UNIVERSITY OF CAMBRIDGE

FUTURE CIRCULAR COLLIDER

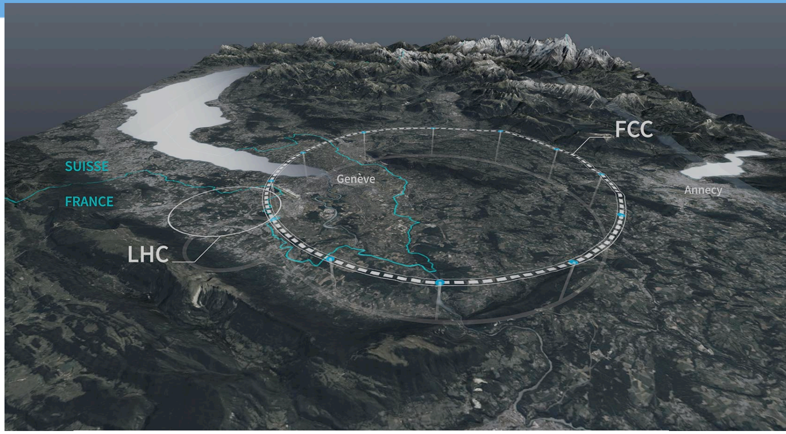
Long-lived particle production at FCC-ee

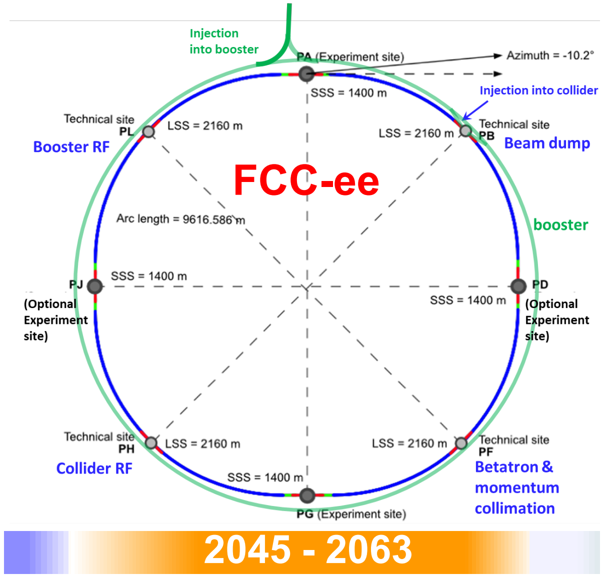
FCC UK meeting @QMUL 29/11/2023

Sarah Williams (University of Cambridge)

Introduction

- I am going to give a very brief overview of FCC ee LLP studies.
- My work:
    - BSM MC contact for FCC.
    - Focus so far on HNL studies through masters projects.
    - ECFA “expert team” on LLPs as part of the e+e- Higgs factory study.
- Key message: there’s lots to do, but we are a friendly group and theres lots of support to get involved.





Physics landscape at FCC-ee

Higgs
factory

m_H, σ, Γ_H
self-coupling
$H\to bb, cc, ss, gg$
$H\to inv$
$ee\to H$
$H\to bs$, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
“boosted” B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau\nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau\tau$
$B \to K^* \nu\nu$
$B_s \to \varphi \nu\nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

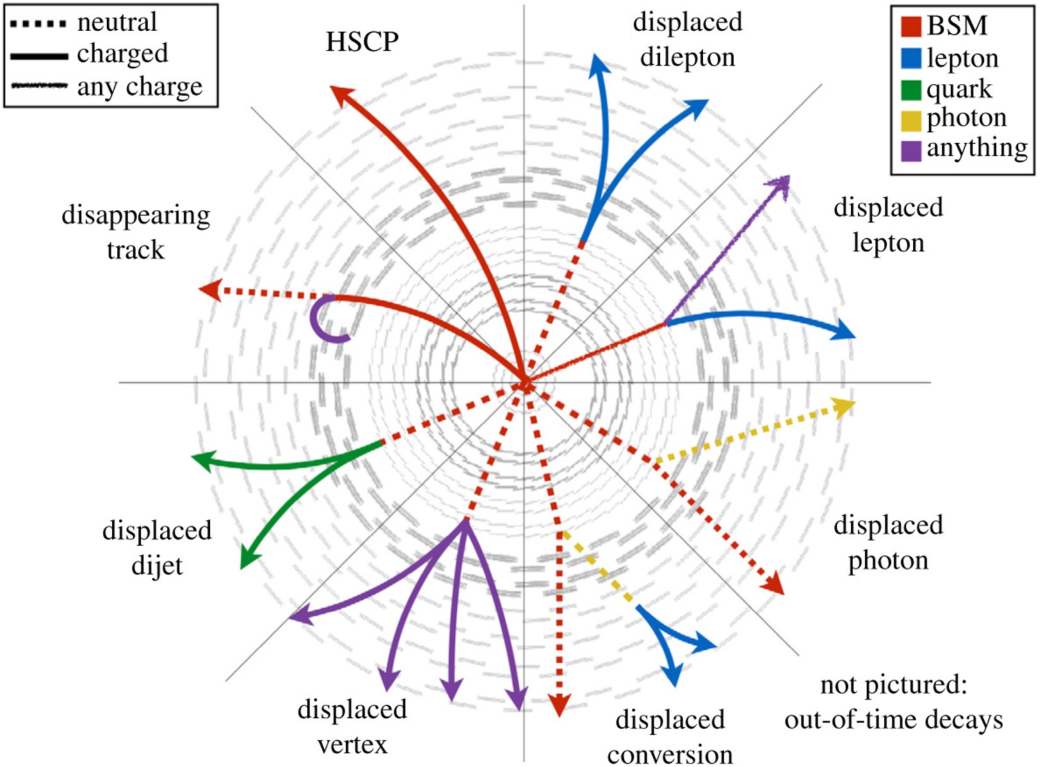
Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

- Broad landscape of physics opportunities which include direct and indirect sensitivity to new physics.
- Unique sensitivity to feebly interacting particles and LLPs means we are in an exciting position to design detectors with these scenarios in mind.

Long-lived signatures at colliders



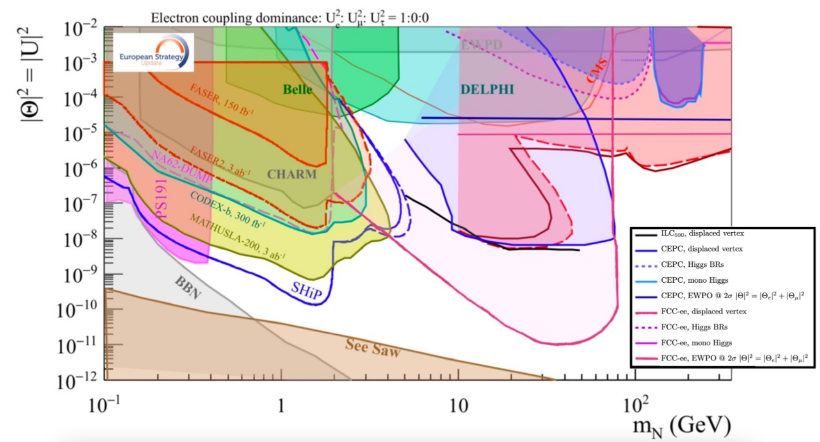
LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

