FUTURE CIRCULAR COLLIDER

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UPPSALA UNIVERSITET

LLPs from Exotic Higgs Decays at FCC-ee

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

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2024-11-05

Why search for long-lived particles?

- Long-lived particles (LLPs) are abundant in the SM…

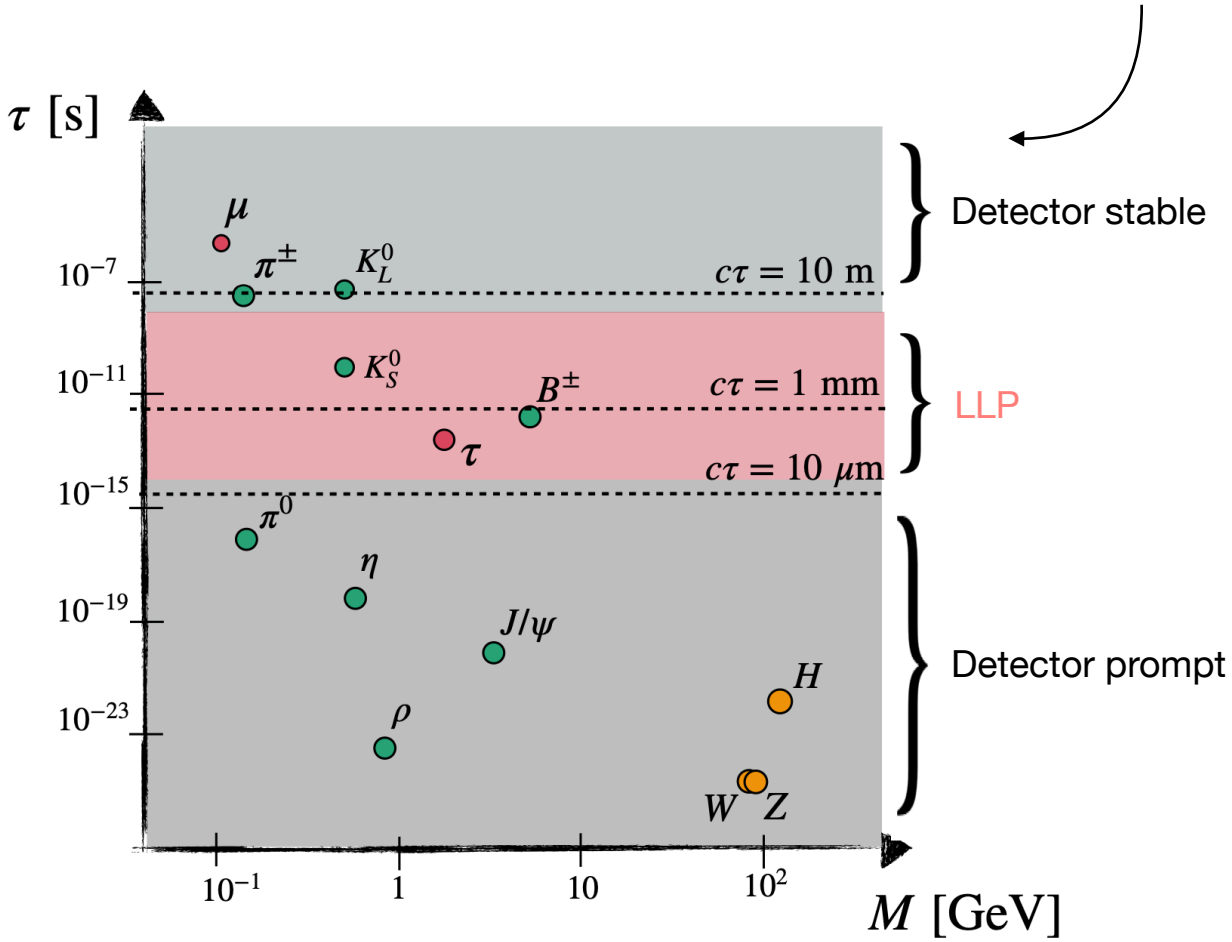


Image credit: Jackson Burzynski

Why search for long-lived particles?

- Long-lived particles (LLPs) are abundant in the SM… and well motivated in many BSM models

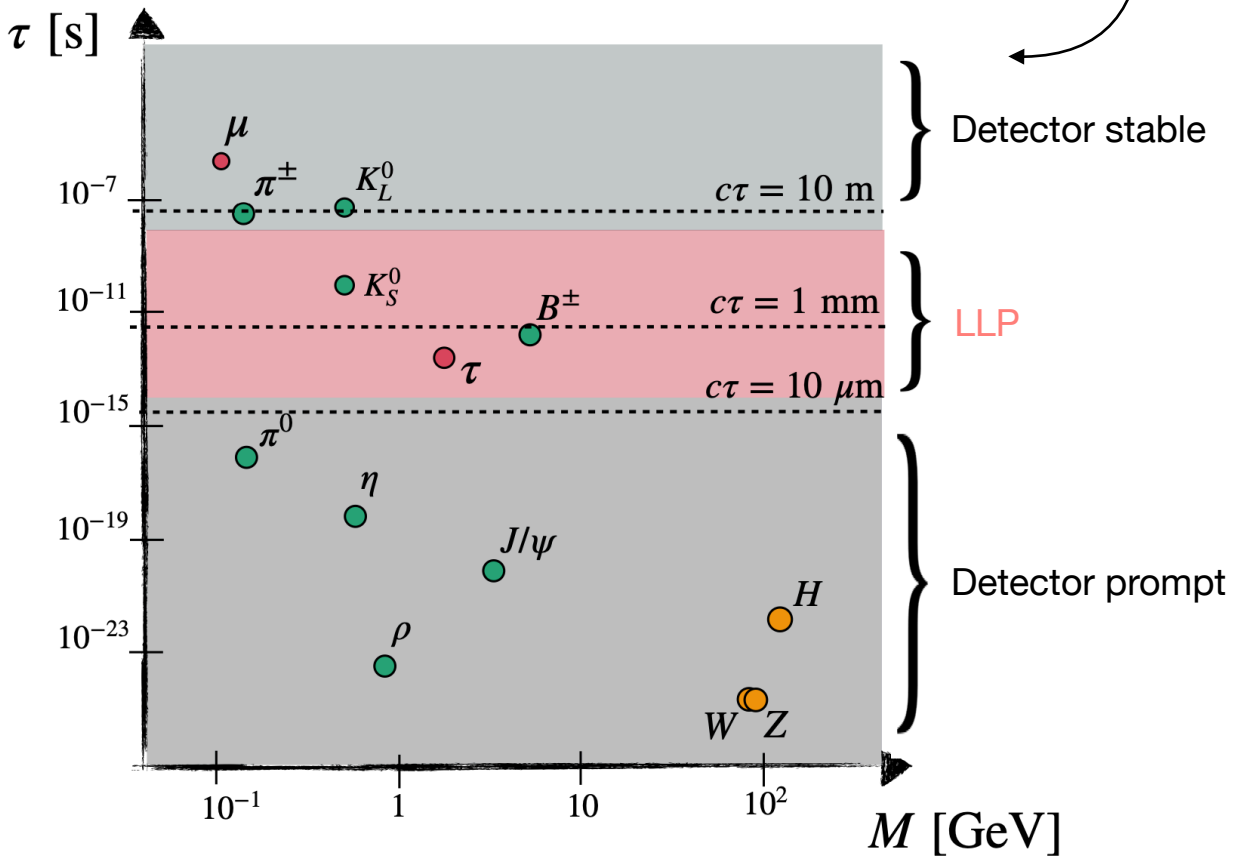
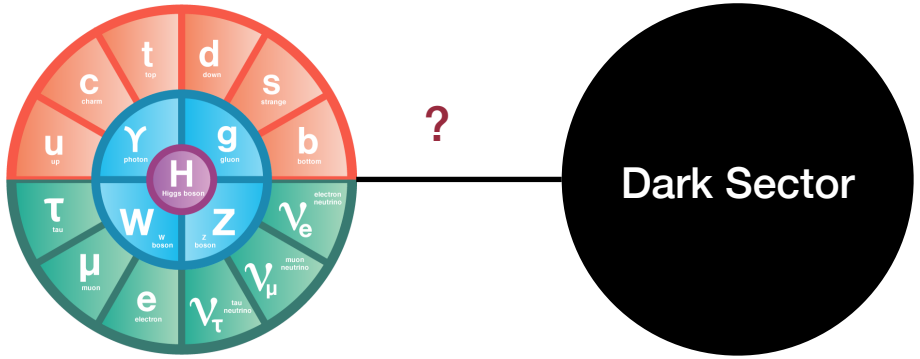


Image credit: Jackson Burzynski

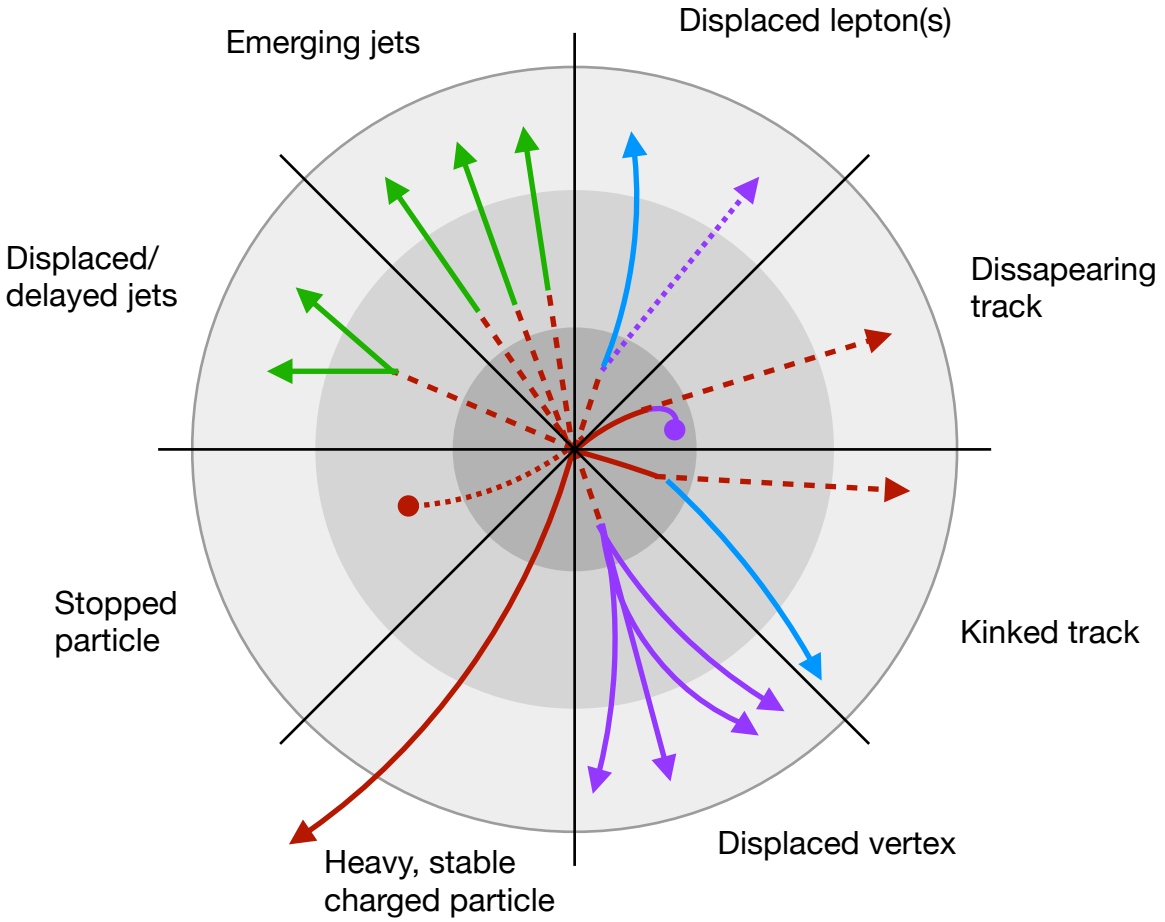
e.g Hidden sector models



Small portal couplings between dark and visible sectors → LLPs

LLP searches at colliders

Unconventional experimental signatures



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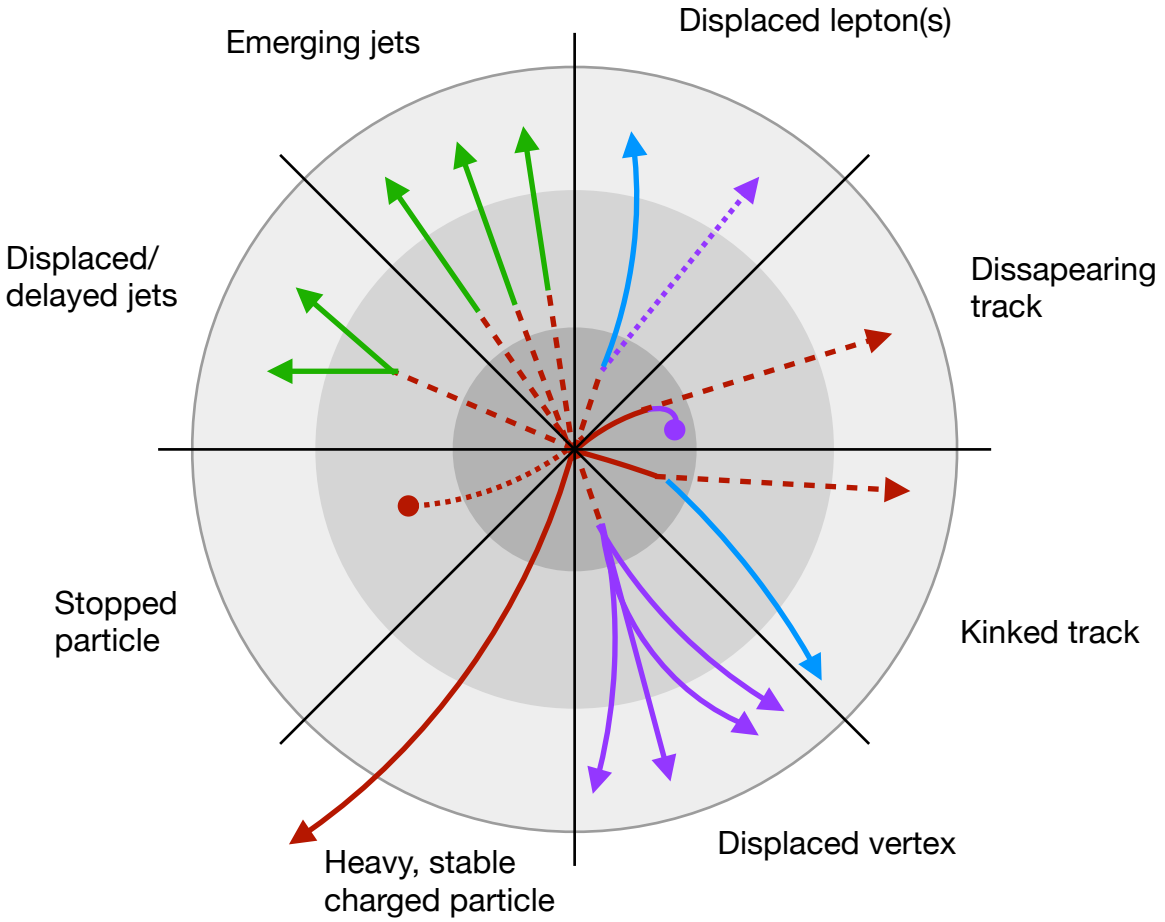


