Measuring lepton number violation at colliders

Jan Hajer

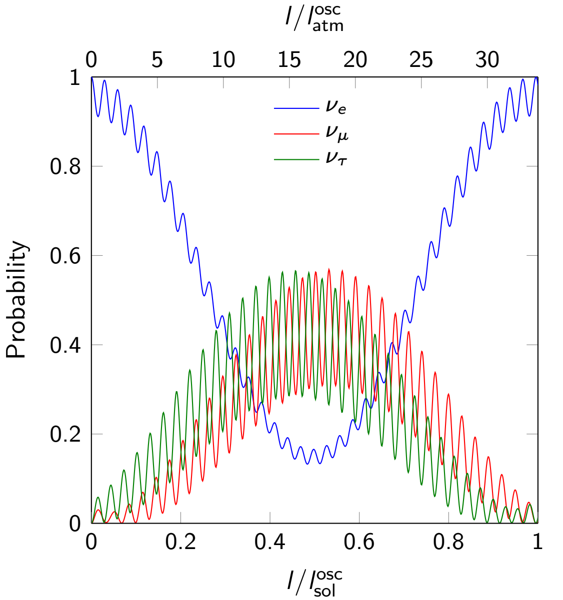
Centro de Física Teórica de Partículas, Instituto Superior Técnico, Universidade de Lisboa

Planck 2024
The 26th international conference from the Planck scale to the electroweak scale

fct Fundação para a Ciência e a Tecnologia
COMPETE 2020
PORTUGAL 2020
Funded by the European Union

Neutrino flavour oscillations and seesaw mechanism

Observed neutrino flavour oscillations



Can be explained by

at least to massive neutrinos

Right-handed Majorana neutrino N

$$\mathcal{L}_m = \begin{pmatrix} \vec{\nu} \\ N \end{pmatrix}^t \begin{pmatrix} 0 & \vec{m}_D \\ \vec{m}_D^\mathsf{T} & m_M \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ N \end{pmatrix}$$

Interaction governed by mixing parameter

$$\vec{\theta} = \frac{\vec{m}_D}{m_M} \qquad \begin{matrix} \text{Dirac mass} \\ \text{Majorana mass} \end{matrix}$$

Neutrino masses

$$m_\nu = \frac{\vec{m}_D \vec{m}_D^\mathsf{T}}{m_M} = \frac{\vec{\theta}\vec{\theta}^\mathsf{T}}{m_M}$$

