Institute of Experimental Particle Physics

Karlsruher Institut für Technologie

# HEAVY NEUTRAL LEPTONS SEARCHES AT FCC-ee

2nd FCC Italy-France workshop
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# THEORY AND SIMULATION

# Heavy neutral leptons

- **Type I seesaw model** with n $> 1$ heavy neutral leptons (HNLs) can address multiple issues of the SM Phys. Rev. Lett. 128, 051801

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

- Parameter-dependent **decay length:**

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

# Heavy neutral leptons

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- Simplified scenario: **one Majorana** or Dirac **HNL**
- Minimal realistic scenarios (lepton number-like symmetry):
  - $M_1 = M_2$ single Dirac HNL
  - $M_1 \approx M_2$ **pseudo-Dirac HNL** arXiv: 1712.07611
  - $M_1 \neq M_2$ two distinct Majorana HNLs

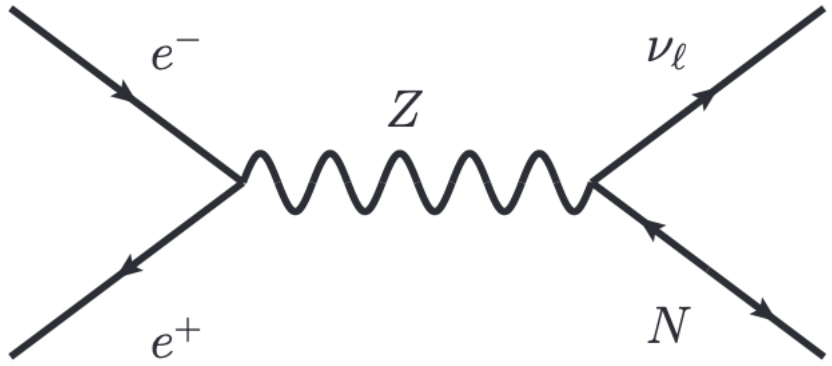
# Simulation setup

**Model**
Heavy N UFO
arXiv:1411.7305
arXiv:1602.06957

**Generation**
Madgraph5 + Pythia8

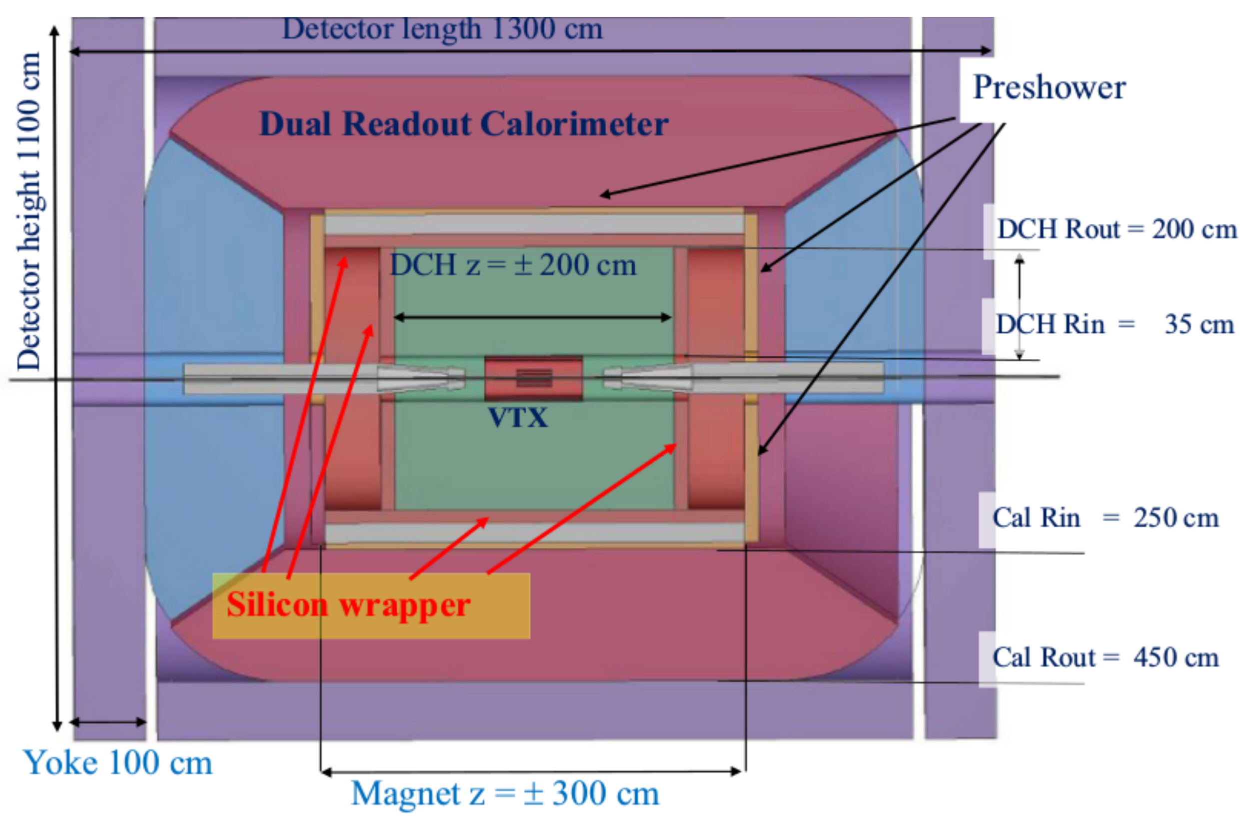
**Detector**
Delphes

**Analysis**
FCCAnalyses




- **Z pole run at FCC-ee**
- SM processes available from Winter '23 central FCC production (Pythia8 + Delphes)

