HNLs Latest Results and Summaries

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on behalf of the FCC BSM Physics group

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BSM at FCC-ee

◉ Diverse experimental requirements necessary for varying signatures

- Prompt
- Decay within the inner detector
- Decay within the calo/muon detector

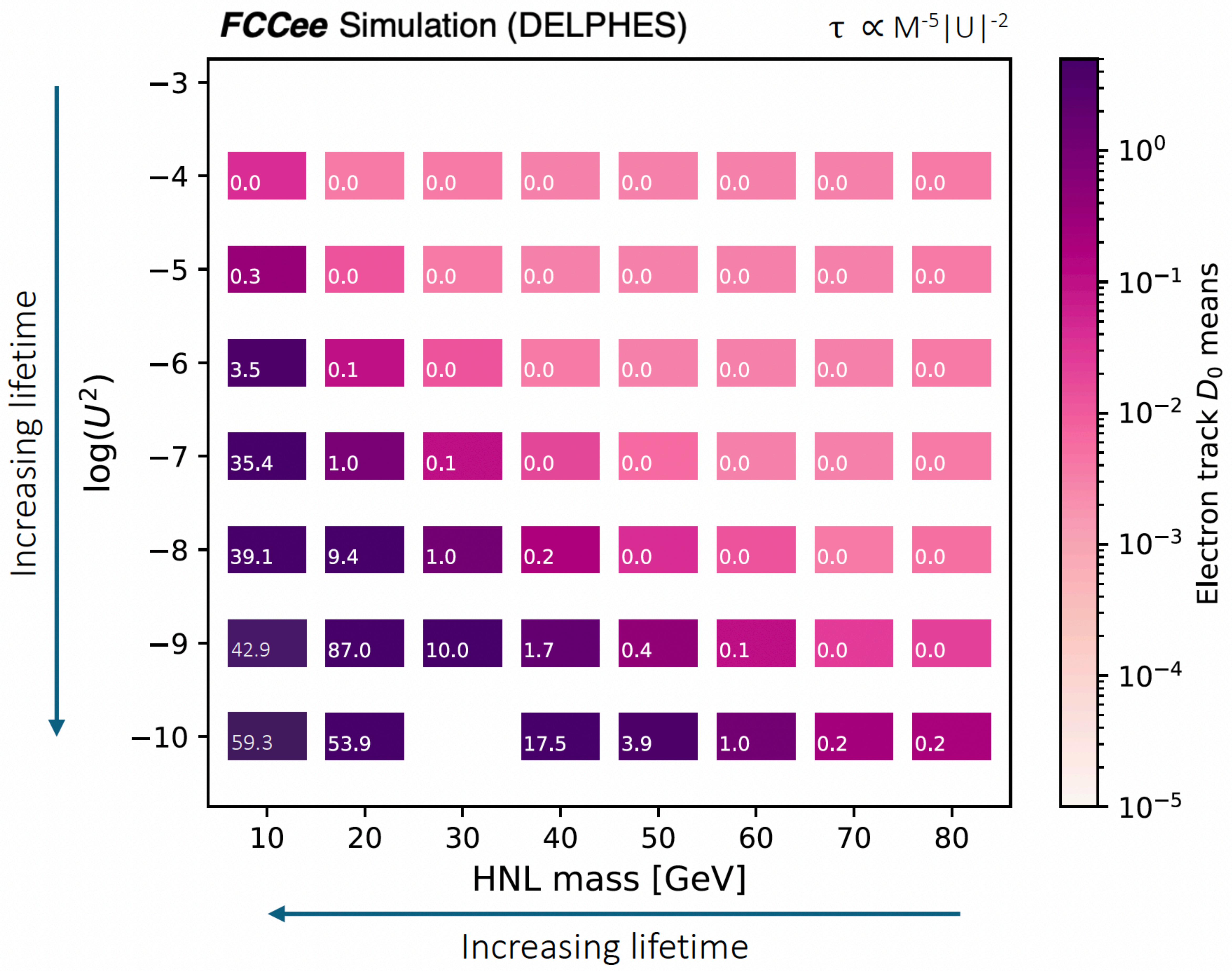
◉ BSM Particles:

- **The FCCee's clean environment and high stats allow to a wide spectrum of couplings and masses**
  - Heavy Neutral Leptons (HNL) ← Studies to be showcased in this talk
  - Axion-Like Particles (ALP) ← See Giacomo's talk
  - Exotic Higgs Decays ← See Axel's talk
  - Z' & dark photons
  - Light SUSY, …

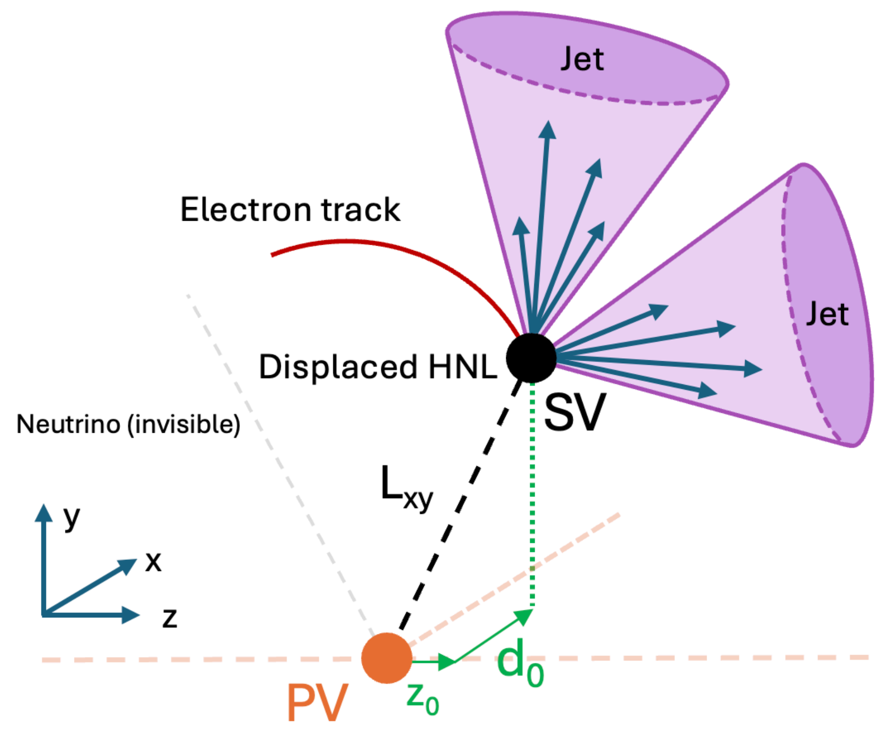
Disclaimer: Due to the wide scope of ongoing HNL research, only a selection of recent results and developments will be highlighted in this presentation

HNL Phenomenology at the FCCee

- **The FCC-ee is expected to produce approximately 10^{12} Z bosons during its Z-channel run (spanning ~3 years of data collection)**
  - High-luminosity & pileup-free environment for the search for HNLs
  - Aim to improve upon the limits previously set by the LEP



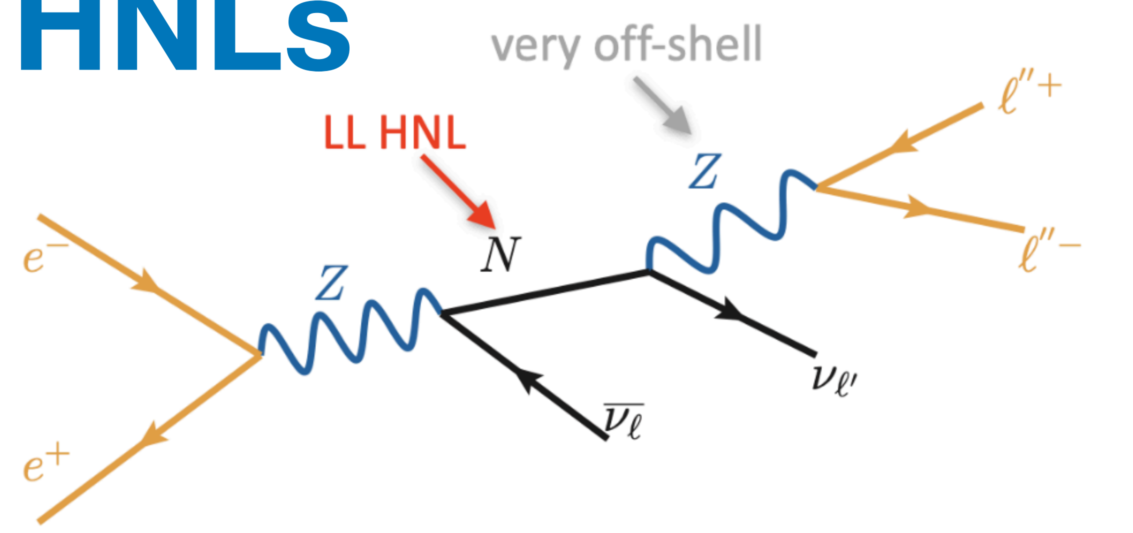
- For many of the mass points under consideration:
  - A displaced topology emerges due to the significant lifetime ($\tau \propto M^{-5}|U|^{-2}$)
  - Can be distinguished from promptly decaying mass points using lifetime metrics, such as decay length or D_0

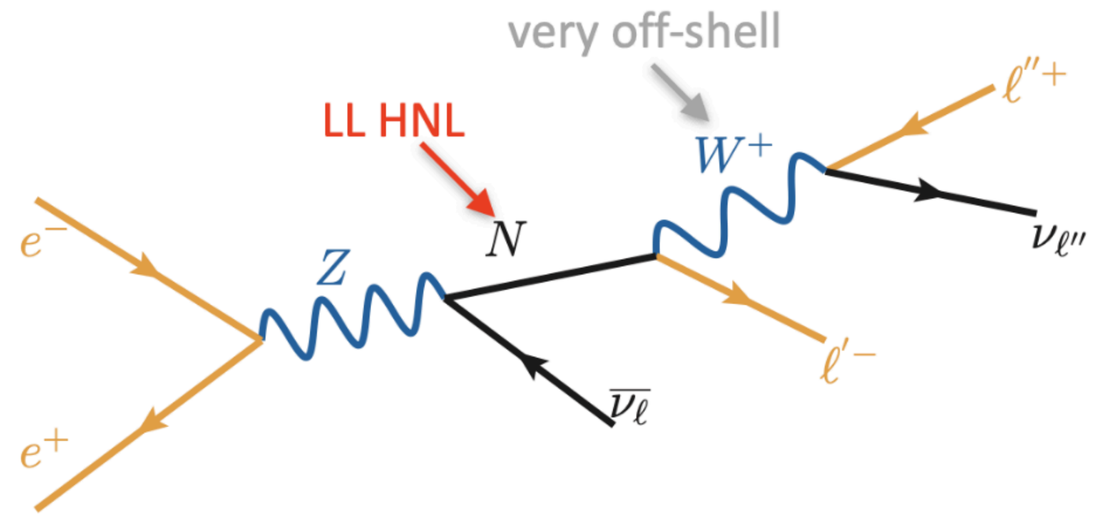


Searching for Type I Seesaw Mechanism in a Two-HNL Scenario

◉ Explore Type I Seesaw mechanism in two quasi-degenerate HNLs

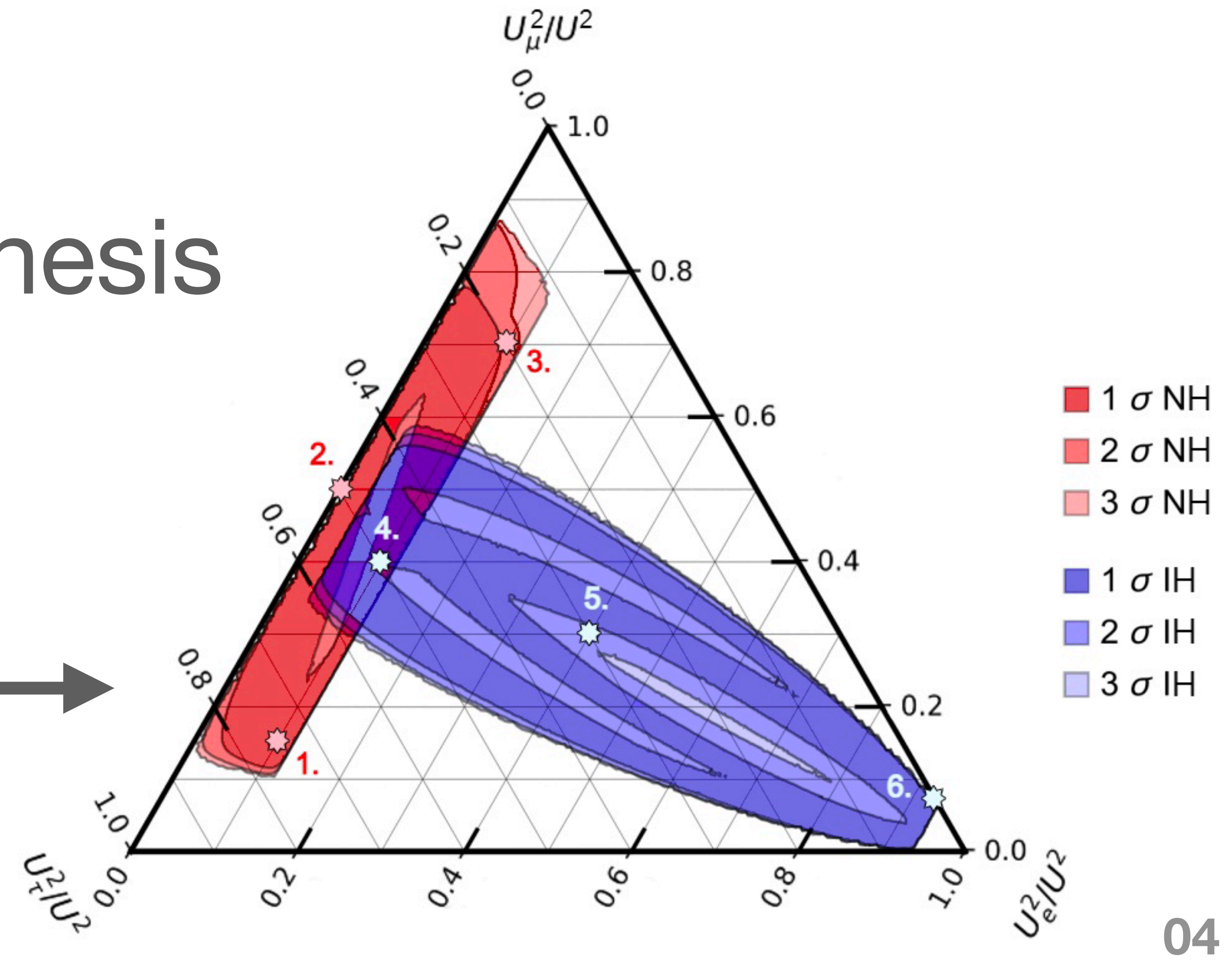
- Couplings to **all leptons**
- **$n_{HNL} > 1$** can explain neutrino oscillations, BA and DM
- Cross-section maximised with quasi-degenerate masses (pseudo-Dirac limit) while reducing the number of free parameters: $\mathbf{M_i \simeq M_j \rightarrow U_{\ell i} \simeq iU_{\ell j}}$





◉ Simulation Setup:

- Parameters chosen to respect constraints from leptogenesis and oscillation data
- M_N = [10, 80] GeV, $|U_{\mu\,1,2}|$ = [10^{-6}, 10^{-4}], $\Delta M = 10^{-5}$
- Six benchmarks selected as illustrated in the picture →



arXiv:2410.03615

Backgrounds & Event Selection

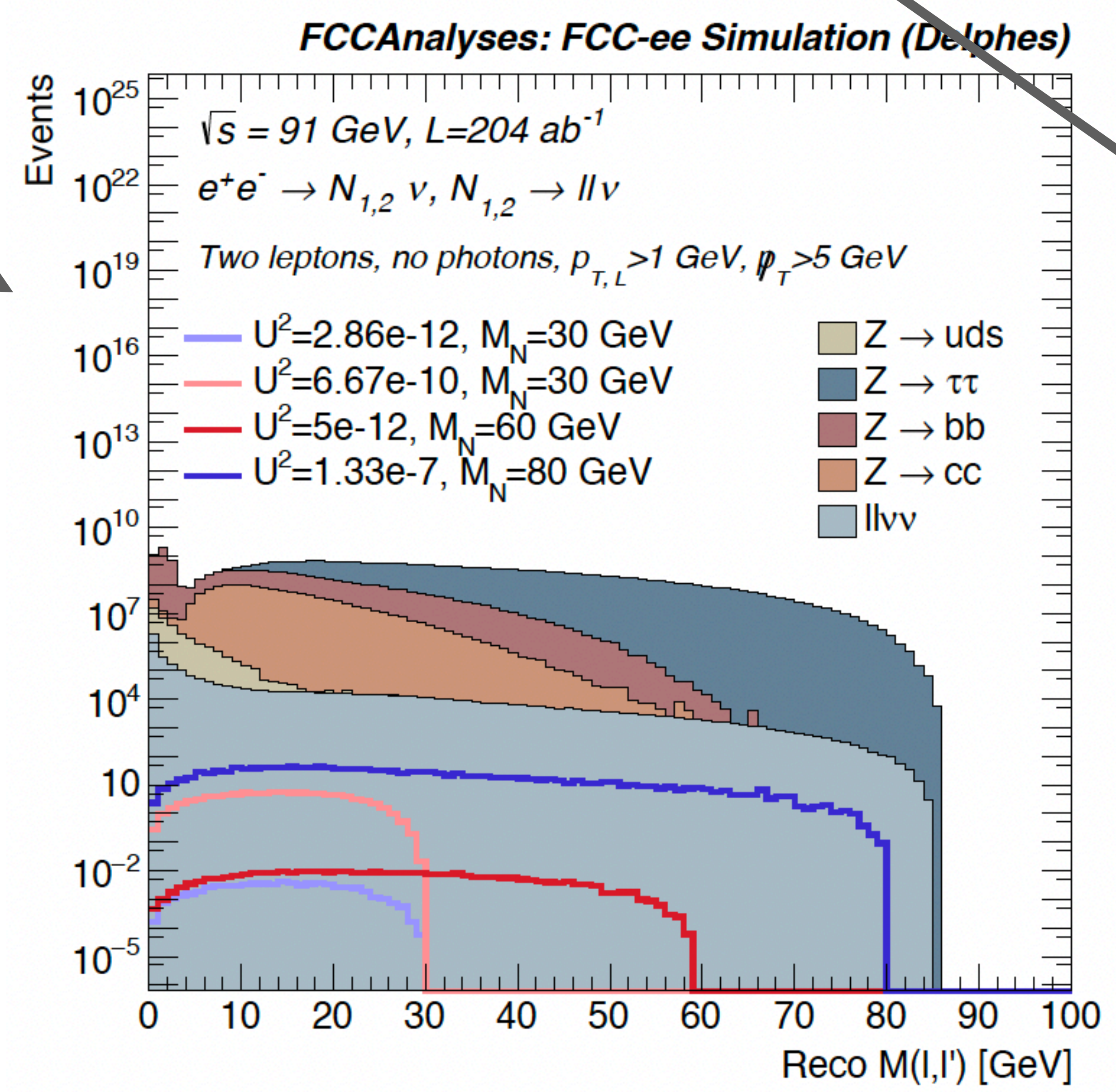
Backgrounds:

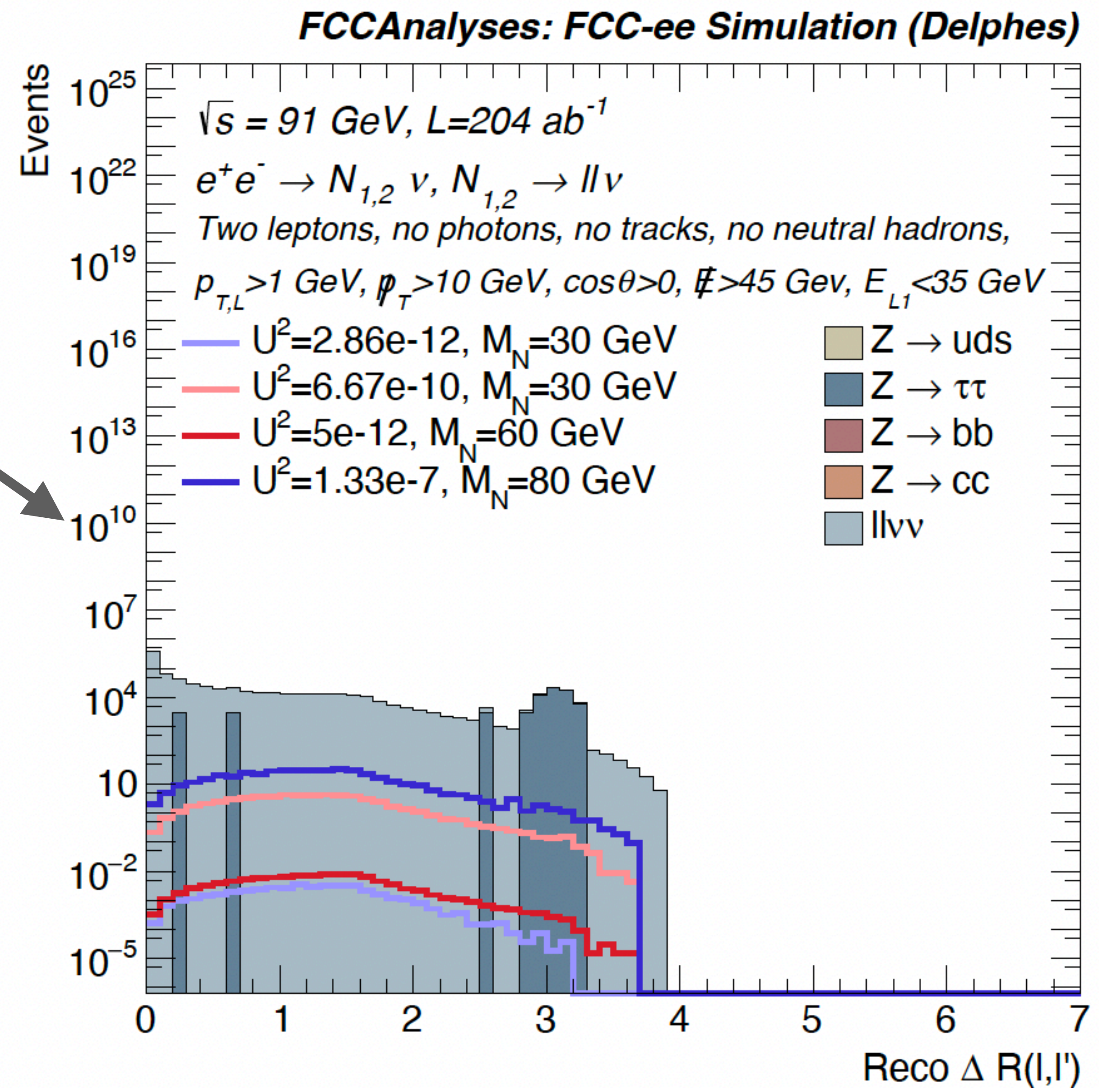
- **Major source: Z→ττ** (ee, μμ negligible due to low MET)
- Also privately produced **SM processes** with **ℓℓ'νν** final states → Irreducible bkg

