Long-Lived Scalars from Exotic Higgs Decays at the FCC-ee

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on behalf of the FCC-ee LLP group

ECFA WG1-SCRH topical meeting: Standard and exotic Scalars at future HET factories

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CERN

FUTURE CIRCULAR COLLIDER

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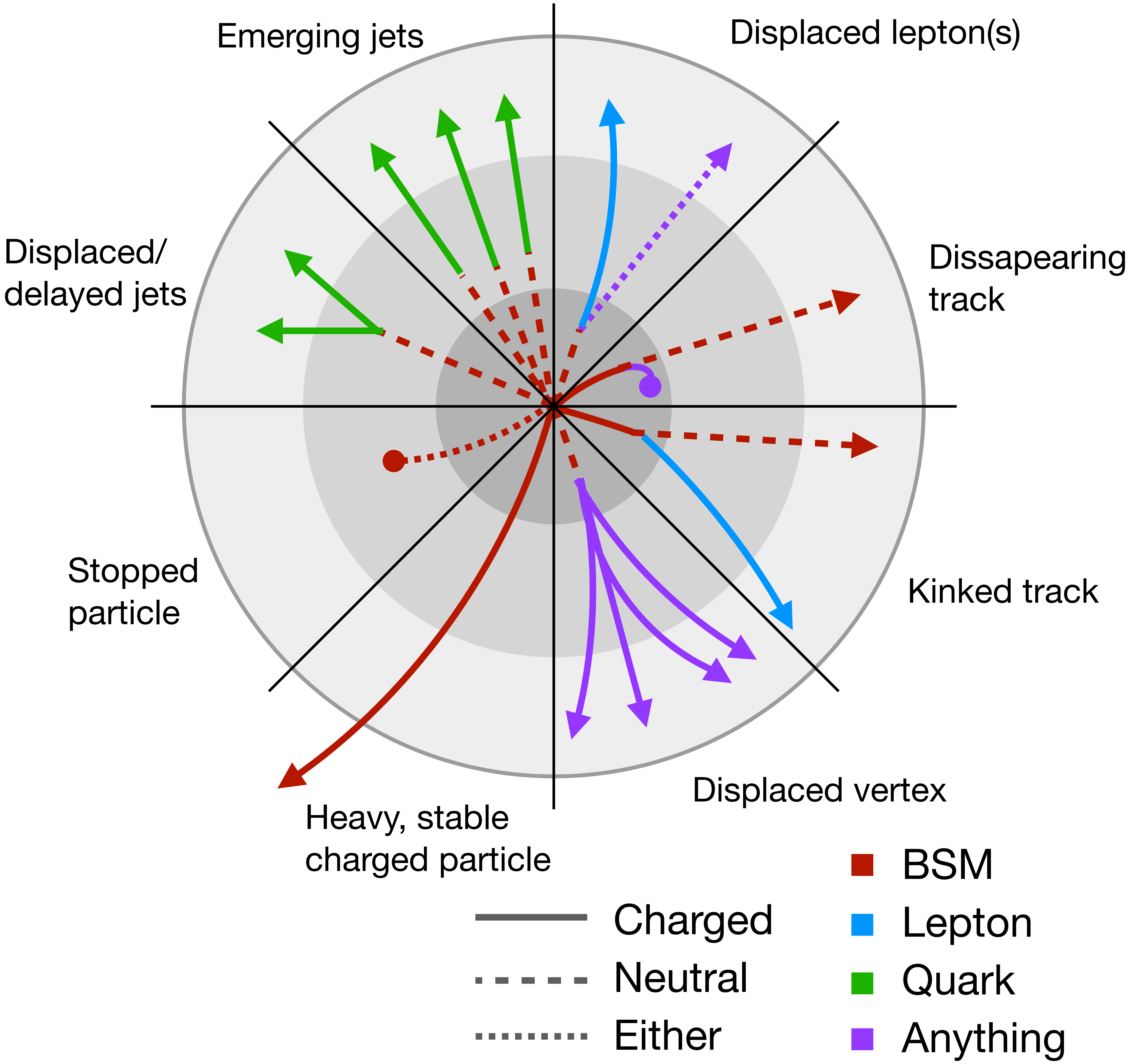
Overview

- Introduction
  - Long-lived particles, the FCC-ee and the IDEA detector, the FCC-ee LLP group
  - Exotic Higgs boson decays to long-lived scalars
- Recent activities
  - Simulations of the long-lived scalars at the FCC-ee
  - A first attempt to displaced vertex reconstruction
  - Preliminary vertex selection and event selection
  - Preliminary sensitivity analysis
- Ongoing and future work

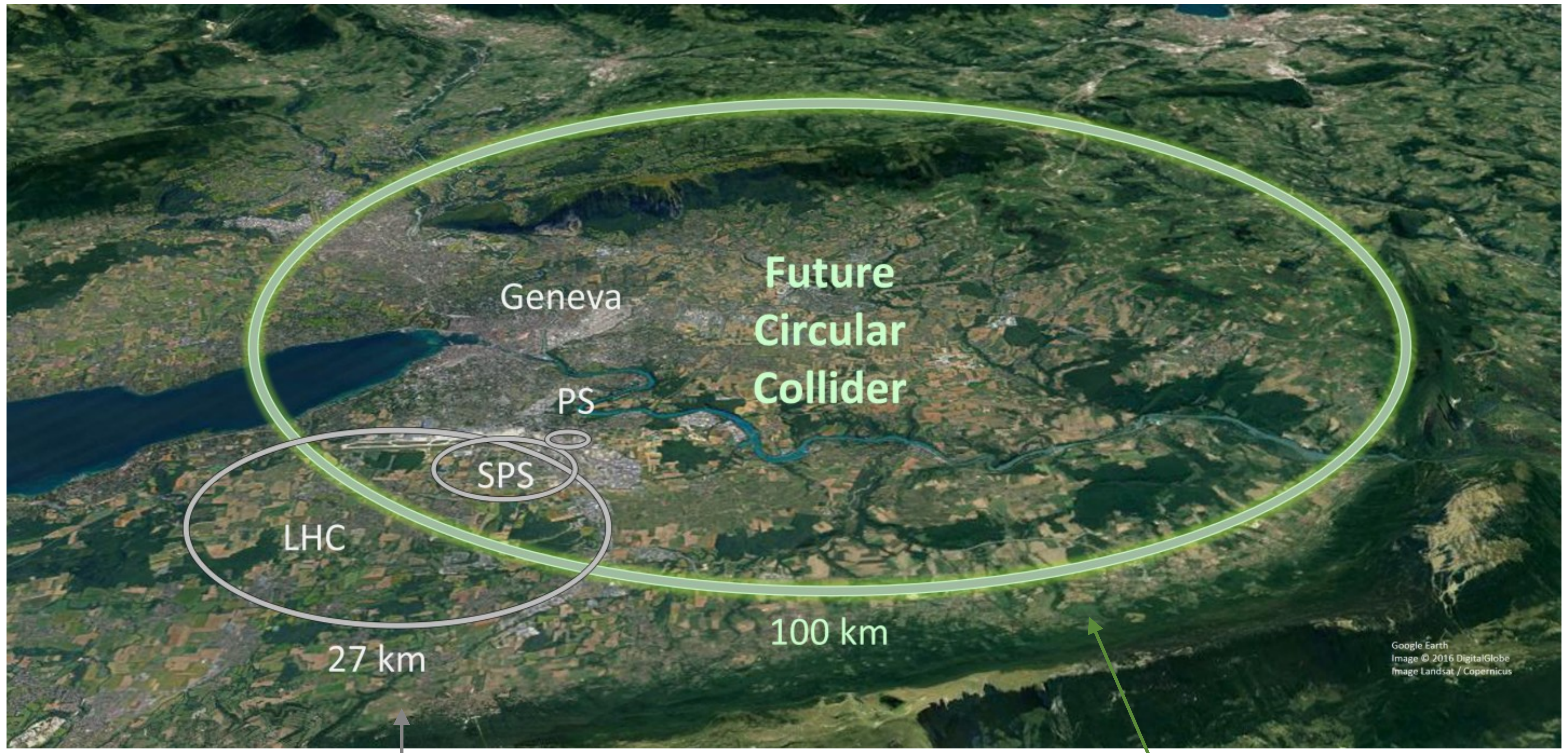
Searches for long-lived particles

- Long-Lived Particles (LLPs) are new BSM particles with sufficient decay lengths resolvable in the detector
  - Well-motivated in several BSM models
- Distinct signatures depending on the LLP lifetime, mass, charge, and decay products
  - Design signature-driven searches
- 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 accelerators!**



The Future Circular Collider (FCC)

- A proposed future accelerator at CERN
- Operate in two stages:
  - The **FCC-ee**: e^+e^- collisions at four energy stages, i.e an EW, Higgs and top factory at high luminosities
  - The **FCC-hh**: an energy frontier with hadron collisions at 100 TeV
- FCC-ee offers good opportunities for LLP searches!
  - Clean experimental signatures
  - No trigger limitations
  - High luminosity



LHC/LEP:
27 km
91-209 GeV (e^+e^- collisions)
14 TeV (pp collisions)

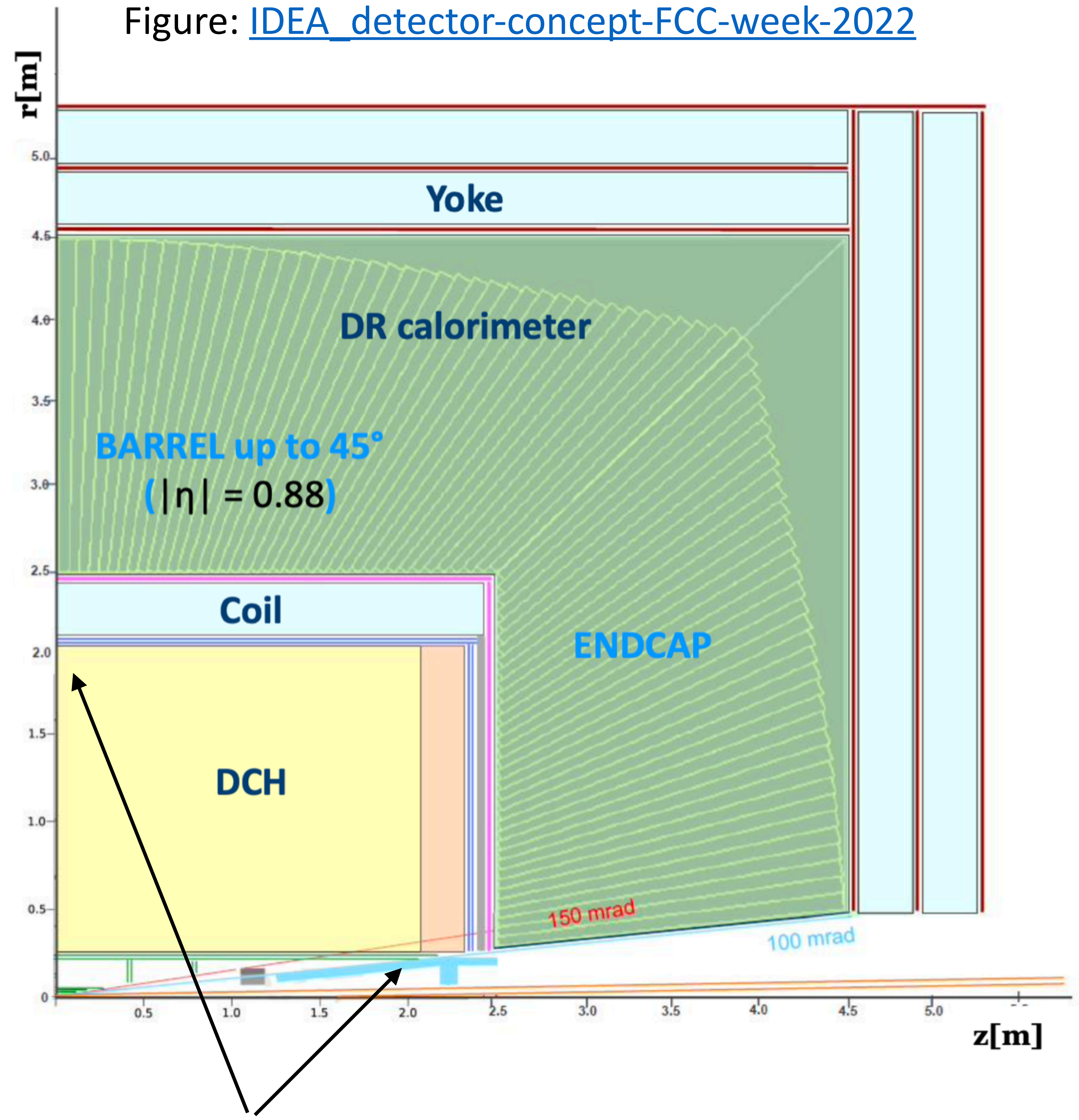
FCC:
90-100 km
91-365 GeV (e^+e^- collisions)
100 TeV (pp collisions)

Center-of-mass energy $\sqrt{s}$ [GeV]	Integrated luminosity L [ab^{-1}]	Event statistics	LEP statistics
91	150	5×10^{12} Z bosons	4×10^6 Z bosons
161	12	10^8 WW pairs	10.000 WW pairs
240	5	10^6 Higgs bosons	Not done
365	1.5	10^6 $t\bar{t}$ pairs	Not done

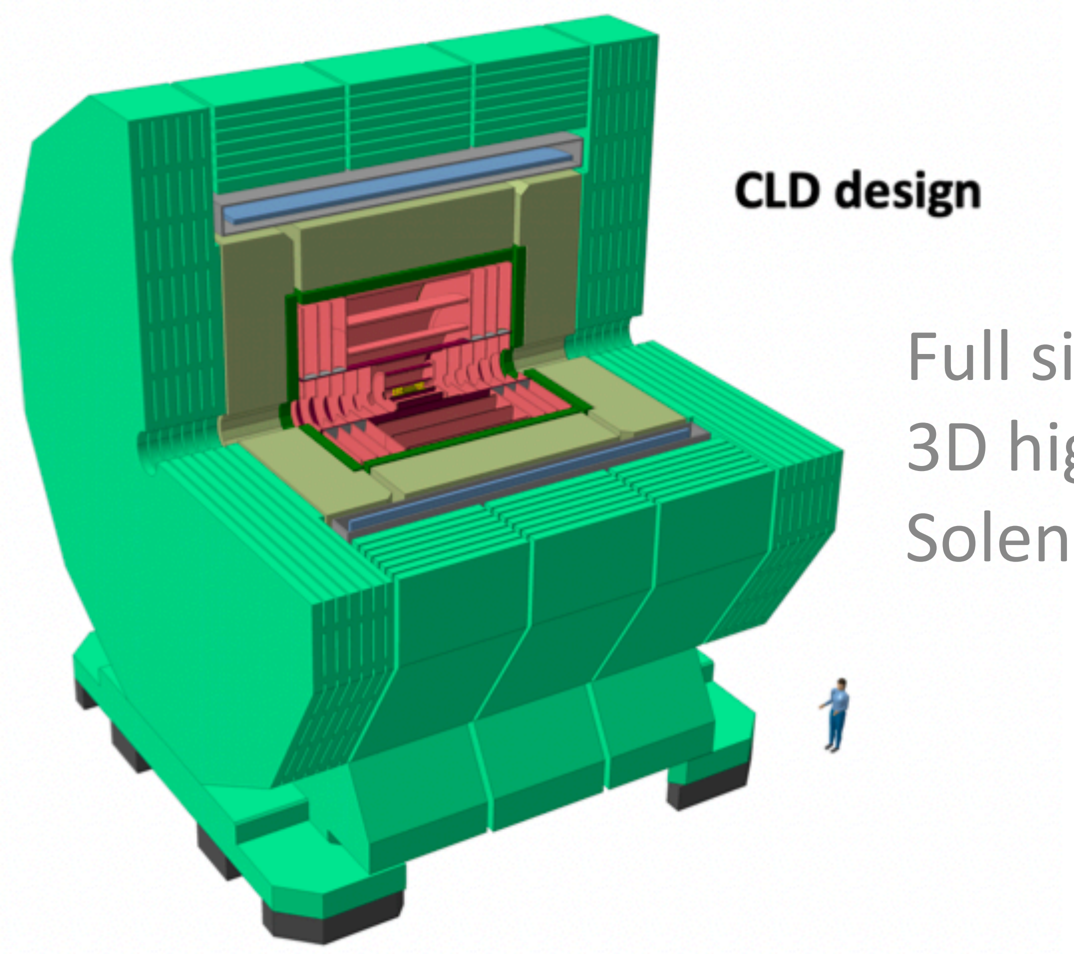
FCC-ee detector concepts

- Two detector concepts used for integration, performance, cost estimates and look at physics potential:
  - CLD design: adapted for the FCC-ee by the CERN Linear Collider (CLIC) Detector group
  - **IDEA design: specifically designed for the FCC-ee**
- Have the opportunity to design general-purpose detectors with LLPs in mind!
  - Can prioritize e.g. displaced tracking and precision timing information

