Opportunities for FIPs searches at FCC-ee

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on behalf of the FCC-ee LLP group

FIPs-2022 Workshop

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FUTURE
CIRCULAR
COLLIDER

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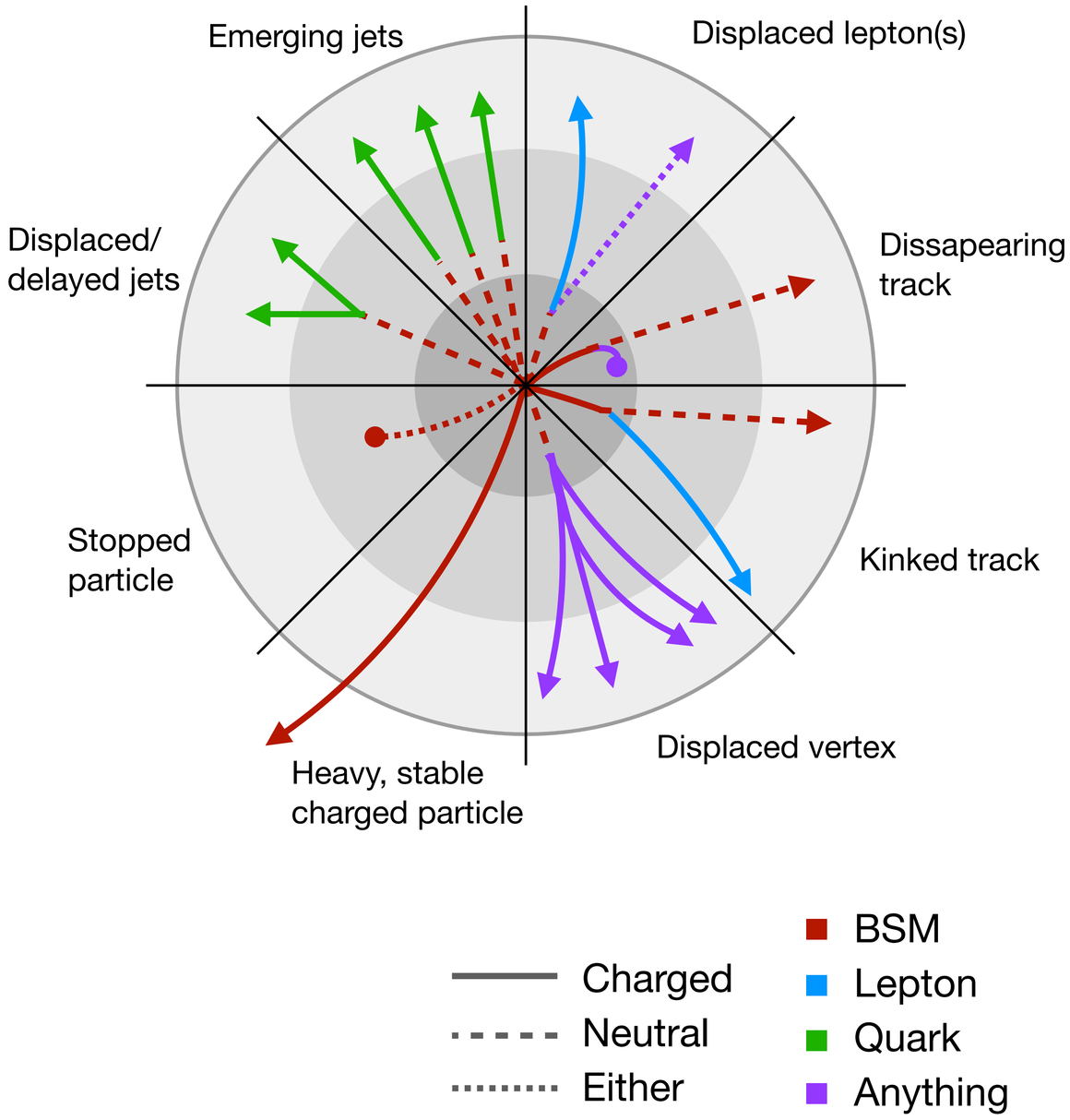
UNIVERSITET

Accelerator searches for FIPs

- A characteristic of weakly interacting particles is the possibility to have a long lifetime
  - Search for long-lived particles (LLPs)!

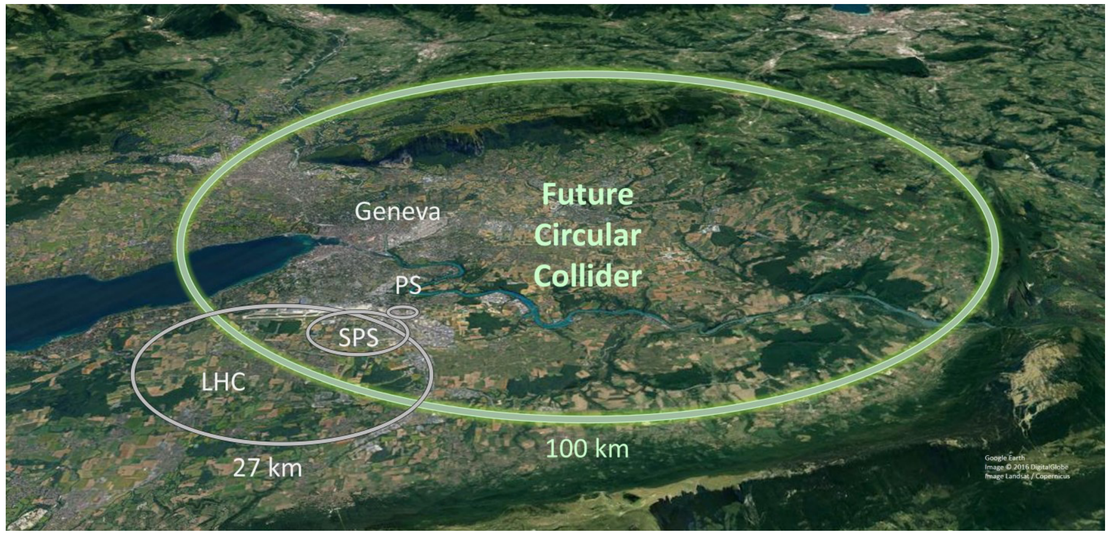
    i.e those with a decay length that can be resolved by the detectors
- Distinct signatures depending on the LLP lifetime, mass, charge, and decay products
  - Targeted by signature-driven searches
- Experimental **benefits**:
  - Little/no backgrounds from SM decays

    ….but atypical backgrounds might be significant (cosmics, beam halo, instrumental effects, etc.)
- Experimental **challenges**:
  - main detectors, triggers, and offline reconstruction not designed for displaced particles
  - Plenty of room for improvement in future accelerator projects!



The Future Circular Collider (FCC)

- Post-LHC high-energy frontier circular colliders at CERN
- One 100 km tunnel operated in 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
- FCC-ee presents excellent opportunities for LLP searches
  - Clean experimental signatures (no underlying event)
  - No trigger limitations
  - High luminosity
- More about the FCC in backup



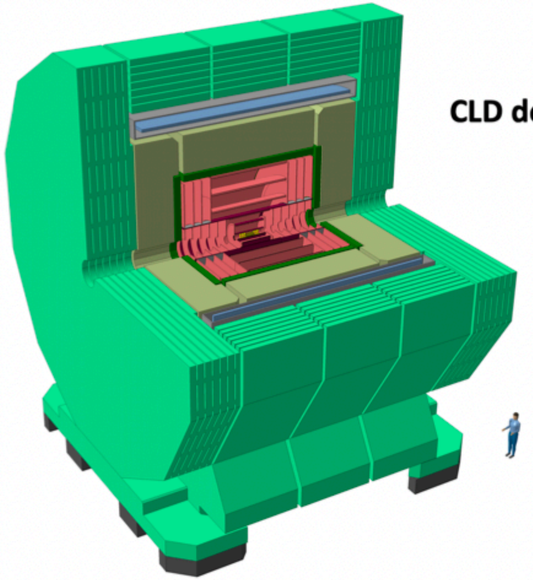
FCC:
90-100 km
100 TeV (pp) 90-350 GeV (e^+e^-)

LHC / LEP:
27 km
14 TeV (pp) 209 GeV (e^+e^-)

