Long-Lived Particles from Exotic Higgs Decays

Master thesis project

Magdalena Vande Voorde

Supervisor: Giulia Ripellino

Uppsala University

FCC-ee Physics and Performance Meeting

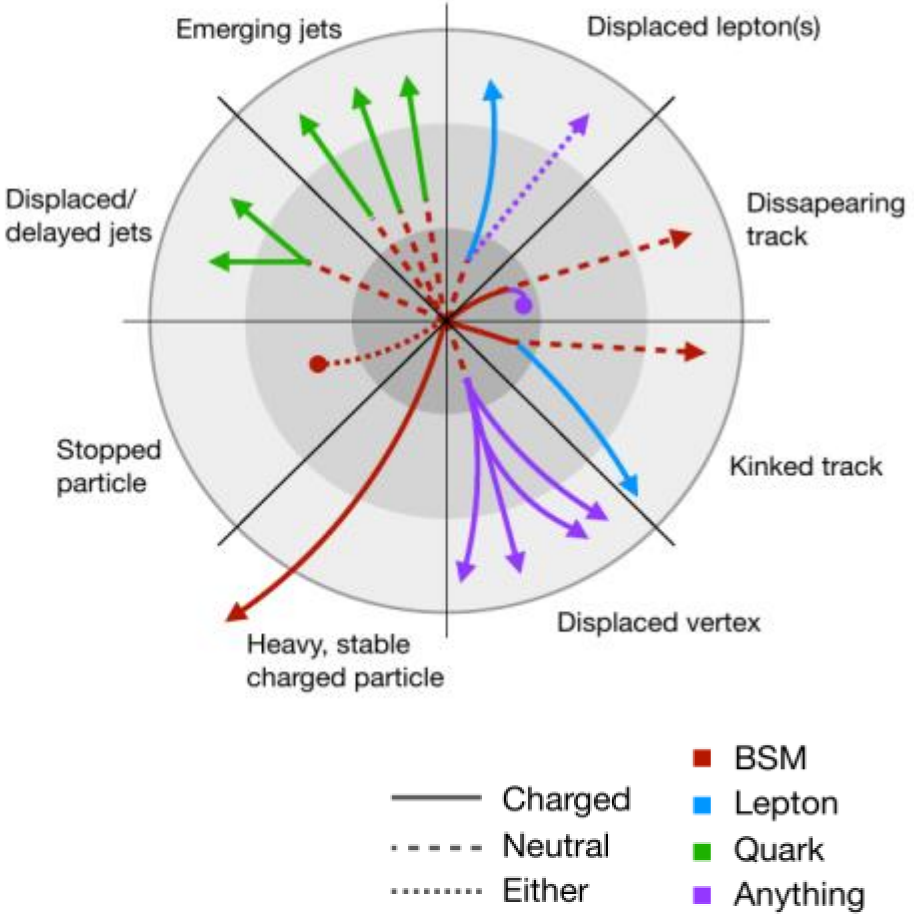
December 12, 2022

UPPSALA UNIVERSITET

Introduction

- The LLP group is working with 3 benchmark cases: LL Heavy Neutral Leptons (HNLs), LL Axion-Like Particles (ALPs) and Exotic Higgs Decays to LLPs (arXiv:2203.05502)
- Today: Exotic Higgs Decays to LLPs
- Different phenomenological models, e.g SM + s, SM + a, SM + v, SM + fermion …
- The new BSM particles can decay promptly, be meta-stable, or be stable → possibility for detectable LLPs with different signatures

- **Aim of study:** Simulate and analyse **long-lived scalars** from exotic Higgs decays within the FCCAnalysis framework



Long-lived scalars from the Higgs boson

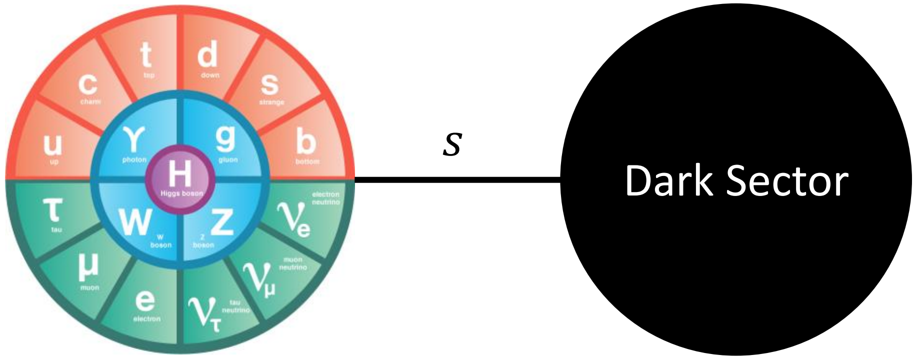
- Our considered model: SM + scalar
- Motivated by Dark Matter: The new scalar is the portal between the SM and a dark sector
- New real scalar field S couples to the Higgs field H at renormalizable level

$$\mathcal{L} = \mathcal{L}_{\text{kin}} + \frac{\mu_s^2}{2} S^2 - \frac{\lambda_s}{4!} S^4 - \frac{\kappa}{2} S^2 |H|^2 + \mu^2 |H|^2 - \lambda |H|^4$$

- If both the fields H and S have non-zero vevs, the Higgs boson h and the scalar s mix with a mixing angle sin θ
- After symmetry breaking and mixing the scalar inherits its couplings to the SM particles from the Higgs

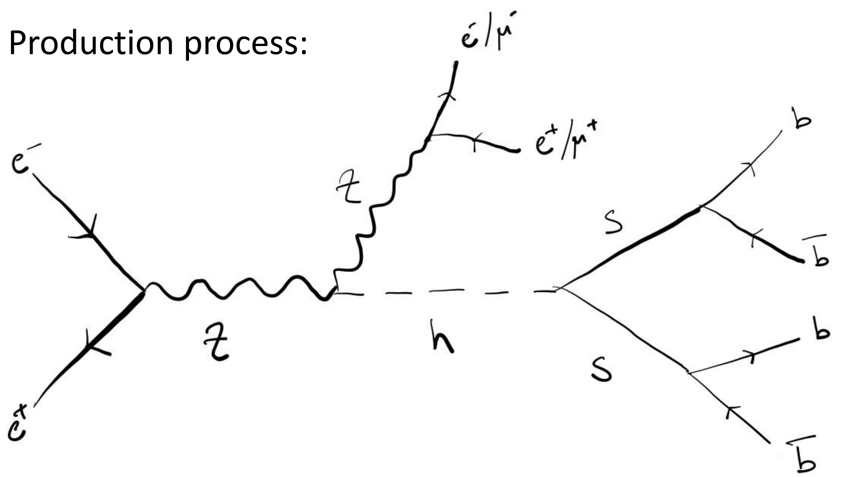
$$\Gamma\left(s \rightarrow X_{\text{SM}} X_{\text{SM}}\right) = \sin^2\theta\, \Gamma\left(h(m_s) \rightarrow X_{\text{SM}} X_{\text{SM}}\right)$$

