UNIVERSITY OF CAMBRIDGE

FUTURE CIRCULAR COLLIDER

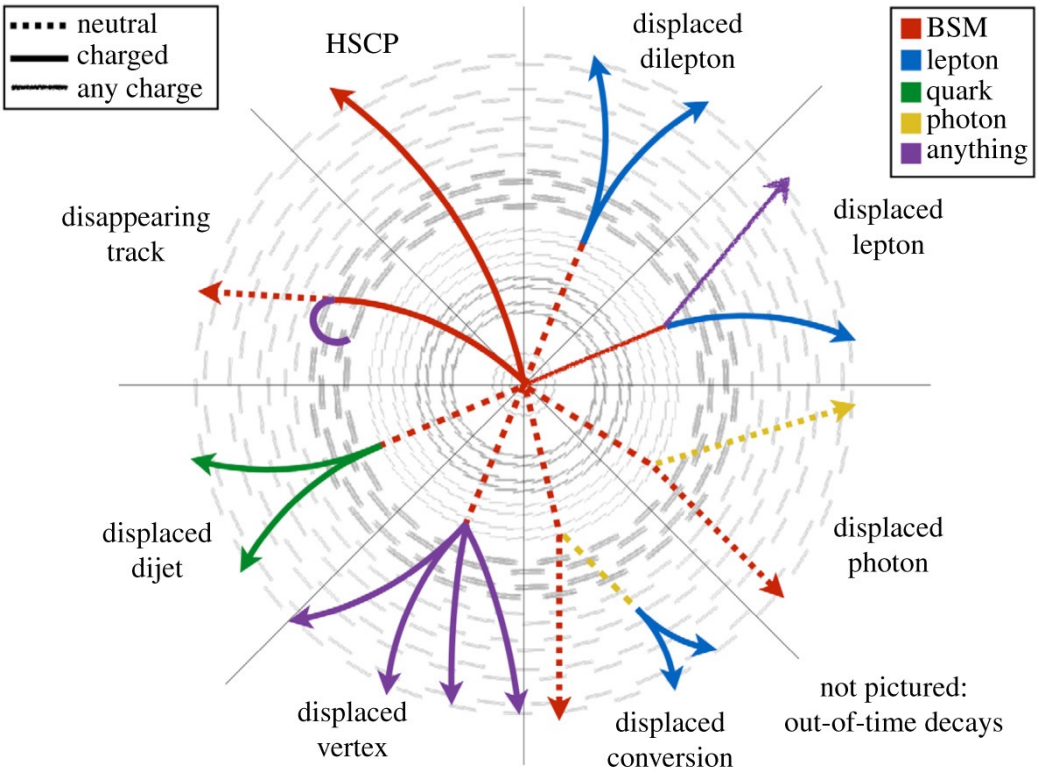
LLP searches at FCC-ee

1st November 2022

Sarah Williams (University of Cambridge), on behalf of the FCC-ee LLP group

Introduction

Thanks to Giulia Ripellino who's slides from FIPs-2022 provided great input from this talk!



LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- Dark photons
- ALPs
- Dark sector models

The range of unconventional signatures and rich phenomenology means that understanding the impact of detector design/performance on the sensitivity of future experiments is key!

Collider physics beyond the (High-Luminosity) LHC

The 2020 Update to the European Strategy for Particle Physics, and the Energy Frontier Discussions in the 2021 Snowmass process, sent coherent messages about future colliders beyond the LHC.

2020 European Strategy Update

"An electron-positron Higgs factory is the highest priority next collider."