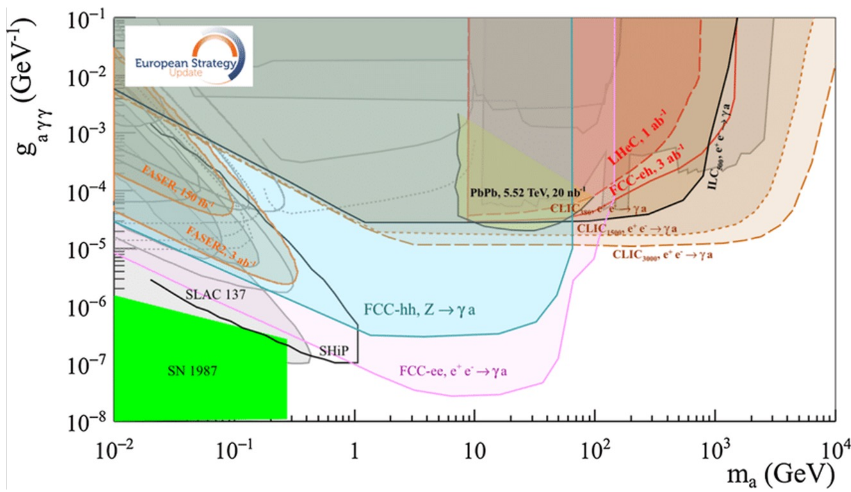
- Heavy Neutral Leptons (HNLs)
- RPV SUSY
- ALPs
- Dark sector models

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!

LLPs @ FCC-ee

- Targeting precision measurements of EWK/Higgs/top sector of SM.
- Unique sensitivity to LLPs coupling to Z or Higgs.
    - No trigger requirements.
    - Excellent vertex reconstruction and impact parameter resolution can target low LLP lifetimes (this can drive hardware choices).
    - **Projections often assume background-free searches** (should check these assumptions).

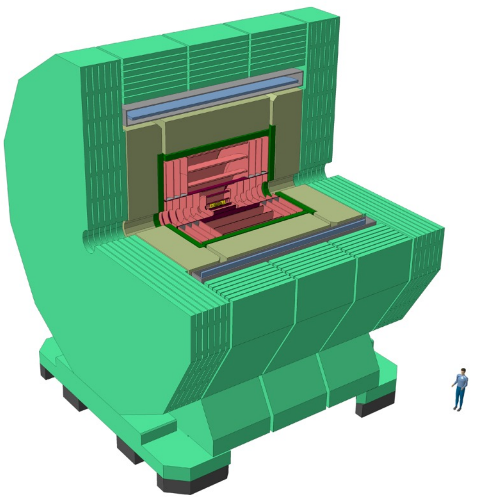




Detector concepts for FCC-ee

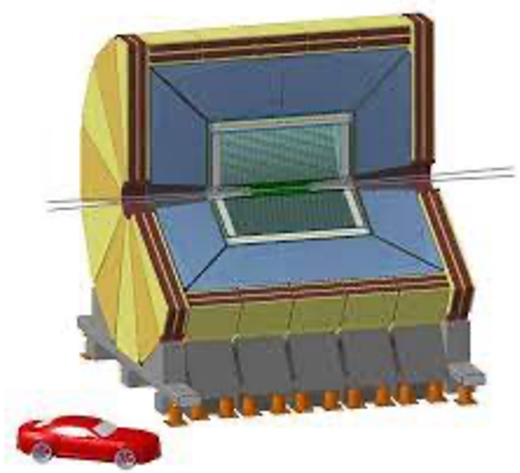
See HECATE article for discussion on gains in sensitivity with additional instrumentation on the cavern walls

CLD ("CLIC-like Detector")



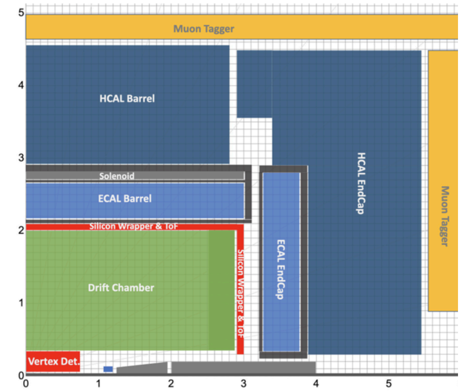
Full silicon vertex-detector+ tracker
3D high-granularity calorimeter
Solenoid outside calorimeter

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



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

Noble-liquid ECAL (newest proposal)



HG noble liquid ECAL. LAr or LAr+lead absorber

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

FCC-ee LLP group: past and present

- 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.
- Currently a very active community, with meetings on Thursdays 13:00 CERN time.

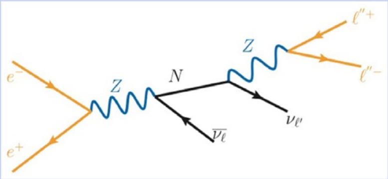
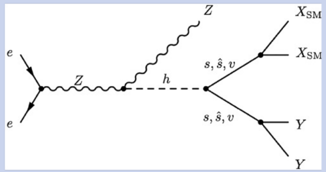
Searches for long-lived particles at the future FCC-ee

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

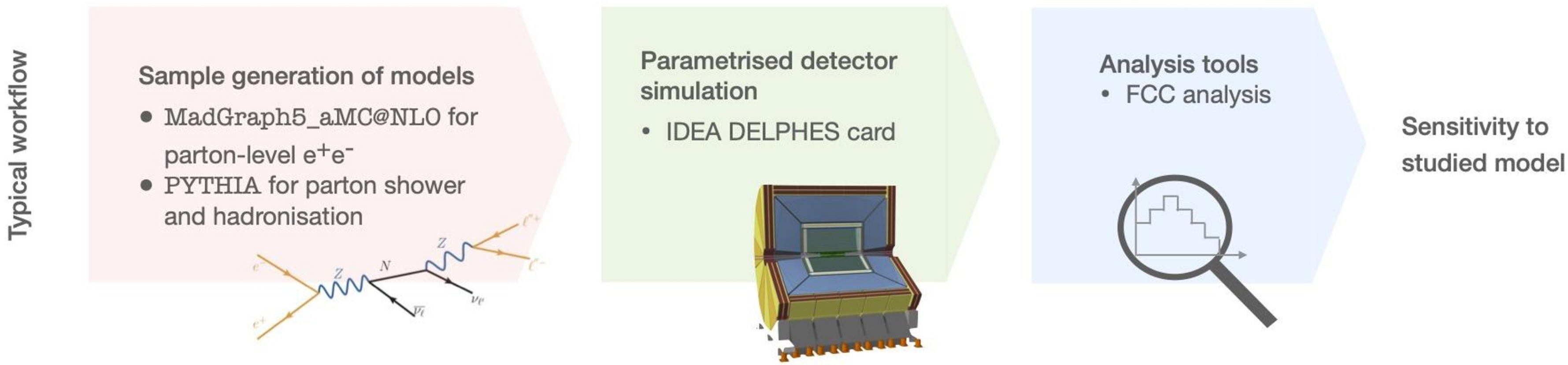
Will summarise (some) recent activities (further details in backup and in LLP talk at the London FCC week) and look ahead…

Summary of snowmass studies + ongoing activities in LLP group (as of mid-term report)

Physics scenario	FCC-ee signature	Studies for snowmass	Ongoing work
Heavy neutral leptons (HNLs)	Displaced vertices 	Generator validation and detector-level selection studies for ee$\nu\nu$. First look at Dirac vs Majorana	• Update ee$\nu\nu$ studies for winter23 samples. • First look at $\mu\mu\nu\nu$ channel (prompt +LLP) • First look at $\mu\nu$jj (prompt+LLP) • First look at eνjj including Dirac vs majorana (prompt)
Axion-like particles (ALPs)	Displaced photon/lepton pair	Generator-level validation for a→γγ at Z-pole run.	*No studies ongoing currently!*
Exotic Higgs decays	e.g. 	Theoretical discussion and motivation for studies at ZH-pole	• Reco-level studies (inc. vertexing) for h→ss→bbbb

Current workflow

Most studies so far use Pythia+Delphes for backgrounds- would like to move to FullSim and be able to consider alternative generators.

