Lepton number violation via heavy neutrino-antineutrino oscillations

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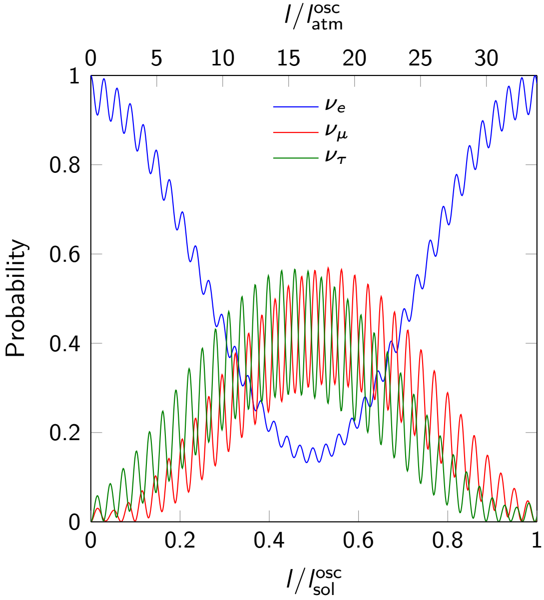
Neutrino flavour oscillations and seesaw mechanism

Observed neutrino flavour oscillations



Can be explained by

at least to massive neutrinos

Right-handed Majorana neutrino N

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

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

$$M_\nu = \frac{\vec{m}_D \vec{m}_D^\intercal}{m_M} = \frac{\vec{\theta}\vec{\theta}^\intercal}{m_M}$$

Tiny neutrino masses are ensured for

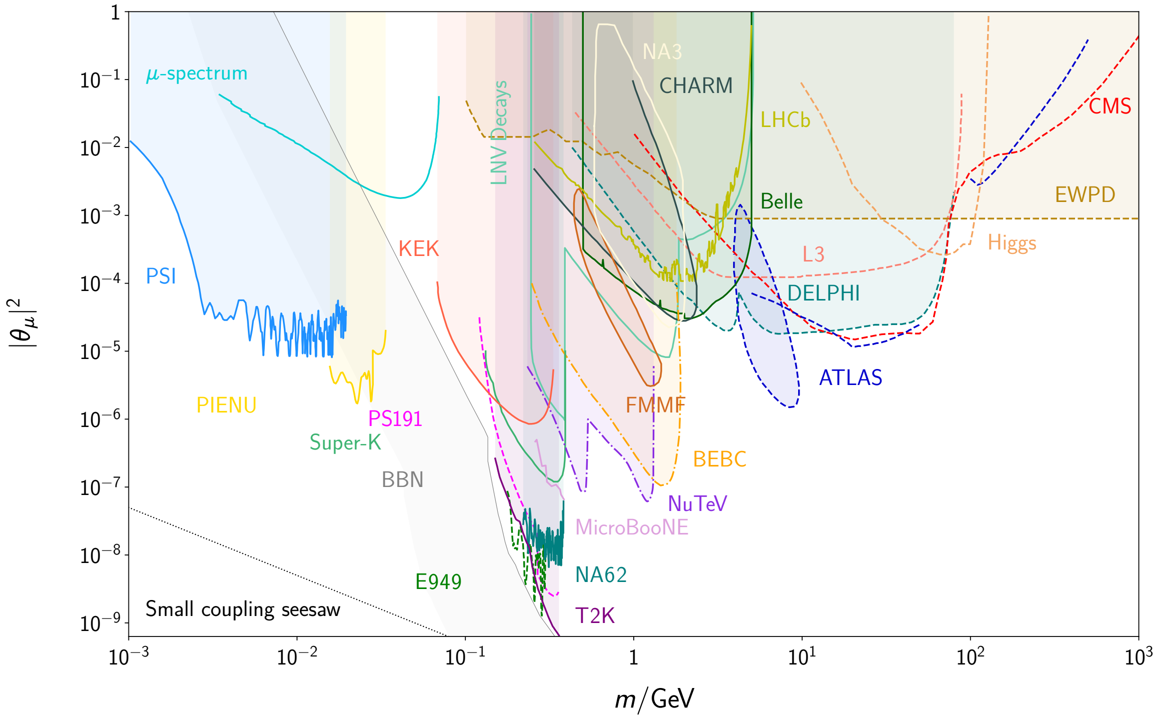
large m_M	High scale seesaw
small $\vec{m}_D$	Small coupling seesaw

Sterile neutrinos/Heavy neutral leptons (HNLs)

- Inaccessibly heavy or
- Tiny interactions

Experimental searches

[sterile-neutrino.org]



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

$$\mathcal{L}_m = \begin{pmatrix} \vec{\nu} \\ N_1 \\ N_2 \end{pmatrix}^t \begin{pmatrix} 0 & \vec{m}_D & \vec{\mu}_D \\ \vec{m}_D^\mathsf{T} & \mu'_M & m_M \\ \vec{\mu}_D^\mathsf{T} & m_M & \mu_M \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ N_1 \\ N_2 \end{pmatrix}$$