(Taken from the European Strategy Update brochure)

Snowmass 2021

"The intermediate future is an e^+e^- Higgs factory, either based on a linear (ILC, C^3) or circular collider (FCC-ee, CepC)"

(Taken from Energy Frontier Plenary by Alessandro Tricoli)

As well as indirect sensitivity to a broad range of BSM phenomena through ultra-precise measurements of the EWK, top and Higgs sectors of the SM, future lepton colliders could have unique sensitivity to LLPs…

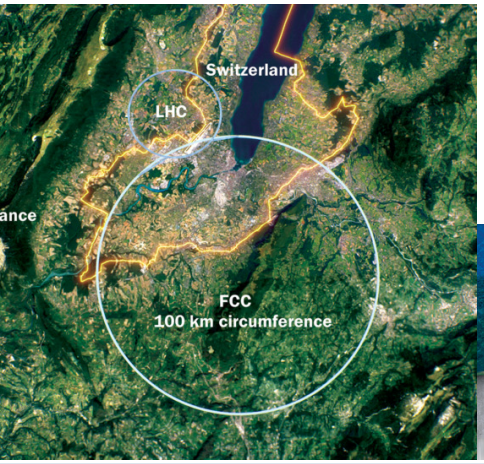
e^+e^- colliders: circular or linear?

Circular colliders

- Multi-pass at IP
- Modest accelerating gradients
- Limited by synchrotron radiation
- No beam polarization
- Potential to re-use tunnel for hadron collisions.

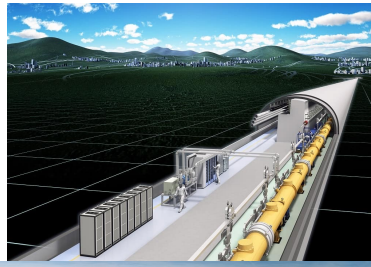
Linear colliders

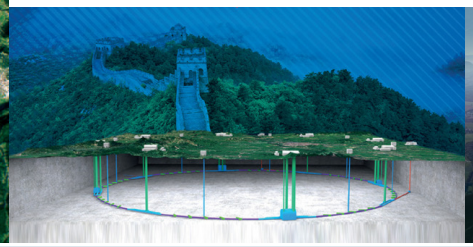
- Single pass at IP
- Maximum accelerating gradients
- No synchrotron radiation
- Can exploit beam polarization
- Can take staged approach to higher energies (energy~length)

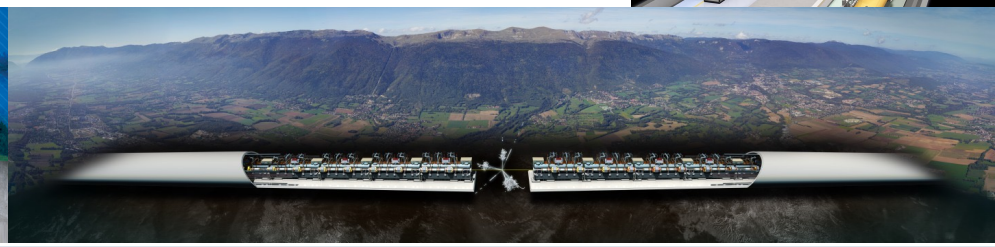


Left: FCC-ee (CERN)
Below: CEPC (China)

Right: ILC (Japan?)
Below: CLIC (CERN)