Event Selection:

- Focus on final states with **two leptons** and **missing energy**
- Selection reduces the bkgs significantly while keeping high signal efficiency
- M(ℓ,ℓ′) selection for low HNL masses
- Maximum sensitivity obtained from angular distance between the two leptons

Two leptons, no photons $p_{T,miss} > 5\ GeV, p_{T,\ell} > 1\ GeV, E_\ell > 2\ GeV$
No other track and no neutral hadron
$p_{T,miss} > 10\ GeV$
$cos\theta_{ll} > 0$
$E_{miss} > 45\ GeV$
$E_{l,\ leading} < 35\ GeV$
$M(l, l') < M_{HNL}$





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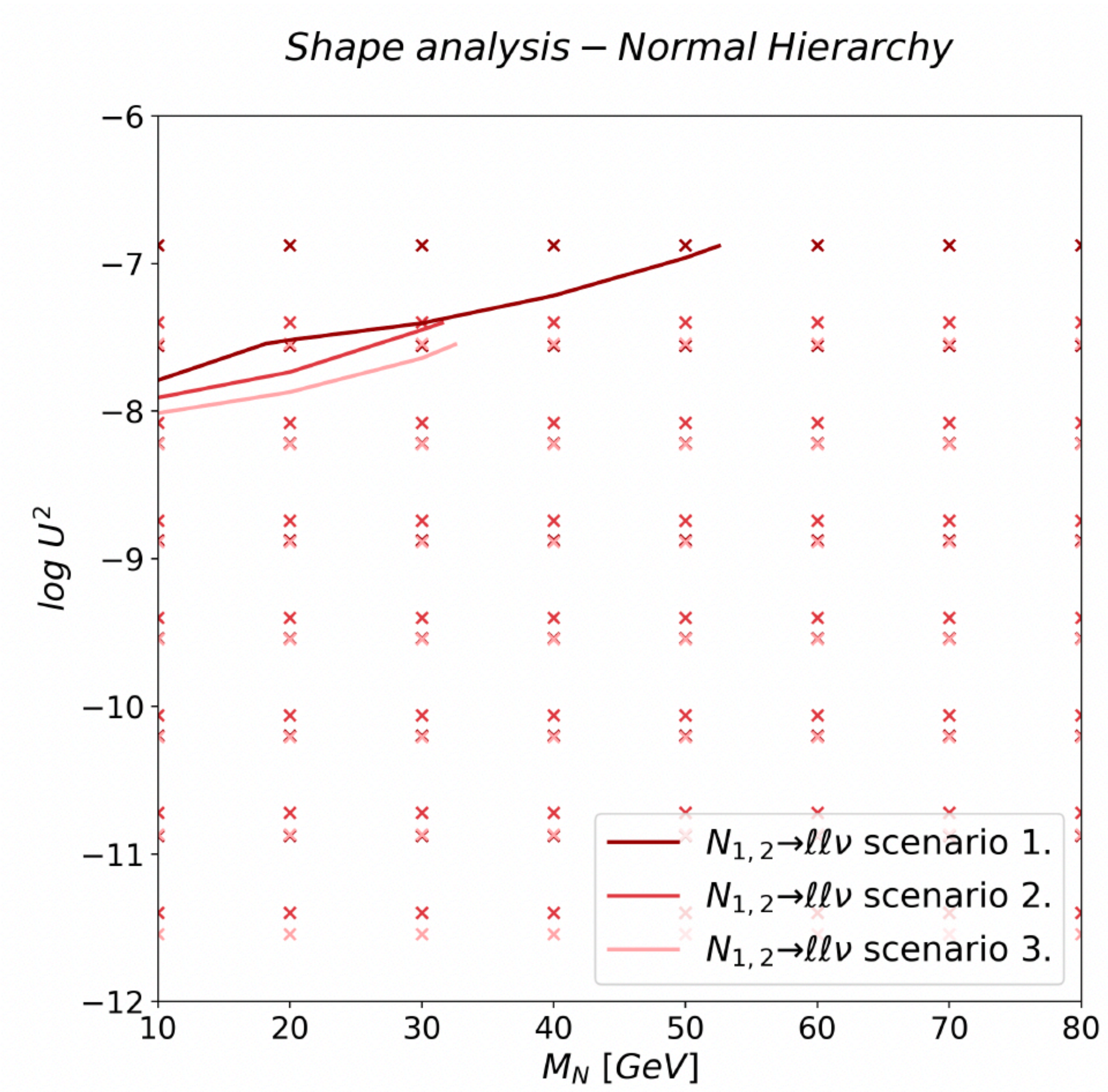
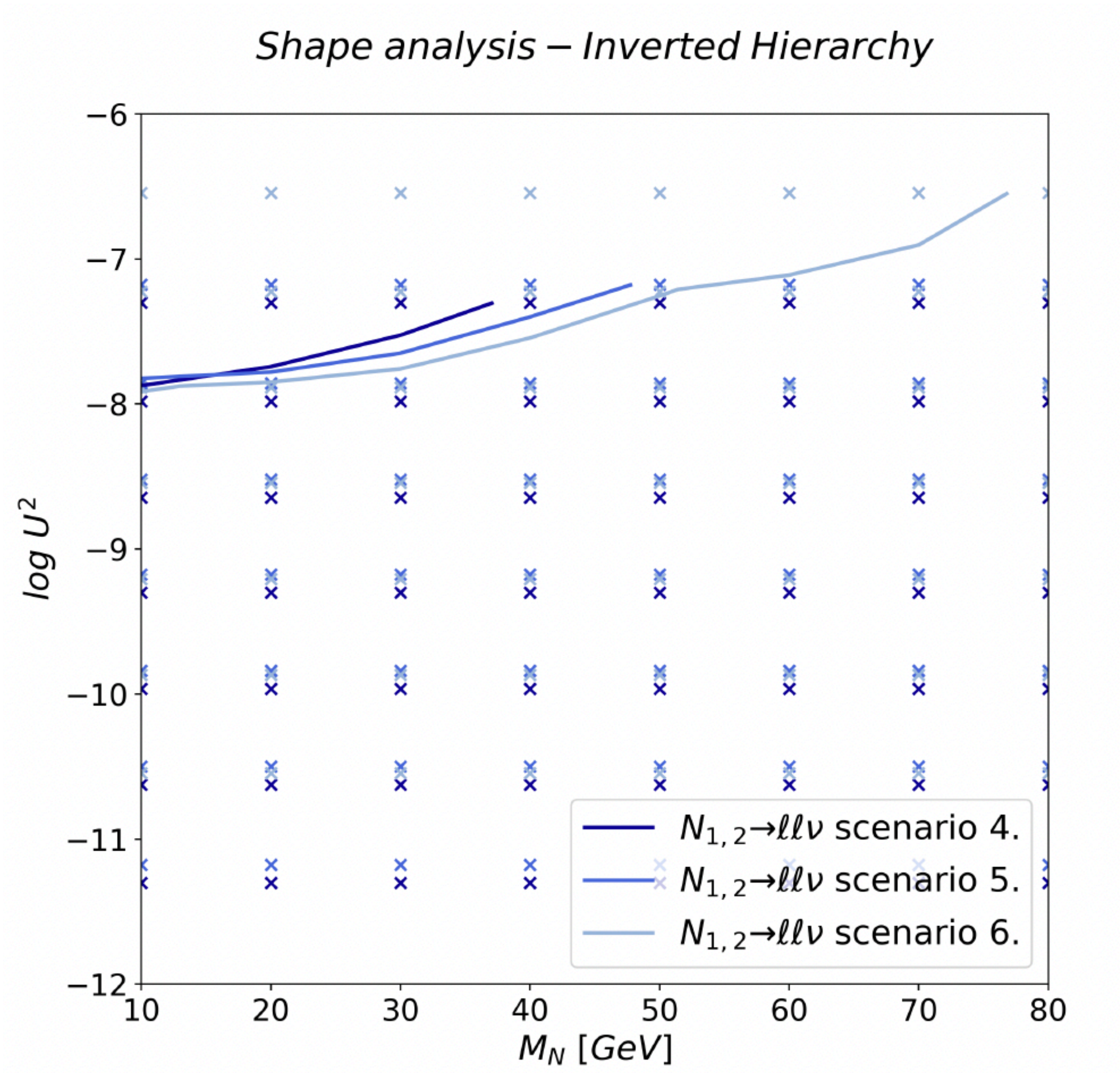
Significance for Inclusive Selection

Statistical significance:

- Shape-based analysis on ΔR with maximum likelihood fit
- Contours showing **5σ significance**
- Sensitivity maximised at low HNL masses and high mixing angles (prompt HNLs)
- Scenario 6 exhibits a mixing pattern most similar to the single-HNL case and offers better space coverage





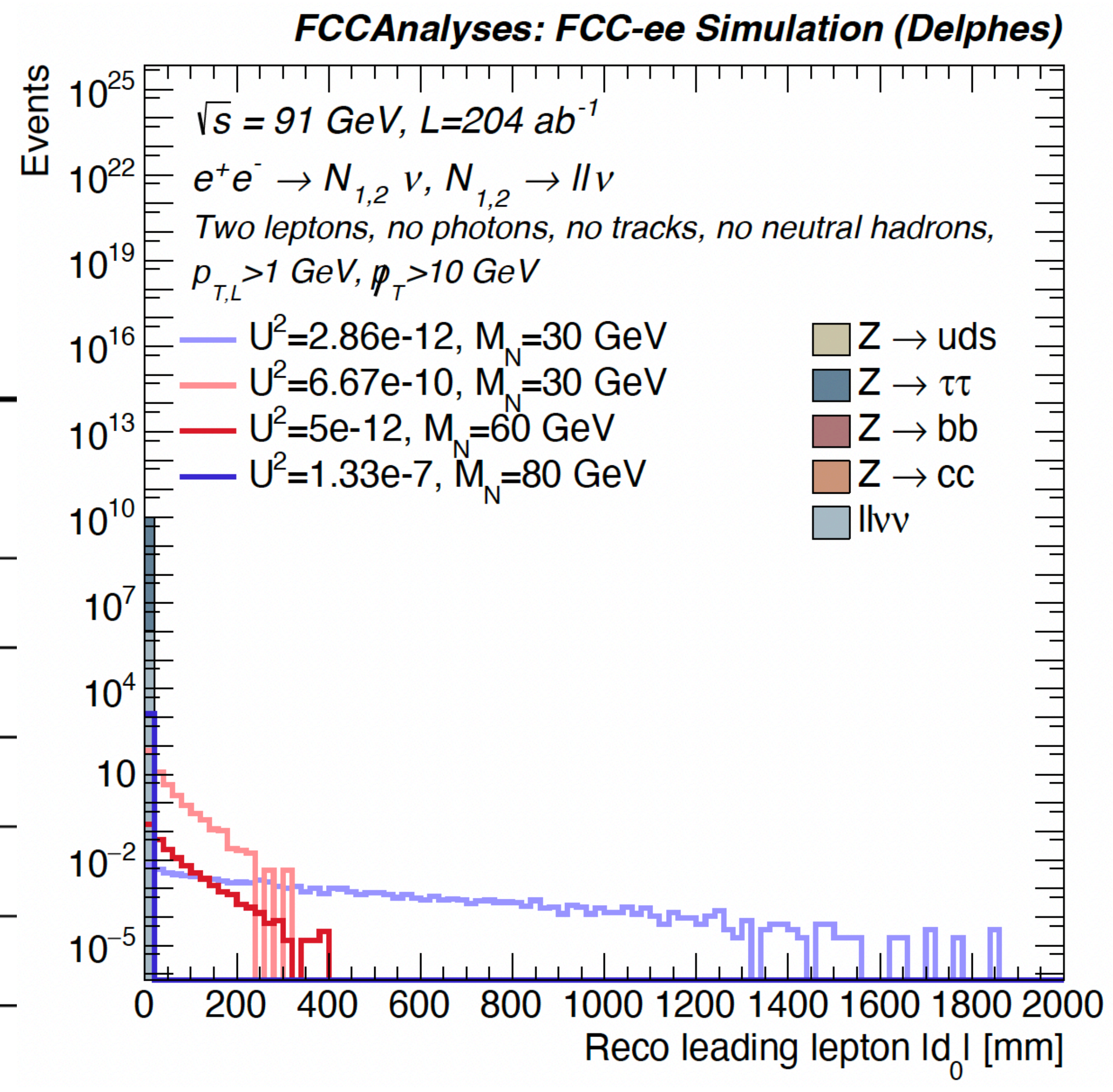
arXiv:2410.03615

LLP Event Selection & Sensitivity

◉ Re-optimized selection

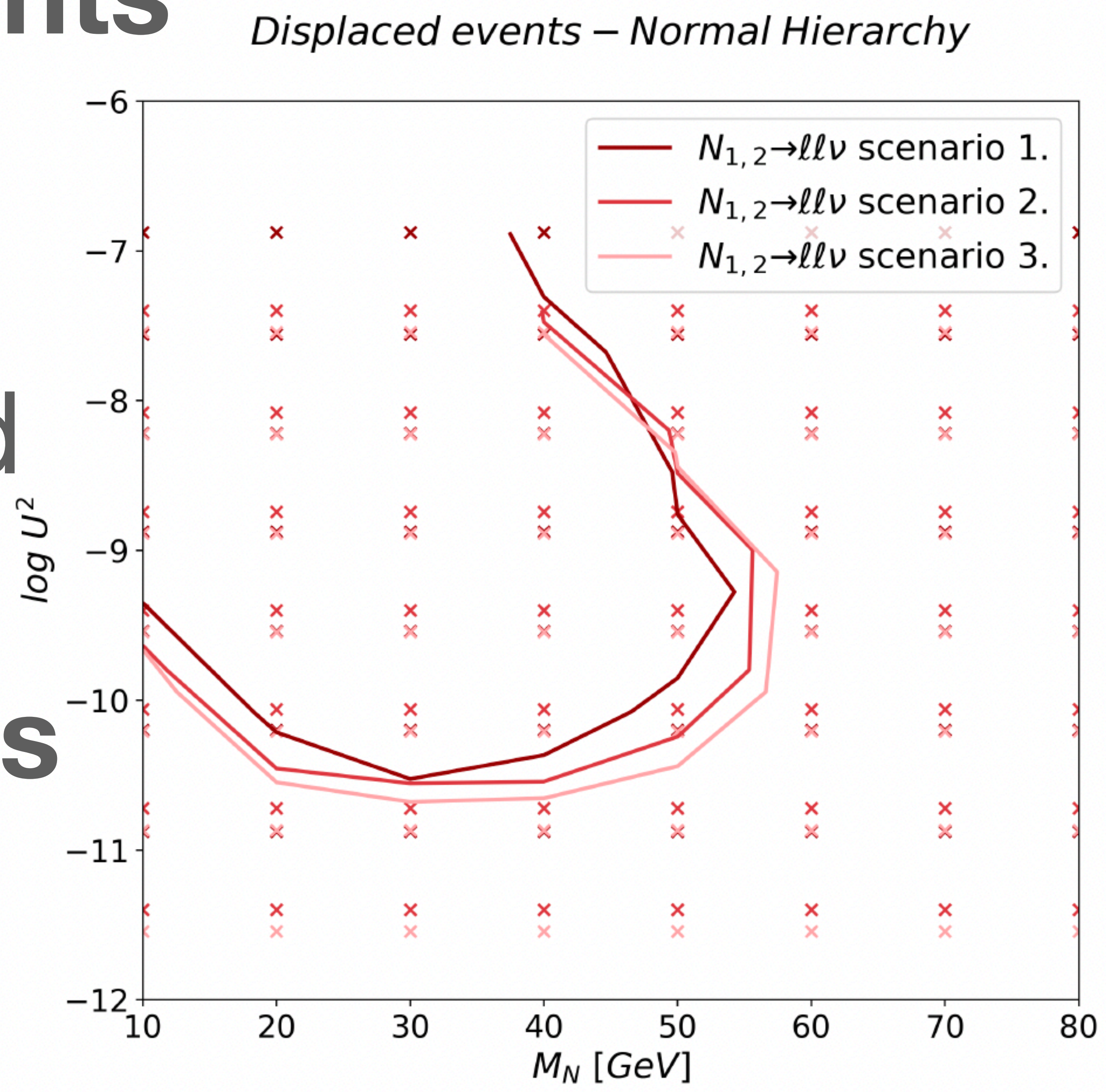
- Depending on their parameters, HNLs can be **long-lived**
- Bkg-free regions for displaced signatures as SM processes are prompt
- Robust cuts on HNL decay vertex variables

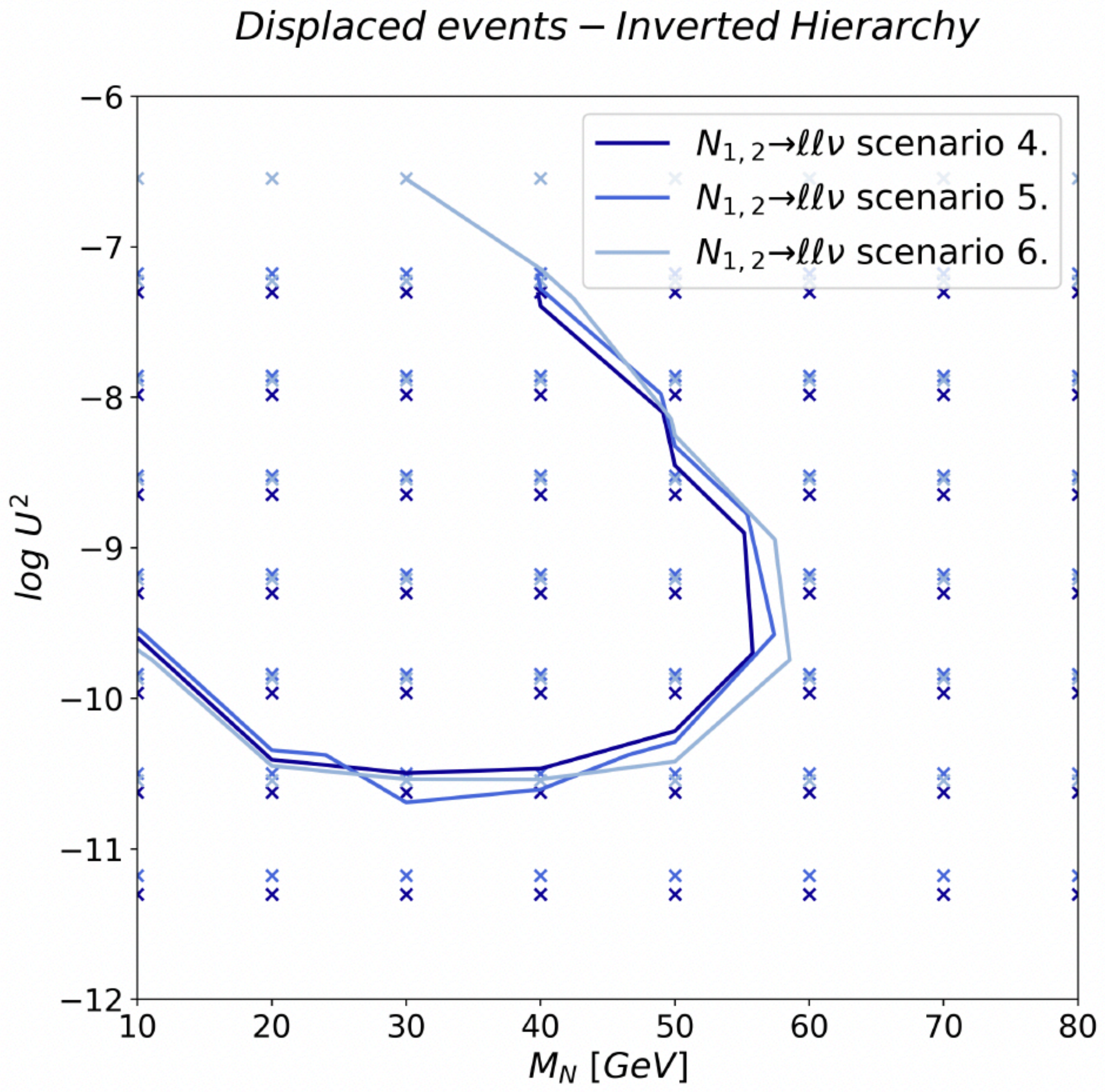
Two leptons, no photons
$p_{T,miss} > 5$ GeV, $p_{T,\ell} > 1$ GeV, $E_\ell > 2$ GeV
No other track and no neutral hadron
$p_{T,miss} > 10$ GeV
$cos\theta_{ll} > -0.8$
$M(l,l') < 80$ GeV
$\chi^2 < 10$
$\lvert d_0 \rvert > 0.64$ mm



◉ LLP Results

- **Contours for four long-live HNL events** demonstrate robust performance across the explored parameter space
- **Lower coupling values** indicate good sensitivity
- Reduced sensitivity for **higher masses** due to shorter lifetimes