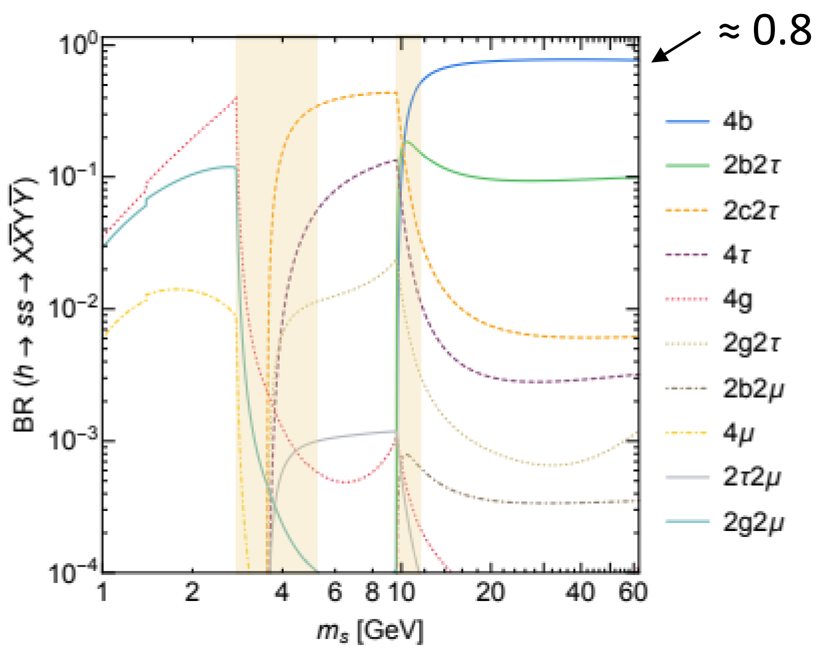
- For sufficiently small mixing, the scalar can be long-lived
  - cτ ~ meters if θ < 1e-6



Possible production and decay at FCC-ee

Production process:





arXiv:1312.4992

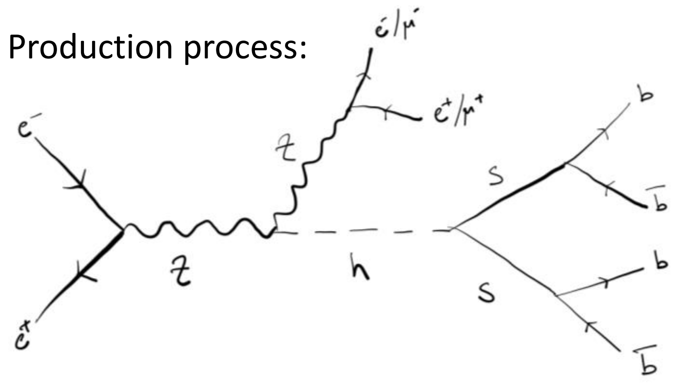
- Higgs produced at ZH-stage of FCC-ee: $\sqrt{s} = 240\ GeV$
- **Signal process:** $e^+e^- \to Z\ h$ with $Z \to e^+e^-$ or $\mu^+\mu^-$ and $h \to ss \to b\bar{b}b\bar{b}$
- **Experimental signature:** - Z boson reconstructed from e^+e^- or $\mu^+\mu^-$ pair
  - At least 1 Displaced Vertex (DV)

Simulation of long-lived scalars

- The scalars can be simulated with the MadGraph5 HAHM model (arXiv:1312.4992, arXiv:1412.0018)
- The HAHM model includes both a dark photon and a dark scalar
- It has four input parameters:
  - mZDinput : mass of dark photon
  - mHS input : mass of scalar
  - κ : the Higgs-scalar coupling constant
  - ε : kinetic mixing, coupling of the dark photon

- Following the procedure of LHC WG twiki
  - Decouple the dark photon by setting ε = 1e-10 and mZDinput = 1000 GeV
  - Set mHSinput and κ
  - Generate e+ e- > z > z h, z > l+ l-, (h > hs hs, hs > b b~, hs > b b~)
  - Set width of scalar to achieve long lifetime
  - Rescale to correct cross section

Production process:



Model parameters

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

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

- Approximate the cross section with

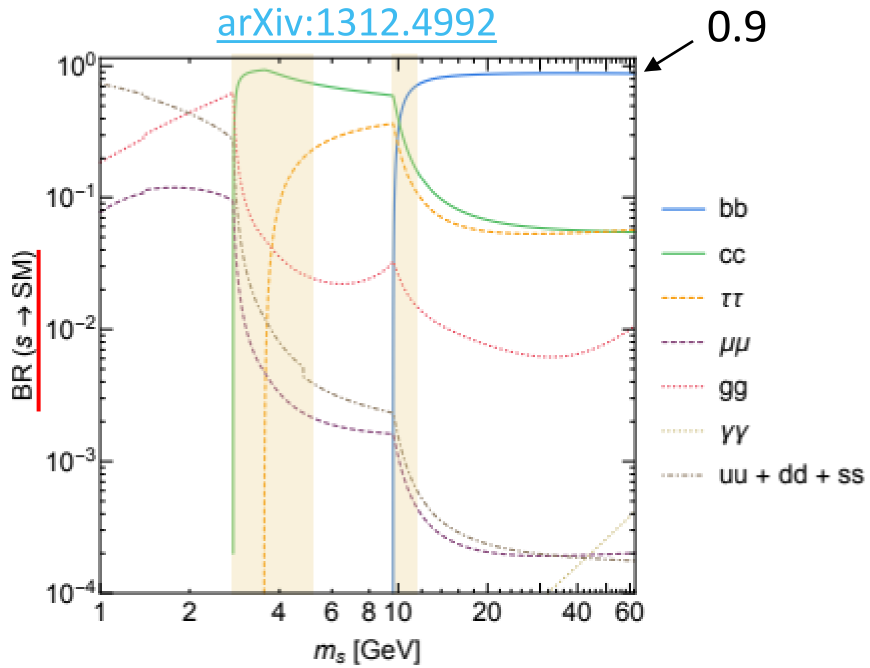
$$\sigma = \sigma_{ZH} \times BR(h \to ss) \times BR(s \to b\bar{b})^2$$

- 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 = 1e-3 s.t $BR(h \to ss) = O(10^{-4})$, lower than current constraints and within reach for FCC-ee shown by previous studies, see backup
- $\sigma_{ZH} = 0.259 \pm 9.972\text{e-}5$ pb, from MG output
- $BR(s \to b\bar{b})^2 = 0.9^2$, from plot