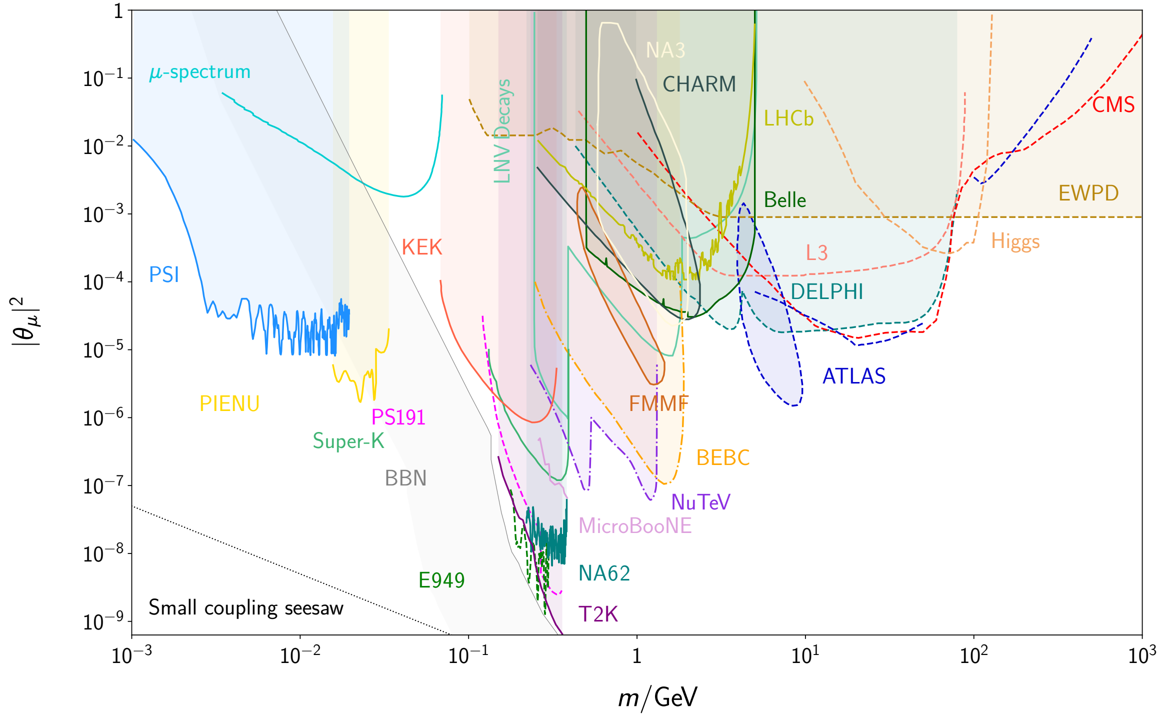
Tiny neutrino masses are ensured for

- large m_M — High scale seesaw
- small $\vec{m}_D$ — Small coupling seesaw

Sterile neutrinos/Heavy neutral leptons (HNLs)

- Inaccessibly heavy or
- Tiny interactions

Experimental searches



Inaccessible: ▪ Small coupling seesaw ▪ High scale seesaw (at the GUT scale)

Symmetry-protected low-scale seesaw

Lepton number $L = n_\ell - n_{\bar\ell}$

Accidentally conserved in the Standard Model

Generalisation: 'Lepton number'-like symmetry

e.g. $U(1)_L$ with charges

	$\vec\nu$	N_1	N_2
L	$+1$	-1	$+1$

Symmetry breaking in the mass matrix

$$\mathcal{L}_m = \begin{pmatrix} \vec\nu \\ N_1 \\ N_2 \end{pmatrix}^t \begin{pmatrix} 0 & \vec m_D & \vec\mu_D \\ \vec m_D^\intercal & \mu'_M & m_M \\ \vec\mu_D^\intercal & m_M & \mu_M \end{pmatrix} \begin{pmatrix} \vec\nu \\ N_1 \\ N_2 \end{pmatrix}$$

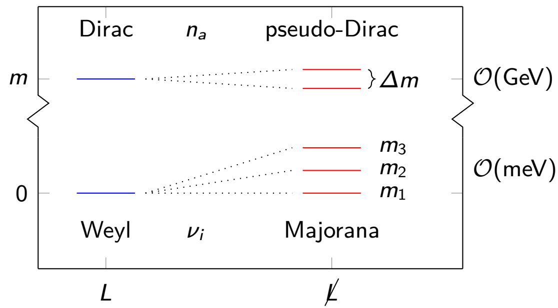
Symmetry L conserved

- Three massless neutrinos
- Single Dirac heavy neutrino
  Corresponds to two degenerate Majoranas

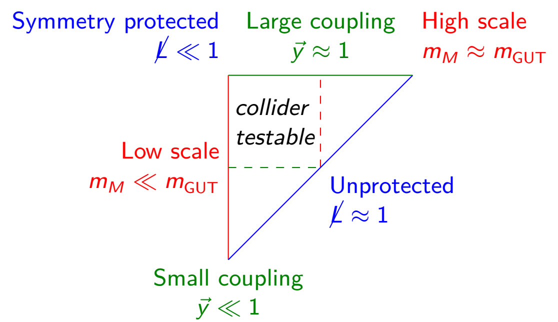
Small symmetry breaking $\not{L}$

- Light neutrino masses $m_\nu \propto \not{L}$
- Heavy neutrino mass splitting $\Delta m \propto \not{L}$