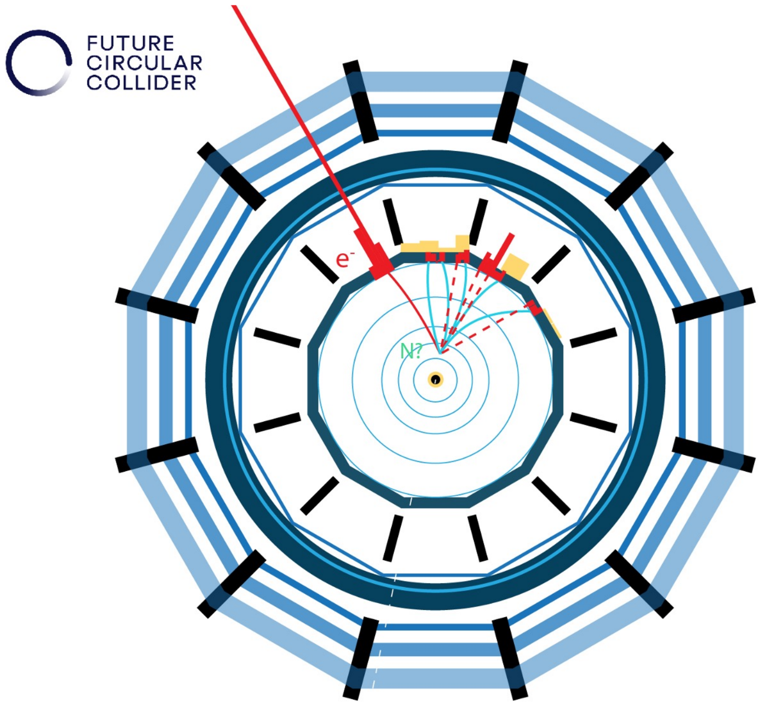


- Use FCCAnalysis software to analyse centrally generated EDM4HEP files, though some signal files produced privately.
- Dedicated LLP tutorial prepared by Juliette Alimena enables full workflow.
- Current limitations include scalability of code and limited MC statistics (more on that later).

Heavy Neutral Leptons (HNL) at FCC-ee

Snowmass review: arXiv:2203.08039 Front. Phys. 10:967881 (2022)

- Right- handed (sterile) neutrinos could provide an explanation for neutrino masses, the baryon asymmetry in the universe and dark matter.
- For small mixing angles with their LH counterparts- long-lived.
- Obvious benchmark for LLP searches with displaced vertices.



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

c_{det}= 1 (majorana) or ½ (dirac)

arXiv:2210.17110

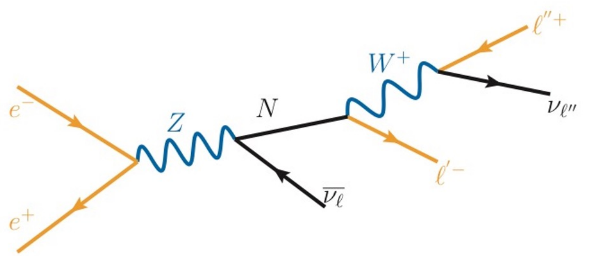
i.e. LLPs when couplings and masses are small!

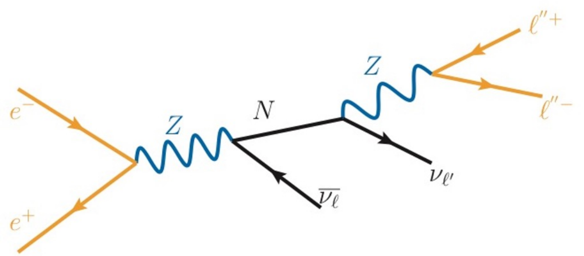
HNL searches at FCC-ee Tera-Z run

[Front. Phys. 10:967881 (2022)]

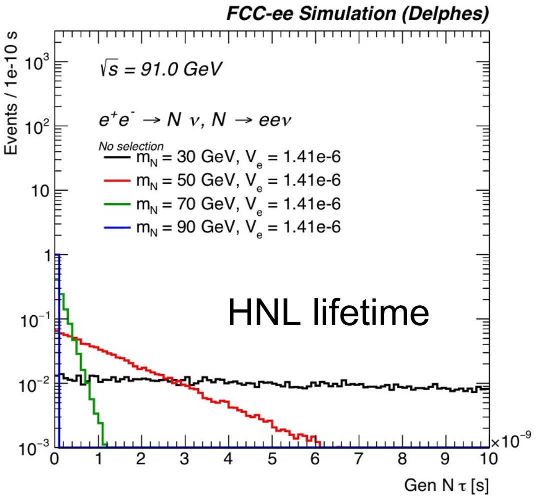
Searches for displaced HNL decays are most efficient at the Z-pole run (larger luminosity and cross-section from $Z \to N\nu$ decays). Benefit from:

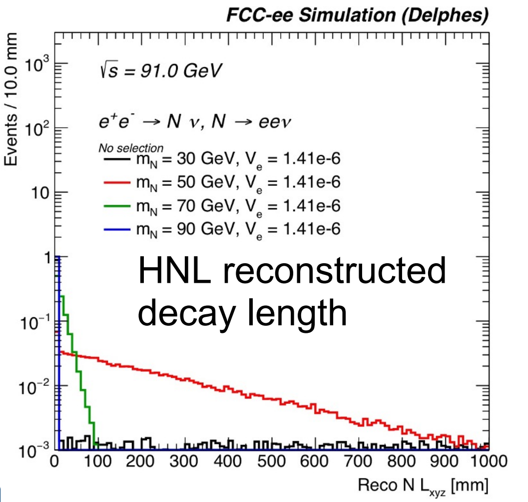
- Low SM backgrounds with displaced vertex.
- Small beam pipe radius.
- Clean experimental conditions.