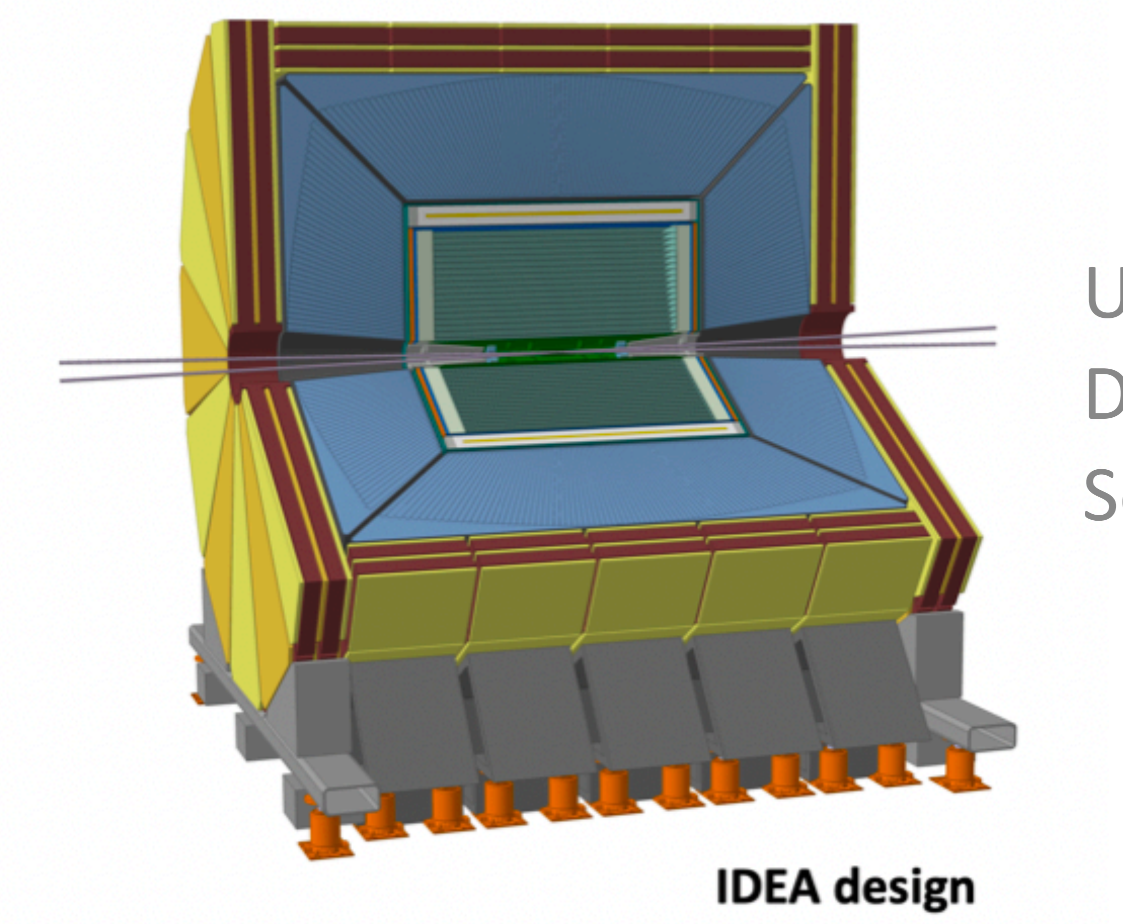
Figure: [IDEA_detector-concept-FCC-week-2022]



DCHs outer radius = 2 meters



Full silicon tracker
3D high granularity calorimeter
Solenoid outside calorimeter



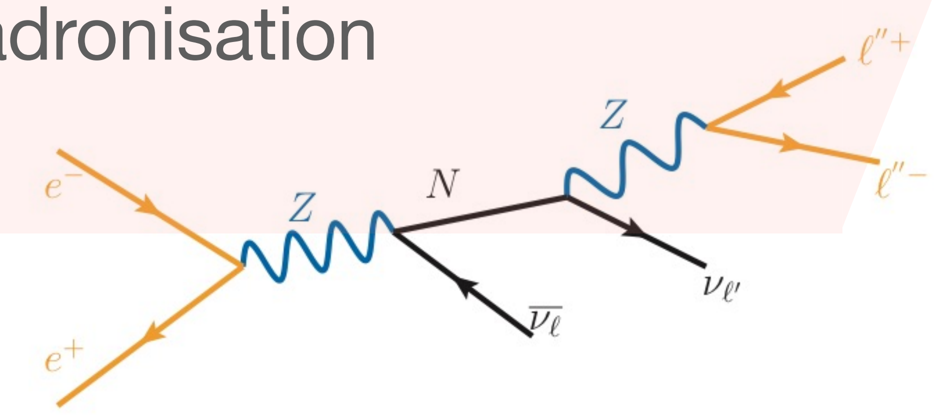
Ultra-light drift chamber
Dual read-out calorimeter
Solenoid inside calorimeter

The FCC-ee LLP group

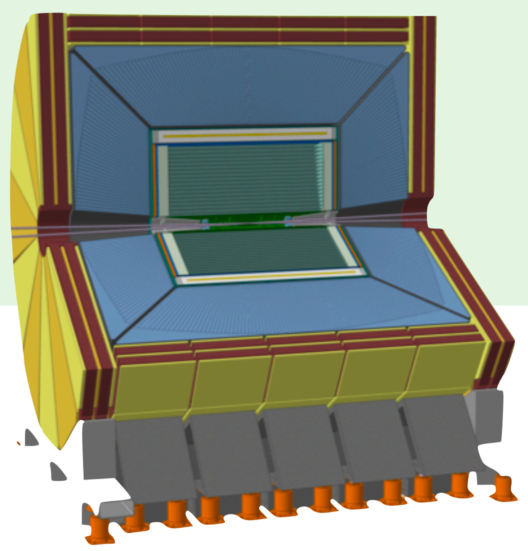
- The FCC-ee LLP group is dedicated to determine the physics potential to motivate detector design or reconstruction algorithms optimized for LLPs
- Perform case studies with the common FCC analysis tools
  - The FCCAnalyses framework, privately and centrally-produced samples, Delphes, etc
- 3 benchmark physics cases: Heavy Neutral Leptons (HNLs), Axion-like Particles (ALPs) and LLPs from exotic Higgs decays
- **Today: A first simulation and analysis of long-lived scalars from exotic Higgs decays**

Typical workflow

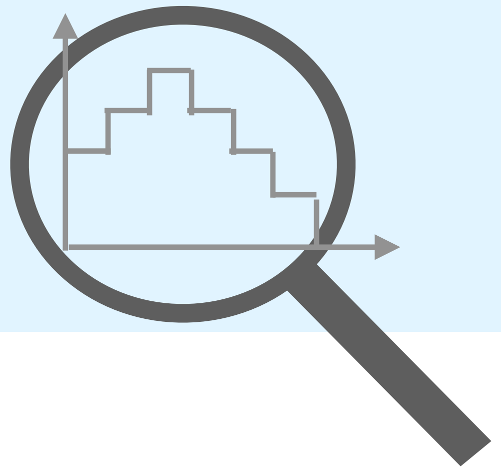
Sample generation of models
- MadGraph5_aMC@NLO for parton-level e^+e^-
- PYTHIA for parton shower and hadronisation



Parametrised detector simulation
- IDEA DELPHES card



Analysis tools
- FCC analysis



Sensitivity to studied model

Long-lived scalars from exotic Higgs decays

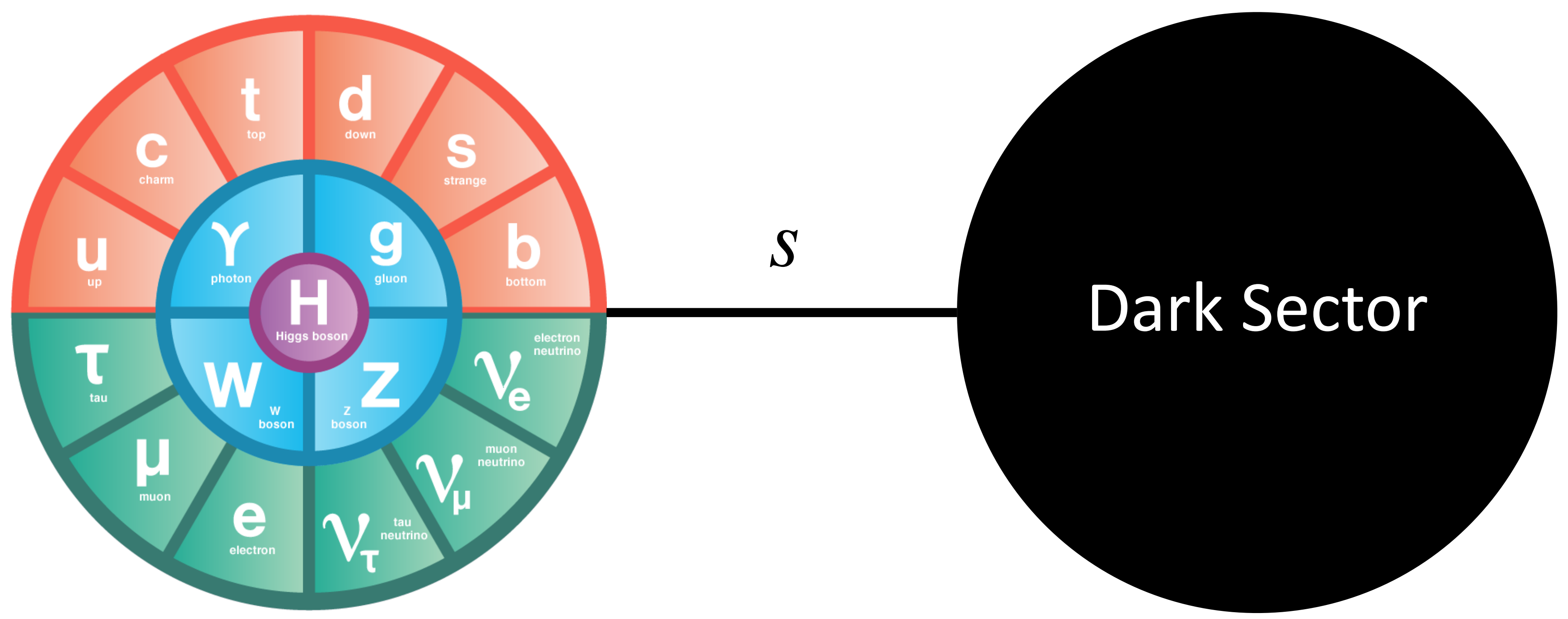
- The Higgs boson can have sizeable couplings to new particles → exotic Higgs decays
- Our considered model: SM + scalar (arXiv:1312.4992, arXiv:1412.0018)
- The new scalar could be a portal between the SM and a dark sector, motivated by e.g Dark Matter
- New real scalar field S couples to the Higgs 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

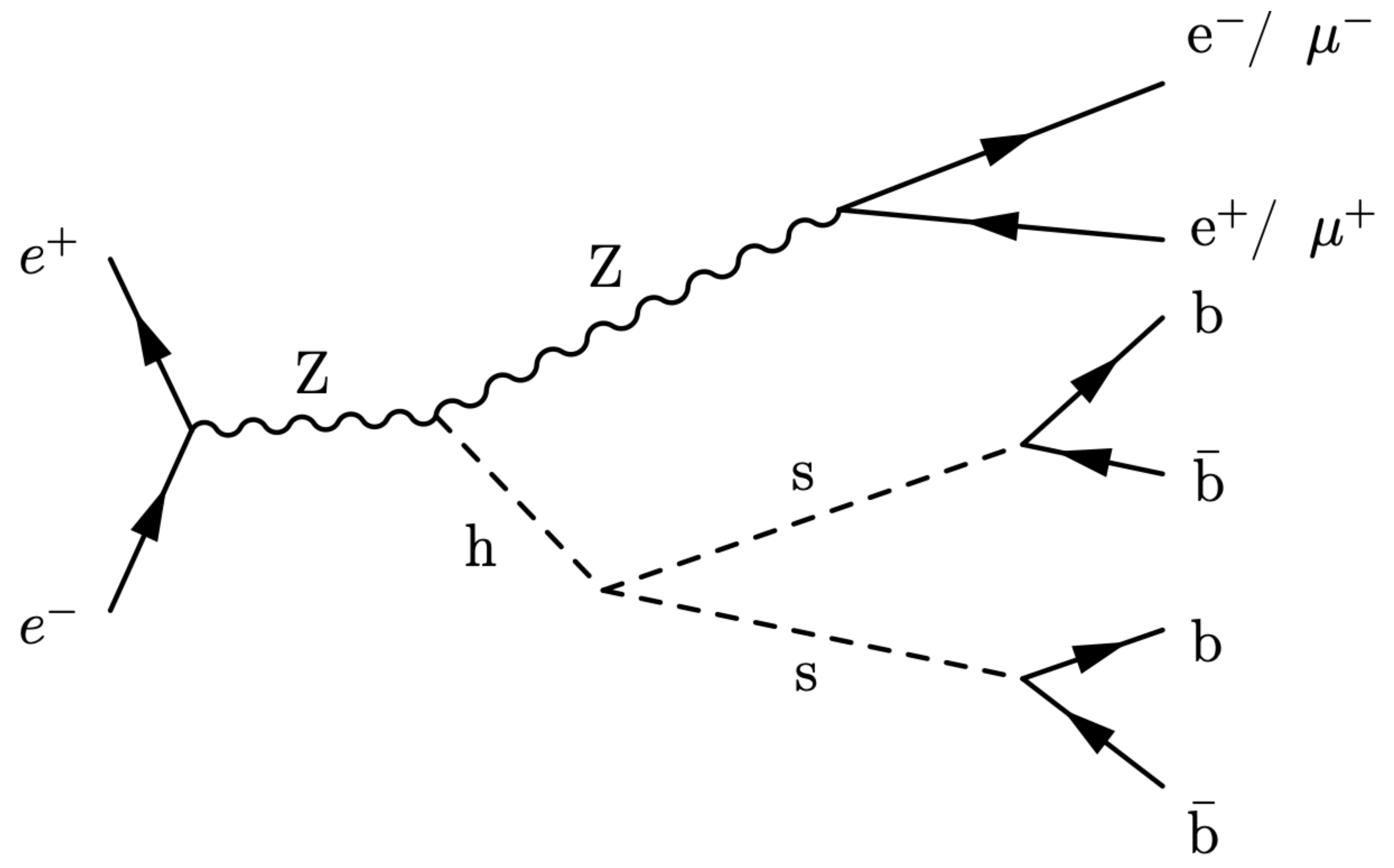
$$\Gamma\left(s \to X_{\mathrm{SM}} X_{\mathrm{SM}}\right) = \sin^2\theta\, \Gamma\left(h(m_s) \to X_{\mathrm{SM}} X_{\mathrm{SM}}\right)$$

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



Simulation of long-lived scalars @ FCC-ee

- Generated signal samples: $e^+e^- \rightarrow Z\,h$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
- 10.000 privately generated events
- Full chain using MadGraph v3.4.1 + Pythia8 + Delphes, with the spring2021 IDEA Delphes 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
- Parameter choices:
  - $\sqrt{s} = 240\ GeV$ and $L = 5\ ab^{-1}$
  - m_s = 20 GeV and m_s = 60 GeV
  - sin θ = 1e-5, 1e-6, 1e-7, corresponding to cτ of order 1 mm – 10 m
  - κ = 1e-3 s.t $BR(h \rightarrow ss) = \mathrm{O}(10^{-4})$ lower than current constraints, but within reach for FCC-ee (see backup)



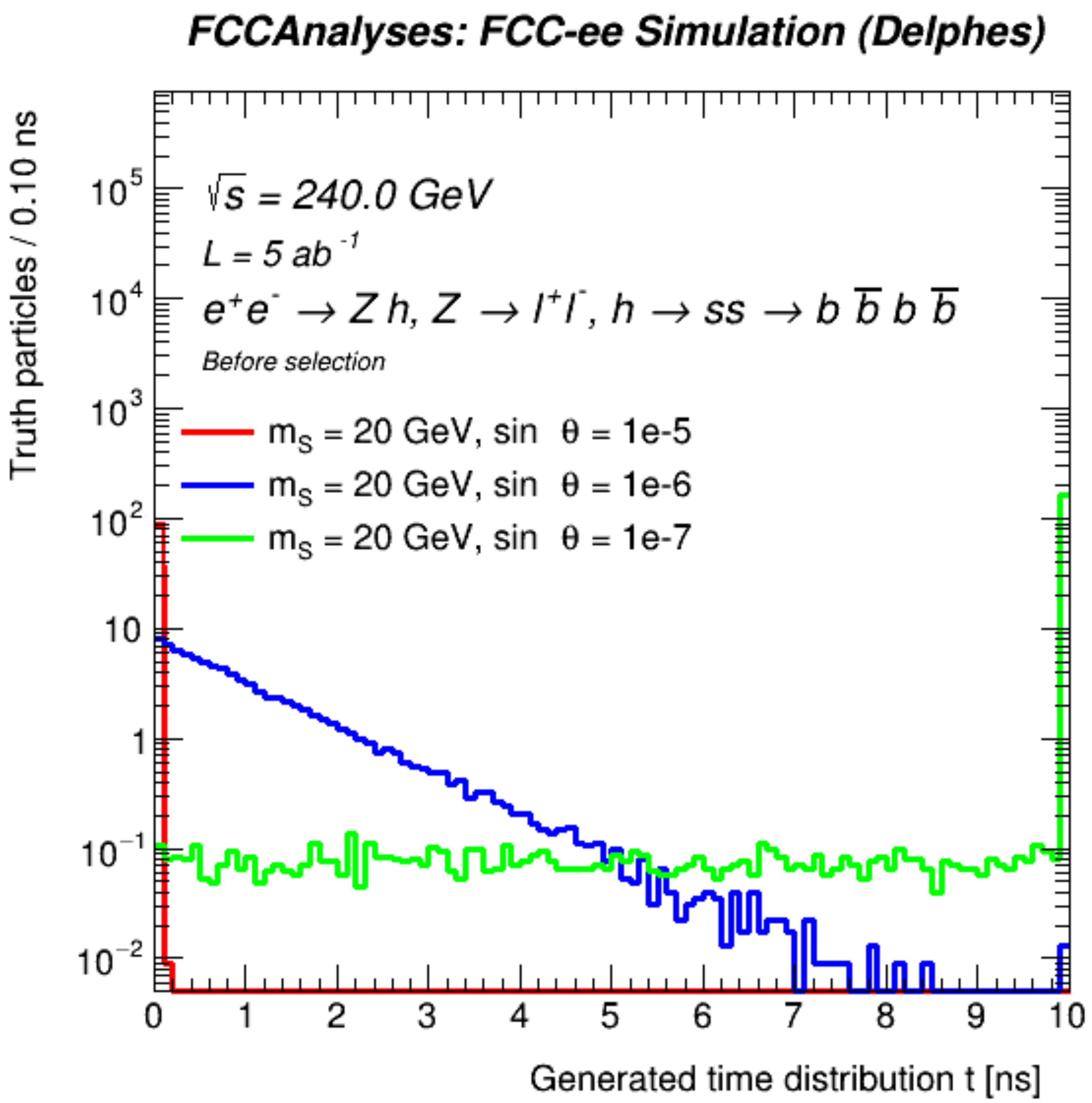
$$\mathrm{BR}(h \rightarrow ss) = \frac{\kappa^2 v_h^2}{32\pi m_h \Gamma_h}\sqrt{1 - 4\frac{m_s^2}{m_h^2}}$$

