LLPs from Exotic Higgs Decays at FCC-ee

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3rd ECFA workshop on e+e- Higgs, Electroweak and Top Factories

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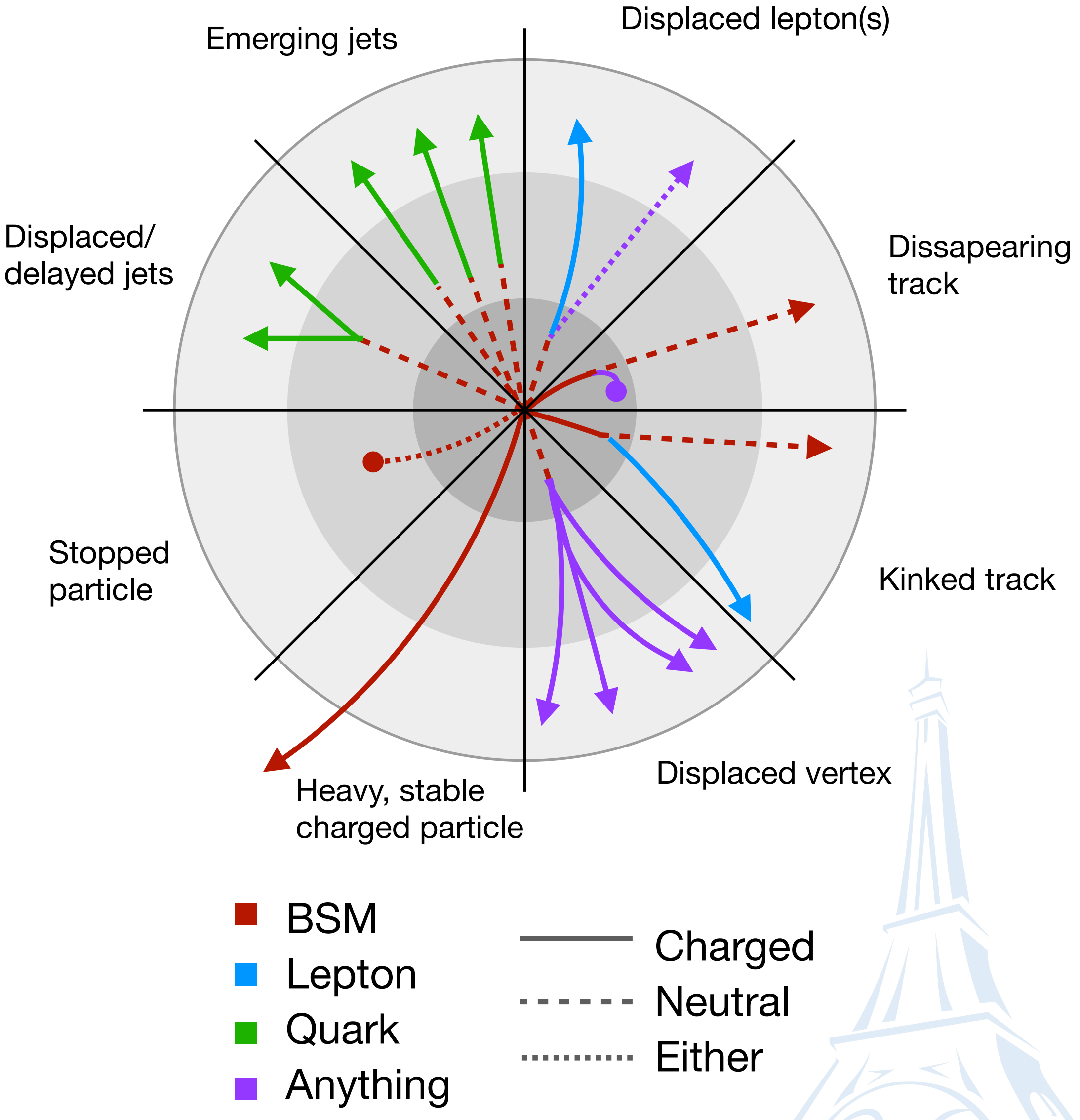
FUTURE CIRCULAR COLLIDER

Searches for long-lived particles

- **Long-Lived Particles** (LLPs) are abundant in the SM and well-motivated in several BSM models
    - Searching for LLP signatures is technically challenging → new physics could have evaded detection until now!
- 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

Room for improvement at future colliders!

Distinct signatures depending on the LLP lifetime, mass, charge, and decay products

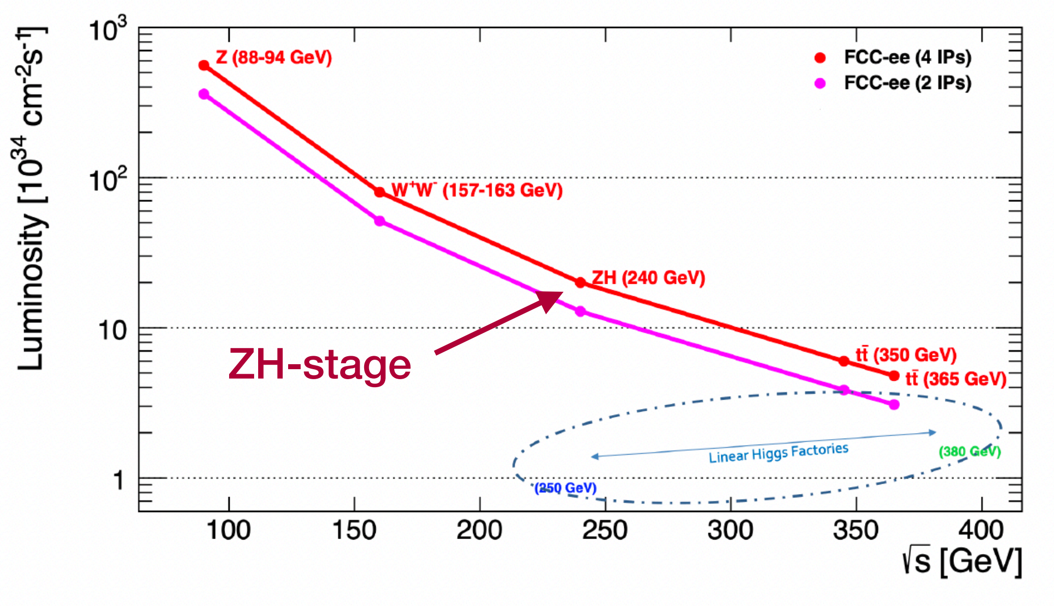


New physics from Higgs decays

FCC-ee as a discovery machine

- The Higgs boson is and can be connected to many open physics questions
  - The electroweak phase transition
  - Dark Matter
  - Naturalness
  - Flavour (wide hierarchy of fermion masses)
- To study its properties is a powerful probe to new physics!
- The ZH-stage of FCC-ee will produce $1.45 \cdot 10^6$ ZH events in a very clean environment!
- Currently predict 1% precision on the total Higgs width, and BR(H -> inv) < 0.18%
  - Will set indirect constraints on BSM physics
  - Still the Higgs boson can have sizeable couplings to new particles → exotic Higgs decays

Baseline luminosities for FCC-ee



Reference: FCC Midterm Report

Great potential to directly search for BSM physics!

