LLPs from Exotic Higgs Decays at FCC-ee

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

7th FCC Physics Workshop - LAPP Annecy

2024-02-01

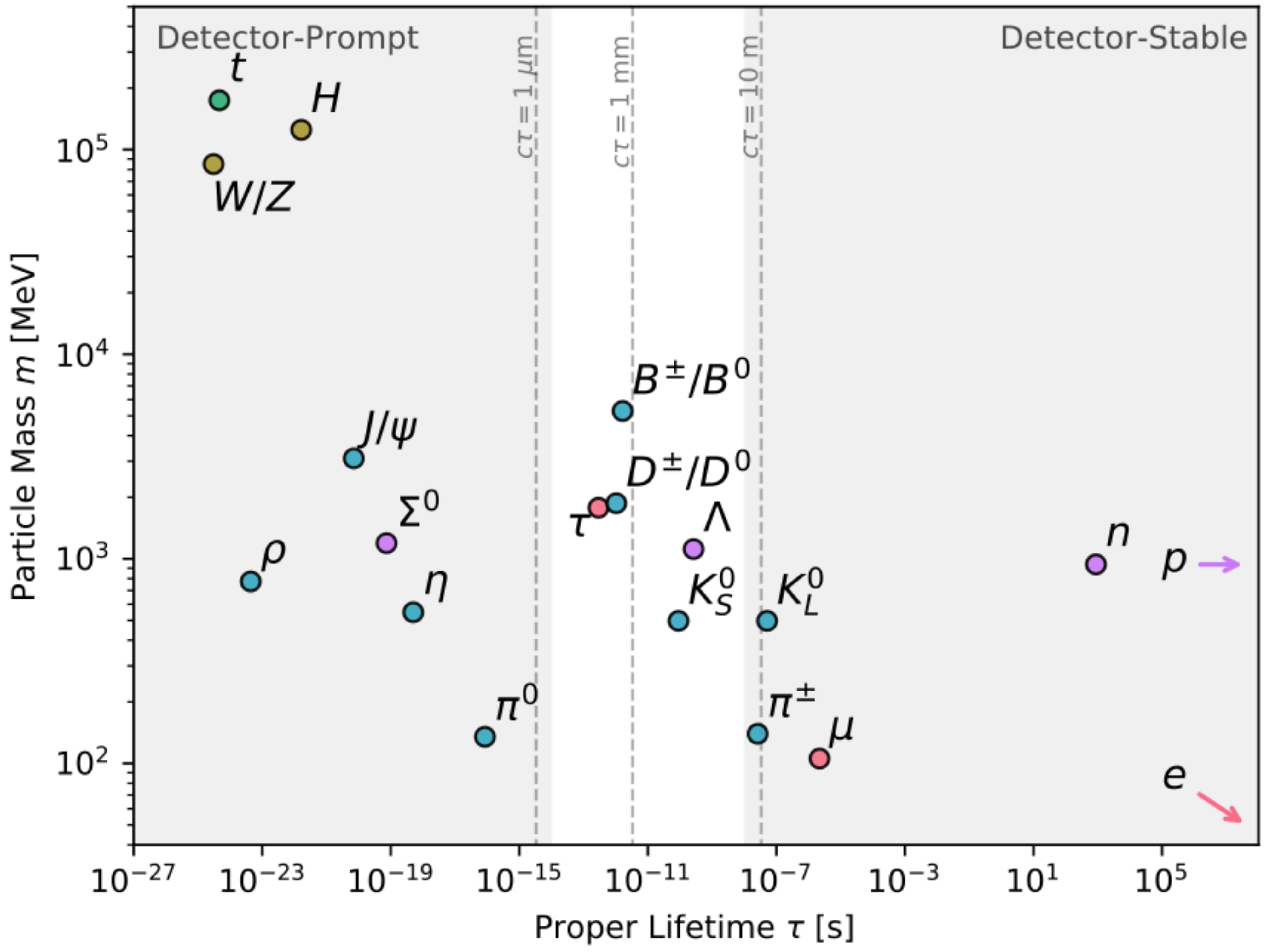
FUTURE CIRCULAR COLLIDER

UPPSALA UNIVERSITET

KTH VETENSKAP OCH KONST

What are LLPs?

- The SM particles has a wide range of lifetimes, the same is expected for new particles
- Long lifetime can be achieved by e.g small couplings
- A **long-lived particle (LLP)** is defined as a **new particle** with **sufficient decay length resolvable in the detector**

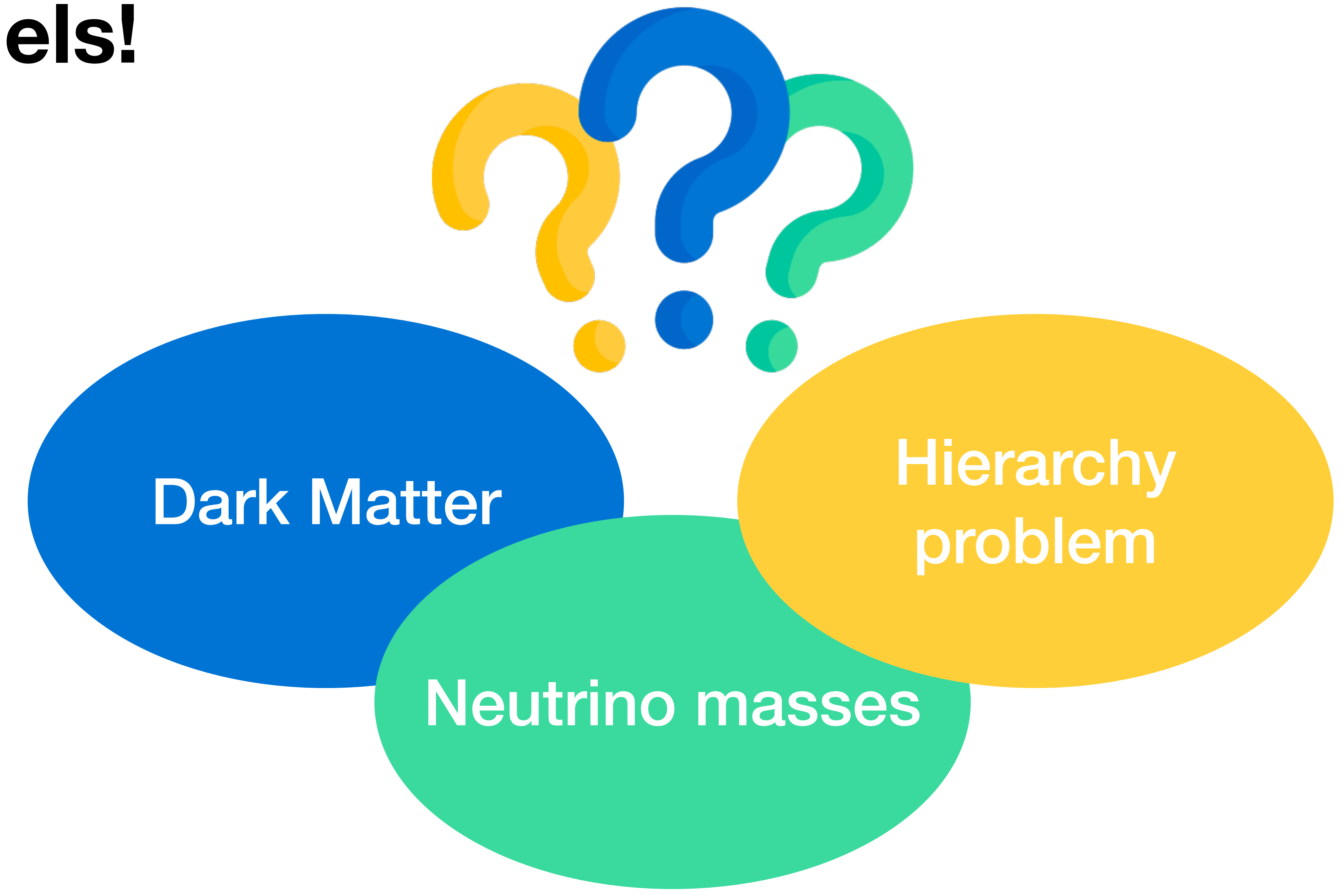


arXiv:1810.1260

Why search for LLPs?

LLPs are well-motivated in several BSM models!

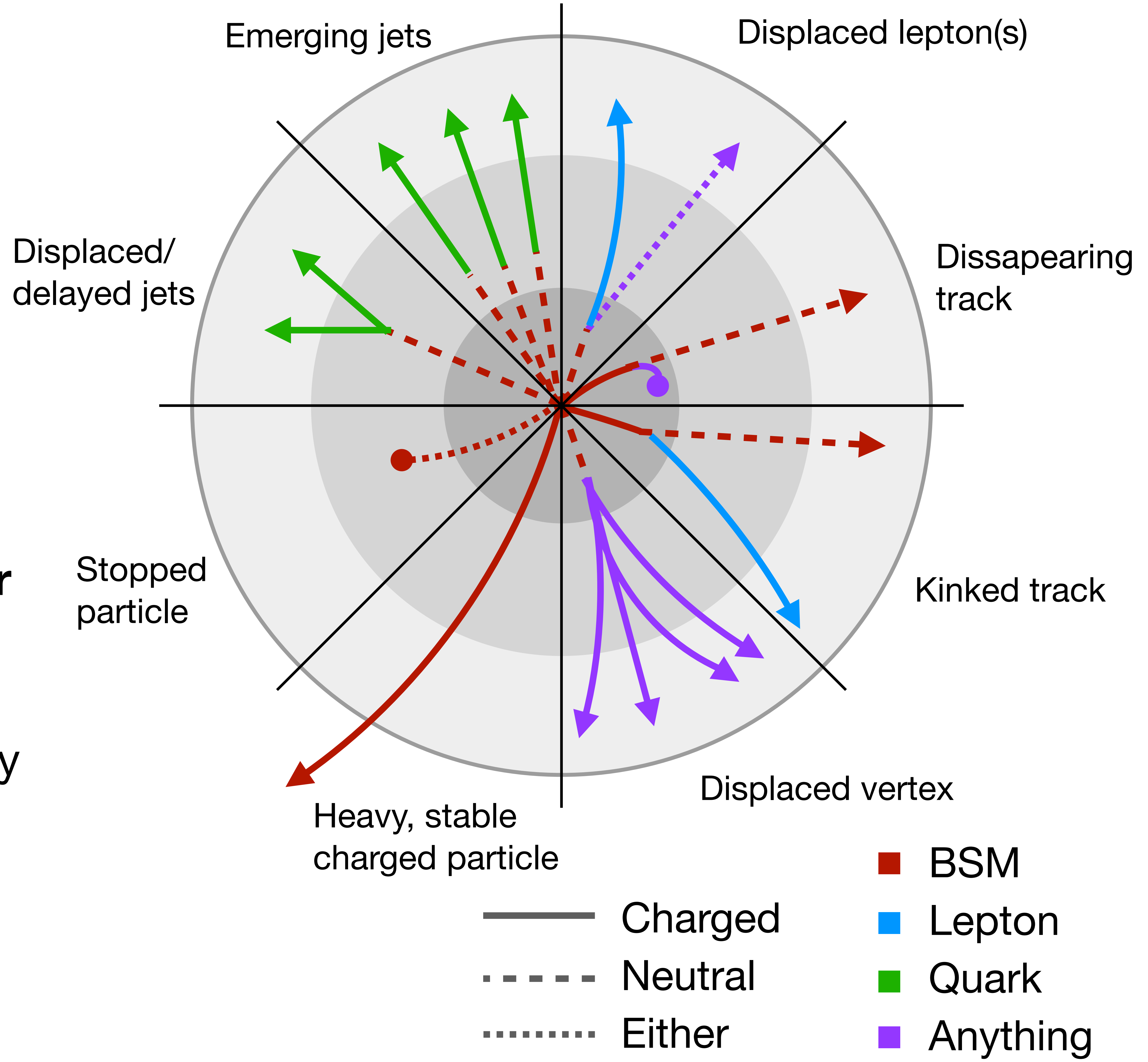
- There are several open questions…
  - The matter anti-matter asymmetry
  - The origin of the electroweak symmetry breaking
  - Dark Matter, etc
- And many possible BSM models
  - Hidden Valleys
  - SUSY
  - Effective portal theories, etc.