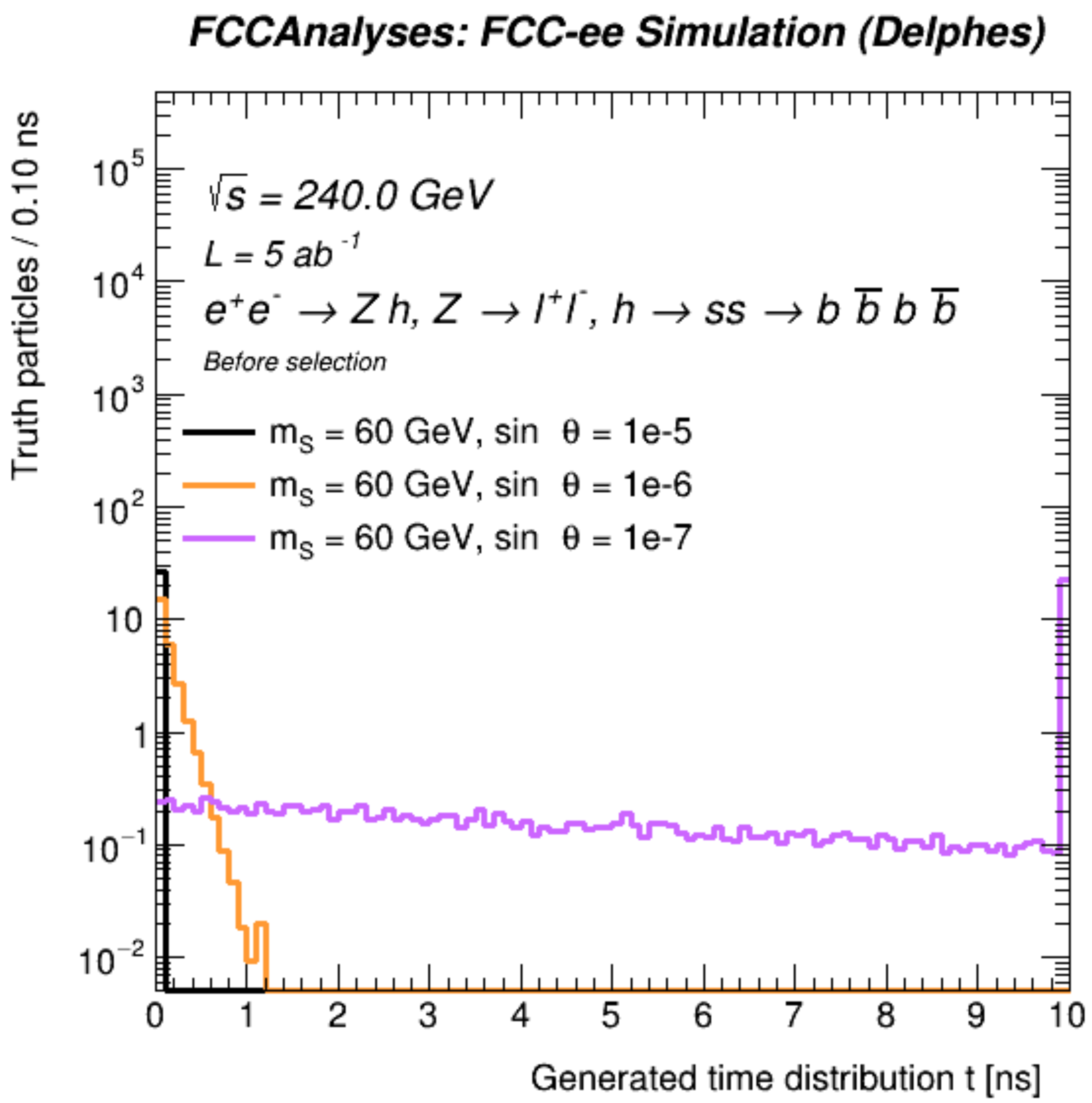
κ: Higgs-scalar coupling constant

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

θ: Mixing angle

Generated kinematics

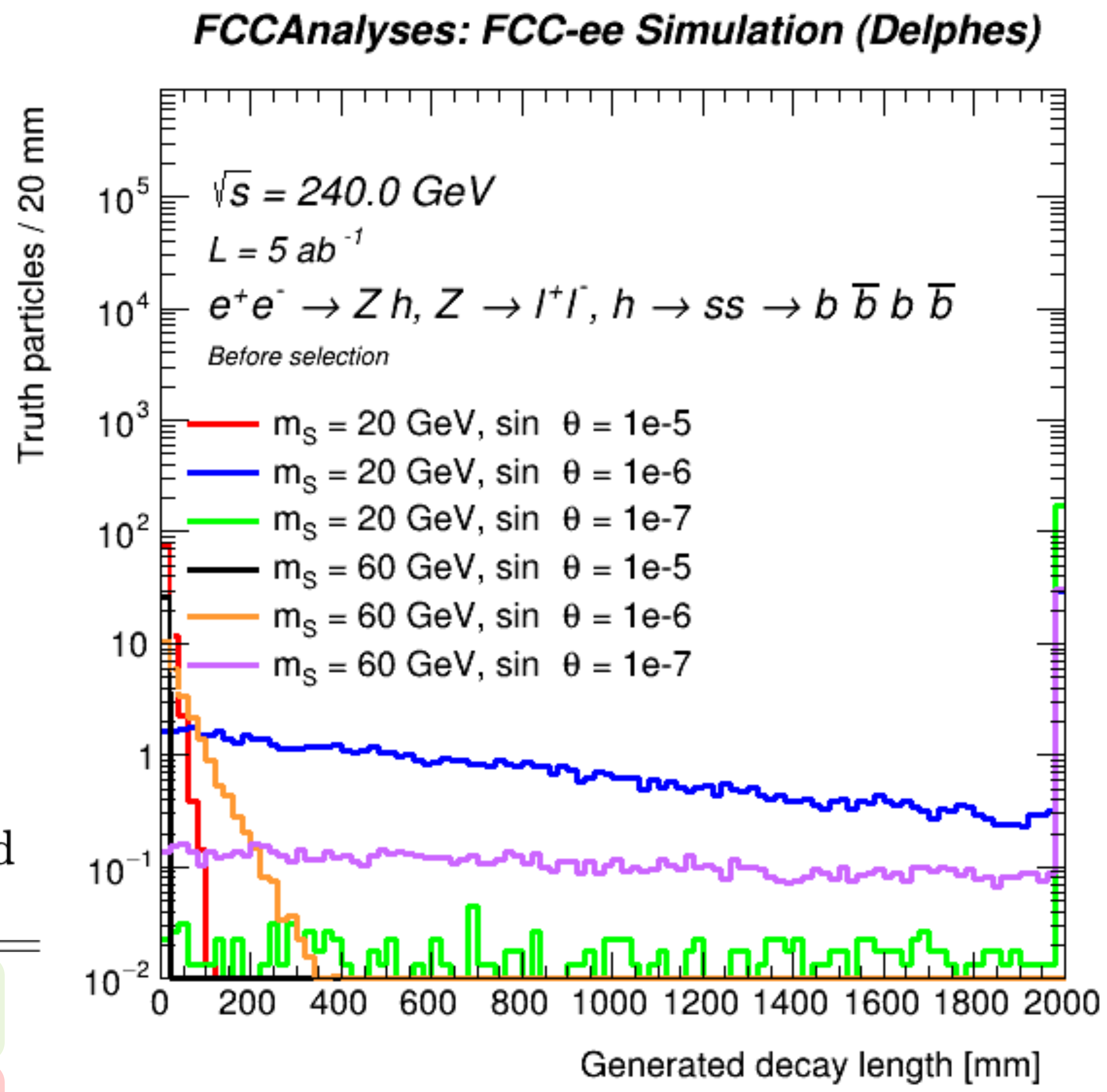




- Lifetime increases for smaller mixing angle, sin θ, and smaller masses, m_s, as expected
- The generated mean proper lifetimes (from fit of the distributions):
  - 0.0107 ± 0.0001 ns
  - 1.0622 ± 0.0108 ns
  - 118.326 ± 1.2412 ns

Sensitivity analysis at gen level

- 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($h \rightarrow ss$)	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

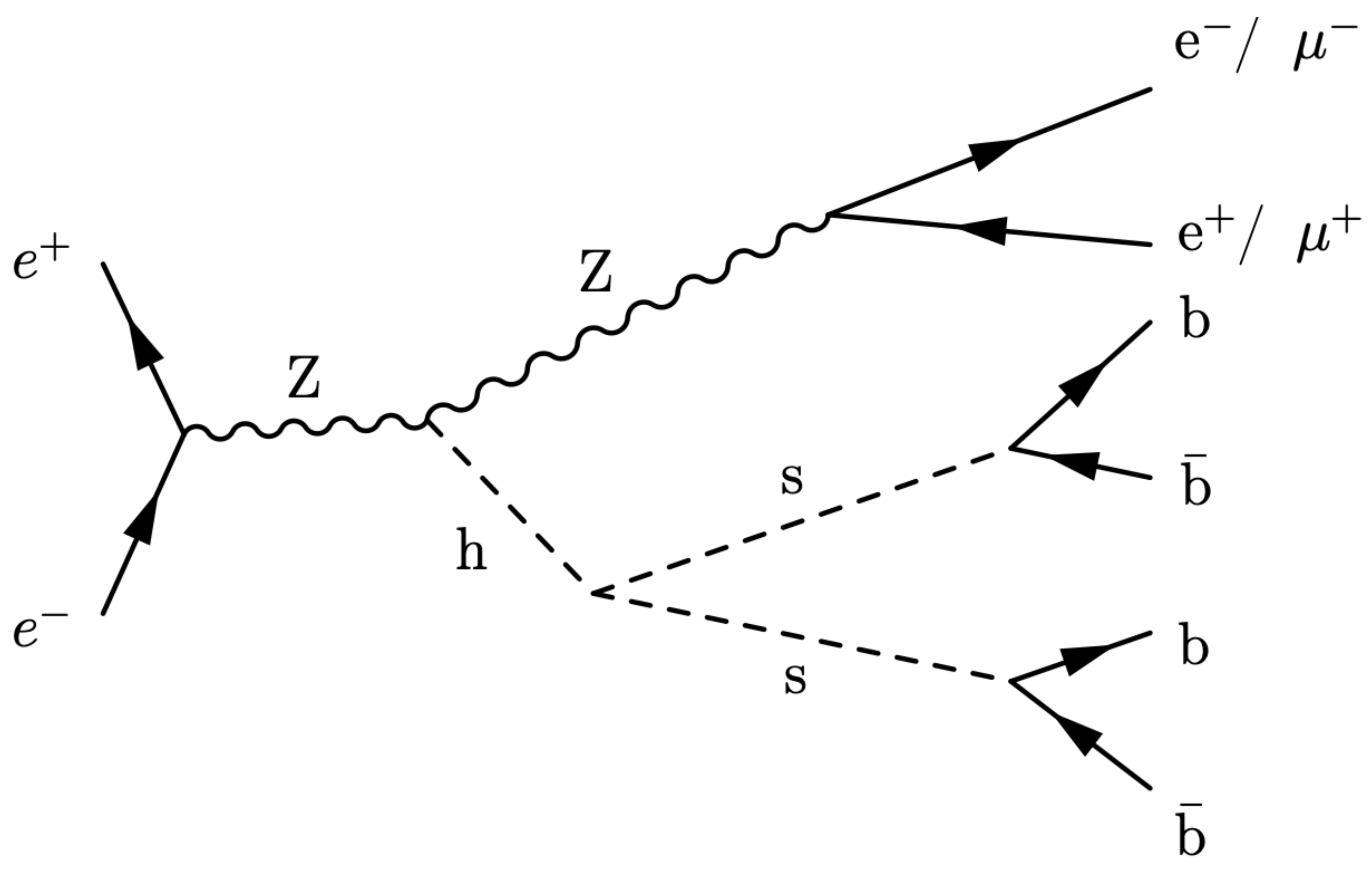
$N = L \times \sigma$ with $L = 5\ ab^{-1}$ and

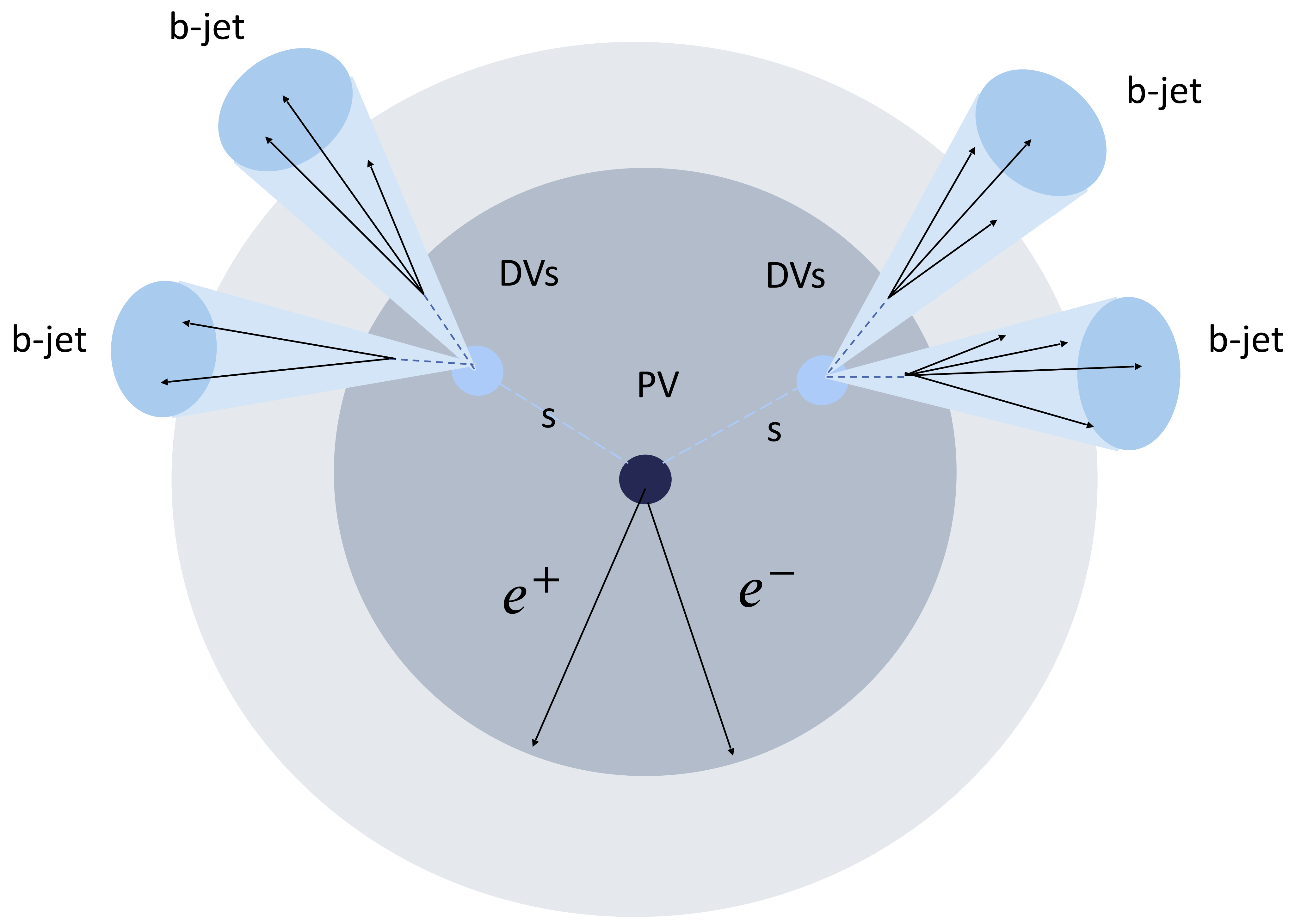
$$\sigma = \sigma_{ZH} \times BR(h \rightarrow ss) \times BR(s \rightarrow b\bar{b})^2 \times BR(Z \rightarrow l^+l^-)$$

