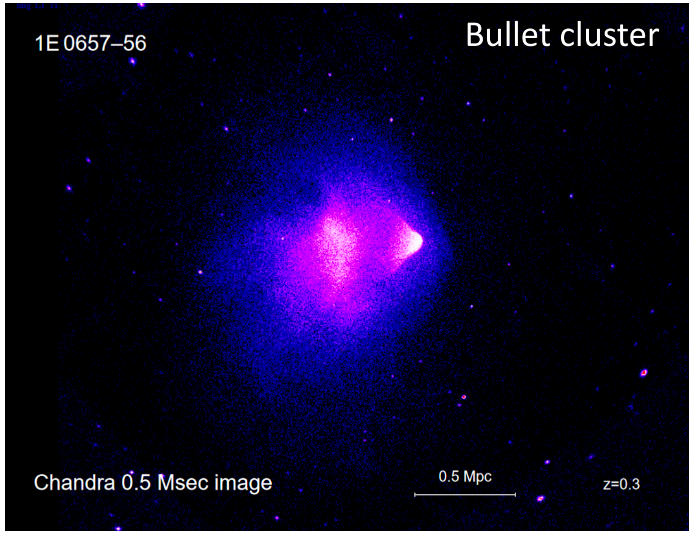
Exploring the frontiers of fundamental physics at the FCC-ee

Juliette Alimena (DESY), on behalf of the FCC BSM group

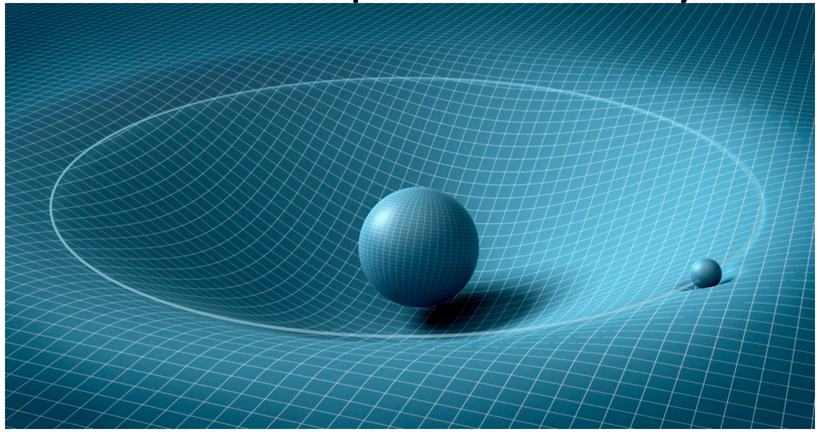
EPS-HEP, Hamburg, Germany

August 23, 2023

What is the particle nature of dark matter?

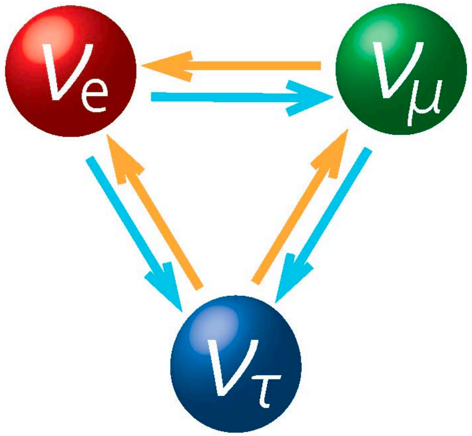


How do we incorporate gravity into a consistent particle theory?

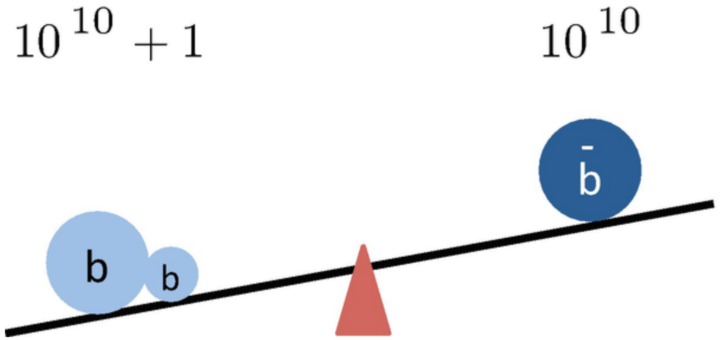


Unanswered Questions in Physics

How do neutrinos have mass?

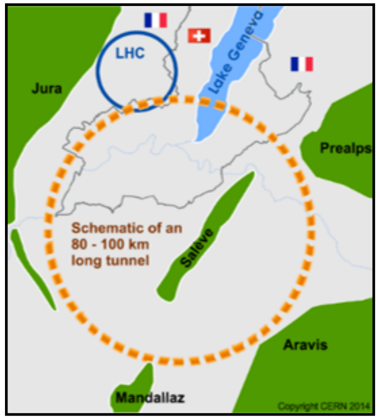


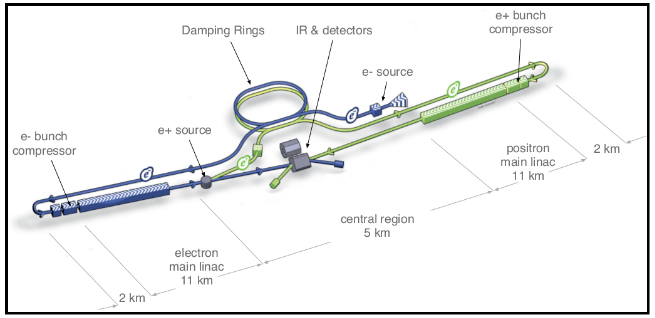
Why is there more matter than antimatter in the universe?

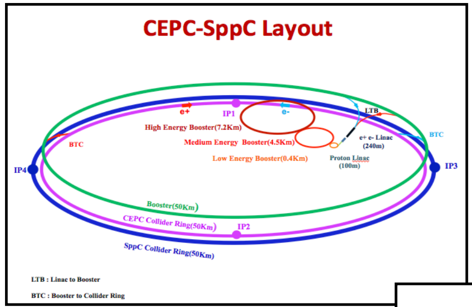


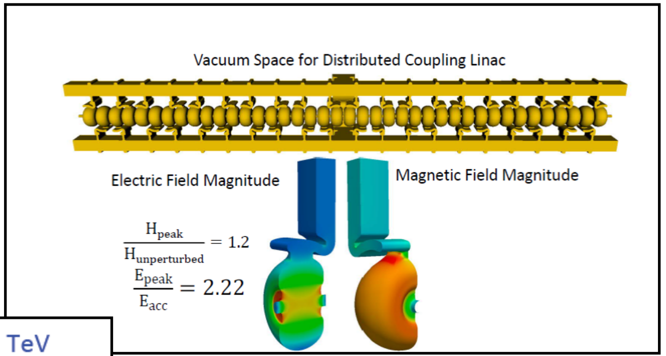
Future Colliders

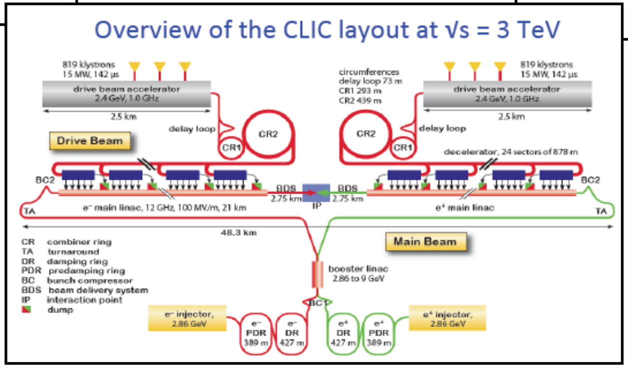
- Future colliders will provide **unique opportunities** to learn more about **how nature works**
- There's **no other way** to explore the **Higgs** boson!
- Cutting edge scientific and technological frontiers
- ***Future colliders are absolutely necessary!***