For $N \to Wl$ decays, depending on the W decay final states include $ll'\nu\nu$ or $l\nu jj$





HNL sensitivity study: N→eeν

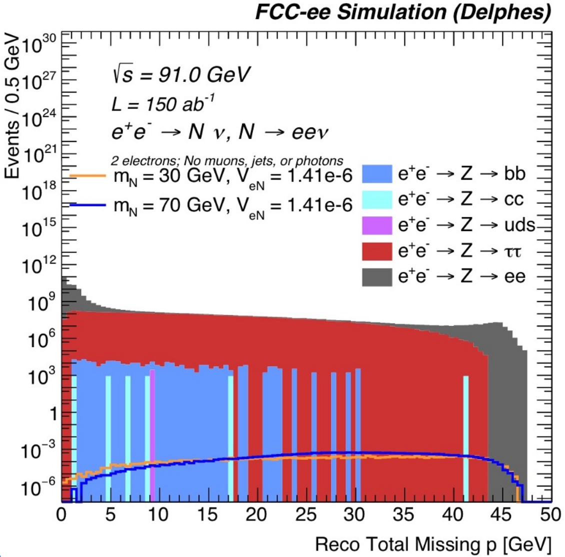
Note: ongoing investigation show these distributions look different with the 2023 samples (in backup)

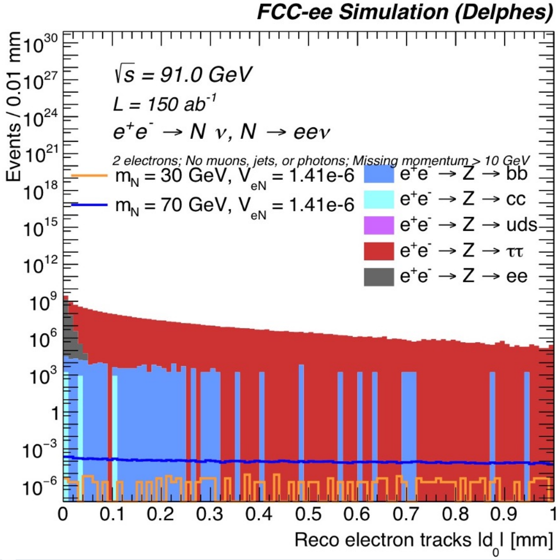
Front. Phys. 10:967881 (2022)

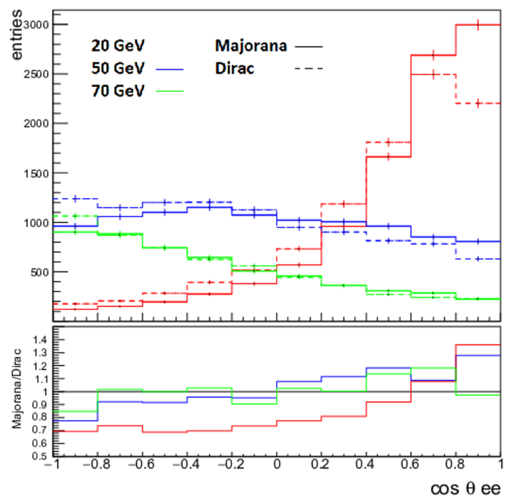
Initial study developed an event selection to reduce the backgrounds:

- 2 electrons with a veto on additional photons, jets, muons.
- p^{Miss}> 10 GeV to reduce the Z→ee background with instrumental missing momentum.
- Electron $|d_0|$>0.5 mm

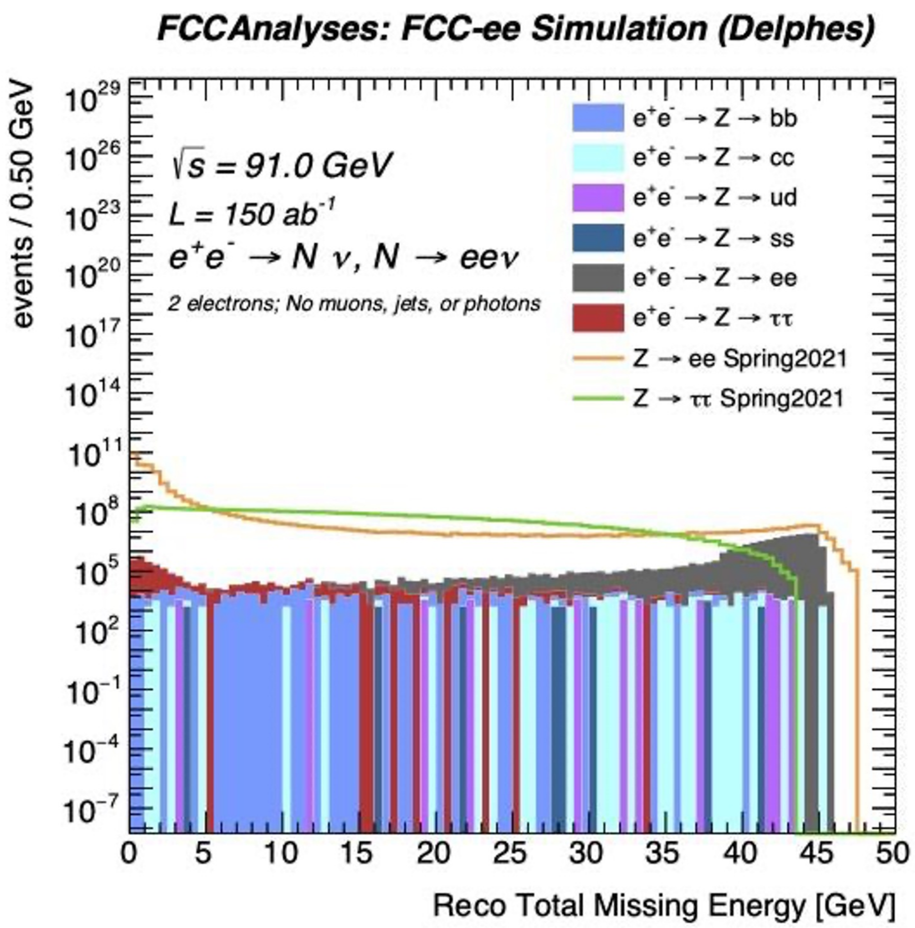
Also studied angular distributions sensitive to majorana vs Dirac nature of HNLs…







Ongoing HNL studies : winter 2023 production



MC Statistics of spring 2021 campaign

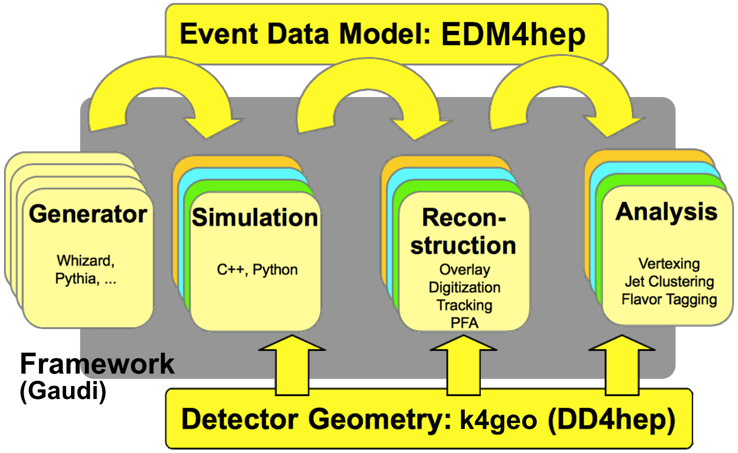
Sample	Integrated lumi/ ab^{-1}
p8_ee_Zee_ecm91	0.01
p8_ee_Zbb_ecm91	0.15
p8_ee_Ztautau_ecm91	0.01
p8_ee_Zuds_ecm91	0.05
p8_ee_Zcc_ecm91	0.19

Improvements/changes in winter2023 samples have a visible difference on shape, and MC statistics still present significant limitations (under discussion).