Reconstruction of the signal

Experimental signature:

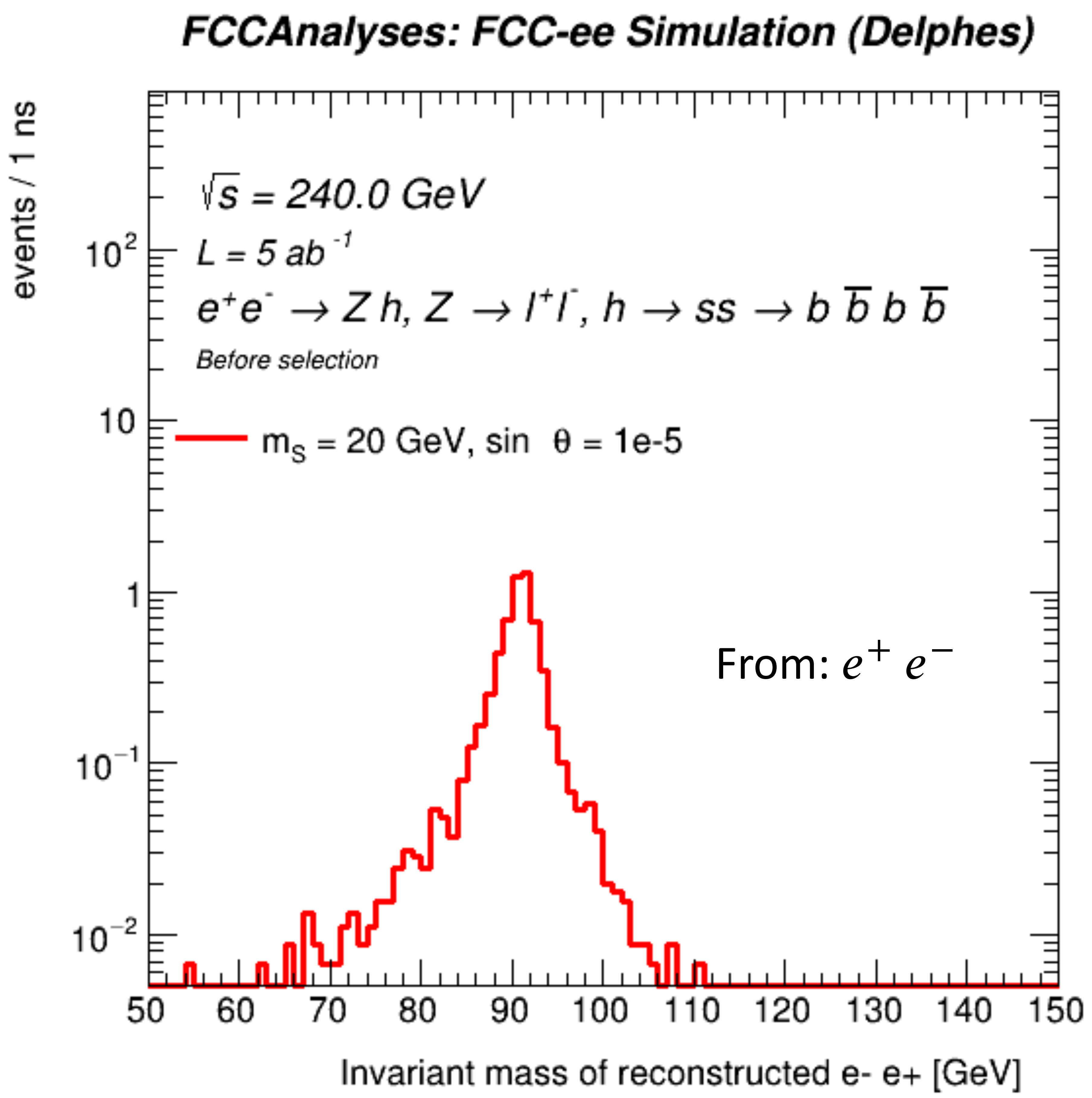
- Z boson reconstructed from e^+e^- or $\mu^+\mu^-$ pair
- Displaced Vertices (DVs)

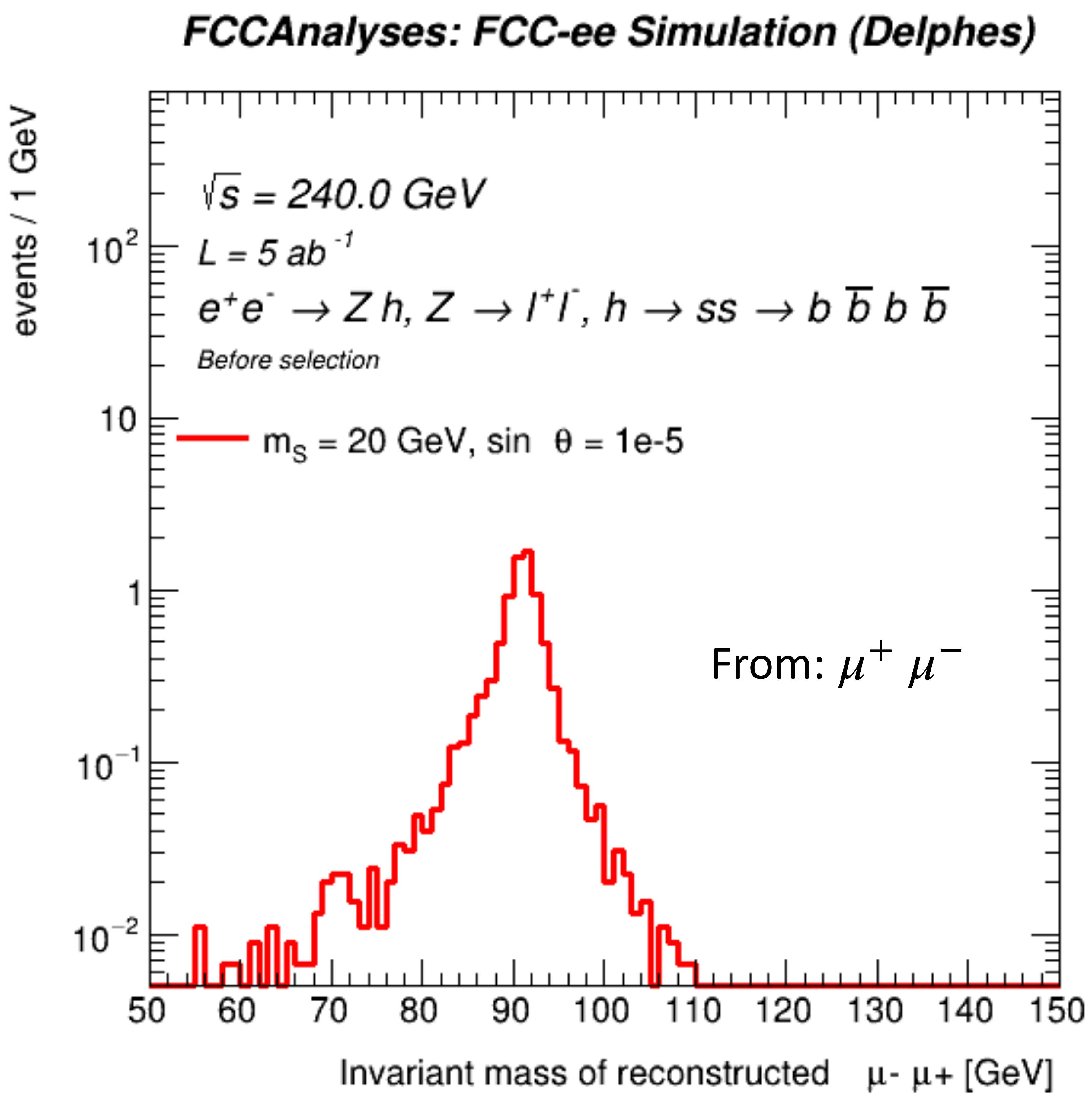




Reconstruction of the Z boson with e^+e^- and $\mu^+\mu^-$

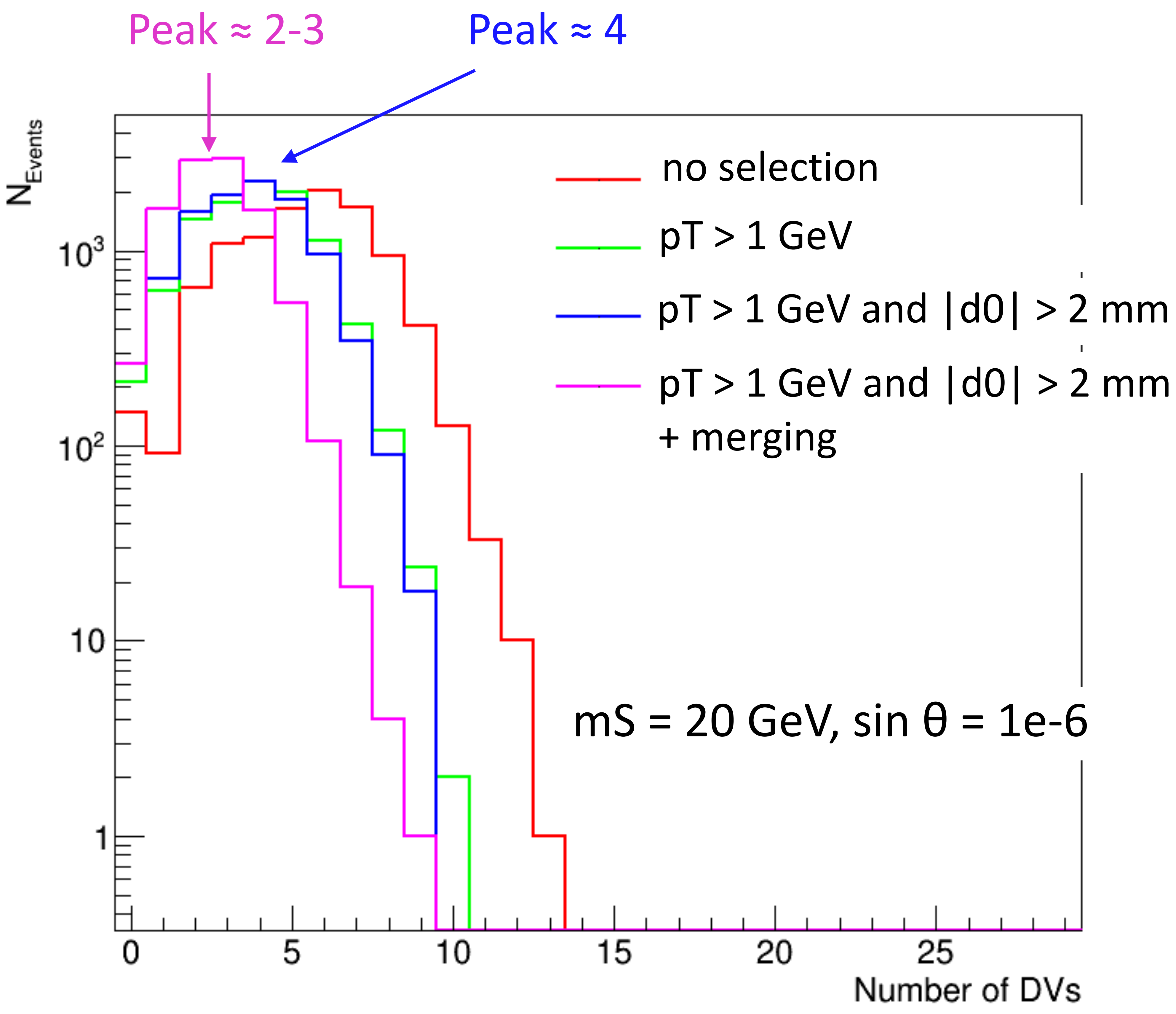
- The Z boson mass reconstructed from the invariant mass of either of the lepton pairs
- Can be used to tag the signal

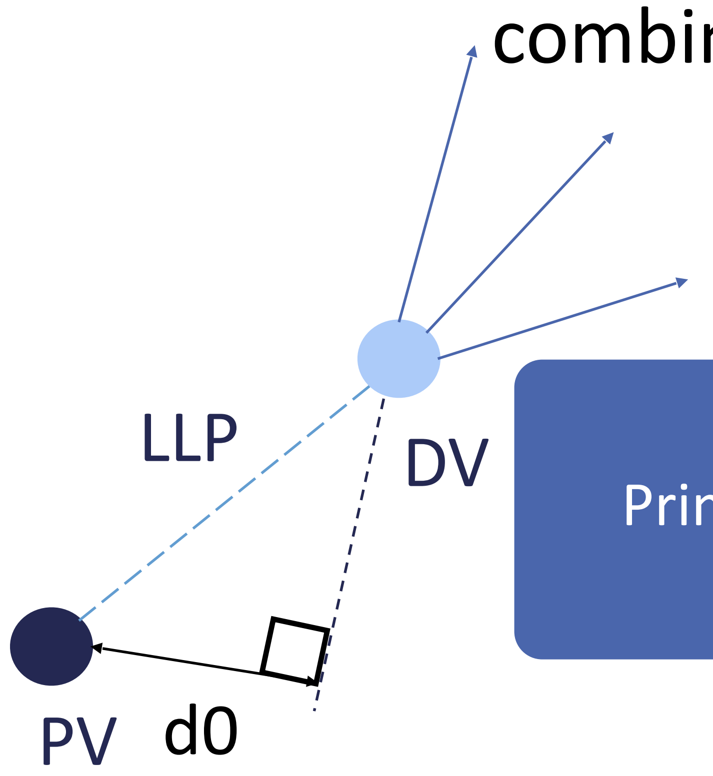




Displaced Vertex reconstruction

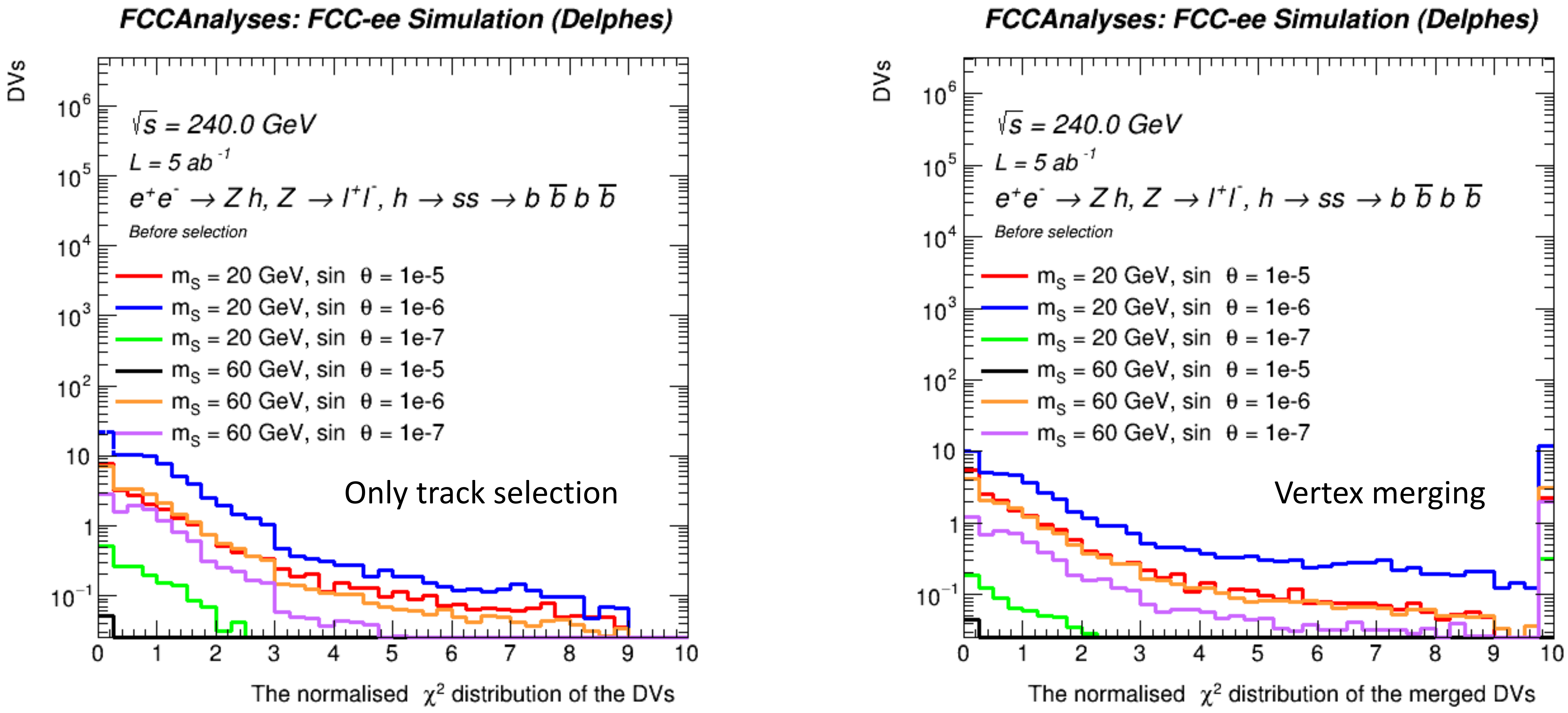
- Two options of DV reconstruction implemented and tested, using current tools in the FCCAnalyses framework with extra constraints and functions inspired by ATLAS DV reconstruction ([cds](cds))
- SV finder of the LCFI+ algorithm (arXiv:1506.08371)
  - **Track selection**: pT > 1 GeV and |d0| > 2 mm, to reconstruct DVs from the $s \rightarrow b\bar{b}$ decay
  - Inputs for vertex seed: M_{inv} < 40 GeV and $\chi^2 < 9$
  - Vertexing: $\chi^2 < 5$ for adding track to vertex seed
- Added **vertex merging** in attempt to reconstruct the scalar DVs
  - 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