Long-lived scalars from exotic Higgs decays

- Our considered model: SM + scalar (arXiv:1312.4992, arXiv:1412.0018)
- The new scalar can be a portal between the SM and a dark sector, motivated by e.g Dark Matter
- New real scalar field S couples to the Higgs doublet H at renormalizable level, via the **Higgs-Scalar coupling κ**

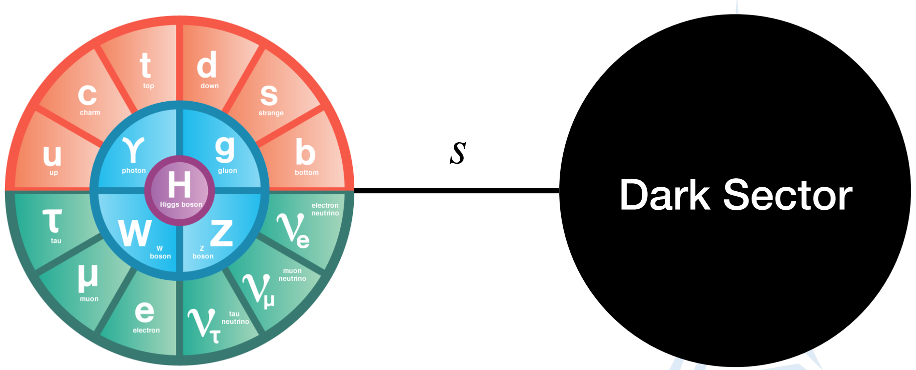
$$\mathcal{L}_{SM} \ni \underbrace{\frac{1}{2}\mu_S^2 S^2 - \frac{1}{4!}\lambda_s S^4}_{\text{scalar potential}} - \underbrace{\frac{1}{2}\kappa S^2 |H|^2}_{\text{portal term}} + \underbrace{\mu^2 |H|^2 - \lambda |H|^4}_{\text{Higgs potential}}$$

$$\mathrm{BR}(h \to ss) = \frac{\kappa^2 v_h^2}{32\pi m_h \Gamma_h}\sqrt{1 - 4\frac{m_s^2}{m_h^2}}$$

- The physical Higgs boson h and the scalar s mix with a **mixing angle sin θ**
- The scalar inherits its couplings to the SM particles from the Higgs

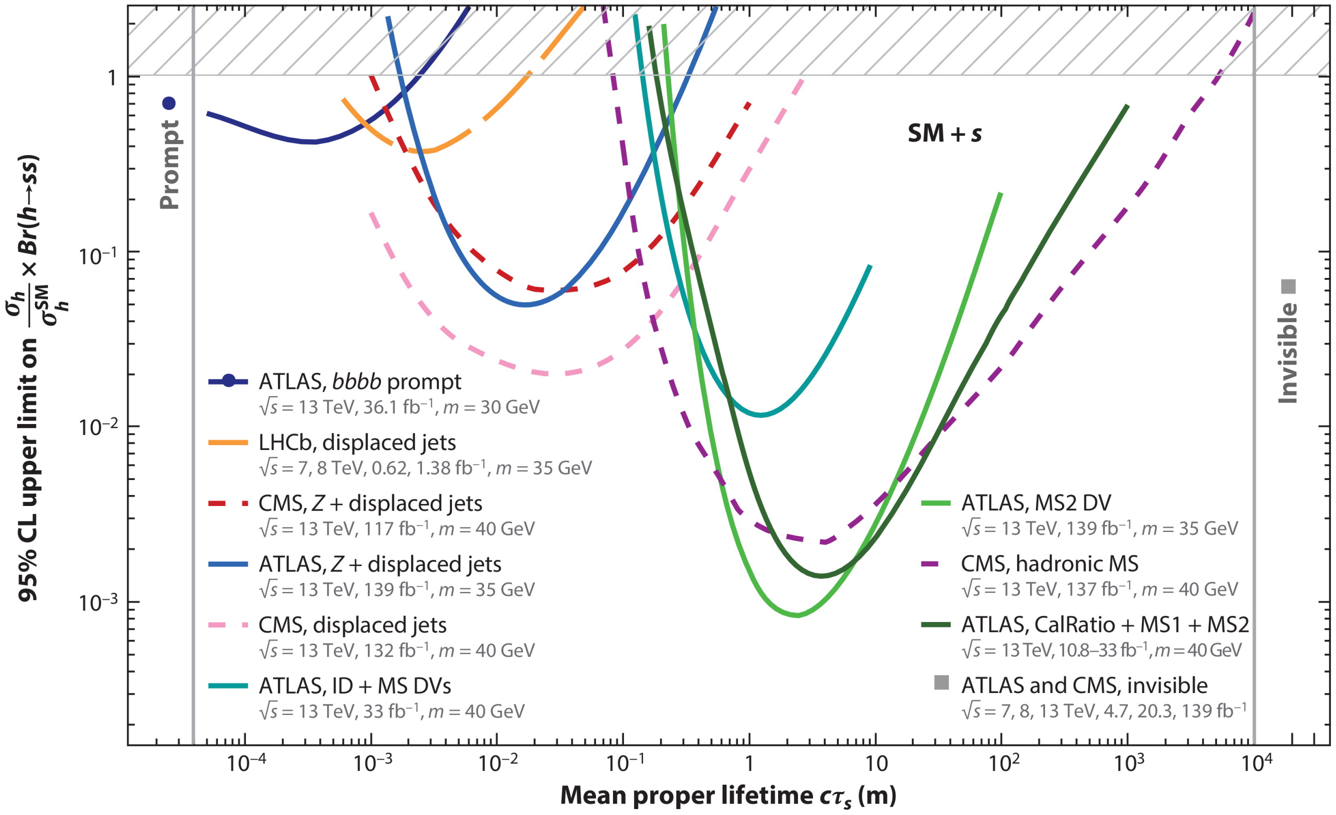
$$\Gamma\left(s \to X_{\mathrm{SM}} X_{\mathrm{SM}}\right) = \sin^2\theta\, \Gamma\left(h(m_s) \to X_{\mathrm{SM}} X_{\mathrm{SM}}\right)$$

- For sufficiently small mixing, the scalar can be long-lived
  - cτ ~ meters if θ < 1e-6 → **LLP signature**



Long-lived scalars are already a hot topic!

Existing limits from several LHC experiments



Cepeda M, et al. 2022
Annu. Rev. Nucl. Part. Sci. 72:119–49

Reference: Exotic Higgs Decays
DOI: 10.1146/annurev-nucl-102319-024147

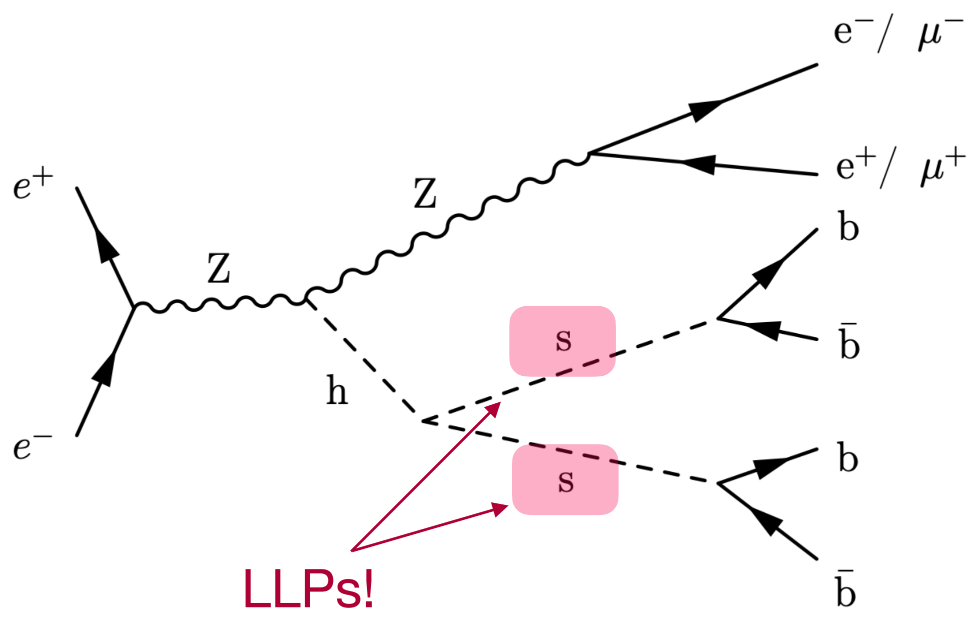
- Searches at ATLAS, CMS and LHCb
  - Exotic Higgs decay to a pair of long-lived scalars in the mass range 30-40 GeV
- For shorter LLP lifetimes the LHC backgrounds are high