**IDEA detector**

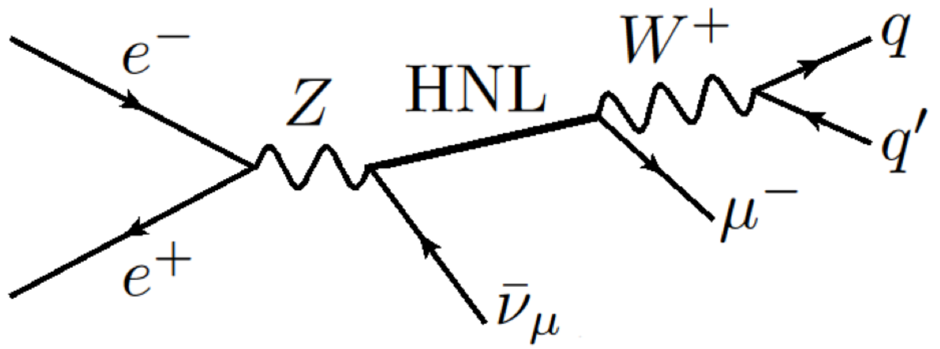


# EXCLUSION LIMITS

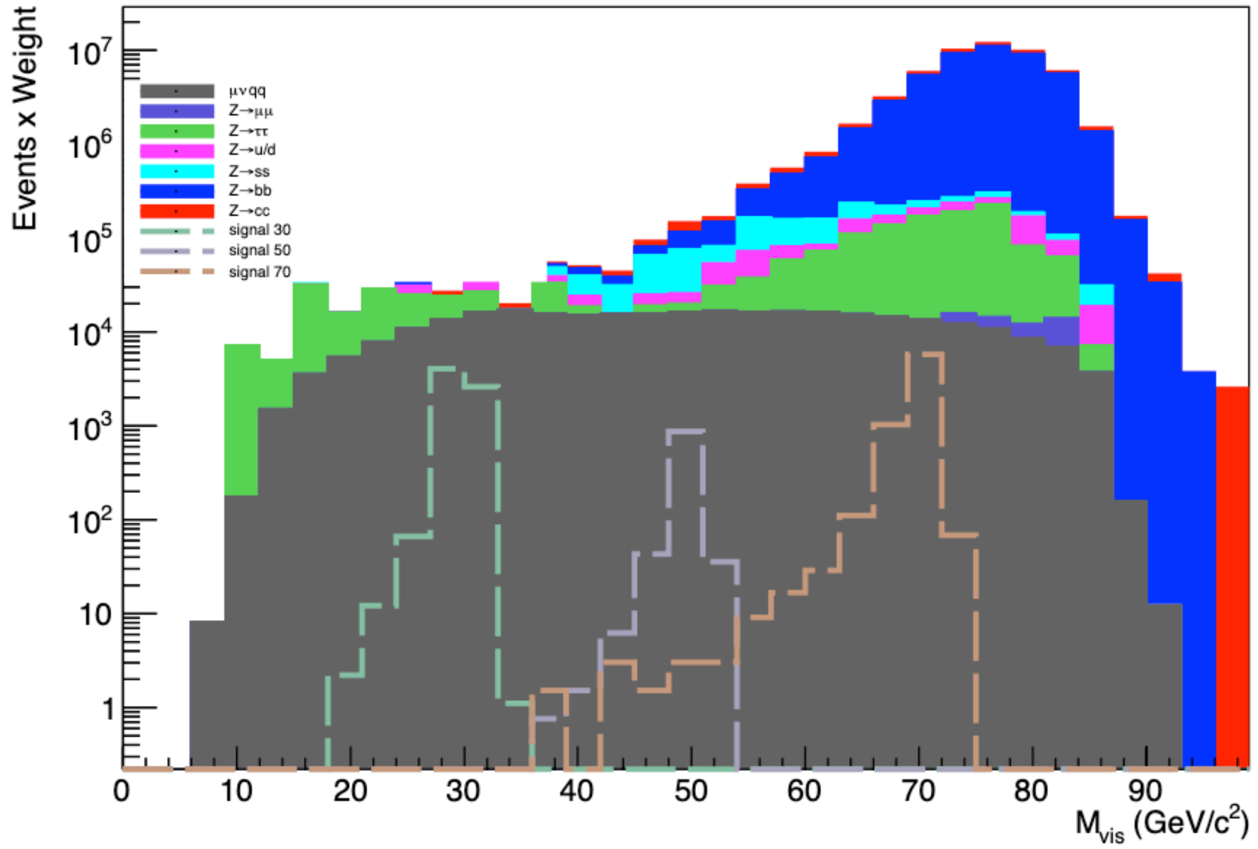
# One muon HNL

Polesello and Valle
doi:10.17181/9pc9x-kcn56

- **Majorana N → μ j j**, coupling to muons
- Privately produced $e^+e^- \rightarrow \nu_\mu \mu jj$ SM background




- At least **three tracks and one muon** not in jets (cut list in backup)
- Exclusive $k_T$ jet clustering $n_{jets} = 2$



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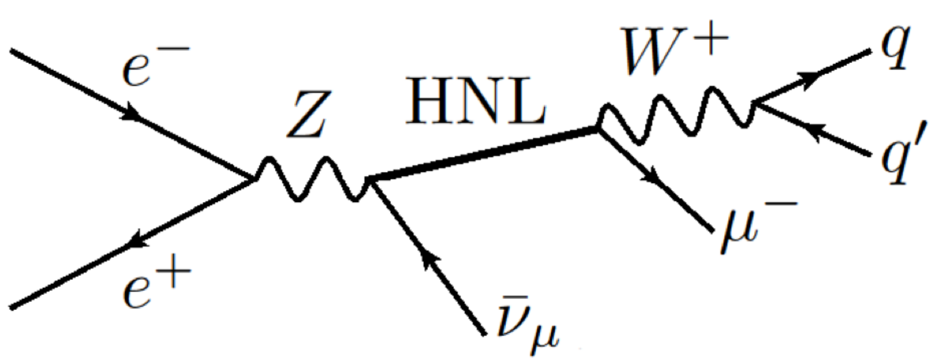
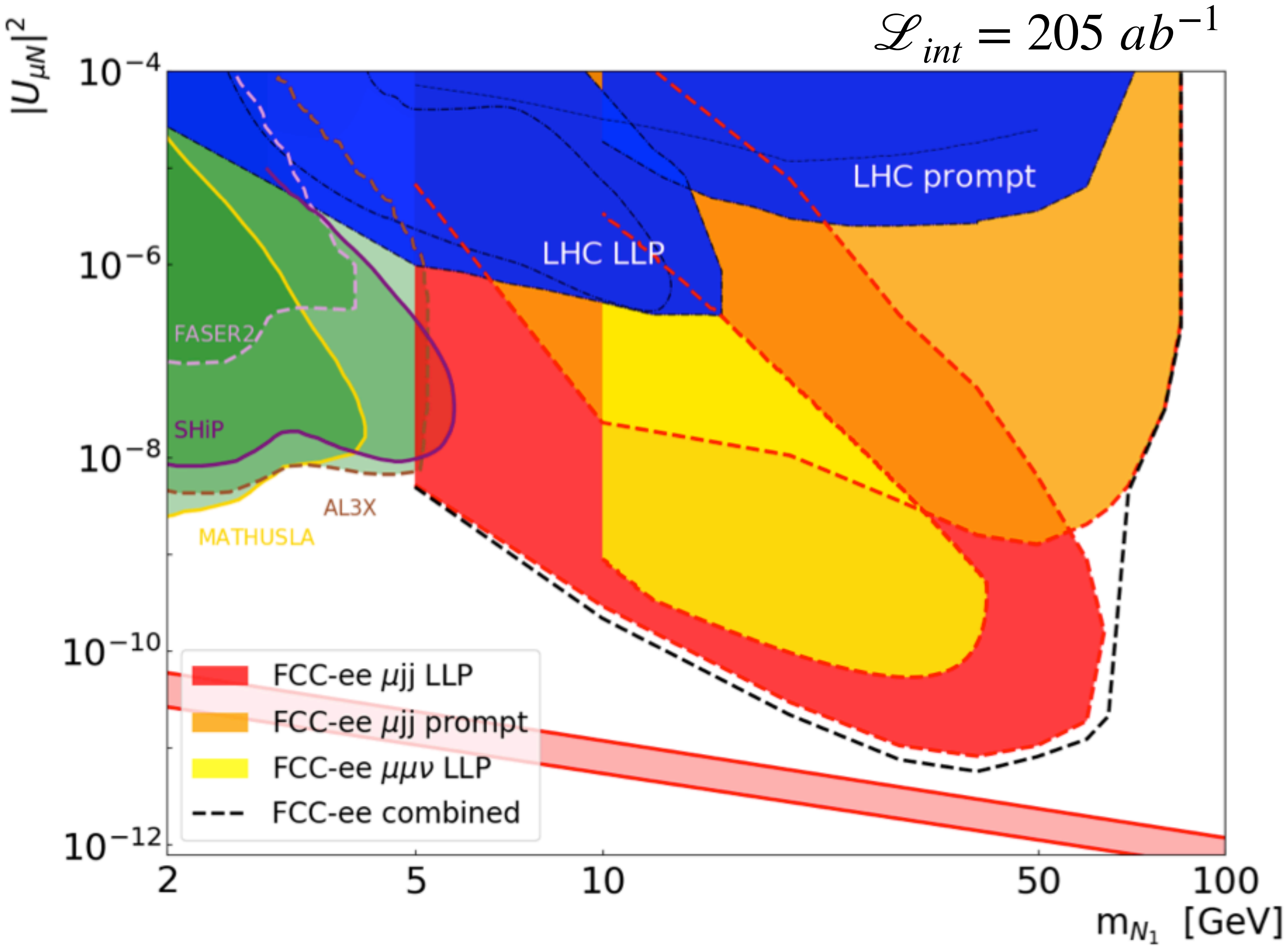
- **Prompt vs. long-lived HNL** (background-free): $L_{xy} \lesssim 0.5\ mm$