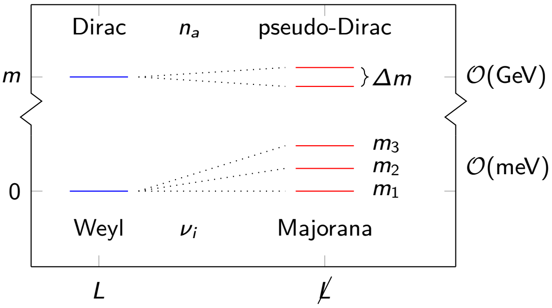
Symmetry L conserved

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

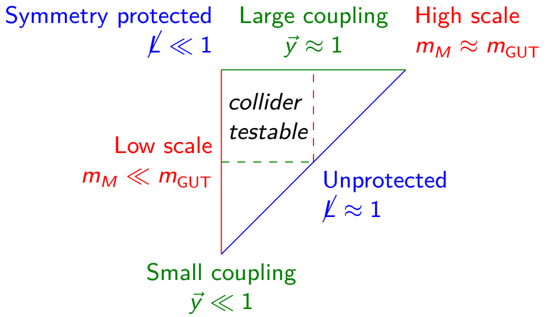
Small symmetry breaking $\cancel{L}$

- Light neutrino masses $m_\nu \propto \cancel{L}$
- Heavy neutrino mass splitting $\Delta m \propto \cancel{L}$

Breaking induced neutrino mass splitting



Viable seesaw limits



Special cases captured by the symmetry protected seesaw scenario [2210.10738]

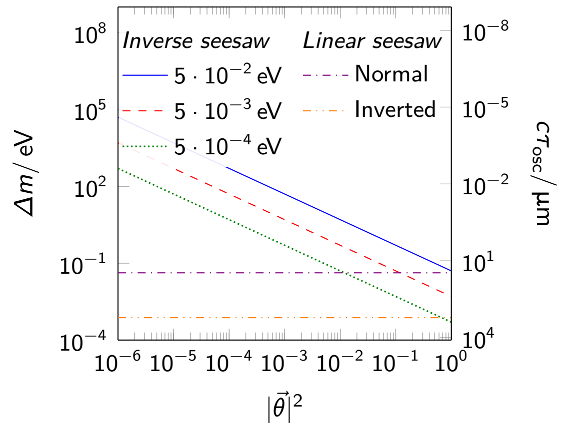
	Linear seesaw $\vec{\mu}_D$	Inverse seesaw μ_M	Seesaw independent μ'_M
$M_n =$	$\begin{pmatrix} 0 & \vec{m}_D & \vec{\mu}_D \\ \vec{m}_D^{\mathsf{T}} & 0 & m_M \\ \vec{\mu}_D^{\mathsf{T}} & m_M & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \vec{m}_D & 0 \\ \vec{m}_D^{\mathsf{T}} & 0 & m_M \\ 0 & m_M & \mu_M \end{pmatrix}$	$\begin{pmatrix} 0 & \vec{m}_D & 0 \\ \vec{m}_D^{\mathsf{T}} & \mu'_M & m_M \\ 0 & m_M & 0 \end{pmatrix}$
$M_\nu =$	$\vec{\mu}_D \otimes \vec{\theta}$	$\mu_M \vec{\theta} \otimes \vec{\theta}$	0 (at tree level)
$\Delta m =$	Δm_ν	$m_\nu \lvert\vec{\theta}\rvert^{-2}$	$\lvert\mu'_M\rvert$

Benchmark models (BMs)

