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

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mainly based on my Master thesis with supervisor Giulia Ripellino, and Rebeca Gonzalez Suarez

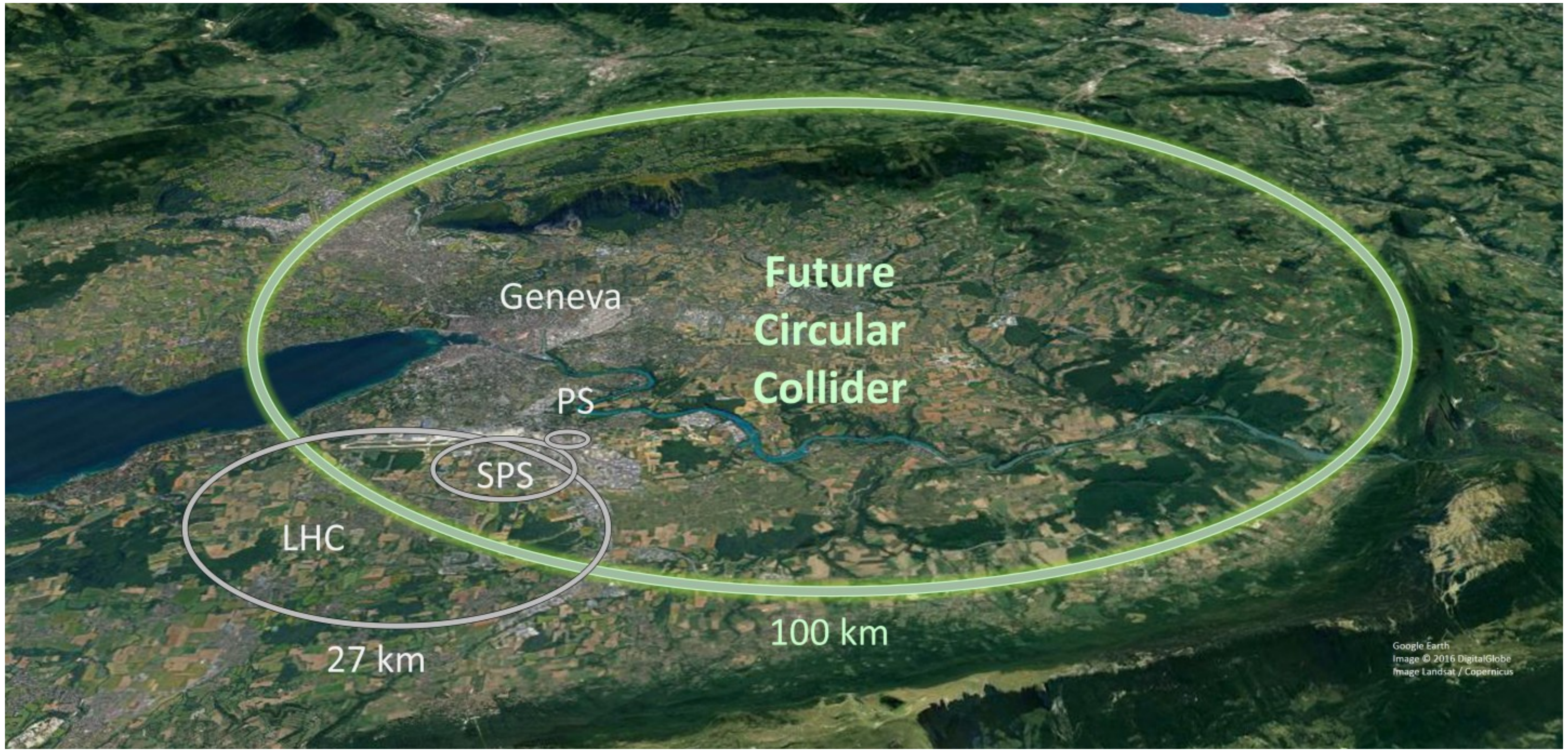
Partikeldagarna

2023-06-16

Now that you've been introduced to the great potential of FCC

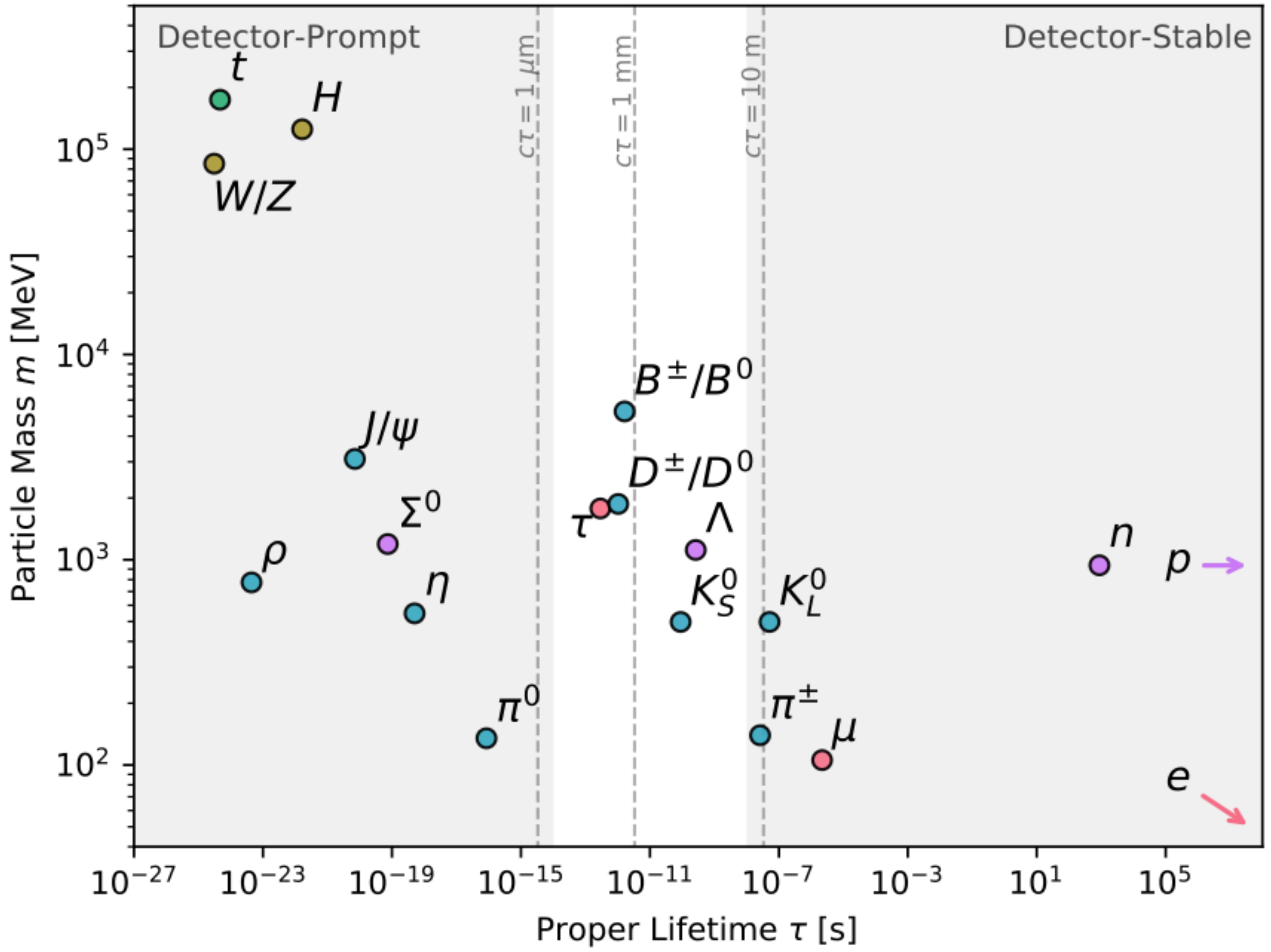
(From Rebeca's talk)

Let's look more into the good opportunities for long-lived particle searches at FCC-ee!



What are long-lived particles?

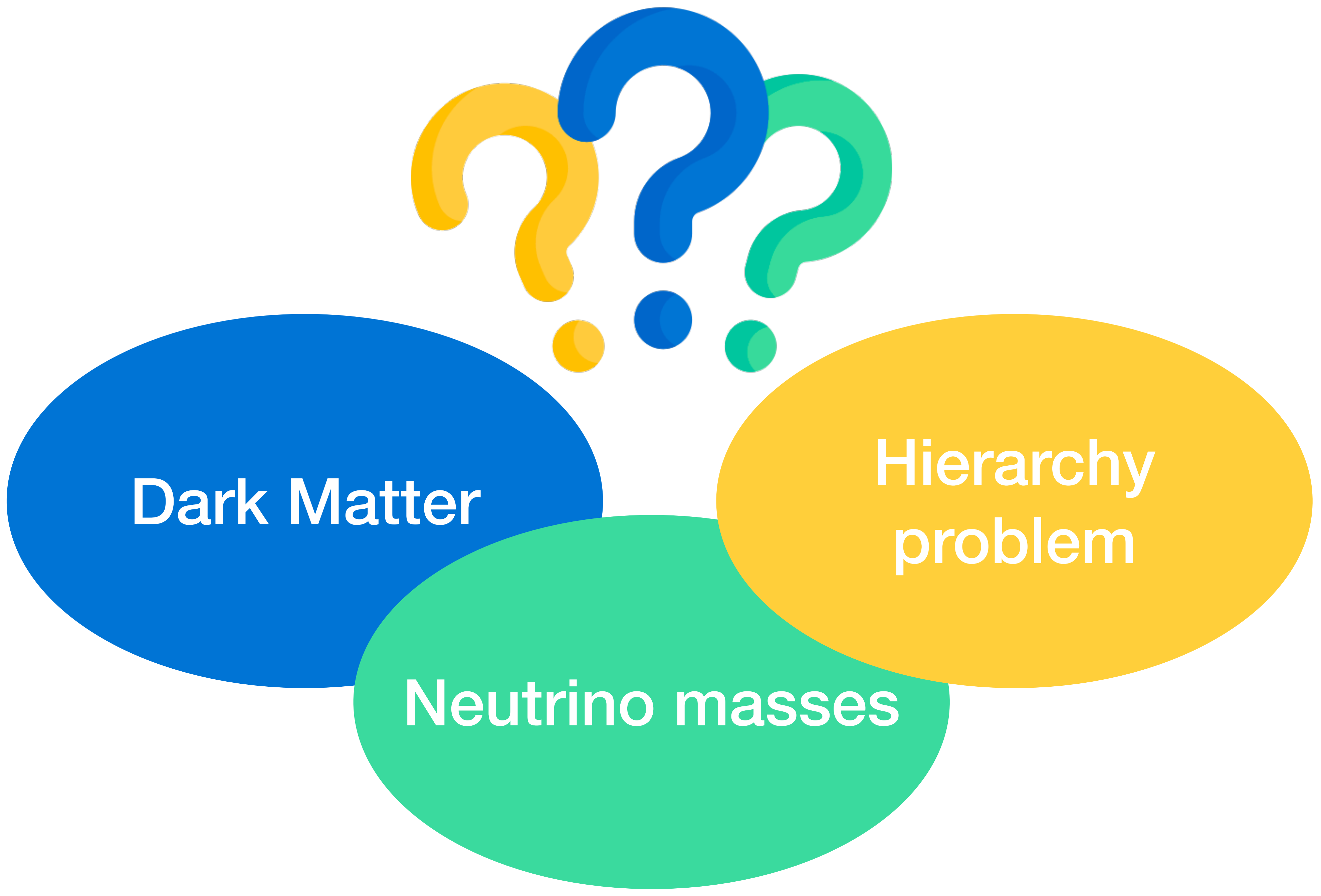
- The SM particles has a wide range of lifetimes, the same is expected for new particles
- Long lifetime can be achieved by e.g small couplings
- A **long-lived particle (LLP)** is defined as a **new particle** with **sufficient decay length resolvable in the detector**



arXiv:1810.1260

Why search for long-lived particles?

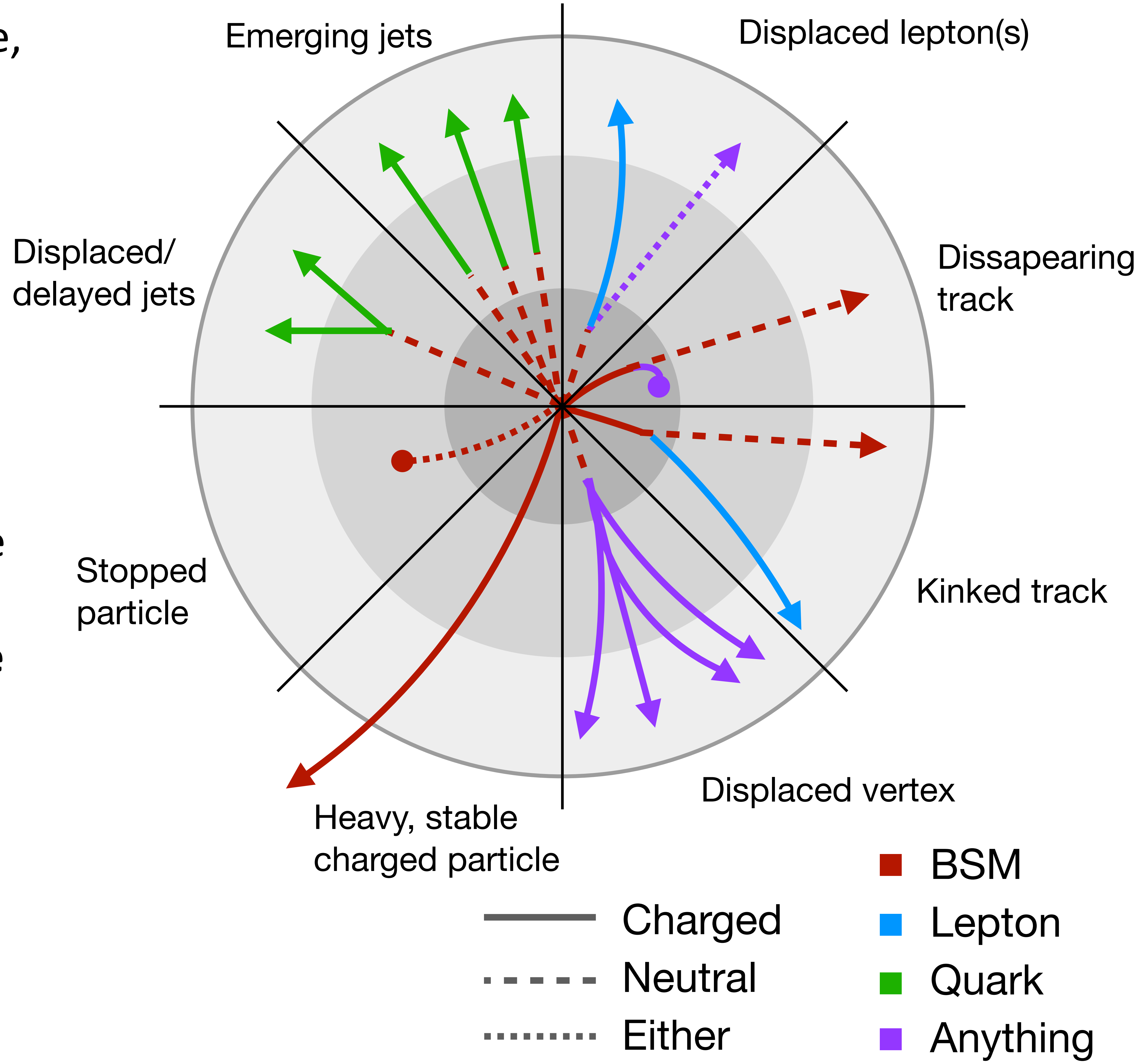
LLPs are well-motivated in several BSM models!



- 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 David Brunner (Summary of BSM searches in ATLAS) and Giulia Ripellino (Oseen Medal Award Presentation) for an ATLAS search

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



Let’s search for LLPs at FCC-ee!

And possibly design the FCC-ee detectors with LLPs in mind

- The mission of the FCC-ee LLP group is to study experimental conditions and analysis techniques optimized for LLP searches at FCC-ee
- Following a Snowmass LoI, a Snowmass white paper for LLP searches at FCC-ee was published in Front. Phys. 10:967881 (2022)
- Initial studies has motivated further work, see talk at FCC week for a summary of recent activities
- 3 benchmark physics cases:
  - Heavy Neutral Leptons (HNLs)
  - Axion-like Particles (ALPs)
  - LLPs from exotic Higgs decays ← Topic of this talk!