- Conventional searches primarily designed for prompt decays, and searching for signatures of LLPs is technically challenging → new physics could have evaded detection until now
  - This motivates dedicated searches for LLPs at collider experiments, e.g see previous talks this week by Nicolo Valle, Giacomo Polesello, and Juliette Alimena

How to search for LLPs at colliders

- LLPs leave **distinct signatures** depending on their lifetime, mass, charge, and decay products
- Experimental **benefits**:
  - Little background from SM decays
  - ….but atypical backgrounds might be significant (e.g cosmic rays, instrumental effects)
- Experimental **challenges**:
  - main detectors, triggers, and offline reconstruction are <u>not</u> designed for displaced particles → **room for improvement and to do something different at future accelerators!**
- Apart from being a Higgs, Electroweak and Top-factory FCC-ee offers good opportunities for LLP searches:
  - Clean experimental signatures
  - No trigger limitations
  - High luminosity



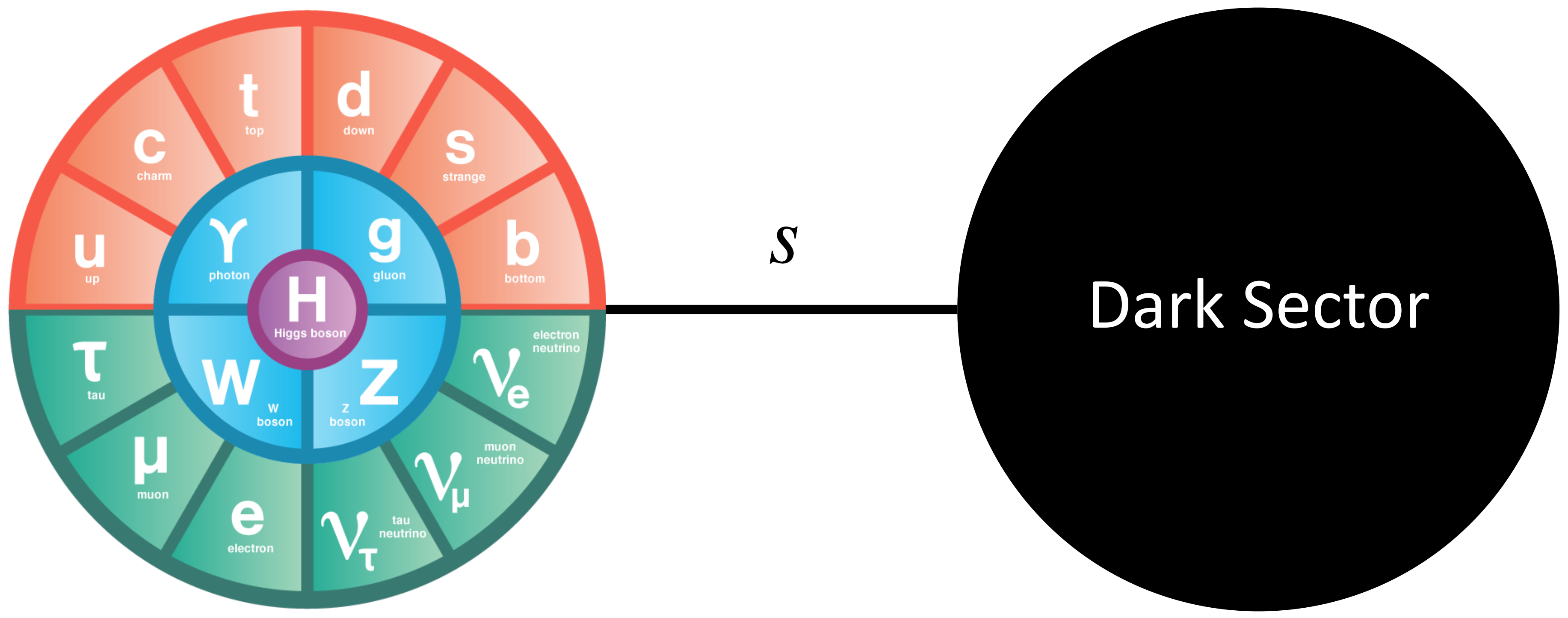
Long-lived scalars from exotic Higgs decays

- The Higgs boson can have sizeable couplings to new particles → exotic Higgs decays
- Our considered model: SM + scalar (arXiv:1312.4992, arXiv:1412.0018)
- The new scalar could 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**

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

- 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

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



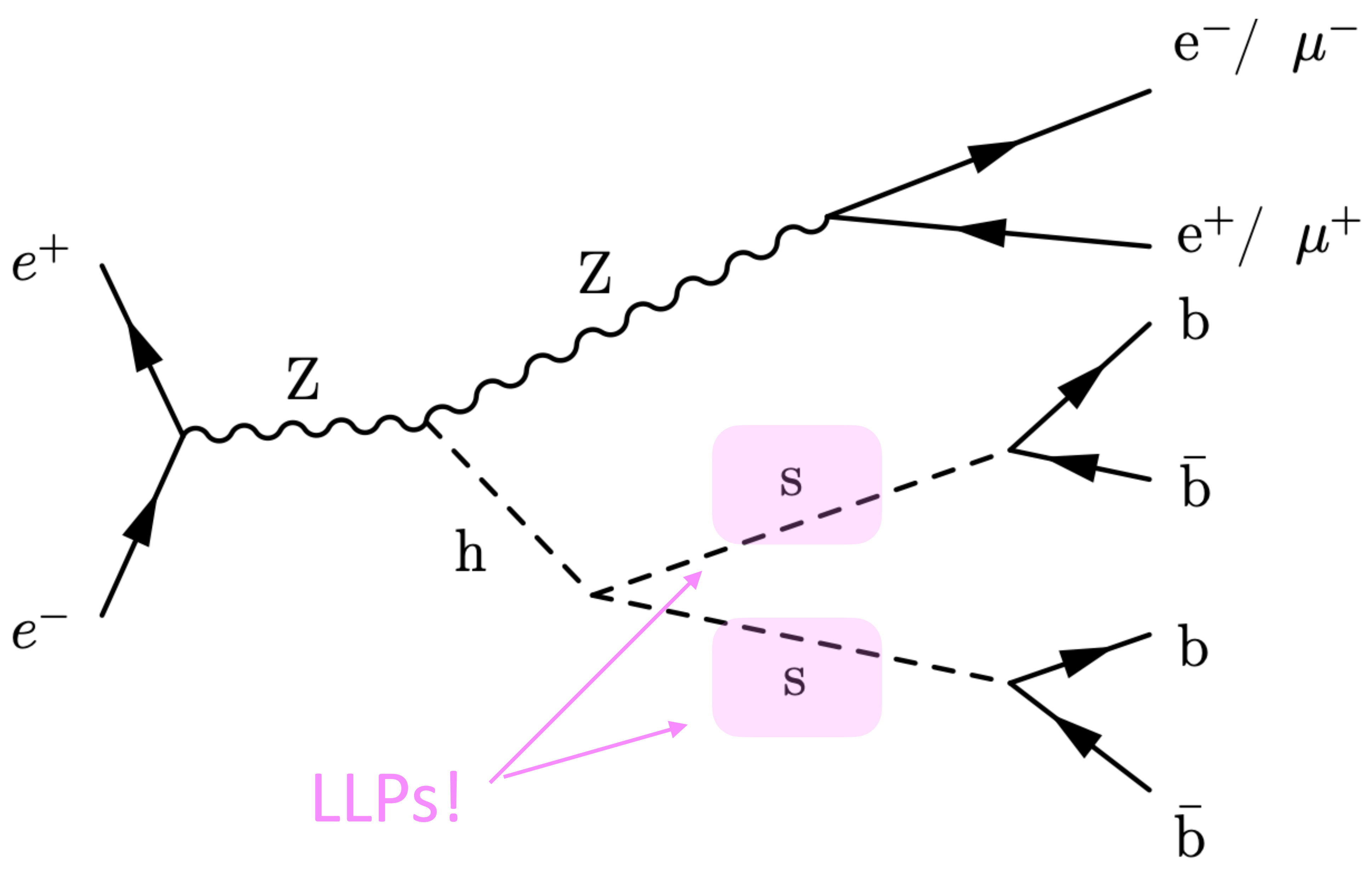
- For sufficiently small mixing, the scalar can be long-lived
  - cτ ~ meters if θ < 1e-6 → **LLP signature**

