Searching for Heavy Neutral Leptons and measuring them with the IDEA detector at the FCC-ee

Giacomo Polesello *, Nicolò Valle*, on behalf of the PED-BSM Physics Group

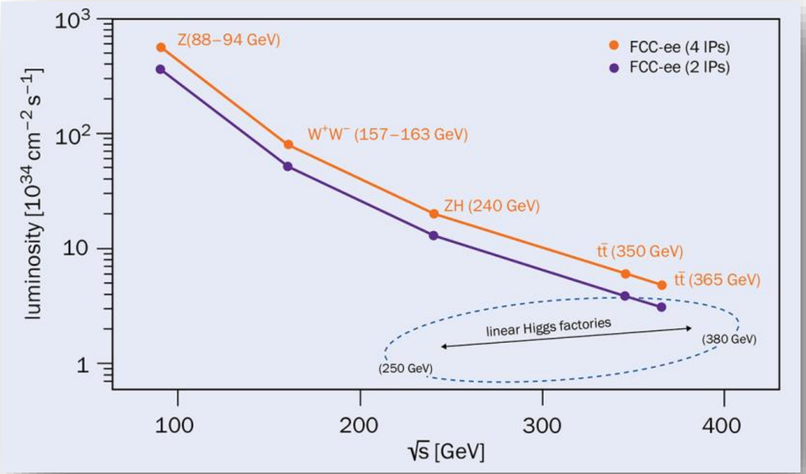
* INFN, Sezione di PAVIA

(BSM at) FCC-ee

A Higgs, top, EW and flavour factory, for tests of the Standard Model at an unprecedented level

Key words:
clean environment and **high statistics**

https://cerncourier.com



Tera-Z run (5 orders of magnitude more than LEP)

- Huge gain in **sensitivity for feebly-coupled new particles** with mass in ~ 1 - 91 GeV
- Broad search program, mostly model-independent
- Severe detector requirements

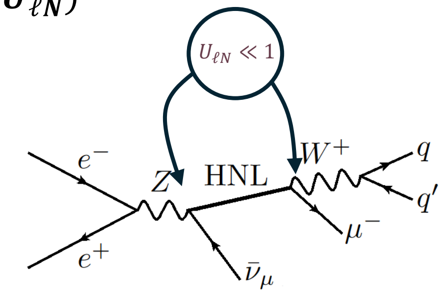
HNLs, a promising new physics channel

Open **key questions** on SM neutrinos (mass ordering, mass mechanism, Dirac/Majorana nature…)

Experimental point of view: **a heavy fermion with suppressed interactions**

Minimal scenario, production and decay are controlled by two model parameters: $(\boldsymbol{m_N}, \boldsymbol{U_{\ell N}})$

Small mixing $U_{\ell N}$ with SM leptons → **suppressed production**, and **long decay path**



In this talk:

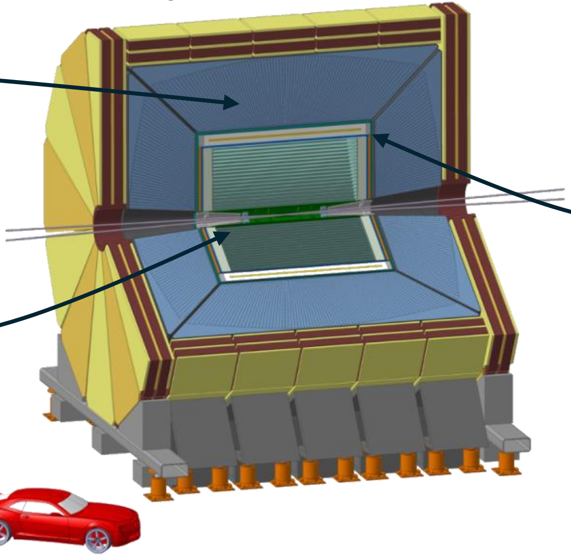
- **Exclusion limits**
- **Measurement of the parameters of the model in a realistic experiment**
  - $N - \overline{N}$ **oscillations**
  - **Dirac / Majorana behaviour**

The simulation setup

Model (UFO) → Samples generation ◊ MG5aMC@NLO ◊ PYTHIA8 → IDEA parametrisation ◊ DELPHES → Analysis tools

IDEA layout

Calorimetry: High resolution, segmented, dual-readout fiber calorimeter



Timing layer

- TOF precision within few tens of ps

Tracker: MAPS sensors + drift chambers

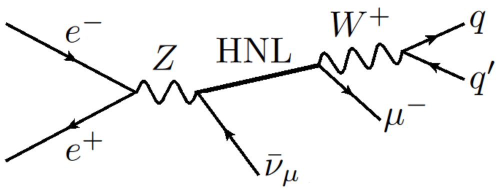
DELPHES:

- Advanced simulation of the full geometry + efficient tracking and vertexing code
- [1.2-31 cm]: 5 cylindrical layers (down to 3 μm resolution) + 6 endcap disks (7 μm resolution)
- [34-200 cm]: 112 4m-long coaxial layers modelling the drift chambers