arXiv:1312.4992

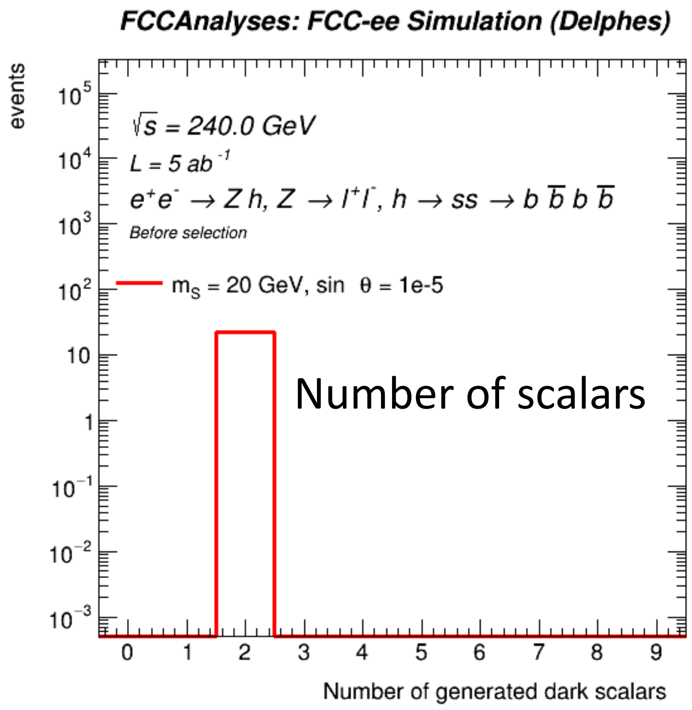


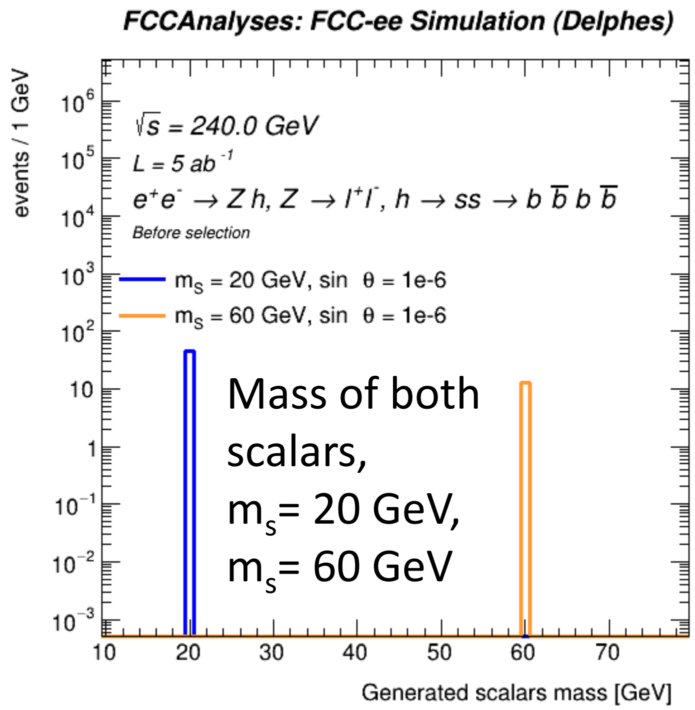
Parameter choices

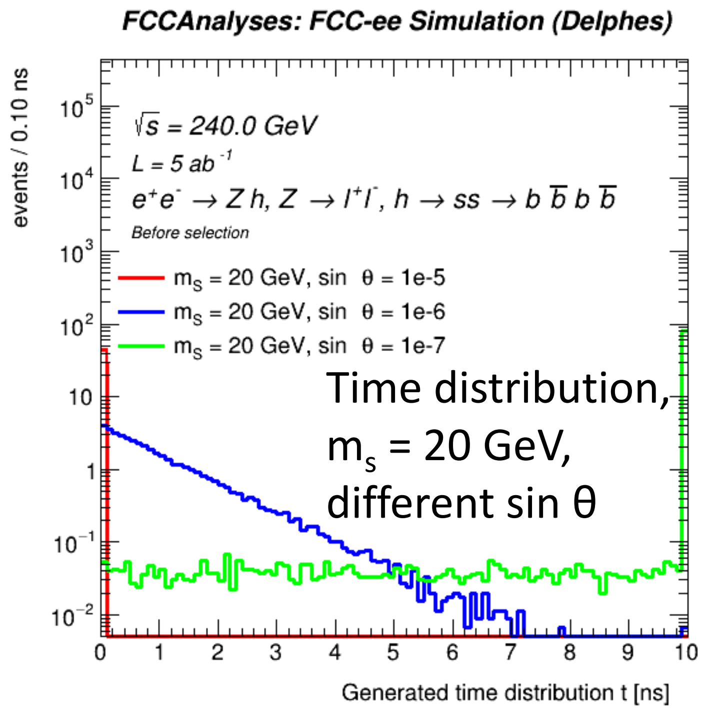
- We generate samples for two different masses, m_s = 20 GeV and m_s = 60 GeV
- And three different mixing angles sin θ = 1e-5, 1e-6, 1e-7 for each mass
- Full chain using MadGraph v3.4.1 + Pythia8 + Delphes, with the spring2021 IDEA Delphes card
- 10 000 events privately produced for each mass and mixing angle
- In GitHub: Sample Generation

Mass of Scalar [GeV]	Mixing angle sin θ	Width of Scalar [GeV]	Cross section [pb]
20	1e-5	5.779e-14	1.316e-4
20	1e-6	5.779e-16	1.316e-4
20	1e-7	5.779e-18	1.316e-4
60	1e-5	2.252e-13	3.889e-5
60	1e-6	2.252e-15	3.889e-5
60	1e-7	2.252e-17	3.889e-5