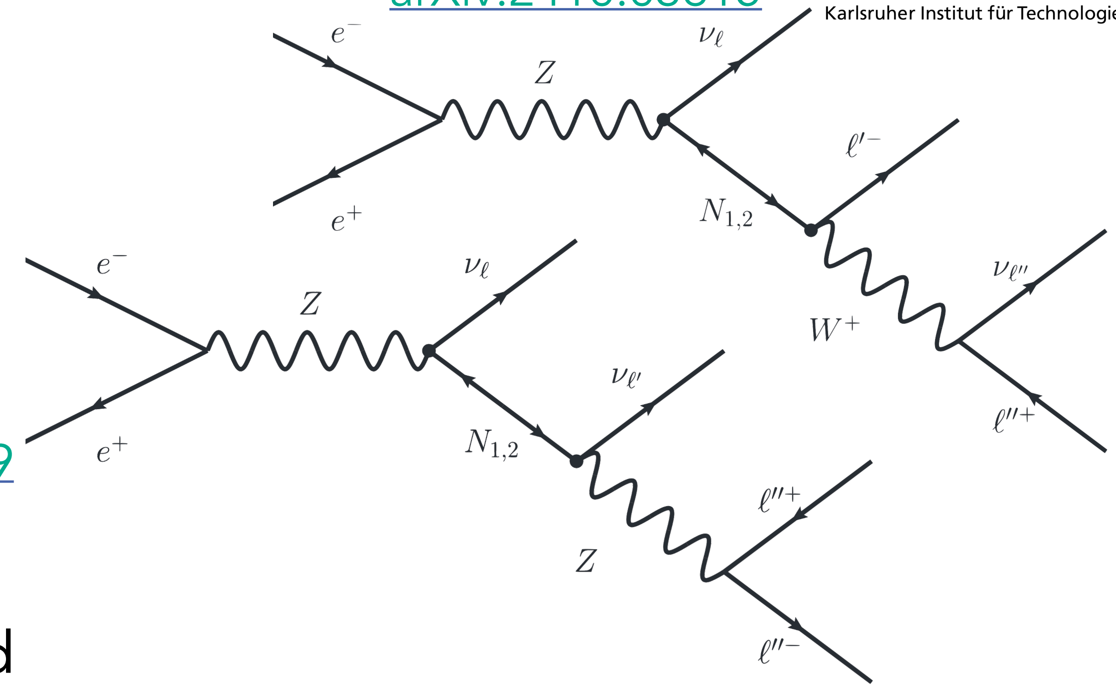


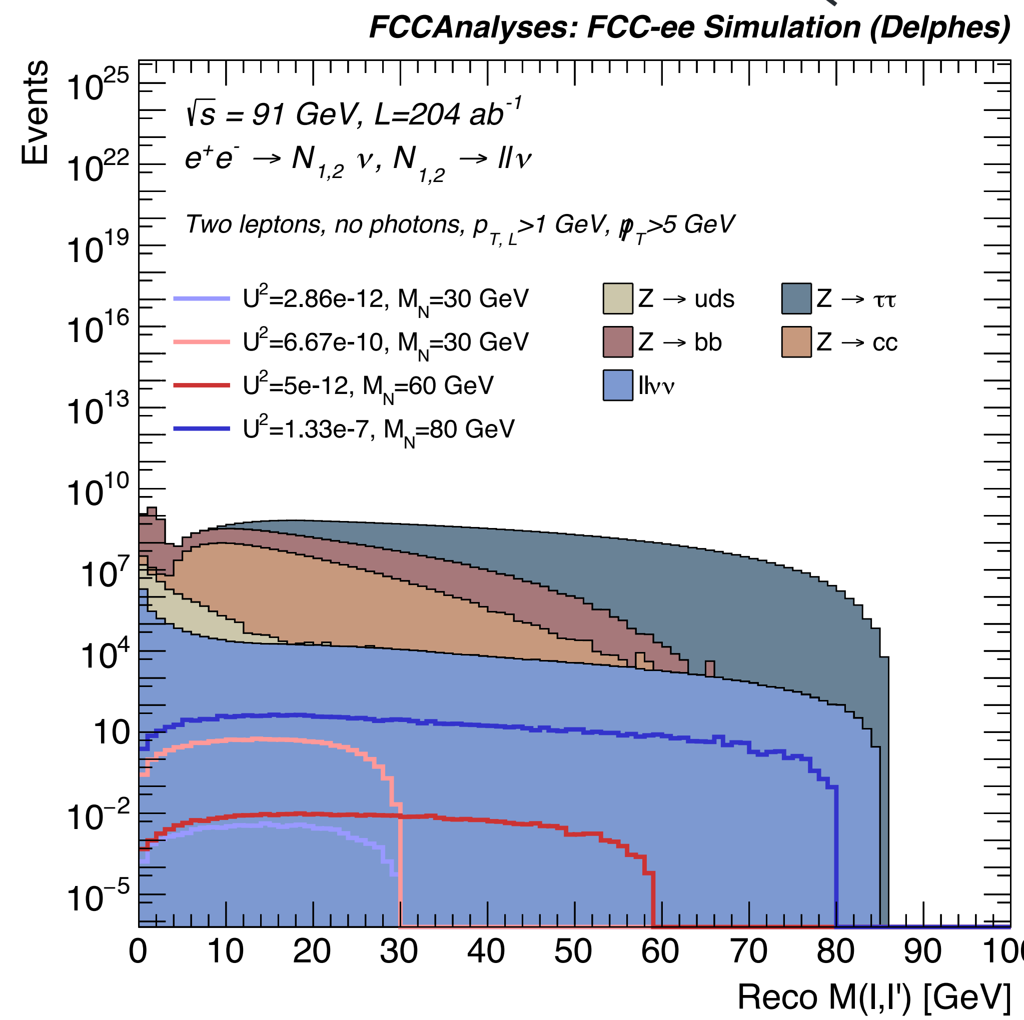



# Two HNLs

Giappichini et al.
arXiv:2410.03615

- Pseudo-Dirac pair $\mathbf{N_{1,2}} \rightarrow \boldsymbol{\ell\,\ell\,\nu}$, coupling to all leptons
- Parameters in agreement with leptogenesis Phys. Rev. D 108 (2023) L101302 and oscillation data JHEP 09 (2020) 178
- Privately produced $e^+e^- \rightarrow \ell\ell\nu\nu$ SM background
- **Leptonic $\tau$ decays + missing energy** (cut list in backup)



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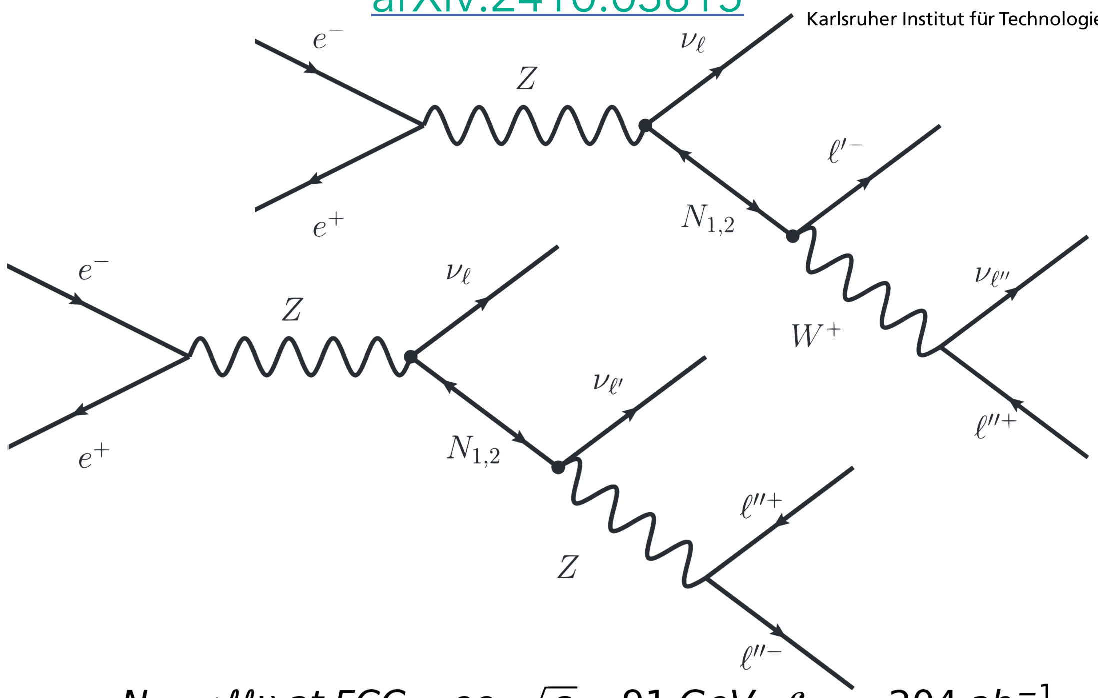
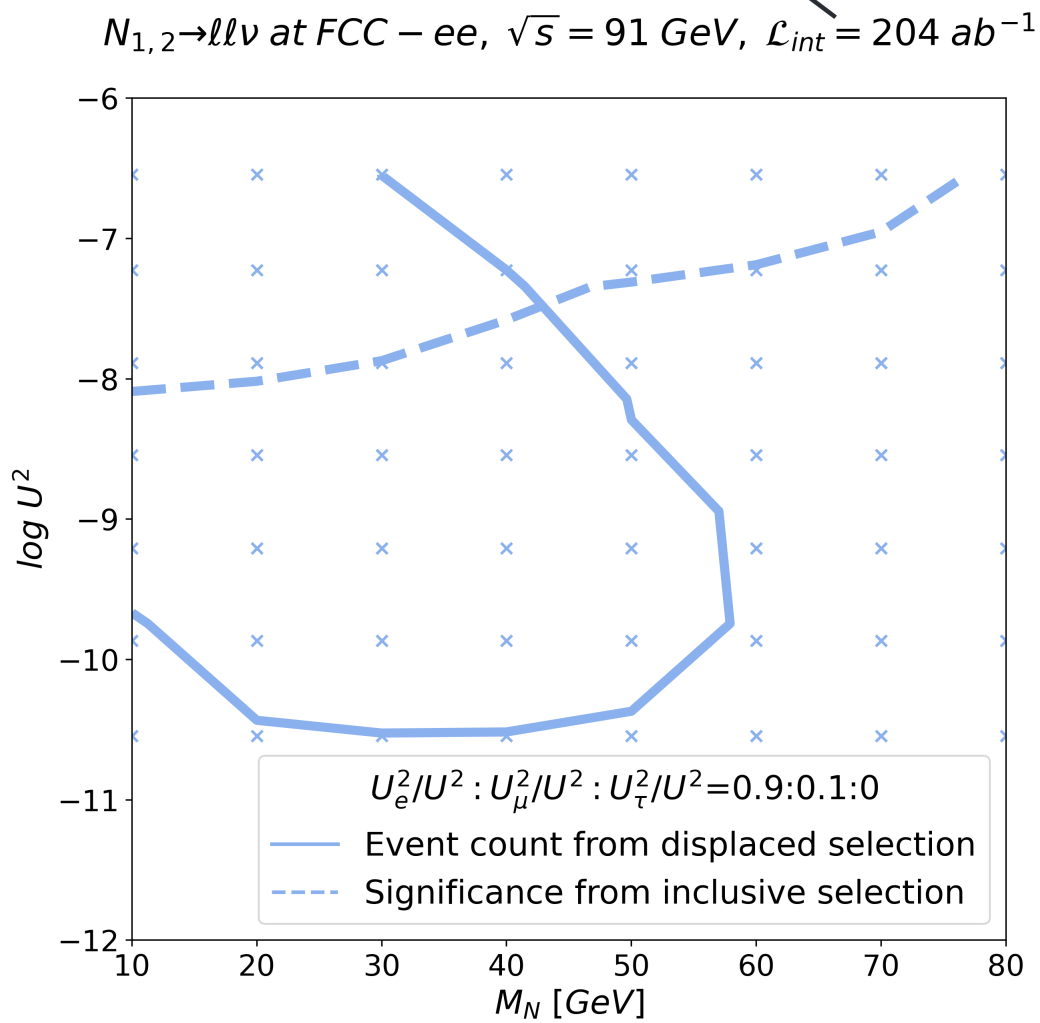
- **Inclusive vs. long-lived analysis** (background-free): $|d_0| > 0.64\ mm$

