UNIVERSITÉ DE GENÈVE

FUTURE CIRCULAR COLLIDER

Probing Heavy Neutral Leptons at the FCC-ee

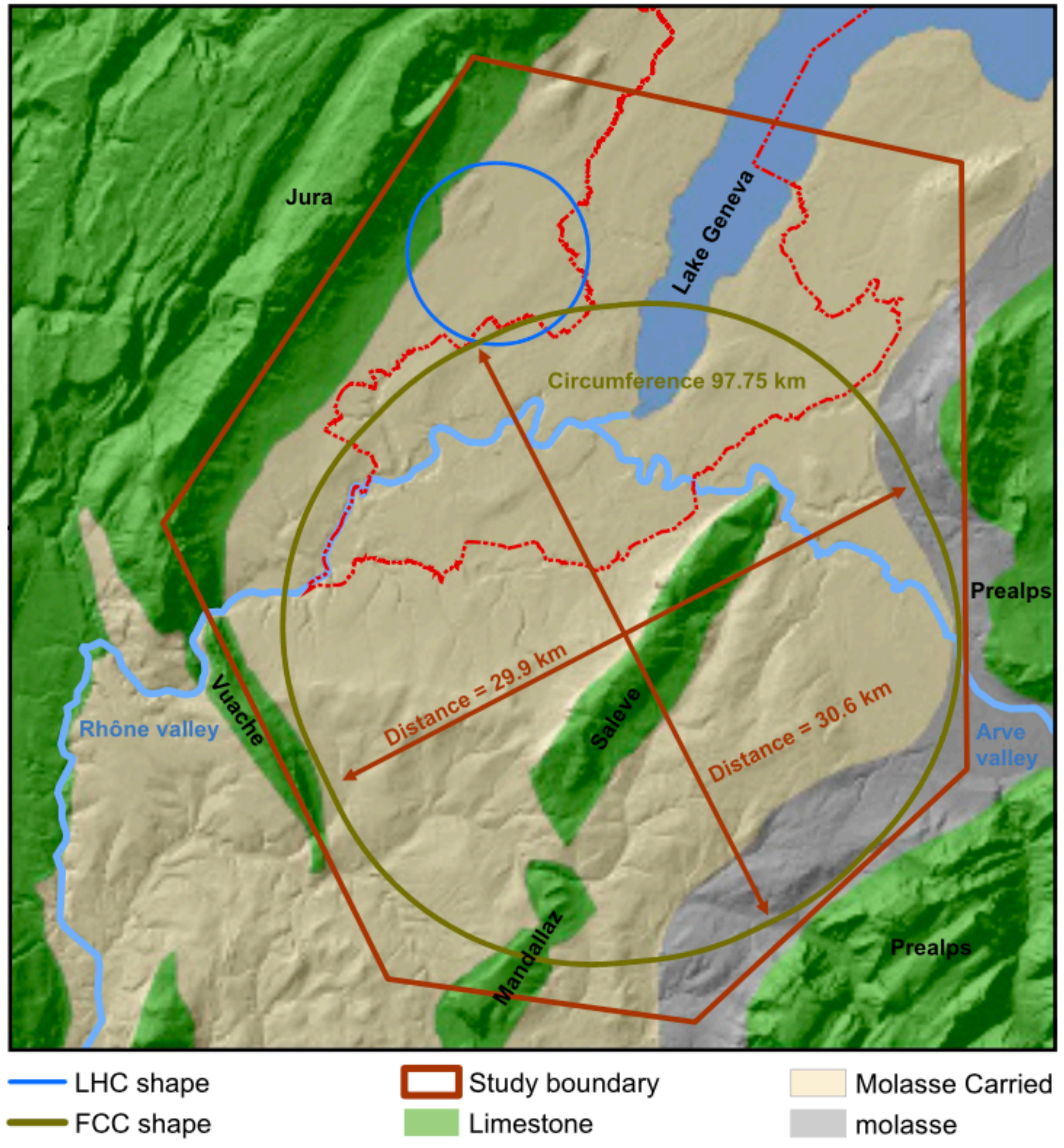
Pantelis Kontaxakis
on behalf of the FCC BSM Physics group

Brookhaven Forum 2023

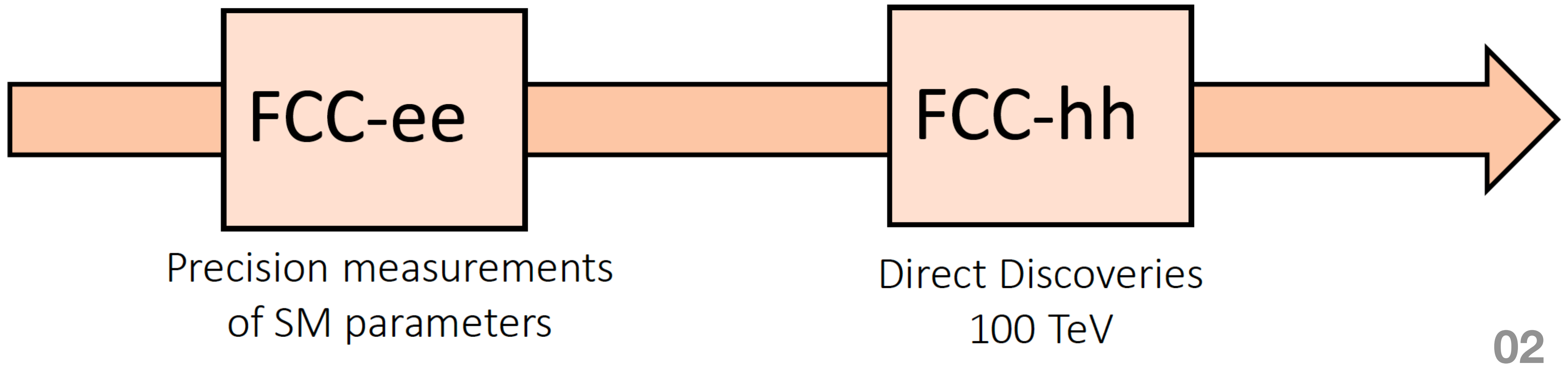
October 4, 2023

Future Circular Collider

- **Future colliders will offer exclusive insights into understanding the mechanisms of nature**
- **Pioneering advances in science and technology**
- **Future Circular Collider (FCC):**
  - **91km circumference**
  - **Two stages:**
    - Stage 1: FCC-ee (Z, W, H, tt) as a high luminosity factory for Higgs, EW and top
    - Stage 2: FCC-hh (~100 TeV) logical progression at energy frontier, with ion and e-h options



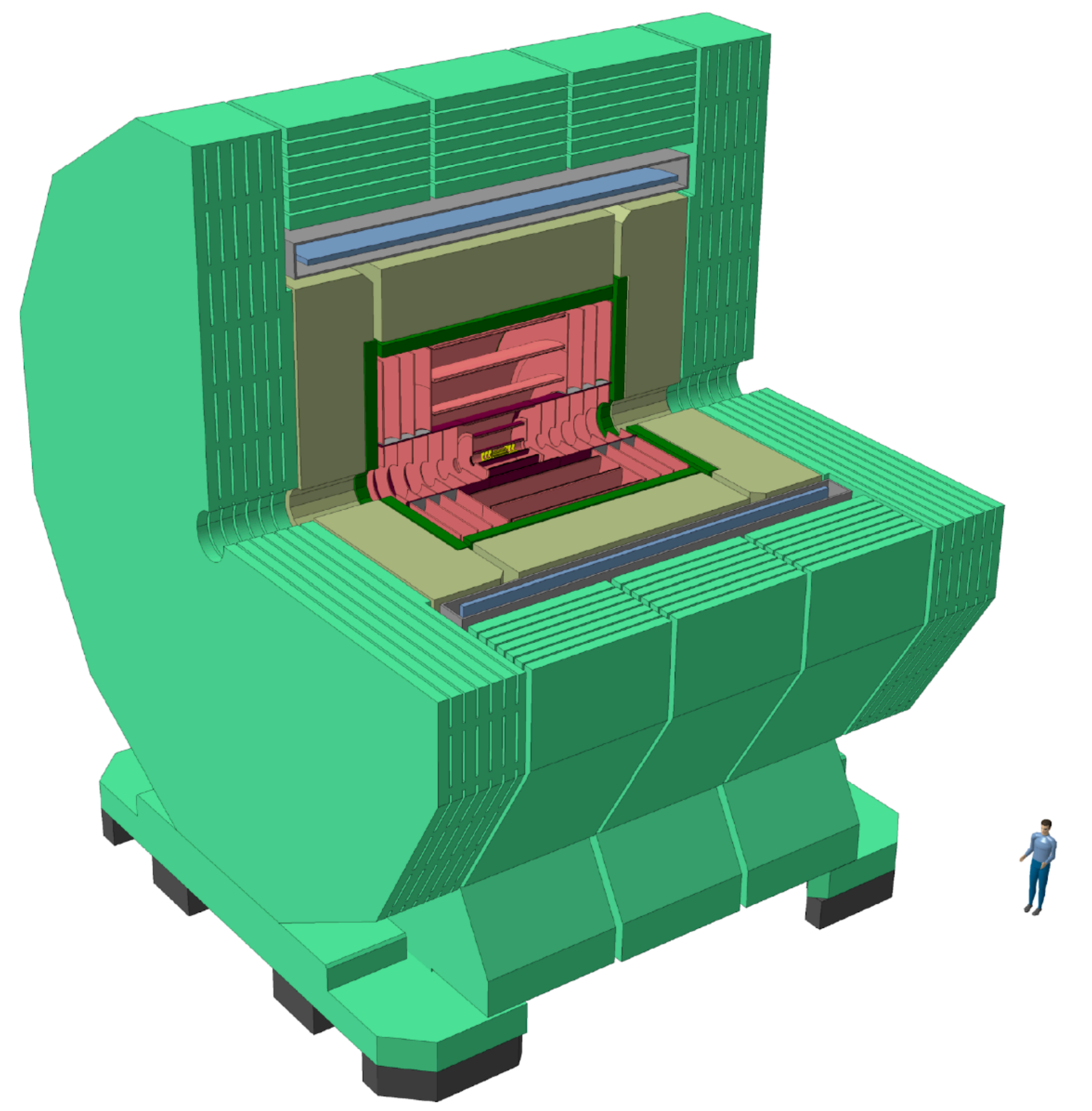
The FCC is a leading-edge facility for direct discovery of new physics!



Detector concepts at the FCC-ee

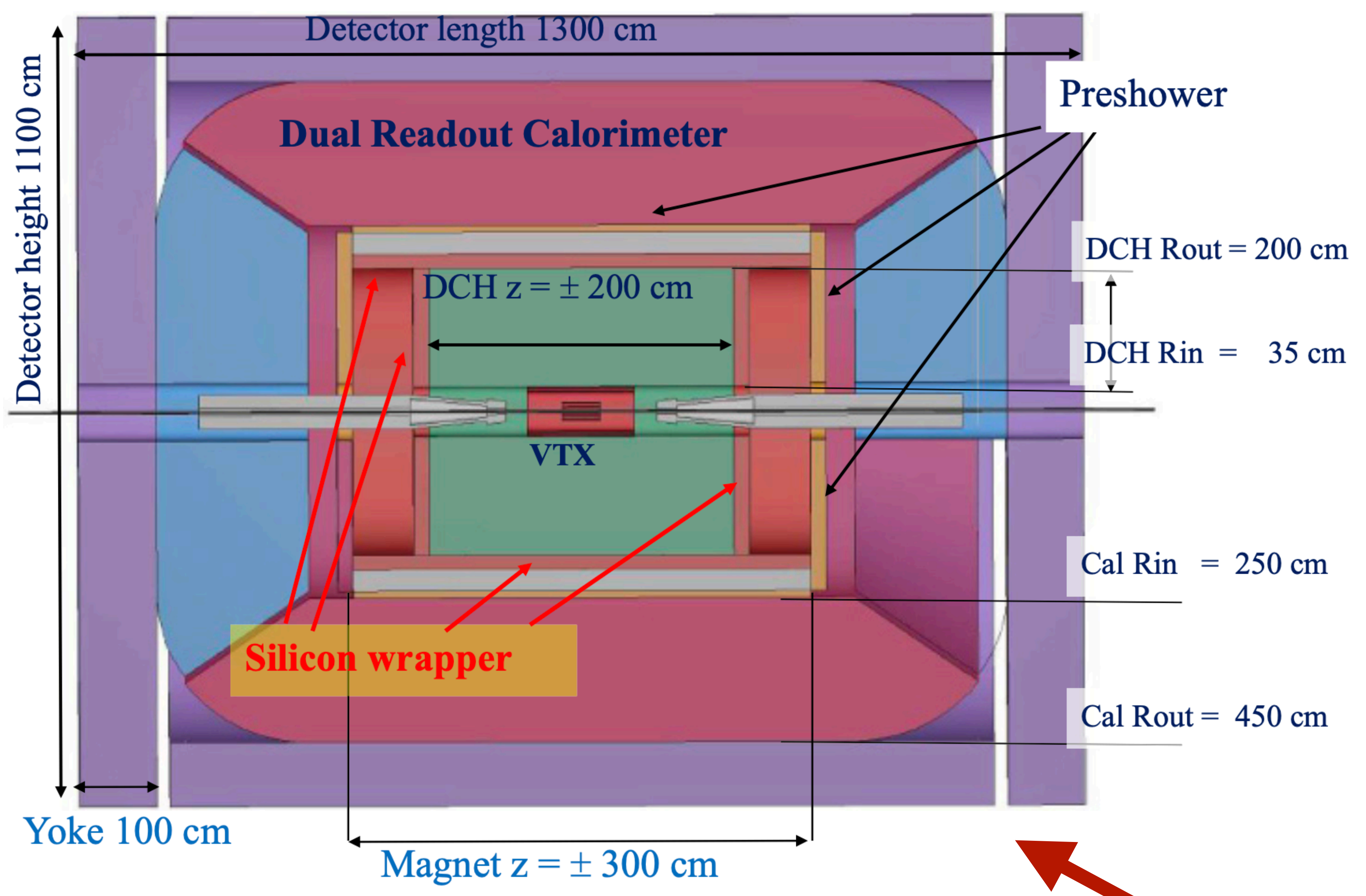
CLIC-like Detector (CLD)

- Full silicon vertex-detector+ tracker
- 3D HG calorimeter
- Solenoid outside calorimeter



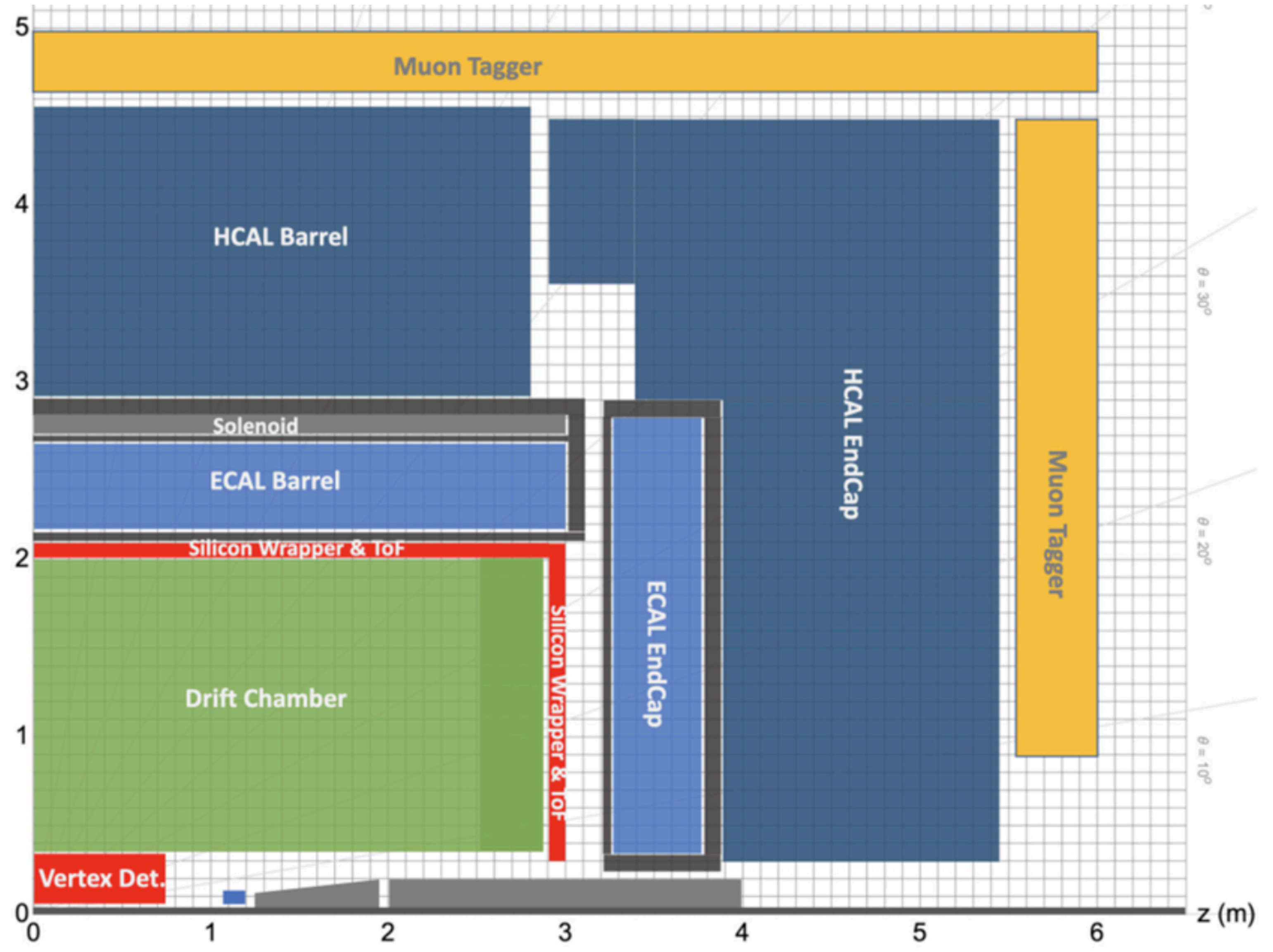
Innovative Detector for an Electron-Positron Accelerator (IDEA)

- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter



Allegro

- HG noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Latest proposal



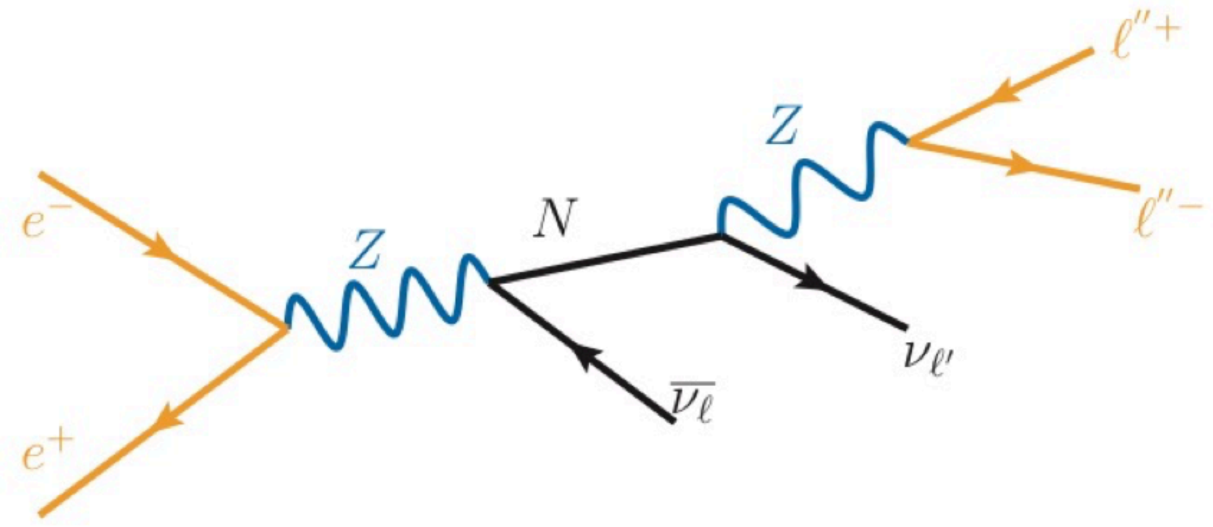
Consider IDEA detector for the upcoming studies

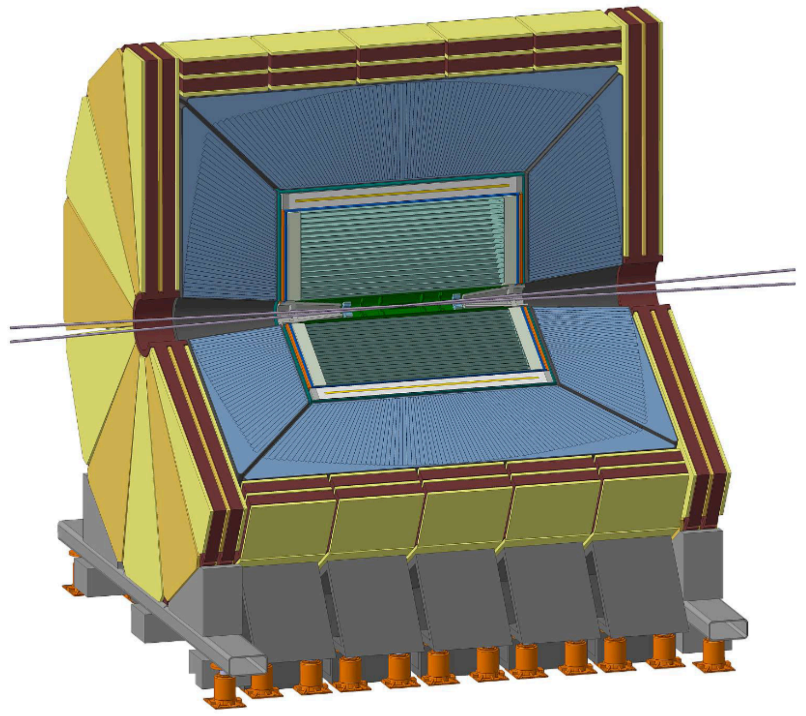
Event Generation & Workflow

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

BSM at FCC-ee

◉ Diverse experimental requirements necessary for varying signatures

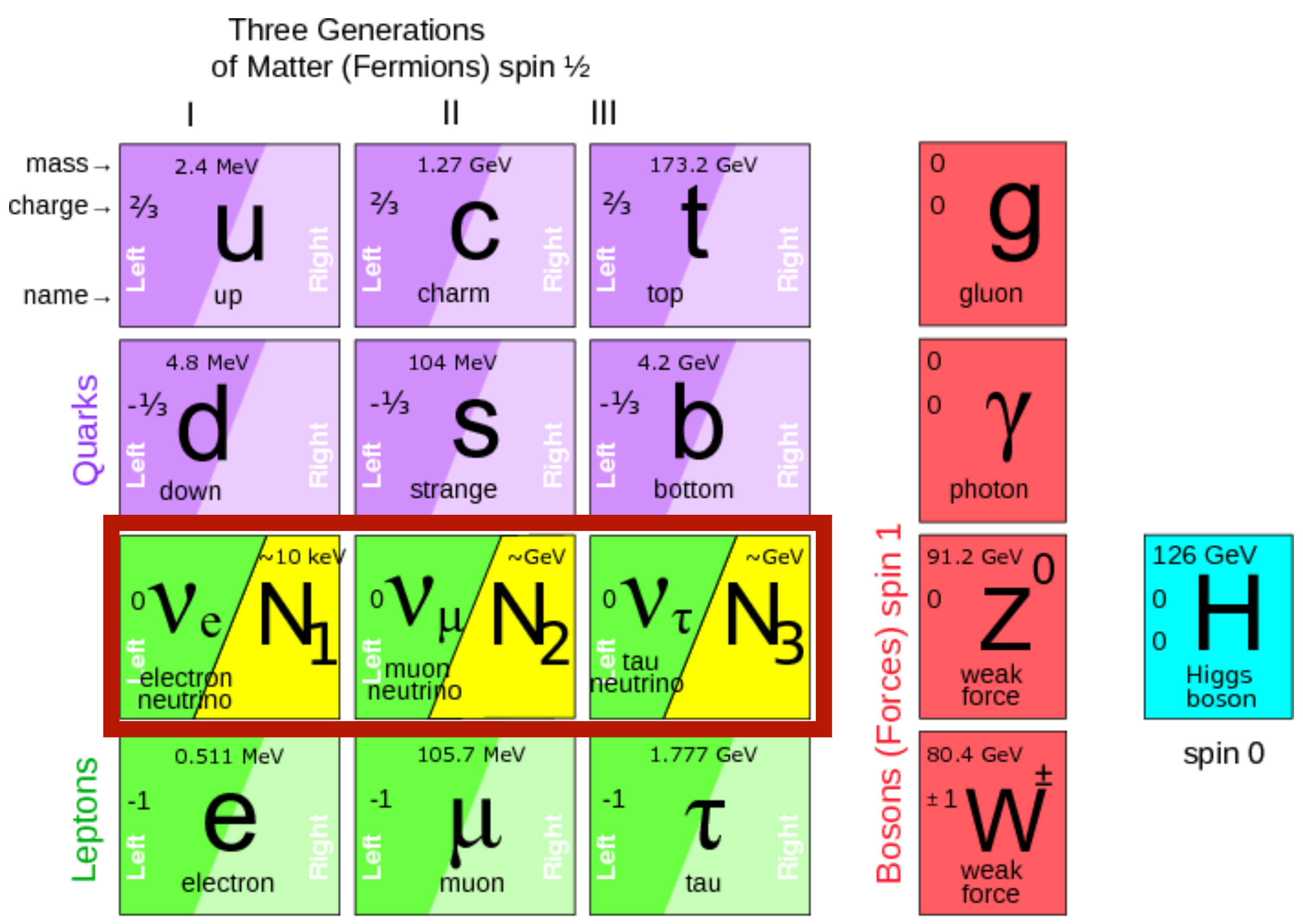
- Prompt
- Decay within the inner detector
- Decay within the calo/muon detector