Generated kinematics

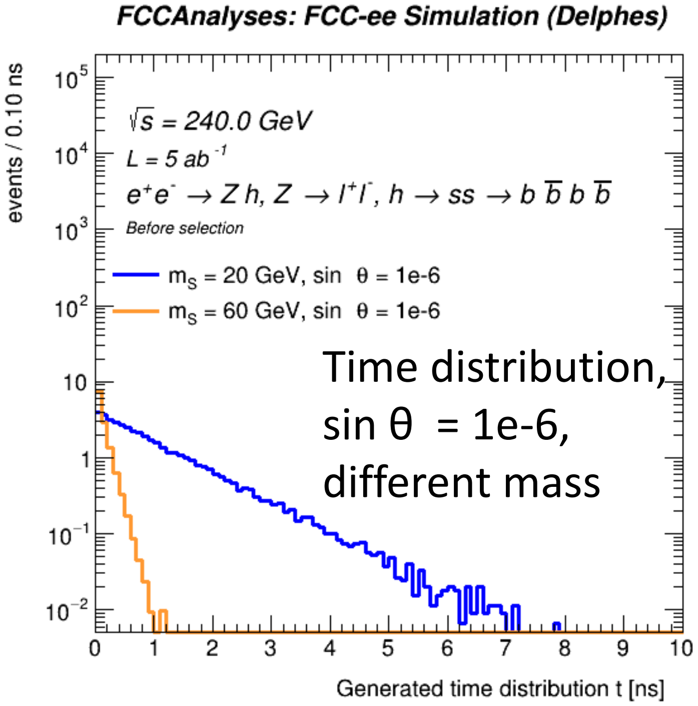


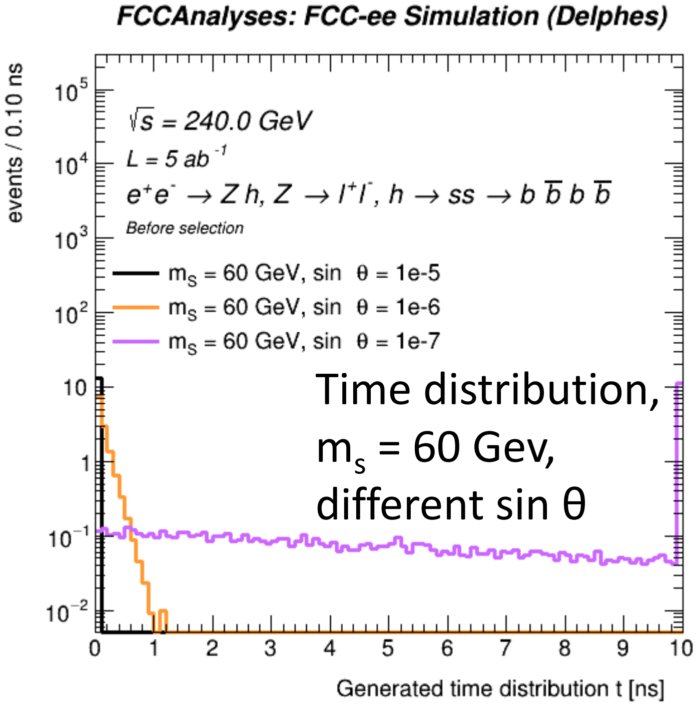


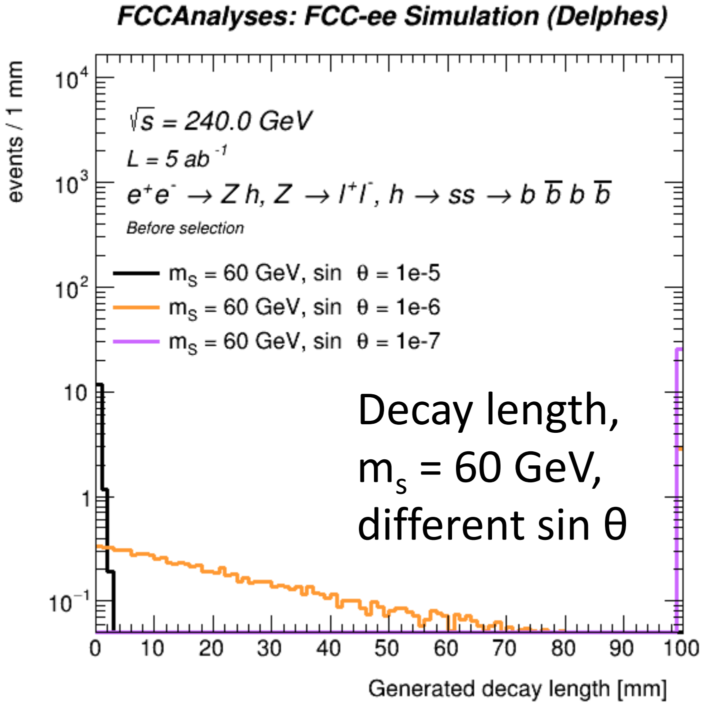


- Generates 2 scalars for every event
- Generates the two different scalar masses, m_s = 20 GeV and m_s = 60 GeV
- The generated mean proper lifetimes τ (from fit of the distributions) behaves as expected:
  - 0.0107 ± 0.0001 ns
  - 1.0622 ± 0.0108 ns
  - 118.326 ± 1.2412 ns

Generated kinematics



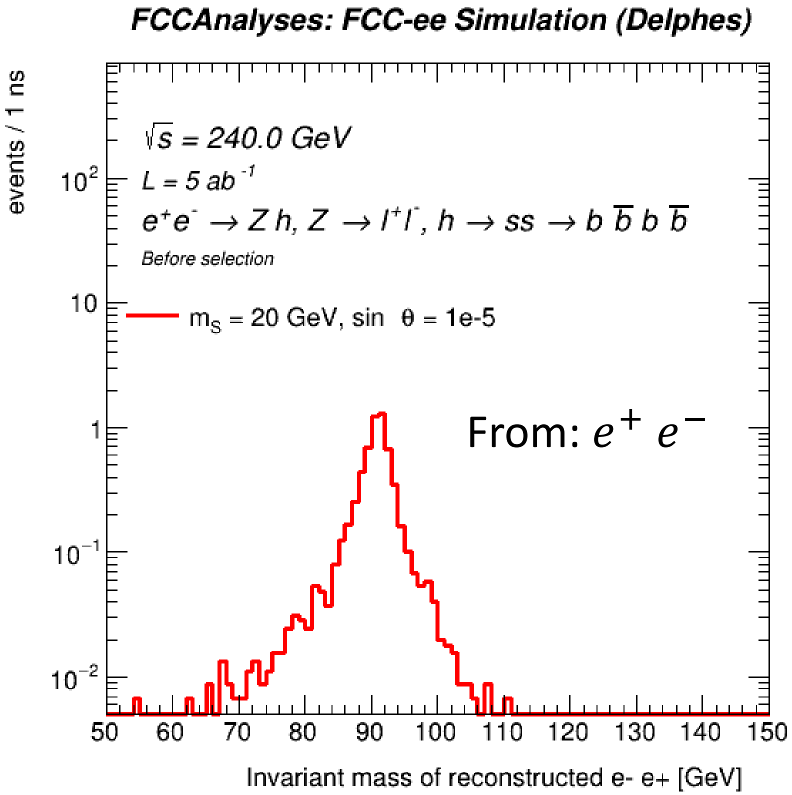


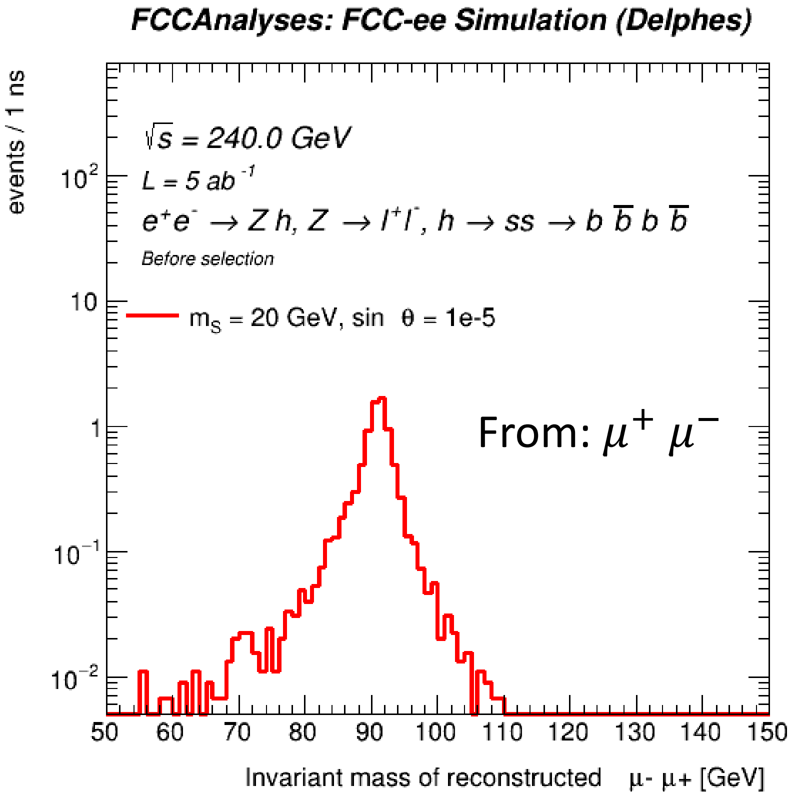


- The heavier mass m_s = 60 GeV has a shorter lifetime than the lighter mass m_s = 20 GeV for the same mixing angle sin θ, as expected

Reconstruction of the Z boson with $e^+e^-$and $\mu^+\mu^-$

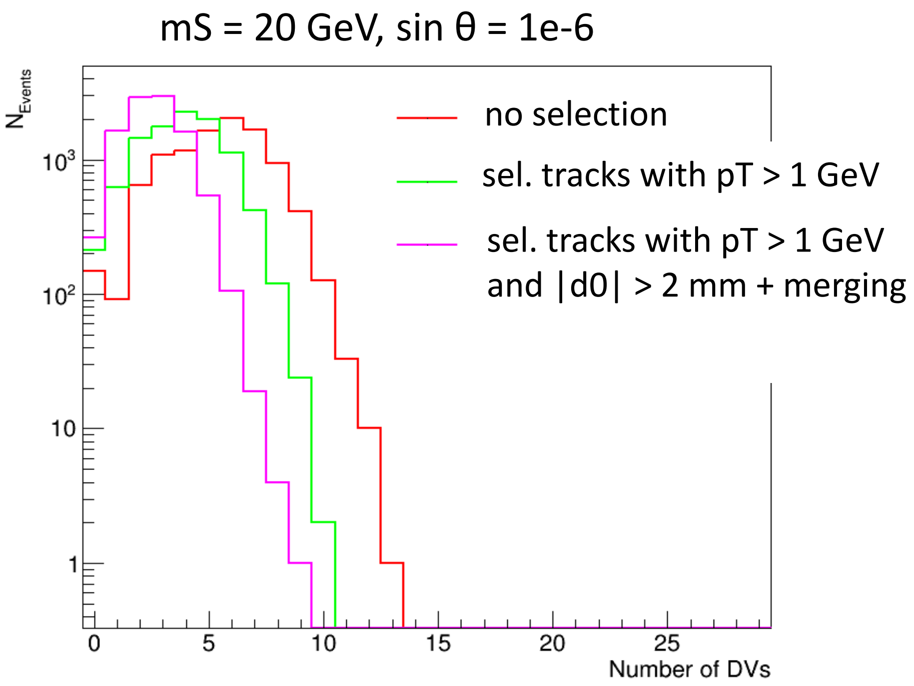
- The Z boson mass reconstructed from the invariant mass of either the reconstructed e^+e^- or $\mu^+\mu^-$ pair
- Can be used to tag the signal

