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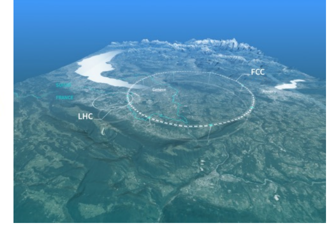

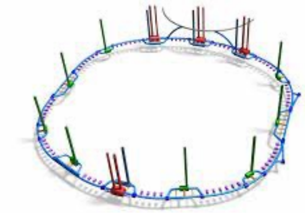

Searches for Long-Lived particles at the Future FCC-ee

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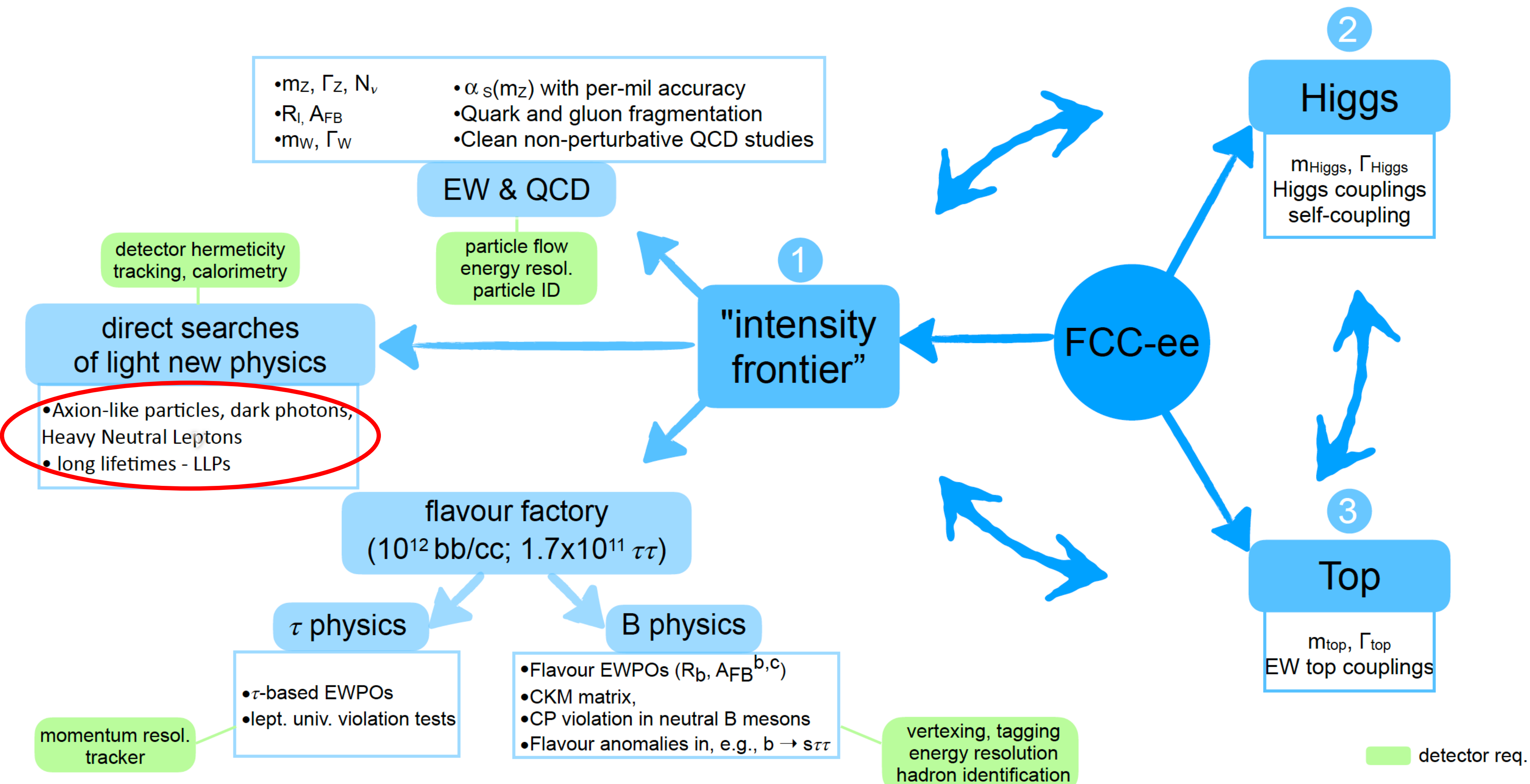
LCWS2024 International Workshop on Future Linear Colliders

FCC-ee physics program



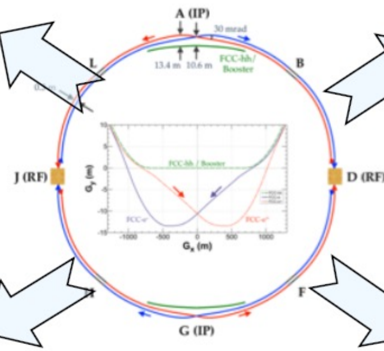
Detector requirements for an experiment at the FCC-ee

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of $30\%/\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from $\mu\mu$)
- Stability of B-field to 10^{-6} : stability of $\sqrt{s}$ meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few $\%/\sqrt{E}$ level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: $Z \rightarrow \nu N$, with N decaying late

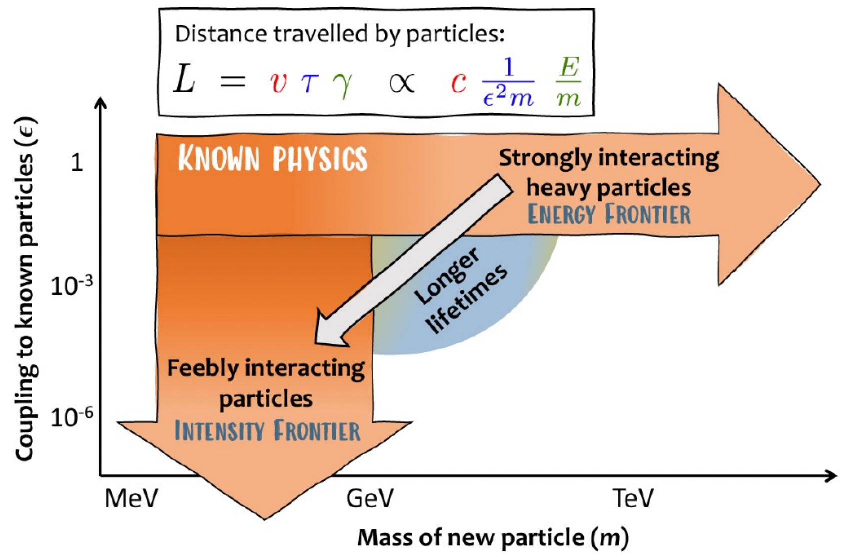
- Sensitivity to far detached vertices (mm $\rightarrow$ m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths $\Rightarrow$ extended detector volume
- Hermeticity