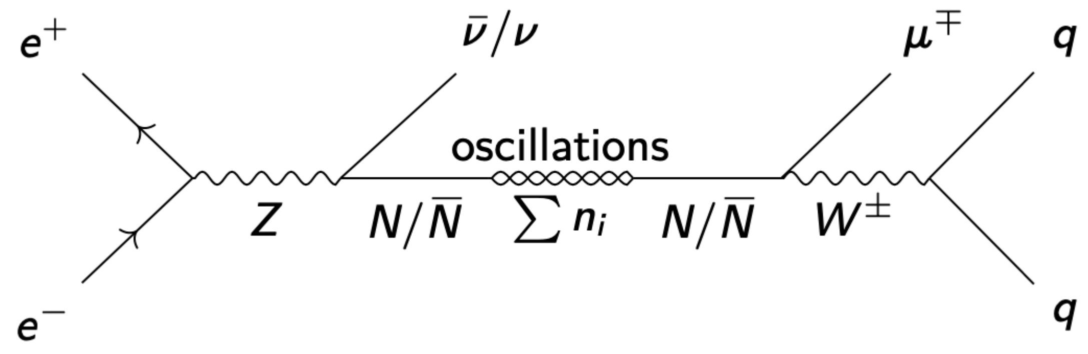


# OSCILLATIONS

# $N\bar{N}$ oscillations

Hajer et al.
JHEP 10 (2023), p.129

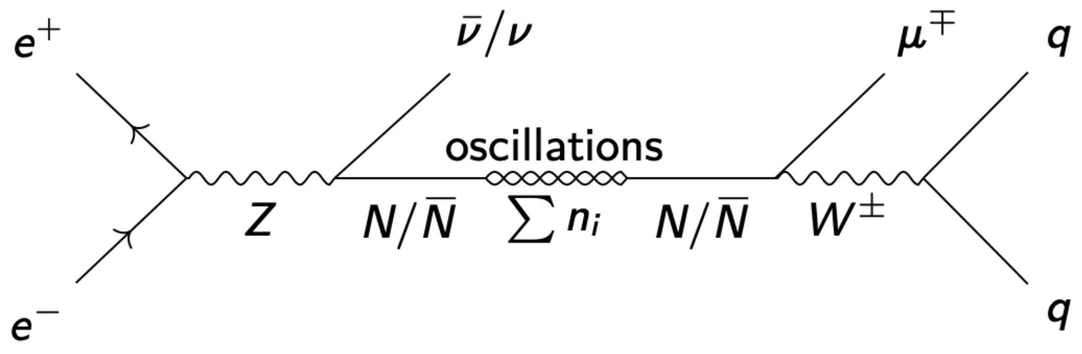



- Pseudo-Dirac pair **N → μ j j**, coupling to muons
- Oscillations implemented in *pSPSS* UFO (phenomenological symmetry protected seesaw)

# $N\bar{N}$ oscillations

Hajer et al.
JHEP 10 (2023), p.129





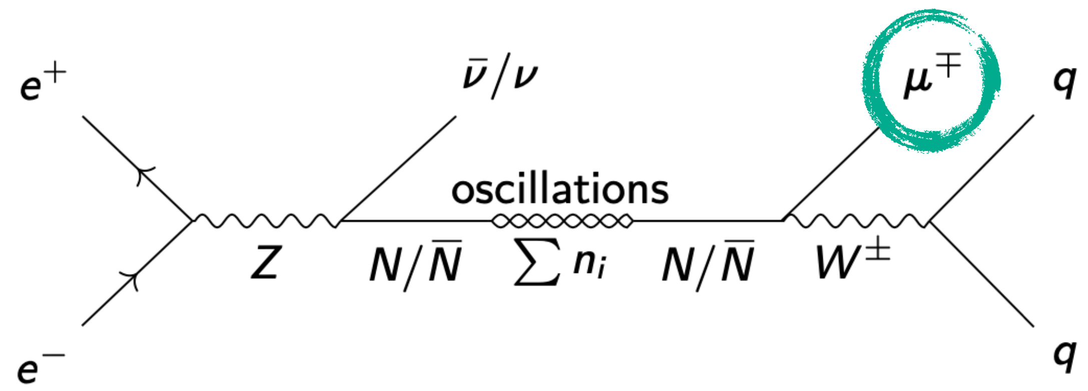

- Pseudo-Dirac pair **N → μ j j**, coupling to muons
- Oscillations implemented in *pSPSS* UFO
- $N\bar{N}$ oscillation probability:

$$P_{osc}^{LNC/LNV}(\tau) = \frac{1 \pm \cos(\Delta m \tau)\exp(-\lambda)}{2}$$

- Damping parameter $\lambda$=0 for long-lived HNLs JHEP 09 (2023), p.170

# Final state distributions

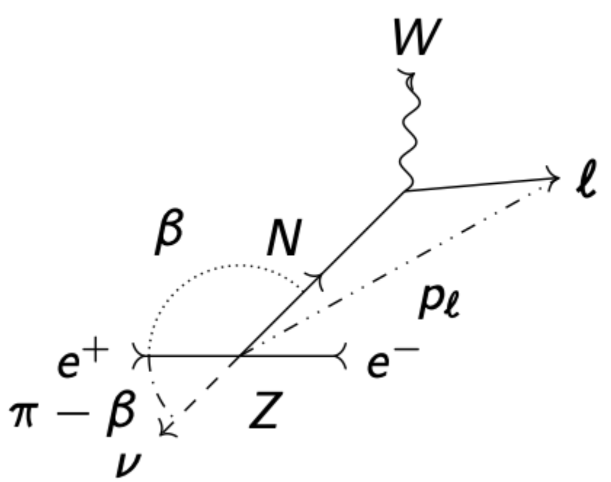
Hajer et al.
[JHEP 10 (2023), p.129]



