Sensitivity to HNL discovery and oscillation

- a case study for FCCee -

FCC Physics Workshop
Annecy, 30 Jan 2024

G. Polesello, N.Valle – INFN Pavia

Introduction

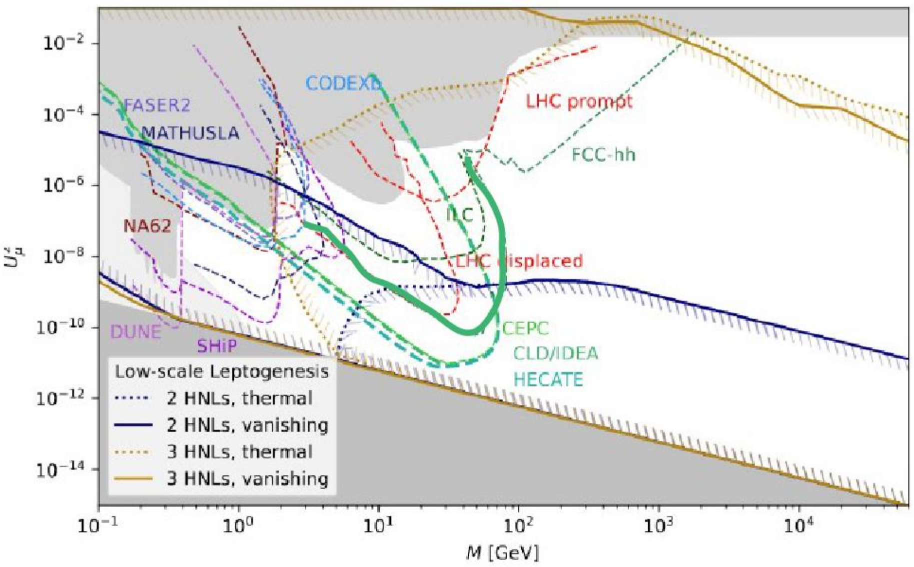
HNLs: one of the most promising new physics channels for FCC-ee at the Z pole – 1411.5230

FCC will probe space not constrained by astrophysics or cosmology and complementary to other facilities.

Different activities on HNLs in BSM FCC groups

- Generator validation, selection studies at the detector level, multiple decay channels, Dirac vs Majorana studies.

- Detector performances, mass resolution, timing, ML selections, ...



Introduction

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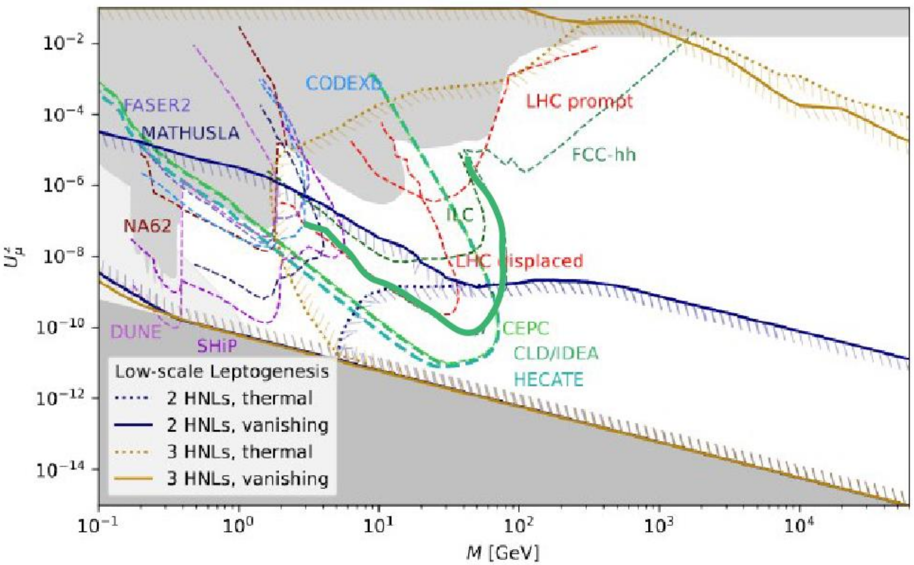


Different activities on HNLs in BSM FCC groups

Generator validation, selection studies at the detector
y channels, Dirac vs Majorana studies.

Talk by Juliette Alimena, Thursday plenary session.

Detector performances, mass resolution, timing, ML selections, ...

Talk by Giacomo Polesello, afternoon session, today.

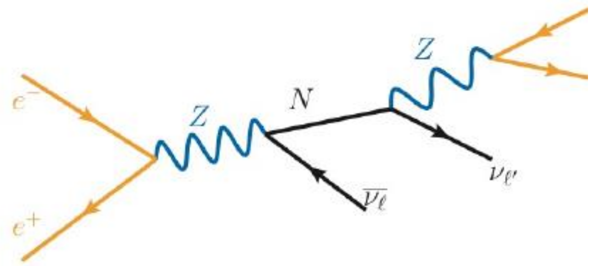
Outline of this talk:

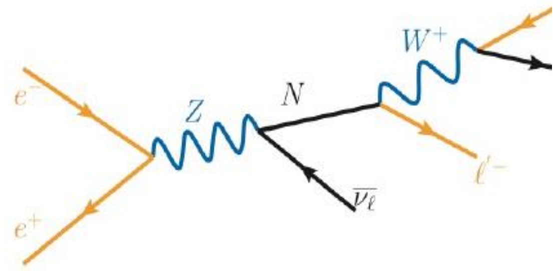
HN→ $\mu j j'$

- Sensitivity studies.
- Event selection optimization based on IDEA design.
- Experimental insight into HNL oscillation.

Introduction

Production of HNL in Z decay through mixing with light neutrinos.





One HNL flavour assumed → two parameters m_N and U (mixing with SM ν) – 2210.17110

$$\mathrm{BR}(Z \to \nu N) = \frac{2}{3}|U_N|^2\ \mathrm{BR}(Z \to \mathrm{invisible}) \left(1 + \frac{{m_N}^2}{2{m_Z}^2}\right)\left(1 - \frac{{m_N}^2}{{m_Z}^2}\right) \qquad \Gamma_N \simeq c_{\mathrm{dec}} \frac{a}{96\pi^3} U^2 M^5 G_F^2$$

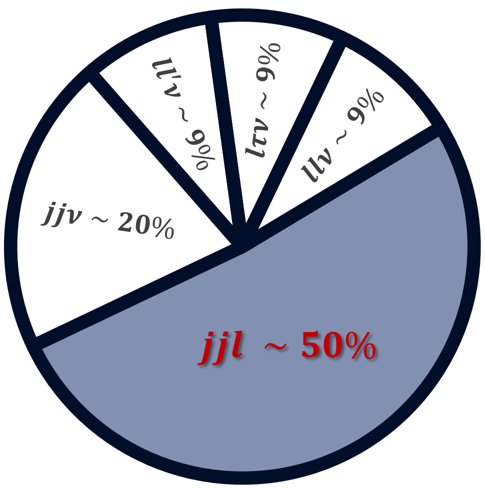
Decay width ($m_N < 80 GeV$)

Discovery possible over a large range of parameters space

- Prompt signal → jet resolution, vertexing
- Displaced → vertexing, timing

HNL → $jj\mu$

Final state (M < 80 GeV)



High production rate.