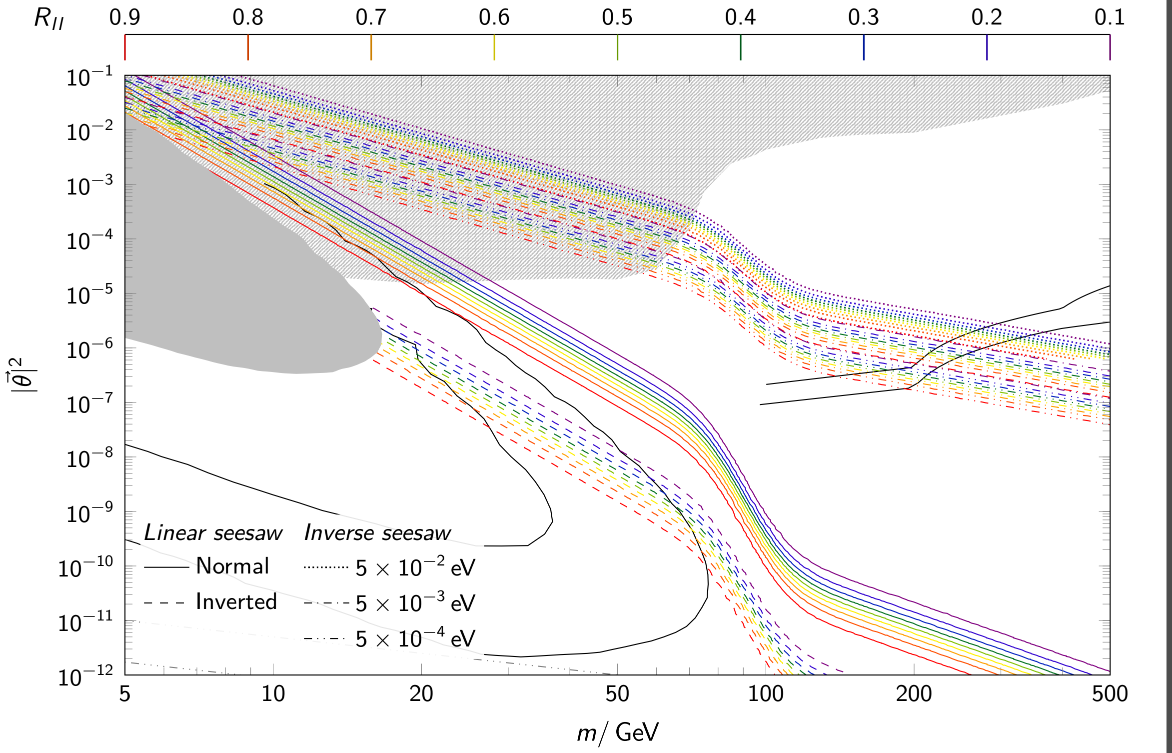
Seesaw	Hierarchy	BM
Linear	Normal	$\Delta m_\nu = 42.3\,\text{meV}$
	Inverted	$\Delta m_\nu = 748\,\mu\text{eV}$
Inverse		$m_\nu = 0.5\,\text{meV}$
		$m_\nu = 5\,\text{meV}$
		$m_\nu = 50\,\text{meV}$

Generic seesaw

All small parameter μ are nonzero

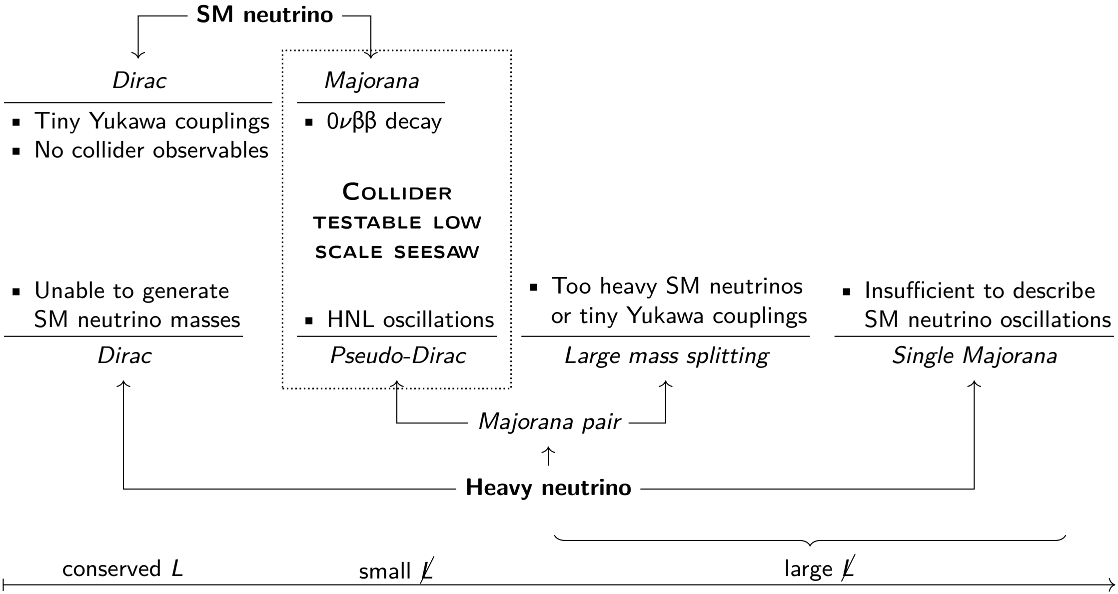


Naive lepton number violation in the BMs



Are HNLs Dirac or Majorana fermions?