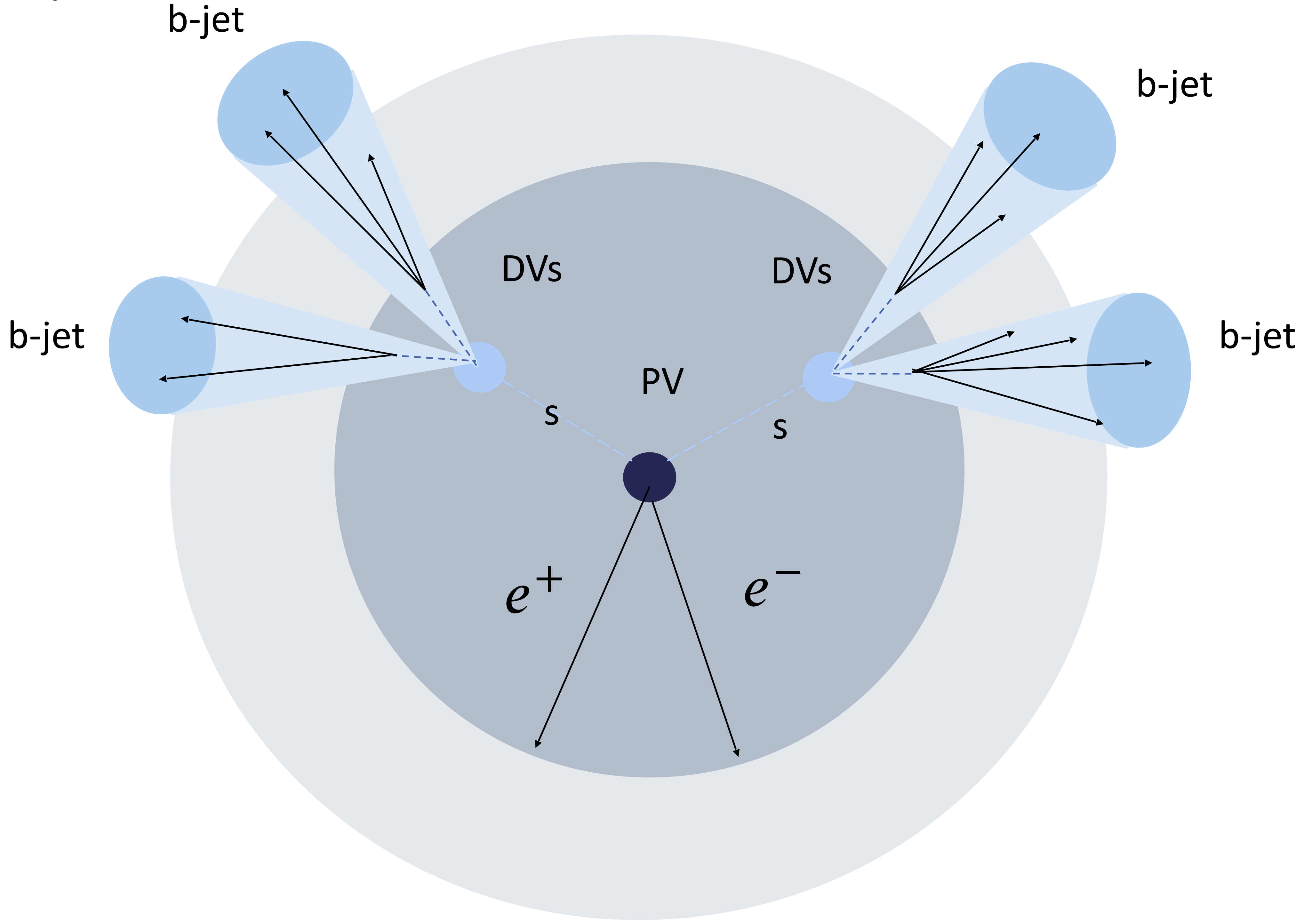
LLPs from exotic Higgs decays @ FCC-ee

- Targeting the *Zh* stage of FCC-ee and 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 reconstructed *Z* boson from the e^+e^- or $\mu^+\mu^-$ pairs
  - Displaced vertices (DVs) from the long-lived scalar decays





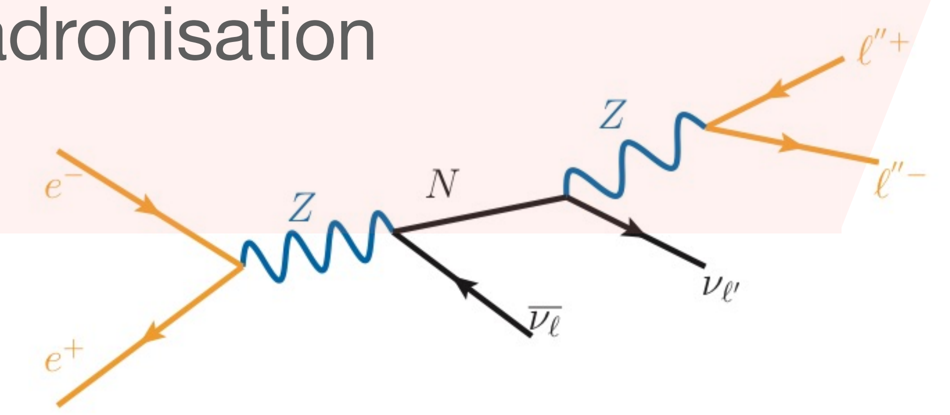
Simulation of long-lived scalars @ FCC-ee

- Full chain using MadGraph v3.4.1 + Pythia8 + Delphes, with the **winter2023** IDEA Delphes card
  - Updated! The results in our note for the midterm report was obtained with the spring2021 card
- The scalars can be simulated with the MadGraph5 HAHM model (arXiv:1312.4992, arXiv:1412.0018)
  - It includes both a dark photon (that is decoupled) and a dark scalar
  - Set width of scalar to achieve long lifetime
- Link to analysis code
- Privately produced samples available here: /eos/experiment/fcc/ee/analyses_storage/BSM/LLPs/ExoticHiggsDecays/MC_generation

Typical workflow

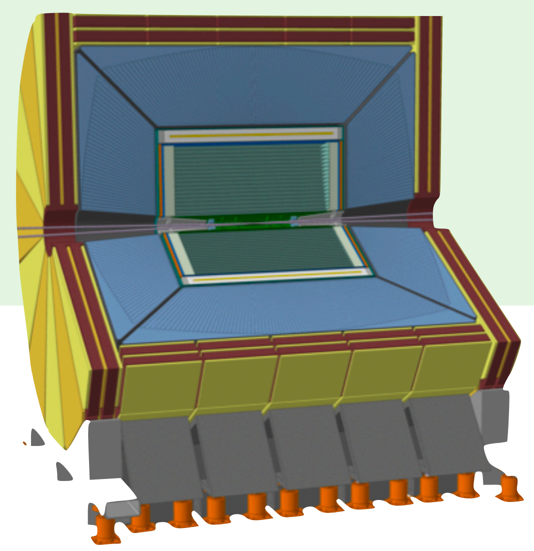
Sample generation of models

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



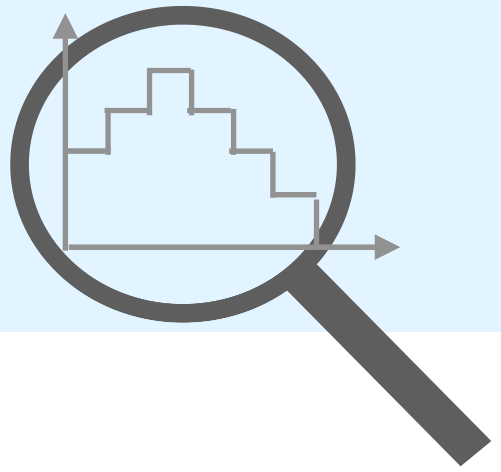
Parametrised detector simulation

- IDEA DELPHES card



Analysis tools

- FCC analysis



Sensitivity to studied model

Generated signals

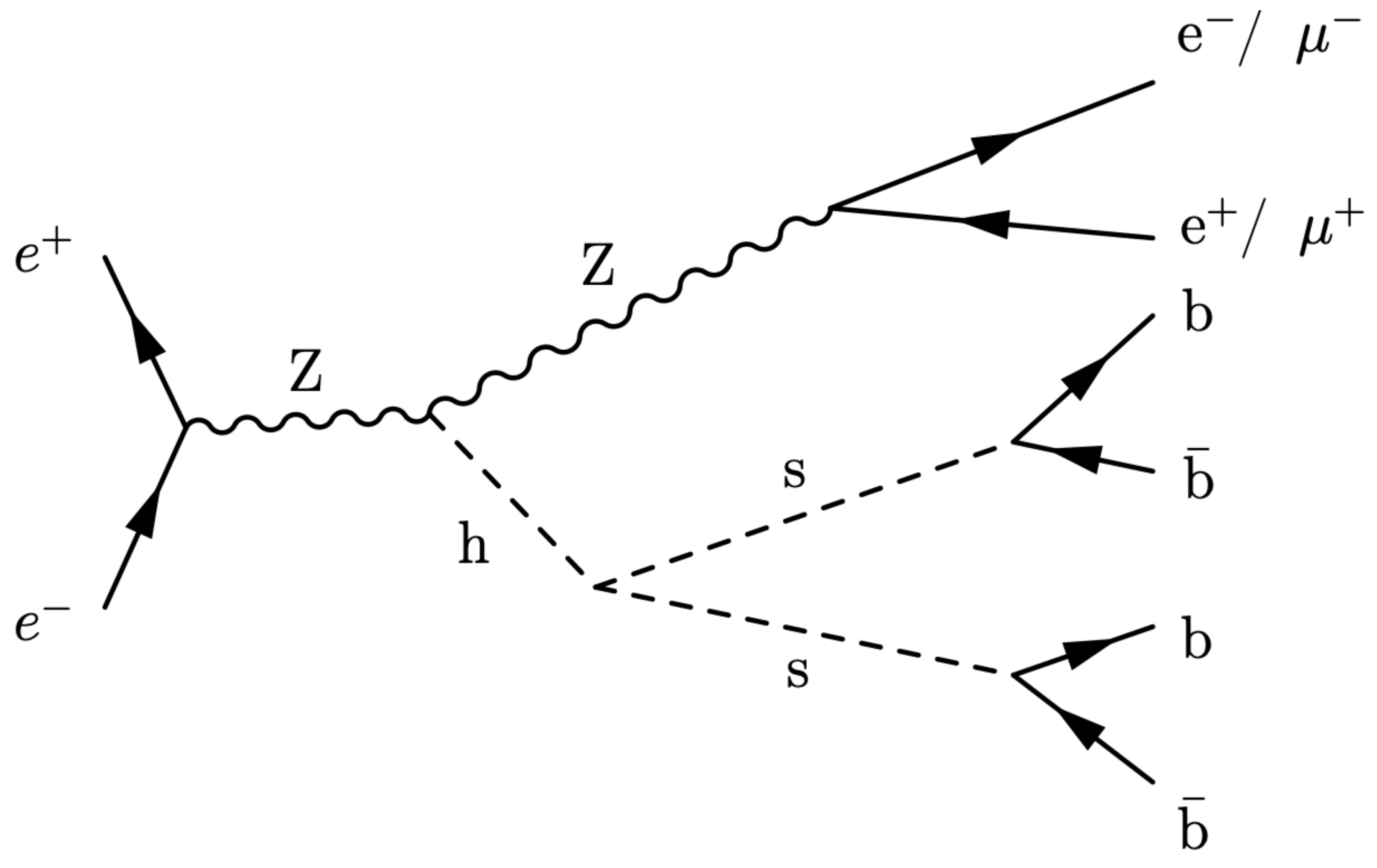
- Generated process: $e^+e^- \rightarrow Z\,h$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
- Parameter choices:
  - **m_s = 20 GeV and m_s = 60 GeV**
  - **sin θ = 1e-5, 1e-6, 1e-7**, corresponding to mean proper lifetimes cτ of O(1 mm – 10 m)
  - κ = 7e-4, s.t we have less than 1% addition to the Higgs width
    - Updated! The results in our note for the midterm report was obtained with κ = 1e-3