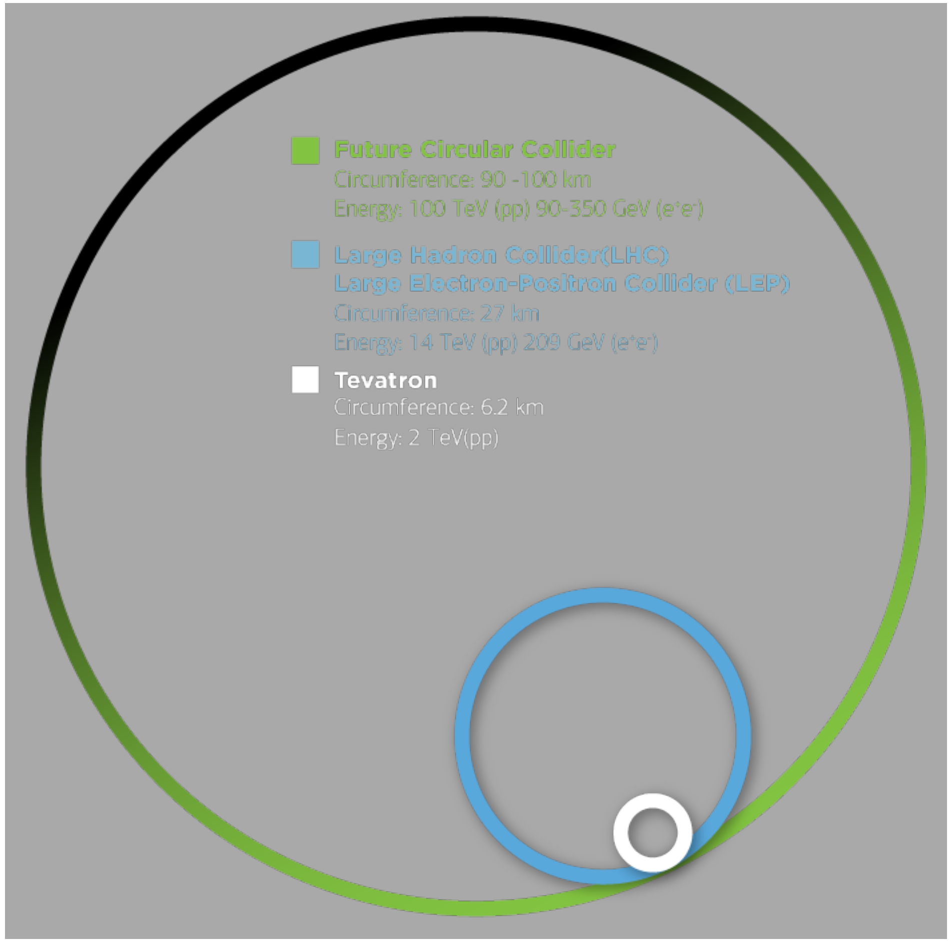




Future Circular Collider

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

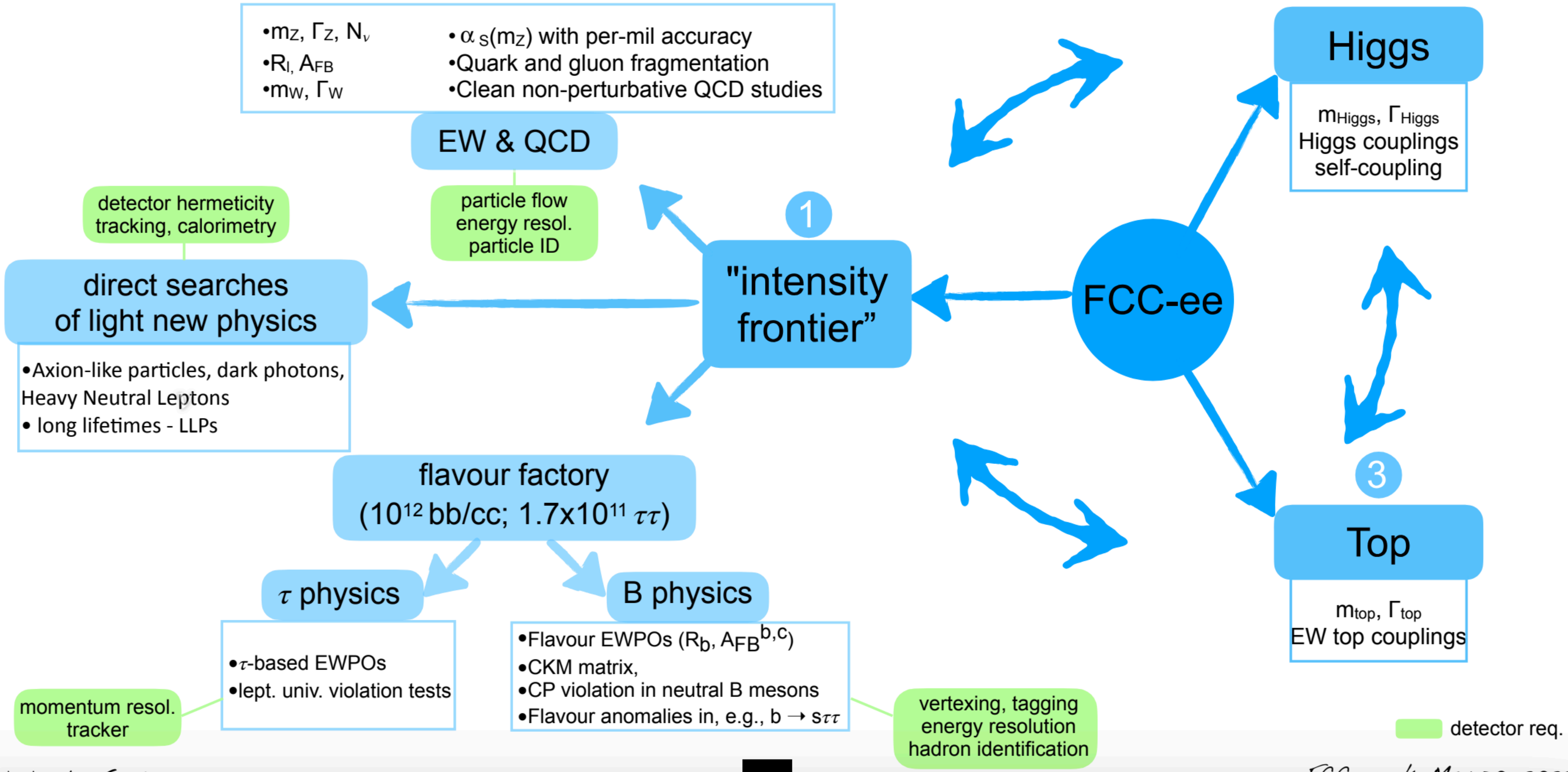
- Stage 1: FCC-ee (Z, W, H , tt) as Higgs EW and top factory at high luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options



The FCC is is a frontier Higgs, top, electroweak, and flavor factory where we can

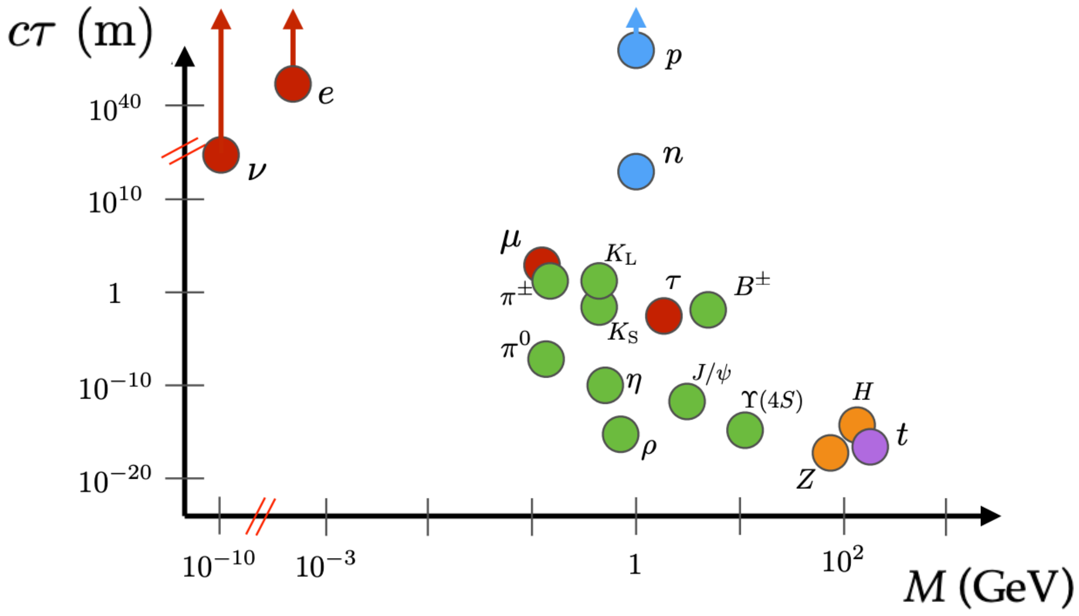
directly discover new physics!

FCC-ee Physics Program



Long-Lived Particles (LLPs)

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



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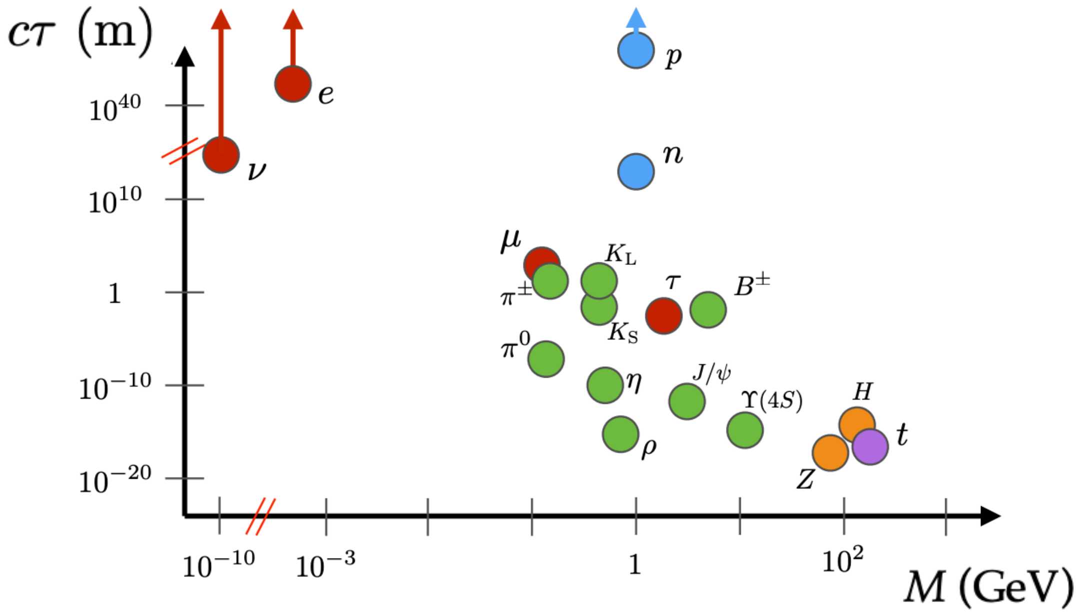
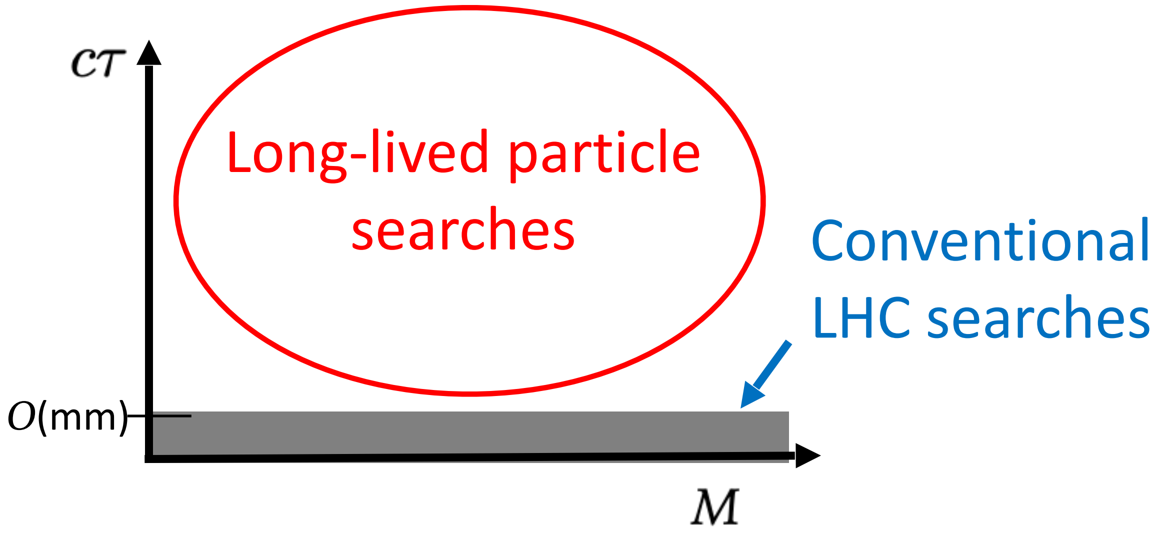