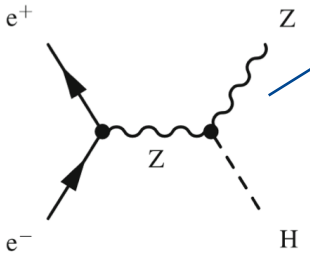
- Experimental **benefits**:
  - Generally low backgrounds from SM decays
- Experimental **challenges**:
  - Main detectors, triggers, and offline reconstruction not designed for LLPs

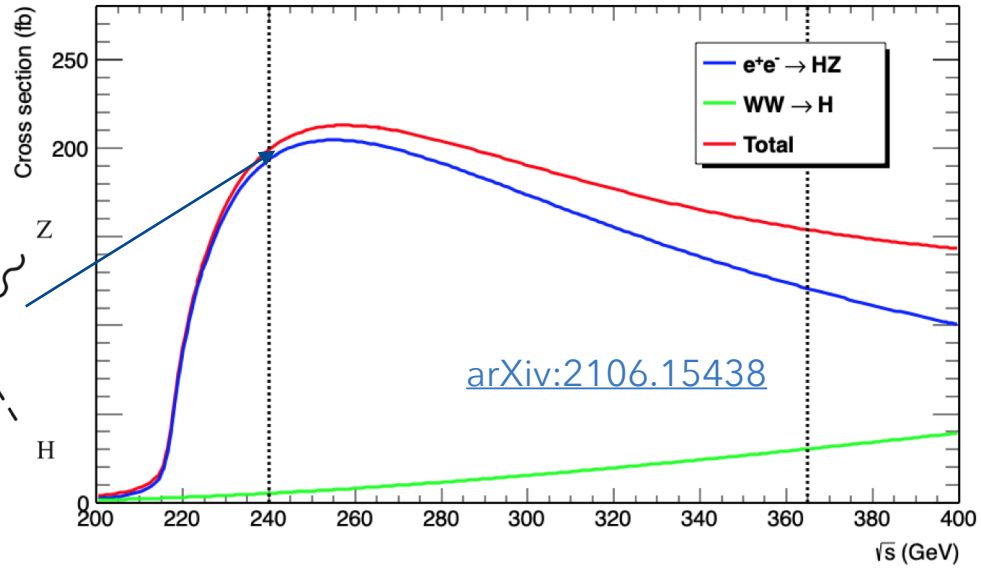
Room for improvement at future colliders!

Higgs physics at the FCC-ee

Indirect and direct probe of BSM physics

- FCC-ee will give us 2M ZH events at 240 GeV





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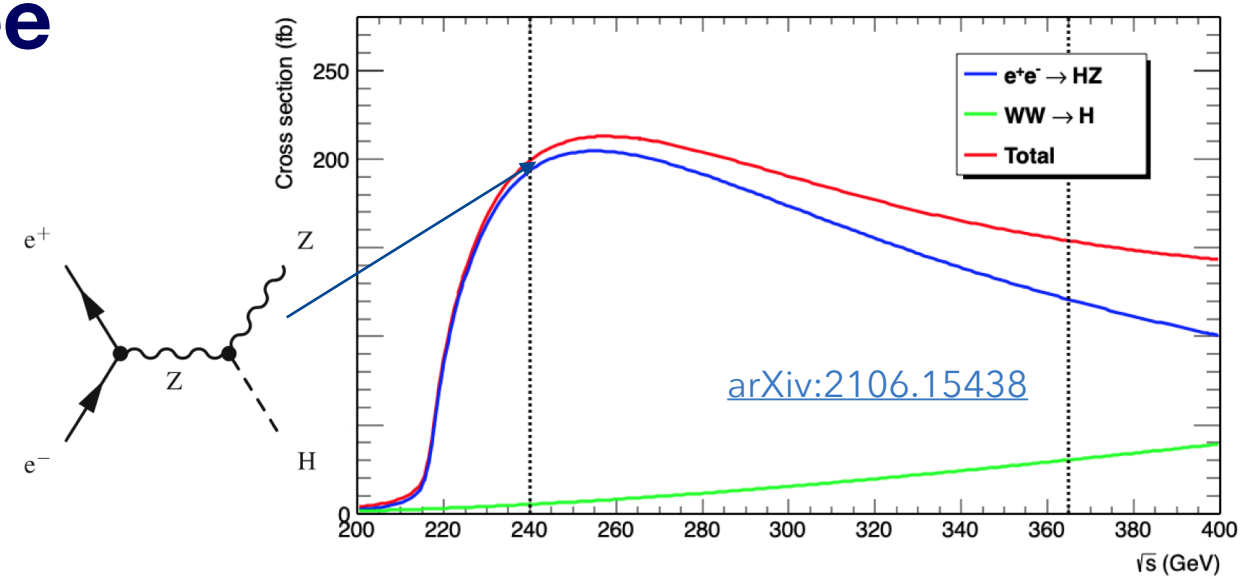
- Precision Higgs program will constrain BR(H→exotics) to <1%



Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
	...	
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.0 / 0.88

Numbers from arXiv:1905.03764

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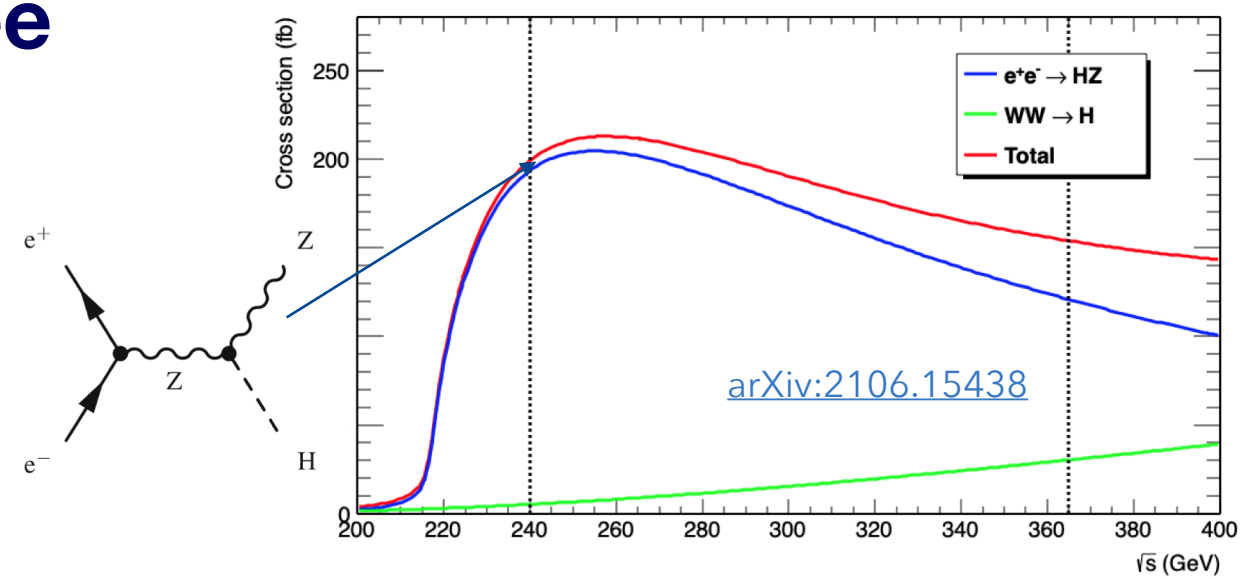
- Precision Higgs program will constrain BR(H→exotics) to <1%
- Still room for particles and sectors whose couplings to the Higgs are nonzero
  …as long as they are small → LLPs!
- FCC-ee conditions are great for finding LLPs:
  Clean events, No trigger, High luminosity



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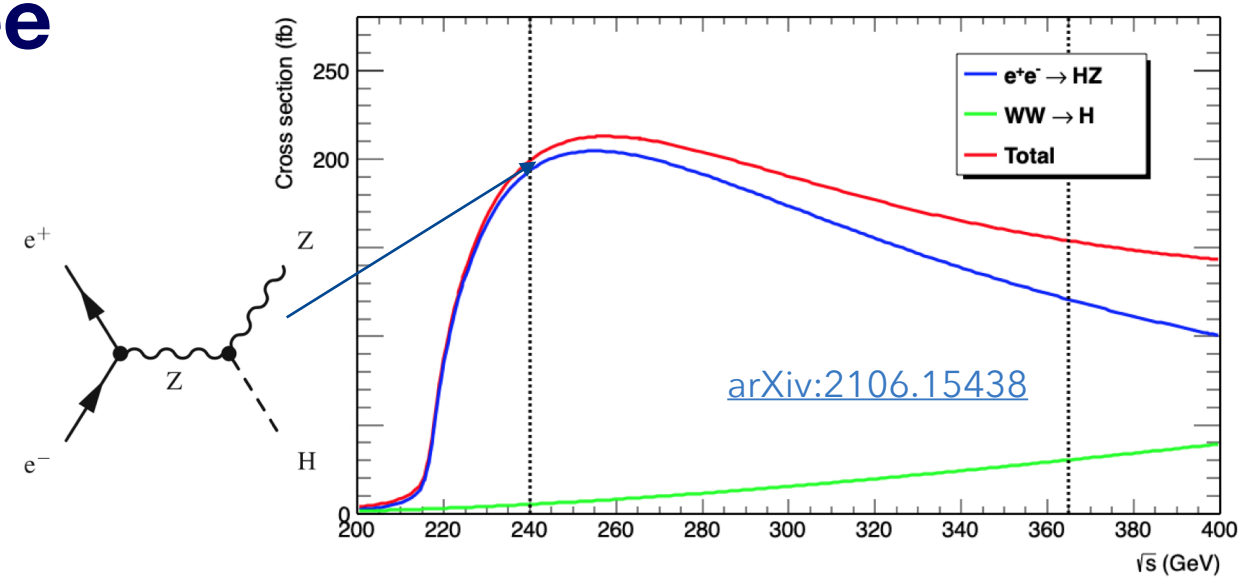
Searches for Exotic Higgs Boson decays into LLPs is a crucial complement to the FCC-ee precision program



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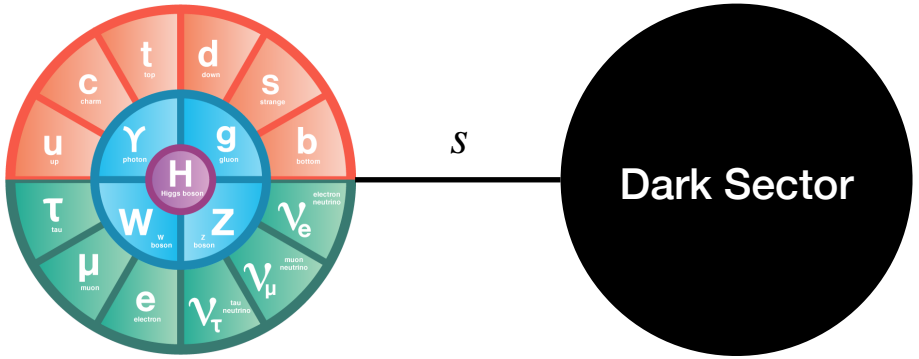
Long-lived scalars from exotic Higgs decays

- Target a hidden sector model with a scalar portal

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

- The physical Higgs boson H and the dark scalar S mix with a mixing angle sinθ.