[2210.10738]



SM neutrino

Dirac

- Tiny Yukawa couplings
- No collider observables

Majorana

- $0\nu\beta\beta$ decay

Collider testable low scale seesaw

- Unable to generate SM neutrino masses

Dirac

- HNL oscillations

Pseudo-Dirac

- Too heavy SM neutrinos or tiny Yukawa couplings

Large mass splitting

- Insufficient to describe SM neutrino oscillations

Single Majorana

Majorana pair

Heavy neutrino

conserved L

small $\cancel{L}$

large $\cancel{L}$

Dirac vs. Majorana

Correct BMs contain pseudo-Dirac HNLs

With care some properties can be correctly approximated by simpler BMs

Dirac BM

- ✓ Correct production cross section
- ✓ Correct decay width
- ϟ No lepton number violation (LNV)
- ϟ No neutrino masses

Majorana BM

- ✓ Correct production cross section
- ϟ Wrong decay width
- ✓ LNV
- ϟ Generically too much LNV

Displaced vertex searches for Dirac HNLs

Generically correct

Prompt searches for LNV with Majorana HNLs

- Generically the bounds are too strong
- In many cases no bounds can be extracted
- Can be correct for some parameter points

→ Model depended reinterpretation necessary

Distinguishing Dirac from Majorana HNL

is not a well posed research question/goal

Particle content of BM candidates

[pSPSS]

Good BM

- Reproduces neutrino mass scale
- Captures dominant collider effects
- Minimal possible number of parameters

Minimal parameter set for single pseudo-Dirac

- Mass m
- Coupling vector $\vec{\theta}$
- Mass splitting Δm

Number of Majorana degree of freedoms (DOFs)

DOF	Particles	Properties	
1	Majorana	One massive light neutrino / Γ wrong	ϟ
2	Dirac	No massive light neutrino	ϟ
	pseudo-Dirac	Minimal linear seesaw / pSPSS	✓
	2 Majorana	Light neutrinos too heavy	ϟ
3	pseudo-Dirac + Majorana	νMSM (Dark Matter)	✓
		Majorana active (no Dark Matter)	✓
4	2 pseudo-Dirac	Minimal inverse seesaw	✓
5	2 pseudo-Dirac + Majorana	. . .	
6	3 pseudo-Dirac	. . .	

The symmetry protected seesaw scenario is the minimal viable model; The phenomenological symmetry protected seesaw scenario (pSPSS) is its most minimal implementation

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

[2210.10738]

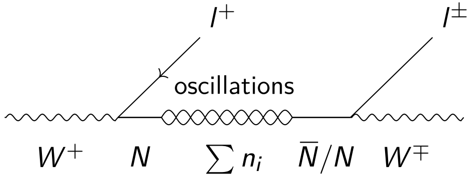
Oscillations between events that have

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

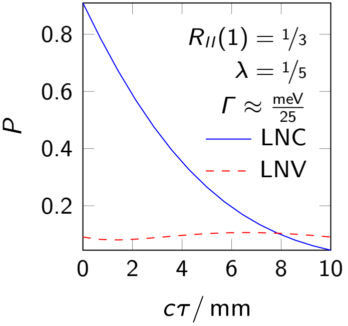
Oscillation frequency governed by Δm

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

Oscillating mass eigenstates n_i

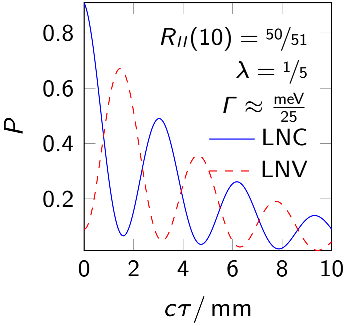


Slow oscillation



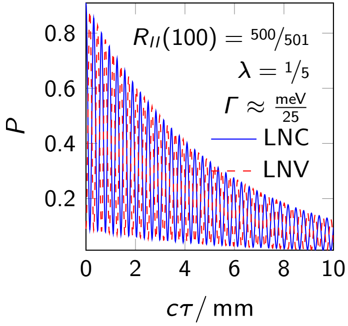
- Mostly LNC
- ‘Dirac BM’-like

Intermediate oscillation



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

Fast oscillation



- Unresolvable
- LNV as frequent as LNC
- ‘Majorana BM’-like

Decaying oscillations

[2210.10738]

HNLs can be long-lived particless

$$P_{\mathrm{decay}}(\tau) = -\frac{d}{d\tau}\exp(-\Gamma\tau) = \Gamma\exp(-\Gamma\tau)$$

Since they are pseudo-Dirac they oscillate

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

Collider signature: Decaying oscillations

$$P^{\mathrm{LNC}/\mathrm{LNV}}_{ll}(\tau) = P_{\mathrm{decay}}(\tau)P^{\mathrm{LNC}/\mathrm{LNV}}_{\mathrm{osc}}(\tau)$$

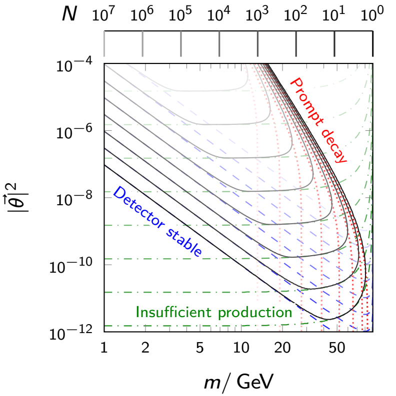
Time-integrated oscillations

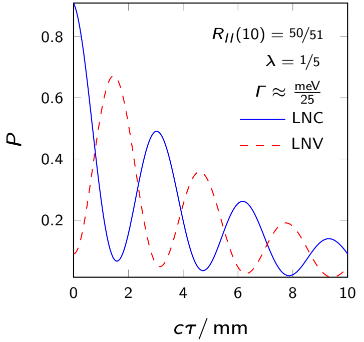
[2307.06208]

$$P^{\mathrm{LNC}/\mathrm{LNV}}_{ll} = \frac{1}{2} \pm \frac{1}{2}\frac{\Gamma^2}{\Gamma^2 + \Delta m^2}$$

