Track IP distributions in Winter2023 samples

FCC LLP Meeting, August 29th 2024

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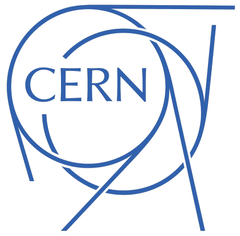

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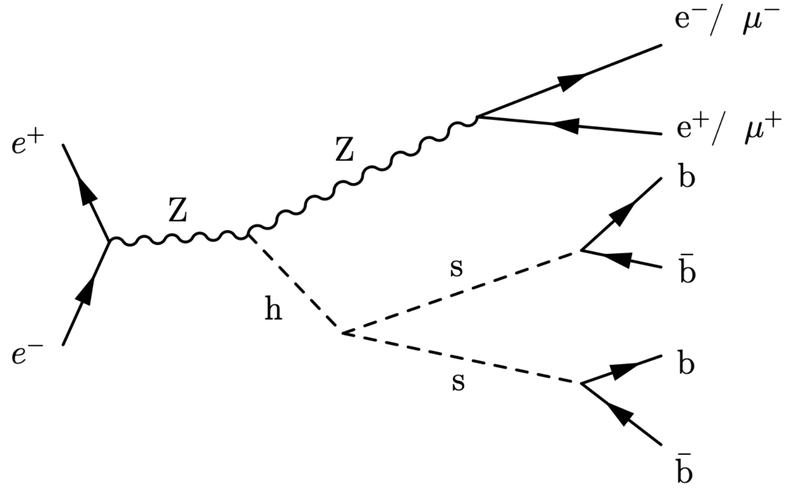
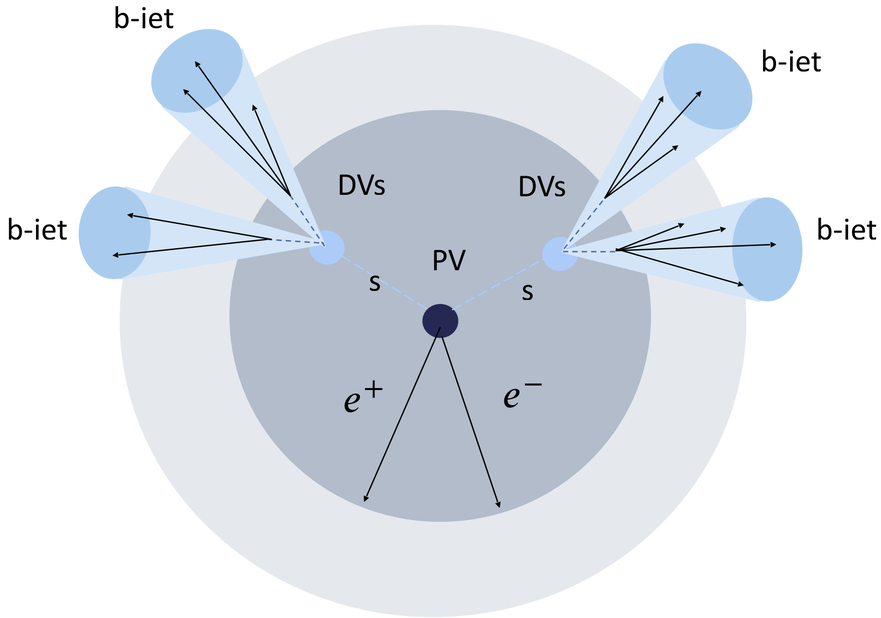
Recap: our analysis

- We are studying the FCC-ee sensitivity towards **long-lived scalars** from exotic Higgs decays
- Targeting the **FCC-ee Zh** stage and the signal process:

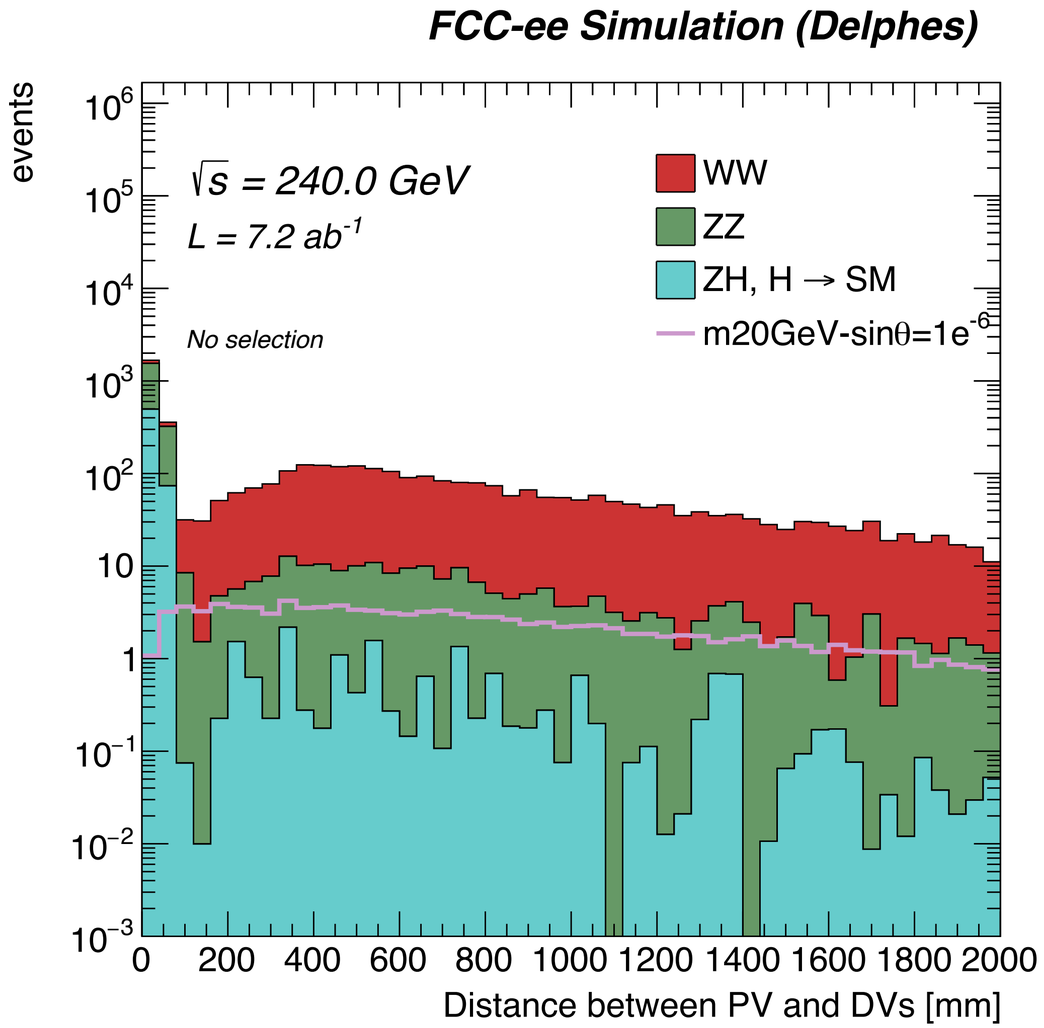
  $e^+e^- \rightarrow Z\,h$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
- Experimental signature:
  - A **displaced vertex (DV)** from the long-lived scalar decay
  - A reconstructed **Z boson from ee or μμ**
- Generator-level studies show sensitivity to the signal points with
  ms=20GeV and sin θ = 1e-5, 1e-6 → cτ ≈ 3 mm and 30 cm
  ms=60GeV and sin θ = 1e-6, 1e-7 → cτ ≈ 9 cm and 9 m
- Currently working on a refined background study with the FCCee Winter2023 campaign samples





