arXiv:2410.03615

Karlsruher Institut für Technologie

SEARCHING FOR TYPE I SEESAW MECHANISM IN A TWO HEAVY NEUTRAL LEPTONS SCENARIO AT FCC-ee

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HEAVY NEUTRAL LEPTONS

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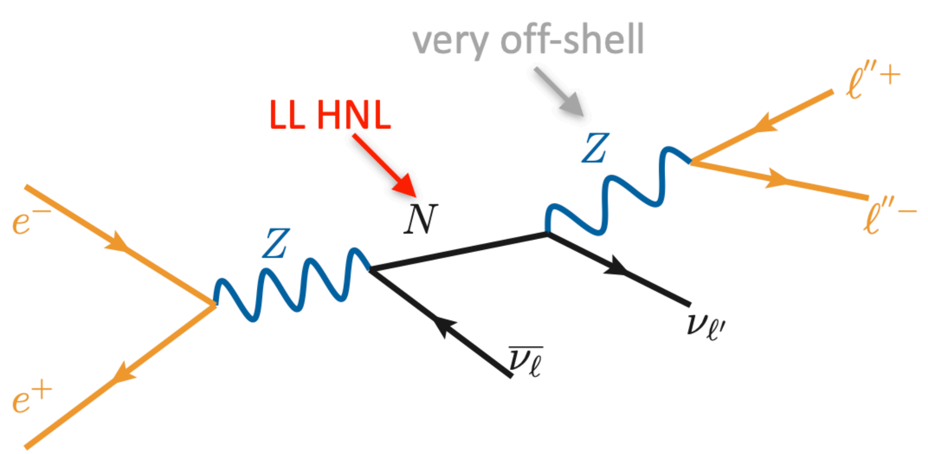
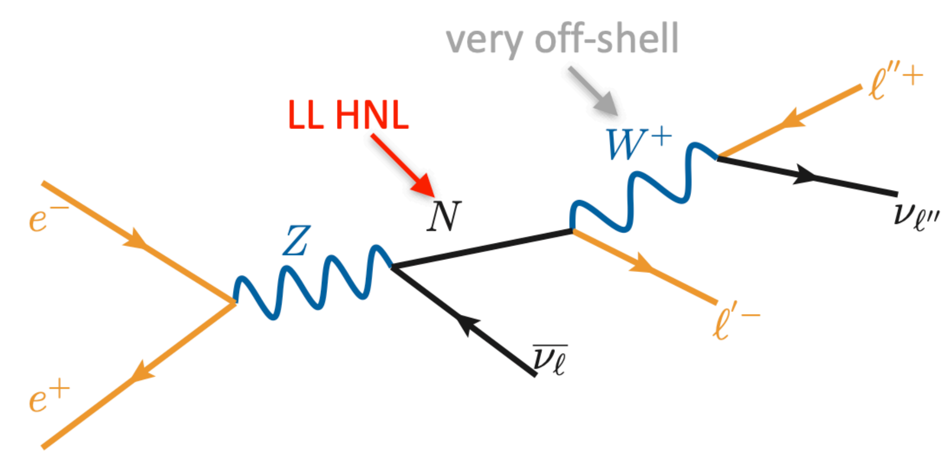
- Production of "***n***" heavy neutral leptons (HNLs) in **type I seesaw model** with **couplings to all leptons** Phys. Rev. Lett. 128, 051801

$$\mathscr{L}_{type\ I} = \frac{1}{2}\sum_{i=1}^{n} \bar{N}_i(i\partial\!\!\!/ - M_i)N_i - \frac{g}{\sqrt{2}}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i} W^+_\mu \gamma^\mu \ell^-_L$$
$$-\frac{g}{2\cos\theta_W}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i} Z_\mu \gamma^\mu \nu_{L,\ell} - \frac{gHM_i}{2M_W}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i}\nu_{L,\ell} + H.c.$$

- If $n > 1$ the model can explain neutrino oscillations, baryon asymmetry, and dark matter
- The cross-section is maximized with quasi-degenerate masses, **pseudo-Dirac limit** arXiv: 1712.07611, while also reducing the number of free parameters

$$M_i \simeq M_j \quad \Longrightarrow \quad U_{\ell i} \simeq iU_{\ell j}$$





FUTURE CIRCOLAR COLLIDER

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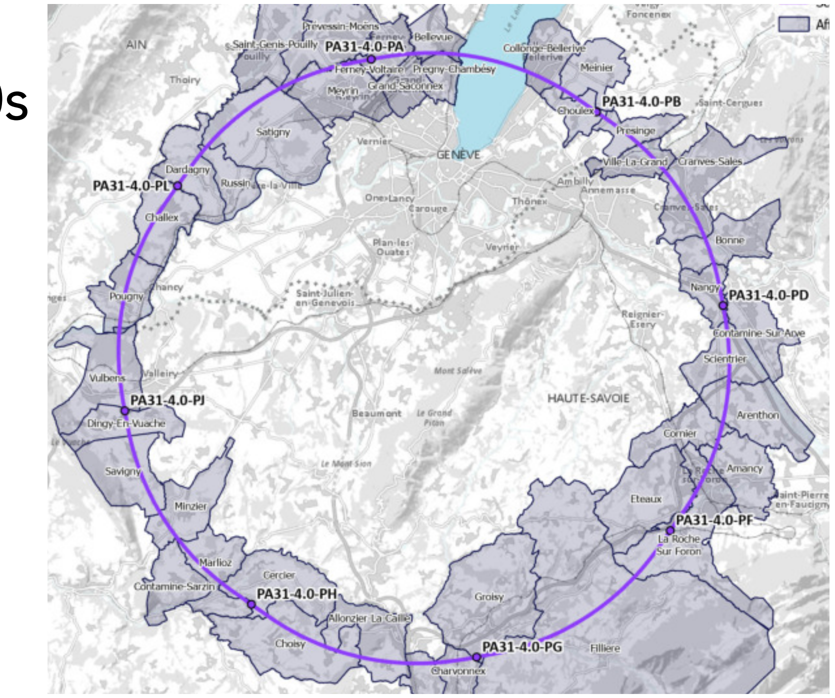
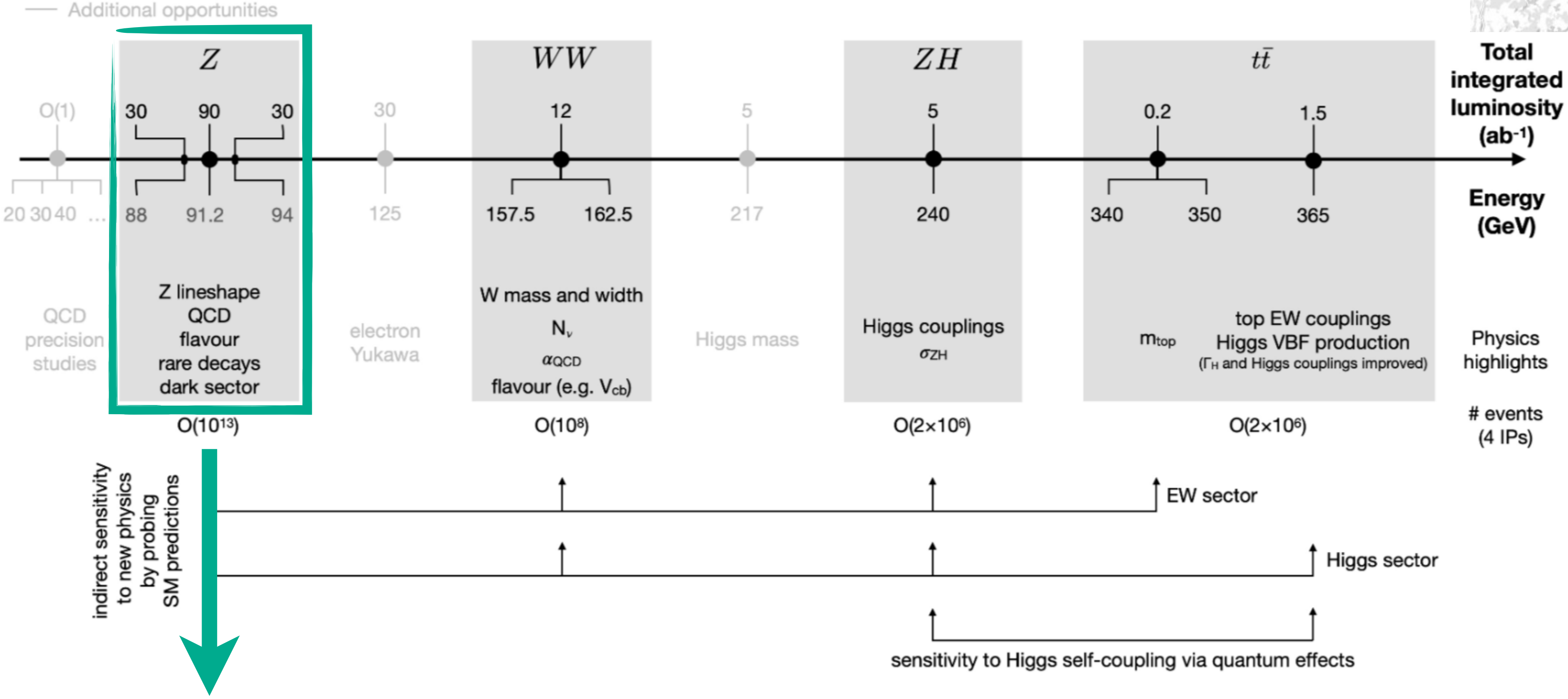
- Proposed to be built at CERN, starting operations in mid-2040s
- 90.7 km circumference with 4 experimental sites
- Two stages: FCC-ee (Z, WW, ZH, $t\bar{t}$) and FCC-hh at 100TeV



FCC-ee Physics Runs Ordered by Energy

doi:10.17181/qttzk-wpe74

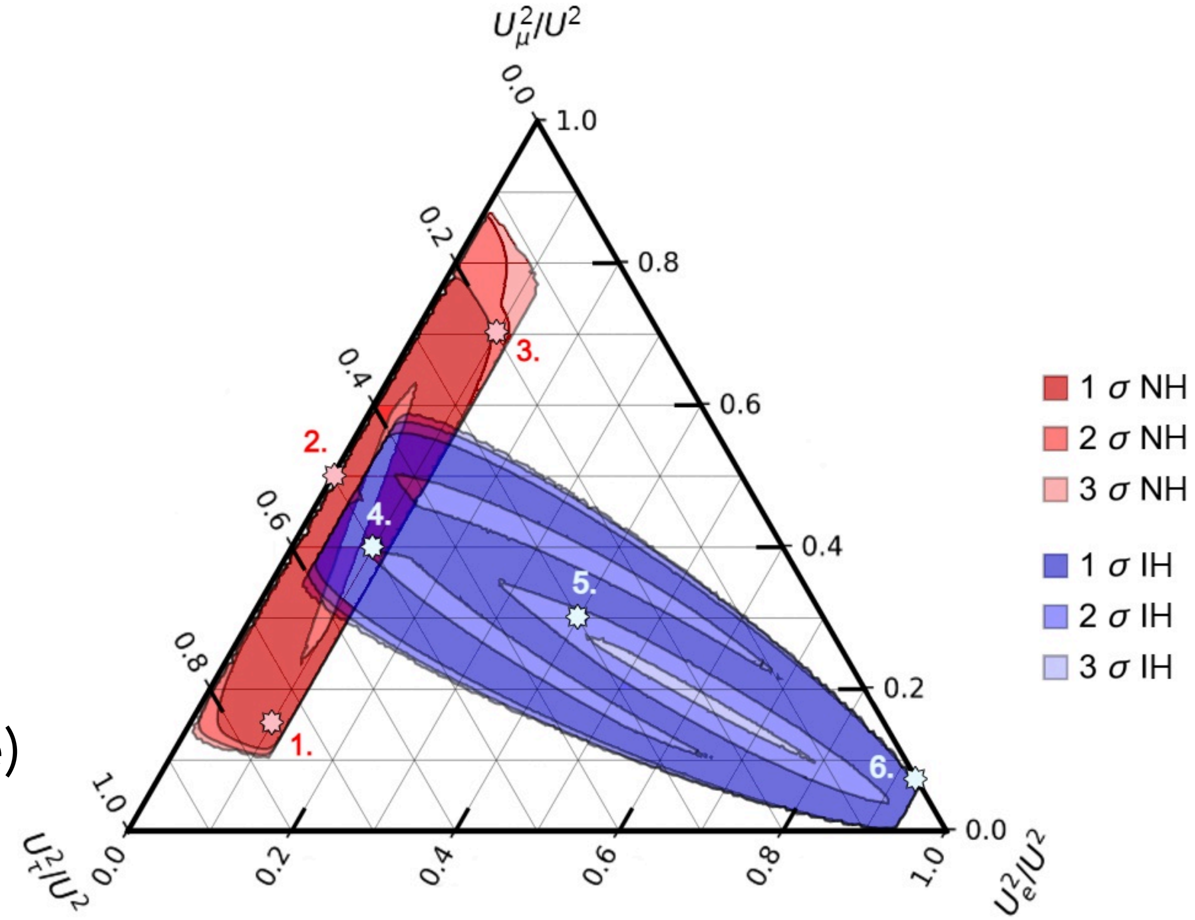


Mid-term report doi:10.17181/mhas5-1f263: $\sqrt{s}$= 91 GeV, $\mathscr{L}_{int} = 204$ ab^{-1}

SIGNAL SIMULATION

- Simulation of **n=2 Majorana HNLs at FCC-ee Z pole run** looking at fully leptonic decays, following Ref. JHEP 12(2021)182
  - `Madgraph5` + *SM_HeavyN_CKM_AllMasses_LO* arXiv:1411.7305, arXiv:1602.06957
  - `Pythia8` + `Delphes` (IDEA detector for FCC-ee) + `FCCAnalyses` (based on EDM4Hep)

- Parameters are chosen in agreement with leptogenesis Phys. Rev. D 108 (2023) L101302 and oscillation data JHEP 09 (2020) 178:
  - $\Delta M = |M_1 - M_2| = 1 \cdot 10^{-5}$ GeV
  - $M_N = M_1 \in [10, 80]$ GeV
- Unitarity of the mixing matrix $U_e^2/U^2 + U_\mu^2/U^2 + U_\tau^2/U^2 = 1$ to set:
  - $|U_{\mu\ 1,2}| \in [1 \cdot 10^{-6}, 1 \cdot 10^{-4}]$
- Six benchmarks selected (shown in the picture)



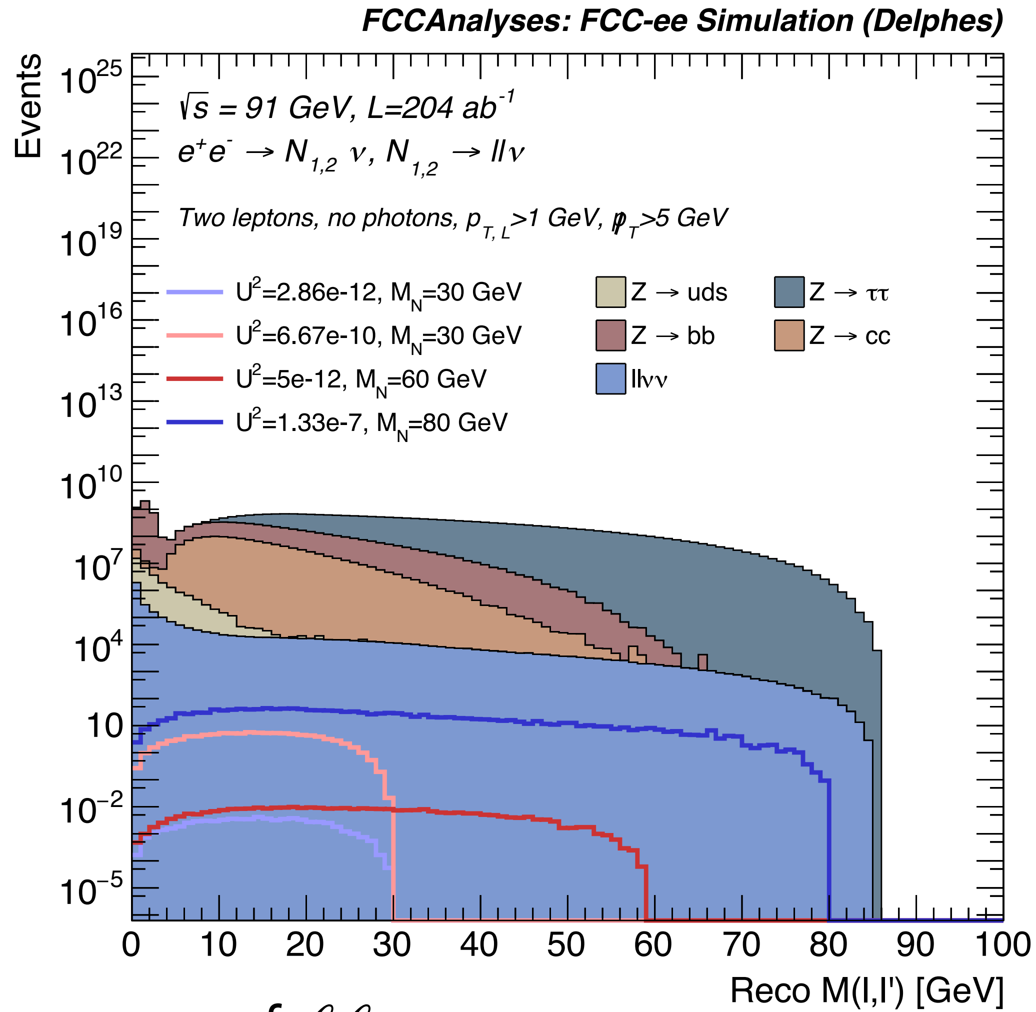
BACKGROUND SIMULATION

- The main source of background is $Z \to \tau\tau$ from the central FCC production (Pythia8 + Delphes)
  - $Z \to ee, \mu\mu$ are negligible due to low transverse missing energy

- We also privately produced the **SM process** with $\ell\ell'\nu\nu$ final states with the same simulation setup used for the signals (sm-lepton_masses)
  - In $\ell\tau\nu\nu$ the biggest contribution comes from $e^+e^- \to Z \to \tau\tau(\to \ell\nu\nu)$ so there is overlap with the central sample $Z \to \tau\tau$, we excluded those diagrams from ours
  - $\tau\tau\nu\nu$ is negligible compared to all other backgrounds so we can exclude it to avoid overlap with $Z \to \tau\tau$ while maintaining sufficient background modeling
- It was necessary to apply **generator cuts** in Madgraph5 to avoid divergencies that break the simulation, we then propagated them to the rest of the processes for consistency (values in the tables in the next slide)

EVENT SELECTION

- We target final states with **two leptons** (electrons or muons) with **missing energy** from the neutrinos
  - Therefore, we analyze only leptonic τ decays in the signal
- Leptons and photons with $E < 2\ GeV$ are not reconstructed in the detector, we applied the same reconstruction efficiency to neutral hadrons too

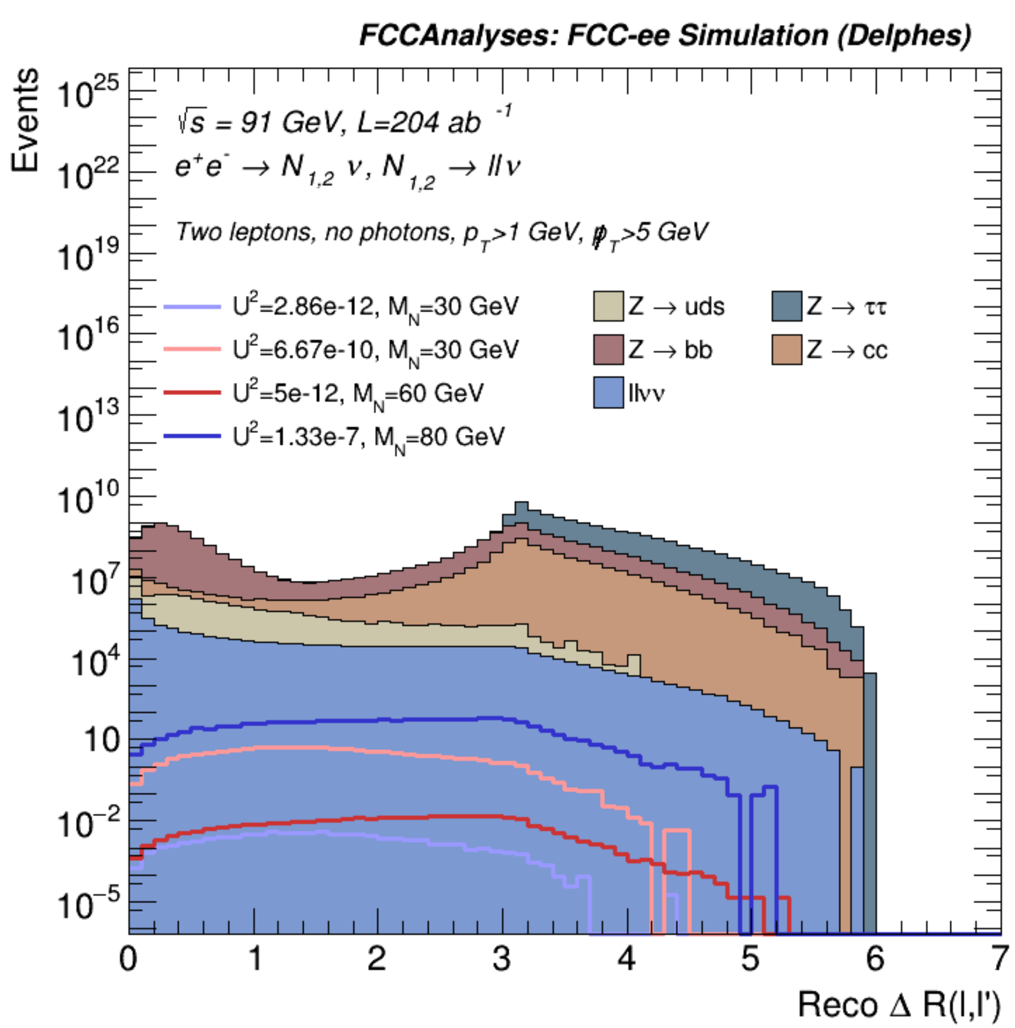


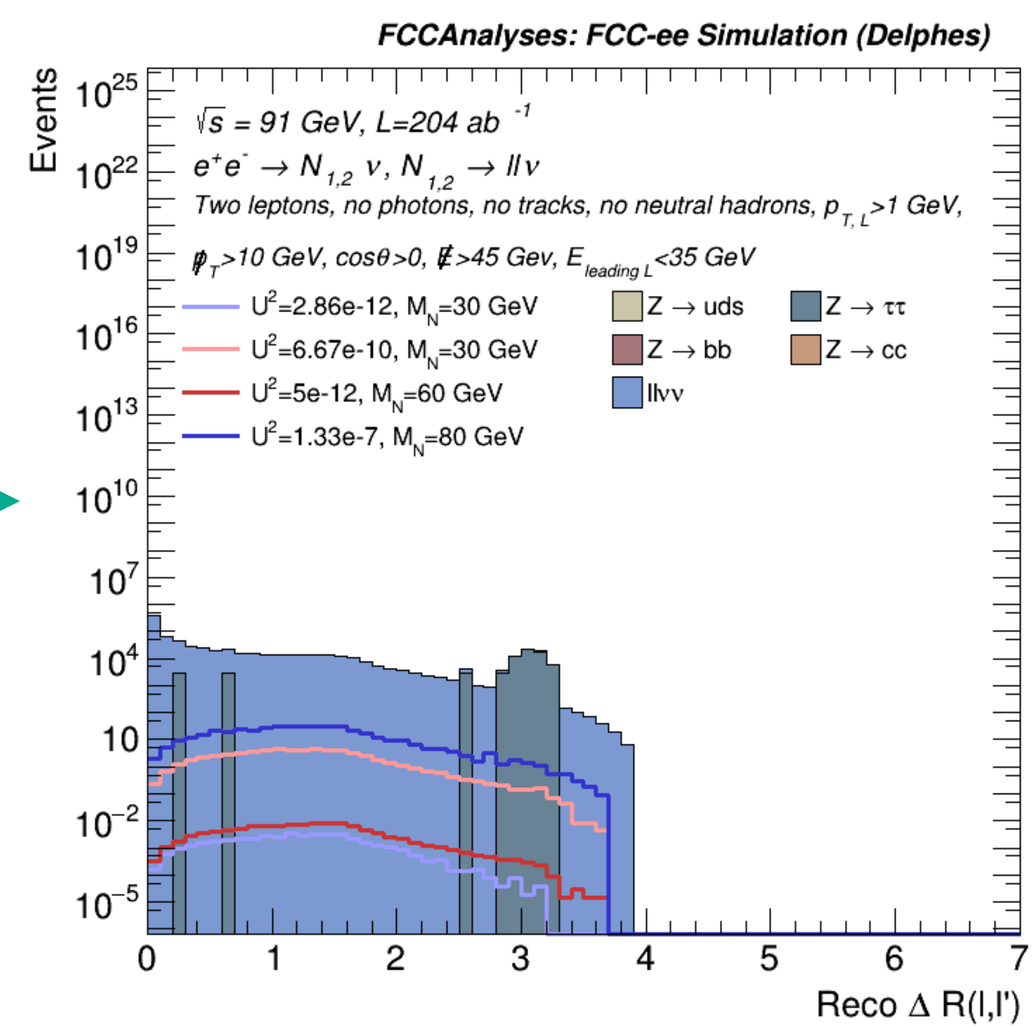
Selection:

Selection	
Two leptons, no photons $p_{T,miss} > 5\ GeV$, $p_{T,\ell} > 1\ GeV$, $E_\ell > 2\ GeV$	→ generator cuts of $\ell\ell\nu\nu$
No other track and no neutral hadron	→ excludes all hadronic backgrounds
$p_{T,miss} > 10\ GeV$	
$cos\theta_{ll} > 0$	→ asymmetry for low HNL masses
$E_{miss} > 45\ GeV$	
$E_{l,\ leading} < 35\ GeV$	
$M(l, l') < M_{HNL}$	→ tailored to HNL masses

RECONSTRUCTED EVENTS

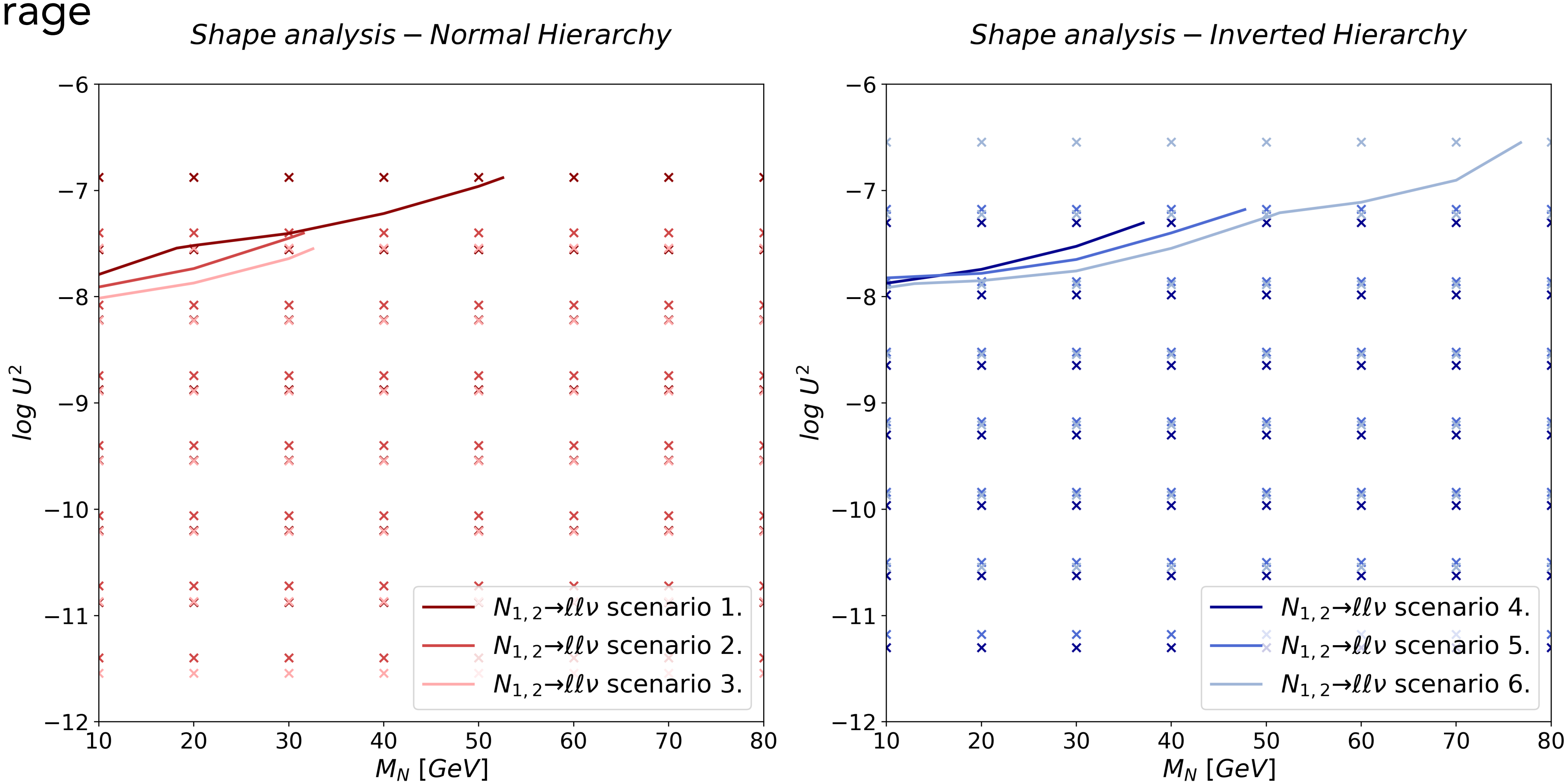
- The event selection can reduce the backgrounds significantly while retaining most of the signal events
- The maximum sensitivity is obtained from the angular distance between the two final state leptons, ΔR: it has good background modeling compared to other observables





SIGNIFICANCE RESULTS

- Shape-based analysis on ΔR with maximum likelihood fit, statistical significance computed with CMS **Combine tool** arXiv:2404.06614
- The results show contours for $5\ \sigma$ **significance**: the analysis is most sensitive to lower masses and higher couplings (prompt HNLs, the selection is inclusive at this stage)
- Scenario 6. has the closest mixing pattern to the one-HNL case (mostly $U_{e\ 1,2}$) and better coverage



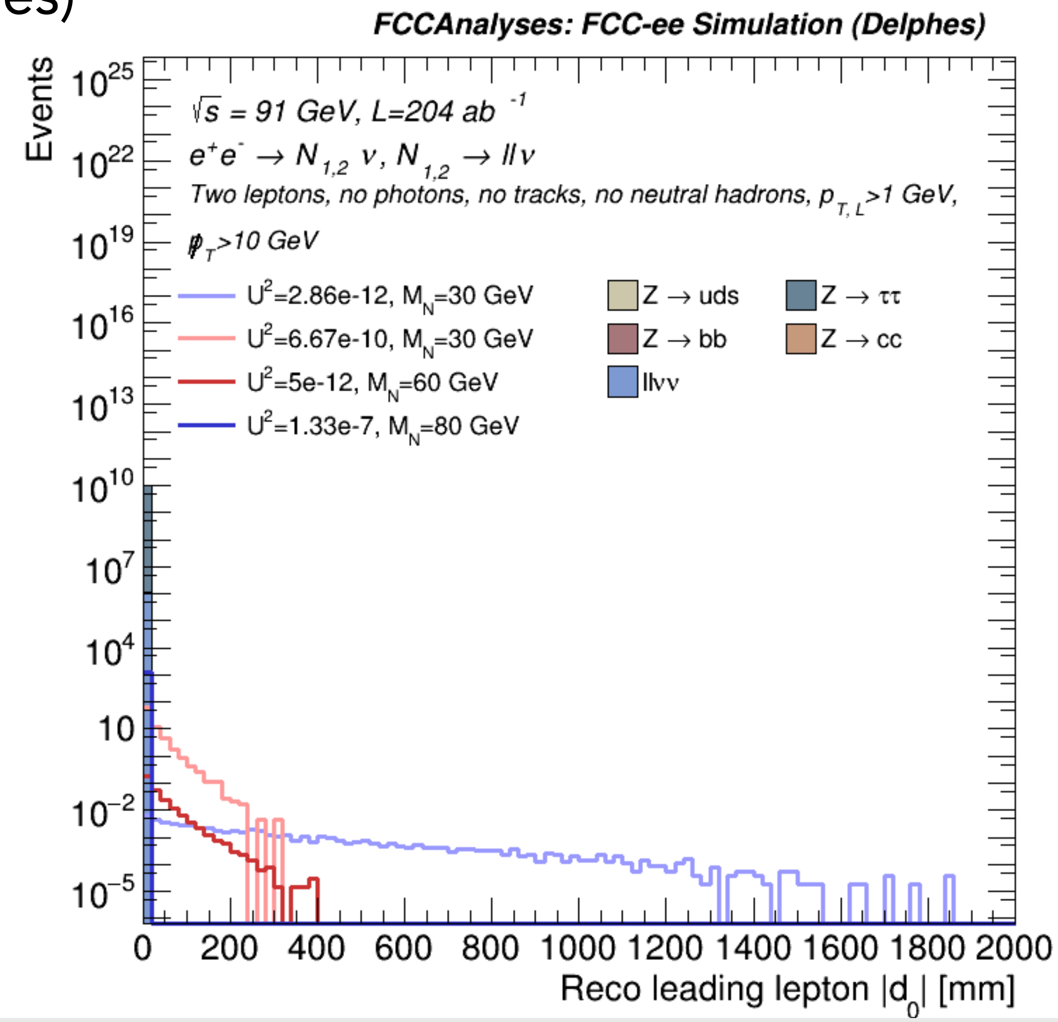
LLP EVENT SELECTION

- HNLs can be **long-lived** depending on their parameters PoS ICHEP2022 (2022) 608

$$L_{N_i} = \simeq \frac{1.6}{U_i^2}\left(\frac{M_i}{GeV}\right)^{-6}\left(1-(M_i/M_Z)^2\right)\ cm$$

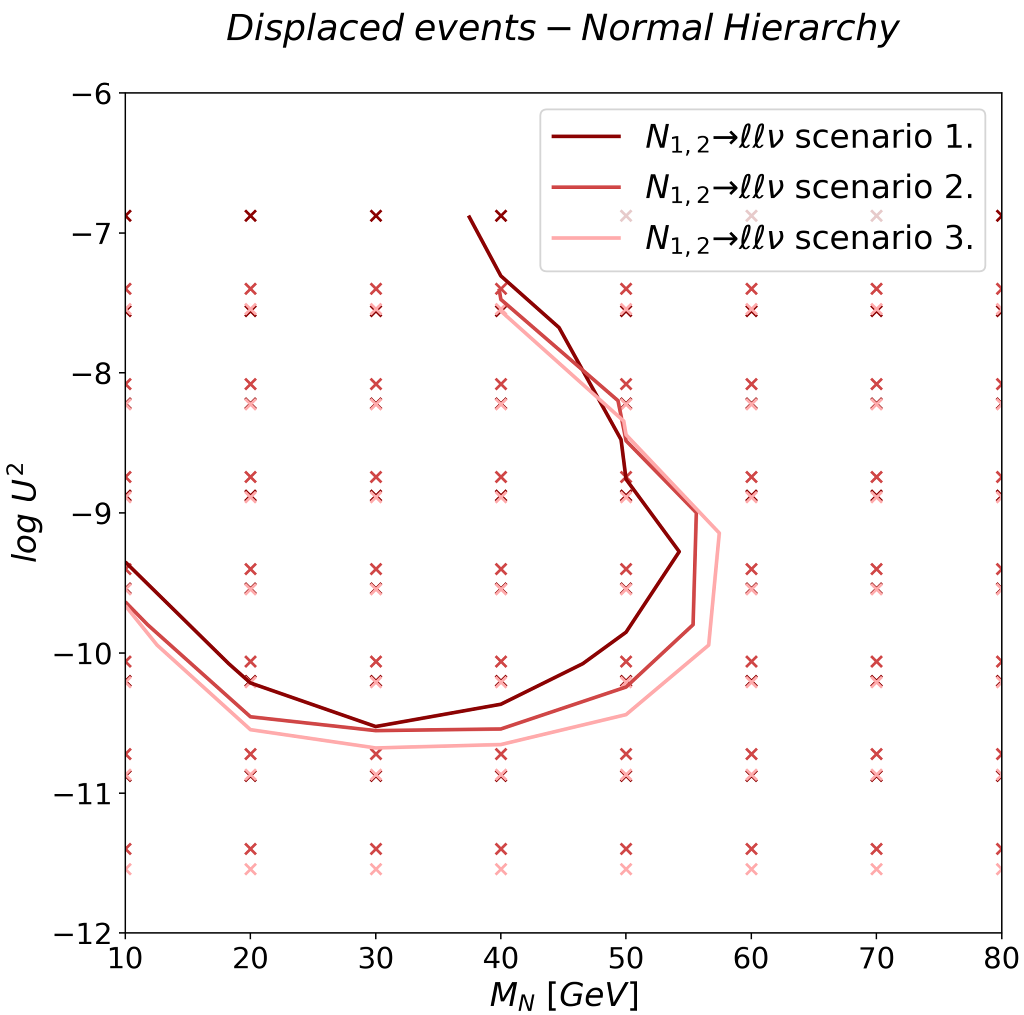
- SM processes are **prompt:** LLP HNL signatures can be **background-free**
- The event selection is reoptimized with critical cuts on HNL decay vertex variables, limited to the simulation available (efficiencies in backup slides)

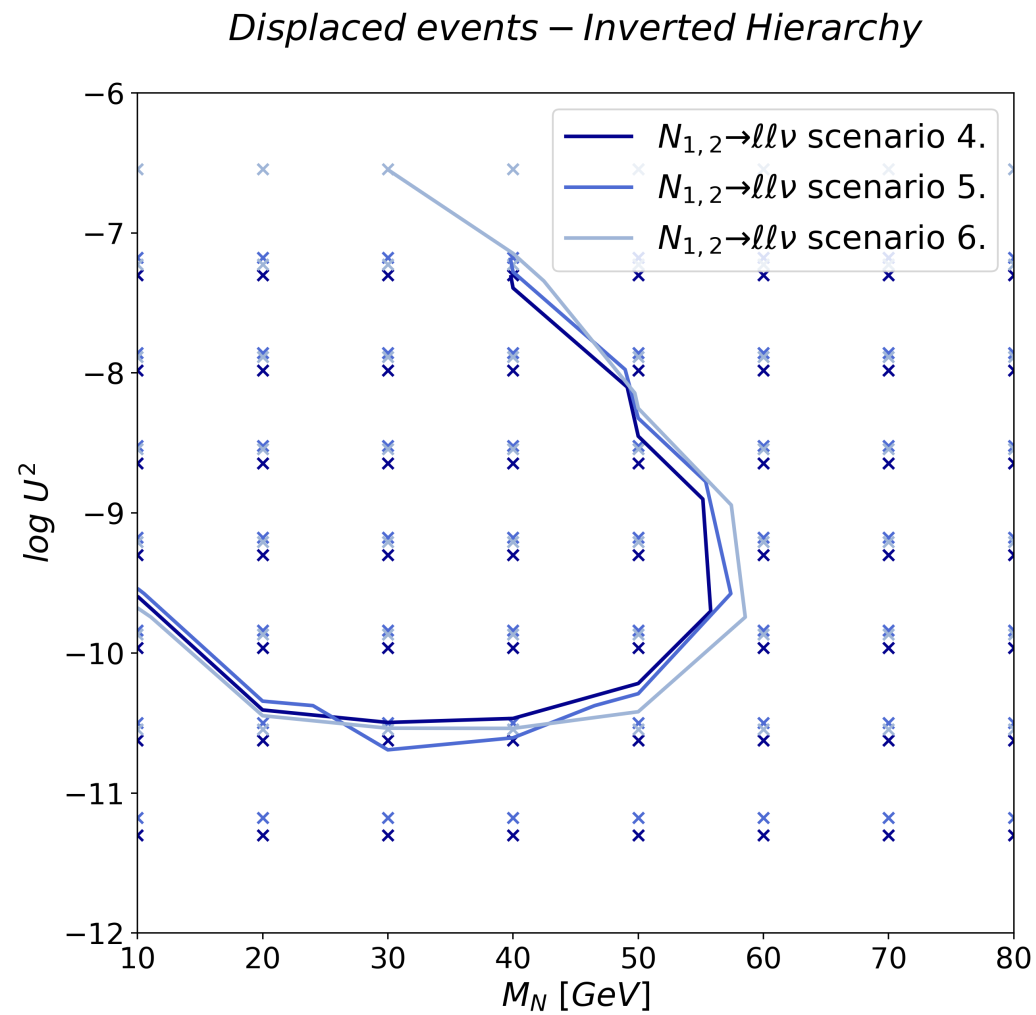
Selection:
Two leptons, no photons $p_{T,miss} > 5\ GeV,\ p_{T,\ell} > 1\ GeV,\ E_\ell > 2\ GeV$
No other track and no neutral hadron
$p_{T,miss} > 10\ GeV$
$cos\theta_{ll} > -0.8$
$M(l,l') < 80\ GeV$
$\chi^2 < 10$
$\lvert d_0 \rvert > 0.64\ mm$



LLP RESULTS

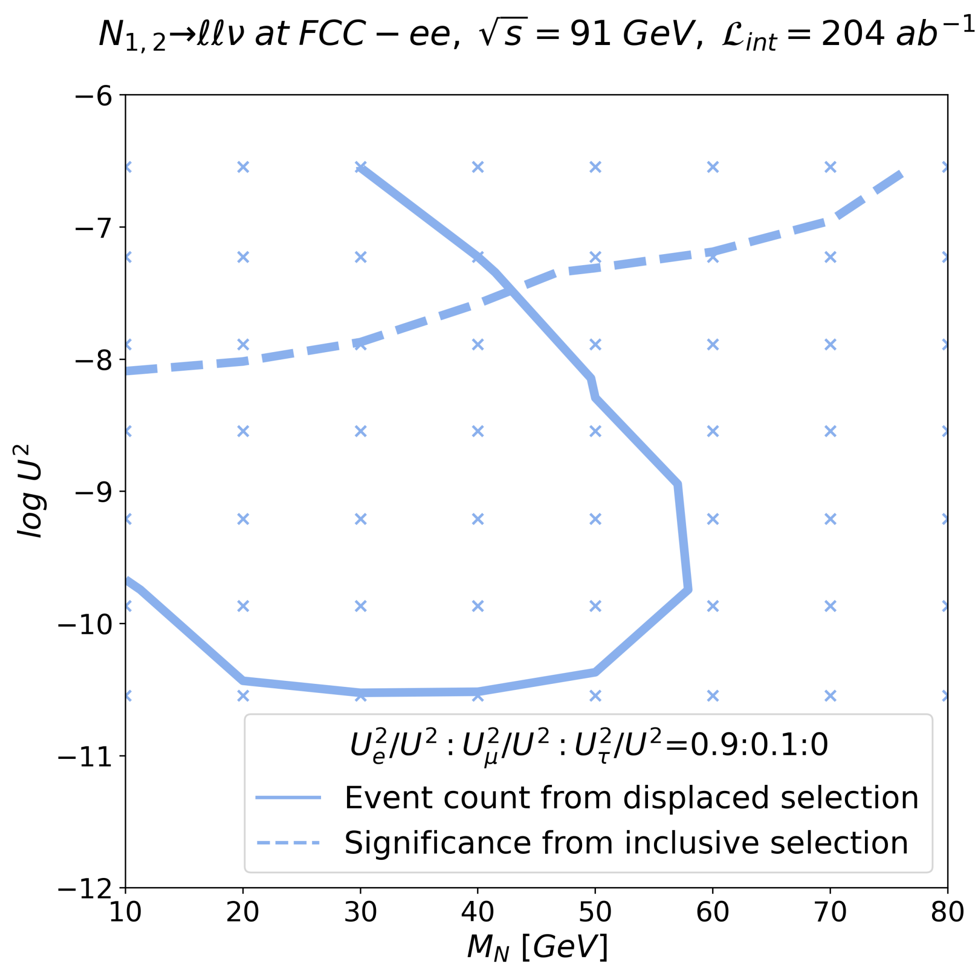
- Contours for **4 long-lived HNL events** show good performance across the parameter space sampled
- The lower couplings region is accessible
- Not so sensitive for higher masses (shorter lifetime)
- The different mixing hypotheses give similar results





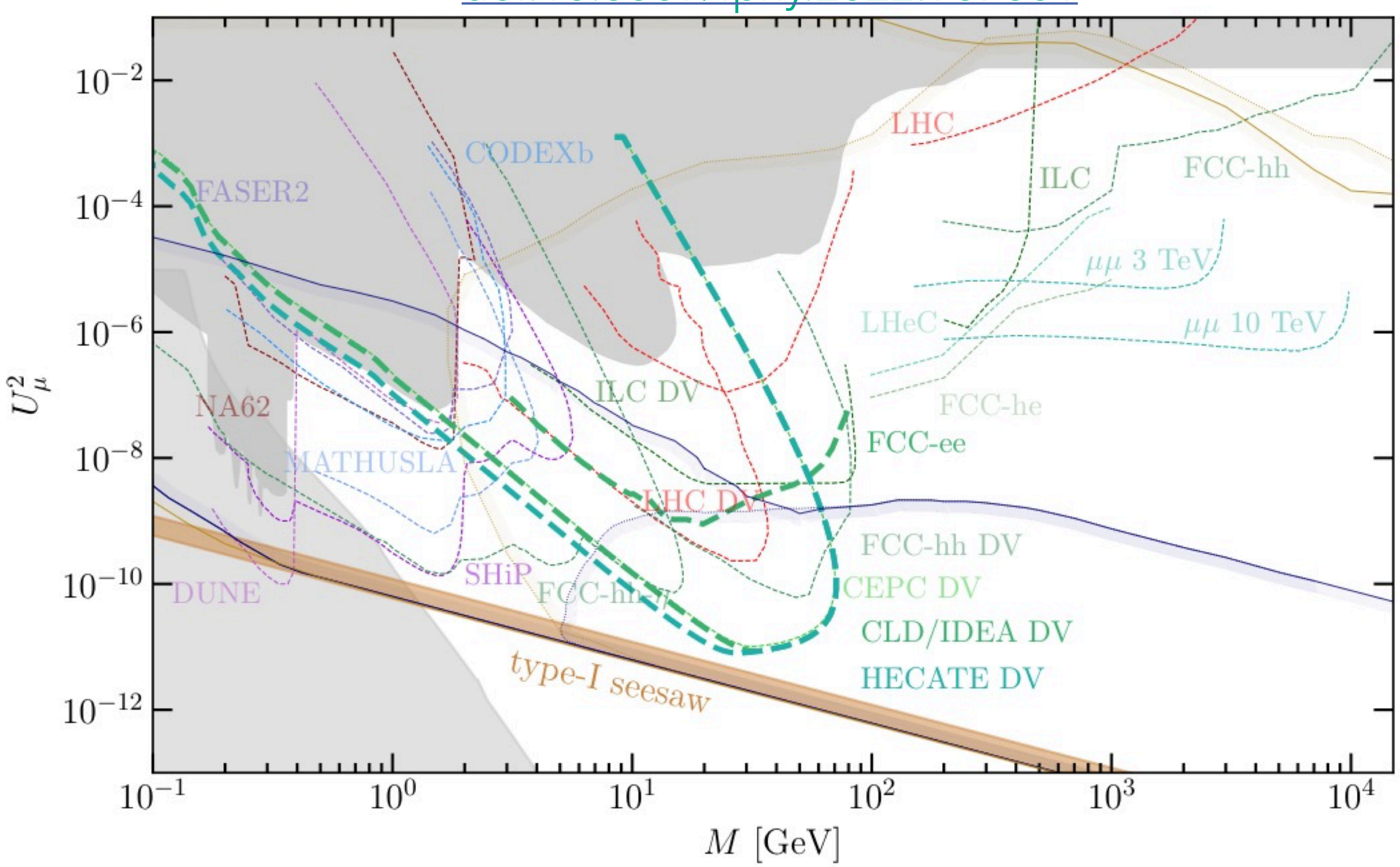
CONCLUSIONS

- We presented the first simultaneous study of **two HNLs at FCC-ee** with a realistic simulation setup, showing that FCC-ee would be capable of exploring a wide region of the parameter space
- Pre-print of paper available on Arxiv



Summary plot of our study

doi:10.3389/fphy.2022.967881



Old theoretical prediction for one HNL coupling exclusively to electrons, recent analyses show good agreement with it for displaced HNLs

BACKUP

EFFICIENCIES

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	Cross-section (pb)	N_{gen}	Inclusive selection	Displaced selection
$Z \to ee$	1462.09	100000000	$\leq$ 3.42e-13	$\leq$ 4.38e-17
$Z \to \mu\mu$	1462.08	100000000	1.20e-08	$\leq$ 4.69e-16
$Z \to \tau\tau$	1476.58	100000000	2.41e-06	$\leq$ 8.29e-11
$Z \to bb$	6645.46	438738637	$\leq$ 4.08e-14	$\leq$ 4.23e-14
$Z \to cc$	5215.46	499786495	$\leq$ 7.65e-12	$\leq$ 4.10e-13
$Z \to ud$	11870.5	497658654	$\leq$ 2.04e-15	$\leq$ 6.18e-16
$Z \to ss$	5215.46	499842440	$\leq$ 7.03e-15	$\leq$ 3.46e-15
$ee\nu\nu$	1.09e-02	1000000	2.25e-01	$\leq$ 1.23e-07
$\mu\mu\nu\nu$	4.78e-03	1000000	2.27e-01	$\leq$ 1.12e-07
$\tau\tau\nu\nu$	1.42e-03	1000000	1.04e-01	$\leq$ 2.92e-07
$\ell\ell'\nu\nu$	4.59e-03	1000000	2.66e-01	$\leq$7.43e-09
U^2 =2.86e-12, M_N=30 GeV	4.48e-09	50000	6.01e-01	7.83e-01
U^2 =6.67e-10, M_N=30 GeV	1.04e-06	50000	5.79e-01	6.27e-01
U^2 =5e-12, M_N=60 GeV	3.75e-09	50000	3.11e-01	5.89e-01
U^2 =1.33e-7, M_N=80 GeV	2.27e-05	50000	2.98e-01	$\leq$ 3.59e-06