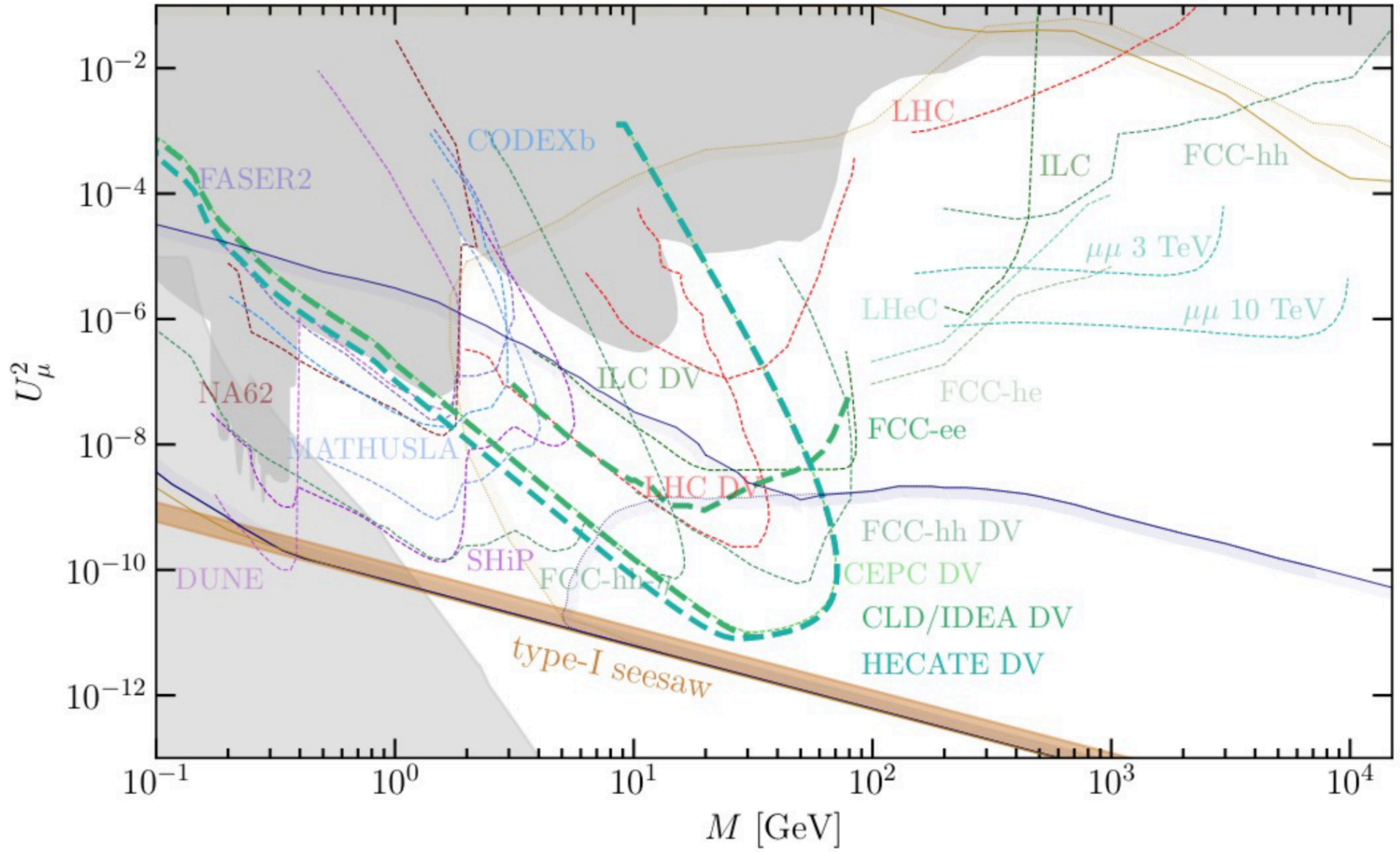
◉ BSM Particles:

- **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)
  - Exotic Higgs Decays
  - Z' & dark photons
  - Light SUSY, …

Heavy Neutral Leptons

- **One of the most promising BSM channels for FCC-ee at the Z-pole**
  - **Could provide answers to several unresolved questions of the SM:**
    - Neutrino masses, Dark Matter, Baryon Asymmetry…
- **Sterile neutrinos with small mixing angle with SM neutrinos**
  - Diverse final state signatures: both prompt and long lived





arxiv:2203.05502

Discovery analyses

- **HNL (N_e) → ejj (Prompt)**
  - *Dimitri Moulin, Pantelis Kontaxakis, Anna Sfyrla*

- **HNL (N_μ) → μjj (Prompt + Displaced)**
  - *Nicolo Valle, Giacomo Polesello*

- **HNL (N_e) → eeν (Displaced)**
  - *Lovisa Rygaard, Juliette Alimena, Rebeca Gonzalez Suarez, Suchita Kulkarni*

- **HNL (N_μ) → μμν (Prompt + Displaced)**
  - *Lorenzo Bellagamba*

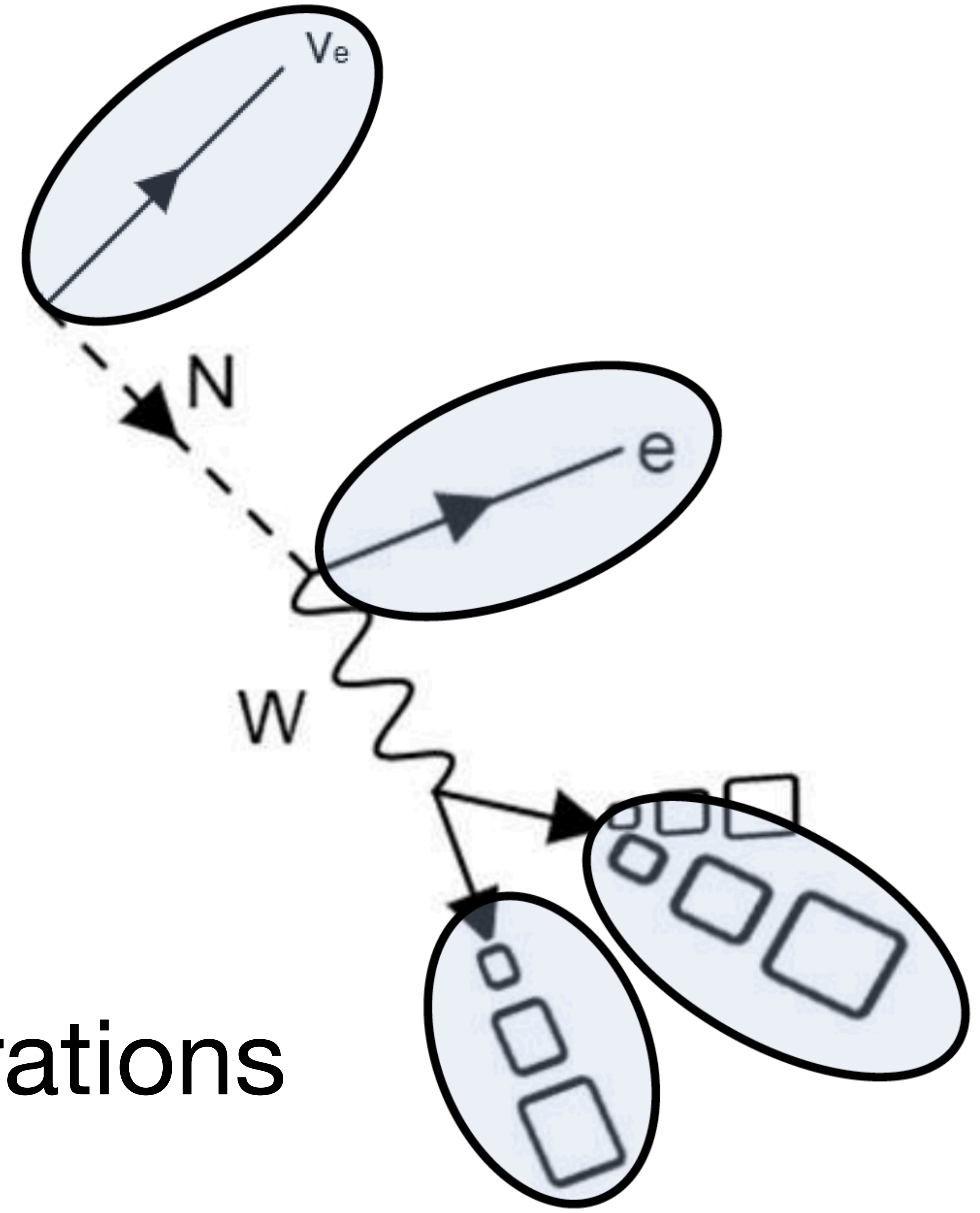
HNL → ejj Analysis

- **High branching fraction ~ 50%**

- **Significant background rejection mostly by applying selection on E_{miss} & distances between the decaying particles**

- **Signal:**
  - M_N=10 - 80 GeV, V_{eN} = 10^{-5} - 10^{-2}

- **Backgrounds:**
  - **Z→bb, Z→cc, e^+e^-→eνqq**
    - Official Winter2023 FCCee samples and configurations

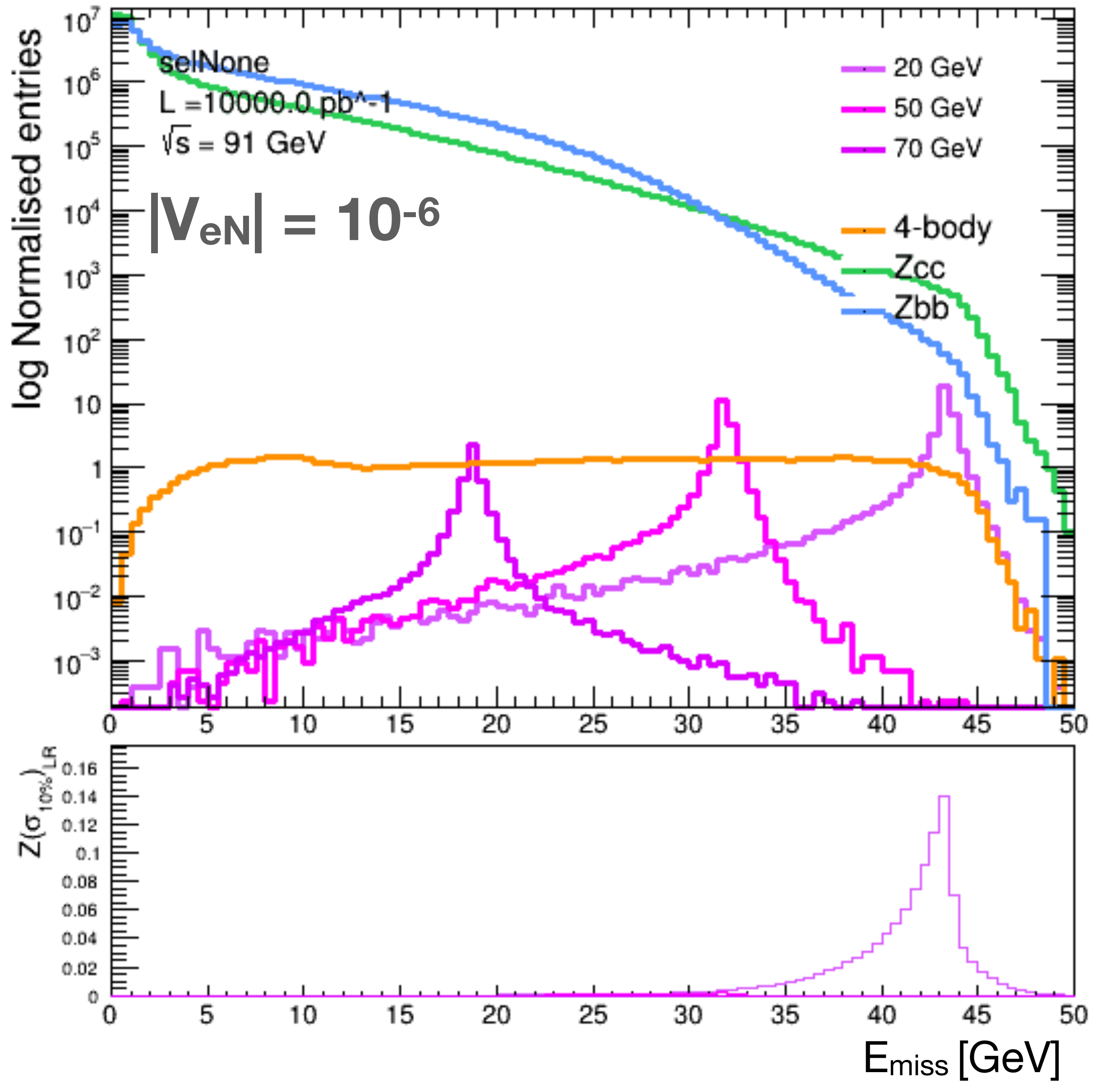


Methodology

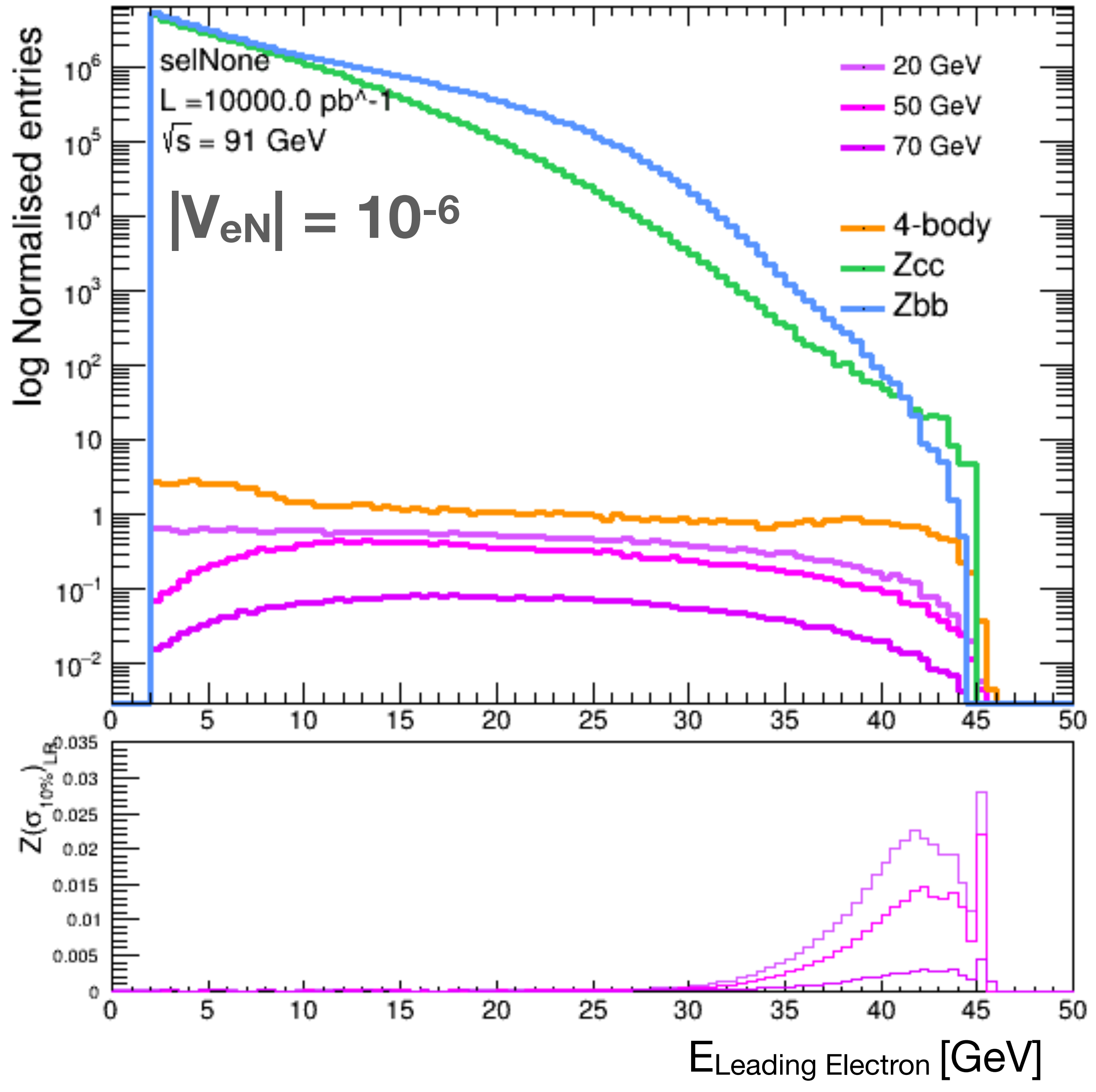
◉ Event Selection:

- **Apply selections on discriminating variables (cut & count)**

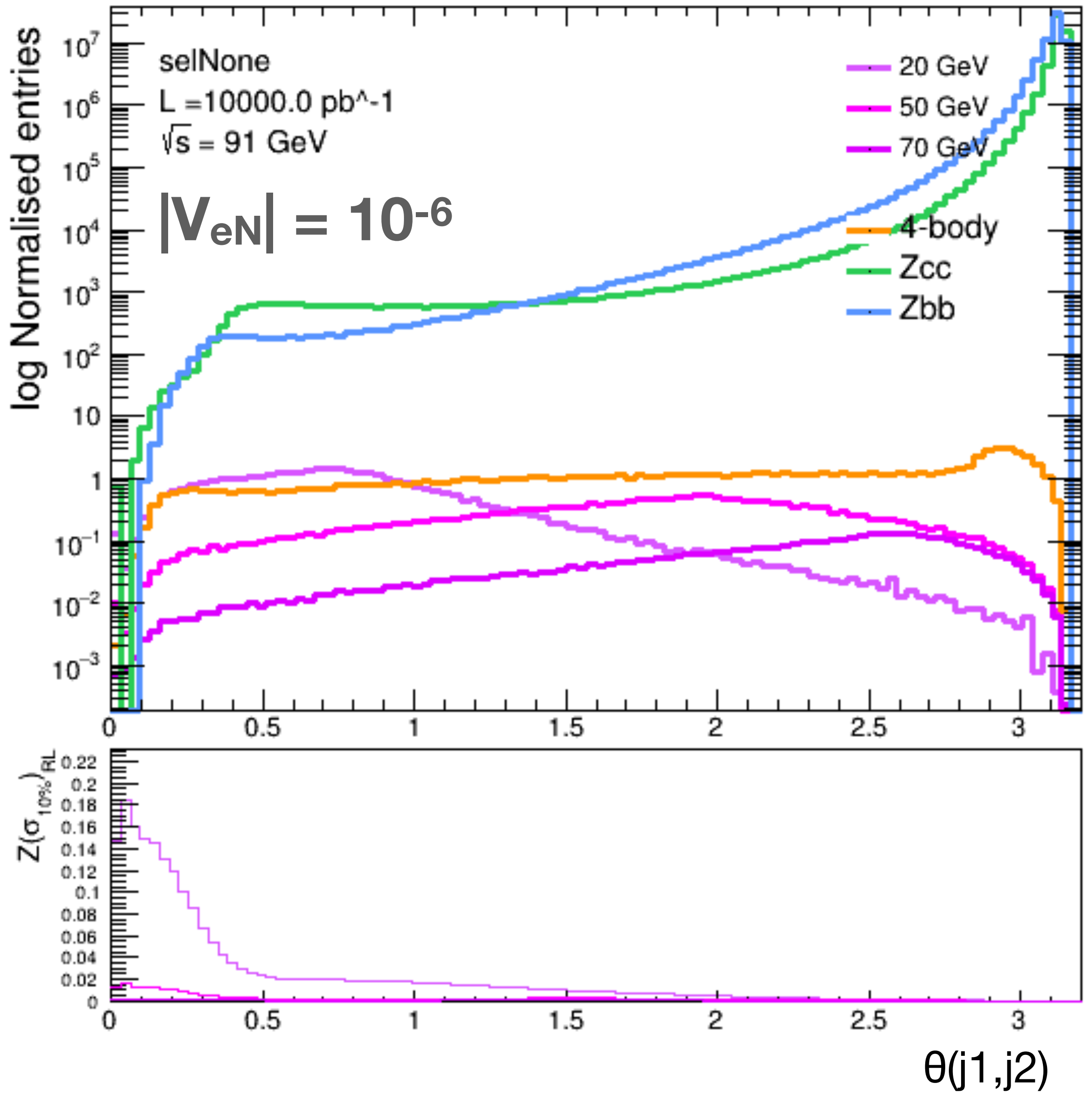
$E_{miss} > 12$ GeV



Leading e energy > 35 GeV
Removes most of the electrons from jets



$\theta(j_1, j_2) < 2.4$ rad & $\Delta R(e, jj) < 3$



- **Selections based on significance, with 10% syst. uncertainty:**

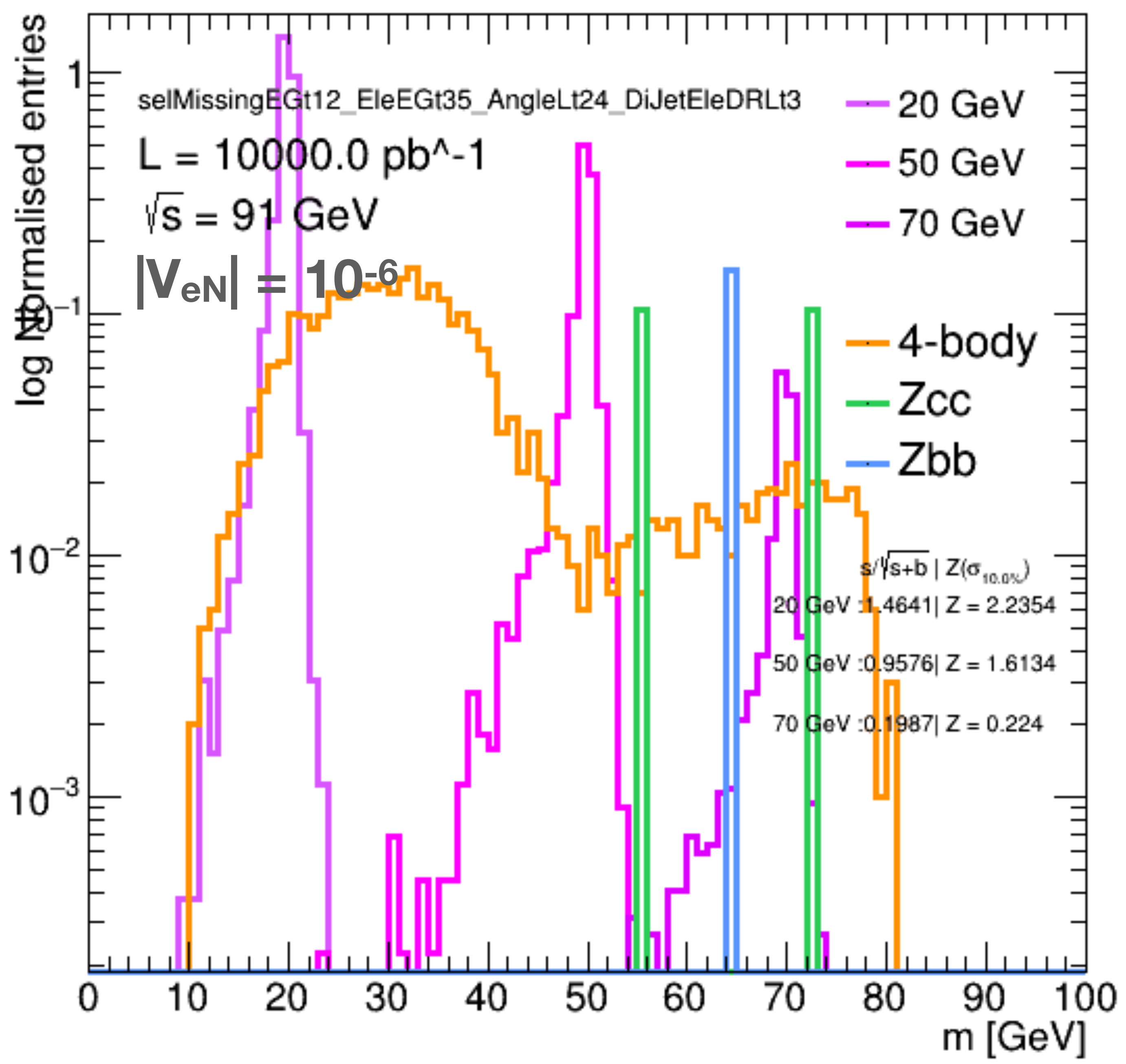
$$Z = \sqrt{2\left(n \ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} = 2$$