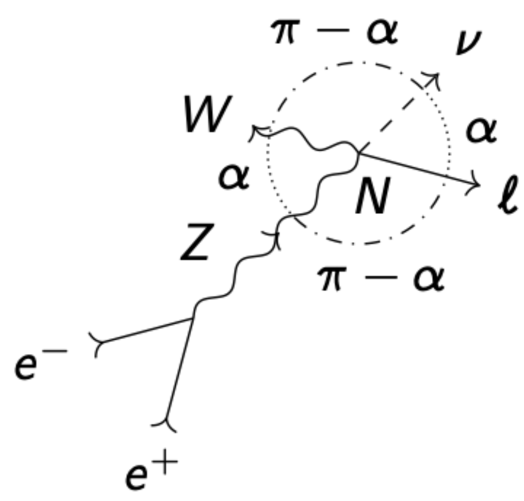

- Angular-dependent probability

$$P_{\ell^\pm}(cos\theta, \tau) = \frac{1}{\sigma}\frac{d\sigma(\cos\theta)}{d\cos\theta}P_{osc}^{LNC/LNV}(\tau)$$

- **Forward-backward asymmetry**




- **Opening angle asymmetry**



# Final state distributions

Polesello and Valle
doi:10.17181/recsm-v3k46

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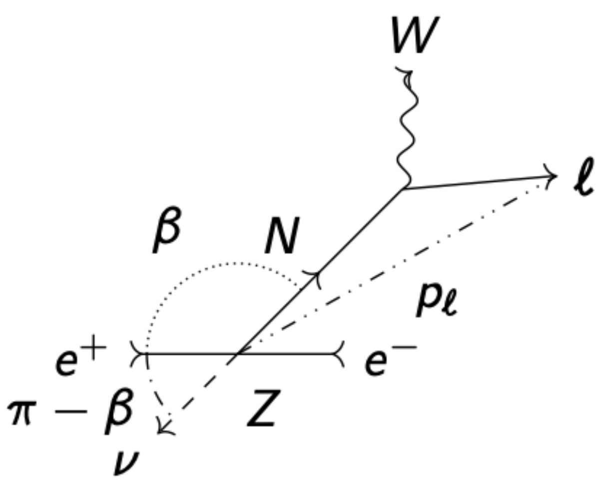
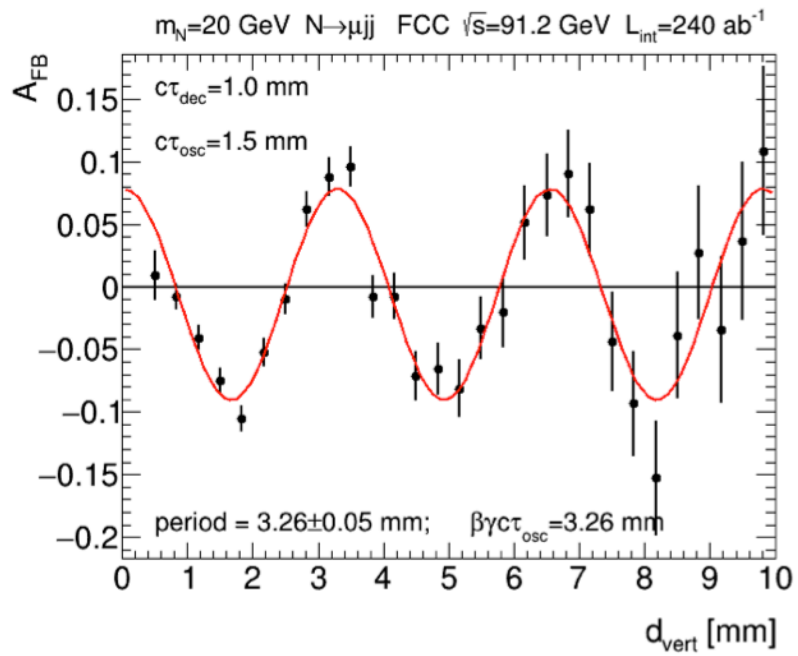
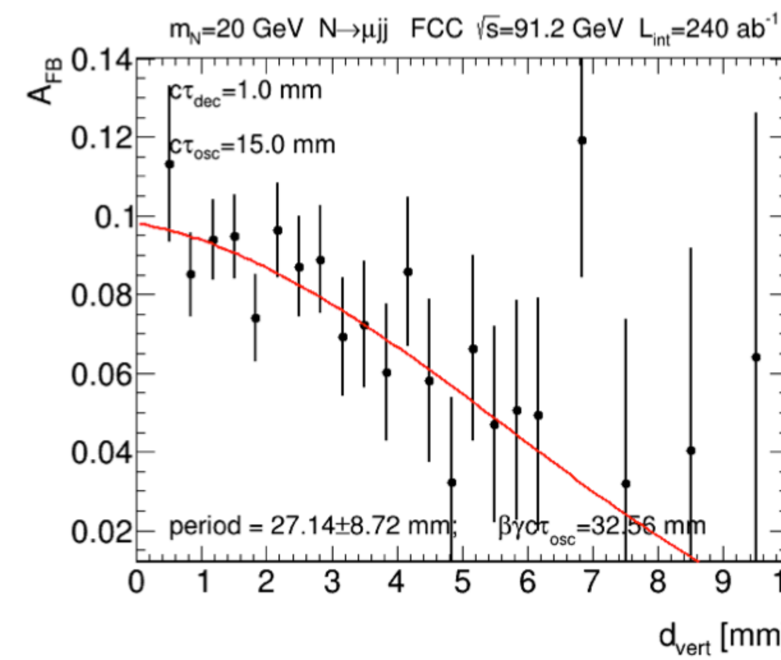
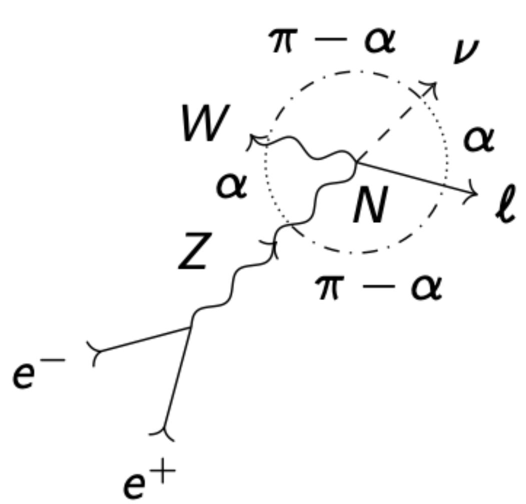
Forward-backward asymmetry