Searches for long-lived particles at the future FCC-ee

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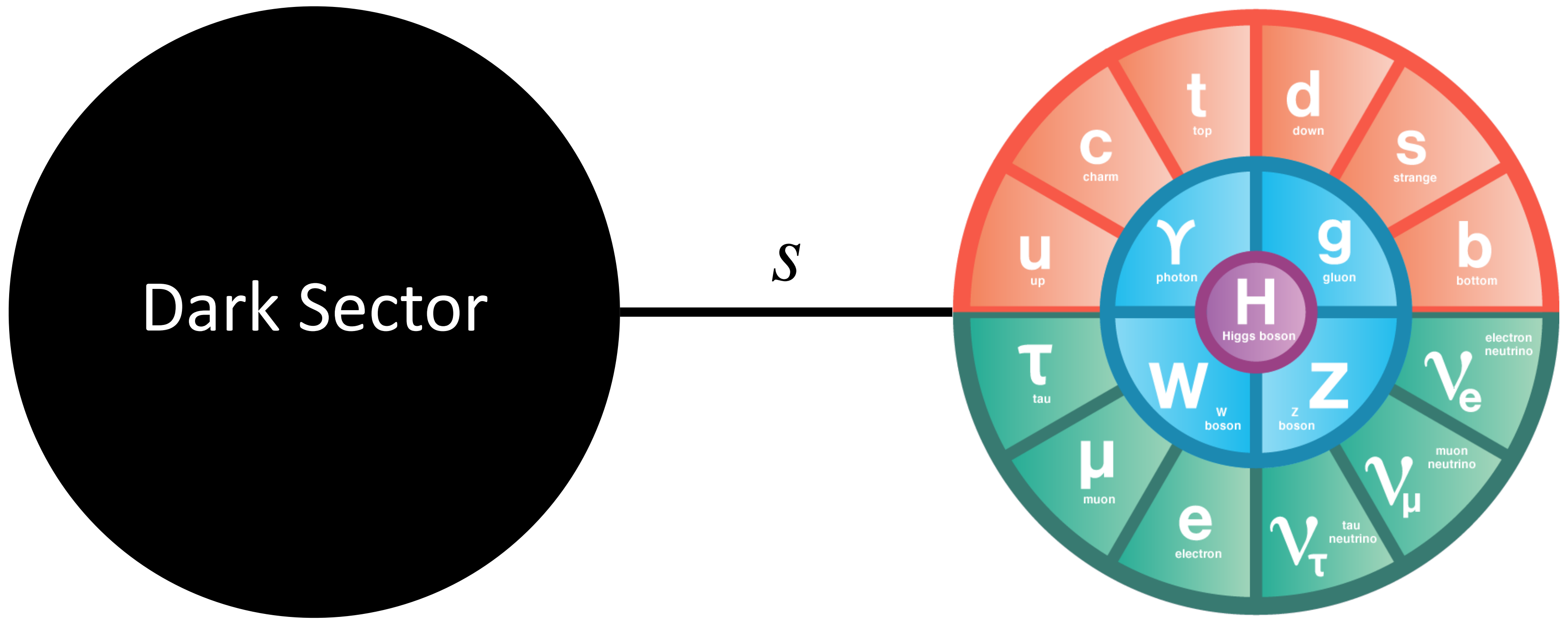
Long-lived scalars from exotic Higgs decays

- 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 can be a portal between the SM and a dark sector, motivated by e.g Dark Matter
- There are 3 important free parameters determining the phenomenology:
    - The Higgs-scalar coupling κ
    - The mass of the scalar m_S
    - The mixing angle sin θ
        - For sufficiently small mixing, the scalar can be long-lived
        - cτ ~ meters if θ < 1e-6 → **LLP signature**

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



κ: the Higgs-scalar coupling

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

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

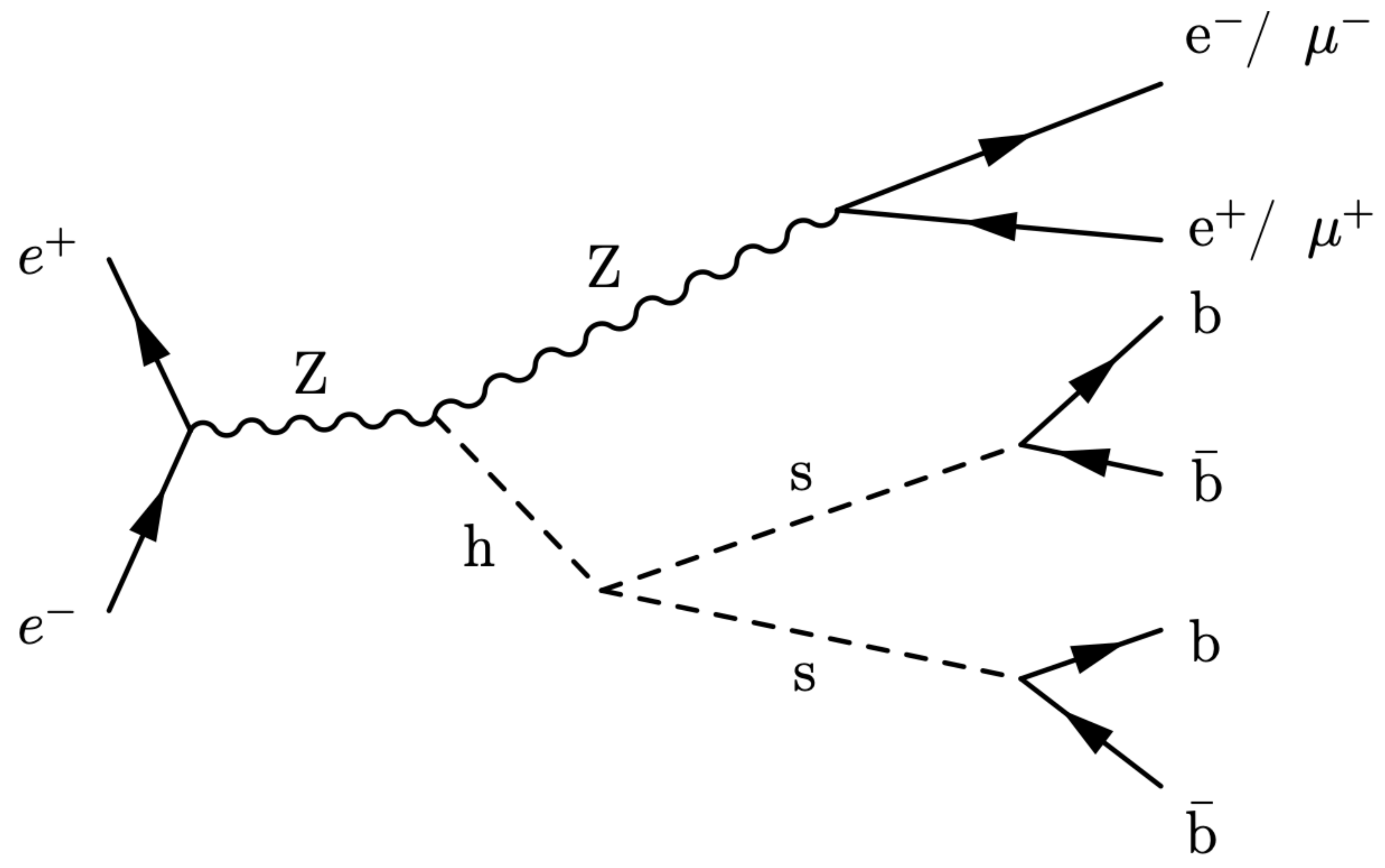
s: the scalar

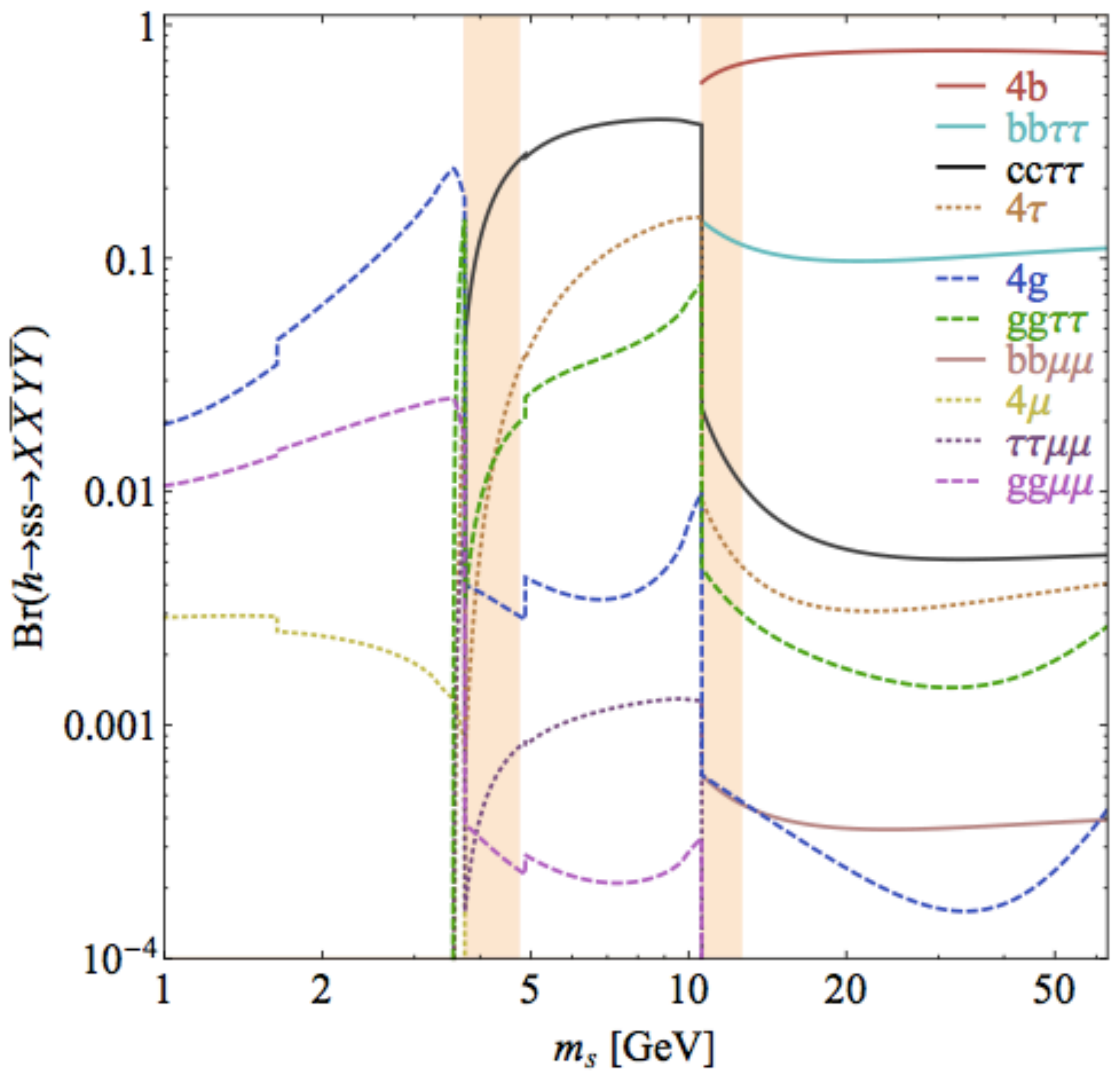
sin θ: the mixing angle

SM particle

Possible production and decay at FCC-ee

Production process:





$h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$

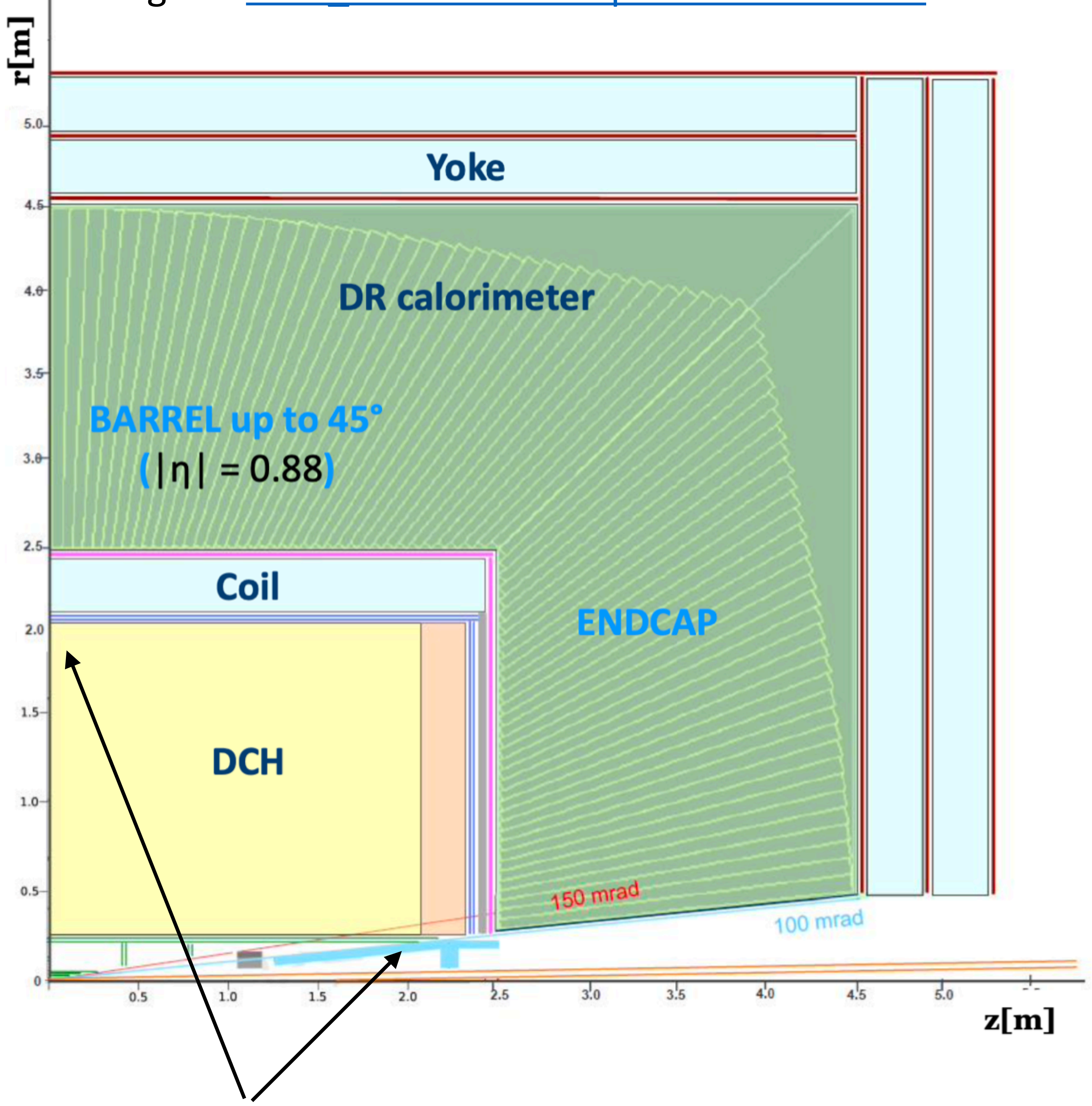
arXiv:1312.4992

- 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 $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$

IDEA: The detector design and simulation

- Proposed detector designs for FCC-ee are the CLD design, the IDEA design, and the Noble Liquid ECAL Base design
  - Opportunities for new creative detectors, e.g designed for LLP searches such as HECATE (arXiv:2011.01005)
- The **IDEA detector is used for our study** and it consists of e.g:
  - Silicon pixel vertex detector
  - An ultralight drift chamber (DCH)
  - A Dual Readout (DR) calorimeter
- The detector simulation of IDEA is done in DELPHES with a fast parametric simulation

Figure: IDEA_detector-concept-FCC-week-2022



DCHs outer radius = 2 meters

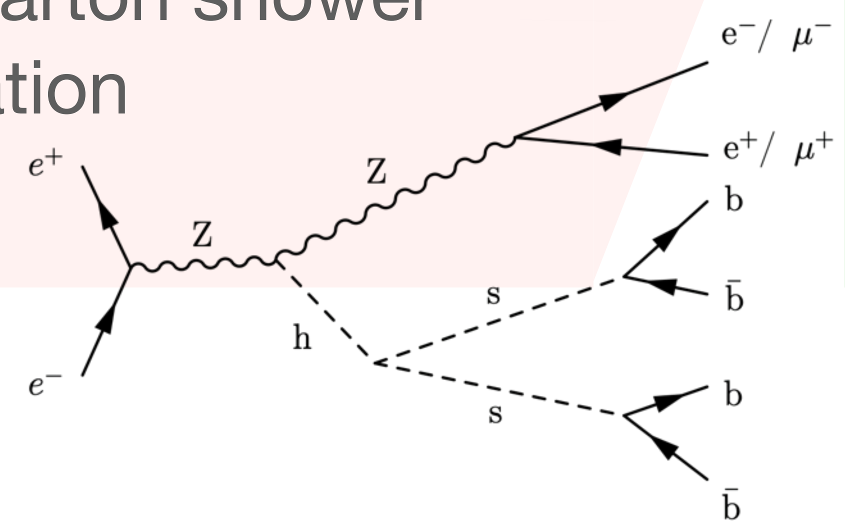
Simulation of the signal

- Generated signal samples: $e^+e^- \rightarrow Z\,h, Z \rightarrow e^+e^-$ or $\mu^+\mu^-, h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
  - Privately produced using MadGraph v3.4.1 + Pythia8 + DELPHES
  - With the MadGraph5 HAHM (arXiv:1312.4992, arXiv:1412.0018) and the spring2021 IDEA DELPHES card
- Parameters:
  - $\sqrt{s} = 240\ GeV$ and $L = 5\ ab^{-1}$
  - m_s = 20 GeV and m_s = 60 GeV
  - sin θ = 1e-5, 1e-6, 1e-7, corresponding to mean proper lifetimes cτ of O(1 mm – 10 m)
  - κ = 1e-3