Results

Raw number of events

Cutflow:

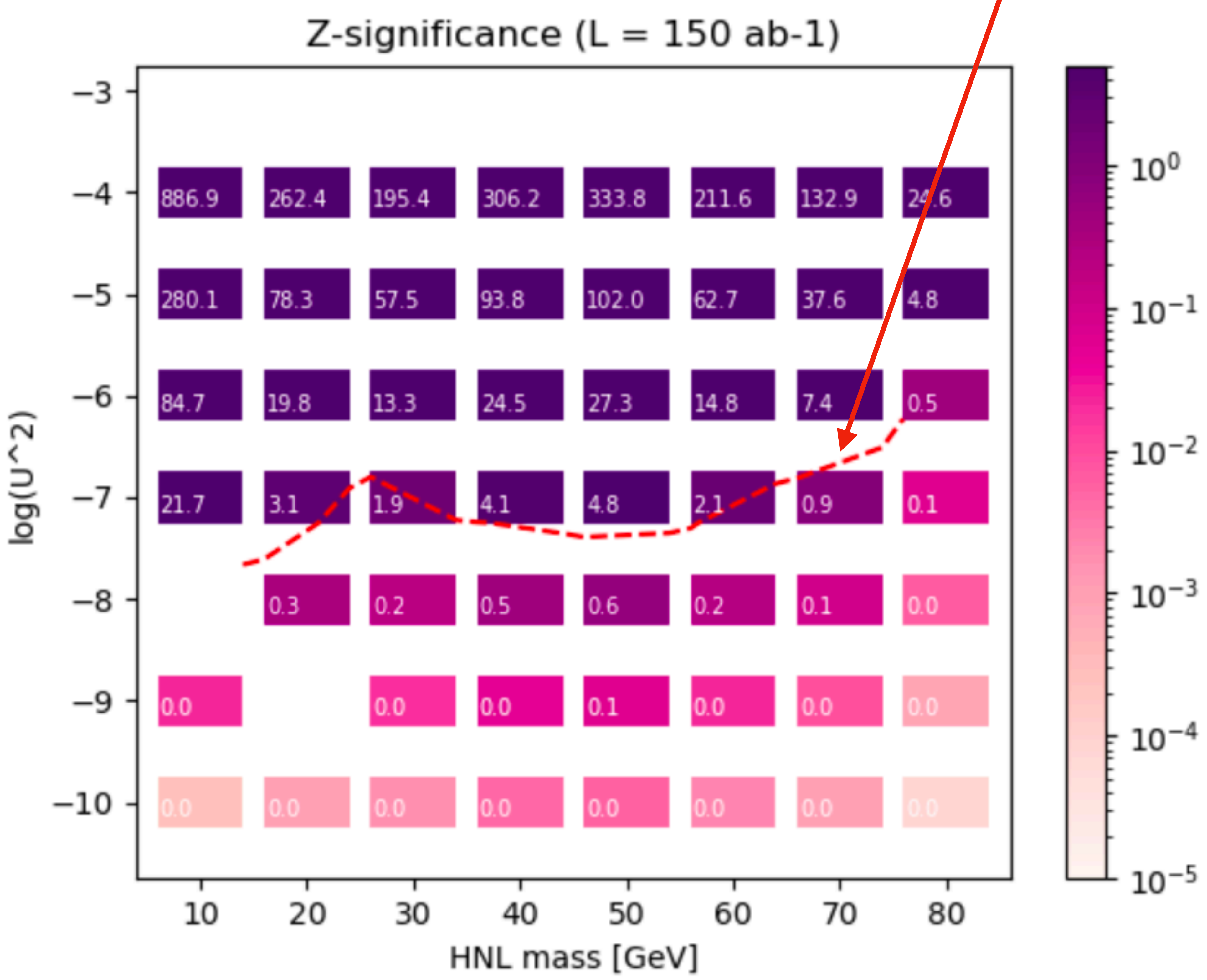
Selection	20 GeV	50 GeV	70 GeV	4-body	$Z \to cc$	$Z \to bb$
No selection	10^5	10^5	10^5	10^5	4.9×10^8	4.4×10^8
$\not{E} > 12$	9.9×10^4	9.9×10^4	9.9×10^4	7.8×10^4	3.3×10^7	5.6×10^7
$\not{E} > 12$ & $E_{e^-} > 35$	8079	8090	8541	5206	101	817
$\not{E} > 12$ & $E_{e^-} > 35$ & $\Psi < 2.4$	7780	7290	8333	4853	60	46
$\not{E} > 12$ & $E_{e^-} > 35$ & $\Psi < 2.4$ & $\Delta R < 3$	7478	5035	3017	3184	2	1



Focus on the HNL invariant mass as an observed quantity

Selection extended for entire mass - coupling plane

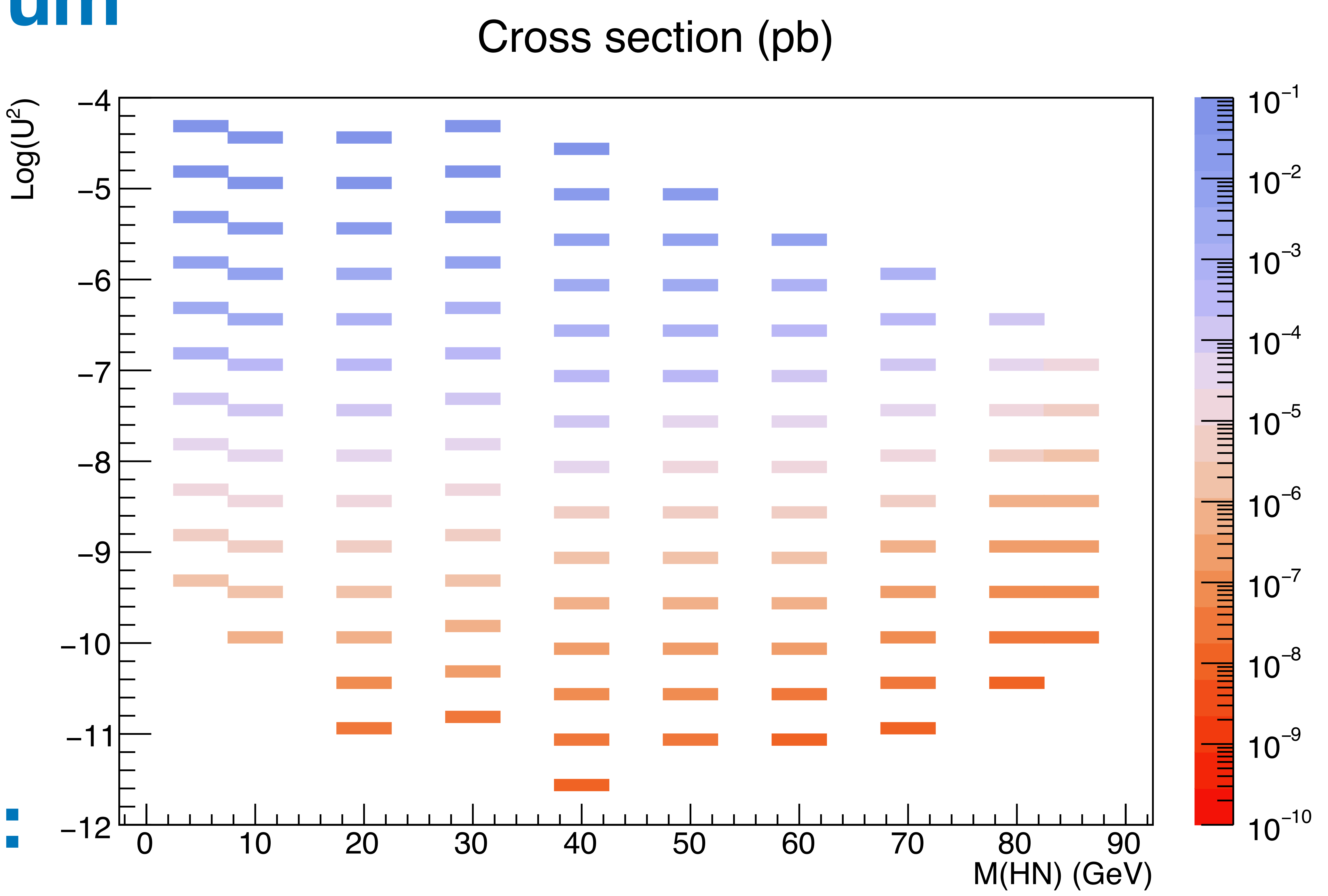
Contour: Z = 2



HNL → μjj Analysis

- **Same high BR as previous analysis**

- **Discovery feasible across a broad spectrum of the parameters space of interest**
  - **High mass → Prompt signals**
  - **Low mass → Delayed signals**



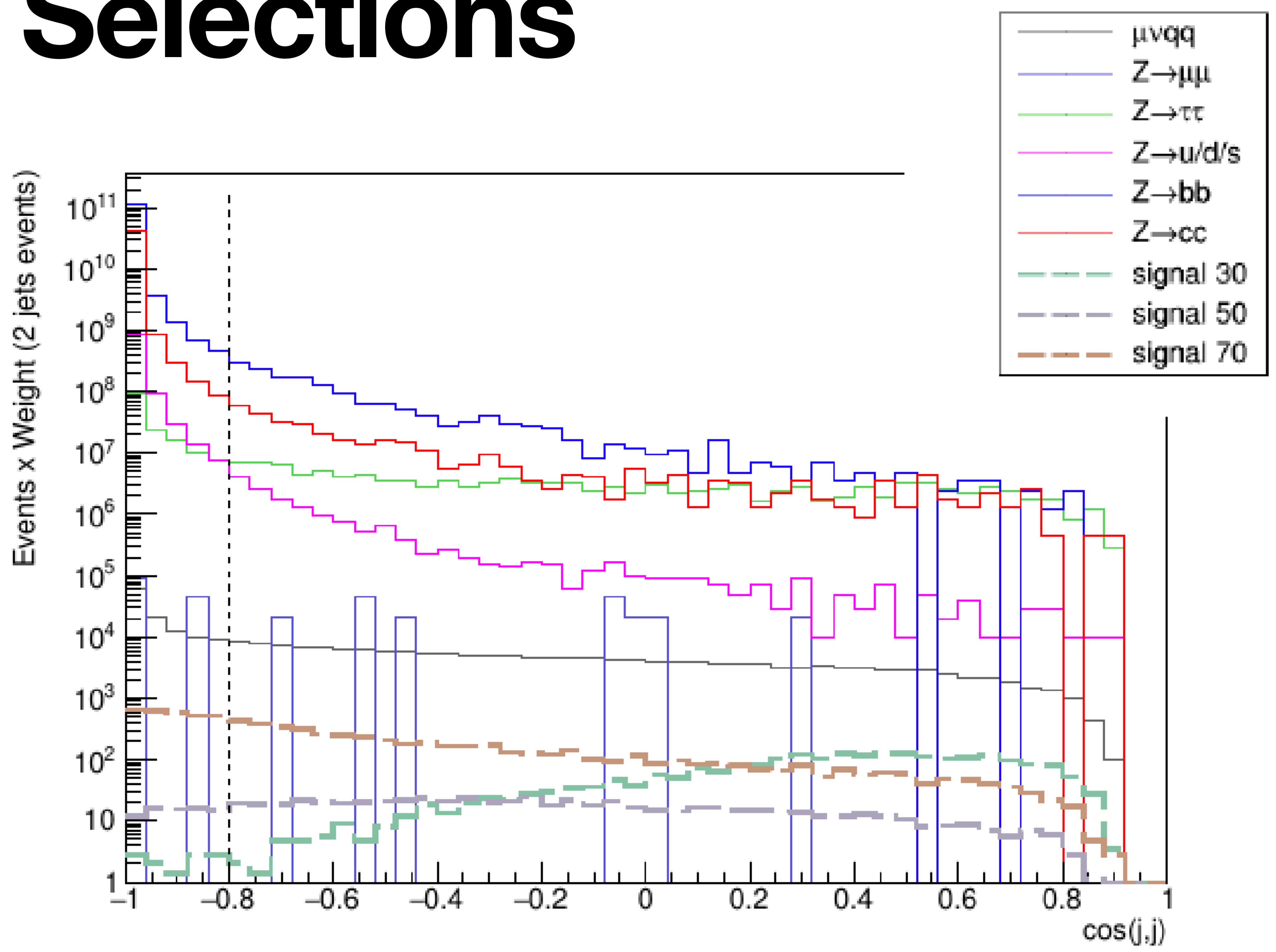
- **Large signal grid generated in mass - coupling plane**

- **Z Decay backgrounds and 4-fermion μνjj:**
  - **Official <u>Winter23</u> production & configurations**

Analysis Flow - Selections

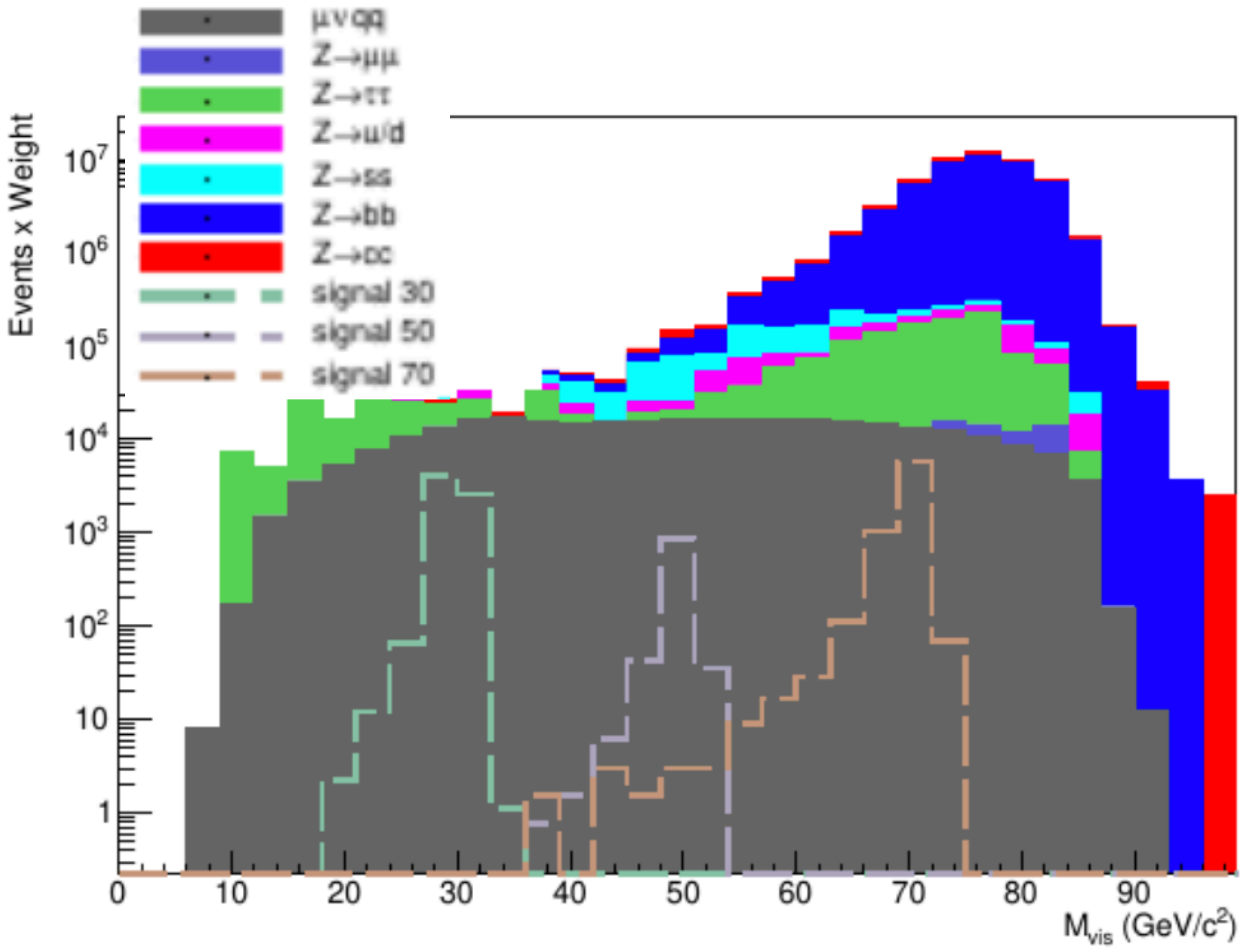
◉ Kinematic selection

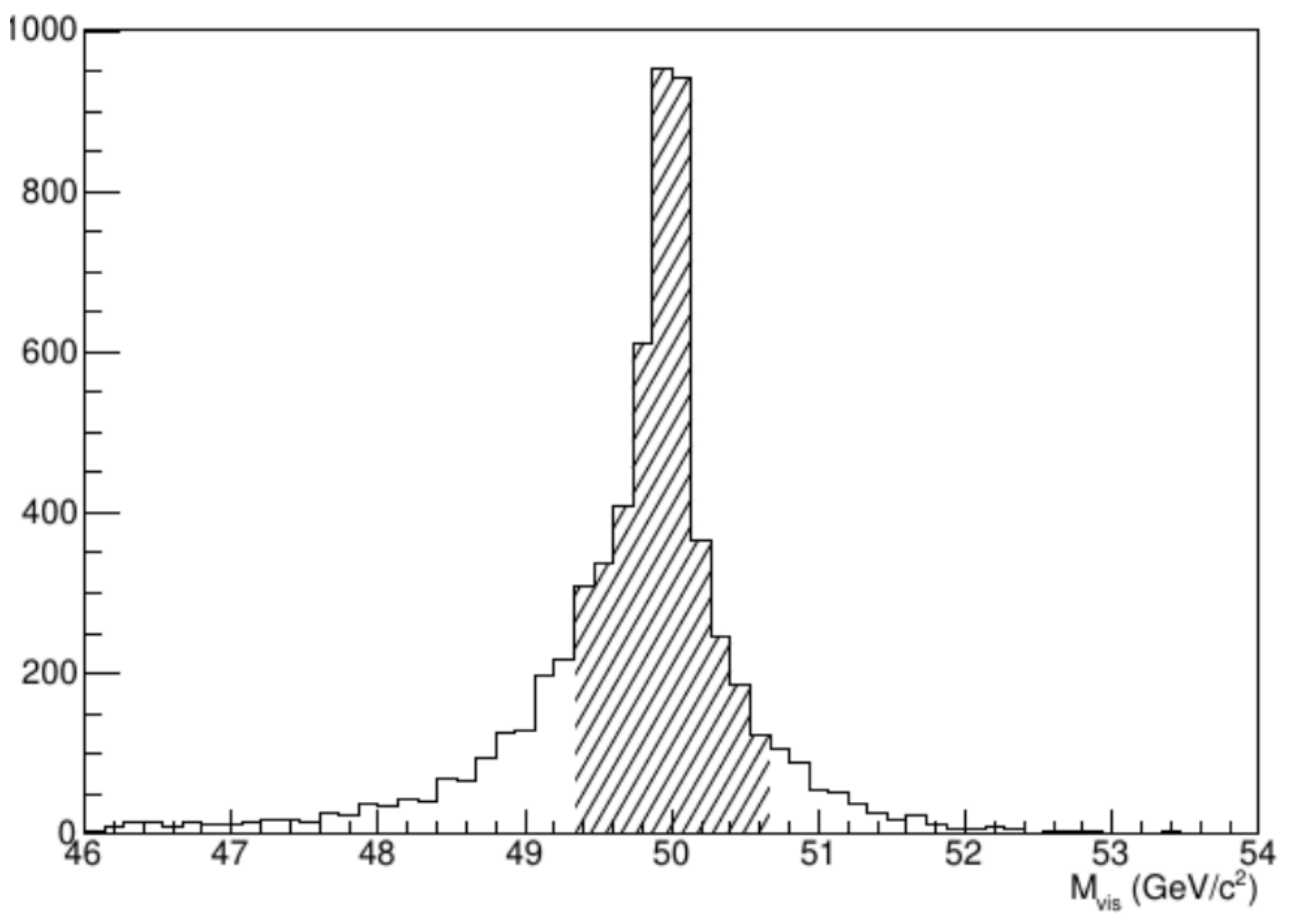
- Two different SRs depending on n_{jets}
  - 2jets: Dominant at m > 50 GeV
  - 1jet: Dominant at lower masses
- For each region: Investigation variables providing discrimination. E.g. ⟶



◉ Mass-dependent selection

- Require visible HNL mass and E_{miss} to be within 2 - 10% of the resolution in distributions





Analysis Flow - Selections

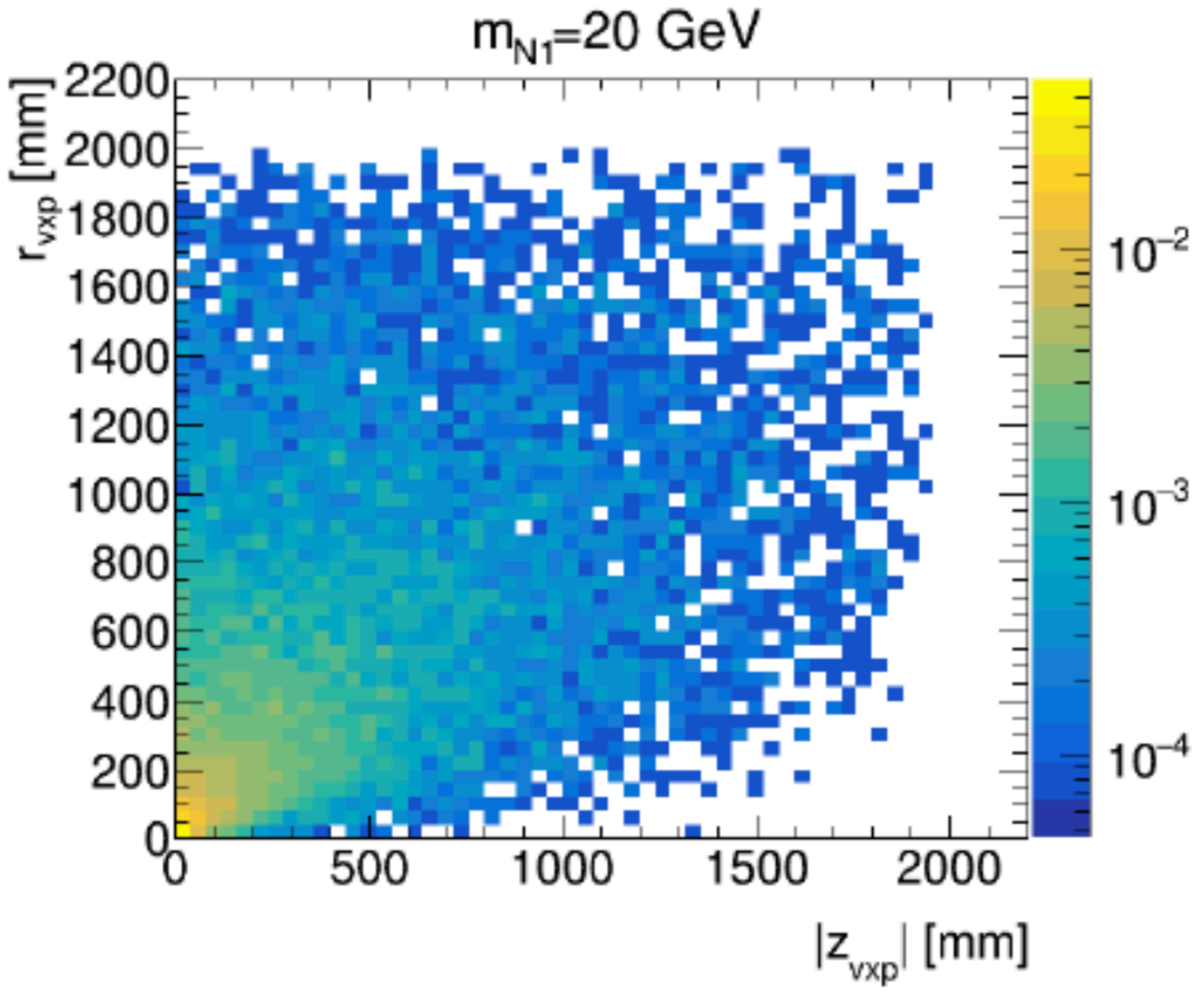
◉ Vertex-based selection

- Require well-reconstructed primary vertex and most of the Tracks used for primary vertex

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

◉ Prompt vs Long Lived selection

- For separation between prompt and LL
  - Choose transverse position of PV so as bkgs become zero: $r_{vpx} = 0.5$mm