We expect **new phenomena** to have a wide range of lifetimes as well

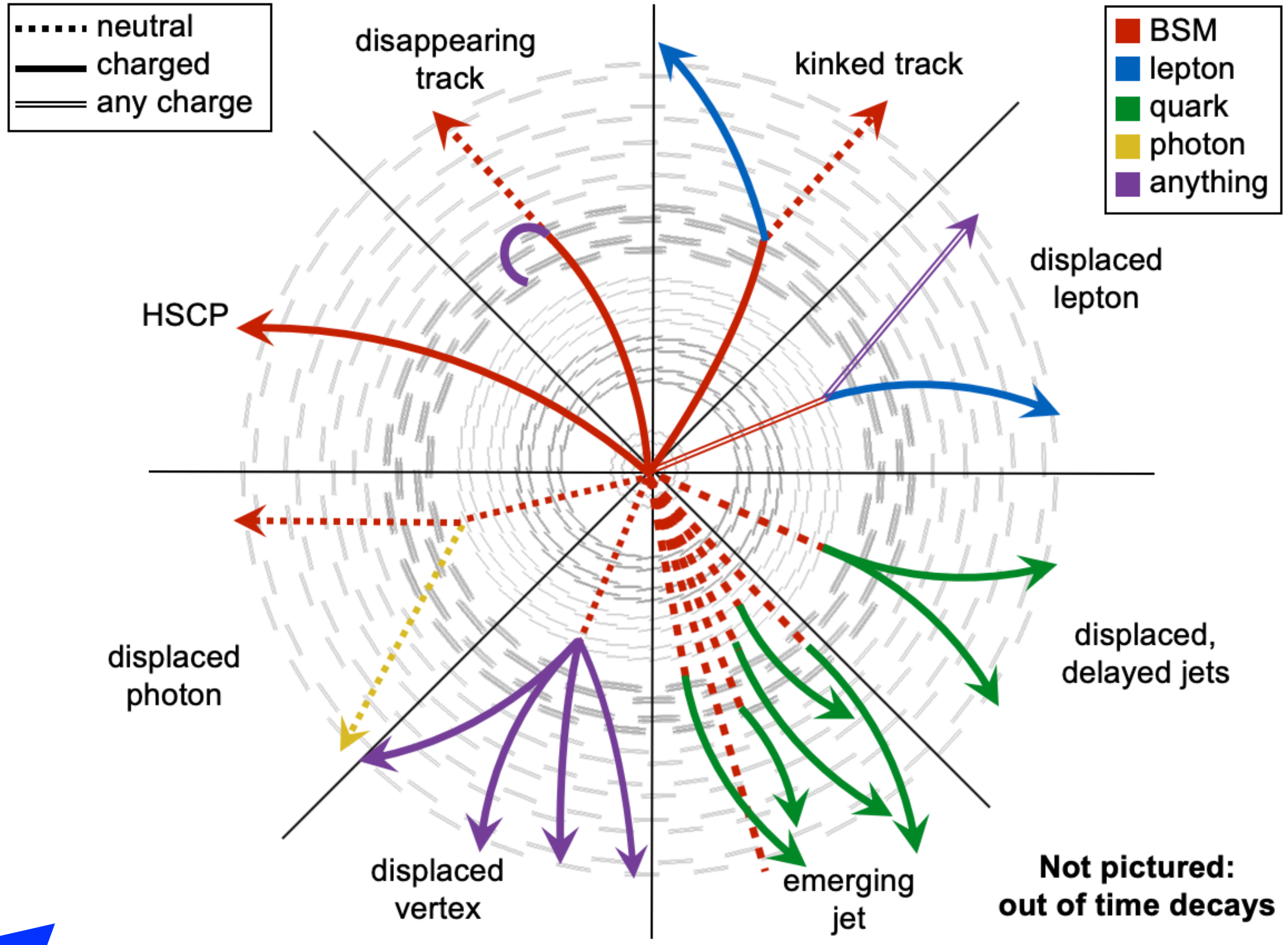
But **conventional searches** for new phenomena at the LHC are for **promptly** decaying particles



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
- **Challenges of the LHC:** main detectors, triggers, offline reconstruction not designed for displaced particles



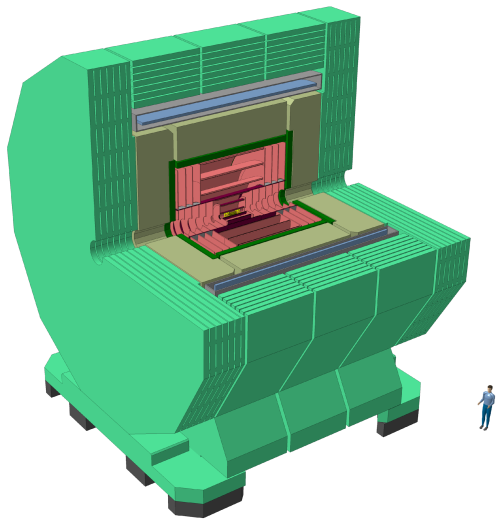
Big opportunity to do something different at the FCC!

Detectors at the FCC-ee

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

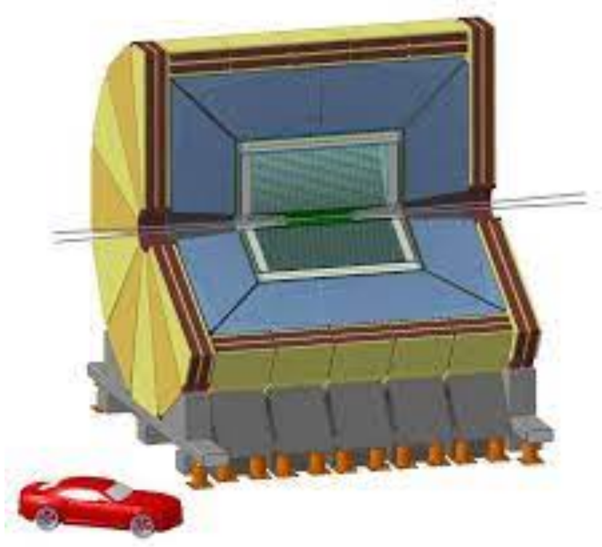
CLIC-like Detector (CLD)

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



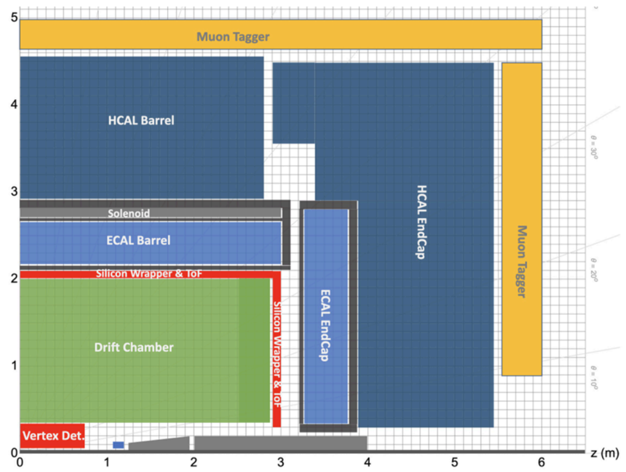
Innovative Detector for an Electron-Positron Accelerator (IDEA)

- 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)
- Dimitri Moulin (University of Geneva, 2023)
- Daniel Beech (University of Cambridge, 2023)

Snowmass:

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

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

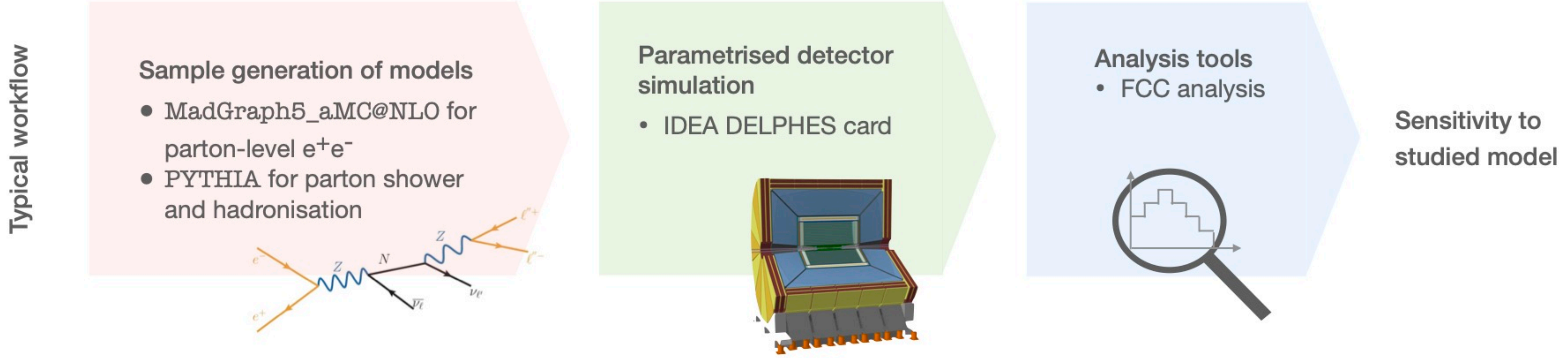
C. B. Verhaaren[1], J. Alimena[2]*, M. Bauer[3], P. Azzi[4], R. Ruiz[5], M. Neubert[6,7], O. Mikulenko[8], M. Ovchynnikov[8], M. Drewes[9], J. Klaric[9], A. Blondel[10], C. Rizzi[10], A. Sfyrla[10], T. Sharma[10], S. Kulkarni[11], A. Thamm[12], A. Blondel[13], R. Gonzalez Suarez[14] and L. Rygaard[14]