Visible final state allowing for full reco of HNL kinematics.

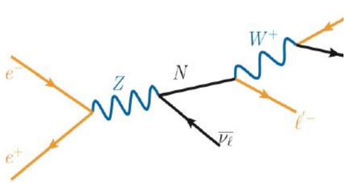
Two different signal regions:

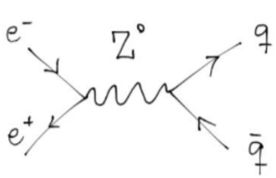
2 jets → At masses ≳ 50 GeV, two jets from HNL decay well separated.

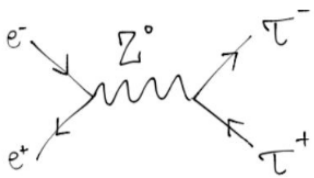
1 jet → collimated jets, dominant at lower masses.

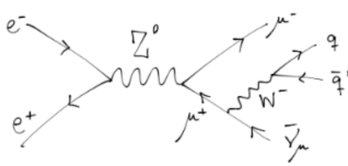
Background:

- $Z \to bb/cc/uds$ especially relevant at high mass.
- $Z \to \mu\mu$, $Z \to \tau\tau$, more easily suppressed.
- Four-fermion process: $e+e- \to \mu\nu qq$, irreducible.









Purely prompt

Sensitivity analysis

Working point: $\sqrt{s} = 91$ GeV $L_{int} = 240\ \text{ab}^{-1}$

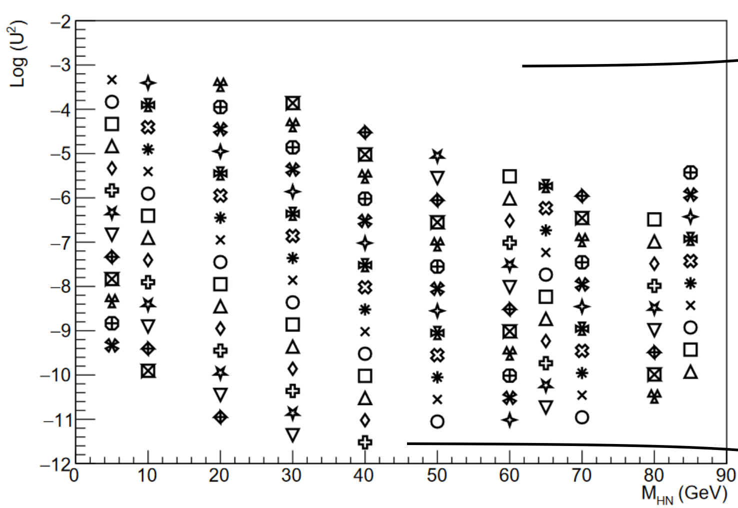
Z bkg: official large-scale production (Winter2023).

Signal and irreducible bkg: private production with same setup.

MadGraph5
↓
Pythia8
↓
DELPHES - IDEA fast sim

→ FCC software and offline macros for event filter, clusterization and selection.

Generated signal, 10k evt per sample

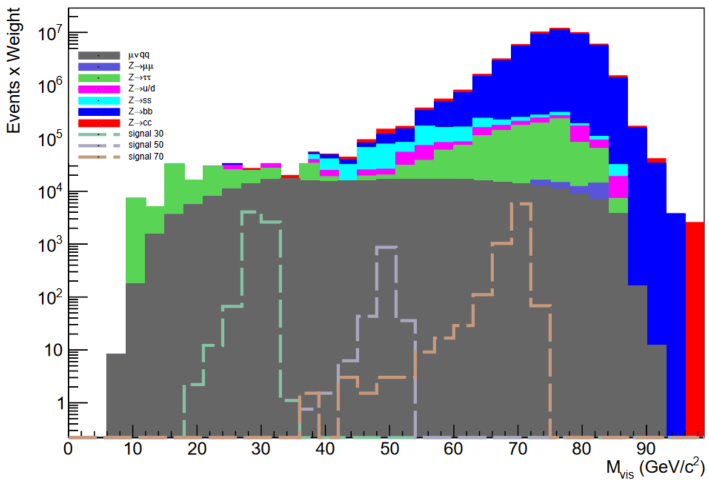


≃ currently excluded

≥ 1 evt within 2.5 m *from interaction point*

Sensitivity analysis

Sketch of the analysis flow:



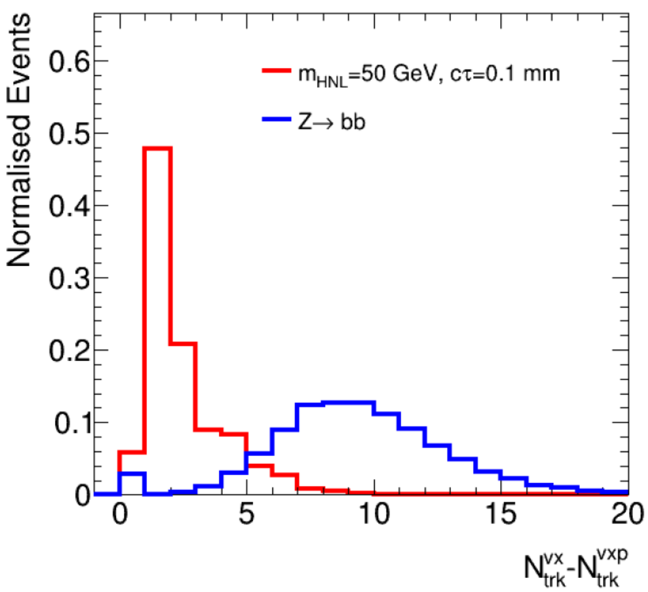
Event selection: kinematics and vertices

Single reconstructed lepton (muon);

Kinematic cuts on 1- or 2-jets clusterized particles;

Requiring primary vertex with good χ^2 and most of the tracks attached to it:

→ heavy flavour rejection.



Prompt vs long-lived separation

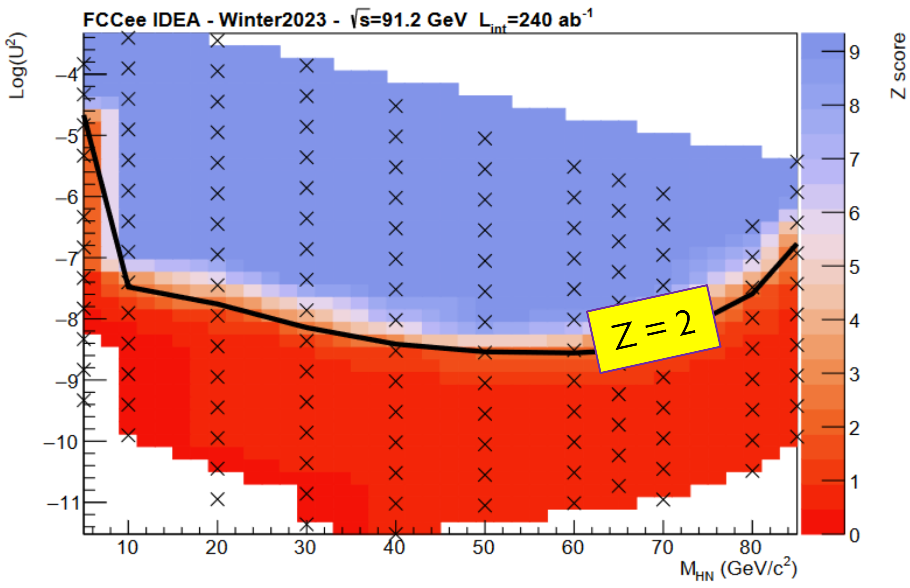
Choose radial vertex position $\lesssim 0.5\ mm$ such that background is zero in long-lived regime.