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics	
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays	LEP x 10^5
FCC-ee-W	2	158-162	12	10^8 WW events	LEP x $2 \cdot 10^3$
FCC-ee-H	3	240	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events	Never done

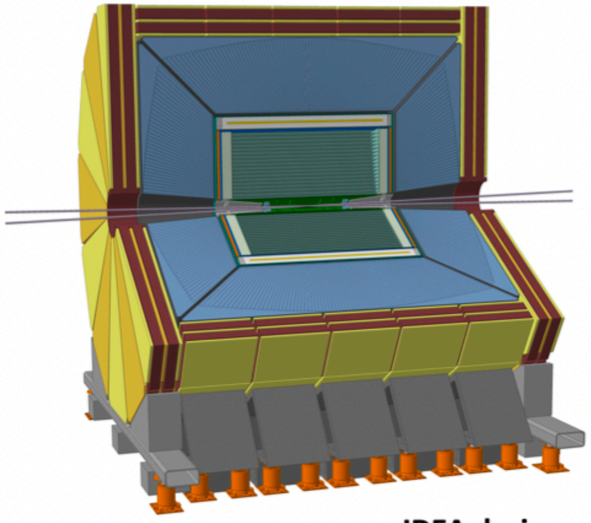
FCC detector concepts

- Two detector concepts used for integration, performance, and cost estimates:
  - **CLD design:** adapted for the FCC-ee by the CERN Linear Collider (CLIC) Detector group
  - **IDEA design:** specifically designed for the FCC-ee
- 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



CLD design

Full silicon tracker
3D high granularity calorimeter
Solenoid outside calorimeter



IDEA design

Ultra-light drift chamber
Dual read-out calorimeter
Solenoid inside calorimeter

FCC-ee LLP group: past and ongoing work

- Work kicked into high gear with a Snowmass LoI
- Snowmass white paper recently published in Frontiers in Physics! Front. Phys. 10:967881 (2022)
  - FCC-ee case studies with the official FCC analysis tools
- Several Masters student theses done or in progress. List in backup!
- LLP studies to motivate out-of-the-box optimization of experimental conditions and analysis techniques
  - Detector design, Reconstruction algorithms, Trigger

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

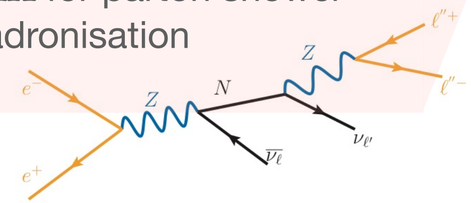
C. B. Verhaaren[1], J. Alimena[2]*, M. Bauer[3], P. Azzi[4], R. Ruiz[5], M. Neubert[6,7], O. Mikulenko[8], M. Ovchynnikov[8], M. Drewes[9], J. Klaric[9], A. Blondel[10], C. Rizzi[10], A. Sfyrla[10], T. Sharma[10], S. Kulkarni[11], A. Thamm[12], A. Blondel[13], R. Gonzalez Suarez[14] and L. Rygaard[14]

[1]Department of Physics and Astronomy, Brigham Young University, Provo, UT, United States, [2]Experimental Physics Department, CERN, Geneva, Switzerland, [3]Department of Physics, Durham University, Durham, United Kingdom, [4]INFN, Section of Padova, Padova, Italy, [5]Institute of Nuclear Physics, Polish Academy of Sciences, Kracow, Poland, [6]Johannes Gutenberg University, Mainz, Germany, [7]Cornell University, Ithaca, NY, United States, [8]Leiden University, Leiden, Netherlands, [9]Université Catholique de Louvain, Louvain-la-Neuve, Belgium, [10]University of Geneva, Geneva, Switzerland, [11]University of Graz, Graz, Austria, [12]The University of Melbourne, Parkville, VIC, Australia, [13]LPNHE, Université Paris-Sorbonne, Paris, France, [14]Uppsala University, Uppsala, Sweden

Typical workflow

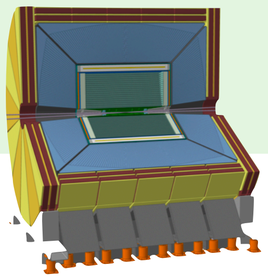
Sample generation of models, e.g.

- `MadGraph5_aMC@NLO` for parton-level e^+e^-
- `PYTHIA` for parton shower and hadronisation