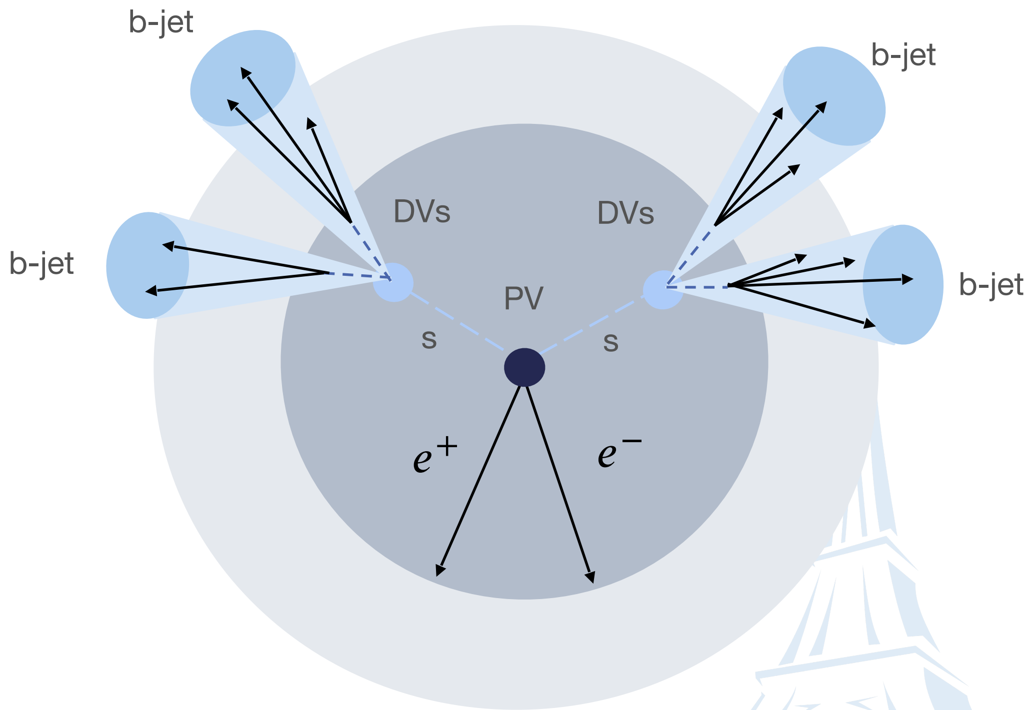
→ The parameter space at shorter distances, cτ < 1 m, is an interesting target for future lepton colliders!

LLPs from exotic Higgs decays @ FCC-ee

- Targeting the ZH stage of FCC-ee: 240 GeV c.o.m and $L = 7.2\ ab^{-1}$
- Signal process: $e^+ e^- \rightarrow ZH$ with $Z \rightarrow e^+ e^-$ or $\mu^+ \mu^-$ and $H \rightarrow ss \rightarrow 4b$
- Experimental signature:
  - A reconstructed Z boson from the e^+e^- or $\mu^+\mu^-$ - pairs
  - Displaced vertices (DVs) from the long-lived scalar decays

Main SM backgrounds from WW, ZZ and ZH processes with heavy-flavor and tau decays



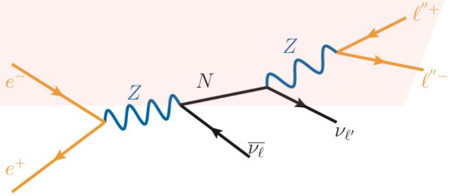


Simulation and analysis of long-lived scalars @ FCC-ee

Typical workflow

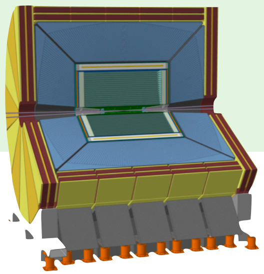
Sample generation of models

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



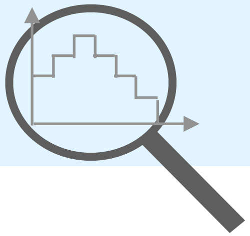
Parametrised detector simulation

- IDEA DELPHES card



Analysis tools

- FCCAnalyses framework



Sensitivity to studied model

- The scalars can be simulated with the MadGraph5 HAHM model (arXiv:1312.4992, arXiv:1412.0018)
- Simulation of background processes
  - SM processes in the Winter2023 campaign
    - Centrally produced samples within the FCCAnalyses framework
  - Sample generation with Pythia8 or Pythia6 + Wizard
  - $37 \cdot 10^7$ raw WW events, $56 \cdot 10^6$ raw ZZ events and $32 \cdot 10^6$ raw ZH events (all with inclusive decays)