Sensitivity results

Prompt results

Looking for U^2 producing 95% CL excess of events.

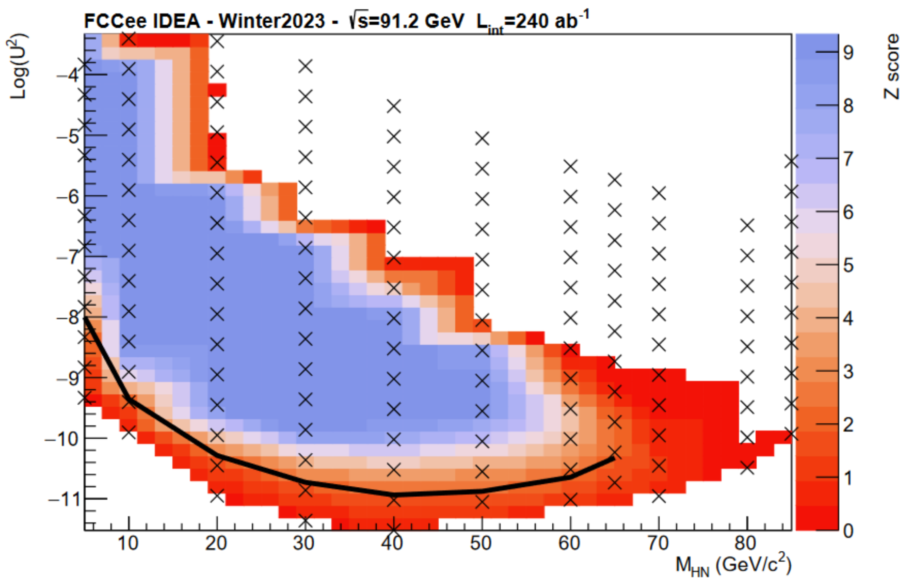
$L_{int} = 240\ ab^{-1} \leftrightarrow 8 \times 10^{12}$ Z events.



Long-lived results

No background.

Sensitivity coinciding with 3-events limit.



HNL oscillation

Model described in arxiv.org/2210.10738.

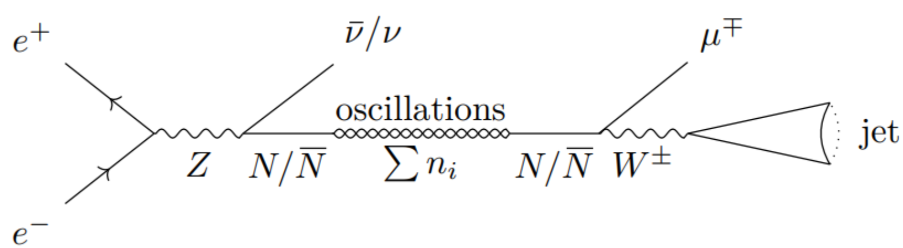
Talk by Jan Hajer in this session

11:22 **Heavy neutrino-antineutrino oscillations at the FCC-ee**
Relatore: Jan Hajer (Universidade de Lisboa)

Sterile pseudo-Dirac neutrinos almost mass-degenerate.

Same mixing to SM, generating superposition of $N, \bar{N}$ during Z decay.

Oscillation between lepton-number conserving and lepton-number violating processes.



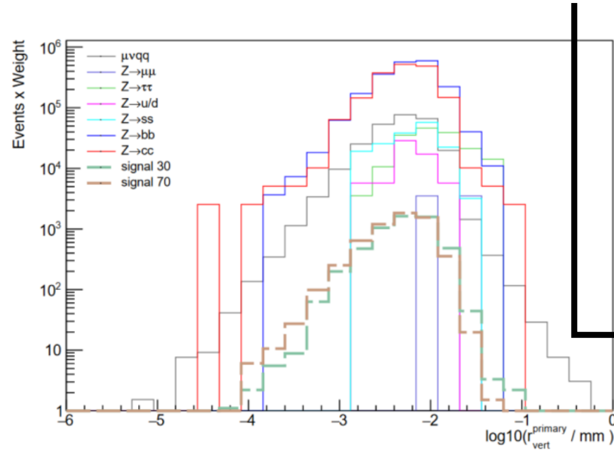
arxiv.org/2308.07297

LNC: neutrino at interaction vertex → μ^+ from $\bar{N}$ decay
LNV: antineutrino at the interaction vertex → μ^- from N decay

Oscillation detection

Implementing it in stanard FCC-ee software setup.

- Can we detect oscillations at FCC-ee ?
- In what parameter space ?
- Can we measure model parameters ?

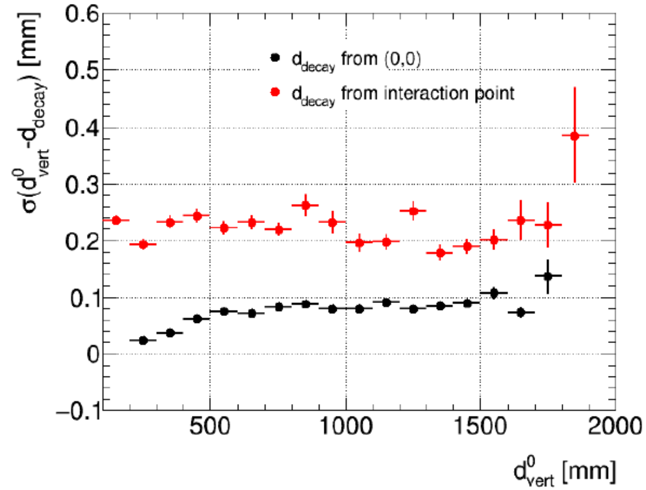


Selection on primary vertex position, high background rejection

Kinematic cuts providing zero SM background.

Studied as a function of HNL decay length τ_{dec} and oscillation period τ_{osc} (mass splitting).

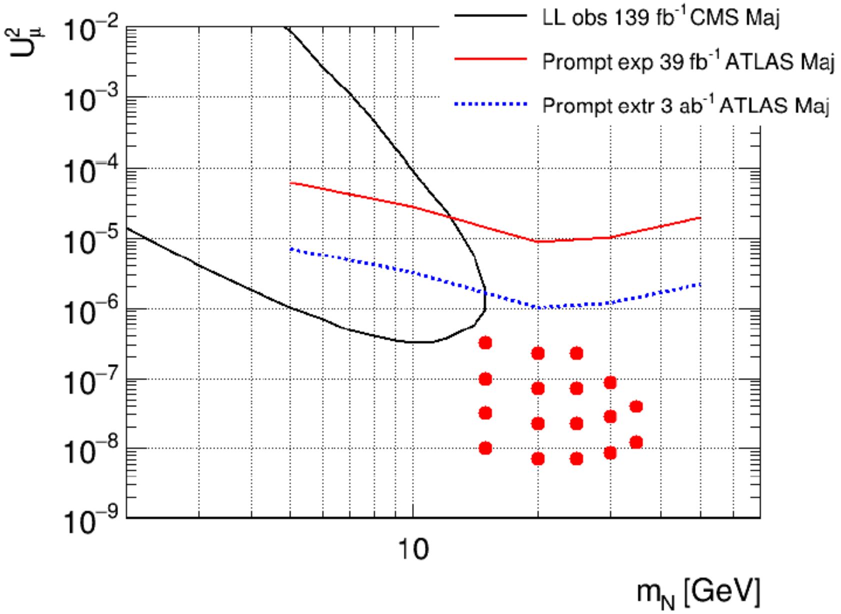
Vertex position uncertainity dominated by lack of information on interaction vertex; good enough to resolve oscillations in the relevant τ_{osc} range.