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

θ: Mixing angle

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

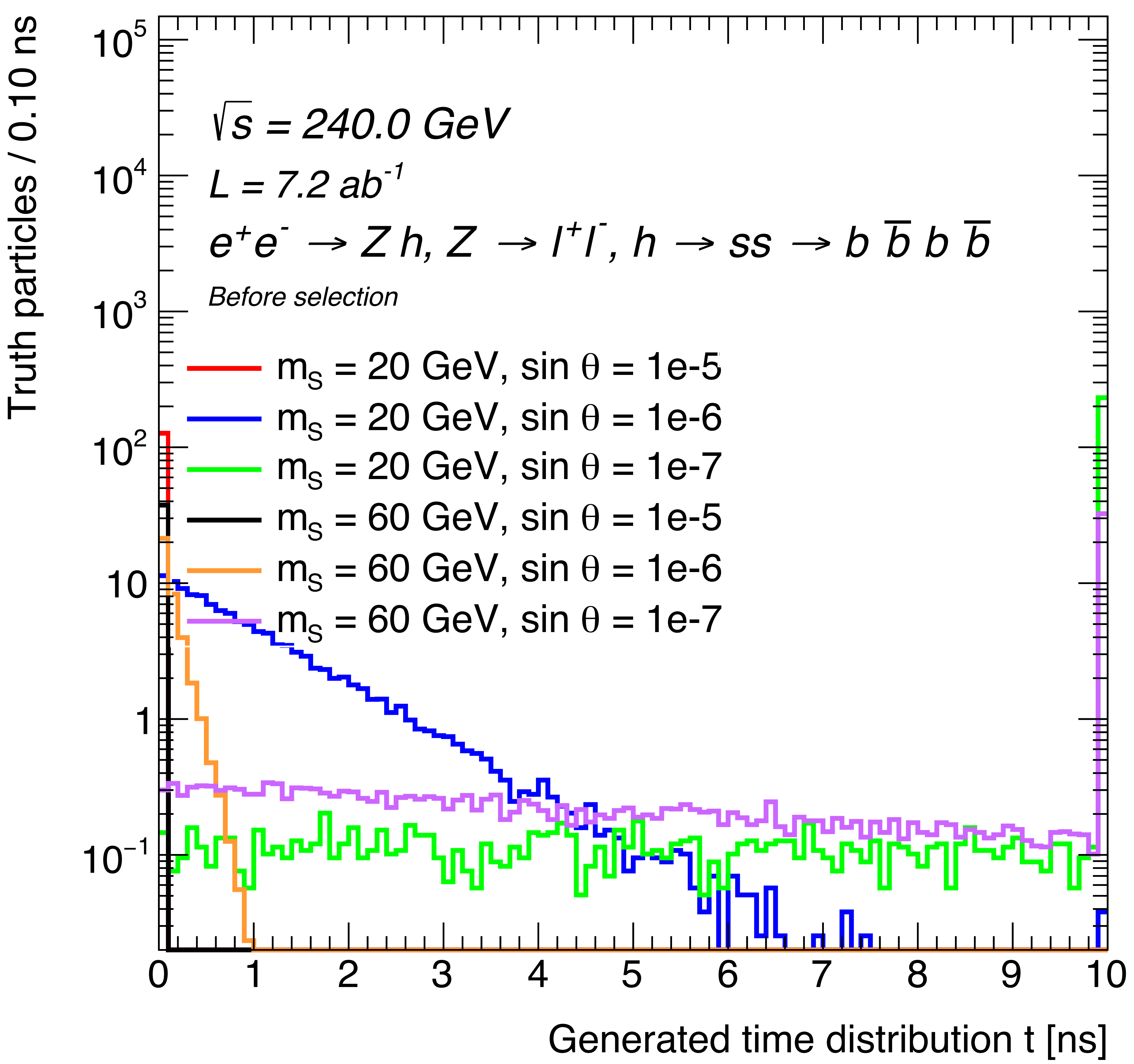
κ: Higgs-scalar coupling constant



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

Generated lifetime distribution

- Lifetime increases for smaller mixing angle, sin θ, and smaller masses, ms, as expected

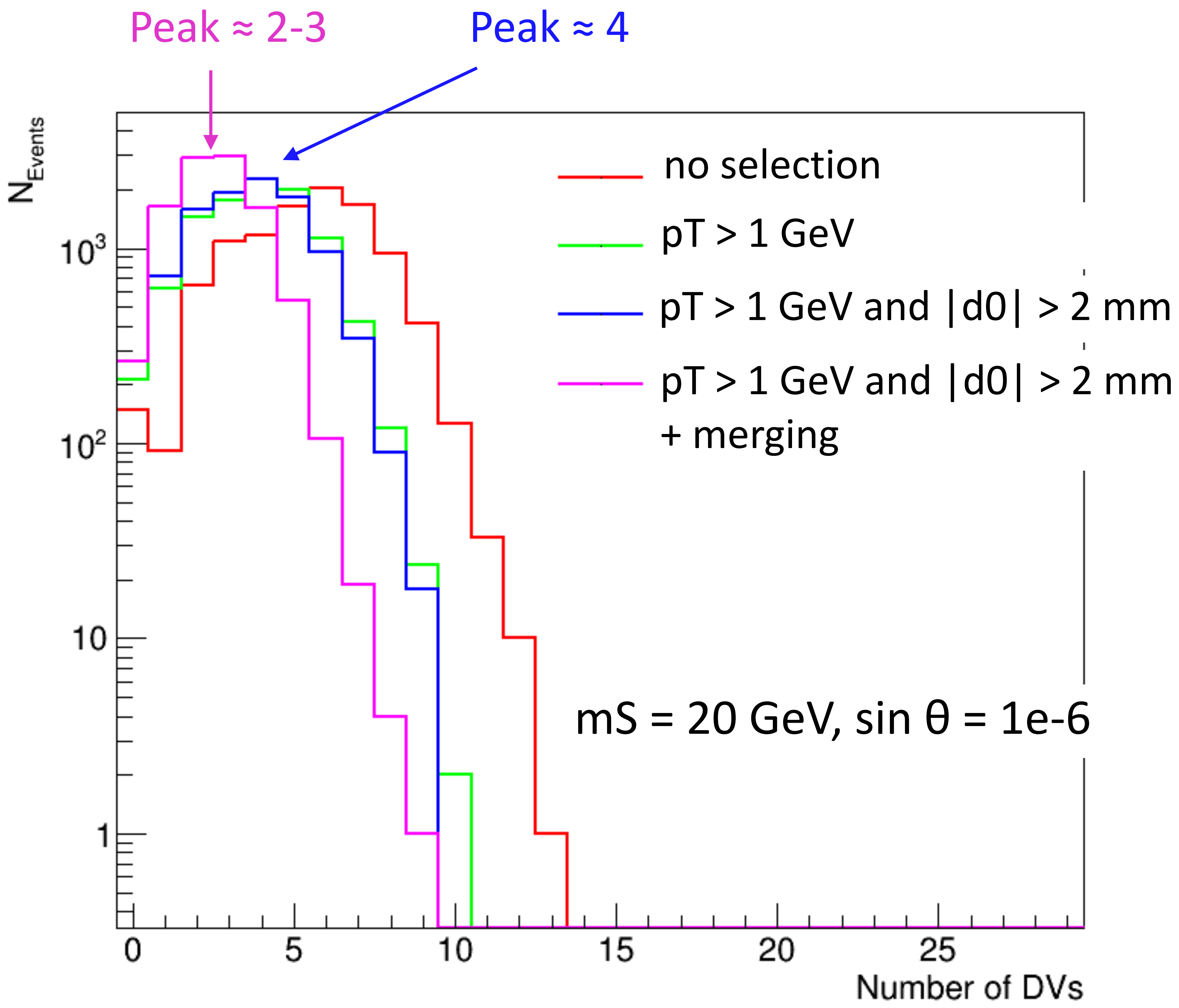


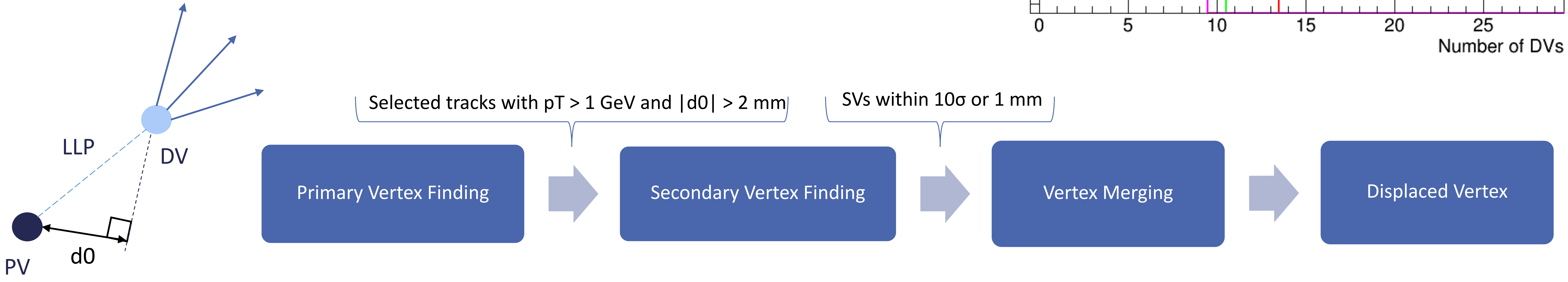
Generator-level acceptance for scalar decays within the fiducial volume 4mm<r<2m

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

DV reconstruction

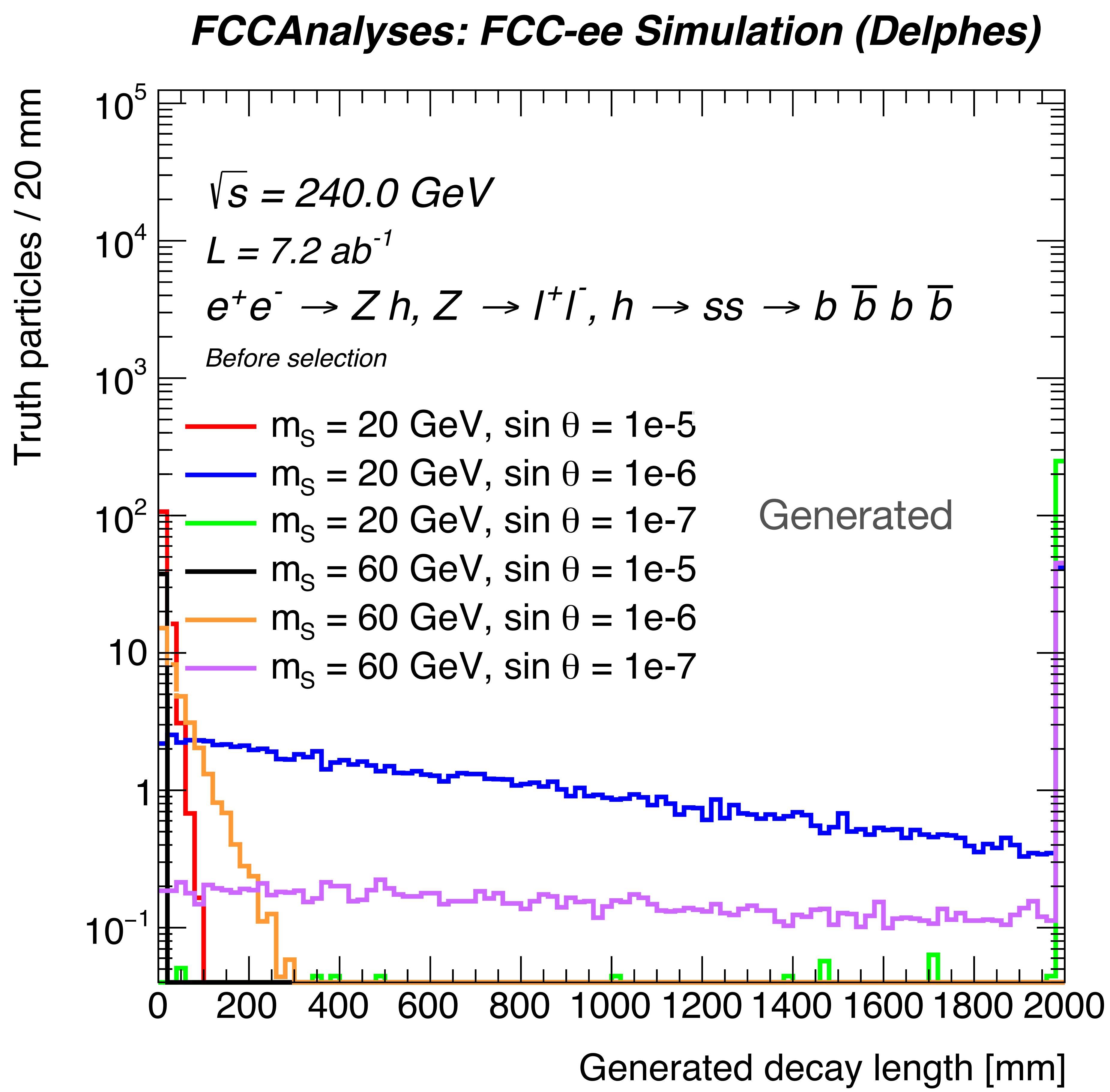
- Using current tools in the FCCAnalyses framework
  - Extra constraints and functions inspired by ATLAS DV reconstruction (cds)
- Secondary vertex finder of the LCFI+ algorithm (arXiv:1506.08371), see more in backup
  - Added track selection: non-primary, pT > 1 GeV and |d0| > 2 mm
  - Also studied and developed vertex merging in attempt to reconstruct the scalar DVs
    - Merge vertices within 10σ or 1 mm
    - Not applied to results shown today