Typical workflow

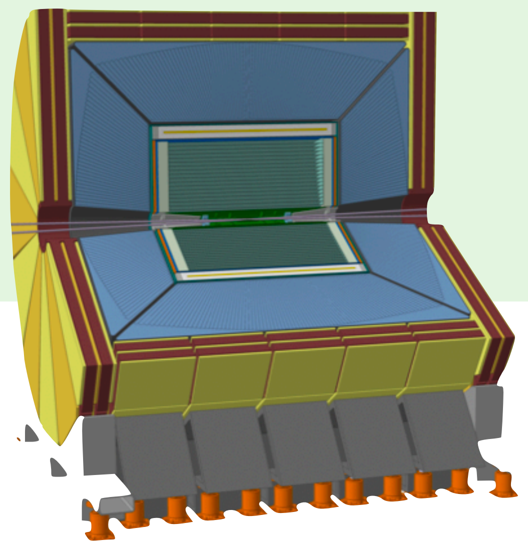
Sample generation of model

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



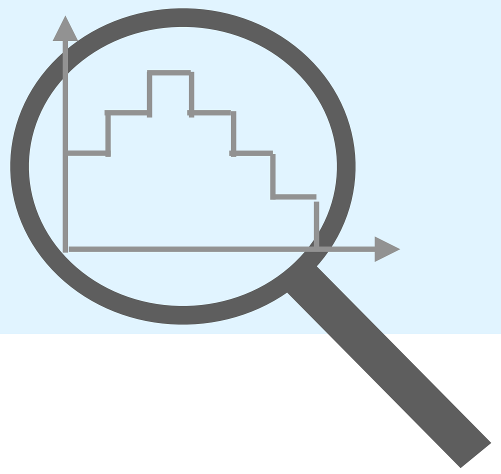
Parametrised detector simulation

- IDEA DELPHES card



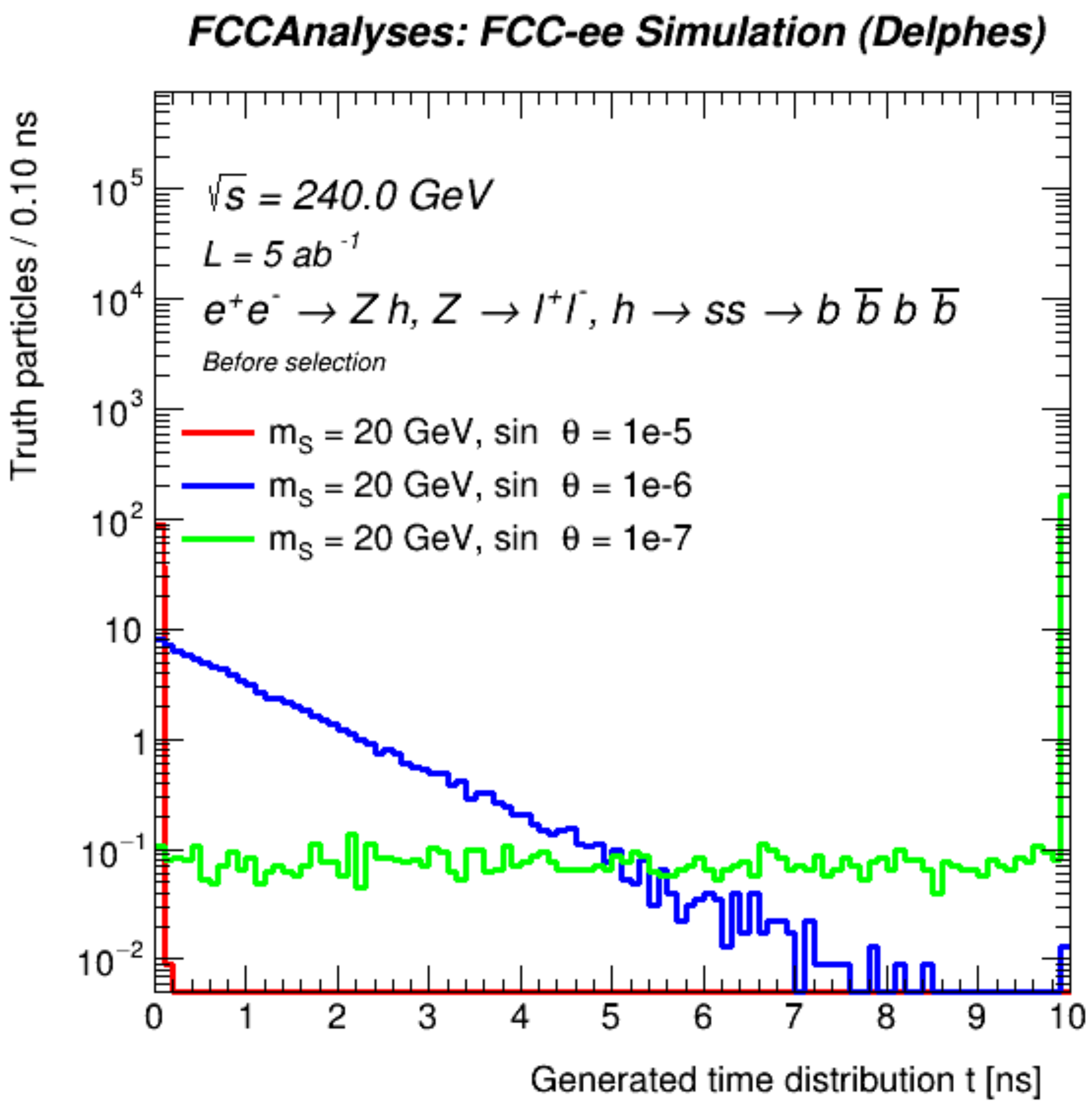
Analysis tools

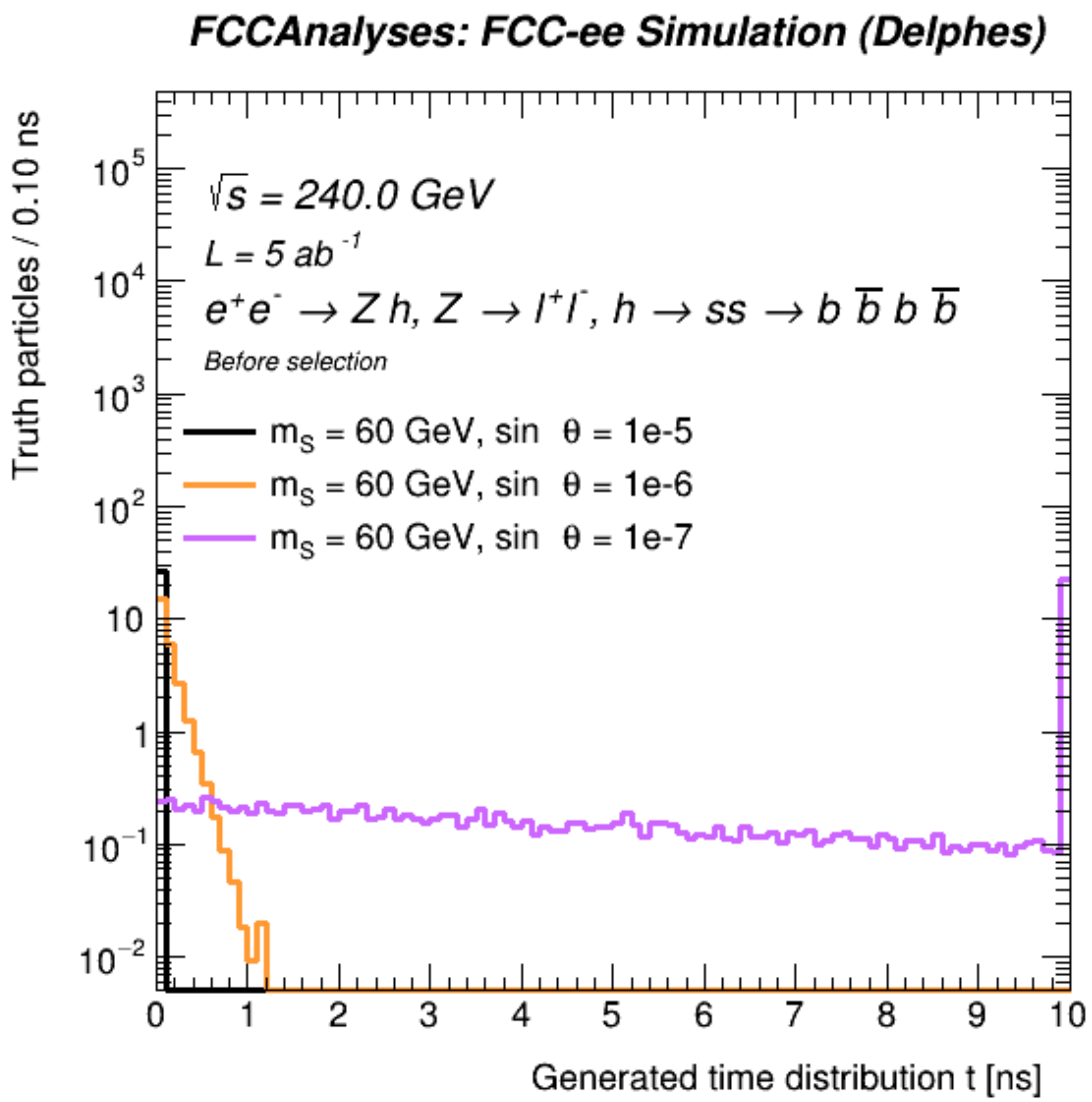
- FCCAnalyses framework



Sensitivity to studied model

Generated lifetime of the signal





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

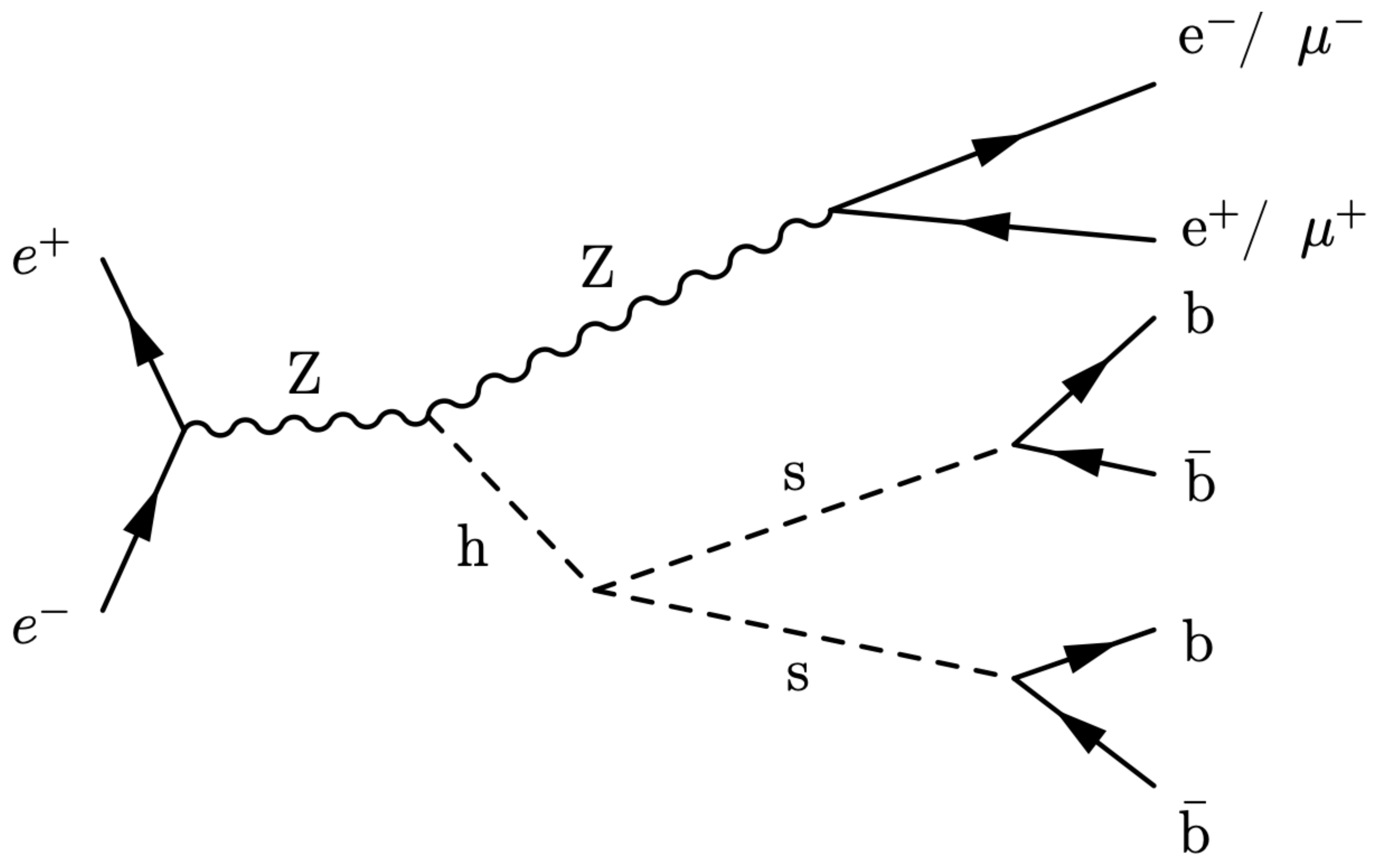
Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Mean proper lifetime $c\tau$ [mm]
20	1×10^{-5}	3.4
20	1×10^{-6}	341.7
20	1×10^{-7}	34167.0
60	1×10^{-5}	0.9
60	1×10^{-6}	87.7
60	1×10^{-7}	8769.1

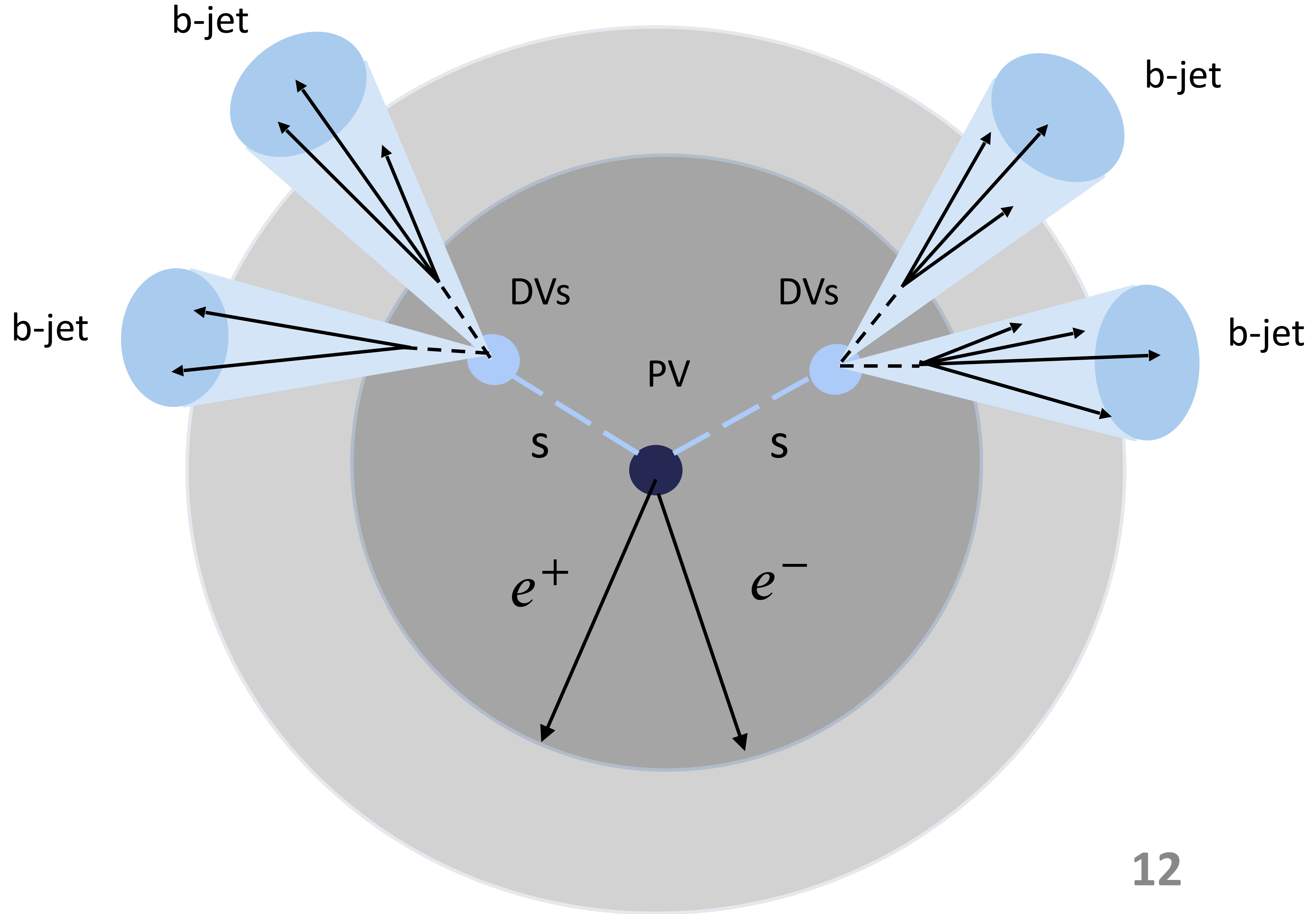
- Lifetime increases for smaller mixing angle, sin θ, and smaller masses, m_s, as expected

Reconstruction of the LLP-signal

Experimental signature:

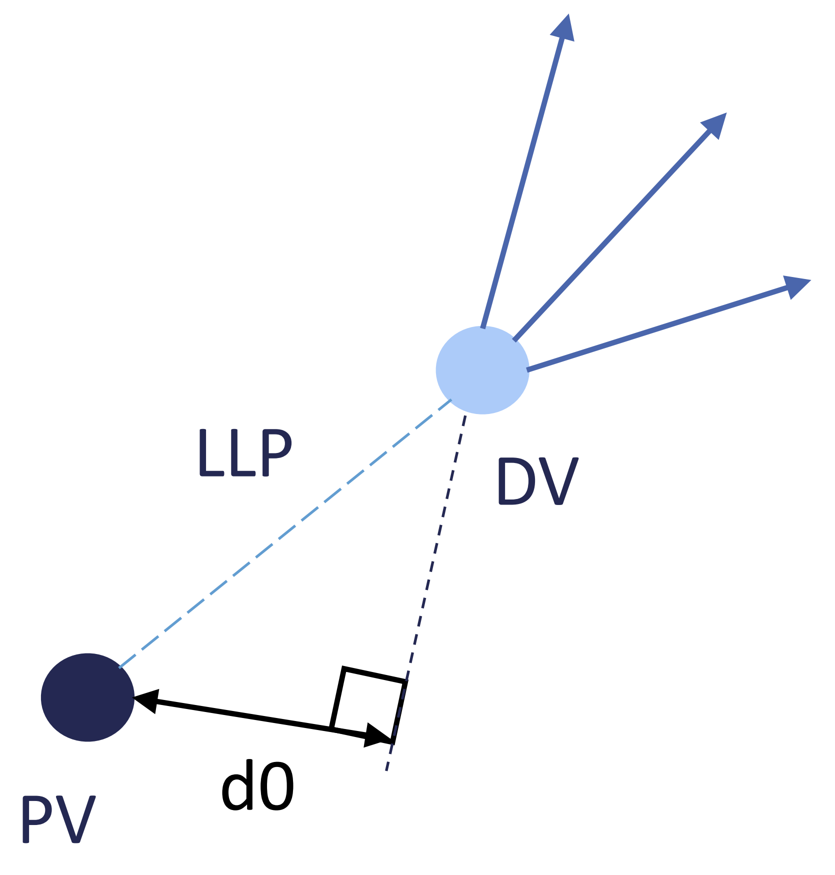
- Tag Z boson
  - Cut on the invariant mass reconstructed from the e^+e^- or $\mu^+\mu^-$ pairs
- Presence of Displaced Vertices (DVs) within the DCH
  - For a fully hadronic signature
  - **Not done for FCC-ee and IDEA before → need to develop a reconstruction procedure for DVs**

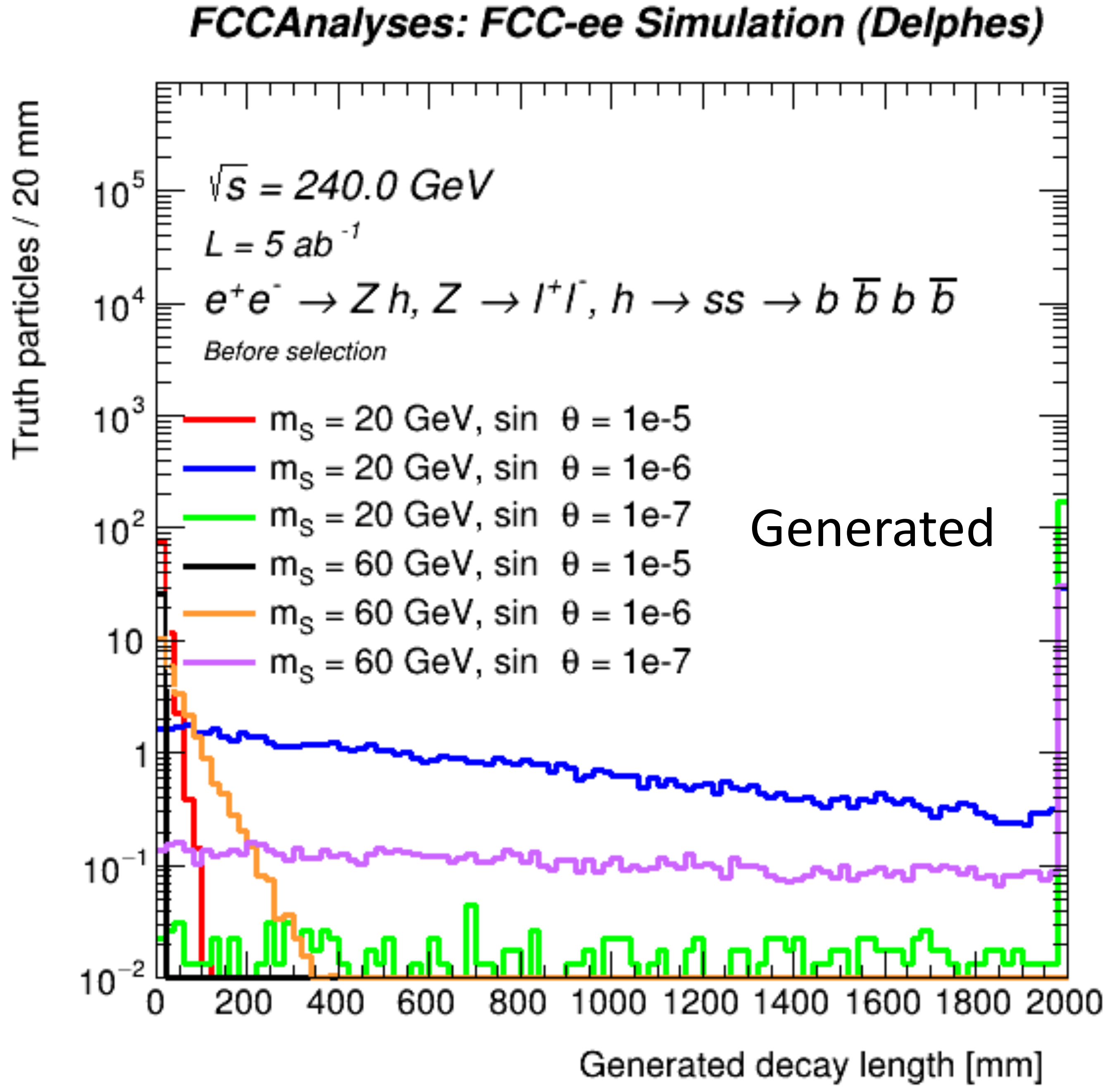


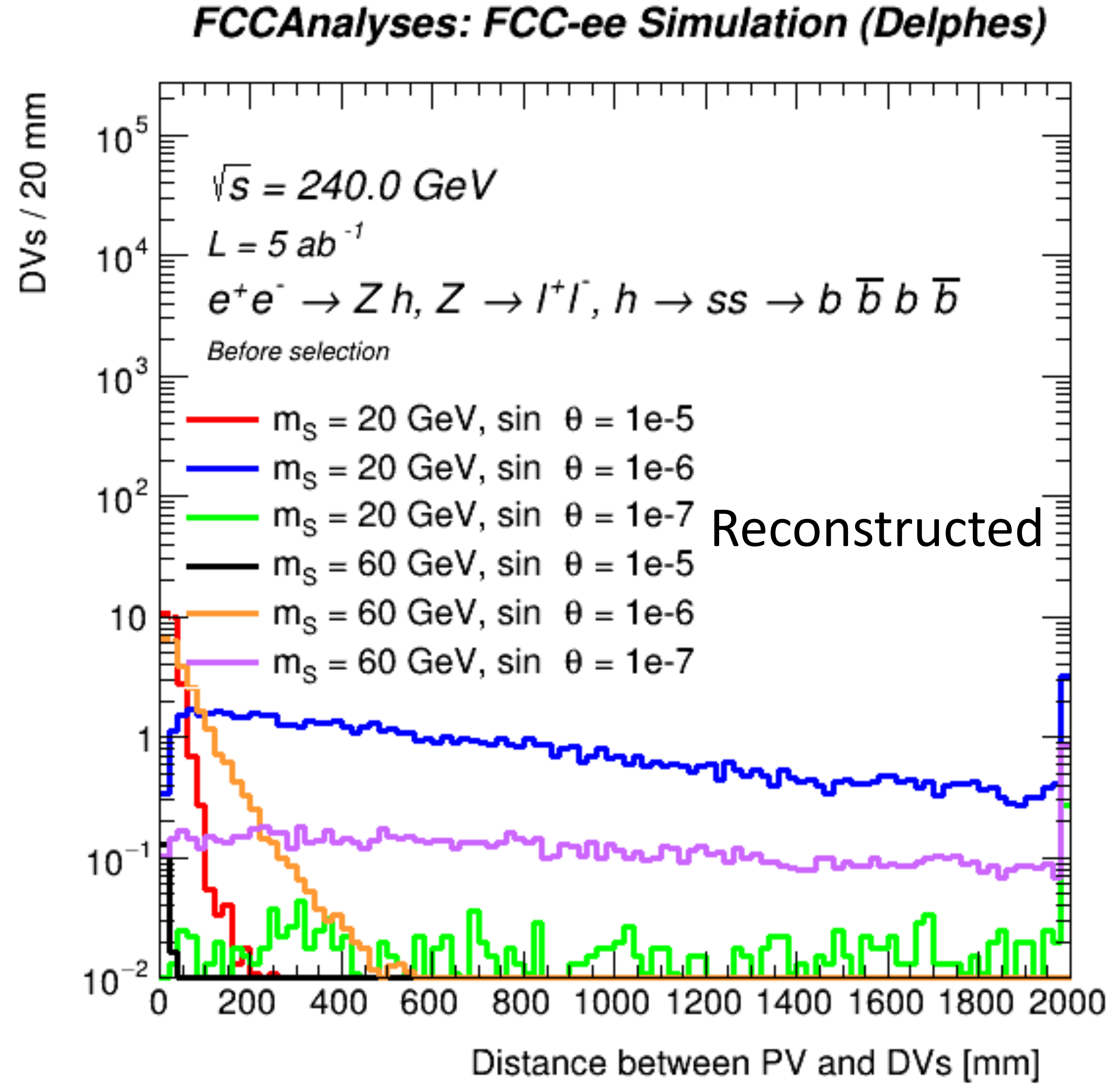


Displaced Vertex reconstruction

- Using current tools in the FCCAnalyses framework adapted to our model
  - Extra constraints and functions inspired by ATLAS DV reconstruction (cds)
- Secondary vertex finder of the LCFI+ algorithm (arXiv:1506.08371)
  - Designed for ILC/CLIC and primarily used for flavour-tagging jets
  - Added track selection: non-primary, pT > 1 GeV and |d0| > 2 mm
  - Added and tested vertex merging, but this was not applied further in the analysis





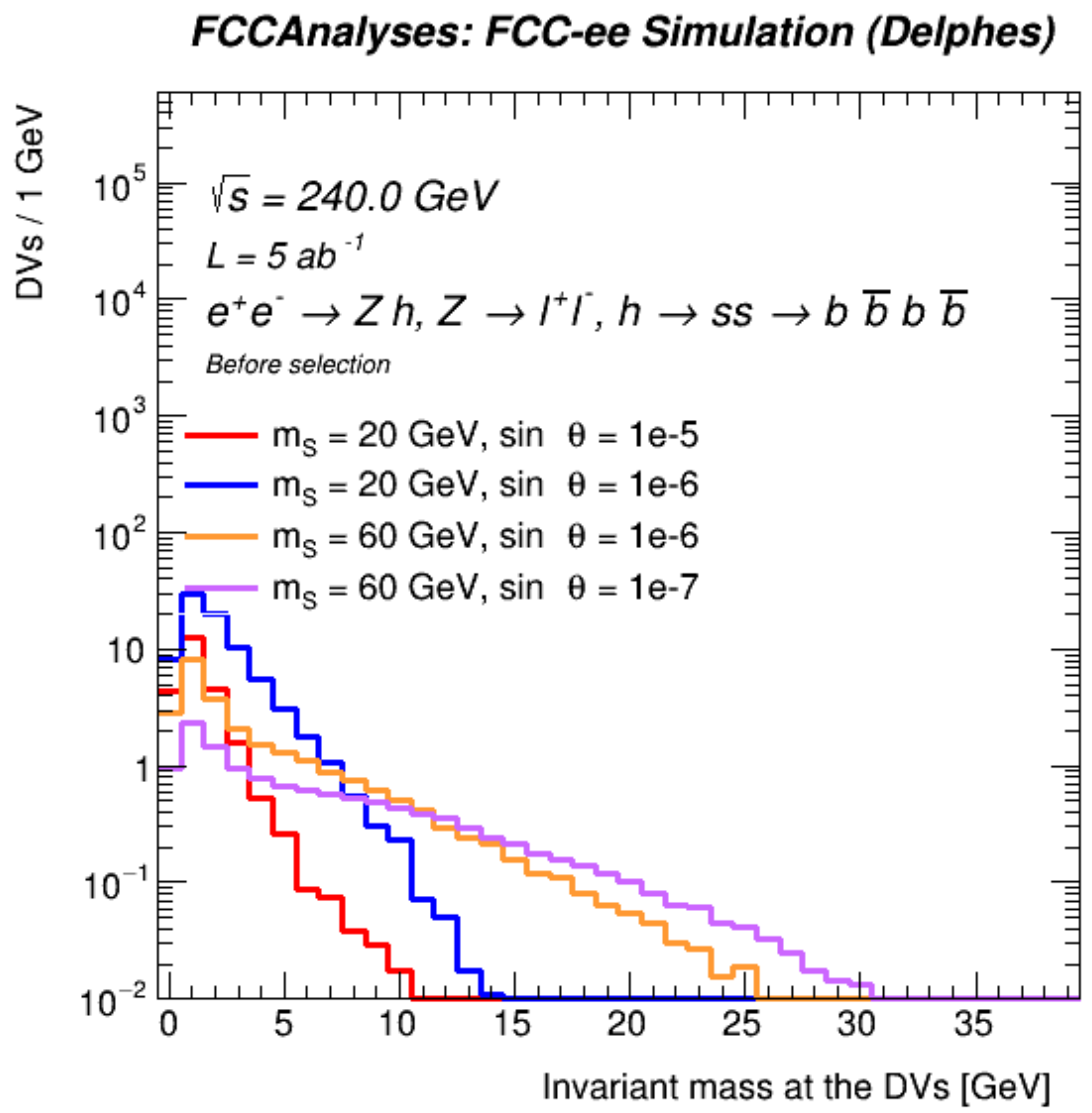


Preliminary vertex selection

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

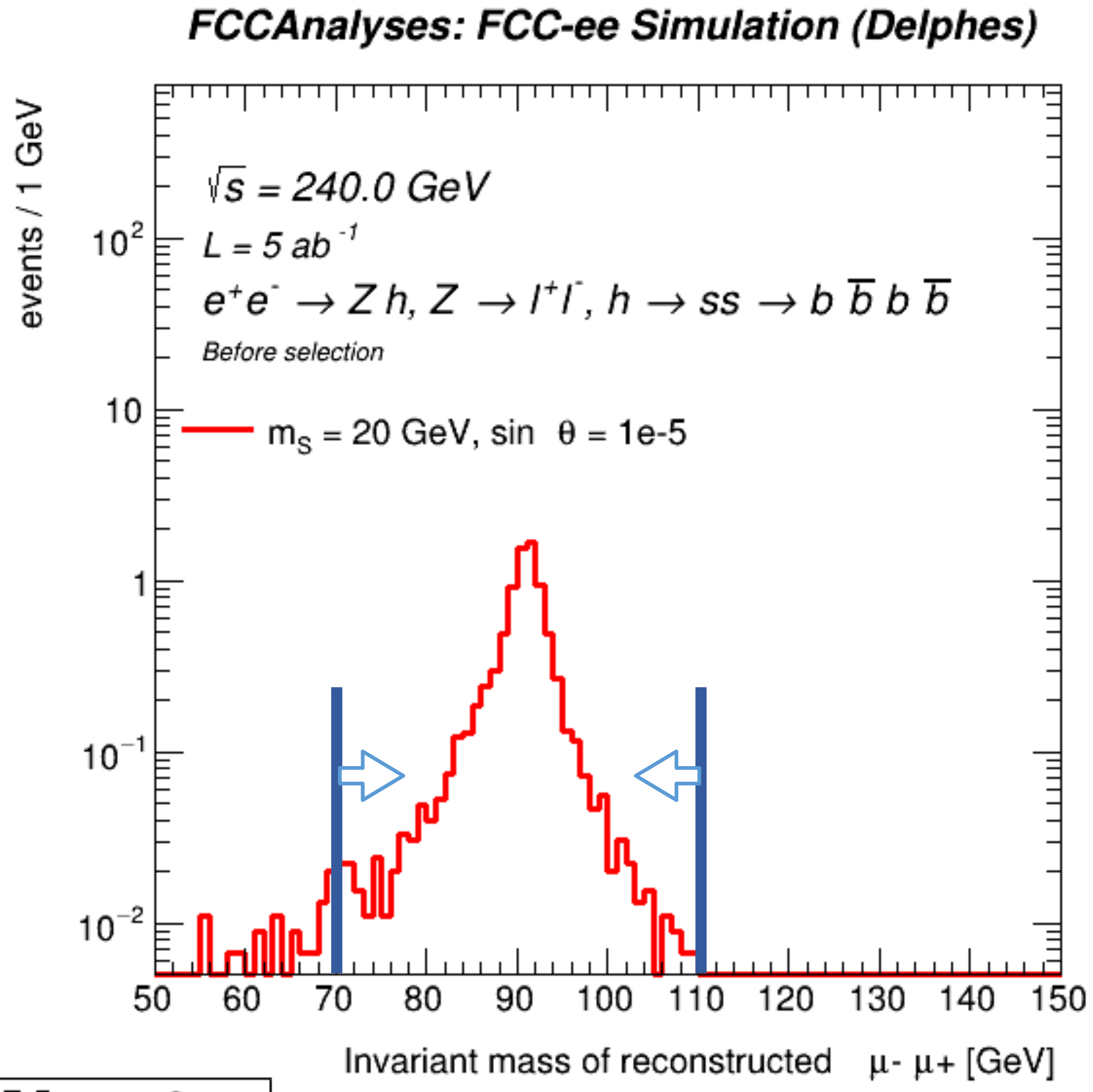
Charged invariant mass at DV: To remove background DVs



Visible/charged invariant mass at the DVs

Towards a sensitivity analysis

- Potential event selection:
  - Pre-selection: require at least 2 oppositely charged electrons or muons
  - Tag Z-boson with di-muon/electron invariant mass in 70 - 110 GeV
  - Require at least 2 reconstructed DVs
- Given zero background, signal points with at least 3 expected events can be excluded to CL 95%
  - Potential sensitivity for all signal samples except the shortest and longest lifetime sample!



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 (≤ 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

Uncertainties are only statistical

Summary

- To discover new phenomena, it is important to carry out searches in the largest possible regions of phase space
  - One way to do this: long-lived particles!