Parameter choice

(U^2, M_N) grid
chosen such to have >5k events and with decay length in the tracker (0.5 mm to 2 m).

For each point, 3 values of $c\tau_{osc}$: 1.5, 15, 150 mm



arxiv.org/2201.05578
arxiv.org/1905.09787

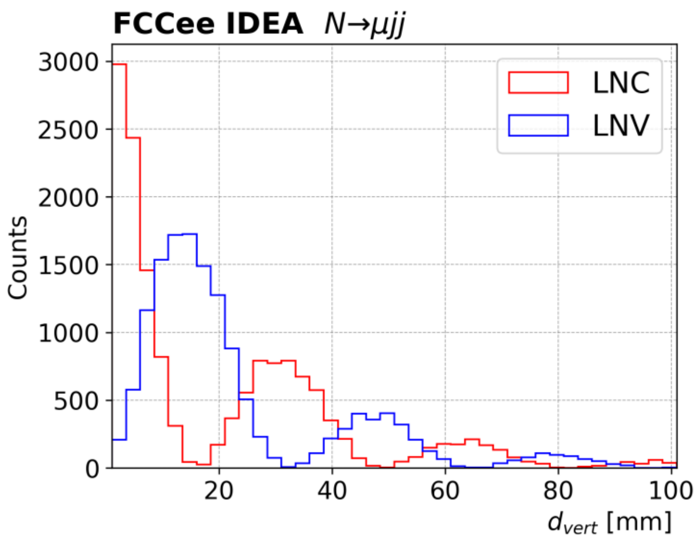
Analysis workflow and cuts are based on the ones described before → signal efficiency between 55 and 65%.

Oscillation detection

One cannot detect wether N recoils against ν or $\bar{\nu}$ → use angular asymmetry from Z polarization.

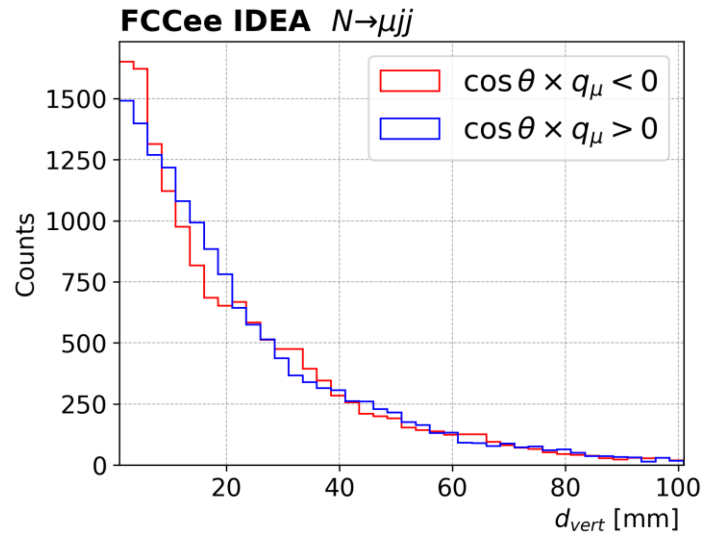
$$P_{osc}^{LNC^{(+)},LNV^{(-)}}(d) = \frac{1 \pm \cos(\Delta m\, d)}{2}$$

Complete oscillation: ν detected



$c\tau_{dec} = 10$ mm; $c\tau_{osc} = 15$ mm

Residual oscillation: matching angular distr. with lepton charge



$c\tau_{dec} = 10$ mm; $c\tau_{osc} = 15$ mm

Oscillation detection

One cannot detect wether N recoils against ν or $\bar{\nu}$ $\rightarrow$ use angular asymmetry from Z polarization.

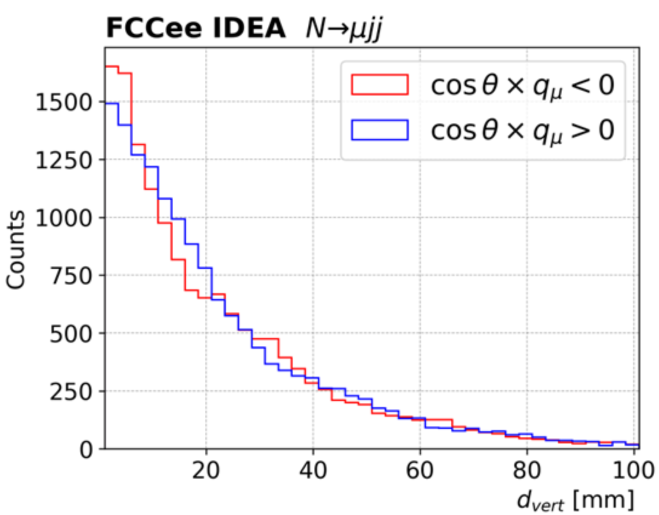
$$P_{osc}^{LNC^{(+)},LNV^{(-)}}(d) = \frac{1 \pm \cos(\Delta m\, d)}{2}$$

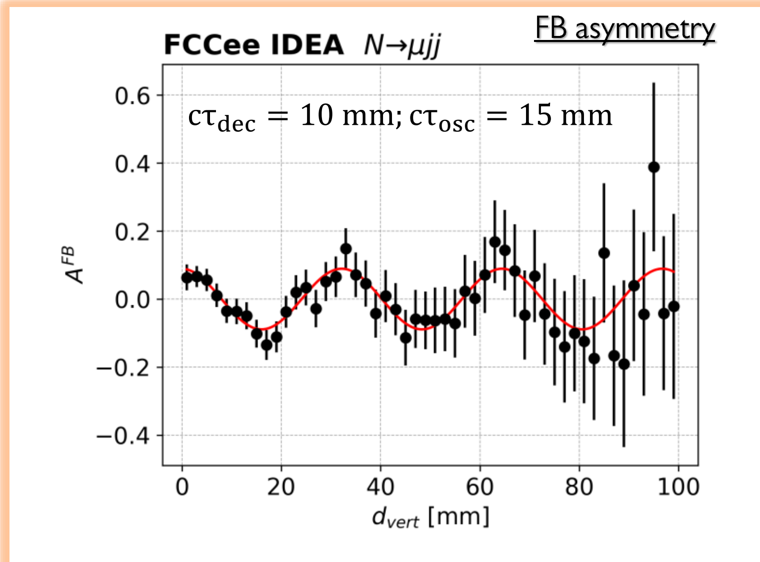
$$P_{osc}^{LNC} - P_{osc}^{LNV} = \cos(\Delta m\, d)$$