BSM 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 BSM FCC analyses

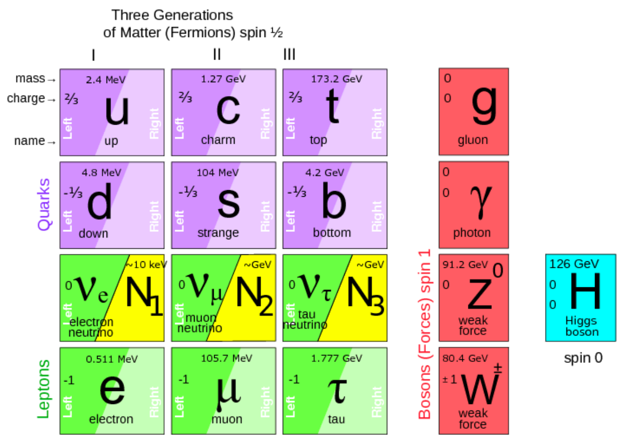
Workflow



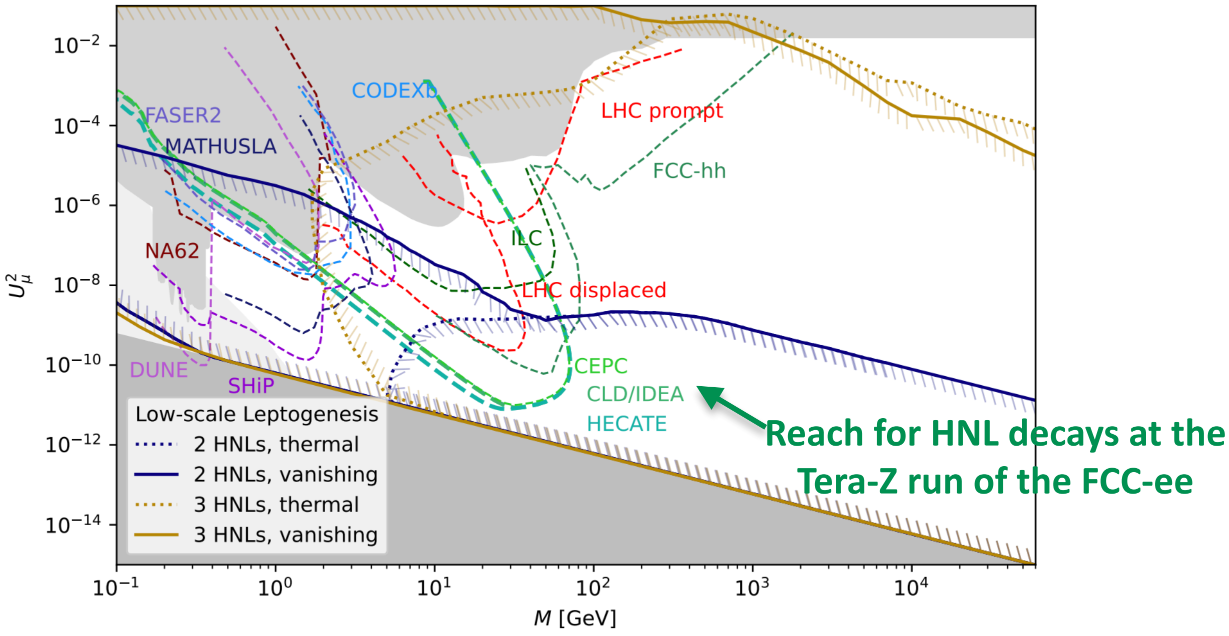
- Perform an FCC case studies with the **"official" analysis tools and framework** available for the FCC
  - **Use FCCAnalysis software** to analyze centrally-produced **EDM4HEP** samples with the **IDEA** detector in **Delphes**, although some signal samples produced privately
  - Dedicated tutorial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

1st Physics Case: Heavy Neutral Leptons (HNLs)

- Dirac or Majorana **sterile neutrinos** with **very small mixing** with active neutrinos
- **Could provide answers** to some open questions of the SM: Neutrino masses, Baryon asymmetry, Dark matter
- FCC will probe space not constrained by astrophysics or cosmology, complementary to fixed target, neutrino, and 0vbb prospects
- Get **long-lived HNLs** when coupling and mass are small

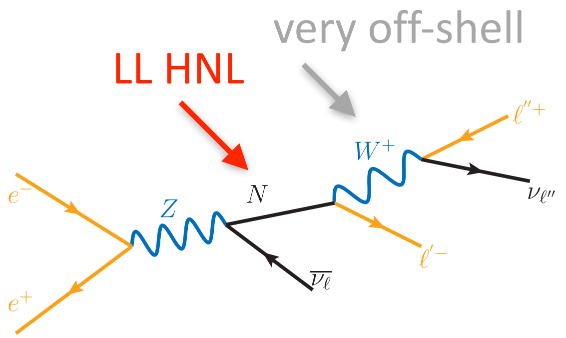


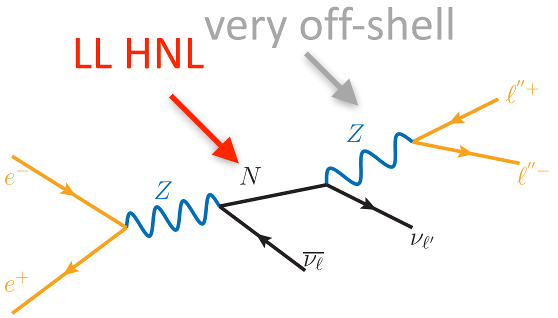
arXiv:2203.05502



Lovisa Rygaard

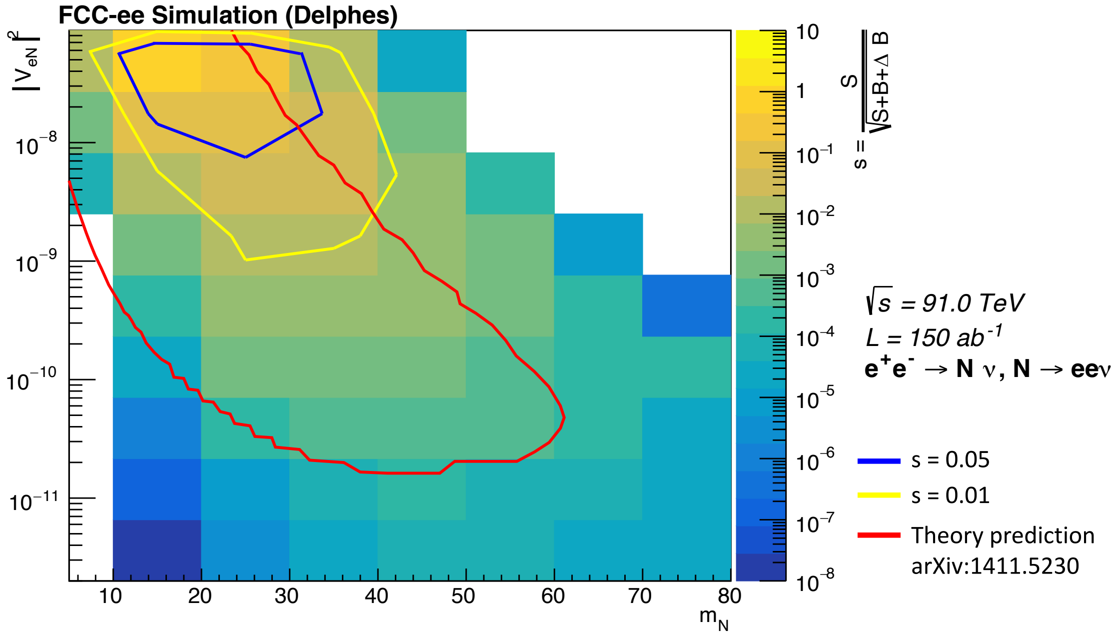
$N \to ee\nu$: Snowmass Results





- 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

- **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)



Tanishq Sharma

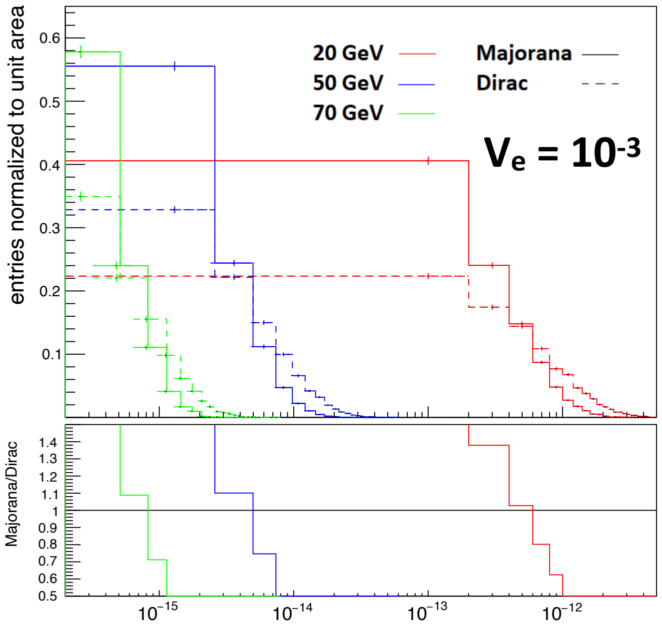
$N \rightarrow ee\nu$: Dirac vs Majorana

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

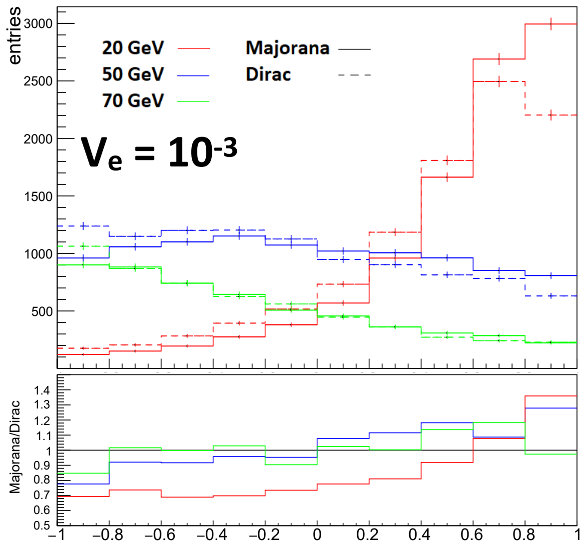
(model-dependent)



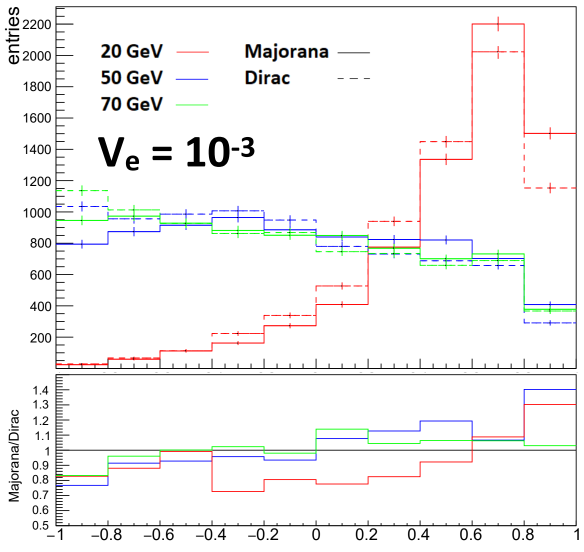
Gen HNL lifetime [s]

$\cos\theta_{ee}$

(opening angle between final state electron/positron)