DVs distance distribution

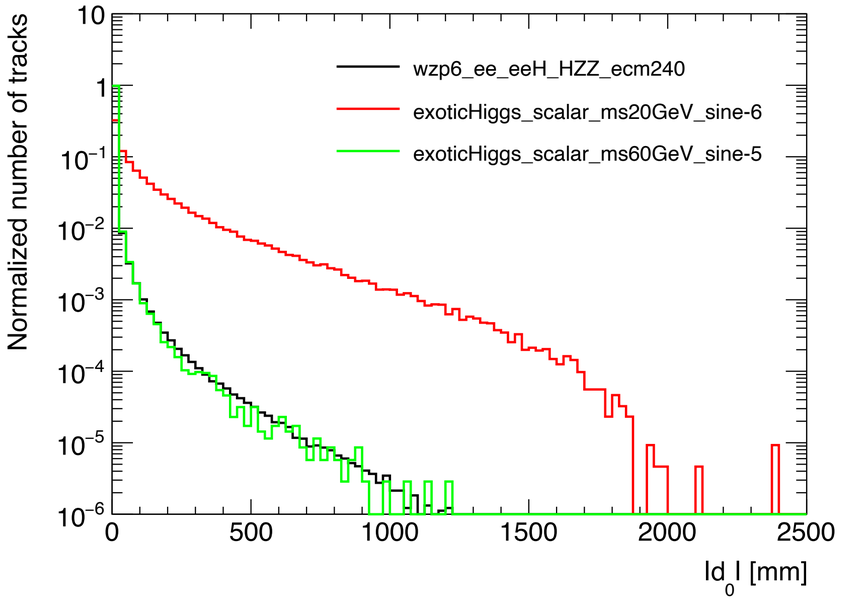
- We were surprised to see background DVs at distances up to 2 meters from the PV
- We have been investigating this and will show our findings in these slides
- Details on DV reconstruction in backup (but not super relevant for the main message in the rest of the slides)



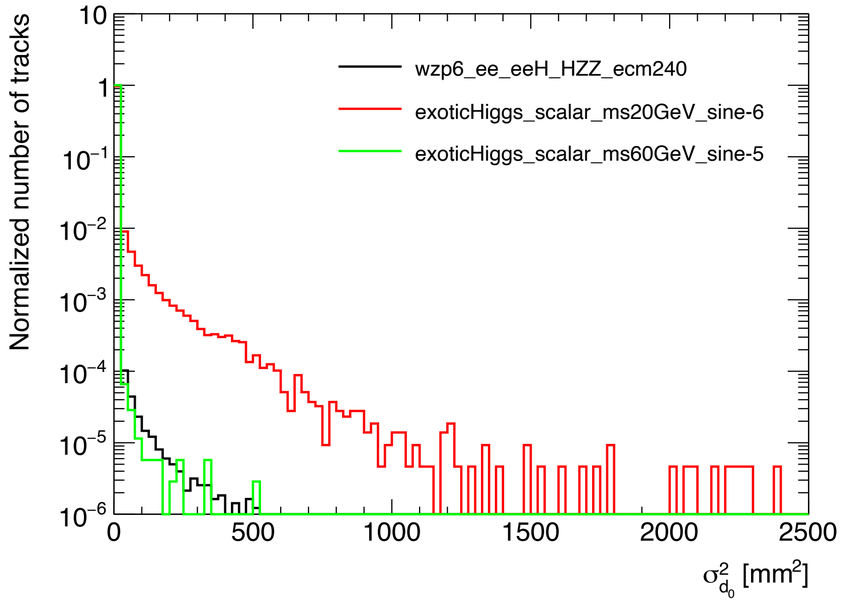
Track d0-distributions

- Here looking at all tracks in two signal samples with small and large displacement and one background sample
  - No selections applied
  - Tracks from EFlowTrack_1 collection
- Tracks with d0 values up to more than 1 meter → explains large radius bkg DVs
  - But what are those large-d0 tracks?

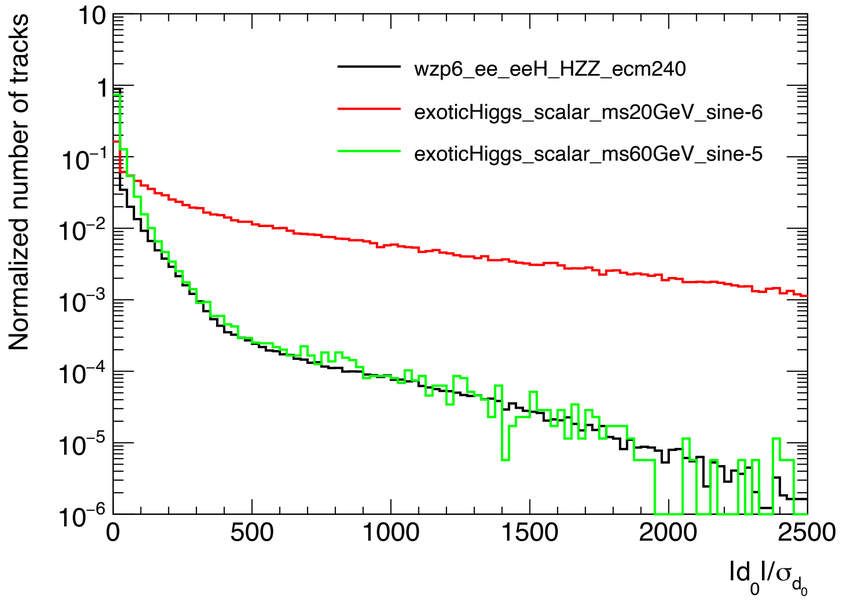
wzp6_ee_eeH_HZZ_ecm240
exoticHiggs_scalar_ms20GeV_sine-6
exoticHiggs_scalar_ms60GeV_sine-5