Ongoing work: implementing MC filters

In order to get adequate MC statistics at the Z-pole run for LLP studies- need filtered MC samples!

- Significant technical work ongoing to implement flexible MC filtered that can be used in the key4hep framework and the FCC production system.
- Aiming to use filtered samples to perform further sensitivity and detector optimisations.



https://github.com/key4hep

For more details on key4hep see my talk from last week at the Swift HEP workshop, which contains a lot of additional links.

Conclusions/outlook

- **If they exist- LLPs would be a "win-win" scenario for FCC-ee – we need to ensure we are prepared to measure them!**
  - Typically ~ background-free analyses- checking these assumptions is important as well as considering **signal acceptance**
  - Aim for **discovery** - need to study detector implications for our ability to **characterise** the new physics, not just uncover it.

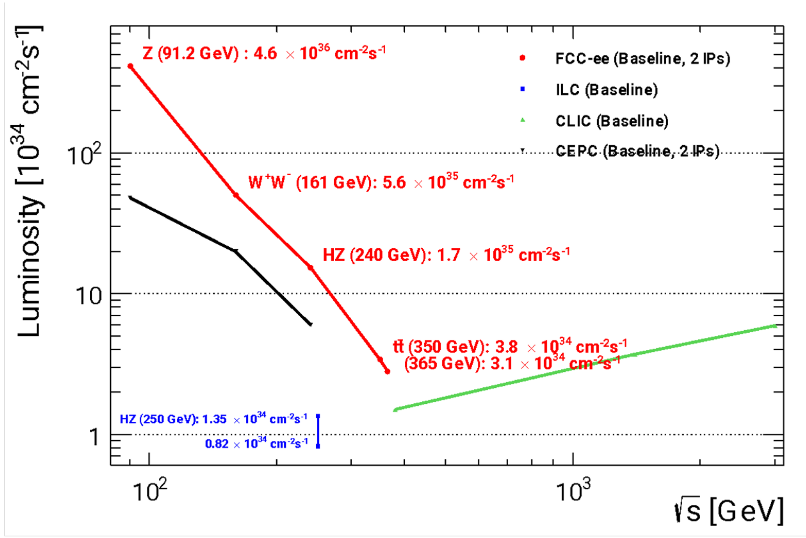
Moving on from the mid-term review- there's a lot to do by the end of the feasibility study. It's a fun and exciting area to contribute. Interested? Get in touch…

Backup: FCC-ee LLP 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)
- Magdalena Vande Voorde (Uppsala University, 2023)
- Daniel Beech (University of Cambridge, 2023)
- Dimitri Moulin (University of Geneva, 2023)

...and more on the way!

Backup: FCC-ee



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

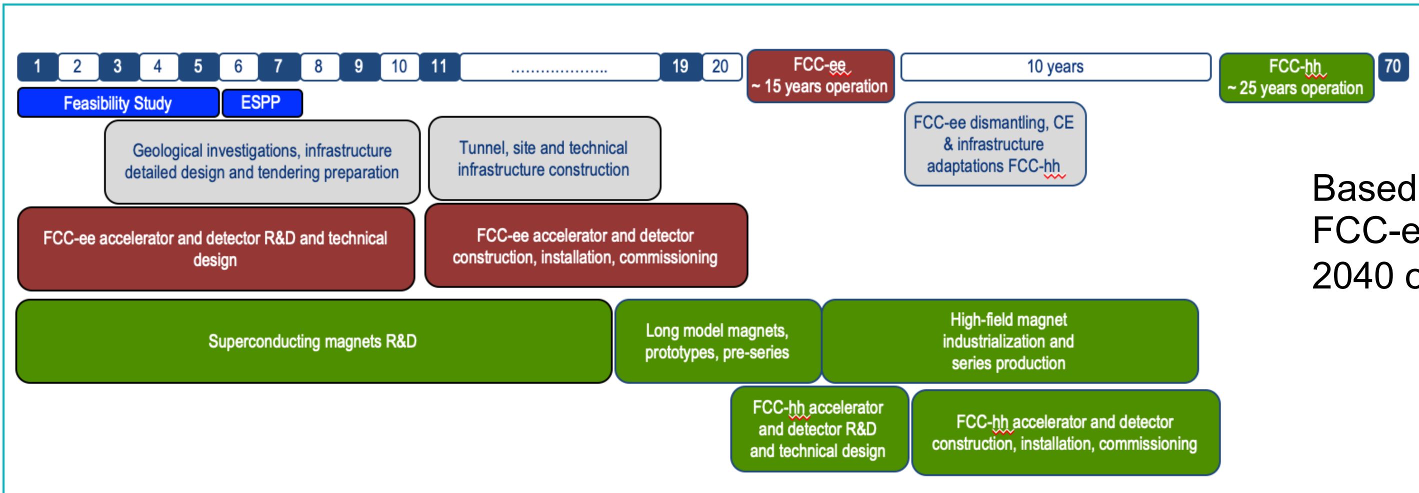
- Unconventional signatures (including displaced vertices).
- Exotic Higgs decays.

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

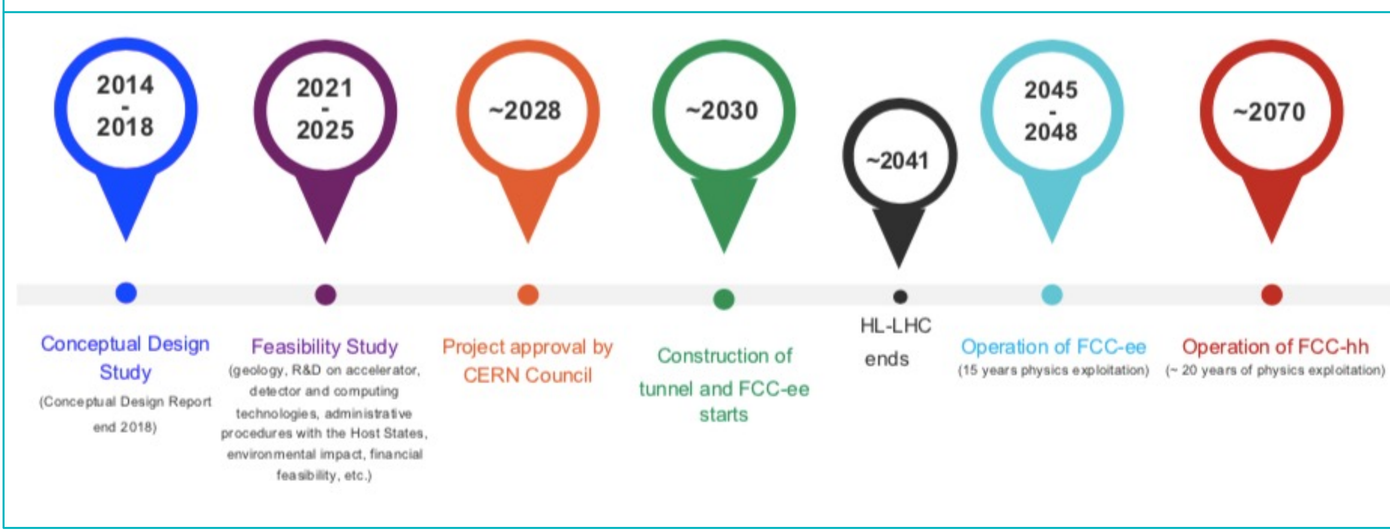
Taken from FCC: physics opportunities (CDR volume 1)

Backup: FCC timelines

Taken from slides by F. Gianotti at FCC week.