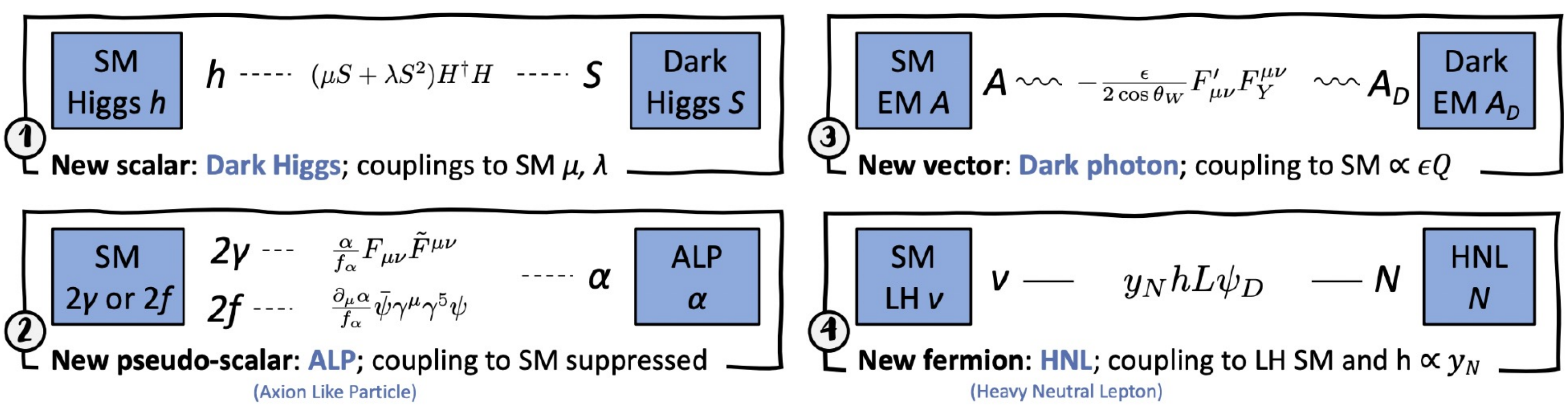
➢ M. Dam, ECFA Det. R&D Roadmap, 2021, https://indico.cern.ch/event/994685/

Feebly Interacting particles (FIPs)

The **dark sector** could contain a multitude of hidden particles:

- tipically a stable particle
- one or more mediators feebly interacting, coupled to the SM via neutral portal
- the spin of the mediator particle defines the portal:
  - vector boson (dark photon)
  - scalar/pseudoscalar (dark Higgs, ALP)
  - fermion (sterile neutrino)





New Physics could be light and feebly interacting with SM

FCC-ee will give us huge statistics and a clean environment

N. De Filippis

Long-lived particles

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

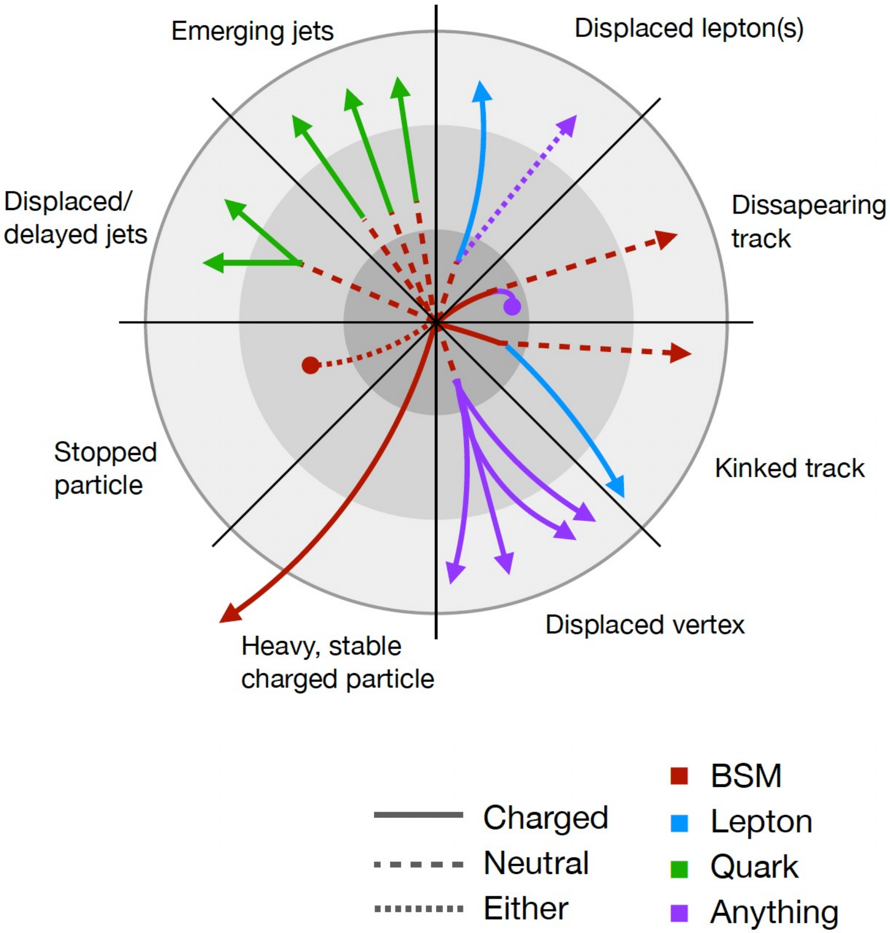
- Targeted by signature-driven searches

Experimental benefits:

- Little/no backgrounds from SM decays ….but atypical backgrounds might be significant (cosmics, beam halo, instrumental effects, etc.)

Experimental challenges at the LHC:

- main detectors, triggers, and offline reconstruction not designed for displaced particles
- plenty of room for improvement in future accelerator projects!



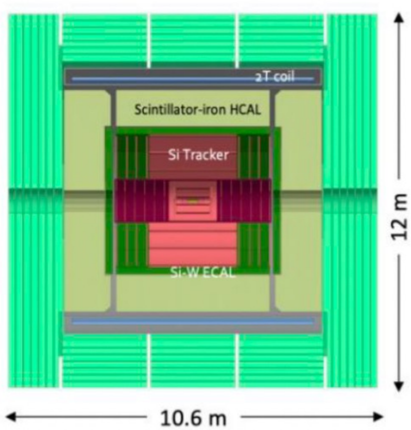
Can design general-purpose detectors at the FCC with LLPs in mind!