d0



d0 variance

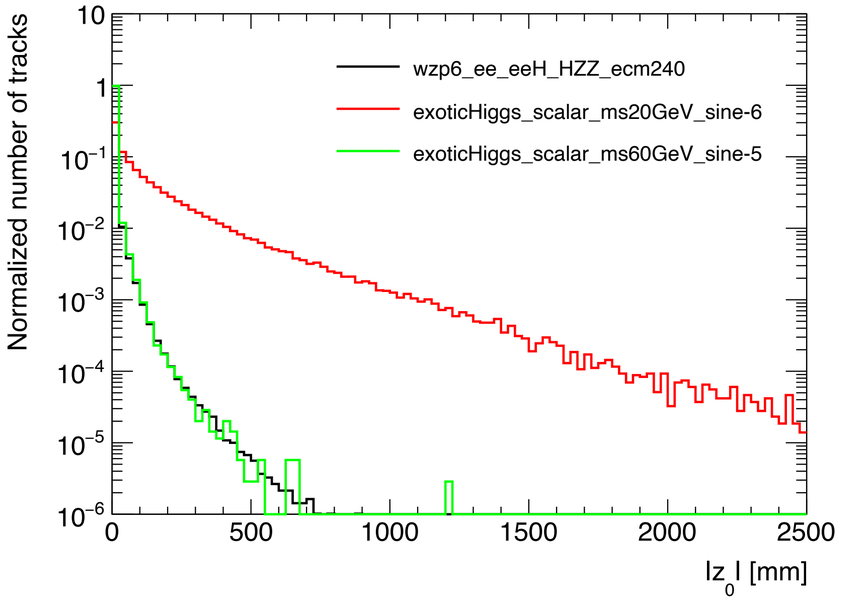


d0 significance

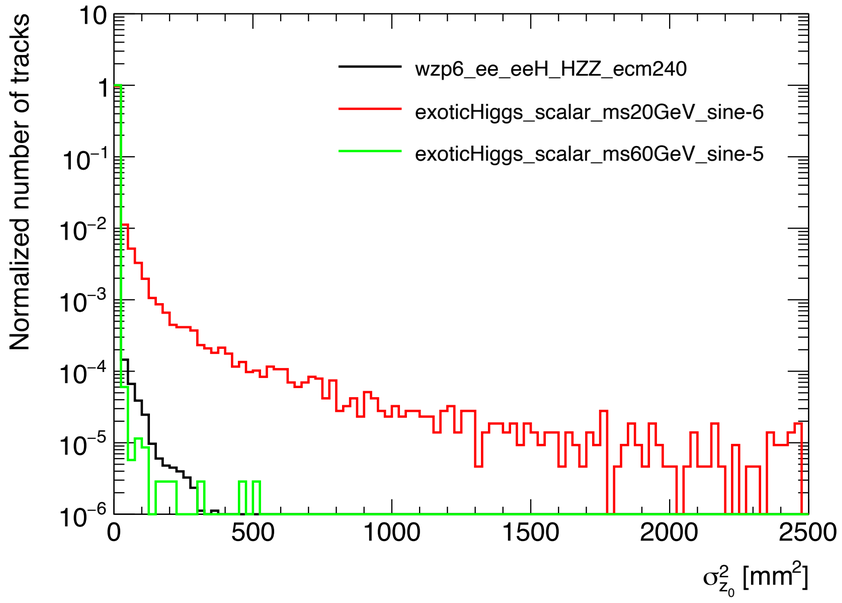
Track z0-distributions

- Here looking at all tracks in two signal samples with small and large displacement and one background sample
  - No selections applied
  - Tracks from EFlowTrack_1 collection
- Also see very large z0 values

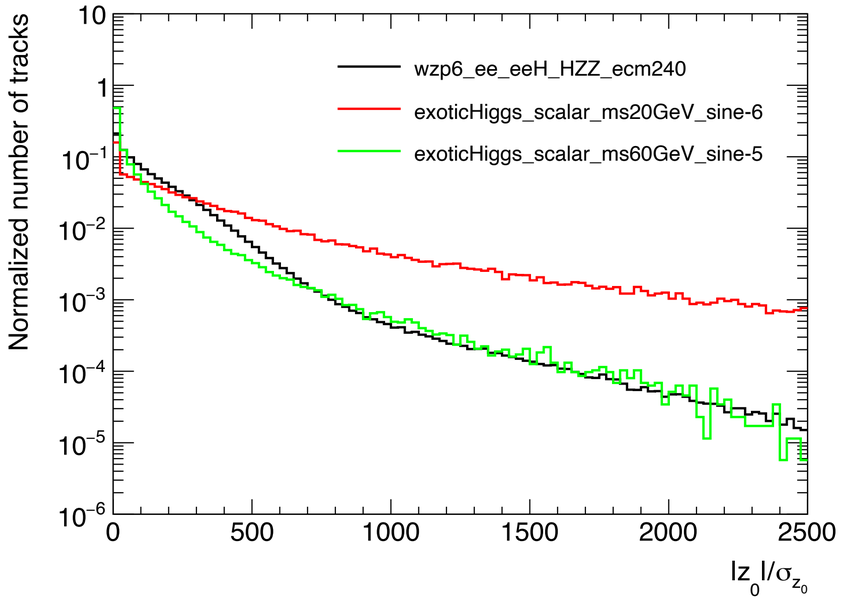
wzp6_ee_eeH_HZZ_ecm240
exoticHiggs_scalar_ms20GeV_sine-6
exoticHiggs_scalar_ms60GeV_sine-5