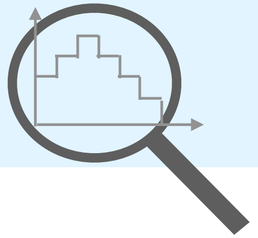
Parametrised detector simulation, e.g

- IDEA DELPHES card



Analysis tools, e.g

- FCC analysis

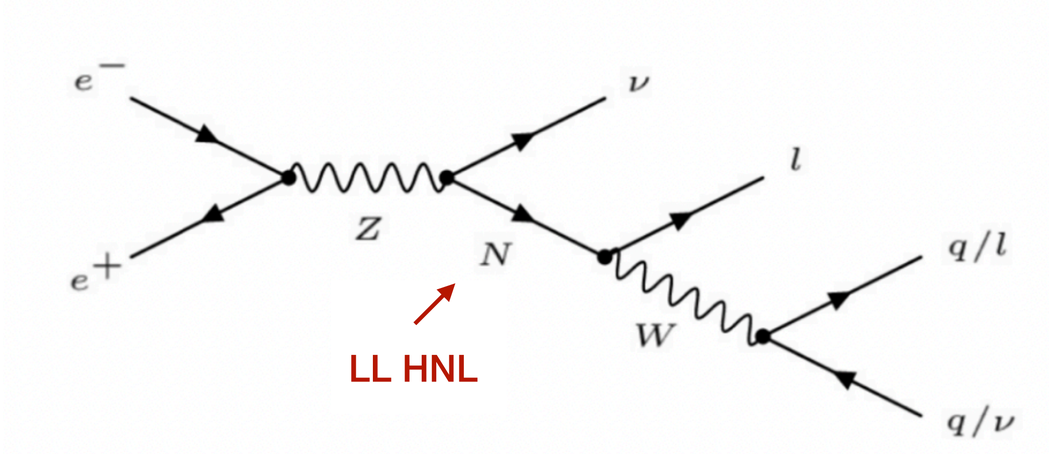


Sensitivity to studied model

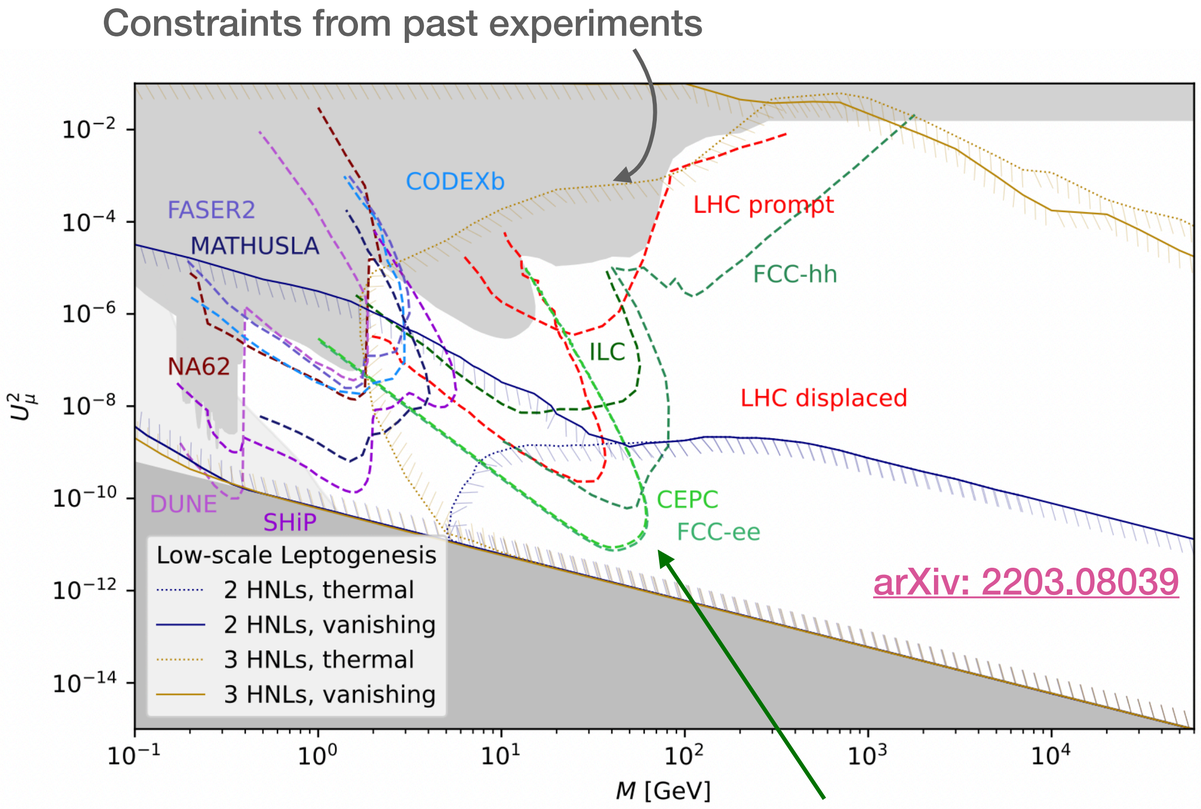
Heavy Neutral Leptons (HNLs) at FCC-ee

Flagship BSM case for FCC-ee! arXiv:1411.5230

- Many of the current HNL limits cover large neutrino mixing angles…
- …For small values of the mixing angle, the decay length of the HNL can be significant → **LLP signature**
  - Suitable benchmark model for displaced vertex (DV) searches
- The FCC-ee will offer an unbeatable reach for HNLs at the Z-Pole
  - Production via $e^+e^- \to Z \to \nu N,\ N \to lW$



Production and possible decay at FCC-ee



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

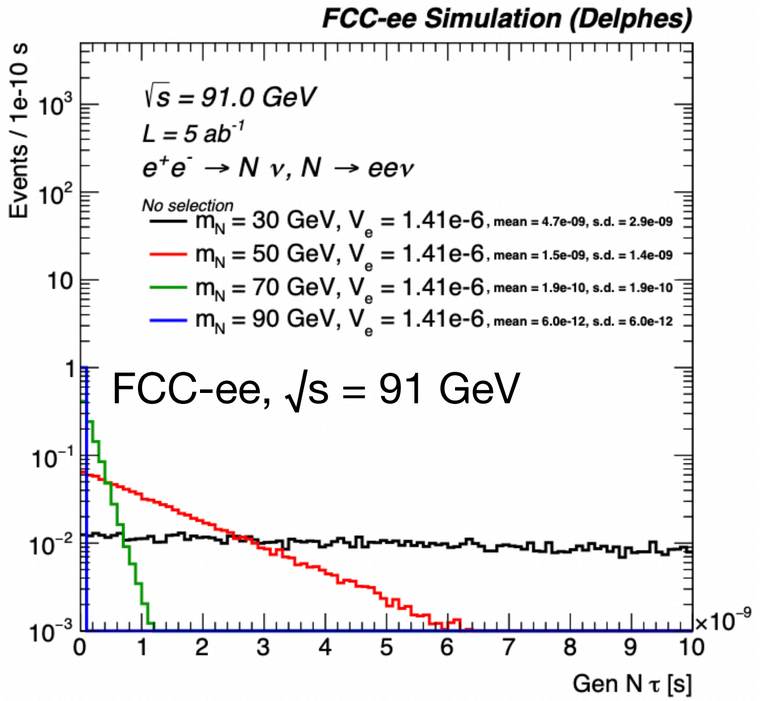
$$L \sim 0.025\text{m}\left(\frac{10^{-6}}{V_l}\right)^2\left(\frac{100\ \text{GeV}}{m_N}\right)^5$$

Long-lived HNLs when coupling and mass are small

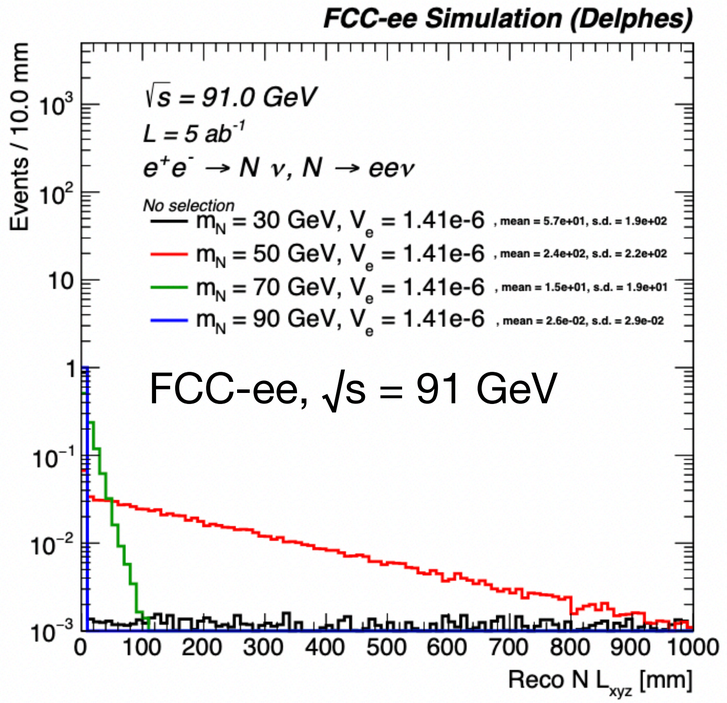
Towards an HNL FCC-ee sensitivity study - I

- Generated samples with Majorana and Dirac HNLs at √s = 91 GeV
  - Models: SM_HeavyN_CKM_AllMasses_LO, SM_HeavyN_Dirac_CKM_Masses_LO (arXiv:1411.7305, arXiv:1602.06957)
  - Full chain: Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card
- First study in the $ee\nu$ final state (other final states to be added)