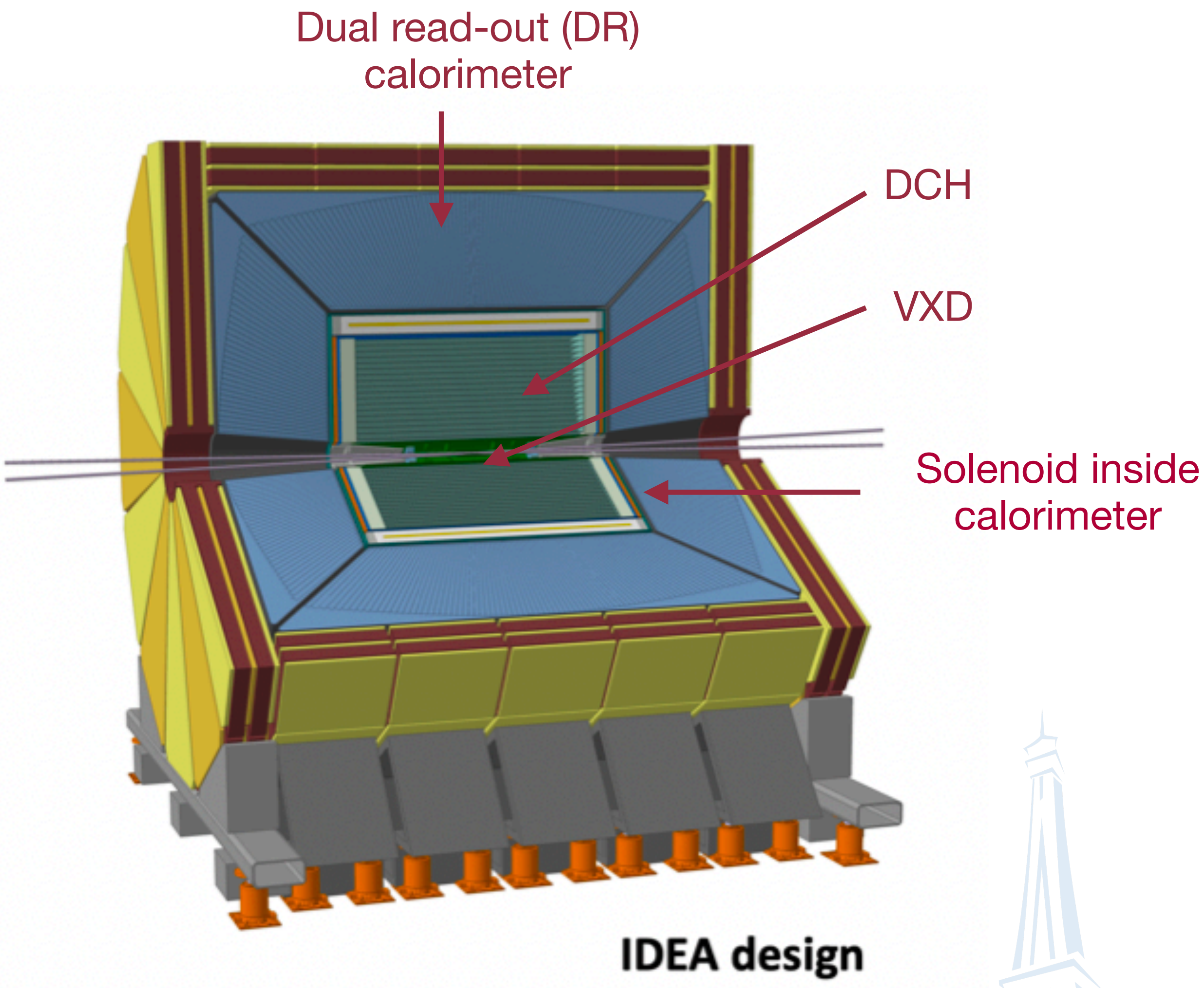
Detector simulation

The IDEA detector

- Current detector design consists of e.g:
  - Silicon vertex detector (VXD)
    - **1.2-31.5 cm**: 5 cylindrical barrel layers and 6 endcap discs (3 on each side)
  - An ultralight drift chamber (DCH)
    - **35-200 cm**: 112 layers of wires

→ **Many tracking layers!**

- The full geometry of the detector is simulated in DELPHES



Generated signals

- Parameter choices:
  - m_s = 20-60 GeV
  - sin θ = 10^{-5}-10^{-7} corresponding to mean proper lifetimes cτ of O(1 mm – 10 m)
  - κ = 7e-4, s.t we have less than 1% addition to the Higgs width

κ: the Higgs-scalar coupling

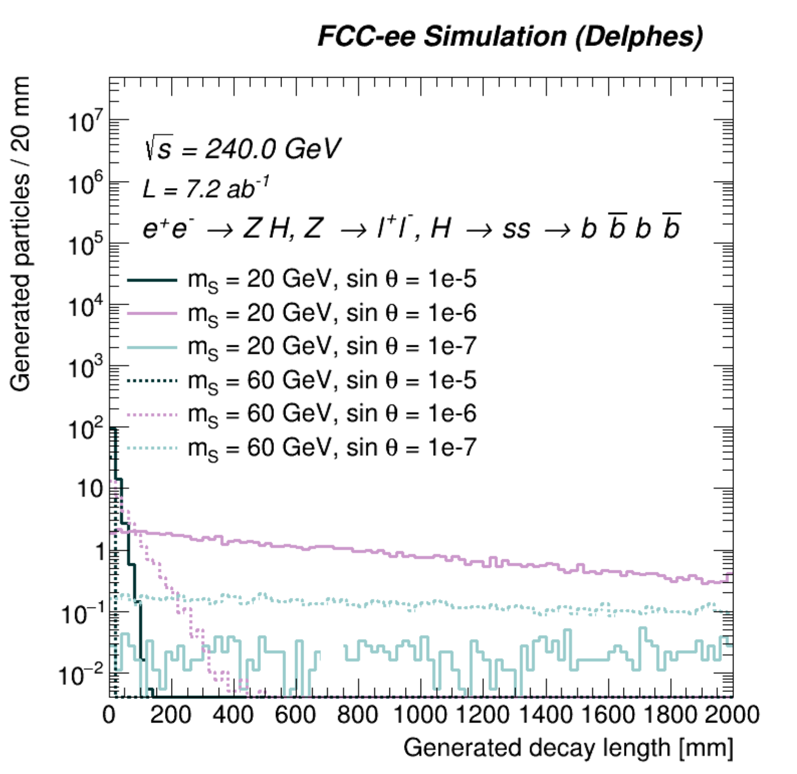
$$\mathrm{BR}(h \to ss) = \frac{\kappa^2 v_h^2}{32\pi m_h \Gamma_h}\sqrt{1 - 4\frac{m_s^2}{m_h^2}}$$

$$\Gamma_s = \sin^2\theta \frac{3}{0.9 \times 8\pi} \frac{m_s m_b^2}{v_h^2}\left(1 - \frac{4m_b^2}{m_s^2}\right)^{3/2}$$

sin θ: Mixing angle

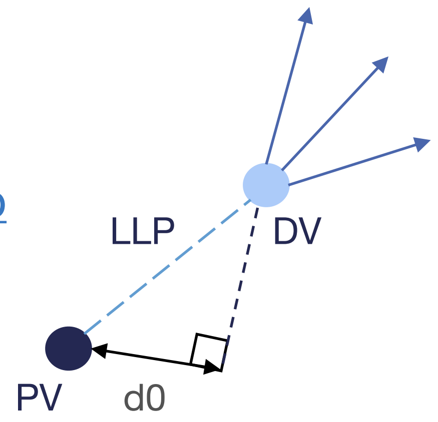
Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Width of Scalar Γ_s [GeV]	Branching Ratio $\mathrm{BR}(h \to ss)$	Mean proper lifetime $c\tau$ [mm]
20	1×10^{-5}	5.779×10^{-14}	6.98×10^{-4}	3.4
20	1×10^{-6}	5.779×10^{-16}	6.98×10^{-4}	341.7
20	1×10^{-7}	5.779×10^{-18}	6.98×10^{-4}	34167.0
40	1×10^{-5}	1.445×10^{-13}	5.66×10^{-4}	1.4
40	1×10^{-6}	1.445×10^{-15}	5.66×10^{-4}	136.6
40	1×10^{-7}	$1.445\mathrm{e} \times 10^{-17}$	5.66×10^{-4}	13662.8
60	1×10^{-5}	2.252×10^{-13}	2.06×10^{-4}	0.9
60	1×10^{-6}	2.252×10^{-15}	2.06×10^{-4}	87.7
60	1×10^{-7}	2.252×10^{-17}	2.06×10^{-4}	8769.1