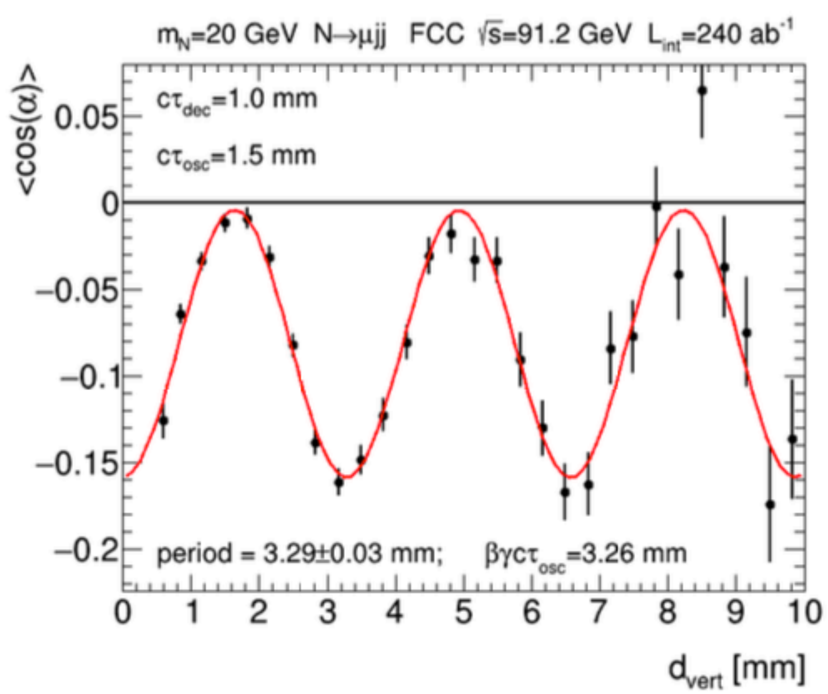


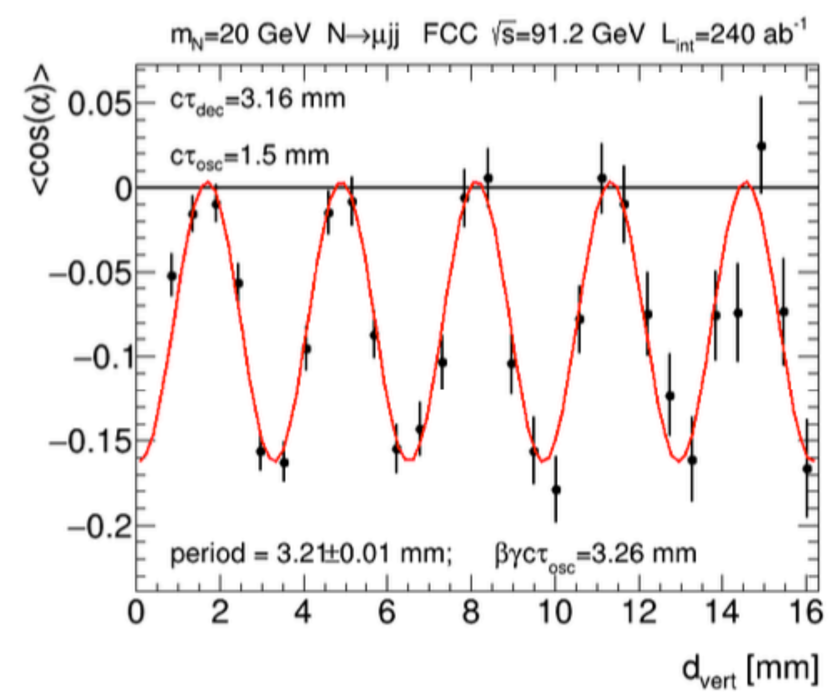




Opening angle asymmetry



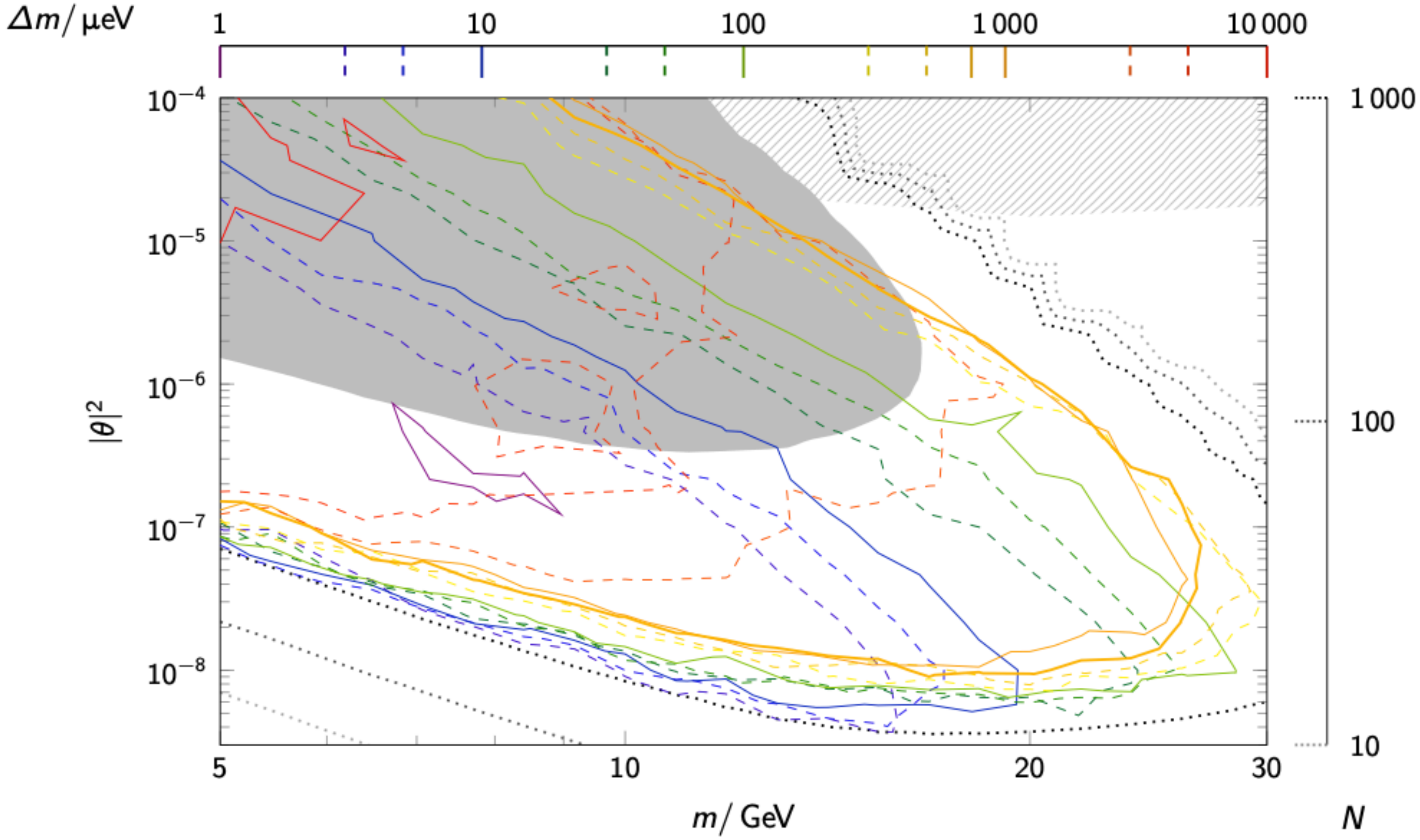



# NN̄ oscillations sensitivity

Hajer et al.
[arxiv:2408.01389](https://arxiv.org/abs/2408.01389)