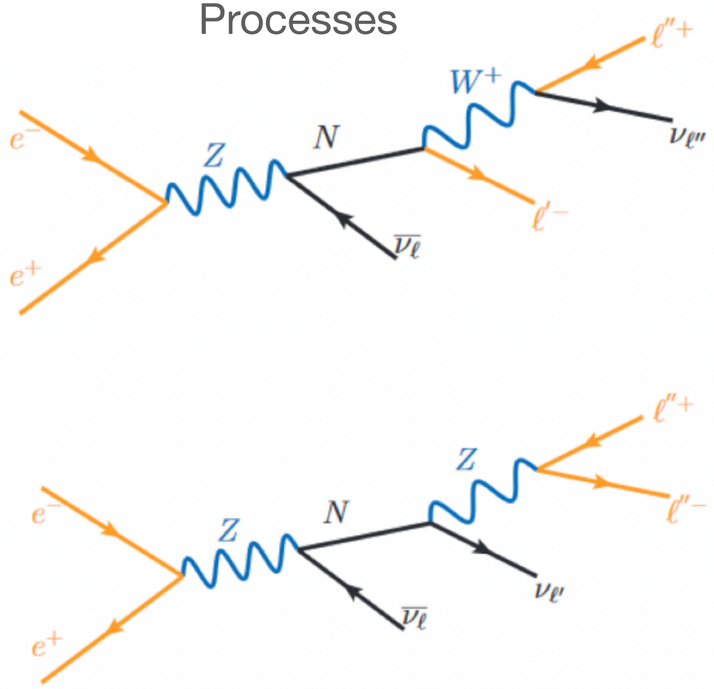
HNL lifetime



HNL reconstructed decay length



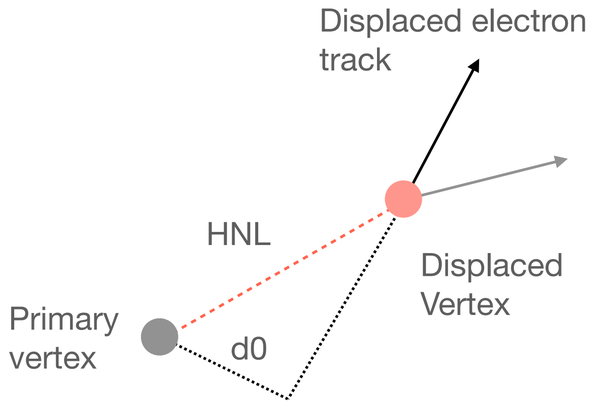
Processes



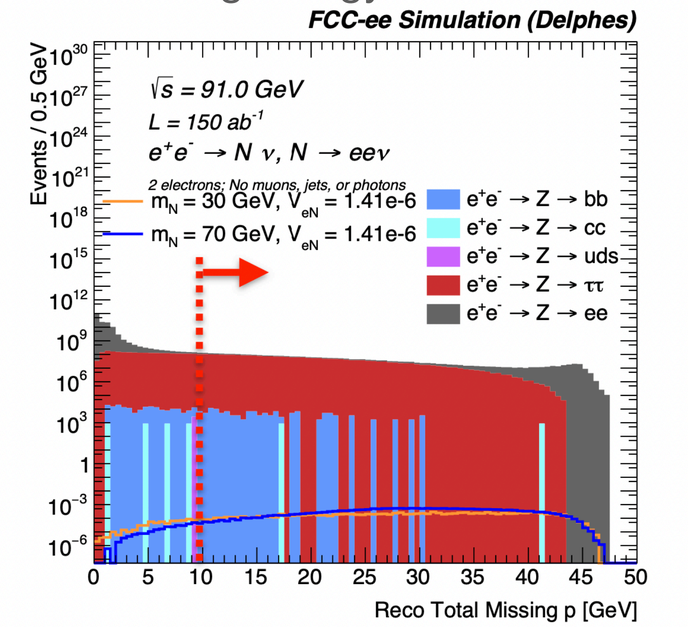
Towards an HNL FCC-ee sensitivity study - II

Preliminary event selection studied:

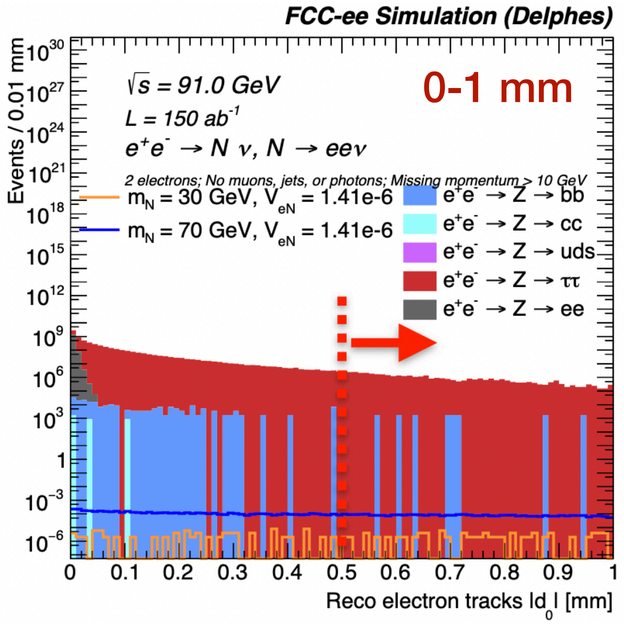
- Exactly two electrons & veto against photons, jets, muons
  - Reducing the background from light and heavy quarks
- Missing energy > 10 GeV
  - Reducing Z → ee with missing energy from finite detector resolution
- Both electrons displaced by |d0| > 0.5 mm

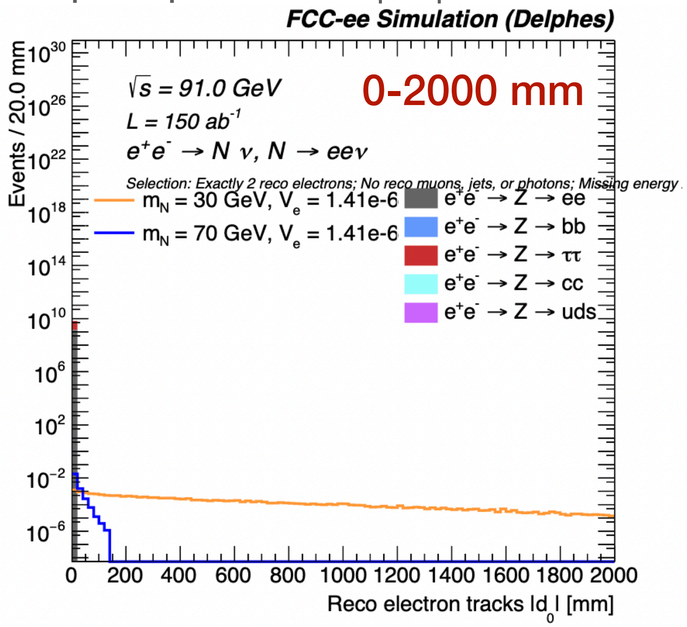


Missing energy



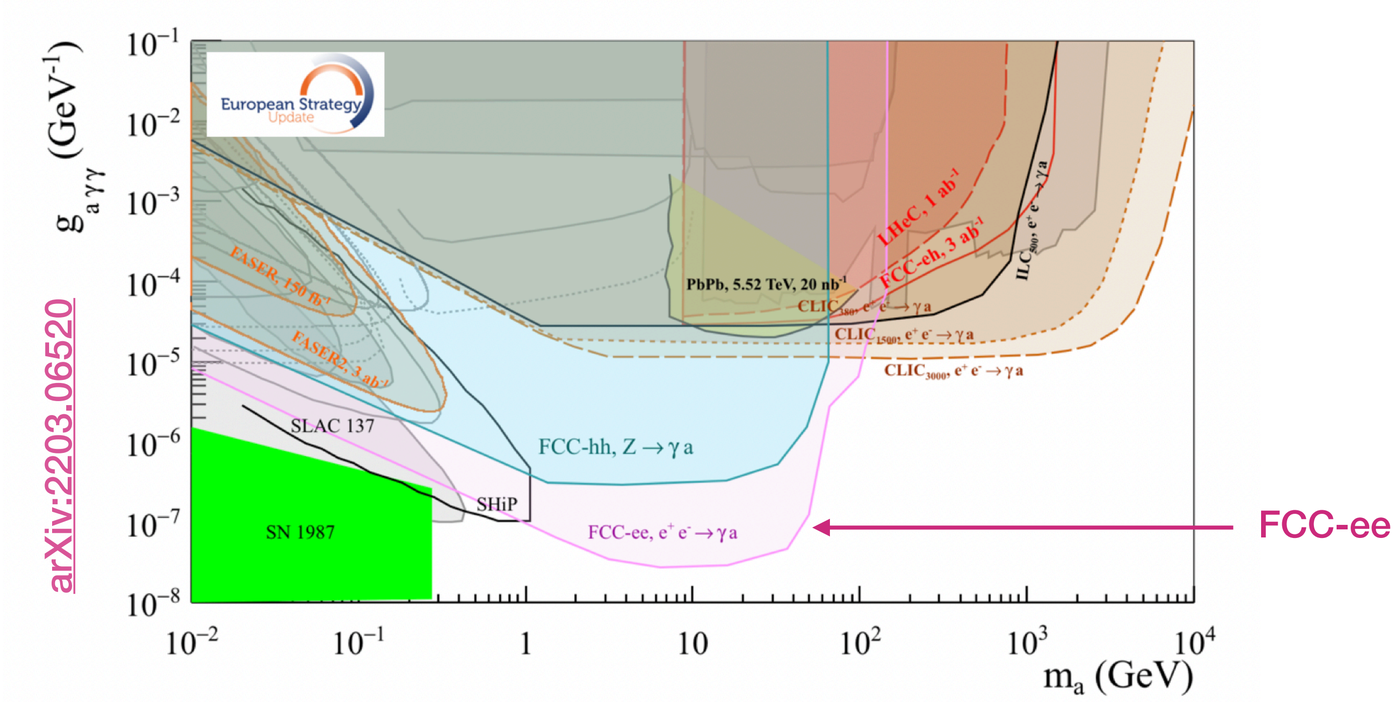
Electron track transverse impact parameter |d0|