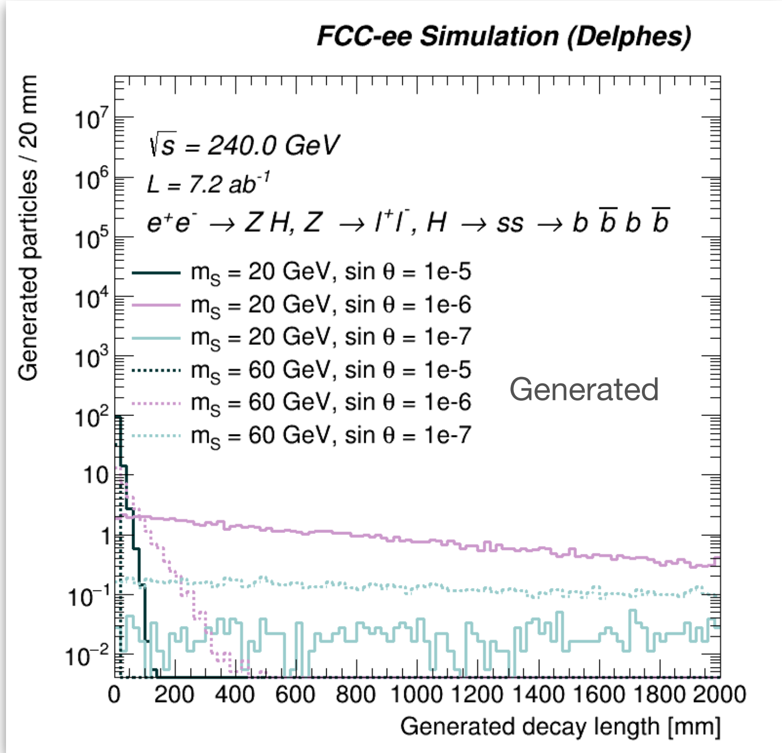
Table of some of the generated signals

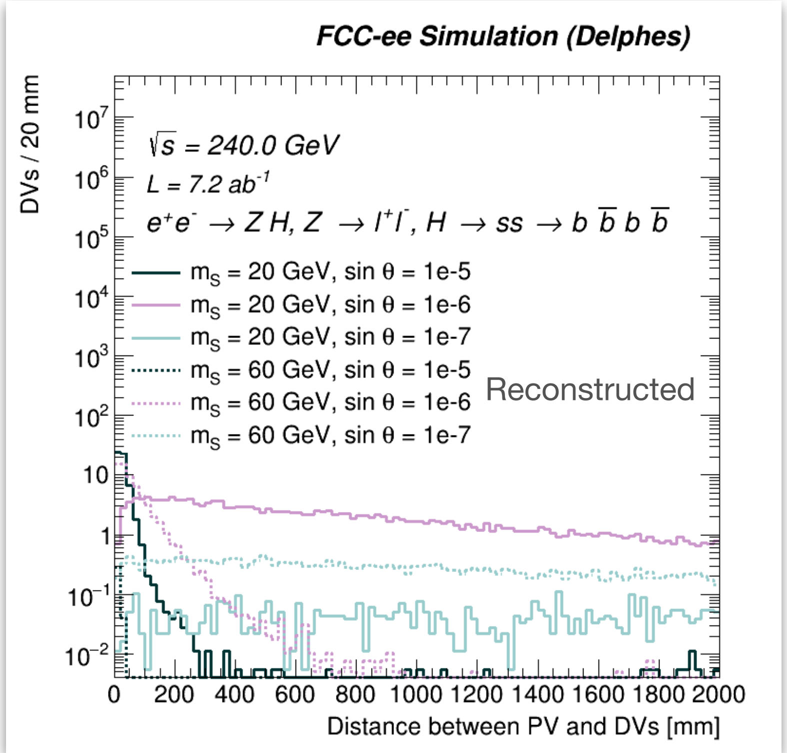


DV reconstruction

- Using current tools in the FCCAnalyses framework
- Secondary vertex finder of the LCFI+ algorithm (arXiv:1506.08371), see more in backup
  - Designed for ILC/CLIC and primarily used for flavour-tagging jets
  - Added **track selection:** non-primary, pT > 1 GeV and |d0| > 2 mm