Charged lepton ratio

$$R_{ll} = \frac{P^{\mathrm{LNV}}_{ll}}{P^{\mathrm{LNC}}_{ll}} = \frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2}$$





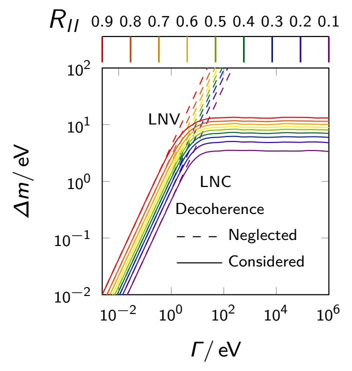
Problems measuring R_{ll}

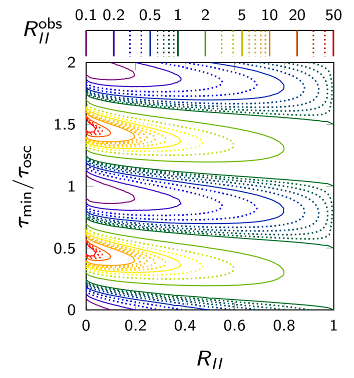
Integration limits correspond to [2210.10738]

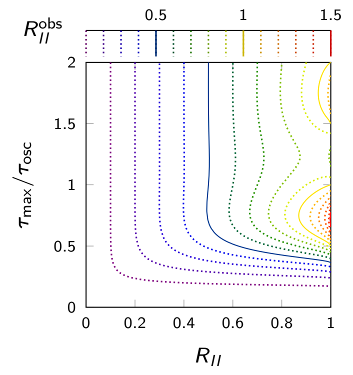
- Minimal distance cut
- Maximal measurable vertex distance

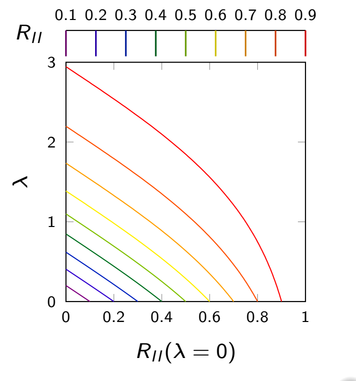
Decoherence [2307.06208]

- Quantum mechanical oscillations can suffer from decoherence
- Calculation in external wave packet formalism
- Can increase measurable LNV drastically
- Captured by single parameter λ









Oscillating particles in quantum field theory (QFT)

[2307.06208]