Gen $\cos\theta_{ee}$

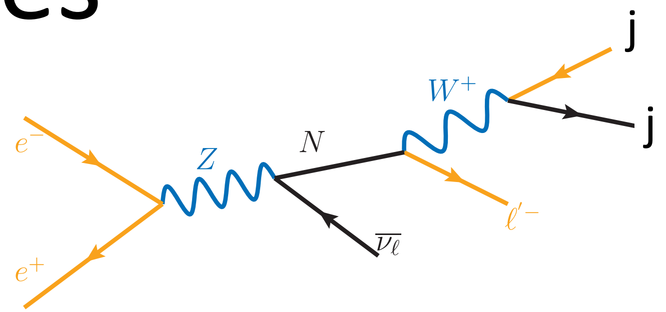


Reco $\cos\theta_{ee}$

Next: improve reconstruction, find more discriminating variables

$N \to \mu jj$: Ongoing Studies

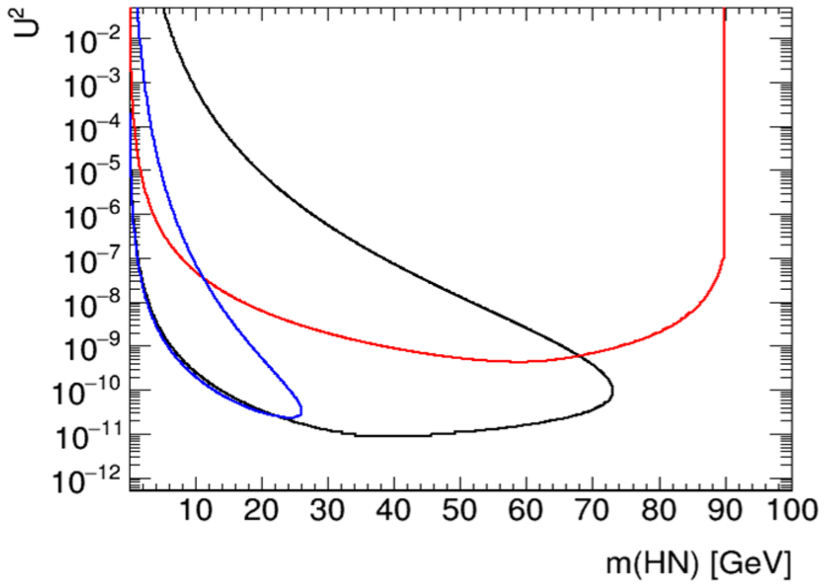
Nicolò Valle, Giacomo Polesello



- High branching fraction: ~50%
- **Selections:**
    - >= 3 tracks
    - 1 muon with p > 3 GeV
    - E_{miss} > 5 GeV
    - Other selections to remove backgrounds from Z decays
- Performing two subanalyses:
    - **Prompt analysis** for **high HNL mass (> 50 GeV)**
        - Require muon $|d_0| < 8\sigma$
    - **Long-lived analysis** for **low HNL mass**
        - Require muon $|d_0|$> 1 mm

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



Nicolò Valle, Giacomo Polesello

$N \rightarrow \mu jj$: Ongoing Studies

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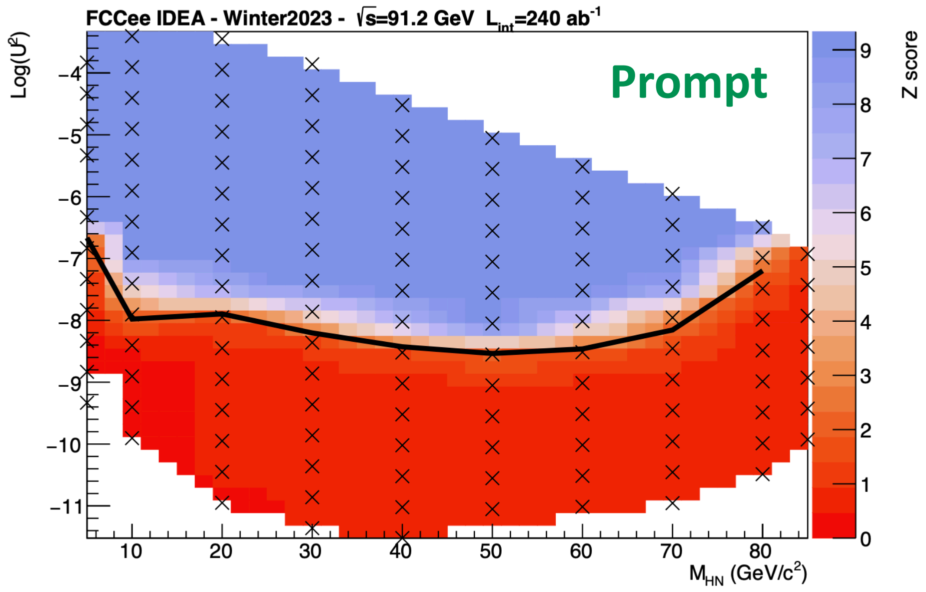
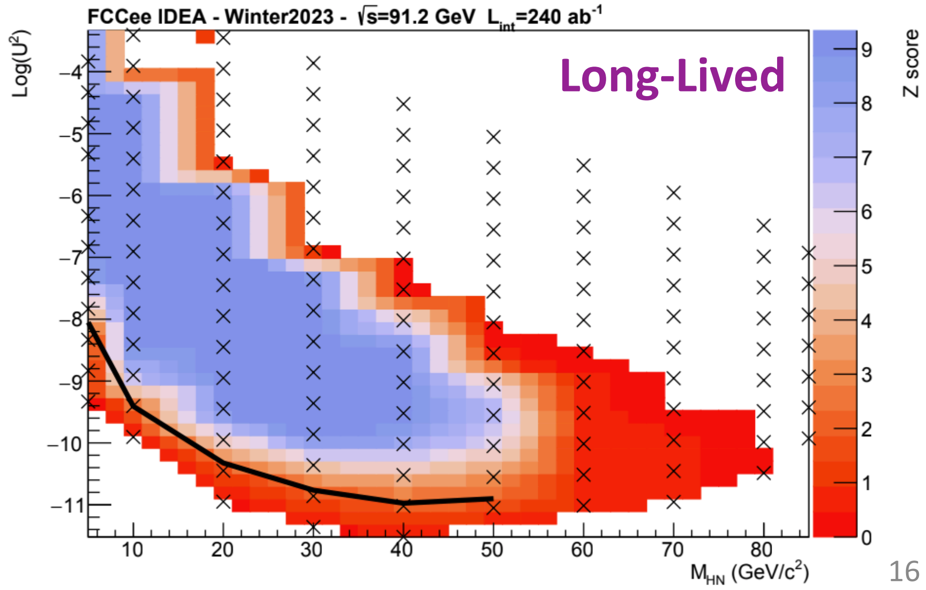
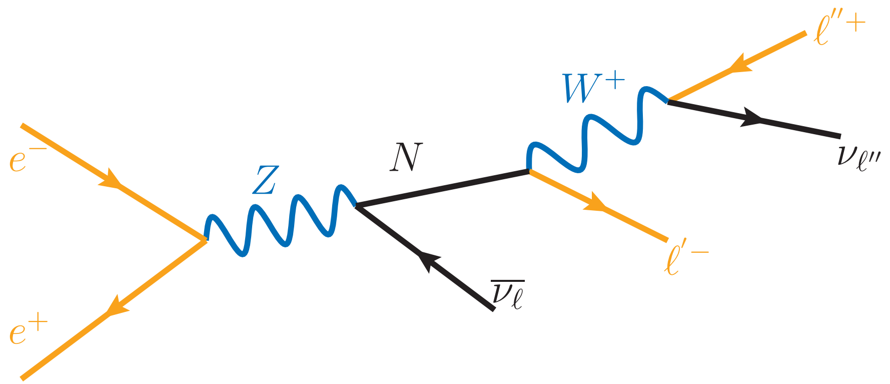