Detector requirements

- Identifying long-lived particles places distinct detector requirements
  - Impact parameter resolution for large displacements
  - Tracking detectors: additional layers / continuous tracking
  - Calorimetry: high radial segmentation, tracking capability
  - Muon detectors: standalone tracking capability
- Large decay lengths implies extended detector volume
- Invisible final states → hermetic detectors
- Triggerless readout
- Precise timing for velocity (mass) estimates

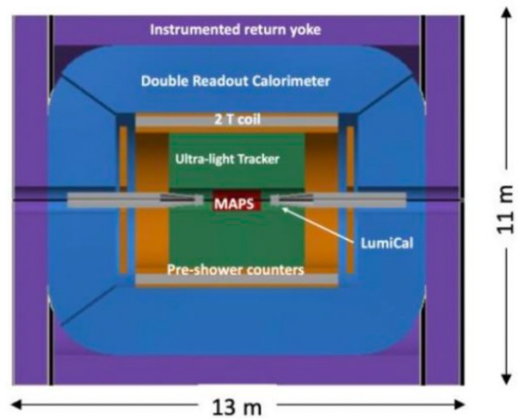
FCC-ee detector benchmarks

CLD

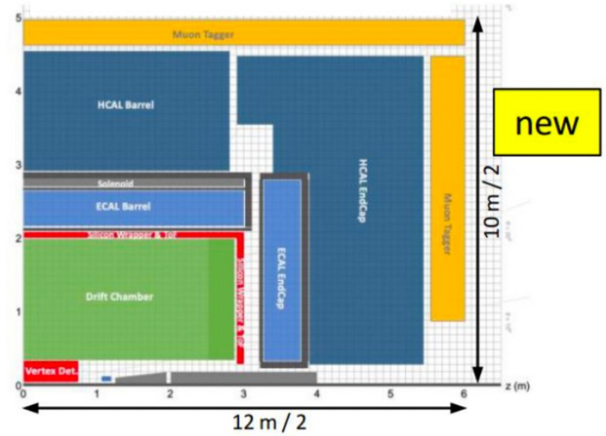


CDR

IDEA



ALLEGRO



Imported from CLIC

- Full Si tracker
- SiW Ecal HG
- SciFe Hcal HG
- Large coil outside

FCCee specific design

- Si Vtx + wrapper (LGAD)
- Large drift chamber (PID)
- DR calorimeter
- Small coil inside

FCCee specific design

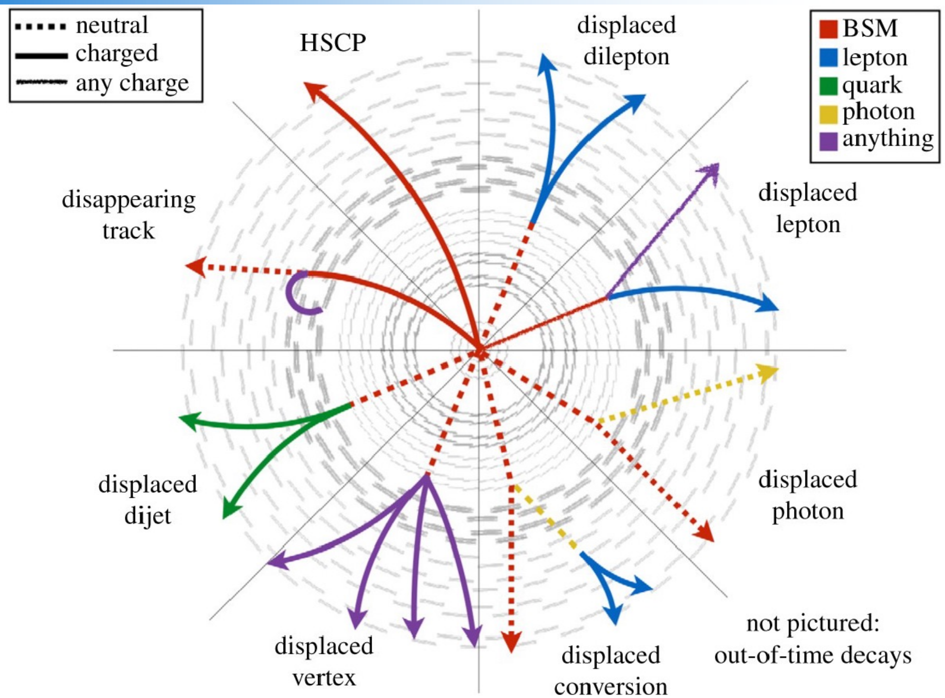
- Tracker as IDEA
- LAr EM calorimeter
- Coil integrated
- Hcal not specified

Opportunity to design general-purpose detectors with LLPs in mind!

So far:

- we rely on **Delphes** with baseline card on the IDEA detector performance
- analysis tools to provide variations of resolutions to study dependence or precision or sensitivity

Long-lived particles simulation and workflow



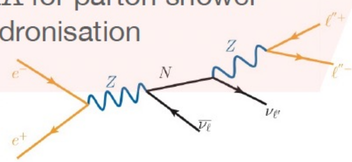
LLPs that are semi-stable or decay in the sub-detectors are predicted in a variety of BSM models:

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

Typical workflow

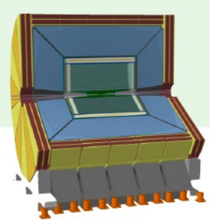
Sample generation of models, e.g.

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



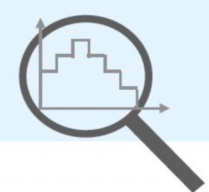
Parametrised detector simulation, e.g

- IDEA DELPHES card



Analysis tools, e.g

- FCC analysis



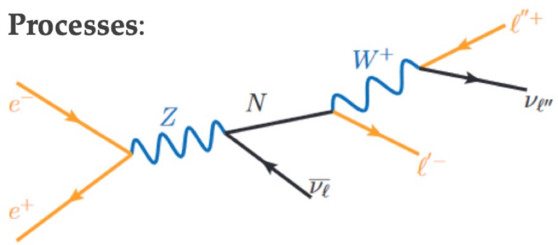
Sensitivity to studied model

FIPs studies are included in the FCC midterm report

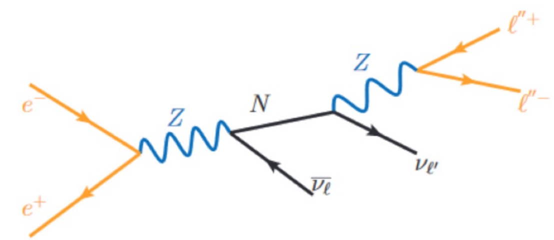
1st Physics Case: Heavy neutral leptons (HNLs) at FCC-ee

arXiv:1411.5230, arXiv:2203.05502

- Dirac or Majorana sterile neutrinos with very small mixing with active neutrinos
- Could provide answers to open questions of the SM: Neutrino masses, Baryon asymmetry, DM