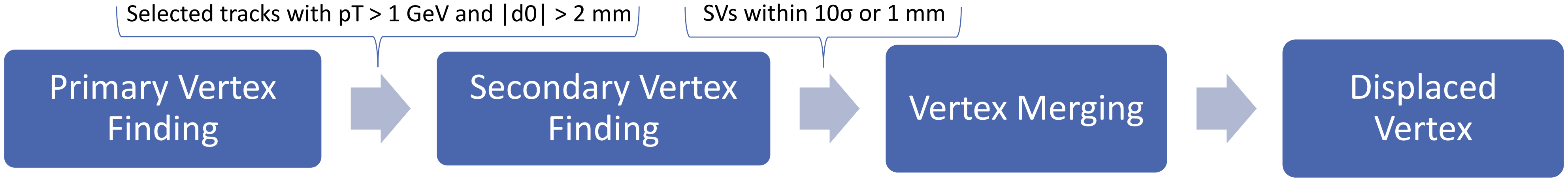




Displaced Vertex Reconstruction

- Using current tools of FCCAnalysis with extra constraints and functions, inspired by Atlas DV reconstruction algorithm (cern record)
- Finding PV with the vertexfitter (link)
- Using the SV finder (PR) of the LCFI+ algorithm (arXiv:1506.08371)
  - Our inputs for vertex seed: Minv < 40 GeV (standard 10 GeV), $\chi^2 < 9$, and $\chi^2 < 5$ for adding track to vertex seed
- Added for our purpose: selected tracks and vertex merging (link)
  - To minimize SVs from the final state b quarks
  - Compare the vertices positions pair-wise and merge if they are within 10σ (σ = error of vertex position) or 1 mm
  - Merging done by taking the associated tracks of the merged vertices, combine and rerun the vertexfitter





Vertexfitter of Franco
BSC of PV from Emmanuel & Clement: talk

SV finder from Kunal Gautam: talk

DV Reconstruction Performance

DV properly reconstructed!

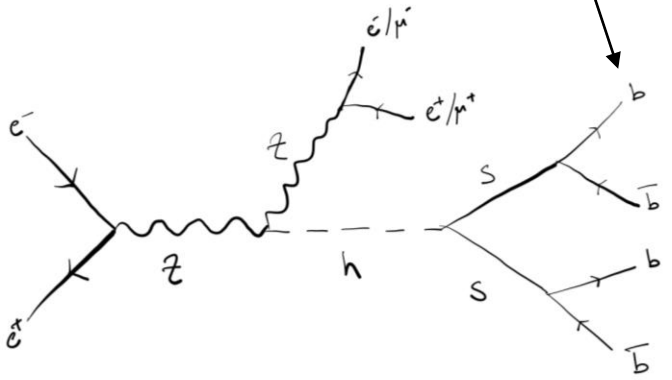
Example for one event from signal sample mS = 20 GeV, sin θ = 1e-6

Vertex	x [mm]	y [mm]	z [mm]	Inv. Mass at DV [GeV]
MC scalar 1	72.97	719.83	138.51	
MC scalar 2	-1600.13	-1561.34	-761.00	
DVs	72.95 ± 0.019	721.67 ± 0.074	138.68 ± 0.148	6.94
	74.73 ± 0.026	731.47 ± 0.152	140.96 ± 0.155	2.12

SV from b quark decays

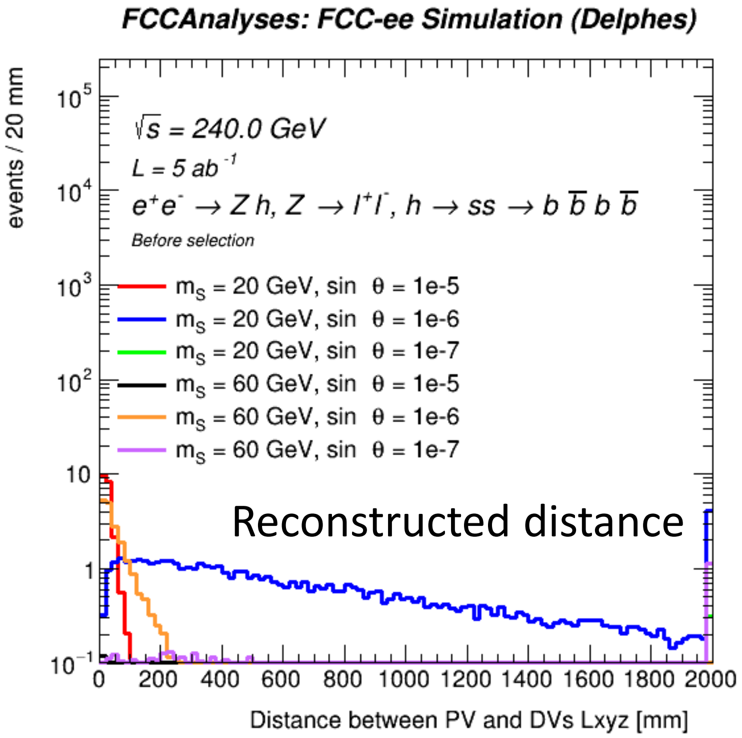
Example of merging effect for one event from signal sample mS = 20 GeV, sin θ :

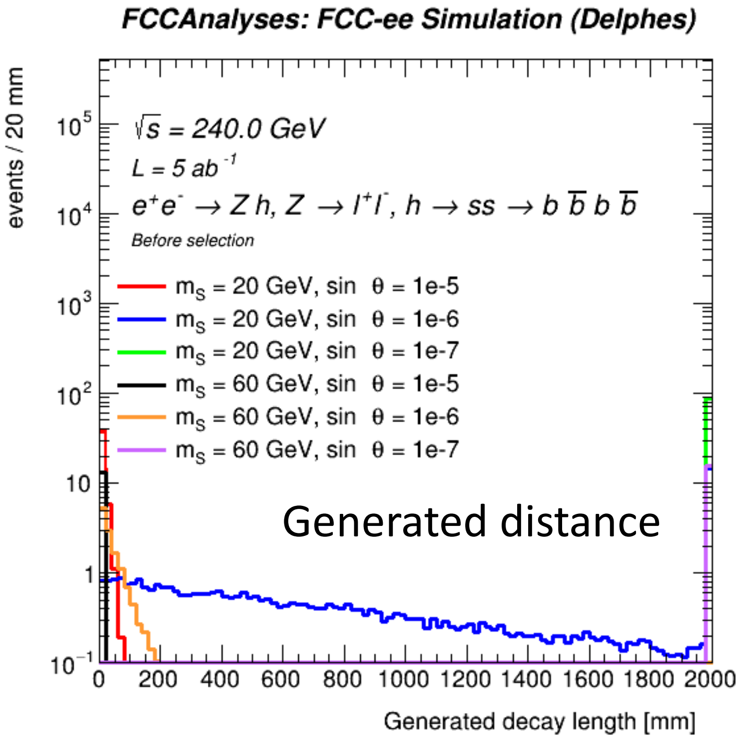
Vertex	x [mm]	y [mm]	z [mm]
MC scalar 1	-6.13	-0.63	-2.98
MC scalar 2	8.94	8.42	6.47
SVs	-5.68 ± 0.260	-0.64 ± 0.022	-2.75 ± 0.096
	-6.22 ± 0.044	-0.61 ± 0.005	-3.00 ± 0.019
	8.94 ± 0.018	8.41 ± 0.016	6.47 ± 0.005
	9.66 ± 0.019	8.88 ± 0.013	6.82 ± 0.008
	17.40 ± 0.015	17.86 ± 0.016	14.81 ± 0.013
	16.14 ± 0.010	16.36 ± 0.010	13.48 ± 0.010
	-8.27 ± 0.024	-1.60 ± 0.016	-4.75 ± 0.016
DVs	-6.17 ± 0.043	-0.61 ± 0.004	-2.97 ± 0.018
	8.90 ± 0.007	8.37 ± 0.006	6.48 ± 0.003
	17.40 ± 0.015	17.86 ± 0.016	14.81 ± 0.013
	16.14 ± 0.010	16.36 ± 0.010	13.48 ± 0.010
	-8.27 ± 0.024	-1.60 ± 0.016	-4.75 ± 0.016