Breaking induced neutrino mass splitting



Viable seesaw limits



Heavy neutrino-antineutrino oscillations ($N\overline{N}$Os) [2210.10738]

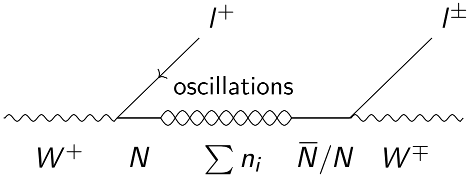
Oscillations between events that have

- Lepton number conservation (LNC) $l^\pm l^\mp$
- Lepton number violation (LNV) $l^\pm l^\pm$

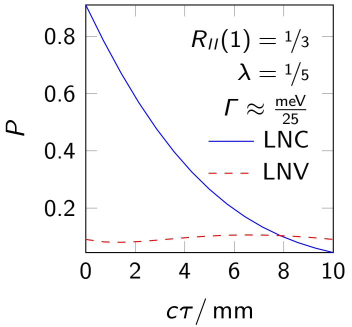
Oscillation frequency governed by Δm

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

Oscillating mass eigenstates n_i

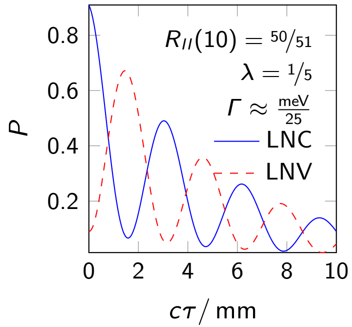


Slow oscillation



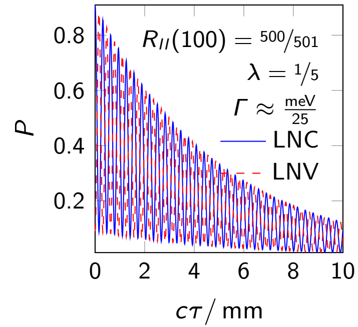
- Mostly LNC
- 'Dirac BM'-like

Intermediate oscillation

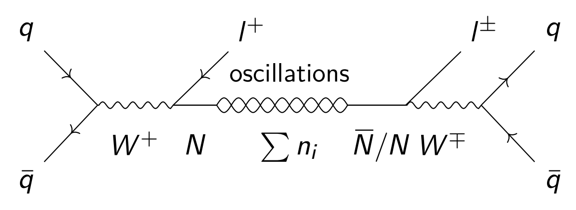


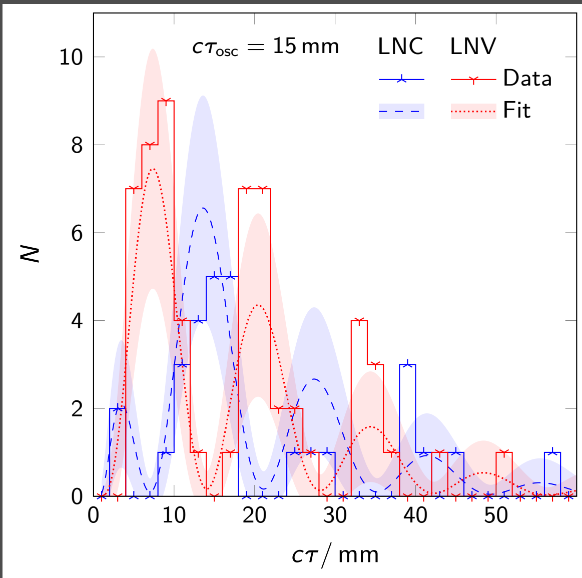
- Potentially resolvable
- $0 \leq R_{ll} = \dfrac{P_{\text{LNC}}}{P_{\text{LNV}}} \leq 1$