Based on **technical schedule**, FCC-ee operation could start in 2040 or earlier.

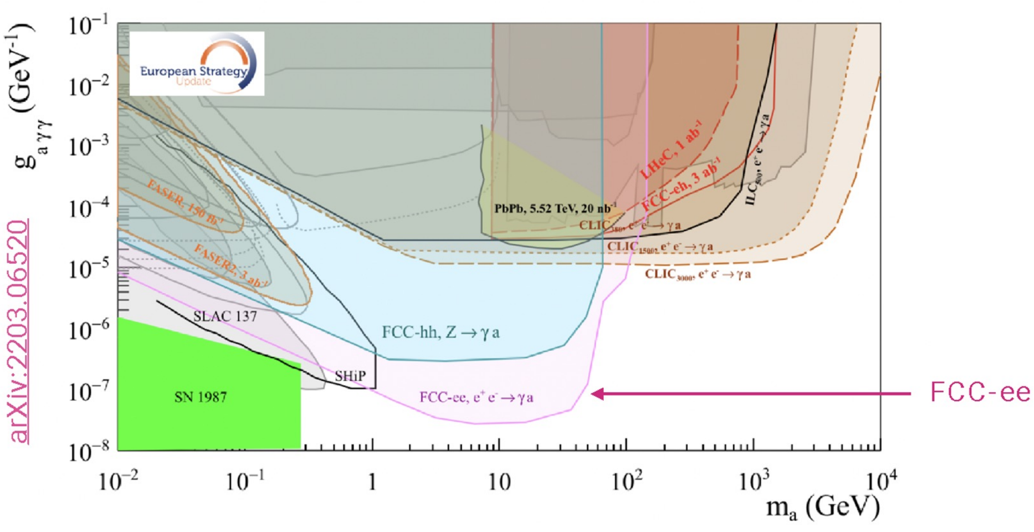


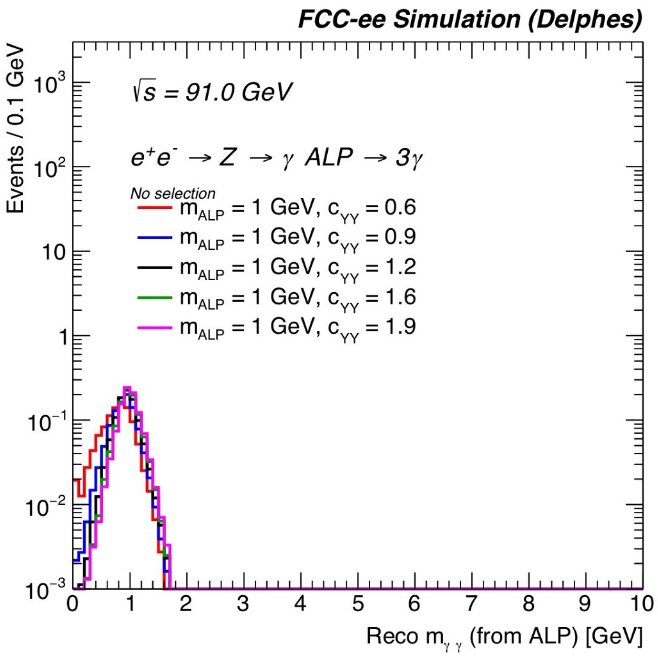
More **realistic schedule**, accounting for past experience of building colliders, approval timelines, HL-LHC operation…

Backup: Axion-like particles at FCC-ee

Calorimeter and timing information will improve these studies in future

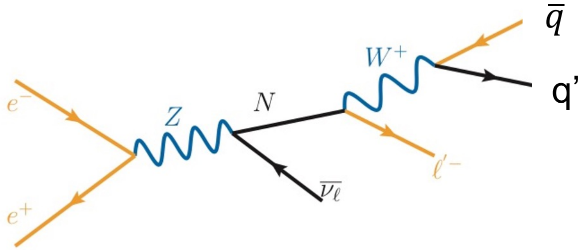
- For small couplings and light ALPs → LLP signature.
- Initial validation of signal samples and kinematic distributions presented- more to come in future.



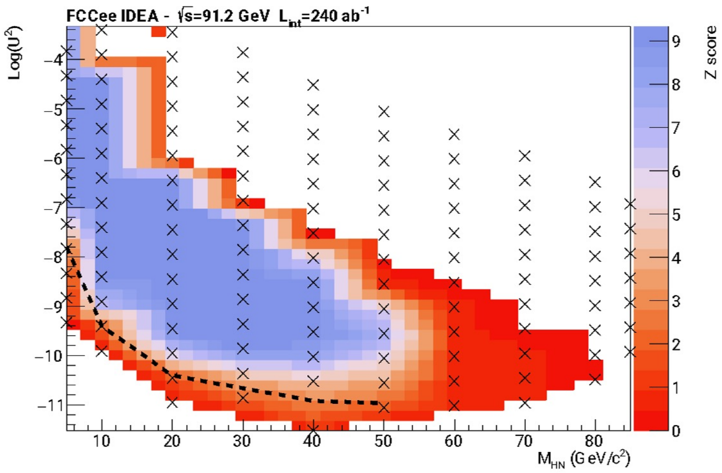


Backup: Ongoing HNL studies: N→μjj

Nicolo Valle, Giacomo Polesello



Target decay N→μjj in HNL mass range 5 to 85 GeV with scan over $|U|^2$. Aim for prompt analysis at high (>50 GeV) HNL mass, with Long-lived analysis at low HNL mass (longer lifetime)



- Develop pre-selection (1 muon with p> 3 GeV, >= 3 tracks, E_{miss}>5 GeV).
- Detailed study of jet reconstruction algorithms for truth vs reco-level distributions.

Preliminary proto-analysis requiring muon $|d_0|$>1mm. Investigating further selection requirements using vertex fitter. Further discussion in recent physics+performance meeting here and in next talk !