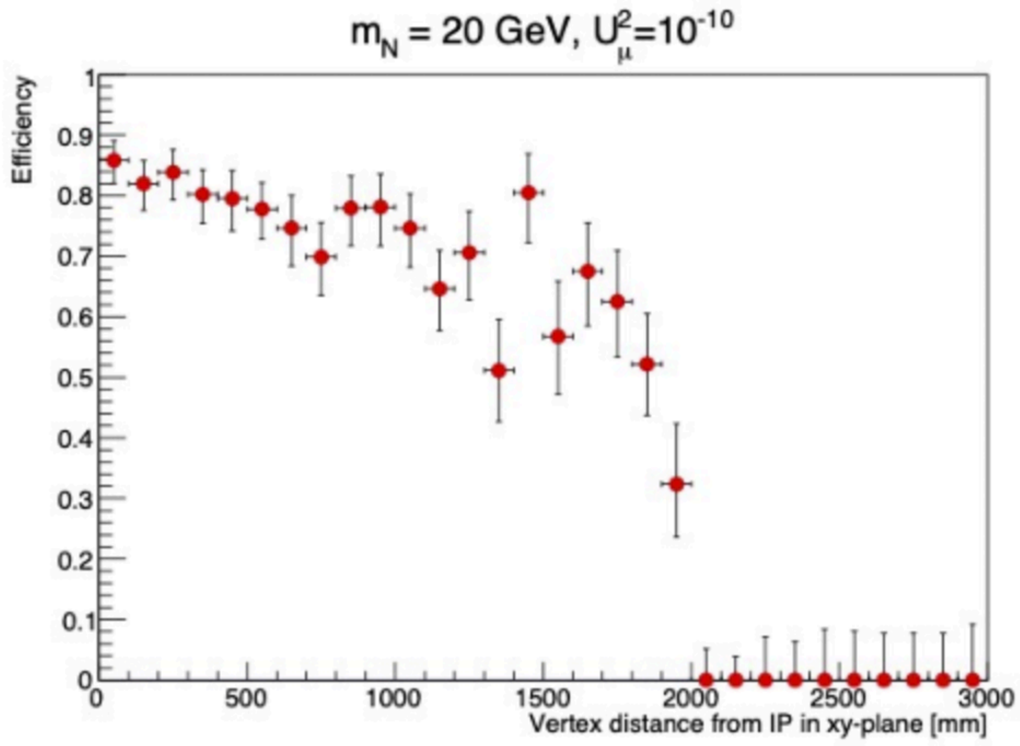


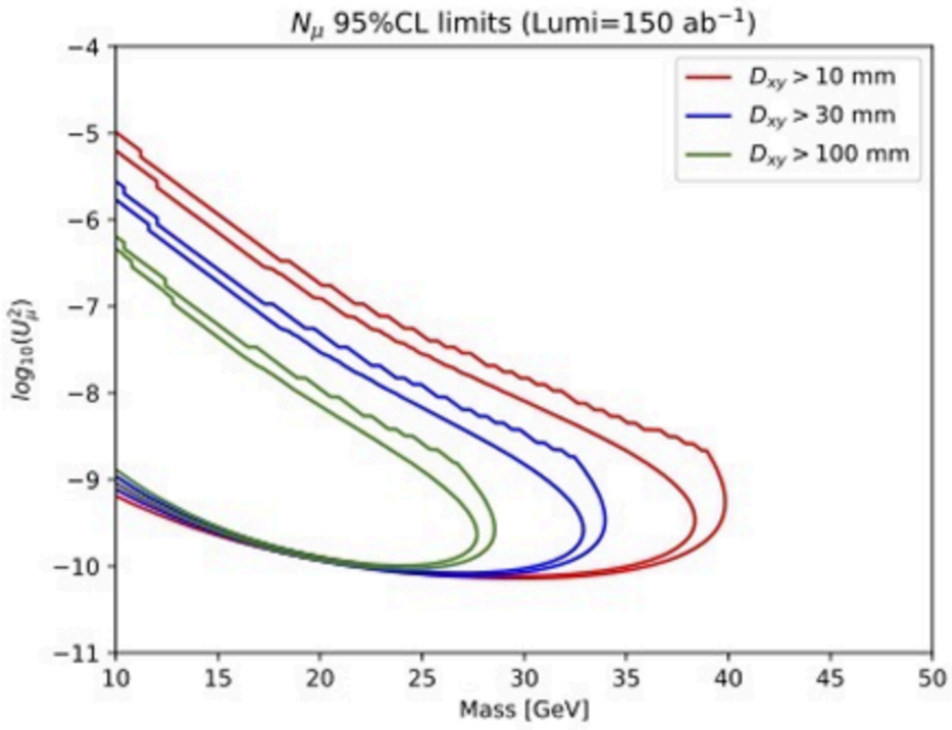
$N \to \mu\mu\nu$: Ongoing Studies

Lorenzo Bellagamba

- 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



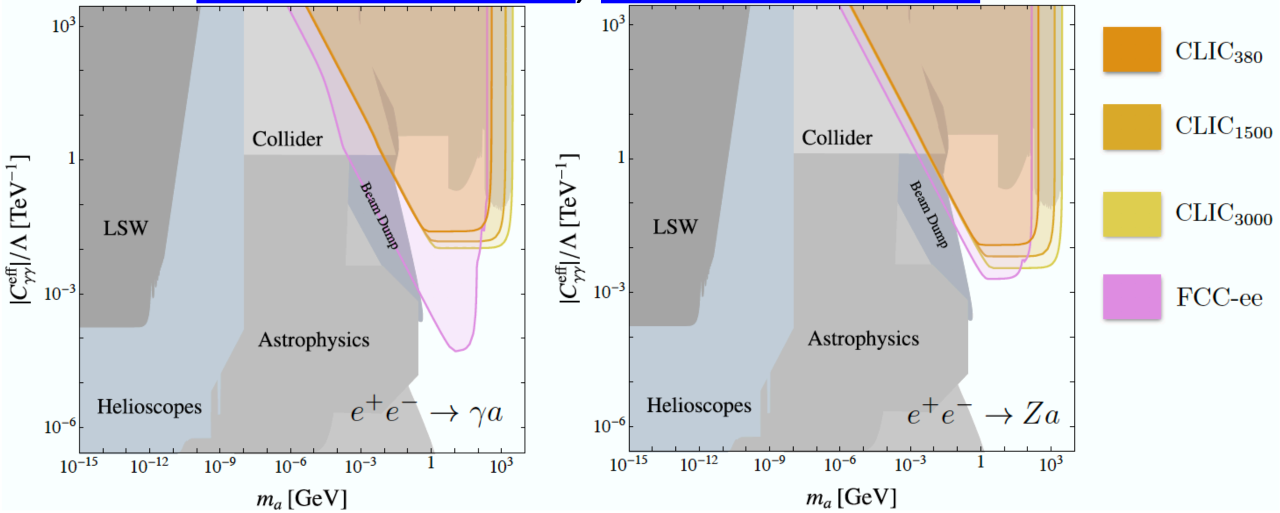


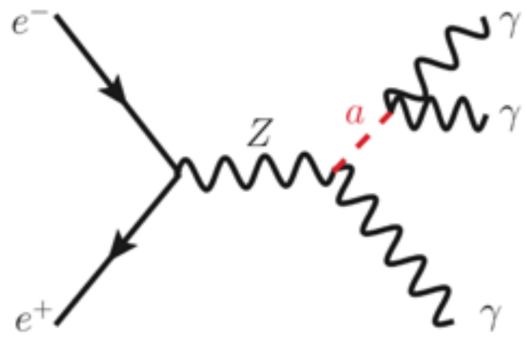


2nd Physics Case: Axion-Like Particles (ALPs)

- Axion-like Particles (ALPs) are pseudoscalars in models with spontaneously broken global symmetries
- 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)**
- **Ready for more personpower to step in and complete an analysis, guidance available!**

arXiv:1808.10323, arXiv:2108.08949

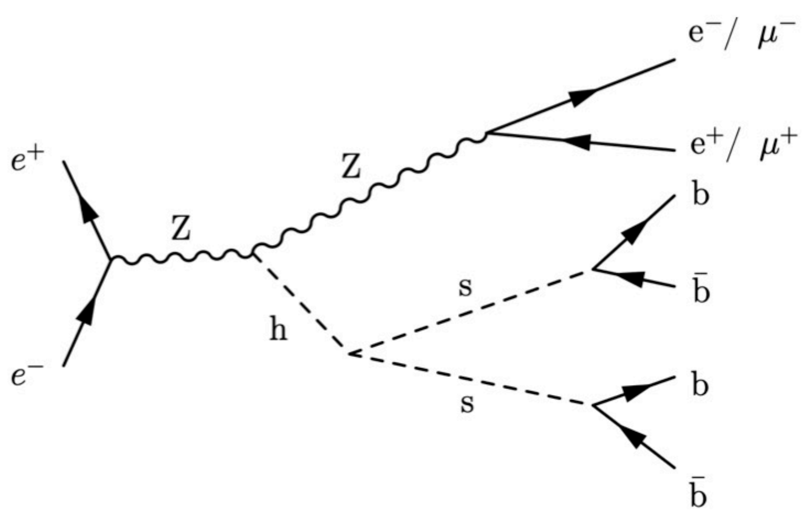


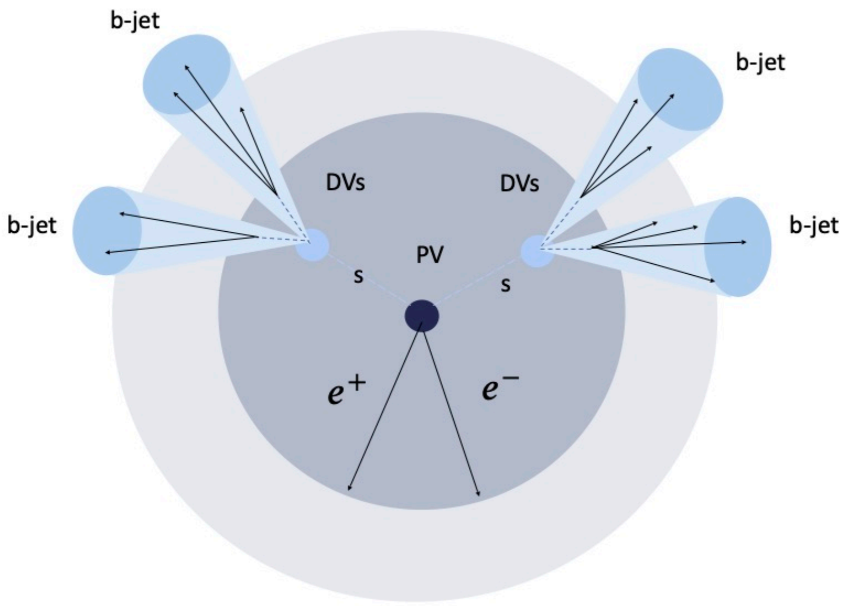


Magdalena Vande Voorde, Giulia Ripellino

3rd 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: 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:

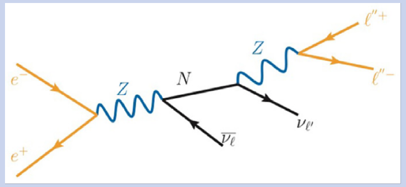
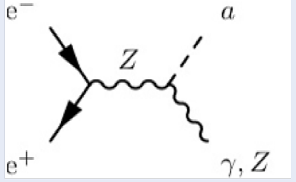
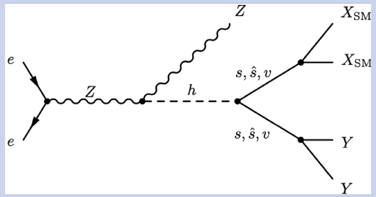
	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
WW	8.22e+07 $\pm$ 7.45e+06	2.11e+06 $\pm$ 4.16e+04	4.68e+05 $\pm$ 1.96e+04	0 ($\leq$ 1.96e+04)
ZZ	6.79e+06 $\pm$ 1.77e+05	8.91e+05 $\pm$ 7.78e+03	5.85e+05 $\pm$ 6.31e+03	0 ($\leq$ 6.31e+03)
ZH	1.01e+06 $\pm$ 1.01e+04	5.97e+04 $\pm$ 7.76e+02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

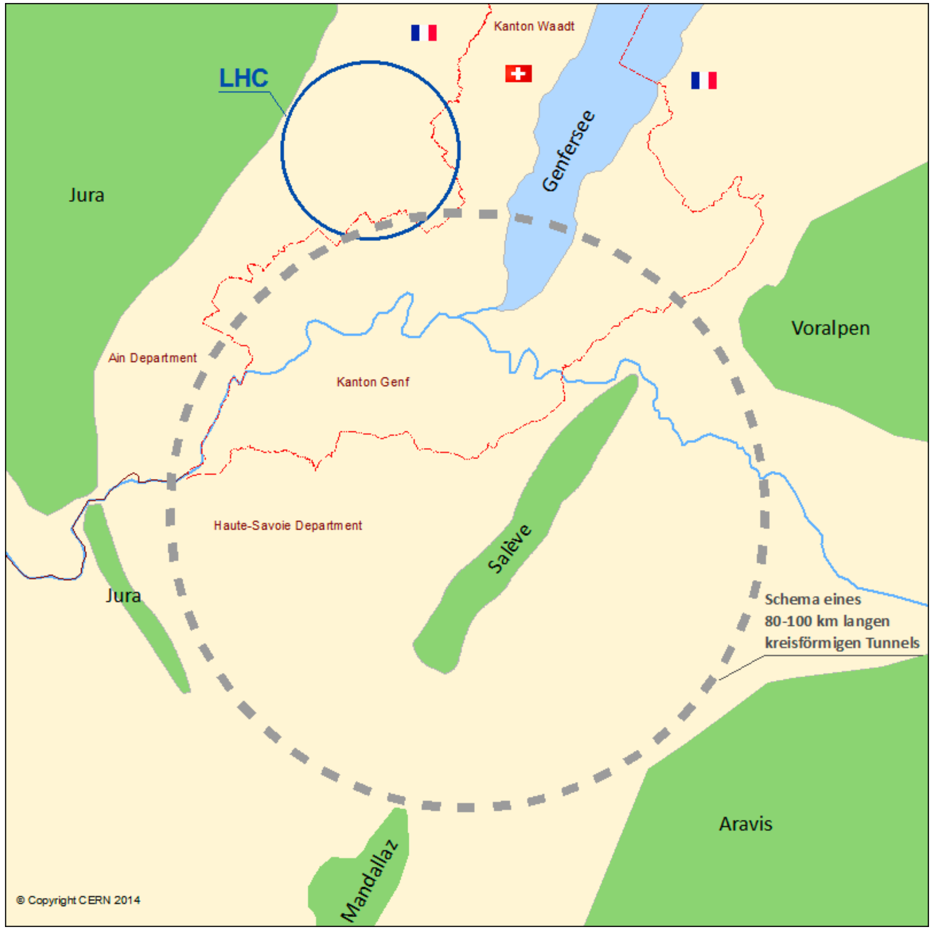
Overview of Analyses

Physics scenario	FCC-ee signature	Studies for snowmass	Ongoing work
Heavy neutral leptons (HNLs)	Displaced vertices 	Generator validation and reco-level analysis for HNL->eeν. First look at Dirac vs Majorana HNLs	• Update HNL->eeν studies with winter23 samples. • Dirac vs Majorana in eνjj channel • Mature HNL->μjj channel • First look at HNL->$\mu\mu\nu$ channel
Axion-like particles (ALPs)	Displaced photon/ lepton pair 	Generator-level validation for a→γγ at Z-pole run	• Efforts being renewed now ***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

Thanks!