Fast oscillation

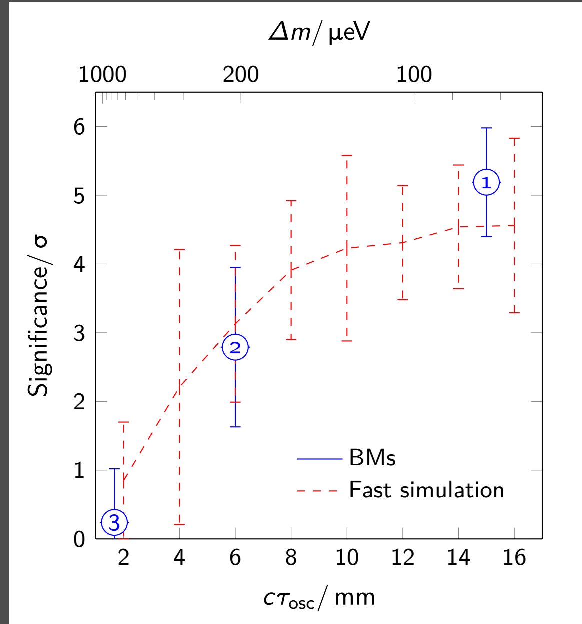


- Unresolvable
- LNV as frequent as LNC
- 'Majorana BM'-like





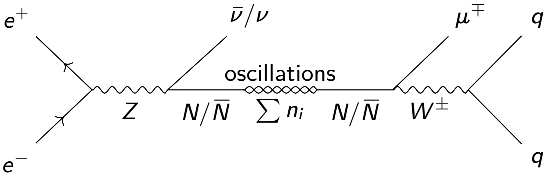
LNV is measured by comparing the charges of the two leptons



During the Z-pole run of the FCC-ee

[2308.07297]

Single charged lepton



Measurement

- LNV cannot be measured using two charges
- One can still measure angular distributions

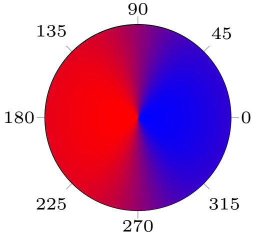
Angular dependent probability

$$P_{l^\mp}(\cos\theta, \tau) := \frac{1}{\sigma}\frac{d\sigma(\cos\theta)}{d\cos\theta} P_{\text{osc}}^{\text{LNC/LNV}}(\tau)$$

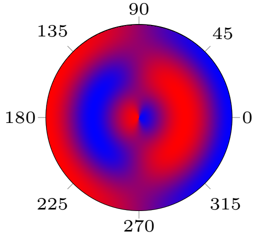
Probability of measuring charged leptons

- linked to forward backward asymmetry of neutrino production (see 'Dirac BM'-like)
- l^- from non-oscillating N or from oscillating $\overline{N}$ (similar for l^+)