- At the Tera-Z run, FCC-ee can search for HNLs using a large sample of Z bosons **produced resonantly**
- s-channel production of $Z \to \nu N$ with $N \to l W^*$, $N \to \nu Z^*$
- the BR Z into HNLs is proportional to the squares of the mixing angles U^2_{ij} between the SM neutrinos and the HNL, i, j = three neutrino flavours
- large number of Z decays → the exploration of very low values of the U^2_{ij} couplings for HNL masses below the Z mass
- the values of U^2_{ij} → HNLs with a measurable path → jets or leptons displaced, no SM bkg



- For $1\text{mm} < c\tau < 2\text{m}$, discovery would be possible down to couplings of order $U^2_{ij} \sim 10^{-11}$ for HNL masses up to 60-70 GeV
- For larger HNL masses up to the kinematic limit of the Z mass a prompt analysis would be needed → significant SM backgrounds → limit the discovery region to values of the coupling U^2_{ij} larger than about 10^{-9} to 10^{-8}

1st Physics Case: Heavy neutral leptons (HNLs) at FCC-ee

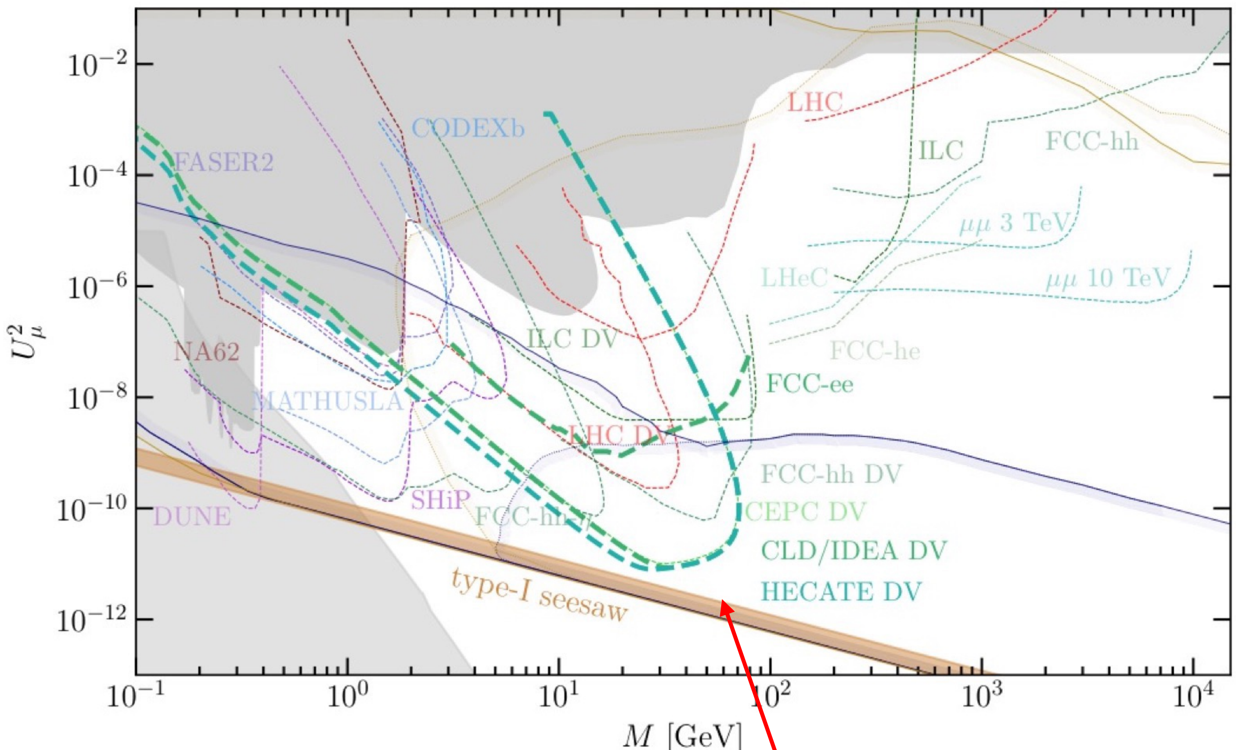
Most efficient of displaced HNLs at the Z-pole run

- larger luminosity and cross-section from $Z \to N\nu$ decays).

Benefit from:

- low SM backgrounds with displaced vertex
- clean experimental conditions

Semileptonic and fully leptonic decays of the HNL studied for the LLP analyses



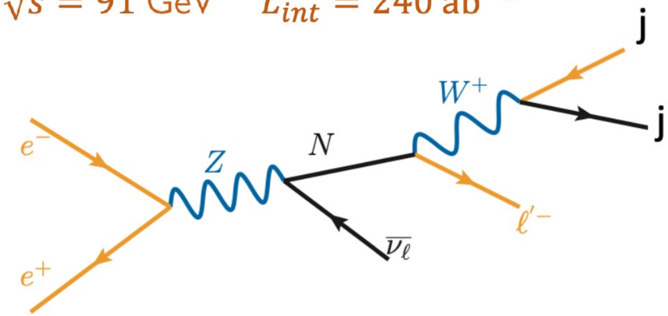
The prompt analyses focussed on the HNL → $l\,j\,j$ which has the highest BR and allows full kinematic reconstruction of the neutrino decay.

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

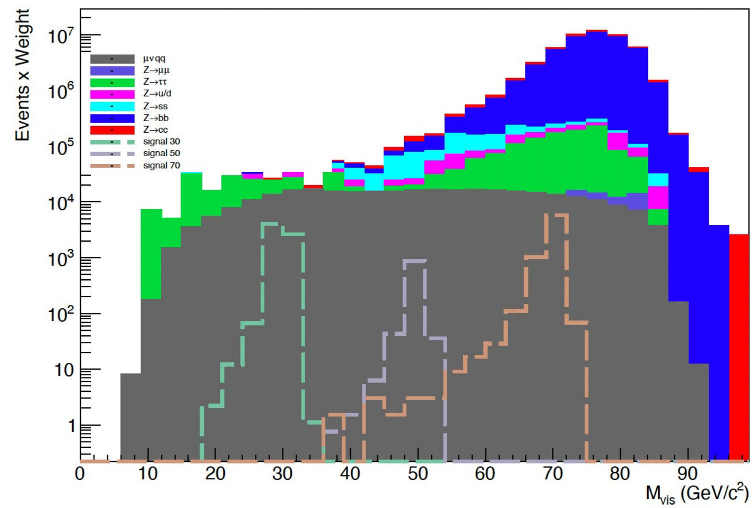
1st Physics Case: Prompt & Displaced HNL → μjj