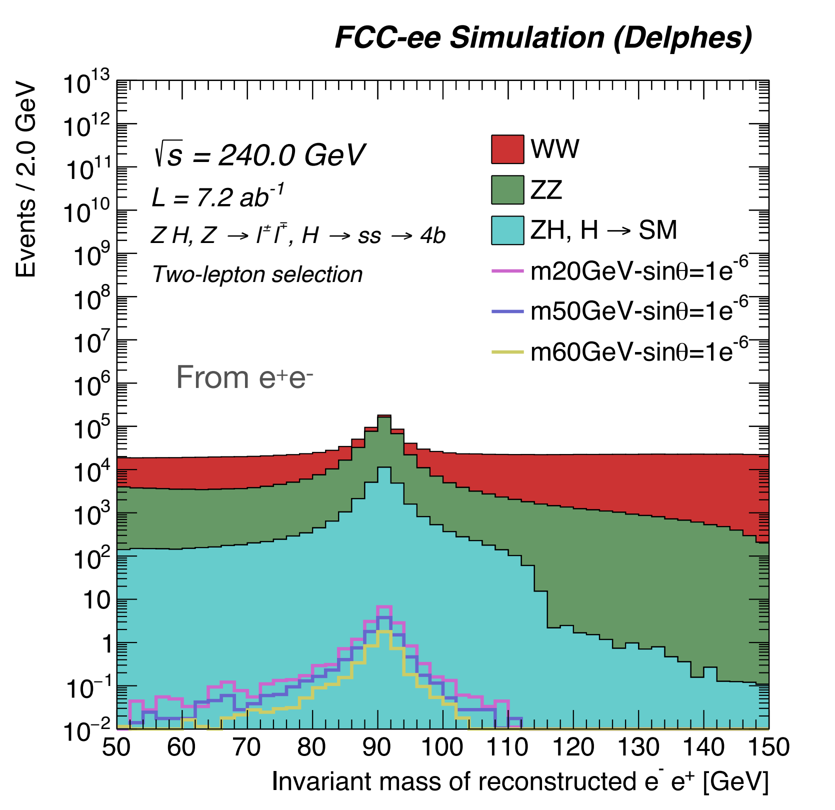


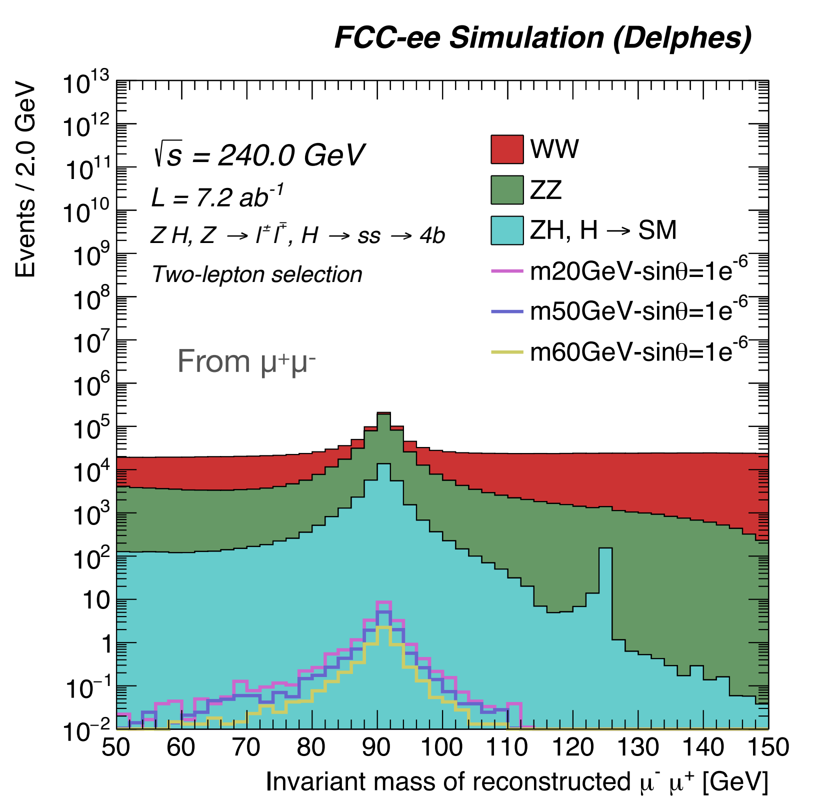




Reconstruction of the Z-boson

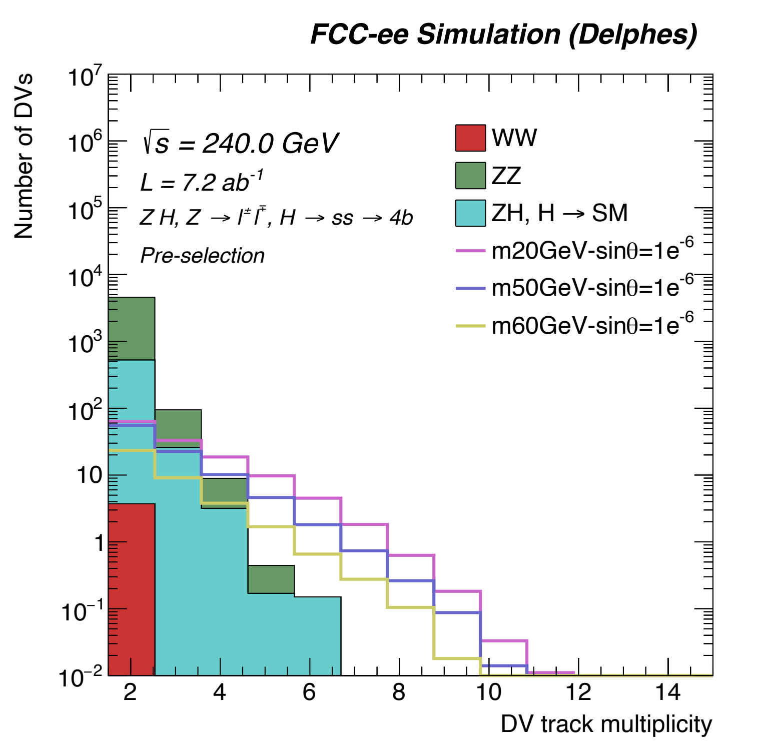
- Require exactly 2 oppositely charged isolated electrons or muons
- Tag the Z-boson with the e^+e^- or $\mu^+\mu^-$ invariant mass
  - Pre-selection: set a mass window between 70-110 GeV

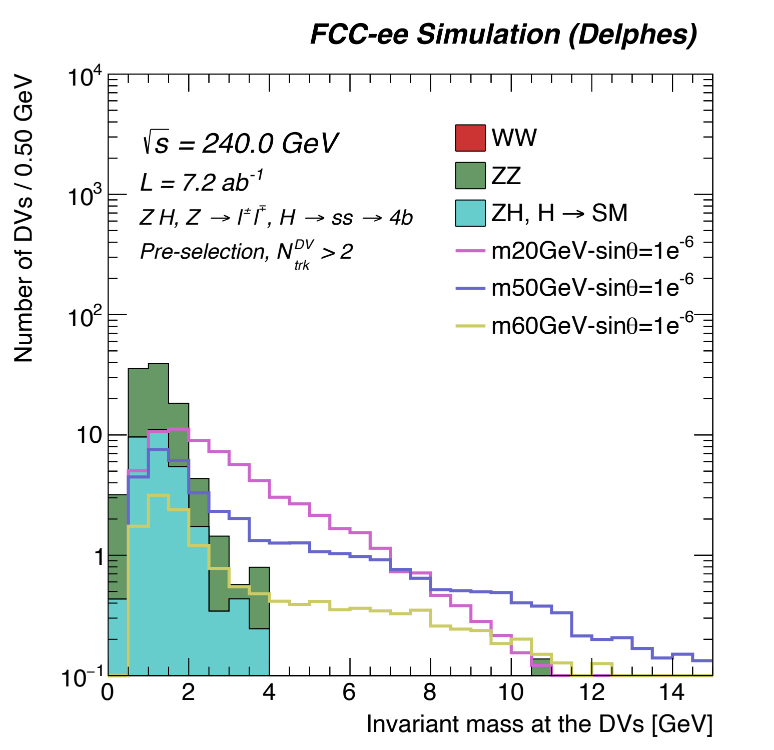


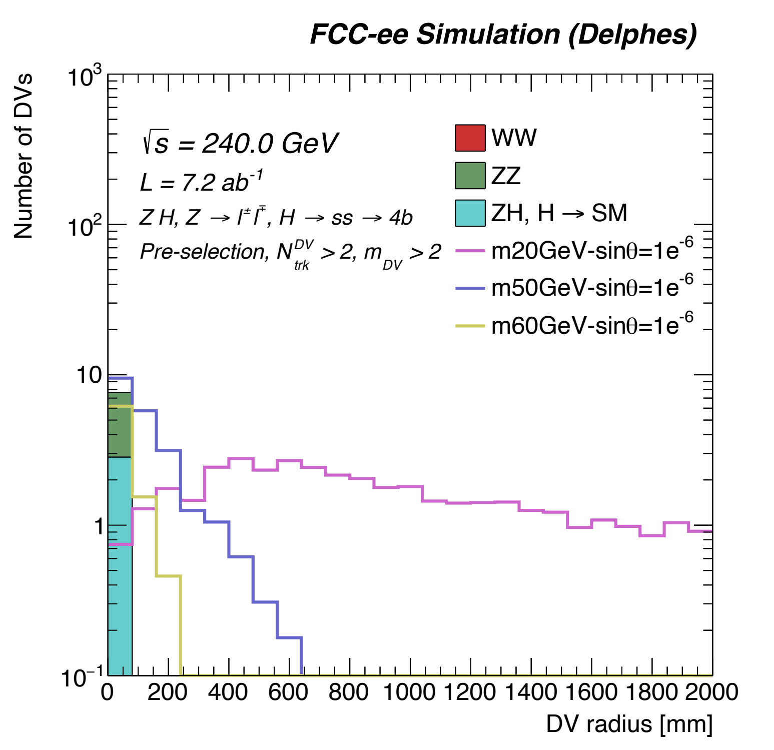


Discriminating variables of the DVs

- The **number of tracks per DV**, the charged **invariant mass of the DVs** and the **radius** are three efficient variables to separate signal from background!
- Event pre-selection applied in all, following requirements on DVs applied
  - N tracks > 2 (in the middle and right plot)
  - M_{inv} > 2 GeV (in the right plot)