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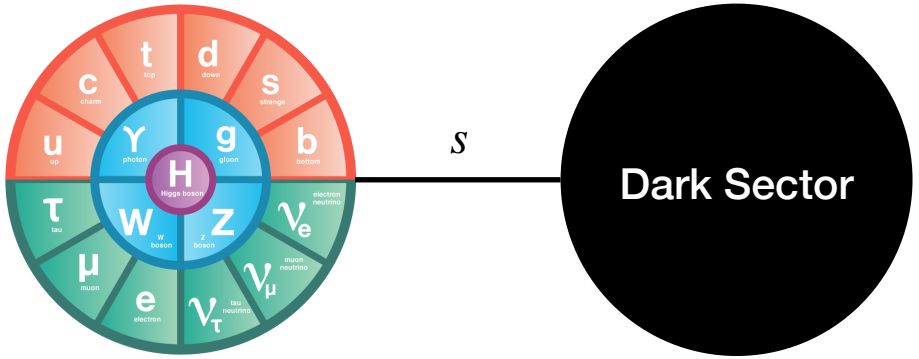

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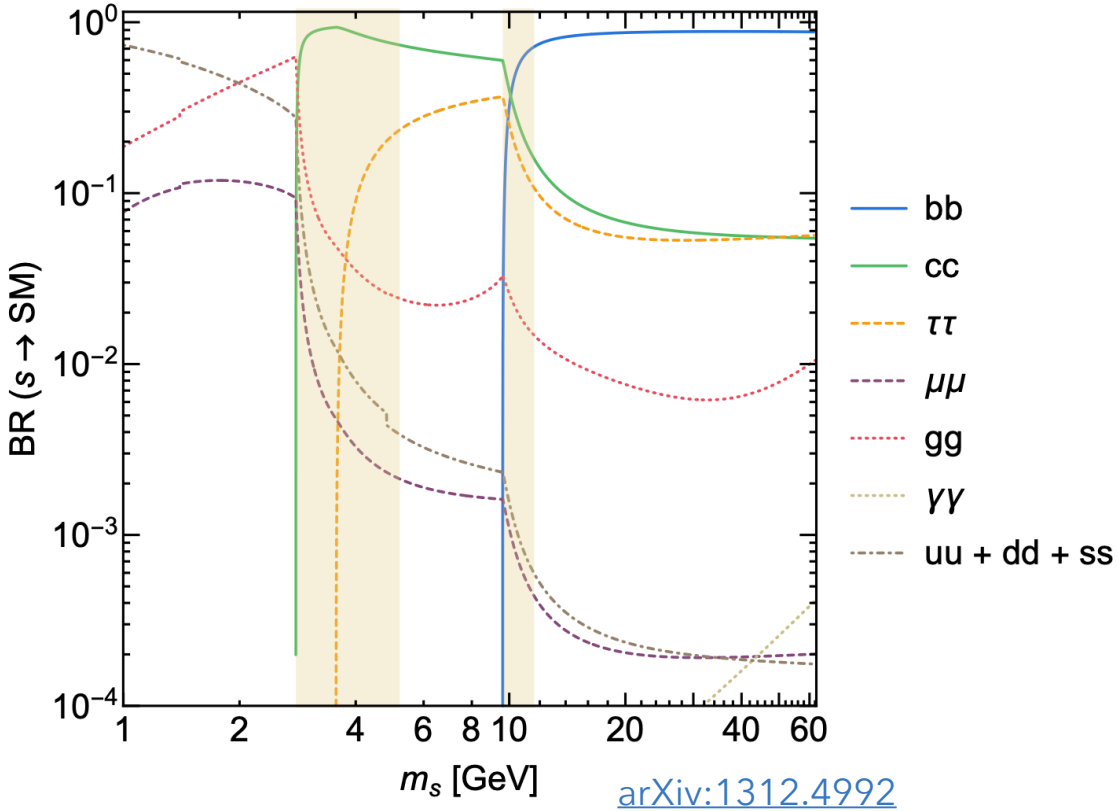
- Two key phenomenological implications:
  - Exotic decays of the Higgs Boson H→SS
  - Decays of the dark scalar back to SM states

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



arXiv:1312.4992

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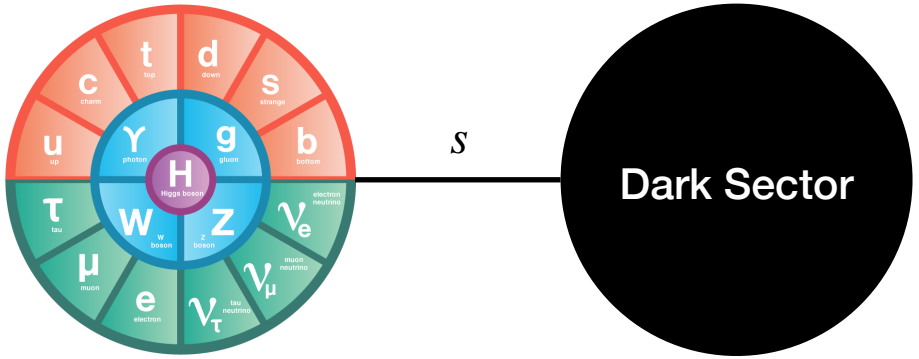

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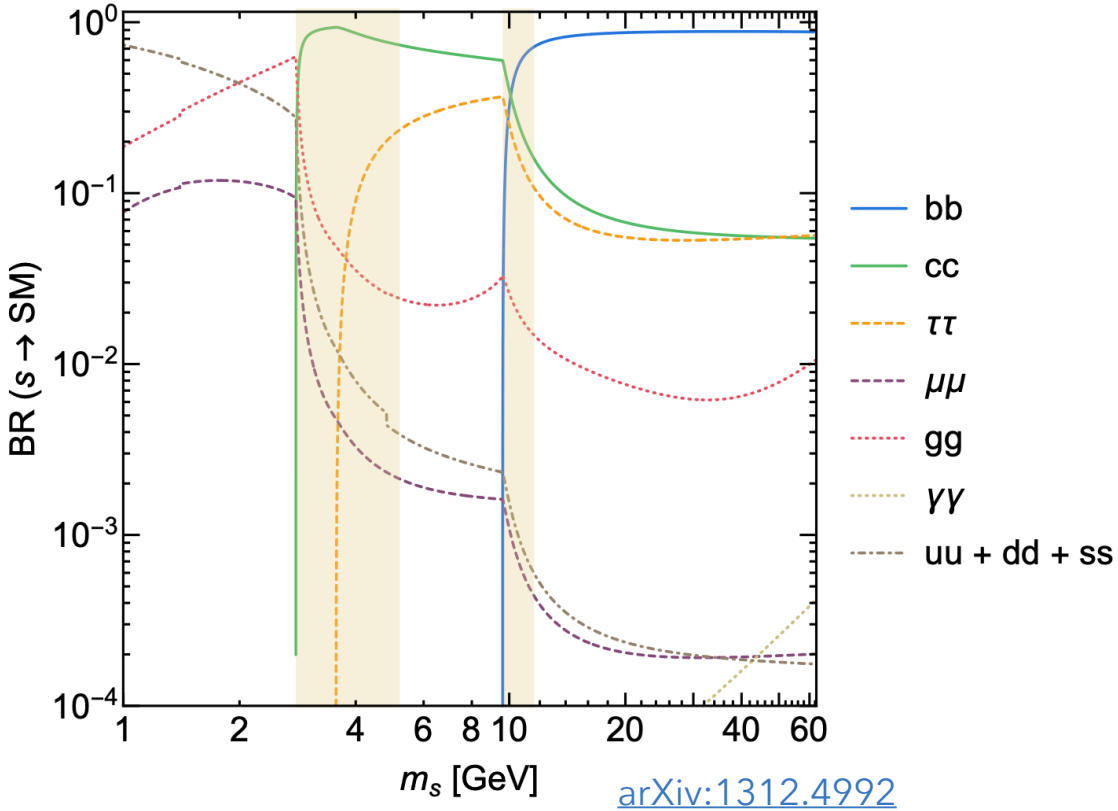
- Small mixing angles give rise to long-lived scalars

  Expect displaced hadronic vertex signatures



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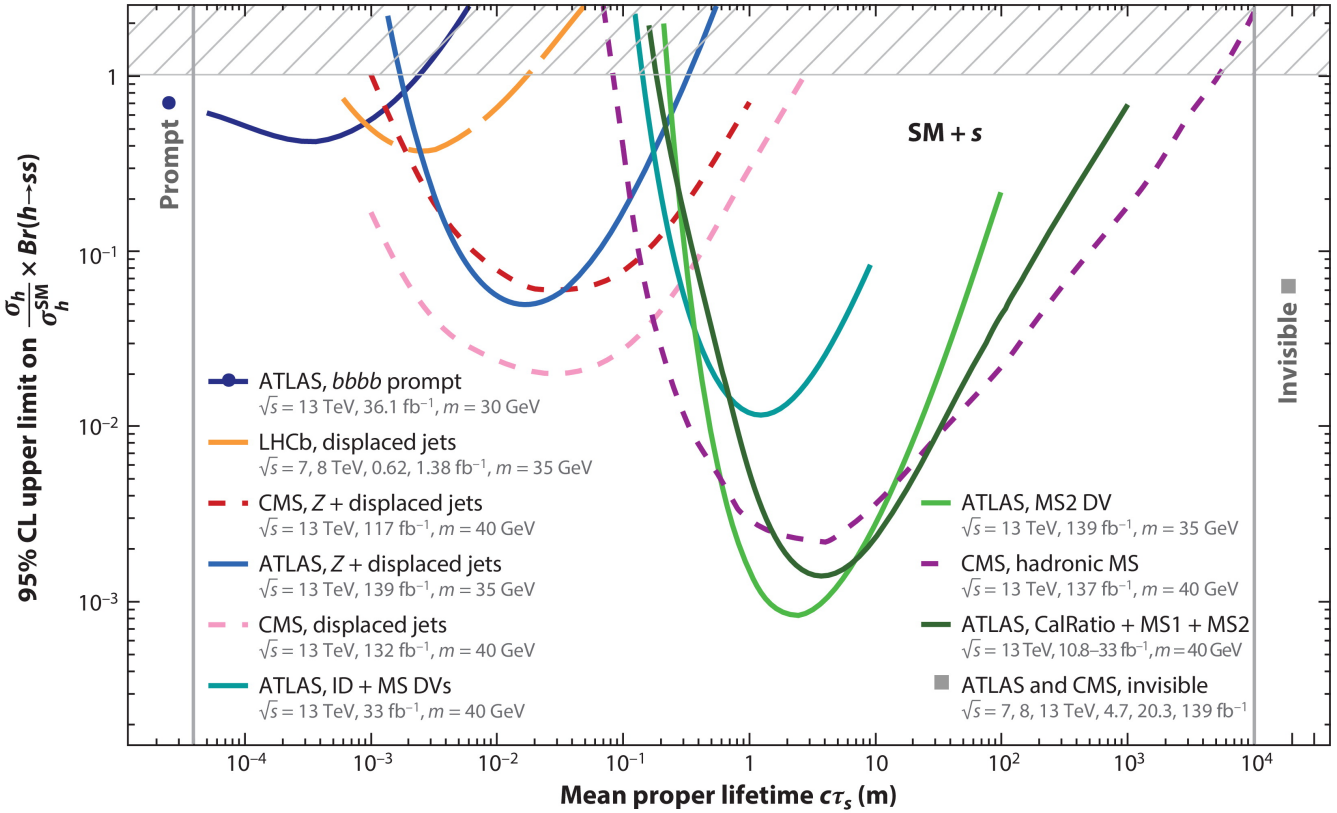
Experimental landscape

Existing limits from several LHC experiments



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

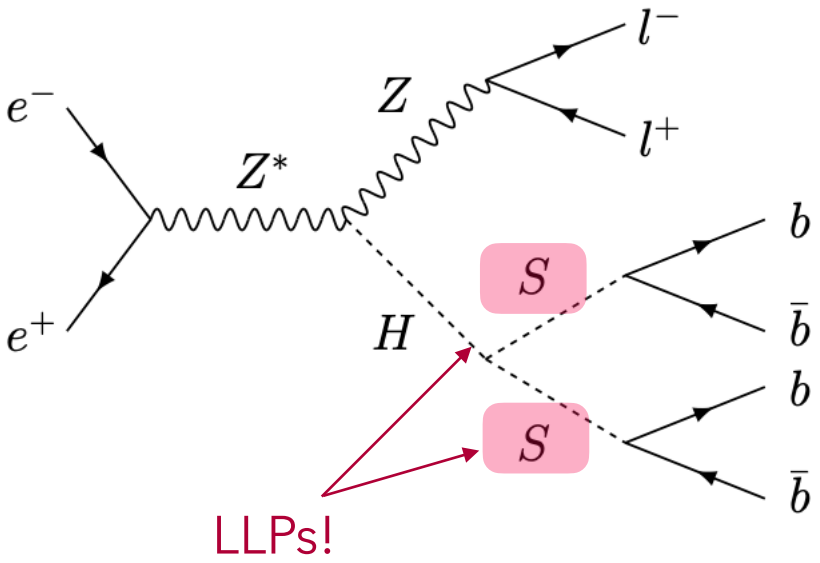
arXiv:2111.12751

- Searches at ATLAS, CMS and LHCb have probed exotic Higgs decay to long-lived scalars in the mass range 30-40 GeV
- Excluding BR(H→SS)≳1% for $c\tau$ between 0.1 m and 10 m
- For shorter LLP lifetimes the LHC backgrounds are high

Interesting target for future lepton colliders!