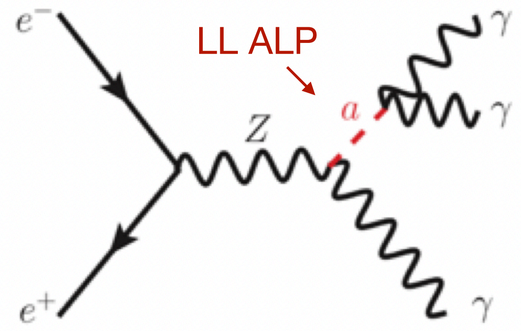


Axion-like particles at FCC-ee

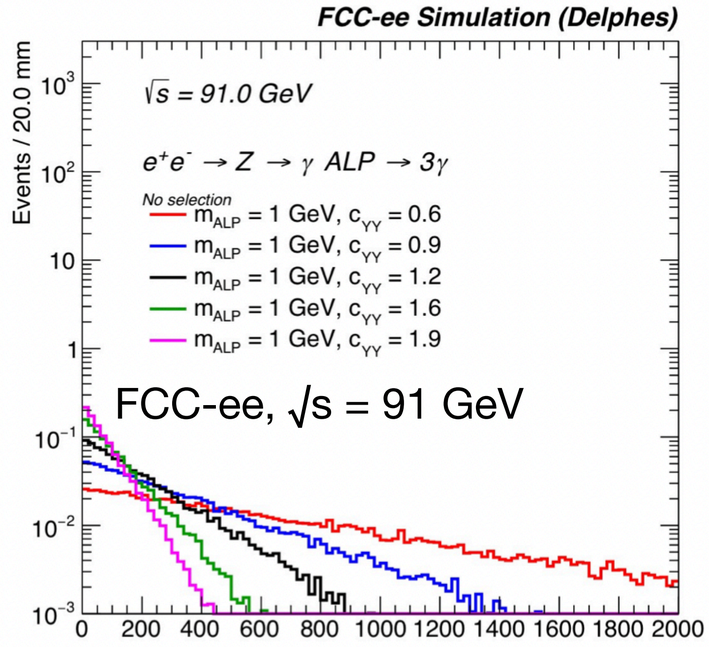
- For small couplings and light ALPs, the ALP decay length can be significant → **LLP signature**
- Orders of magnitude of parameter space accessible at the FCC-ee
  - Especially sensitive to final states with at least 1 photon
- Towards an FCC-ee sensitivity analysis:
  - Simulated samples for $e^+e^- \to Z \to \gamma a,\ a \to \gamma\gamma$
  - Studying key observables for background separation, e.g $M_{\gamma\gamma}$ and L_{xyz}



Production and decay at FCC-ee at Z-pole

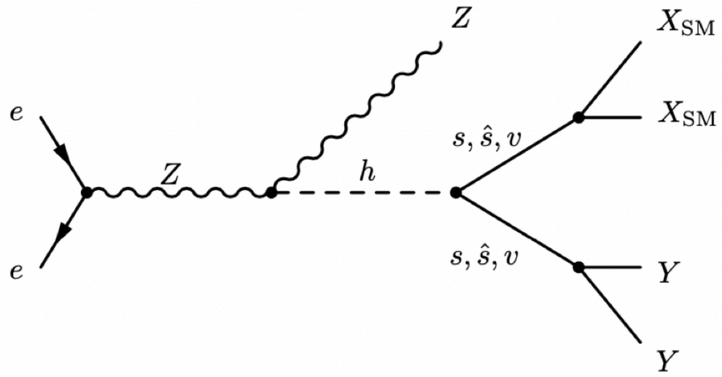


ALP simulation for FCC-ee at Z-pole

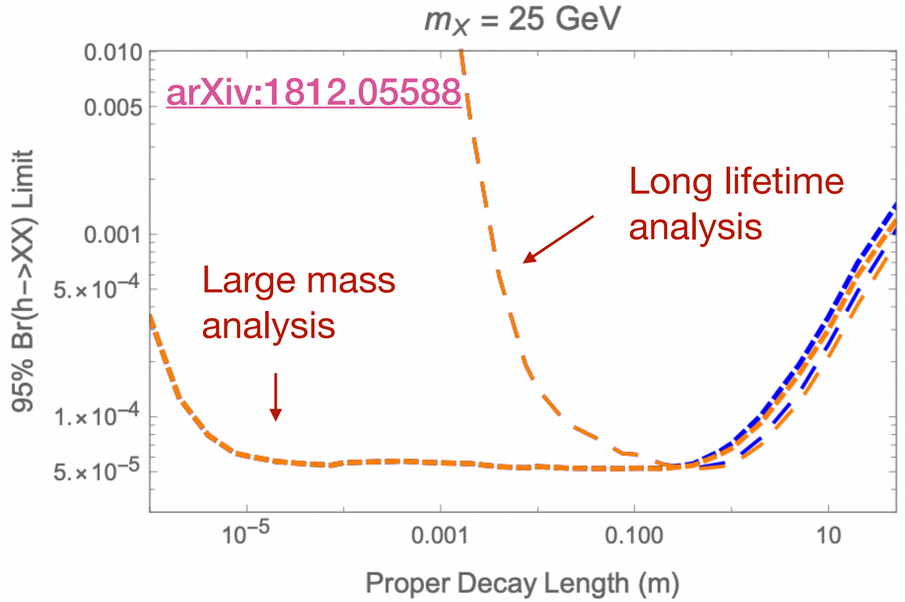


Exotic Higgs decays at FCC-ee

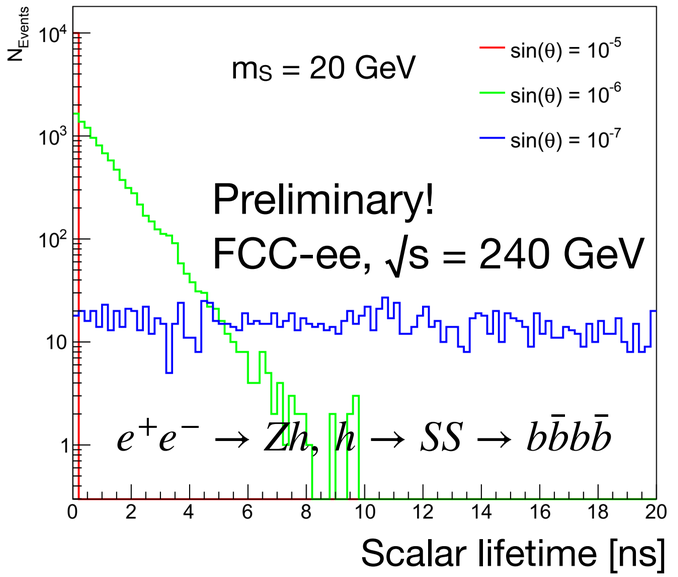
- The Higgs boson can have sizeable couplings to new particles
  - Several interesting models: SM extensions with scalars/fermions/vectors, MSSM, NMSSM, Hidden Valleys arXiv:1312.4992
- Example production of LLPs through exotic decays of the Higgs boson to scalars, pseudo-scalars, or vectors:



- Studies ongoing with a SM + S model (arXiv:1312.4992, arXiv:1412.0018)
  - Long-lived scalars for sufficiently small mixing between the Higgs and the scalar
  - Targeting the FCC-ee Zh stage and a DV signature from $e^+e^- \to Zh,\ h \to SS \to q\bar{q}q\bar{q}$