G. Polesello, N. Valle, https://doi.org/10.17181/wnd8t-1k526

$\sqrt{s} = 91$ GeV $L_{int} = 240\ \text{ab}^{-1}$



Discriminant variable = visible mass, which corresponds to the HNL mass

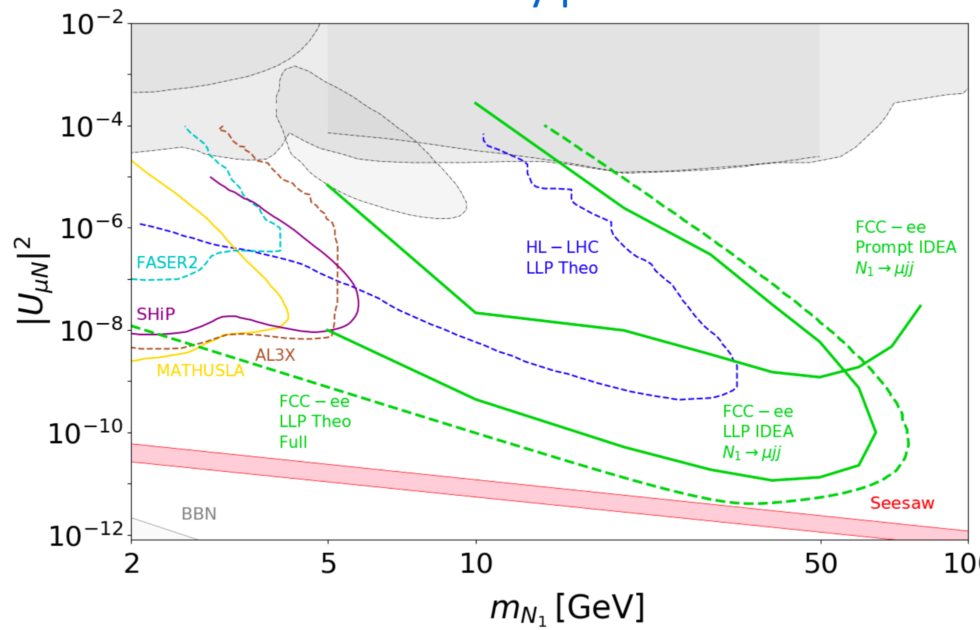


- High production rate (~50% of the BR)
- Jets can be well separated or collimated
- Primary backgrounds from Z :
  - $Z \to bb/cc/uds$, $Z \to \mu\mu$ / $\tau\tau$
  - $ee \to \mu\nu qq$ => irreducible

- Prompt analysis targeting high HNL mass (> 50 GeV)
  - 1 muon, 1 or 2 jets, good PV
  - Require vertex radius < 0.5 mm

- Long-lived analysis targeting low HNL mass
  - Require vertex radius > 0.5 mm

Discovery potential



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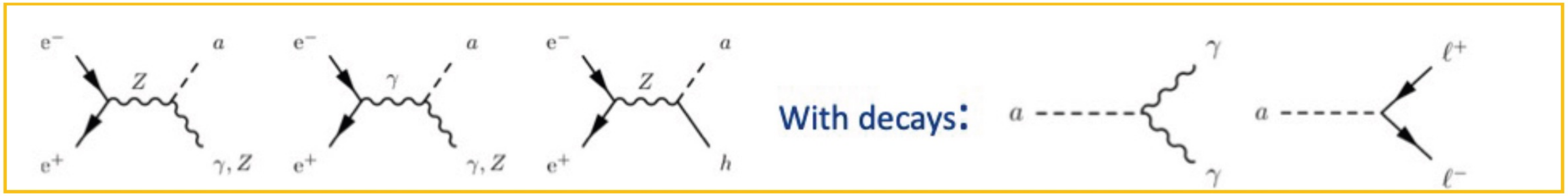
2nd Physics Case: Axion-like particles at FCC-ee

- ALPs are pseudoscalars that can be heavier than the QCD axion and serve as mediators to the dark sector.
- Astrophysical and beam-dump experiments constrain the ALP-photon coupling at low masses, but are less stringent in the $0.1 < m_a < 100$ GeV range, potentially accessible at FCC via $e^+e^- \rightarrow a\gamma$ and $e^+e^- \rightarrow a$ via $\gamma\gamma$ fusion, with the ALP decaying as $a \rightarrow \gamma\gamma$.

- **At small coupling values and light ALP, the ALP lifetime is large enough → macroscopic $c\tau$**

- Detector requirements from $e^+e^- \rightarrow a\gamma \rightarrow (\gamma\gamma)\,\gamma$ with 3 photons in the final state.
  - Depending on the mass of the ALP, the ability to separate the 3 γ showers, and to determine their common (secondary) pointing vertex, can vary significantly, and the impact of the position resolution can become comparable with that of the energy resolution

- The ALP coupling to Z and Higgs bosons probed also via $e^+e^- \rightarrow Za, Ha$ with visible Z boson decays or $H \rightarrow bb$, and either $a \rightarrow \gamma\gamma$ or $a \rightarrow l^+l^-$. Decays to SM particles other than γ are less constrained and provide an additional opportunity for ALP discovery at FCC-ee.

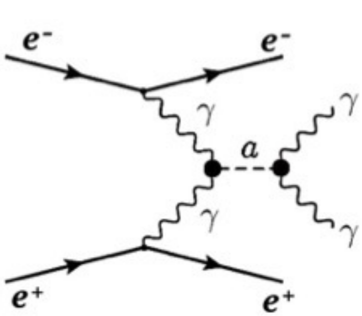


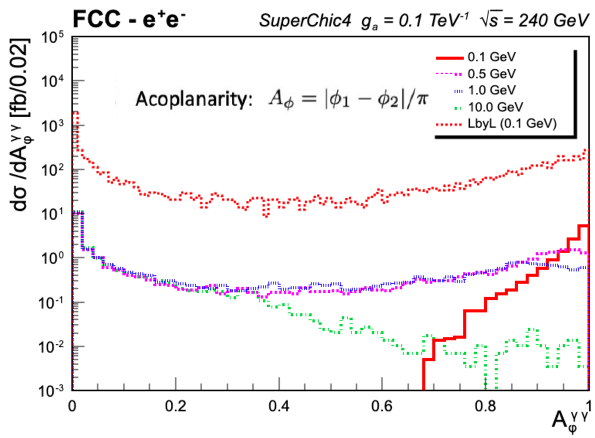
2^{nd} Physics Case: Axion-like particles at FCC-ee