LLPs from exotic Higgs decays @ FCC-ee

- Targeting the ZH stage of FCC-ee: $\sqrt{s}$=240 GeV and L = 10.8 ab^{-1}
- Signal process: $e^+ e^-$ → ZH with Z → $e^+ e^-$ or $\mu^+\mu^-$ and H → SS → 4b



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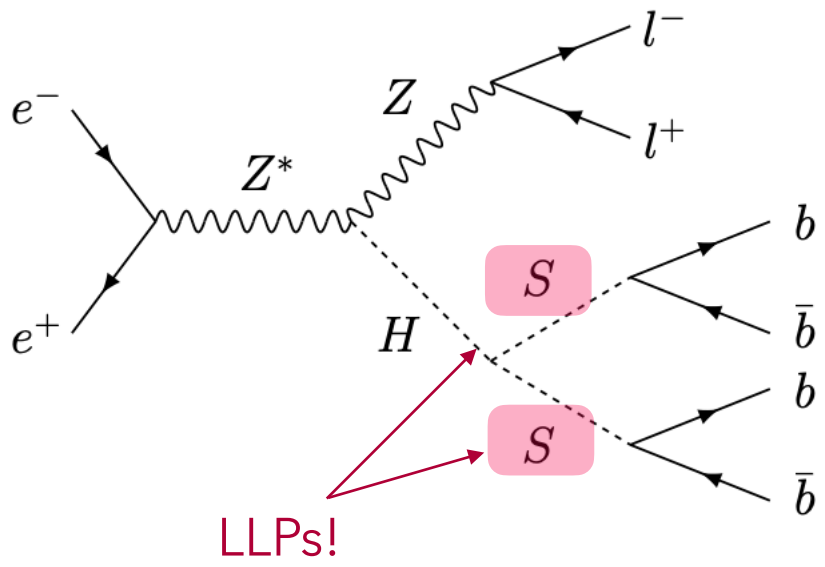
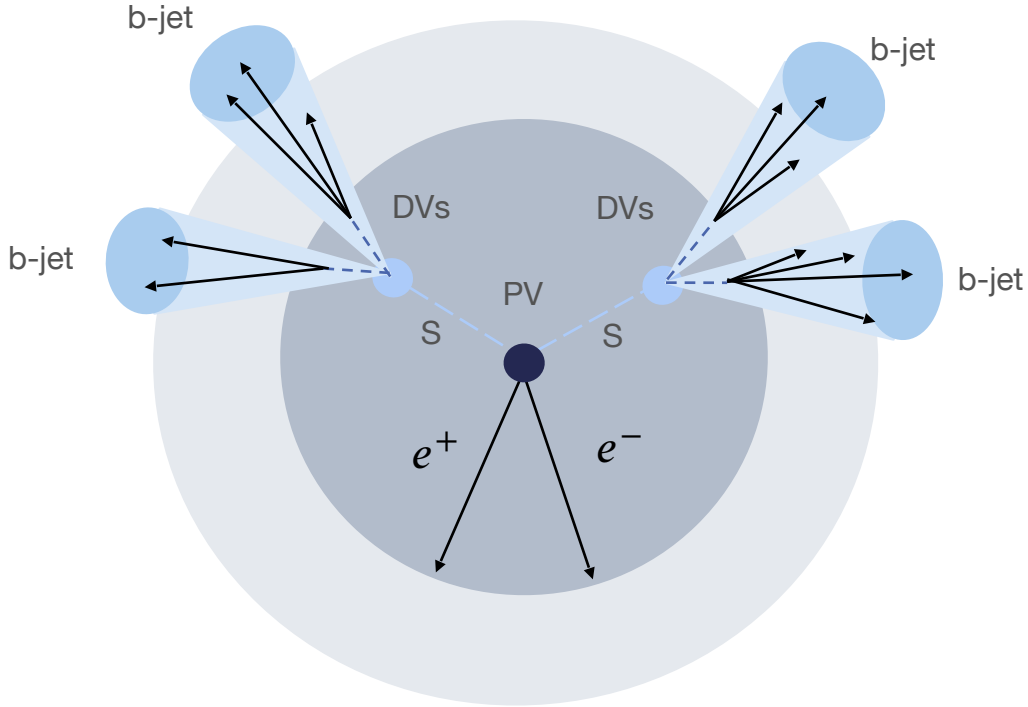
- Experimental signature:
  - A reconstructed Z boson from the e^+e^- or $\mu^+\mu^-$ - pairs
  - Displaced vertices (DVs) from the long-lived scalar decays

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



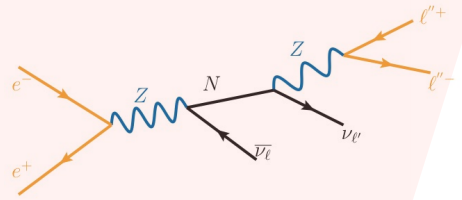


Simulation and analysis of long-lived scalars @ FCC-ee

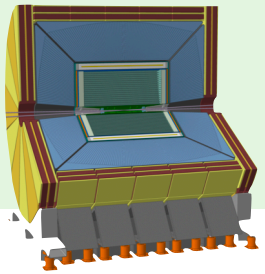
First analysis targeting LLPs from exotic Higgs decays within the official FCC framework

Typical workflow

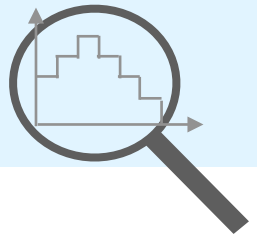
Sample generation
- Signal
- Background



Parametrised detector simulation
- IDEA Delphes card



Analysis tools
- FCCAnalyses framework



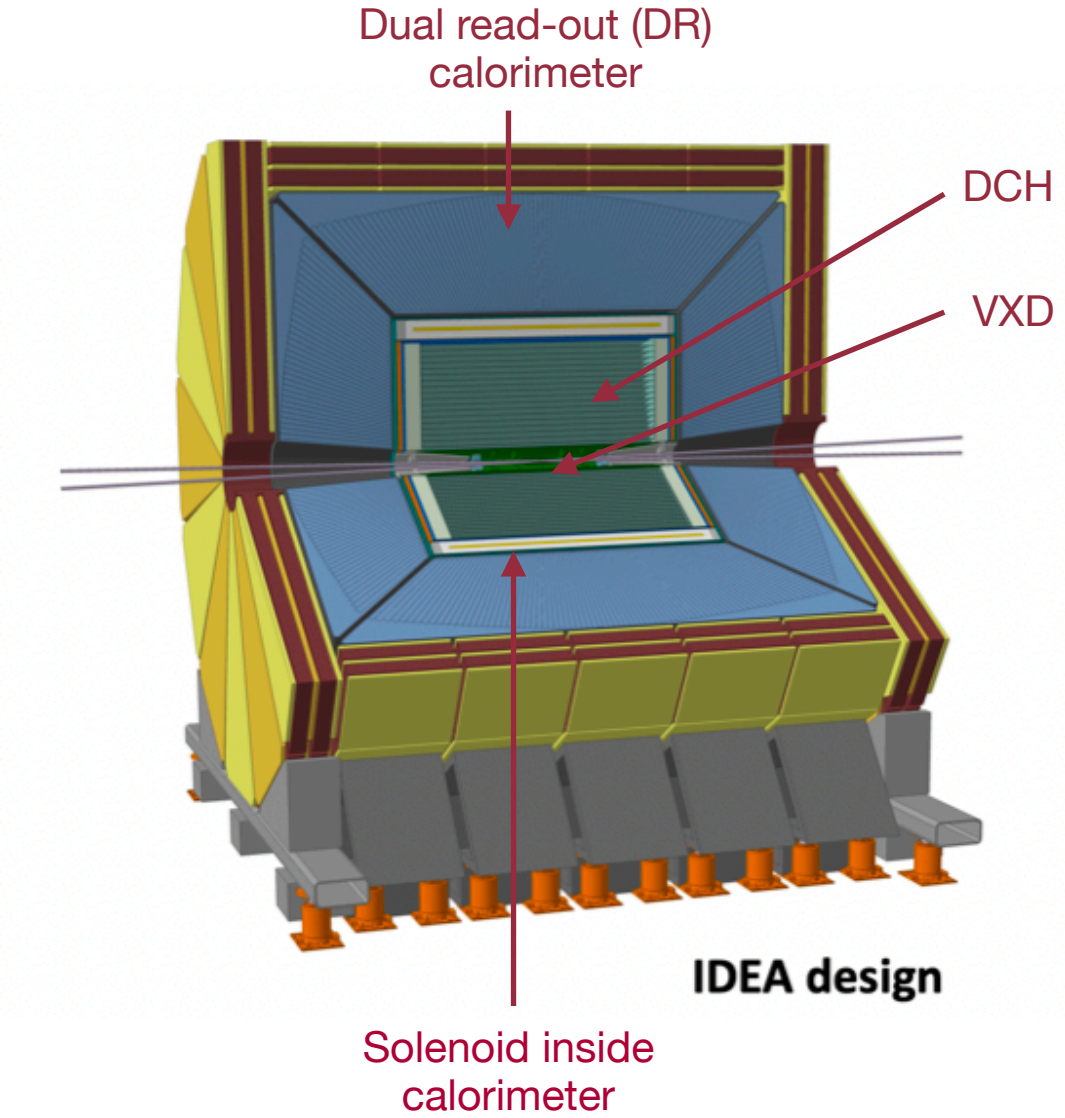
Sensitivity to studied model

- Signal simulated with the MadGraph5 HAHM model (arXiv:1312.4992, arXiv:1412.0018)
  - Madgraph for parton level e^+e^-, Pythia for parton shower and hadronisation
- Background processes centrally produced within the FCC-ee community ("Winter 2023" campaign)
  - 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

Excellent tracking and vertexing opportunities in IDEA detector concept

- Silicon vertex detector (VXD)
  - 5 barrel layers (R=1.2-31.5 cm) + endcap discs
  - ~3 μm point resolution
  - 100% efficiency and extremely low fake rate
- An ultralight drift chamber (DCH)
  - 112 layers of wires (R= 35-200 cm)
- Full detector geometry is simulated in Delphes



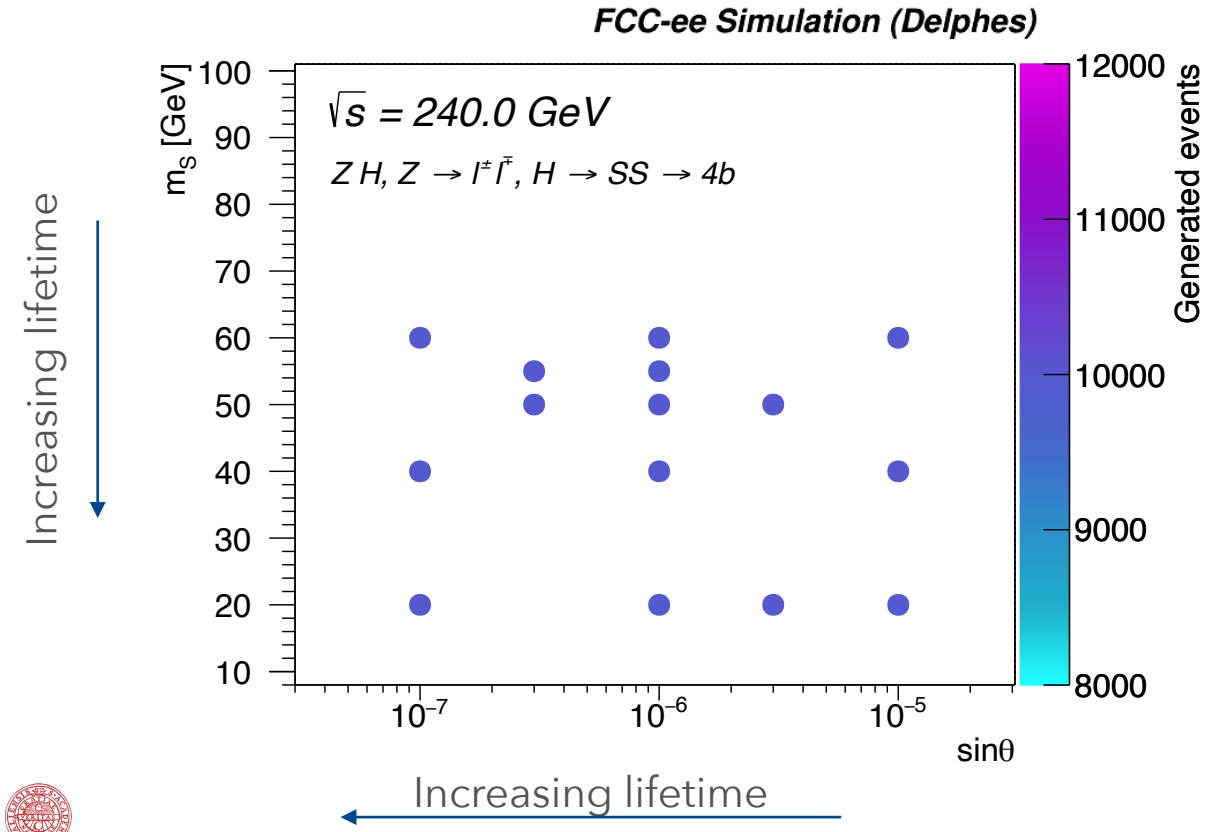
Signal grid

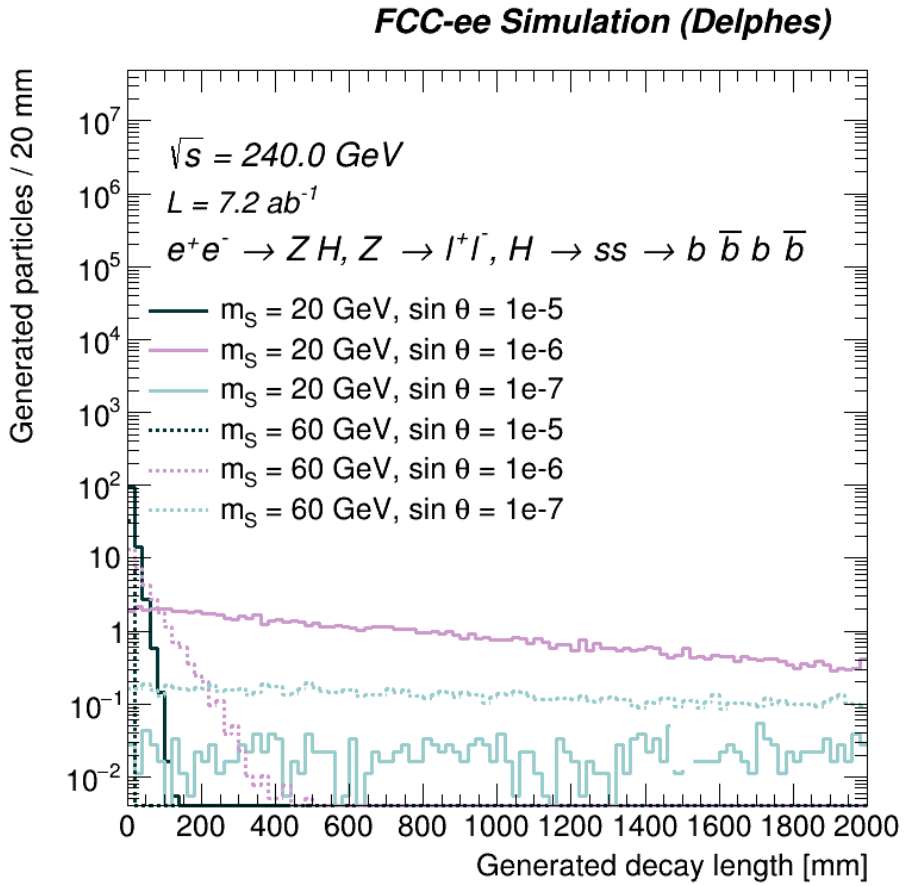
- m_S = 20-60 GeV
- sin θ = 10^{-5}-10^{-7} → $c\tau$ ~1 mm – 10 m
- κ = 7e-4 → <1% addition to the Higgs width