Benchmark channel: N→μjj

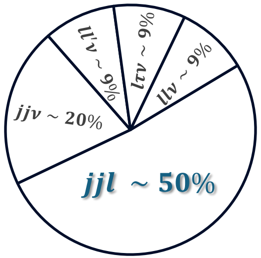
One HNL flavour assumed → two parameters, (m_N, U)

$$\Gamma_N \simeq c_{dec} \frac{a}{96\pi^3} G_F^2 U^2 m_N^5$$ $(m_N < 80 \text{ GeV})$



$$N \to \mu jj$$

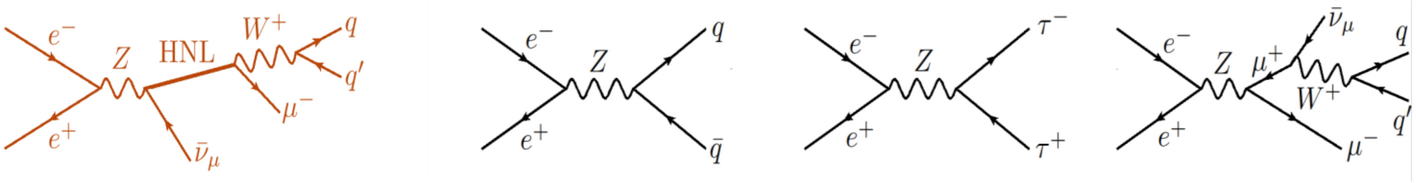
- **Large branching fraction**
- Visible final state allowing for **full reconstruction** of the kinematics



Displaced and prompt signatures are both accessible at the FCC-ee: severe requirements on the performance of the detector

Benchmark channel: N→μjj

Event reconstruction and selection (outline):



- At least three tracks, and **one single lepton** (muon), excluded from clusterization
- FASTJET **clusterization**, allowing for max 2 jets (exclusive k_T)

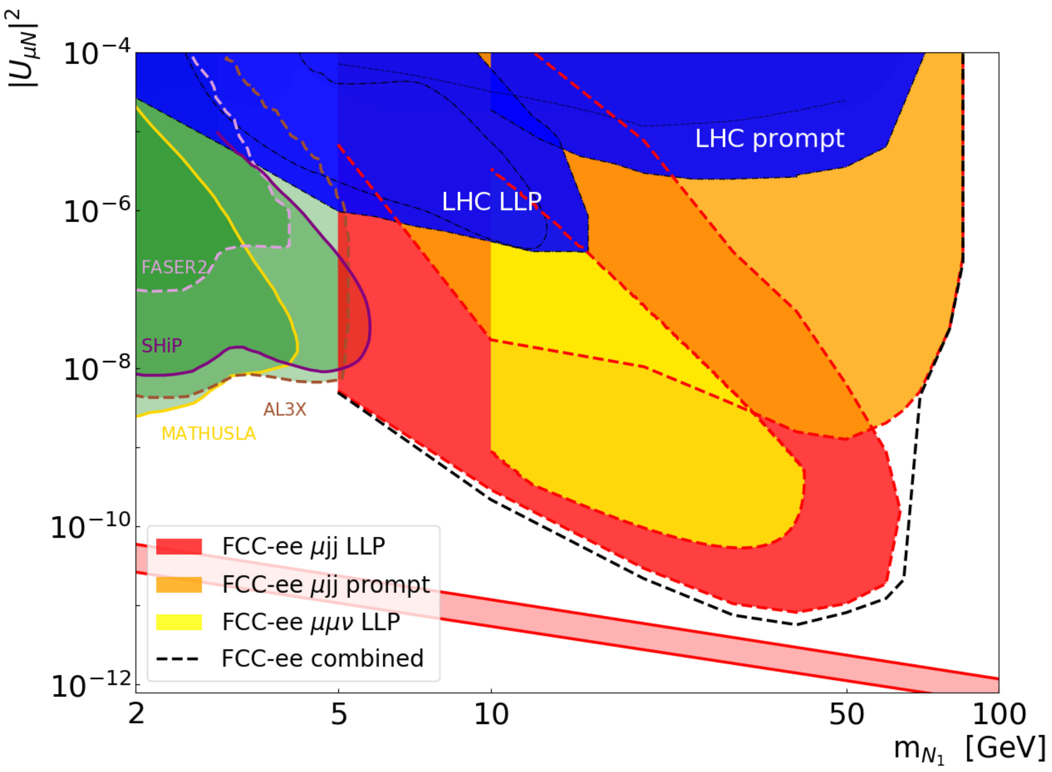
- qq, $\mu\mu$, $\tau\tau$ signatures suppressed by cuts on angular distributions, visible and invisible energy and mass
- Requiring **primary vertex** with good χ^2 and many contributors → high heavy flavour rejection

- 4-leptons **irreducible background: purely prompt** topology

- HNL mass -and missing energy- from the sum of all **visible** 4-momenta
  - ✓ Good mass resolution also from HNL vertex position and time-of-flight

Details in the backup slides

N→μjj sensitivity



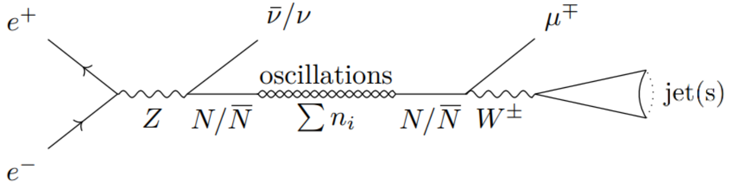
Prompt vs **long-lived** separation [radial vertex position ≲ 0.5 mm]

Selection for long-lived analysis reduced to minimal one, so to have **no background** in the long-lived regime

N-$\bar{N}$ scillation model

Two HNL states, with same mixing to SM and masses M-Δm/2 and M+Δm/2

Superposition of $N, \bar{N}$ during Z decay → **oscillation** between lepton-number conserving (**LNC**) and lepton-number violating (**LNV**) processes



Definition of the model: arXiv 2210.10738

J. Hajer,

Exploring the nature of heavy neutral leptons in final state distributions

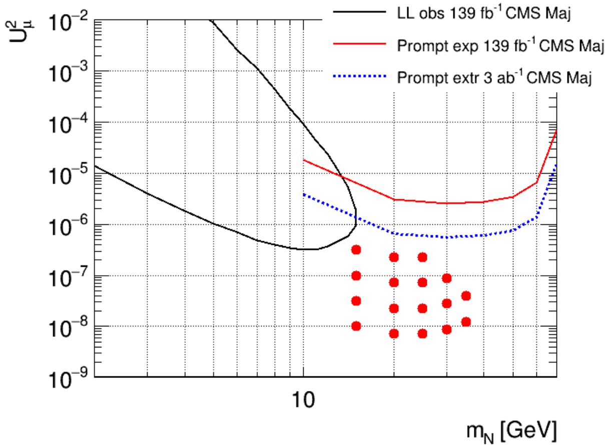
In what parameter space can we detect oscillations at FCC-ee ?
Which features of the model can we measure?