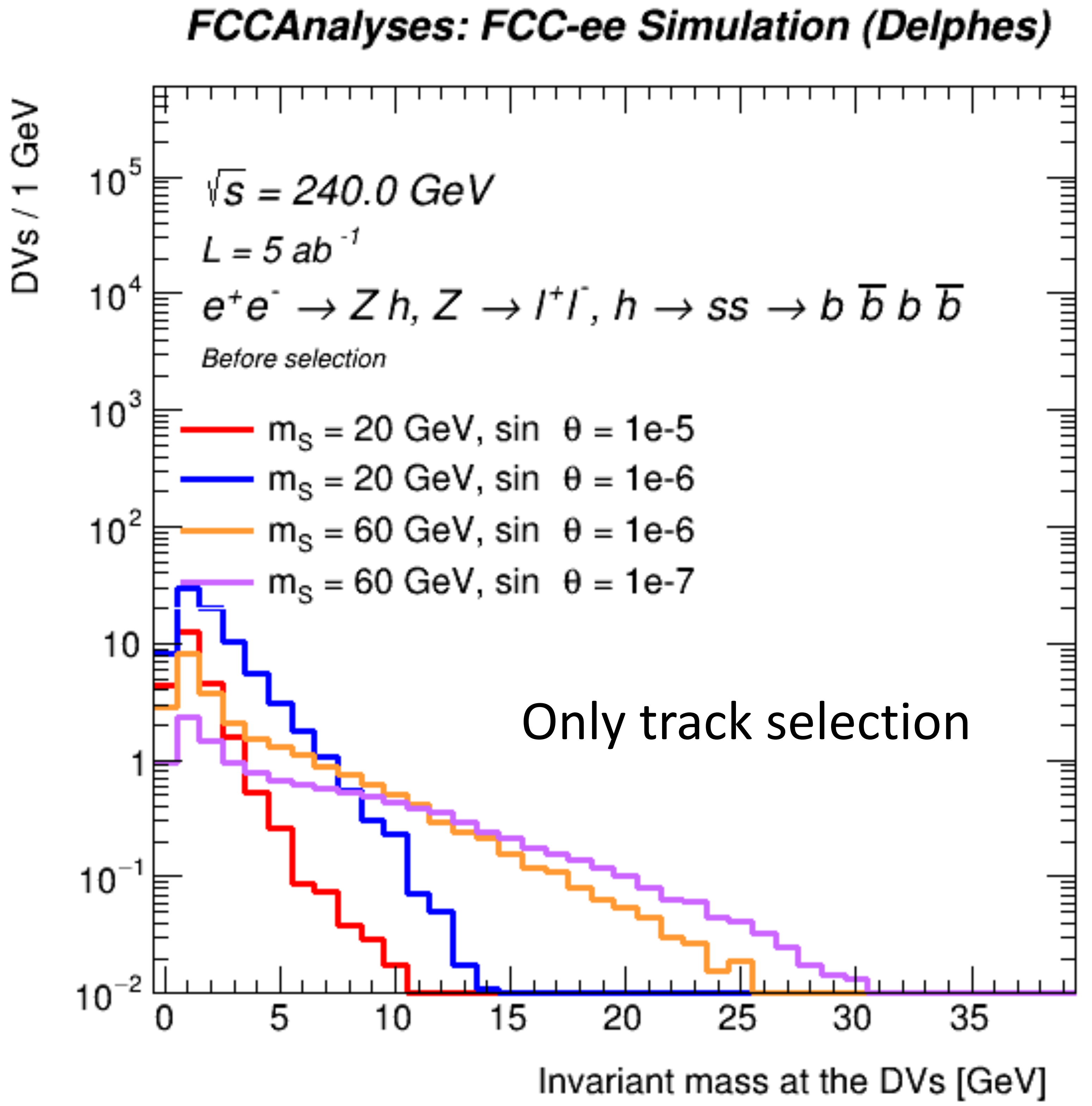
Primary Vertex Finding → (Selected tracks with pT > 1 GeV and |d0| > 2 mm) → Secondary Vertex Finding → (SVs within 10σ or 1 mm) → Vertex Merging → Displaced Vertex

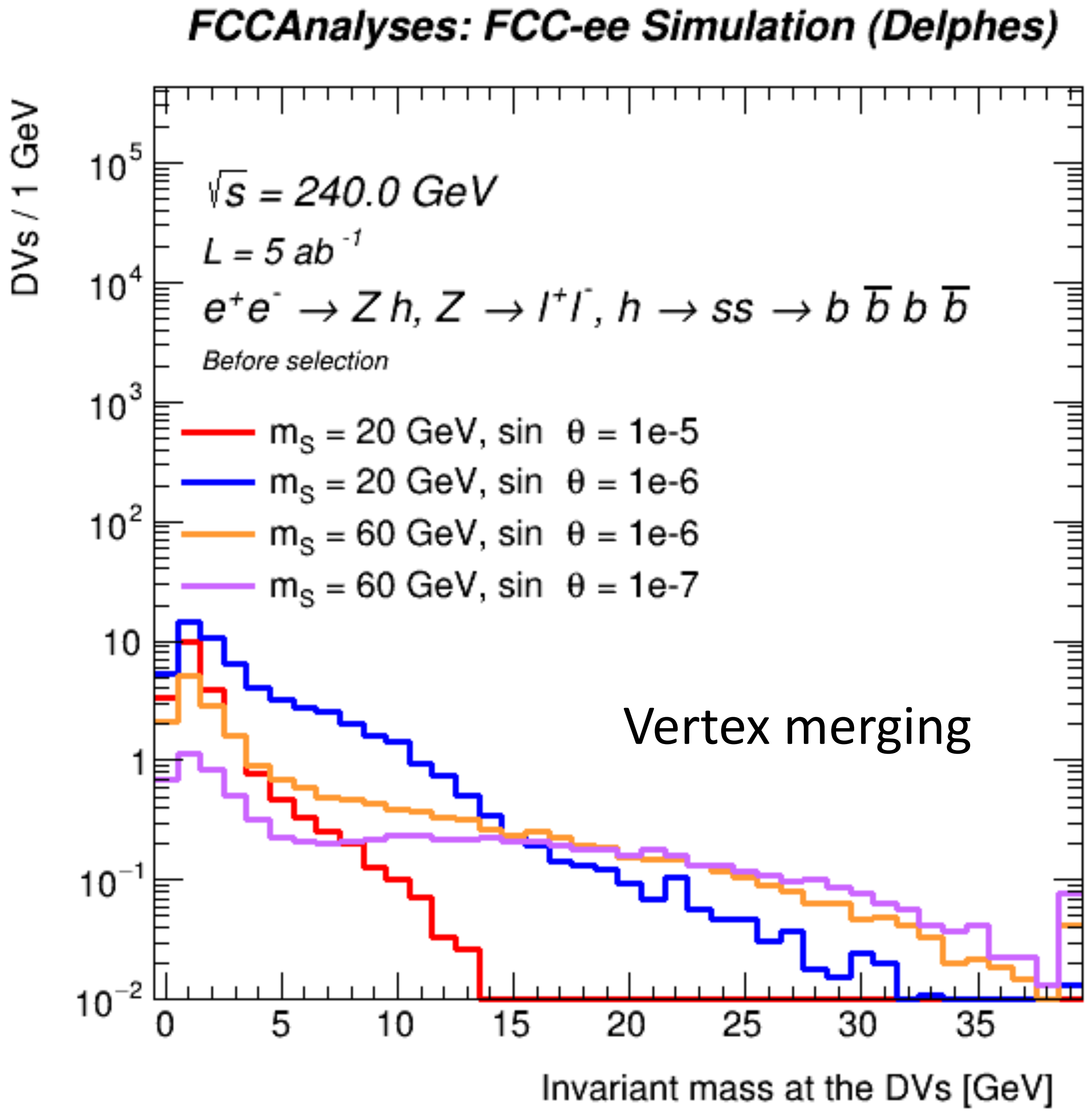
Goodness-of-fit of the DVs



- The χ^2/dof distributions tends to higher values for vertex merging
- Smeared out distribution for m_s = 20 GeV, sin θ = 1e-6
- With vertex merging all signal points have values in the overflow → worse fit

Invariant mass at the DVs

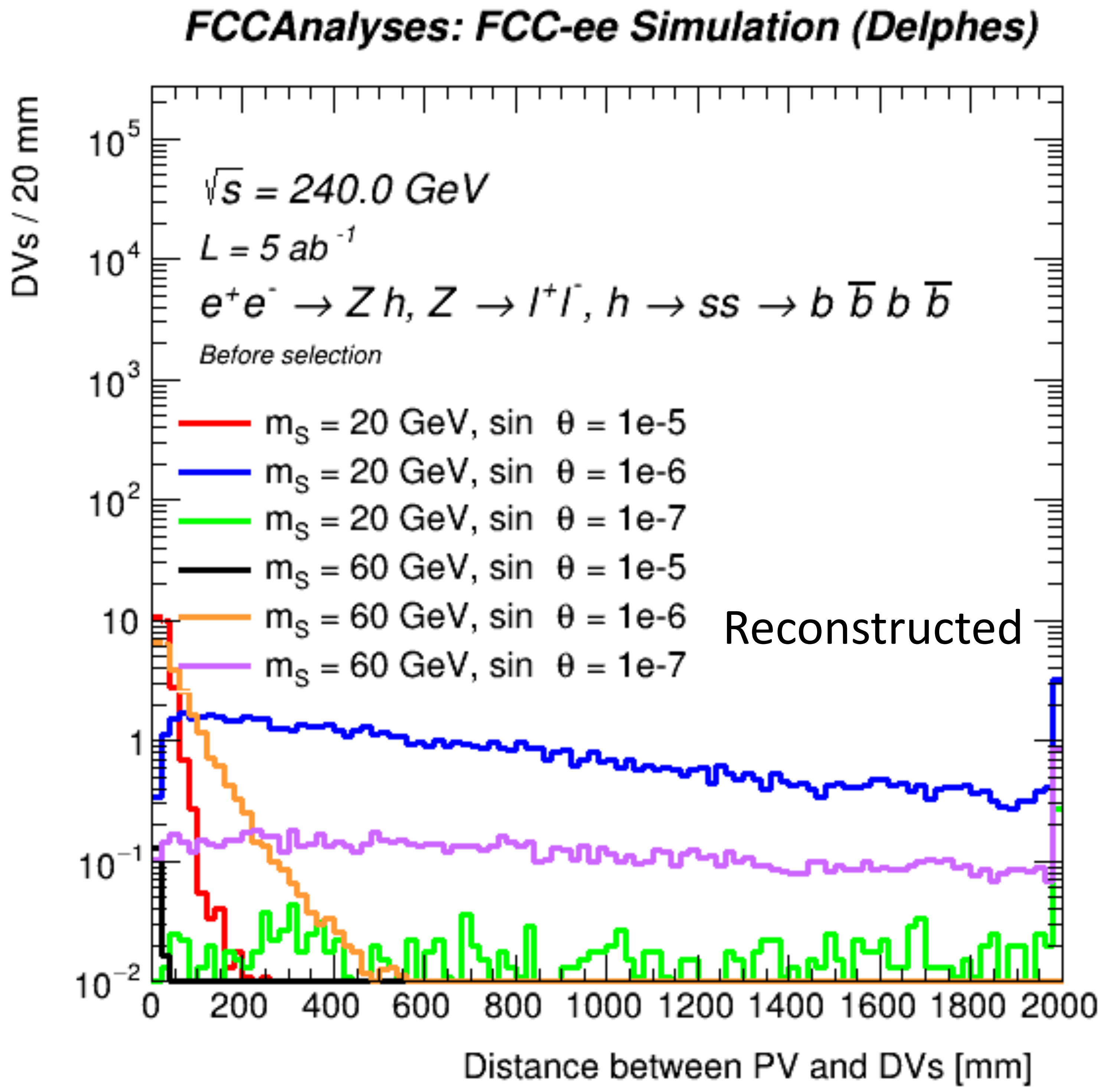


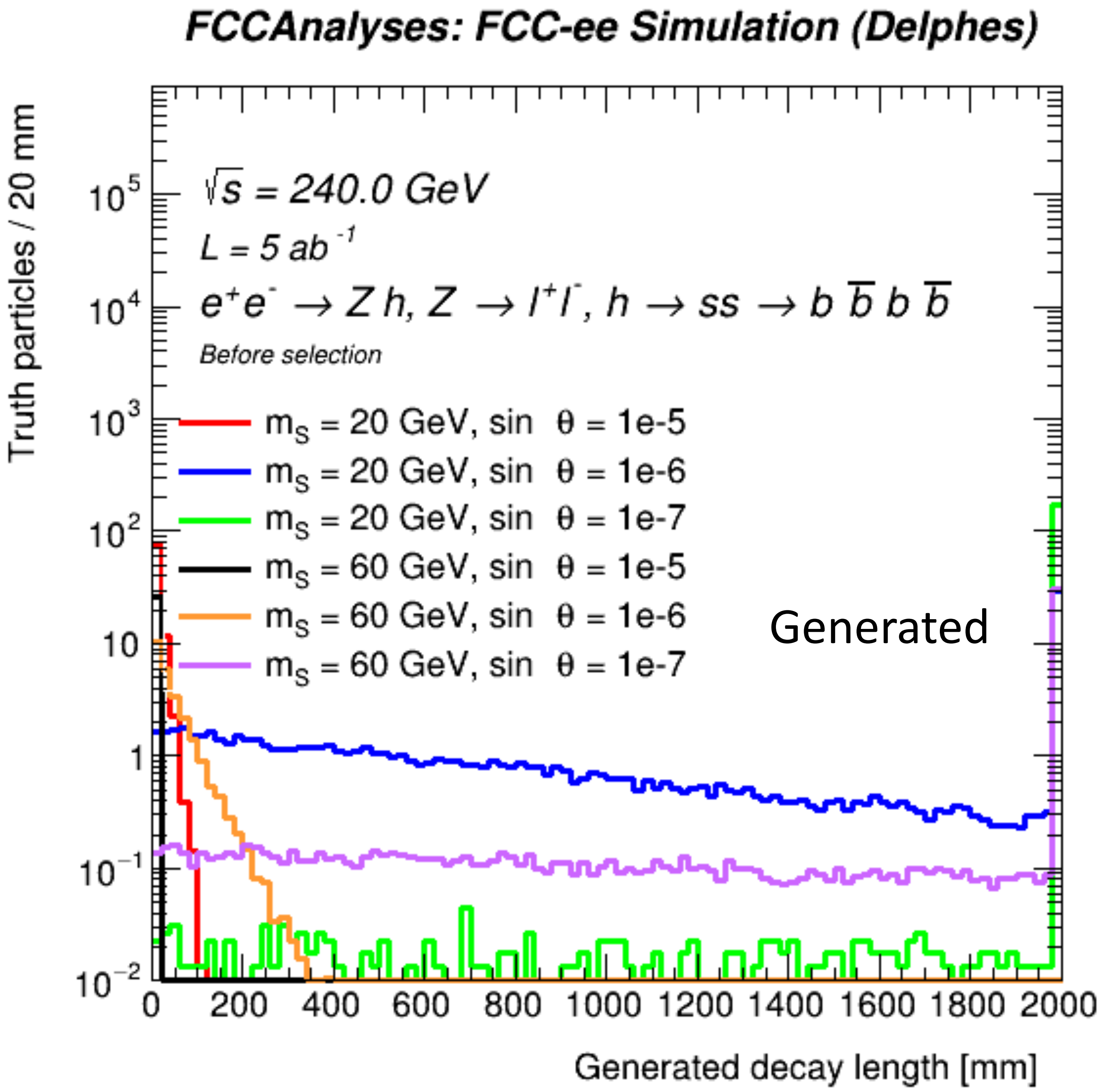


- Usually a good discriminating variable between a DV from an LLP and a fake vertex
- Invariant mass at vertex calculated assuming all tracks to come from pions, this only captures the charged component of the jet fragmentation → expected peak around half of the particle's mass
- More of a structure around higher masses for the merged vertices
- Tradeoff between goodness-of-fit and invariant mass → no vertex merging at this stage, more truth studies needed!