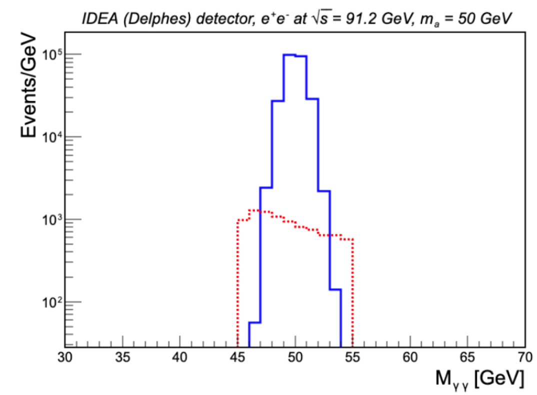
Patricia Rebello Teles, David d'Enterria, Victor Gonçalves, Daniel Martins

ALP production via photon-photon fusion: Using SC4 MC generator for the ALP signal and Light-by-Light continuum background (irreducible background) + IDEA sim

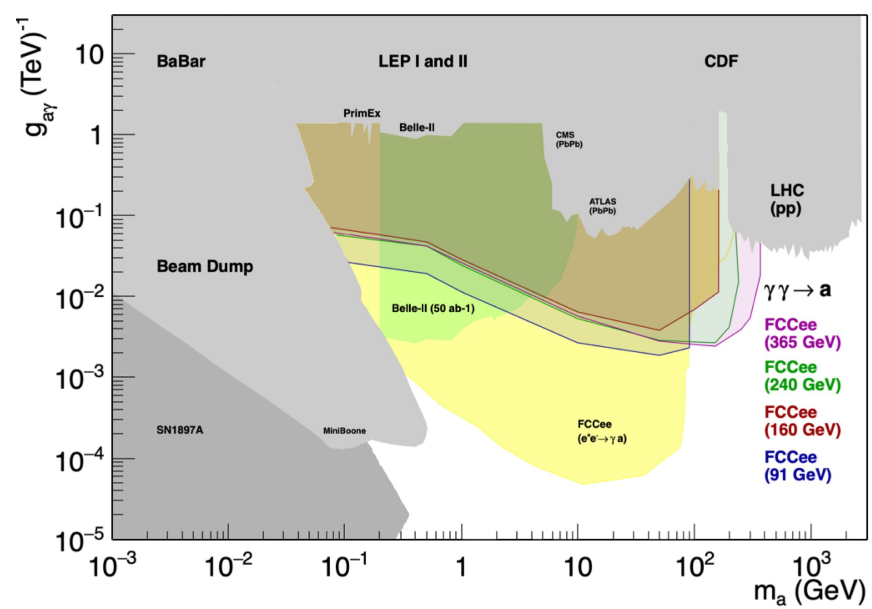
arXiv:2310.17270







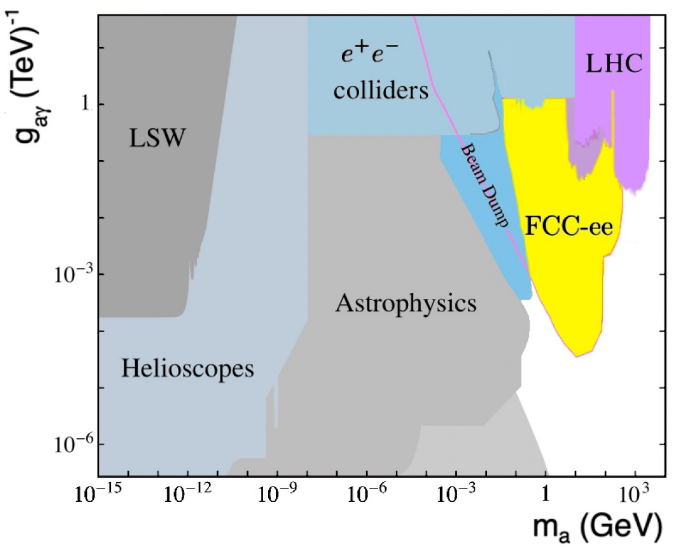
photon coupling versus ALP mass

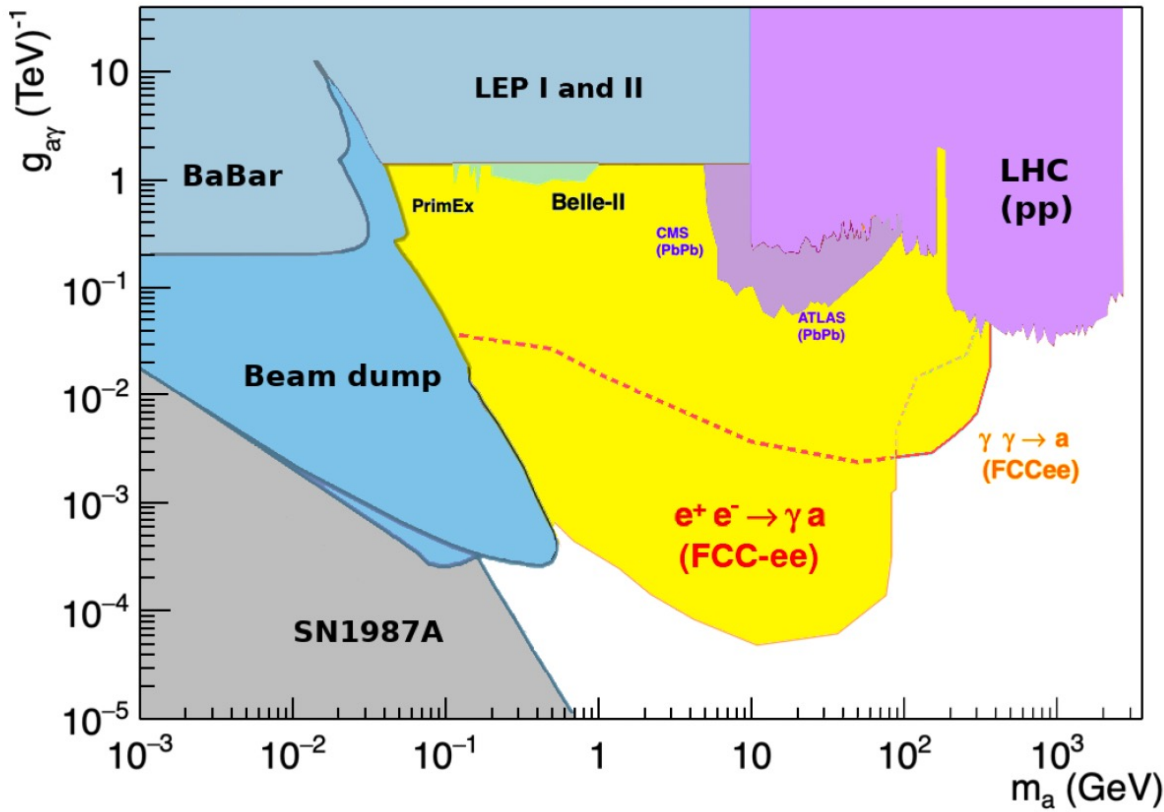


- $\gamma\gamma \to a$ extends current LHC limits for m_a = 5 – 350 GeV by 2(O) magnitude