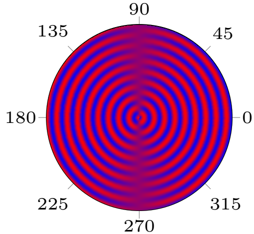
'Dirac BM'-like



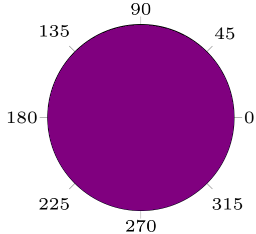
Slow oscillation



Fast oscillation



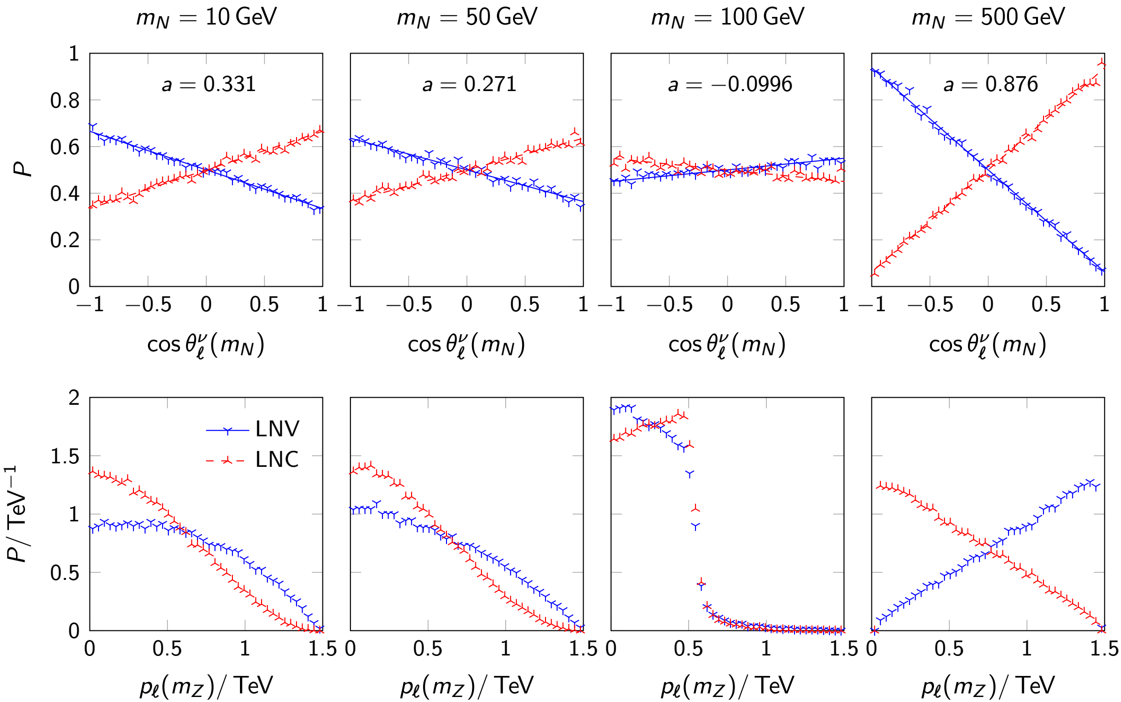
'Majorana BM'-like



LNV in distributions at future lepton colliders

[To appear]

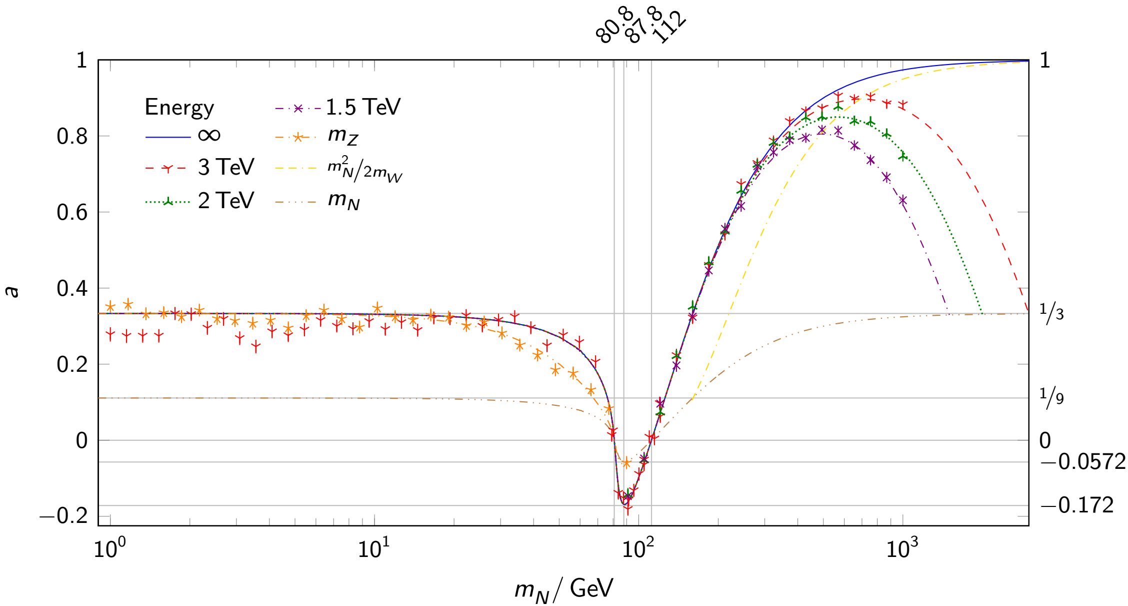
$$d\sigma_{c/v}(\cos\alpha) \propto (\sigma_0 \mp \sigma_1 \cos\alpha)\, d\cos\alpha, \qquad P^M_{c/v}(\cos\alpha) = (1 \mp a\cos\alpha)/2\,, \qquad a = \sigma_1/\sigma_0\,,$$