Concentrate on forward-backward asymmetry of charged lepton from N decay:

$$A_{\ell^{\mp}}^{FB} = \frac{P_{\ell^{\mp}}^{[\pi/2,0]} - P_{\ell^{\mp}}^{[\pi,\pi/2]}}{P_{\ell^{\mp}}^{[\pi/2,0]} + P_{\ell^{\mp}}^{[\pi,\pi/2]}} = A_{N,\bar{N}}^{FB}\, \Delta P_{osc}$$

$$A_{\ell}^{FB}(d) = \frac{A_{\ell^-}^{FB}(d) - A_{\ell^+}^{FB}(d)}{2}$$



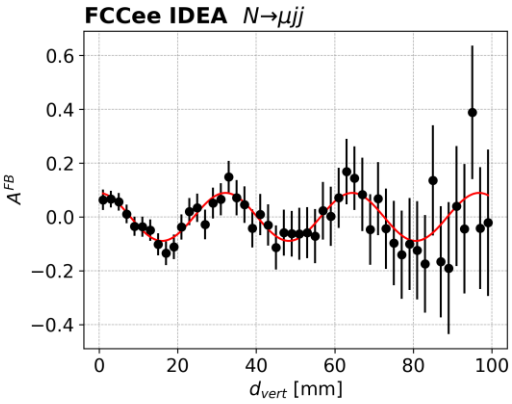


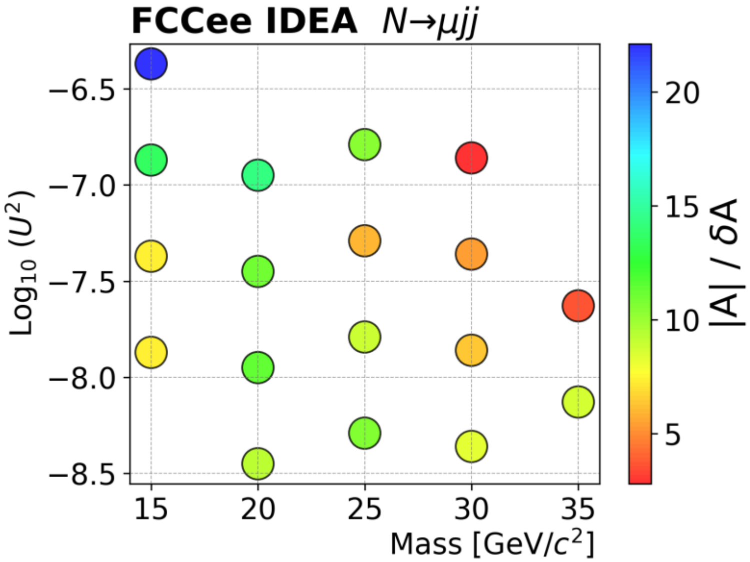
Oscillation detection

Fit of the distribution of the asymmetry vs position of primary vertex: insights on oscilation detection capability and sensitivity to τ_{osc}.

$$k = 2\pi M / pc\tau_{osc}$$

$$A_\ell^{FB}(d) \sim A * \cos(kd + \varphi)$$





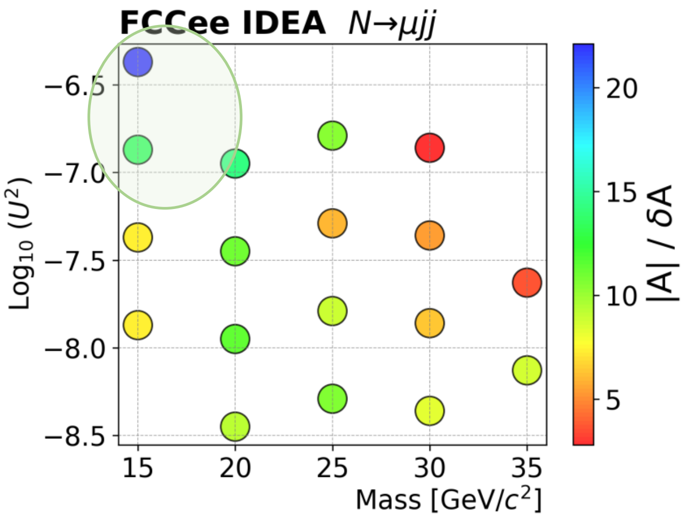
Oscillation detection

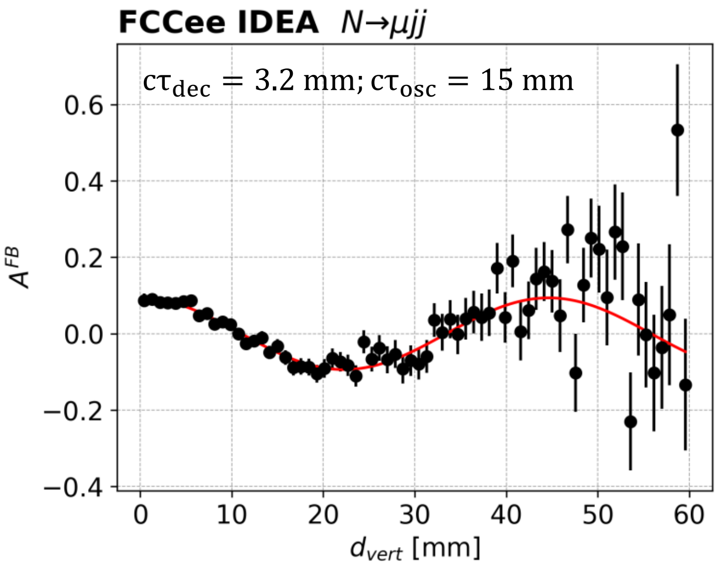
$\tau_{osc} \gtrsim \tau_{dec}$

Statistics allows for good sampling of the sinusoid for at least ~half a period.

Visible oscillation signal and great sensitivity to τ_{osc}.