The simulated parameter space

Parameters chosen to have >5k HNLs with decay length **in between 0.5 mm [no SM after minimal cuts] and 2m [IDEA tracker extension]**

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

Analysis efficiency $\gtrsim$ 60%



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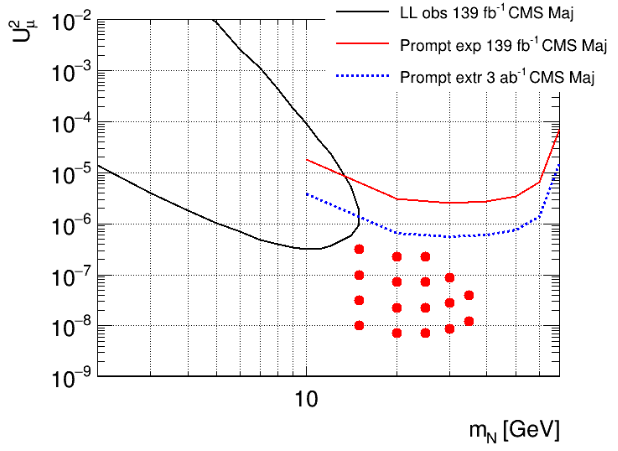
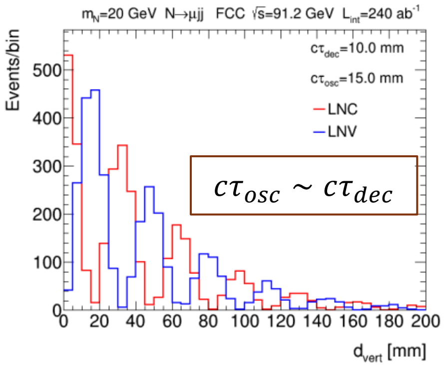
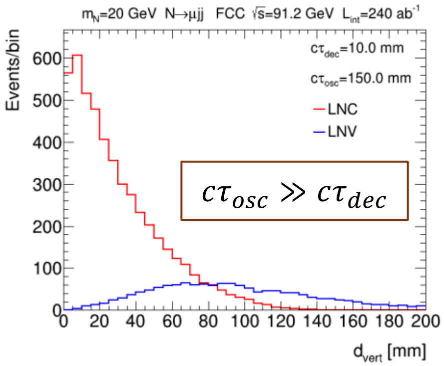




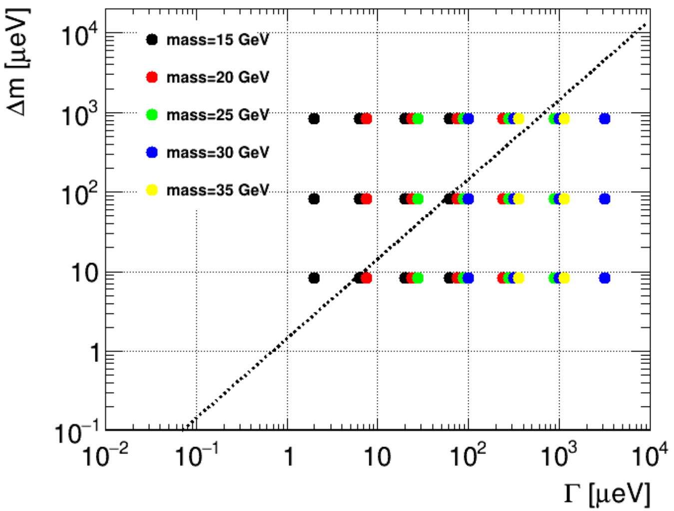


Truth oscillation, as a function of the distance of the reconstructed vertex from the origin (d_{vert})

The simulated parameter space

S. Antusch, J. Hajer, et al
pseudo-Dirac model arXiv 2210.10738
phenomenology at the Z-pole: arXiv 2408.01389

Simulated samples in the $(\mathrm{M}, \Delta m, \Gamma)$ space:



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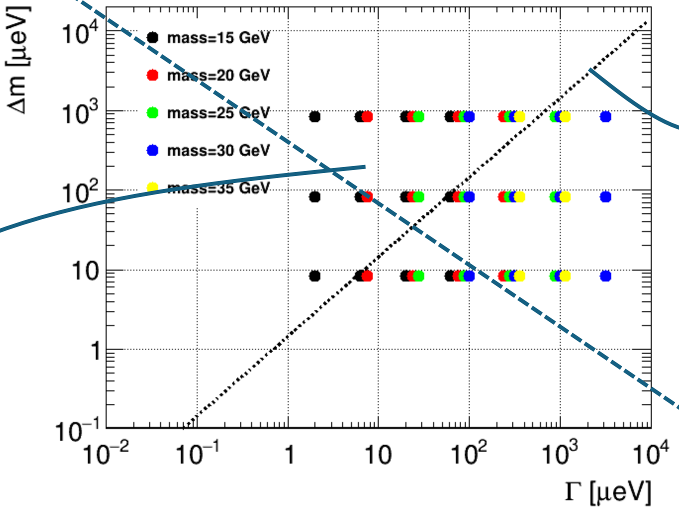
Simulated samples in the $(\mathrm{M}, \Delta m, \Gamma)$ space:

extremely fast oscillations

↓

independent Majorana HNLs



$$\frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2} = 0.05$$

resolvable oscillations expected

~ no oscillations before the decay
~ no lepton number violation

↓

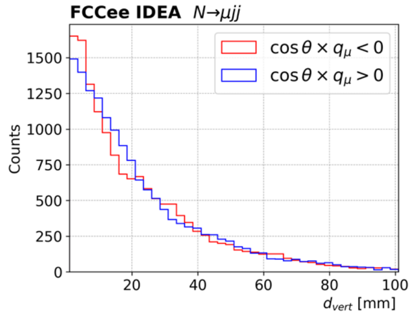
~ pure Dirac HNLs

The analysis - oscillations

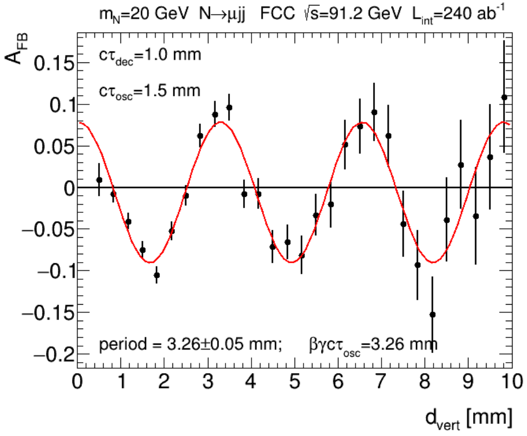
Main signature: production of **LNV final states**
One cannot detect whether N recoils against ν or $\bar{\nu}$ → use **angular asymmetry from Z polarization**

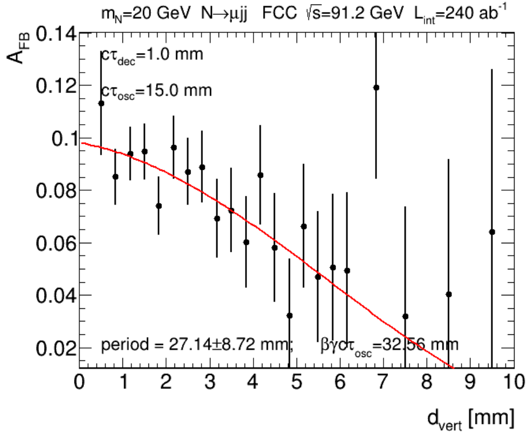
Forward/backward asymmetry
$\sim 10\%$ residual oscillation

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



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





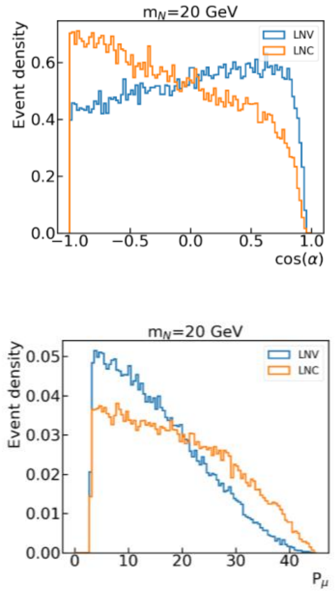
Potential capability to measure τ_{osc} at the percent level, depending on the value of the coupling

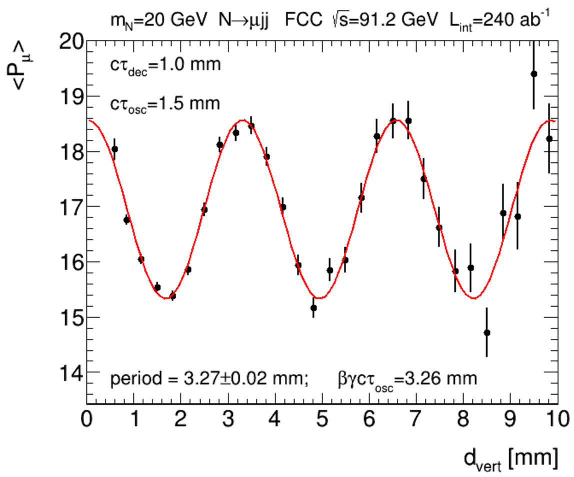
The analysis - oscillations

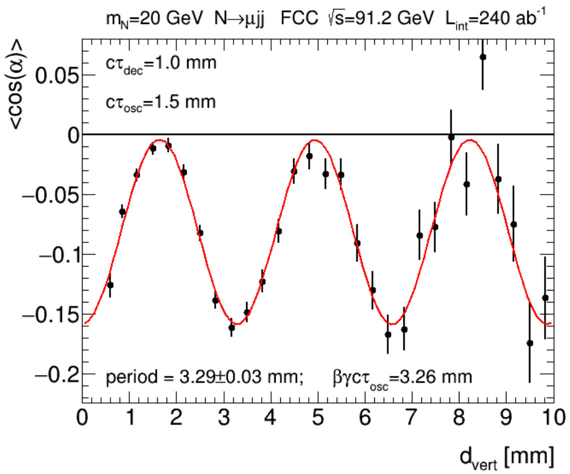
... or **exploit polarization of the HNL decay**

- ✓ Angle between muon and missing momentum (in the HNL rest frame)
- ✓ Muon momentum (in the lab frame)

MC truth







Error bars for full FCC-ee Z-pole statistics.
Comparable analysing power.