- A first simulation and analysis of LLPs from exotic Higgs decays at FCC-ee has been done and is ongoing!
  - Within the FCCAnalyses framework using a fast simulation of the IDEA detector
  - Looking at the signal: $e^+e^- \rightarrow Zh$ with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and $h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$
  - A DV reconstruction algorithm has been implemented with the LCFI+ SV finder and custom track selection: non-primary, pT > 1 GeV and |d0| > 2 mm
  - 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
  - Potential sensitivity for all signal samples except the shortest and longest lifetime sample!

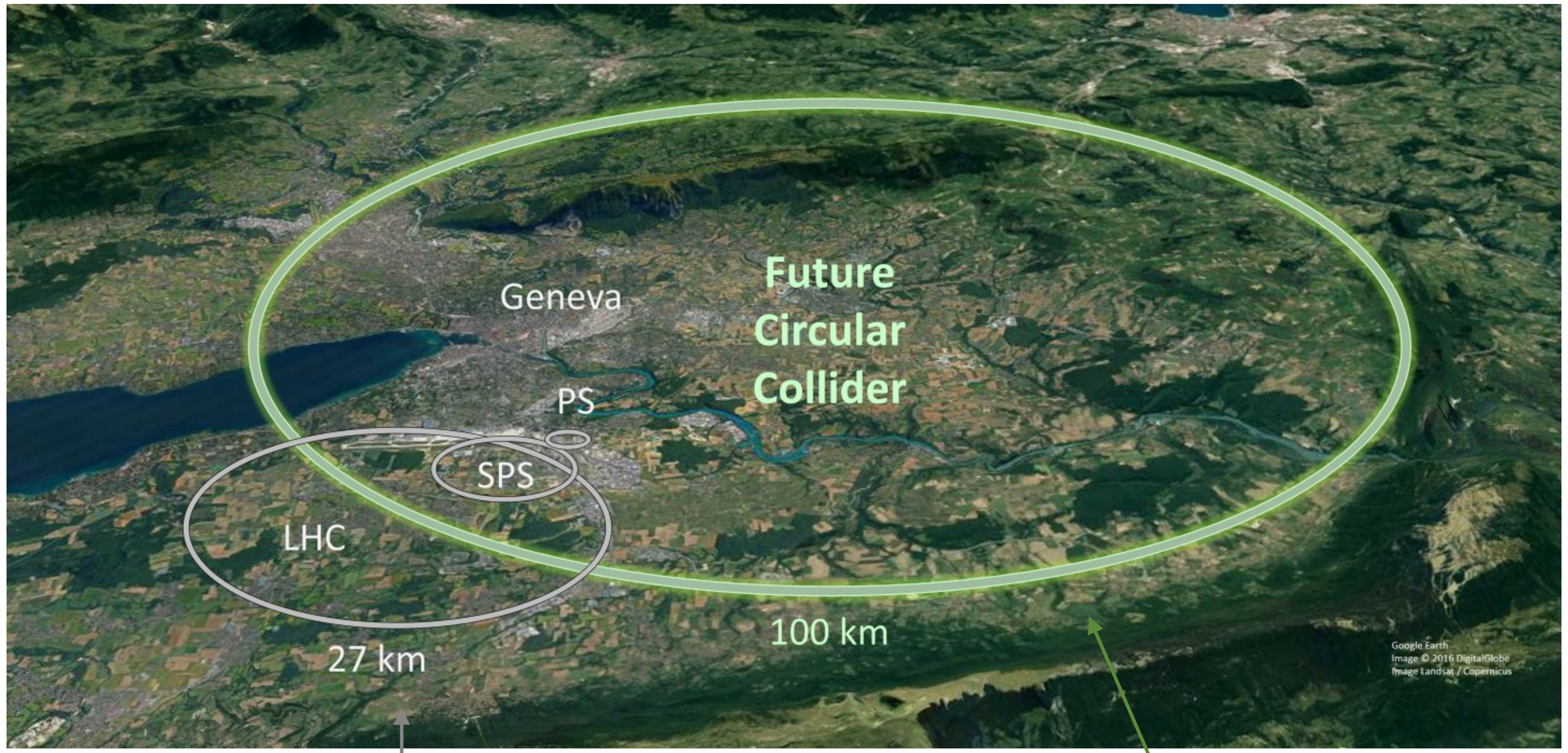
Thank you for your attention!

- Possible next steps, explore the FCC-ee conditions further!
  - Optimize the DV reconstruction algorithm
  - Look at other experimental signatures, e.g hadronic decay of the Z, jets, timing information etc.
  - Use a full detector simulation (work in progress atm for IDEA!) to study typical LLP backgrounds, e.g hadronic interactions with the detector material

Backup slides

The Future Circular Collider (FCC)

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



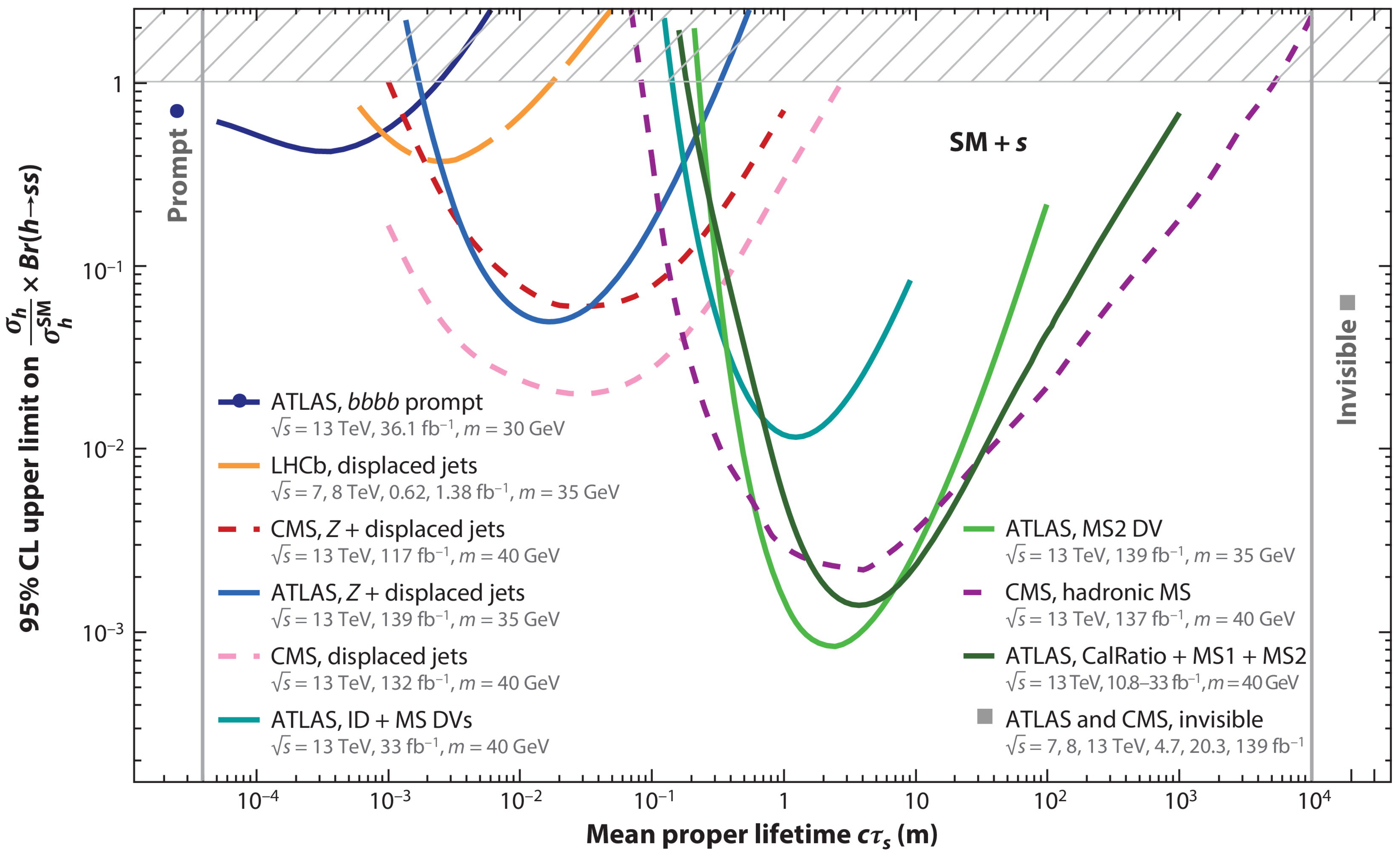
LHC/LEP:
27 km
91-209 GeV (e^+e^- collisions)
14 TeV (pp collisions)

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 tt pairs	Not done

Summary of current constraints from LHC

Review: Exotic Higgs Decays arXiv:2111.12751

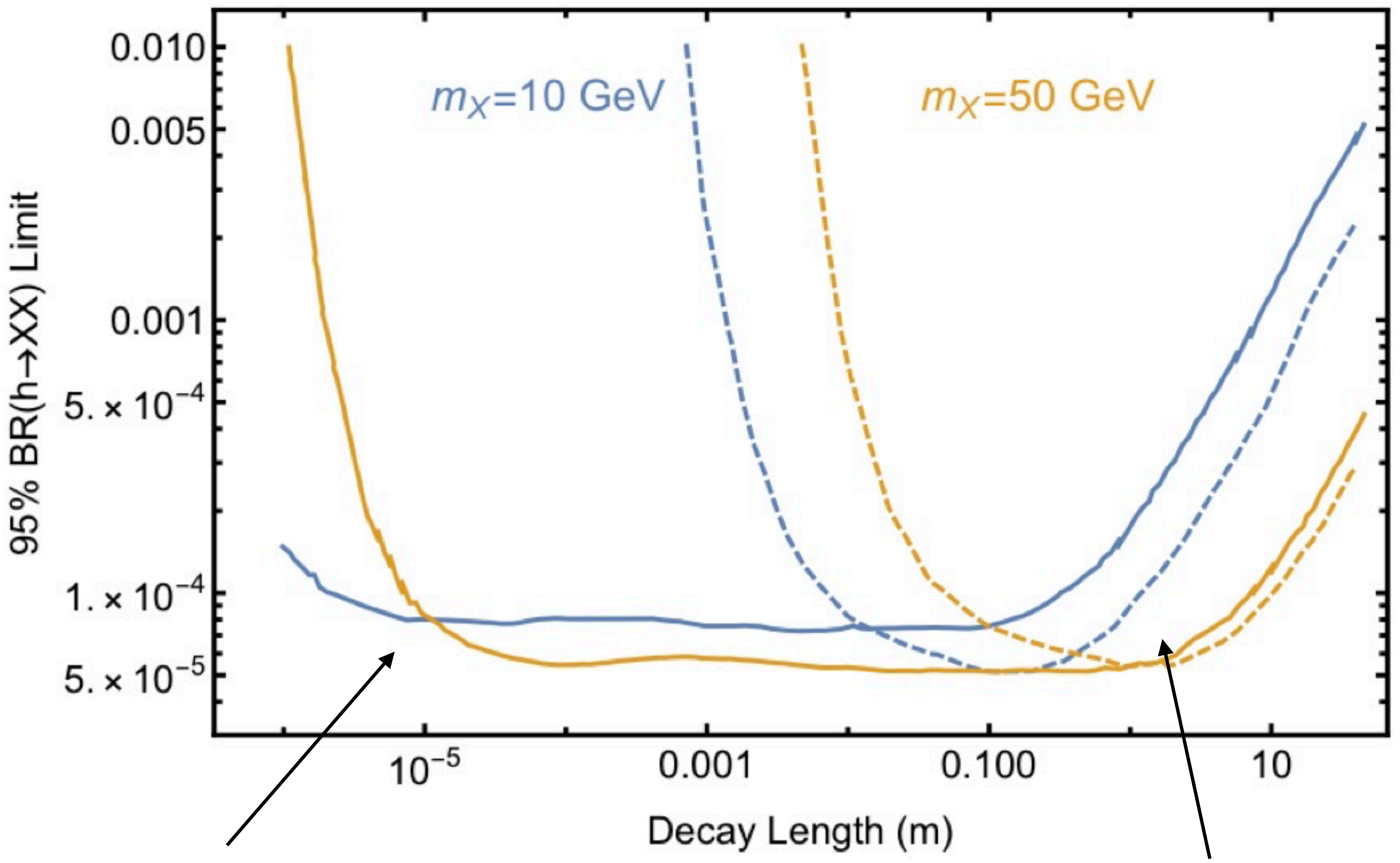


Cepeda M, et al. 2022
Annu. Rev. Nucl. Part. Sci. 72:119–49

- 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
- ”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]



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.

Other LLP topics to explore for FCC

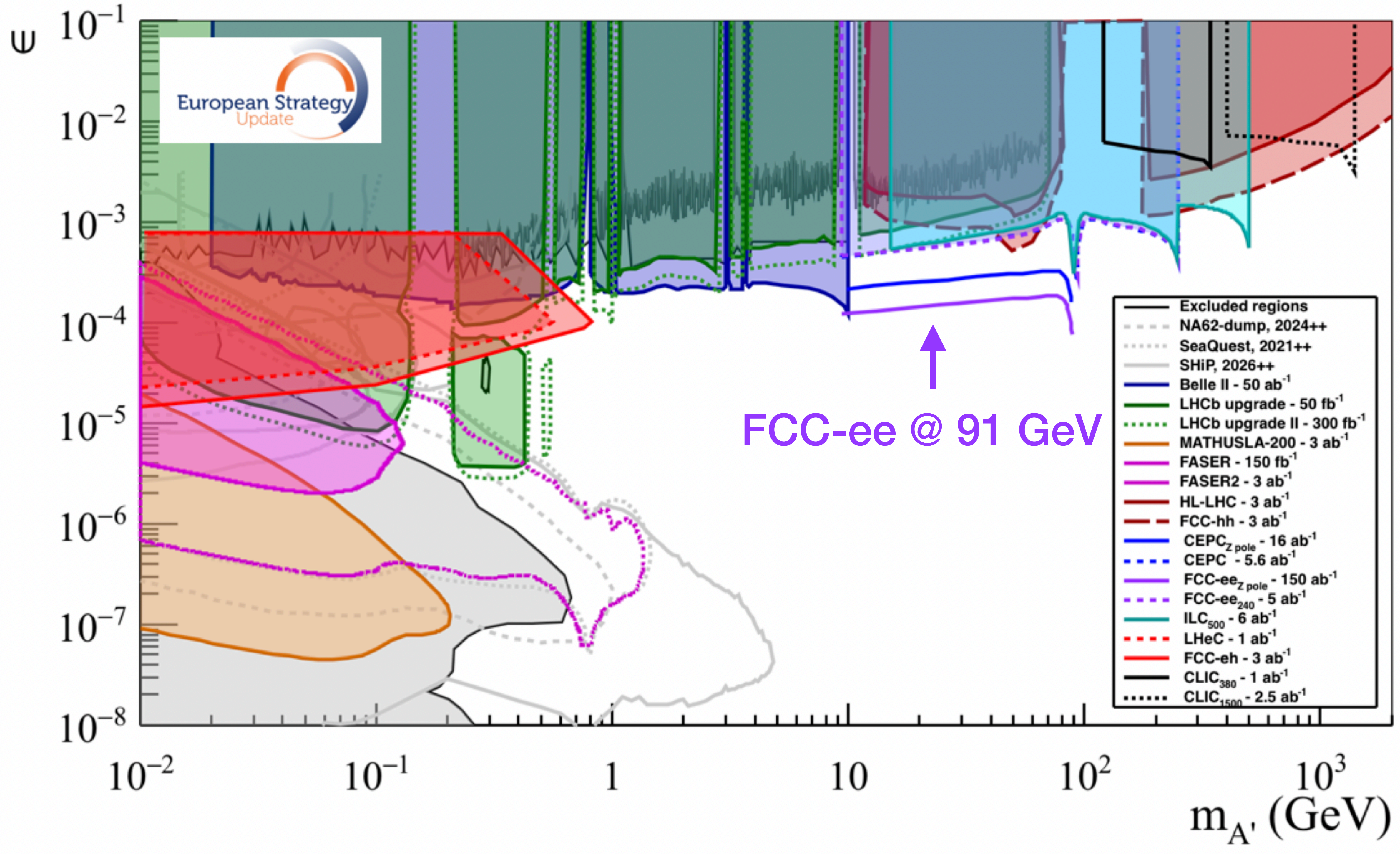
Other benchmark models

- RPV SUSY
- Vector portals - dark photons
- …

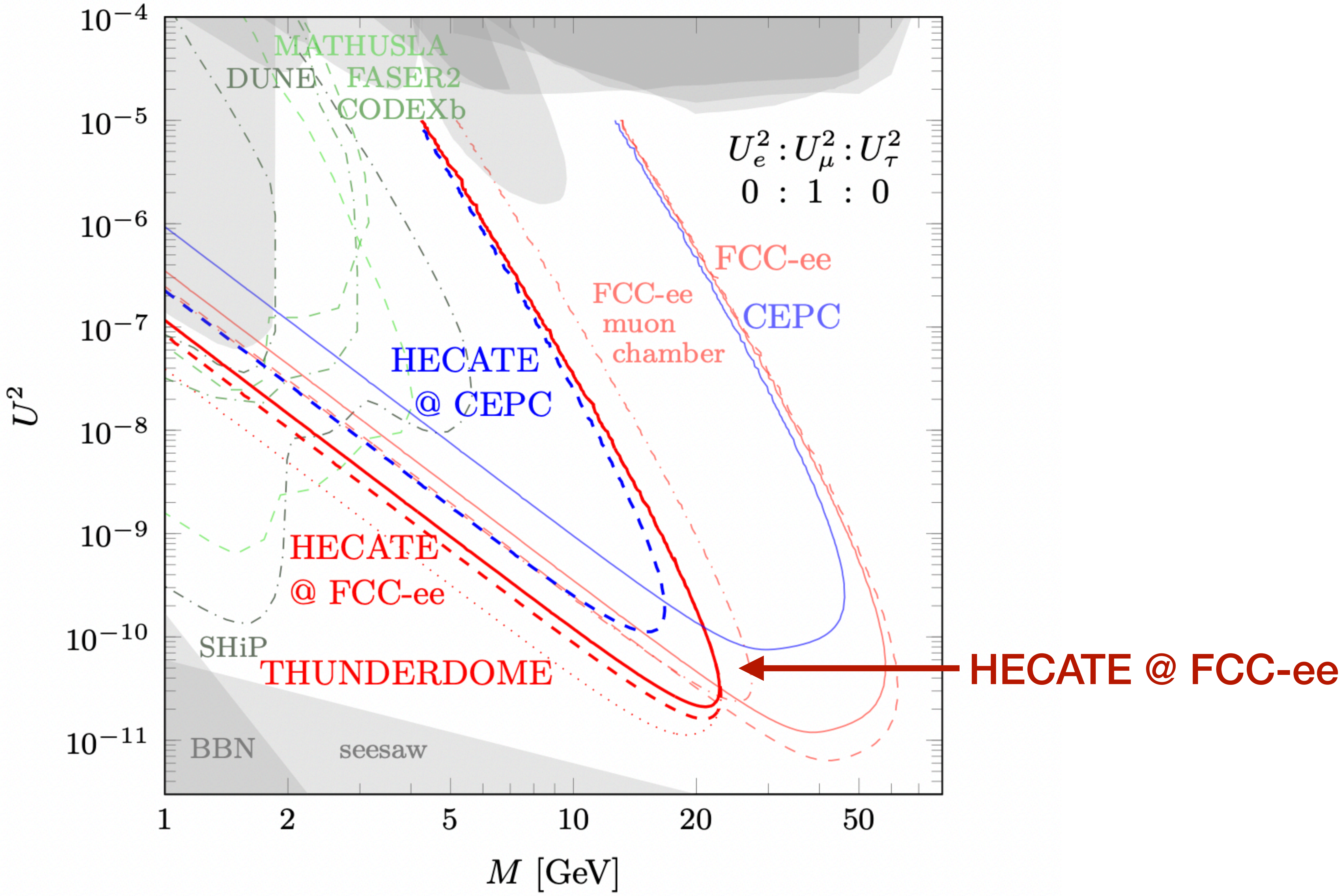
New detector concepts

- Following the plans for LLP experiments at the HL-LHC it is possible to also envision similar concepts at future colliders
- HECATE: LLP detector concept for the FCC-ee or CEPC