LNV in distributions at future lepton colliders

[To appear]

Opening angle asymmetry is sensitive to LNV



For the achievable sensitivity see talk by Bruno Oliveira

at Thursday after lunch in parallel session PII.4 in Room QA 1.4

Inadequate frameworks for oscillating relativistic particles

- Quantum mechanics
- Plane-wave QFT

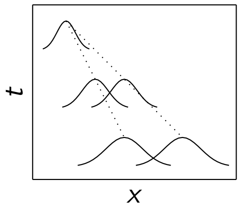
QFT with external wave packets

- Gaussian wave packets with width σ
- External widths are experiment depended parameters
- Internal widths are calculated

Transition amplitude in QFT with external wave packets Φ

$$\mathcal{A}(x) = \left\langle \Phi(x'') \middle| \mathcal{T} \exp\left[-\mathrm{i} \int \mathcal{H}(x^{\backprime})\, d^4x^{\backprime}\right] - \mathbb{1} \middle| \Phi(x') \right\rangle$$

Decoherence



Result can be expressed with

effective damping parameter λ

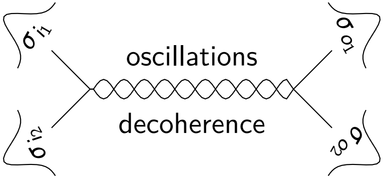
Damped oscillations

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

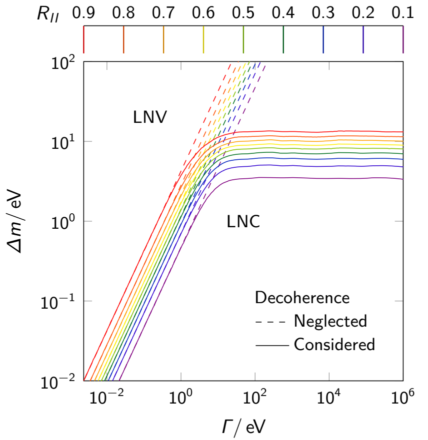
LNV can be

drastically enhanced

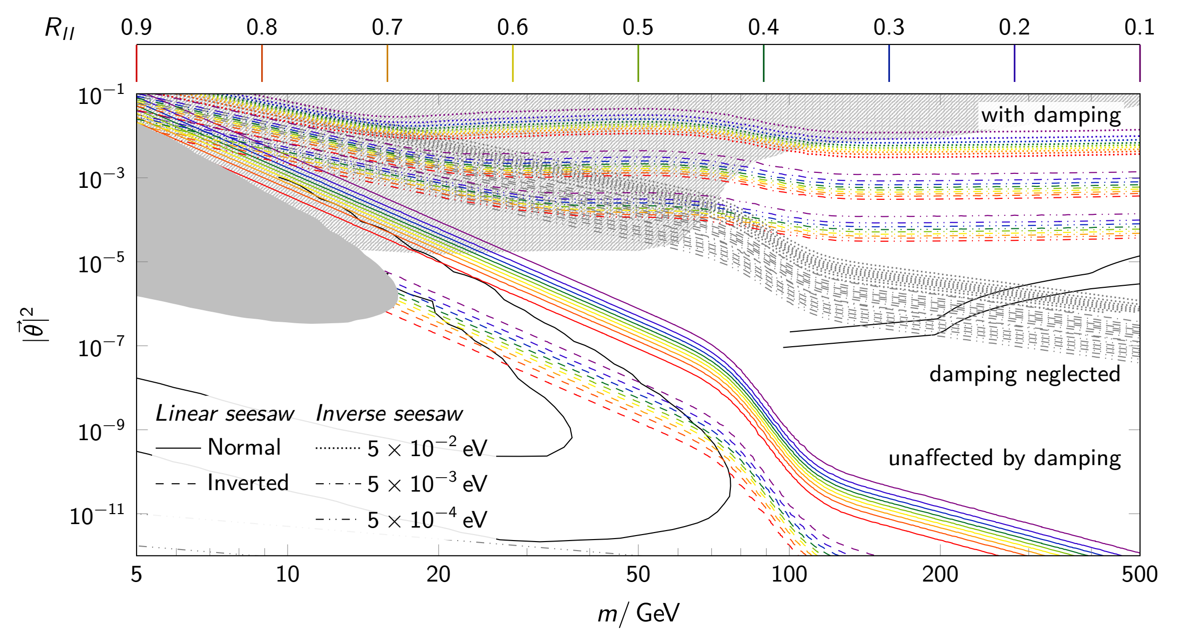
Width of external wave packets σ



Impact on $N\bar{N}$Os



Decoherence at the LHC



Minimal linear seesaw	Inverse seesaw
Not affected by decoherence	LNV significantly increased

Conclusions

- Collider testable Type I seesaw models predict pseudo-Dirac HNLs
- Collider testable single Majorana or Dirac HNLs cannot explain neutrino masses
- Pseudo-Dirac HNLs can oscillate between LNC and LNV events