Distance from PV to DVs

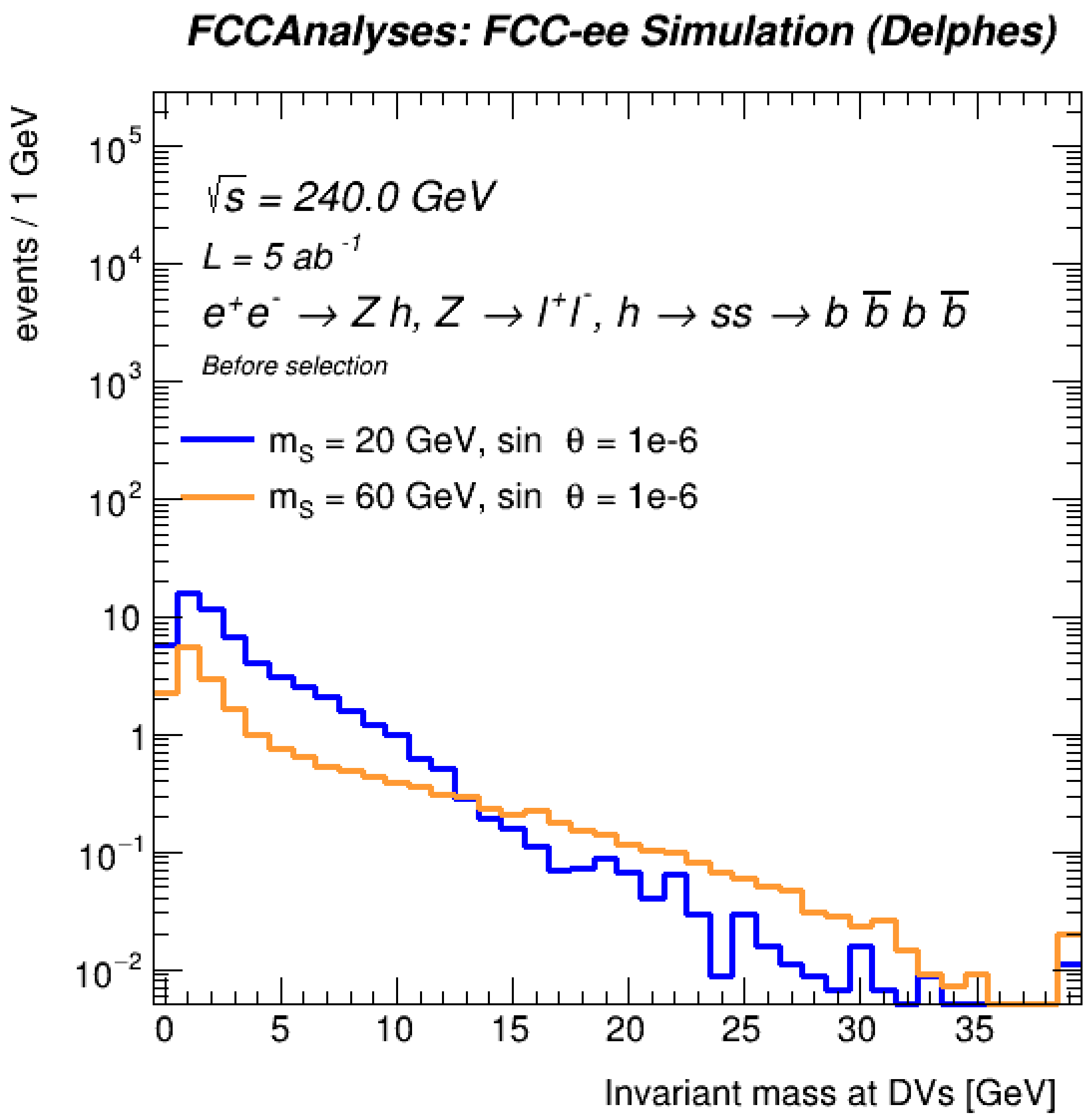
- m_s = 20 GeV, sin θ = 1e-5, m_s = 20 GeV, sin θ = 1e-6 and m_s = 60 GeV, sin θ = 1e-6 good for our analysis!
- m_s = 60 GeV, sin θ = 1e-5 is too short lived to be properly reconstructed with the DV algorithm
- Both m_s = 20 GeV and m_s = 60 GeV with sin θ = 1e-7 are too long-lived so we get very few reconstructed events
- Reconstructed quantity nicely follows the generated quantity





Invariant Mass at the DVs

- Invariant mass at vertex calculated assuming all tracks to come from pions
- Captures only the charged component of the jet fragmentation
- The distribution of the heavier signal sample, m_s = 60 GeV, extends to higher values, as expected



Suggested event selection

- Suggested variables and selections
  - Tag Z-boson with invariant mass of electrons/positrons and muons
  - Require at least 1 reconstructed DV
- Suggested variables for further study for selections
  - Distance of DVs from PV: Required to be in fiducial volume of the ID/Drift Chamber (DCH) of IDEA, to ensure vertexing efficiency, and outside the innermost region to exclude heavy-flavour decays
  - Invariant mass at DV: To remove background DVs

	Variable/Selection
Tag Z-boson	$80 < m_{l^+l^-} < 100$ GeV
Multiplicity of DV	nDV $\geq$ 1
Distance of DV	L_{xyz}
Charged invariant mass at DV	$M_{charged}^{DV}$

Sensitivity Analysis

- The cross section is given by $\sigma\ = \sigma_{ZH} \times BR(h \to ss \to b\bar{b}b\bar{b})$
- Including the Z boson decaying to e^+e^- or $\mu^+\mu^-$ pairs we get

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

- Expected events calculated as $N = L\ \times\ \sigma$ with $L = 5\ ab^{-1}$
- Times the fraction of decays within DCHs outer radius R_{out} = 200 cm
  - 83.8% for m_s=20 GeV, sinθ=1e-6
  - 100% for m_s=20 GeV, sinθ=1e-5 and m_s=60 GeV, sinθ=1e-6

Signal sample	Cross section [pb]	Expected events	Cross section [pb] including Z to l+l-	Expected events	Expected events within ID/DCH
m_s=20 GeV, sinθ=1e-5	1.316e-4	658	4.434e-6	22	22
m_s=20 GeV, sinθ=1e-6	1.316e-4	658	4.434e-6	22	18
m_s=60 GeV, sinθ=1e-6	3.889e-5	194	1.311e-6	6.5	6.5

- Assuming zero background, signal points with at least three expected events can be excluded

→ Acceptance times efficiency needs to be at least 50% for the m_s = 60 GeV point

Preliminary next steps for the LLP group

- Performe truth matching with MC vertices of the scalars vs the reconstructed DVs
  - What is the reconstruction effiency?
- Possibly improve DV finder
  - Are there other cuts that can be done to improve the reconstruction?
  - Can other choices of pT and |d0| thresholds improve the reconstruction?
- Increase signal sample size and consider several different masses and mixing angles to properly span the parameter space
- Perform background study and event selection
  - Use centrally produced samples at ZH stage
  - Confirm zero background?
- Study other possible exotic Higgs decays to LLPs
  - E.g Dark Photon in the HAHM model

- More person power needed, please come and join this effort!