Reach for dark photons arXiv:1910.11775



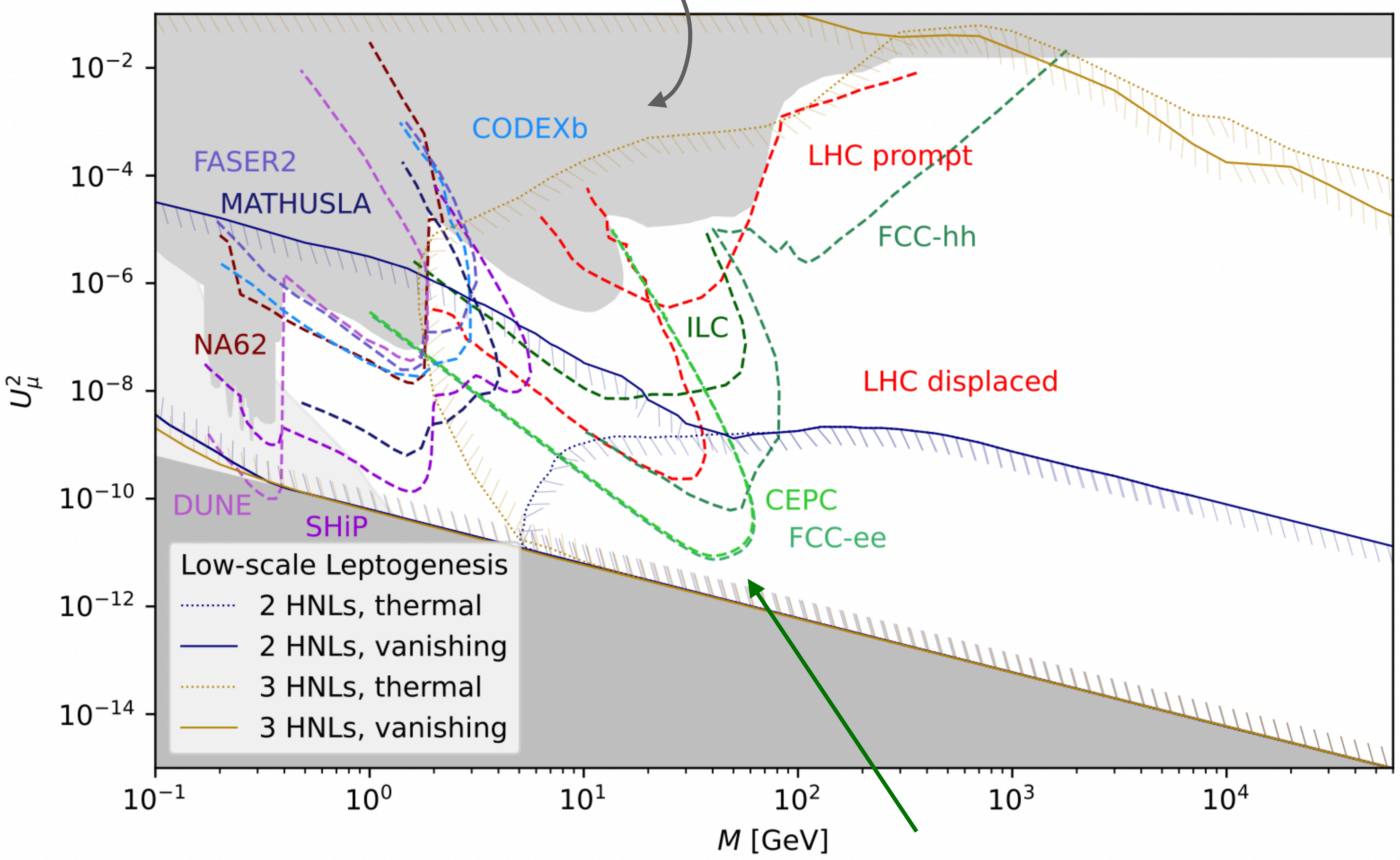
HECATE reach for HNLs arXiv:2011.01005



HNLs: existing and future sensitivity

The Present and Future Status of Heavy Neutral Leptons [arXiv: 2203.08039]

Constraints from past experiments

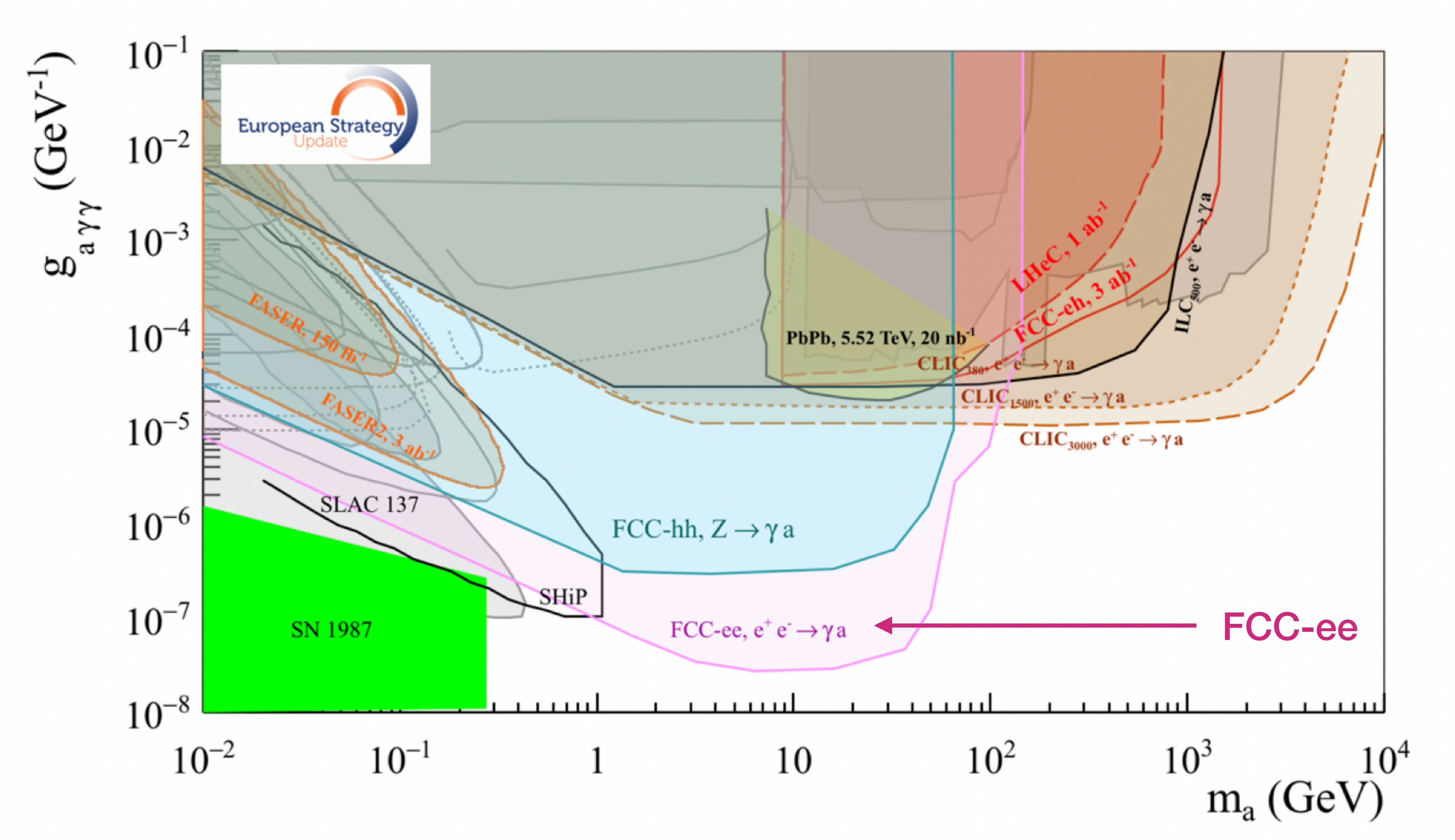


Reach for HNL decays at the Tera-Z run of the FCC-ee

- Sensitivity of displaced vertex searches at FCC-ee
- Parameter region inside the curves corresponds to more than four observed HNL decays from 5×10^{12} Z bosons
- Assuming:
  - No background events
  - 95% reconstructed HNL decays (i.e., all decays except the invisible decay) inside the main detectors based on the IDEA or CLD design
  - Displacement over 400 μm
  - Fiducial volume: cylinder
    l = 8.6 m and radius r = 5 m (CLD)
    l = 11 m and r = 4.5 m (IDEA)
- Curves for the CLD and IDEA detectors are visually indistinguishable

ALPs: existing and future sensitivity

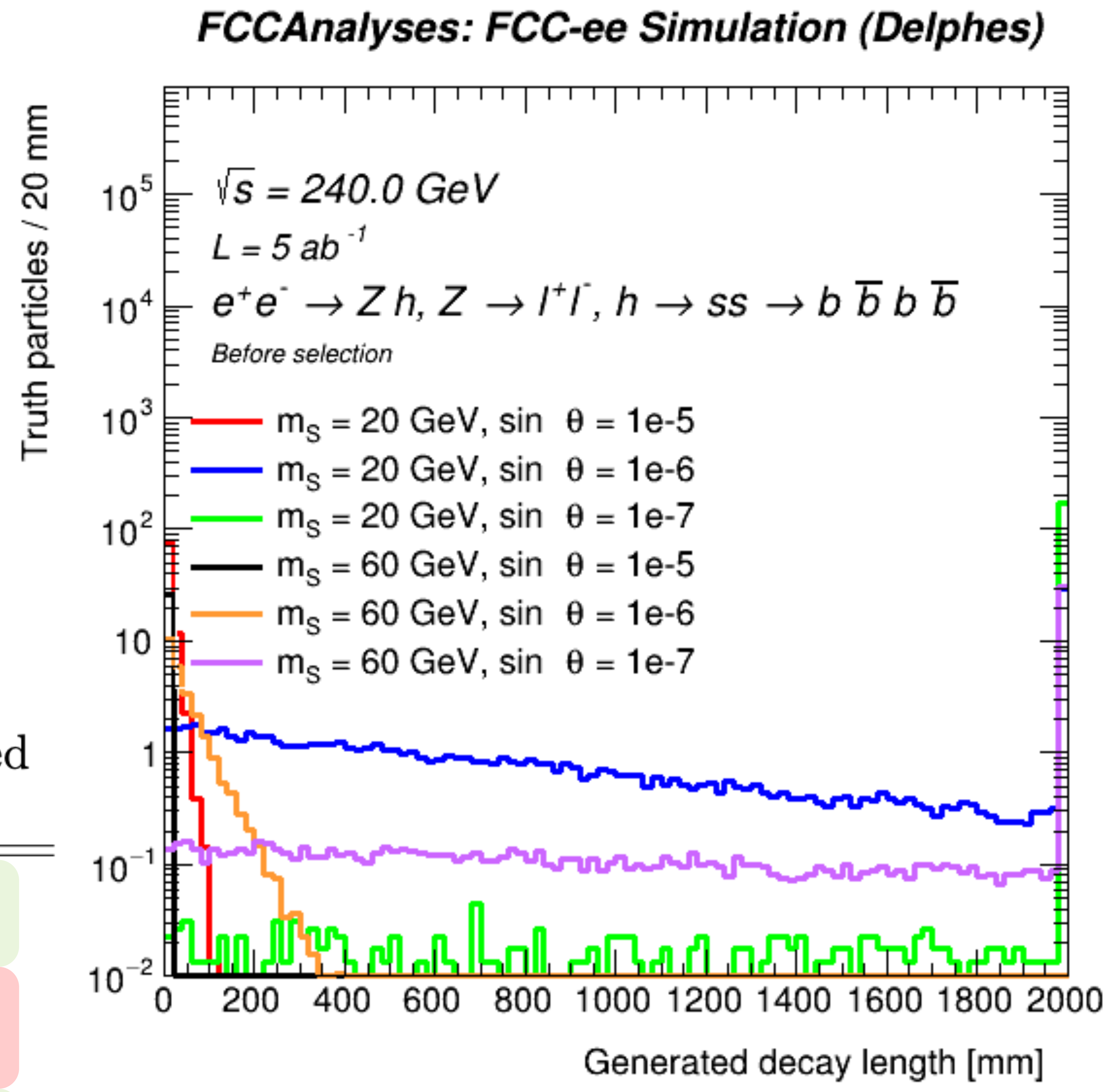
The Future Circular Collider: a Summary for the US 2021 Snowmass Process arXiv: 2203.06520



- Parameter region inside the curves corresponds to four or more signal events
- Assumptions:
  - 100% BR to studied final state
  - Fiducial region: Decays before the calorimeters (radius of 1.5 m)
- Estimate corresponds to the combined results for integrated luminosities of 145, 20, and 5 ab^{-1} at $\sqrt{s}$ = 91, 161, and 250 GeV, respectively

Sensitivity analysis at generating 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 $BR(h \to ss)$	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

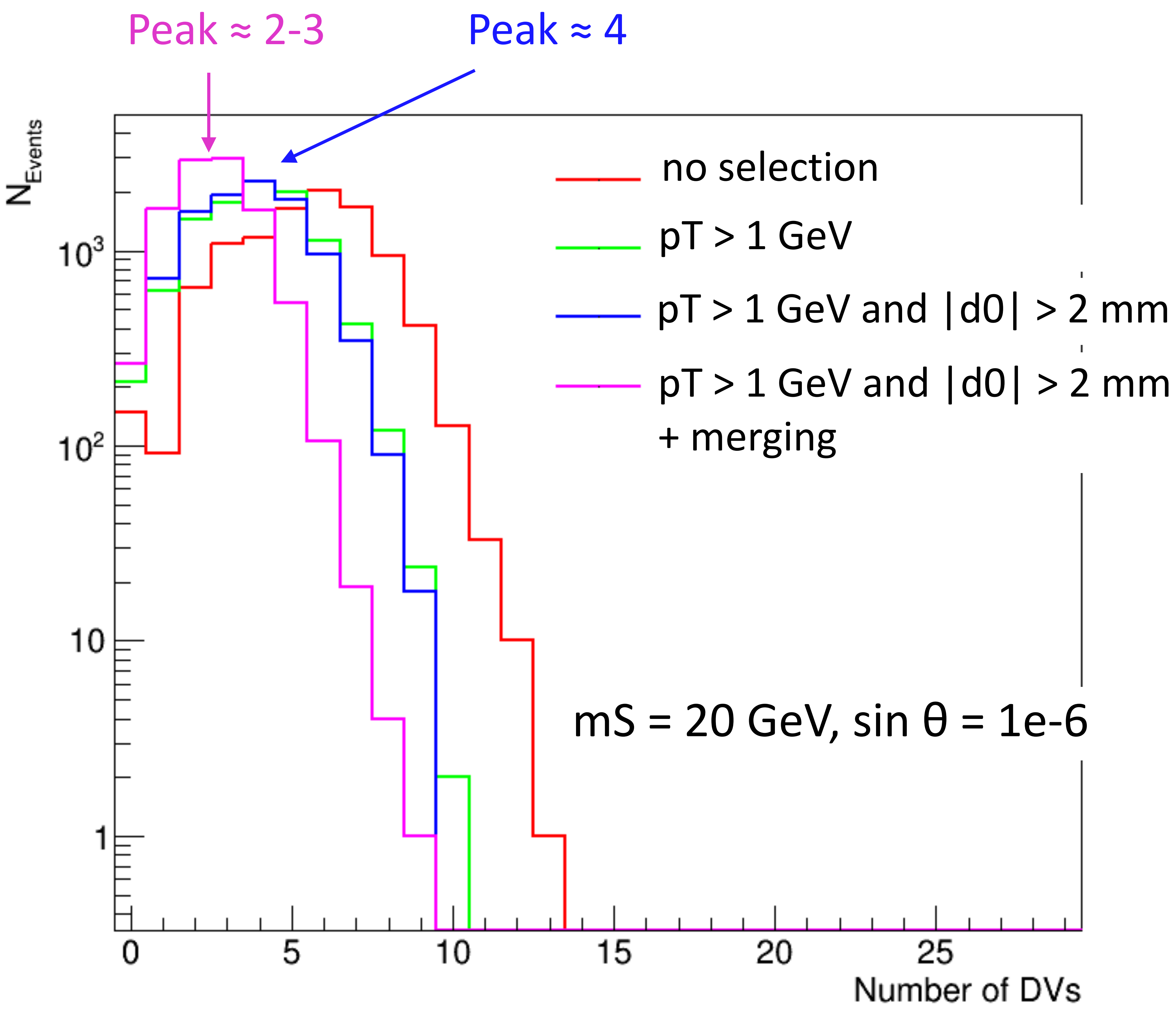
$$\sigma = \sigma_{ZH} \times BR(h \to ss) \times BR(s \to b\bar{b})^2 \times BR(Z \to l^+l^-)$$