Inadequate frameworks for oscillating relativistic particles

- Quantum mechanics
- Plane-wave QFT

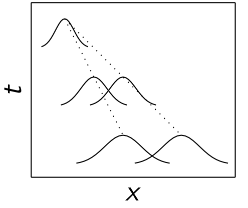
QFT with external wave packets

- 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

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

Decoherence



Result can be expressed with

effective damping parameter λ

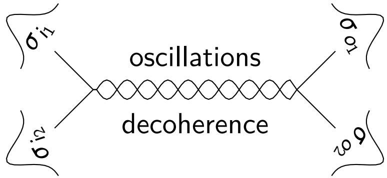
Damped oscillations

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

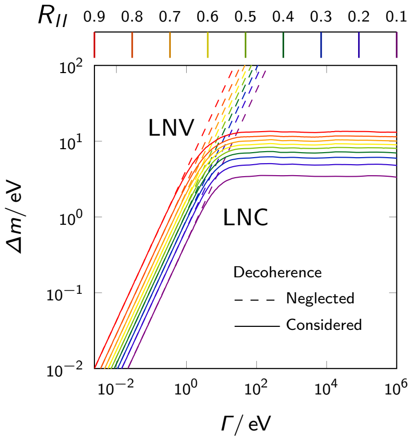
LNV can be

drastically enhanced

Width of external wave packets σ

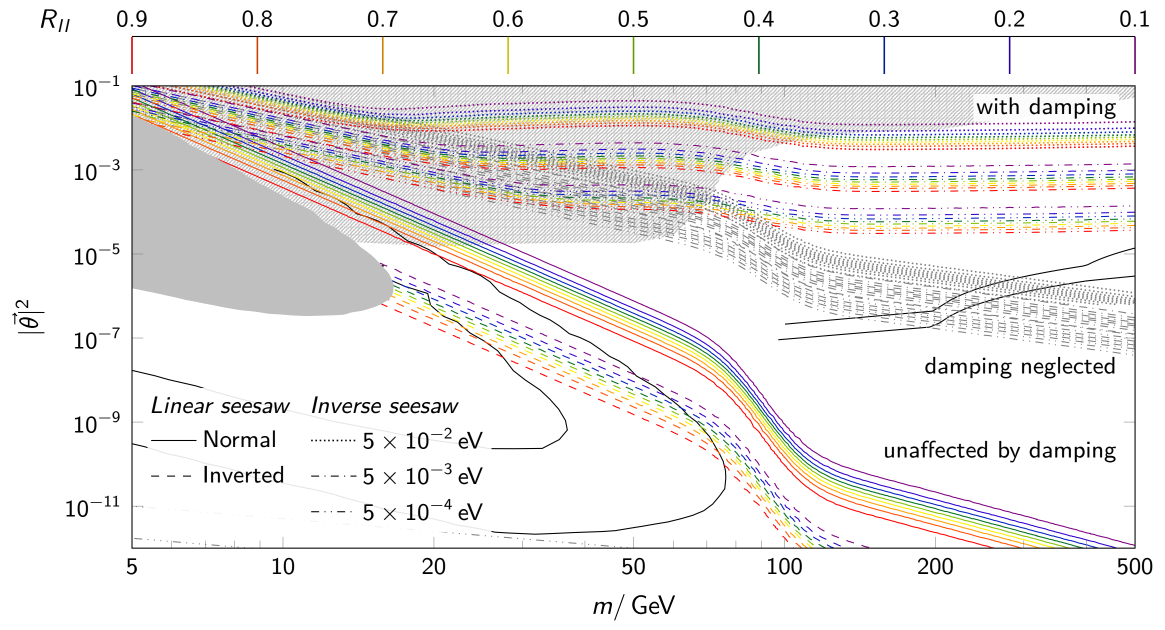


Impact on $N\overline{N}$Os



Decoherence at the LHC

[2307.06208]



Minimal linear seesaw

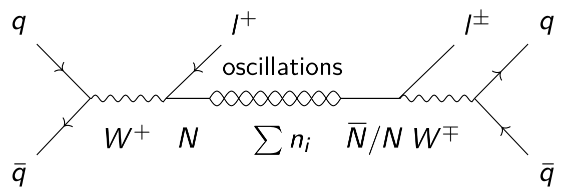
Not affected by decoherence

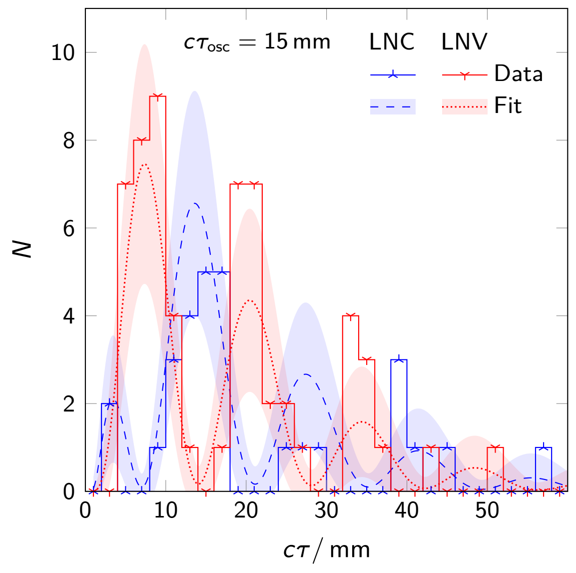
Inverse seesaw

LNV significantly increased

Measuring LNV at the HL-LHC

[pSPSS, 2212.00562]