Distance from PV to DVs

- Another good discriminating variable between signal and background is the distance between the PV and the DVs
- DVs reconstructed only with selected tracks, the reconstructed quantity nicely follows the generated quantity
- m_s = 20 GeV, sin θ = 1e-5, m_s = 20 GeV, sin θ = 1e-6, m_s = 60 GeV, sin θ = 1e-7 and m_s = 60 GeV, sin θ = 1e-6 good for the analysis!
- m_s = 60 GeV, sin θ = 1e-5 is too short lived to be properly reconstructed with the DV algorithm
- m_s = 20 GeV, sin θ = 1e-7 might be too long-lived to have enough DVs in the tracker volume





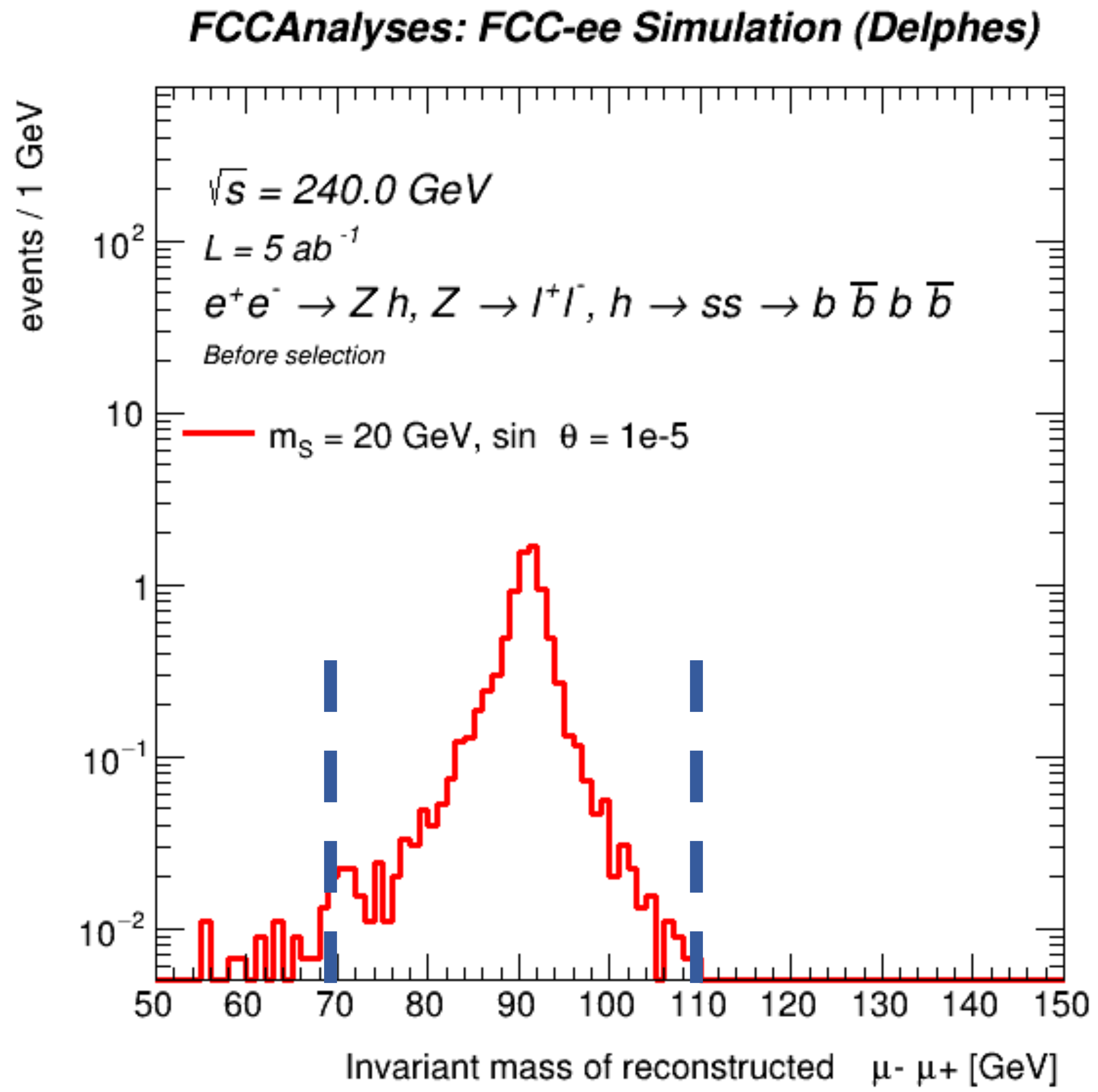
Preliminary vertex selection & event selection

- Considered backgrounds: $e^+e^- \rightarrow Z\,h$, $e^+e^- \rightarrow Z\,Z$ and $e^+e^- \rightarrow W\,W$
- Using 100.000 generated raw events from the centrally-produced samples in the spring2021 production campaign

Type	Parameter	Value
Track Selection	Min p_T	1 GeV
	Min $\lvert d_0 \rvert$	2 mm
Vertex Reconstruction	V^0 rejection	True
	Max χ^2	9
	Max M_{inv}	40 GeV
	Max χ^2 added track	5
	Vertex merging	False
Vertex Selection	Min r_{DV-PV}	4 mm
	Max r_{DV-PV}	2000 mm
	Min $M_{charged}$	1 GeV

Distance of DVs from PV: Required to be in the tracker volume and outside the innermost region to exclude heavy-flavour decays

Charged invariant mass at DV: To remove background DVs



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

n_DVs: For each final state b of one of the scalars

Sensitivity analysis with reconstructed quantities

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

- Given zero background, signal points with at least 3 expected events can be excluded to CL 95%
- More truth studies needs to be done to determine reconstruction efficiency and fake vertex rate!

Ongoing and future work

- Truth matching of DVs to determine reconstruction efficiency, fake vertex rate, etc.

- Rerun the event selection for the background processes to decrease the statistical uncertainties, use all the available centrally-produced samples:
  - 10.000.000 events each for WW and Zh, and 60.000.000 events for ZZ

- Further optimize the DV reconstruction for the FCC-ee

- Lots of room for newcomers in the FCC-ee LLP group – please join the pursuit!
  - Mailing list: <LLP-FCCee-informal@cern.ch>

Summary

- A first simulation and analysis of long-lived scalars from exotic Higgs decays within the FCCAnalyses framework has been done and is ongoing!
- Generated the signal process $e^+e^- \rightarrow Z\,h$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
  - At $\sqrt{s} = 240\ GeV$ and $L = 5\ ab^{-1}$
  - Signal points: m_s = 20 GeV and m_s = 60 GeV with lifetimes of order 1 mm - 10 m

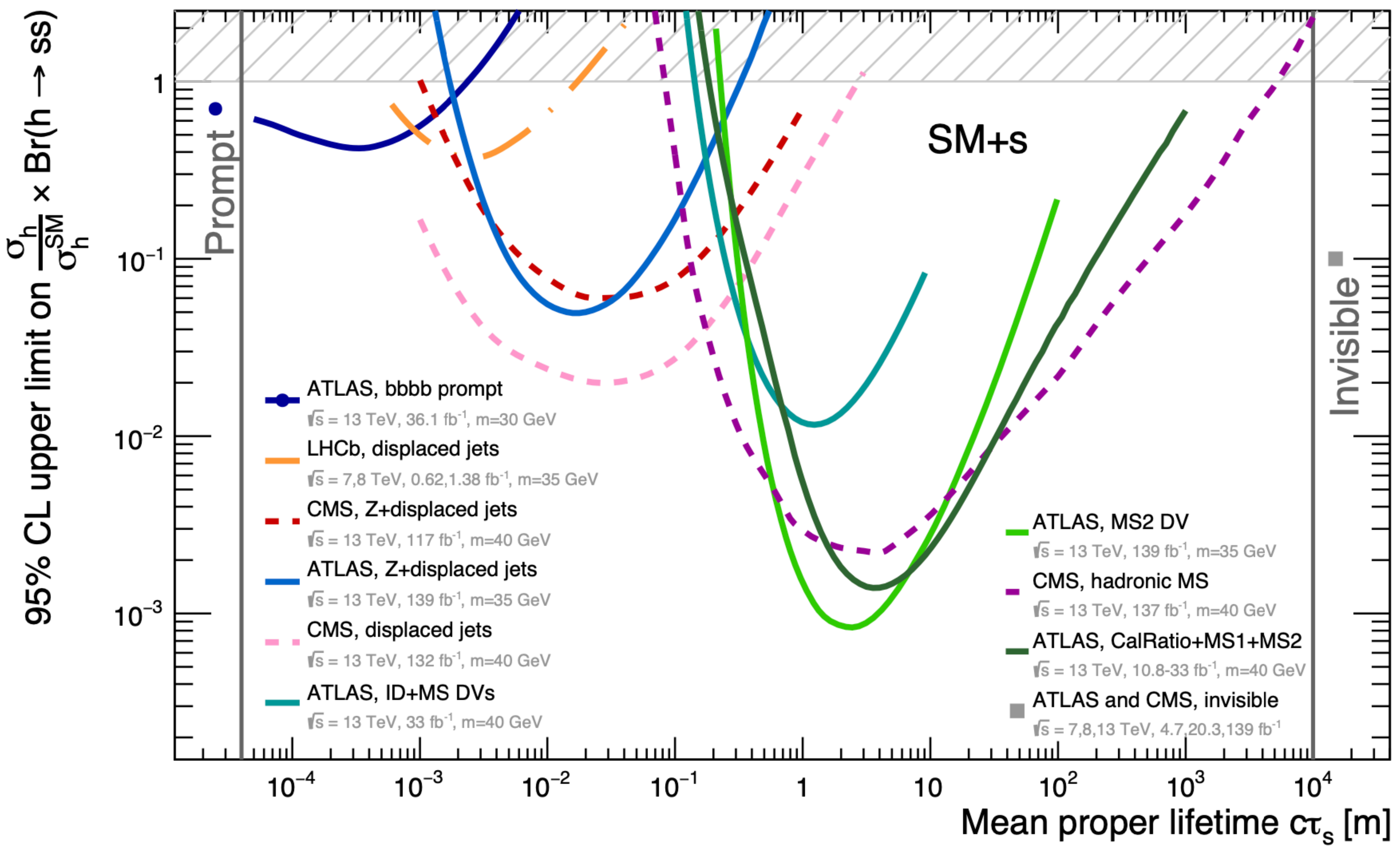
- Two options of reconstruction of the DVs, using the LCFI+ SV finder with:
  - Custom track selection: pT > 1 GeV and |d0| > 2 mm
  - Track selection + vertex merging → needs more studies to be implemented

- A first sensitivity analysis
  - With vertex selection: M_{inv} > 1 GeV and 4 mm < r < 2000 mm
  - And event selection: tagging the Z boson and requiring at least 2 DVs
  - Backgrounds efficiently suppressed to zero!
  - Sensitivity for all signal samples except the shortest and longest lifetime!

Backup slides

Summary of current constraints from LHC

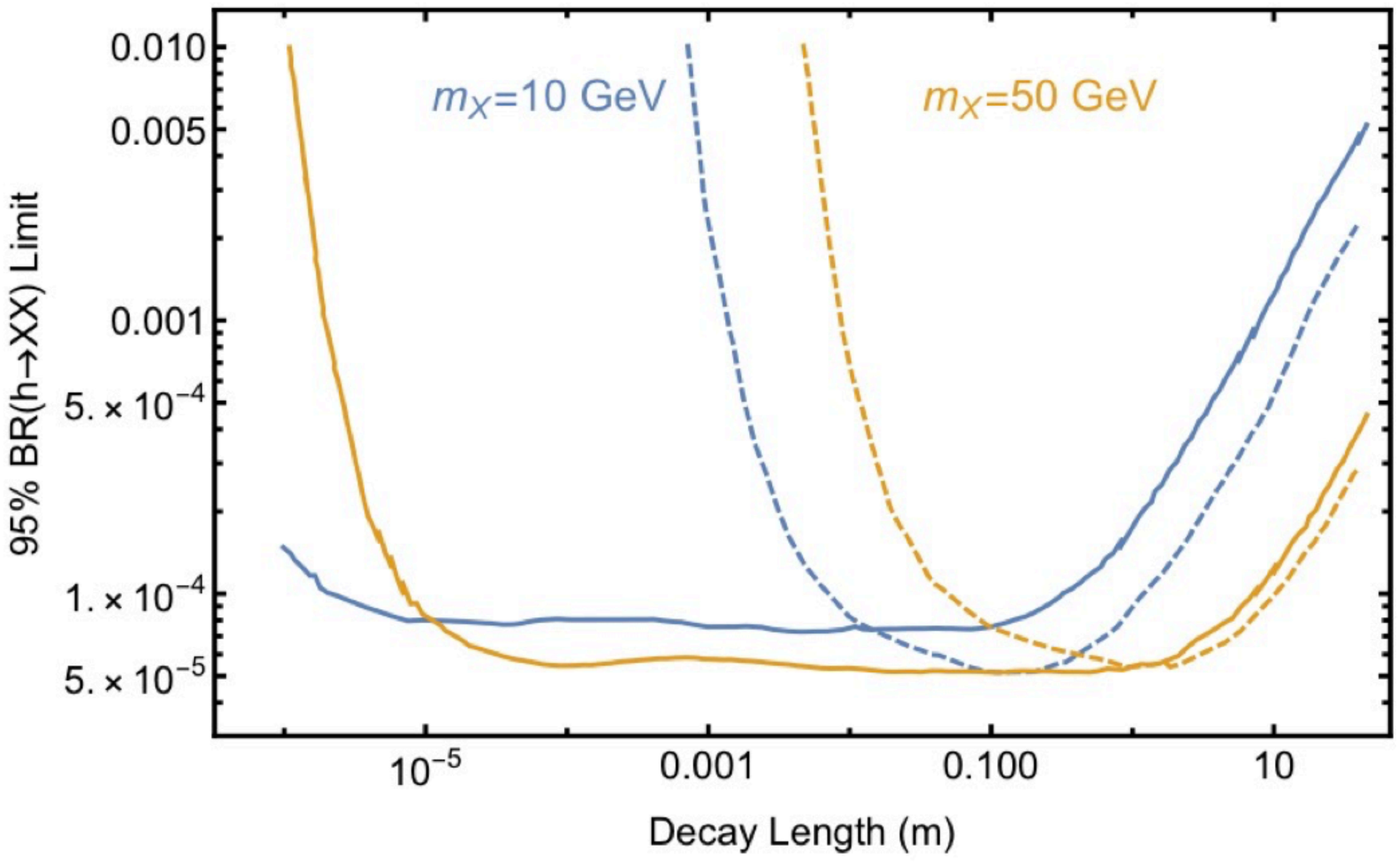
Review: Exotic Higgs Decays [arXiv:2111.12751]



- 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 $(\sigma h/\sigma h^{SM}) \times Br(h \to ss)$ 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
- ”The HL-LHC is expected to produce a large sample of $O(10^8)$ Higgs bosons”
- ”The lower background environments of lepton colliders, together with detectors constructed with BSM LLP signatures in mind, can potentially make LLP searches at Higgs factories competitive with those at the LHC at the shorter LLP lifetimes where LHC backgrounds are higher, or in other scenarios where the event presents a particular trigger or background rejection challenge at the LHC”

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



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 larger dashes are the ‘long lifetime’ analysis and the smaller dashes are the ‘large mass’ analysis
- Realistic tracker-based search strategy involving the reconstruction of displaced secondary vertices and the imposition of selection cuts appropriate for eliminating the largest irreducible backgrounds.