κ: the Higgs-scalar coupling

$$\mathrm{BR}(H \to SS) = \frac{\kappa^2 v_H^2}{32\pi m_H \Gamma_H}\sqrt{1-4\frac{m_S^2}{m_H^2}}$$

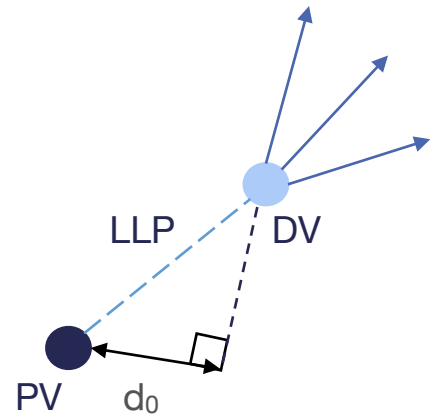
$$\Gamma_S = \sin^2\theta \frac{3}{0.9\times 8\pi}\frac{m_S m_b^2}{v_H^2}\left(1-\frac{4m_b^2}{m_S^2}\right)^{3/2}$$

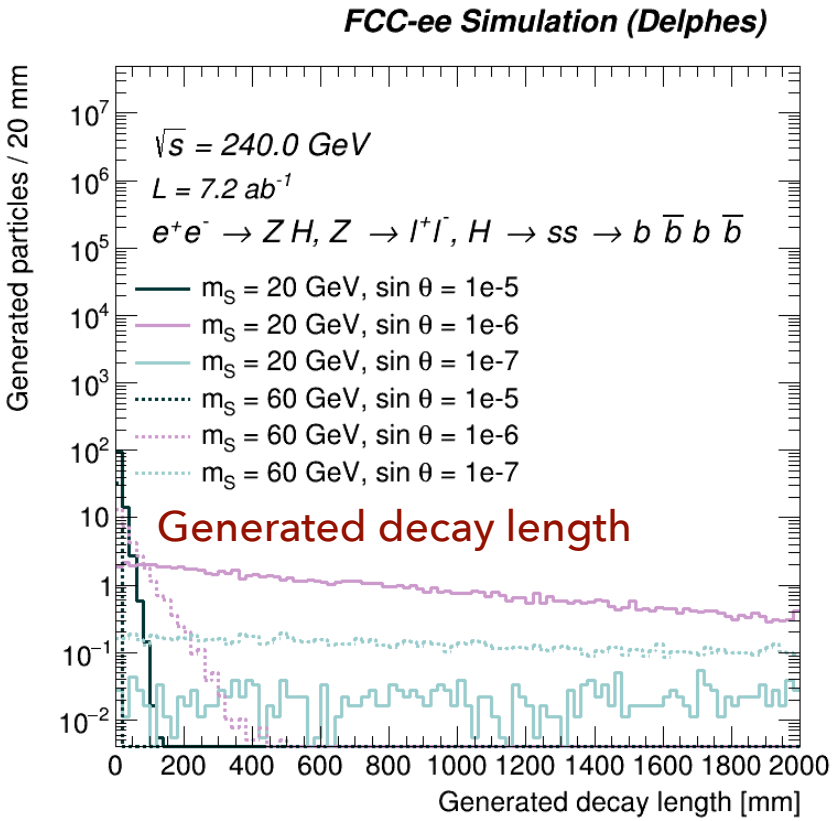


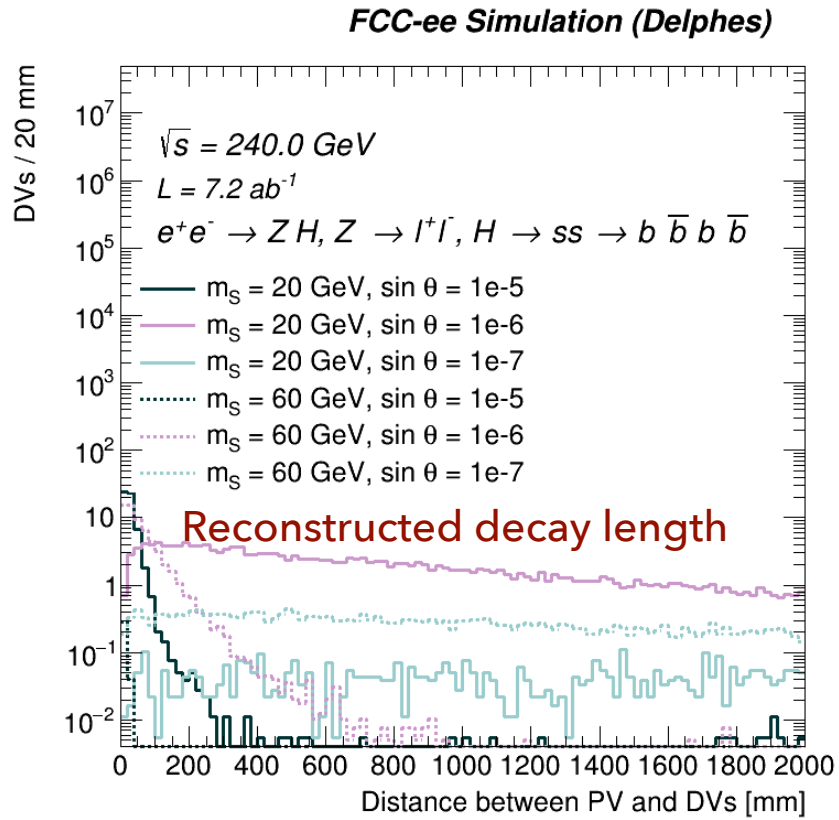


DV reconstruction

- Secondary vertex finder of the LCFI+ algorithm (arXiv:1506.08371)
  - Designed for ILC/CLIC and primarily used for jet flavor-tagging
  - Custom track selection for this search: non-primary, $p_T > 1$ GeV and $|d_0| > 2$ mm

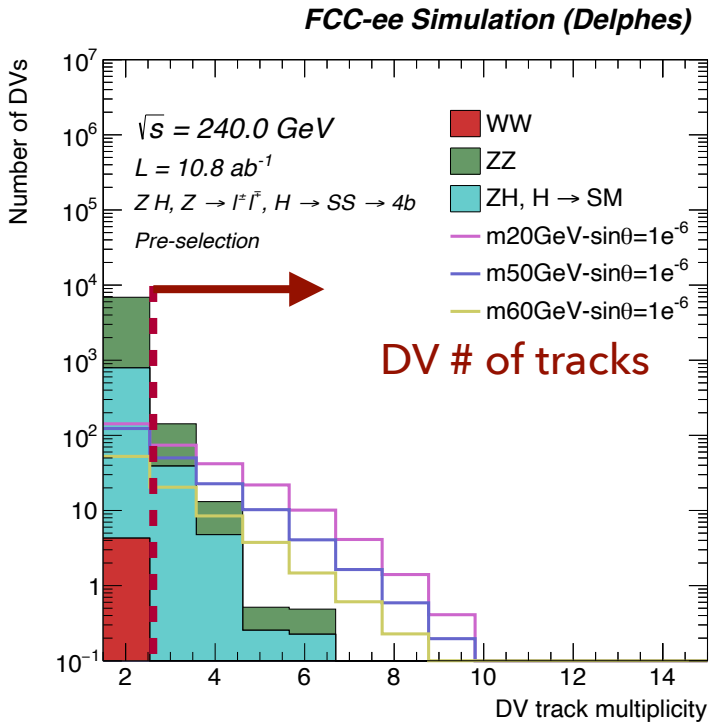


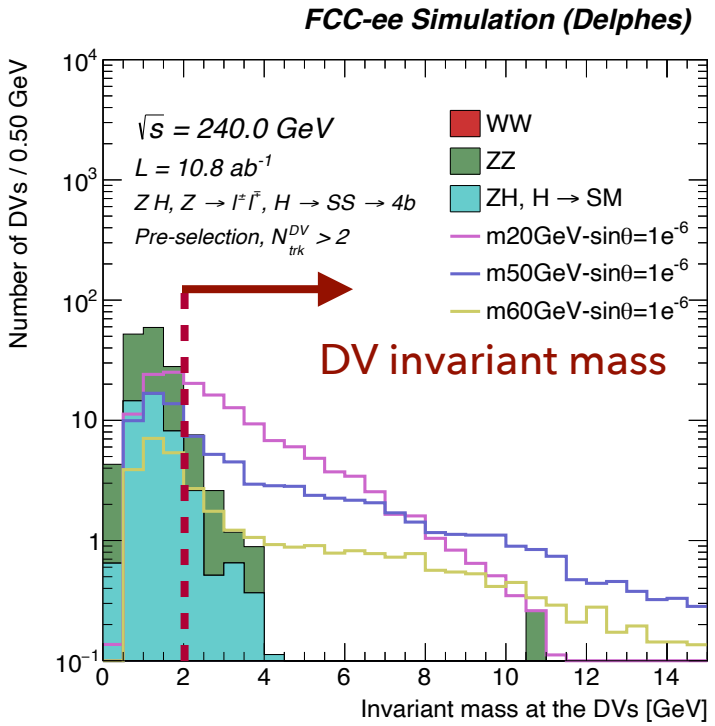


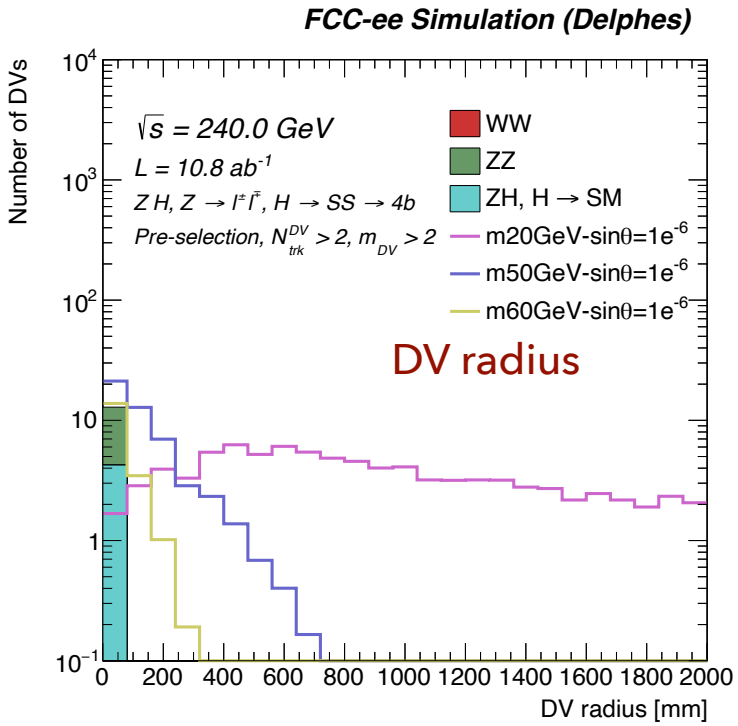


DV selection

- The **number of tracks per DV**, the charged **invariant mass of the DV** and the **DV radius** are three efficient variables to separate signal DVs from background DVs!
- DV selection: $N_{tracks} \geq 3$, $M_{inv} > 2$ GeV, 4 mm < R_{xy} < 2 m