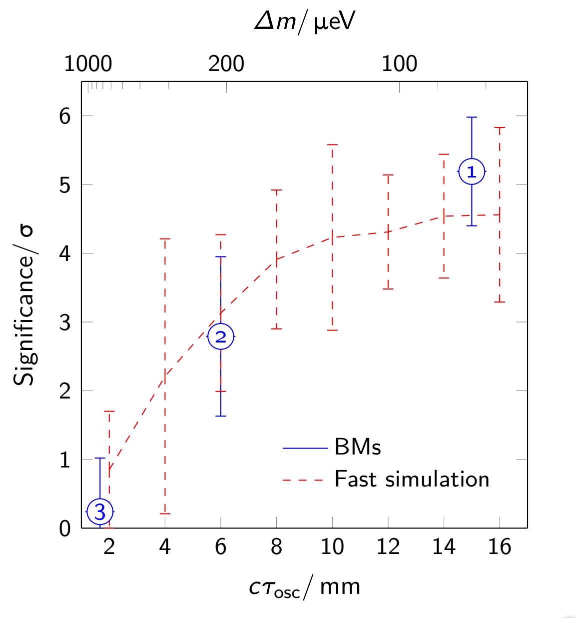




LNV can be measured

by counting the charges of the two leptons

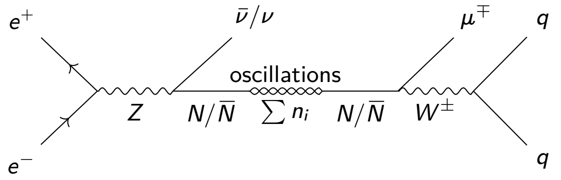
Significance for a BM



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

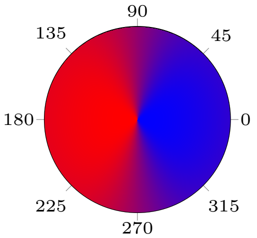
Angular dependent probability

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

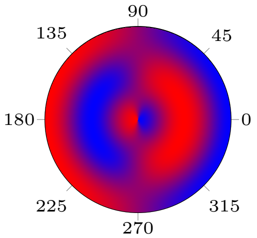
Probability of measuring charged leptons