FCC-ee (IDEA) 5$\sigma$ discovery reach



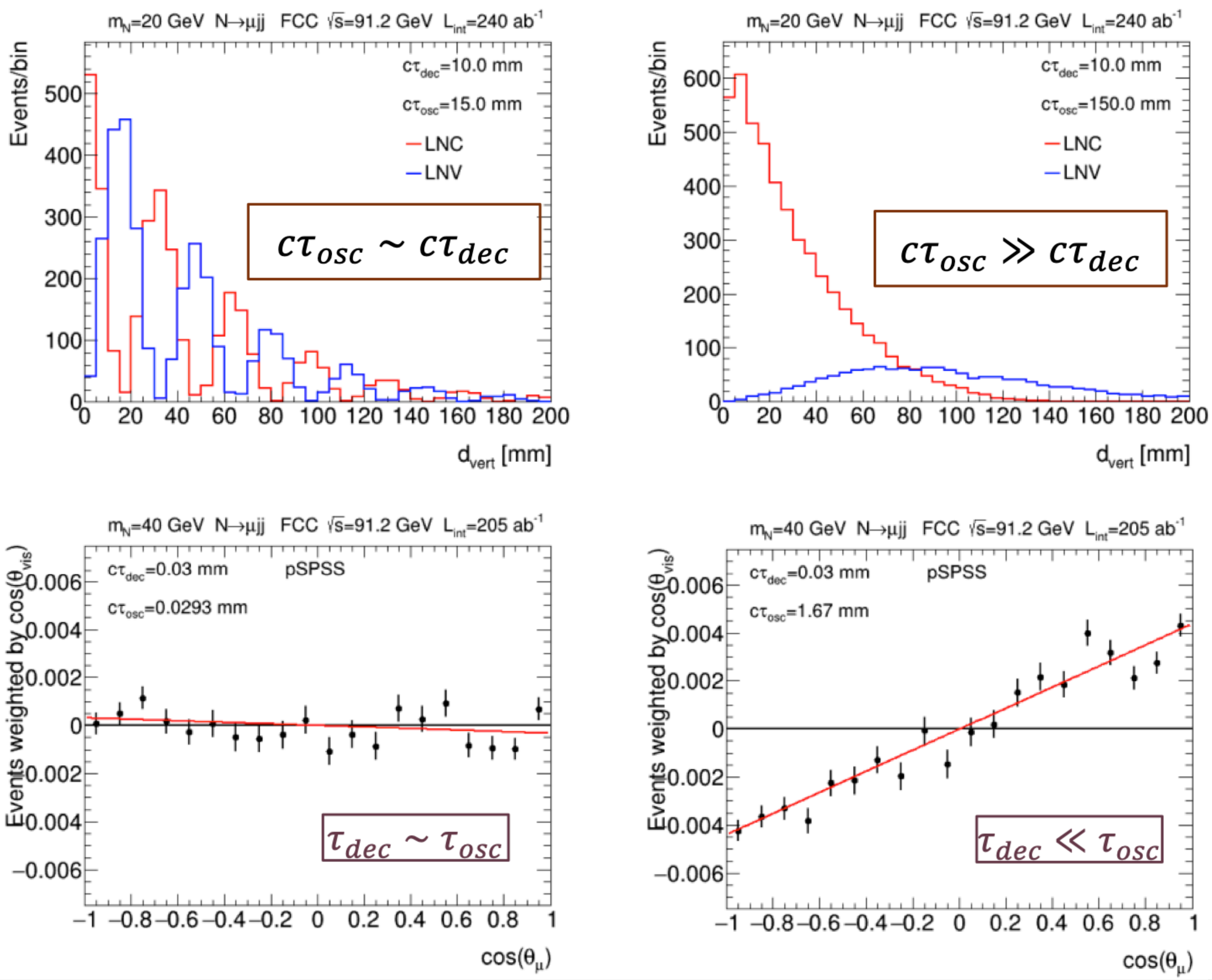

- Assuming background-free analysis (cut list in backup)
- Likelihood ratio test on the opening angle asymmetry

# Dirac vs. Majorana

Polesello and Valle
doi:10.17181/recsm-v3k46

$\Delta m\tau \gg 1$ two Majorana HNLs

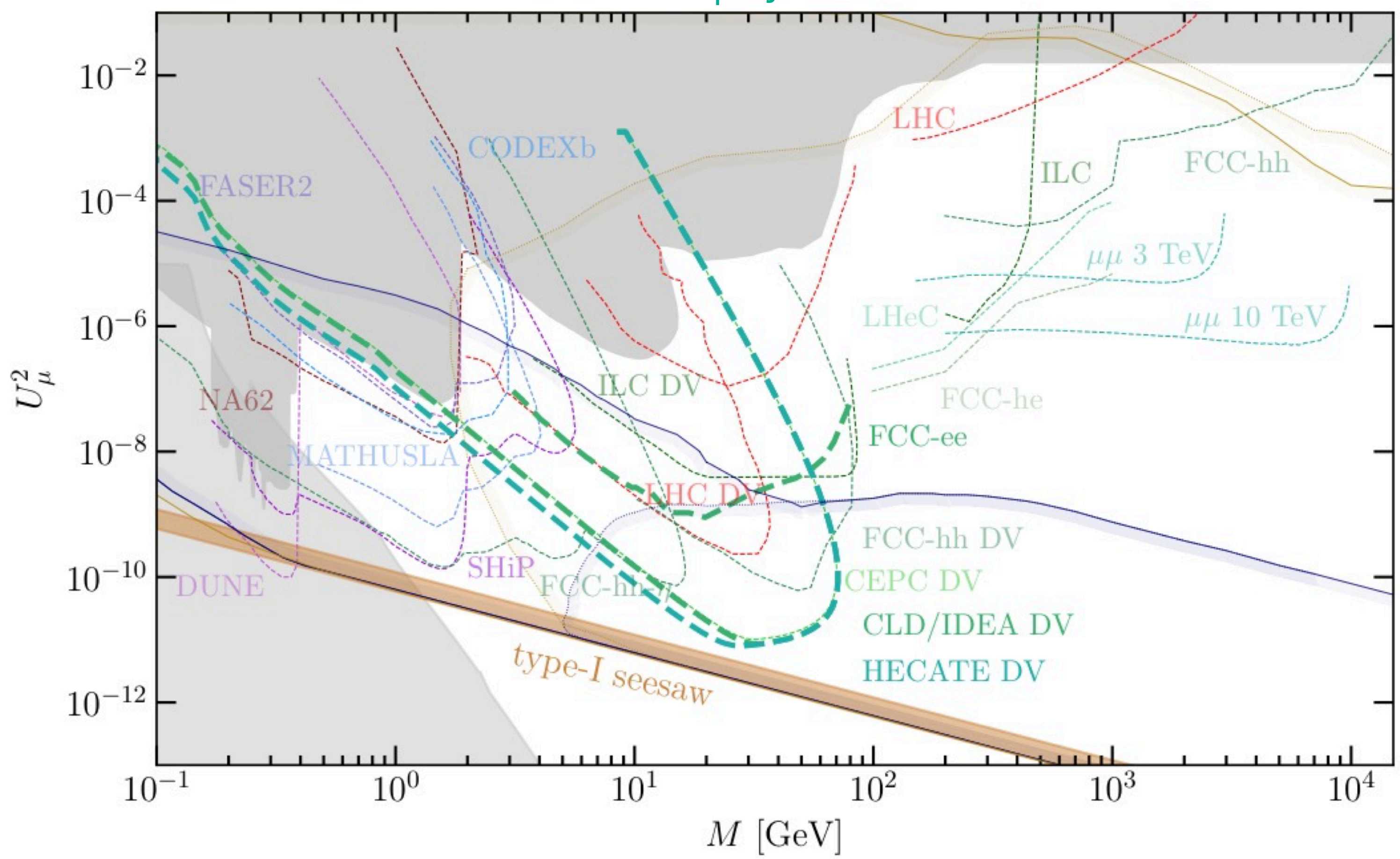
$\Delta m\tau \approx 1$ single Dirac HNL



# Conclusions

- Analyses of different **HNL coupling scenarios** show FCC-ee great potential for direct searches in both **prompt** and **long-lived** channels
- **N$\bar{\text{N}}$** oscillations could also be observed and their period measured in a sub-region of the accessible parameter space
- If not, **Dirac and Majorana** limits can be used to assess the phenomenon