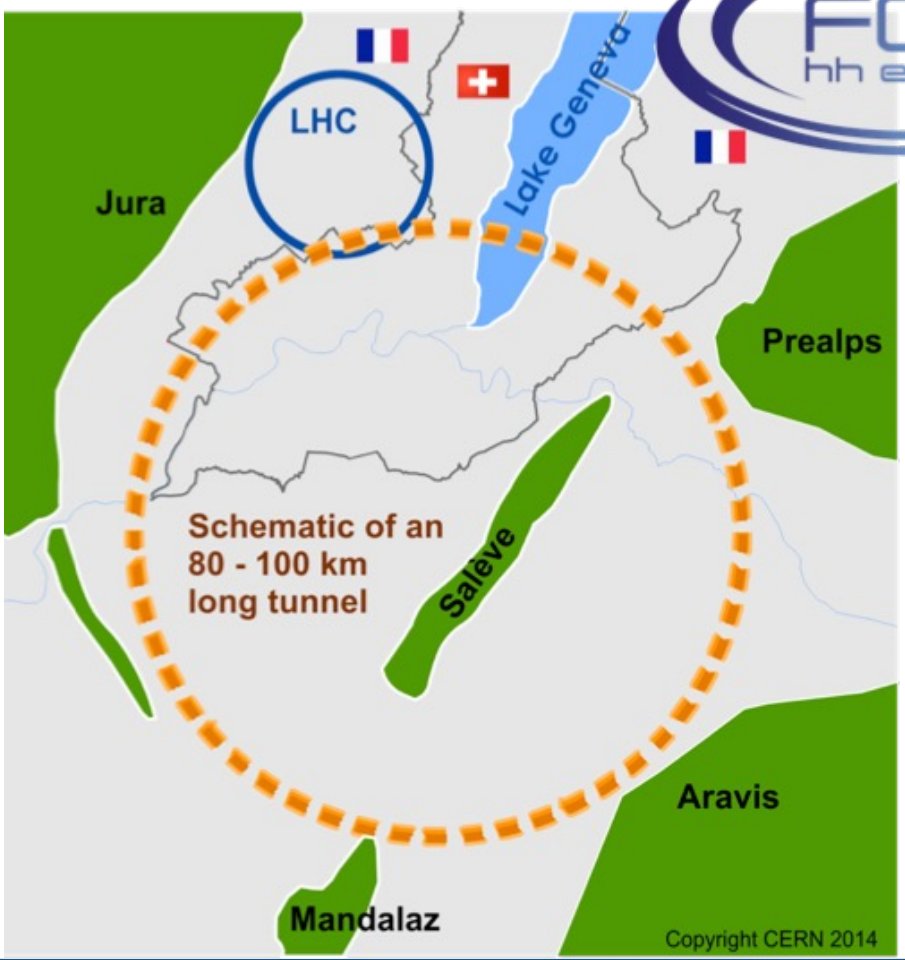






The FCC project

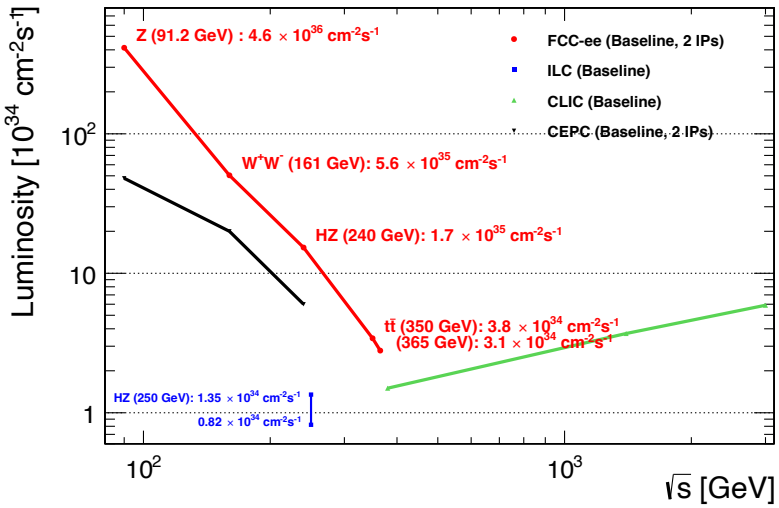
The "FCC" feasibility study was launched in 2021, aiming to provide key input by 2025 ahead of the next European Strategy Update



~90-100km tunnel at CERN to be used first for e^+e^- and later for 100 TeV pp collisions (a-la LEP/LHC)

- FCC-ee: dedicated runs to study Z, WW, (Z)H and $t\bar{t}$ to unpresented precision
- FCC-hh: push energy frontier an order of magnitude higher, enabling unrivaled direct BSM sensitivity, access to HH coupling, plus options for dedicated ion and e-p running.