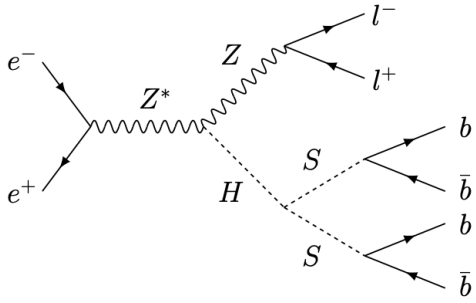


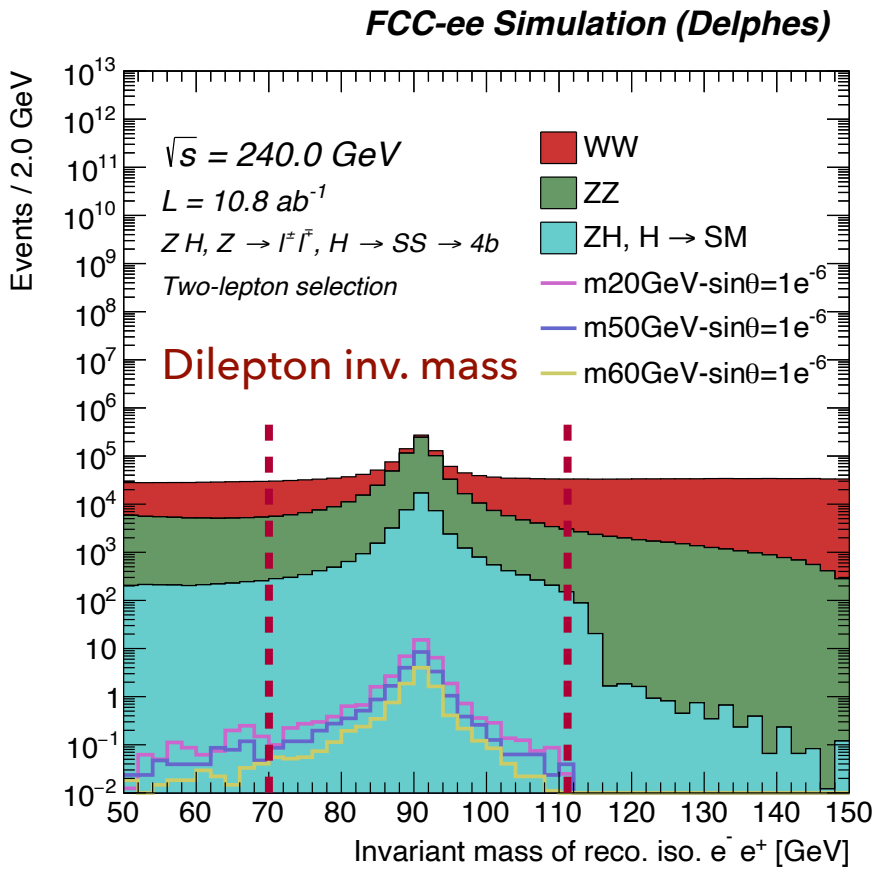


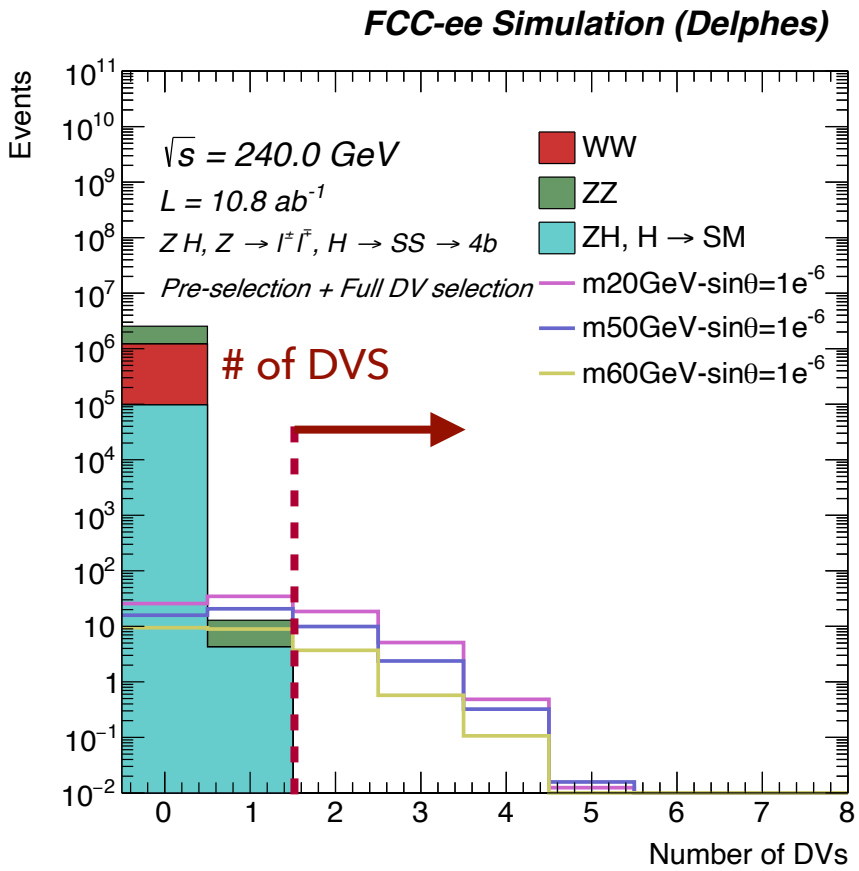


Event selection

- Two oppositely charged isolated leptons with invariant mass in the range 70-110 GeV
- At least 2 DVs passing the full DV selection





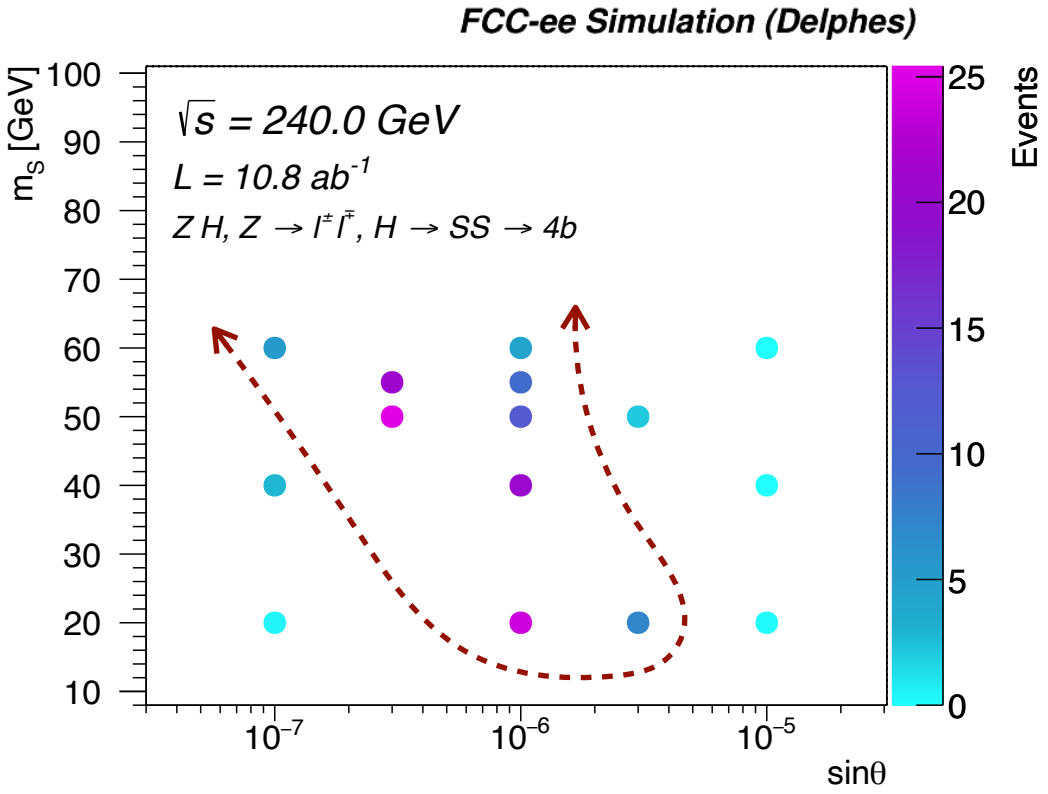


Requiring ≥2 DVs efficiently removes all background

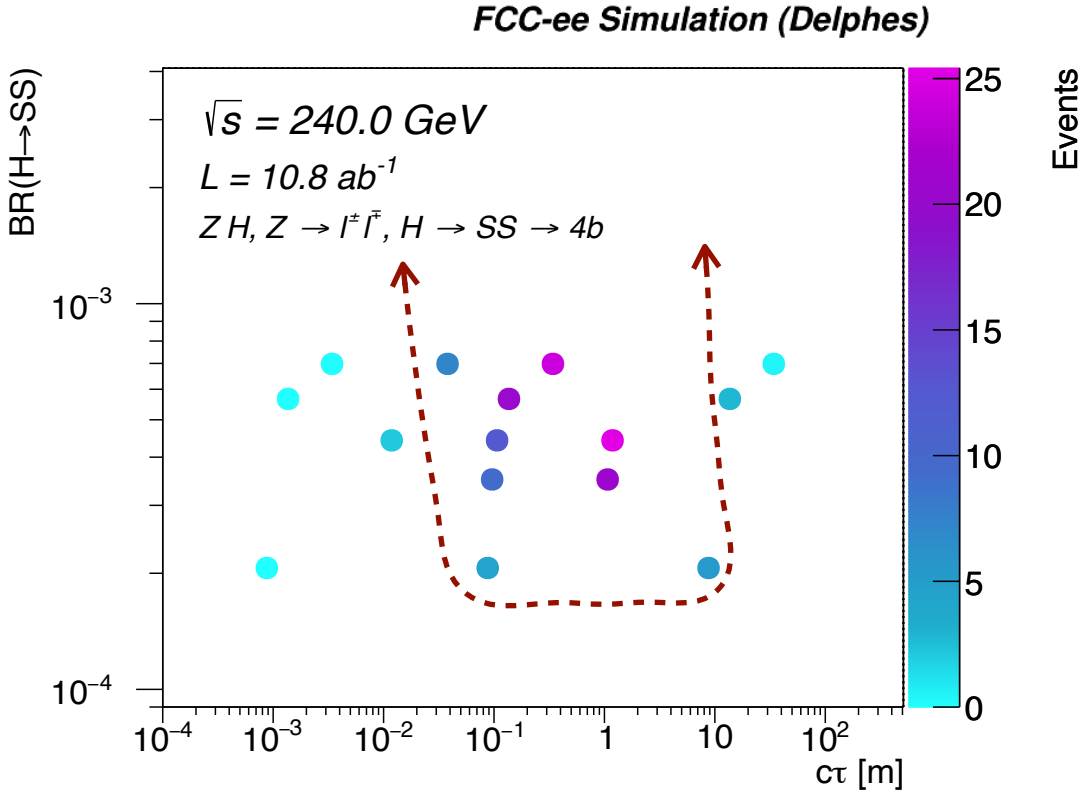
Results - sensitivity analysis

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

sinθ-m_S parameter space



cτ-BR(H→SS) parameter space

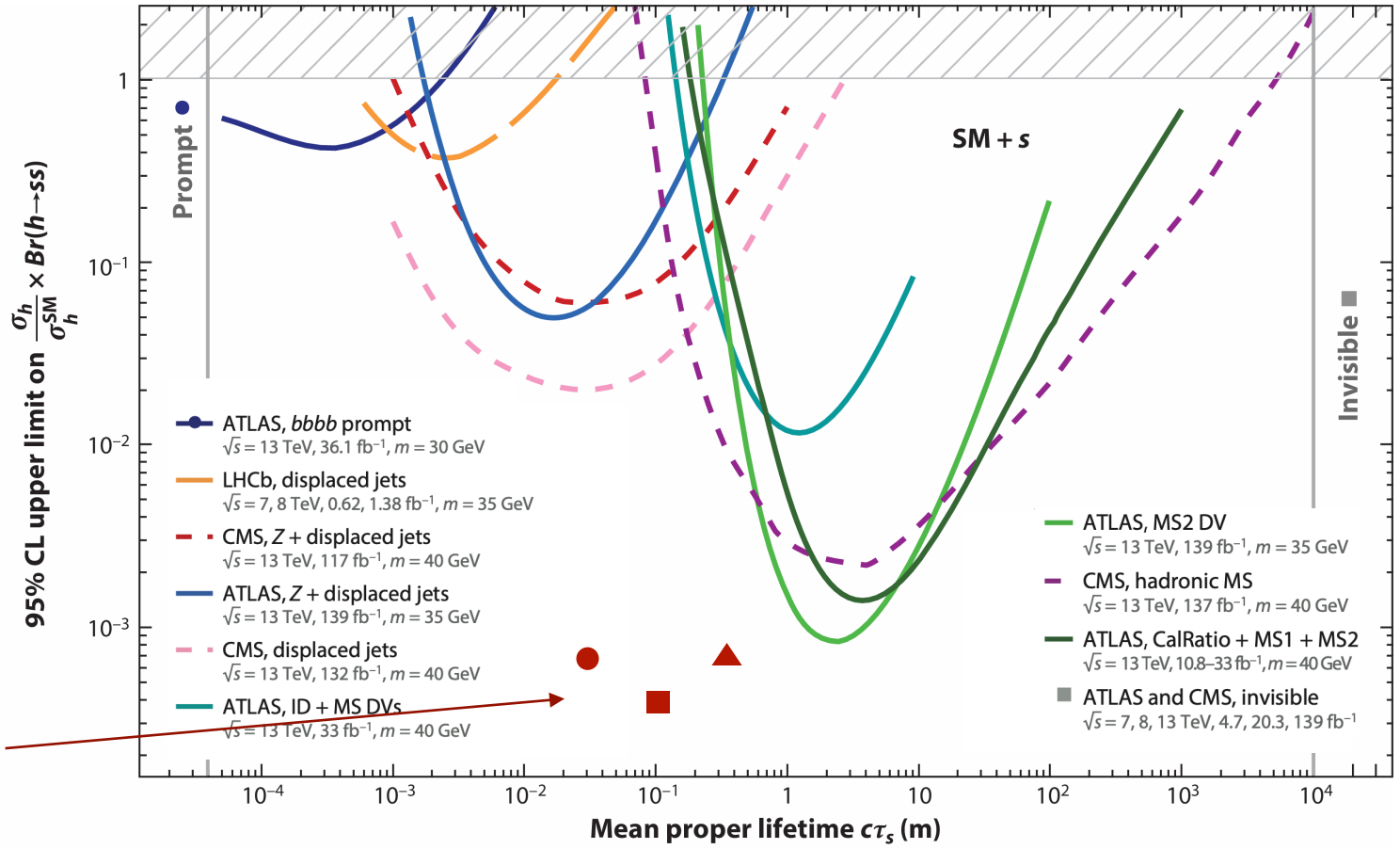


Rough contour of signal points with at least three selected events

Comparison to existing limits

Excellent complementary to the LHC searches!

