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HEAVY NEUTRAL LEPTONS SEARCH IN A REALISTIC NEUTRINO OSCILLATION MODEL AT FCC-EE

FCC Physics Performance meeting, 15th July 2024

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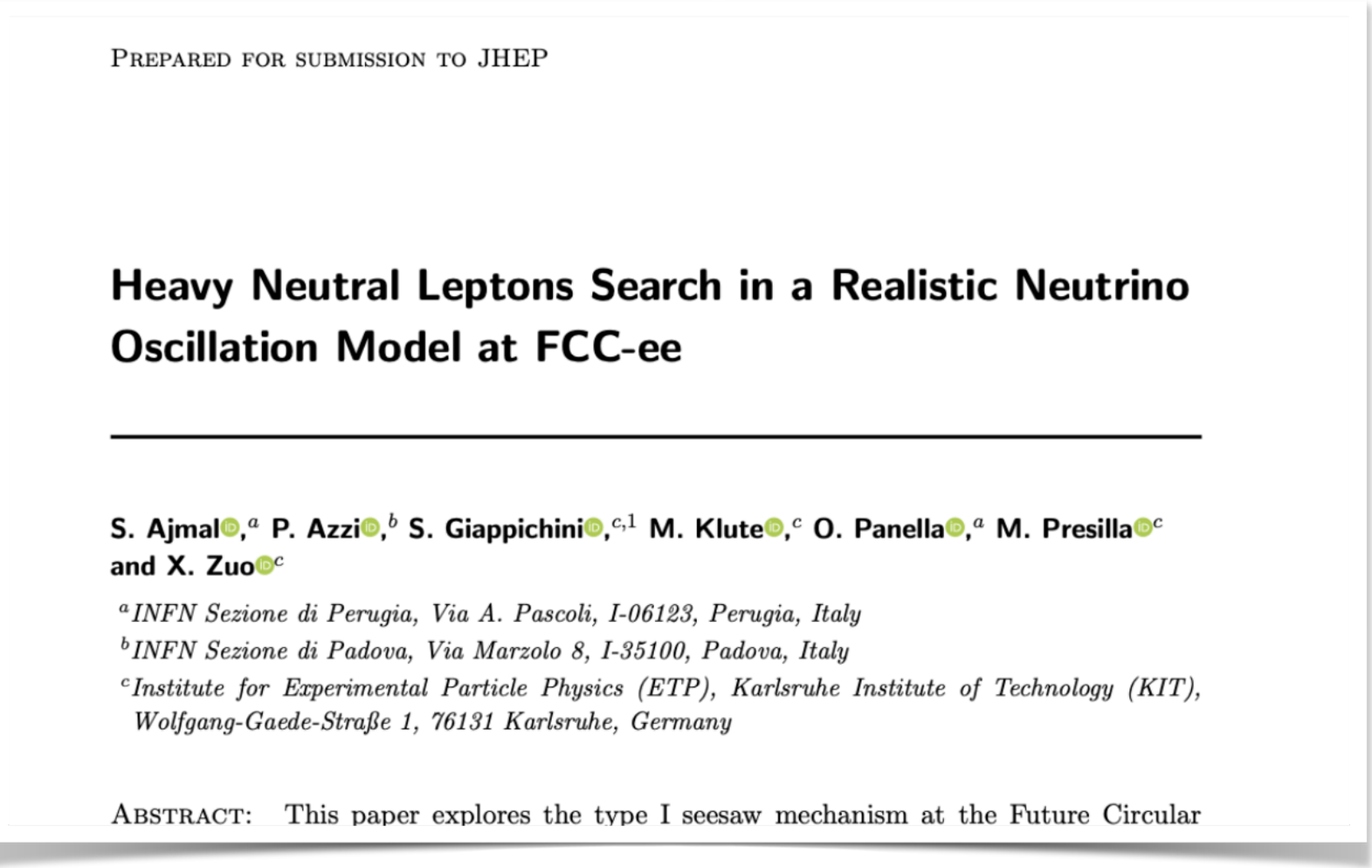
GENERAL INFORMATION

- Started as Master Thesis project from S. Giappichini (graduated in September 2023), then updated to FCC software and now fully documented in a CdS note
- Previous presentations within LLP subgroup:
  - 11th Jan 2024, 16th May 2024



PREPARED FOR SUBMISSION TO JHEP

Heavy Neutral Leptons Search in a Realistic Neutrino Oscillation Model at FCC-ee

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ABSTRACT: This paper explores the type I seesaw mechanism at the Future Circular

- We are thankful to the conveners for the helpful comments and careful review
- Collecting Q/A from reviewers at this Google Doc, we are working on the answers
- Meanwhile, we're finalizing a paper draft (a shorter version of the CdS note) with the ultimate target of submitting to JHEP

HEAVY NEUTRAL LEPTONS

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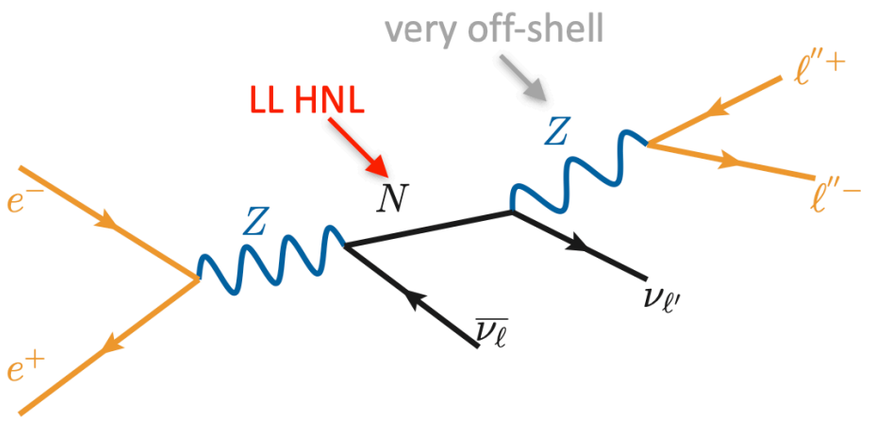
- Production of "***n***" heavy neutral leptons (HNLs) in a **realistic seesaw I model** with **couplings to all leptons** Phys. Rev. Lett. 128, 051801

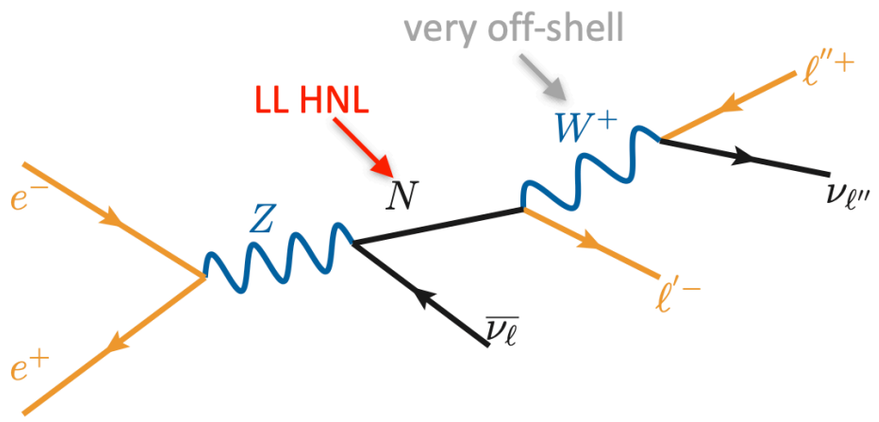
$$\mathscr{L}_{type\ I} = \frac{1}{2}\sum_{i=1}^{n} \bar{N}_i(i\partial\!\!\!/ - M_i)N_i - \frac{g}{\sqrt{2}}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i} W^+_\mu \gamma^\mu \ell^-_L$$

$$-\frac{g}{2\cos\theta_W}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i} Z_\mu \gamma^\mu \nu_{L,\ell} - \frac{gHM_i}{2M_W}\sum_{i=1}^{n}\sum_{\ell=e,\mu,\tau} \bar{N}_i U^*_{\ell i}\nu_{L,\ell} + H.c.$$

- With $n > 1$ 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

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

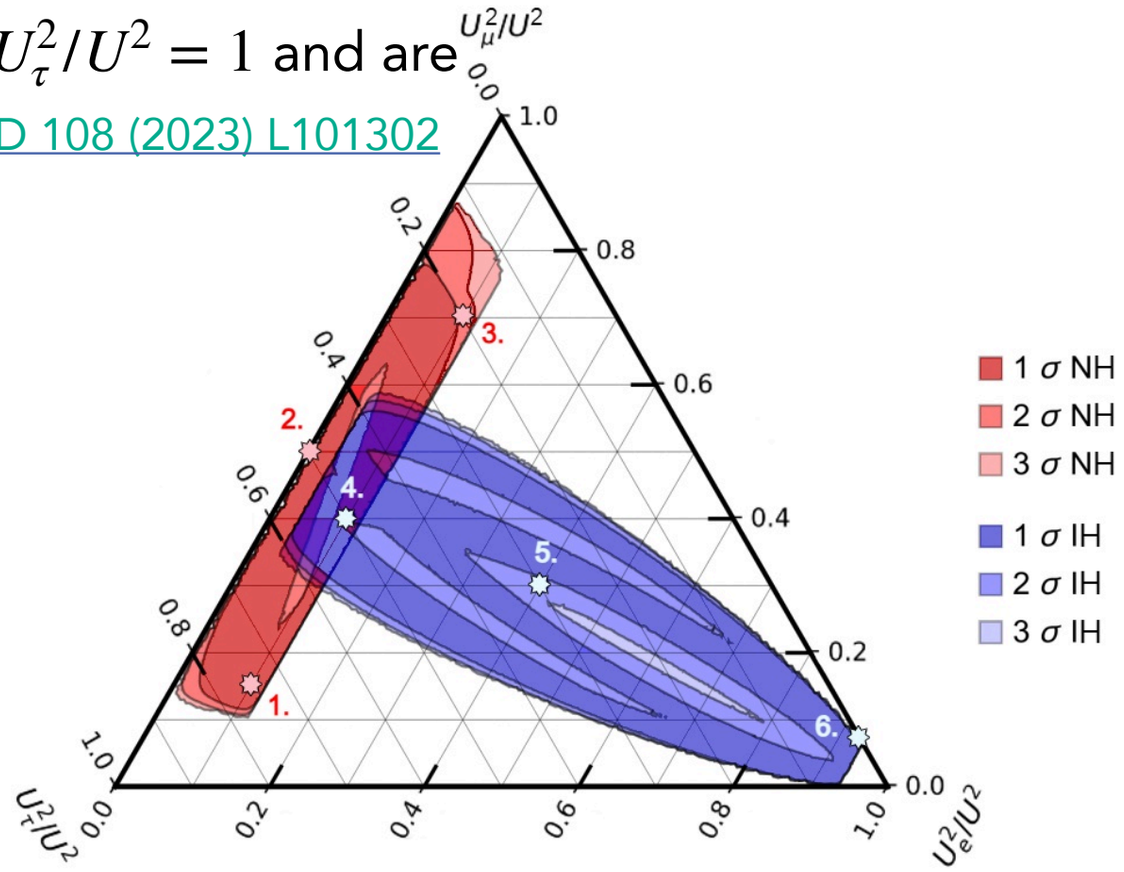




SIGNAL SIMULATION

- Simulation of **n=2 Majorana HNLs** at FCC-ee, following Ref. JHEP 12(2021)182, looking at the leptonic decays, with $\sqrt{s}$= 91 GeV, $\mathscr{L}_{int} = 204$ ab^{-1}
  - Madgraph5 (SM_HeavyN_CKM_AllMasses_LO arXiv:1411.7305, arXiv:1602.06957) + Pythia8 + Delphes with IDEA detector in FCCAnalyses
  - link to Madgraph cards

- Mixing angles need to satisfy $U_e^2/U^2 + U_\mu^2/U^2 + U_\tau^2/U^2 = 1$ and 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
  - $|U_{\mu 1,2}| \in [1 \cdot 10^{-6}, 1 \cdot 10^{-4}]$



MC BACKGROUNDS

- Centrally produced samples from the Winter 23 campaign
- Plus privately produced $\ell\ell\nu\nu$ ($ee\nu\nu, e\mu\nu\nu, \mu\mu\nu\nu, \tau\tau\nu\nu$) in SM, Madgraph cards

	Cross-section (pb)	N_{gen}
$Z \to ee$	1462.09	100000000
$Z \to \mu\mu$	1462.08	100000000
$Z \to \tau\tau$	1476.58	100000000
$Z \to bb$	6645.46	438738637
$Z \to cc$	5215.46	499786495
$Z \to ud$	11870.5	497658654
$Z \to ss$	5215.46	499842440
$e\mu\nu\nu$	7.619e-4	1000000
$\tau\tau\nu\nu$	2.855e-4	1000000

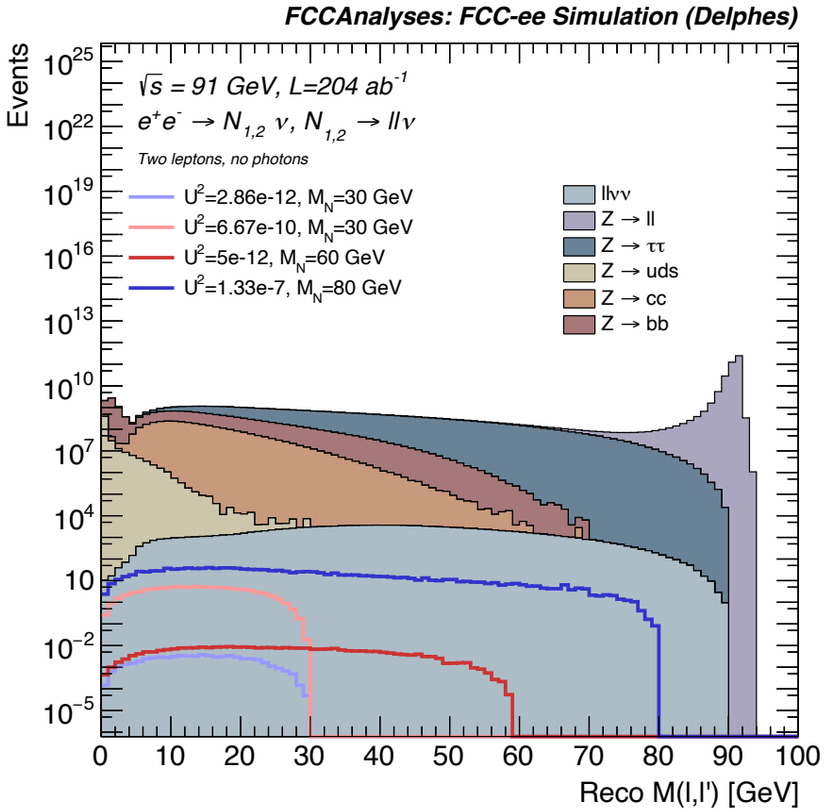
- Ongoing studies on the MC generation of the irreducible backgrounds $\ell\ell\nu\nu$:
  - We are currently trying to understand the impact of possible overlap with the other backgrounds
  - Following a comment by Michele, we also noticed that MG adopts harder default cuts than other generators for SM processes to avoid singularities in the integration, e.g. p_T(lep)>10 GeV, we will investigate how we can loosen those cuts to model the missing phase space

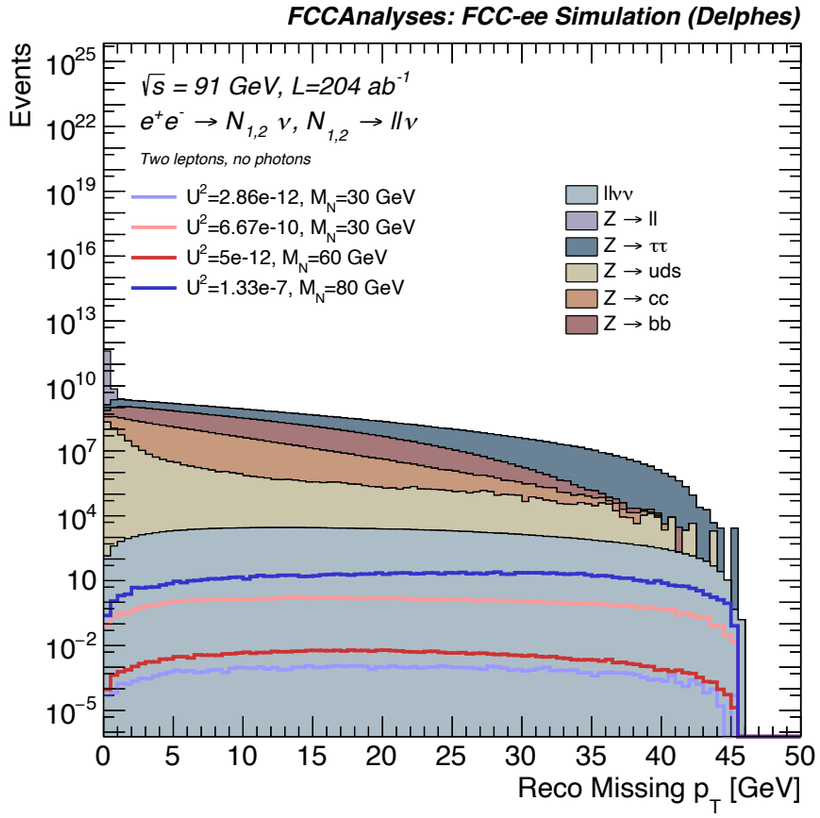
EVENT SELECTION

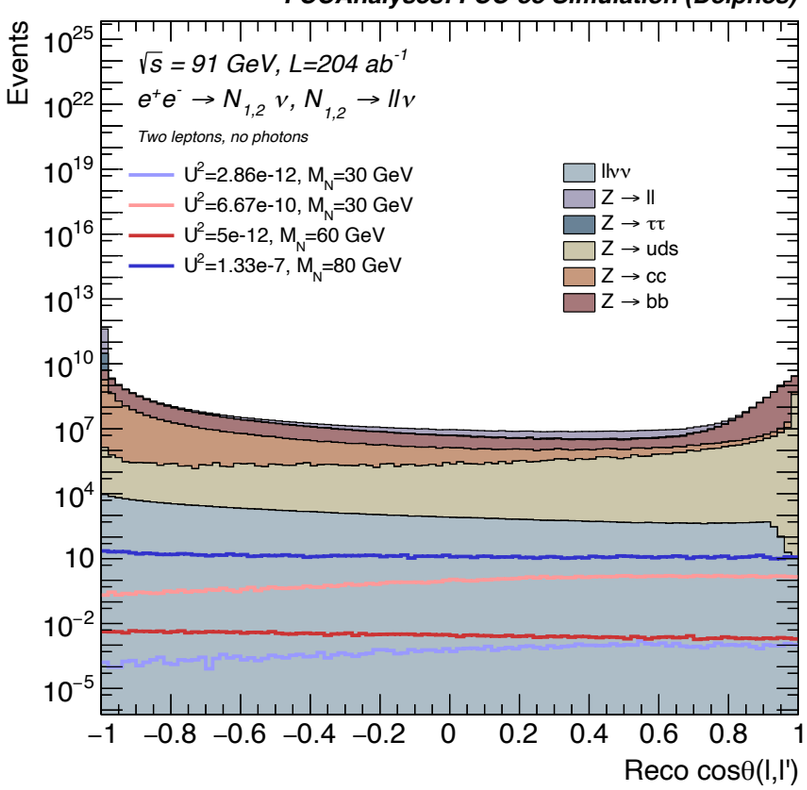
- We only want to analyze $\tau \to e/\mu\nu\nu$
- So the HNL final state is then given by **two leptons** (electrons or muons) plus **missing energy** from the neutrinos
- The jets are reconstructed using the **anti-k_T inclusive algorithm** with $R = 0.4$ and $p_{T,j} > 5$ GeV
- The event selection proposed excludes hadronic backgrounds completely (efficiency table in the backups)

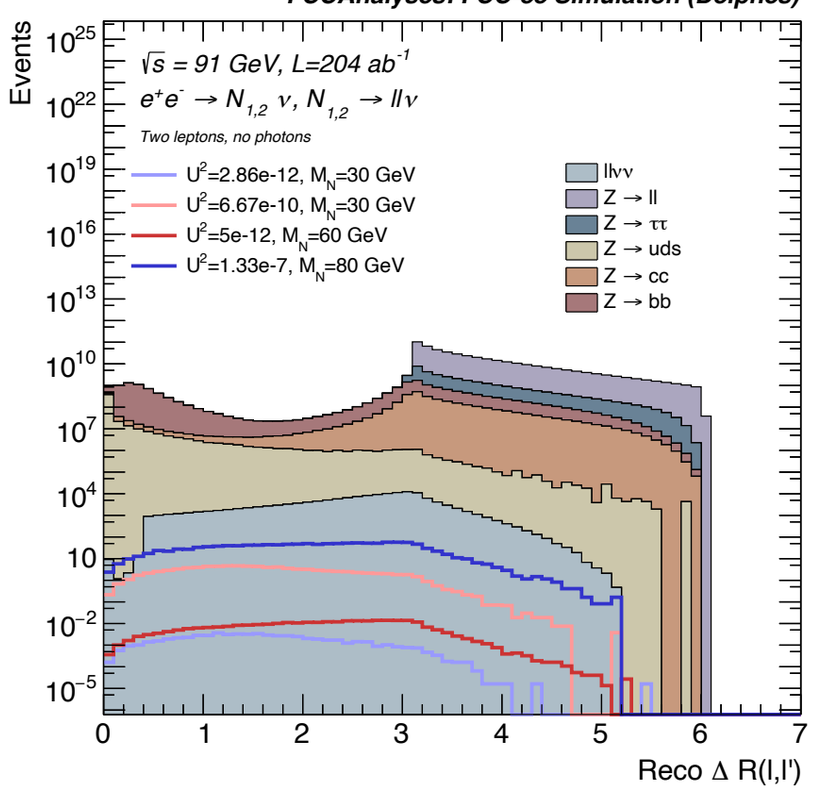
1. Selection	Two leptons with opposite charges, no photons
2. Reconstructed tracks	No other tracks
3. Jets	No jets
4. Invariant mass	$M(\ell, \ell') < 80$ GeV
5. Missing transverse momentum	$\not{p}_T > 10$ GeV
6. Cosine between the leptons	$\cos\theta > -0.8$

Selection applied: two leptons with opposite charges, no photons

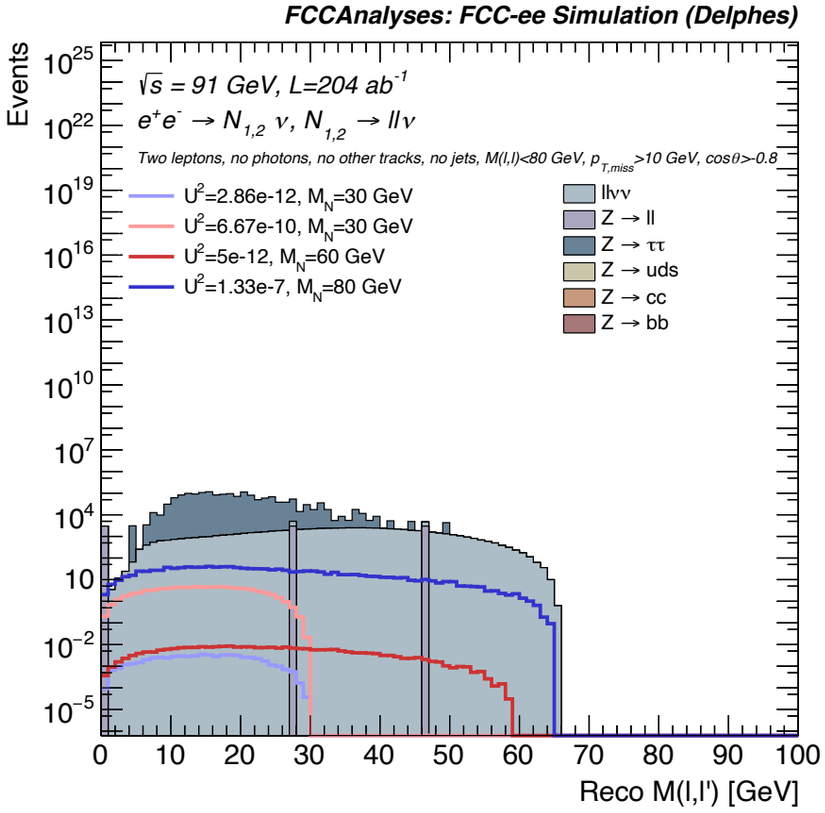


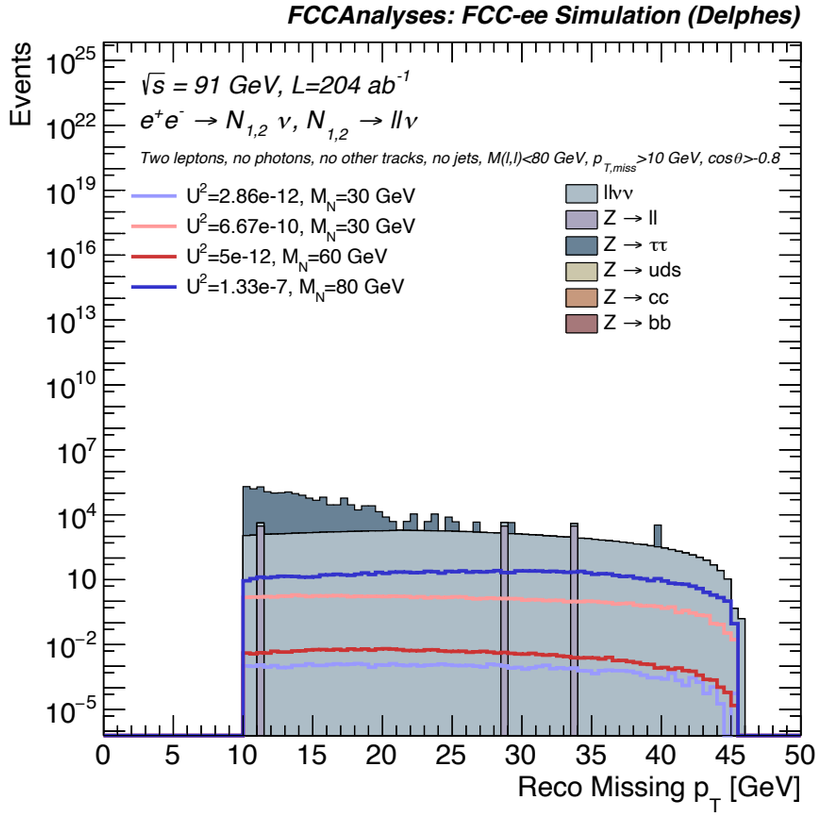


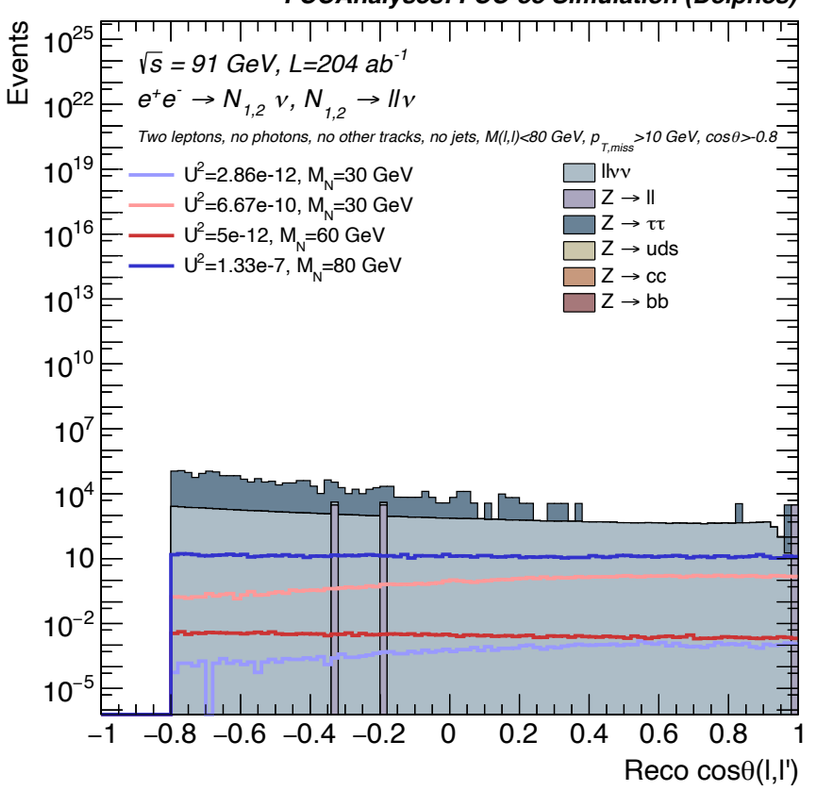


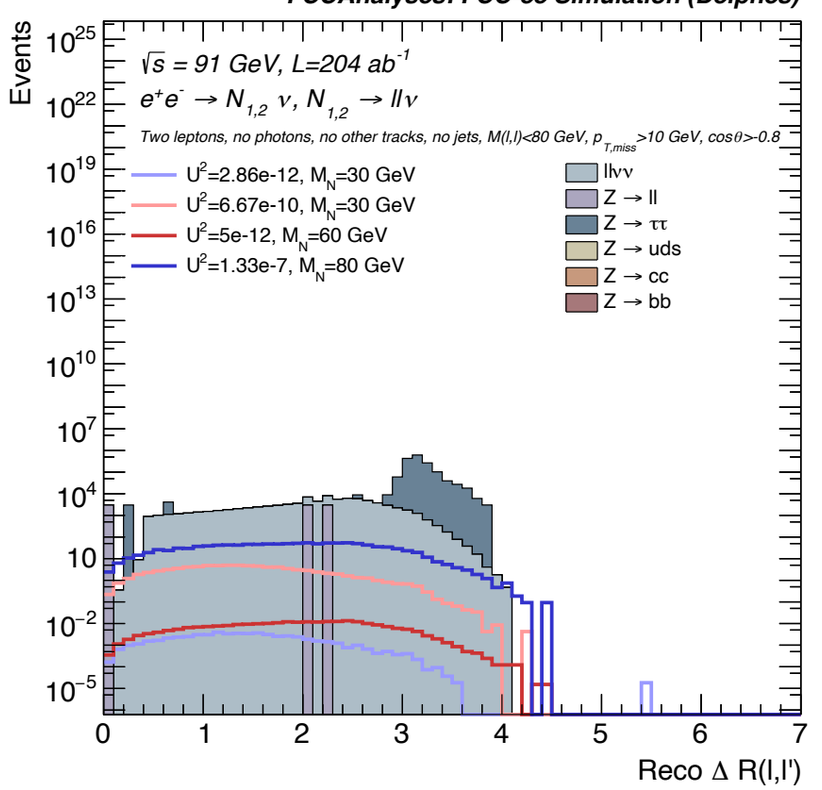


Selection applied: two leptons with opposite charges, no photons, no jets, no other tracks, $M(\ell, \ell') < 80\ GeV$, $\not{p}_T > 10\ GeV$, $cos\theta > -0.8$









SIGNIFICANCE

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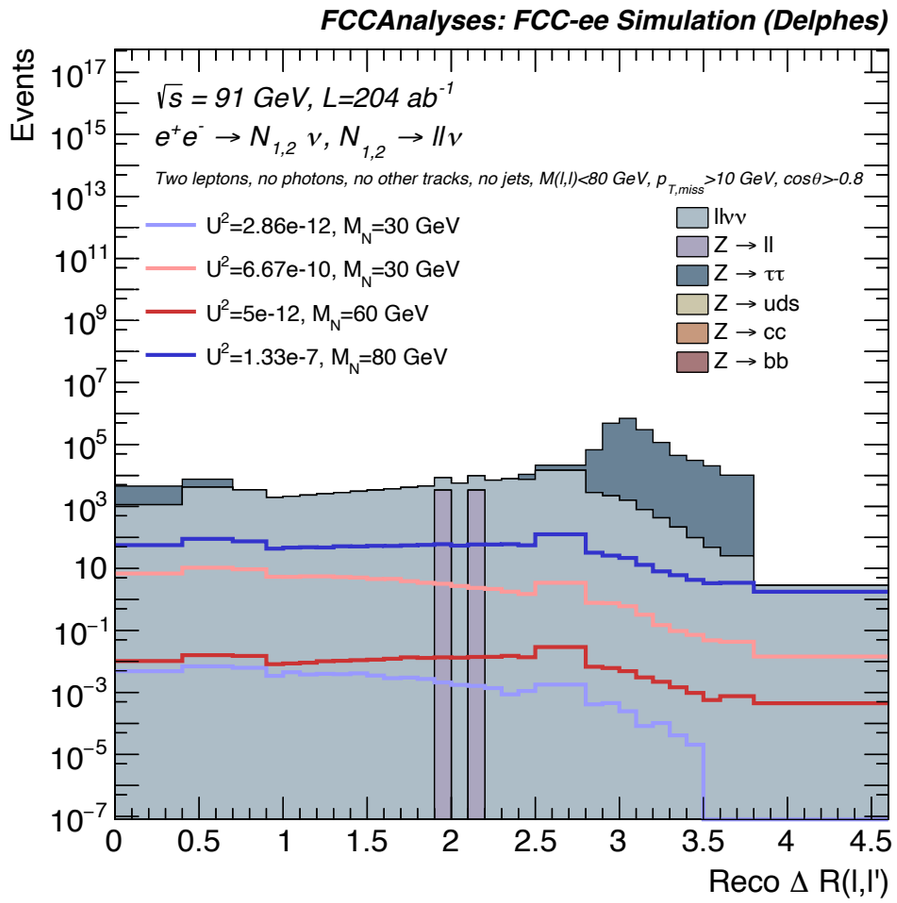
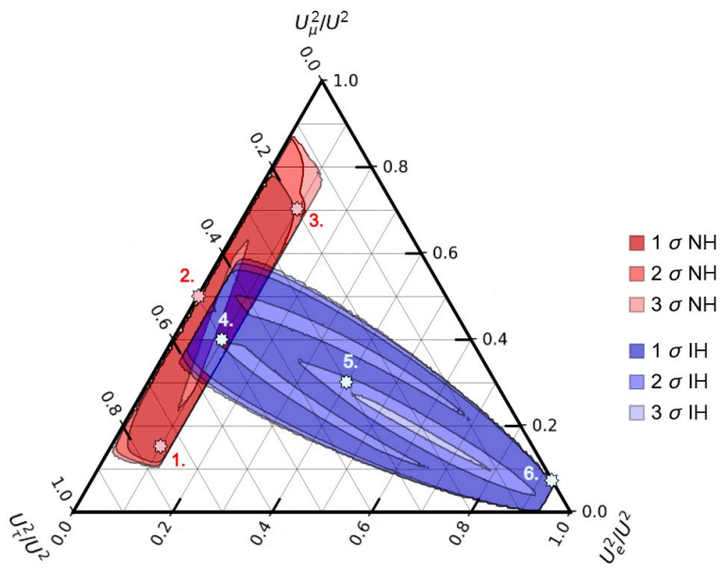
- The maximum sensitivity is obtained with a fit on the angular distance between the leptons, ΔR
- It has good background modeling that minimizes statistic fluctuations
- We made sure that there are enough backgrounds events in each bin to minimize the overestimation of the significance

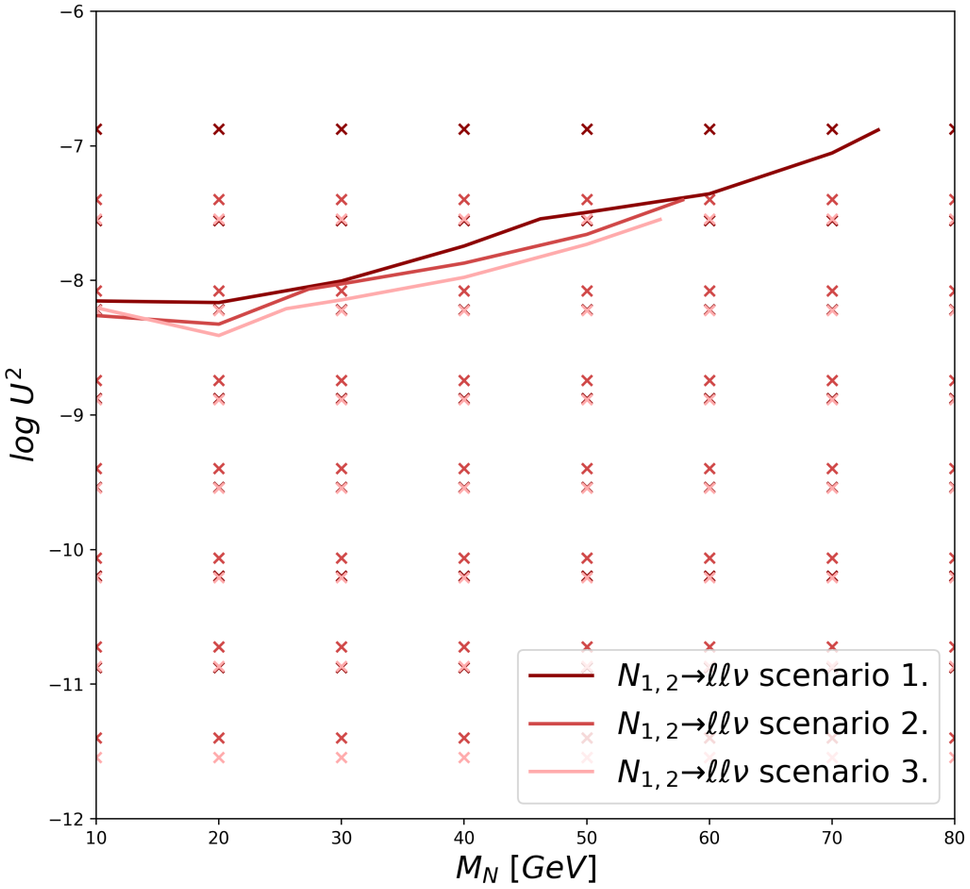


RESULTS

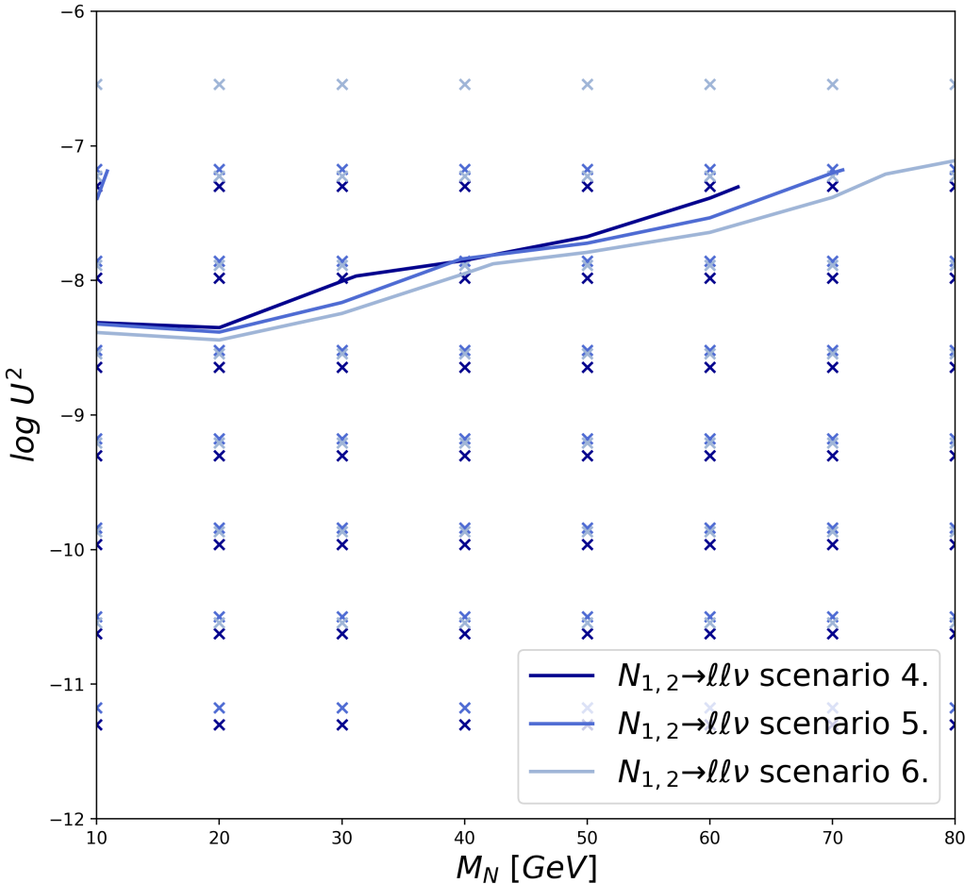
- Shape-based analysis from ΔR with maximum likelihood fit, statistical significance computed with **Combine Higgs tool** arXiv:2404.06614
- The results (at $\sigma = 5$) show improvement from previous studies where only the number of signal and background events was considered



Shape analysis – Normal Hierarchy



Shape analysis – Inverted Hierarchy



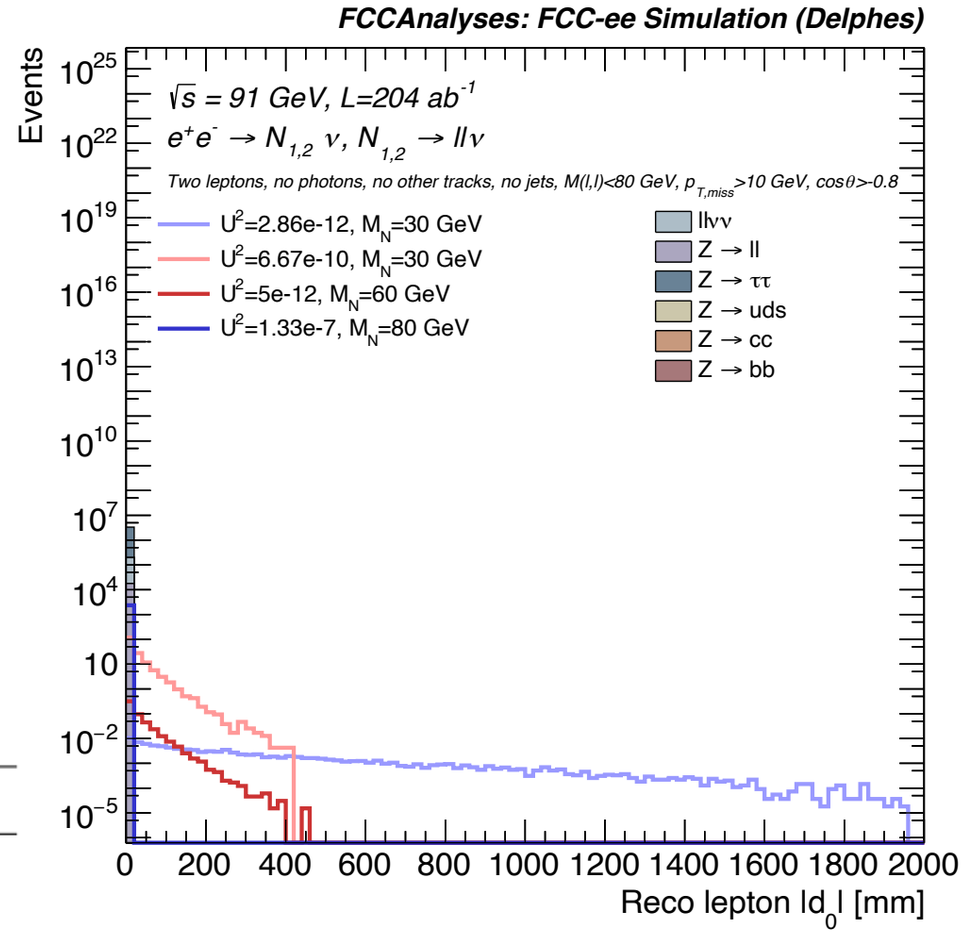
LLP EVENT SELECTION

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

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

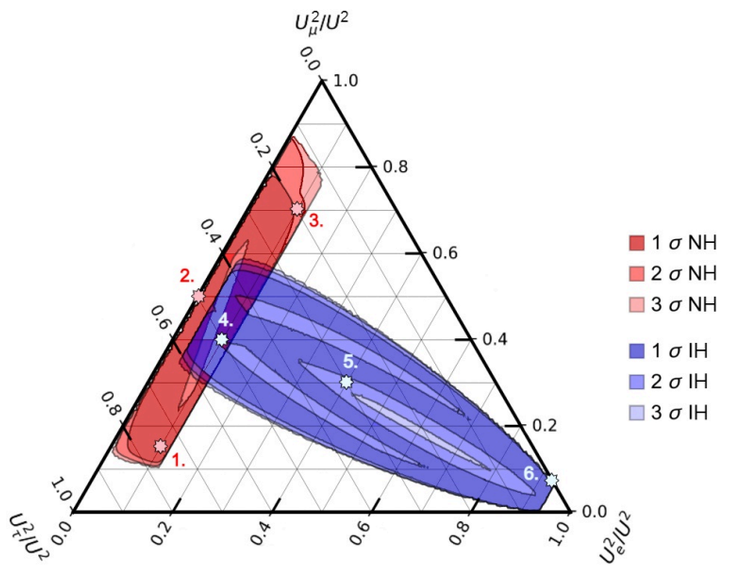
- Adding requirements on the reconstructed vertex allows us to define a region of the parameter space where the HNLs events are background-free

6. Previous selection	Two final state leptons, no photons, no other tracks, no jets and cuts
7. Vertex χ^2	$\chi^2 < 10$
8. Tracker dimensions	$L_{xy} < 2000$ mm $\lvert z\rvert < 2000$ mm
9. Lepton impact parameter	$\lvert d_0\rvert > 0.57$ mm

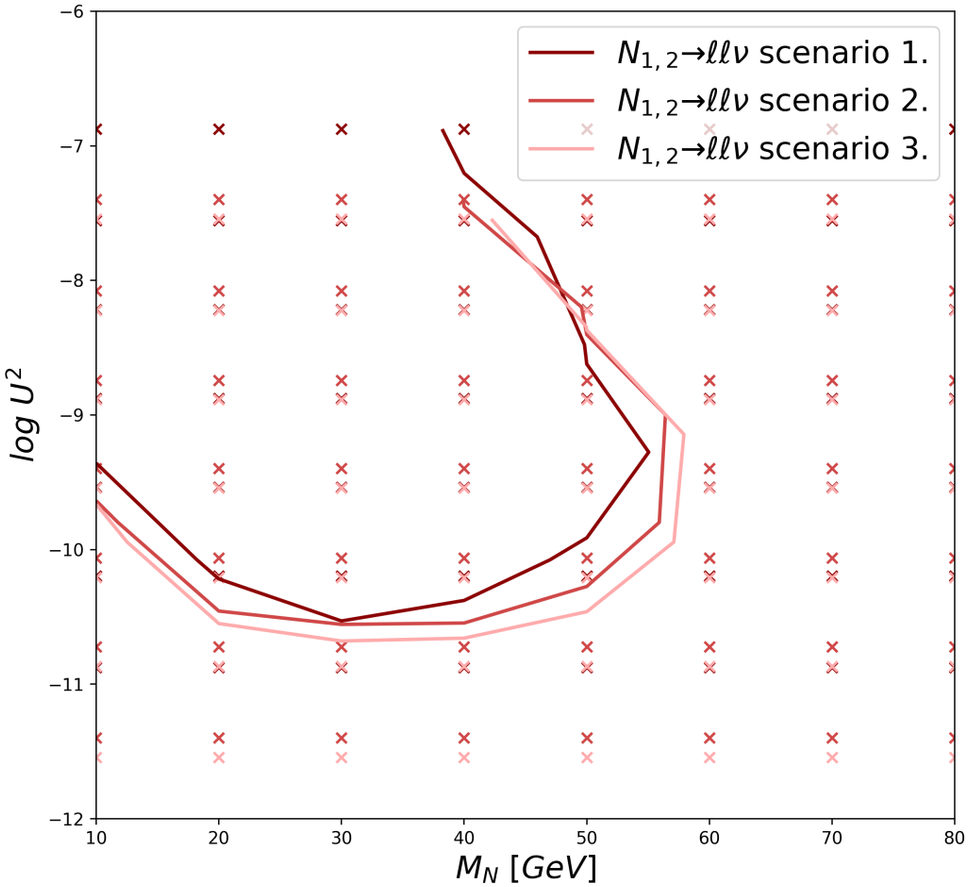


LLP RESULTS

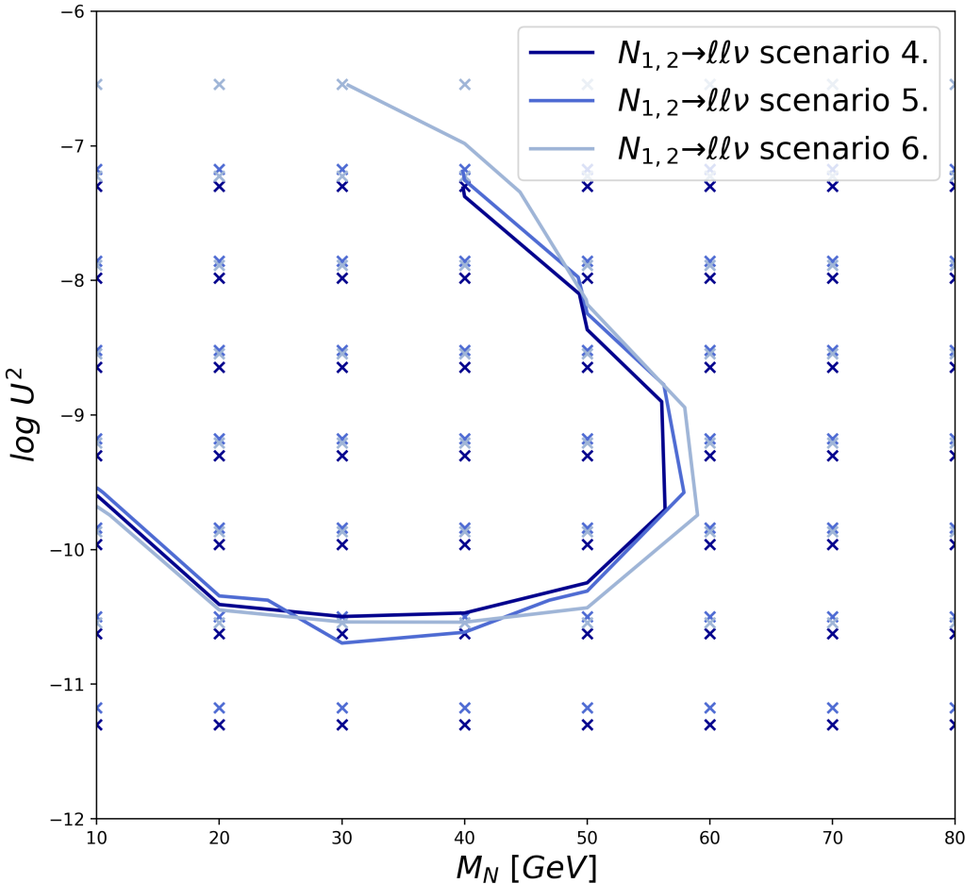
- Showing contours for signal event counting greater than 4
- Lower couplings region is now accessible
- Not so sensitive at higher masses (shorter life time)



Displaced events – Normal Hierarchy



Displaced events – Inverted Hierarchy



SUMMARY OF THE RESULTS

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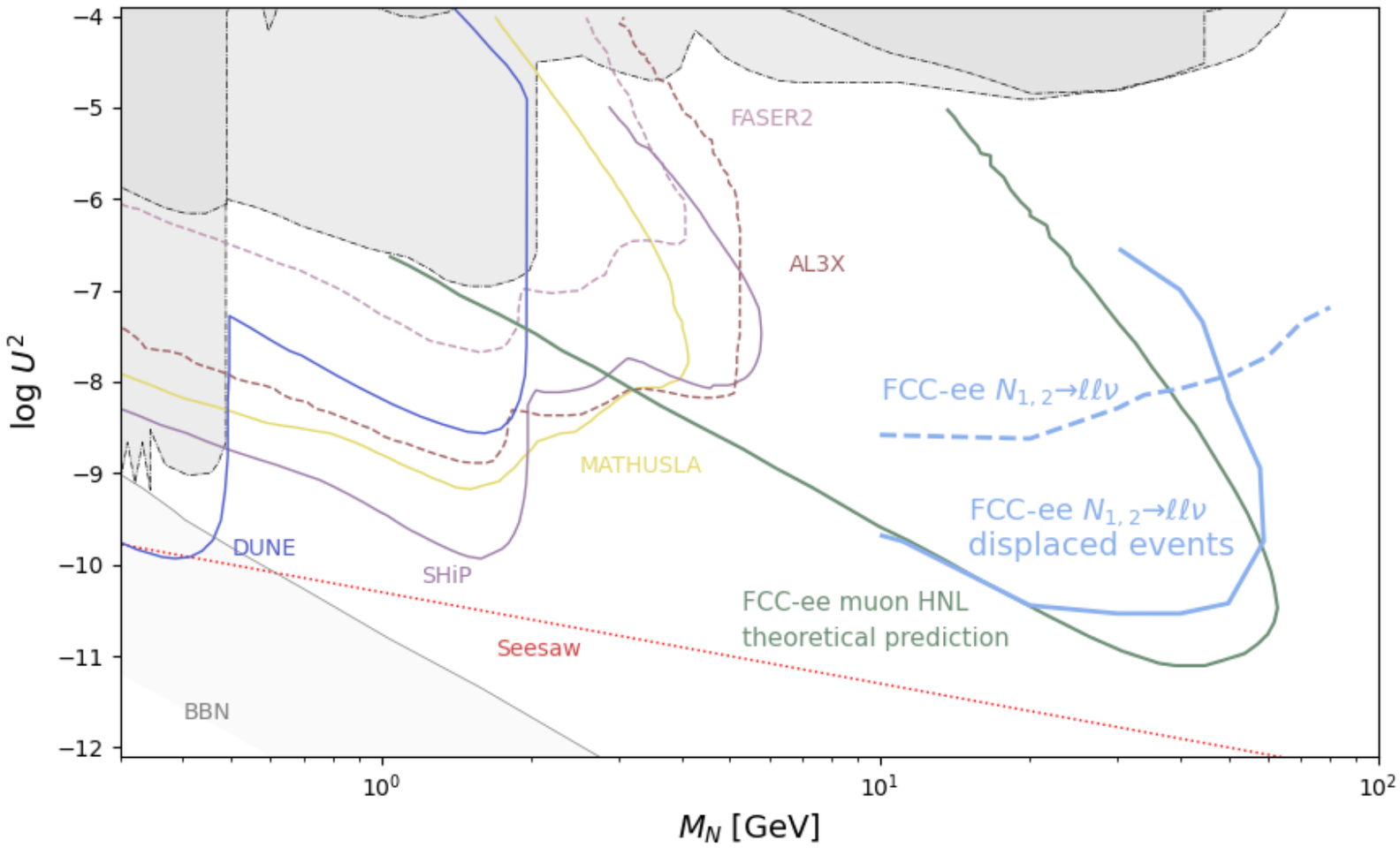
- Comparison (different models!) with exclusion limits from other experiments, and theoretical predictions of HNLs at FCC coupling exclusively to muons
- Curves for σ=5 from the shape analysis and 4 events for the displaced selection, shown here the HNLs mixing closest to the one HNL case (scenario 6.)



CONCLUSIONS AND PLANS

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- We presented the first study of two HNLs at FCC-ee with a realistic simulation setup
- Review from conveners ongoing, answers collected in our google Doc
- While we reply to the comments received, we are completing studies to understand the possible overlap of $\ell\ell\nu\nu$ with the other backgrounds, and alternative generations for these processes
- We will produced updated documentation with all the details

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BACKUP

CUMULATIVE EFFICIENCIES

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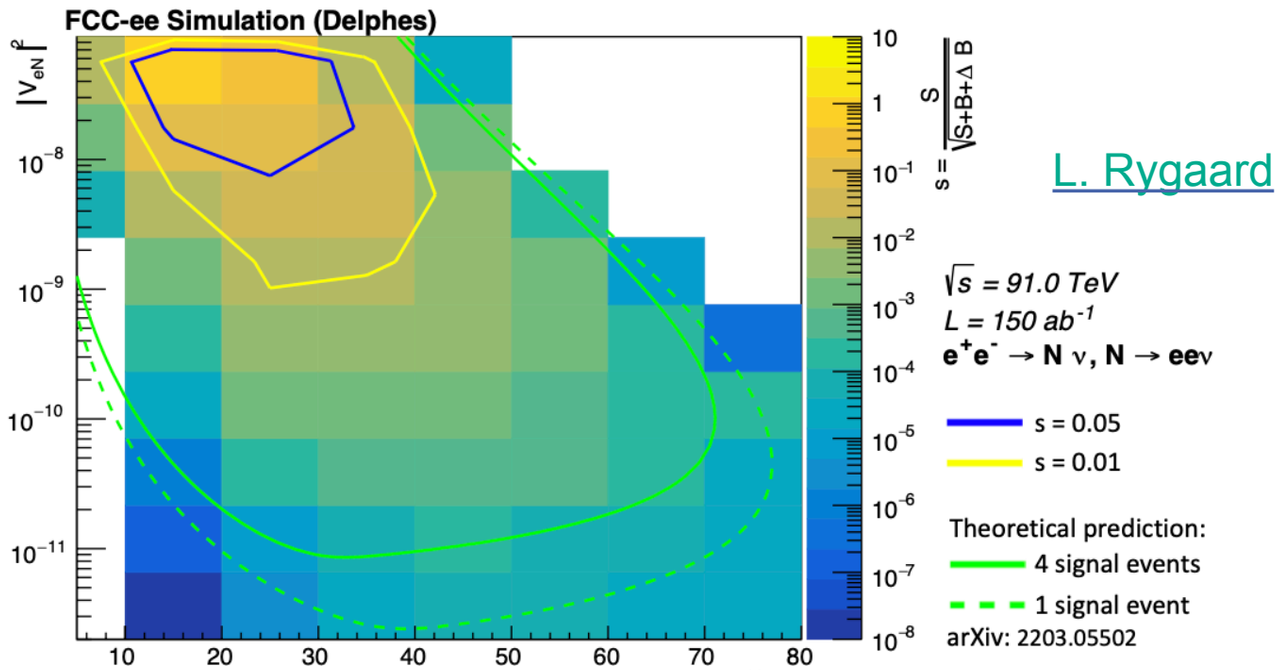
1. Selection	Two leptons with opposite charges, no photons
2. Reconstructed tracks	No other tracks
3. Jets	No jets
4. Invariant mass	$M(\ell, \ell') < 80$ GeV
5. Missing transverse momentum	$\not{p}_T > 10$ GeV
6. Cosine between the leptons	$\cos\theta > -0.8$
7. Vertex χ^2	$\chi^2 < 10$
8. Tracker dimensions	$L_{xy} < 2000$ mm $\lvert z\rvert < 2000$ mm
9. Lepton impact parameter	$\lvert d_0\rvert > 0.57$ mm

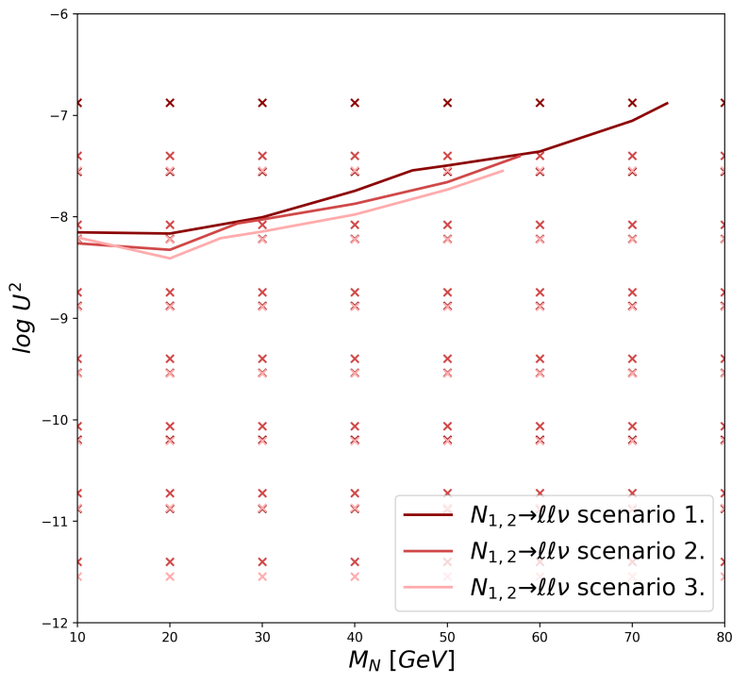
	1.	2.	3.	4.	5.	6.	9.
$Z \to ee$	7.40e-01	7.39e-01	7.38e-01	1.60e-03	4.00e-08	1.00e-08	$\leq$ 9.97e-17
$Z \to \mu\mu$	8.34e-01	8.32e-01	8.32e-01	1.73e-03	3.00e-08	2.00e-08	$\leq$ 1.99e-16
$Z \to \tau\tau$	9.54e-02	9.49e-02	9.49e-02	9.47e-02	3.27e-02	5.23e-06	$\leq$ 4.85e-12
$Z \to bb$	1.16e-02	1.14e-08	1.14e-08	1.14e-08	$\leq$ 5.87e-09	$\leq$ 2.81e-09	$\leq$ 2.22e-13
$Z \to cc$	3.32e-03	2.40e-08	4.00e-09	4.00e-09	$\leq$ 1.41e-09	$\leq$ 1.68e-10	$\leq$ 2.30e-16
$Z \to ud$	1.46e-04	$\leq$ 2.93e-13	$\leq$ 3.59e-15	$\leq$ 3.43e-15	$\leq$ 1.47e-16	$\leq$ 1.39e-16	$\leq$ 41.96e-22
$Z \to ss$	1.78e-04	$\leq$ 3.56e-13	$\leq$ 3.70e-15	$\leq$ 3.58e-15	$\leq$ 2.92e-16	$\leq$ 2.78e-16	$\leq$ 1.34e-21
$e\mu\nu\nu$	9.10e-01	9.09e-01	9.09e-01	9.06e-01	6.99e-01	5.03e-01	$\leq$ 5.02e-07
$\tau\tau\nu\nu$	8.62e-02	8.57e-02	8.57e-02	8.57e-02	3.14e-02	2.23e-02	$\leq$ 9.13e-09
U^2 =2.86e-12, M_N =30 GeV	7.73e-02	7.72e-02	7.72e-02	7.72e-02	6.49e-02	6.41e-02	6.08e-02
U^2 =6.67e-10, M_N =30 GeV	5.02e-01	5.02e-01	5.01e-01	5.01e-01	4.06e-01	4.00e-01	3.21e-01
U^2 =5e-12, M_N =60 GeV	4.46e-01	4.45e-01	4.45e-01	4.45e-01	3.73e-01	3.36e-01	2.66e-01
U^2 =1.33e-7, M_N =80 GeV	3.26e-01	3.25e-01	3.25e-01	3.25e-01	2.88e-01	2.55e-01	$\leq$ 3.64e-06

PRECEDENT STUDY

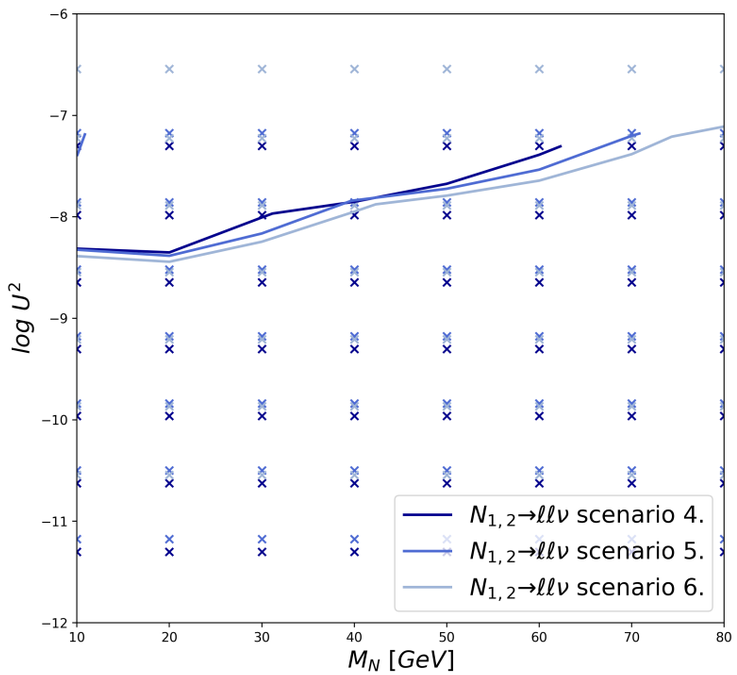


L. Rygaard

Shape analysis – Normal Hierarchy



Shape analysis – Inverted Hierarchy



LLP HNLS PROJECTION

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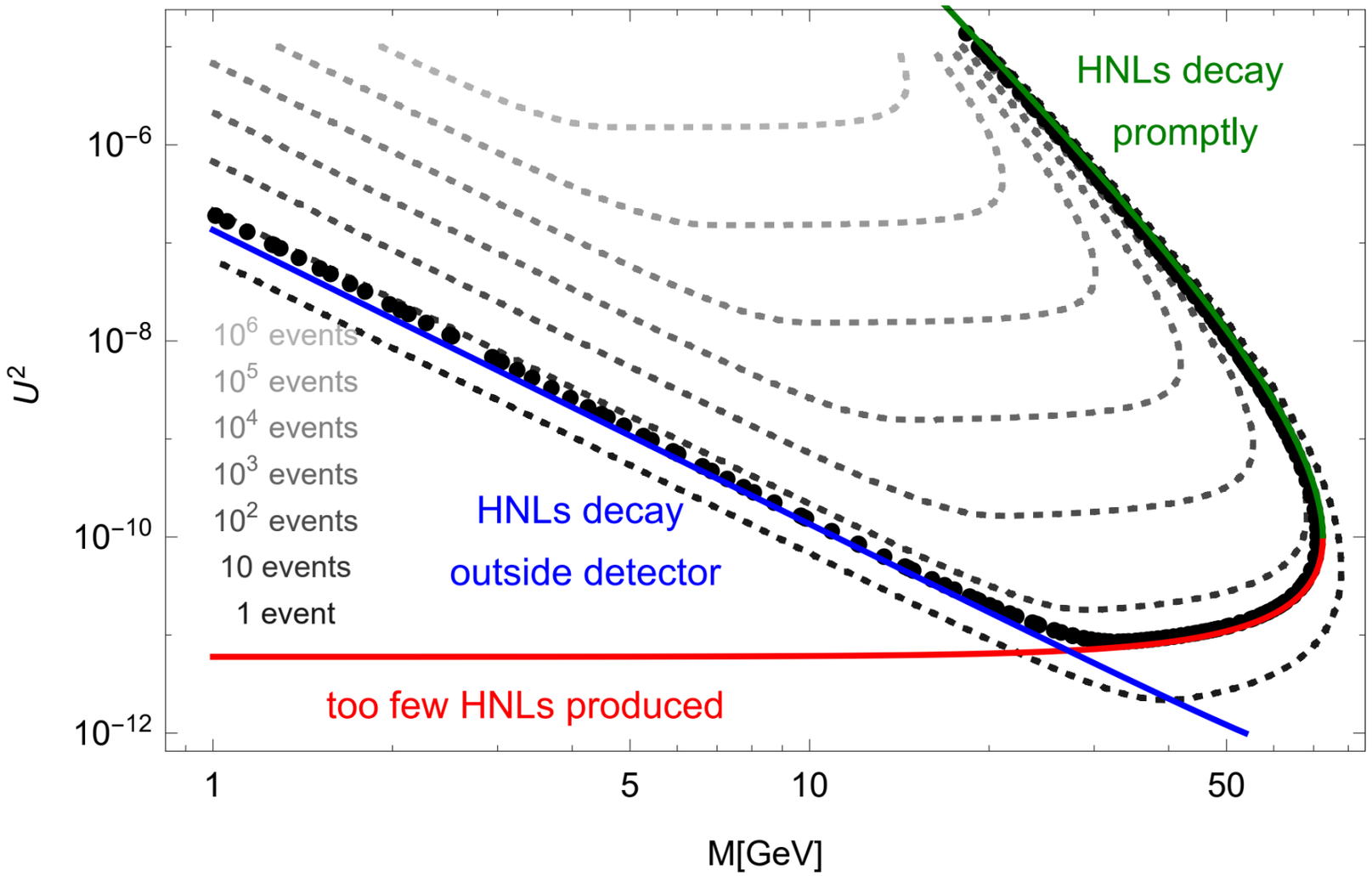
- Number of events of Dirac HNLs coupling to muons PoS ICHEP2022 (2022) 608
- Considers the IDEA detector volume and a cut on decay lenght of HNLs $L_{xyz} > 400\ \mu m$
- No background estimate



MASS DIFFERENCE

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