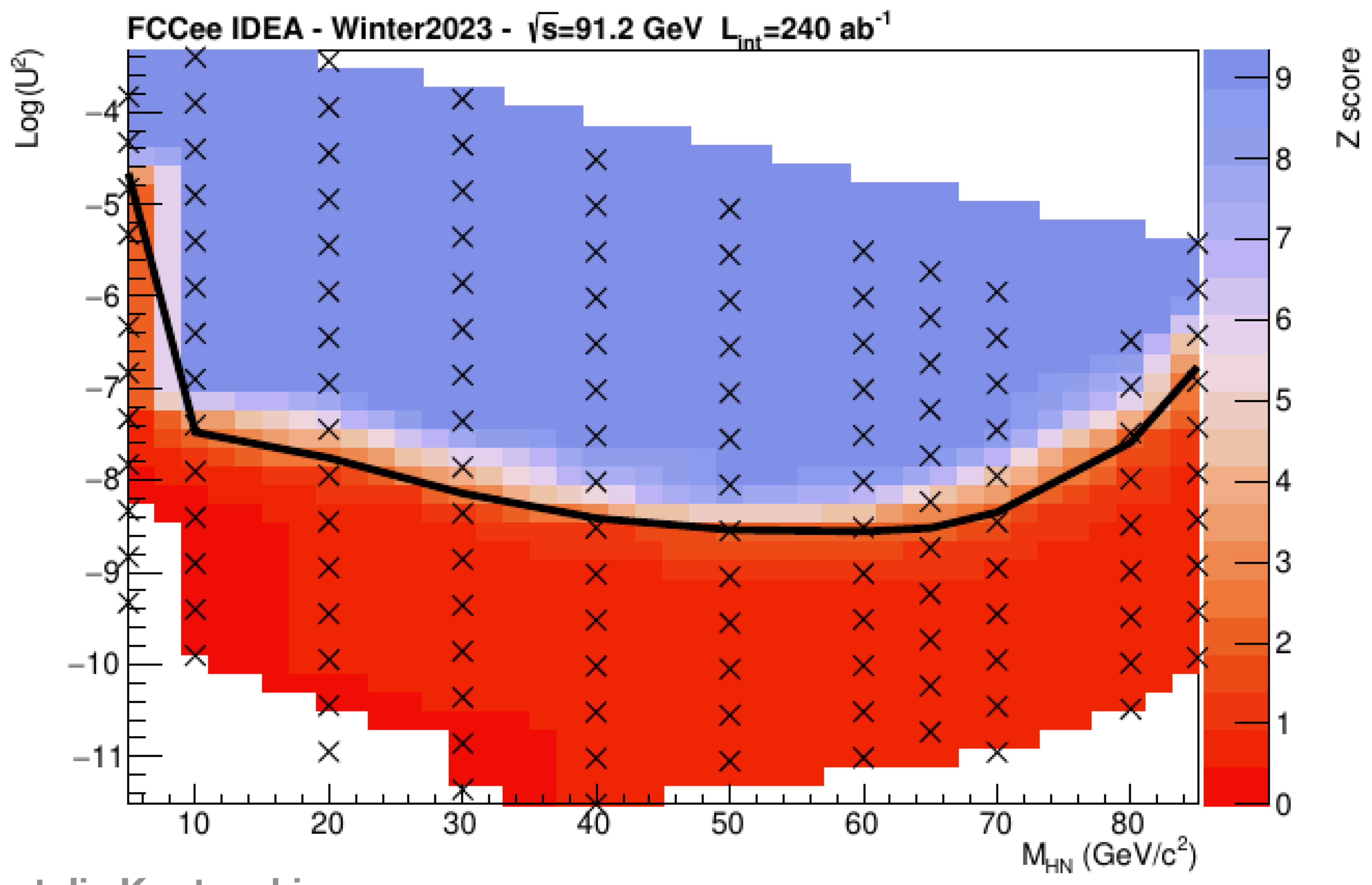


Primary vertex well reconstructed in the volume of the detector

Results

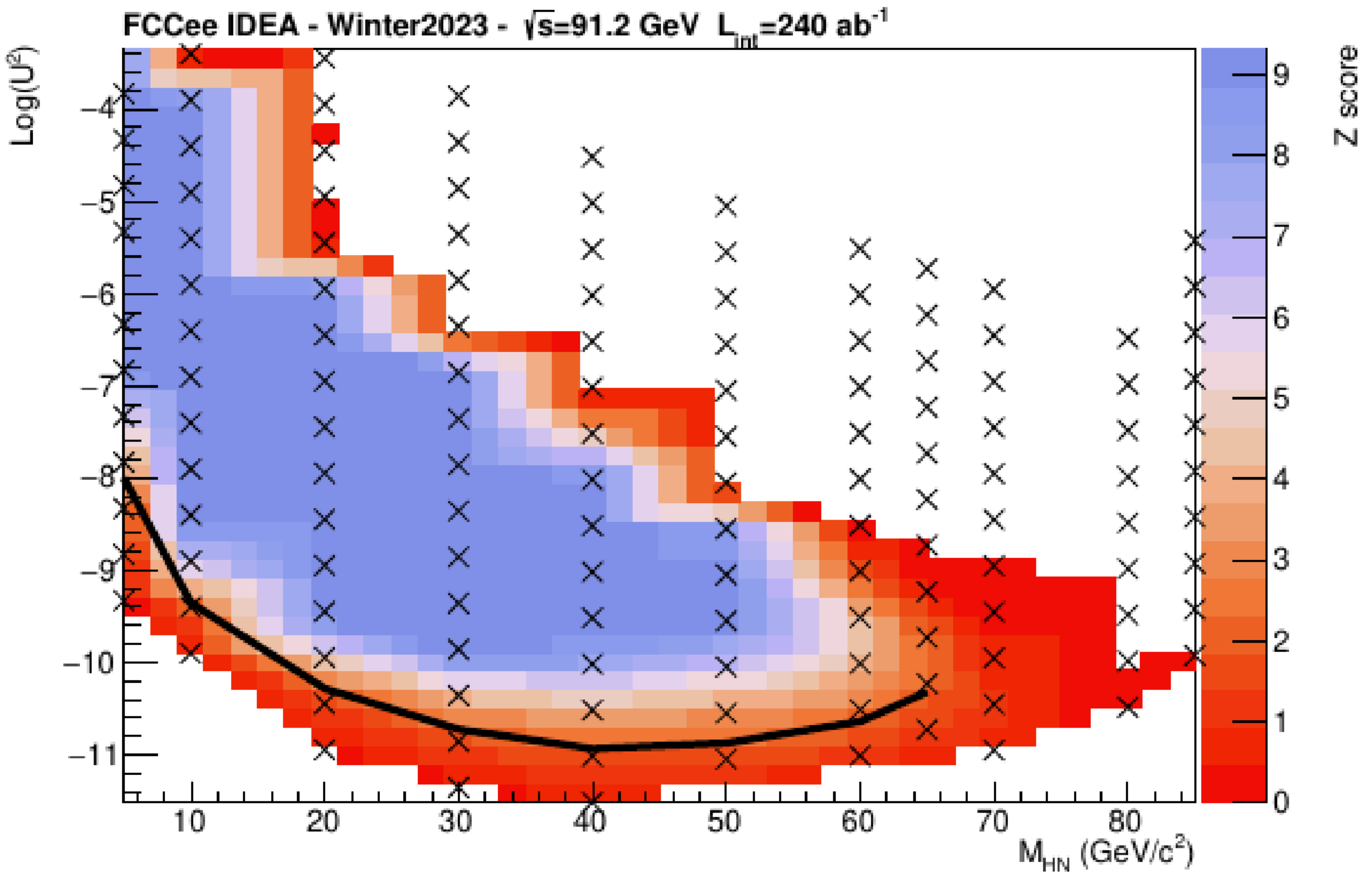
- **Looking for U^2 producing 95% CL excess of events**
- **Integrated Luminosity = 240 ab^{-1}**

Prompt



LLP

- Sensitivity curve: Points in plane where 3 events are expected after cuts
- Background events = 0



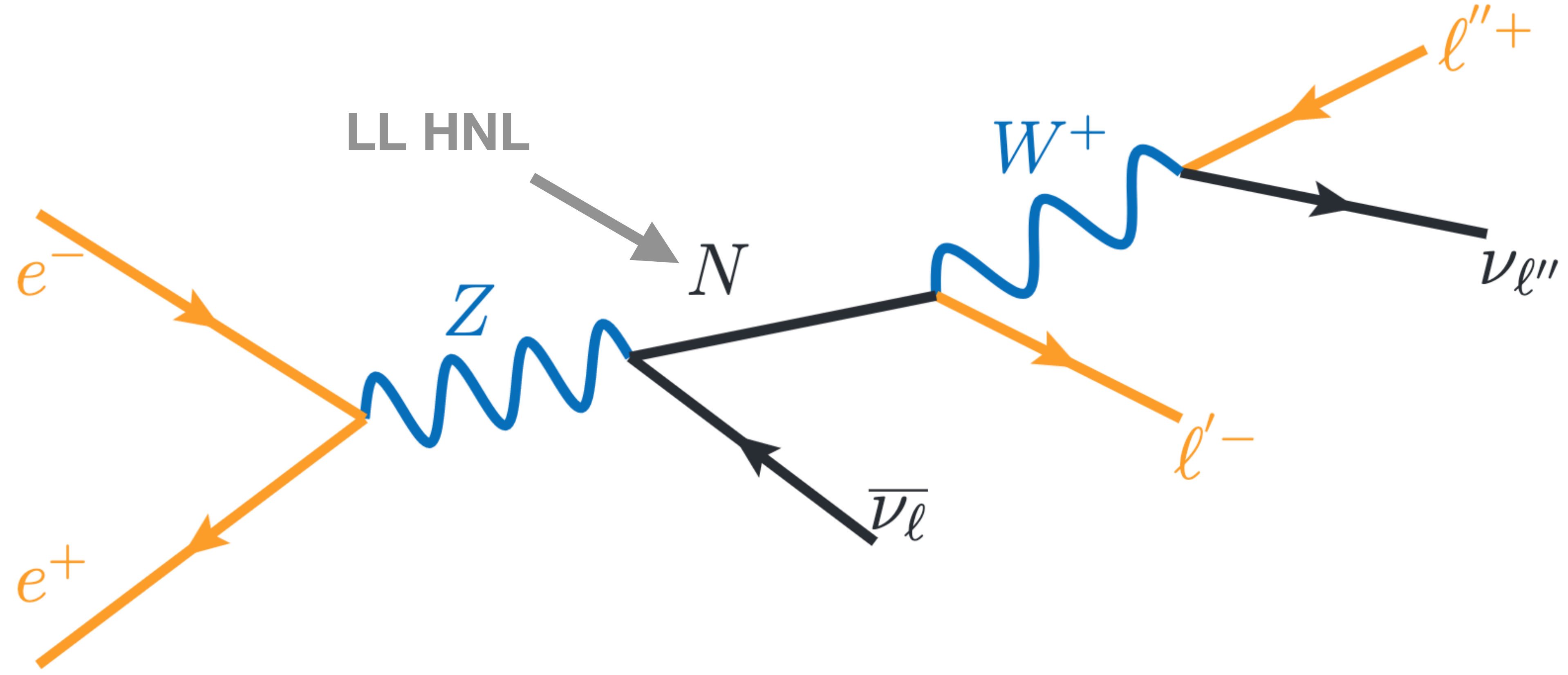
HNL → eev Analysis

◉ Snowmass Results

◉ Sensitivity analysis of long-lived HNLs

◉ Signal simulation using Type I Seesaw mechanism

- Focused on one benchmark HNL mixing with electron flavours
- Leptonic final states featuring e and ν_e

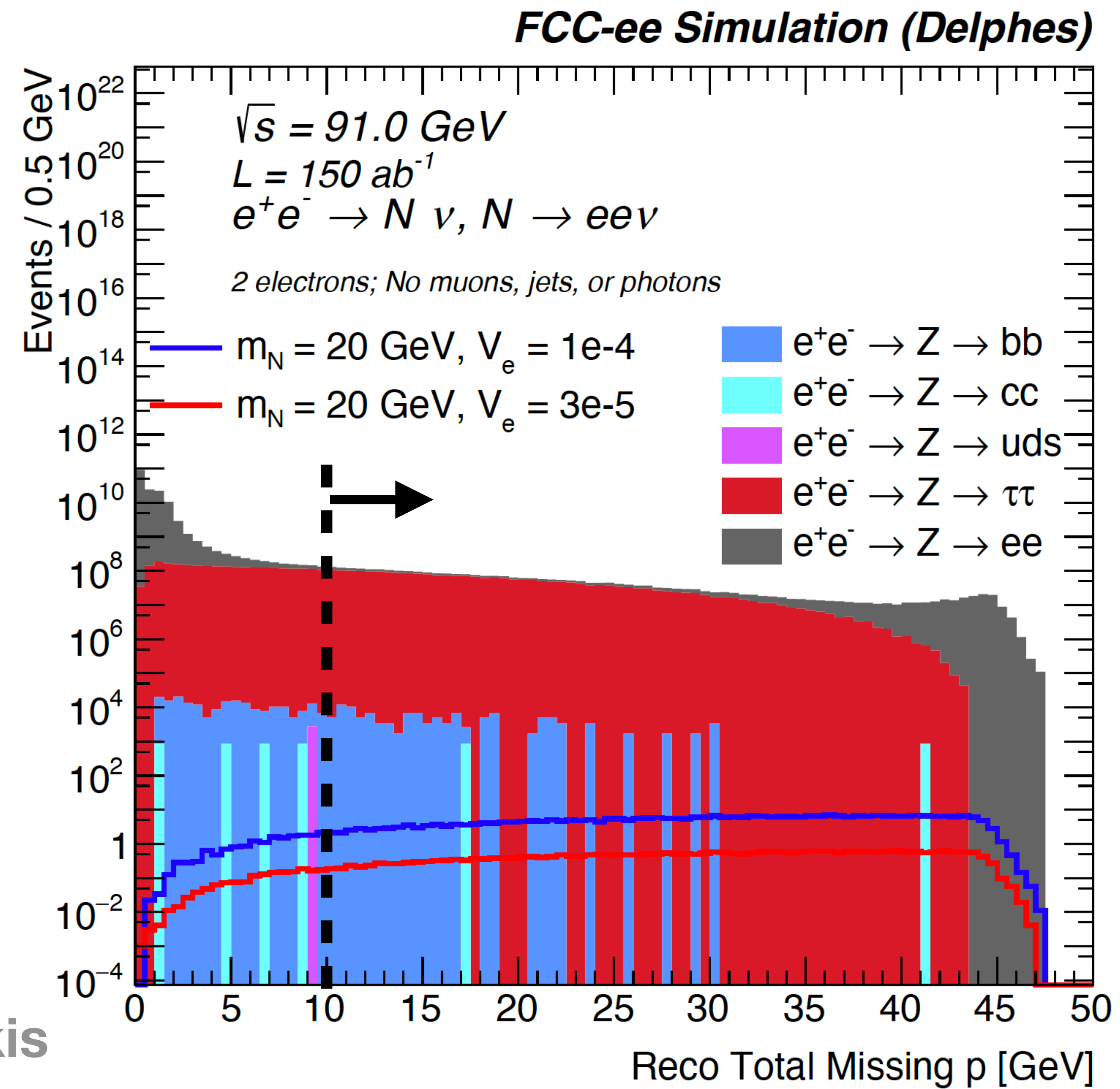


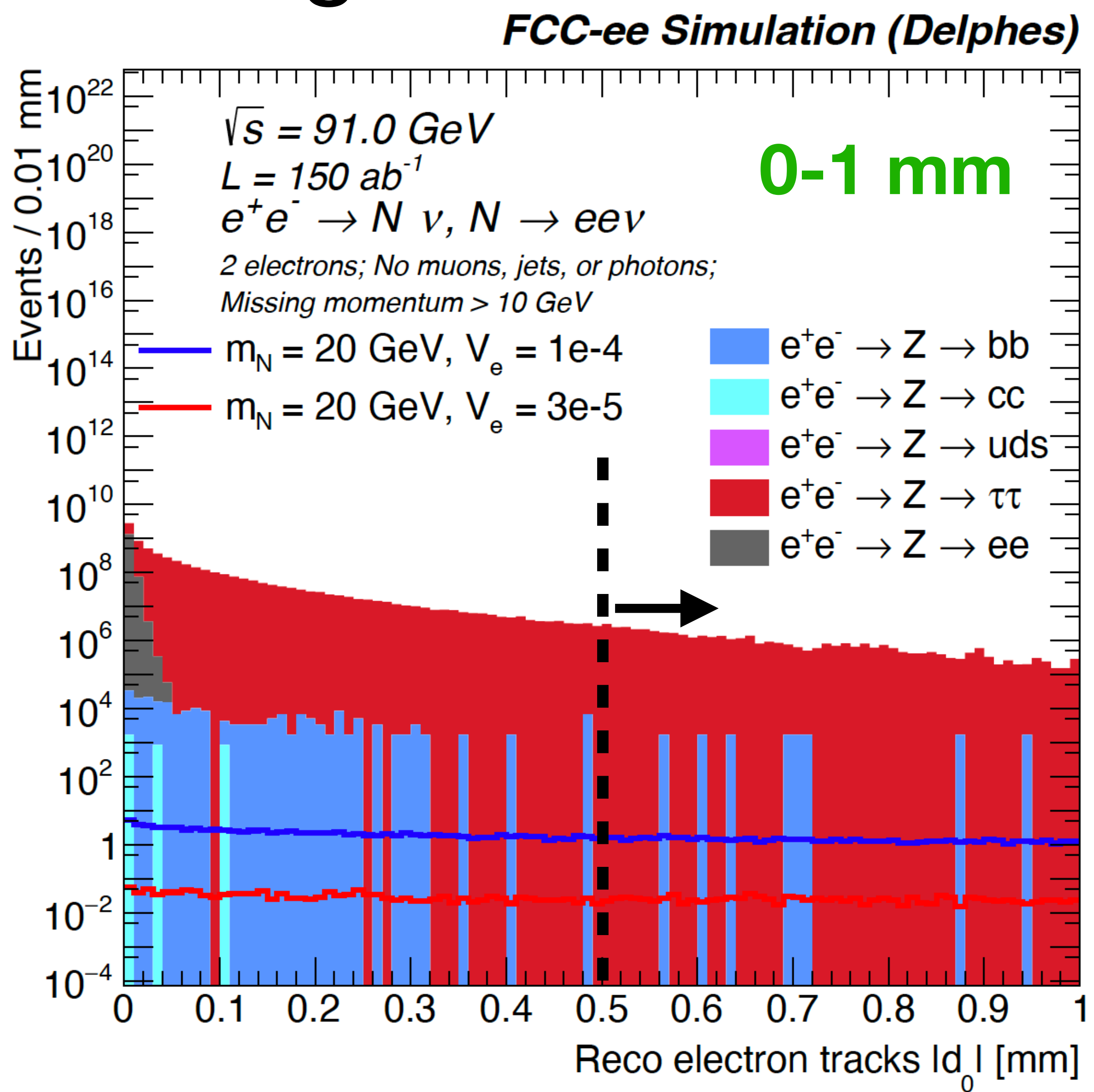
◉ Background simulation using Spring2021 campaign

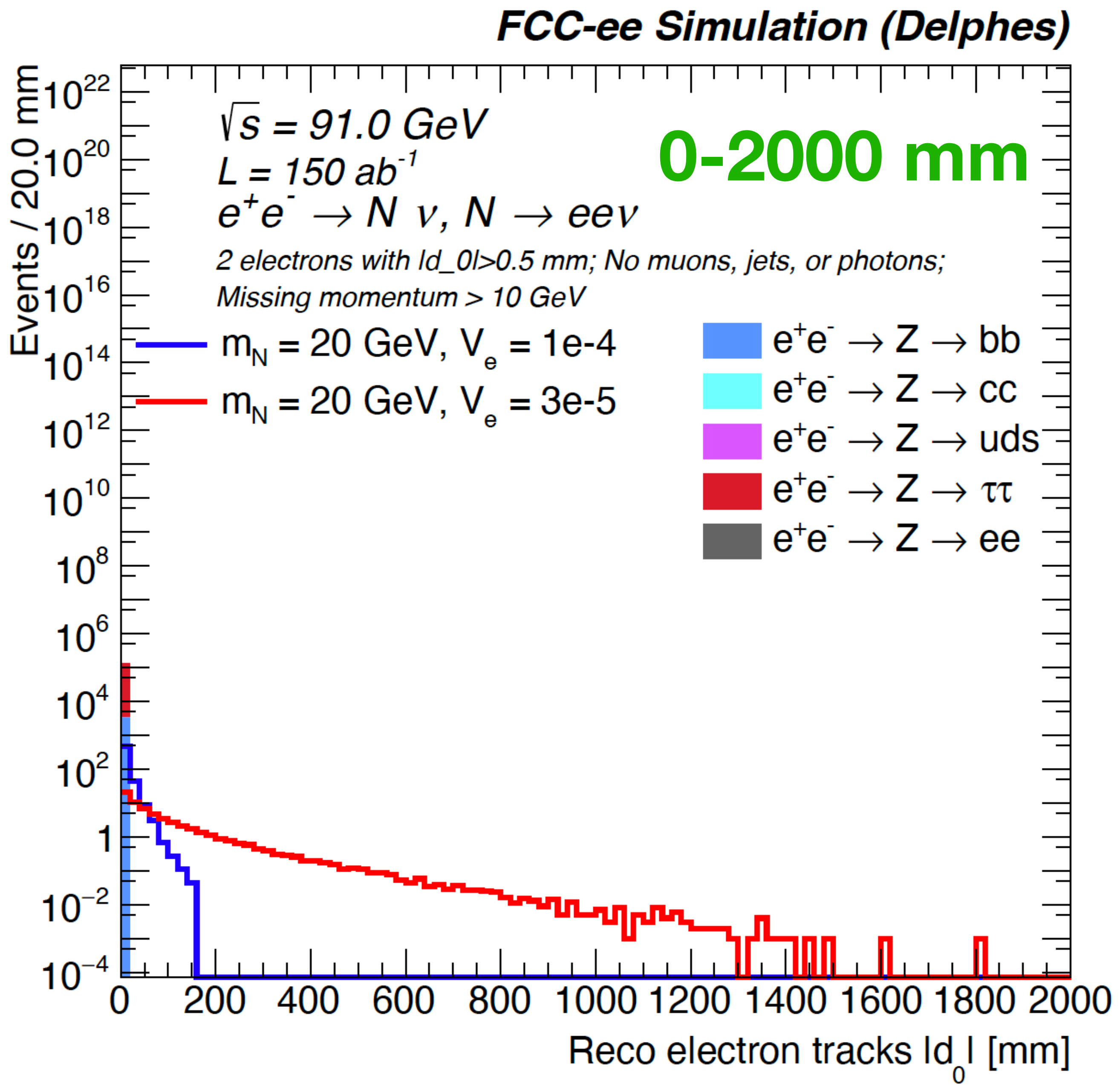
- Five different decay modes of Z considered as background

Event Selection

- **Discrimination variables: E_{miss} and transverse impact parameter of the electron track $|d_0|$**
- **Main selection:**
  - **Exactly two electrons, veto on additional photons muons and jets**
    - Reduce backgrounds with hadronic decays
  - **E_{miss} > 10 GeV**
    - Reduce Z→ee bkg with fake missing momentum
  - **$|d_0|$ > 0.5 mm**
    - Remove most of the rest of SM background





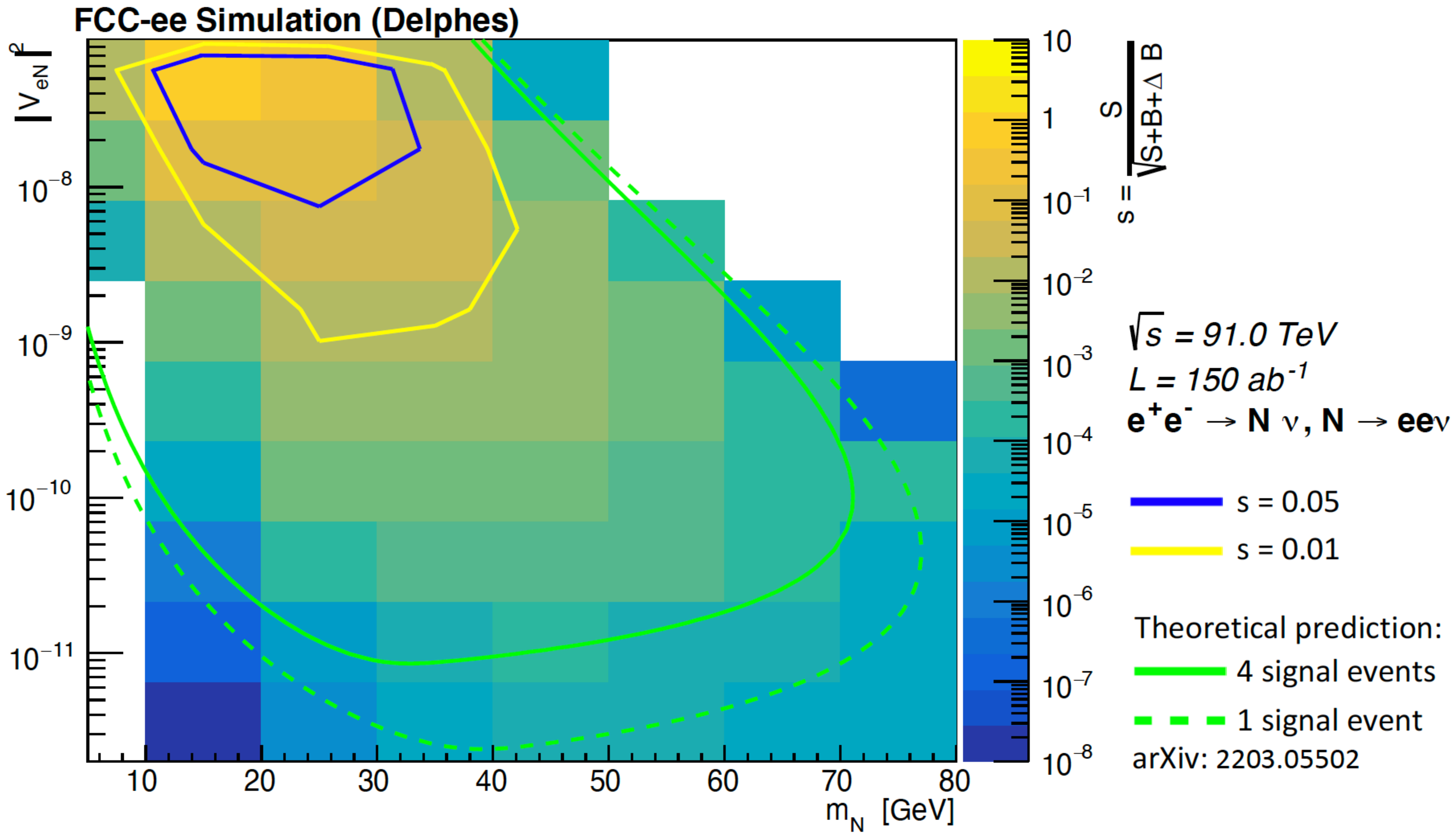


Sensitivity

- **Figure of merit used for sensitivity:** $s = \frac{S}{\sqrt{S + B + \Delta B}},$