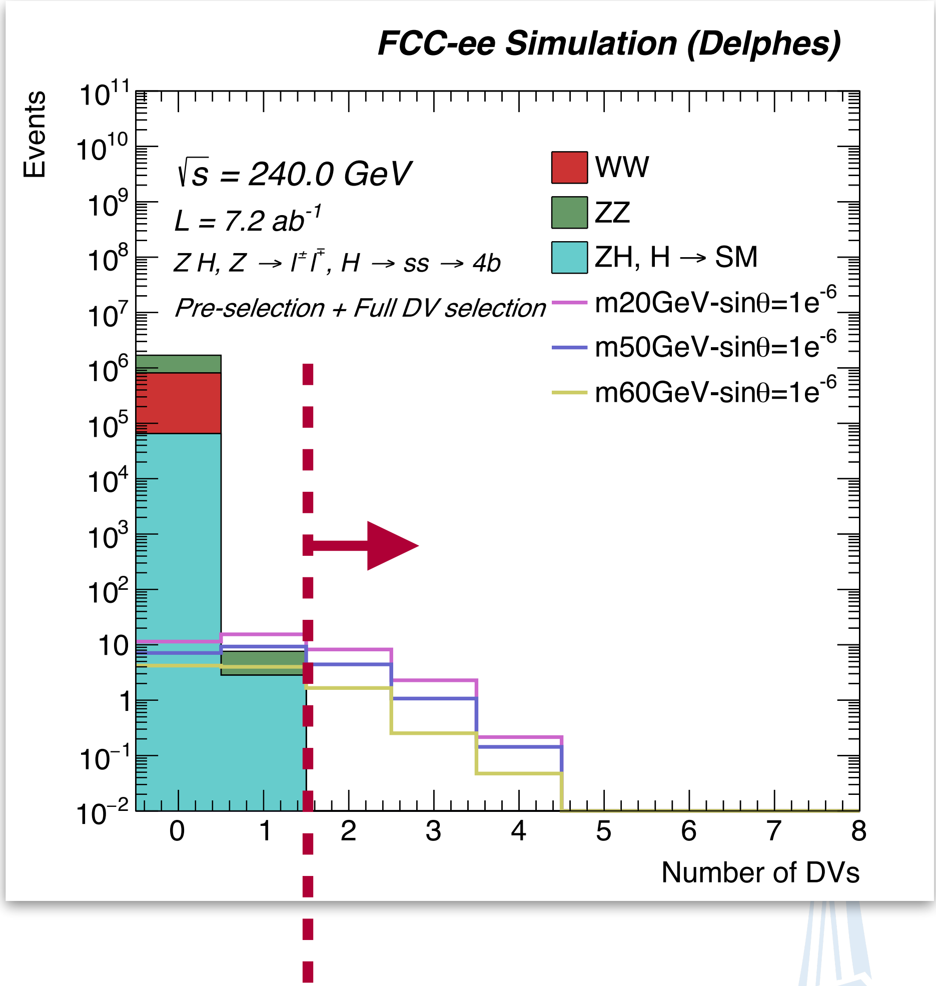




Vertex and event selection

- **Vertex selection:**
  - At least 3 tracks
  - Min (charged) invariant mass of 2 GeV
  - Distance between the DV and PV between 4 mm and 2000 mm

- **Event selection:**
  - Pre-selection - Two oppositely charged isolated leptons with invariant mass in the range 70-110 GeV
  - At least 2 DVs passing the full vertex selection



Pre-selection + full vertex selection: n DVs >= 2

Results - sensitivity analysis

SM background free with sensitivity to part of the generated parameter space!

- Given zero background, signal points with at least 3 expected events can be excluded to CL 95%

	Before selection	Exactly 2 oppositely charged leptons	Pre-selection	Pre-selection + Full DV-selection
ZH, H→SM	938,471 ± 527	74,931 ± 66	65,085 ± 62	$0(\leq 62)$
WW	118,357,200 ± 3,668	3,324,881 ± 1,059	746,175 ± 502	$0(\leq 502)$
ZZ	9,784,728 ± 429.730	1,319,337 ± 426	883,991 ± 348	$0(\leq 349)$
Total Background	129,080,399 ± 4,625	4,719,149 ± 1,551	1,695,251 ± 912	$0(\leq 912)$
ms20GeV_sine-5	55.195 ± 0.041	38.300 ± 0.460	36.964 ± 0.452	0.077 ± 0.021
ms20GeV_sine-6	55.195 ± 0.041	38.919 ± 0.464	37.621 ± 0.456	10.739 ± 0.243
ms20GeV_sin3e-6	55.195 ± 0.041	37.713 ± 0.456	36.350 ± 0.448	3.262 ± 0.134
ms20GeV_sine-7	55.195 ± 0.041	48.307 ± 0.516	47.026 ± 0.509	0.215 ± 0.034
ms40GeV_sine-5	44.770 ± 0.030	29.382 ± 0.363	28.357 ± 0.356	0.031 ± 0.012
ms40GeV_sine-6	44.770 ± 0.030	29.504 ± 0.364	28.510 ± 0.357	9.169 ± 0.203
ms40GeV_sine-7	44.770 ± 0.030	37.942 ± 0.412	36.827 ± 0.406	1.280 ± 0.076
ms50GeV_sine-6	34.963 ± 0.021	22.858 ± 0.283	22.060 ± 0.278	5.649 ± 0.141
ms60GeV_sine-5	16.322 ± 0.007	10.425 ± 0.130	10.105 ± 0.128	$0(\leq 0.128)$
ms60GeV_sine-6	16.322 ± 0.007	10.518 ± 0.131	10.172 ± 0.129	1.961 ± 0.057
ms60GeV_sine-7	16.322 ± 0.007	12.615 ± 0.144	12.282 ± 0.142	2.344 ± 0.062

- Applied event selections from left to right, results given in number of expected events and uncertainties are only statistical

Comparison to existing limits

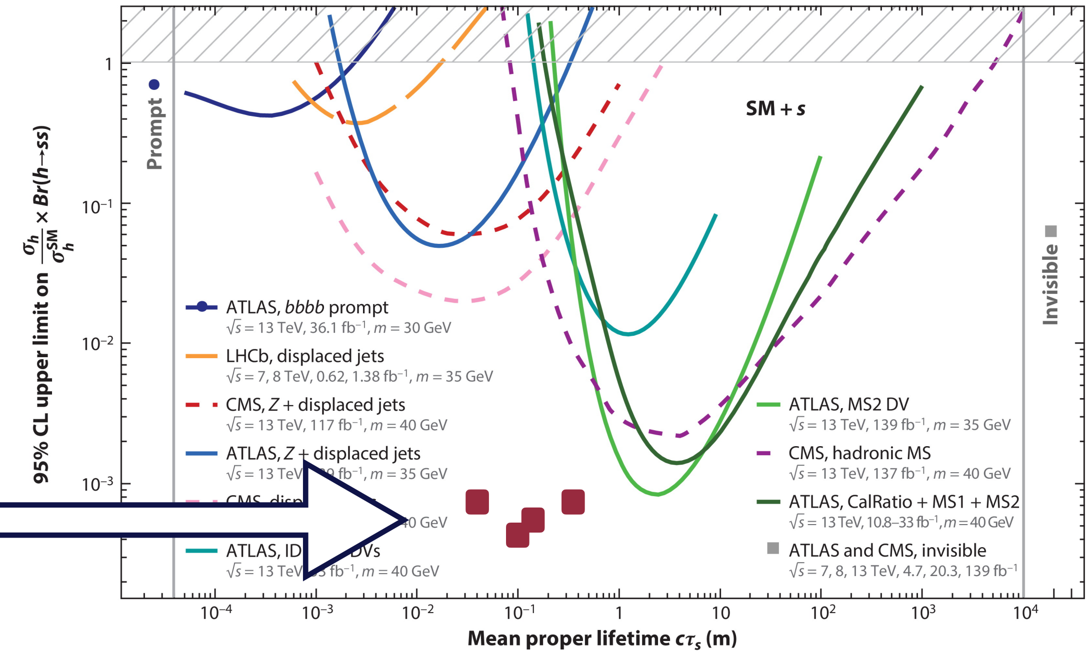
Complementary to the LHC searches!

- The sensitive signal points probes BRs ~ 4-7·10^{-4} and span the mean proper lifetimes of ~ 40-400 mm
- Reaching slightly **shorter lifetimes** compared to the best existing limits
  - LHC: BR ~ 10^{-3} for lifetimes 1-10m
- About two orders **better sensitivity** at similar lifetimes
  - LHC: BR ~ 2·10^{-2} for lifetimes 1mm - 1m

Reference: Exotic Higgs Decays
DOI: 10.1146/annurev-nucl-102319-024147

m_s, sin θ	$c\tau$ [mm]	BR($h \to ss$)	Full event selection
20 GeV, 1e-6	341.7	6.981×10^{-4}	10.739 ± 0.243
20 GeV, 3e-6	38.0	6.981×10^{-4}	3.262 ± 0.134
40 GeV, 1e-6	136.6	5.663×10^{-4}	9.169 ± 0.203
50 GeV, 1e-6	106.6	4.422×10^{-4}	5.649 ± 0.141

Our sensitive signal points



Cepeda M, et al. 2022
Annu. Rev. Nucl. Part. Sci. 72:119–49

Summary

Exotic Higgs decays to long-lived scalars can be targeted at FCC-ee!