The analysis – Dirac/Majorana limits

1) Toy models used to define variables separating Dirac/Majorana:

- Pure Dirac model
- Majorana model: two Majorana neutrinos with Δm mass split

2) Once the variables are definded:

arXiv 2408.01389

- study distributions of discriminant variables for SPSS model in parameter space defined by $(\Gamma, \Delta m)$

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arXiv 2408.01389
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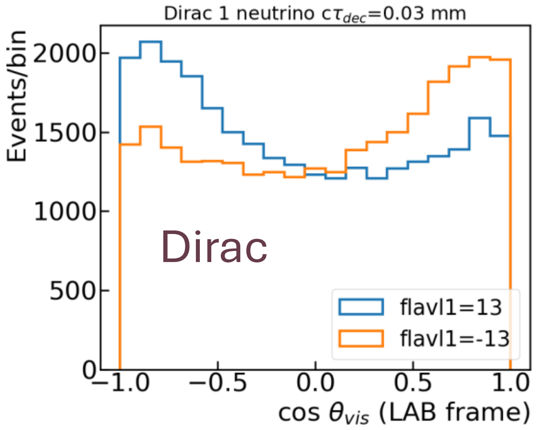
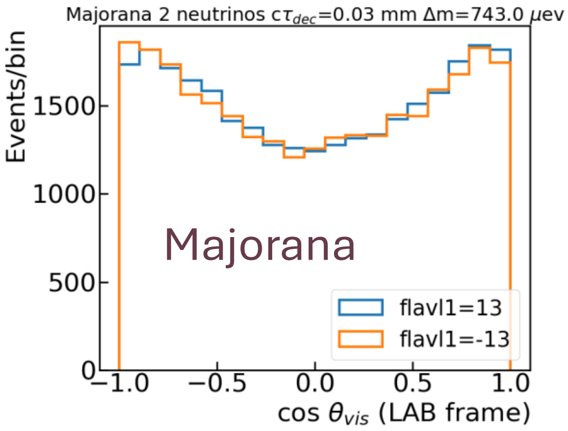
$\cos(\theta_{HNL})$
(LAB frame)





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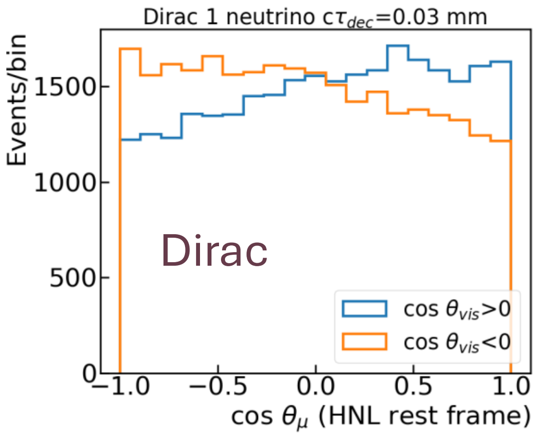
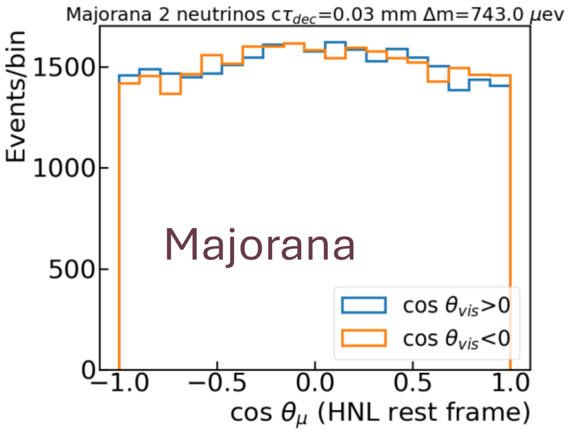
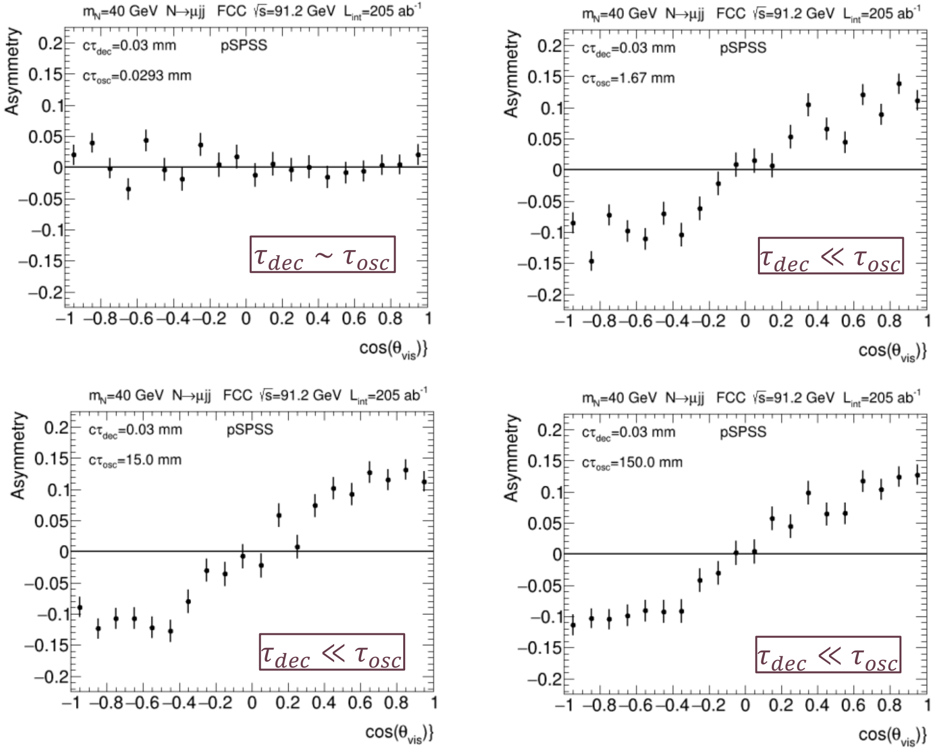
$\cos(\theta_\mu)$
(HNL rest frame)