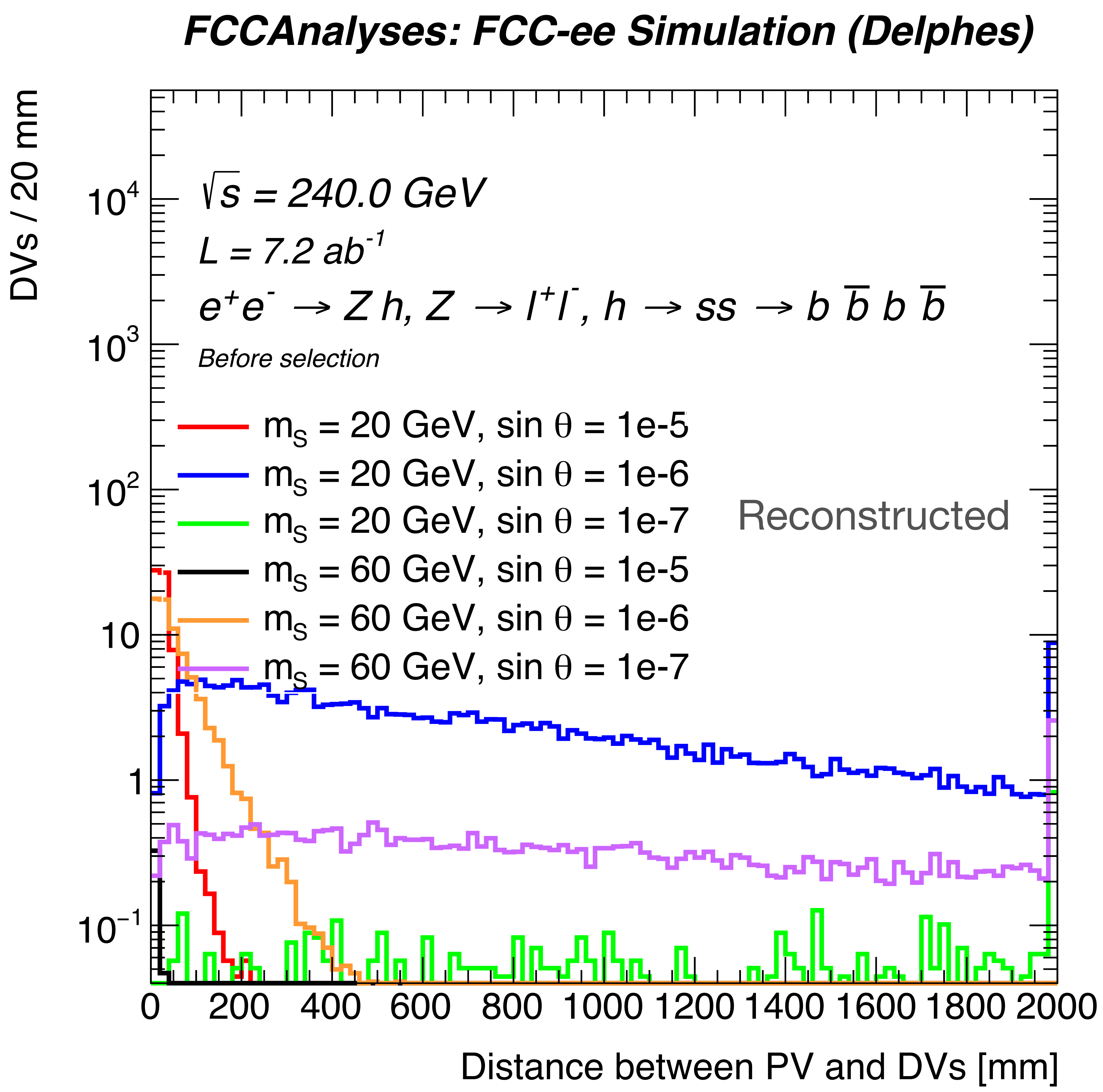




Reconstructed decay length

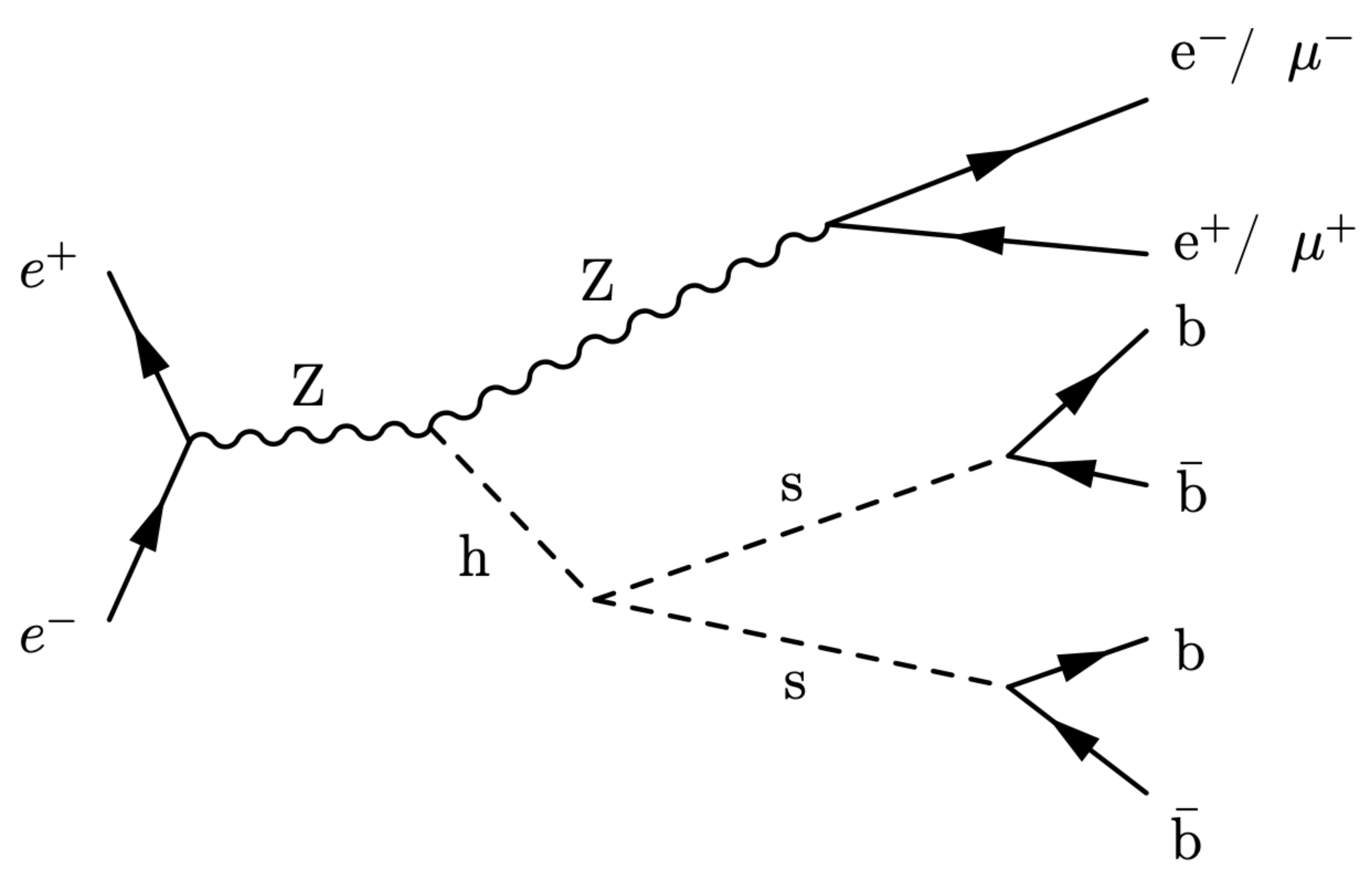
- The distance between PV and DV nicely follows the generated decay length
- A good discriminating variable between signal and background!





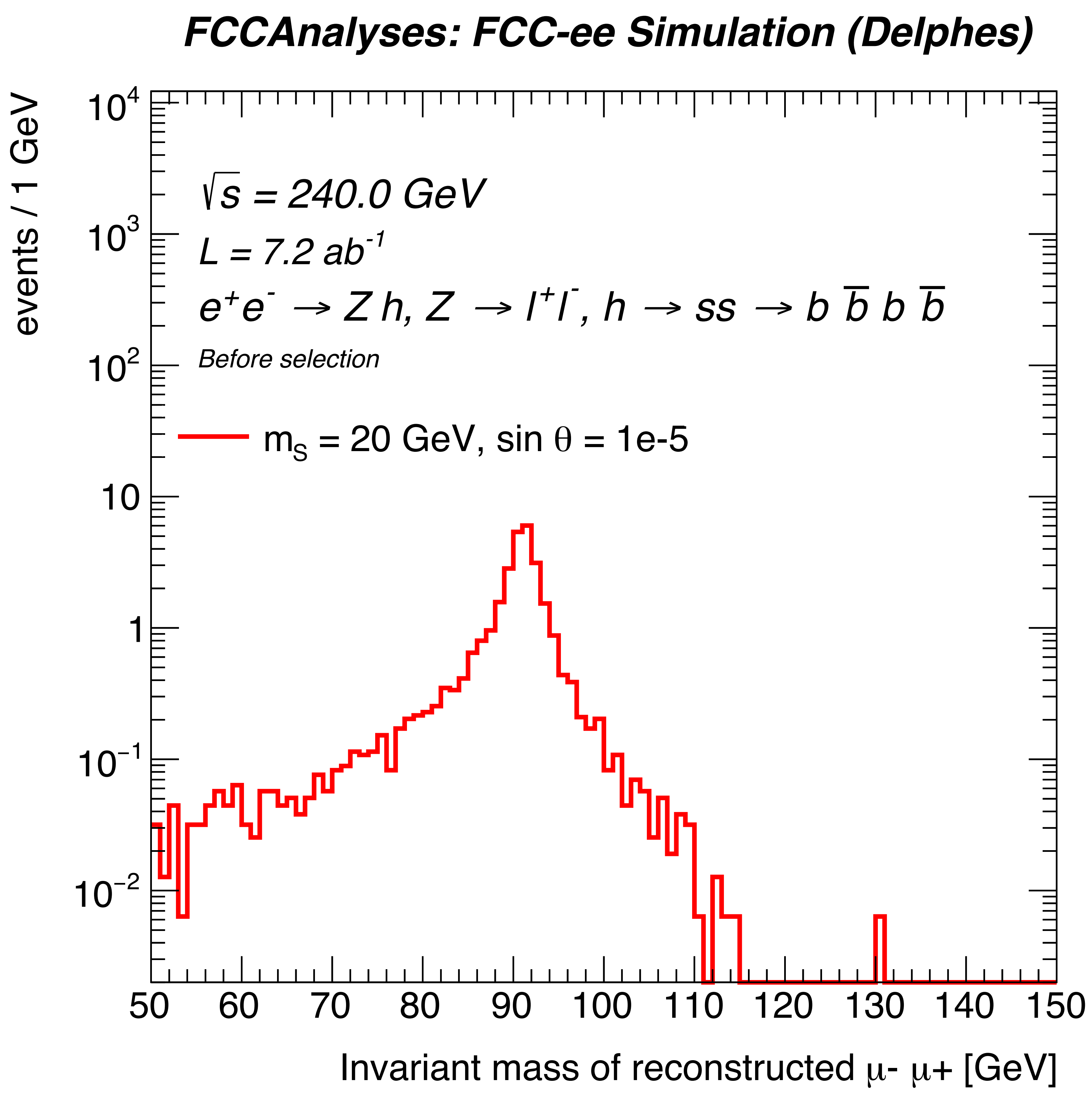
Event selection

- Selecting events with a Z boson and at least 2 DVs
- DV selection:
  - Required to be in the tracker volume and outside the innermost region to exclude heavy-flavour decays
  - Large charged invariant mass to remove background DVs