$A_\ell^{FB}(d) \sim A * \cos(kd + \varphi)$





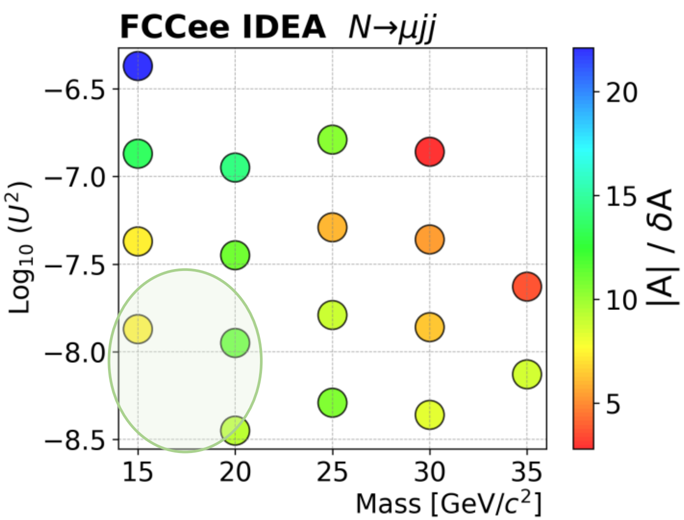
Oscillation detection

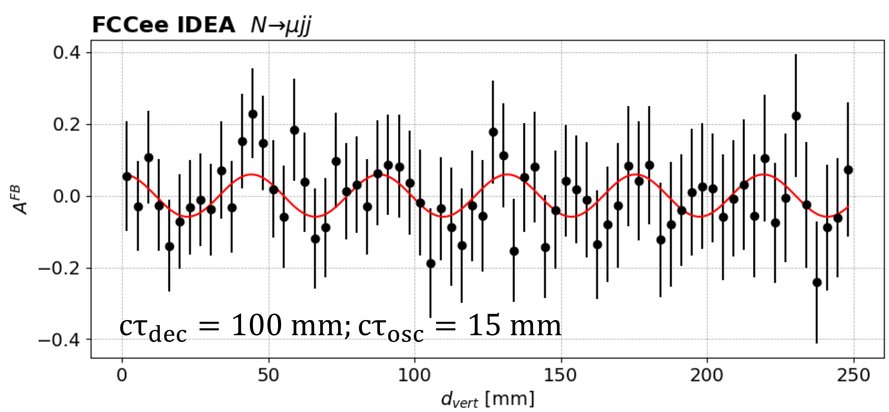
$\tau_{osc} \ll \tau_{dec}$

Much less statistics per period, but several periods can be fitted within the exponential decay.

Oscillation signal and great sensitivity to τ_{osc}.

$A_{\ell}^{FB}(d) \sim A * \cos(kd + \varphi)$





Oscillation detection

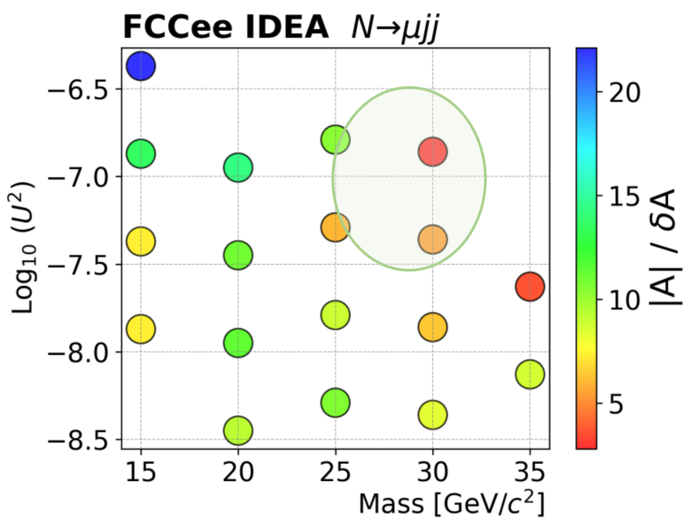
$\tau_{osc} \gg \tau_{dec}$

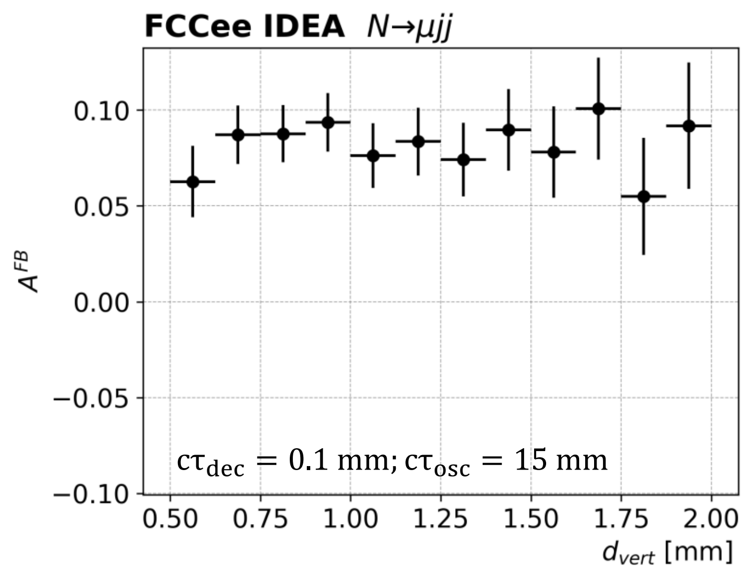
Positive asymmetry for any position of the measured vertex.

Evident deviation from 0 even without binning.

The period cannot be measured.

$A_\ell^{FB}(d) \sim A * \cos(kd + \varphi)$





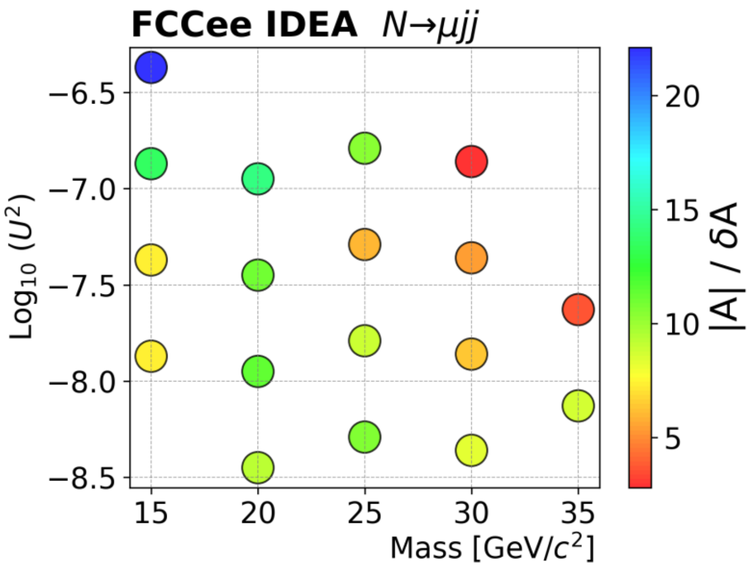
Oscillation detection

Fit of the distribution of the asymmetry vs position of primary vertex: insights on oscilation detection capability and sensitivity to τ_{osc}.

The asymmetry observable enhances the information.

Good discrimination against non-oscillating model for every point in the chosen parameter space.

The oscillation period seems to be measureable, if $c\tau_{osc} \lesssim c\tau_{dec}$.



Conclusions and outlook

Heavy neutral leptons as key BSM production at FCC-ee at the Z-pole.

Many signatures, benchmark for studies on detector requirements.

Sensitivy and discovery potential in the $N \to \mu jj$ channel has been presented.
Limits measured out of official IDEA fast simulations, in a wide mass range.

Exclusion limits in the the $N\nu$ coupling space in the same ballpark of the theoretical expectations, drawing hints on both the needed luminosity and detector resolution.

Analysis extended by oscillation model and EW Z polarization.
The simulation clearly shows evidence of angular asymmetry in the investigated parameter space.

Working on a better statistical model to enhance the discrimination and to determine when the model parameters can be measured.