The analysis – Dirac/Majorana limits

$\cos(\theta_{HNL})$ (LAB frame) $\rightarrow$ Asymmetry, defined as $\frac{\#(\mu^+)-\#(\mu^-)}{\#(\mu^+)+\#(\mu^-)}$

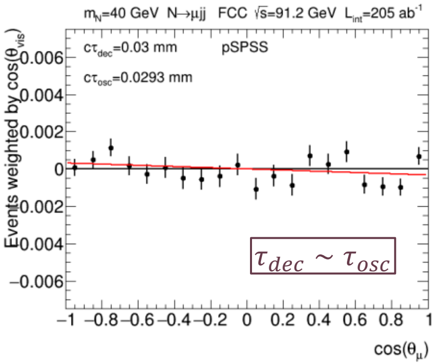


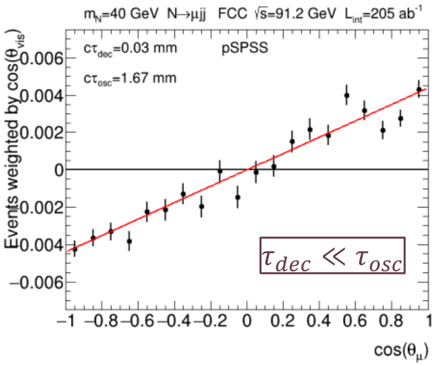
Majorana behaviour for $\tau_{dec} \sim \tau_{osc}$

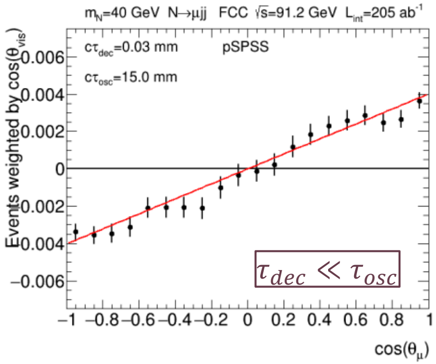
Dirac behaviour for $\tau_{dec} \ll \tau_{osc}$

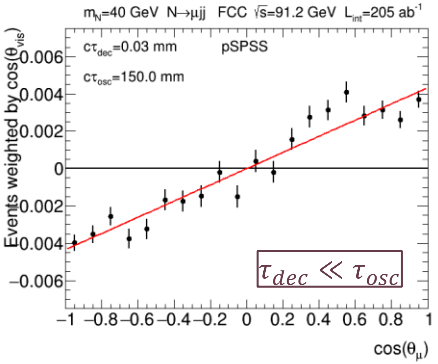
The analysis – Dirac/Majorana limits

$\cos(\theta_\mu)$
(HNL rest frame) $\rightarrow$ Bins with number of events weighted by $\cos(\theta_{HNL})$









Majorana behaviour for $\tau_{dec} \sim \tau_{osc}$

Dirac behaviour for $\tau_{dec} \ll \tau_{osc}$

Summary

Great FCC-ee potential for direct searches of HNL signatures both in **prompt** and **long-lived** channels

Analyses prove high S/B ratio, especially for displaced events, and **sensitivity** down to small mixing angles

Benchmark of model parameters, at the moment based on parametrised performance of detectors

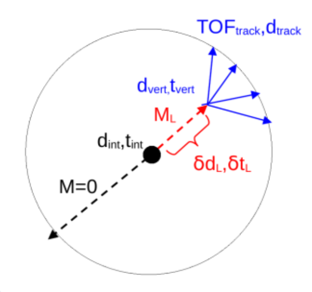
- Implemented in FCC software model of Antusch et al. yielding **striking signature of a N-$\bar{N}$ oscillation** inside the detector
- For an appropriate choice of parameters the **oscillation period is measurable** through forward/backward asymmetry
- Study of **Dirac/Majorana variables** can be used to assess parameter region of the model even when oscillations cannot be observed

Thank you

Extra material

Mass measurement through timing

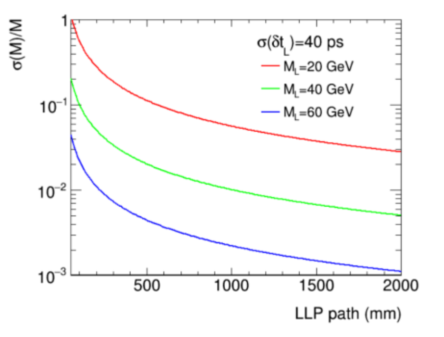
$$m_N = E_{cm}\sqrt{\frac{1-\beta_N}{1+\beta_N}} = E_{cm}\,F(\beta_N) \qquad \sigma(m_N) \sim E_{cm}F'(\beta_N)\,\sigma(\beta_N) \qquad \beta_N = \frac{\delta d_N}{\delta t_N}$$



The **HNL mass** can be constrained by measuring its decay **timing and path**

Resolution controlled by the uncertainty on HNL decay time and on the **undetected interaction point** *