z0



z0 variance

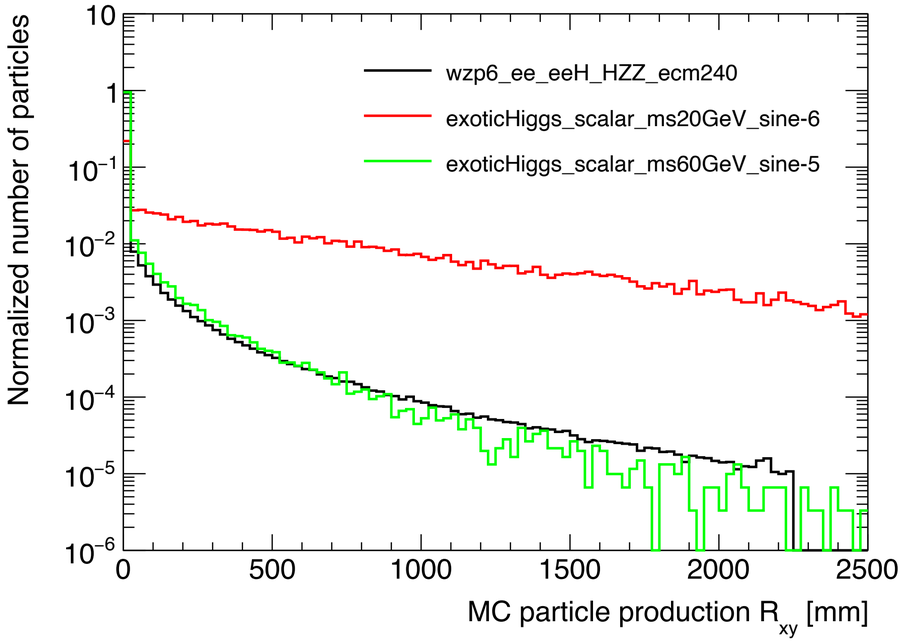


z0 significance

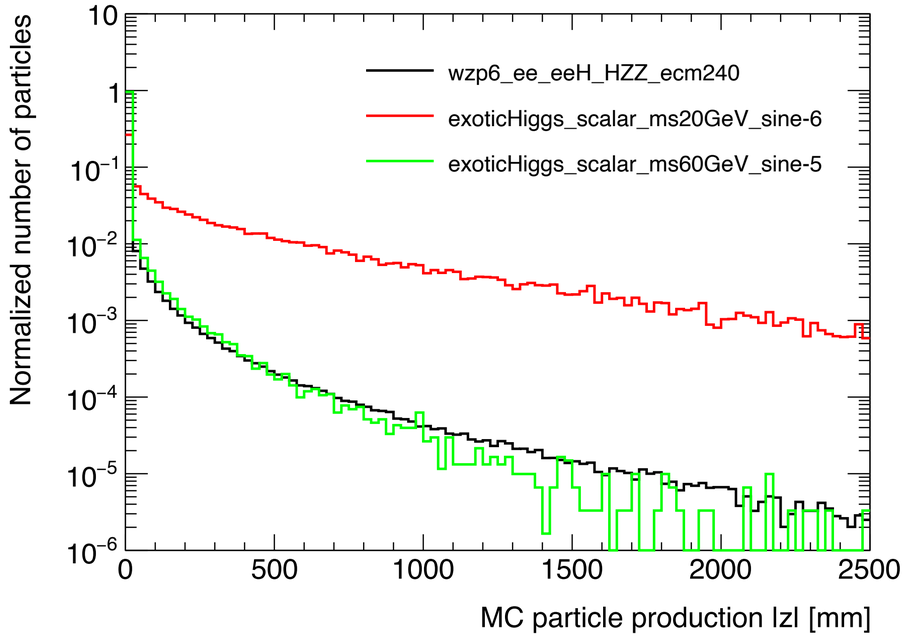
Production position of MC particles

- Here looking at the production position of all charged MC particles in the same three samples
- Can the charged particles at large radius be matched to the large-d0 tracks?
  - We performed a basic truth matching study to find out

wzp6_ee_eeH_HZZ_ecm240
exoticHiggs_scalar_ms20GeV_sine-6
exoticHiggs_scalar_ms60GeV_sine-5



Production position R_{xy}



Production position z

MC ancestry example 1

- This large-d0 track can be traced back to a Kshort coming from the fragmentation of a b-quark
  - Travels 1.3 meters before decaying

Sample:
wzp6_ee_eeH_Hbb_ecm240

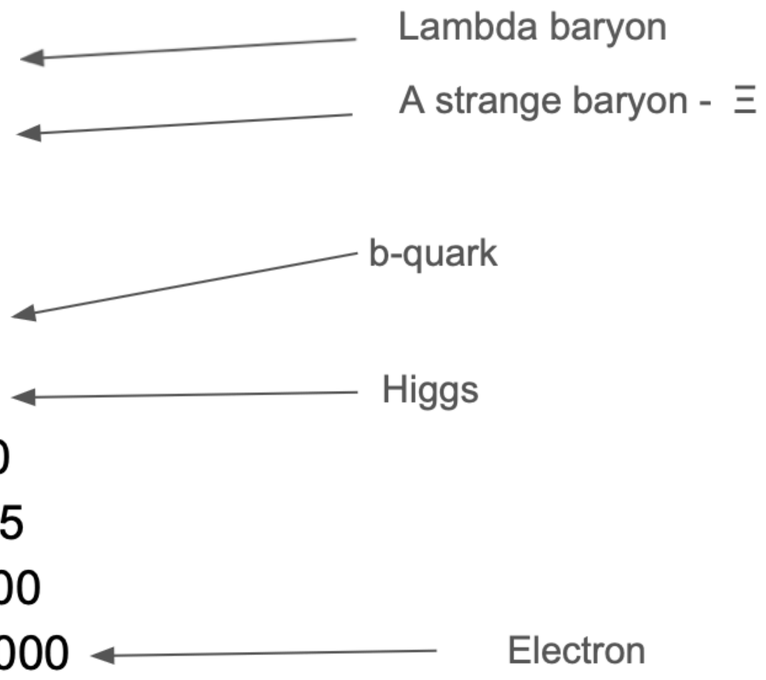
Track index d0 = 1038.21252
MC ancestry:
Prod R = 1285.9357, PDG = -11, Momentum = 0.5182 ← Electron
Prod R = 1285.9355, PDG = 111, Momentum = 1.0741 ← Pion
Prod R = 6.7446, PDG = 310, Momentum = 8.8709 ← Kshort
Prod R = 6.7446, PDG = -311, Momentum = 8.8709
Prod R = 5.4603, PDG = 421, Momentum = 26.7207
Prod R = 5.4603, PDG = 423, Momentum = 29.4849
Prod R = 0.0059, PDG = -511, Momentum = 59.6281
Prod R = 0.0059, PDG = 92, Momentum = 50.5960
Prod R = 0.0059, PDG = 5, Momentum = 63.0715
Prod R = 0.0059, PDG = 5, Momentum = 74.1999 ← b-quark
Prod R = 0.0000, PDG = 25, Momentum = 50.5960 ← Higgs
Prod R = 0.0000, PDG = 11, Momentum = 119.9815
Prod R = 0.0000, PDG = 11, Momentum = 119.9892
Prod R = 0.0000, PDG = 11, Momentum = 120.0000
Prod R = 0.0000, PDG = -11, Momentum = 120.0000 ← Electron