Efficiencies

	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]	Cross Section σ [pb]	Branching Ratio BR($h \to ss$)
20	1×10^{-5}	3.4	8.858×10^{-6}	6.27×10^{-4}
20	1×10^{-6}	341.7	8.858×10^{-6}	6.27×10^{-4}
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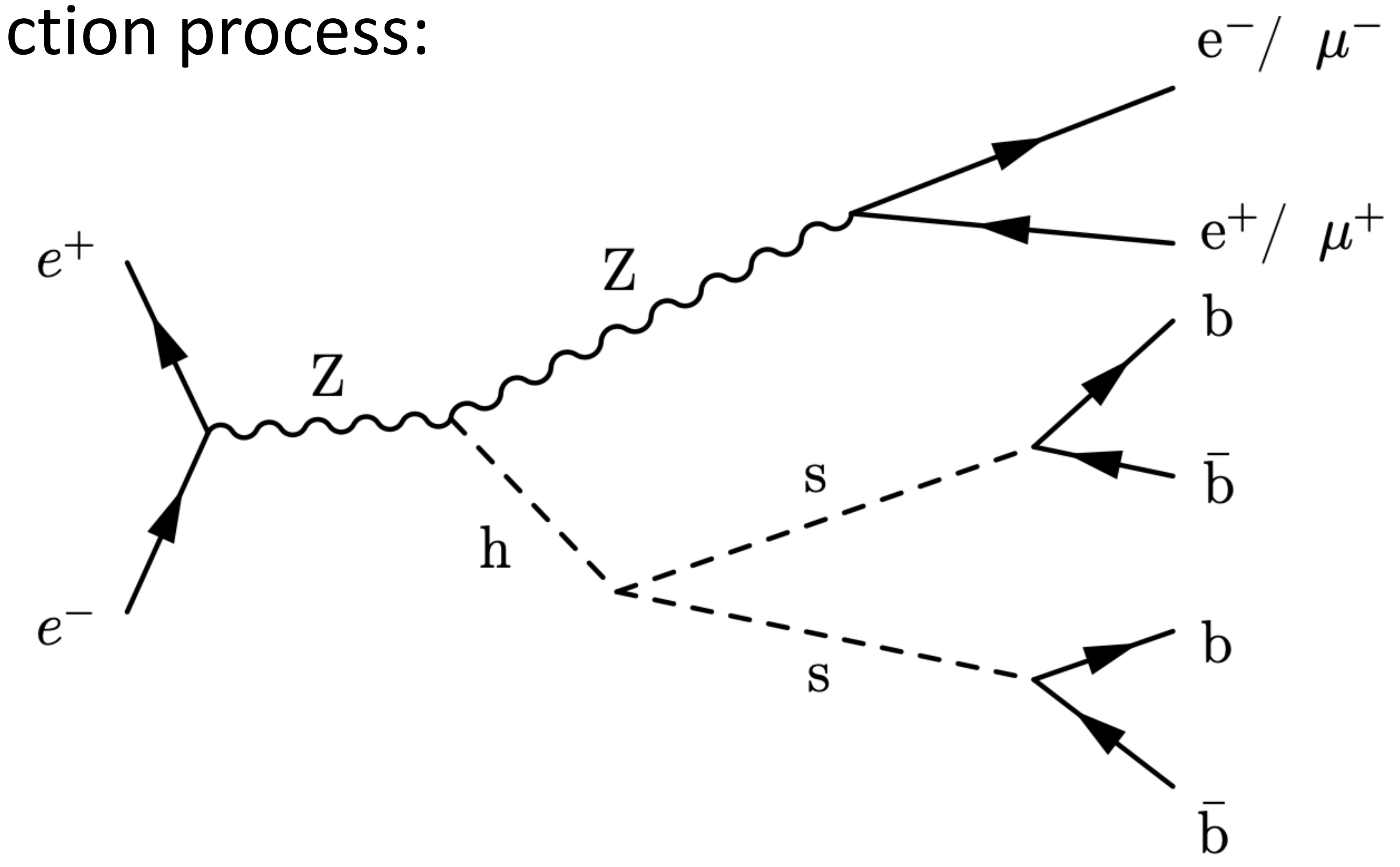
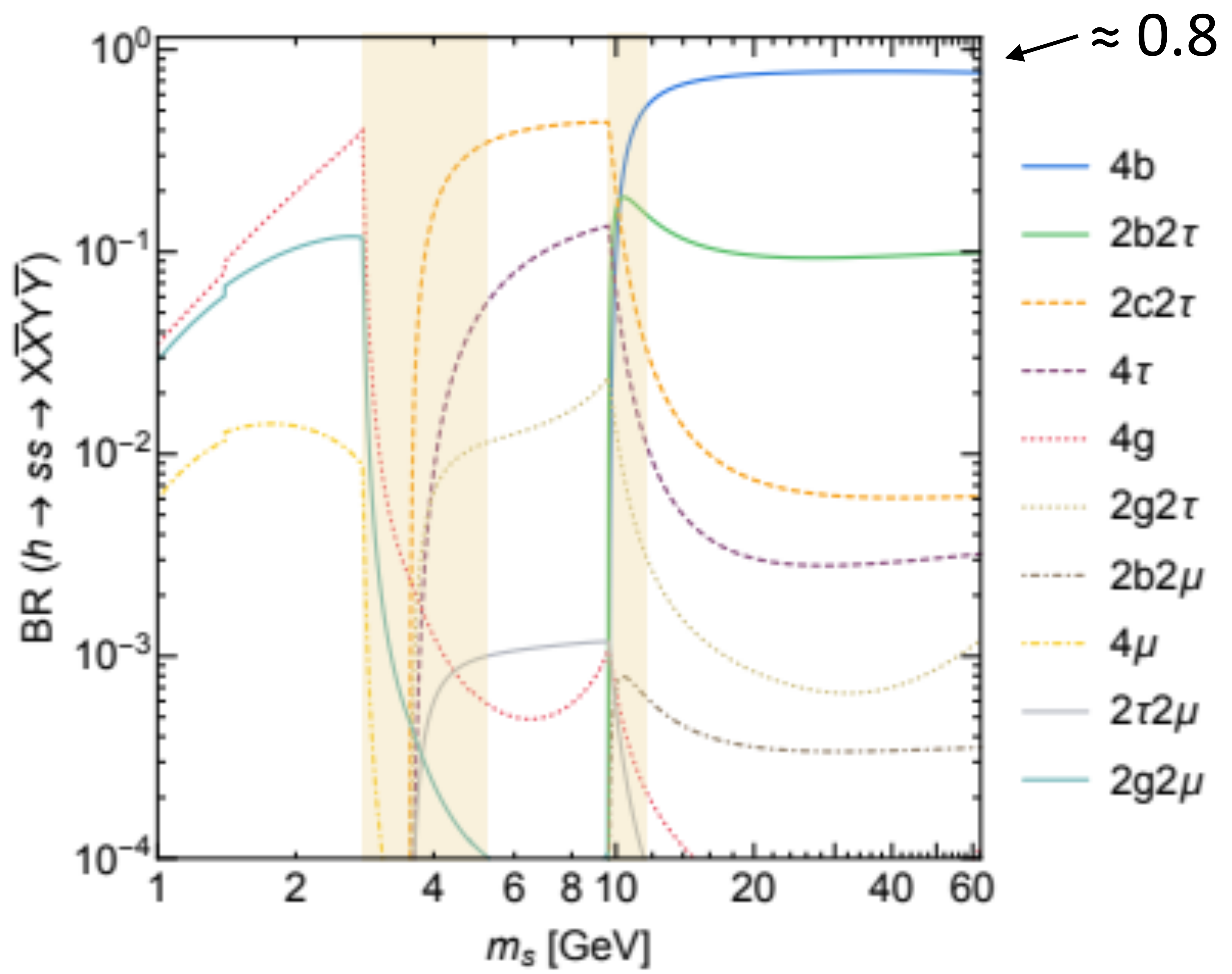
60	1×10^{-5}	0.9	2.618×10^{-6}	1.85×10^{-4}
60	1×10^{-6}	87.7	2.618×10^{-6}	1.85×10^{-4}
60	1×10^{-7}	8769.1	2.618×10^{-6}	1.85×10^{-4}

	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

Possible production and decay at FCC-ee

Production process:

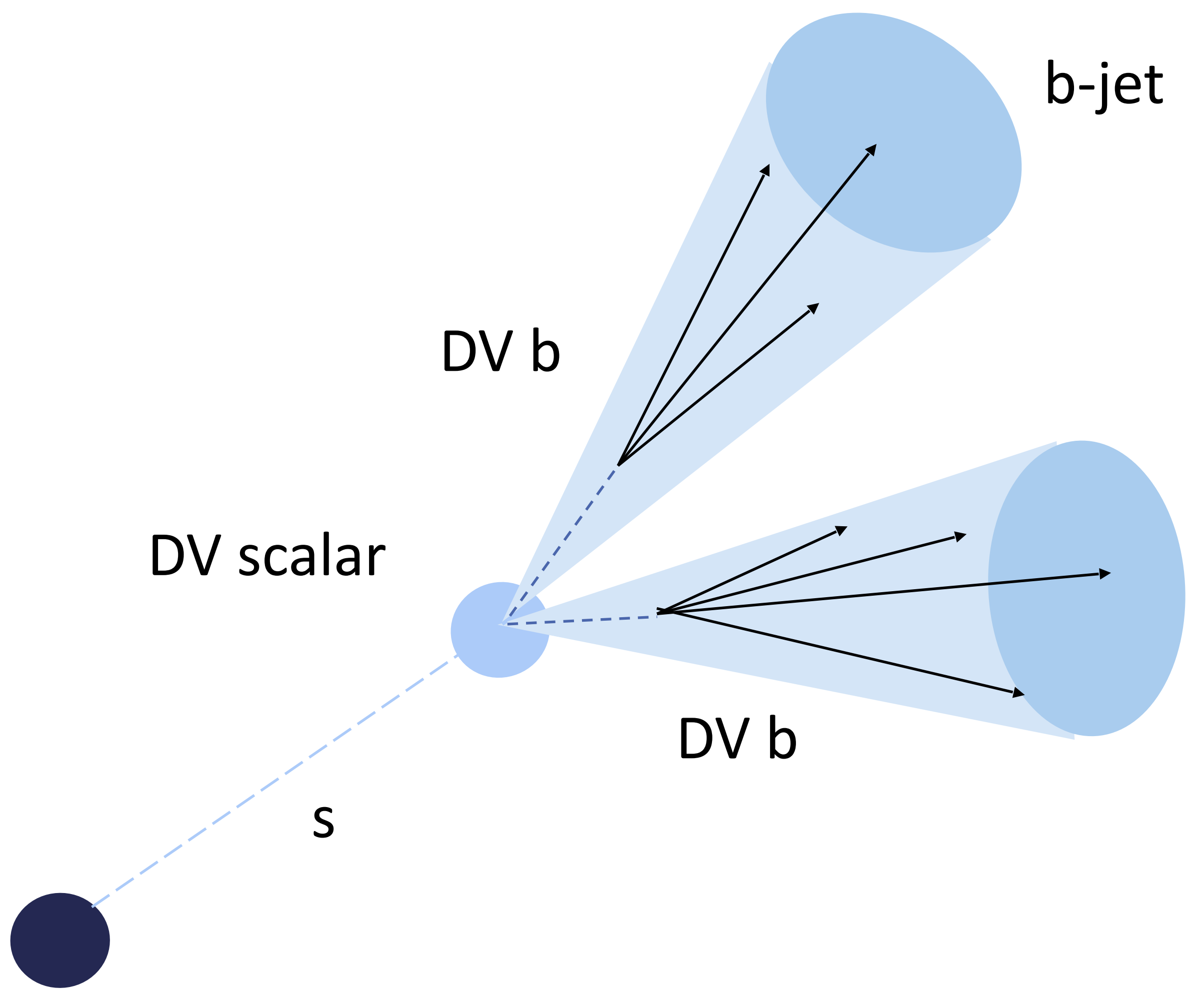




arXiv:1312.4992

- Higgs produced at ZH-stage of FCC-ee: $\sqrt{s} = 240\ GeV$ and $L = 5\ ab^{-1}$
- Signal process: $e^+e^- \rightarrow Z\,h$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$

DV reconstruction performance



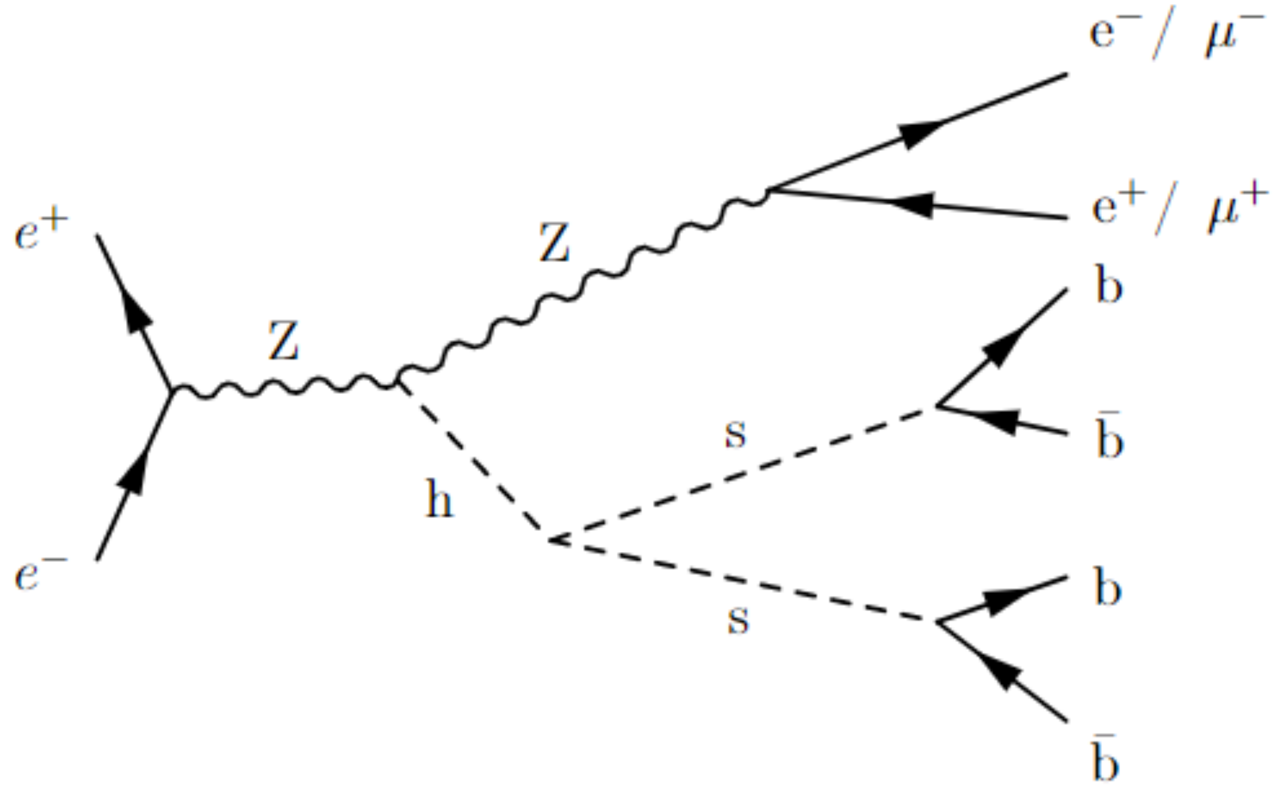
Example event with only track selection:

Vertex	x [mm]	y [mm]	z [mm]
MC scalar 1	-349.00	-22.47	-870.76
MC scalar 2	-189.32	220.82	546.42
DVs	-349.70 $\pm$ 0.106	-21.76 $\pm$ 0.040	-874.69 $\pm$ 0.415
	-349.03 $\pm$ 0.095	-23.93 $\pm$ 0.099	-873.98 $\pm$ 0.514
	-190.76 $\pm$ 0.021	221.69 $\pm$ 0.010	550.38 $\pm$ 0.040
	-190.17 $\pm$ 0.016	223.24 $\pm$ 0.069	549.43 $\pm$ 0.072

Two DVs close to each truth scalar decay position

Example event with track selection + merging:

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



Fake vertices? More truth studies needed!

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 cross section with

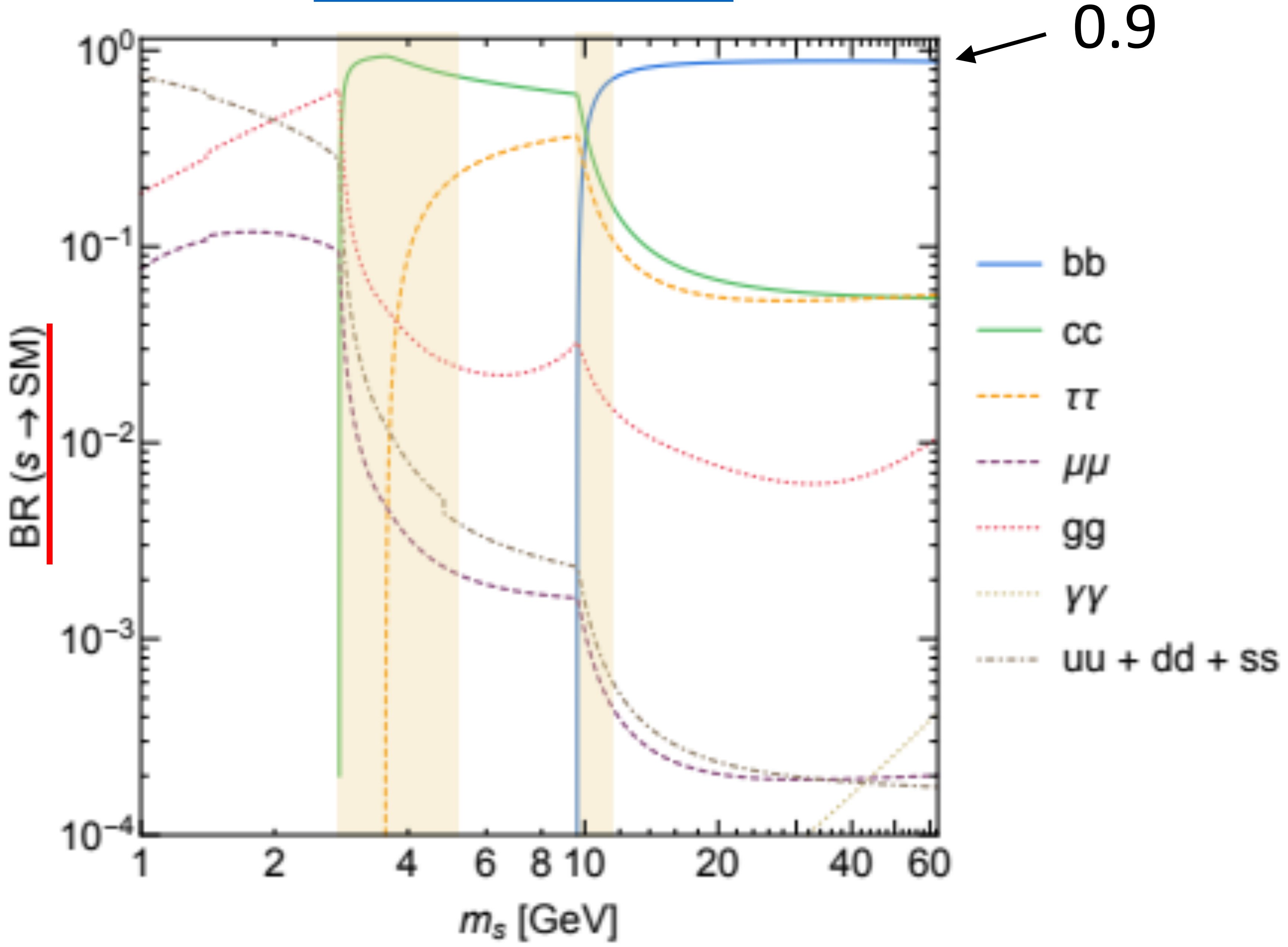
$$\sigma = \sigma_{ZH} \times BR(h \to ss) \times BR(s \to b\bar{b})^2 \times BR(Z \to l^+l^-)$$