For low ALP mass, sophisticated detectors & techniques are needed to isolate the overlapping photons

2^{nd} Physics Case: Axion-like particles at FCC-ee





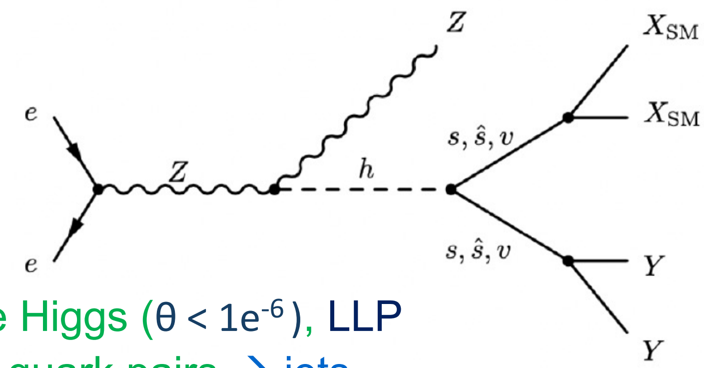
Projected sensitivity of the ALP search:

- $e^+ e^- \to Z \to \gamma\, a$ extends current LHC limits for m_a = 0.1 – 90 GeV by 3(O) magnitude
- $\gamma\gamma \to a$ extends current LHC limits for m_a = 5 – 350 GeV by 2(O) magnitude

3rd Physics Case: Exotic Higgs decays at FCC-ee

- Higgs bosons could undergo exotic decays to LLPs → portal to dark sectors with small but nonzero couplings to the Higgs.
- several interesting models: SM extensions with scalars/fermions/vectors, MSSM, NMSSM, Hidden Valleys

arXiv:1312.4992, arXiv:1412.0018

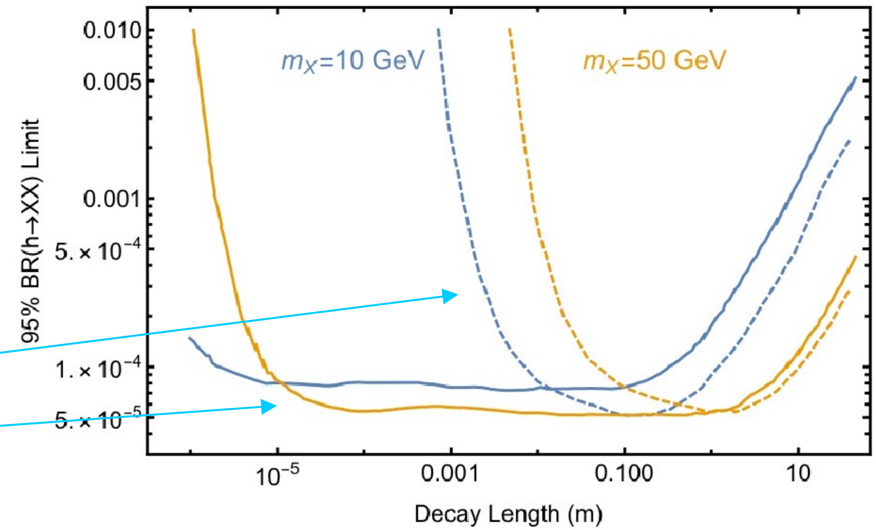


- For sufficiently small mixing angle between LLP and the Higgs ($\theta < 1e^{-6}$), LLP could travel a macroscopic distance before decaying to quark pairs → jets containing candidate secondary/displaced vertices (exotic Higgs decays with decay lengths $c\tau$ ranging from microns to meters)

$$e^+e^- \to hZ \to XX + \ell\bar{\ell} \text{ at } \sqrt{s} = 240 \text{ GeV}$$

Tracker-based searches optimal for decay lengths below 1 meter, with sensitivity to shorter LLP decay lengths down to the tracker resolution (impact parameter res. 2-3 μm)

- 'long lifetime': $m_x < 10$ GeV and $c\tau \gtrsim 1$cm
- 'large mass': $m_x \gtrsim 10$ GeV and $c\tau \gtrsim 1\mu$m



Improvement of the vertex resolution → better sensitivity to LLPs with relatively short lifetimes

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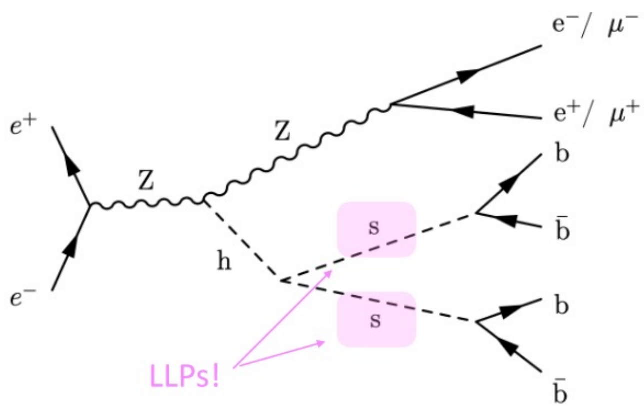
3rd Physics Case: Exotic Higgs decays at FCC-ee

Axel Gallén, Giulia Ripellino, Magdalena Vande Voorde, Rebeca Gonzalez Suarez

Target FCC-ee Zh stage (240 GeV):

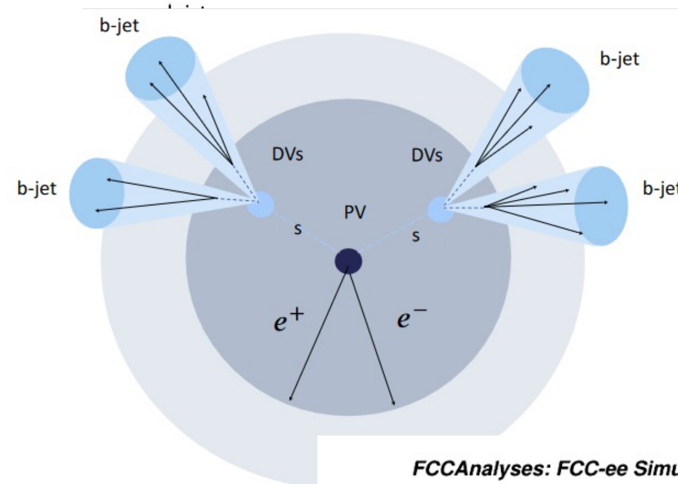
$e^+e^- \rightarrow Zh$ with $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$ and