MC ancestry example 1

- This large-d0 track can be traced back to a strange baryons from the fragmentation of a b-quark
  - Travel 0.8 meters before decaying

Sample:
wzp6_ee_eeH_Hbb_ecm240

Track index d0 = 1158.57812
MC ancestry:
Prod R = 1666.4452, PDG = -211, Momentum = 0.4344
Prod R = 804.6375, PDG = 3122, Momentum = 5.8103
Prod R = 0.0000, PDG = 3322, Momentum = 7.4246
Prod R = 0.0000, PDG = 92, Momentum = 30.5610
Prod R = 0.0000, PDG = 5, Momentum = 75.0108
Prod R = 0.0000, PDG = 5, Momentum = 75.8163
Prod R = 0.0000, PDG = 25, Momentum = 31.8578
Prod R = 0.0000, PDG = 11, Momentum = 119.7210
Prod R = 0.0000, PDG = 11, Momentum = 119.7265
Prod R = 0.0000, PDG = 11, Momentum = 120.0000
Prod R = 0.0000, PDG = -11, Momentum = 120.0000



MC ancestry example 3

- This large-d0 track can be traced back to a Kshort coming from the fragmentation of an s-quark
  - Travels 1.7 meters before decaying

Sample:
wzp6_ee_eeH_HZZ_ecm240

Track index d0 = 1455.03845
MC ancestry:
Prod R = 1715.1966, PDG = -11, Momentum = 0.3211
Prod R = 1715.1966, PDG = 111, Momentum = 1.3012
Prod R = 0.0025, PDG = 310, Momentum = 13.0639 ← Kshort
Prod R = 0.0025, PDG = -311, Momentum = 13.0639
Prod R = 0.0025, PDG = -325, Momentum = 30.4770
Prod R = 0.0025, PDG = 92, Momentum = 22.7933
Prod R = 0.0025, PDG = 3, Momentum = 41.6041
Prod R = 0.0025, PDG = 3, Momentum = 41.9388 ← s-quark
Prod R = 0.0025, PDG = 23, Momentum = 22.7933 ← Z
Prod R = 0.0000, PDG = 25, Momentum = 51.5848 ← Higgs
Prod R = 0.0000, PDG = 11, Momentum = 120.2711
Prod R = 0.0000, PDG = 11, Momentum = 120.2730
Prod R = 0.0000, PDG = 11, Momentum = 120.0000
Prod R = 0.0000, PDG = -11, Momentum = 120.0000 ← Electron

Summary

- What we first thought were unphysical IP distributions seem perfectly physical :)
  - All large-d0 tracks can be truth matched to charged particles from the fragmentation of quarks
  - With the many layers of the IDEA tracker and Delphes, it seems reasonable that these are reconstructed as tracks
  - Previous studies of the track IPs (e.g by Juliette here) where made selecting only electron or muon tracks and therefore look more like we expect with our ATLAS/CMS glasses on
- We have realised that it will take more than a d0 requirement to make this a background-free search…
- Our ideas to remove background:
  - These large radius background decays are always in prompt jets
    → Add an event-level selection on jets (e.g # of jets, jet pT, etc…)
  - Add requirement on number of tracks in DV. Already tried out and gives improvement.
  - Increase track pT threshold in vertexing (currently at 1 GeV)
  - Add a track d0-significance requirement in vertexing
- Any other ideas for us?

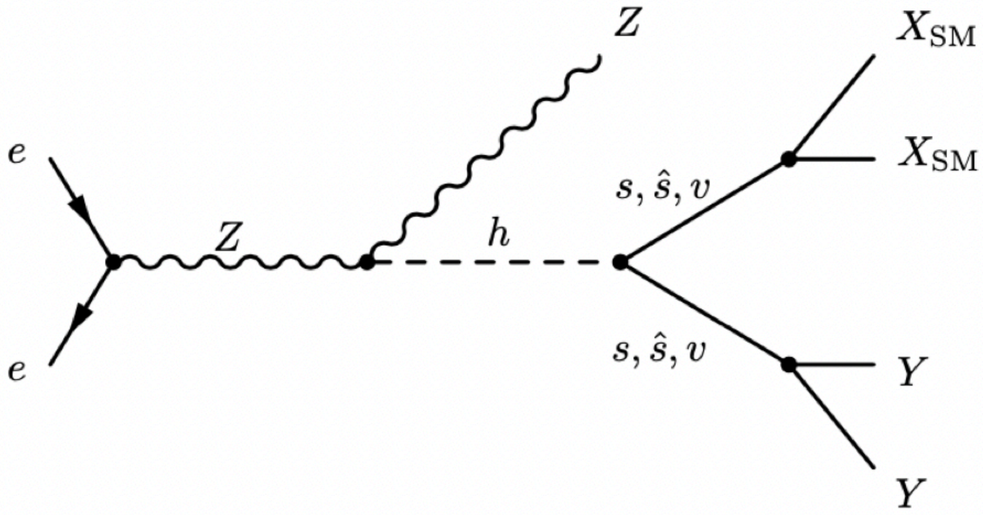
Backup

Exotic Higgs decays

- The Higgs boson can have sizeable couplings to new particles
  - Several interesting models: SM extensions with scalars/ fermions/vectors, MSSM, NMSSM, Hidden Valleys arXiv:1312.4992

- We are studying the FCC-ee sensitivity towards long-lived scalars from exotic Higgs decays
  - SM+S extension using the Hidden Abelian Higgs Model (HAHM) arXiv:1312.4992, arXiv:1412.0018
  - Long-lived scalars for sufficiently small mixing between the Higgs and the scalar

Example decay of the Higgs boson to scalars, pseudo-scalars, or vectors:

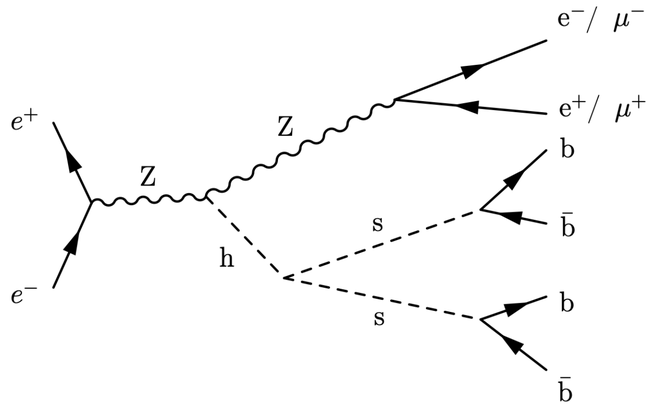


$$\mathcal{L}_{SM} \ni \underbrace{\frac{1}{2}\mu_S^2 S^2 - \frac{1}{4!}\lambda_s S^4}_{\text{scalar potential}} - \underbrace{\frac{1}{2}\kappa S^2 |H|^2}_{\text{portal term}} + \underbrace{\mu^2 |H|^2 - \lambda |H|^4}_{\text{Higgs potential}}$$

Simulation of long-lived scalars @ FCC-ee

- The signal is simulated with the MadGraph5 HAHM model
  - Includes both a dark photon (that is decoupled) and a dark scalar
  - Setting the width of the scalar to achieve long lifetime
- MadGraph v3.4.1 + Pythia8 + Delphes, with the spring2021 IDEA Delphes card
- Parameter choices:
  - ms = 20 GeV and ms = 60 GeV
  - sin θ = 1e-5, 1e-6, 1e-7, corresponding to cτ of order 1 mm – 10 m
  - κ = 1e-4
- 10.000 privately generated events per signal point, available here:

/eos/experiment/fcc/ee/analyses_storage/BSM/LLPs/ExoticHiggsDecays/MC_generation



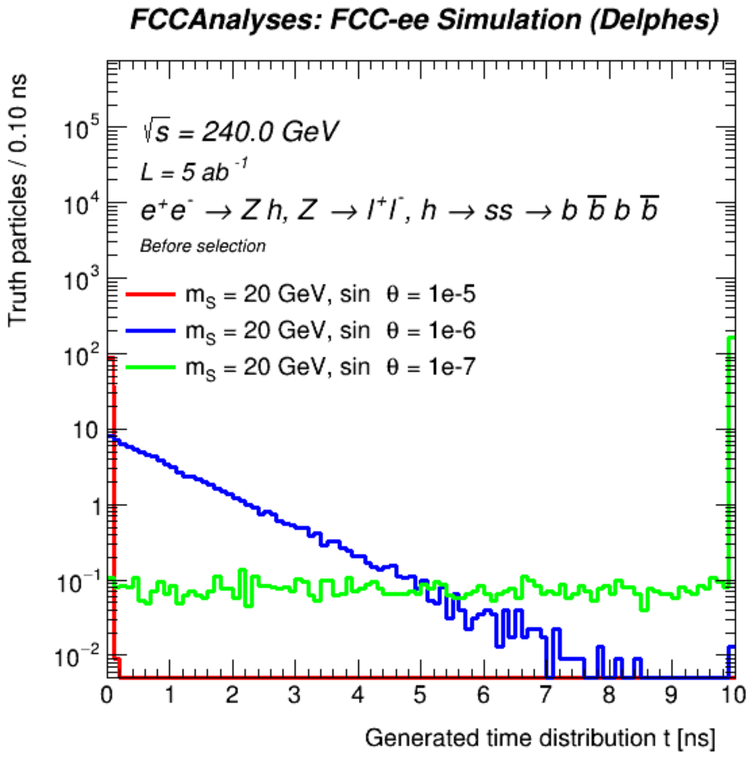
$$\mathrm{BR}(h \to ss) = \frac{\kappa^2 v_h^2}{32\pi m_h \Gamma_h}\sqrt{1-4\frac{m_s^2}{m_h^2}}$$

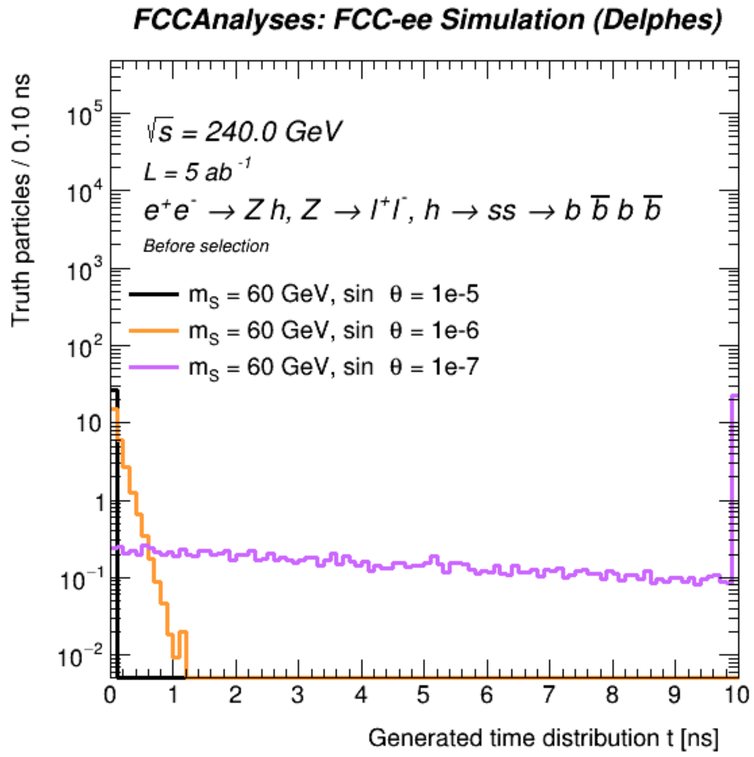
κ: Higgs-scalar coupling constant

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

θ: Mixing angle

Generated lifetime distribution



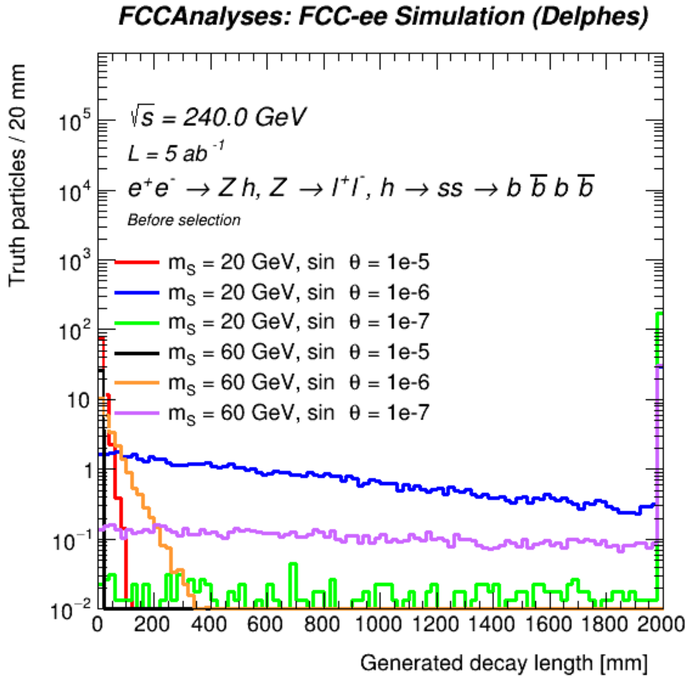


Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Mean proper lifetime $c\tau$ [mm]
20	1×10^{-5}	3.4
20	1×10^{-6}	341.7
20	1×10^{-7}	34167.0
60	1×10^{-5}	0.9
60	1×10^{-6}	87.7
60	1×10^{-7}	8769.1