FCC-ee



The high luminosities and clean experimental environment (no underlying event) make FCC-ee a natural laboratory to study LLPs through:

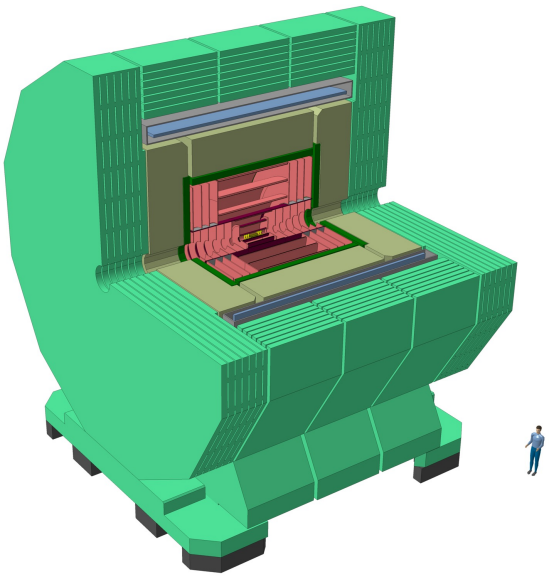
- Uncoventional signatures (including displaced vertices).
- Exotic Higgs decays.

Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated luminosity (ab^{-1})	Event statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt(1)	1	340–350	0.2	$t\bar{t}$ threshold scan
FCC-ee-tt(2)	4	365	1.5	10^6 $t\bar{t}$ events

Taken from FCC: physics opportunities (CDR volume 1)

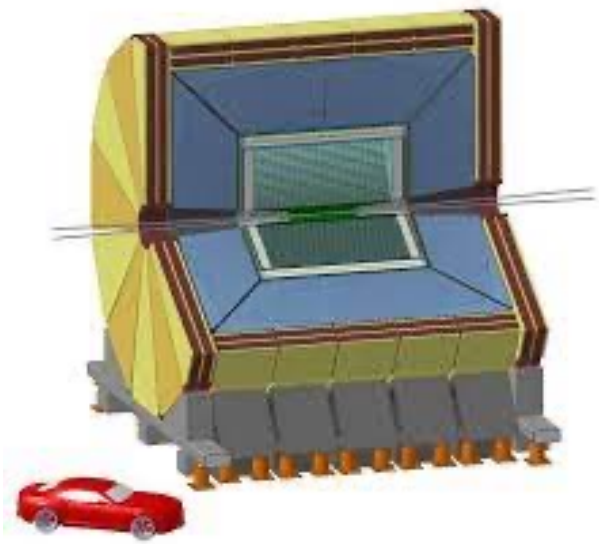
Detector concepts for FCC-ee

CLD ("CLIC-like Detector")



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

IDEA ("Innovative Detector for Electron-positron Accelerator")



Silicon vertex detector
Short-drift, ultra-light wire chamber tracker.
Dual-readout calorimeter, with solenoid inside

We have exciting prospects to optimize detector design with LLP searches in mind!

FCC-ee LLP group: past and present

Disclaimer: whilst I am a 'present' member of the group, all credit for the excellent past work done by the team should go to others

- Following a Snowmass LOI, an LLP white paper was recently published in Front. Phys. 10:967881 (2022) which included case studies with the official FCC analysis tools.
- These initial studies motivate further optimization of experimental conditions and analysis techniques for LLP signatures.

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]

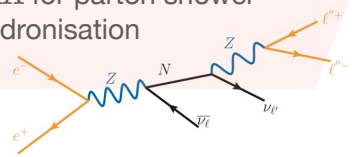
[1]Department of Physics and Astronomy, Brigham Young University, Provo, UT, United States, [2]Experimental Physics Department, CERN, Geneva, Switzerland, [3]Department of Physics, Durham University, Durham, United Kingdom, [4]INFN, Section of Padova, Padova, Italy, [5]Institute of Nuclear Physics, Polish 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

Current workflow

Typical workflow

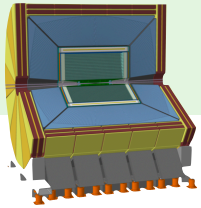
Sample generation of models, e.g.