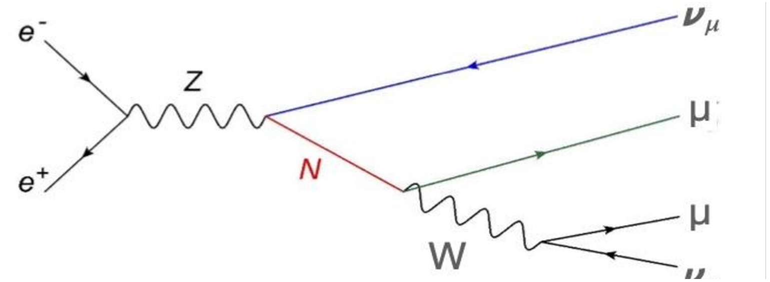
For more details see slides here

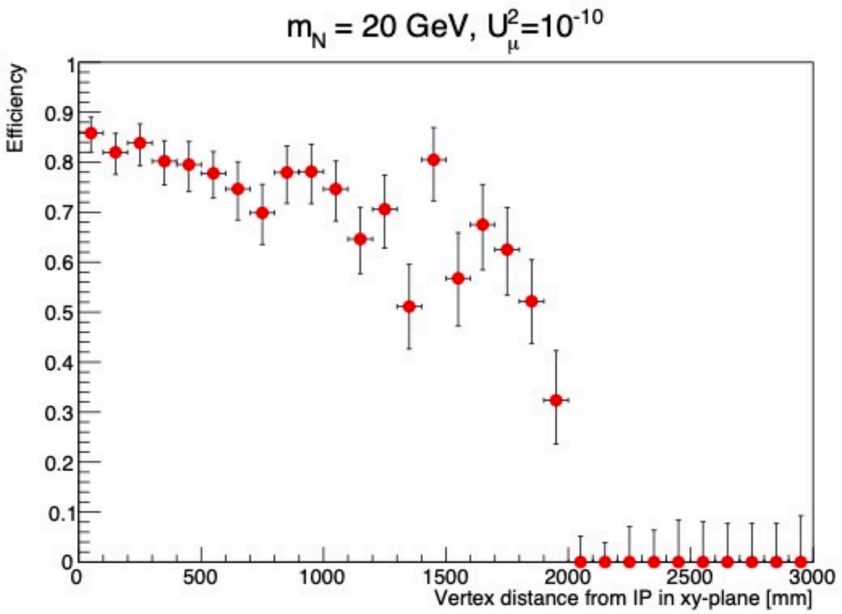
Backup: Ongoing HNL studies: N→$\mu\mu\nu$

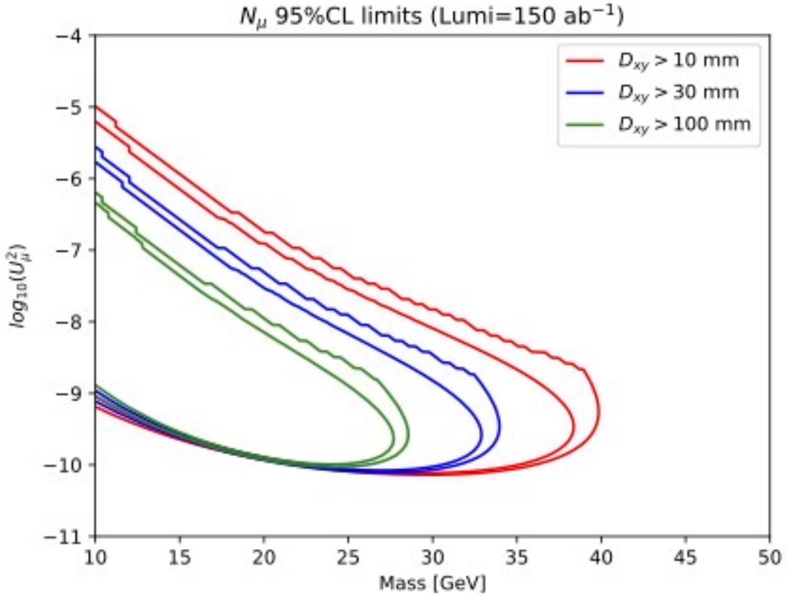
Lorenzo Bellagamba

Early studies of sensitivity with N→$\mu\mu\nu$ channel looking for DV

Optimise search based on the distance from the 2-muon decay vertex to the IP







DV reconstruction efficiency a promising area for further improvements?

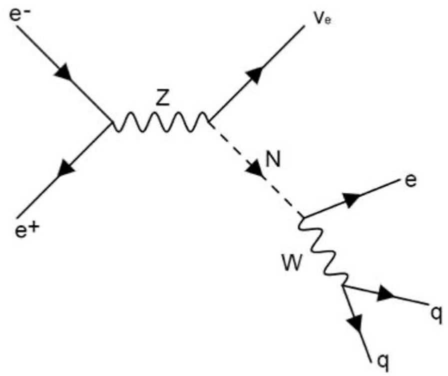
Backup: Ongoing HNL studies: N→ejj

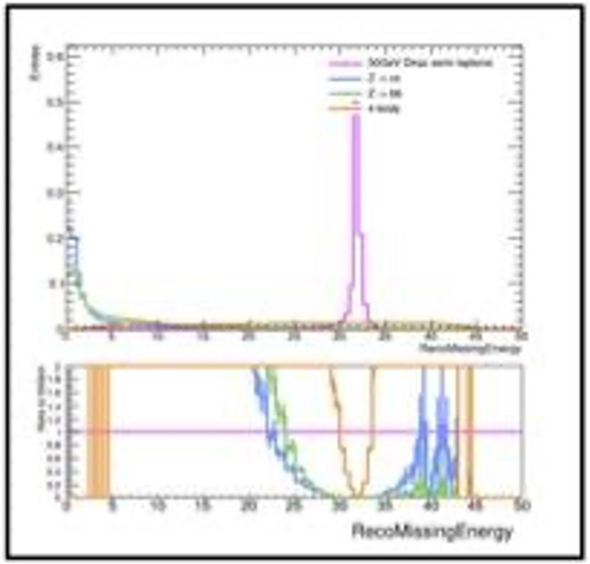
Dimitri Moulin, Anna Sfyrla, Pantelis Kontaxakis

Study semi-leptonic final state to probe majorana vs dirac nature of HNL

- Use dijet + electron invariant mass as a probe for HNL mass.
- Observed some issues with default delphes jet collections- required re-running jet reconstruction at analysis level to improve truth/reco comparisons.
- Next steps: develop full event selection and look at sensitive variables.

-> thinking about reconstruction techniques is important!

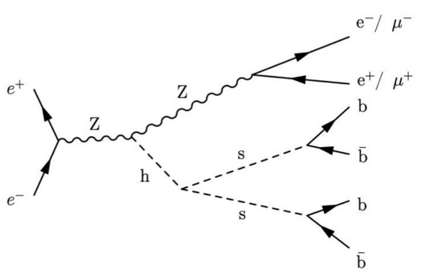


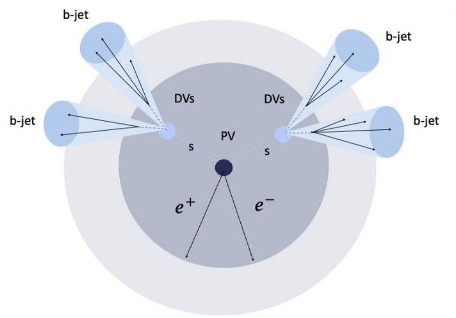


Backup: exotics Higgs decays

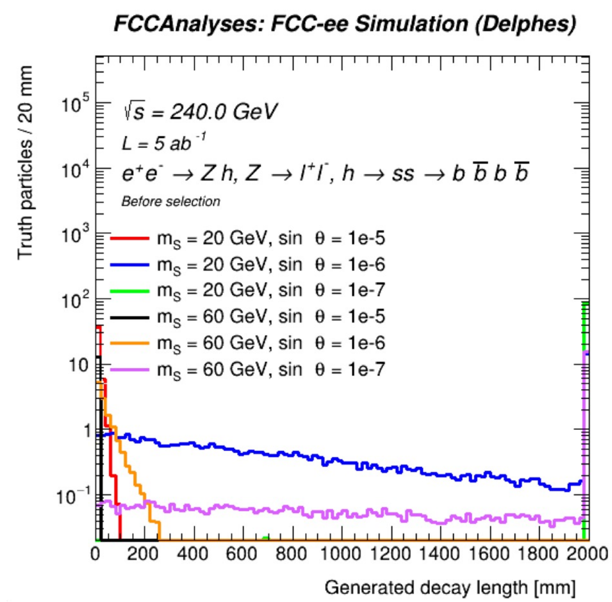
Magdalena Vande Voorde, Giulia Ripellino