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

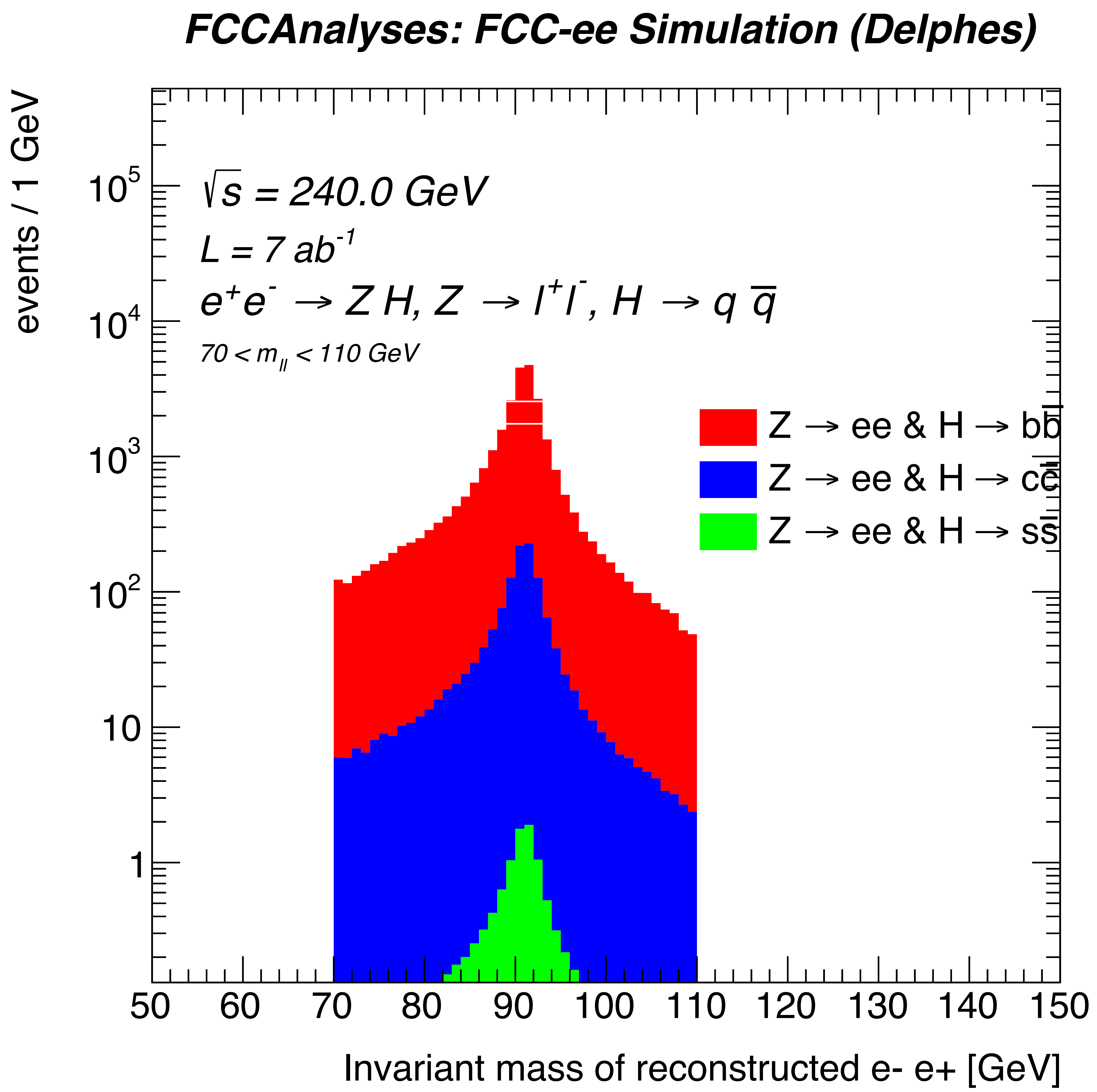
Vertex Selection	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV



WIP: Background studies

Axel Gallén

- Previous study with the spring2021 centrally produced samples was statistically limited
- The winter2023 samples offer more statistics and exclusive decays
- Currently working with a refined background study
  - The full chain is in place to study the background samples!



Sensitivity analysis of the signal

Sensitivity for all signal samples except the shortest and longest lifetime!

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

m_s, sin θ	$c\tau$ [mm]	BR($h \to ss$)	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
20 GeV, 1e-5	3.4	6.98×10^{-4}	55.2 ± 0.552	52.84 ± 0.538	49.02 ± 0.520	5.0 ± 0.166
20 GeV, 1e-6	341.7	6.98×10^{-4}	55.2 ± 0.552	52.44 ± 0.538	49.02 ± 0.521	37.1 ± 0.453
20 GeV, 1e-7	34167.0	6.98×10^{-4}	55.2 ± 0.552	52.38 ± 0.540	49.68 ± 0.524	0.8 ± 0.067
60 GeV, 1e-5	0.9	2.06×10^{-4}	16.32 ± 0.163	15.62 ± 0.127	14.59 ± 0.154	0.0033 ± 0.0023
60 GeV, 1e-6	87.7	2.06×10^{-4}	16.32 ± 0.163	15.62 ± 0.196	14.61 ± 0.196	10.96 ± 0.167
60 GeV, 1e-7	8769.1	2.06×10^{-4}	16.32 ± 0.163	15.52 ± 0.159	14.62 ± 0.155	6.49 ± 0.103

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

Summary

- A simulation and analysis of LLPs from exotic Higgs decays at FCC-ee has been done and is ongoing!
    - Looking at the signal: $e^+e^- \rightarrow Z\,h$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
    - For signal points with ms = 20 GeV and ms = 60 GeV and mean proper lifetimes of order 1 mm - 10 m
    - Event selection: tagging the Z boson and requiring at least 2 DVs
    - Potential sensitivity for all signal samples except the shortest and longest lifetime sample!
    - Ongoing work with the winter2023 IDEA card and samples towards a paper

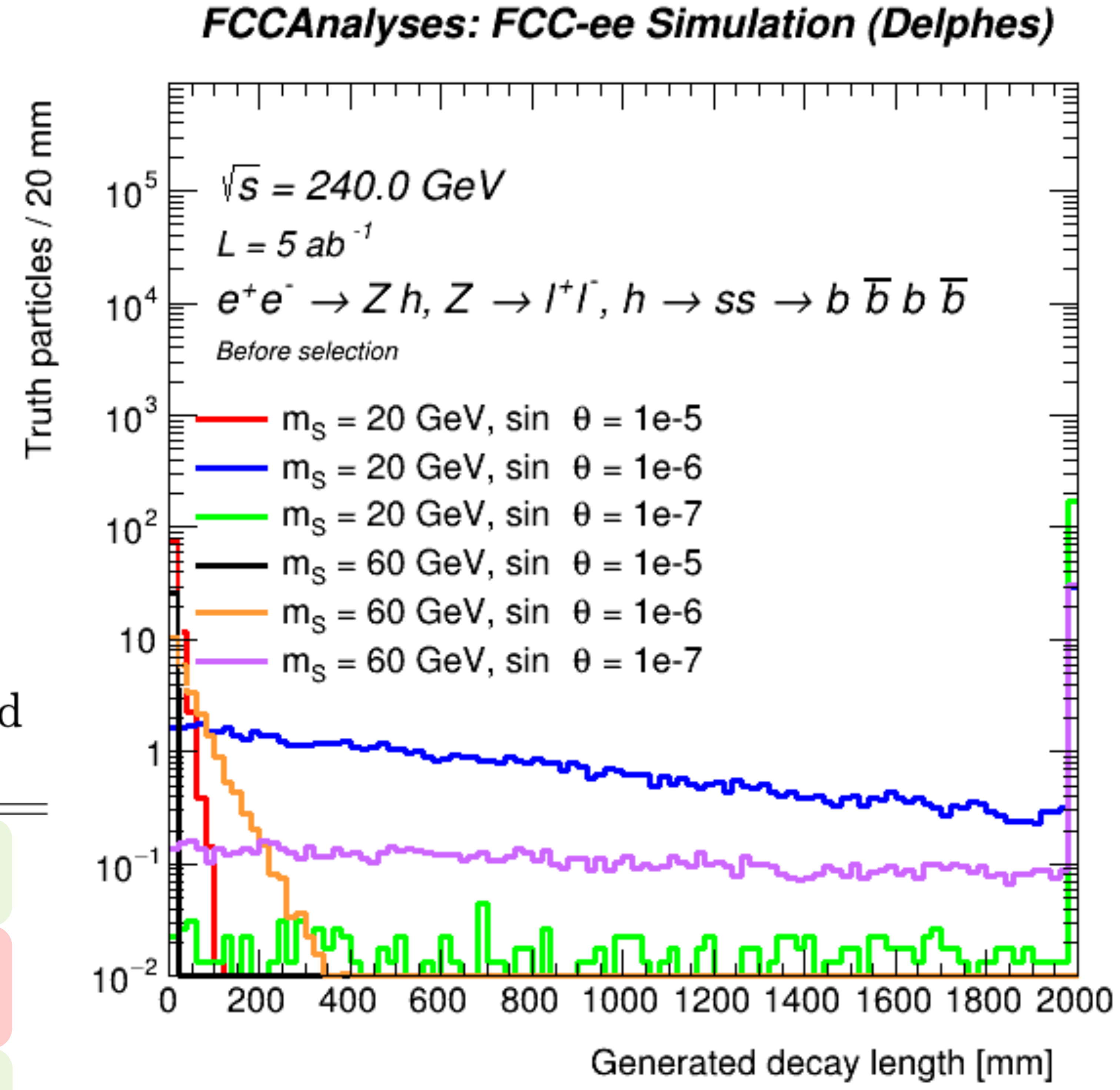
- Next steps:
    - Move to full simulation when available
    - Improve DV reconstruction
    - Study other LLP signatures such as delayed jets

Thank you for your attention!

Backup slides

Sensitivity at gen level - previous results

- Previous results with spring2021 card, and using the cross section
- Selected events that has ≥ 1 scalar within the acceptance region 4 mm < r < 2000 mm
  - All signal samples has ≥ 4 events except the shortest and longest lifetime!