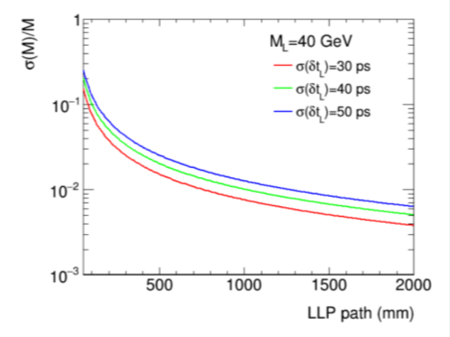
* σ_x = 5.96 μm, σ_y = 23.8 nm, σ_z = 0.397 mm, σ_z = 36.3 ps



Measurement below the percent level is possible with plausible detector performance,

for sufficiently high masses

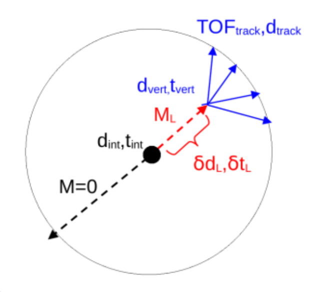
and long lifetimes



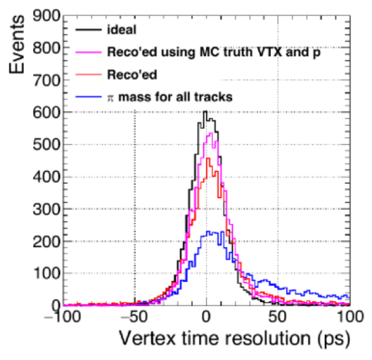
Mass measurement through timing

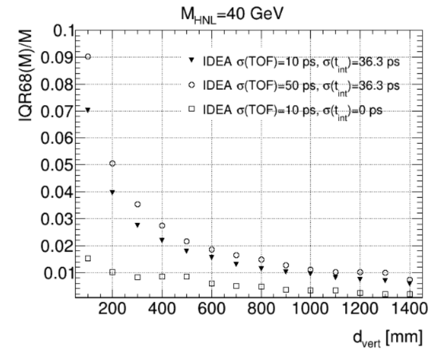
arXiv:2406.05102

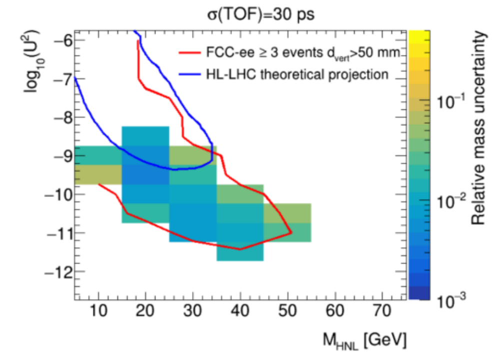
Realistic conditions simulated in IDEA, using the N → μjj channel



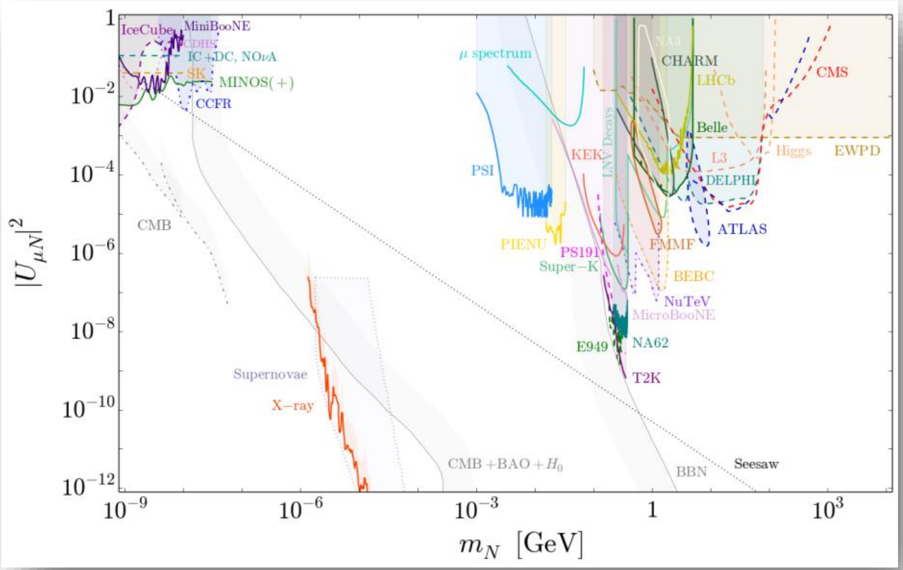
- $\sigma(\mathrm{TOF})$ determined only by detector technology
- The HNL vertex is known and its flight distance is computed
- Iterative procedure set up to optimize the mass hypotheses, possibly spoiled by the long HNL flight distance
- Timing resolution roughly scaling with sqrt of number of tracks
- $200\mu m \simeq \sigma(d_{vert})$ dominated by the uncertainty on the interaction point
- Dependence on HNL yield vs (m_N, U): evaluated with MC for the expected Z-pole run luminosity