- 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

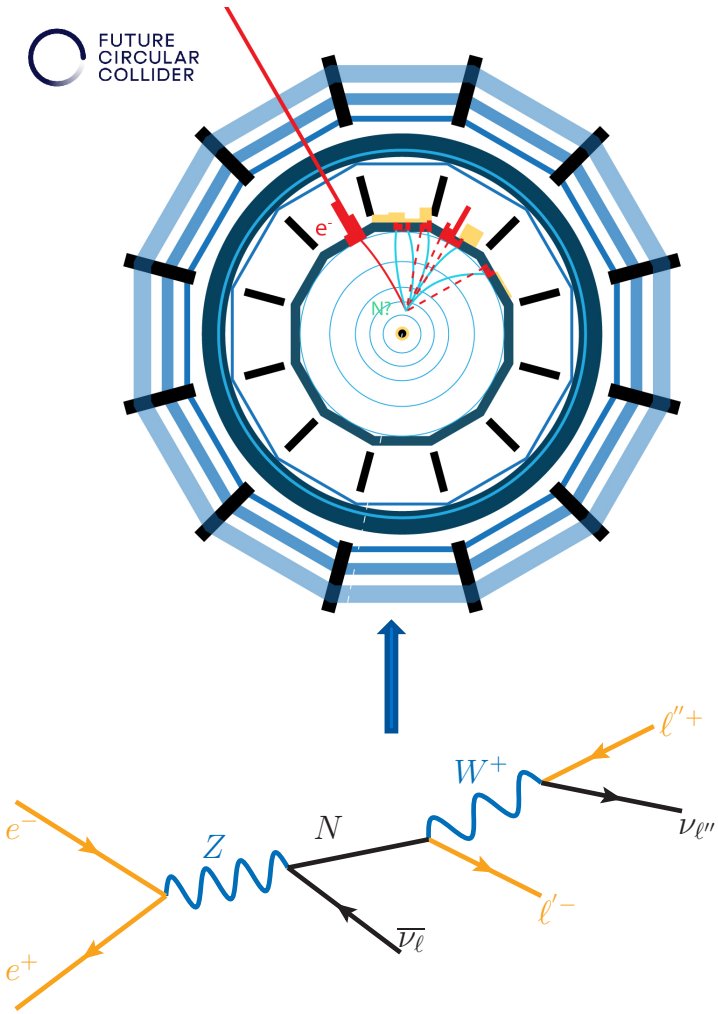
- Work so far performed through past/ongoing masters thesis projects (see backup for details).
- I will now summarise some of the existing case studies.
- Next steps involve expanding these studies to use improved MC statistics for backgrounds, and consider new signatures

Heavy Neutral Leptons (HNL) at FCC-ee

- Right-handed (sterile) neutrinos could provide an explanation for neutrino masses, and (possibly) a route to understanding baryon asymmetry in the universe and dark matter.
- For small mixing angle Θ with their LH counterparts, HNLs are long-lived and so provide an obvious benchmark for LLP searches with displaced vertices at future colliders.

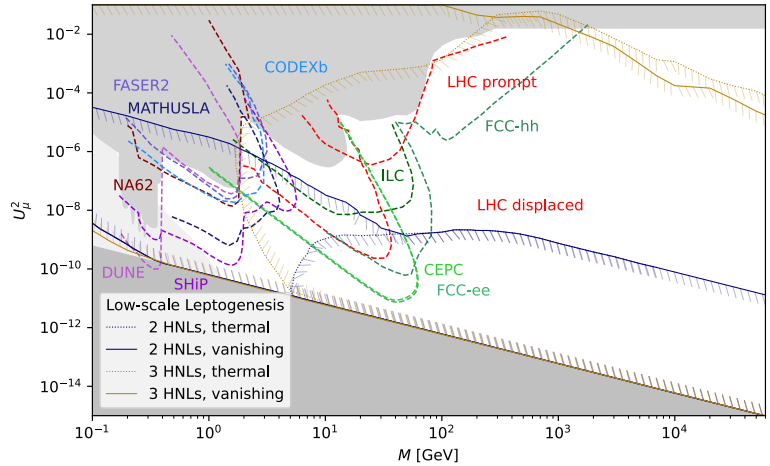
$$L \sim 0.025\ \mathrm{m}\ \left(\frac{10^{-6}}{V_l}\right)\left(\frac{100\ \mathrm{GeV}}{m_N}\right)^2$$

(i.e. LLPs when couplings and masses are small)