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

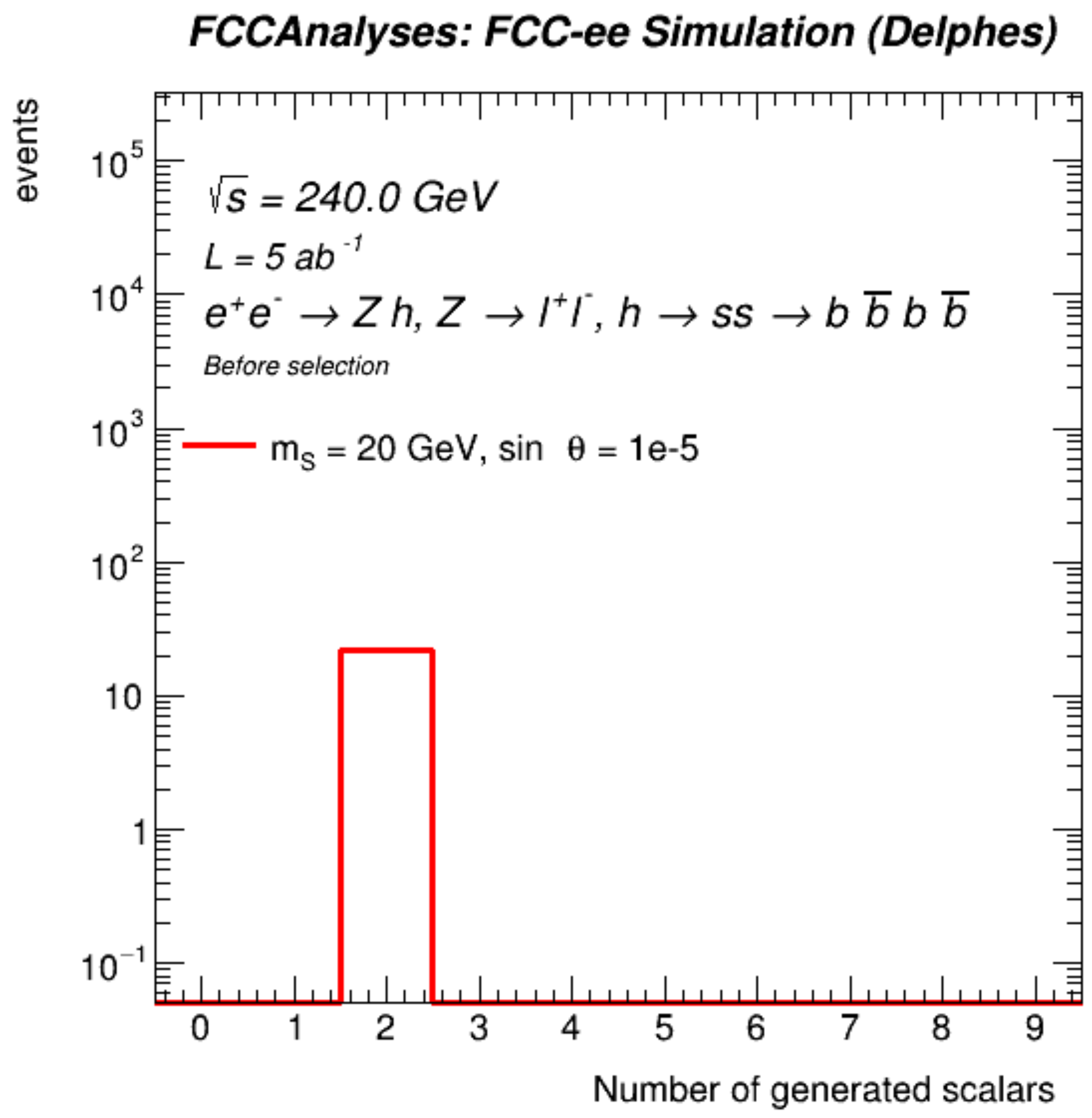
$$BR(h \to ss) = \frac{\kappa^2 v^2}{32\pi m_h \Gamma_h}\sqrt{1 - 4\frac{m_s^2}{m_h^2}}$$

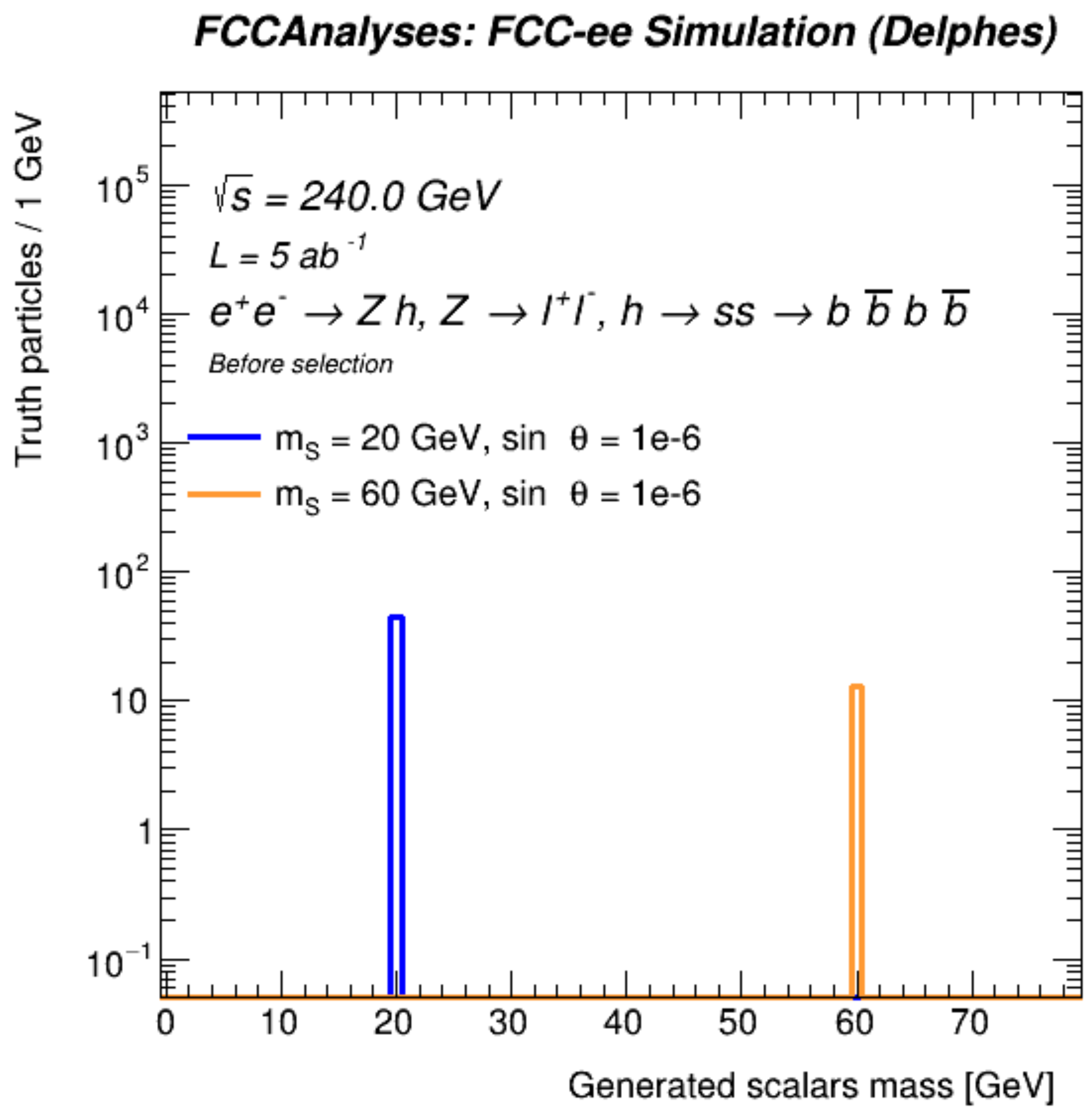
- We set κ = 1e-3 s.t $BR(h \to ss) = O(10^{-4})$, lower than current constraints and within reach for FCC-ee shown by previous studies, see backup
- $\sigma_{ZH} = 0.259 \pm 9.972$e-5 pb, from MG output
- $BR(s \to b\bar{b})^2 = 0.9^2$, from plot

arXiv:1312.4992



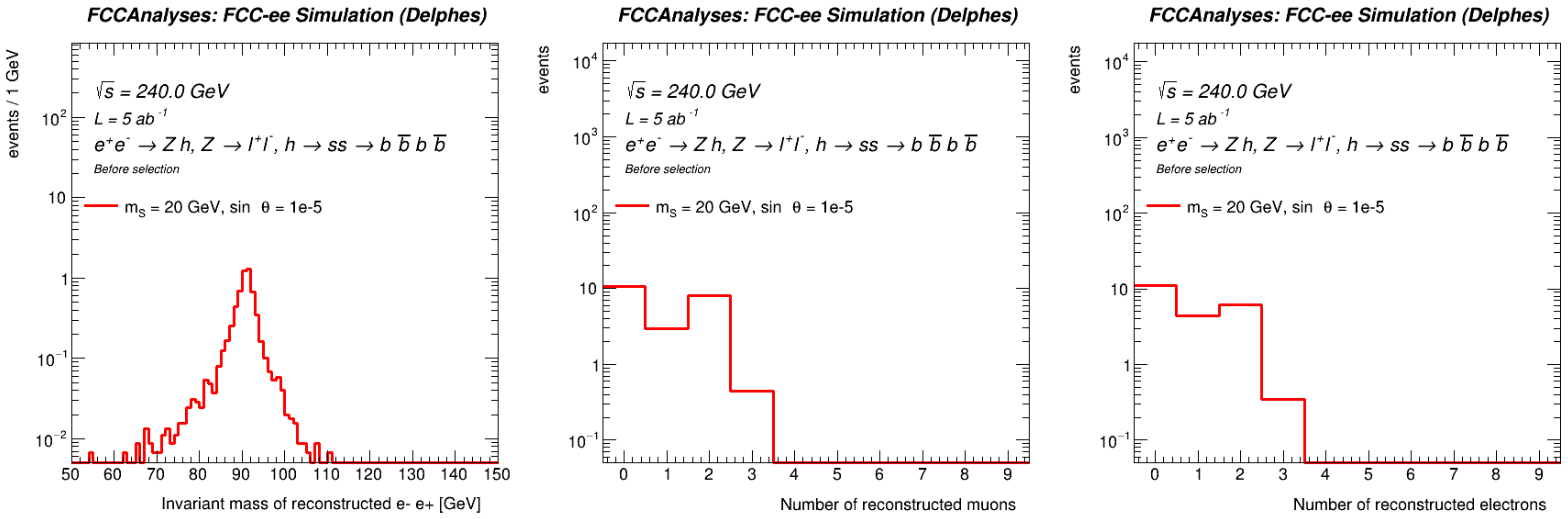
Generated kinematics





- Generates 2 scalars for each event
- Generates the two different scalar masses properly, m_s = 20 GeV and m_s = 60 GeV

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



Vertex reconstruction

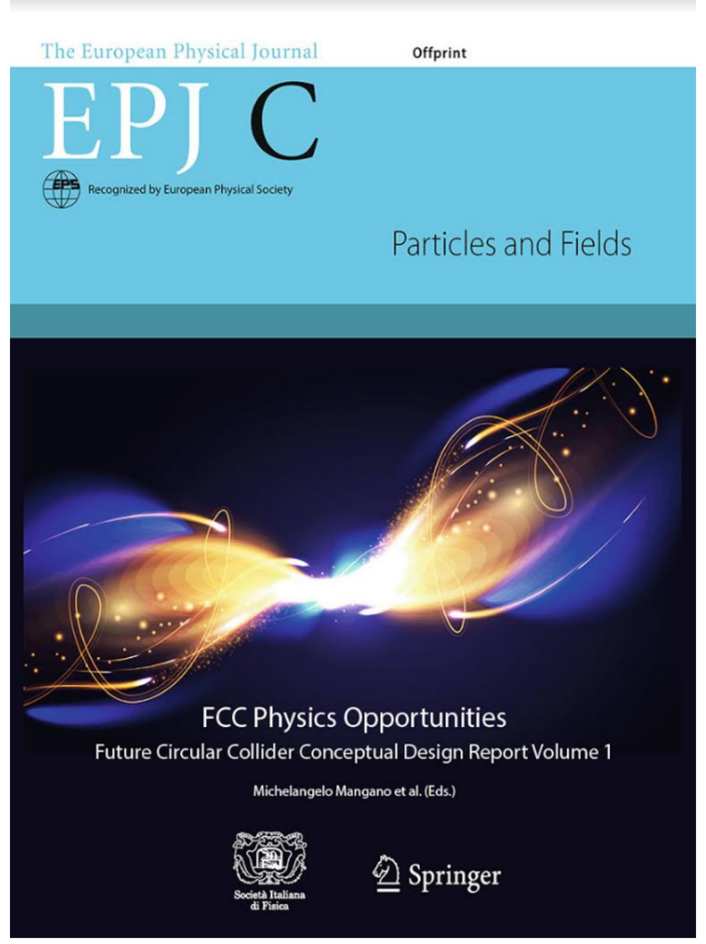
- More details in thesis: DiVA
- LCFIPlus: A Framework for Jet Analysis in Linear Collider Studies: arXiv:1506.08371
- FCCAnalyses framework vertex reconstruction: GitHub

FCC: Find out more

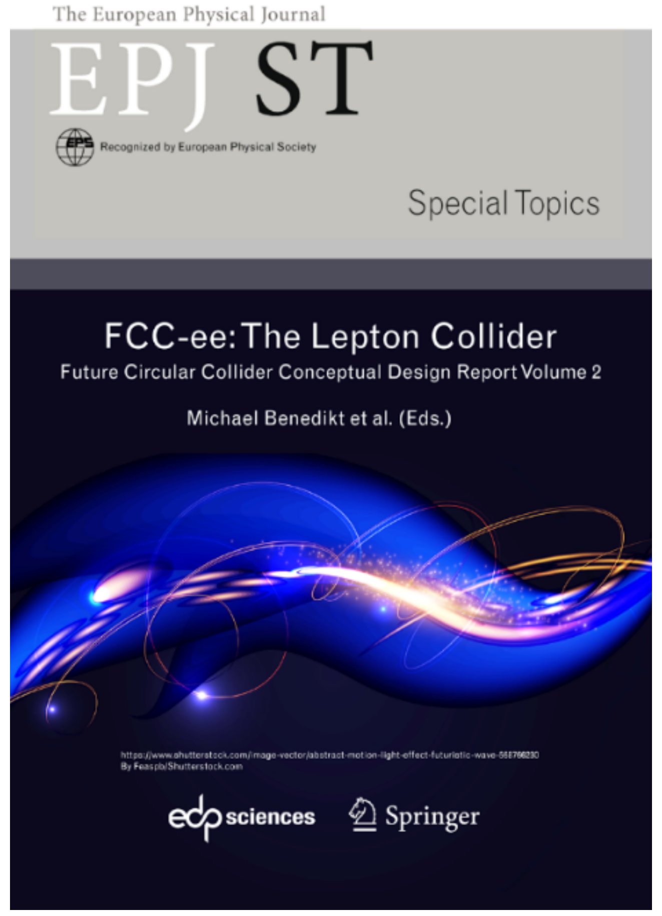
- Future Circular Collider - European Strategy Update Documents
  - (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity
  - arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders
  - arXiv:1901.02648
- Polarization and Centre-of-mass Energy Calibration at FCC-ee
  - arXiv:1909.12245
- FCC-ee Snowmass2021 LoIs: https://indico.cern.ch/event/951830/

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

4 CDR volumes published in EPJ

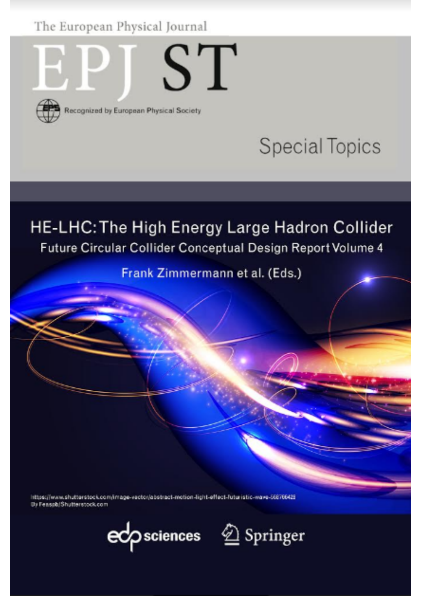


FCC Physics Opportunities



FCC-ee: The Lepton Collider

FCC-hh: The Hadron Collider



HE-LHC: The High Energy Large Hadron Collider

FCC-ee LLP group: past and ongoing work

- Several Masters student theses done or in progress:
- Sissel Bay Nielsen (University of Copenhagen, 2017)
- Rohini Sengupta (Uppsala University, 2021)
- Lovisa Rygaard (Uppsala University, 2022)
- Tanishq Sharma (University of Geneva, 2022)
- Magdalena Vande Voorde (Uppsala University, 2023)
- Dimitri Moulin (University of Geneva, 2023)
- … And more on the way!