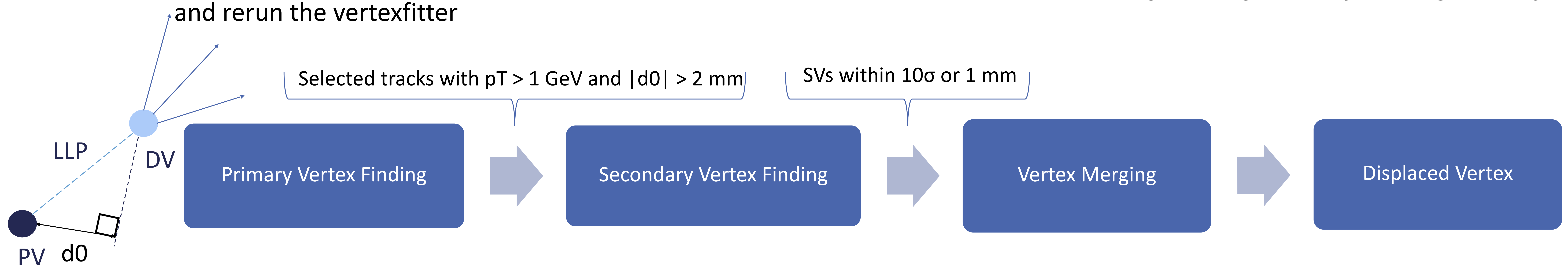
Vertex reconstruction

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

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)
- SV finder of the LCFI+ algorithm (arXiv:1506.08371), primarily used for flavour-tagging jets (see more in backup)
  - **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

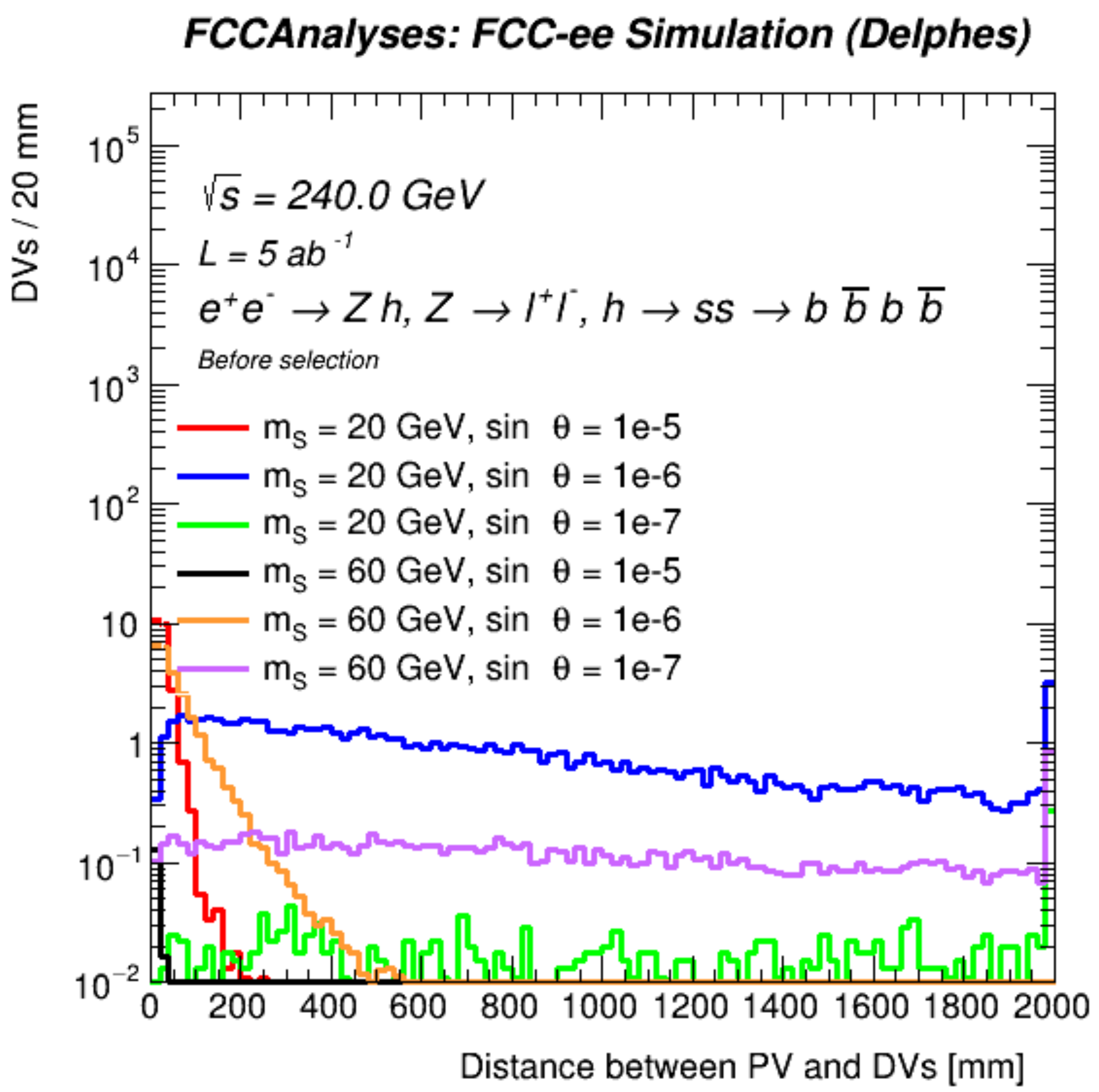


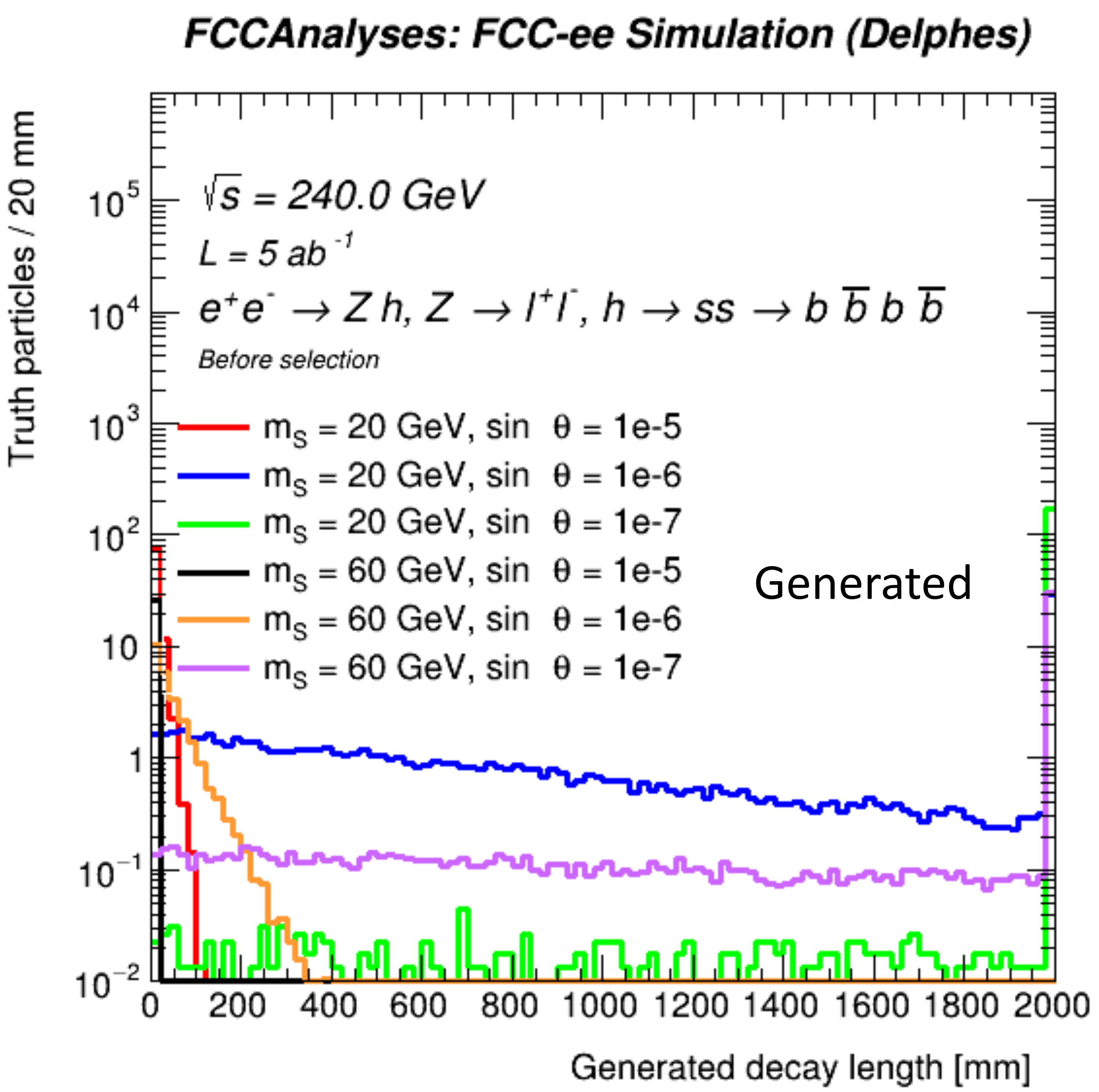


Distance from PV to the DVs

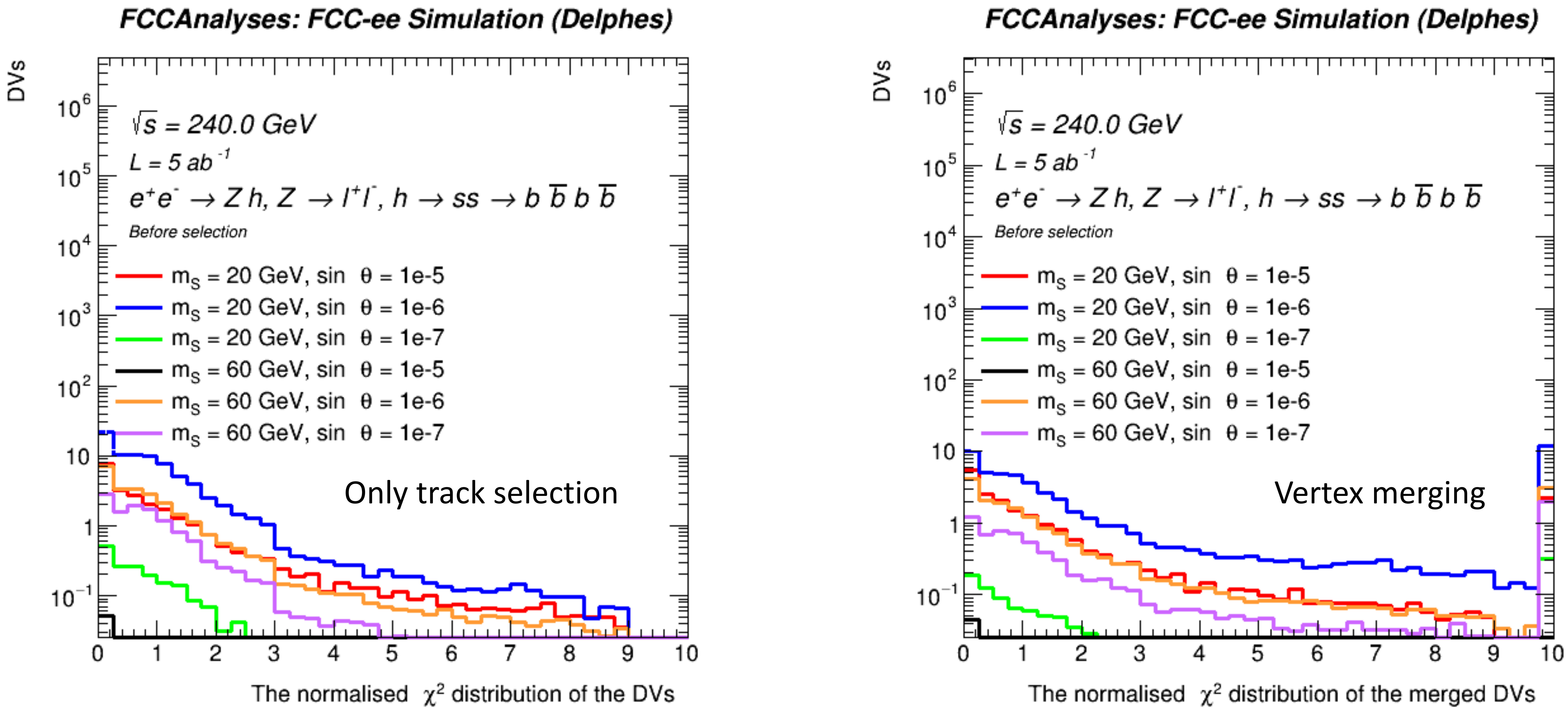
- Usually a good discriminating variable between signal and SM background
- The reconstructed quantity nicely follows the generated quantity
- **m_s = 20 GeV, sin θ = 1e-5**, **m_s = 20 GeV, sin θ = 1e-6**, m_s = 60 GeV, sin θ = 1e-7 and m_s = 60 GeV, sin θ = 1e-6 good for the analysis!
- **m_s = 60 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 within DCH