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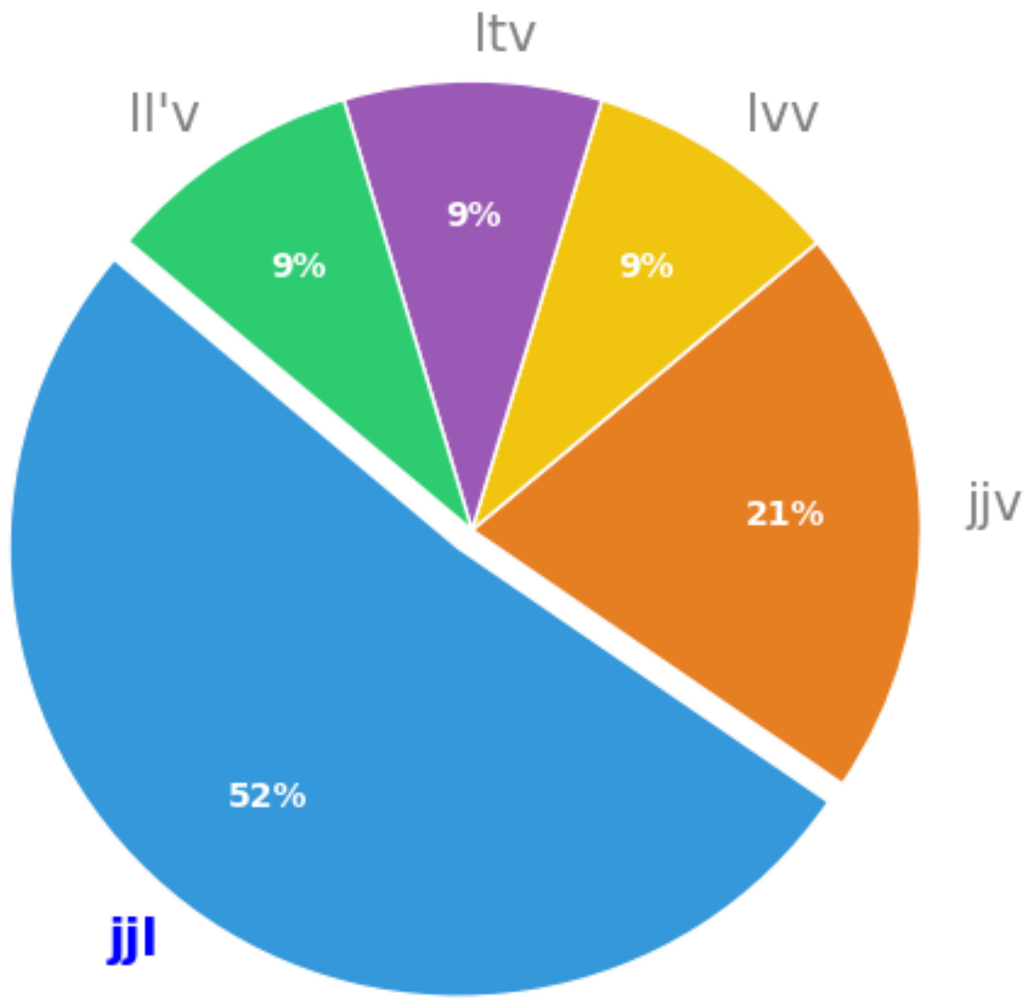
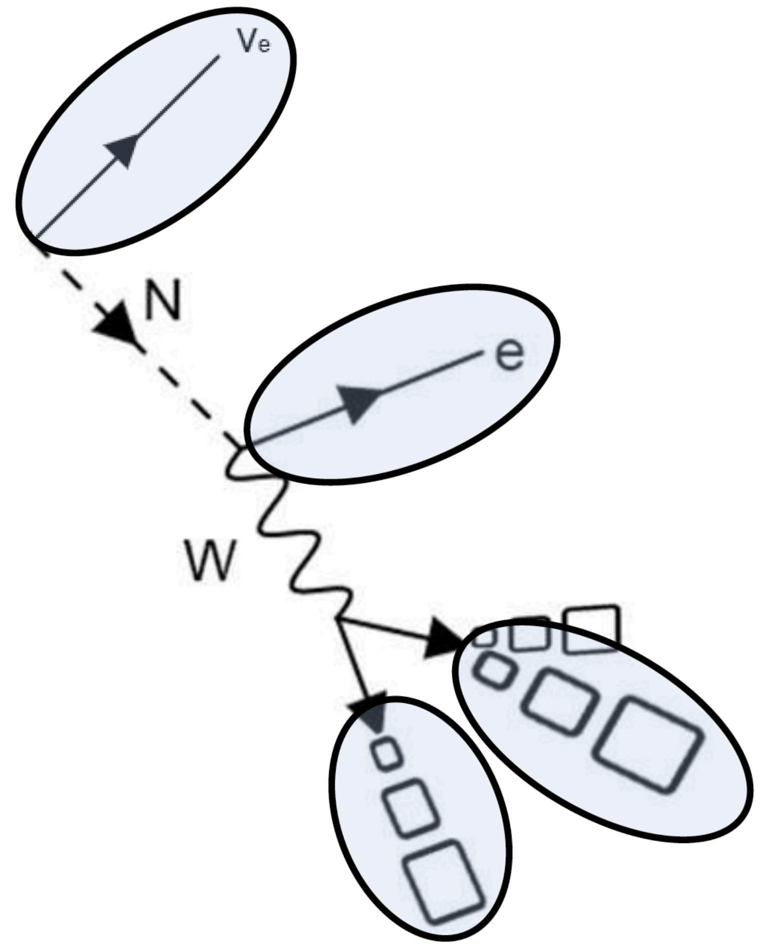
Semi-Leptonic electron Channel with eνjj final state

- **Assuming one HNL flavour**
  - Two parameters characterise the scenario (m_N, U)



- **Large branching fraction (≃ 50%)**
- **Full kinematic reconstruction for a visible final state**
- **Backgrounds:**
  - **Three** dominant SM background processes considered:
    - **Z→bb, cc** or **Z→4 body final state**



Process	σ(pb)	Monte-Carlo events	Production $\mathcal{L}$ (fb^{-1})
$Z \to b\bar{b}$	6.65×10^3	4.39×10^8	6.60×10^1
$Z \to c\bar{c}$	5.22×10^3	4.98×10^8	1.15×10^2
$Z \to$ 4body	1.40×10^{-2}	1.00×10^5	7.14×10^3

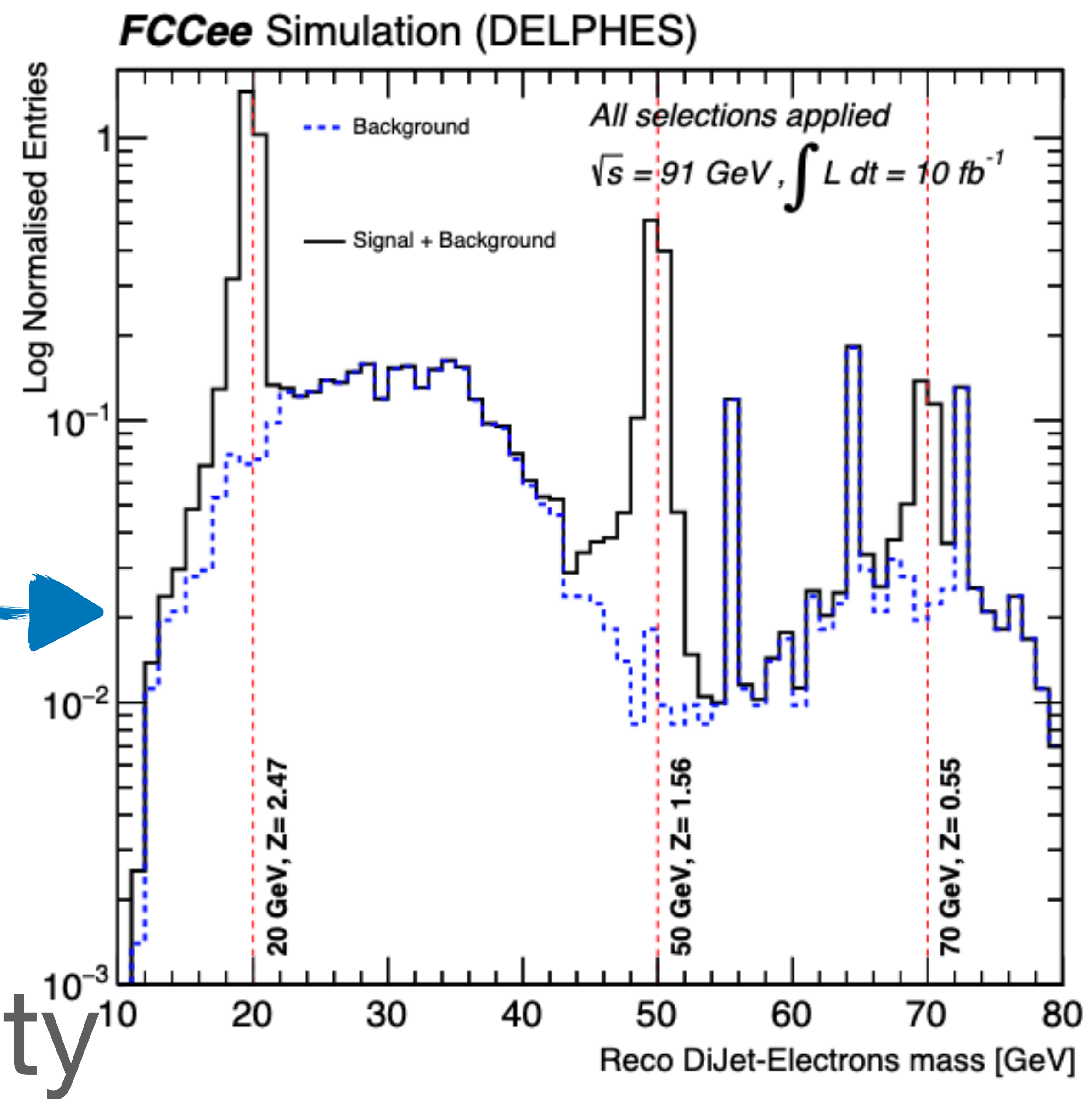
Limited MC statistics for central backgrounds; the analysis is conducted at **10 fb**$^{-1}$

Analysis Methods

◉ Cut & Count Method

- Started with a C&C analysis as the baseline for further optimizations

Variable	Selection
Missing energy	$> 12\,\mathrm{GeV}$
Leading electron energy	$> 35\,\mathrm{GeV}$
3D di-jet Angle	$< 2.4\,\mathrm{rad}$
Di-jet – Electron ΔR	< 3



◉ Machine Learning Methods

- Explored multivariate methods trying to increase the sensitivity

✦BDT Method

- XGBoost in conjuction with TMVA (binary classification)

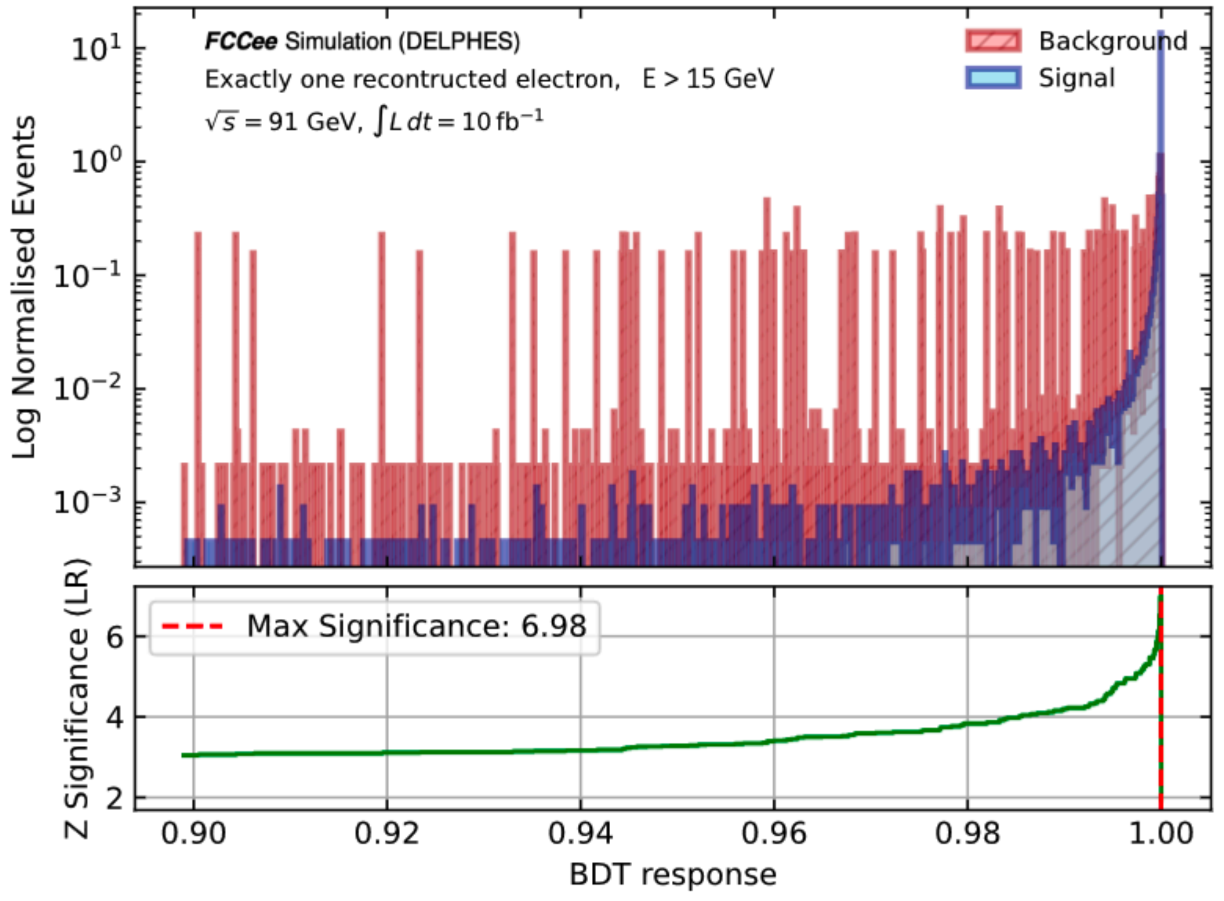
✦DNN Method

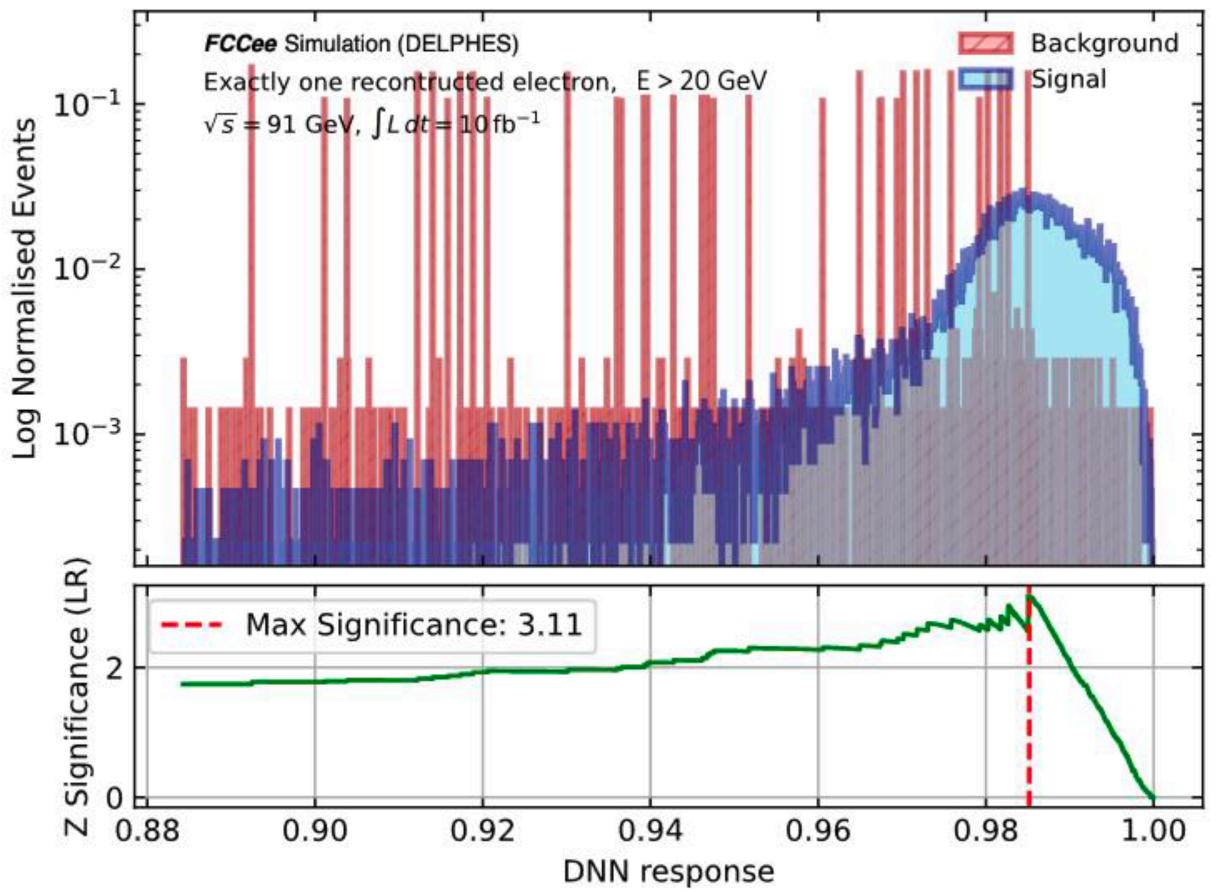
- Keras in Tensorflow with hyperparameter optimization (binary classification)

Object	Variables
Leading electron	$E, \phi, d_0, \sigma_{d_0}, \Delta R_{ejj}$
Neutrino	$E_{\mathrm{miss}}, \theta$
Di-jet system	$\Delta R_{jj}, \phi$
Vertex and tracks	$n_{\mathrm{tracks}}, n_{\mathrm{primary\ tracks}}, \chi^2_{\mathrm{vertex}}$