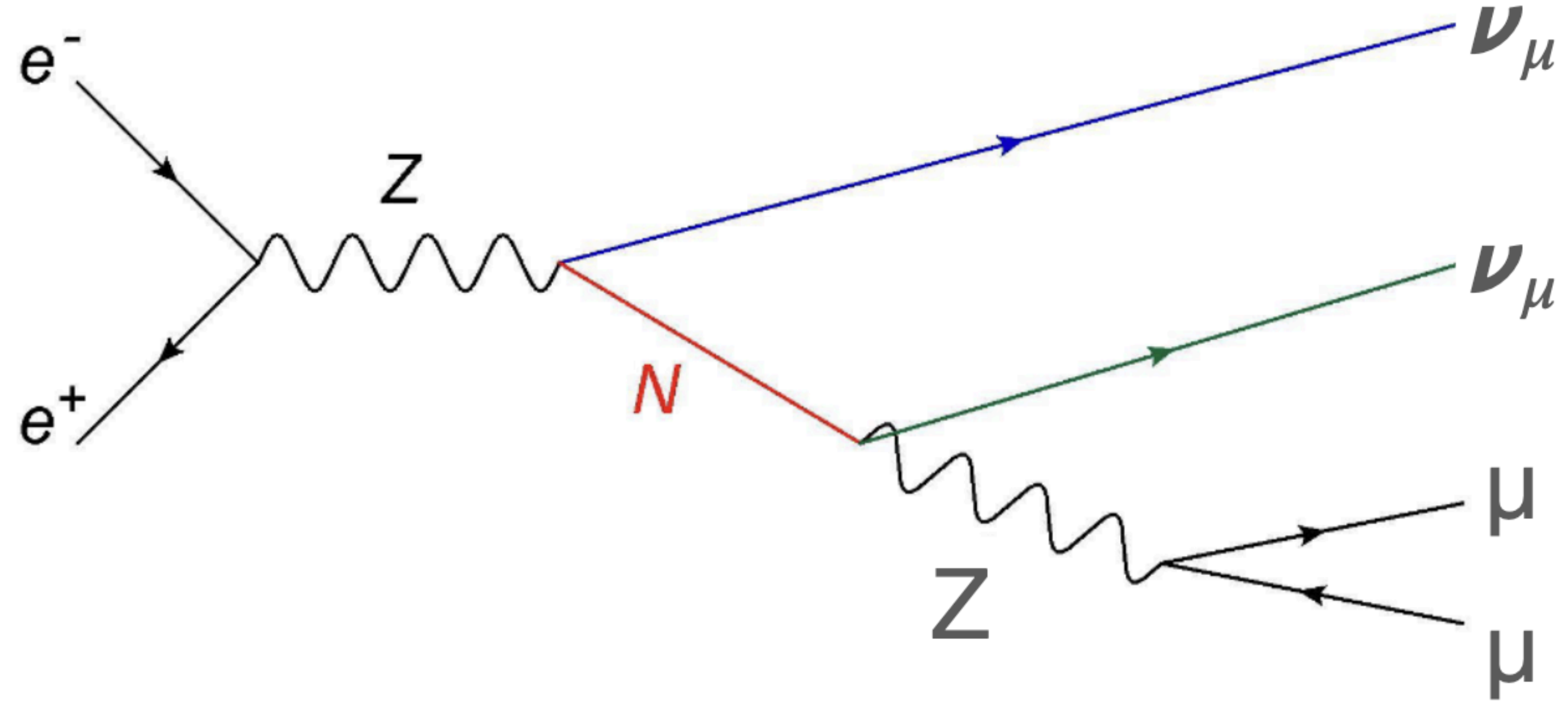
- **Contours for s = 0.01 and 0.05**

- **Theory predictions for 4 and 1 signal events (arXiv:2203.05502)**

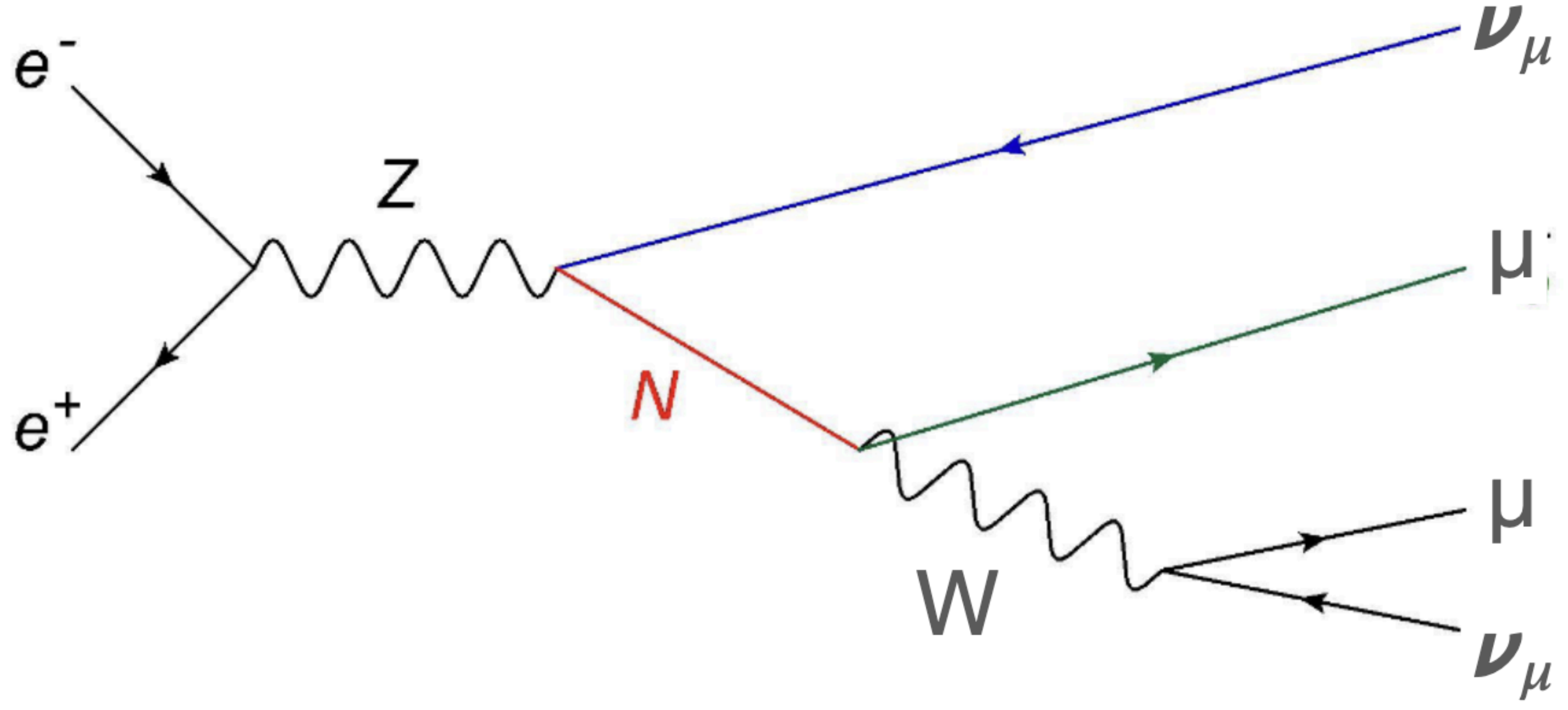


HNL → μμν Analysis

- **Assume that Majorana HNL have mixing coupling different from zero only with the ν_μ**
  - Focus on final states with two μ and E_{miss}



- **Signal samples:**
  - Wide range of masses and couplings
  - Standard tools used



- **Background samples:**
  - Official Winter2023 samples
  - Z→μμ, ττ, bb, cc

Event Selection - Efficiencies

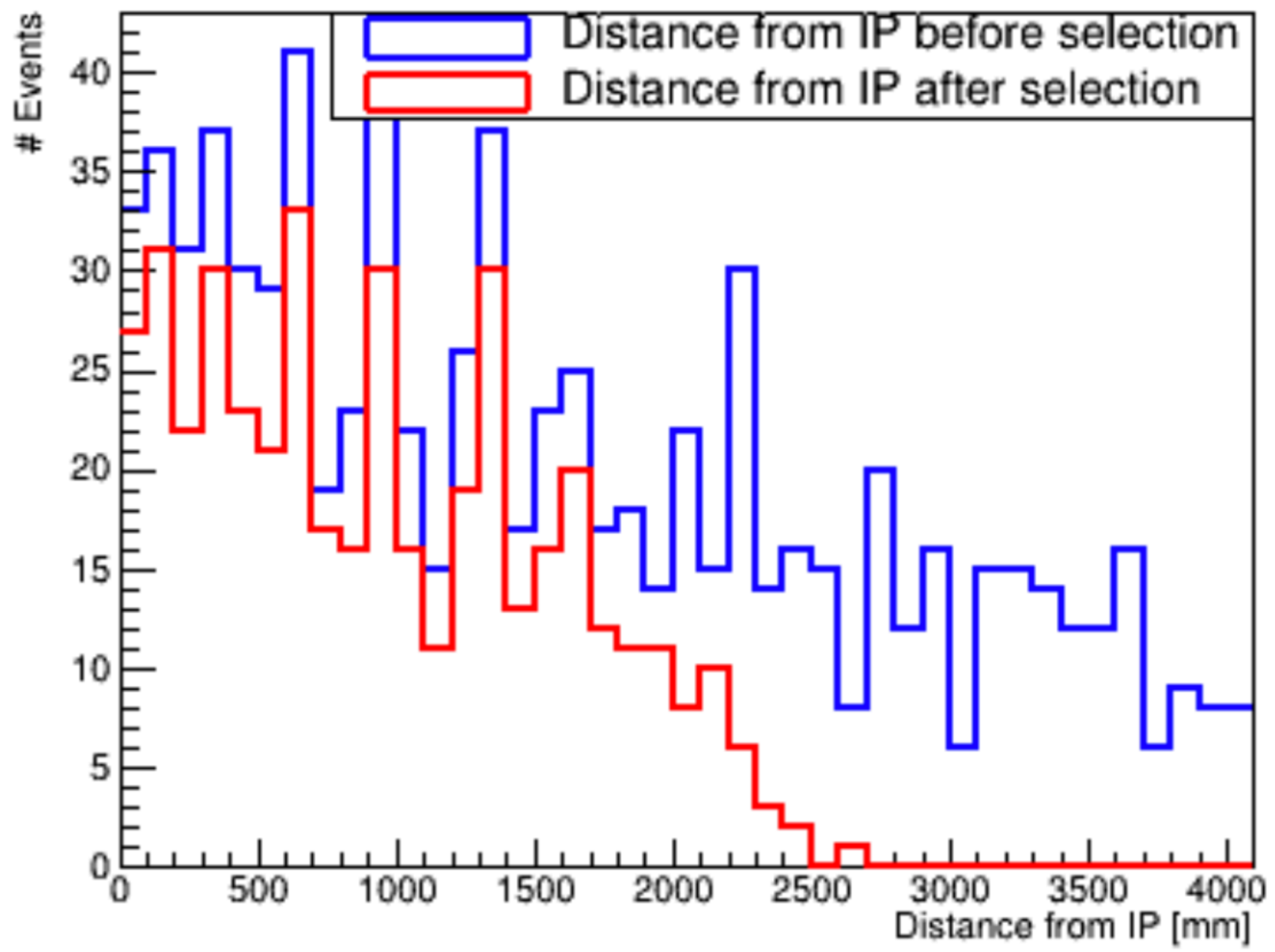
◉ Minimal requests for the preselection:

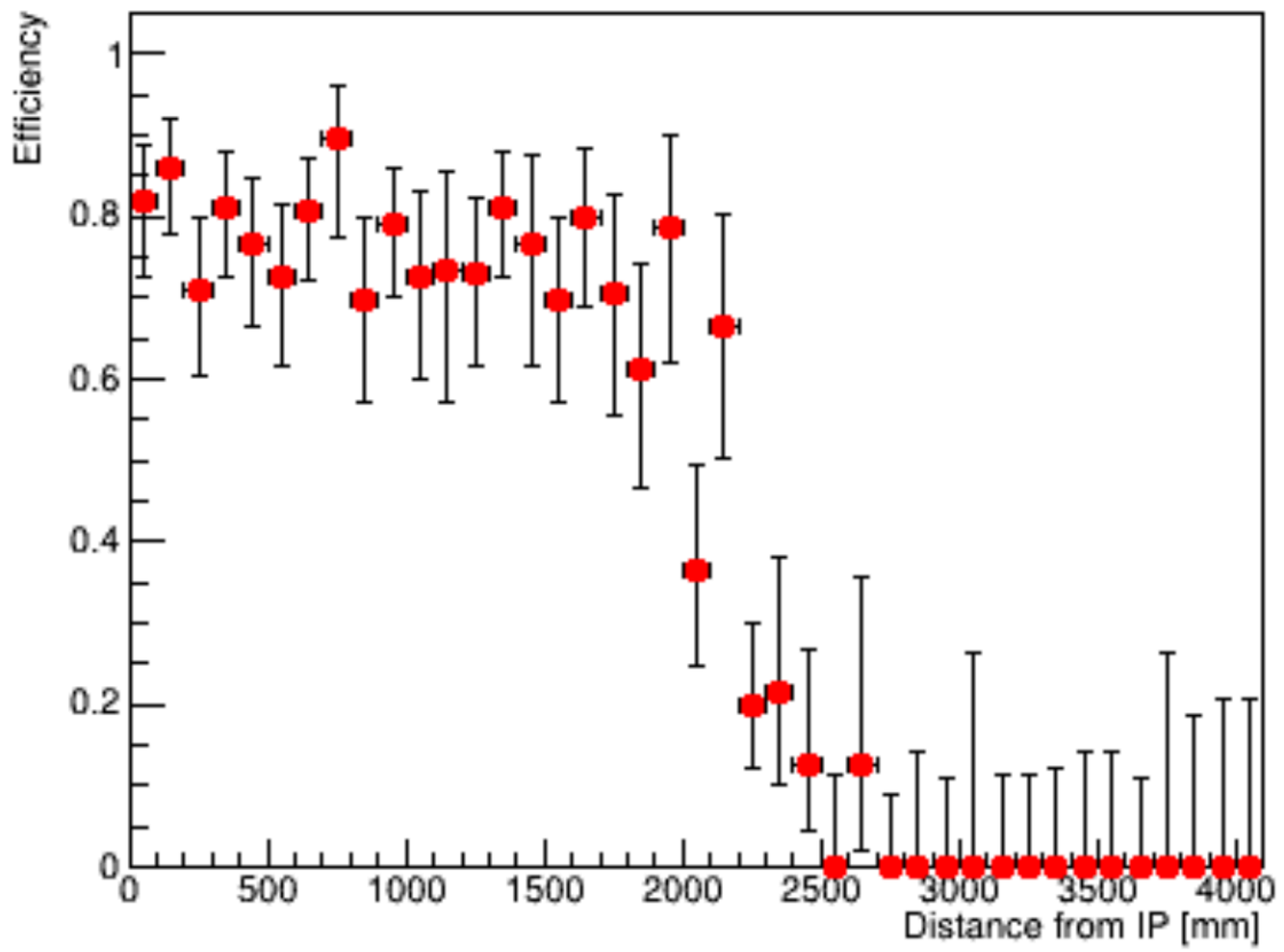
- **Exactly two tracks** in the central detector reconstructed as **muons** with **p > 3 GeV**

◉ Optimizing search based on the distance from the 2-μ decay vertex to the IP (D_{xy})

- **<u>Displaced vertex</u> main selection cut for signal/bkg separation**

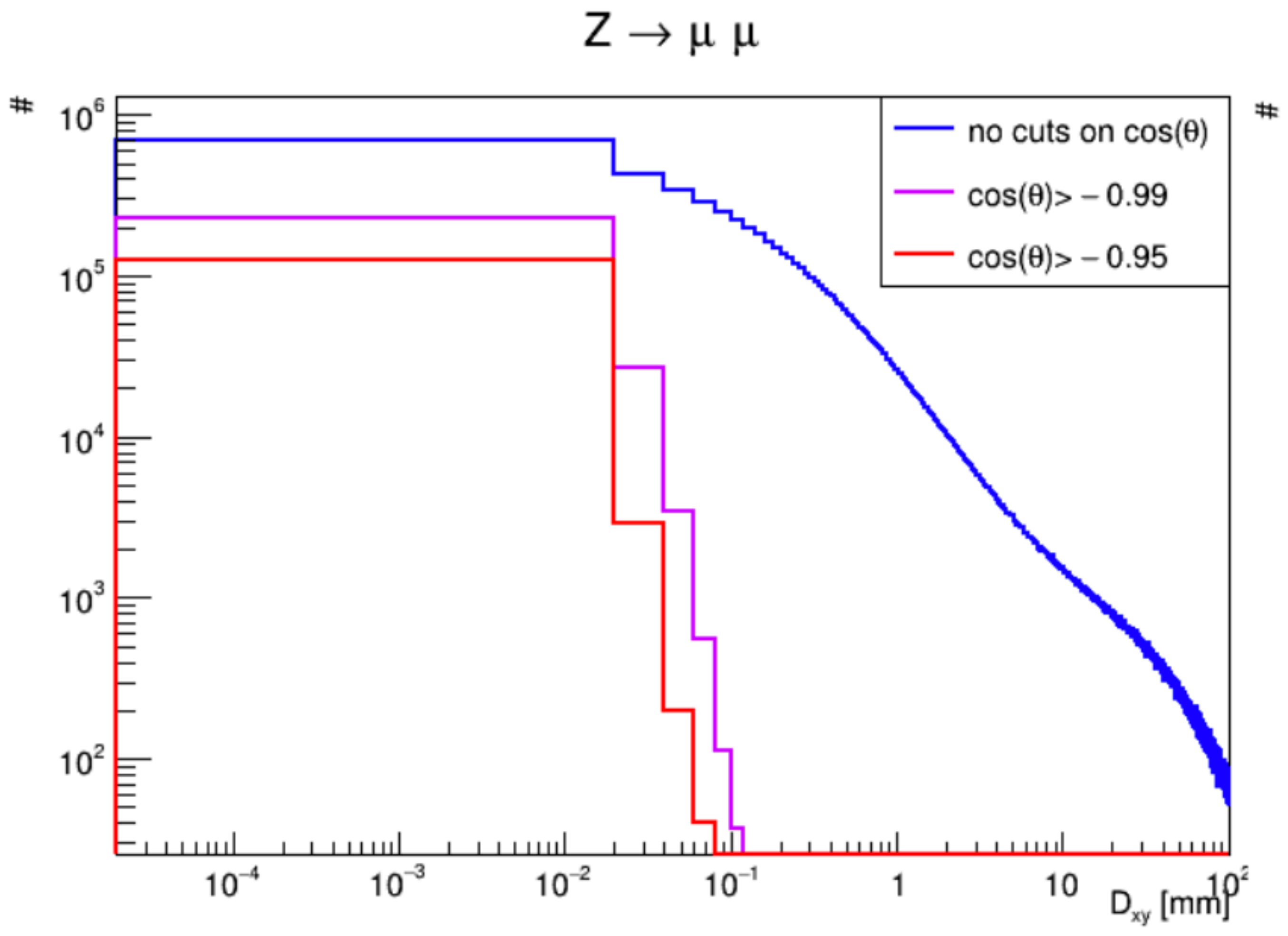
HNL mass = 20 GeV, V_mix = 10^-5

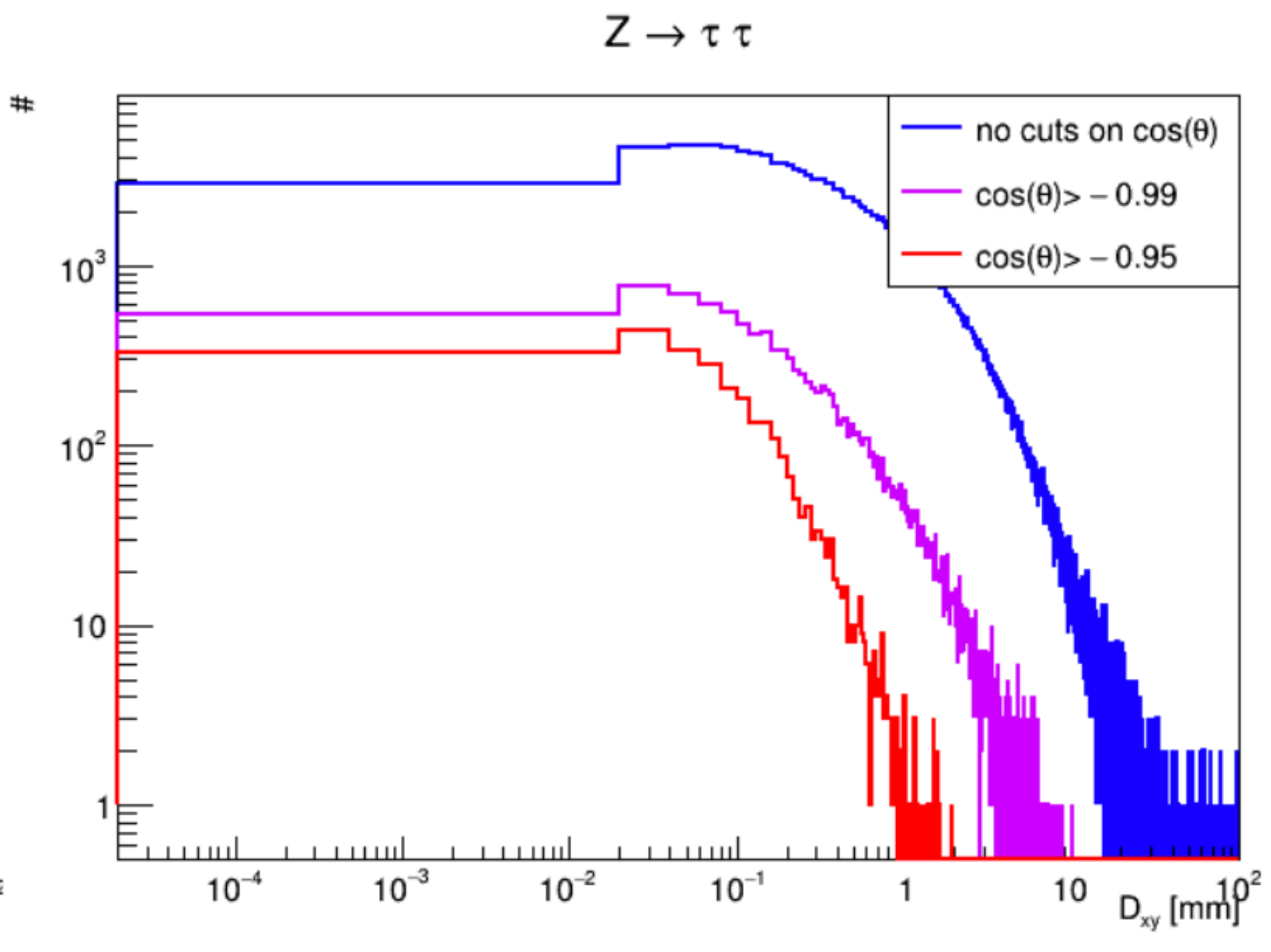


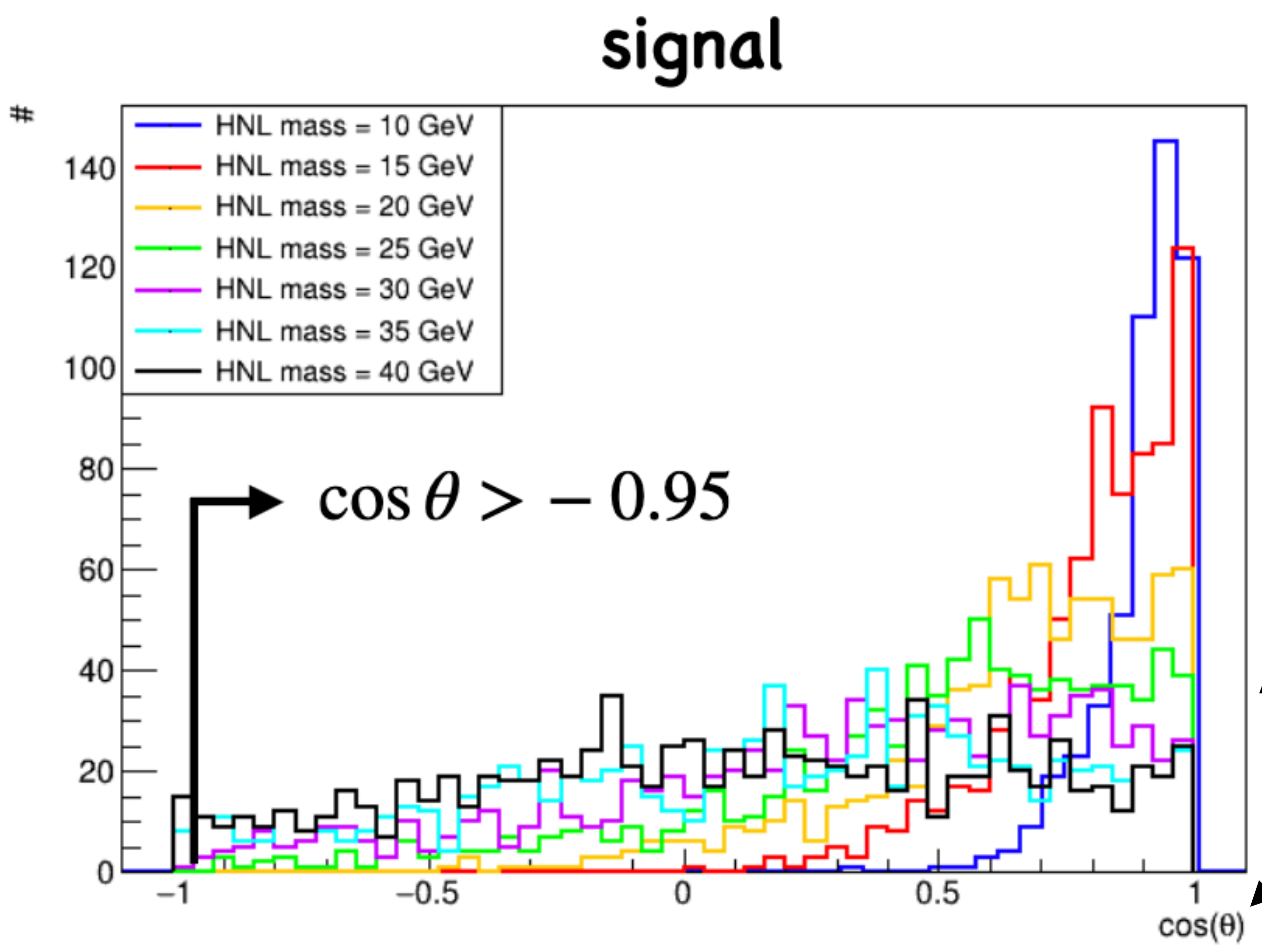


Event Selection - Efficiencies

◉Apply cuts on cosθ:







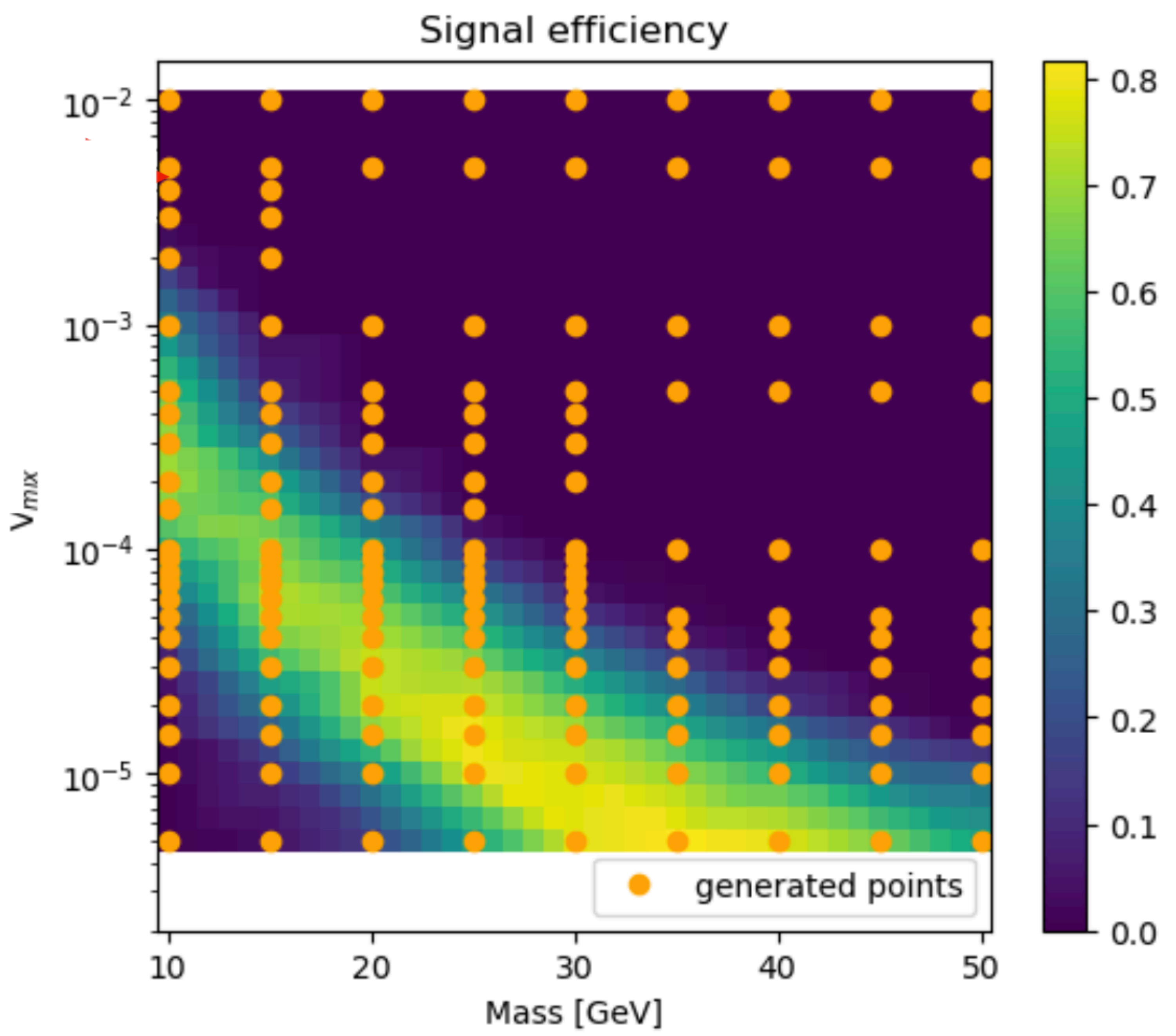
Angle between two muons

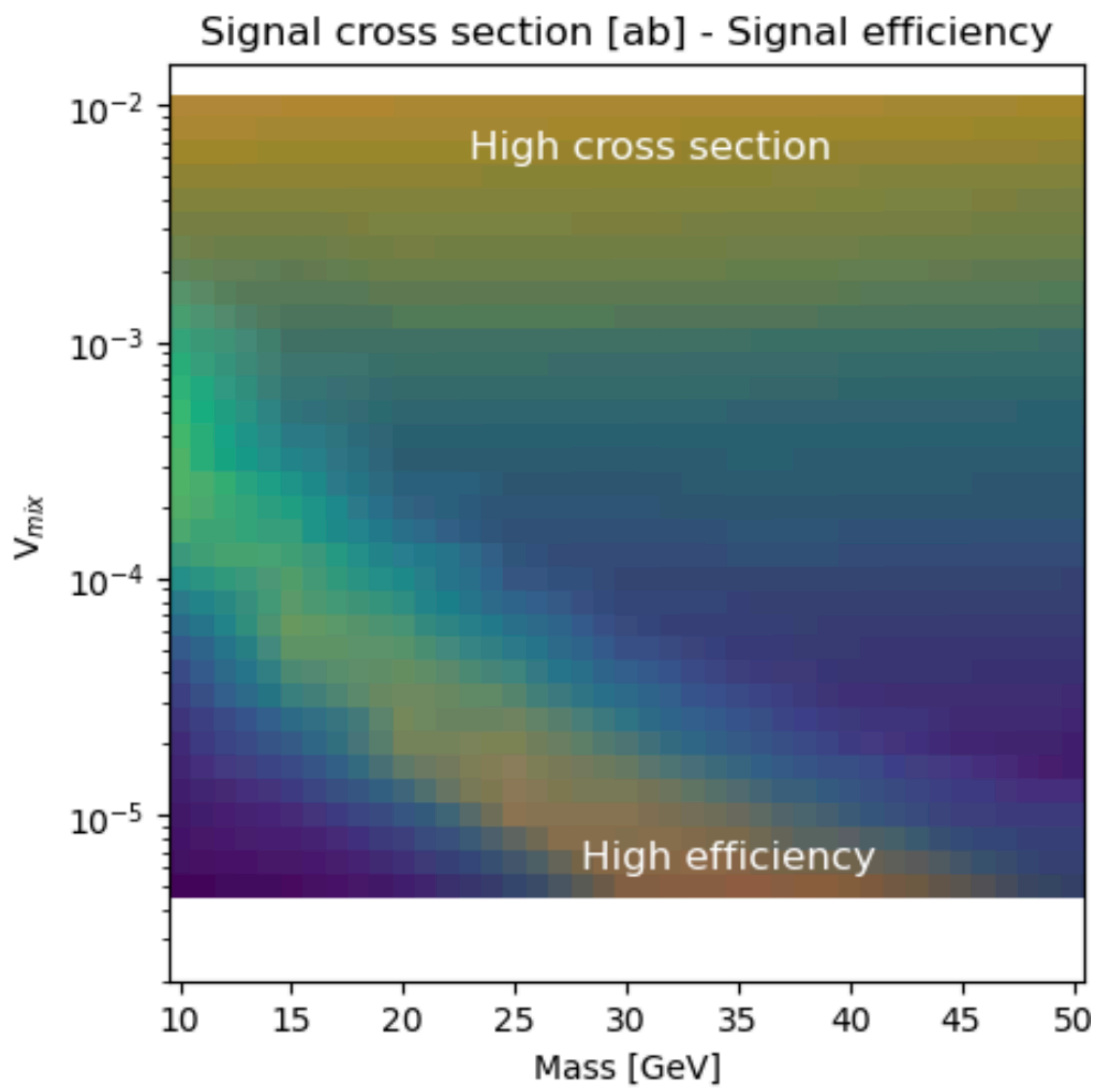
Signal efficiency after requiring:

- preselection

- cosθ > - 0.95

- D_{xy} > 1 cm



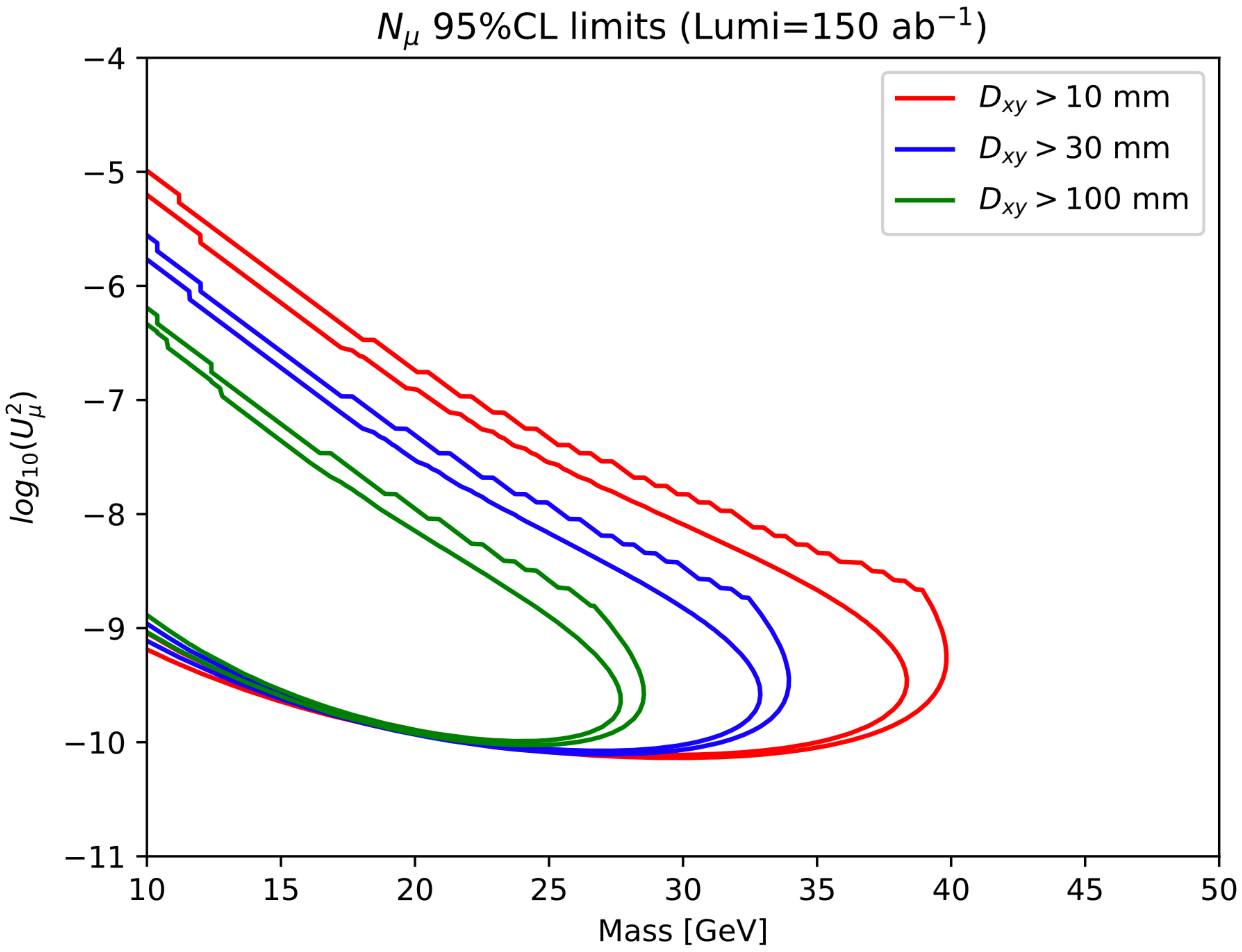


Sensitivity

◉ **Interpolation of the sensitivity contours using parametric fit to parameterize the efficiency vs decay length**

Expected limits

- Results obtained assuming negligible background for the three hypotheses of the D_{xy}
- D_{xy} cut should be tuned once a more reliable estimation of the bkg is obtained



Study of properties

Lepton number violation

Dirac vs Majorana HNLs

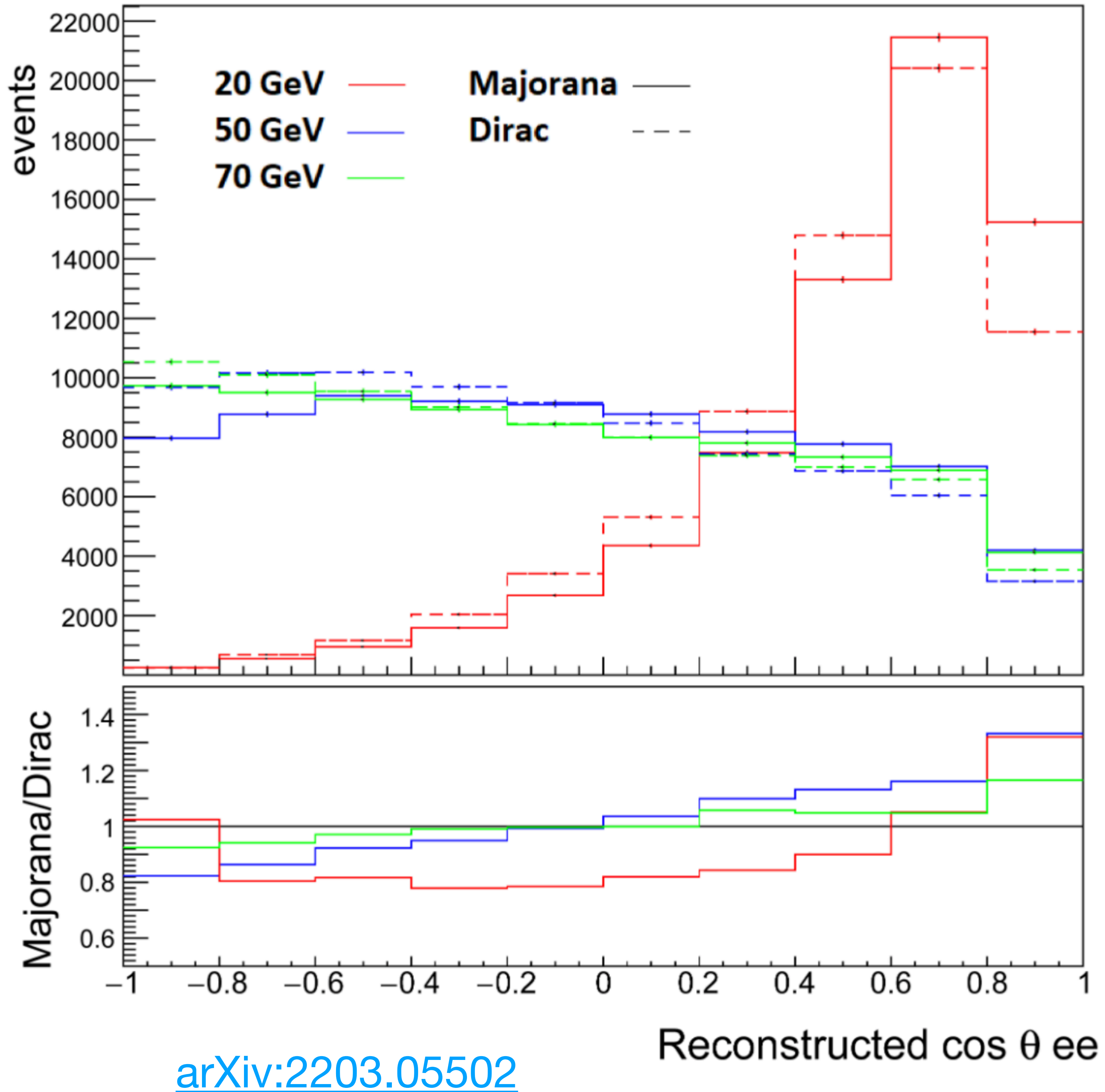
D. Moulin, P. Kontaxakis, T. Sharma, A. Sfyrla

◉ Dirac (LNC) and Majorana (LNC+LNV) HNLs produce distinct kinematic distributions

- Establishing the final state variables wherein the difference between Dirac & Majorana can be observed (arXiv:2105.06576)

H→eeν

Angle between e^- & e^+



arXiv:2203.05502

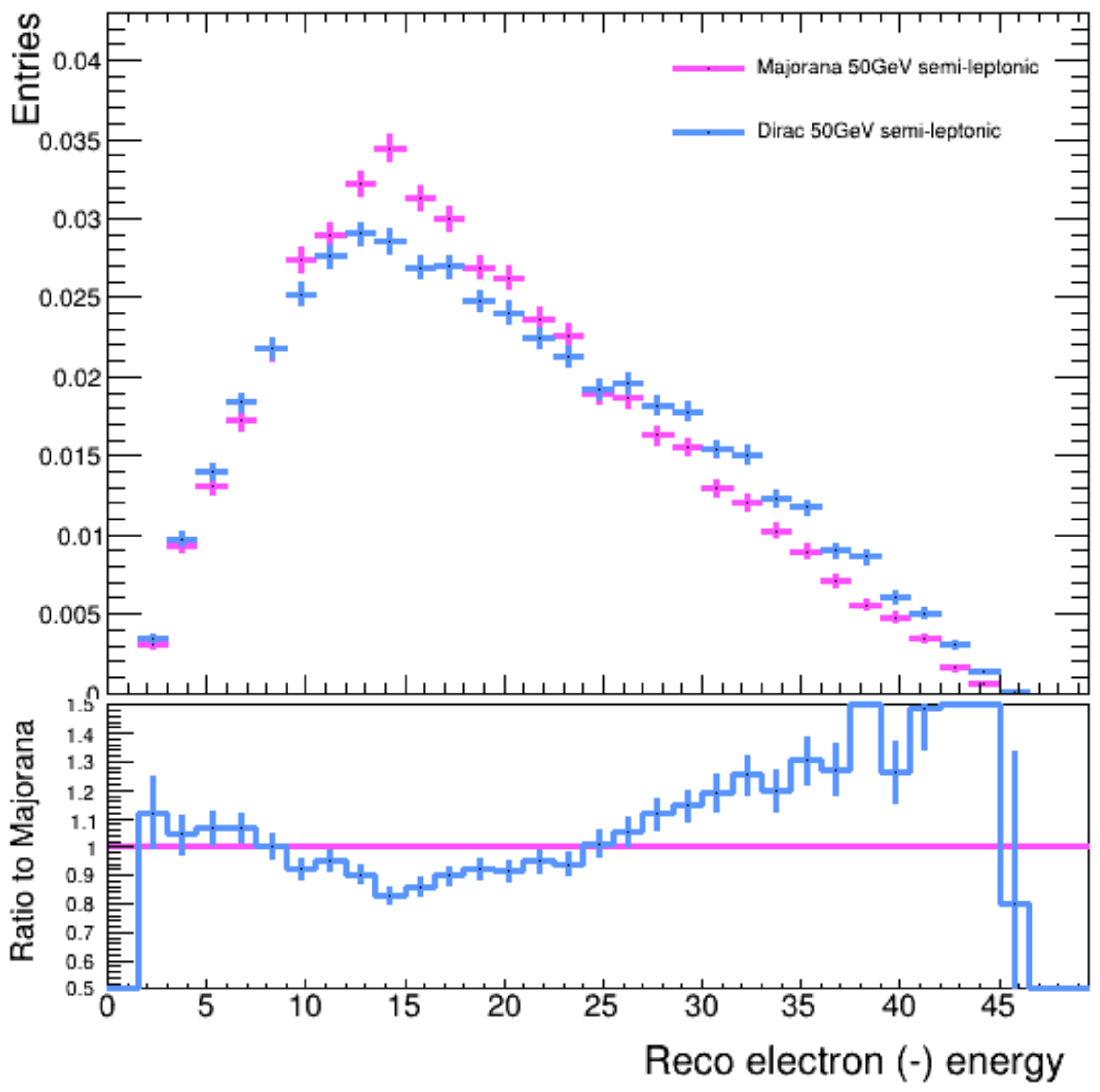
◉ Utilize metrics (asymmetries, angular distributions, …) where the LNV nature of the processes can be identified

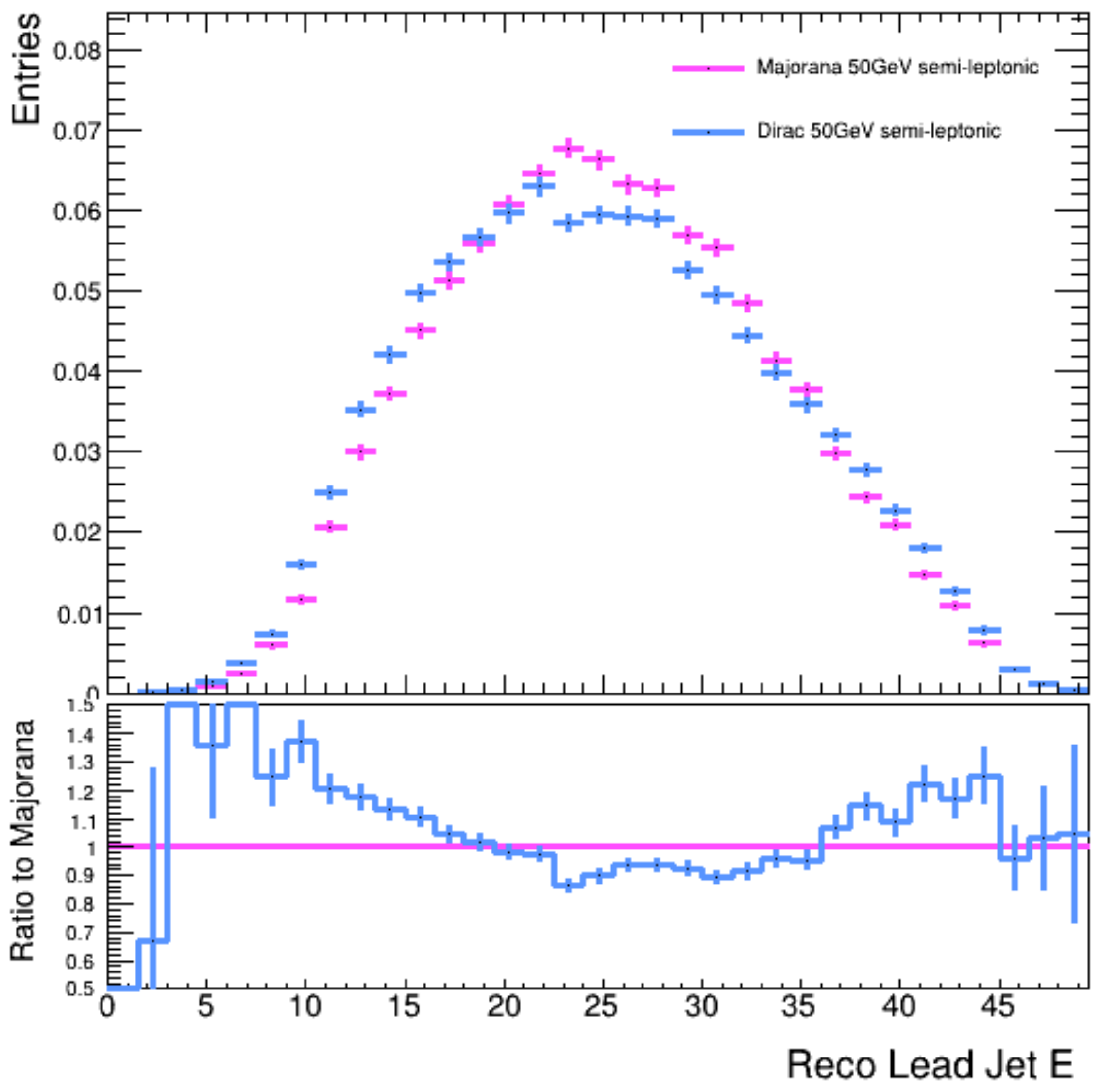
Discrimination Variables (HNL→ejj channel)

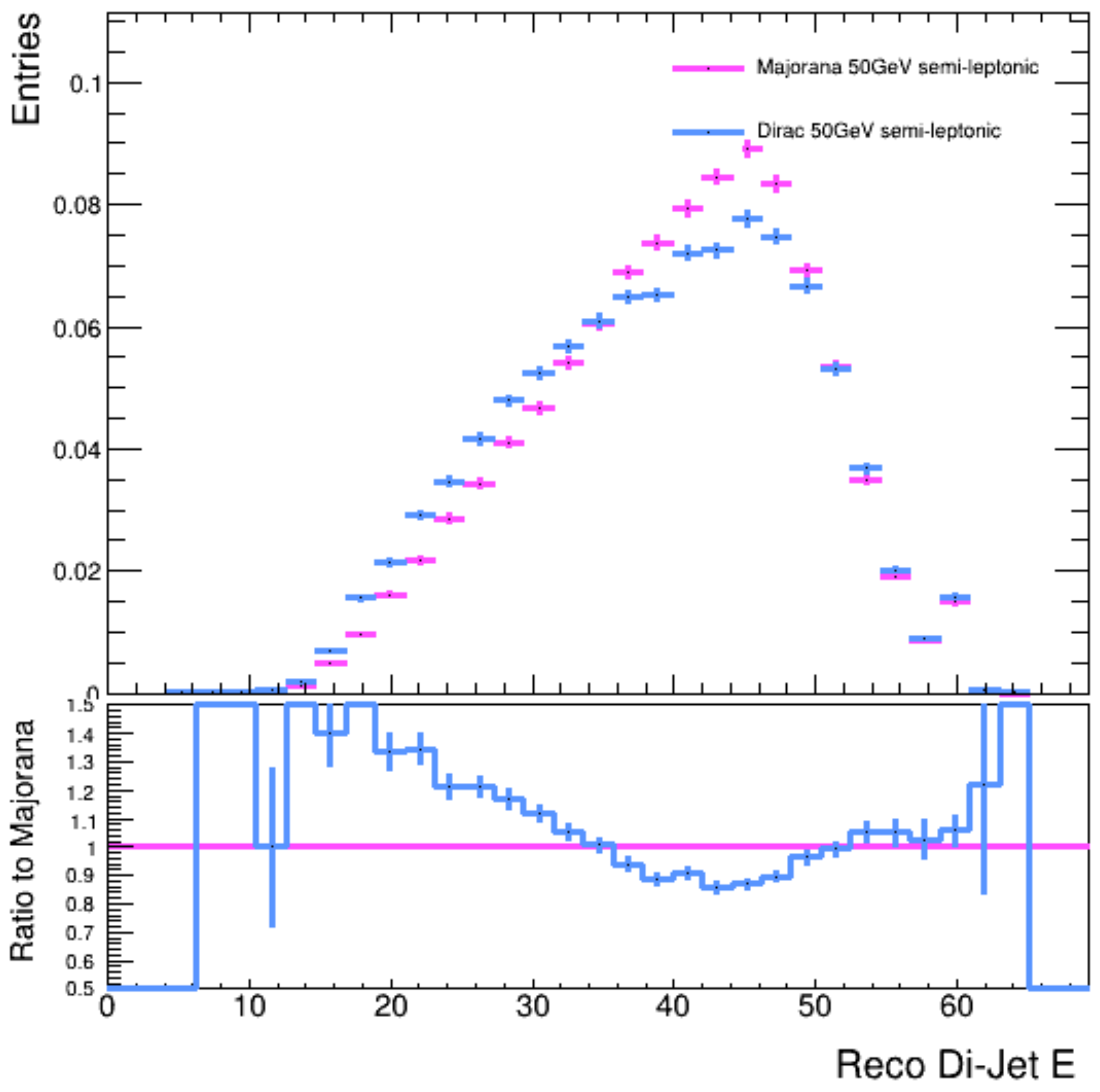
◉ Electron energy, HNL (dijet) energy, Electron - HNL angle and related variables

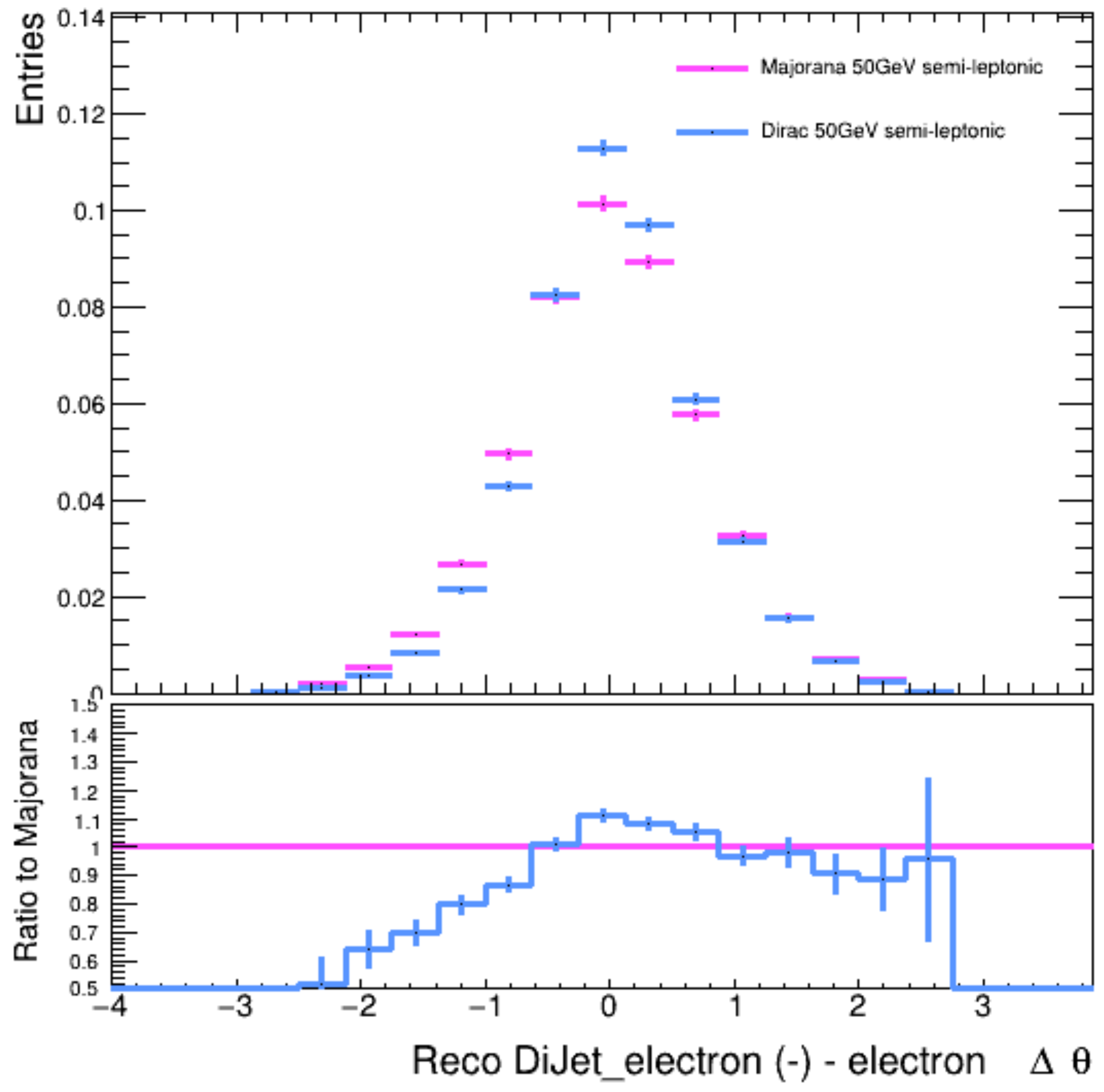
- Studied both at the generation and reconstruction level
- Effective discrimination achieved by separately analyzing the e^+/e^- distributions
- Various HNL masses investigated

Illustrative plots:









Very good discrimination power for several variables

Summary & Outlook

- Outstanding potential of FCC-ee for direct exploration of 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 demonstrating sensitivity to even very small mixing angles
  - Integration of prompt and LLP signatures complementary in covering the entire parameter space
  - Studies show promising results in effectively probing lepton number violation

- Intensive efforts are currently underway on optimizing the sensitivity for benchmark signals

Backup Slides

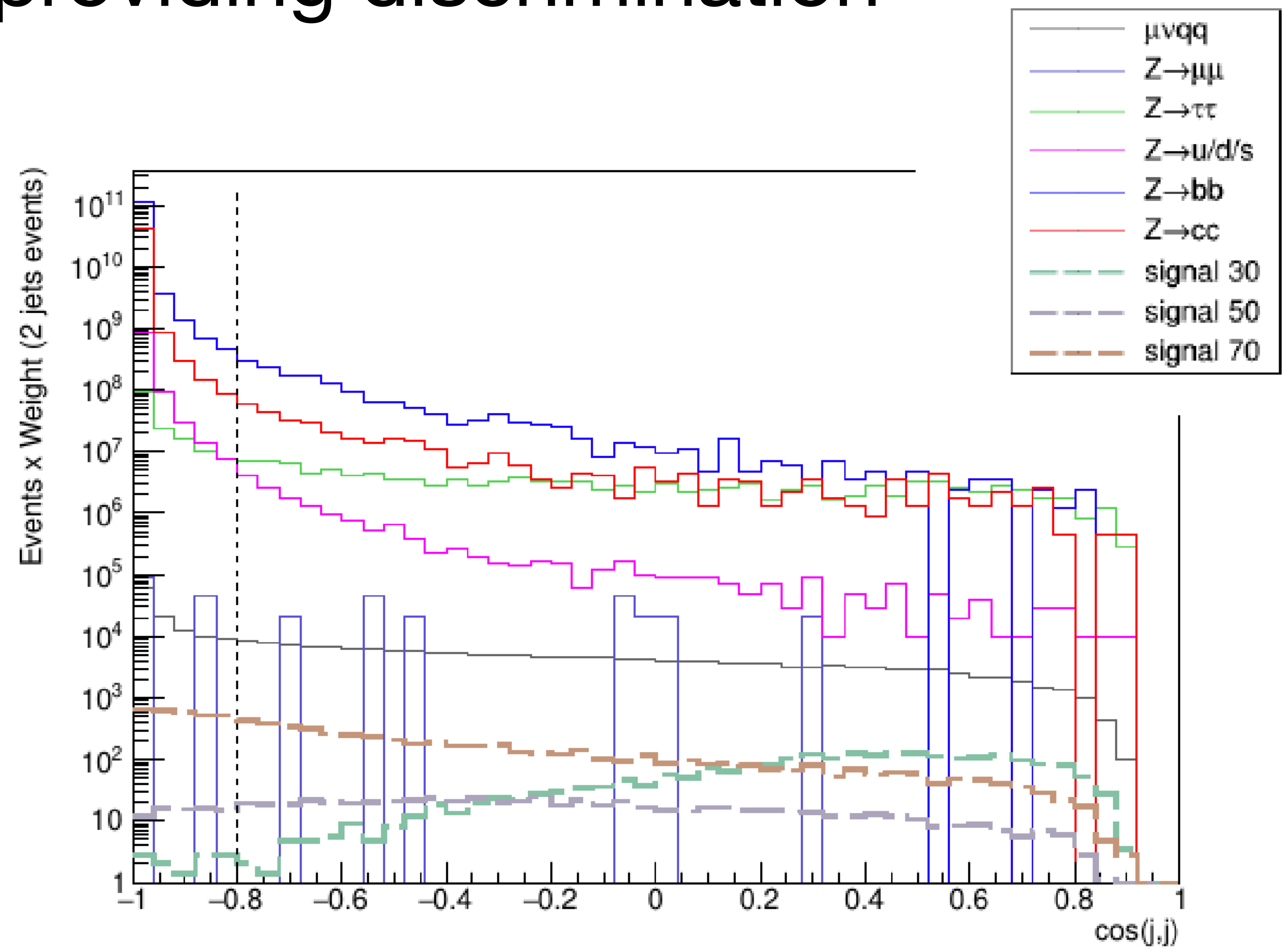
FCC-ee Physics Program

Courtesy of Christophe Grojean

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:

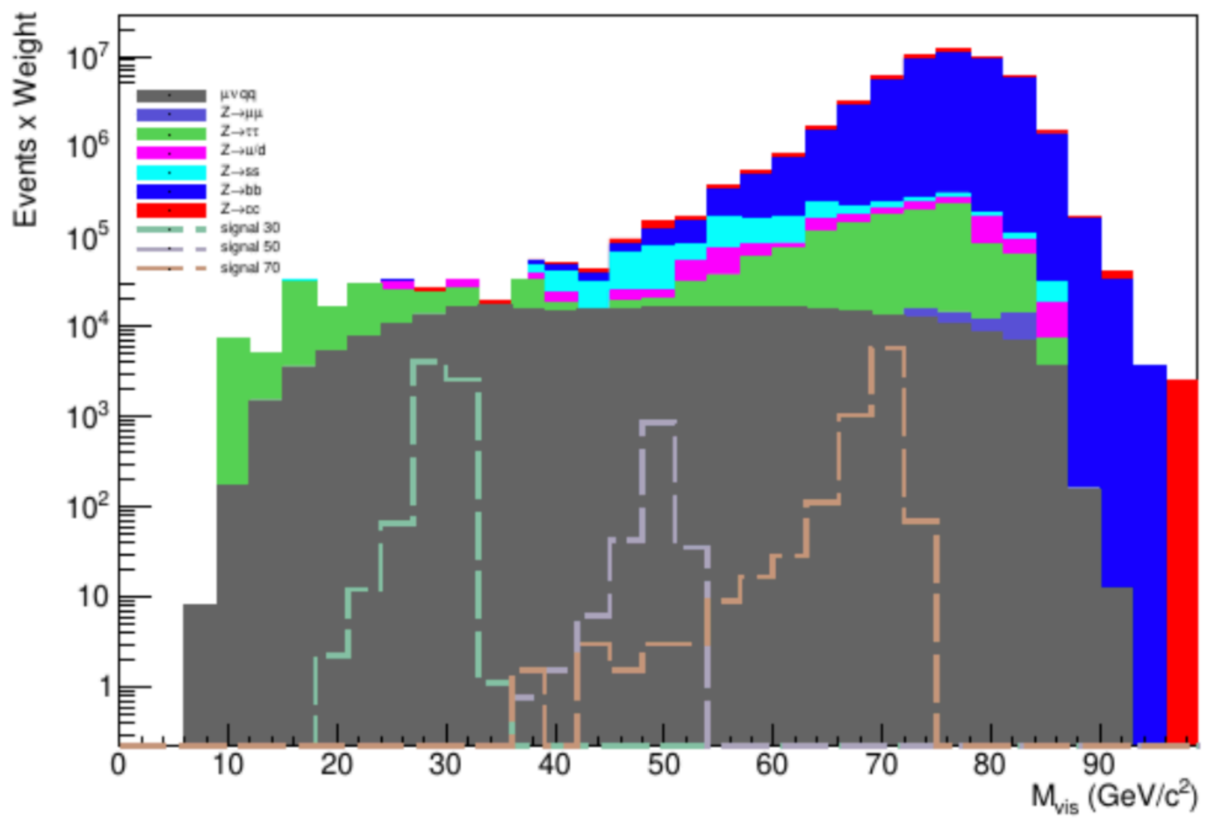
$$M_{vis} \in M_{N_1} \pm 2 \times 10\% \times \sqrt{M_{N_1} / \mathrm{GeV}}$$

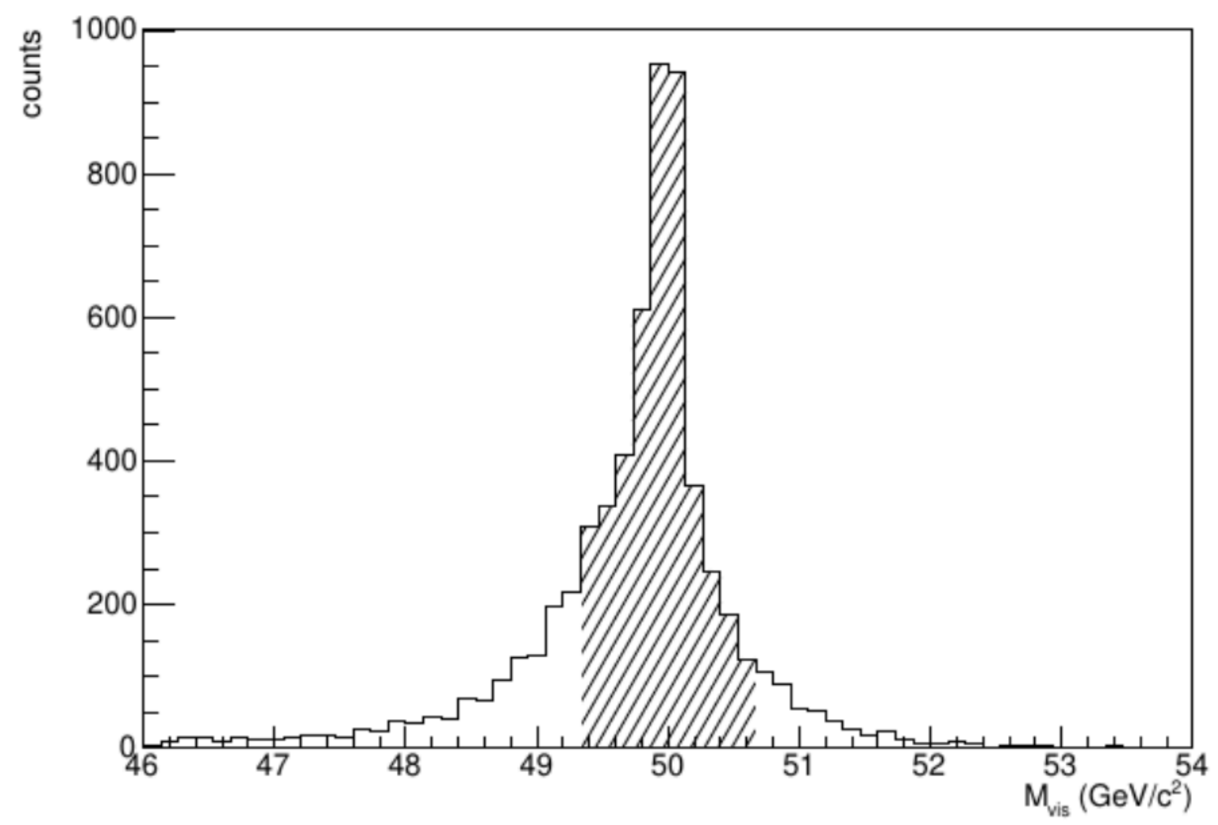
where M_{vis}: sum of visible 4-momenta to select HNL mass and ν recoil energy

- Apply also cut on E_{miss}:

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

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



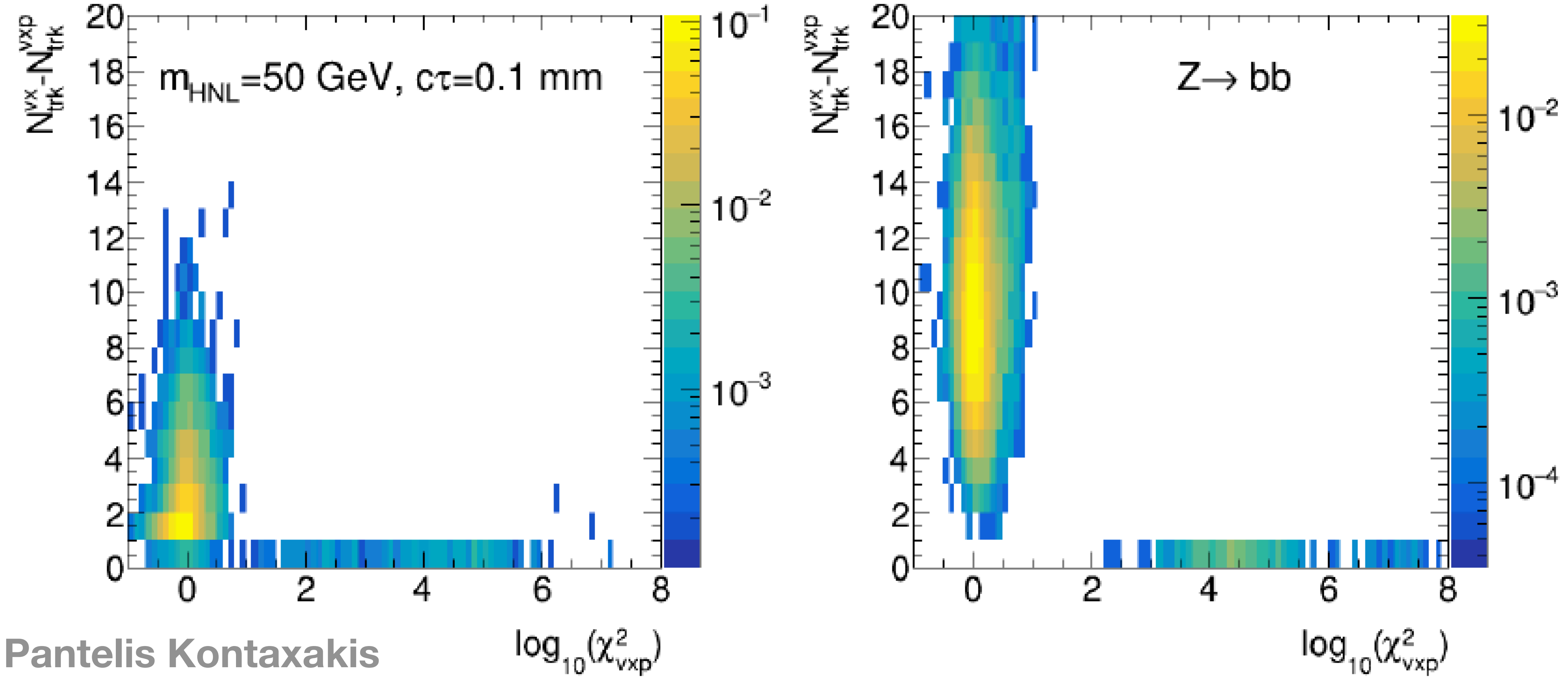


HNL → μjj Selections

Vertex-based selection

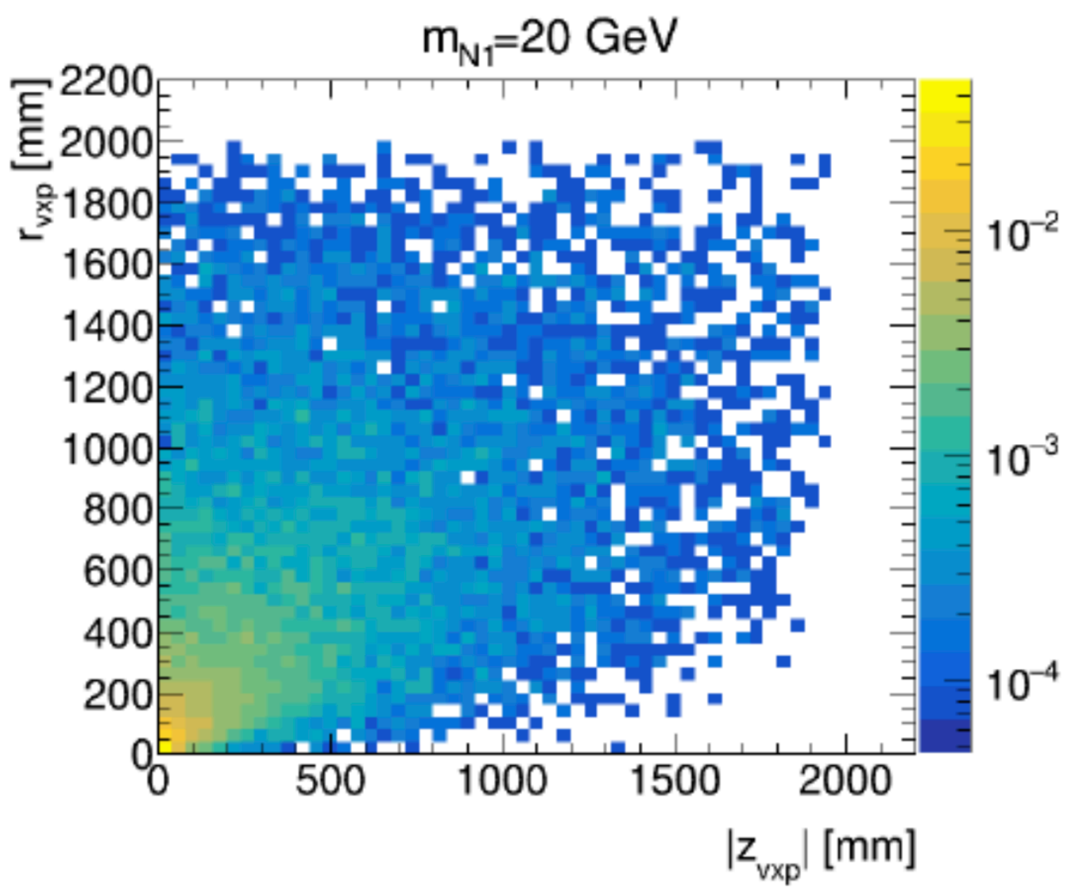
- Require well-reconstructed primary vertex and most of the Tracks used for primary vertex
- Substantial rejection for heavy flavours