Higgs to dark scalar simulation for FCC-ee



Other LLP topics to explore for FCC

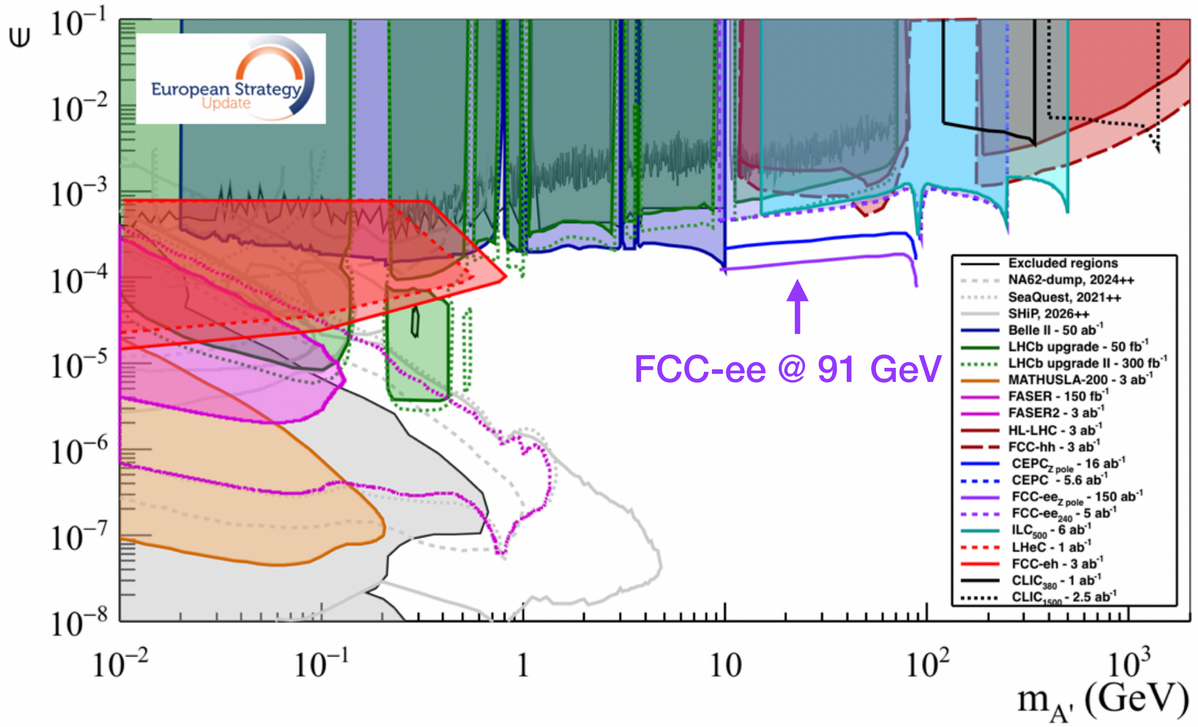
Other benchmark models

- RPV SUSY
- Vector portals - dark photons
- …

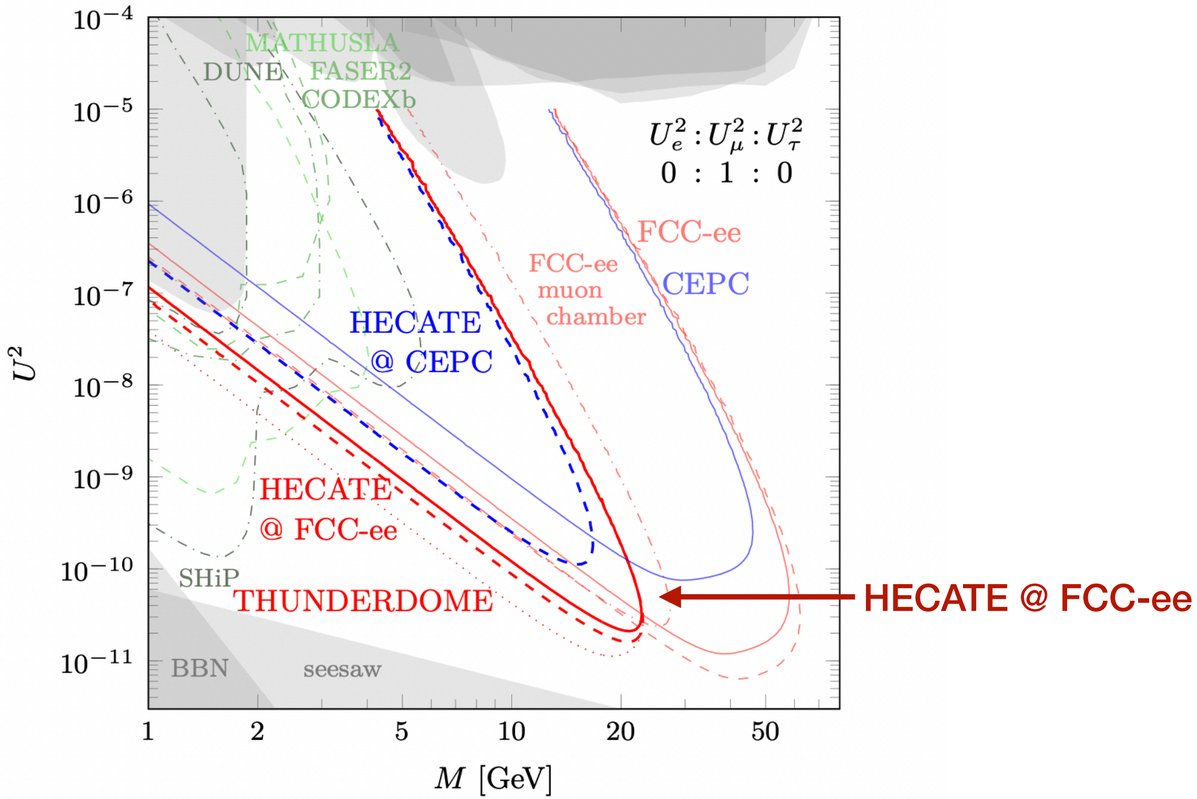
New detector concepts

- Following the plans for LLP experiments at the HL-LHC it is possible to also envision similar concepts at future colliders
- HECATE: LLP detector concept for the FCC-ee or CEPC

Reach for dark photons arXiv:1910.11775



HECATE reach for HNLs arXiv:2011.01005



Summary

- To discover new phenomena, it is important to carry out searches in the largest possible regions of phase space
  - One way to do this: long-lived particles!
- The FCC will have the ability to uniquely probe LLP areas of phase space
- 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
  - Time-of-flight performance, vertexing performance, etc…

- Lots of room for newcomers in the FCC-ee LLP group – please join the pursuit!
  - Mailing list: <LLP-FCCee-informal@cern.ch>

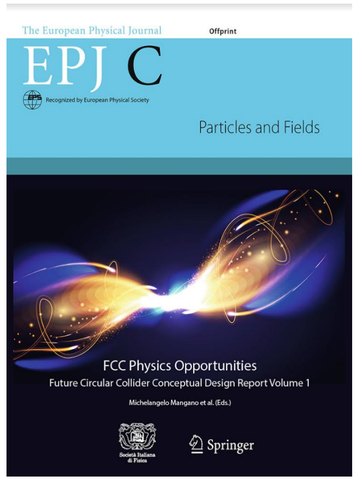
- Plenty of phase space to explore at the FCC! Let’s make sure we don’t miss new physics!

Backup slides

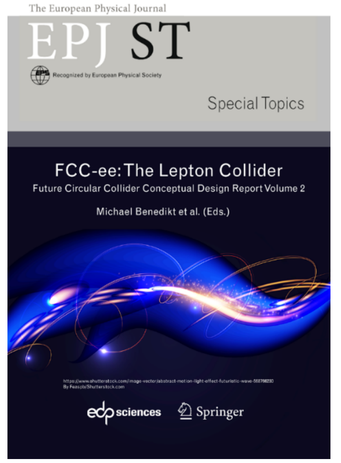
FCC: Find out more

- Future Circular Collider - European Strategy Update Documents
  - (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity
  - arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders
  - arXiv:1901.02648
- Polarization and Centre-of-mass Energy Calibration at FCC-ee
  - arXiv:1909.12245
- FCC-ee Snowmass2021 LoIs: https://indico.cern.ch/event/951830/

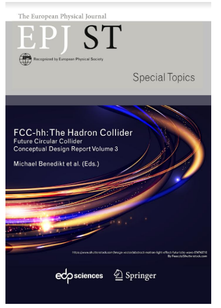
4 CDR volumes published in EPJ



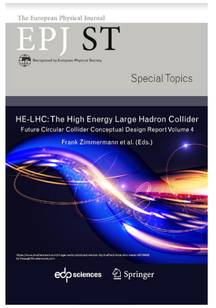
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider

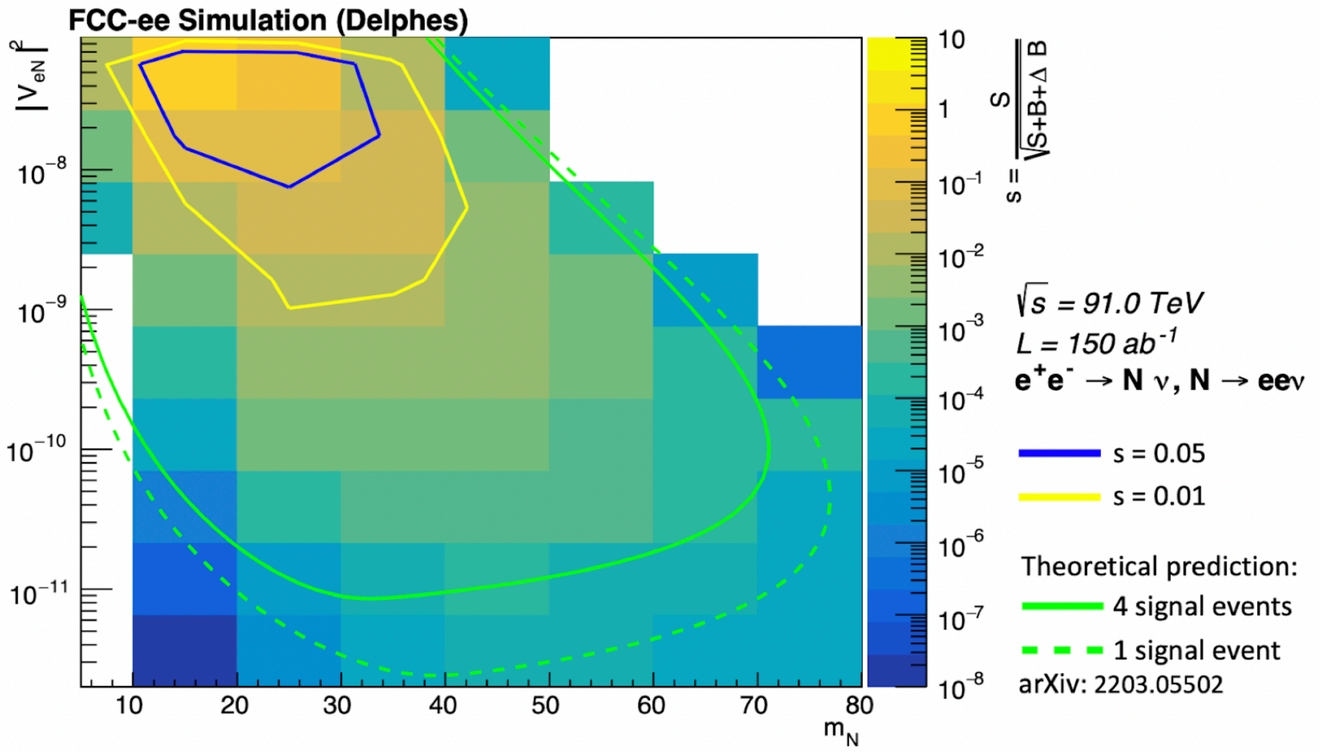


HE-LHC: The High Energy Large Hadron Collider

HNLs: Sensitivity

- Interpreting results in terms of sensitivity
- Experimental analysis
  - Contours show where s = 0.01 and s = 0.05
  - Sensitivity limited by background statistics
- Theory prediction from arXiv: 2203.05502
  - For 1 and 4 signal events
  - Includes all HNL decay modes, not only electrons
  - Assumes no background
  - Displaced vertex between 400 μm and 1.22 m
- **For future studies:** add more decay modes, particularly $N \rightarrow ejj$

$$s = \frac{S}{\sqrt{S + B + \Delta B}}$$



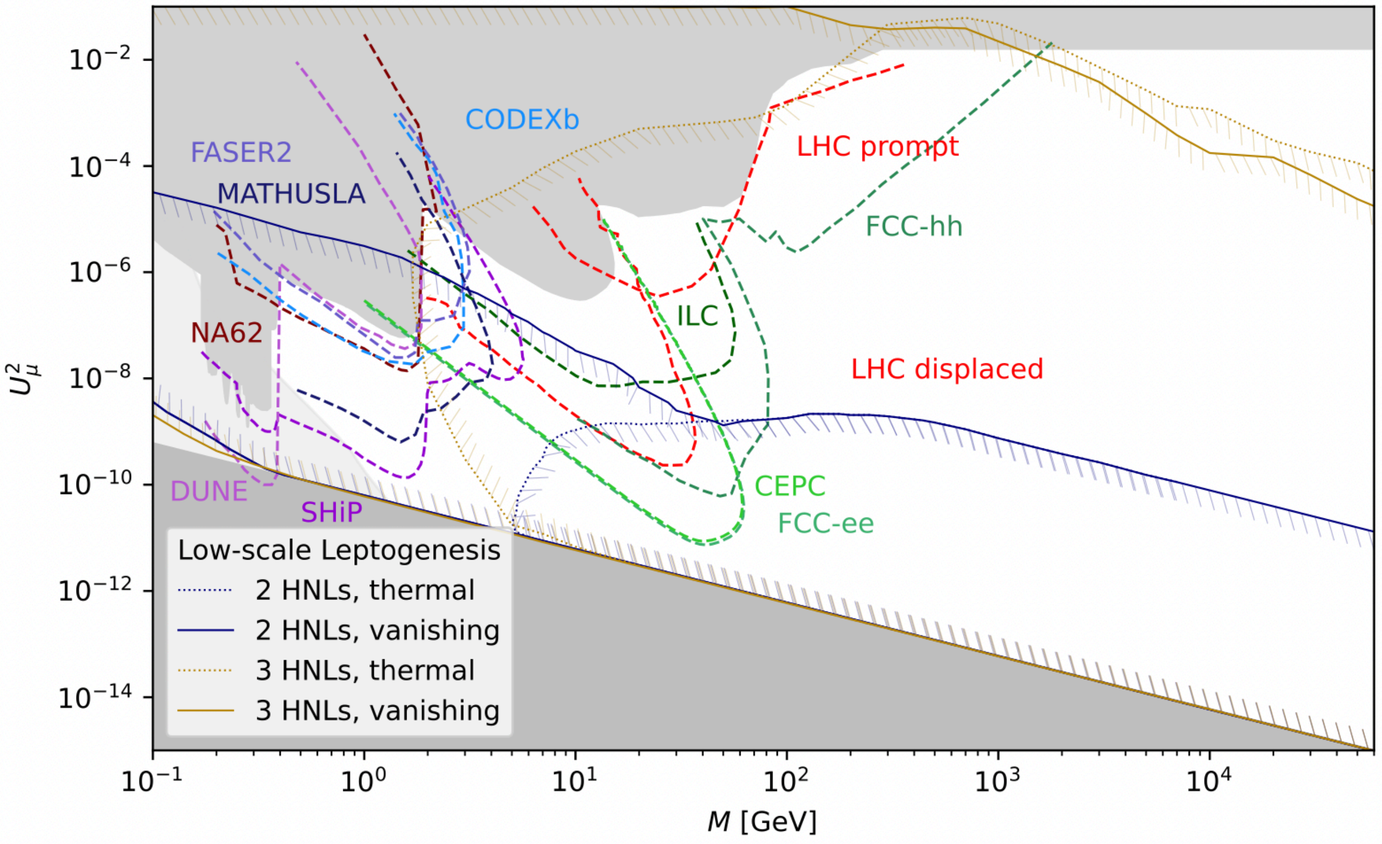
FCC-ee LLP group: past and ongoing work

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)
- Ulrika Magdalena Vande Voorde (Uppsala University, 2023)
- Dimitri Moulin (University of Geneva, 2023)
- … And more on the way!