- In the absence of countable LNV these $N\overline{N}$Os are the only unambiguous measurement of LNV
- Theses $N\overline{N}$Os are detectable at the HL-LHC and future lepton colliders
- Decoherence of $N\overline{N}$Os are extremely relevant

References

[2210.10738] DOI: 10.1007/JHEP03(2023)110. In: *JHEP* 03 (2023), p. 110

S. Antusch, J. Hajer, and J. Rosskopp. 'Simulating lepton number violation induced by heavy neutrino-antineutrino oscillations at colliders'.

[pSPSS] DOI: 10.5281/zenodo.7268418 (Oct. 2022)

S. Antusch, J. Hajer, B. M. S. Oliveira, and J. Rosskopp. 'pSPSS: Phenomenological symmetry protected seesaw scenario'. FeynRules model file. URL: feynrules.irmp.ucl.ac.be/wiki/pSPSS

[2212.00562] DOI: 10.1007/JHEP09(2023)170. In: *JHEP* 09 (2023), p. 170

S. Antusch, J. Hajer, and J. Rosskopp. 'Beyond lepton number violation at the HL-LHC: resolving heavy neutrino-antineutrino oscillations'.

[2308.07297] DOI: 10.1007/JHEP10(2023)129. In: *JHEP* 10 (2023), p. 129

S. Antusch, J. Hajer, and B. M. S. Oliveira. 'Heavy neutrino-antineutrino oscillations at the FCC-*ee*'.

[To appear] (June 2024)

S. Antusch, J. Hajer, and B. M. S. Oliveira. 'Discovering lepton number violation in distributions at future lepton colliders'

[2307.06208] DOI: 10.1007/JHEP11(2023)235. In: *JHEP* 11 (2023), p. 235

S. Antusch, J. Hajer, and J. Rosskopp. 'Decoherence effects on lepton number violation from heavy neutrino-antineutrino oscillations'.