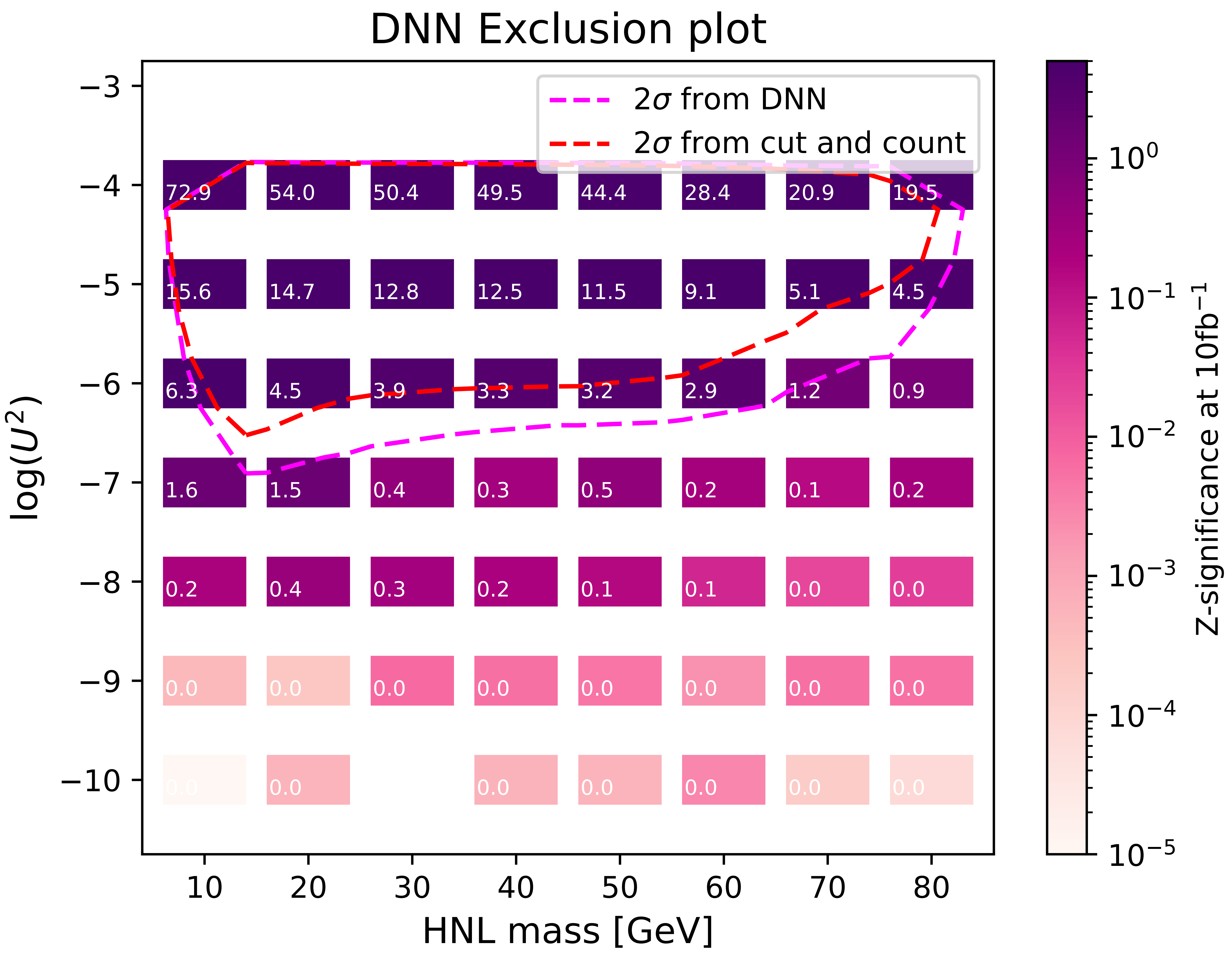
Variables used for the trainings

BDT & DNN response examples





Sensitivity Comparison

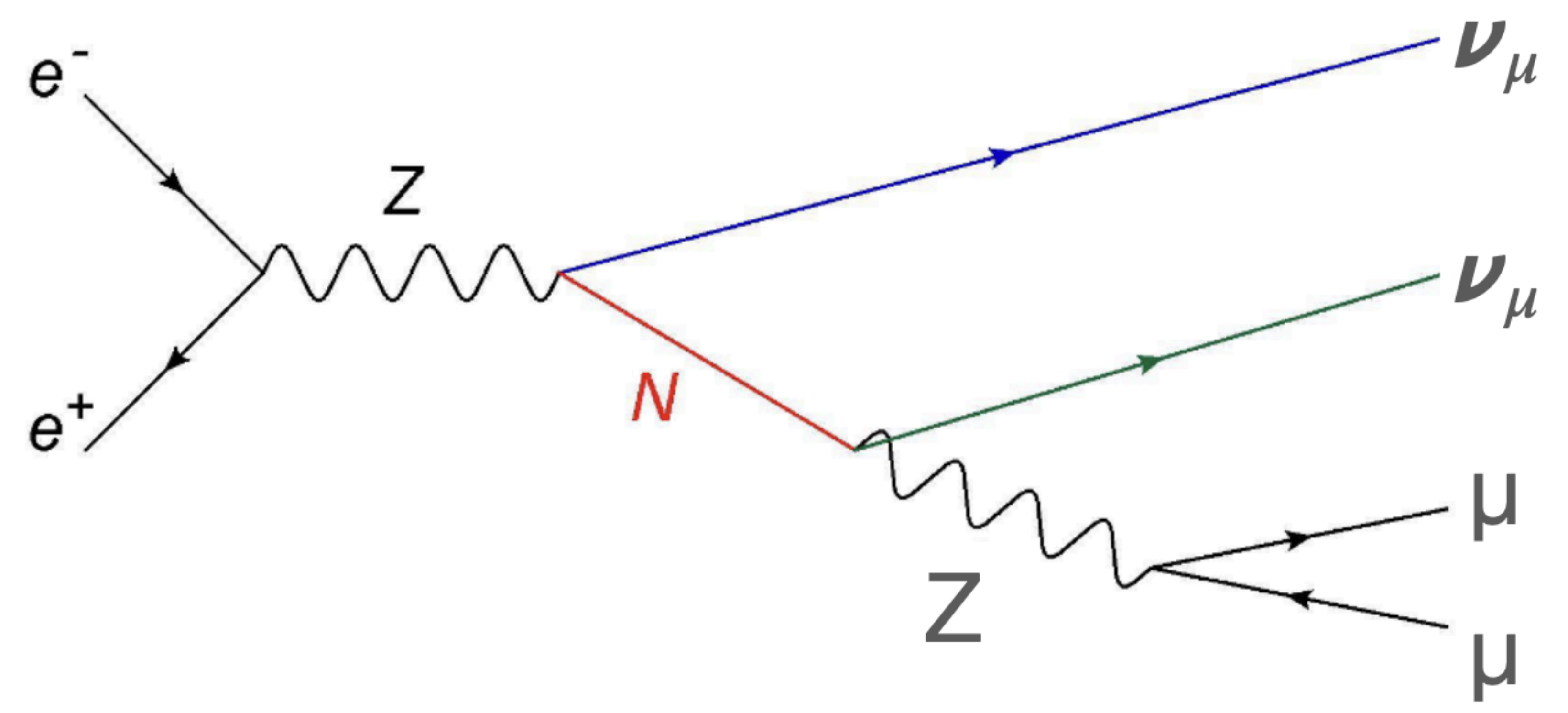


- **Results shown at an integrated luminosity of 10 fb^{-1}**
- **The current DNN model achieves about an order of magnitude improvement in sensitivity over the C&C method**
  - Leveraging more advanced architectures and robust hyperparameter tuning can further boost performance
  - Continued development and optimization efforts are ongoing

HNLs decaying to muon pairs and neutrinos

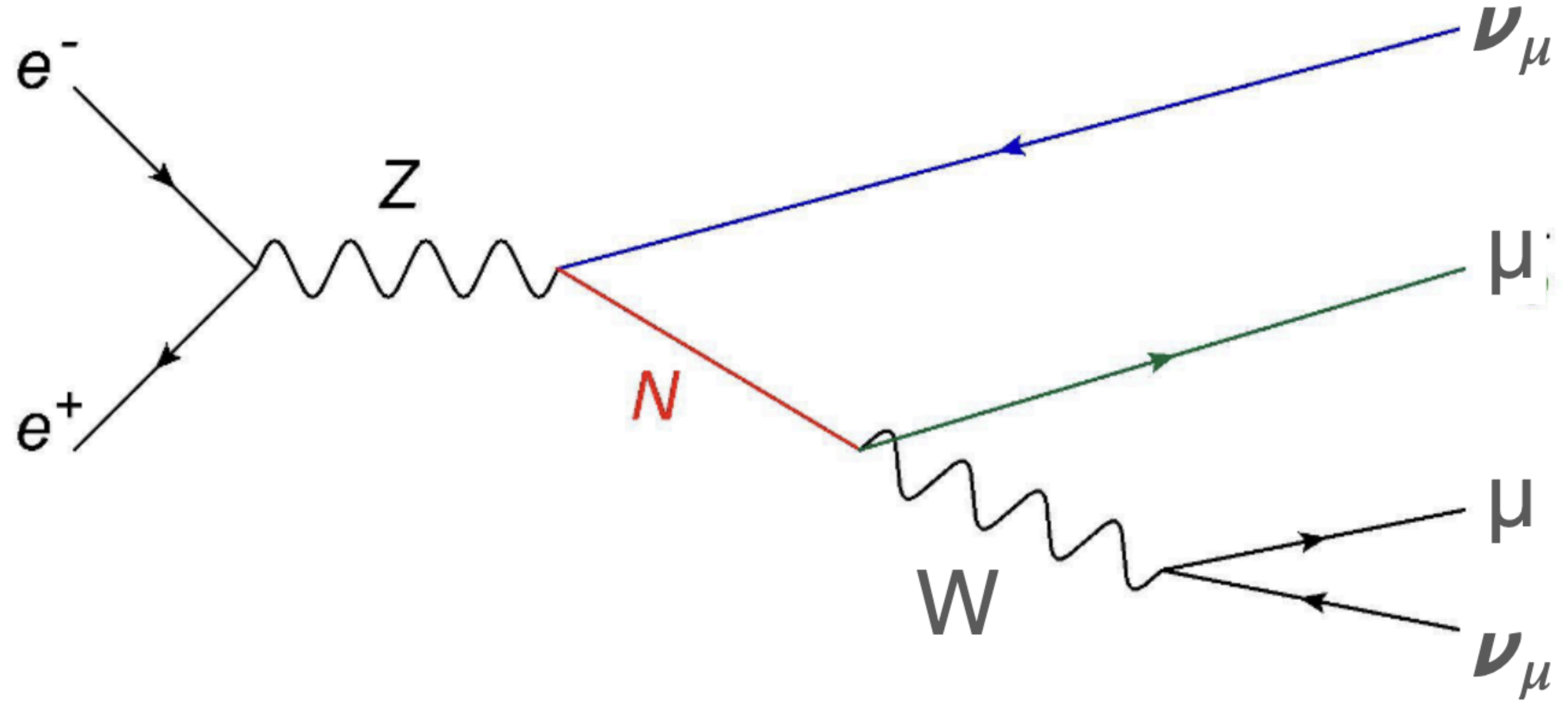
◉ Scenario where Majorana HNLs have non-zero mixing coupling exclusively for ν_μ

- Targeting HNLs decaying into μμν final states
- Leveraging LLP signatures



◉ Goals:

- Evaluate HNL sensitivity in a large mass (10-50 GeV) and mixing angle range (10^{-2}-$5 \cdot 10^{-6}$)
- Explore LLP topology for better discrimination power



◉ Minimal requests for event preselection:

- **Exactly two tracks** in the central detector reconstructed as **muons** with **p > 3 GeV**

Analysis Strategy

Signal Generation:

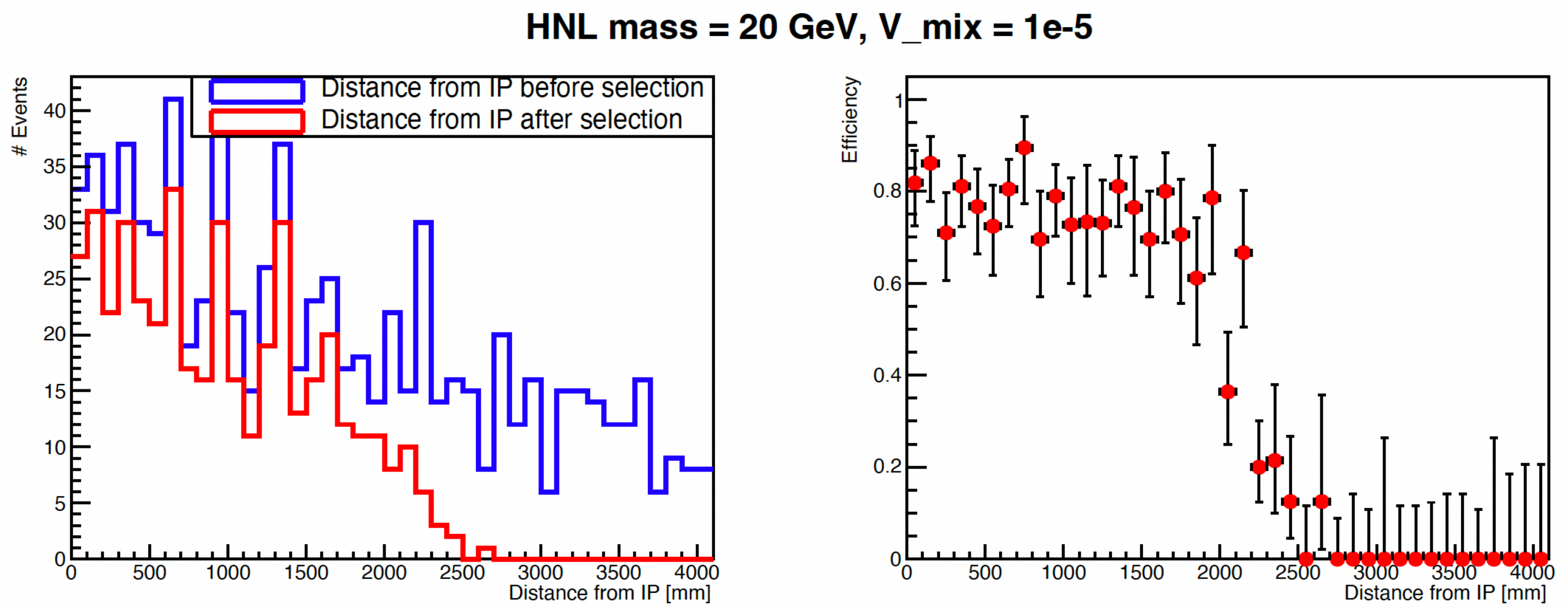
- Simulated using IDEA detector performance (MG5, PYTHIA8)

Backgrounds:

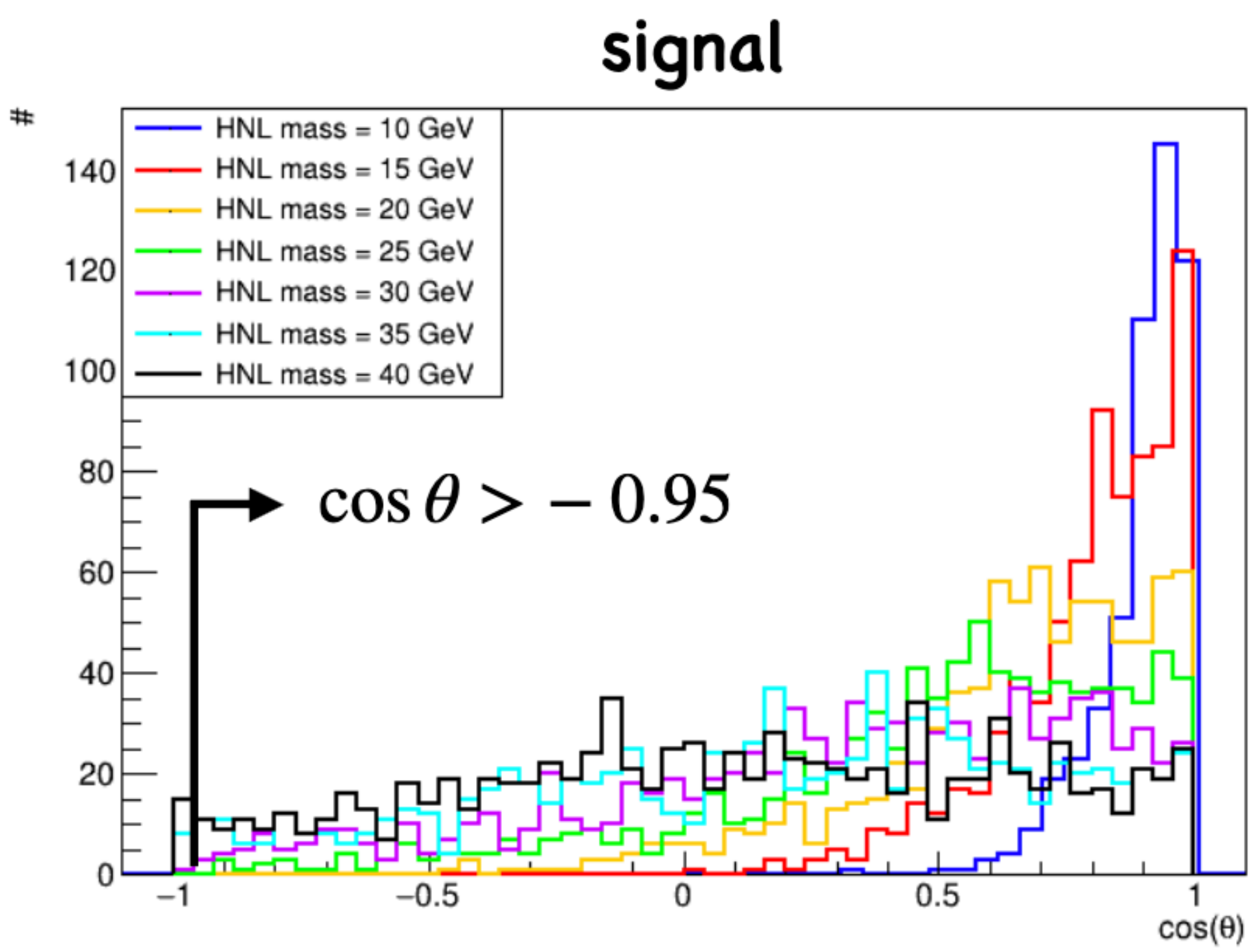
- Dominated by **Z→μμ, Z→ττ** and heavy flavour decays (**bb,cc**)

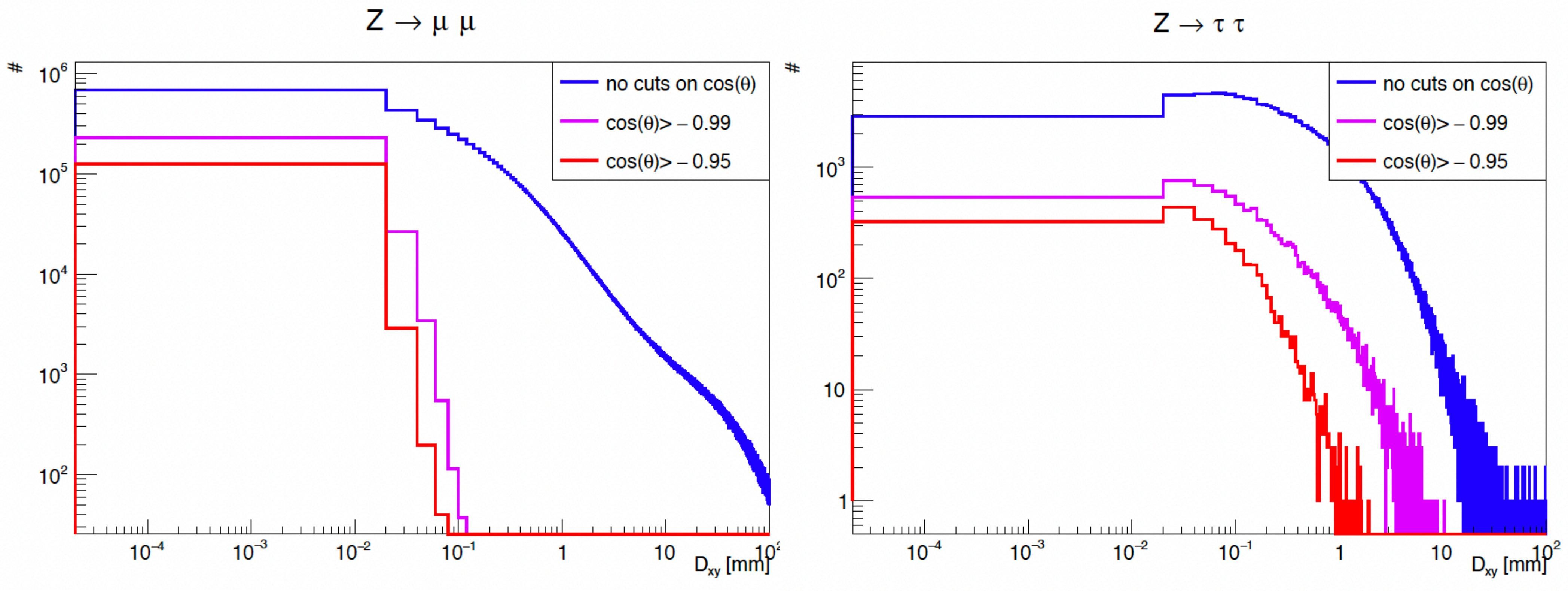
Selection Criteria (after preselection):

- Optimised search based on the distance from the 2-μ decay vertex to the IP (D_{xy})
  - **D_{xy} > 10mm**



- Also applying cuts on cos(θ) (angle between two muons) further increases the sensitivity
  - **cos(θ) > -0.95**