BACKUP

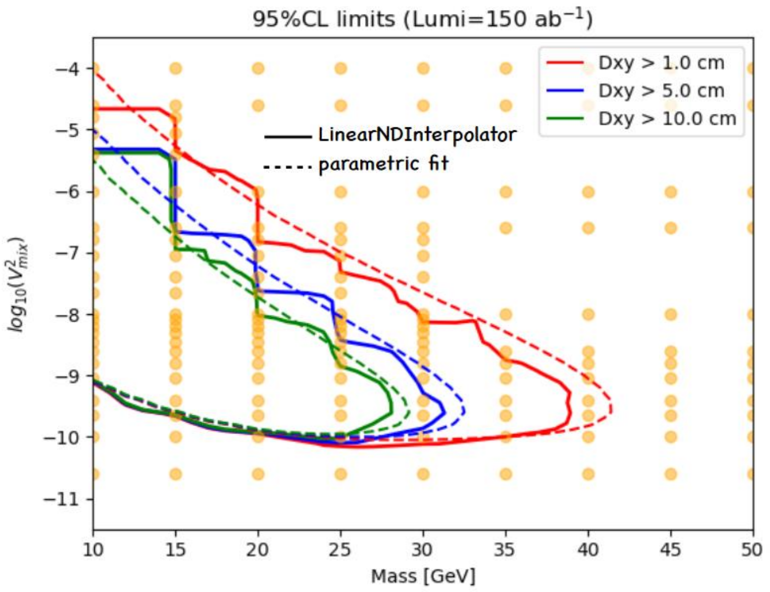
HNL→ $\mu\mu\nu$

L. Bellagamba

Sample selected by requiring exactly 2 tracks in the central detector reconstructed as muons with $p > 3$ GeV.

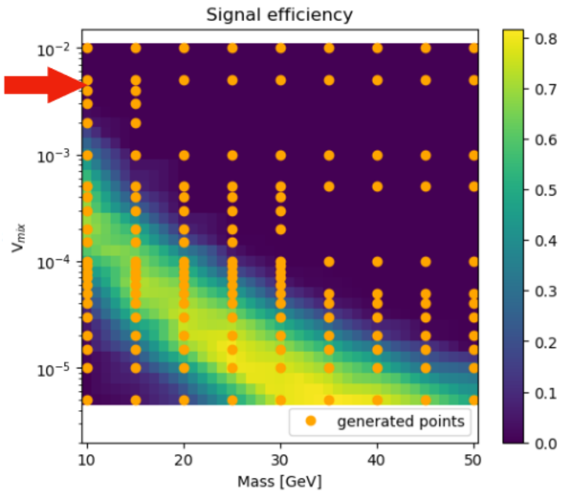
Displaced vertex position as main selection for signal/background separation.

- Sensitiviy estimated for vertex position > 1, 5 and 10 cm assuming negligible background
- Looking for 3-events limit



Signal efficiency:

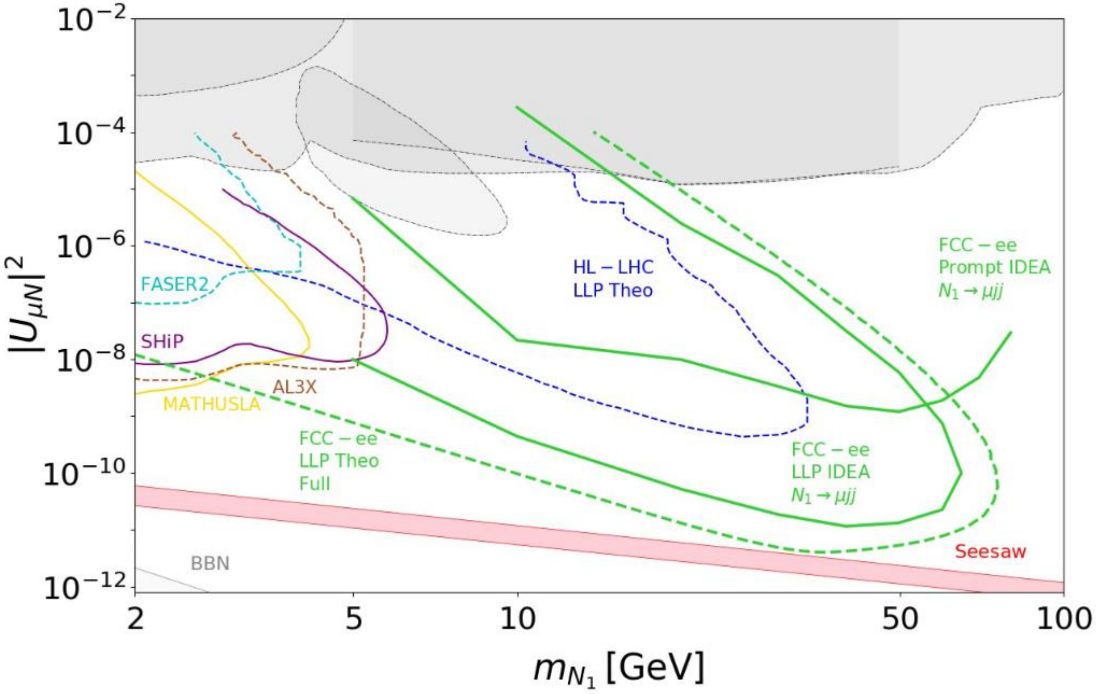
- 2 muons > 3 GeV
- $\cos(\theta)$ cut to reject back-to-back events with bad reco vertex
- XY position of $\mu\mu$ vertex > 1 cm



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→ $jj\mu$ results



https://arxiv.org/abs/1912.03058

HNL→ $jj\mu$

Dependence on hadronic resolution

1. Window for baseline study from DELPHES
2. Assume signal efficiency unchanged after enlarging mass window according to resolution
3. Calculate number of background events for enlarged window and calculate significance

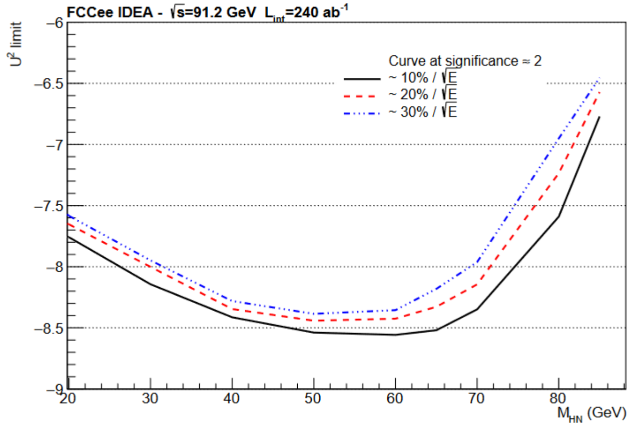


Fig. 24 Curves at Significance = 2 for different values of the assumed hadronic resolution. Each line is a linear interpolation of Z vs. $\log(U)$ at the value $Z = 2$.