$Z \rightarrow ll$ (2 electrons or 2 muons)



Experimental signature

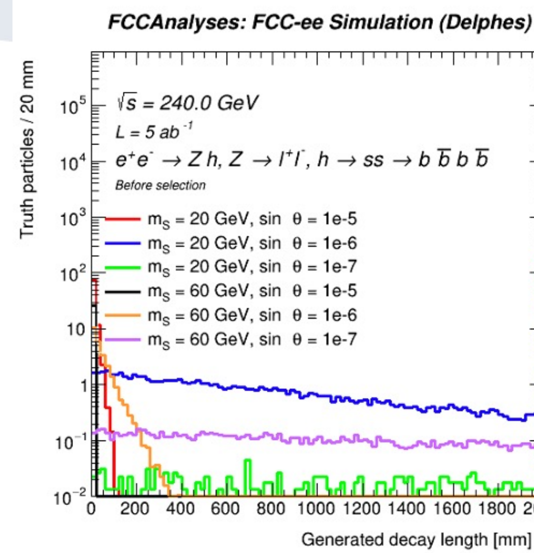
2 displaced vertices (DVs) +
Z boson from ee or mumu



Full chain:

- **MadGraph v3.4.1 (for parton level)**
- **Pythia8 (parton shower / hadronization)**
- **Delphes (winter2023 IDEA)**

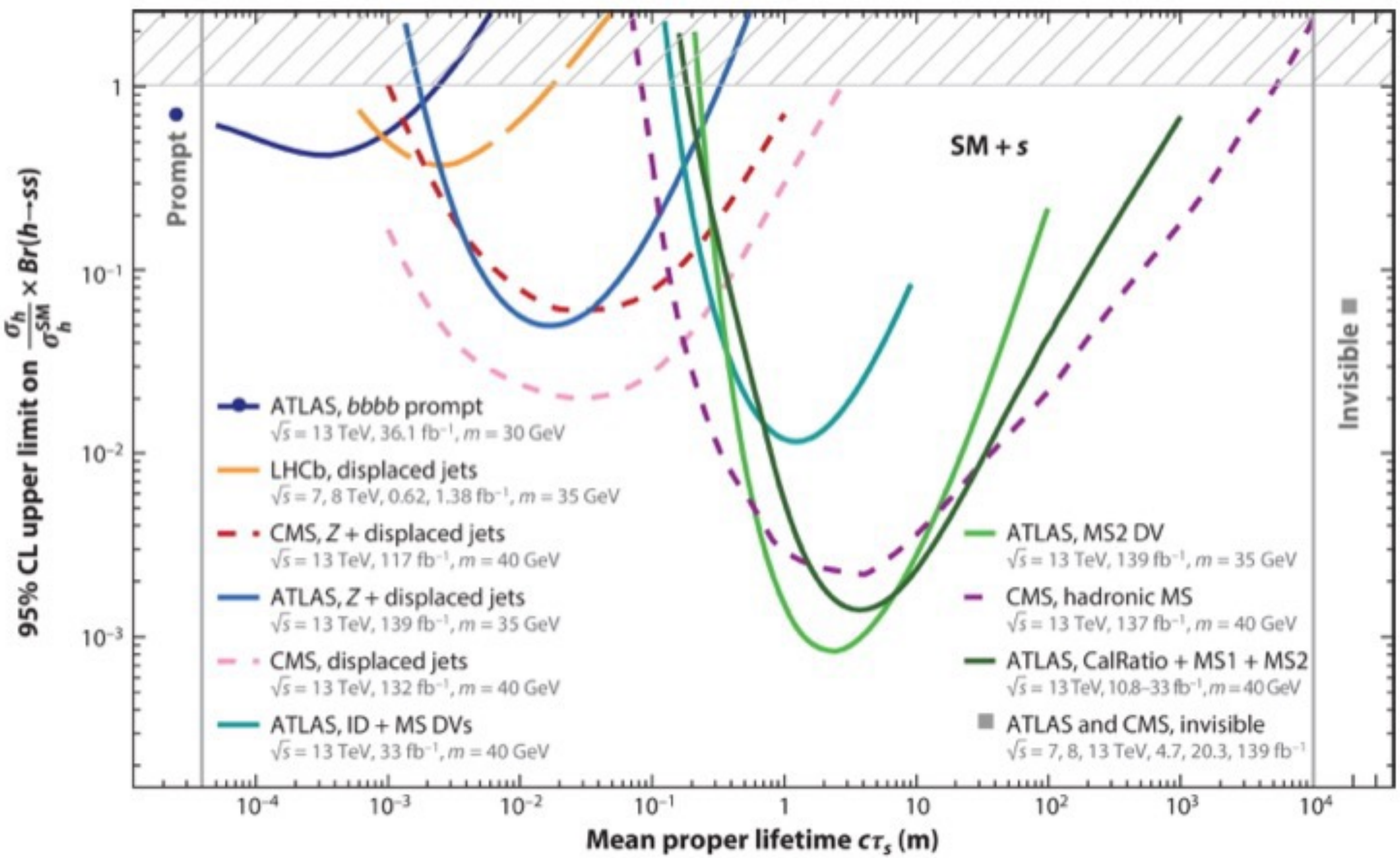
Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Mean proper lifetime $c\tau$ [mm]	Branching Ratio BR($h \to ss$)	Total expected events	Expected selected events
20	1×10^{-5}	3.4	6.98×10^{-4}	55.20	50.19
20	1×10^{-6}	341.7	6.98×10^{-4}	55.20	53.87
20	1×10^{-7}	34167.0	6.98×10^{-4}	55.20	2.09
60	1×10^{-5}	0.9	2.06×10^{-4}	16.32	0.01
60	1×10^{-6}	87.7	2.06×10^{-4}	16.32	16.15
60	1×10^{-7}	8769.1	2.06×10^{-4}	16.32	10.66



3rd Physics Case: Exotic Higgs decays at FCC-ee

ZH → Z (ee/μμ) + H → s s → 4b

Review: Exotic Higgs Decays arXiv:2111.12751



FCC-ee can improve the sensitivity by order of magnitudes

Conclusions

Today's Focus: Dark sector signals, including Heavy Neutral Leptons, Axionlike particles, and exotic Higgs decays

The FCC offers numerous opportunities for LLP studies, with the Z pole and ZH pole runs being especially crucial

Working on designing our detectors to maximize these opportunities!

Working full steam toward completion of the Feasibility Study by Spring 2025 to build the strongest case for the FCC project for the next European Strategy

FCC: A Gateway to Discovery !

Backup