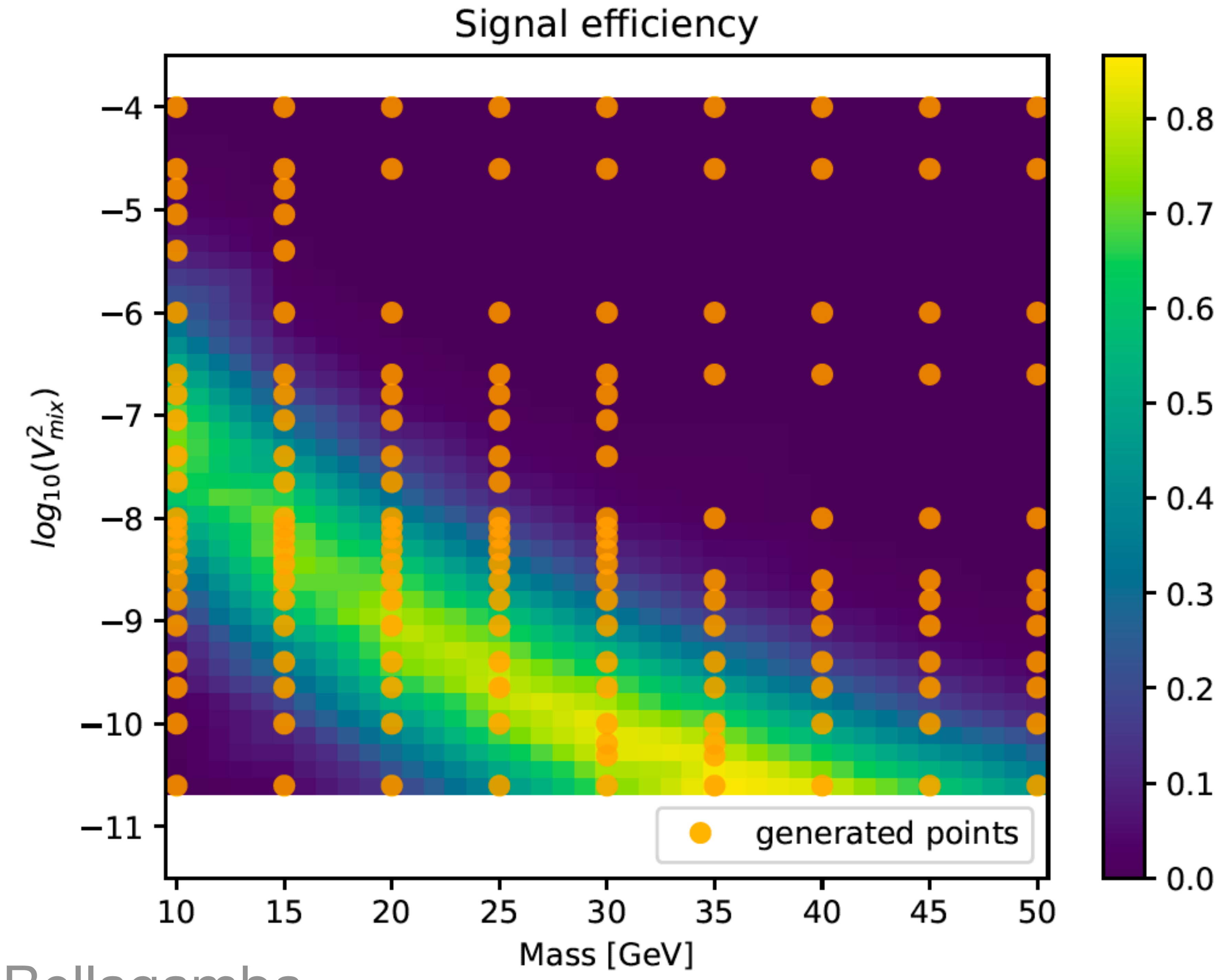
Efficiency & Sensitivity

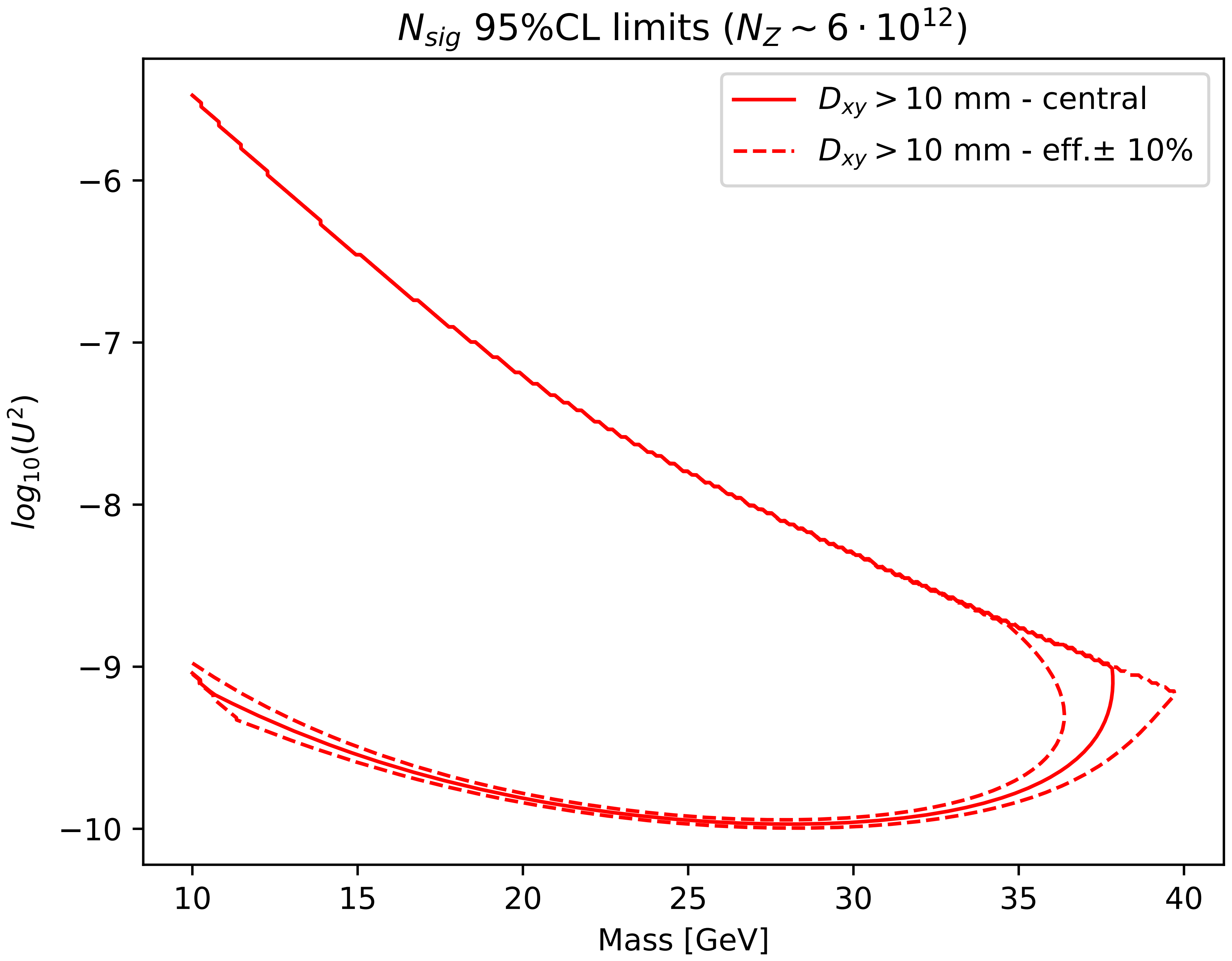
Signal Efficiency:

- Evaluated after parameterizing efficiencies for each point vs $\log_{10}(c\tau)$ using Gaussian fit

Sensitivity:

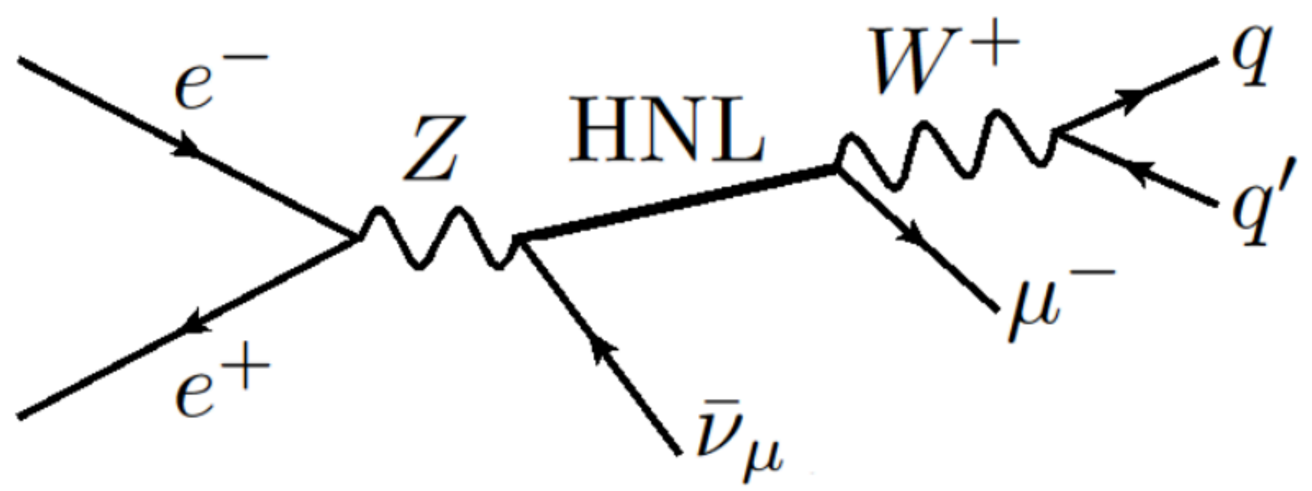
- Interpolation between the points performed using linear fit on the Gaussian fit parameters
- Results obtained assuming negligible background and no observed events
- Significant improvement over HL-LHC predictions





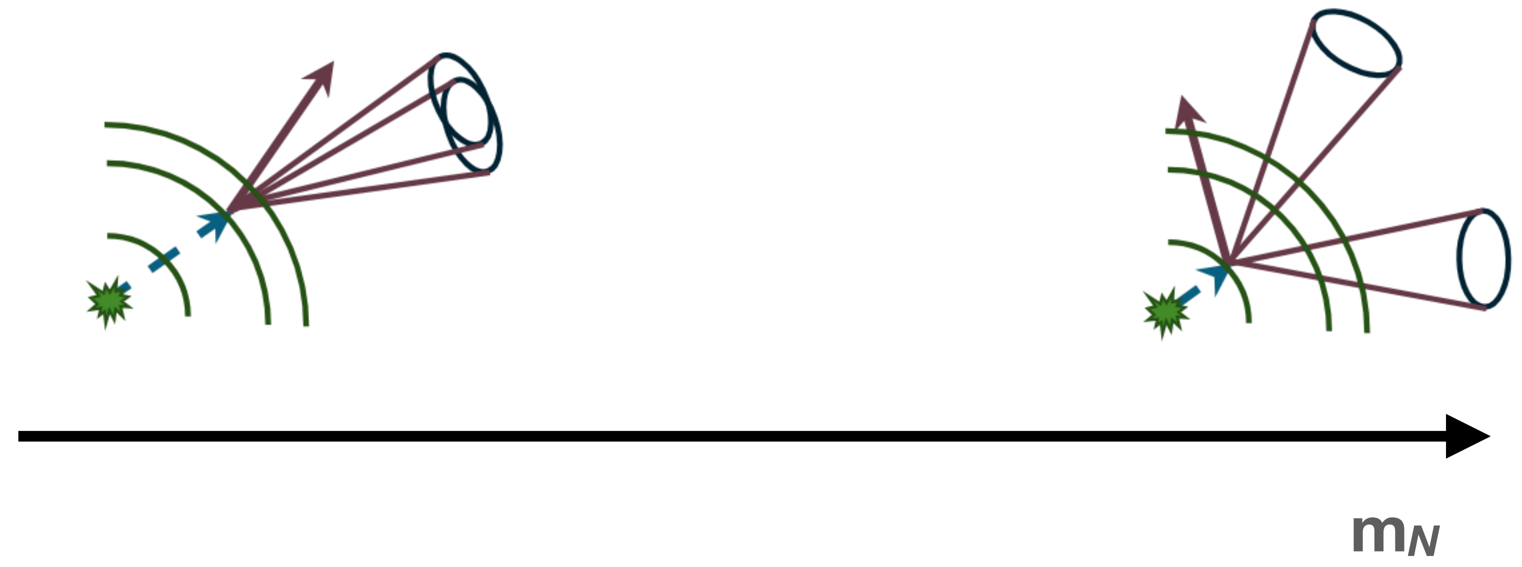
Semi-Leptonic muon Channel with μνjj final state

◉Same high branching fraction as e-channel analysis (~50%)



◉Discovery feasible across a broad spectrum of parameters space

- Low mass → (Delayed) signals likely to display a one-jet signature
- High mass → (Prompt) signals has the two jets well separated



◉Base event selection

- Two different SRs depending on n_{jets}
- For each region: Utilised dedicated kinematic variables providing good discrimination

Analysis Flow - Selections

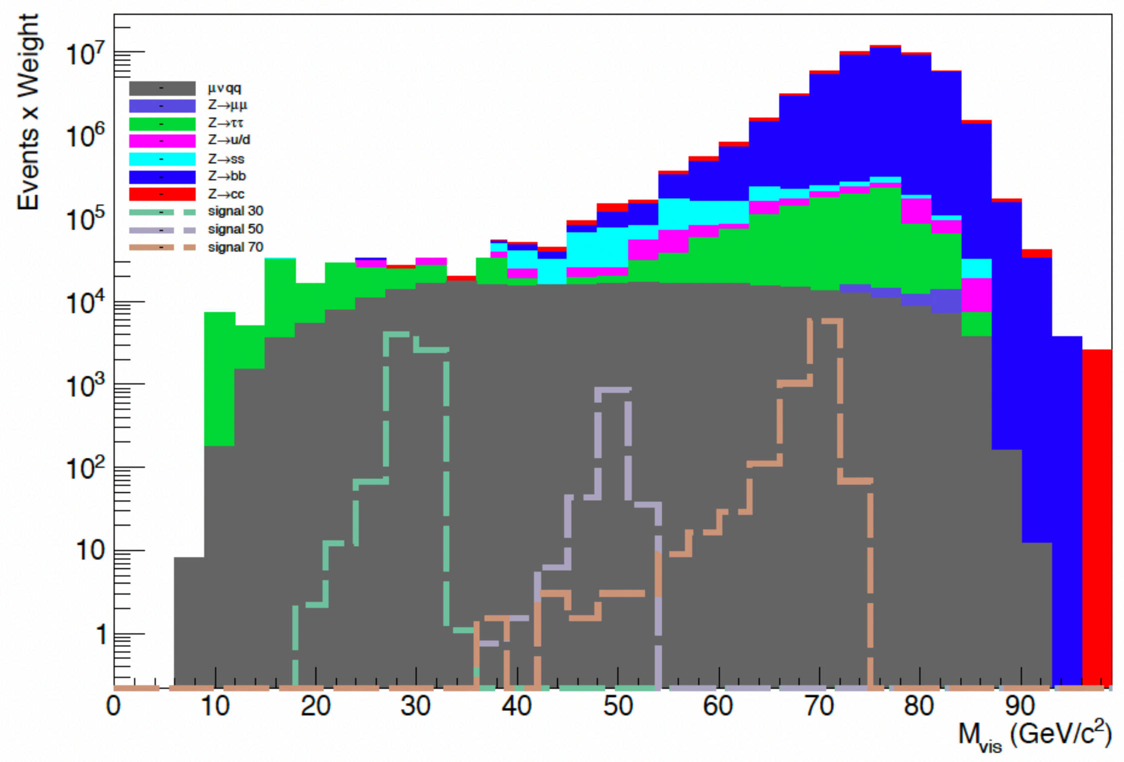
Vertex-based selection:

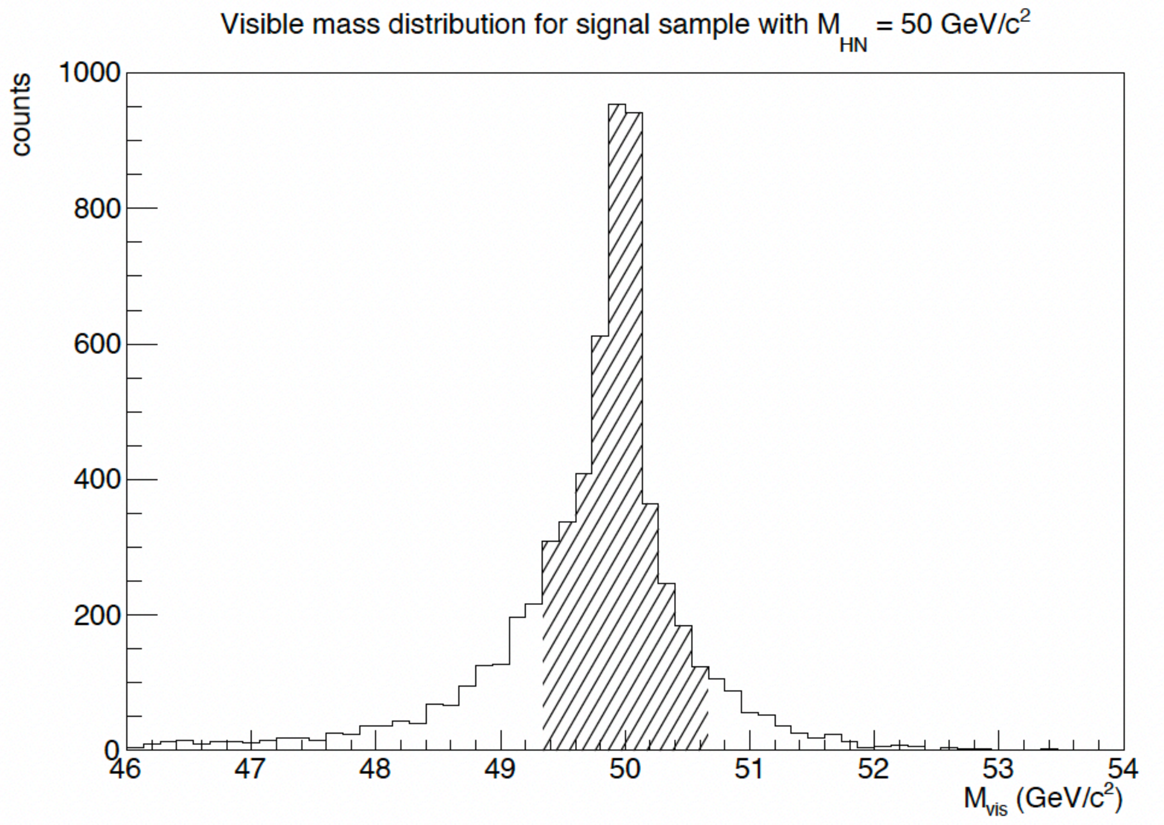
- Require a well-reconstructed primary vertex, utilizing most of the available tracks for its reconstruction →

$$N_{tracks} - N_{tracks}^{primary} < 5$$
$$\chi^2_{vtx,primary} < 10$$

Mass-dependent selection

- Require visible HNL mass and missing energy to be within 2x of the resolution in distributions →





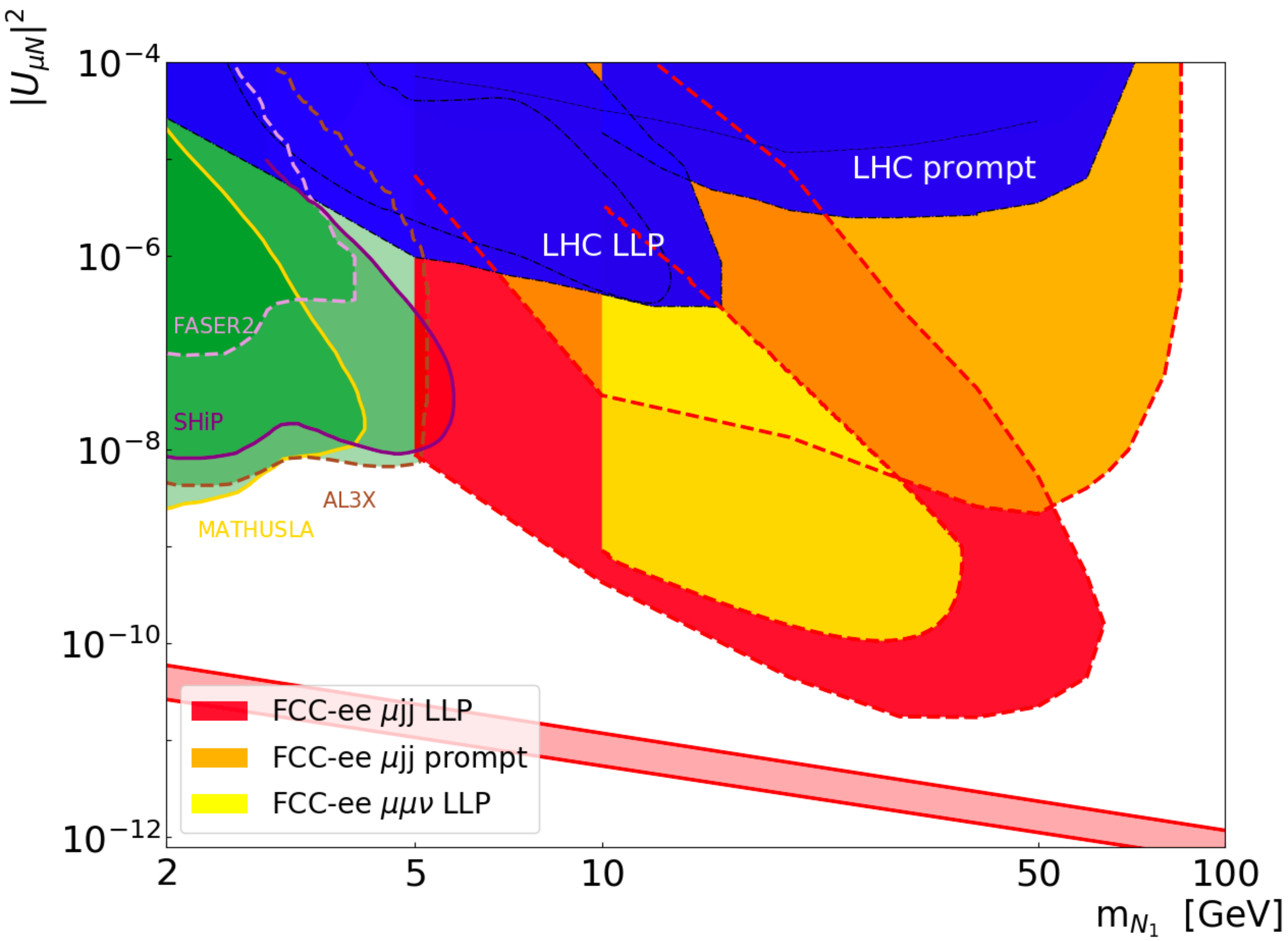
Prompt vs Long Lived selection

- Choose transverse position of PV so as backgrounds become zero:

$$r^{primary}_{vertex} \leqslant 0.5\ \text{mm}$$

Analysis Sensitivity

- **A minimal selection is applied in the long-lived analysis to ensure that no background remains for the long-lived regime**
- **Poissonian statistics used for the expected number of events**
- **Sensitivity surpasses HL-LHC theoretical projections for a similar mass range**



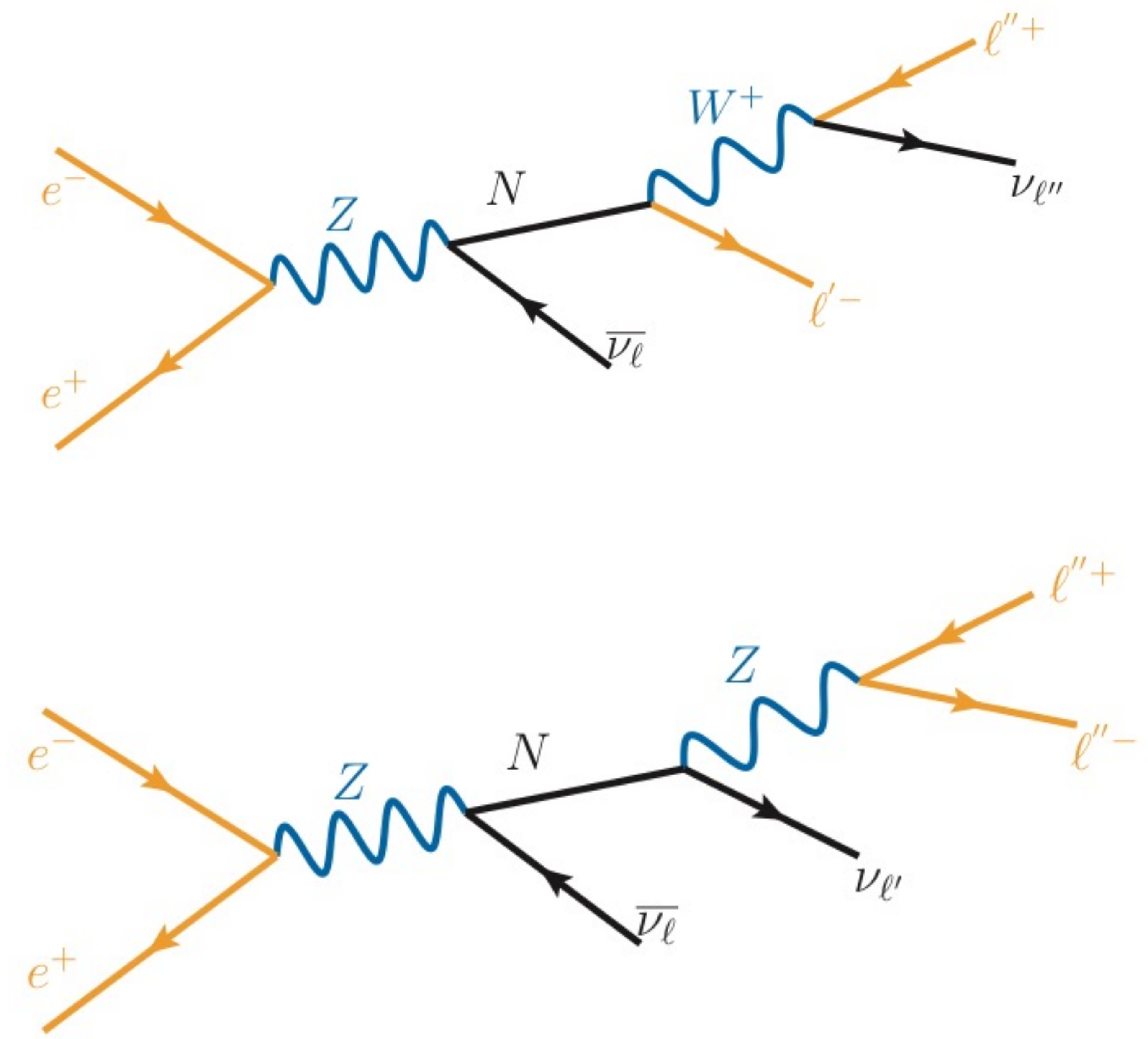
HNLs decaying to electron pairs and neutrinos