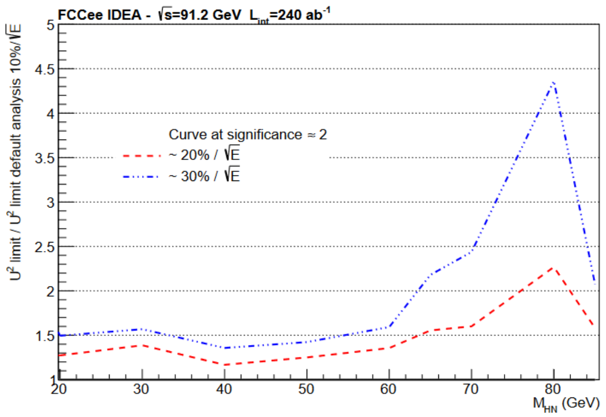
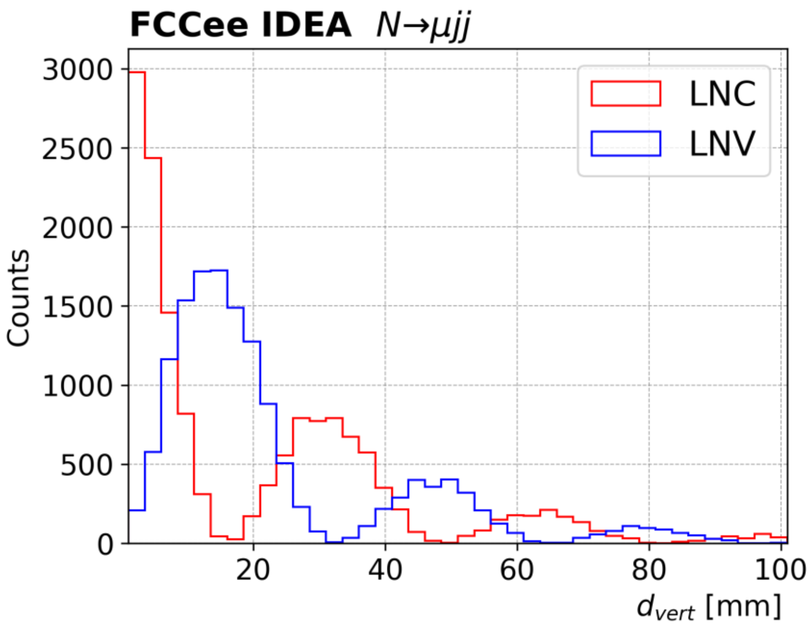
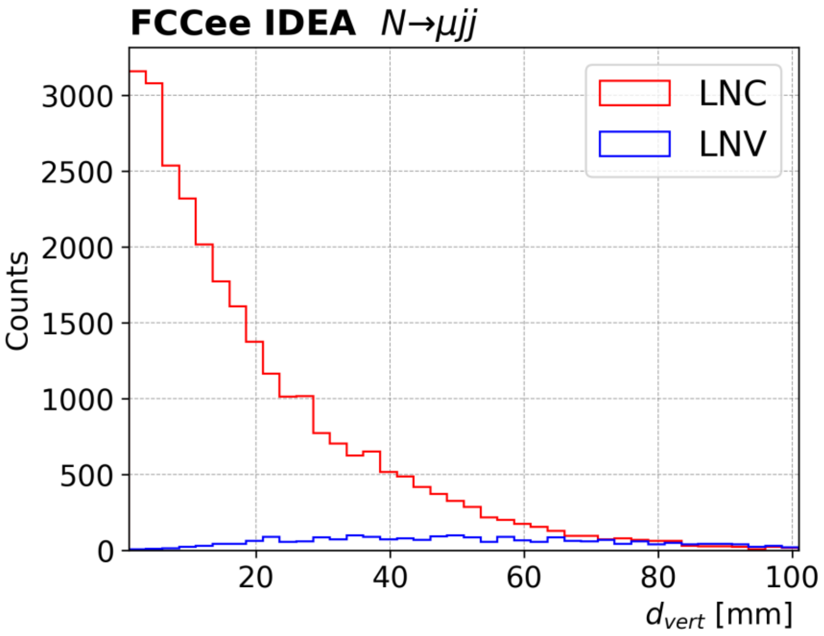


Fig. 25 Ratio of the U^2 limit obtained with 20% and 30% resolutions with respect to the nominal resolution as a function of M_{N_1}.



$c\tau_{dec} = 10$ mm; $c\tau_{osc} = 15$ mm



$c\tau_{dec} = 10$ mm; $c\tau_{osc} = 150$ mm

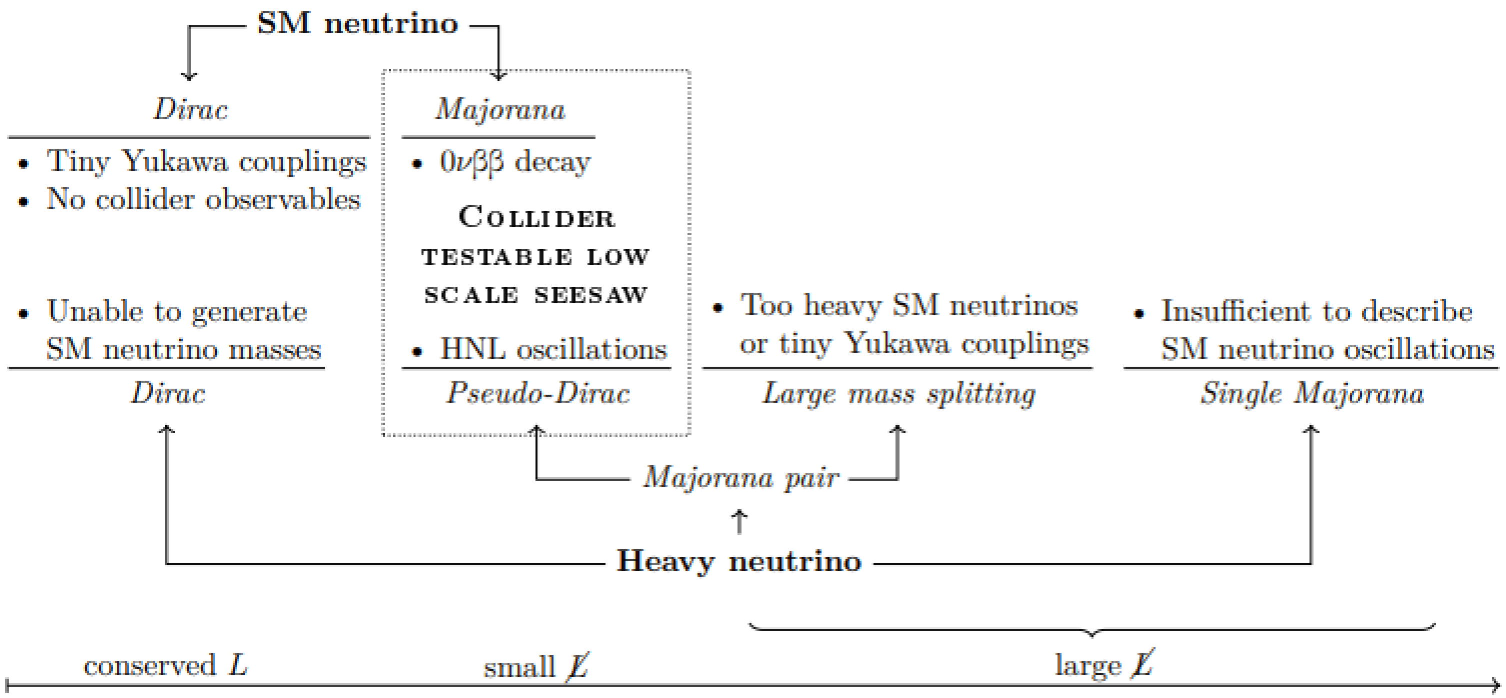


Figure 1: Comparison between the different possible choices for active and sterile neutrinos discussed in the text. Note that for collider-accessible heavy neutrinos that generate Majorana masses for the light neutrinos via a low-scale seesaw with couplings far above the naive seesaw line, only pseudo-Dirac pairs of two nearly mass-degenerate Majorana DOFs are a viable option.

https://arxiv.org/pdf/2210.10738.pdf