- Analysis and simulation within the FCCAnalyses framework with the IDEA detector DELPHES simulation
  - Signal process: $e^+ e^- \rightarrow ZH$ with $Z \rightarrow e^+ e^-$ or $\mu^+ \mu^-$ and $H \rightarrow ss \rightarrow 4b$
  - Signal points: m_s = 20 - 60 GeV with lifetimes $c\tau$ of order 1mm - 10m
- Reconstruction of the DVs using the LCFI+ SV finder
  - Custom track selection: $pT > 1$ GeV and $|d0| > 2$mm
- Sensitivity analysis
  - Vertex selection: N tracks > 2, $M_{inv} > 2$ GeV and 4mm < r < 2000mm
  - Event selection: tagging the Z boson and requiring at least 2 DVs

Thank you for your attention!

Backgrounds efficiently suppressed to zero!
Sensitivity for signals with $c\tau$ ~ 0.04 - 0.4m

Backup slides

Model parameters and calculations

- Width of scalar and branching ratios for s from arXiv:1312.4992

$$\Gamma_s = \frac{\Gamma(s \to b\bar{b})}{BR(s \to b\bar{b})} = \sin^2\theta \frac{N_c m_S m_b^2}{0.9 \times 8\pi v^2}\left(1 - \frac{m_b^2}{m_s^2}\right)^{3/2}$$

- Approximate the number of events with

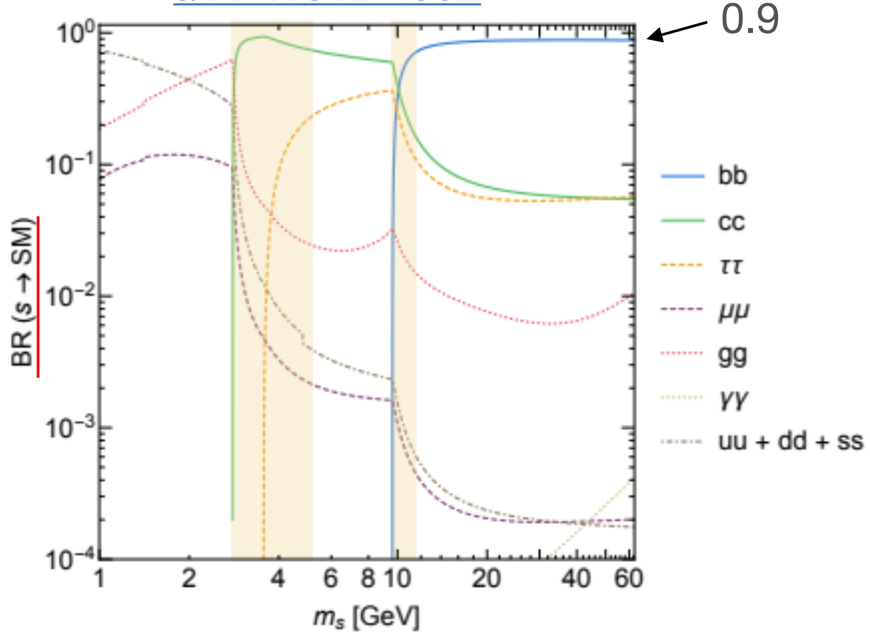
$$N = N_{ZH} \times BR(h \to ss) \times BR(s \to b\bar{b})^2 \times BR(Z \to l^+l^-)$$

- The branching ratio for Higgs to s (arXiv:2111.12751)

$$BR(h \to ss) = \frac{\kappa^2 v^2}{32\pi m_h \Gamma_h}\sqrt{1 - 4\frac{m_s^2}{m_h^2}}$$

- We set κ = 7e-4 s.t $BR(h \to ss) = O(10^{-4})$
- $BR(s \to b\bar{b})^2 = 0.9^2$, from plot
- $N_{ZH} = 1.45e6$, from midterm report

arXiv:1312.4992

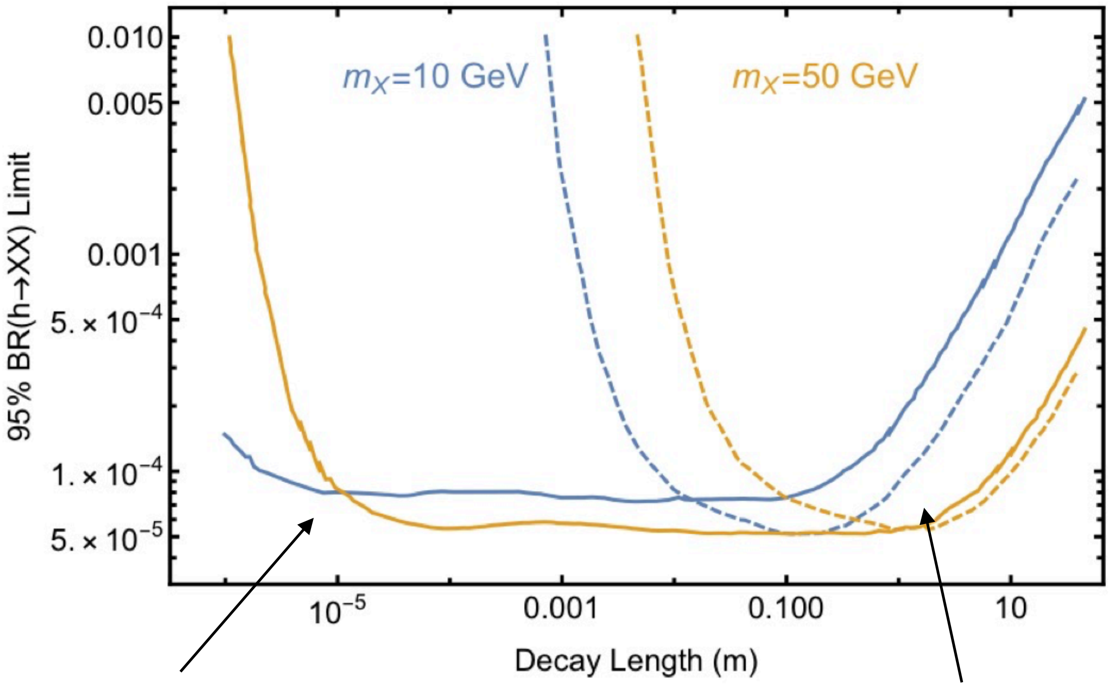


Vertex reconstruction

- More details in thesis: DiVA
- LCFIPlus: A Framework for Jet Analysis in Linear Collider Studies: arXiv:1506.08371
- FCCAnalyses framework vertex reconstruction: GitHub

Previous studies: exotic Higgs decays FCC-ee sensitivity

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



Invariant mass cut to retain sensitivity to shorter decay lengths

Cuts optimised for longer decay lengths

- Projected 95% h → XX branching ratio limits as a function of proper decay length for a variety of X masses.
- The solid line corresponds to the 'large mass' analysis, using an invariant mass cut to retain sensitivity to shorter decay lengths.
- The dashed line corresponds to the 'long lifetime' analysis and depends on longer decay lengths to reduce SM backgrounds
- Realistic tracker-based search strategy involving the reconstruction of displaced secondary vertices and the imposition of selection cuts appropriate for eliminating the largest irreducible SM backgrounds.

Plot from: arXiv:2203.05502
Results from: arXiv:1812.05588