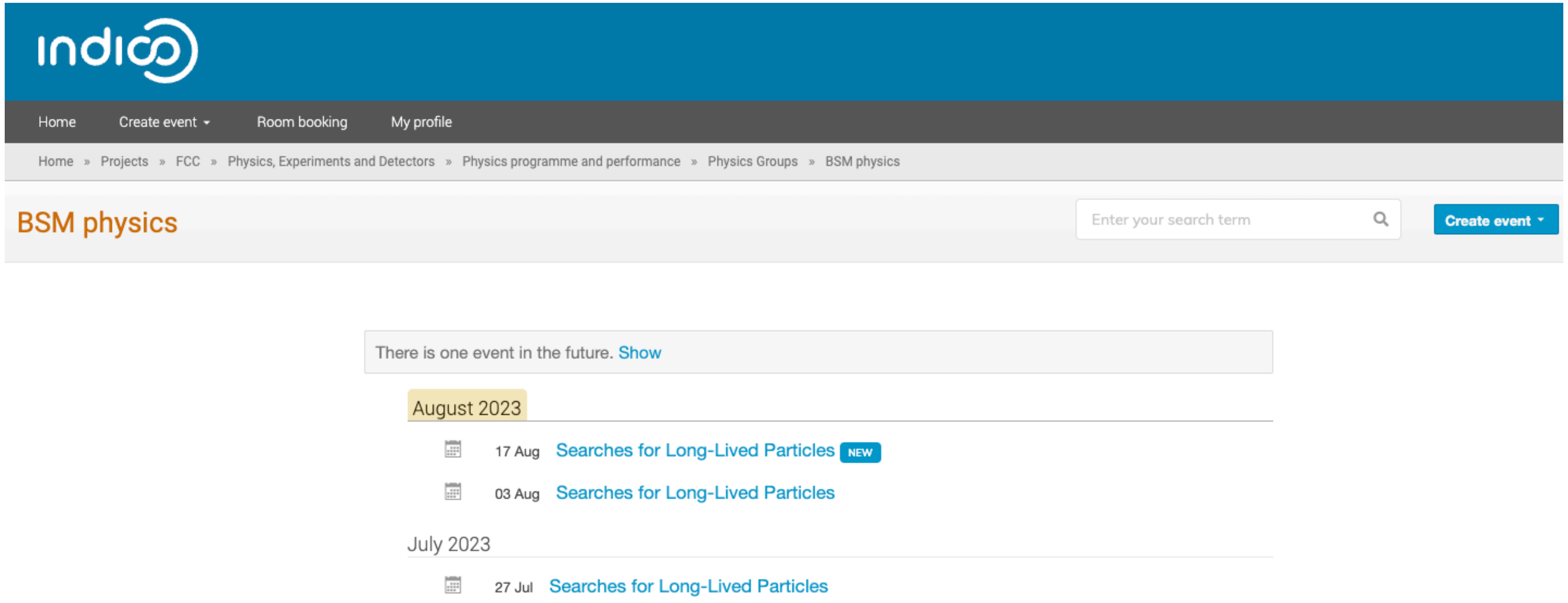
… to all who provided input for this talk

- 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)
- Nicolò Valle (INFN)
- Pantelis Kontaxakis (University of Geneva)
- Rebeca Gonzalez Suarez (Uppsala University)
- Sarah Williams (University of Cambridge)
- Suchita Kulkarni (University of Graz)



BSM & LLPs at the FCC

- 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

- Future colliders are *absolutely* necessary
- A circular Higgs factory like the FCC-ee has a rich potential: Direct and indirect sensitivity to new physics
- 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
- Plenty of phase space to explore at the FCC! Let’s make sure we don’t miss new physics!

Backup

LL HNLs

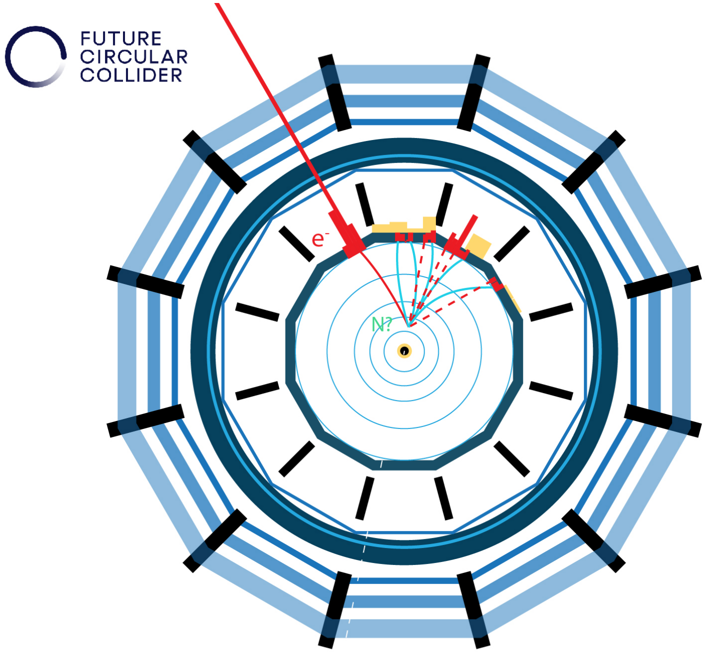
$$\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\rm dec}} \left(\frac{M}{\rm GeV}\right)^{-6} \left(1 - (M/m_Z)^2\right) \,\rm cm$$

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

[arXiv:2210.17110]

