LLP experimental perspectives at FCC-ee: Heavy Neutral Leptons

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(on behalf of the FCC-ee LLP group)

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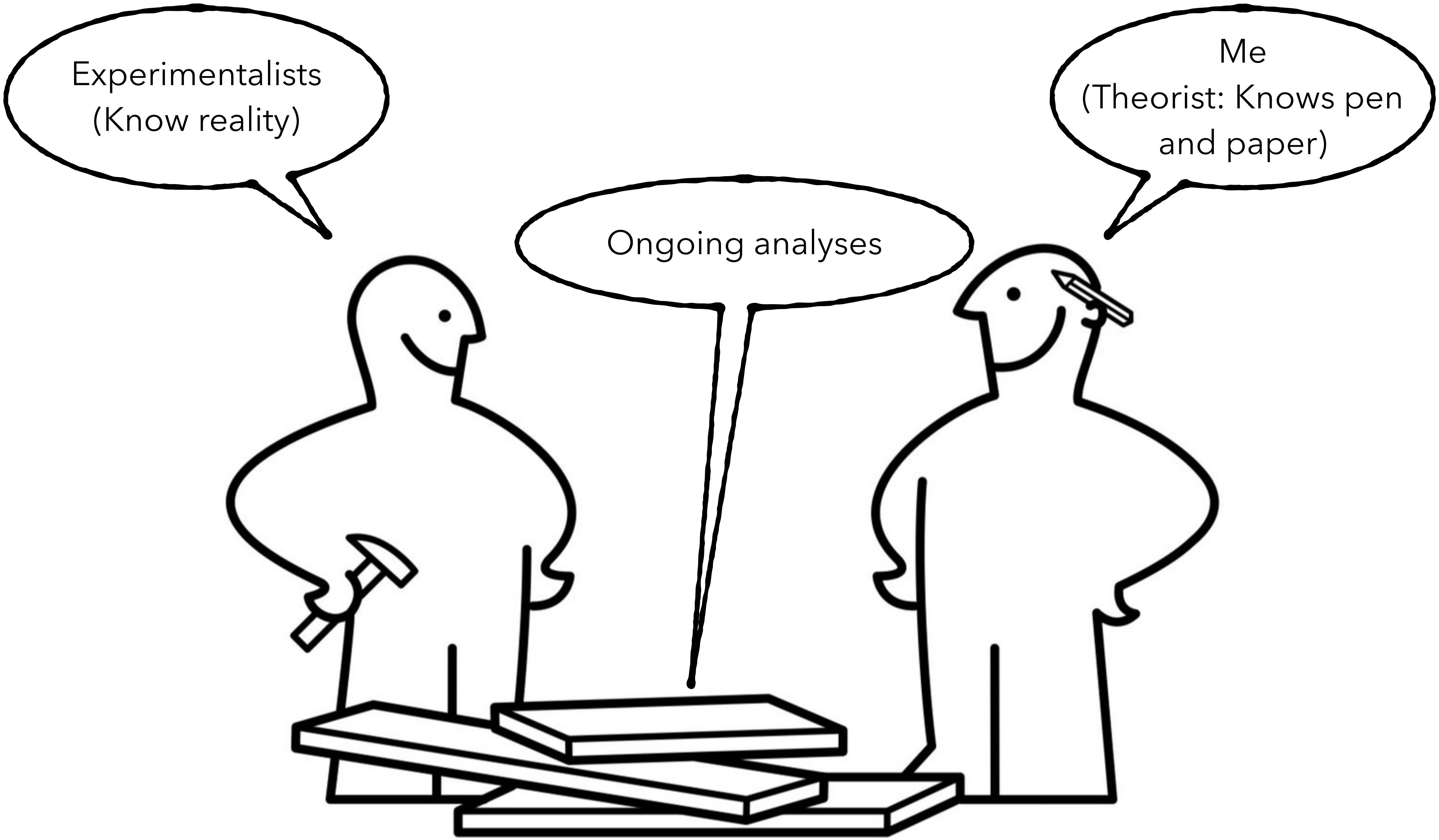
NAWI Graz Natural Sciences

FWF Der Wissenschaftsfonds.

FUTURE CIRCULAR COLLIDER

UNI GRAZ


Experimentalists
(Know reality)
Ongoing analyses
Me
(Theorist: Knows pen and paper)

Neutrino mass generation mechanisms

See e.g. Deppisch et al. arXiv:1502.06541
See also talks by R. Franceschini, B. Karmakar

SM + right handed fields —Tiny Yukawa→ Small Dirac neutrino masses

RH fields mass term —Lepton number violation→ Baryogenesis through leptogenesis

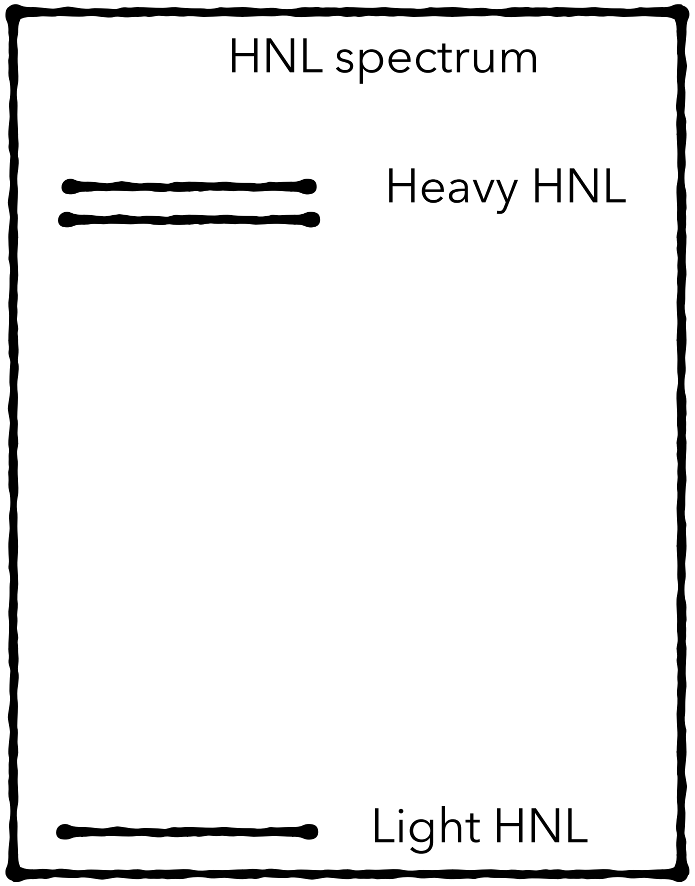
$$\mathcal{L} \supset Y^{\nu}_{ij} \overline{N}_i \; L_j \cdot H - \frac{1}{2} M_{ij} \overline{N}_i \; N^c_j$$

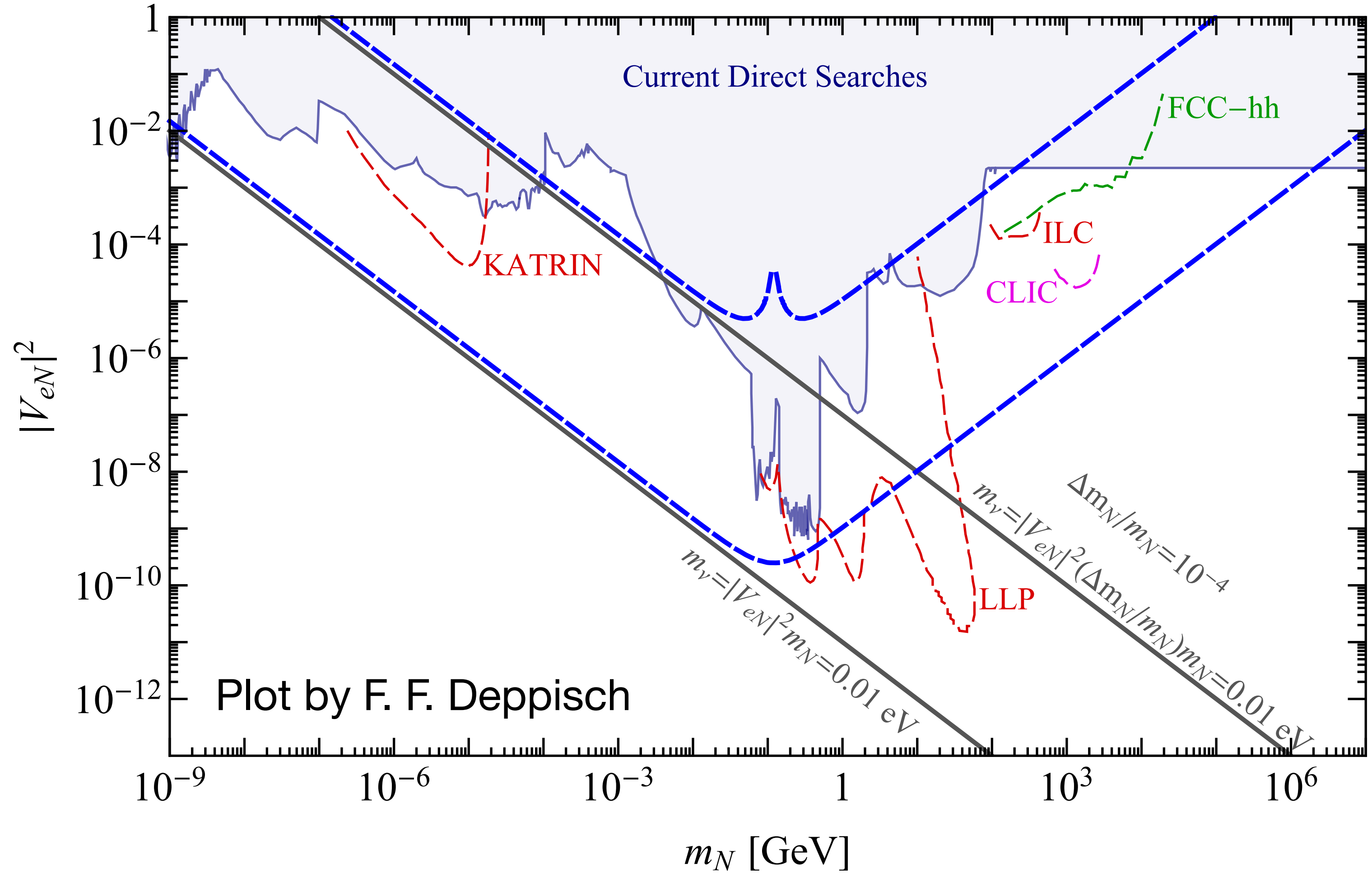
$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