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

Number of expected events given by

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

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

Sensitivity analysis - previous results

- Previous results presented in the note using the spring2021 card
- Given zero background, signal points with at least 3 expected events can be excluded to CL 95%
- Backgrounds:

	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
WW	8.22e+07 ± 7.45e+06	2.11e+06 ± 4.16e+04	4.68e+05 ± 1.96e+04	0 ($\leq$ 1.96e+04)
ZZ	6.79e+06 ± 1.77e+05	8.91e+05 ± 7.78e+03	5.85e+05 ± 6.31e+03	0 ($\leq$ 6.31e+03)
ZH	1.01e+06 ± 1.01e+04	5.97e+04 ± 7.76e+02	4.75e+04 ± 6.93e+02	0 ($\leq$ 6.93e+02)

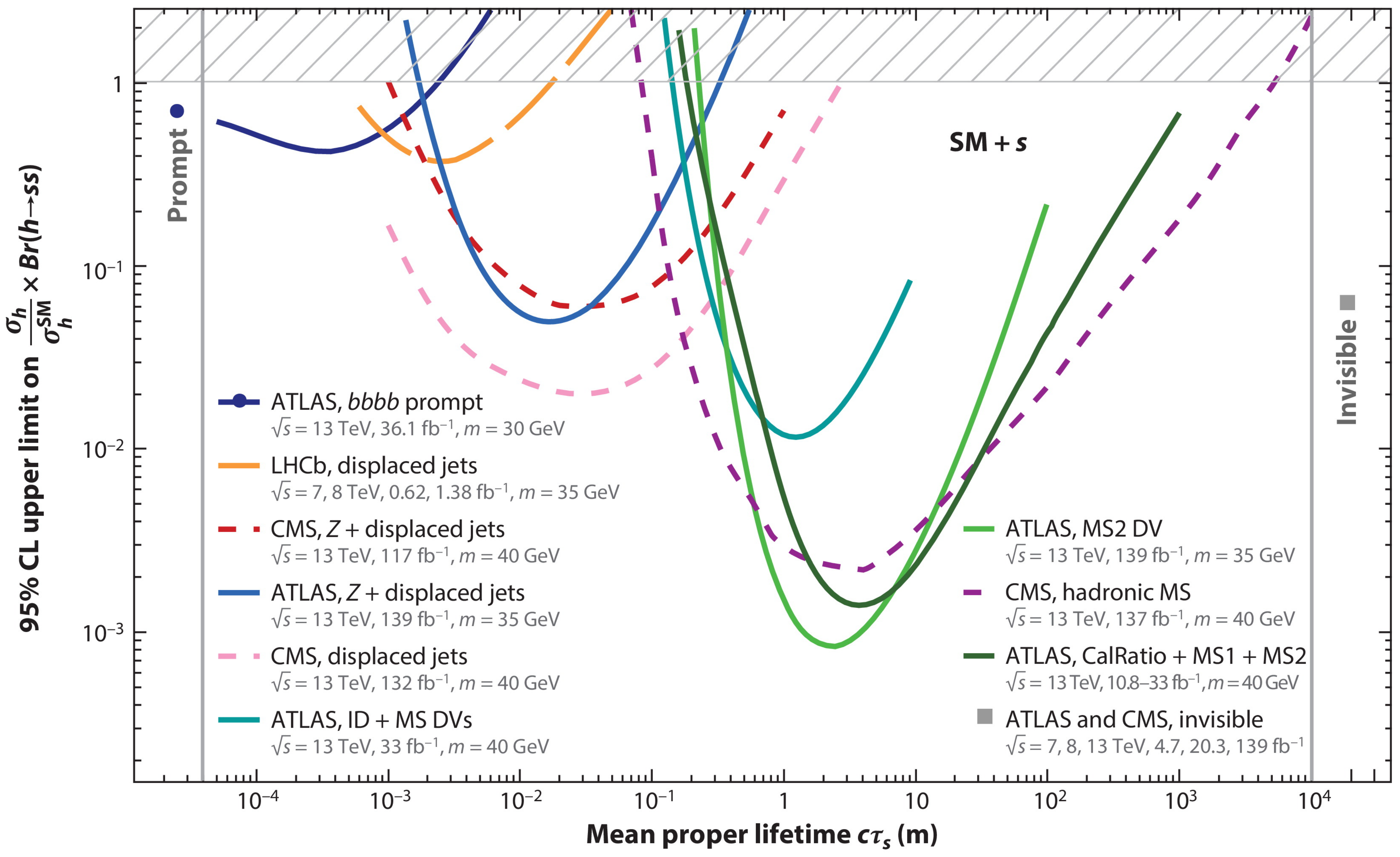
- Signals:

m_s, sin θ	Before selection	Pre-selection	$70 < m_{ll} < 110$ GeV	n_DVs ≥ 2
20 GeV, 1e-5	44.3 ± 0.0295	29.8 ± 0.363	28.9 ± 0.358	3.55 ± 0.125
20 GeV, 1e-6	44.3 ± 0.0295	30.4 ± 0.367	29.7 ± 0.363	22.4 ± 0.315
20 GeV, 1e-7	44.3 ± 0.0295	36.3 ± 0.401	35.6 ± 0.397	0.531 ± 0.0485
60 GeV, 1e-5	13.1 ± 0.00474	8.38 ± 0.105	8.12 ± 0.103	0 ($\leq$ 0.103)
60 GeV, 1e-6	13.1 ± 0.00474	8.34 ± 0.104	8.09 ± 0.103	6.43 ± 0.0917
60 GeV, 1e-7	13.1 ± 0.00474	9.69 ± 0.113	9.45 ± 0.111	4.10 ± 0.0732

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

Summary of current constraints from LHC

Review: Exotic Higgs Decays arXiv:2111.12751

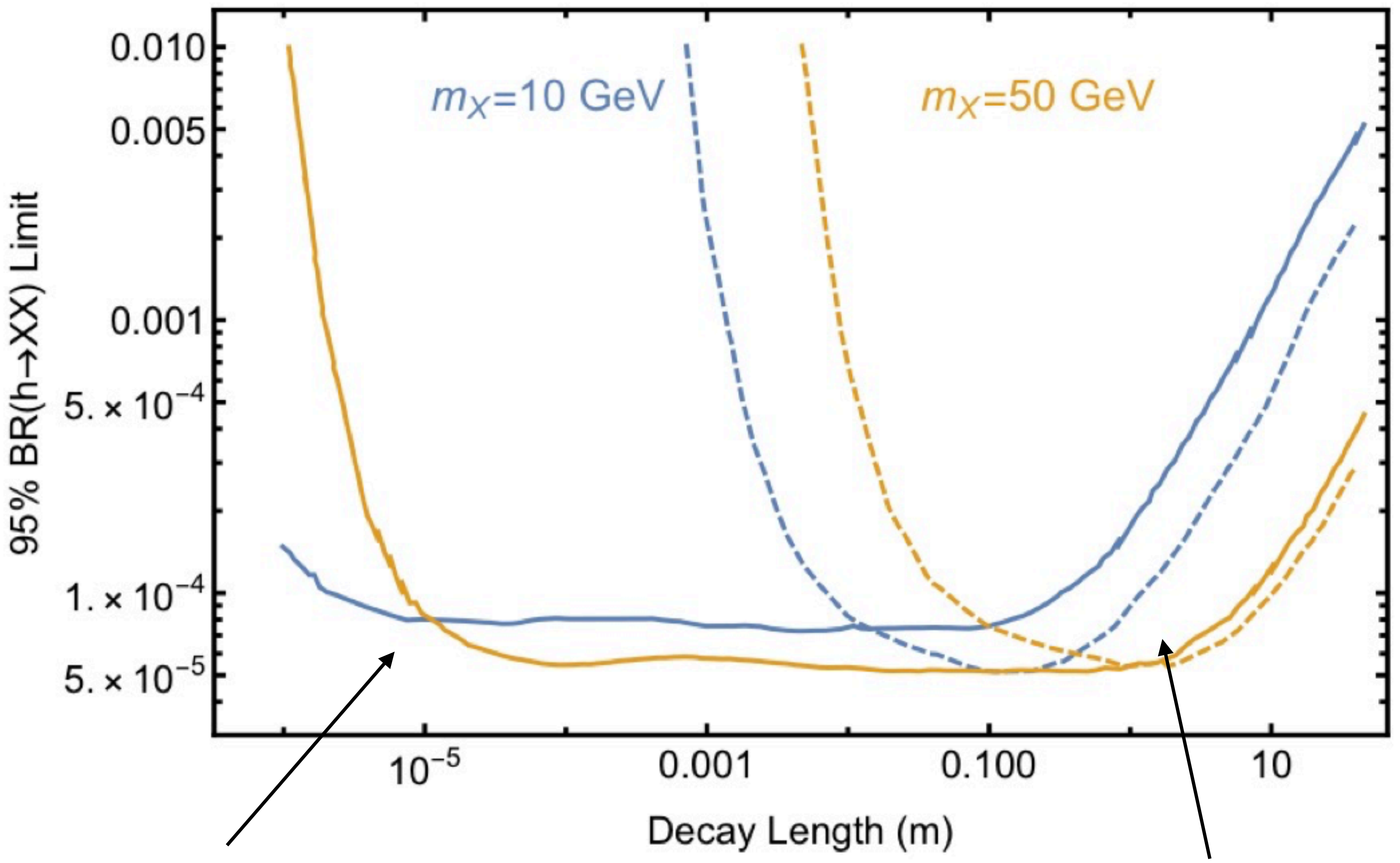


Cepeda M, et al. 2022
Annu. Rev. Nucl. Part. Sci. 72:119–49

- Figure summarizes searches at ATLAS, CMS and LHCb for h → ss where s is a new long-lived scalar in the mass range 30-40 GeV
- In order to compare the results the figure shows the results for ($\sigma h/\sigma h^{SM}$) × Br(h → ss) using the approximated branching ratios Br(s → bb) = 85%, Br(s → cc) = 5% and Br(s → τ τ) = 8% for results with exclusive final states

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

Plot from: arXiv:2203.05502

Results from: arXiv:1812.05588

- 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.