Reconstructed DVs with custom track selection



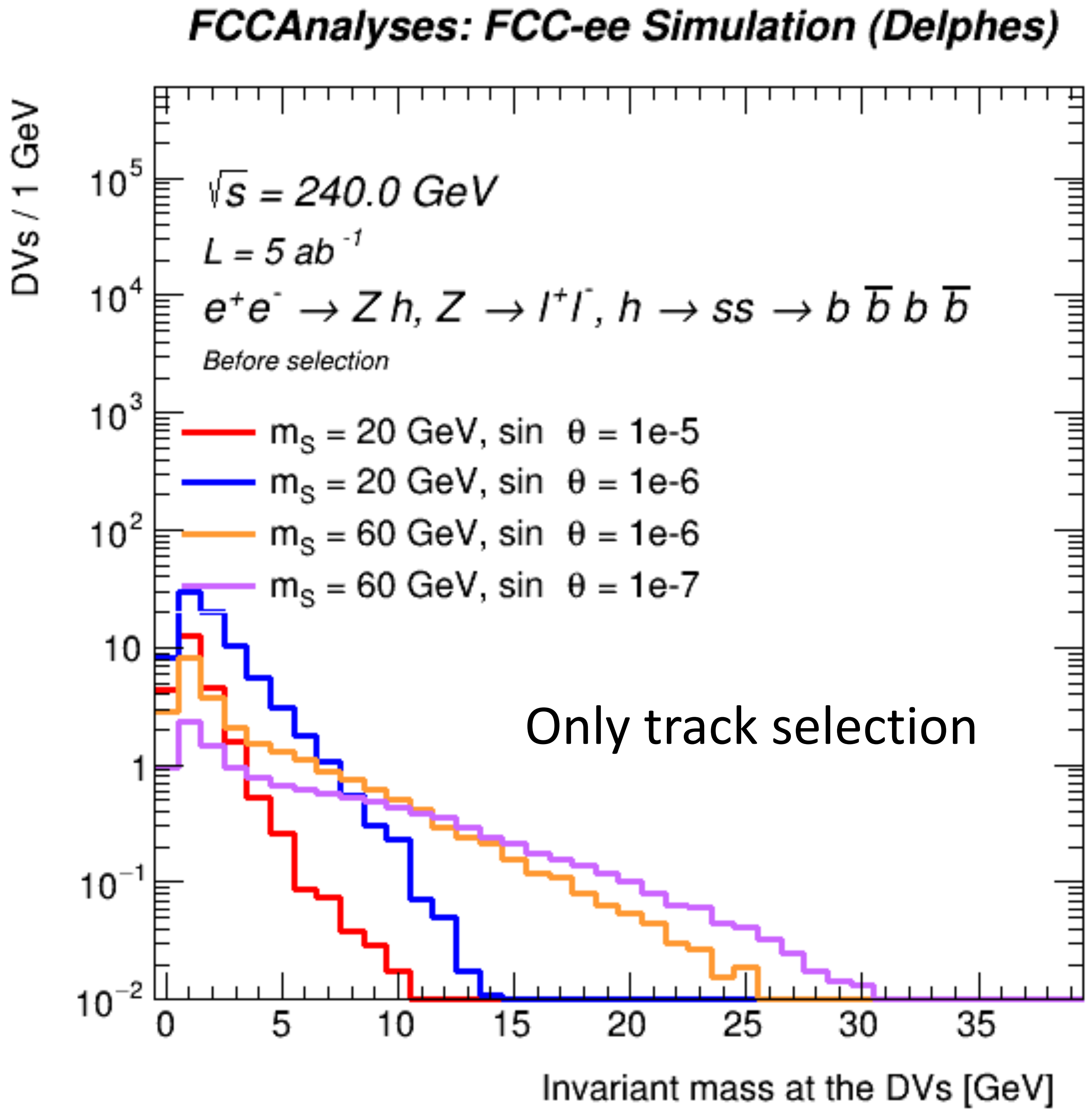


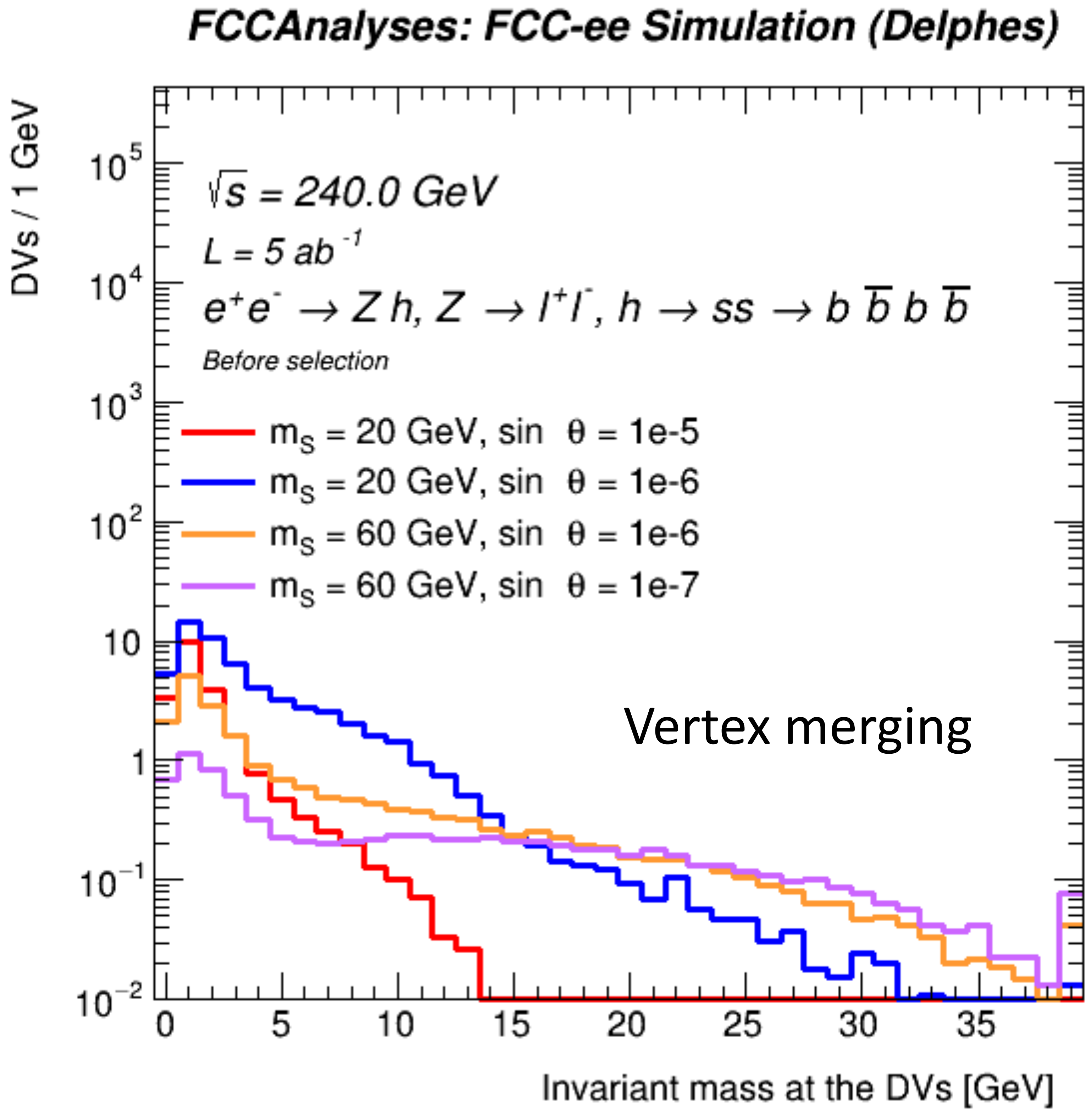
Goodness-of-fit of the DVs



- The χ^2/dof distributions tends to higher values for vertex merging
- Smeared out distribution for m_s = 20 GeV, sin θ = 1e-6 and m_s = 60 GeV, sin θ = 1e-7
- With vertex merging all signal points have values in the overflow → worse fit

Invariant mass at the DVs



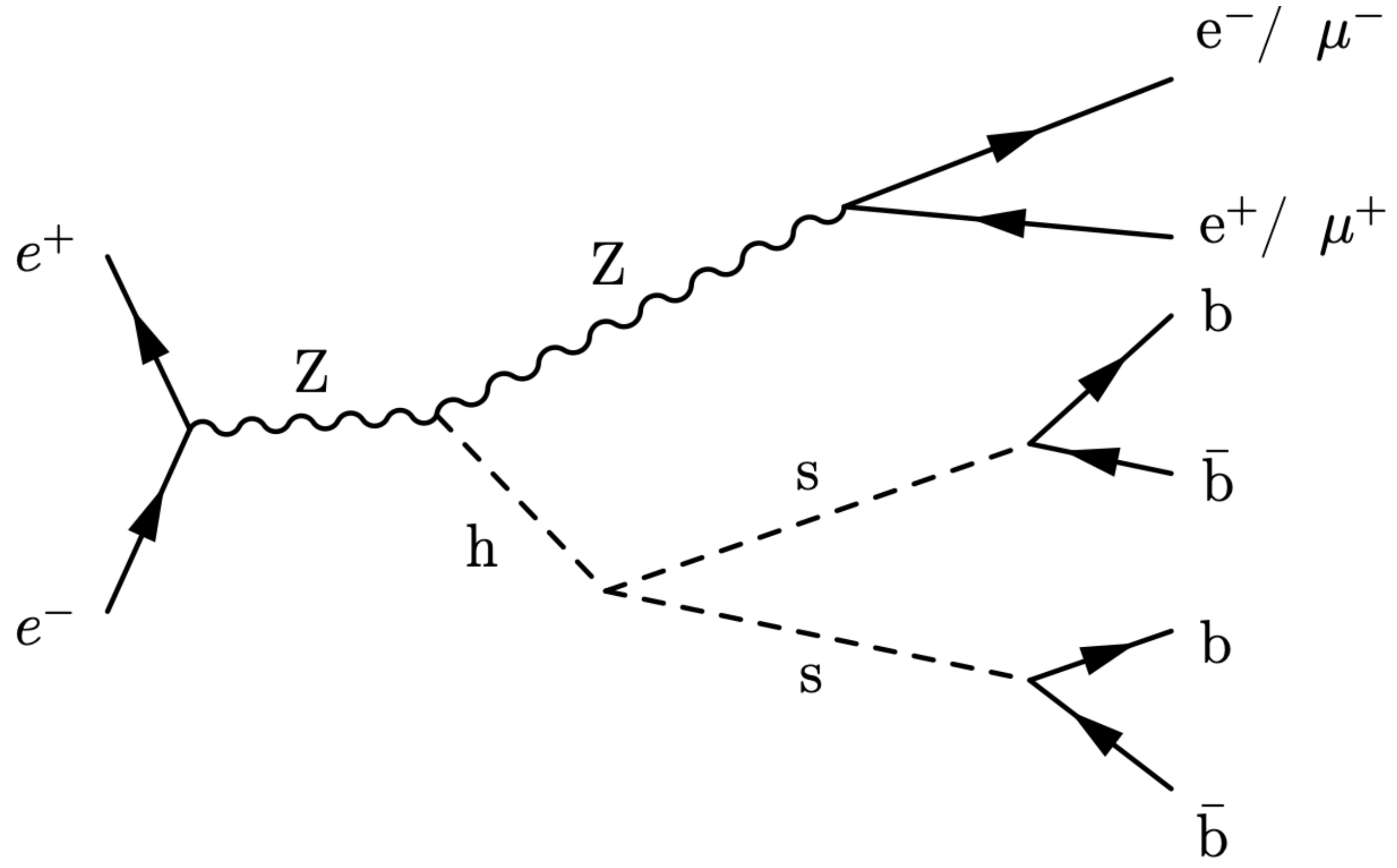


- Usually a good discriminating variable between a DV from an LLP and a fake vertex
- Invariant mass at vertex calculated assuming all tracks to come from pions, this only captures the charged component of the jet fragmentation → expected peak around half of the particle's mass
- More of a structure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

Background samples

- Using 100.000 generated raw events from the centrally-produced samples in FCCAnalyses [spring2021 production campaign]
- Considered backgrounds (produced at $\sqrt{s} = 240\ GeV$ generated with inclusive decays):
  - $e^+e^- \rightarrow Z\,h$, where main background would be from $Z \rightarrow l^+l^-$, $h \rightarrow b\bar{b}$
  - $e^+e^- \rightarrow Z\,Z$, where main background would be from $Z \rightarrow l^+l^-$, $Z \rightarrow b\bar{b}$
  - $e^+e^- \rightarrow WW$, primarily considered to test Z boson tagging

Signal:



Sensitivity analysis with reconstructed quantities

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 $\pm$ 7.45e+06	2.11e+06 $\pm$ 4.16e+04	4.68e+05 $\pm$ 1.96e+04	0 ($\lesssim$ 1.96e+04)
ZZ	6.79e+06 $\pm$ 1.77e+05	8.91e+05 $\pm$ 7.78e+03	5.85e+05 $\pm$ 6.31e+03	0 ($\lesssim$ 6.31e+03)
ZH	1.01e+06 $\pm$ 1.01e+04	5.97e+04 $\pm$ 7.76e+02	4.75e+04 $\pm$ 6.93e+02	0 ($\lesssim$ 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 $\pm$ 0.0295	29.8 $\pm$ 0.363	28.9 $\pm$ 0.358	3.55 $\pm$ 0.125
20 GeV, 1e-6	44.3 $\pm$ 0.0295	30.4 $\pm$ 0.367	29.7 $\pm$ 0.363	22.4 $\pm$ 0.315
20 GeV, 1e-7	44.3 $\pm$ 0.0295	36.3 $\pm$ 0.401	35.6 $\pm$ 0.397	0.531 $\pm$ 0.0485
60 GeV, 1e-5	13.1 $\pm$ 0.00474	8.38 $\pm$ 0.105	8.12 $\pm$ 0.103	0 ($\lesssim$ 0.103)
60 GeV, 1e-6	13.1 $\pm$ 0.00474	8.34 $\pm$ 0.104	8.09 $\pm$ 0.103	6.43 $\pm$ 0.0917
60 GeV, 1e-7	13.1 $\pm$ 0.00474	9.69 $\pm$ 0.113	9.45 $\pm$ 0.111	4.10 $\pm$ 0.0732

- Uncertainties are only statistical

Number of expected events given by

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

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

FCC-ee LLP group: past and ongoing work

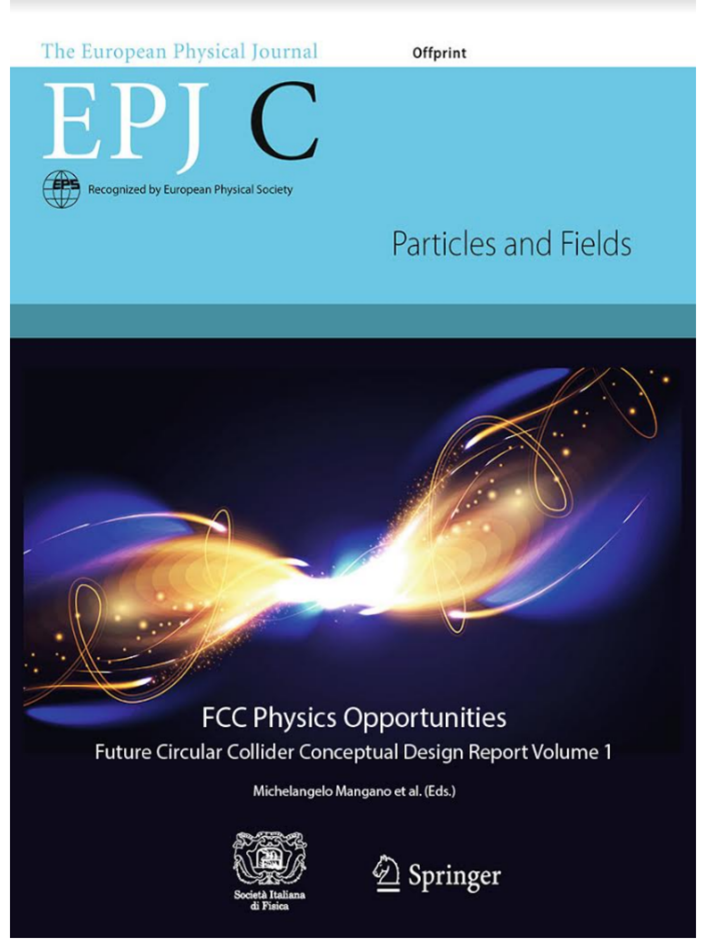
- Several Masters student theses done or in progress:
- Sissel Bay Nielsen (University of Copenhagen, 2017)
- Rohini Sengupta (Uppsala University, 2021)
- Lovisa Rygaard (Uppsala University, 2022)
- Tanishq Sharma (University of Geneva, 2022)
- Magdalena Vande Voorde (Uppsala University, 2023)
- Dimitri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

FCC: Find out more

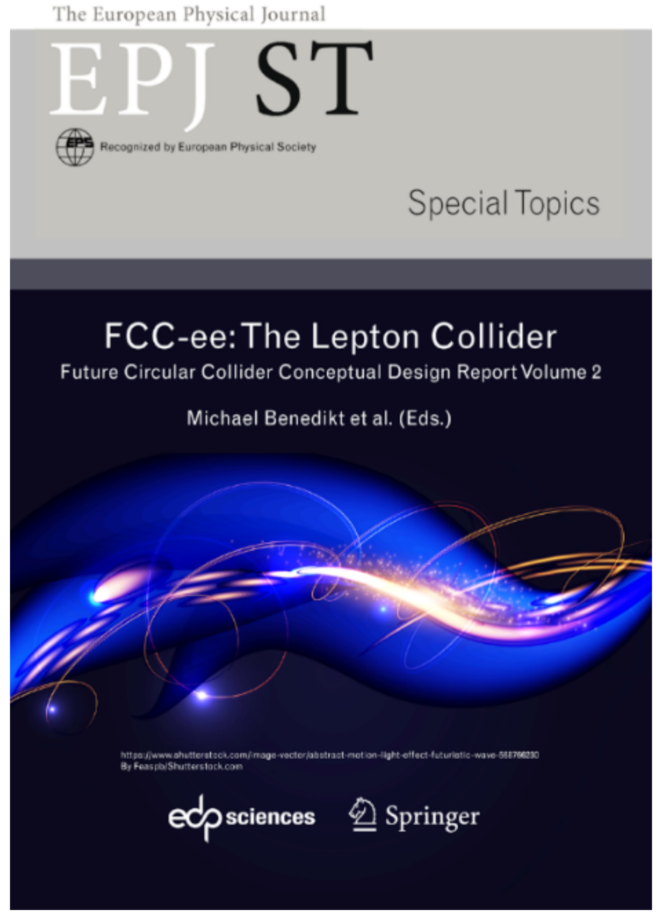
- Future Circular Collider - European Strategy Update Documents
  - (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity
  - arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and 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

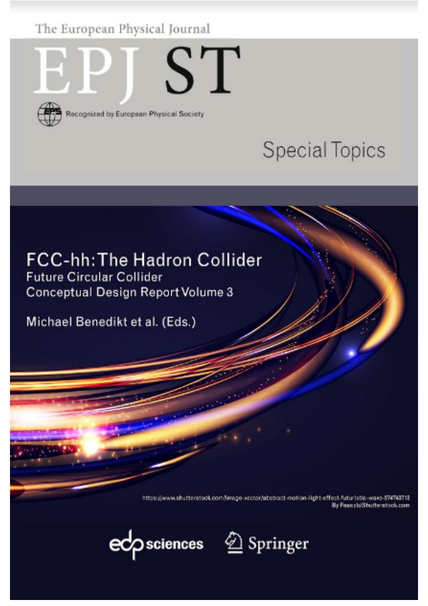
4 CDR volumes published in EPJ



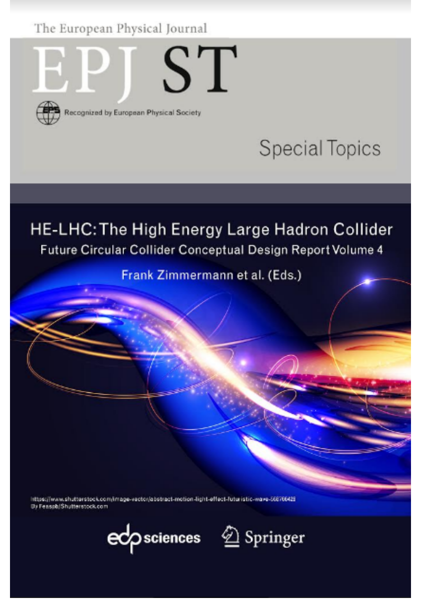
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider



HE-LHC: The High Energy Large Hadron Collider