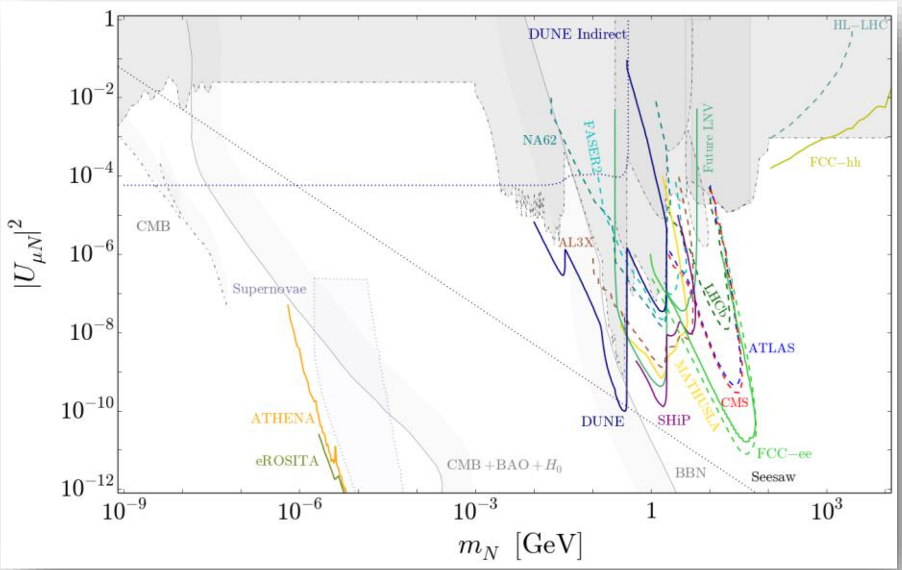






Existing limits and projections





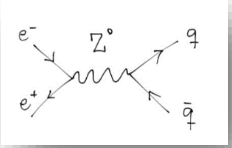
arXiv:1912.03058

The analysis

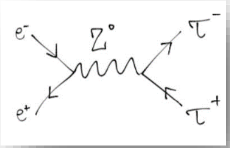
Sensitivity limits extracted over a **wide range** of parameter space

Working with the Z-pole run statistics: $\boldsymbol{L_{int}}$ = **205 ab^{-1}**

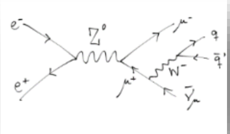
Background



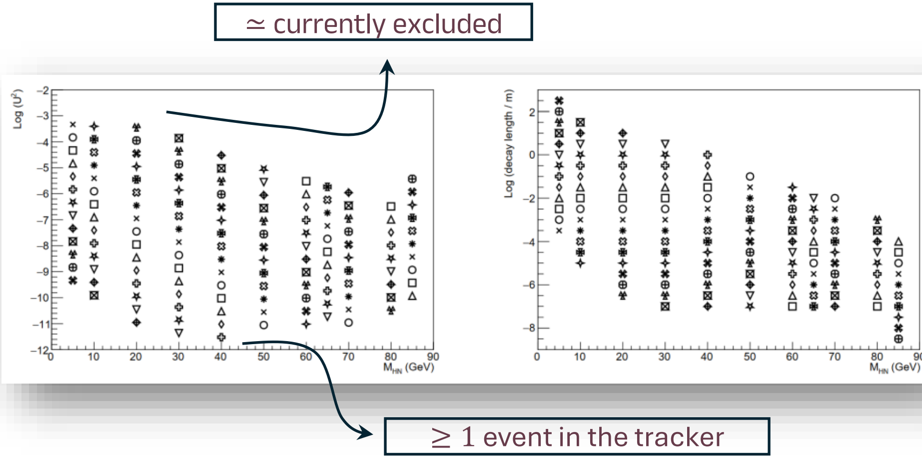
$Z \rightarrow bb/cc/uds$ especially relevant at high mass



$Z \rightarrow \mu\mu, Z \rightarrow \tau\tau$, more easily suppressed



Four-fermion process: irreducible but purely prompt



Crucial role of both **energy resolution** and **vertexing capabilities,** to maximize signal yield over background

Prompt vs **long-lived** separation
[radial vertex position ≲ 0.5 mm]
so to have **no backgound** in the long-lived regime

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

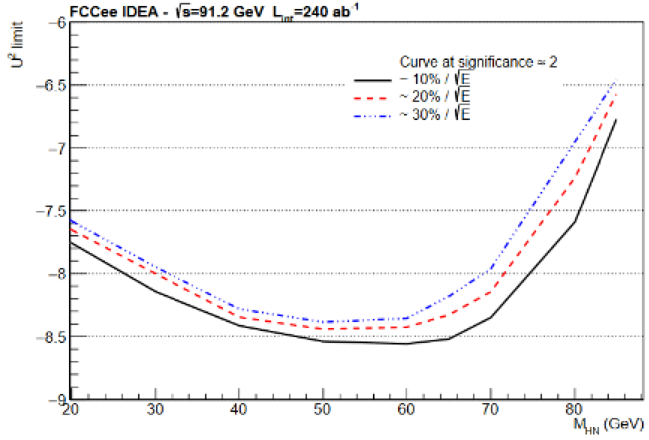


Fig. 24 Curves at Significance = 2 for different values of the assumed hadronic resolution. Each line is a linear interpolation of Z vs. $\log(U)$ at the value $Z = 2$.

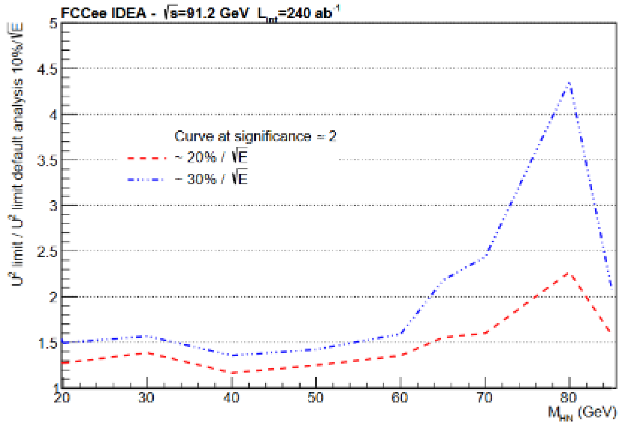


Fig. 25 Ratio of the U^2 limit obtained with 20% and 30% resolutions with respect to the nominal resolution as a function of M_{N_1}.