First simulation and sensitivity studies for Higgs decays to long-lived scalars





- Extend SM with additional scalar.
- Probe h→ss→bbbb in events with 2 displaced vertices, tagged by Z



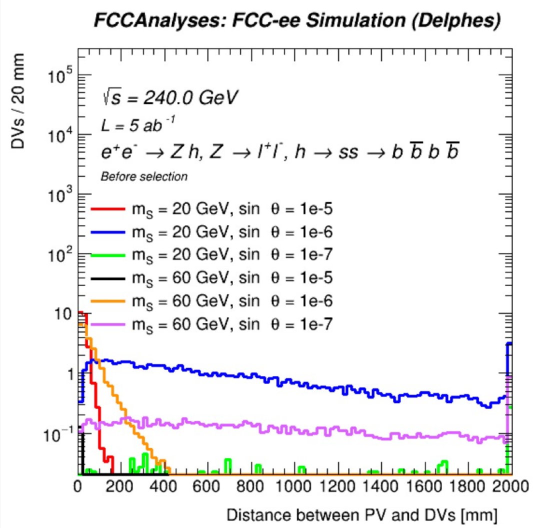
- Look at events with at least one scalar within acceptance region 4mm<r<2000mm- all except longest and shortest lifetimes.
- Aim to develop event selection and perform early sensitivity study.

For further details see presentation by Magda at topical ECFA WG1-SRCH meeting

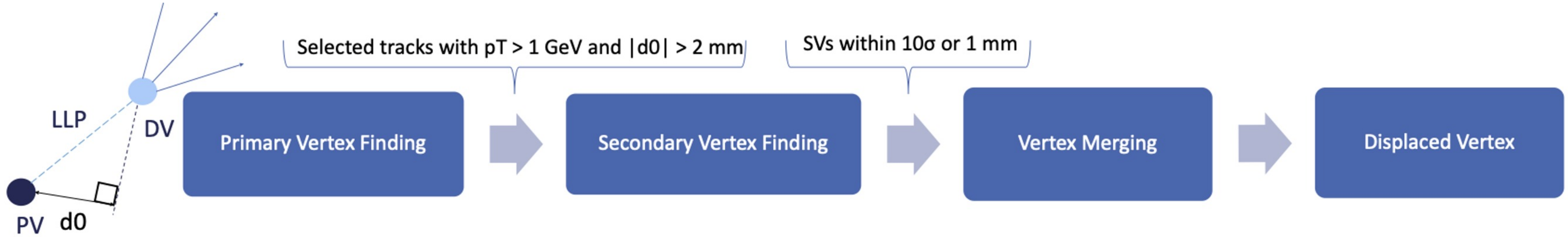
Backup: exotics Higgs decays

Magdalena Vande Voorde, Giulia Ripellino

Studied two options of DV reconstruction implemented in FCCAnalysis framework with additional constraints inspired by ATLAS DV analysis (link here)



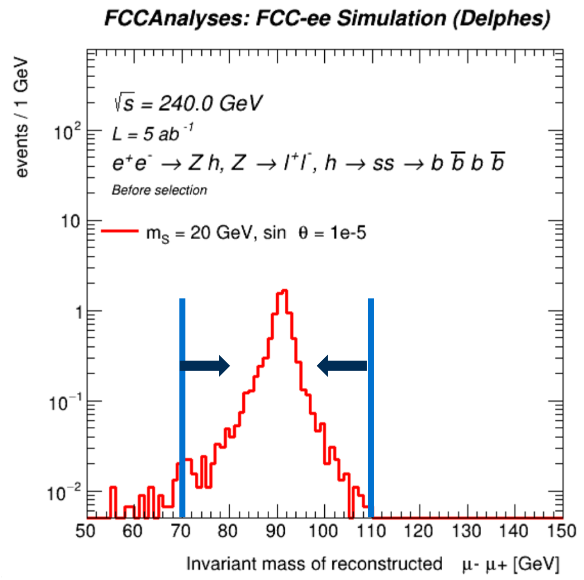
1. SV finder of LCFI+ algorithm (https://arxiv.org/abs/1506.08371)
2. Add vertex merging to recover some DVs from scalars, but need to understand goodness of fit results (more discussion here)



Backup: exotics Higgs decays

Magdalena Vande Voorde, Giulia Ripellino

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



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

All but 2 considered signals could be excluded at 95% CL in background-free search.

Backup: exotics Higgs decays

Magdalena Vande Voorde, Giulia Ripellino

Truth-level sensitivity analysis

- Selected events that has ≥ 1 scalar with decay length 4 mm < d < 2000 mm
  - m_s = 20 GeV, sin θ = 1e-7 is too long-lived and m_s = 60 GeV, sin θ = 1e-5 is too short lived
  - All the other signal samples has ≥ 4 events!

Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Mean proper lifetime $c\tau$ [mm]	Cross Section σ [pb]	Branching Ratio $\mathrm{BR}(h \to ss)$	Expected events at 5 ab^{-1}	Expected selected events
20	1×10^{-5}	3.4	8.858×10^{-6}	6.27×10^{-4}	44.29	40.03
20	1×10^{-6}	341.7	8.858×10^{-6}	6.27×10^{-4}	44.29	43.31
20	1×10^{-7}	34167.0	8.858×10^{-6}	6.27×10^{-4}	44.29	1.57
60	1×10^{-5}	0.9	2.618×10^{-6}	1.85×10^{-4}	13.09	0.01
60	1×10^{-6}	87.7	2.618×10^{-6}	1.85×10^{-4}	13.09	12.98
60	1×10^{-7}	8769.1	2.618×10^{-6}	1.85×10^{-4}	13.09	8.62

Number of expected events given by
$N = L \times \sigma$ with $L = 5\ ab^{-1}$ and

$$\sigma = \sigma_{ZH} \times BR(h \to ss) \times BR(s \to b\bar{b})^2 \times BR(Z \to l^+ l^-)$$

Old baseline results

Backup: further details on exotics Higgs studies

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Efficiency studies

	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7
Before selection	1.0	1.0	1.0
Pre-selection	0.672	0.687	0.819
$70 < m_{ll} < 110$ GeV	0.653	0.670	0.803
n_DVs ≥ 2	0.080	0.505	0.012
	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
Before selection	1.0	1.0	1.0
Pre-selection	0.640	0.637	0.740
$70 < m_{ll} < 110$ GeV	0.620	0.618	0.722
n_DVs ≥ 2	0.0	0.491	0.313

	WW	ZZ	ZH
Before selection	1.0	1.0	1.0
Pre-selection	0.131	0.026	0.059
$70 < m_{ll} < 110$ GeV	0.006	0.086	0.047
n_DVs ≥ 2	0.0	0.0	0.0