- Lifetime increases for smaller mixing angle and smaller masses as expected

Sensitivity at generator level

- Selecting events with at least 1 scalar within the acceptance region
  4 mm < r < 2000 mm
- All signal points have ≥ 4 events except the shortest and longest lifetime!



Number of expected events given by

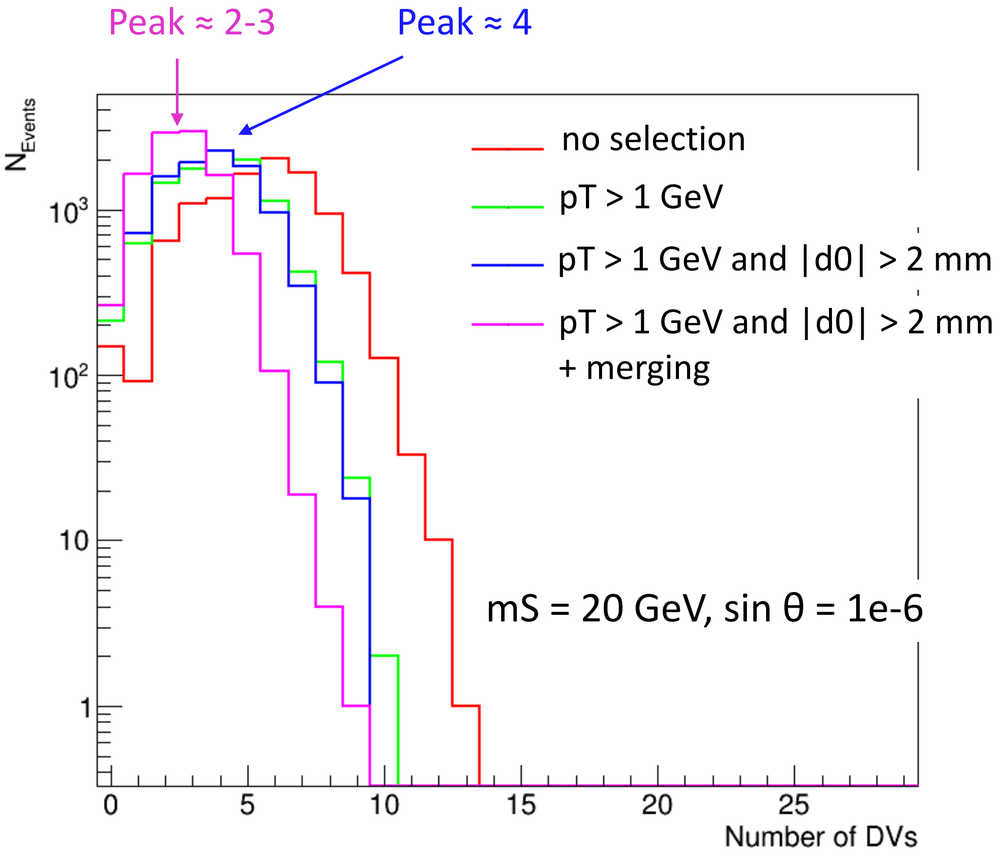
$N = L \times \sigma$ with $L = 5\ ab^{-1}$ and

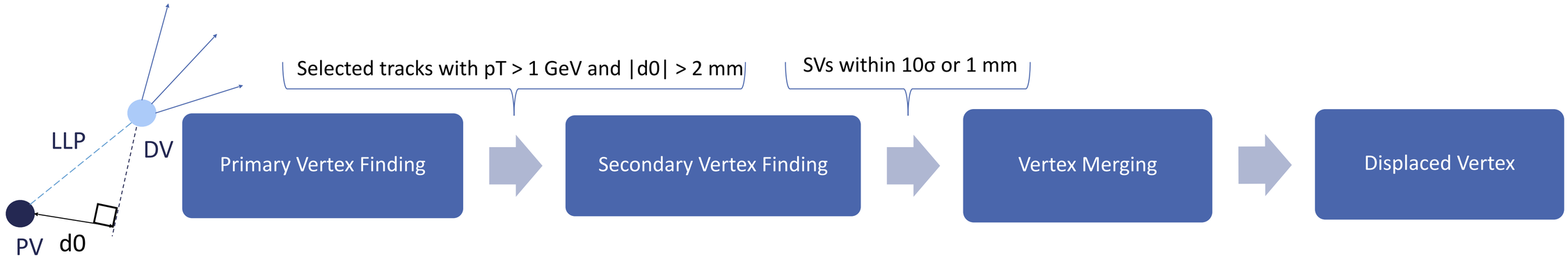
$$\sigma = \sigma_{ZH} \times BR(h \to ss) \times BR(s \to b\bar{b})^2 \times BR(Z \to l^+l^-)$$

Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Mean proper lifetime $c\tau$ [mm]	Cross Section σ [pb]	Branching Ratio 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