Efficiencies - previous result from note

	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7
Before selection	1.0	1.0	1.0
Pre-selection	0.672	0.687	0.819
$70 < m_{ll} < 110$ GeV	0.653	0.670	0.803
n_DVs ≥ 2	0.080	0.505	0.012
	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
Before selection	1.0	1.0	1.0
Pre-selection	0.640	0.637	0.740
$70 < m_{ll} < 110$ GeV	0.620	0.618	0.722
n_DVs ≥ 2	0.0	0.491	0.313

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

	WW	ZZ	ZH
Before selection	1.0	1.0	1.0
Pre-selection	0.131	0.026	0.059
$70 < m_{ll} < 110$ GeV	0.006	0.086	0.047
n_DVs ≥ 2	0.0	0.0	0.0

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)

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

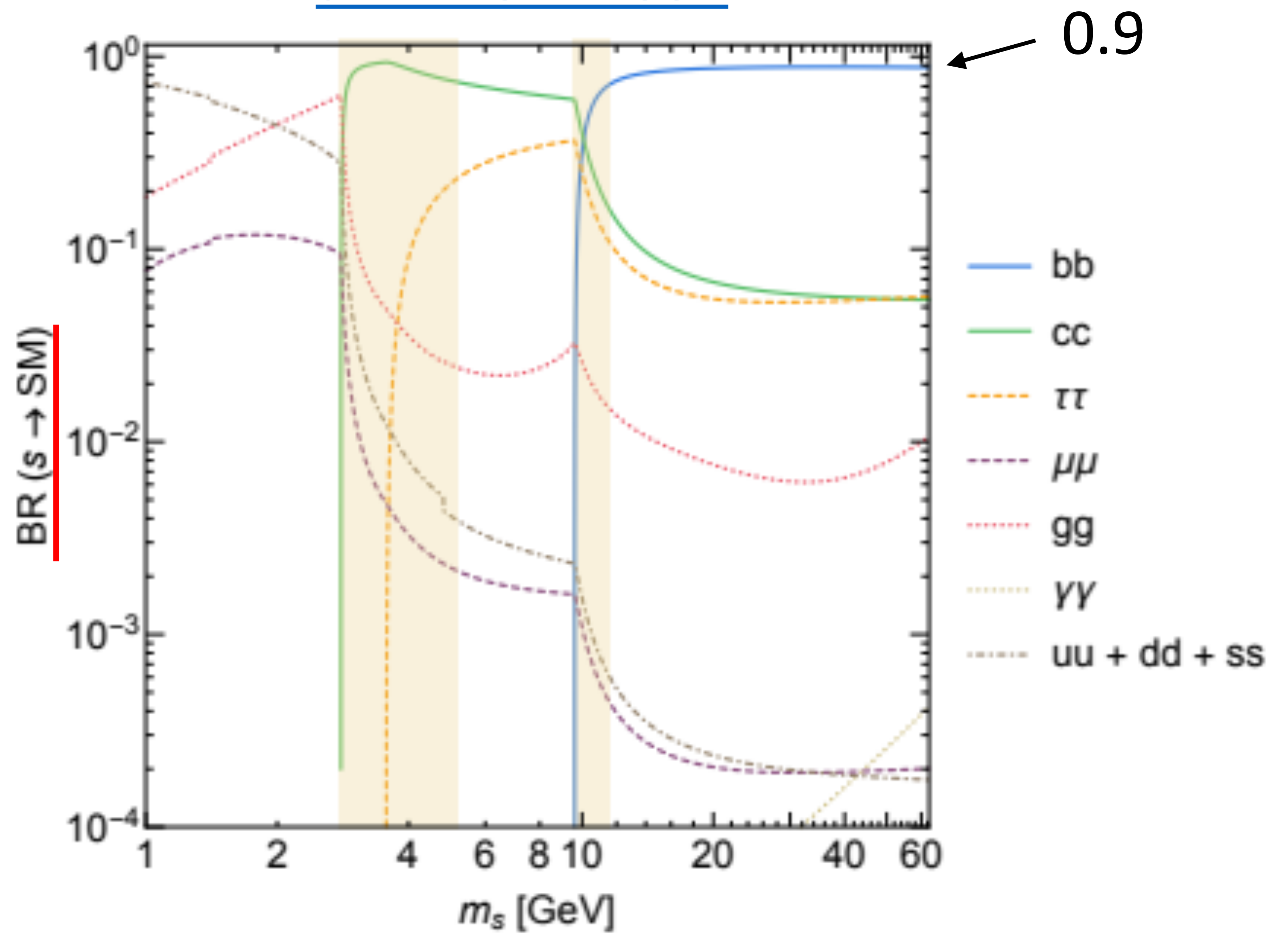
- We set κ = 1e-3 s.t $BR(h \to ss) = \mathrm{O}(10^{-4})$, lower than current constraints and within reach for FCC-ee shown by previous studies, see backup

- $BR(s \to b\bar{b})^2 = 0.9^2$, from plot

- $N_{ZH} = \ldots. \pm \ldots..$, from midterm report

Fill in

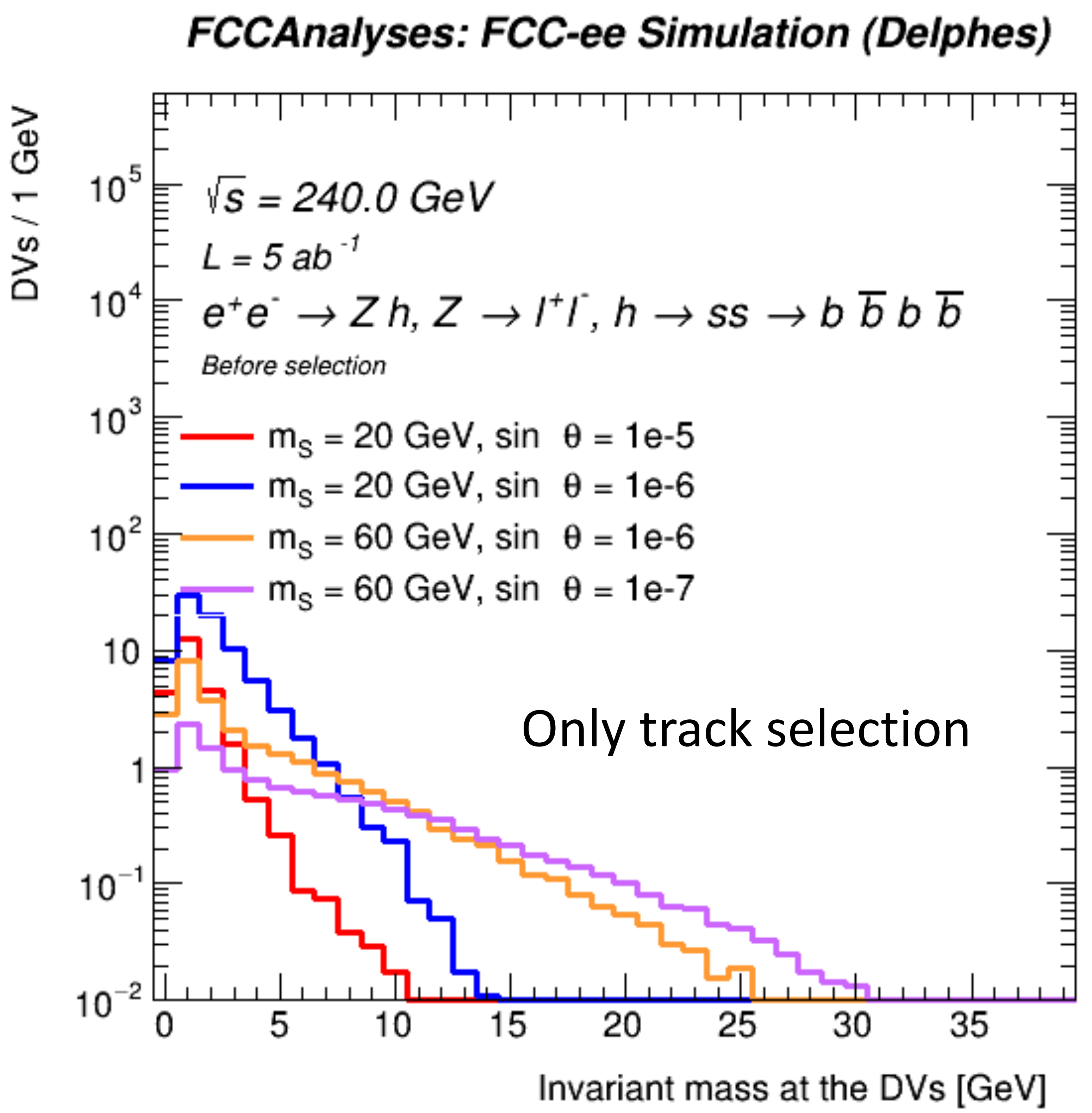
arXiv:1312.4992

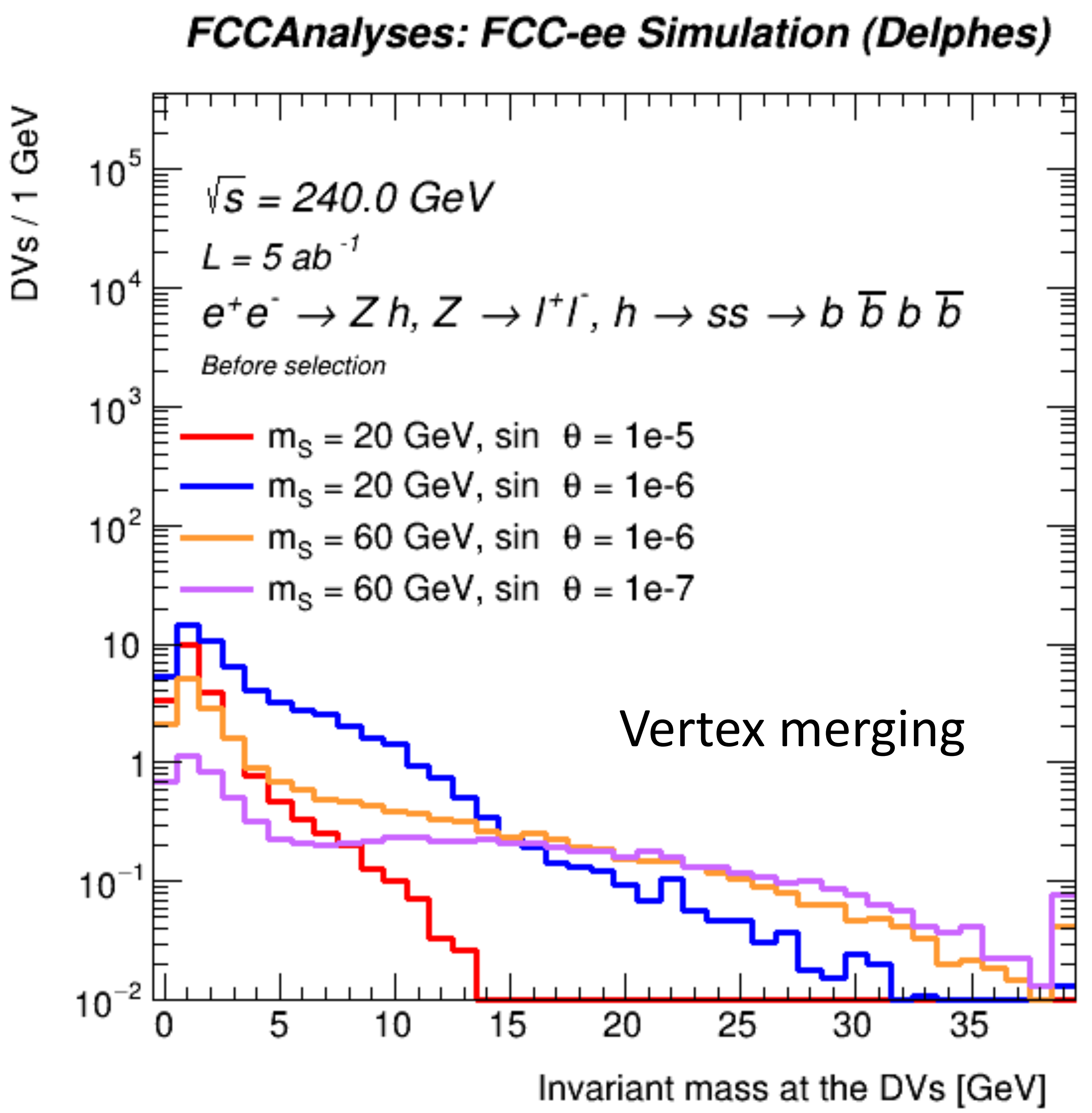


Vertex reconstruction

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

Invariant mass at the DVs





- Previous result from note
- Usually a good discriminating variable between a DV from an LLP and a fake vertex
- Invariant mass at vertex calculated assuming all tracks to come from pions, this only captures the charged component of the jet fragmentation → expected peak around half of the particle's mass
- More of a structure around higher masses for the merged vertices