doi:10.3389/fphy.2022.967881




Old theoretical prediction for one HNL coupling to electrons

# BACKUP

# HNL limits

Hajer et al.
arxiv:2408.01389

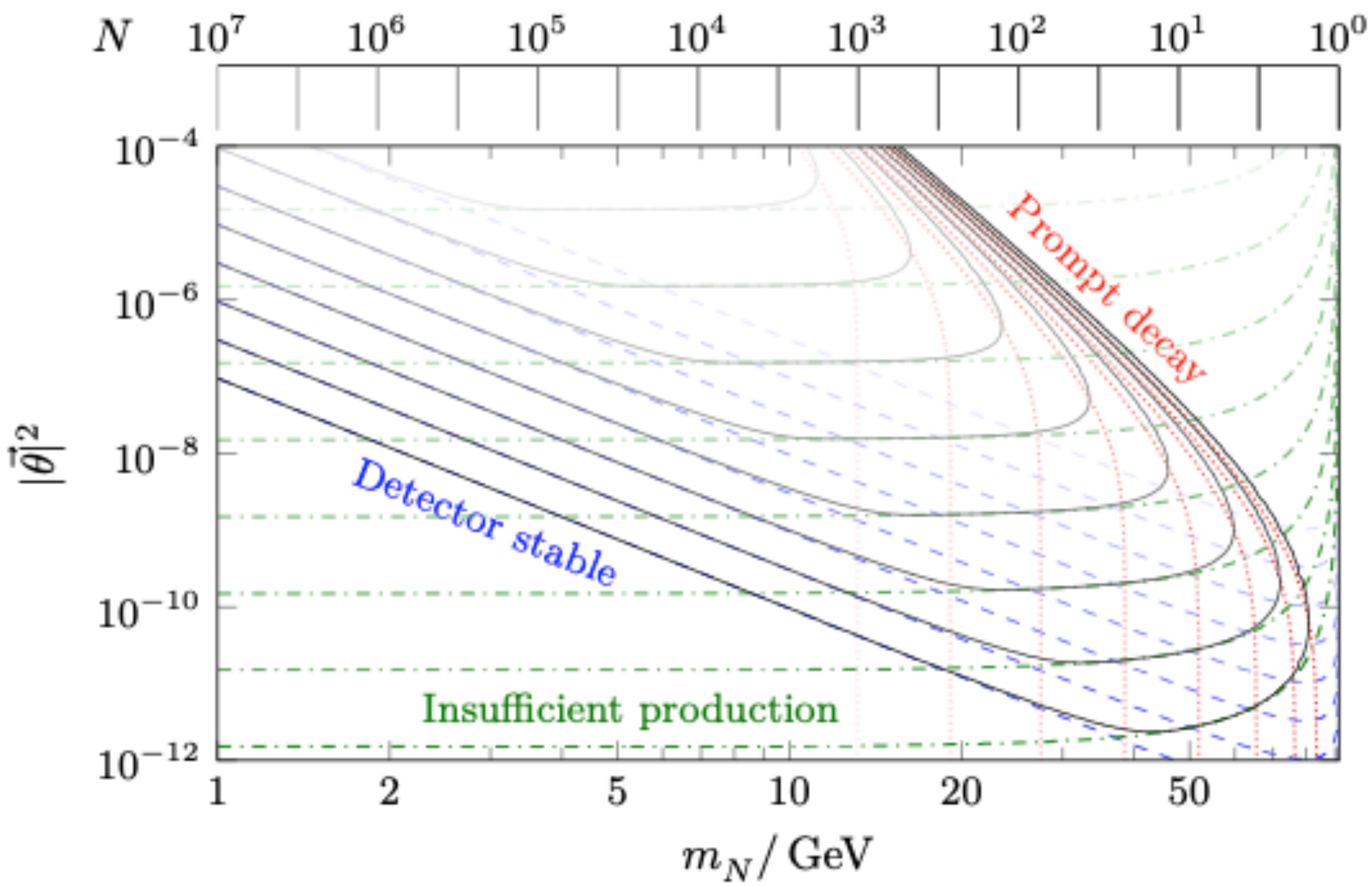



Figure 3: The testable parameter space in displaced vertex searches is constrained by the geometry of the detector. The minimal displacement cut limits the mass range from above (┈┈), while the maximal displacement of the reconstructed vertices limits the mass range from below (- - -). Finally, the cross section of the model imposes a lower limit on the testable couplings (-·-·-). The corresponding analytic approximations are given in [31].

# Cut list - one HNL

Polesello and Valle
doi:10.17181/9pc9x-kcn56

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**Table A1** Steps of event selection implemented in this analysis. The details are given in the text. The name given to each step can be used to interpret the following tables and figures.

| **1. Event Filter** | **2. Event Selection** | **3. Vertex selection** |
|---|---|---|
| 1 muon<br>$\geq 3$ tracks<br>$E_\mu \geq 3$ GeV<br>$E_{miss} \geq 5$ GeV | 1 lepton (muon)<br>Cuts on $p_{miss}$,<br>jets, $\mu$ and visible mass | $N_{tracks} - N_{tracks}^{primary} < 5$<br>$\chi^2_{vtx,primary} < 10$ |
| **4. Mass-dependent kin. selection** | **5a. Displacement: prompt** | **5b. Displacement: LL** |
| $M_{vis}$ within $2 \times 10\%\sqrt{M}$<br>$E_{miss}$ within $2 \times 10\%\sqrt{p_\nu}$ | $r_{vert}^{primary} > 0.5$ mm<br>$D_{0,\mu} < 8\sigma$ if $M_{N_1} > 70$ | $r_{vert}^{primary} < 0.5$ mm |

# Cut list - two HNLs

Giappichini et al.
arXiv:2410.03615

| Inclusive selection: | Displaced selection: |
|---|---|
| Two leptons, no photons<br>$p_{T,miss} > 5\ GeV,\ p_{T,\ell} > 1\ GeV,\ E_\ell > 2\ GeV$ | Two leptons, no photons<br>$p_{T,miss} > 5\ GeV,\ p_{T,\ell} > 1\ GeV,\ E_\ell > 2\ GeV$ |
| No other track and no neutral hadron | No other track and no neutral hadron |
| $p_{T,miss} > 10\ GeV$ | $p_{T,miss} > 10\ GeV$ |
| $cos\theta_{ll} > 0$ | $cos\theta_{ll} > -0.8$ |
| $E_{miss} > 45\ GeV$ | $M(l,l') < 80\ GeV$ |
| $E_{l,\ leading} < 35\ GeV$ | $\chi^2 < 10$ |
| $M(l,l') < M_{HNL}$ | $\|d_0\| > 0.64\ mm$ |

# Efficiencies - two HNLs

Giappichini et al.
arXiv:2410.03615

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| | Cross-section (pb) | $N_{gen}$ | Inclusive selection | Displaced selection |
|---|---|---|---|---|
| $Z \to ee$ | 1462.09 | 100000000 | $\leq$ 3.42e-13 | $\leq$ 4.38e-17 |
| $Z \to \mu\mu$ | 1462.08 | 100000000 | 1.20e-08 | $\leq$ 4.69e-16 |
| $Z \to \tau\tau$ | 1476.58 | 100000000 | 2.41e-06 | $\leq$ 8.29e-11 |
| $Z \to bb$ | 6645.46 | 438738637 | $\leq$ 4.08e-14 | $\leq$ 4.23e-14 |
| $Z \to cc$ | 5215.46 | 499786495 | $\leq$ 7.65e-12 | $\leq$ 4.10e-13 |
| $Z \to ud$ | 11870.5 | 497658654 | $\leq$ 2.04e-15 | $\leq$ 6.18e-16 |
| $Z \to ss$ | 5215.46 | 499842440 | $\leq$ 7.03e-15 | $\leq$ 3.46e-15 |
| $ee\nu\nu$ | 1.09e-02 | 1000000 | 2.25e-01 | $\leq$ 1.23e-07 |
| $\mu\mu\nu\nu$ | 4.78e-03 | 1000000 | 2.27e-01 | $\leq$ 1.12e-07 |
| $\tau\tau\nu\nu$ | 1.42e-03 | 1000000 | 1.04e-01 | $\leq$ 2.92e-07 |
| $\ell\ell'\nu\nu$ | 4.59e-03 | 1000000 | 2.66e-01 | $\leq$7.43e-09 |
| $U^2$ =2.86e-12, $M_N$=30 GeV | 4.48e-09 | 50000 | 6.01e-01 | 7.83e-01 |
| $U^2$ =6.67e-10, $M_N$=30 GeV | 1.04e-06 | 50000 | 5.79e-01 | 6.27e-01 |
| $U^2$ =5e-12, $M_N$=60 GeV | 3.75e-09 | 50000 | 3.11e-01 | 5.89e-01 |
| $U^2$ =1.33e-7, $M_N$=80 GeV | 2.27e-05 | 50000 | 2.98e-01 | $\leq$ 3.59e-06 |

# Oscillation theory

Hajer et al.
arxiv:2408.01389

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- Forward-backward asymmetry:

$$P_{N/\bar{N}}(\cos\beta) = P_+(\cos\beta) \pm P_-(\cos\beta)$$

with

$$P_+(\cos\beta) = \frac{3}{4}\frac{(1+\cos^2\beta)m_Z^2 + (a-\cos^2\beta)m_N^2}{2m_Z^2 + m_N^2}, \qquad P_-(\cos\beta) = \frac{b}{2}\cos\beta$$

- Opening angle asymmetry:

$$P_{c/v}(\cos\alpha) = P_+(\cos\alpha) \pm P_-(\cos\alpha)$$

with

$$P_+(\cos\alpha) = \frac{1}{2}, \qquad P_-(\cos\alpha) = -\frac{a(m_N, m_Z, m_W)}{2}\cos\alpha$$

- where $a$ and $b$ are the corresponding analysis power

# Cut list - oscillations

Hajer et al.
arxiv:2408.01389

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- One displaced muon ($400\ \mu m < L_{xyz} < 1\ m$)
- One jet (soft quarks, at least two tracks within $100\ \mu m$ of the muon vertex)
- Displaced vertex collinear with the HNL momentum $\Delta R \geq 0.1$
- Reconstructed HNL mass in window $\pm 2\ GeV$ of generated HNL mass

| | Events | |
|---|---|---|
| Simulated | 497068 | 100 % |
| Exactly one muon | −56228 | −11.3 % |
| Exactly one jet | −2271 | −0.515 % |
| $N$ mass window | −70177 | −16.0 % |
| Displaced muon | −5444 | −1.48 % |
| Single vertex | −13812 | −3.81 % |
| Vertex direction | −3152 | −0.903 % |
| Remaining | 345984 | 69.6 % |