- Reaching slightly **longer lifetimes** than inner-detector based searches at LHC
- Two orders lower in **branching ratio** for cτ ~0.1m



Probing BR<0.1% for cτ between 40 mm - 0.4 m

● m_S=20 GeV, sinθ=3·10⁻⁶ Event yield: 7.3

■ m_S=50 GeV, sinθ=1·10⁻⁶ Event yield: 12.6

▲ m_S=20 GeV, sinθ=1·10⁻⁶ Event yield: 24

Adapted from arXiv:2111.12751

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: $p_T > 1$ GeV and $|d_0| > 2$mm
- Sensitivity analysis
  - Vertex selection: $N_{tracks} \geq 3$, $M_{inv} > 2$ GeV, 4 mm $< R_{xy} <$ 2 m
  - Event selection: tagging the Z boson and requiring at least 2 DVs

Backgrounds suppressed to zero!
Sensitivity for signals with $c\tau$ ~ 40 mm - 0.4 m

Backup slides

Model parameters and calculations

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

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

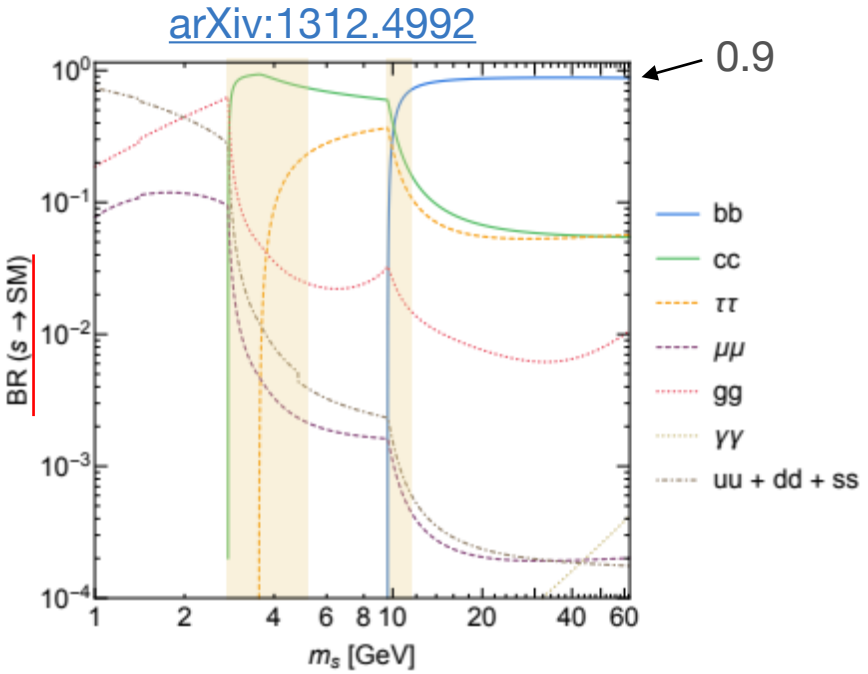
- Approximate the number of events with

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

- 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



Results - sensitivity analysis

- 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 → SM	1,398,876 ± 968	112,397 ± 99	97,291 ± 94	0(≤ 94)
ZZ	14,677,092 ± 1,001	1,978,967 ± 719	1,323,648 ± 588	0(≤ 588)
WW	177,535,800 ± 6,336	4,986,799 ± 1,540	1,119,163 ± 730	0(≤ 730)
Total Background	193,611,768 ± 6,509	7,078,163 ± 1,715	2,540,102 ± 945	0 (≤ 945)
mS_20GeV_sine-5	124.189 ± 0.138	86.175 ± 1.035	82.785 ± 1.014	0.174 ± 0.046
mS_20GeV_sine-6	124.189 ± 0.138	87.567 ± 1.043	84.486 ± 1.024	24.112 ± 0.547
mS_20GeV_sin3e-6	124.189 ± 0.138	84.855 ± 1.027	81.439 ± 1.006	7.291 ± 0.301
mS_20GeV_sine-7	124.189 ± 0.138	108.690 ± 1.162	105.809 ± 1.146	0.484 ± 0.078
mS_40GeV_sine-5	100.732 ± 0.101	66.110 ± 0.816	63.058 ± 0.797	0.071 ± 0.027
mS_40GeV_sine-6	100.732 ± 0.101	66.385 ± 0.818	63.614 ± 0.801	20.459 ± 0.454
mS_40GeV_sine-7	100.732 ± 0.101	85.370 ± 0.927	82.822 ± 0.913	2.861 ± 0.170
mS_50GeV_sine-6	78.667 ± 0.070	51.430 ± 0.636	49.171 ± 0.622	12.631 ± 0.315
mS_50GeV_sin3e-6	78.667 ± 0.070	51.873 ± 0.639	49.686 ± 0.625	2.124 ± 0.129
mS_50GeV_sin3e-7	78.667 ± 0.070	53.145 ± 0.647	51.029 ± 0.634	25.412 ± 0.447
mS_55GeV_sine-6	62.289 ± 0.049	41.262 ± 0.507	39.786 ± 0.498	9.308 ± 0.241
mS_55GeV_sin3e-7	62.289 ± 0.049	41.676 ± 0.510	40.018 ± 0.499	20.832 ± 0.360
mS_60GeV_sine-5	36.725 ± 0.022	23.457 ± 0.294	22.502 ± 0.287	0(≤ 0.287)
mS_60GeV_sine-6	36.725 ± 0.022	23.665 ± 0.295	22.765 ± 0.289	4.382 ± 0.127
mS_60GeV_sine-7	36.725 ± 0.022	28.383 ± 0.323	27.561 ± 0.318	5.264 ± 0.139

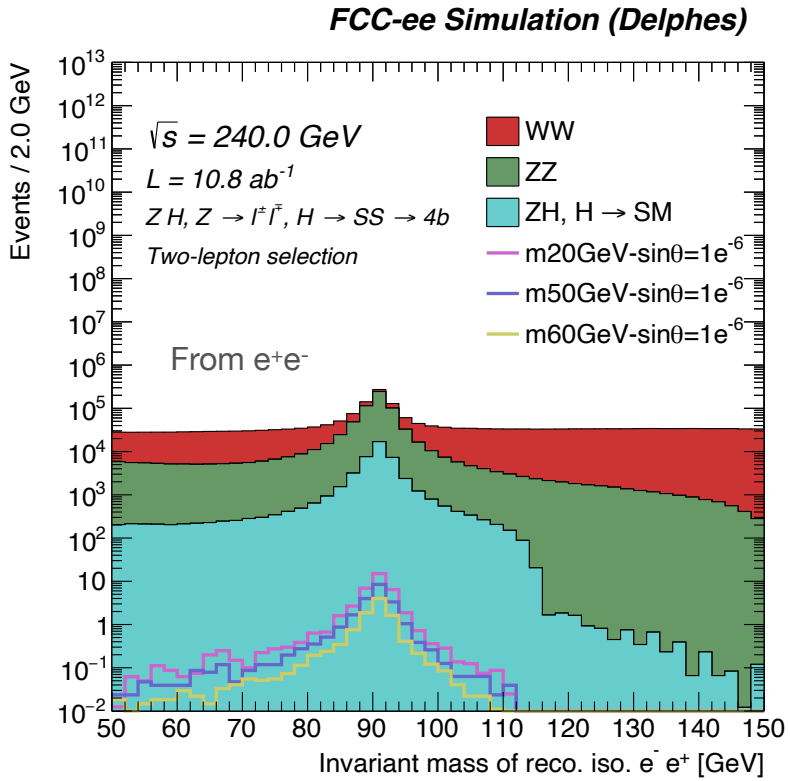
- Applied event selections from left to right, results given in number of expected events and uncertainties are only statistical

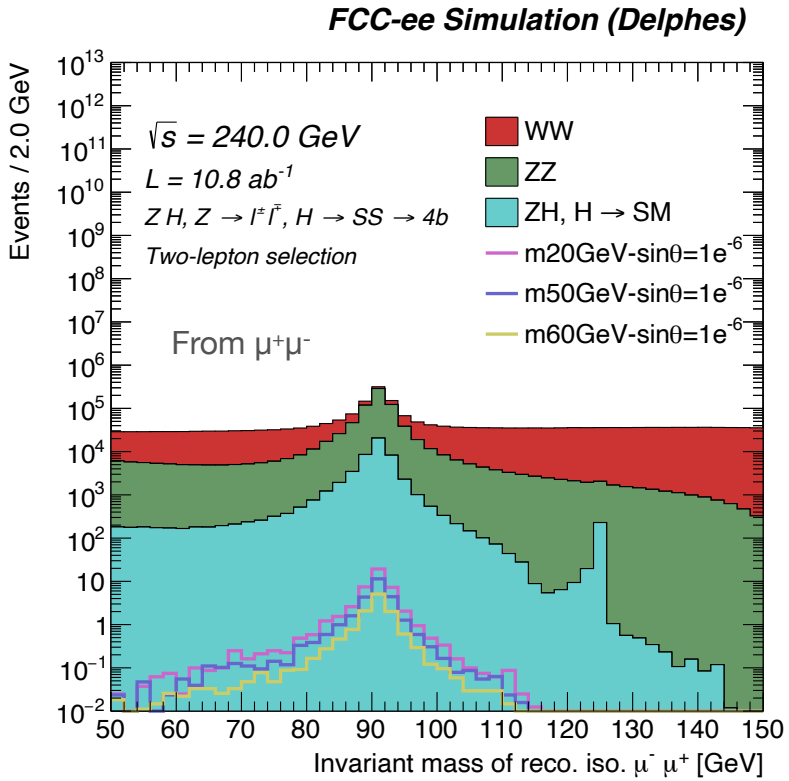
Vertex reconstruction

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

Reconstruction of the Z-boson

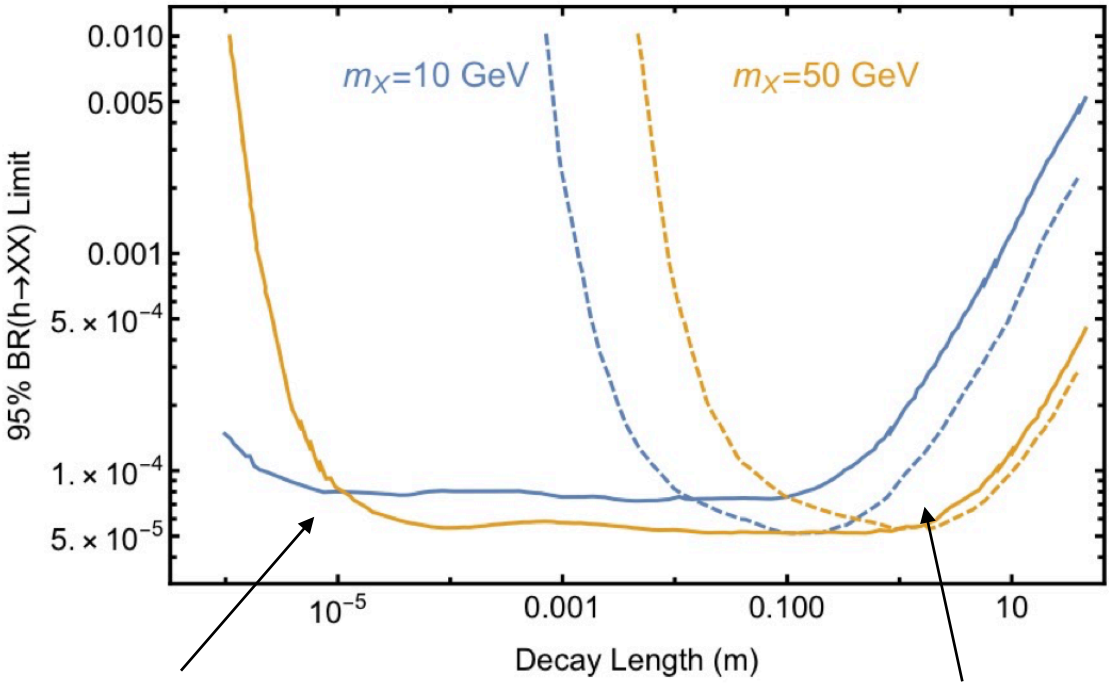
- Require exactly 2 oppositely charged isolated electrons or muons
- Tag the Z-boson with the e^+e^- or $\mu^+\mu^-$ invariant mass
  - Pre-selection: set a mass window between 70-110 GeV





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



Invariant mass cut to retain sensitivity to shorter decay lengths

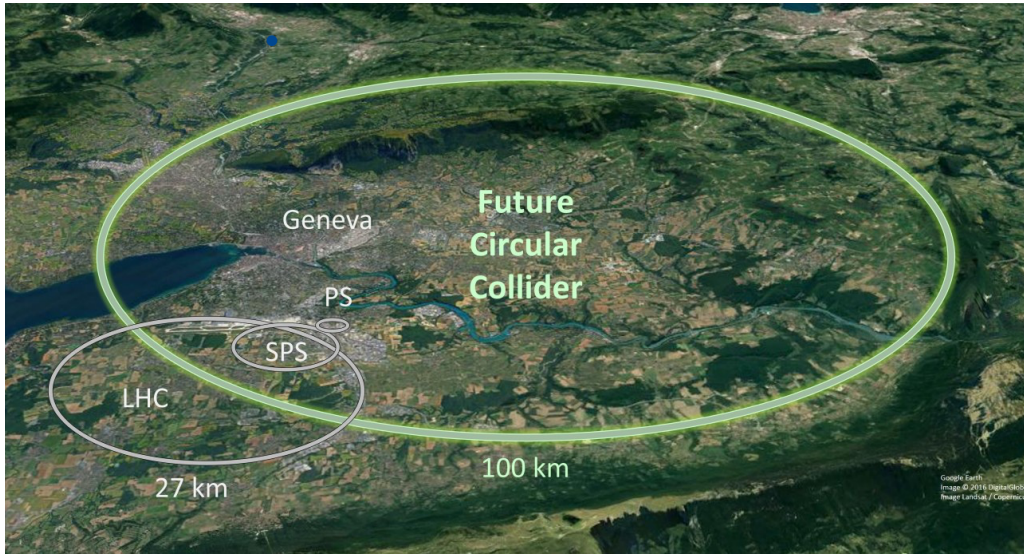
Cuts optimised for longer decay lengths

- 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.

The Future Circular Collider (FCC)

Excellent opportunities for LLP searches

One ~90 km tunnel operated in two stages



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- Post-LHC circular colliders at CERN
  - FCC-ee (Z, W, H, tt) Precision frontier
  - FCC-hh (~100 TeV) Energy frontier

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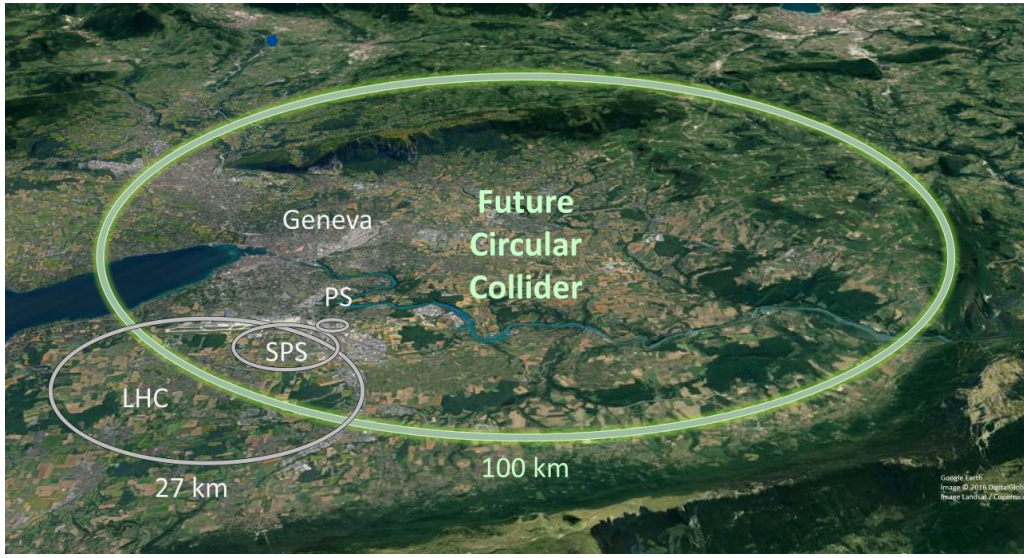

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  - FCC feasibility study to be completed in 2025
  - Construction could start in mid 2030's
- Now is the time to take a look at the physics potential and optimize detector design for a complete physics program!