◉Consider scenario where HNLs only have non-zero mixing with ν_e

- Focus on long-lived scenario and extend work performed for snowmass (Front. Phys. 10:967881 (2022))

◉Goals:

- Study updated (Winter23) signal and background samples using IDEA detector
- Calculate sensitivity for a background-free search requiring exactly one SV

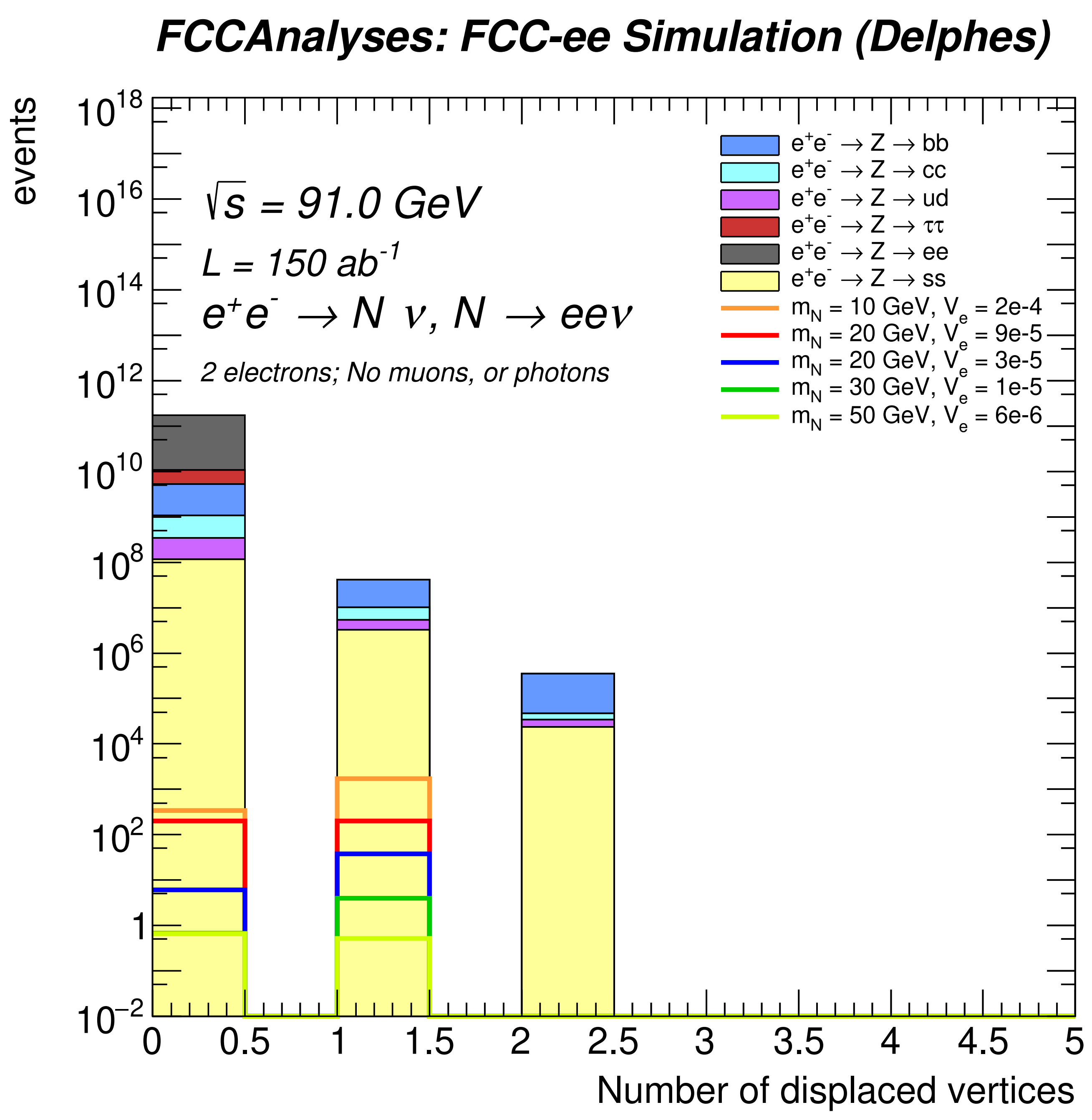


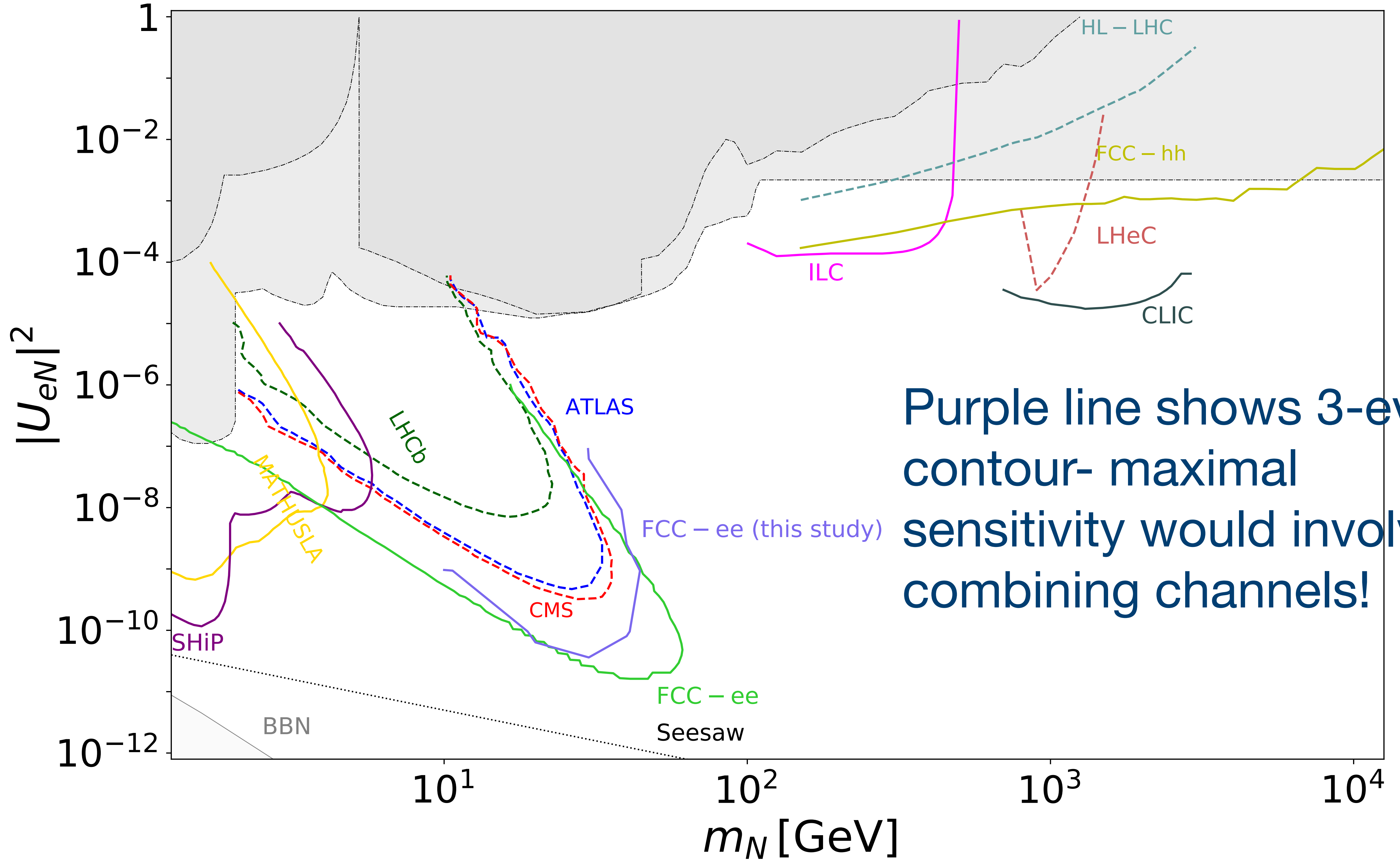
Caveat: work still needed to further verify background-free assumptions and/or perform further optimization. These studies will exploit skimmed MC samples!

Results and Sensitivity

- Background-free search could be performed by vetoing jets, muons and electrons and placing requirement of 1 displaced secondary vertex (reconstructed with tracks with $|d_0|$>2mm).

- Provided 2-page summary for ECFA e^+e^- study updated yields for 205 fb^{-1}:





Purple line shows 3-event contour- maximal sensitivity would involve combining channels!

Summary & Outlook

- **Outstanding potential of FCC-ee for directly exploring BSM signatures in both prompt and long-lived channels**

- **Diverse signals: HNLs, ALPs, unconventional Higgs decays, and more**

- **HNL exciting channel for BSM searches in FCCee**
  - Analyses show sensitivity to very small mixing angles
  - Integration of prompt and LLP signatures offers complementary coverage of the entire parameter space

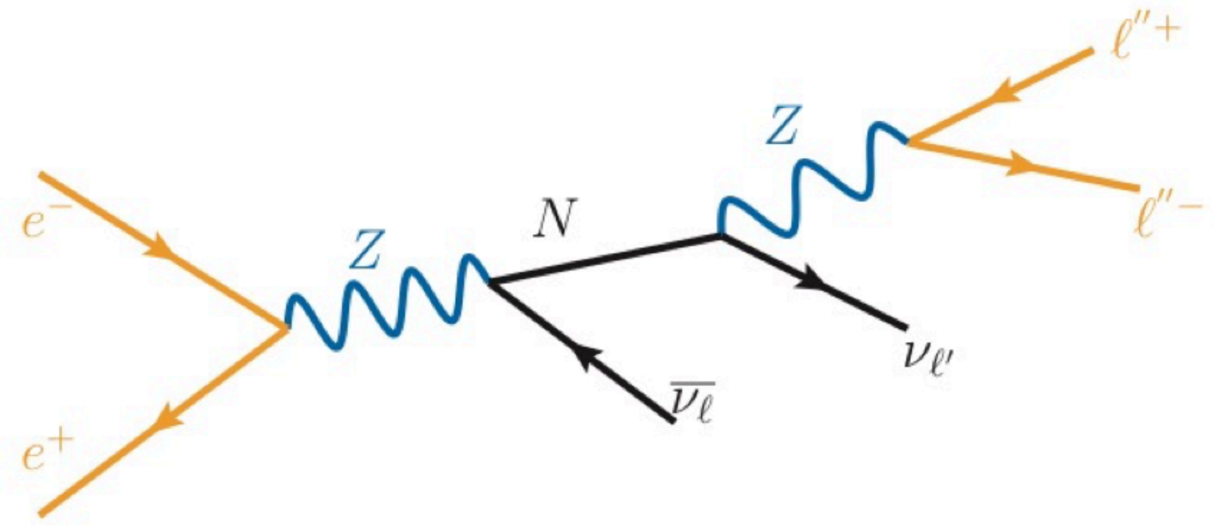
- **Intensive efforts are underway to optimize sensitivity for benchmark signals**

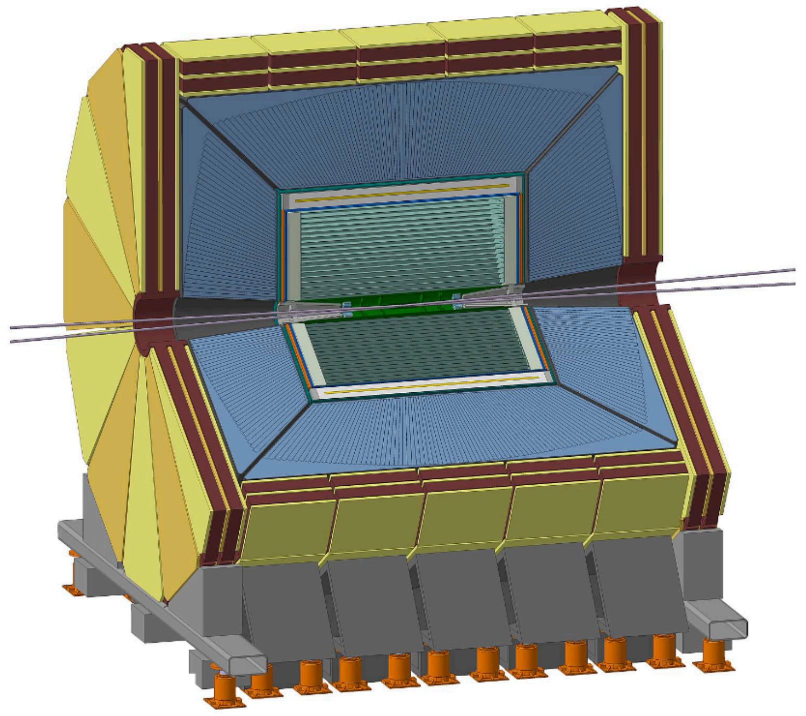
Backup Slides

Event Generation & Workflow

Process Card
(M_N , V_{eN}, N_{events})

Monte Carlo
MadGraph HeavyN models





Detector Simulation + Hadronization
DELPHES + PYTHIA8

Process Card
(Detector parameters,
Custom objects)

Custom Variables,
Event Selection

Analysis
FCCSW Framework

Plotting

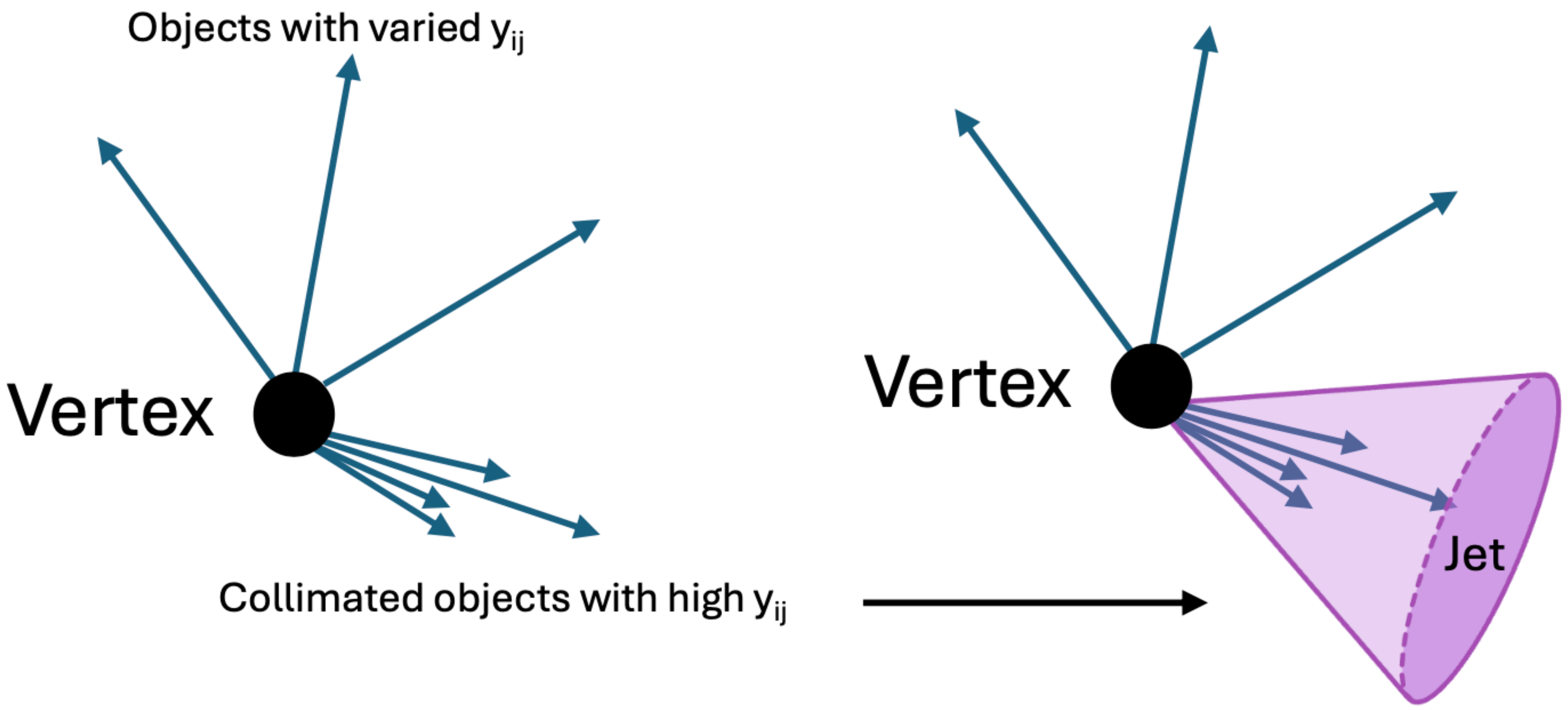
Conduct FCC case studies utilising the “official” analysis tools and framework provided for the FCC

Jet algorithms

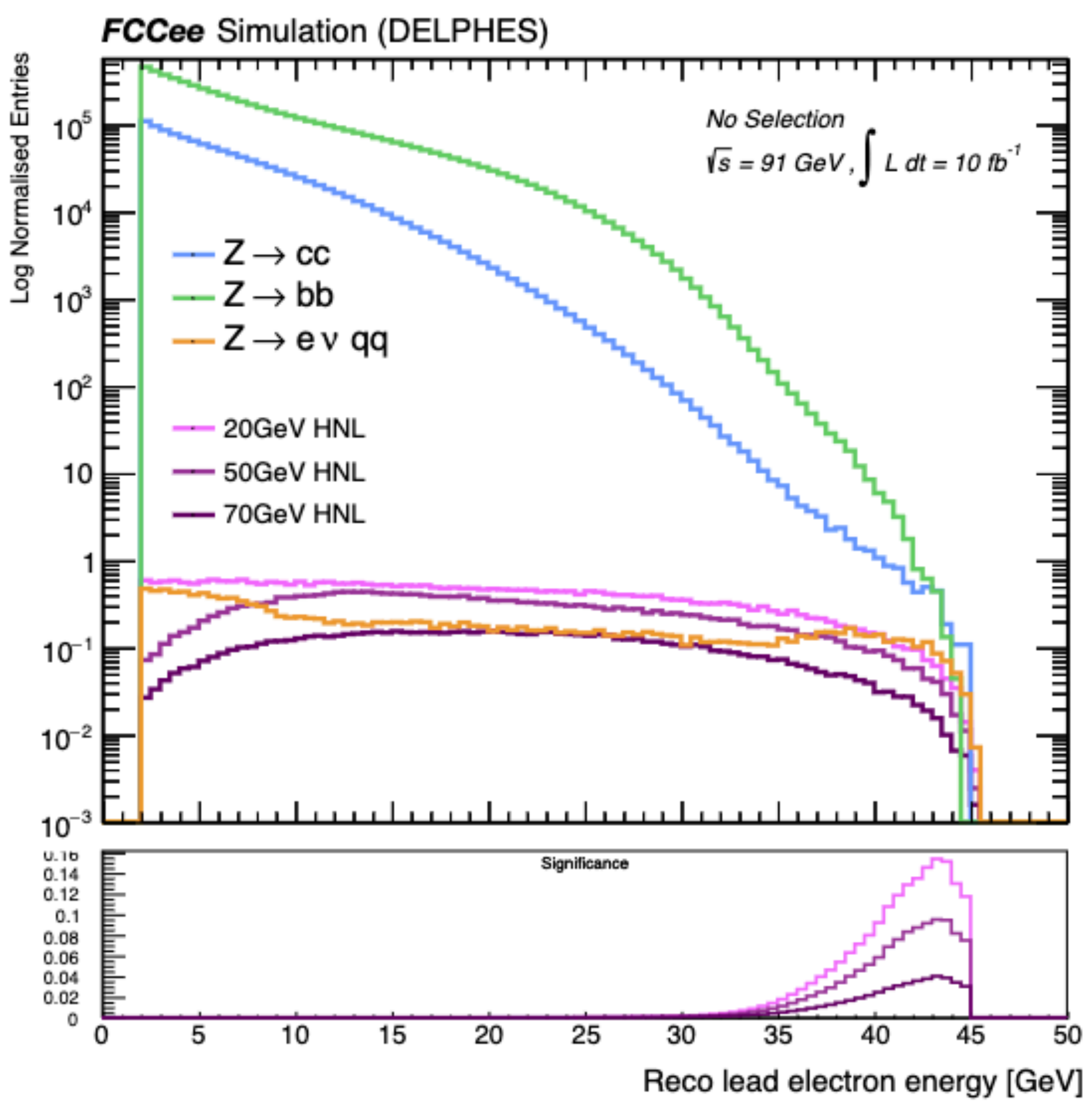
- Jet reconstruction was primarily conducted using the FastJet software, rather the initial event generation phase with Pythia