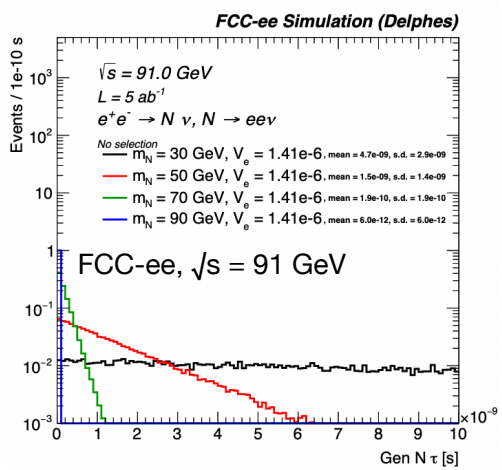


HNL searches at FCC-ee Tera-Z run

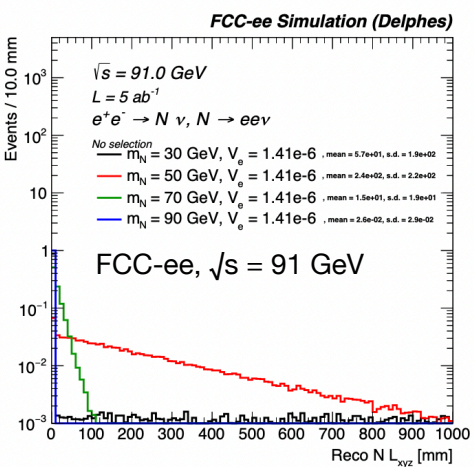
- Searches for displaced HNL decays are most efficient at the Z-pole run (larger luminosity and cross-section from $Z \to N\nu$ decays). Benefit from:
  - Low SM backgrounds with displaced vertex.
  - Small beam pipe radius.
  - Clean experimental conditions.
- Initial study considered $N \to ee\nu$ decay only.



HNL lifetime



HNL reconstructed decay length



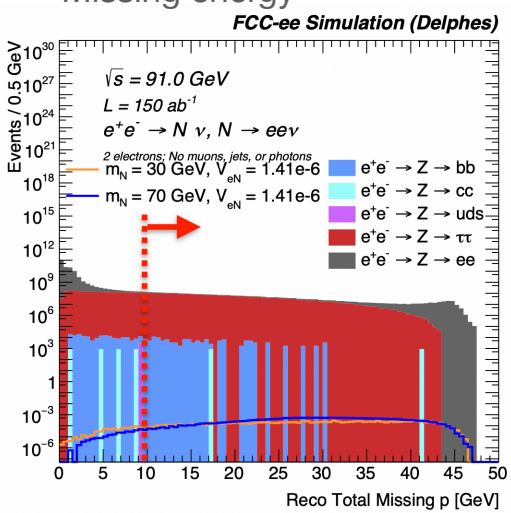
HNL sensitivity study

To further expand these studies- plan to increase background MC statistics, and consider additional variables/timing information etc.

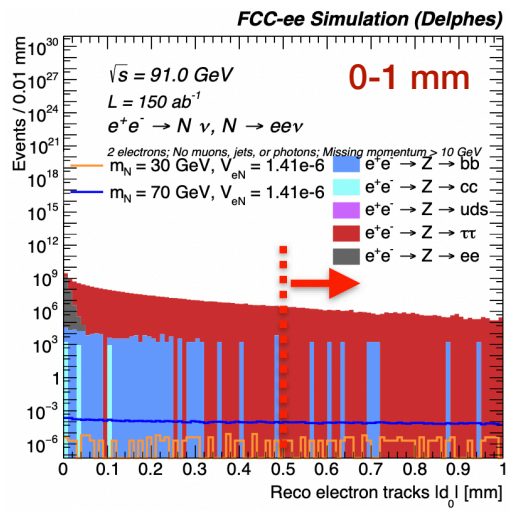
First study developed an event selection to reduce backgrounds:

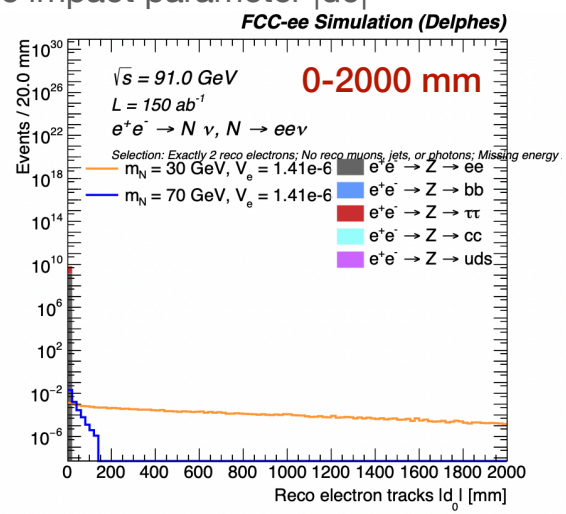
- Exactly two electrons + no additional photons, jets, muons (reduce light and HF quark background).
- $E_T^{miss} > 10$ GeV- reduce background from $Z \to ee$ where E_T^{miss} arises from finite detector resolution.
- Require electron $|d_0| > 0.5$ mm

Missing energy



Electron track transverse impact parameter |d0|

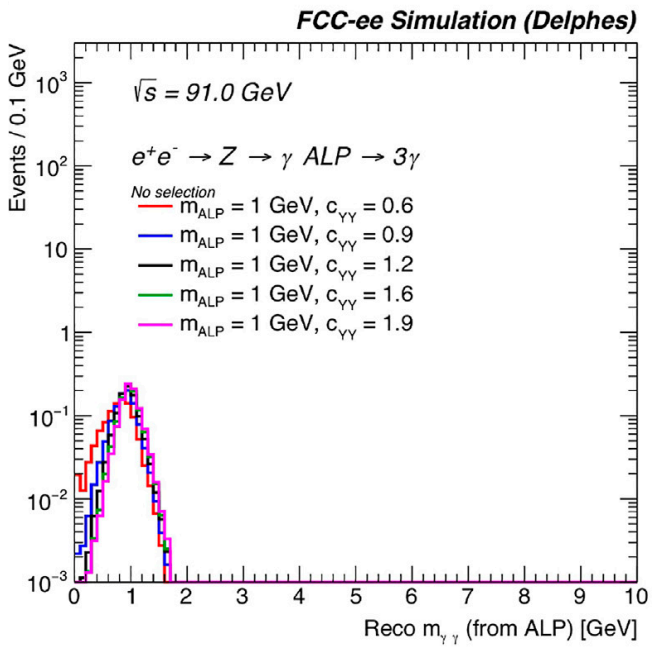


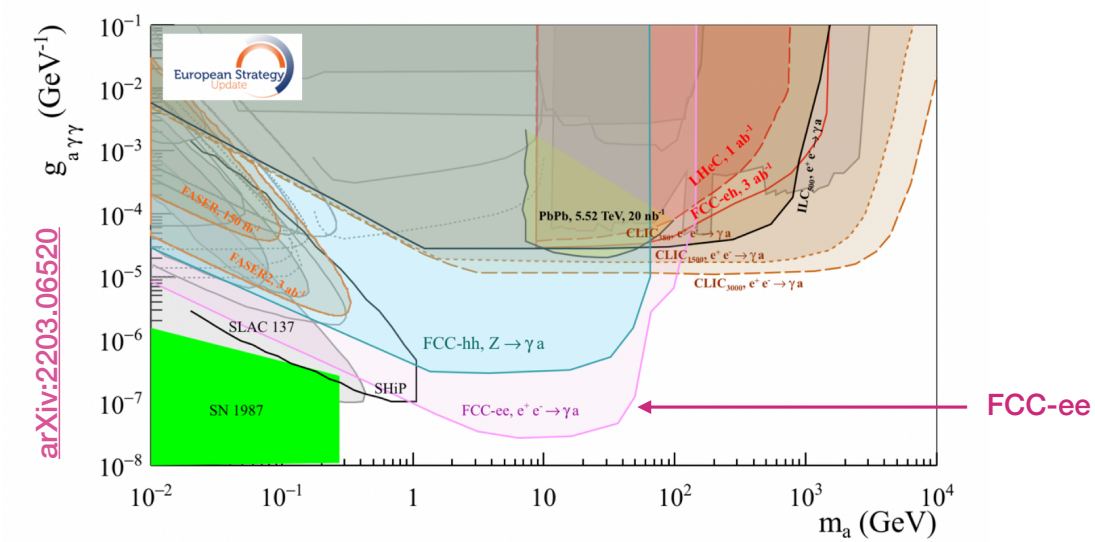


Axion-like particles at FCC-ee

Calorimeter and timing information will improve these studies in future

- For small couplings and light ALPs → LLP signature.
- Initial validation of signal samples and kinematic distributions presented- more to come in future.

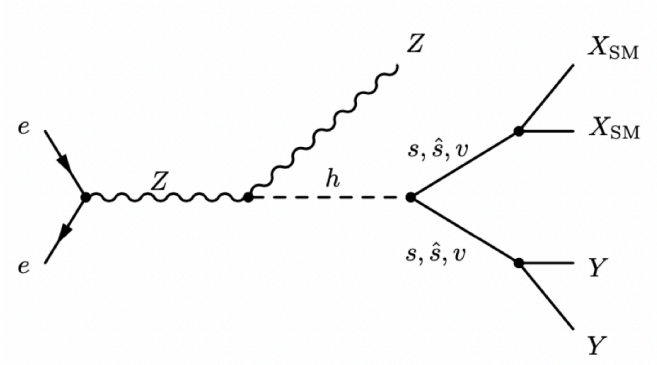


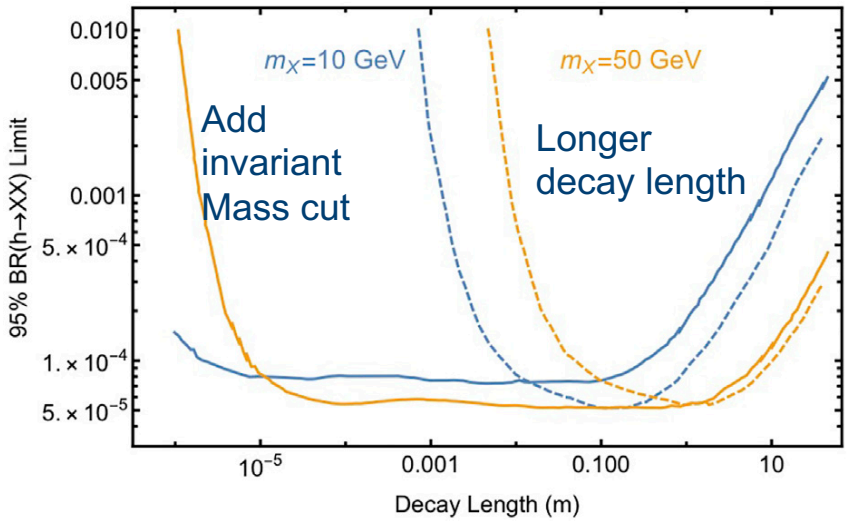


arXiv:2203.06520

Exotic Higgs decays- future work

Higgs decays to LLPs can give exciting portal to dark sectors with small but nonzero couplings to the Higgs.





Aiming to target FCC-ee Zh stage with $h \rightarrow SS \rightarrow q\bar{q}q\bar{q}$

More to come- watch this space ☺

Conclusion/outlook

- There are unique opportunities to probe LLPs at FCC-ee.
- FCC-ee-LLP group is an active community with exciting plans for the coming months (feeding into the FCC feasibility studies). Mailing list: LPP-FCCee-informal@cern.ch
  - Expand coverage of final states for HNL, and perform more detailed optimization/sensitivity projections.
  - Study detailed sensitivity to ALPs, exotic Higgs decays.
  - Consider use of timing information and impact of detector design.
- Thanks for listening- happy to take questions and suggestions!

FCC-ee masters thesis projects

- 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 along the way!