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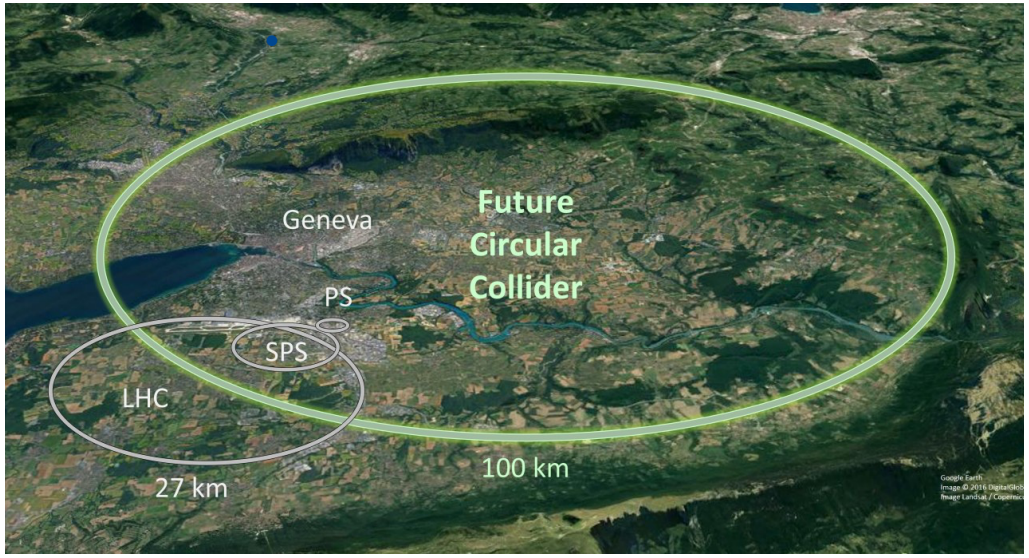

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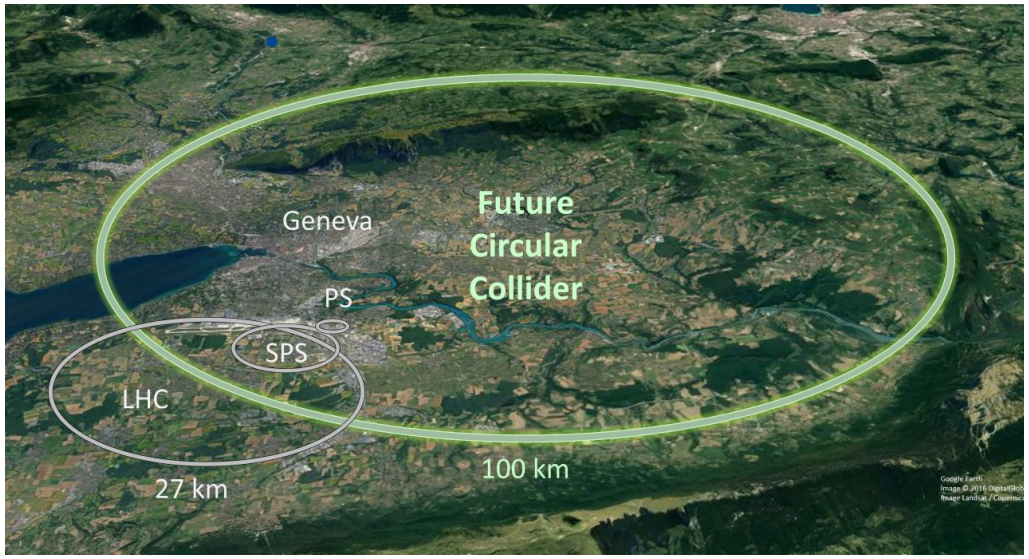
FCC-ee conditions are great for finding LLPs

Clean events, No trigger, High luminosity

One ~90 km tunnel operated in two stages



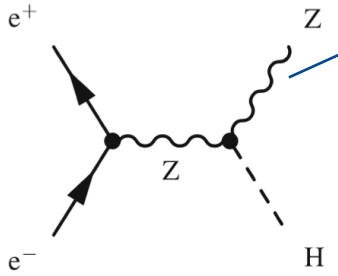
Four FCC-ee phases

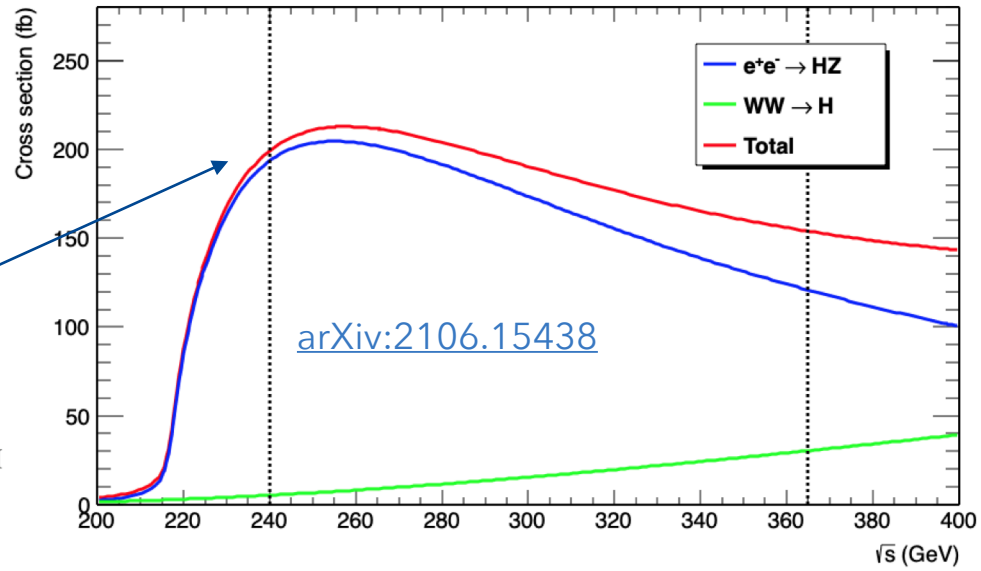
Phase	Duration (y)	√s (GeV)	L_{int} (ab^{-1})	
Z	4	88-95	205	LEP x 10^5
W	2	158-163	19.2	LEP x $2 \cdot 10^3$
ZH	3	240	10.8	Never done
tt	5	345-365	3.06	Never done

FCCeePhysicsPerformance

Higgs physics at the FCC-ee

Indirect and direct probe of BSM physics

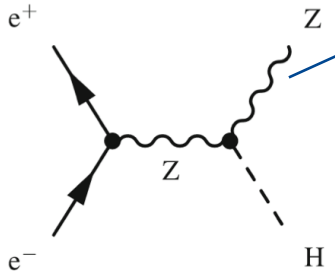


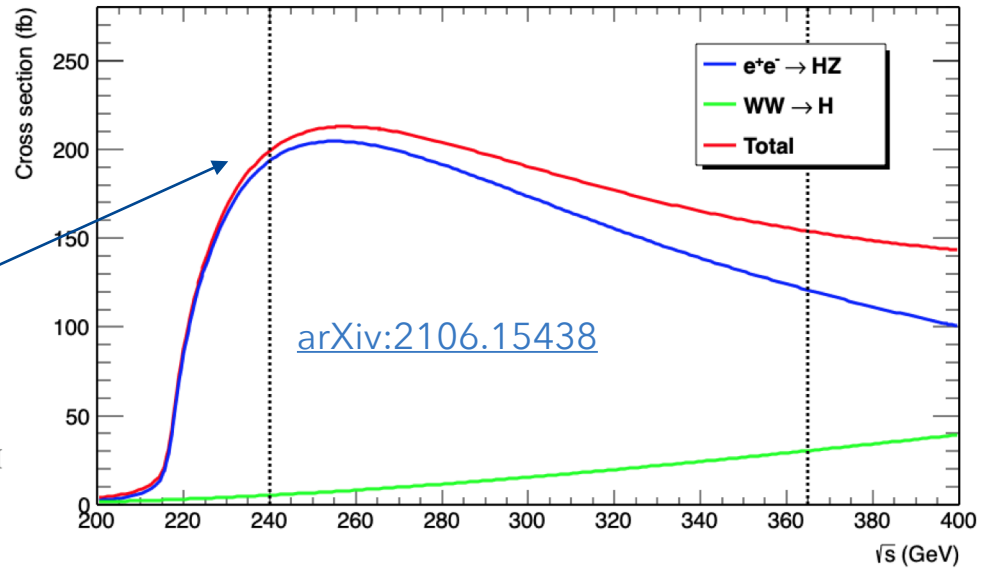


Higgs physics at the FCC-ee

Indirect and direct probe of BSM physics

- FCC-ee will give us 2M ZH events at 240 GeV

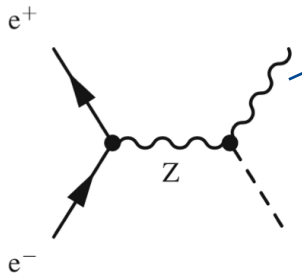


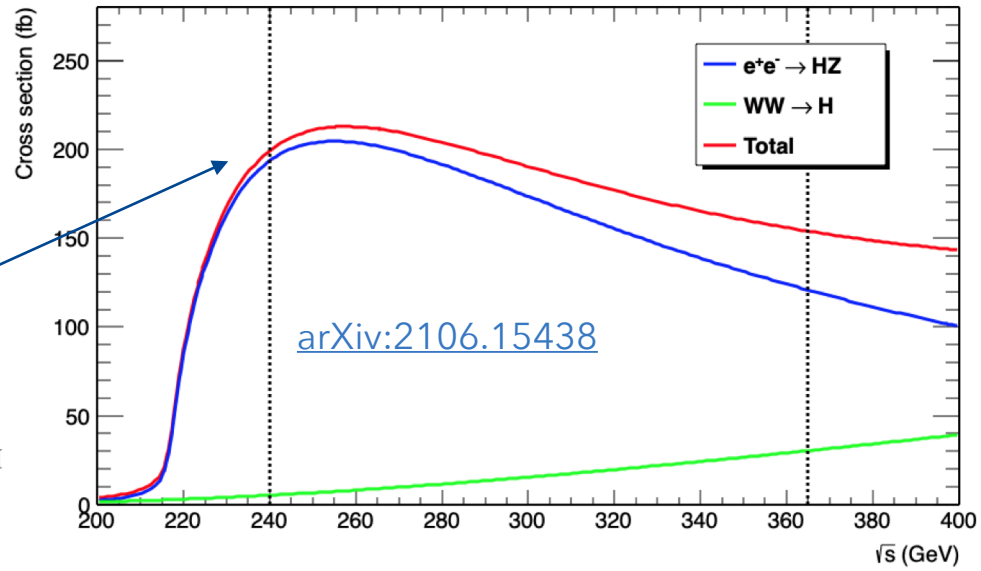


Higgs physics at the FCC-ee

Indirect and direct probe of BSM physics

- FCC-ee will give us 2M ZH events at 240 GeV
- Precision Higgs program will set indirect constraints on BSM physics
  - Predict BR(H→exotics)<1%





Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
	...	
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.0 / 0.88

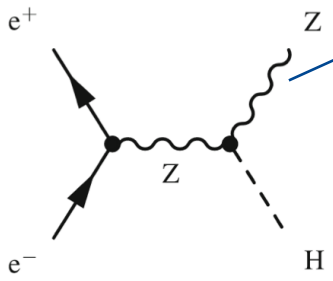
Numbers from arXiv:1905.03764

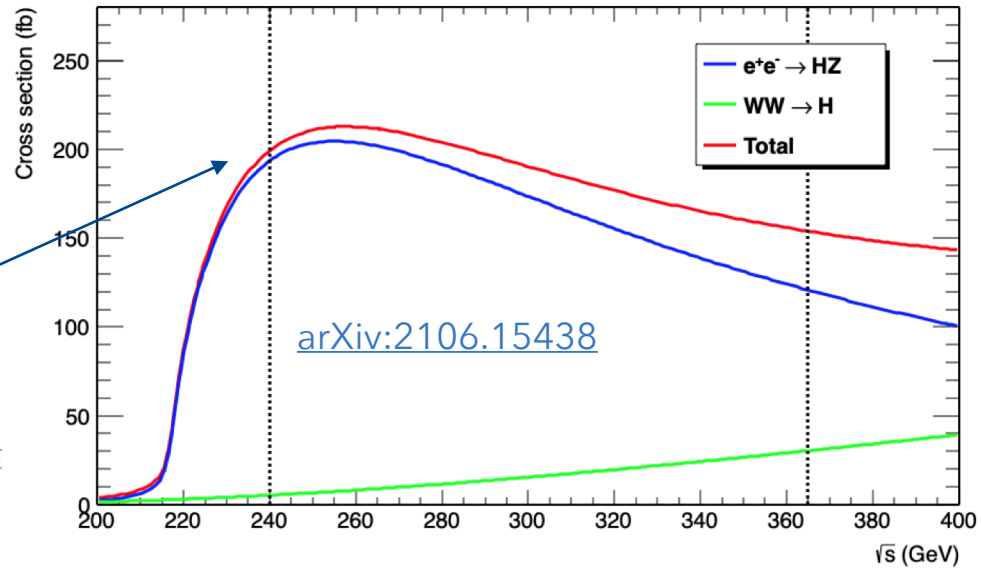
Higgs physics at the FCC-ee

Indirect and direct probe of BSM physics

- FCC-ee will give us 2M ZH events at 240 GeV
- Precision Higgs program will set indirect constraints on BSM physics
  - Predict BR(H→exotics)<1%
- Still room for particles and sectors whose couplings to the Higgs are nonzero
  …as long as they are small → LLPs!

Searches for Exotic Higgs Boson decays into LLPs is a crucial complement to the FCC-ee precision program





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