e+e- → Z→ vN

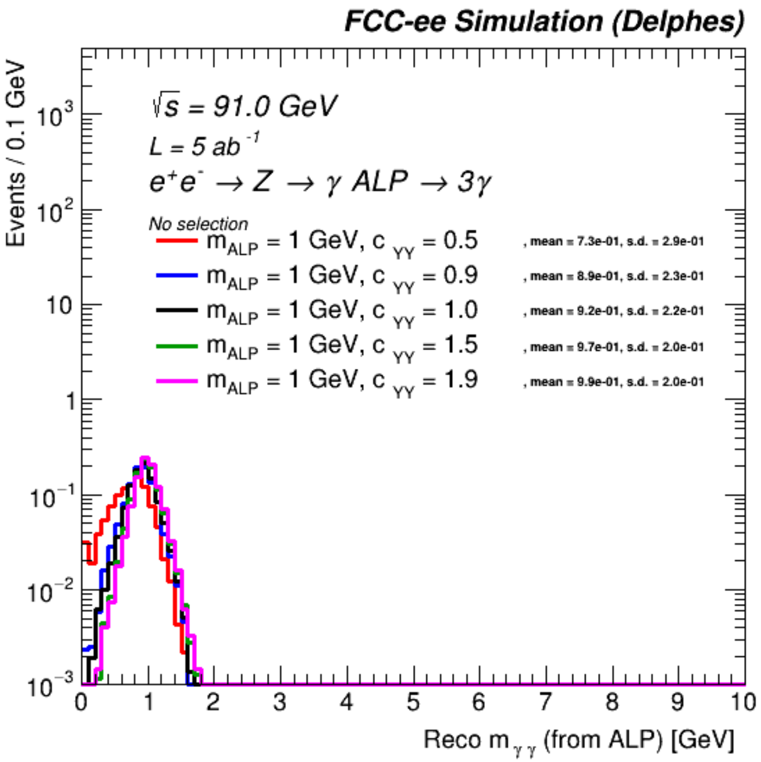
N→ e- + {W+* →jj}

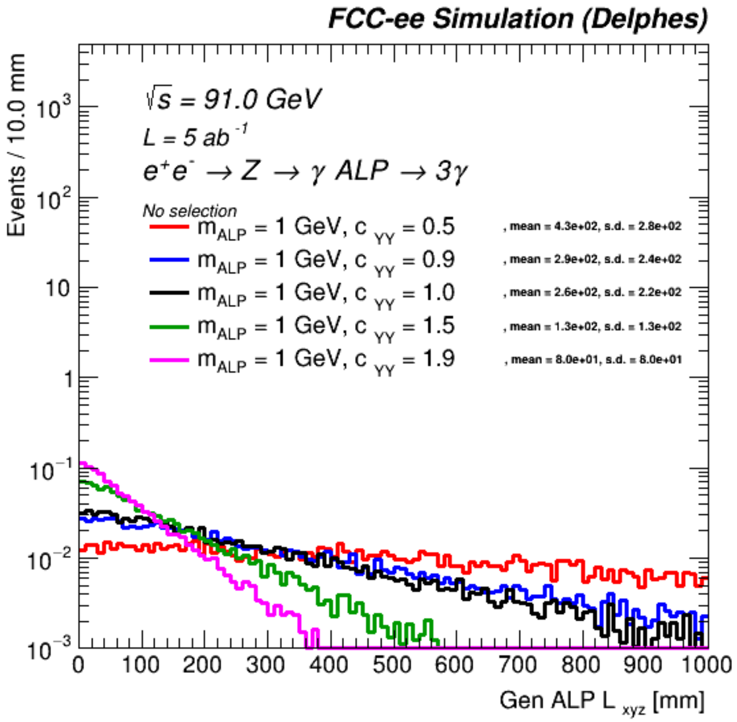


Get long-lived HNLs when coupling and mass are small

Experimental signature of LL HNLs: displaced vertex

ALPs: Variables to Explore



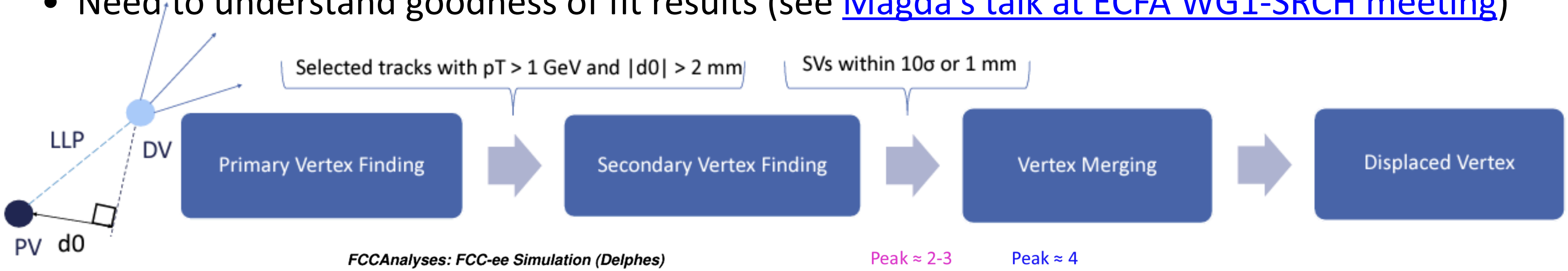


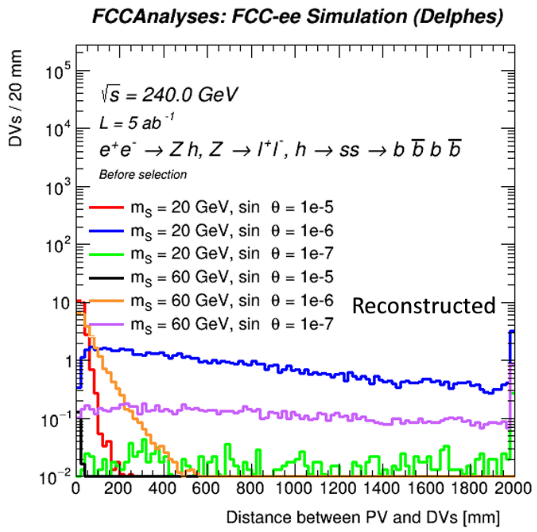
- Started with simulating 1 GeV ALP mass, vary the coupling
- ALP mass confirmed with the reco invariant mass from the 2 photons coming from the ALP
- ALP decay length will also be a nice discriminating variable
- **Ready for more personpower to step in and complete an analysis, guidance available!**

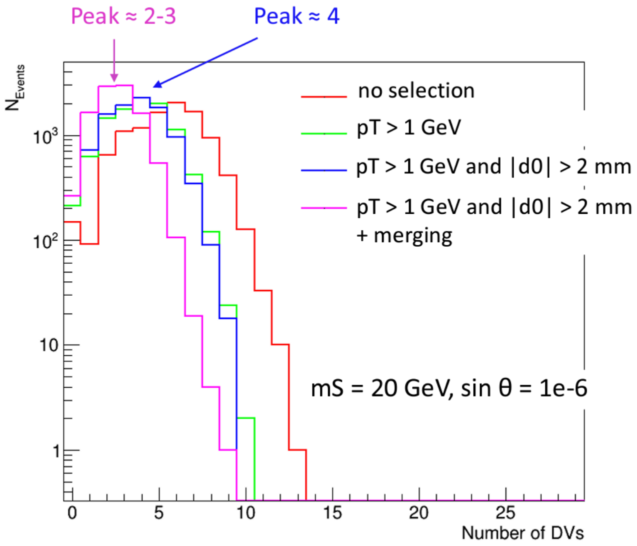
Magdalena Vande Voorde, Giulia Ripellino

Exotic Higgs Decays: Displaced Vertex Reconstruction

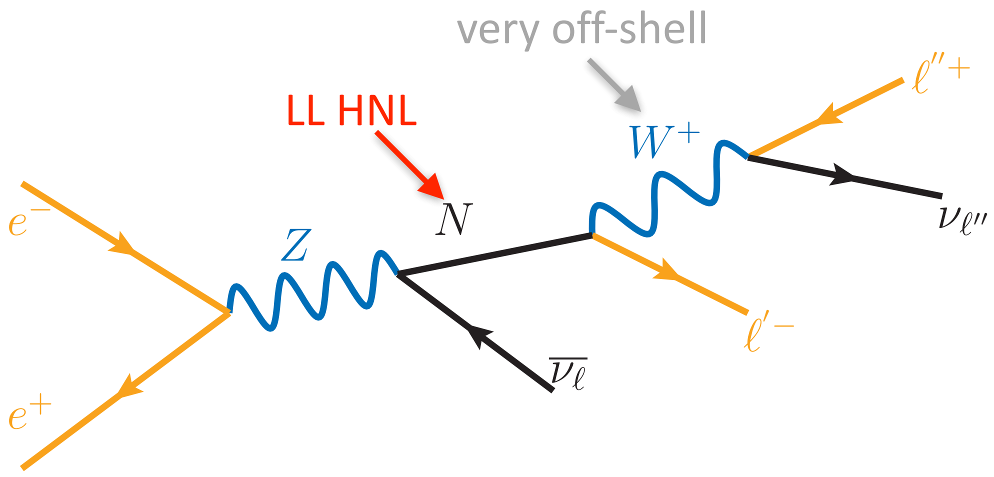
- Studied options of **DV reconstruction implemented in the FCCAnalyses framework** with extra constraints and functions inspired by ATLAS DV reconstruction
  - **SV finder** from **LCFI+ algorithm** (arXiv:1506.08371)
  - Added **vertex merging** to reconstruct the scalar DVs
    - Need to understand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

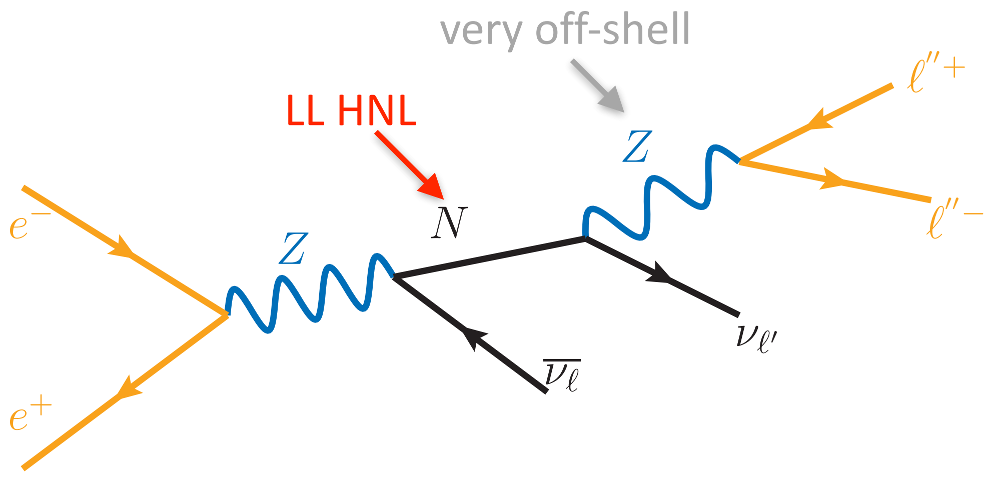




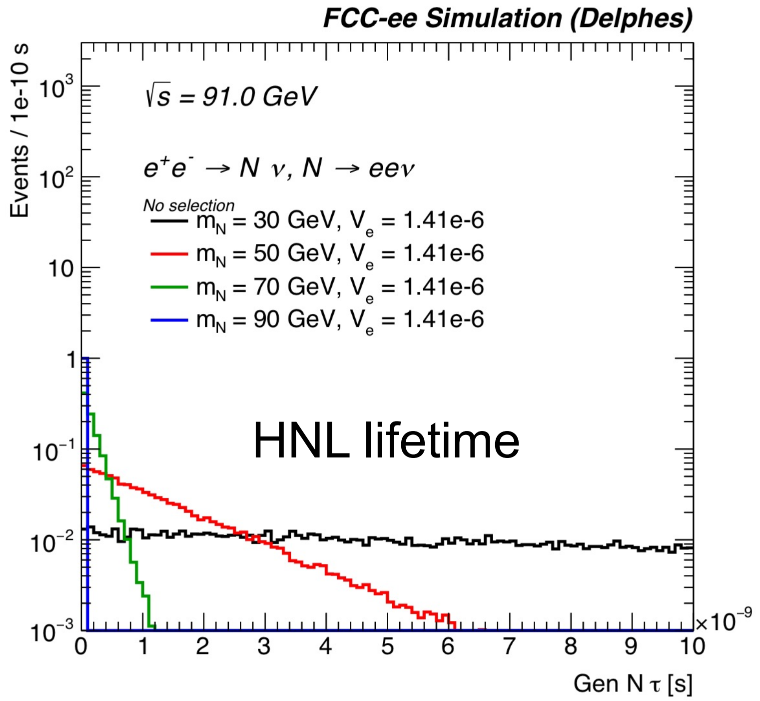


$N \rightarrow ll\nu$ Generation





- 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

$N \rightarrow ee\nu$: Snowmass 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
$Z \rightarrow ee$	$2.19 \times 10^{11} \pm 6.94 \times 10^{7}$	$1.75 \times 10^{11} \pm 6.19 \times 10^{7}$	$1.53 \times 10^{11} \pm 5.80 \times 10^{7}$	$7.07 \times 10^{8} \pm 3.94 \times 10^{6}$	$\leq 3.94 \times 10^{6}$
$Z \rightarrow bb$	$9.97 \times 10^{11} \pm 4.14 \times 10^{7}$	$5.64 \times 10^{8} \pm 9.85 \times 10^{5}$	$3.25 \times 10^{5} \pm 2.36 \times 10^{4}$	$1.22 \times 10^{5} \pm 1.45 \times 10^{4}$	$1.72 \times 10^{3} \pm 1.72 \times 10^{3}$
$Z \rightarrow \tau\tau$	$2.21 \times 10^{11} \pm 7.00 \times 10^{7}$	$5.49 \times 10^{9} \pm 1.10 \times 10^{7}$	$5.10 \times 10^{9} \pm 1.06 \times 10^{7}$	$2.52 \times 10^{9} \pm 7.47 \times 10^{6}$	$6.64 \times 10^{4} \pm 3.84 \times 10^{4}$
$Z \rightarrow cc$	$7.82 \times 10^{11} \pm 2.61 \times 10^{7}$	$1.69 \times 10^{7} \pm 1.21 \times 10^{5}$	$5.22 \times 10^{3} \pm 2.13 \times 10^{3}$	$1.74 \times 10^{3} \pm 1.23 \times 10^{3}$	$\leq 1.23 \times 10^{3}$
$Z \rightarrow uds$	$2.79 \times 10^{12} \pm 8.83 \times 10^{7}$	$2.30 \times 10^{7} \pm 2.54 \times 10^{5}$	$2.79 \times 10^{3} \pm 2.79 \times 10^{3}$	$\leq 2.79 \times 10^{3}$	$\leq 2.79 \times 10^{3}$

	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

$N \to ee\nu$: Snowmass Results

- **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