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

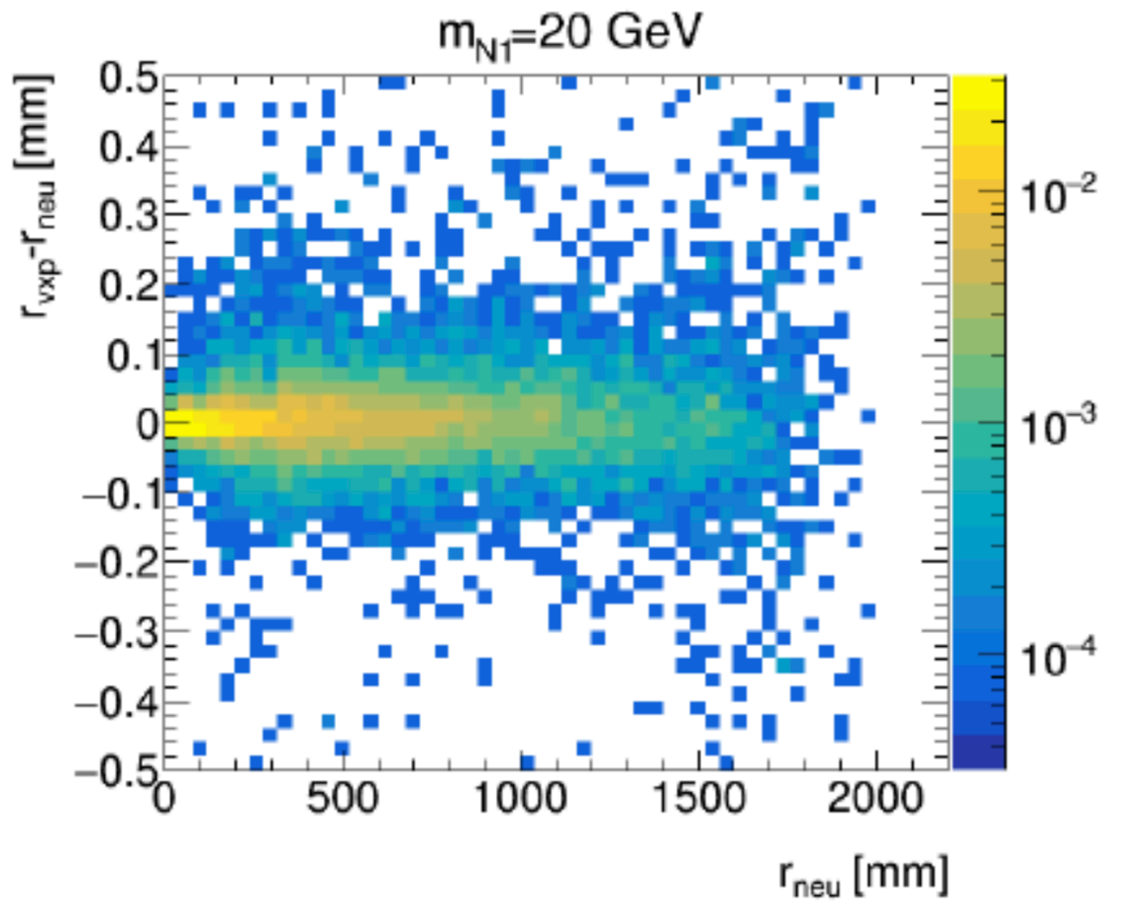


Prompt vs Long Lived selection

- 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

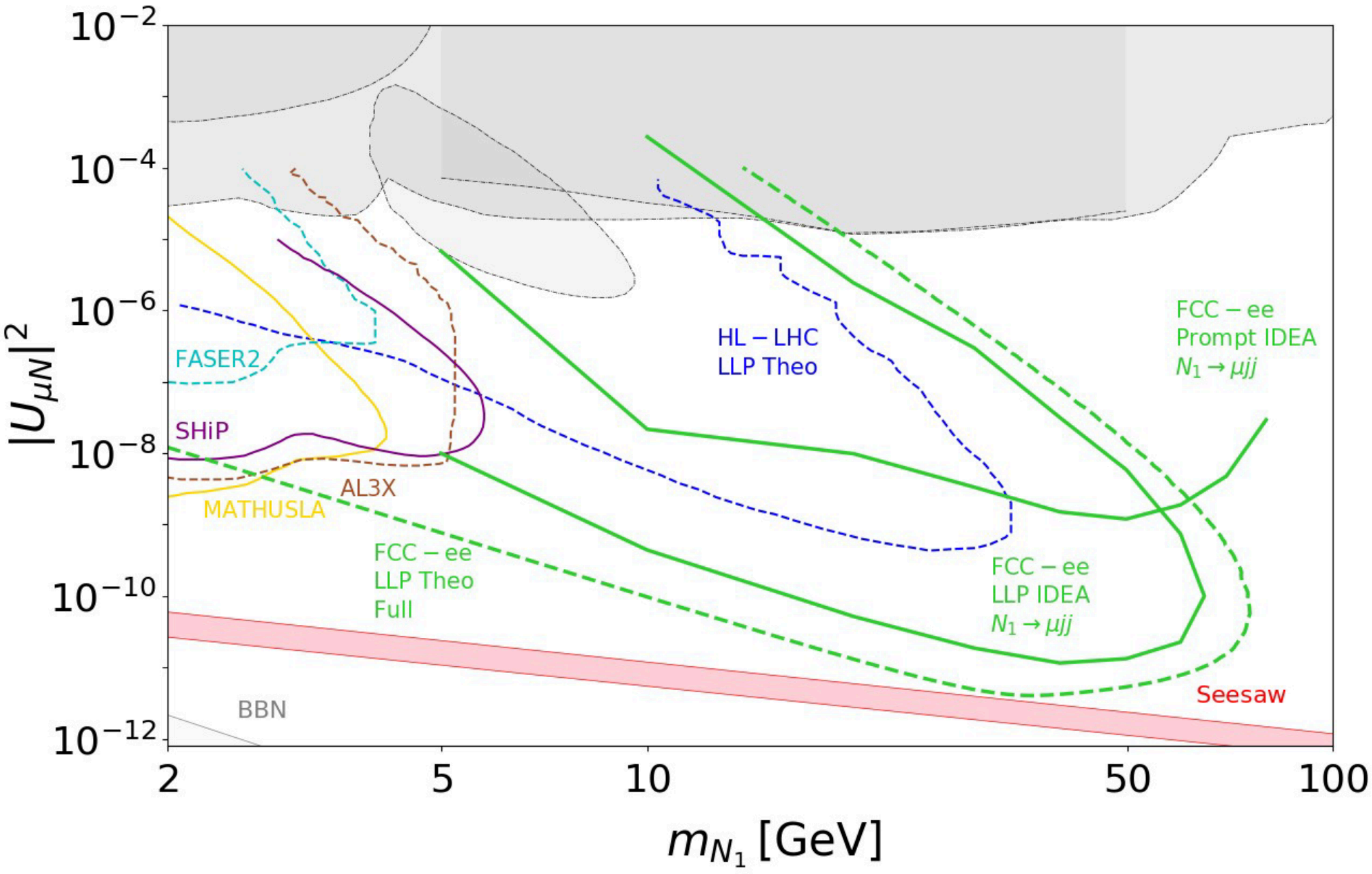


Very good resolution in position of HNL reconstructed vertex

HNL → μjj | Analysis Flow

1. Event Filter	2. Event Selection	3. Vertex selection
1 muon ≥ 3 tracks $E_\mu \geq 3$ GeV $E_{miss} \geq 5$ GeV	1 lepton (muon) Cuts on p_{miss}, jets, μ and visible mass	$N_{tracks} - N_{tracks}^{primary} < 5$ $\chi^2_{vtx,primary} < 10$
4. Mass-dependent kin. selection	**5a. Displacement: prompt**	**5b. Displacement: LL**
M_{vis} within $2 \times 10\%\sqrt{M}$ E_{miss} within $2 \times 10\%\sqrt{p_\nu}$	$r_{vert}^{primary} > 0.5$ mm $D_{0,\mu} < 8\sigma$ if $M_{N_1} > 70$	$r_{vert}^{primary} < 0.5$ mm

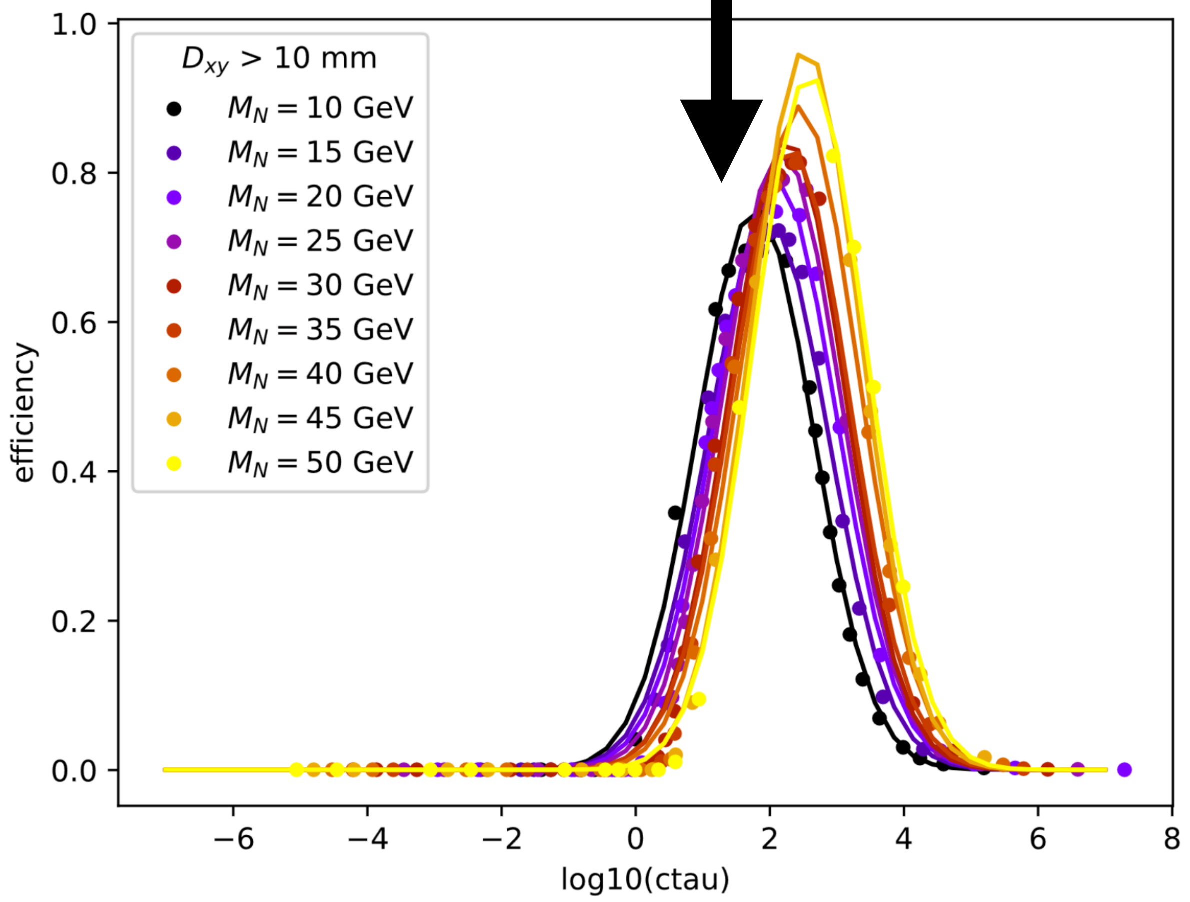
HNL → μjj | Final Result

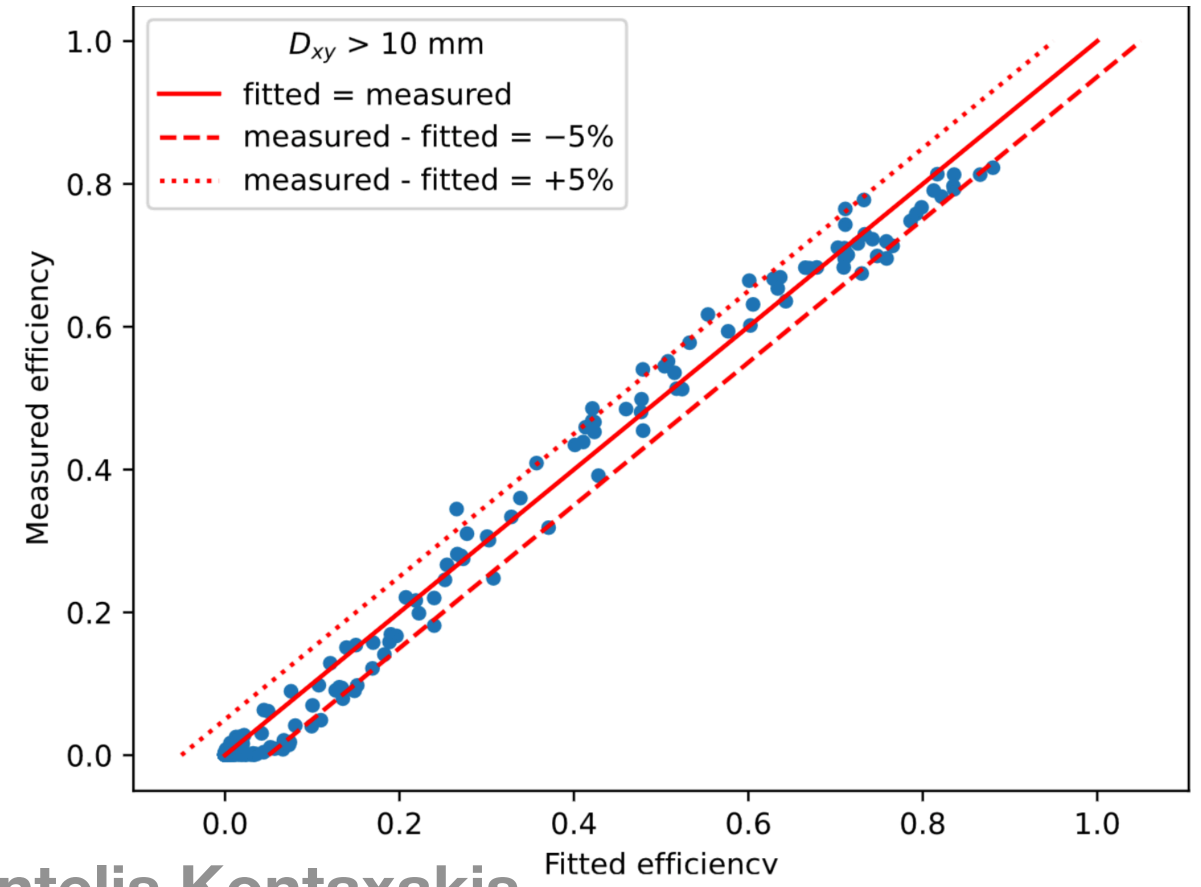


HNL → μμν | Sensitivity

◉ Interpolation of the sensitivity contours tested in two ways:

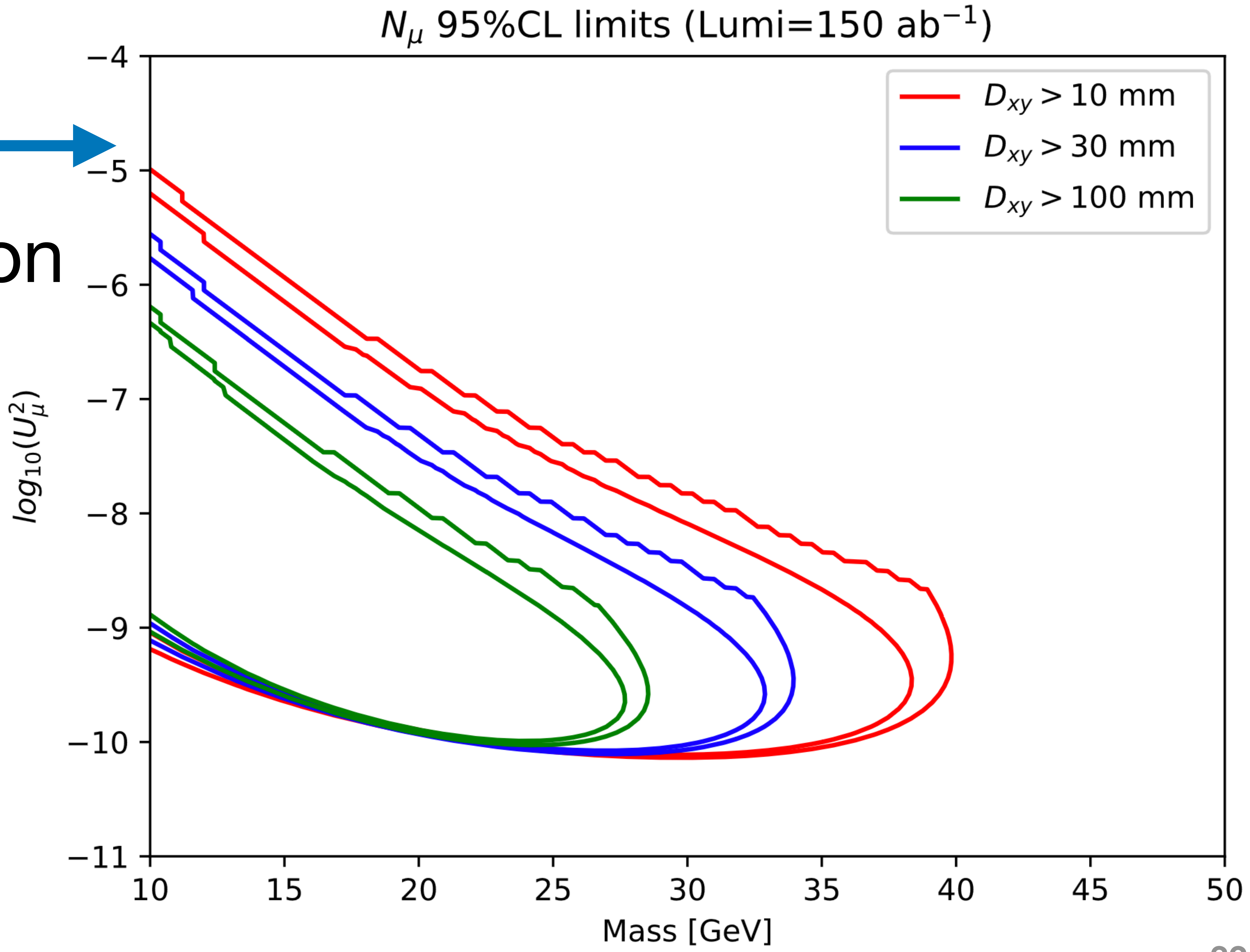
- **Using the python interpolation method “LinearNDInterpolator”**
- **Using parametric fit to parametrize the eff vs decay length**



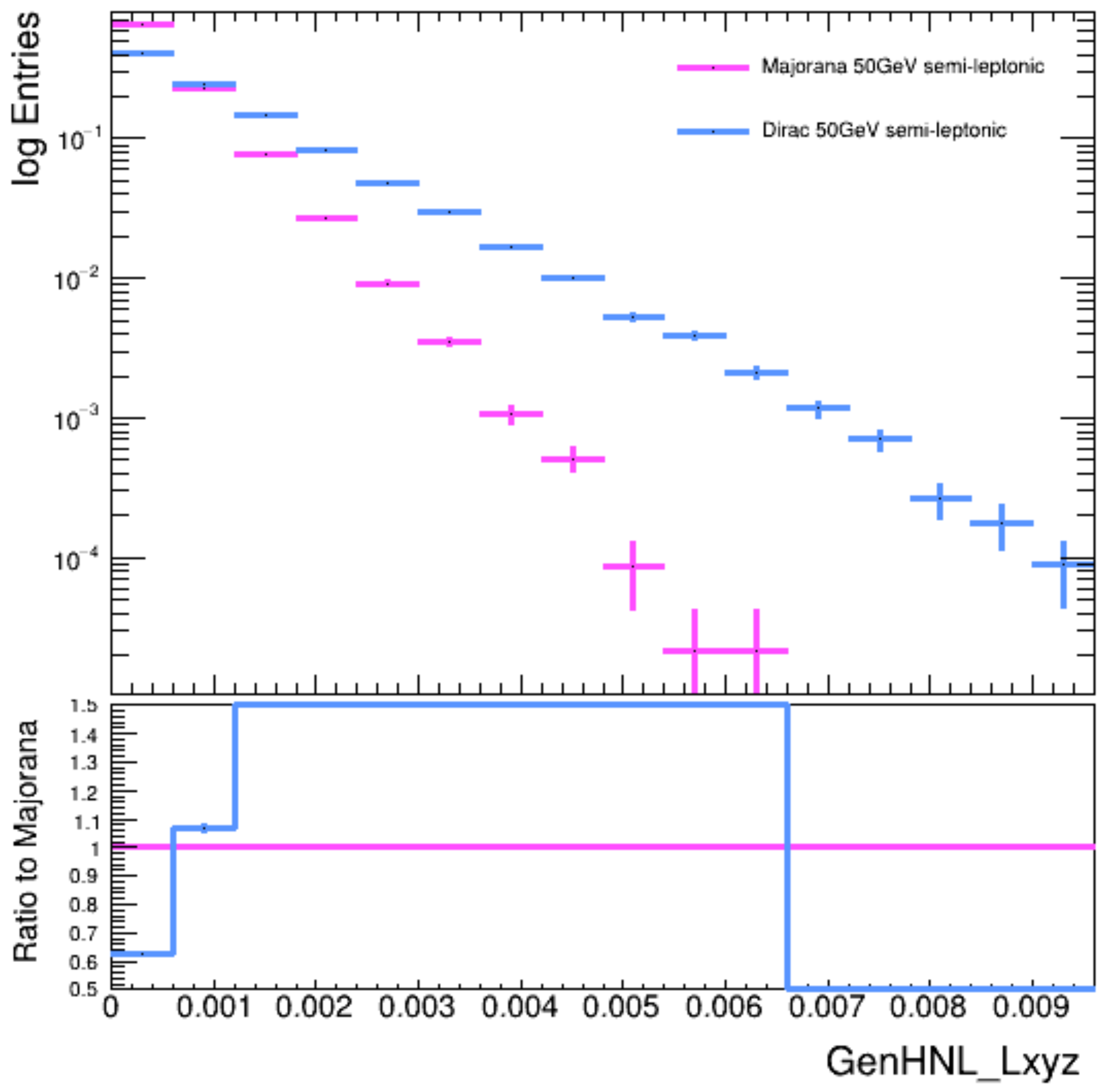


Expected limits

- Reliable estimation of the bkg
- Parametric fit significantly improves the sensitivity



Dirac vs Majorana HNLs



Decay length for Dirac (blue) and Majorana (pink) HNLs of mass $m_N = 50$ GeV and coupling $|V_{eN}| = 10^{-3}$ at the generator level