Dirac mass, usually small Y_ν

Majorana mass, can be heavy, can have $Y_N \sim 1$, introduces Lepton number violation

Heavy neutral leptons - signature space





$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

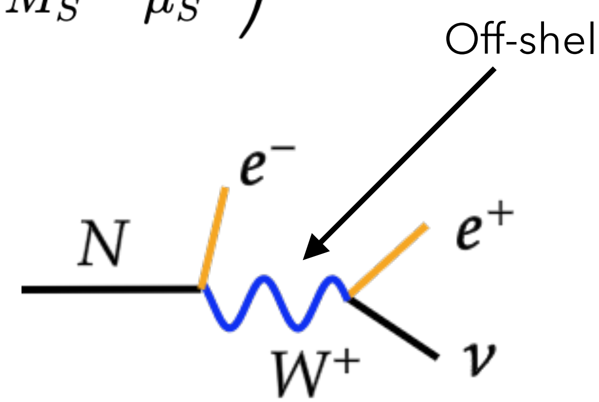
$$m_\nu \approx \frac{m_D^2}{M_R} = |V_{\mu N}|^2 \times m_R$$

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^\mathsf{T} & \mu_R & M_S^\mathsf{T} \\ \mathbf{0} & M_S & \mu_S \end{pmatrix}$$

- Heavy neutrino decay width $M_N < m_Z$ (Drewes arXiv:2210.17110)

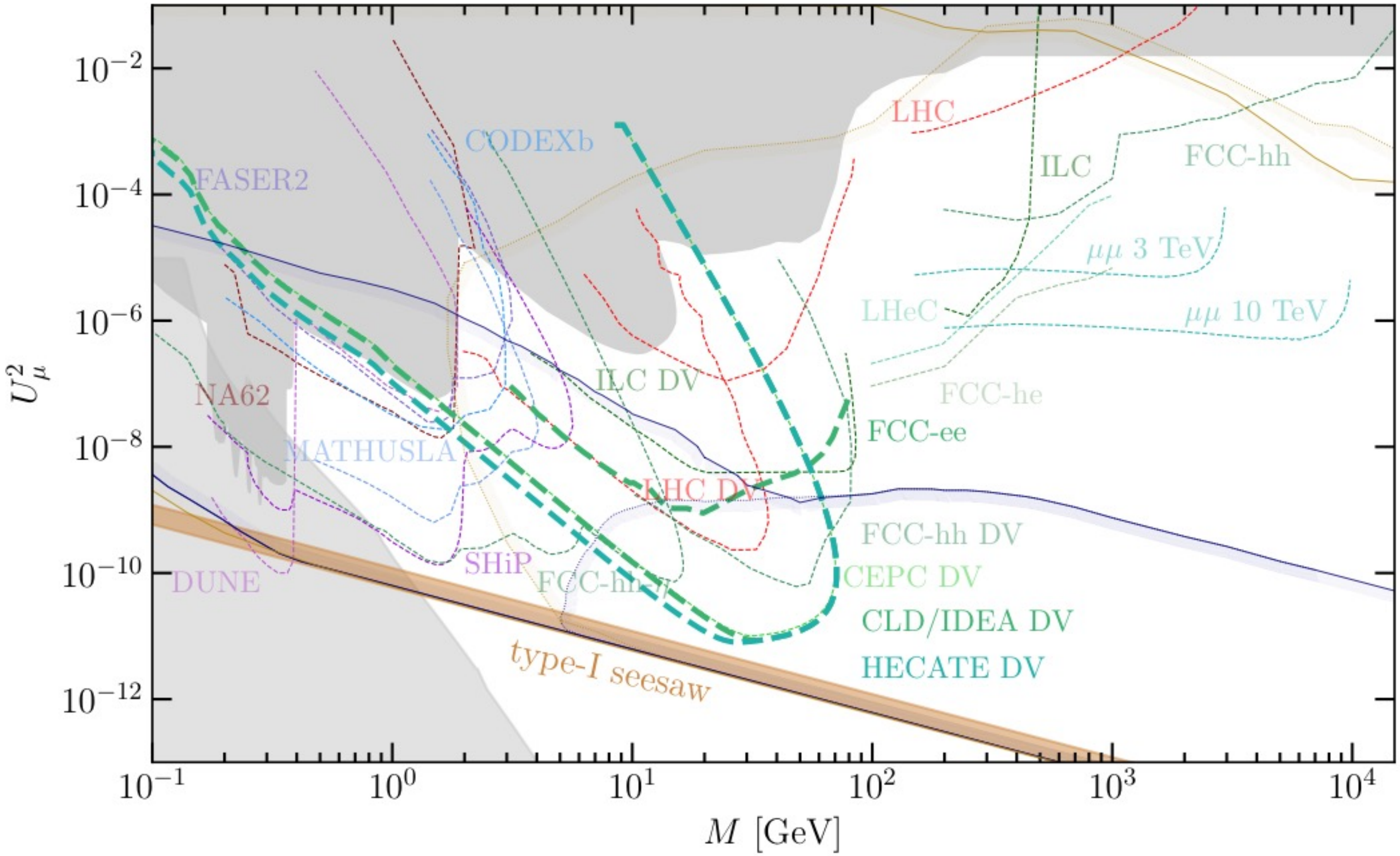
$$\Gamma_N \simeq c_{dec} \frac{a}{96\,\pi^3} G_F^2 V_{lN}^2 M_N^5$$

($c_{dec} = 1$ (Majorana), 1/2 (Dirac); $a \simeq 12$)



Expectations

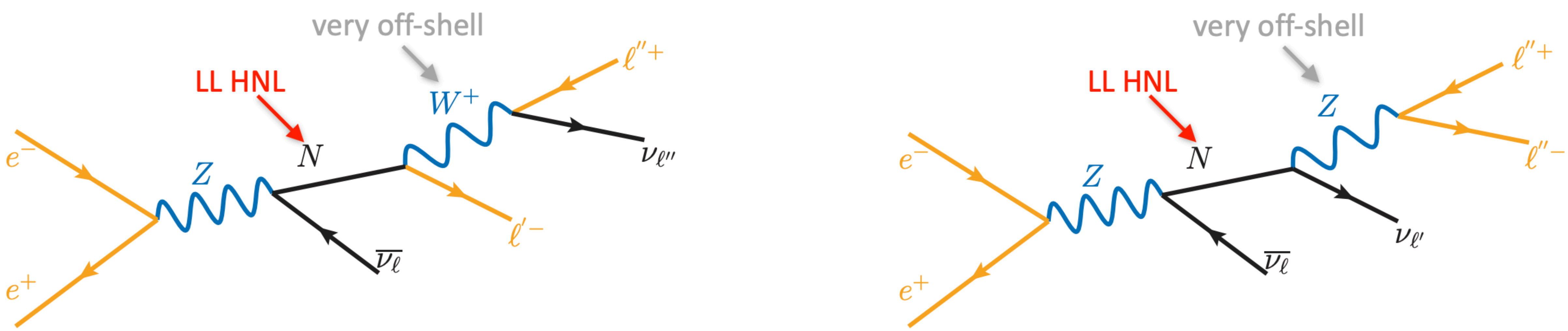
Snowmass arXiv:2203.05502



- Phenomenological study, combination of all final states ≥ 2 charged tracks, corresponds to 4 observed events
- 5×10^{12} Z produced, no backgrounds, ideal detector

Aims and setup

- Aim: Perform an FCC case study with the "official" analysis tools and framework available
  - Generated signal samples in Madgraph5 v3.2.0 + Pythia8 + Delphes, with the latest IDEA card processed with FCCAnalysis machinery (See talk by G. Ganis)
  - Try to be as realistic as possible

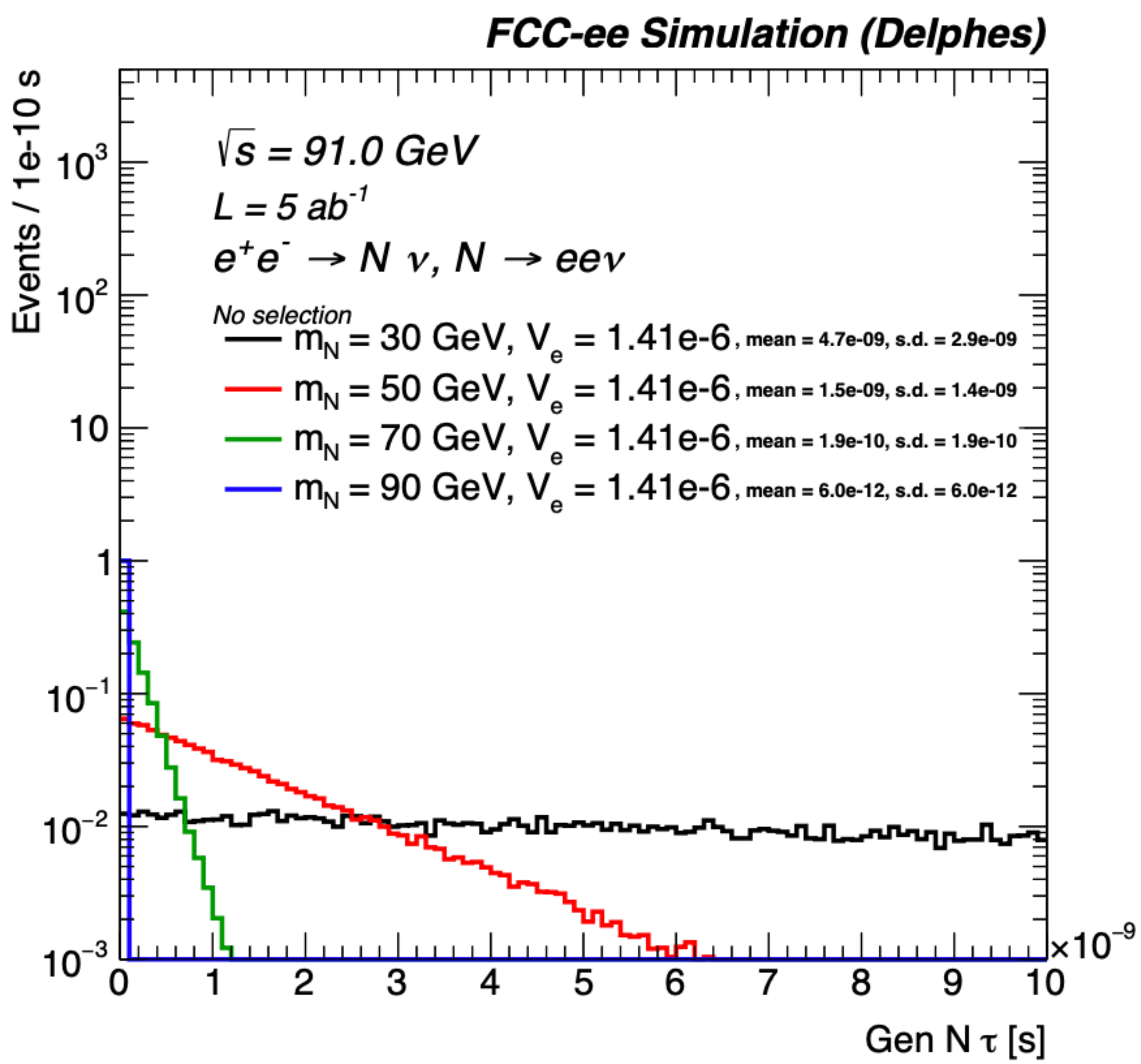


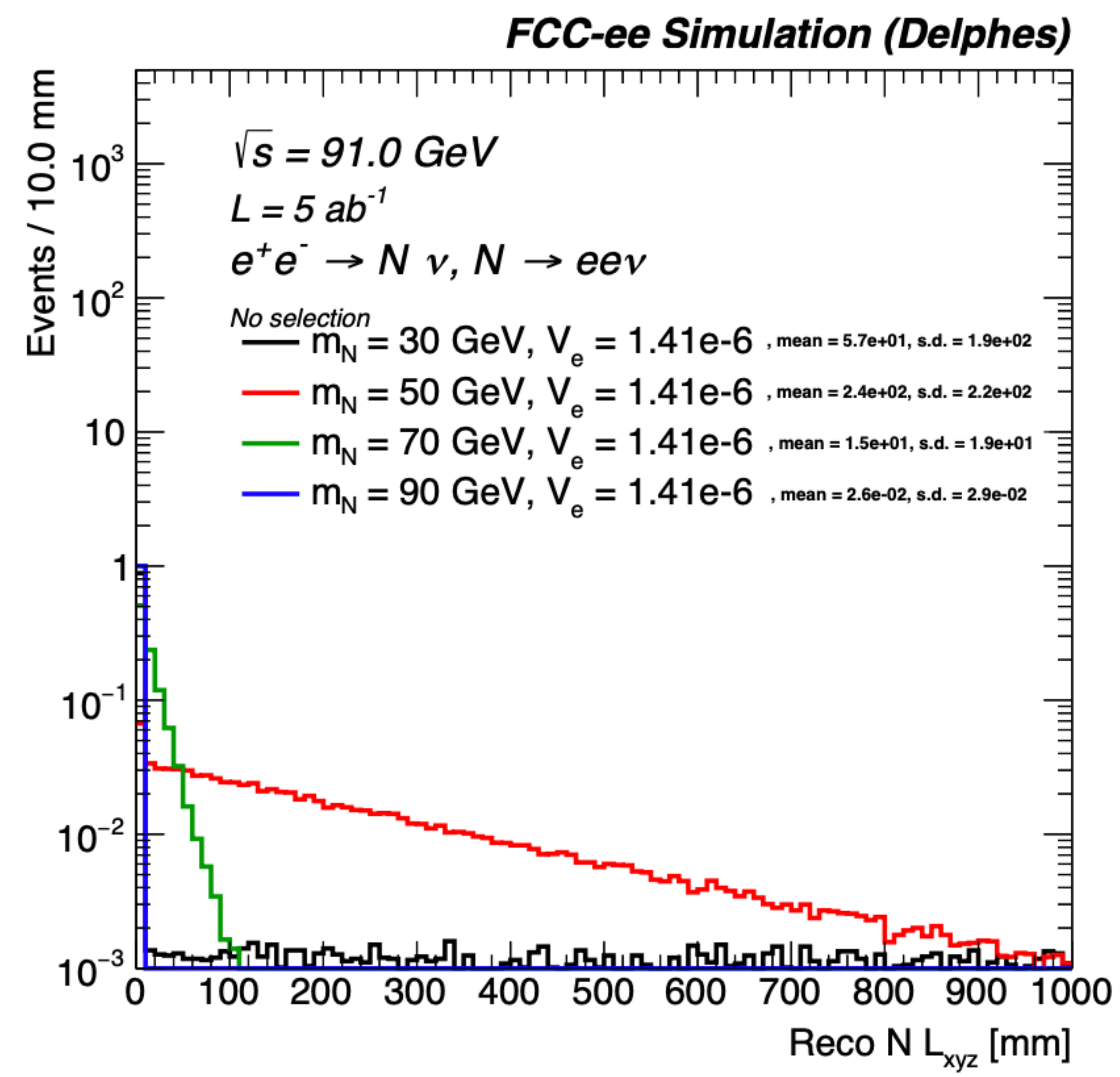
- Generated Majorana and Dirac HNLs with the SM_HeavyN_CKM_AllMasses_LO and SM_HeavyN_Dirac_CKM_Masses_LO models
- Experimental signature:
  - Displaced vertex: small mixing angle, no associated prompt lepton, unlike LHC
  - Prompt final state: larger mixing angle
- Current focus: electron flavoured HNL only, primary studies of $e\,e\,\nu$ final state
- Other final states include: $e\,\mu\,\nu$, $e\,\tau\,\nu$, $e\,j\,j$, $\nu\,j\,j$, $\nu\,b\,b$

Sample validation

[Lovisa Rygaard's master thesis]

[See also Rohini Sengupta's thesis]

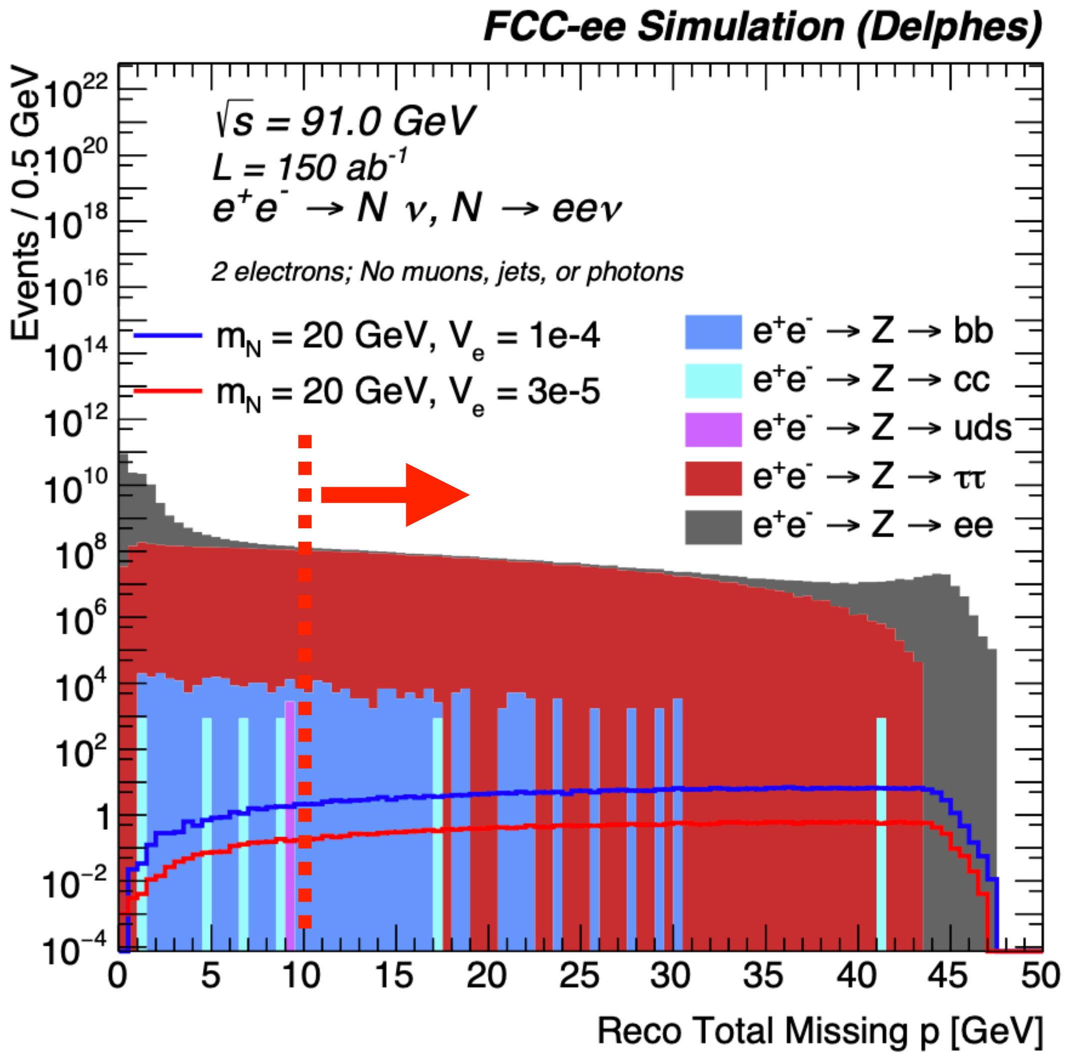


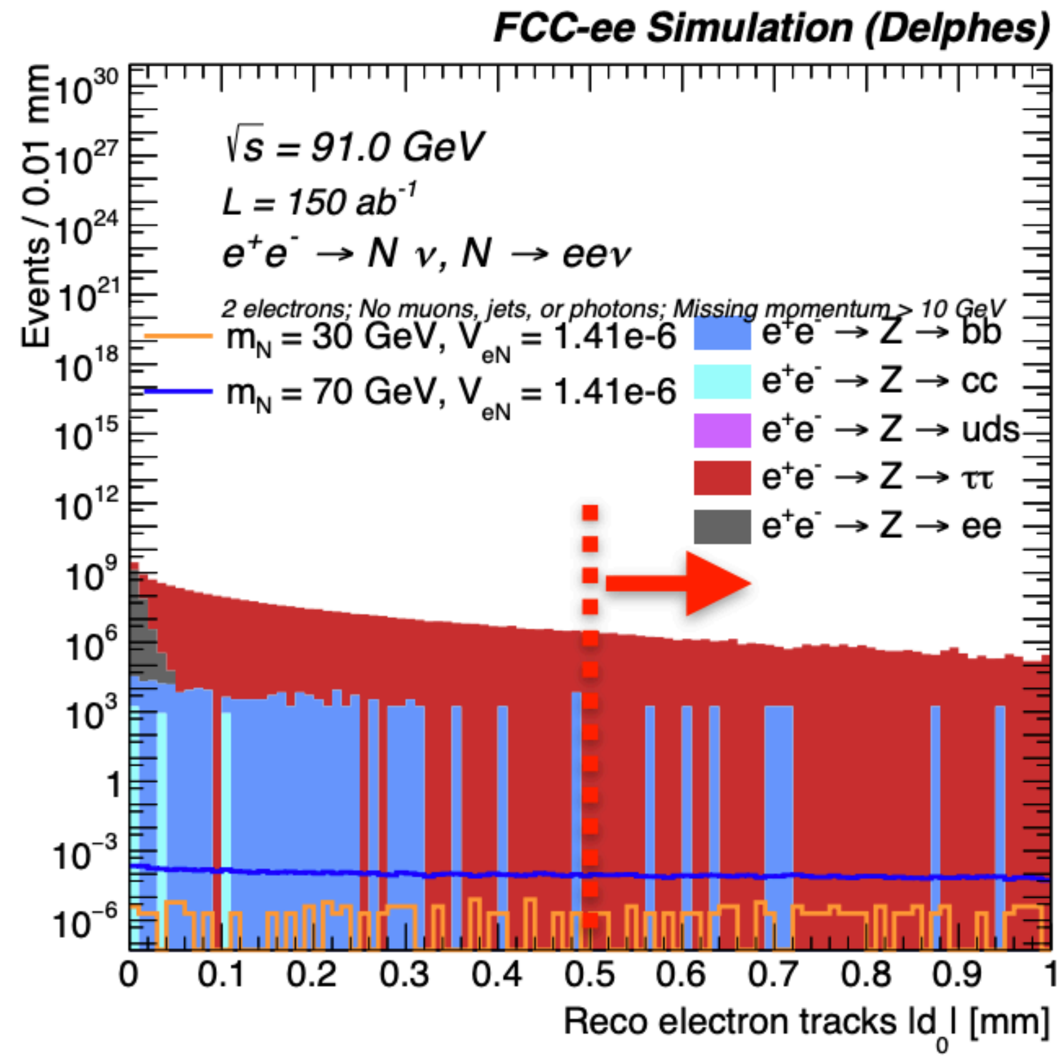


- One of the first implementation and validation of BSM scenarios in FCC frameworks
- Performed validation to retrieve HNl lifetime from gen level distributions

Signal vs background discrimination

Lovisa Rygaard's master thesis





- Centrally-produced "spring2021" background samples with the IDEA detector, at $\sqrt{s} = 91\,\mathrm{GeV}$
- Measuring total missing energy at FCC-ee is possible; $p_{miss} > 10\,\mathrm{GeV}$
- $|d_0| > 0.5\,\mathrm{mm}$ removes the vast majority of SM background

Cutflow

[Lovisa Rygaard's master thesis](#)

- Generated signal samples with enough statistics

	Before selection	Exactly 2 reco e	Vetoes	$\not{p} > 10$ GeV	$\lvert d_0 \rvert > 0.5$ mm
$m_N = 10$ GeV, $\lvert V_{eN} \rvert = 2 \times 10^{-4}$	2534 ± 11	1006 ± 7	996 ± 7	951 ± 7	907 ± 7
$m_N = 20$ GeV, $\lvert V_{eN} \rvert = 9 \times 10^{-5}$	458 ± 2	313 ± 2	308 ± 2	293 ± 2	230 ± 1
$m_N = 20$ GeV, $\lvert V_{eN} \rvert = 3 \times 10^{-5}$	51.0 ± 0.2	34.7 ± 0.2	34.2 ± 0.2	32.6 ± 0.2	31.2 ± 0.2
$m_N = 30$ GeV, $\lvert V_{eN} \rvert = 1 \times 10^{-5}$	5.01 ± 0.02	3.85 ± 0.02	3.76 ± 0.02	3.54 ± 0.02	3.39 ± 0.02
$m_N = 50$ GeV, $\lvert V_{eN} \rvert = 6 \times 10^{-6}$	1.23 ± 0.01	0.99 ± 0.01	0.96 ± 0.01	0.92 ± 0.01	0.729 ± 0.004

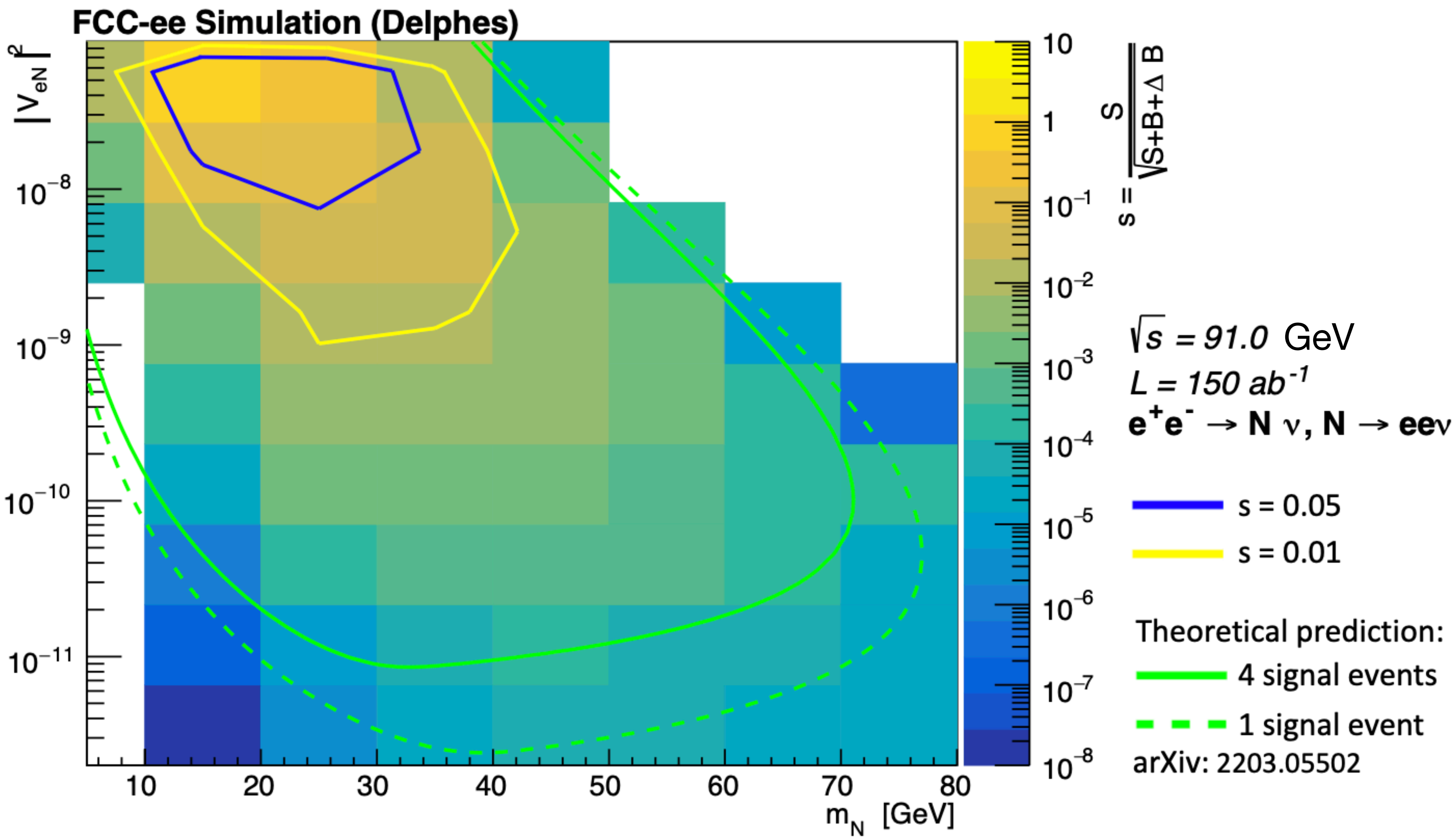
- Need background samples with enough statistics

	Before selection	Exactly 2 reco e	Vetoes	$\not{p} > 10$ GeV	$\lvert d_0 \rvert > 0.5$ mm
$Z \to \tau\tau$	$2.21 \times 10^{11} \pm 7.00 \times 10^{7}$	$5.49 \times 10^{9} \pm 1.10 \times 10^{7}$	$5.10 \times 10^{9} \pm 1.06 \times 10^{7}$	$2.52 \times 10^{9} \pm 7.47 \times 10^{6}$	$6.64 \times 10^{4} \pm 3.84 \times 10^{4}$
$Z \to ee$	$2.19 \times 10^{11} \pm 6.94 \times 10^{7}$	$1.75 \times 10^{11} \pm 6.19 \times 10^{7}$	$1.53 \times 10^{11} \pm 5.80 \times 10^{7}$	$7.07 \times 10^{8} \pm 3.94 \times 10^{6}$	$\leq 3.94 \times 10^{6}$
$Z \to bb$	$9.97 \times 10^{11} \pm 4.14 \times 10^{7}$	$5.64 \times 10^{8} \pm 9.85 \times 10^{5}$	$3.25 \times 10^{5} \pm 2.36 \times 10^{4}$	$1.22 \times 10^{5} \pm 1.45 \times 10^{4}$	$1.72 \times 10^{3} \pm 1.72 \times 10^{3}$
$Z \to cc$	$7.82 \times 10^{11} \pm 2.61 \times 10^{7}$	$1.69 \times 10^{7} \pm 1.21 \times 10^{5}$	$5.22 \times 10^{3} \pm 2.13 \times 10^{3}$	$1.74 \times 10^{3} \pm 1.23 \times 10^{3}$	$\leq 1.23 \times 10^{3}$
$Z \to uds$	$2.79 \times 10^{12} \pm 8.83 \times 10^{7}$	$2.30 \times 10^{7} \pm 2.54 \times 10^{5}$	$2.79 \times 10^{3} \pm 2.79 \times 10^{3}$	$\leq 2.79 \times 10^{3}$	$\leq 2.79 \times 10^{3}$

First sensitivity estimates

Lovisa Rygaard's master thesis

See also Sissel Bay Nielsen's thesis

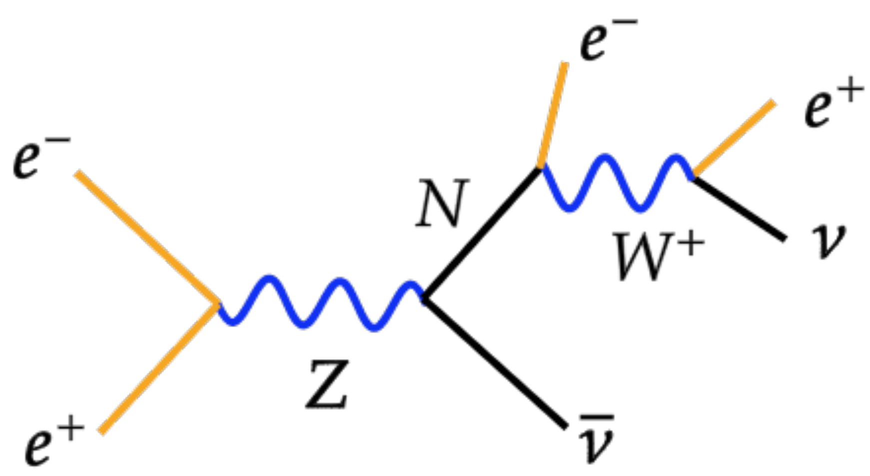


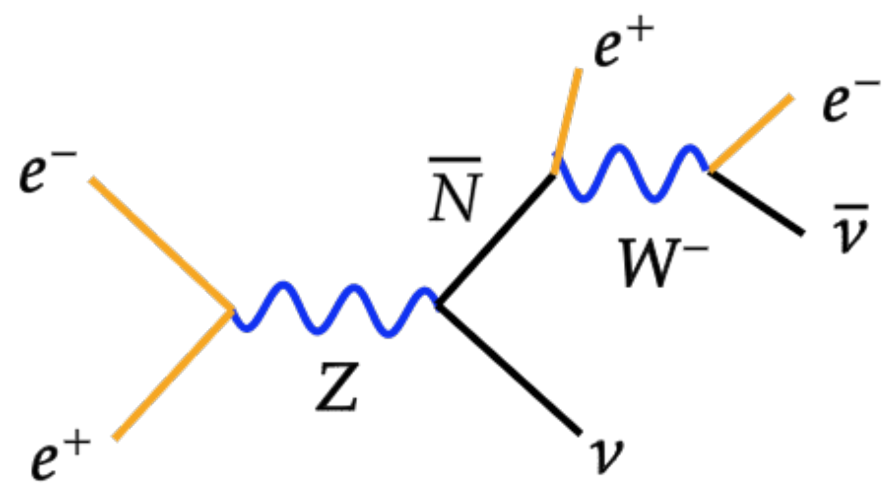
- First estimate using official FCC machinery
- $e\,e\,\nu$ final state only, projections limited by background statistics

Dirac vs Majorana

Blondel et al. arXiv:2105.06576

- Unlike LHC, no same sign vs opposite sign lepton final state at FCC-ee at Z pole





- Dirac neutrinos $(e^+e^- \to Z \to \nu\bar{N};\ e^+e^- \to Z \to \bar{\nu}N)$

$$\frac{1}{\sigma_{N,\bar{N}}}\frac{d\sigma_{N,\bar{N}}}{d\cos\theta} \propto \left(g_R^2\,(1 \mp \cos\theta)^2 + g_L^2\,(1 \pm \cos\theta)^2 + \frac{M_N^2}{m_Z^2}\,(g_L^2 + g_R^2)\ \sin^2\theta \right)$$

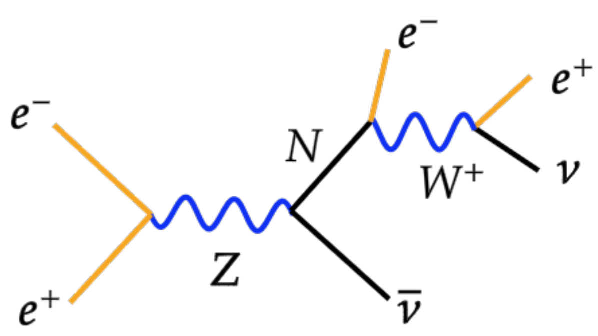
- Majorana neutrinos $(e^+e^- \to Z \to \nu N)$

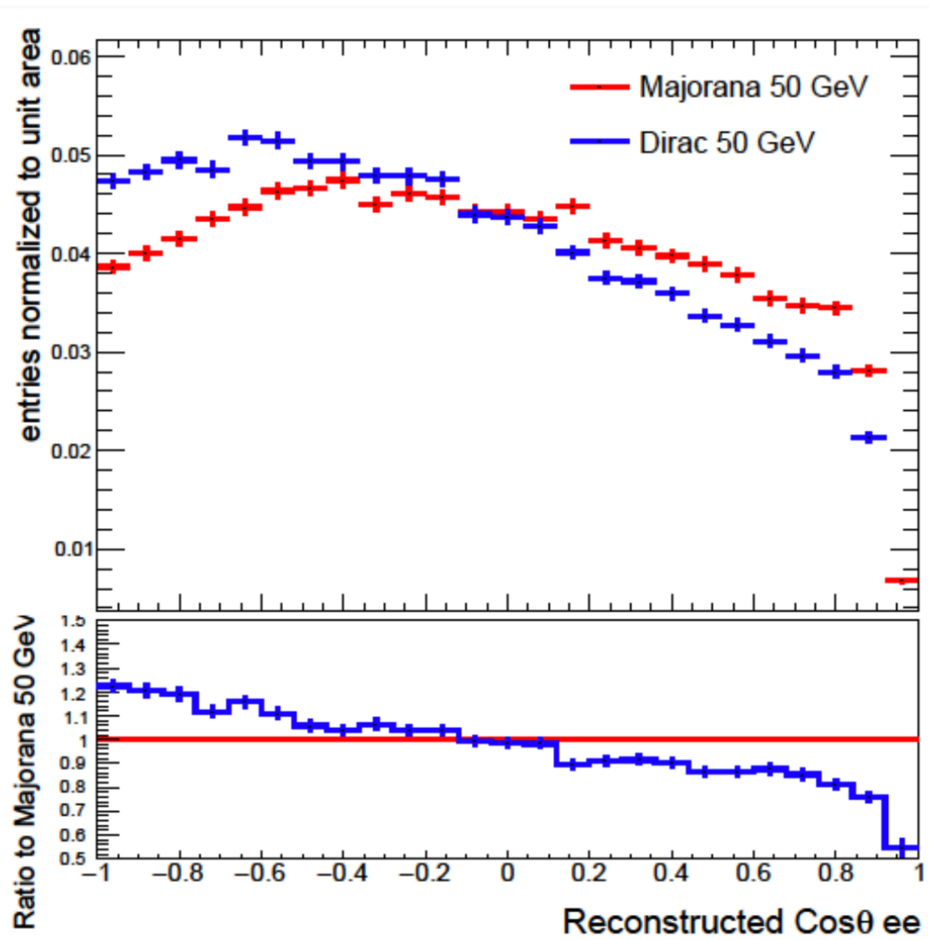
$$\frac{1}{\sigma_N}\frac{d\sigma_N}{d\cos\theta} \propto \left(1 + \cos^2\theta + \frac{M_N^2}{m_Z^2}\sin^2\theta \right)$$

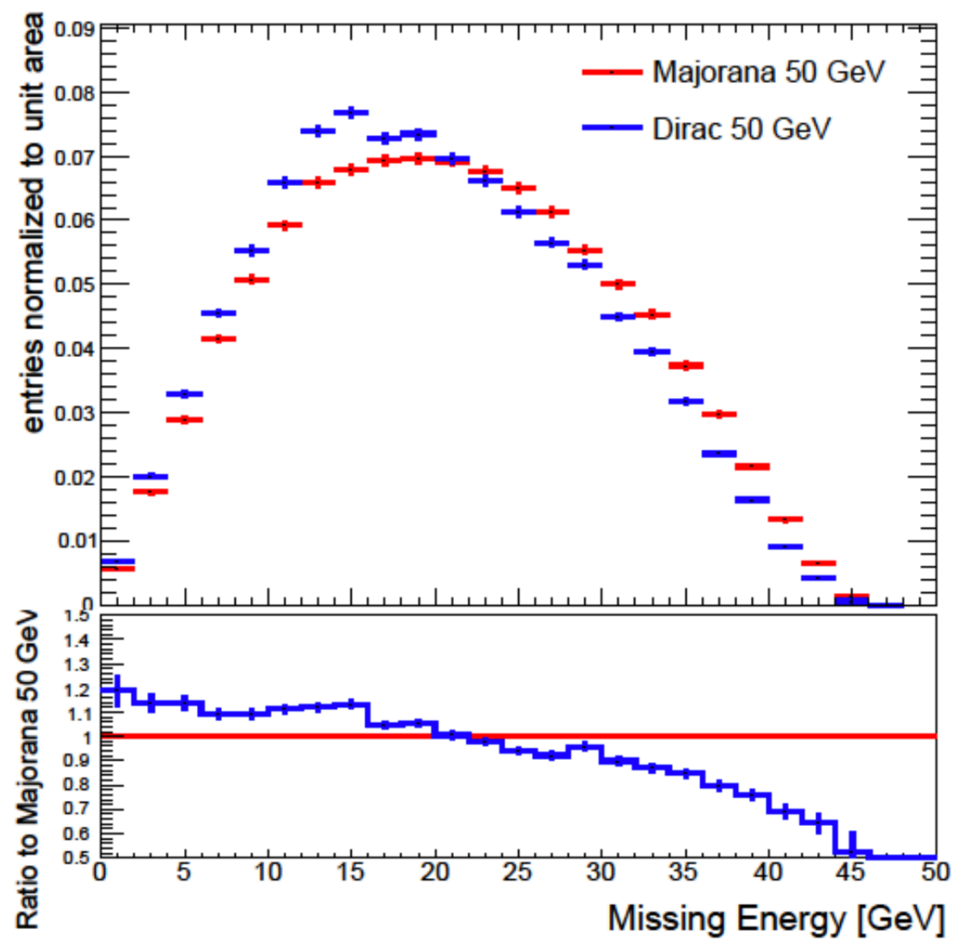
Dirac vs Majorana

Tanishq Sharma's master thesis

- Central question: What are the best kinematic observables to distinguish between Dirac and Majorana neutrinos at FCC-ee?







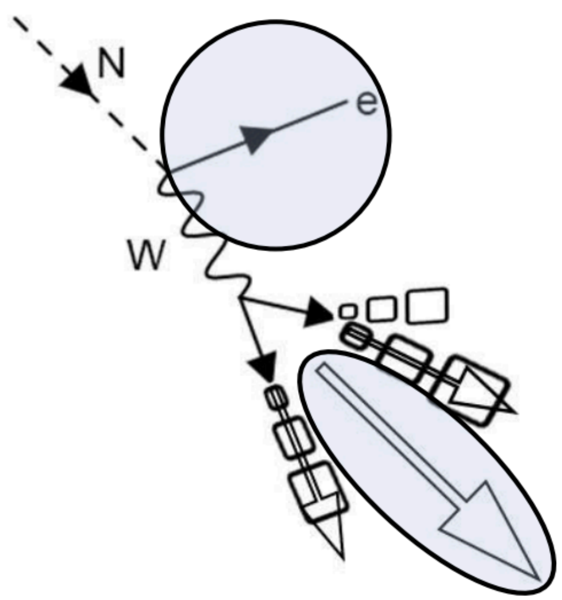
- Most promising variables for $e\,e\,\nu$ final state are angle between final state electron - positron and missing energy

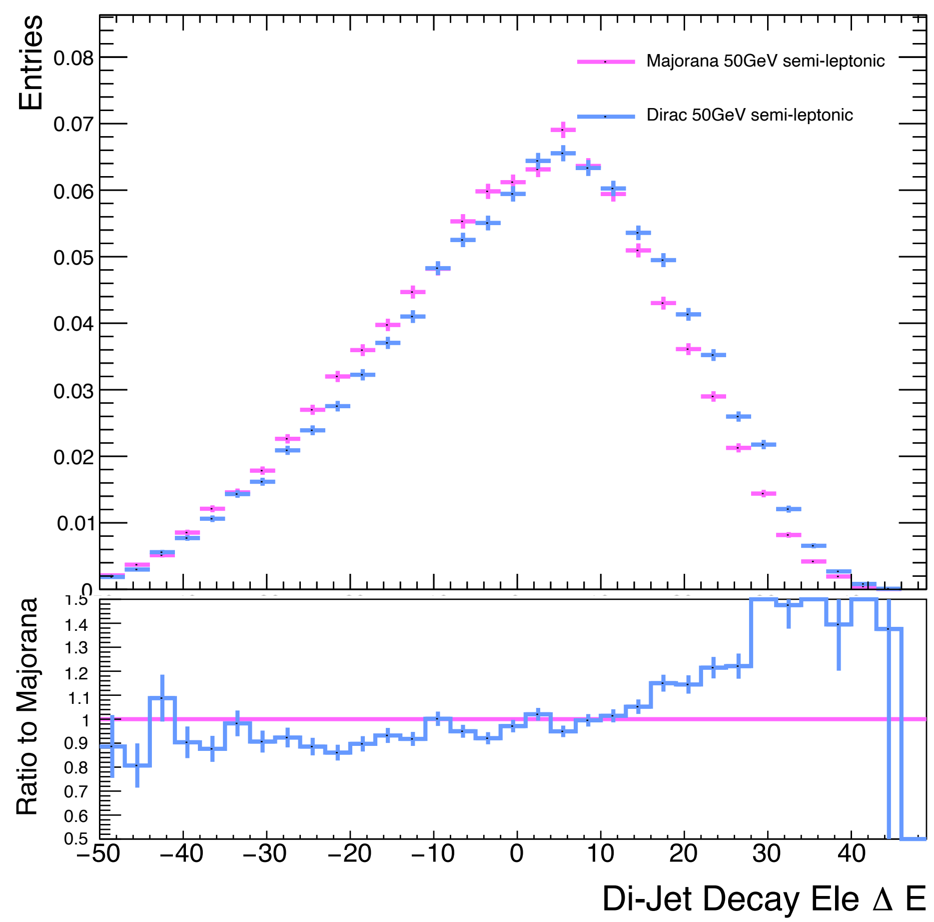
Dirac vs Majorana

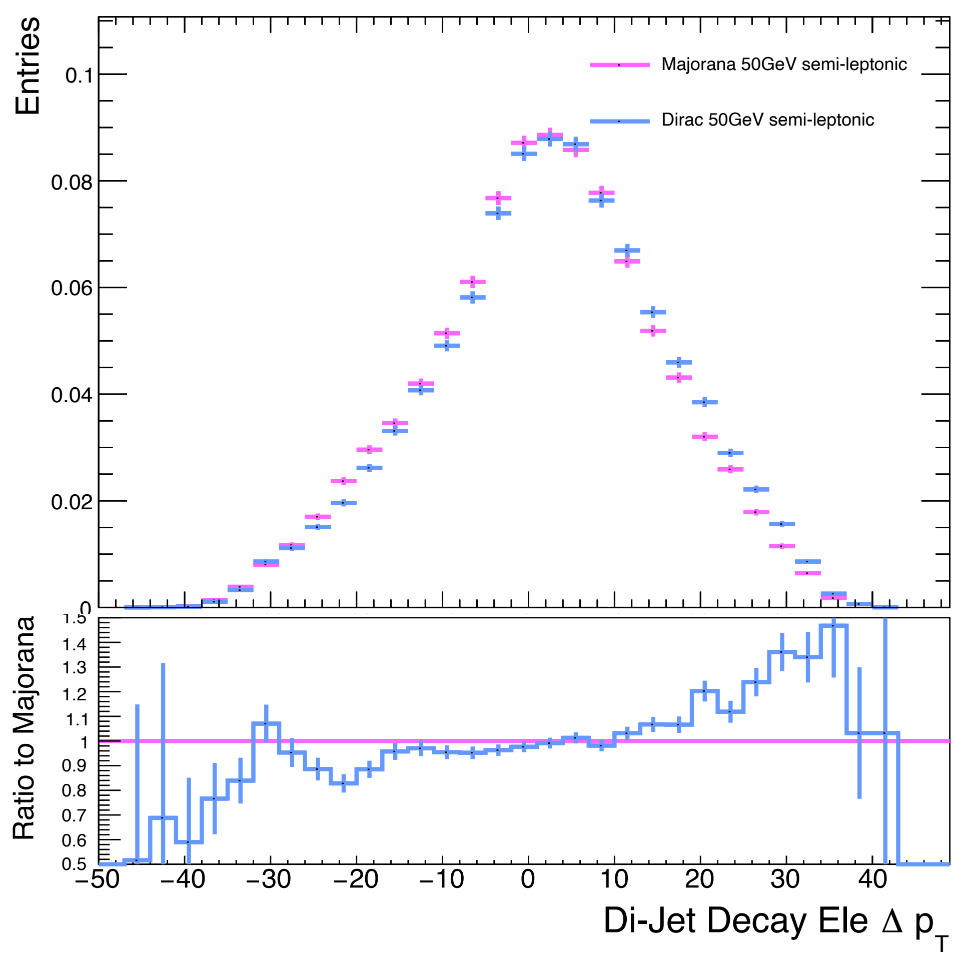
Dimitri Moulin's master thesis

- Central question: What are the best kinematic observables to distinguish between Dirac and Majorana neutrinos at FCC-ee?