HNLs: existing and future sensitivity

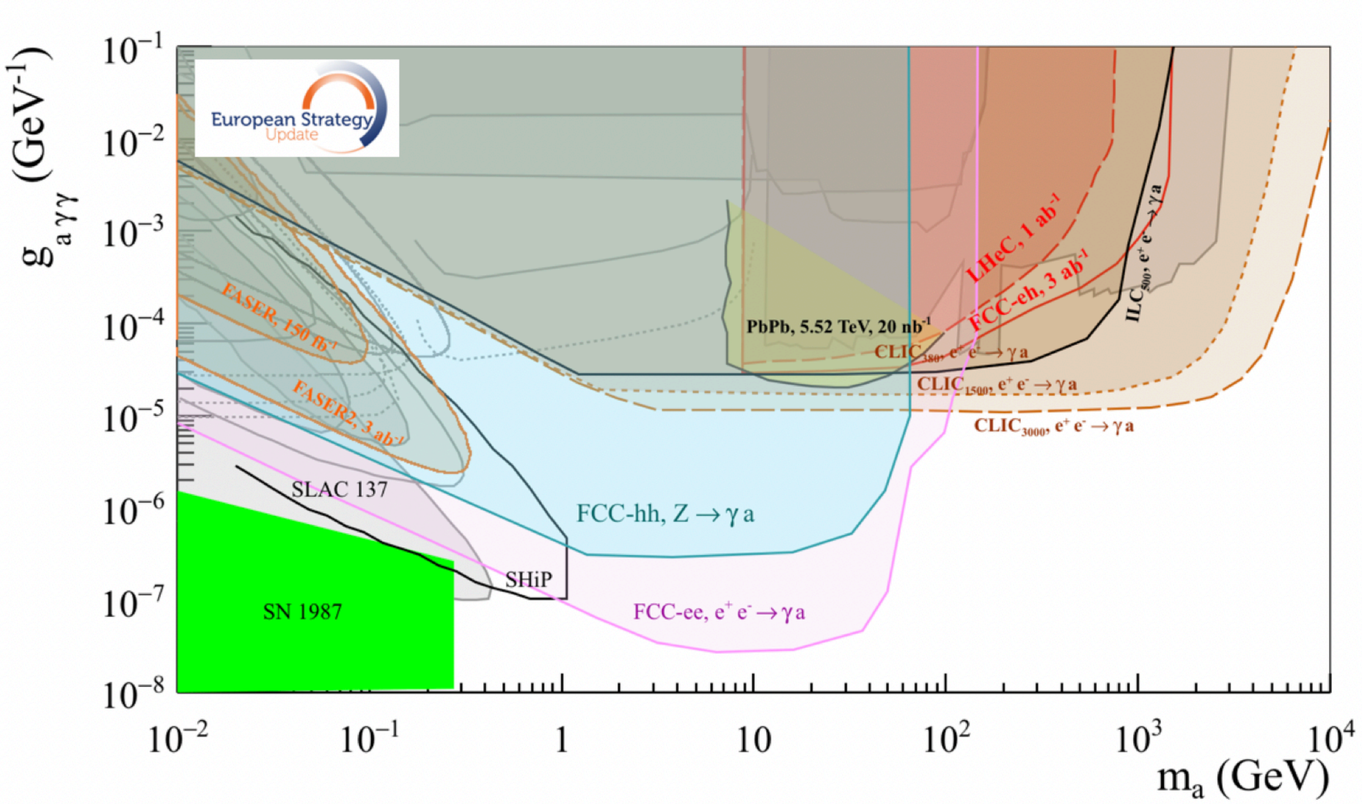
The Present and Future Status of Heavy Neutral Leptons [arXiv: 2203.08039]



- Sensitivity of displaced vertex searches at FCC-ee
- Parameter region inside the curves corresponds to more than four observed HNL decays from 5×10^{12} Z bosons
- Assuming:
  - No background events
  - 95% reconstructed HNL decays (i.e., all decays except the invisible decay) inside the main detectors based on the IDEA or CLD design
  - Displacement over 400 μm
  - Fiducial volume: cylinder
    l = 8.6 m and radius r = 5 m (CLD)
    l = 11 m and r = 4.5 m (IDEA)
- Curves for the CLD and IDEA detectors are visually indistinguishable

ALPs: existing and future sensitivity

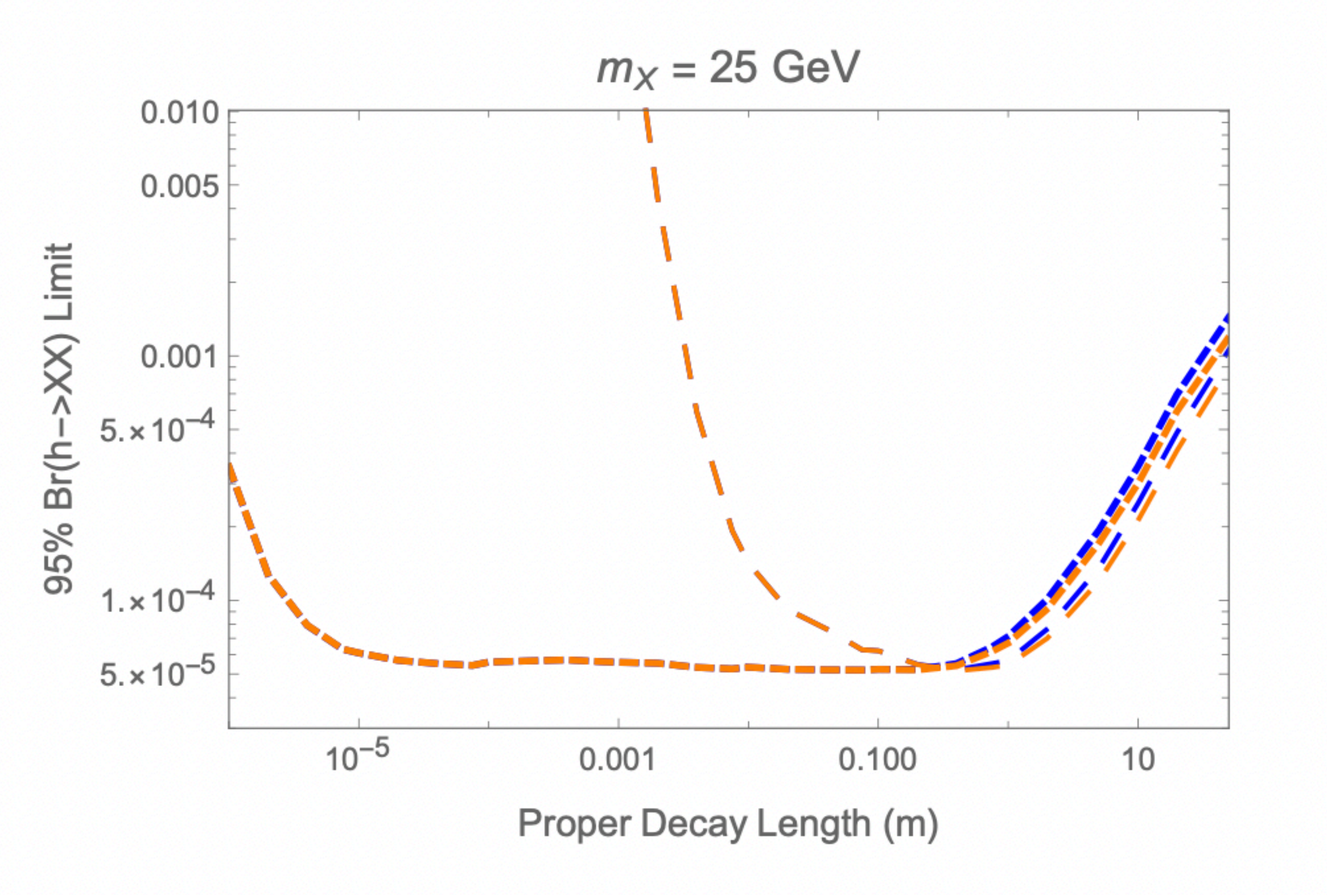
The Future Circular Collider: a Summary for the US 2021 Snowmass Process [arXiv: 2203.06520]



- Parameter region inside the curves corresponds to four or more signal events
- Assumptions:
  - 100% BR to studied final state
  - Fiducial region: Decays before the calorimeters (radius of 1.5 m)
- Estimate corresponds to the combined results for integrated luminosities of 145, 20, and 5 ab^{-1} at $\sqrt{s}$ = 91, 161, and 250 GeV, respectively

Exotic Higgs decays: FCC-ee sensitivity

Long Live the Higgs Factory: Higgs Decays to Long-Lived Particles at Future Lepton Colliders [arXiv: 1812.05588]



- Projected 95% h → XX branching ratio limits as a function of proper decay length for a variety of X masses.
- Blue lines are for CEPC and orange lines are for FCC-ee, and where only one is visible they overlap.
- The larger dashes are the ‘long lifetime’ analysis and the smaller dashes are the ‘large mass’ analysis
- Realistic tracker-based search strategy involving the reconstruction of displaced secondary vertices and the imposition of selection cuts appropriate for eliminating the largest irreducible backgrounds.