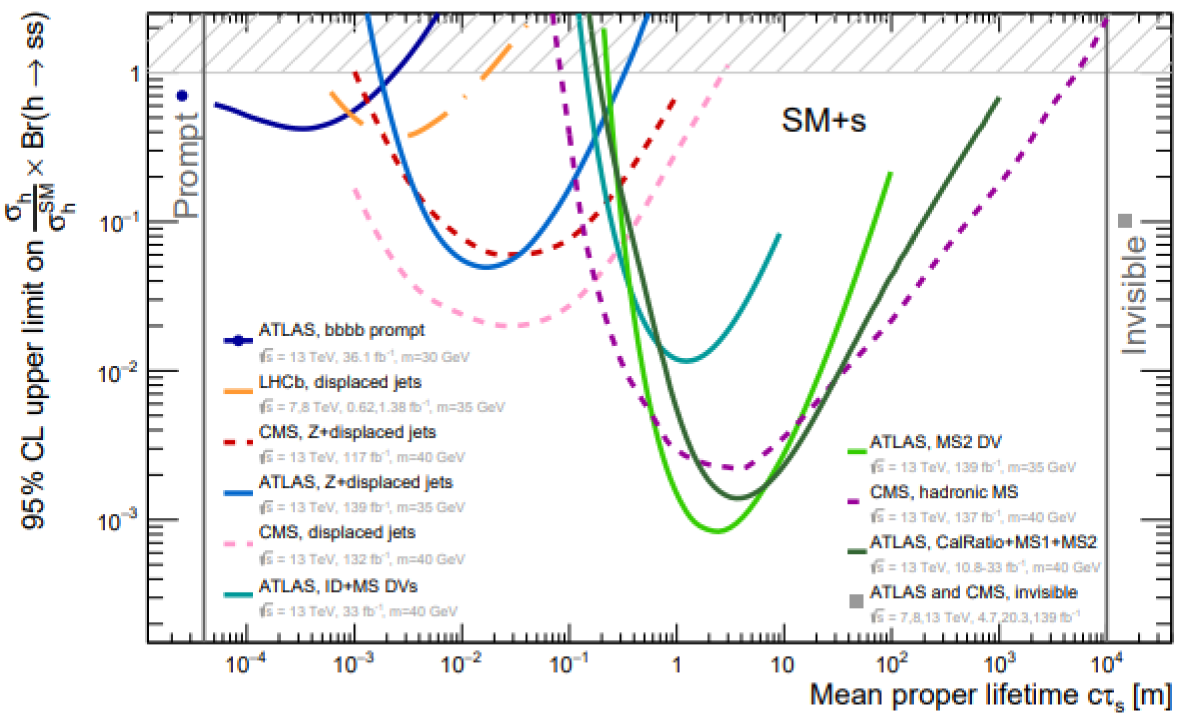
Summary

- Aimed to simulate and analyse exotic Higgs decays to LLPs at FCC-ee within the FCCAnalysis framework
  - Considered the signal process $e^+e^- \rightarrow Z\,h$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
  - Generated signal samples of the long-lived scalars with the MG HAHM model, considering **m_s = 20 GeV and m_s = 60 GeV with lifetimes of 1 mm – 10 m**
- Generated kinematics look sensible
- Look for the experimental signature of reconstructing the Z boson from reconstructed electrons and muons and at least 1 DV
  - The Z boson can be reconstructed well from the invariant mass of the reconstructed electrons and muons
  - Constructed a procedure to reconstruct the DVs, developed from current tools of FCCAnalysis
- The performance of the DV algorithm has been studied to some degree
  - Looked at number of DVs, invariant mass at vertex and distance of the DVs from the PV
  - Need to determine efficiency by e.g truth matching
  - **Needed efficiency 50% for the DV reconstruction** considering high acceptance and no background

Thank you for listening!

Backup Slides

Current Constraints LHC

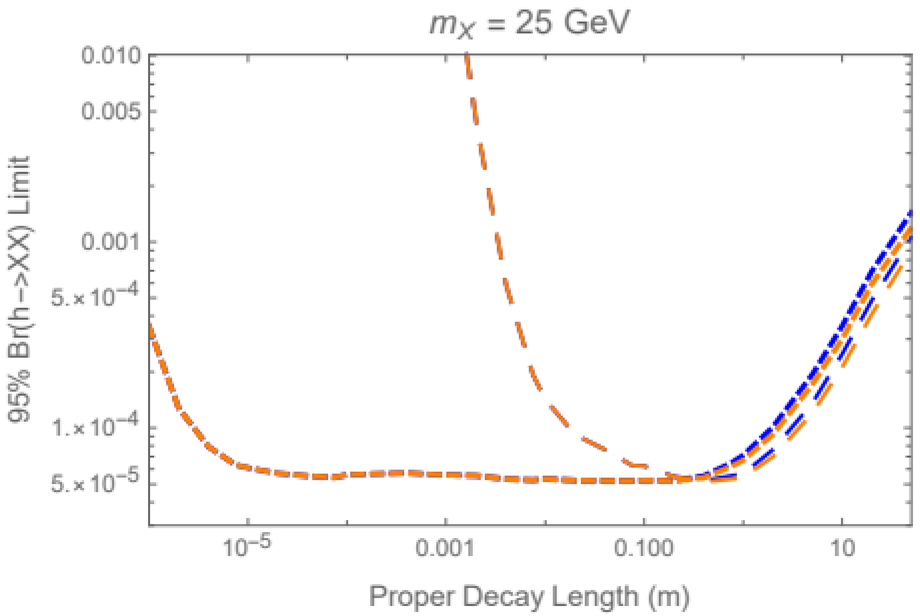


arXiv:2111.12751

Table 2: Summary of the latest LLP searches for $h \to ss/vv$. m and $c\tau$ denote the new particle mass and lifetime, respectively.

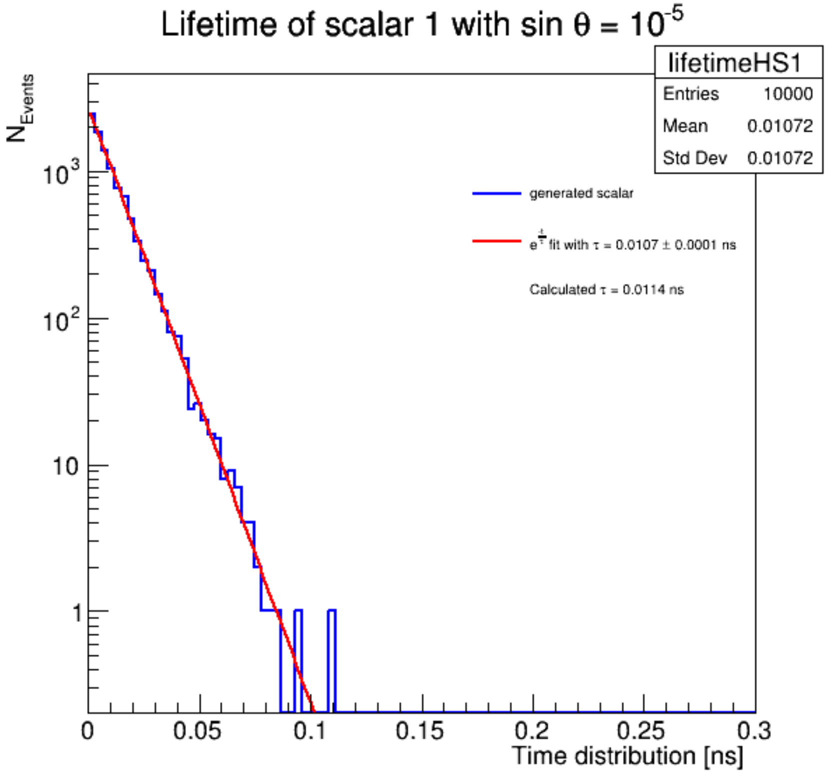
Decay	Mode	Reference	Method	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	m (GeV)	$c\tau$ (m)
SM+s: $h \to ss$ or $s + X$, s long-lived							
$bbbb$	Wh/Zh	ATLAS [76]	prompt reinterp.	13	36.1	20-60	$10^{-4} - 10^{-2}$
$bbbb$ $cccc$ $ssss$	ggF	LHCb [94]	disp. jets	7,8	2.0	25-50	$10^{-3} - 10^{-1}$
$bbbb$ $dddd$	Zh	CMS [95]	Z+disp. jets	13	117	15-55	$10^{-3} - 1$
$bbbb$	Zh	ATLAS [96]	Z+disp. jets	13	139	16-55	$10^{-3} - 1$
$bbbb$ $dddd$	ggF	CMS [97]	disp. jets	13	132	15-55	$10^{-3} - 10$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS [98]	CalRatio	13	10.8, 33.0	5-55	$10^{-1} - 10^{3}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS [99]	ID+MS DVs	13	33.0	8-55	$10^{-1} - 10$
$bbbb$ $dddd$ $\tau\tau\tau\tau$	ggF	CMS [100]	hadronic MS	13	137	14-55 7-55 7-55	$10^{-1} - 10^{4}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS [101]	MS1+MS2 DV	13	36.1	5-40	$10^{-1} - 10^{3}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS [102]	MS2 DV	13	139	5-55	$10^{-1} - 10^{2}$
$e\mu$+X $\mu\mu$+X ee+X	ggF	CMS [103]	disp. leptons	13	113-118	30-50	$10^{-3} - 10^{1}$