DV reconstruction

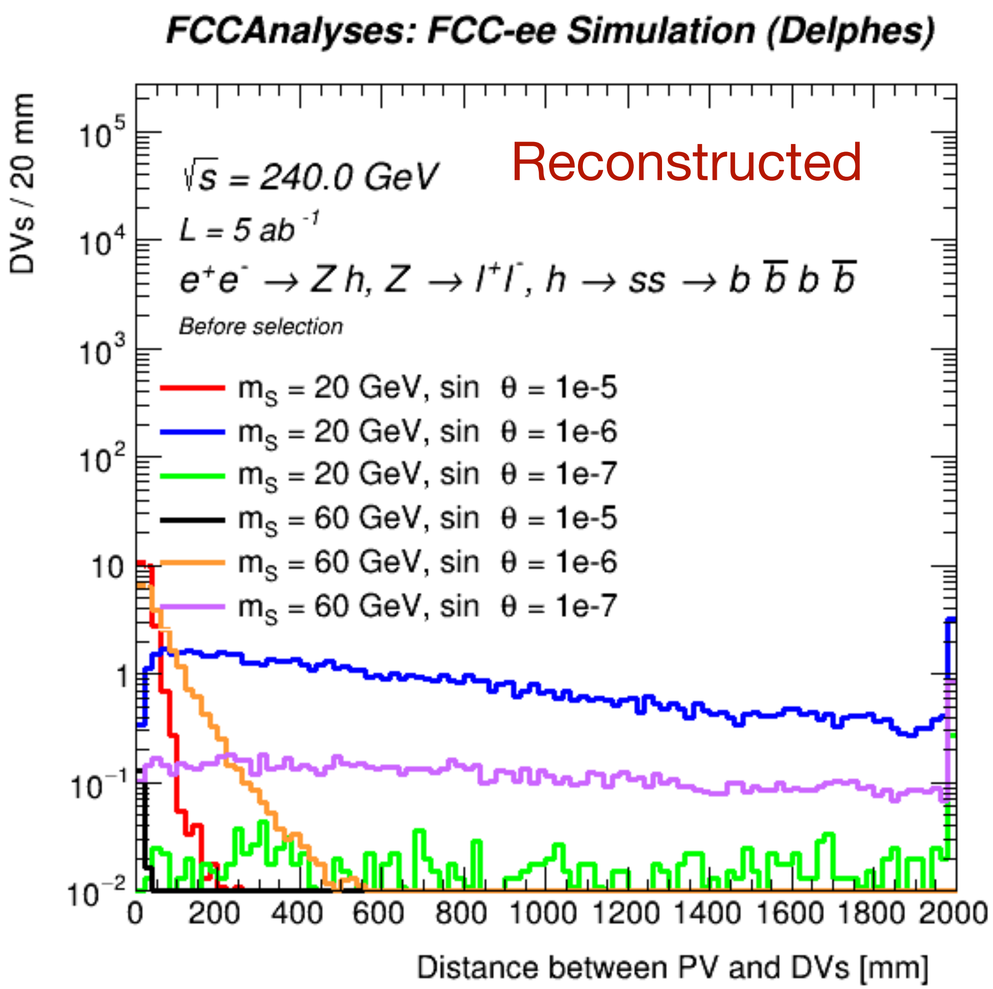
- Using current tools in the FCCAnalyses framework with extra constraints and functions
- LCFI+ algorithm for secondary vertexing arXiv:1506.08371
  - **Custom track selection**: pT > 1 GeV and |d0| > 2 mm
- Added **vertex merging** in attempt to reconstruct the scalar DV
  - Merge vertices within 10σ or 1 mm

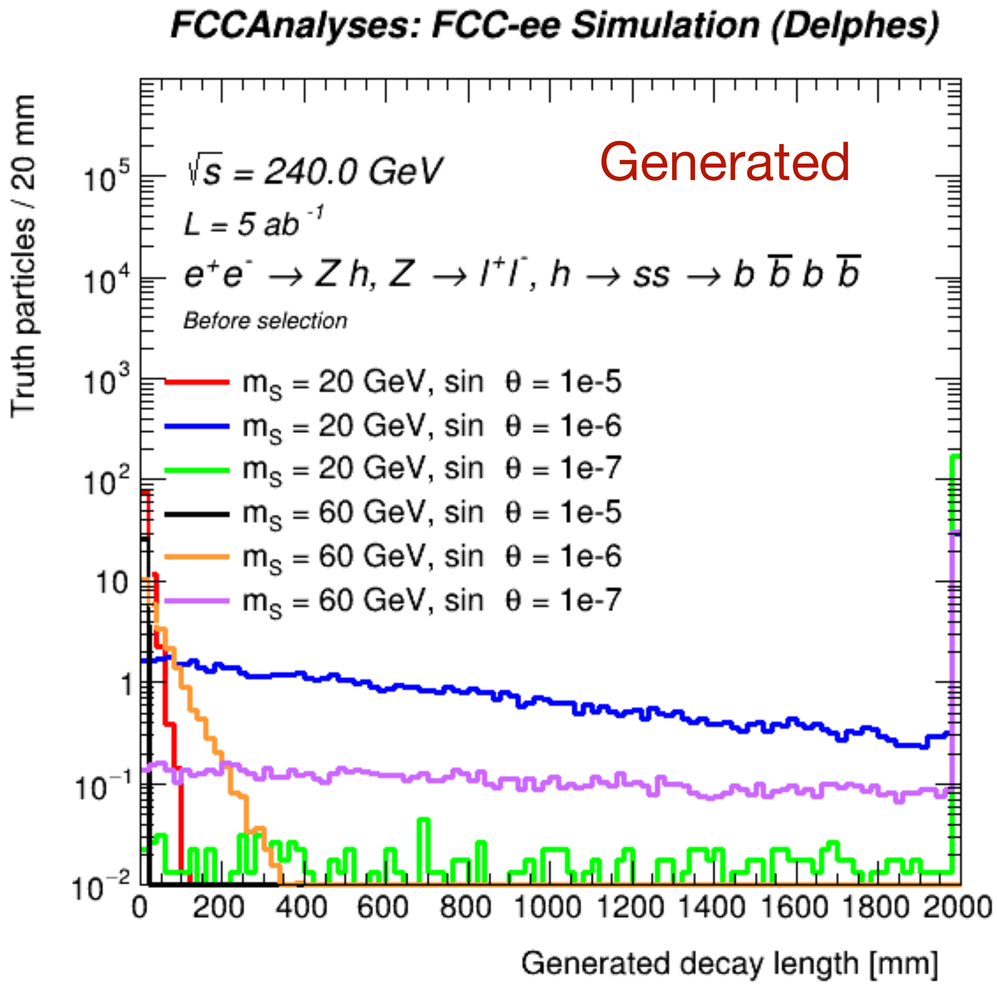




Reconstructed decay length

- Nice qualitative agreement between PV-DV distance and generated decay length!





Event selection

- Selecting events with **a Z boson** and at **least two DVs** (one for each scalar)
- DV selection:
  - Inside the tracker volume
  - Outside innermost region to reduce HF decays
  - Large vertex mass

	Selection
Pre-selection	≥ 2 oppositely charged electrons or muons
Z boson tag	$70 < m_{ll} < 110$ GeV
Multiplicity of DVs	n_DVs ≥ 2

Vertex Selection	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV