LLP at FCC-ee: Heavy Neutral Leptons

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NAWI Graz Natural Sciences

FWF Der Wissenschaftsfonds.

UNI GRAZ

Preparing for the future

- Many options for future lepton colliders (irrespective of the exact luminosity on plot)
- Two energy ranges, either ‘h/Z factories’ or ‘high energy’
- Lots of room for new physics exploration

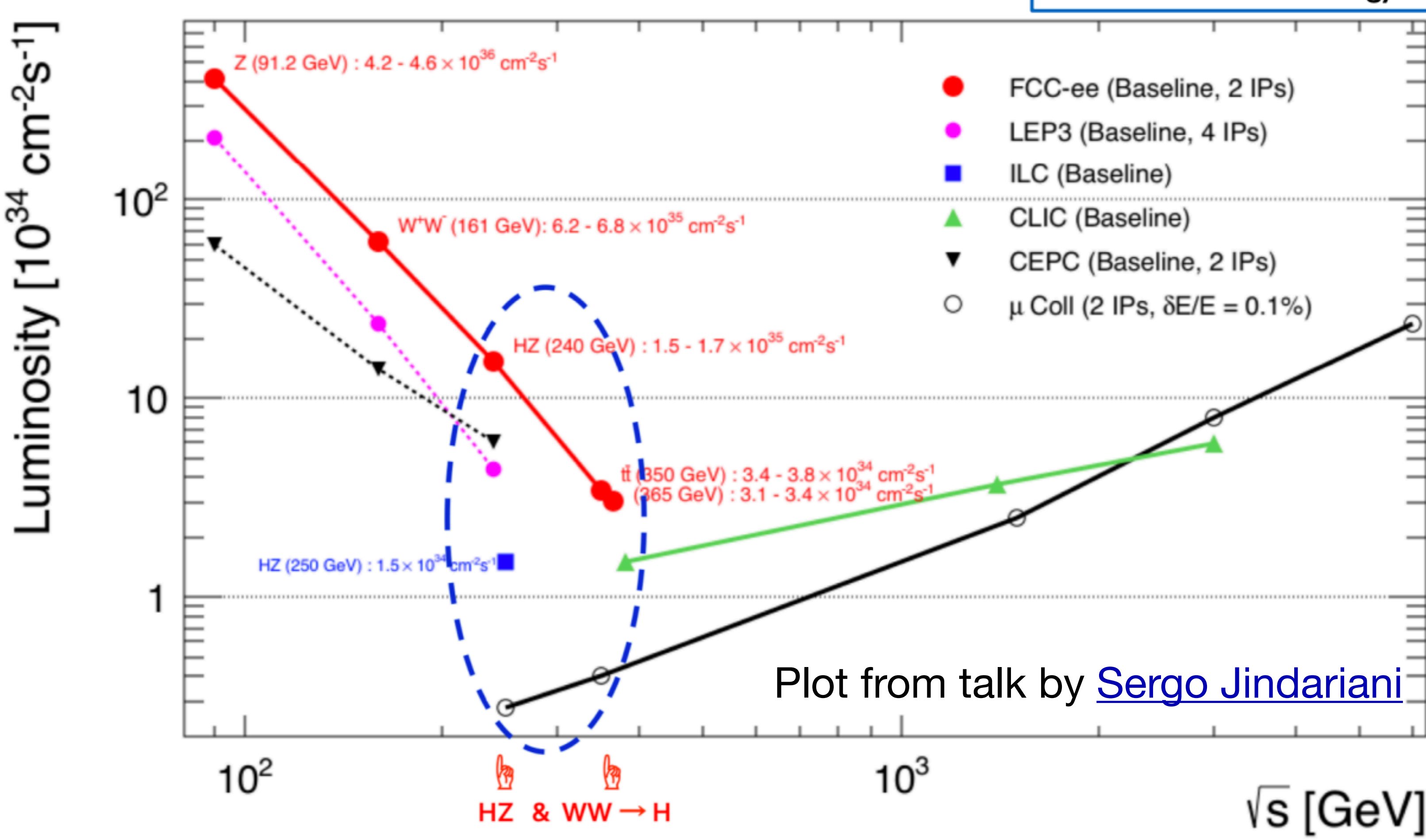
NB: lots of great opportunities for Belle-II physics program as well, however it isn’t ‘future’ collider anymore!

As the trajectory of a charged particle is deflected, it emits “synchrotron radiation”

$$\text{Radiated Power} \propto \frac{1}{\rho^2}\left(\frac{E}{m}\right)^4$$

Radius of curvature

An electron will radiate about 10^9 times more power than a muon of the same energy

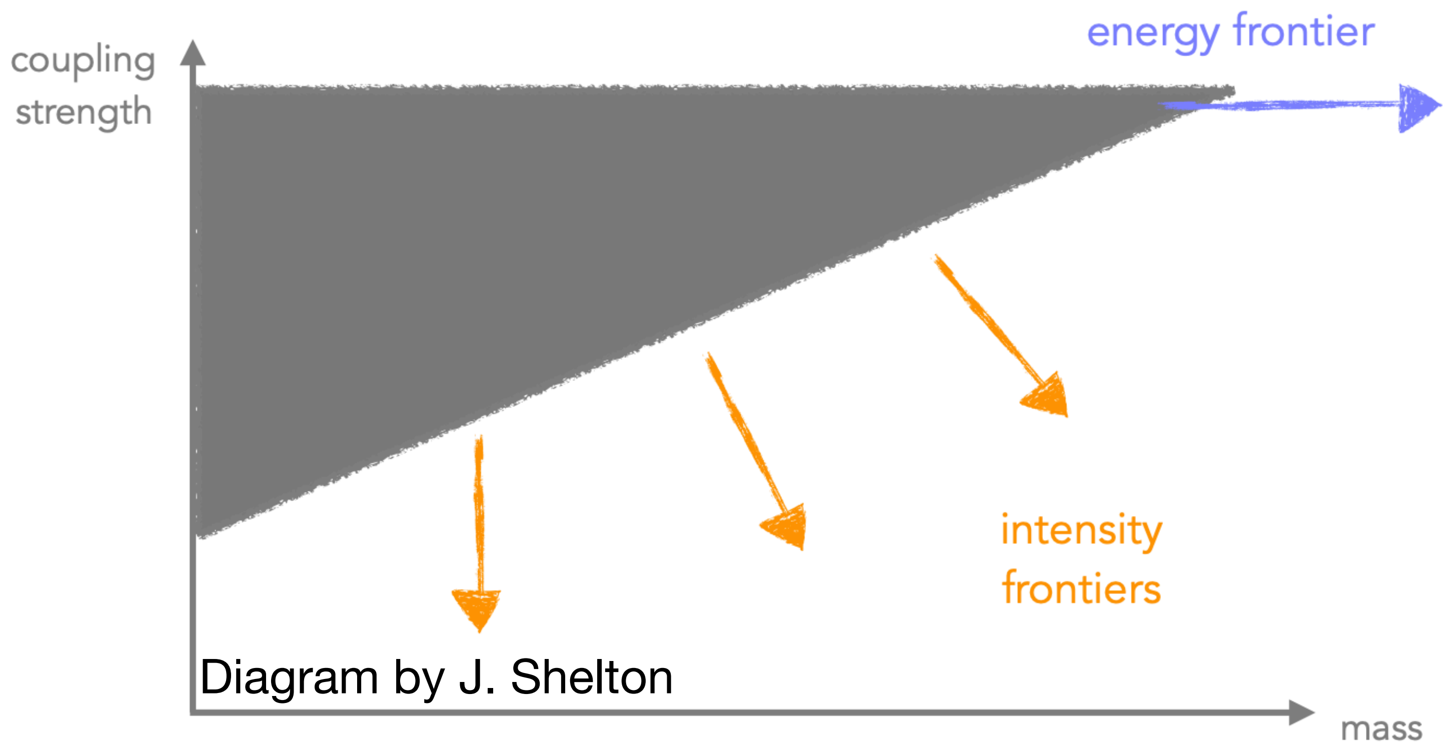


Plot from talk by [Sergo Jindariani]

30 TeV ?

Note logarithmic scale

Preparing for the future



- LLPs arise due to suppressed couplings or small mass splitting
- In this talk, the case of LLPs due to suppressed couplings

- As we prepare for the future colliders we should keep three objectives in mind
  - What is the prime purpose of the said experiment?
  - What other aims it can achieve?
  - Whether we have adequate technology/optimal detector design to fulfil the two above?
- Future (h/Z factories) lepton (ee) colliders prime aim: measurements of properties of the Higgs boson and electroweak precision physics
- Other aims (this talk): searches for long lived particles

Neutrino mass generation mechanisms

See e.g. Deppisch et al. arXiv:1502.06541

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

Future colliders ee options

arXiv:2011.04725

Higgs run

Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	σ_{Zh} [fb]
FCC-ee	240	5	193
ILC	250	2 (pol)	297
CLIC-380	380	1 (pol)	133
CEPC	240	5.6	193

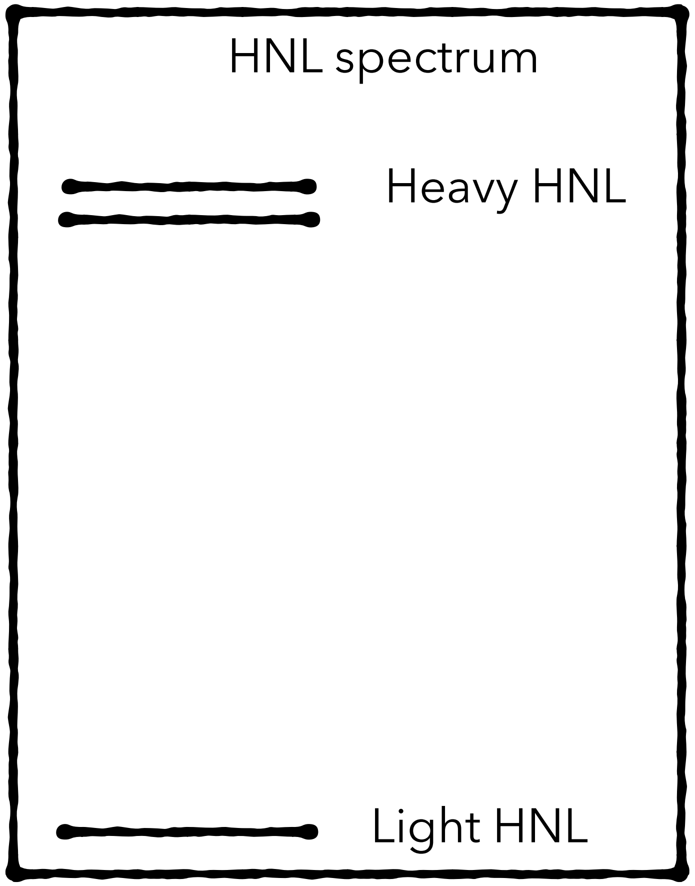
Z pole run

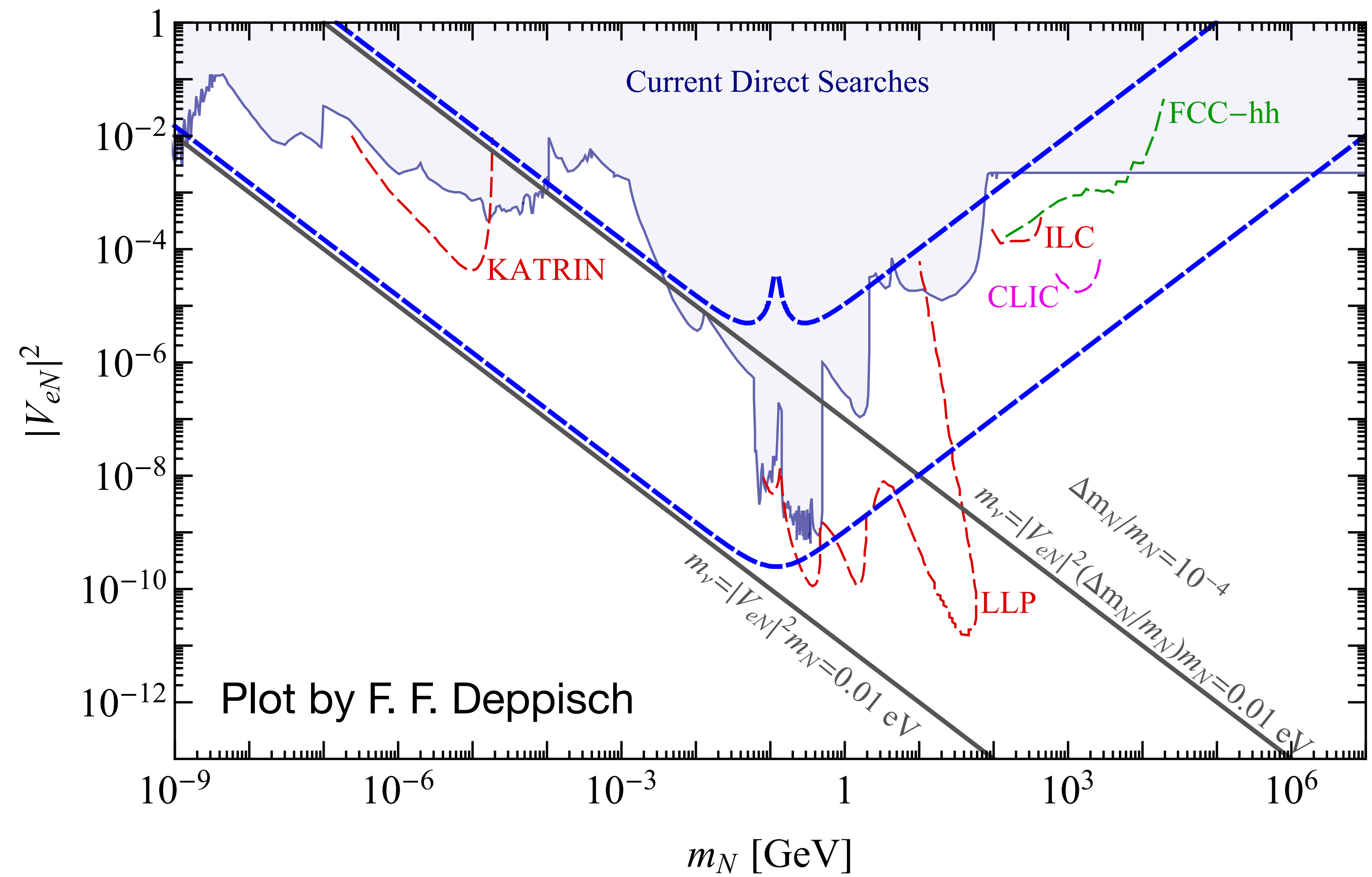
Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	N_Z
FCC-ee	m_Z	150	6.5×10^{12}
CEPC	m_Z	16	6.9×10^{11}

- Limited centre of mass energy, however extremely clear environment
- In this talk, the case of Heavy Neutral Leptons LLPs due to suppressed couplings
- Low energy colliders, charge neutral LLPs (light SM charged new physics constrained)

Portal	Coupling
Dark Photon, A'_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

Heavy neutral leptons - signature space



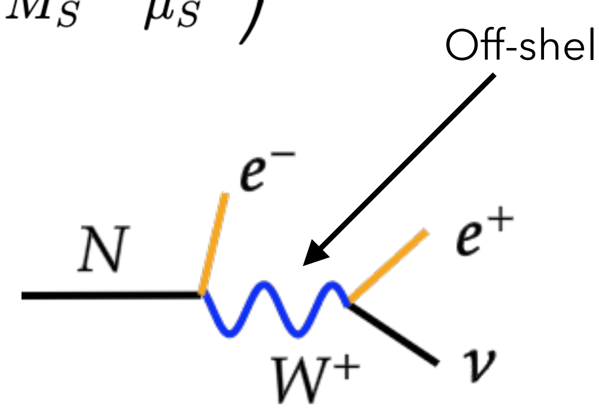


$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \qquad m_\nu \approx \frac{m_D^2}{M_R} = |V_{\mu N}|^2 \times m_R \qquad \mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^T & \mu_R & M_S^T \\ \mathbf{0} & M_S & \mu_S \end{pmatrix}$$

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

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

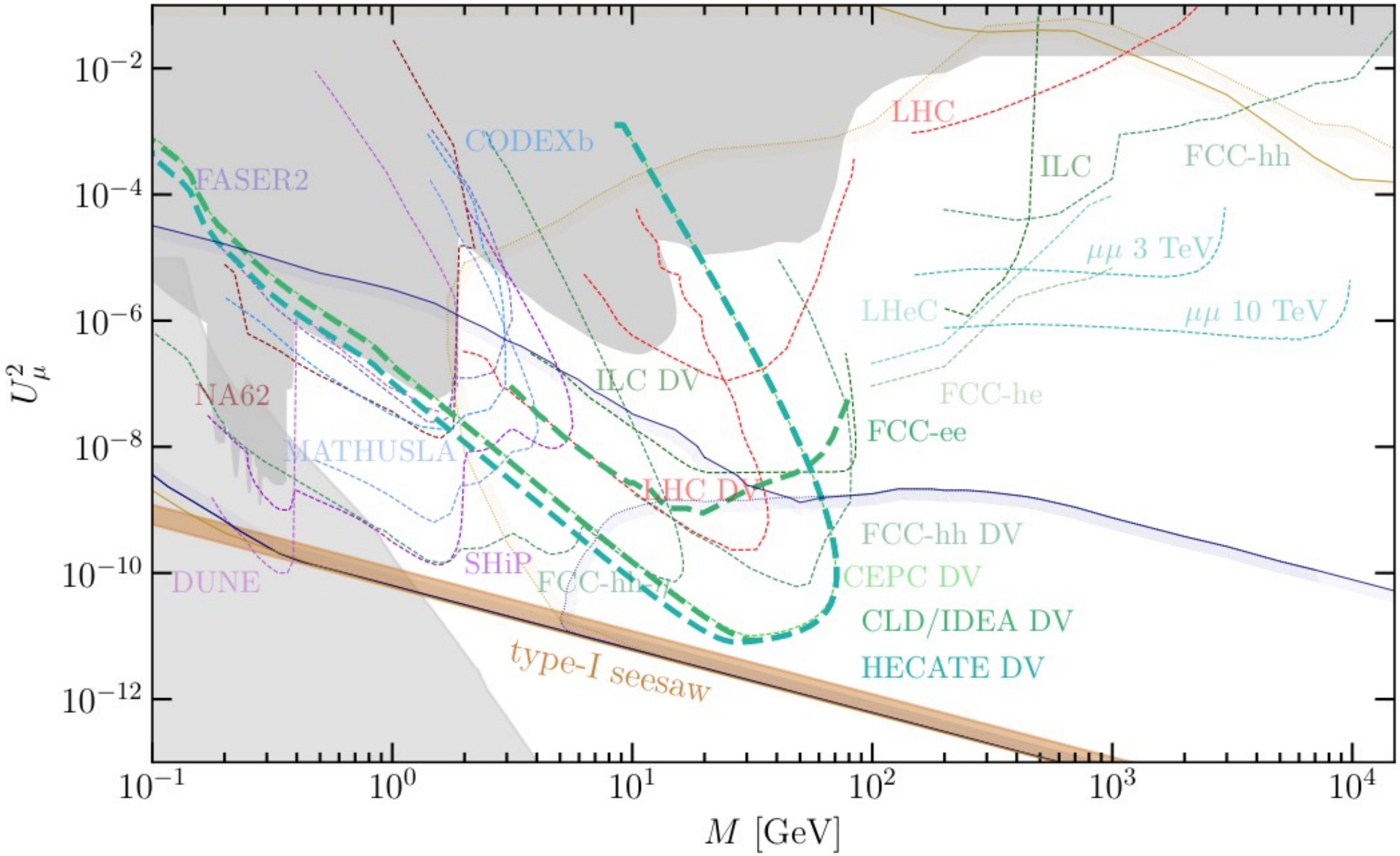
($c_{dec} = 1$ (Majorana), 1/2 (Dirac); $a \simeq 12$)



FCC-ee LLP group

Expectations

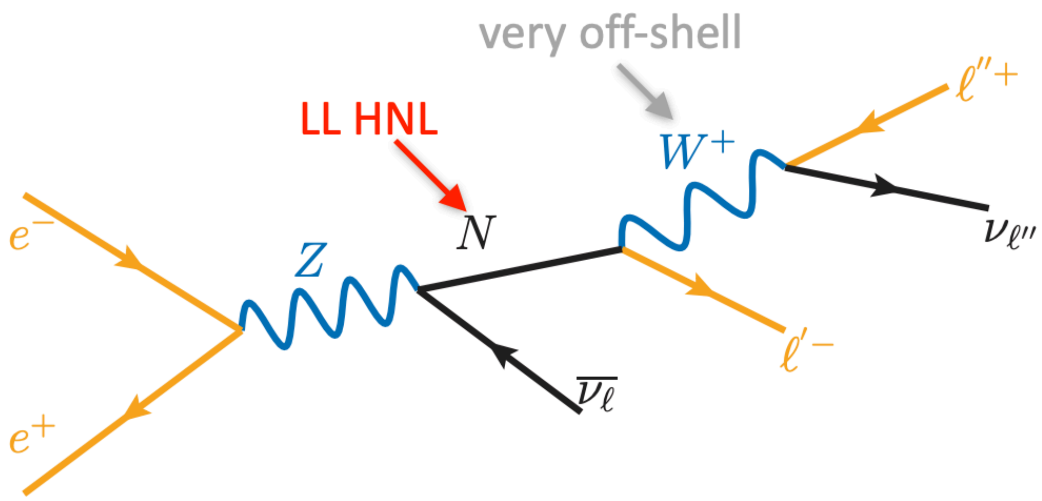
Snowmass [arXiv:2203.05502](https://arxiv.org/abs/2203.05502)

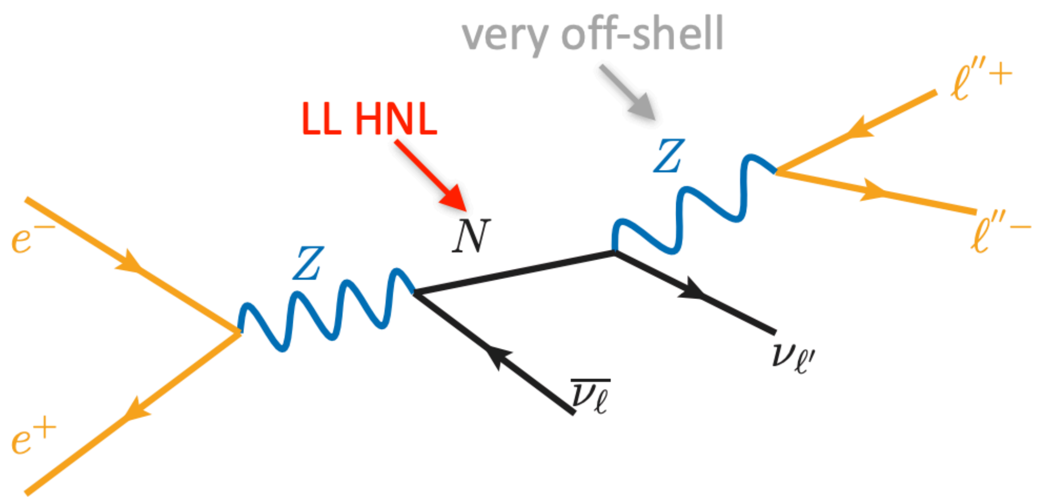


- Phenomenological study, combination of all final states ≥ 2 charged tracks, corresponds to 4 observed events
- 5×10^{12} Z produced, no backgrounds, ideal detector

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



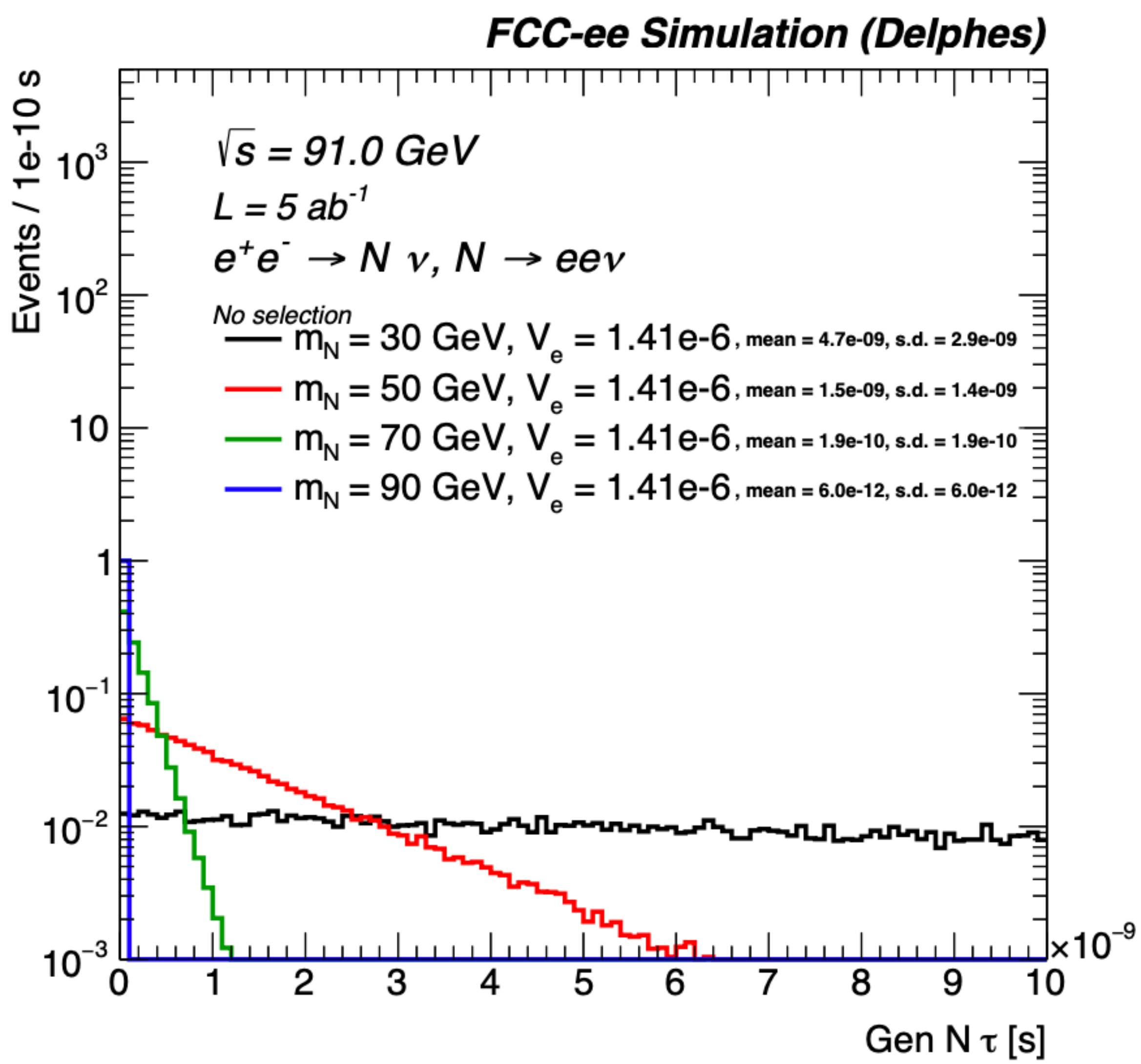


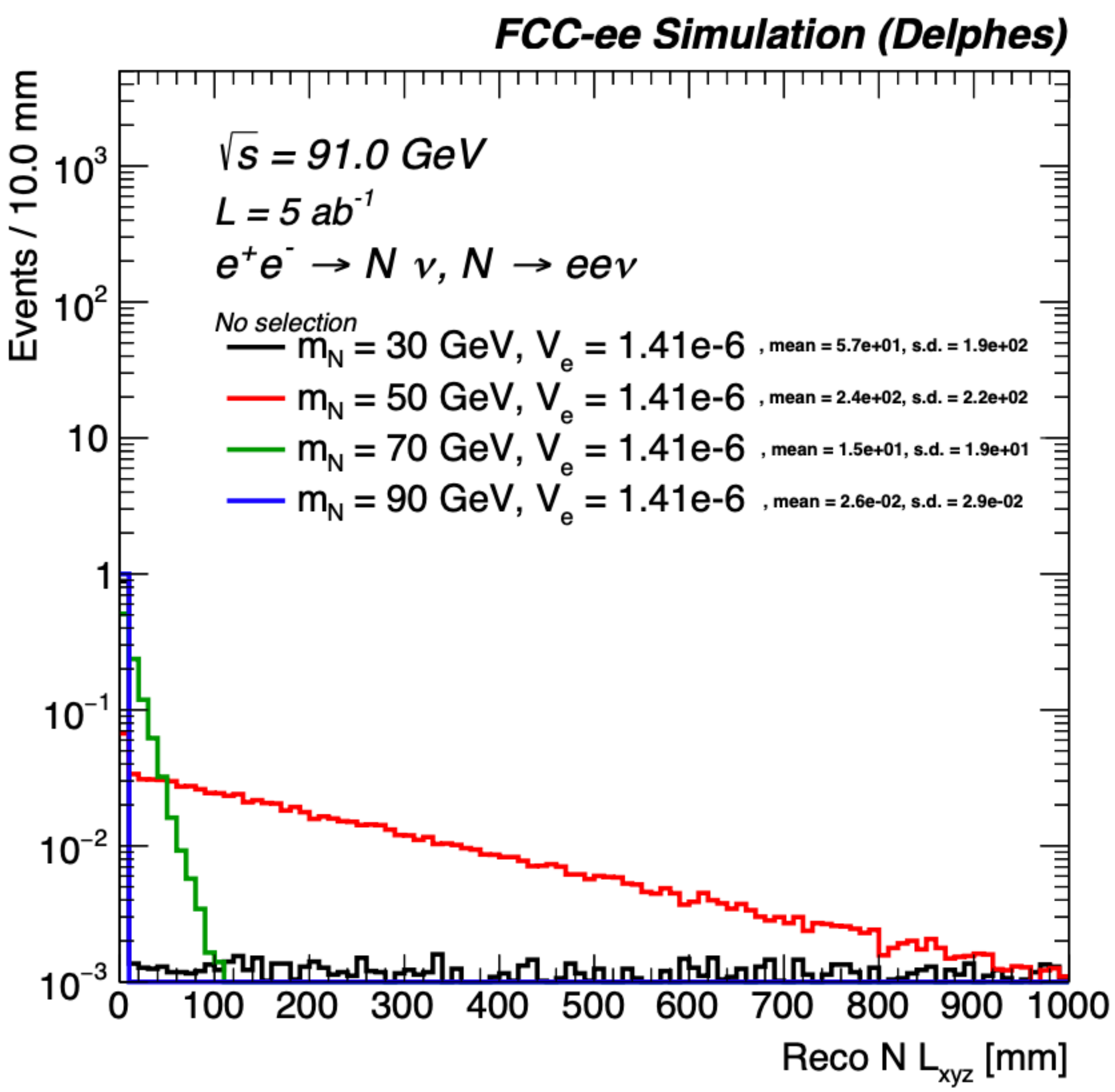
- Generated Majorana and Dirac HNLs with the SM_HeavyN_CKM_AllMasses_LO and SM_HeavyN_Dirac_CKM_Masses_LO models
- Experimental signature:
  - Displaced vertex: small mixing angle, no associated prompt lepton, unlike LHC
  - Prompt final state: larger mixing angle
- Current focus: electron flavoured 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](#)

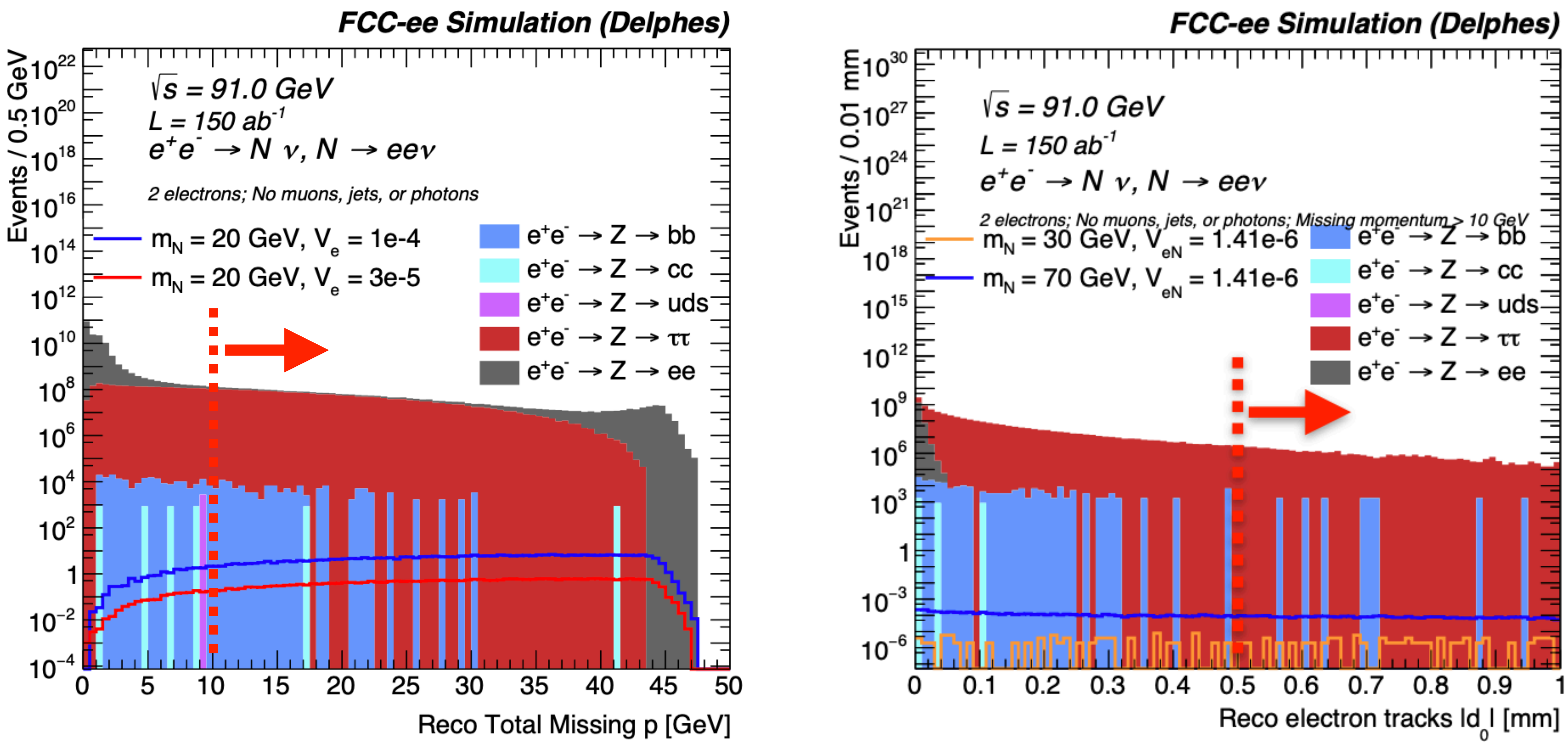




- One of the first implementation and validation of BSM scenarios in FCC frameworks
- Performed validation to retrieve HNl lifetime from gen level distributions

Signal vs background discrimination

Lovisa Rygaard's master thesis



- Centrally-produced "spring2021" background samples with the IDEA detector, at $\sqrt{s} = 91\,\text{GeV}$
- Measuring total missing energy at FCC-ee is possible; $p_{miss} > 10\,\text{GeV}$
- $|d_0| > 0.5\,\text{mm}$ 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, $\lvert V_{eN}\rvert = 2\times10^{-4}$	2534 ± 11	1006 ± 7	996 ± 7	951 ± 7	907 ± 7
$m_N = 20$ GeV, $\lvert V_{eN}\rvert = 9\times10^{-5}$	458 ± 2	313 ± 2	308 ± 2	293 ± 2	230 ± 1
$m_N = 20$ GeV, $\lvert V_{eN}\rvert = 3\times10^{-5}$	51.0 ± 0.2	34.7 ± 0.2	34.2 ± 0.2	32.6 ± 0.2	31.2 ± 0.2
$m_N = 30$ GeV, $\lvert V_{eN}\rvert = 1\times10^{-5}$	5.01 ± 0.02	3.85 ± 0.02	3.76 ± 0.02	3.54 ± 0.02	3.39 ± 0.02
$m_N = 50$ GeV, $\lvert V_{eN}\rvert = 6\times10^{-6}$	1.23 ± 0.01	0.99 ± 0.01	0.96 ± 0.01	0.92 ± 0.01	0.729 ± 0.004

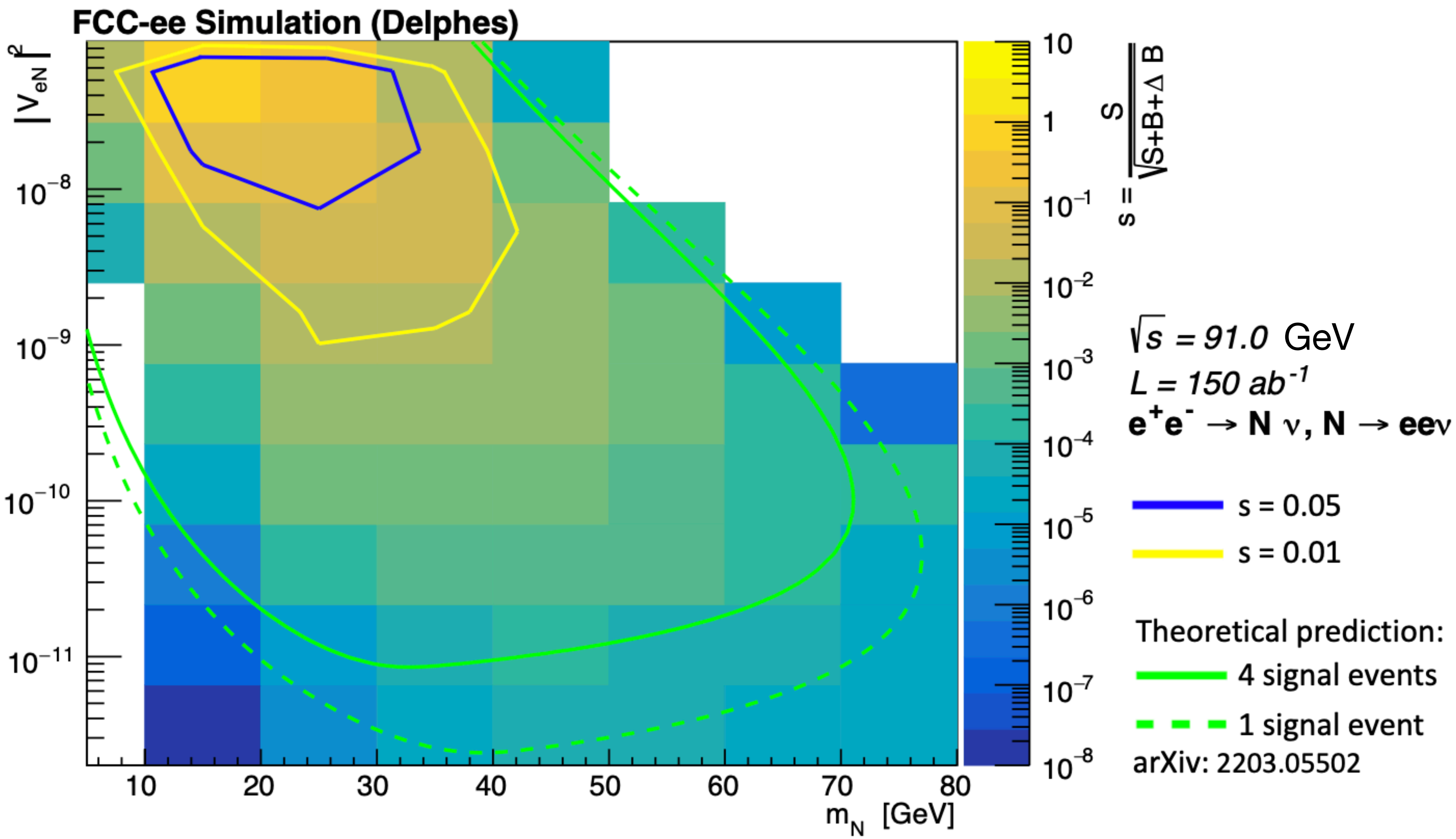
- Need background samples with enough statistics

	Before selection	Exactly 2 reco e	Vetoes	$\not{p} > 10$ GeV	$\lvert d_0\rvert > 0.5$ mm
$Z\to\tau\tau$	$2.21\times10^{11} \pm 7.00\times10^{7}$	$5.49\times10^{9} \pm 1.10\times10^{7}$	$5.10\times10^{9} \pm 1.06\times10^{7}$	$2.52\times10^{9} \pm 7.47\times10^{6}$	$6.64\times10^{4} \pm 3.84\times10^{4}$
$Z\to ee$	$2.19\times10^{11} \pm 6.94\times10^{7}$	$1.75\times10^{11} \pm 6.19\times10^{7}$	$1.53\times10^{11} \pm 5.80\times10^{7}$	$7.07\times10^{8} \pm 3.94\times10^{6}$	$\leq 3.94\times10^{6}$
$Z\to bb$	$9.97\times10^{11} \pm 4.14\times10^{7}$	$5.64\times10^{8} \pm 9.85\times10^{5}$	$3.25\times10^{5} \pm 2.36\times10^{4}$	$1.22\times10^{5} \pm 1.45\times10^{4}$	$1.72\times10^{3} \pm 1.72\times10^{3}$
$Z\to cc$	$7.82\times10^{11} \pm 2.61\times10^{7}$	$1.69\times10^{7} \pm 1.21\times10^{5}$	$5.22\times10^{3} \pm 2.13\times10^{3}$	$1.74\times10^{3} \pm 1.23\times10^{3}$	$\leq 1.23\times10^{3}$
$Z\to uds$	$2.79\times10^{12} \pm 8.83\times10^{7}$	$2.30\times10^{7} \pm 2.54\times10^{5}$	$2.79\times10^{3} \pm 2.79\times10^{3}$	$\leq 2.79\times10^{3}$	$\leq 2.79\times10^{3}$

First sensitivity estimates

[Lovisa Rygaard's master thesis](#)

[See also Sissel Bay Nielsen's thesis](#)

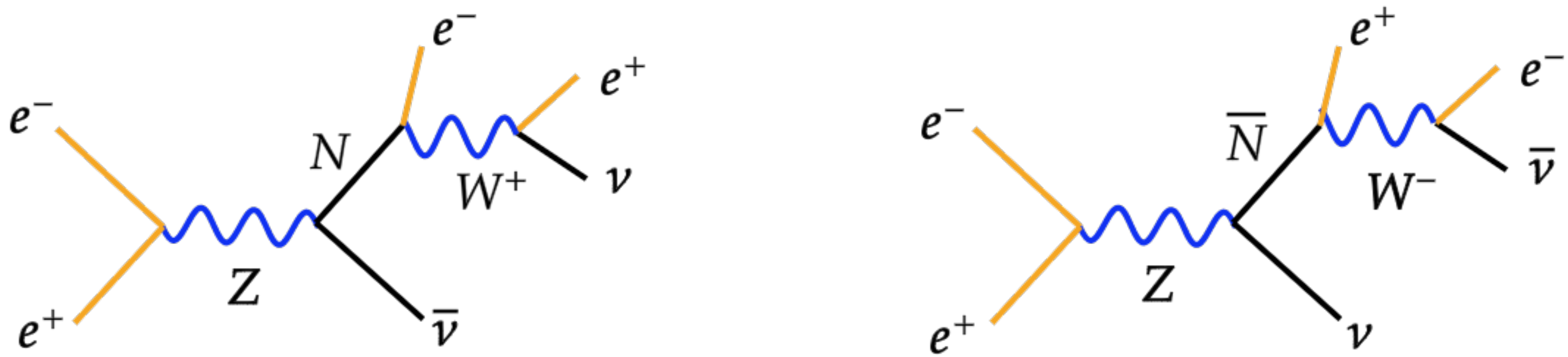


- First estimate using official FCC machinery
- $e\,e\,\nu$ final state only, projections limited by background statistics

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

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

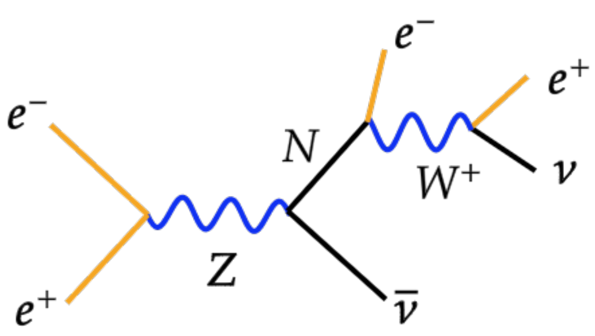
- Majorana neutrinos $(e^+e^- \to Z \to \nu N)$

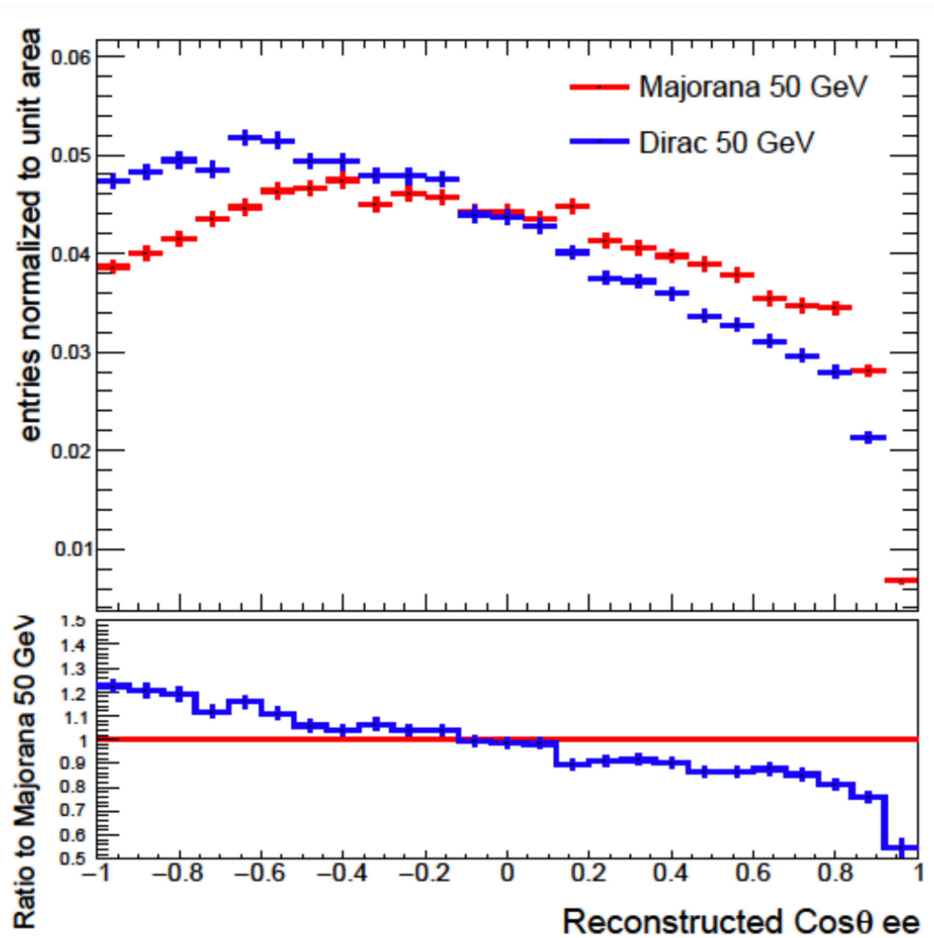
$$\frac{1}{\sigma_N}\frac{d\sigma_N}{d\cos\theta} \propto \left(1 + \cos^2\theta + \frac{M_N^2}{m_Z^2}\sin^2\theta \right)$$

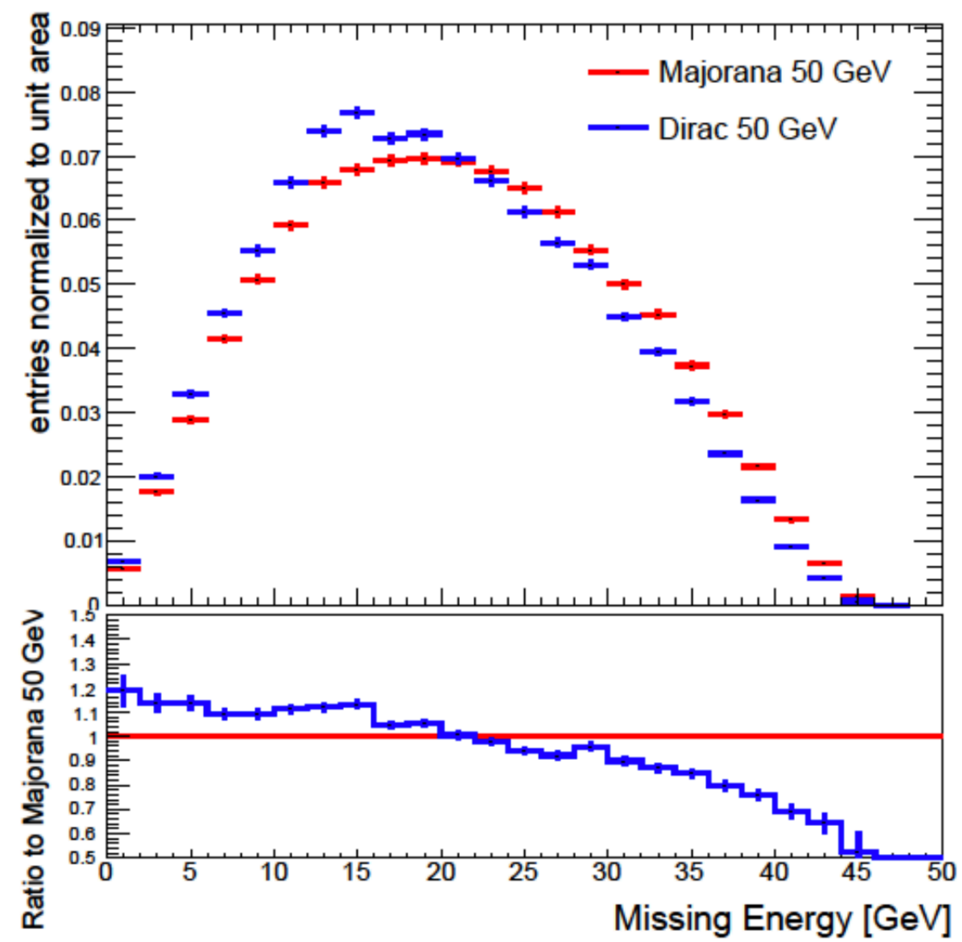
Dirac vs Majorana

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

Theory work

HNL in B-L extensions

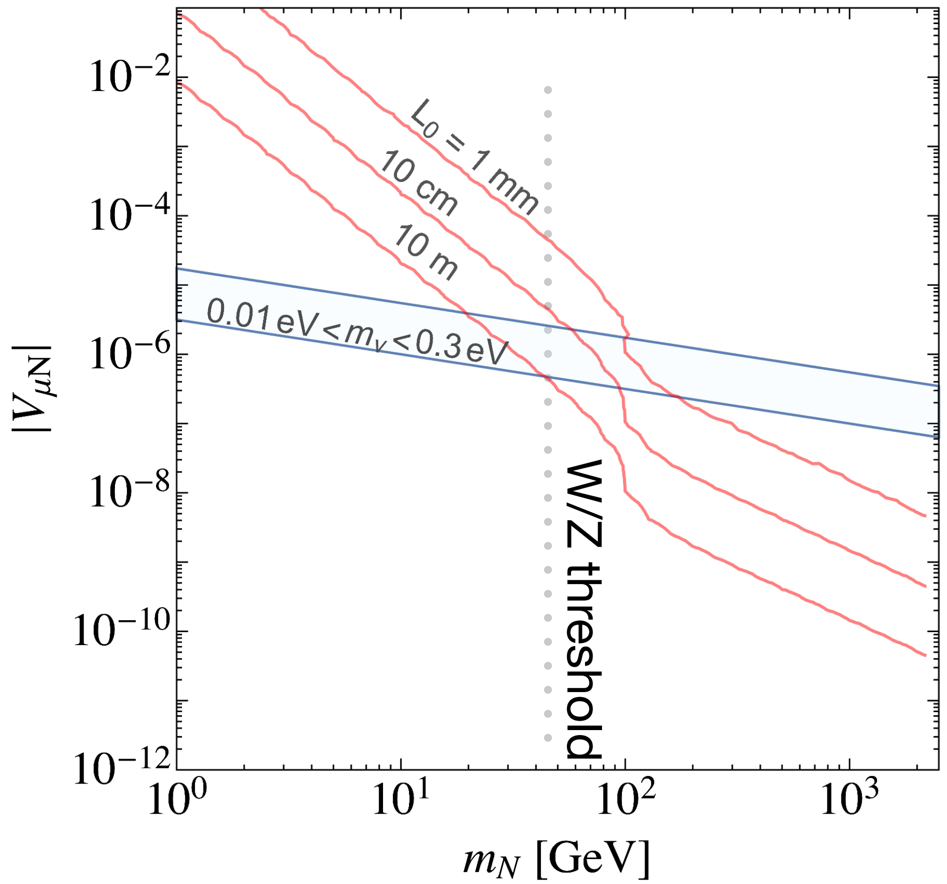
Mohapatra, Marshak (PRL 44 (1980) 1316,1319)

- Gauge group: $SU(3)_C$ X $SU(2)_L$ X $U(1)_Y$ X $U(1)_{B-L}$
- Characteristics
  - Particle content: B-L gauge boson (Z'), Higgs boson (χ_{B-L}), 3 heavy neutrinos (N)
  - Couplings: g'_{B-L} (B-L coupling), sinα (χ_{B-L}, Higgs mixing), V_{lN} (neutrino mixing)
  - Free parameters: 5 masses, 5 couplings (diagonal V_{lN})
    - Assume only light muon neutrino → 3 masses, 3 couplings
  - Charges: χ: +2; N: -1; q: 1/3; l:-1

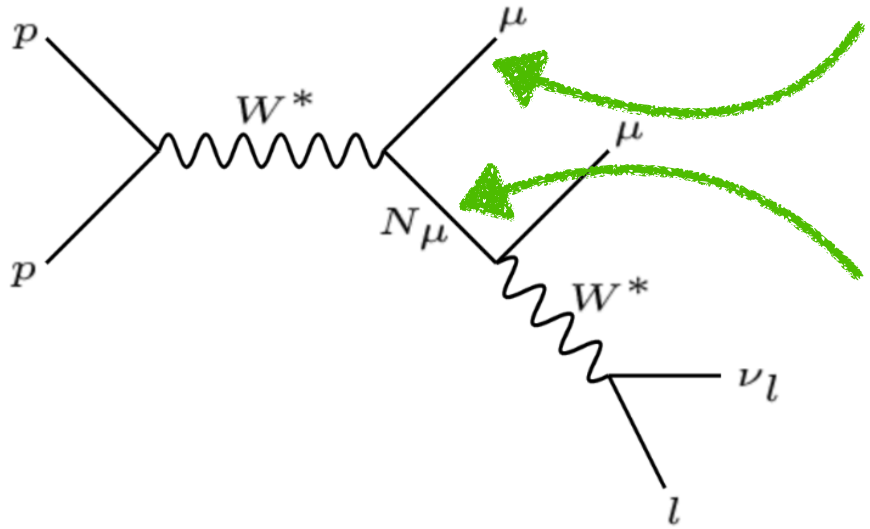
$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \qquad m_\nu \approx -\frac{M_D^2}{M_R} = -V_{lN}^2 M_R$$

  - Heavy neutrino lifetime

$$L_N \approx 0.025 \text{ m} \cdot \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \cdot \left(\frac{100 \text{ GeV}}{m_N}\right)^5$$



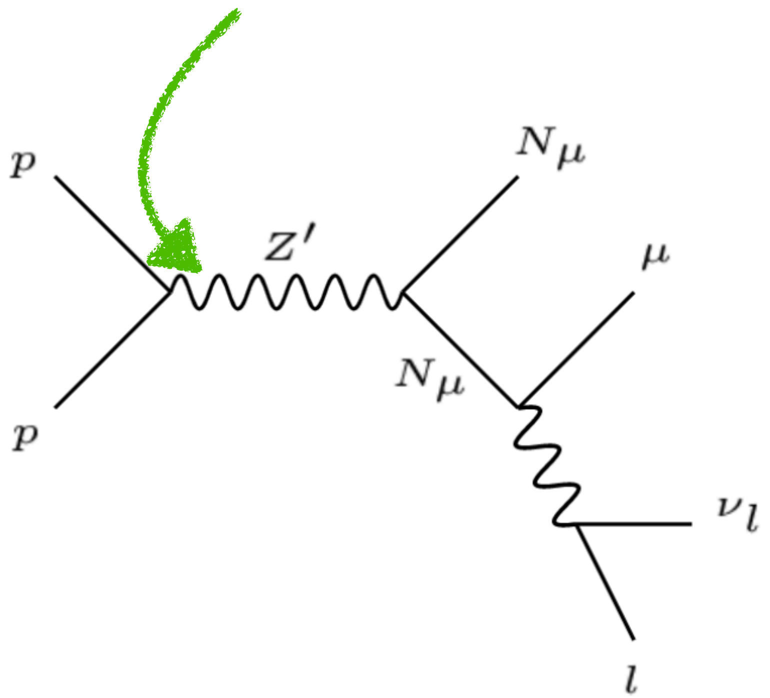
HNL production in B-L



Prompt lepton

Suppressed by $V^2_{\mu N}$

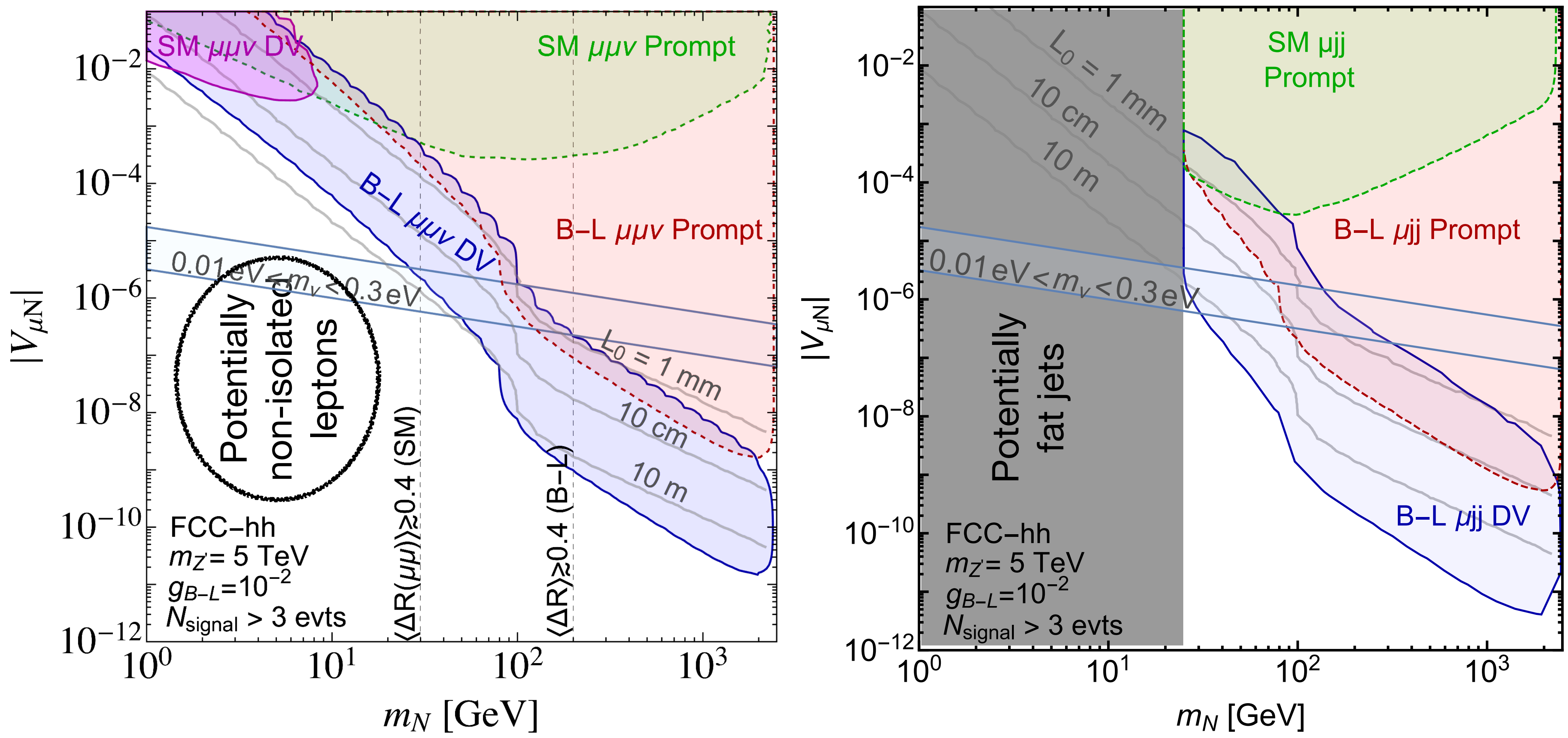
Proportional to g_{B-L}



- Production can occur either via SM mediator or via B-L mediator
  - SM mediators : W, Z, h
  - B-L mediators: Z′, h′
  - h, h′ mediated production suppressed by Yukawa
  - Z mediated production leads to SM neutrino in final state
  - Only consider W and Z′ channels

- $\sigma(p\,p \rightarrow W^*) \times BR(W^* \rightarrow \mu\, N)$ Suppressed by $V^2_{\mu N}$
- BR(Z′ ➜ N N) constant (8% for only one light neutrinos 20% for three light neutrinos)
- $\sigma(p\,p \rightarrow Z') \times BR(Z' \rightarrow N\,N)$ ~ constant, independent of $V_{\mu N}$ mixing angle

Sensitivity estimates



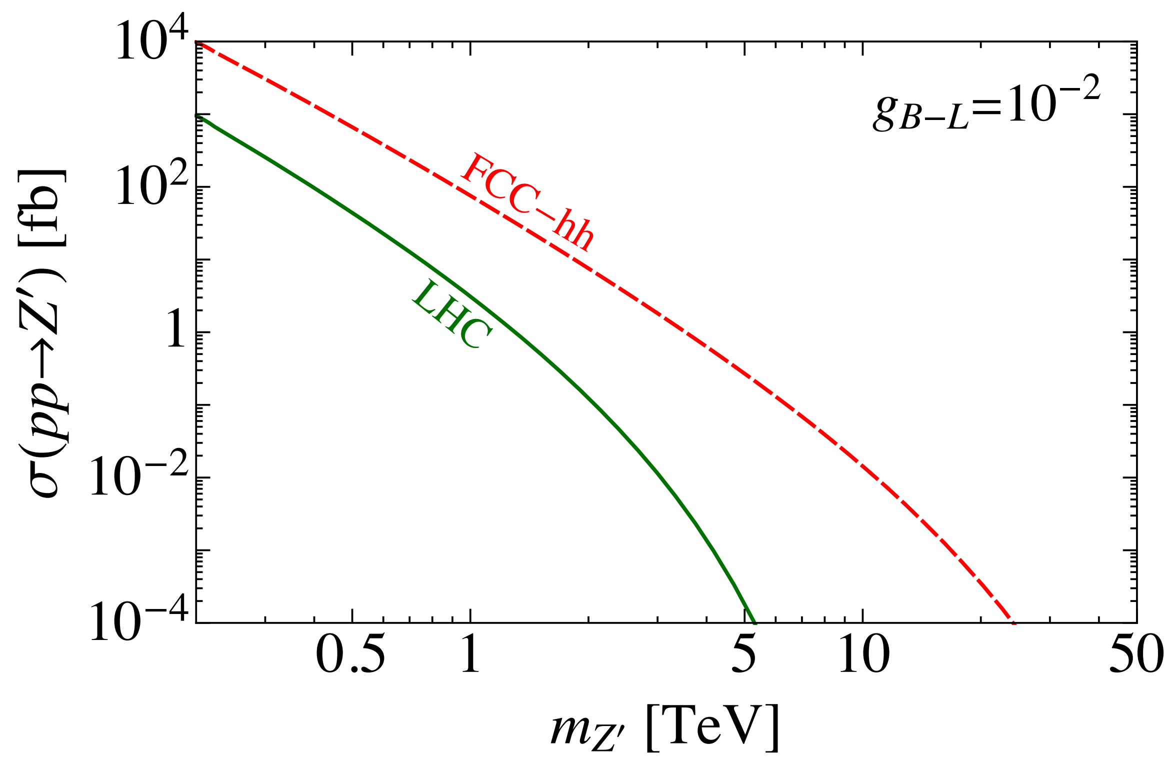
- Background free estimates , 100% reconstruction efficiency
- Boost received by Z' helps probe smaller neutrino mixing angles
- FCC-hh may not be more sensitive than LHC for SM mediated HNL production due to increased p_T cuts on the final states
- B-L models at colliders have potential to probe parameter space for neutrino mass generation

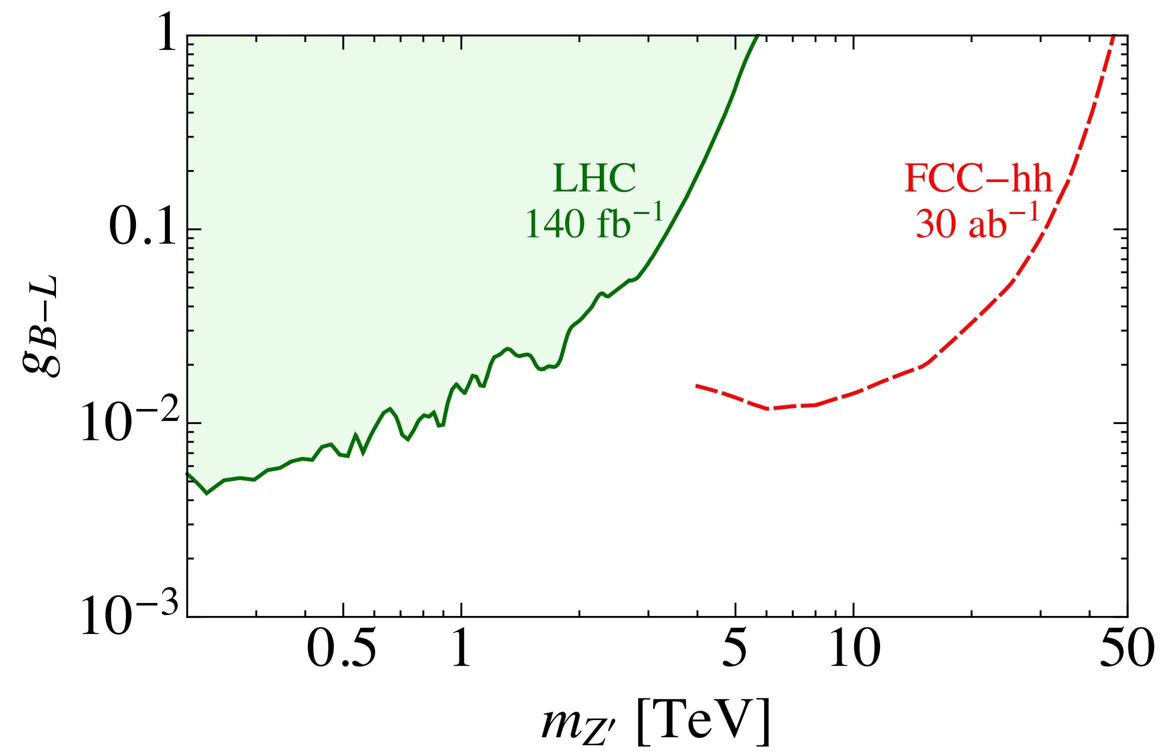
Conclusion

- 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
- 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

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

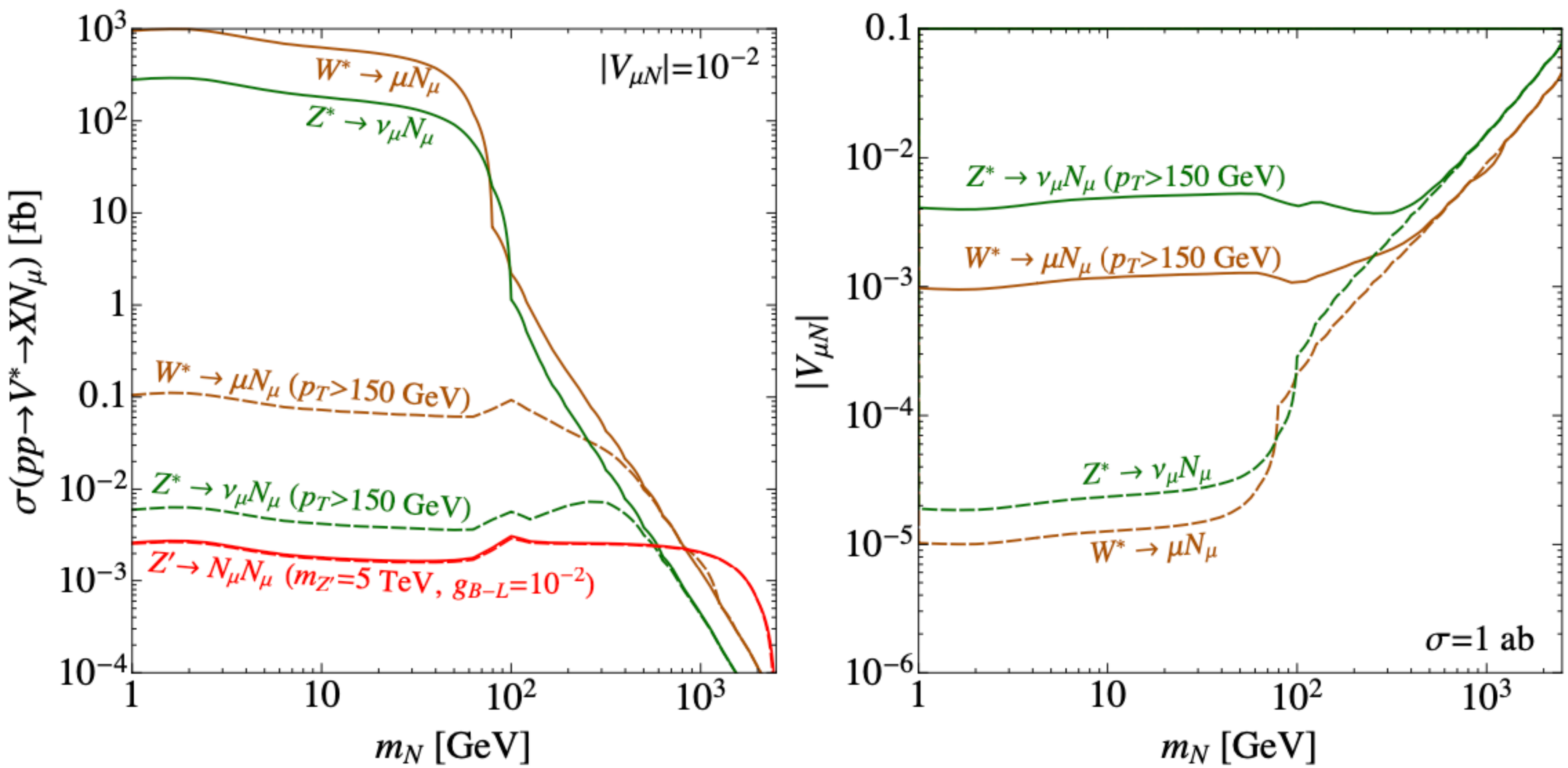
Z' sensitivity





- Limits recast from arXiv:1902.11217 (Helsens, Jamin, Mangano, Rizzo, Selvaggi)
- FCC-hh has a reach to much heavier Z′
- Limits from dilepton searches give an upper limit on the B-L gauge coupling
- In principle B-L gauge coupling can be larger as the projection is for end of FCC lifetime
- We work in the most 'hopeless' scenario throughout this talk

Cross section estimates



- Cross section for HNL production via SM mediators much larger than Z′ for large mixing angles; for $|V_{\mu N}| \lesssim 10^{-5}$ ($|V_{\mu N}| \lesssim 10^{-3}$) without (with) cuts the situation reverses.
- Effect of p_T cuts much stronger for SM mediated mechanisms vs. Z′ channel

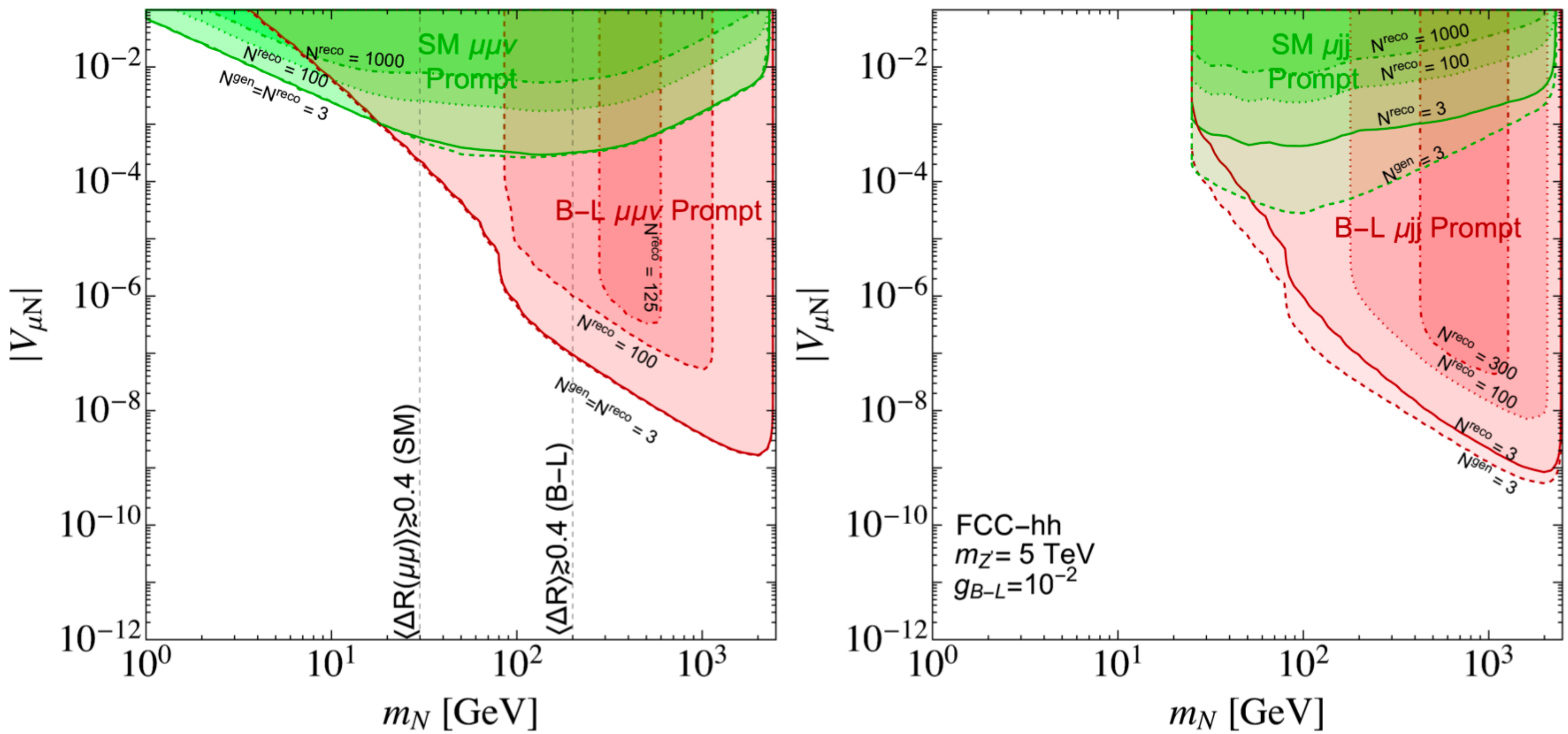
Analysis details

- Truth level analysis
- Consider two production mechanisms
  - SM W mediated
  - B-L Z′ mediated
- Consider two final states
  - W hadronic decays: μ j j
  - W leptonic decays: μ μ ν
- Analysis cuts: two types of analysis, prompt and displaced
  - Detector geometry taken into account for L_{xy} and η cuts

	Prompt	Displaced
Leptonic ($\mu\mu\nu$): $\{p_T(\mu_1), p_T(\mu_2)\} >$	$\{150, 50\}$ GeV	$\{200, 50\}$ GeV
Hadronic (μjj): $\{p_T(\mu), p_T(j)\} >$	$\{50, 300\}$ GeV	$\{50, 300\}$ GeV

- Hard cuts on final states to ensure compatibility with current FCC CDR

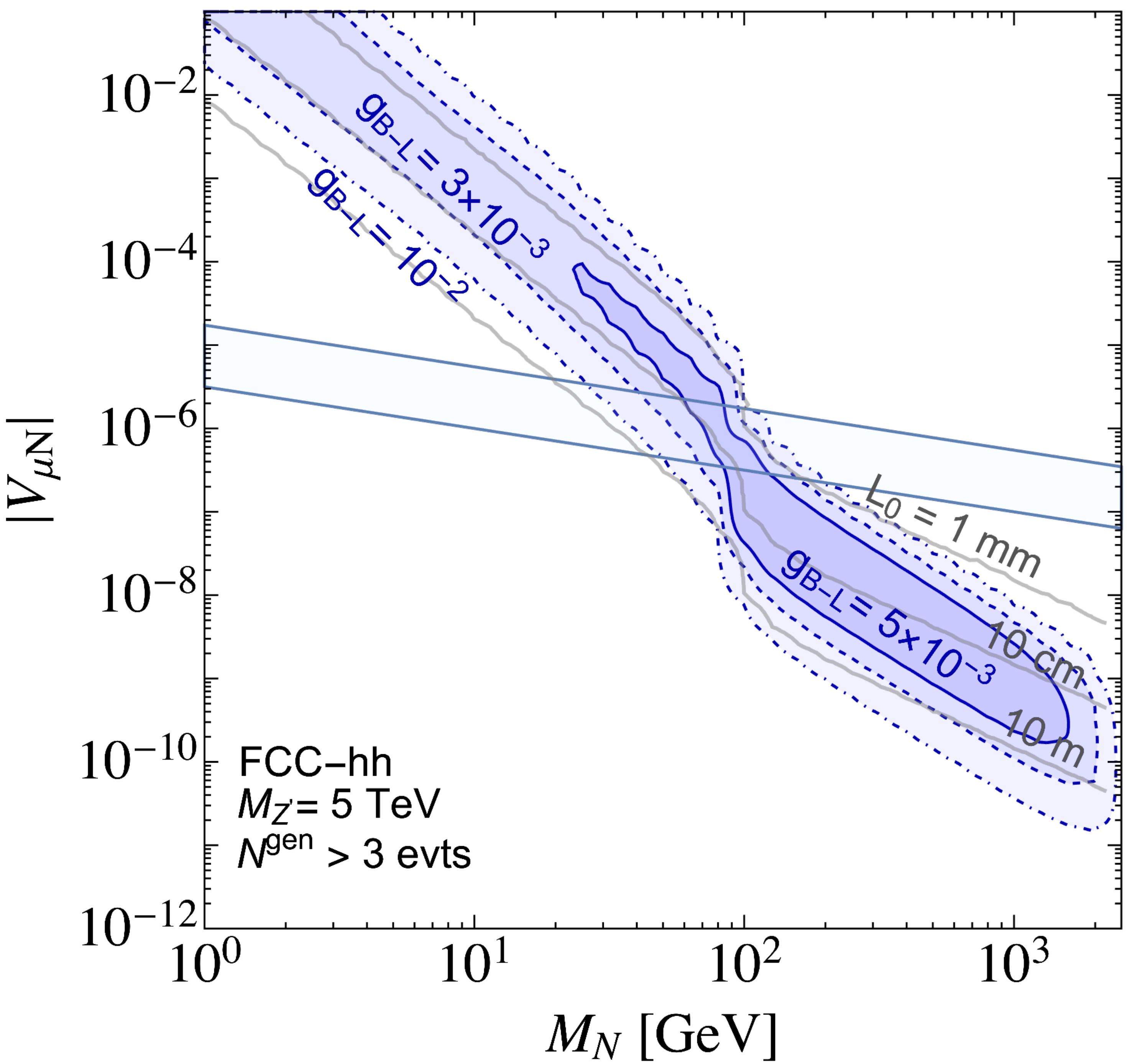
Going to reconstructed level



Default FCC
Delphes card

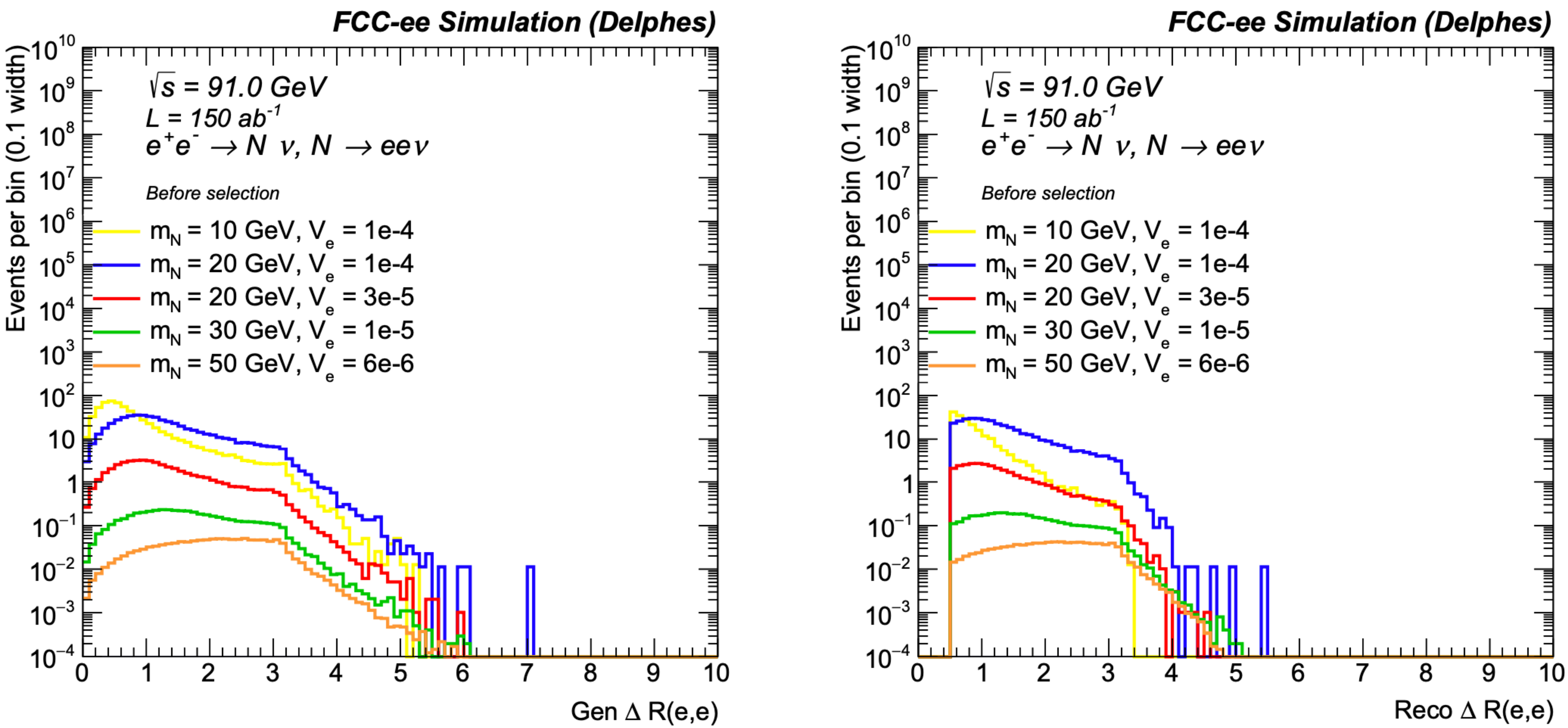
- For μμν channel going to reconstruction level makes small difference, stronger impact on μjj channel
- Non-negligible backgrounds to be expected
- Shown are contours of maximum number of events obtained for B-L channel, comparison with SM channel
- B-L prompt μjj can be hopeful for $g_{B\text{-}L} = 10^{-2}$, prompt μμν may not be realistic

Variation of g_{B-L}



- Displaced final states - no backgrounds accounted for
- In principle can probe even smaller values of g_{B-L}
- Effect of smaller g_{B-L} two fold
  - Reduces the sensitivity from lower and upper side
  - Reduces sensitivity for smaller M_N as they lead to softer final states
- Potential for probing small g_{B-L} and neutrino mass generation mechanisms

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