ejj final state gen level comparisons





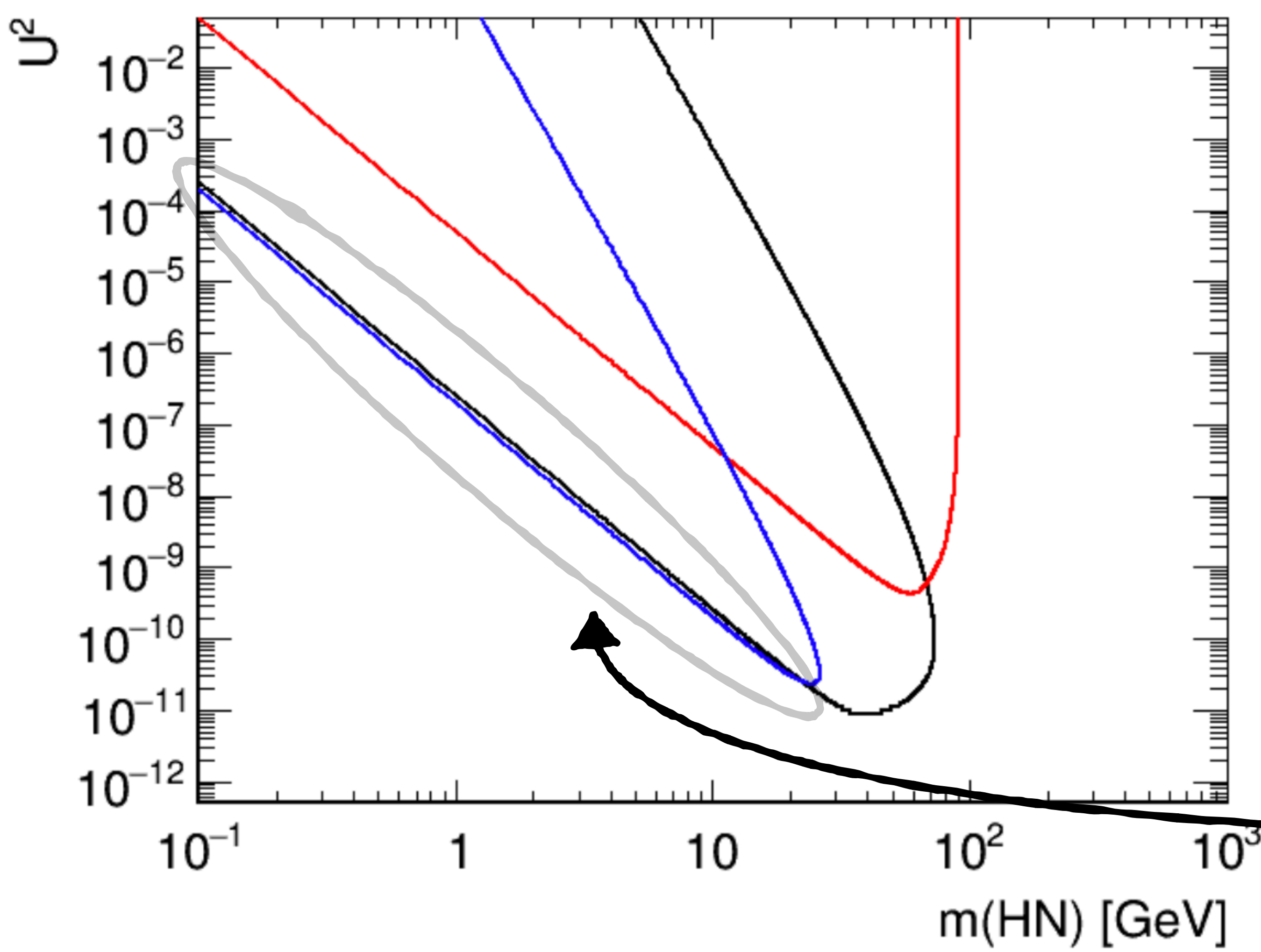


- Further studies ongoing, also considering energy distributions of final state e^- and e^+

Future plans

Plot by Giacomo Polesello

- Finalise existing sensitivity analyses by obtaining more background statistics
- Add more final states for sensitivity studies
- Explore interplay of different flavours
- Develop analyses in different parts of the detector



- Red: Prompt: 0< λ < 1mm
- Black:ID decay 0.04<λ< 150 cm
- Blue: Calo decay 200<λ< 450 cm

25% gain in U^2 wrt ID decays

Questions

See also talk by G. Polesello

- Analysis matrix

Decay final state	Decay length
jjl	Prompt
$jj\nu \quad bb\nu$	LL decay in ID
$ll'\nu$	LL decay in Calo

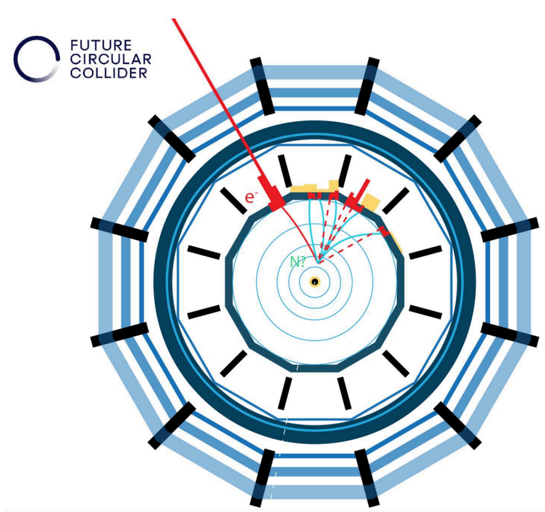
$l, l' = e, \mu, \tau$

$j = u, d, s, c, s$

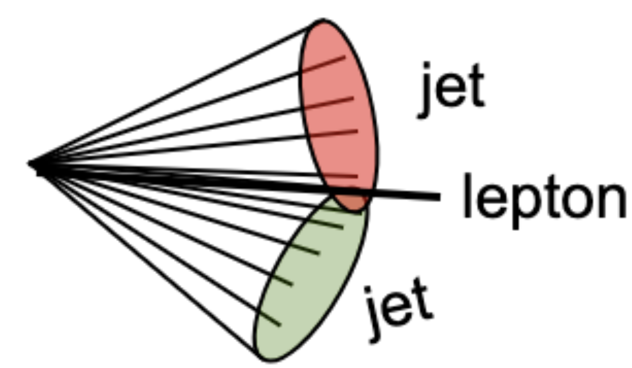
- An active interest in many of the final states and signatures exists
  - Many opportunities for contributions, you are welcome to join
  - Contact: Giacomo Polesello, Rebeca Gonzalez Suarez, Juliette Alimena

N_τ

Special treatment necessary



Rethink object definitions for decays far away from IP



Analyse effects of collimated objects at low masses

Conclusion

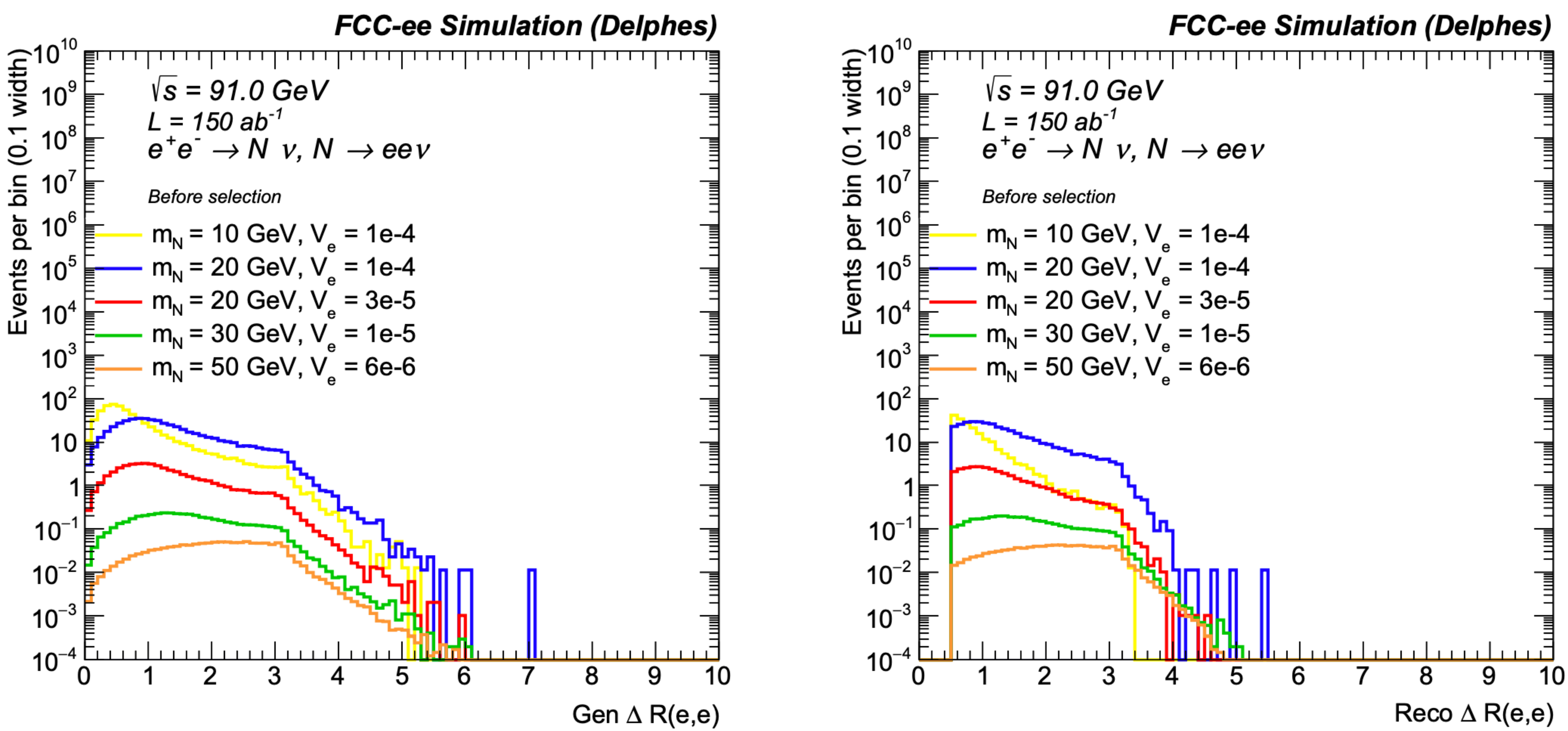
- Heavy neutral leptons are well motivated beyond the Standard Model particles which can help explain neutrino masses
- They provide a test case of long lived particle searches at FCC-ee

  See G. Ripellino's talk for other LLP scenarios

- First studies to 'realistically' estimate FCC-ee sensitivity to explore HNL parameter space underway
- Contains two aspects:
  - Overall sensitivity to HNL mass and mixing parameters
  - Distinction between Dirac and Majorana neutrinos
- First sensitivity studies performed during snowmass process, further avenues including necessity of more background statistics identified
- First studies about differences in angular distributions for Dirac vs. Majorana performed, promising variables identified
- Thanks to the software and computing team for help with analyses developments

Special thanks to our master students who are the drivers behind the scenes: Lovisa Raaygard (2022), Tanishq Sharma (2022) and Dimitri Moulin (ongoing)

Lepton isolation



- For $m_N \lesssim 10$ GeV, the two leptons are increasingly close to each other
- May also result in 'fatjet' for ljj final state