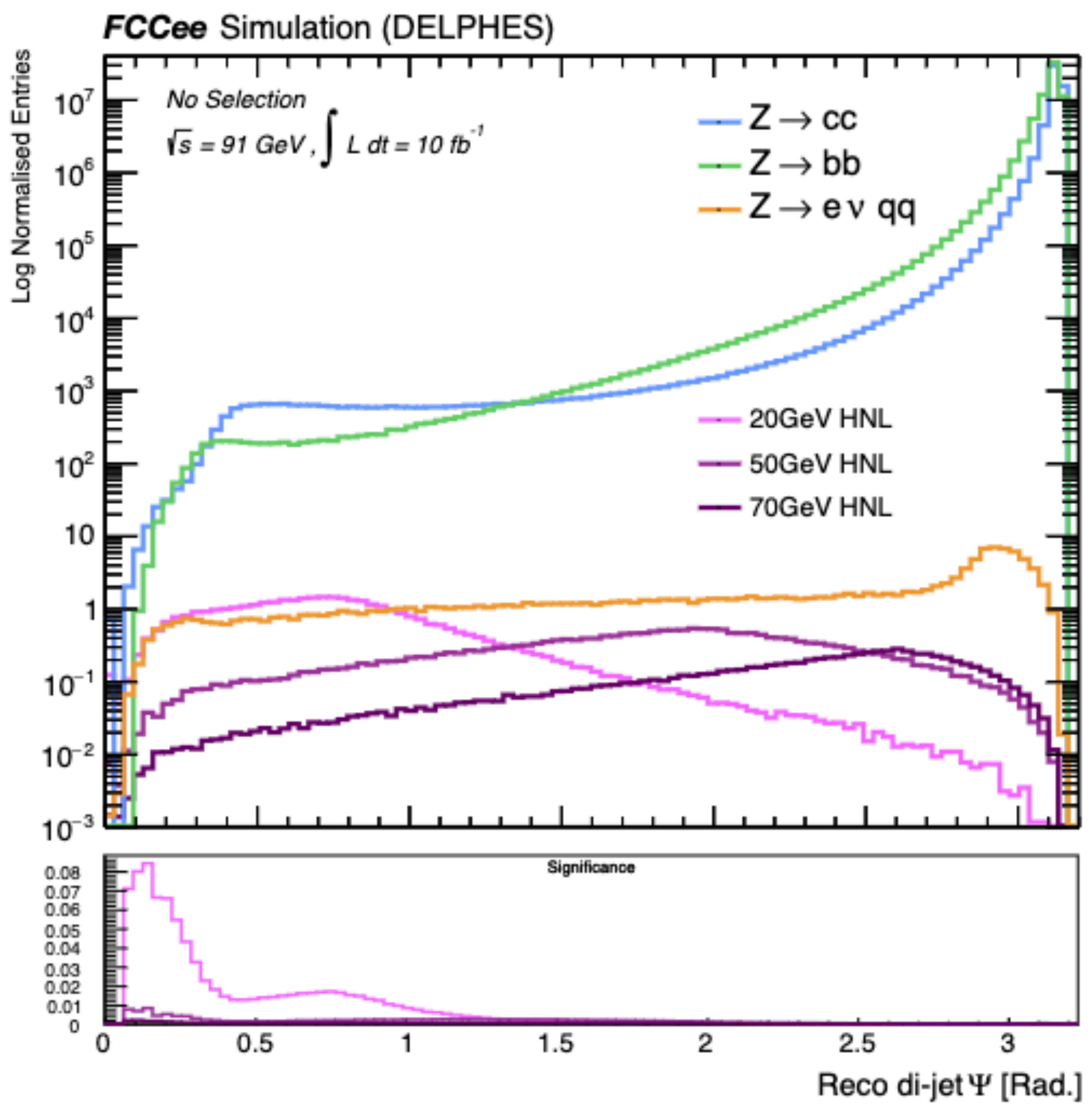
- This approach was chosen for the enhances control and adaptability it provides when working directly with particle data from the EDMHEP files

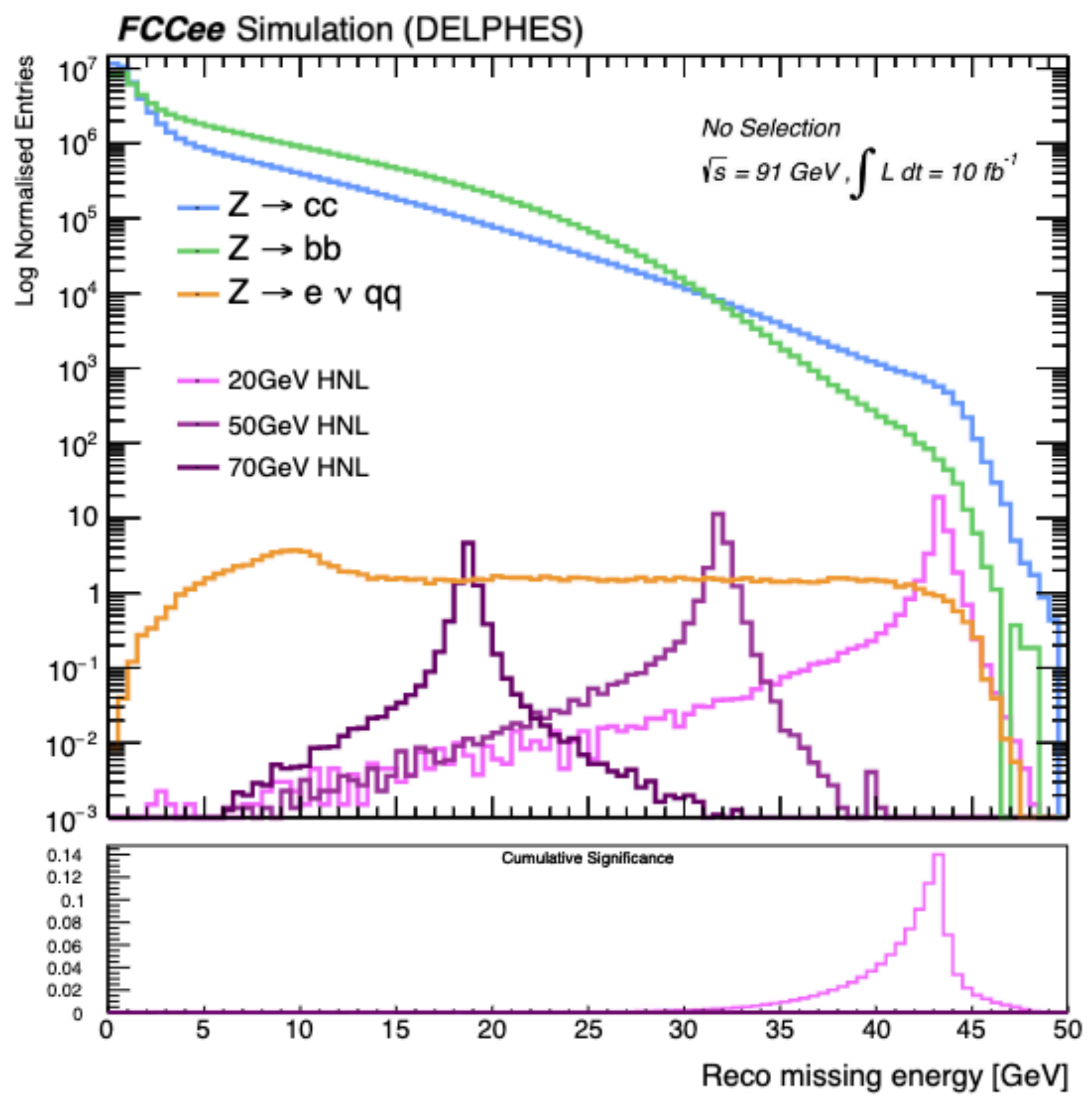
- The **Durham jet algorithm** was used for the clustering jets

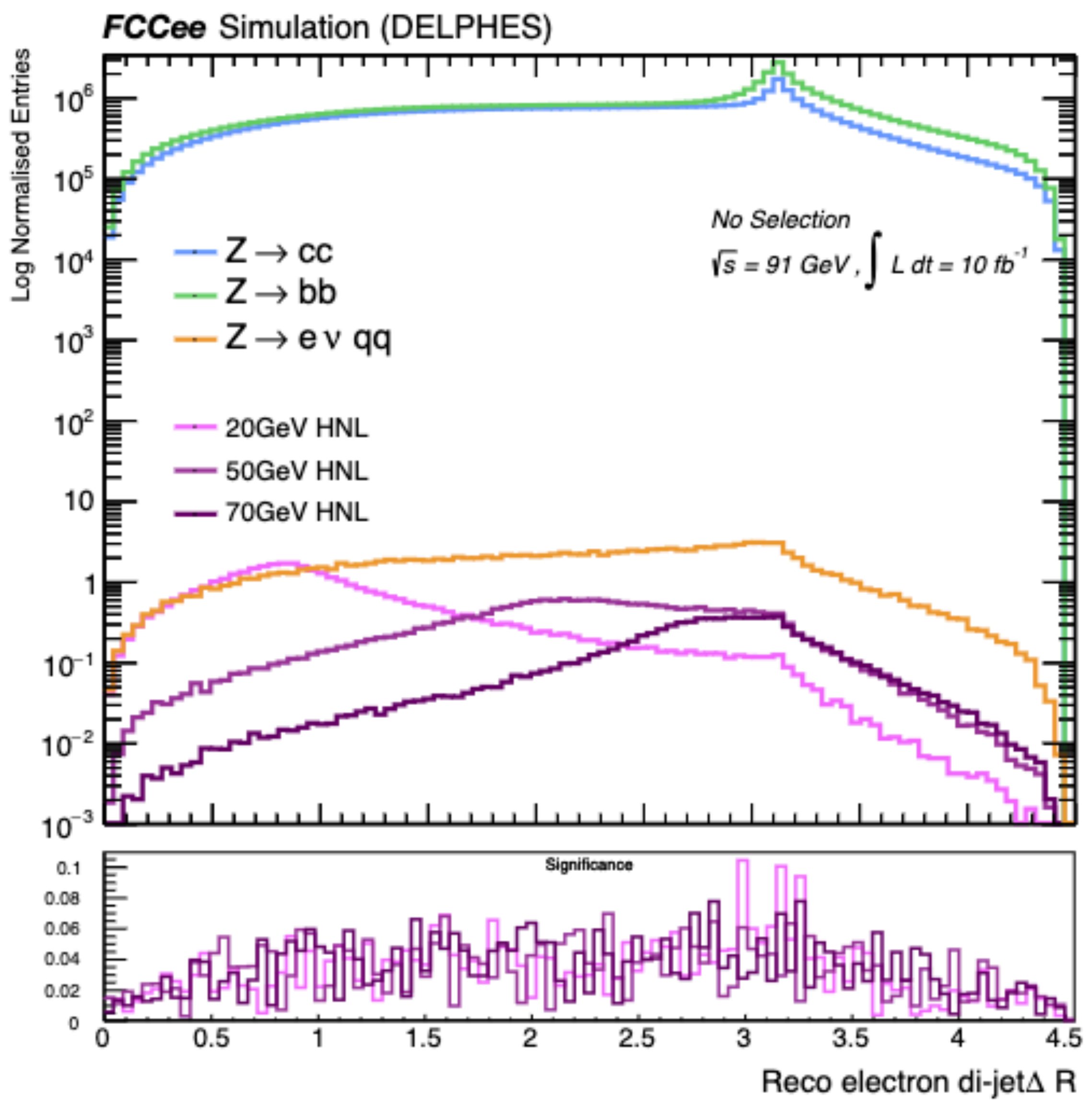


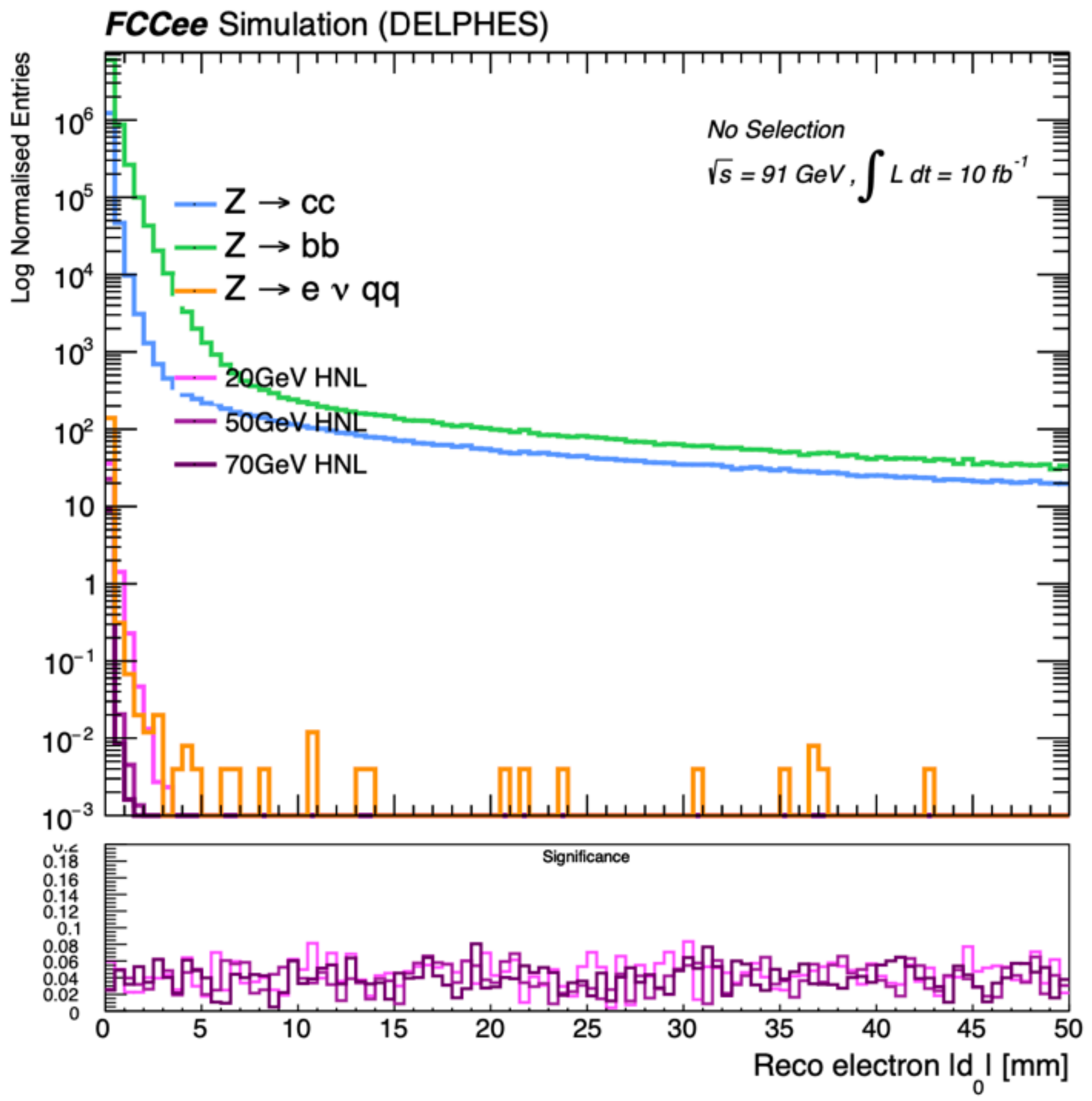
HNL→ ejj Analysis: Variable distributions