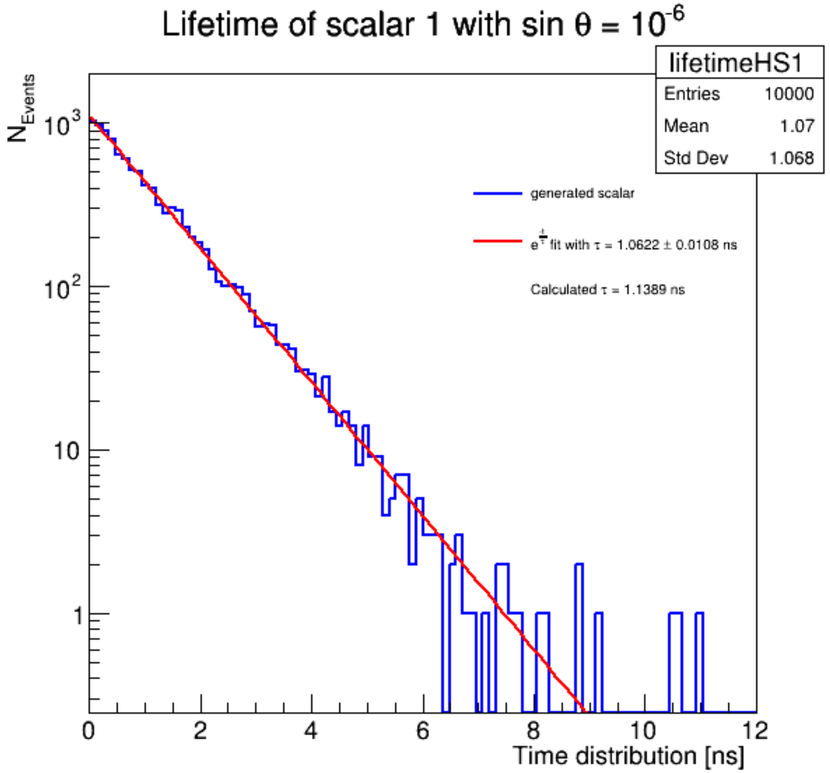
Previous studies

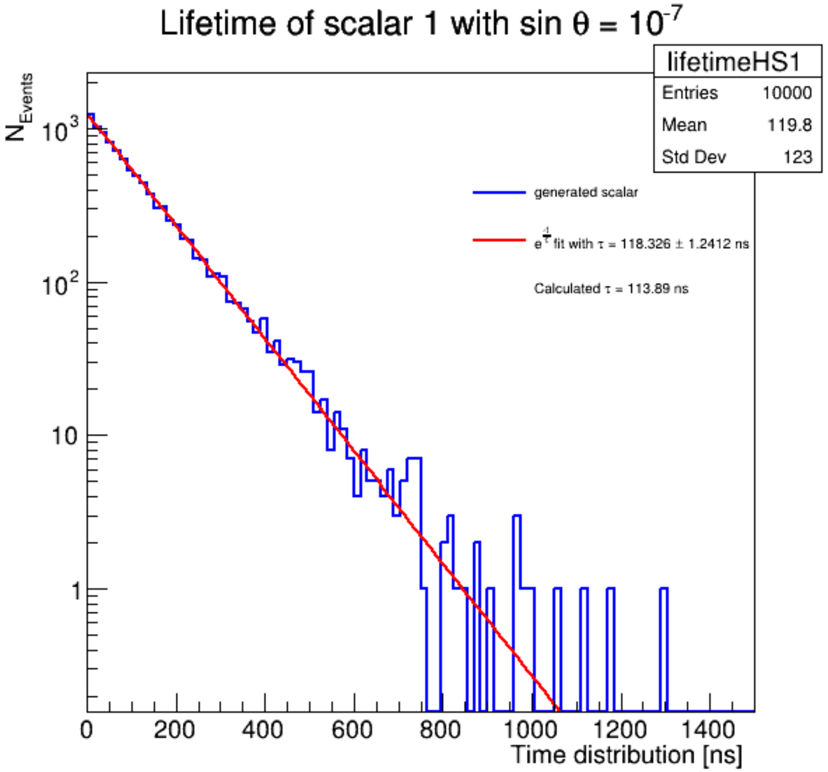


arXiv:1812.05588

Time distributions tau from fit vs calculated







Cross section study of HAHM model

Mass of Scalar m_S [GeV]	Higgs-Scalar coupling κ	Lifetime $c\tau$ [mm]	Cross Section [pb]	Expected events at 5 ab^{-1}
12	10^{-3}	0.0004	$1.133 \times 10^{-5} \pm 1.164 \times 10^{-7}$	57
12	10^{-4}	0.0446	$1.133 \times 10^{-7} \pm 1.164 \times 10^{-9}$	6×10^{-1}
12	10^{-5}	4.4566	$1.133 \times 10^{-9} \pm 1.164 \times 10^{-11}$	6×10^{-3}
20	10^{-3}	0.0001	$1.181 \times 10^{-5} \pm 1.585 \times 10^{-7}$	59
20	10^{-4}	0.0115	$1.181 \times 10^{-7} \pm 1.585 \times 10^{-9}$	6×10^{-1}
20	10^{-5}	1.1505	$1.182 \times 10^{-9} \pm 1.587 \times 10^{-11}$	6×10^{-3}
40	10^{-4}	0.0038	$1.507 \times 10^{-7} \pm 2.105 \times 10^{-9}$	8×10^{-1}
40	10^{-5}	0.3787	$1.507 \times 10^{-9} \pm 2.105 \times 10^{-11}$	8×10^{-3}
50	10^{-4}	0.0026	$1.606 \times 10^{-7} \pm 2.257 \times 10^{-9}$	8×10^{-1}
50	10^{-5}	0.0075	$1.606 \times 10^{-9} \pm 2.256 \times 10^{-11}$	8×10^{-3}

Table 1: Using the HAHM_MG_v3 with $m_{Z_D} = 30$ GeV and $\epsilon = 1 \times 10^{-10}$.