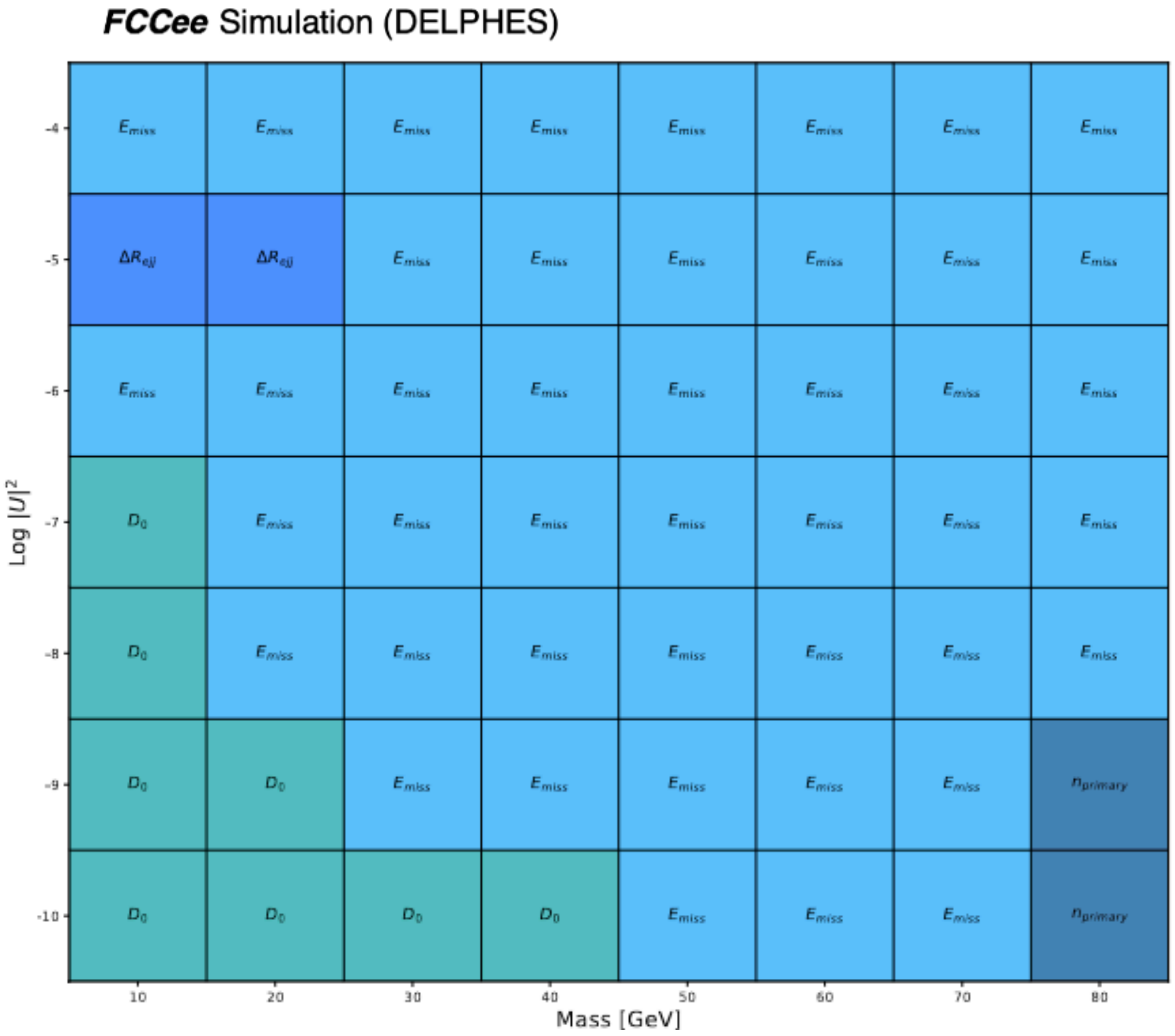


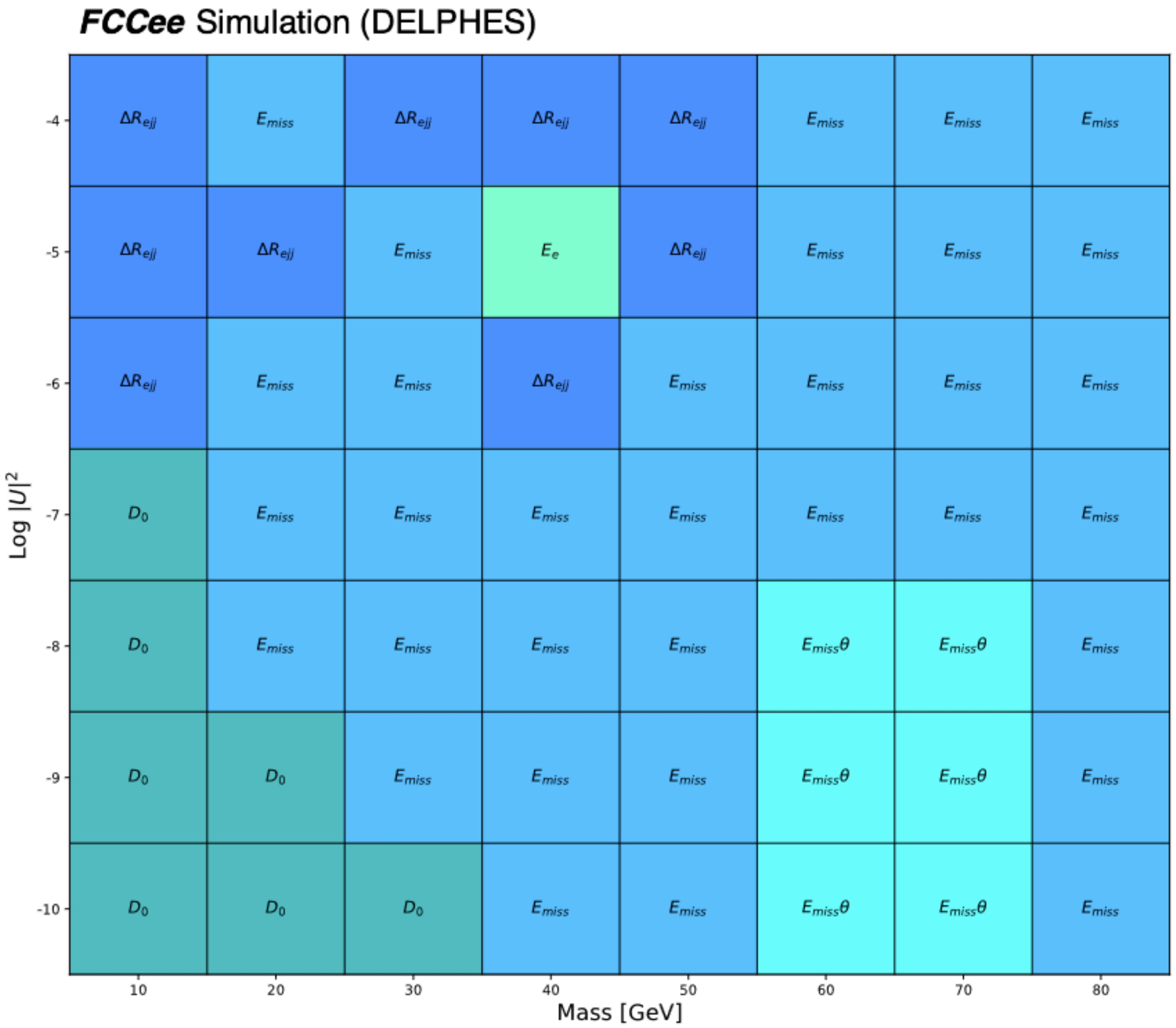






HNL→ ejj Analysis: DNN vs BDT feature importance

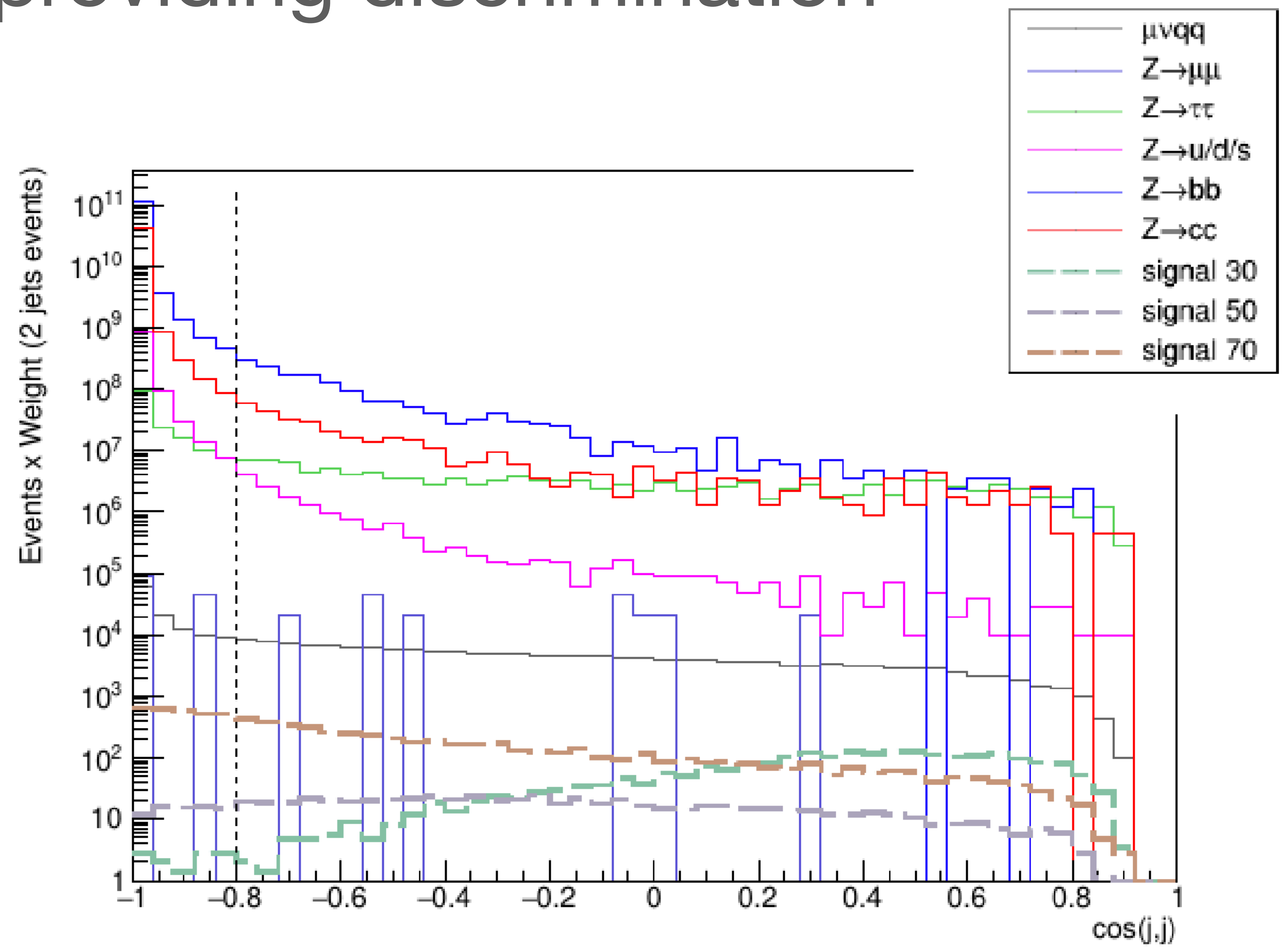




HNL → μjj Selections

Kinematic selection

- Two different SRs depending on n_{jets}
  - 2jets: Dominant at m>50 GeV
  - 1jet: Dominant at lower masses
- For each region: Investigation variables providing discrimination



Mass-dependent selection

- Require:

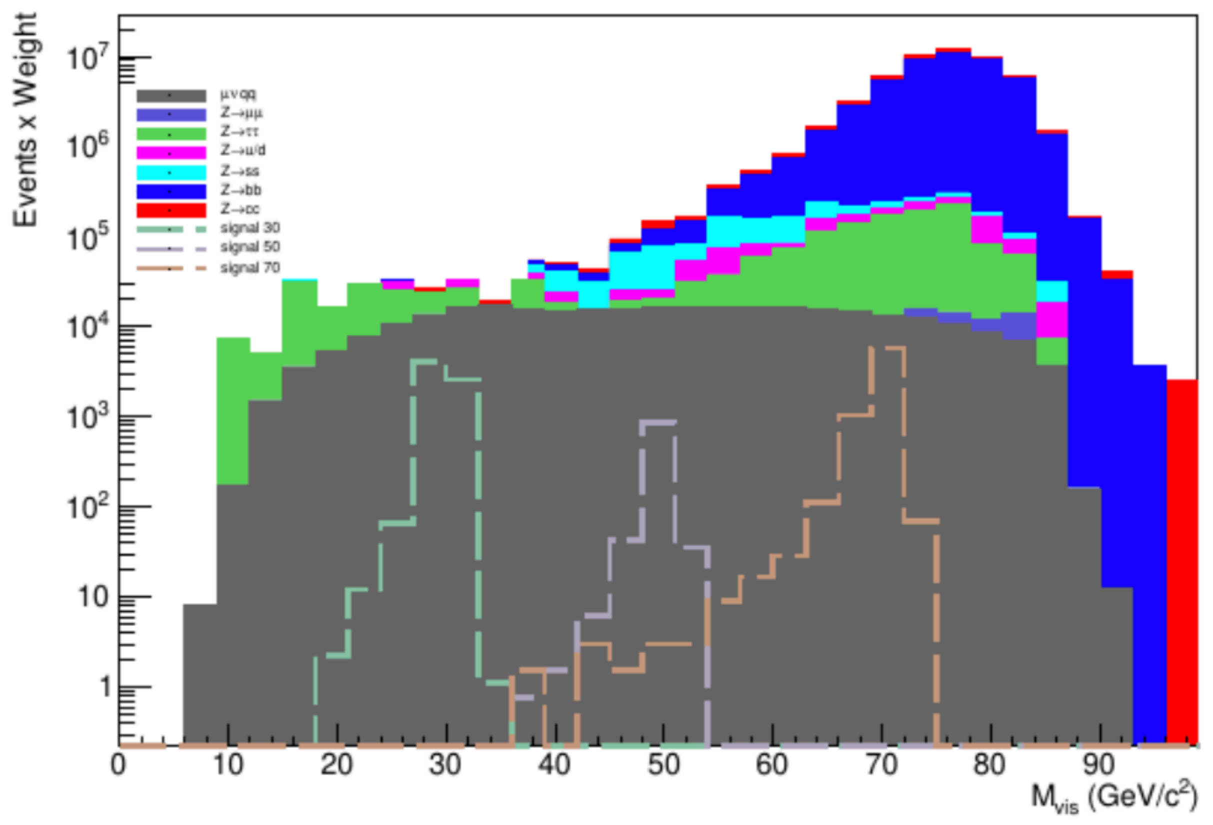
$$M_{vis} \in M_{N_1} \pm 2 \times 10\% \times \sqrt{M_{N_1} / \text{GeV}}$$

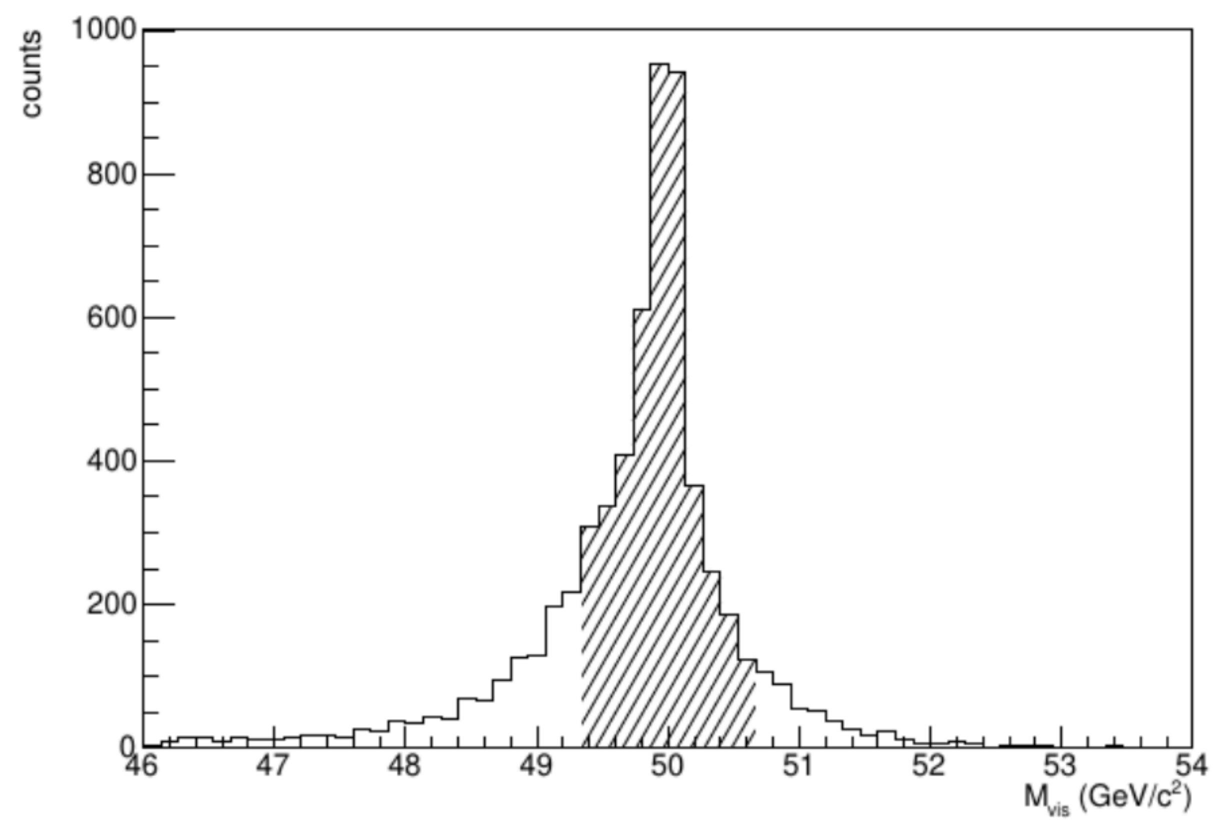
where M_{vis}: sum of visible 4-momenta to select HNL mass and ν recoil energy

- Apply also cut on E_{miss}:

$$E_{miss} \in \hat{p}_\nu(M_{N_1}) \pm 2 \times 10\% \sqrt{\hat{p}_\nu / \text{GeV}/c}$$

where $\hat{p}_\nu(M_{N_1}) = \dfrac{M_Z^2 - M_{N_1}^2}{2\, M_Z}$



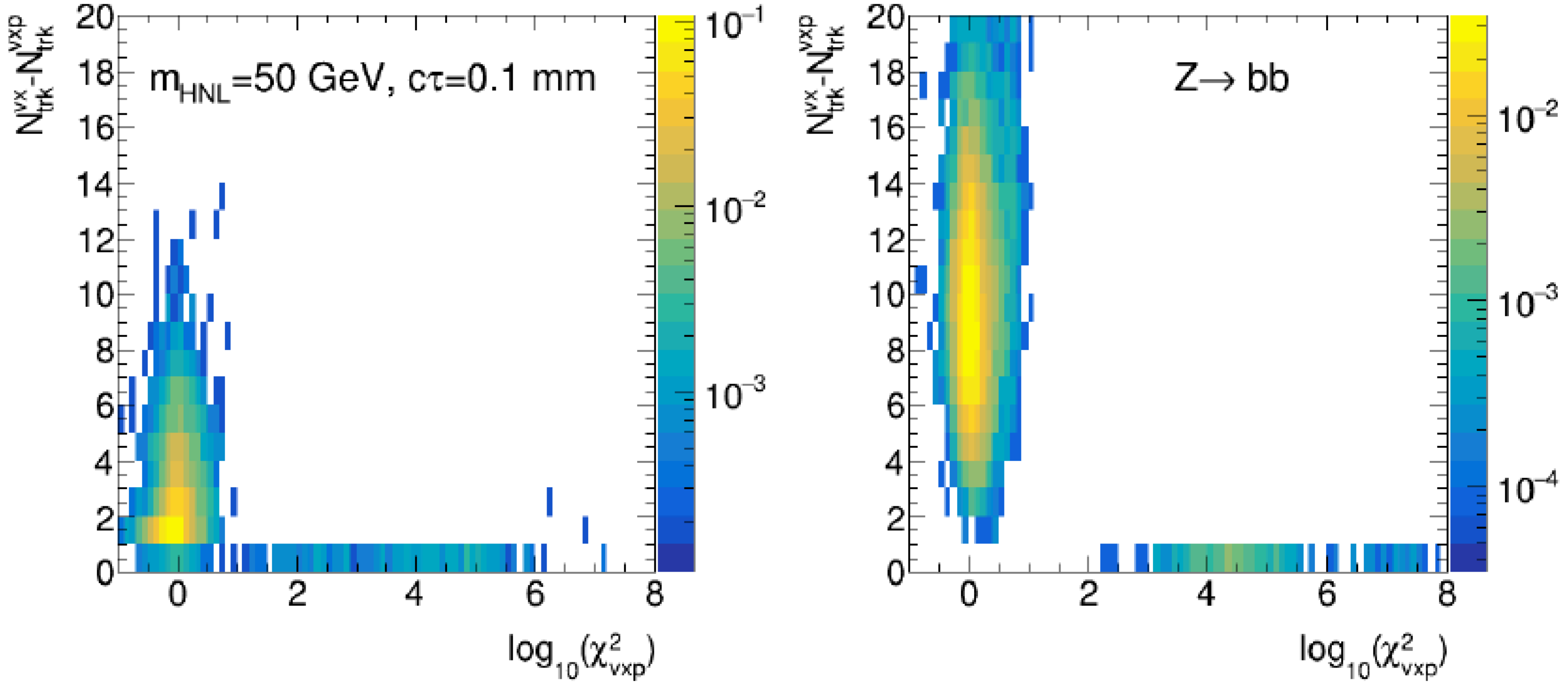


HNL → μjj Selections

Vertex-based selection

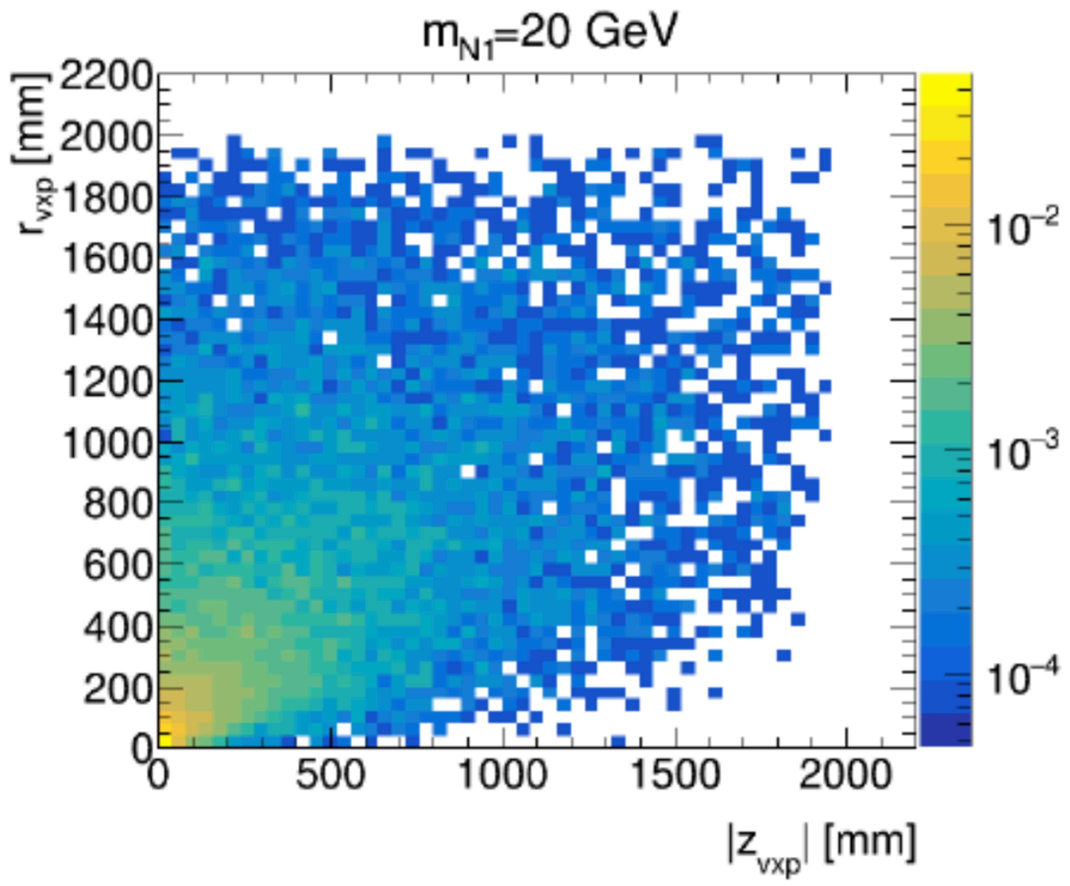
- Require well-reconstructed primary vertex and most of the Tracks used for primary vertex
- Substantial rejection for heavy flavours

$$N_{tracks} - N_{tracks}^{primary} < 5$$
$$\chi^2_{vtx,primary} < 10$$

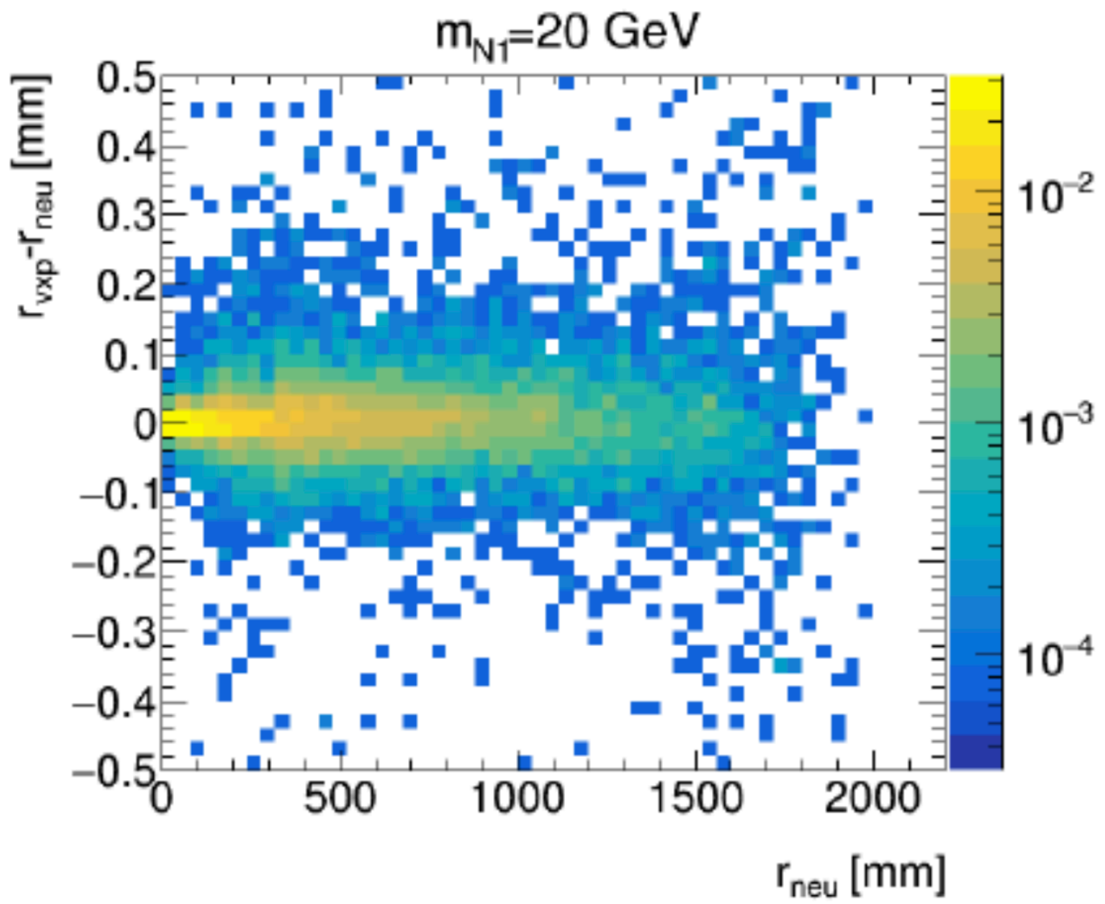


Prompt vs Long Lived selection

- For separation between prompt and LL
  - Choose transverse position of PV so as bkgs become zero: r_{vpx} = 0.5mm
- About five times values r_{vxp} for extreme tails of bkgs



Primary vertex well reconstructed in the volume of the detector



Very good resolution in position of HNL reconstructed vertex