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

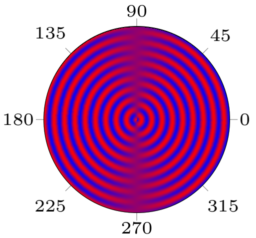
'Dirac BM'-like



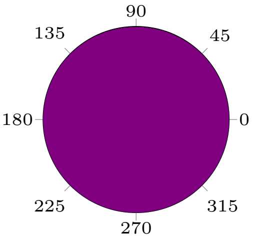
Slow oscillation



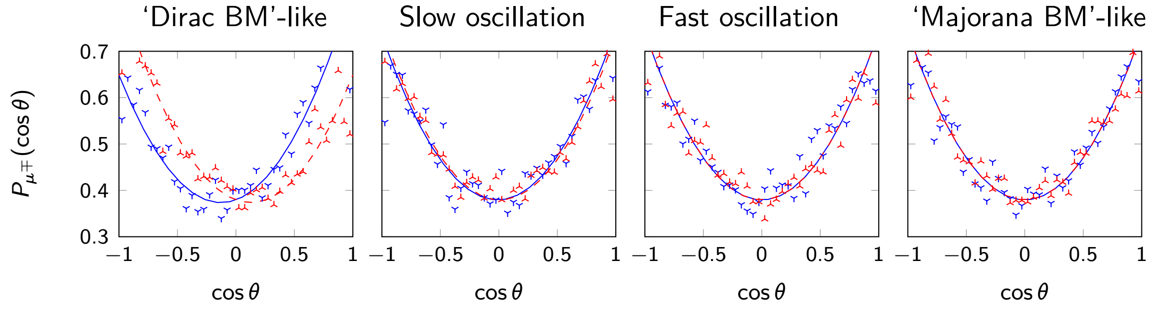
Fast oscillation



'Majorana BM'-like



Time and angular integrated observable

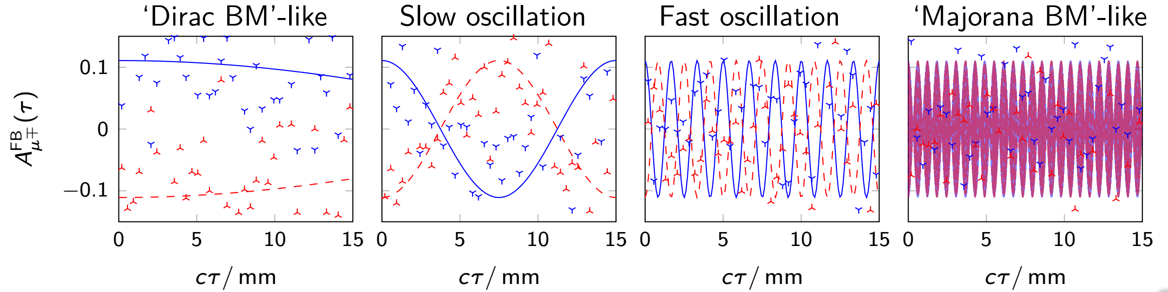


Time integrated probability

$$P_{l\mp}(\cos\theta) := \int_0^\infty P_{l\mp}(\tau, \cos\theta)\, d\tau$$

Angular integrated probability

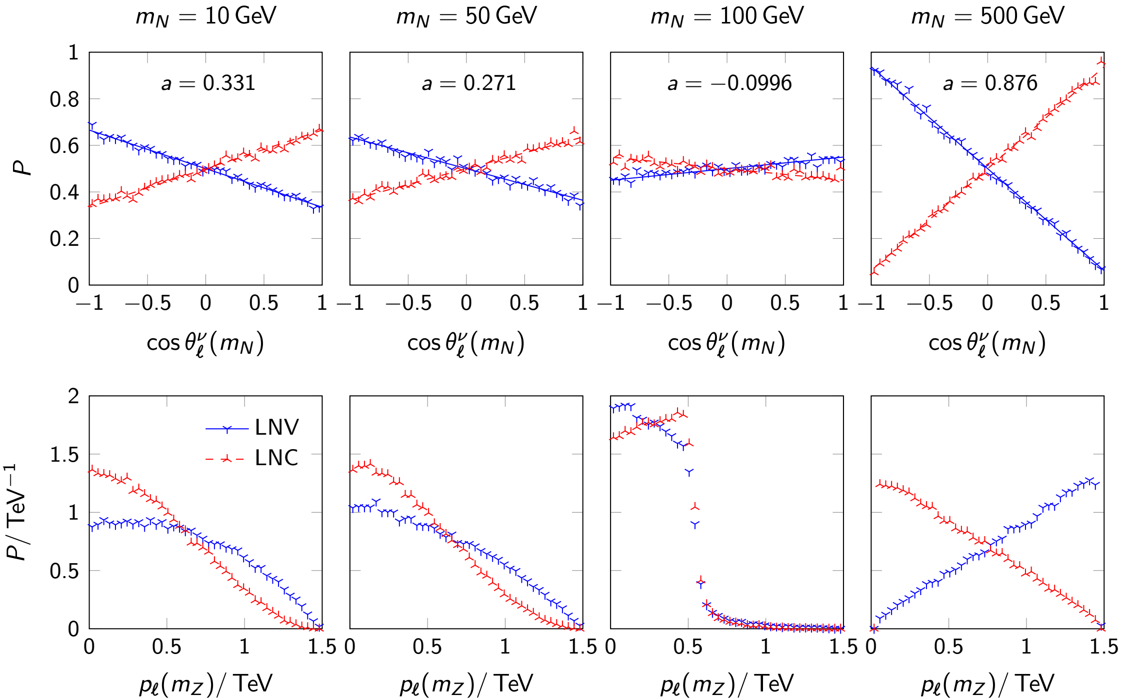
$$P_{l\mp}^{[\theta_{\min},\theta_{\max}]}(\tau) := \int_{\cos\theta_{\min}}^{\cos\theta_{\max}} P_{l\mp}(\tau, \cos\theta)\, d\cos\theta$$



LNV in distributions at future lepton colliders

[To appear]

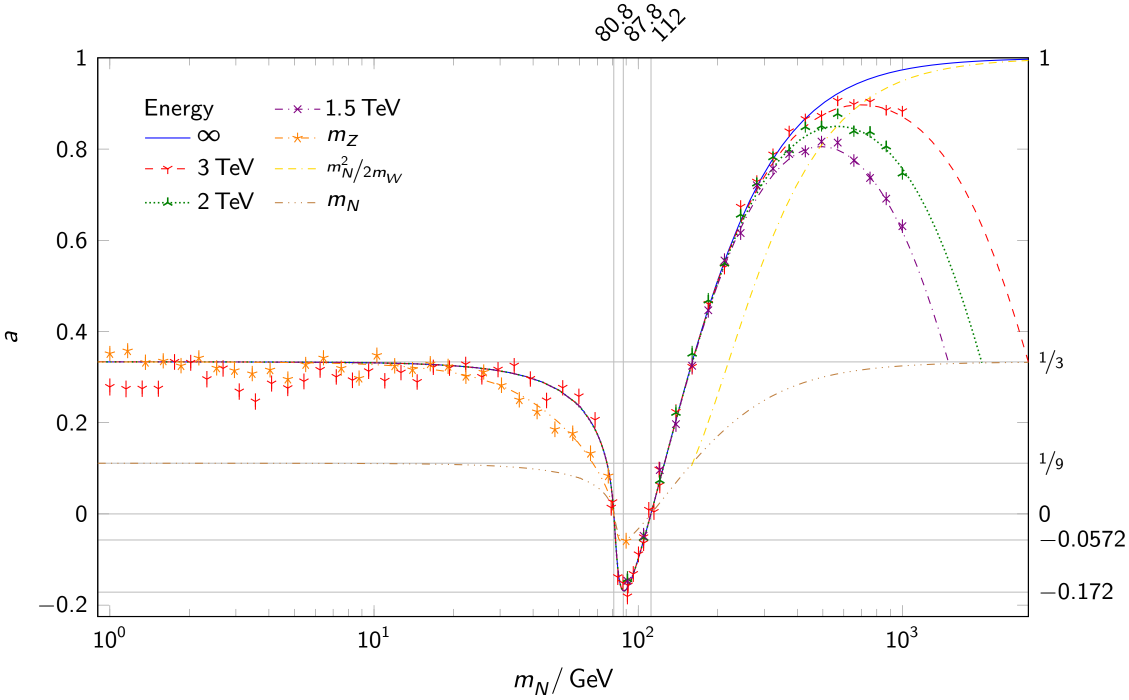
$$d\sigma_{c/v}(\cos\alpha) \propto (\sigma_0 \mp \sigma_1 \cos\alpha)\, d\cos\alpha, \qquad P^{M}_{c/v}(\cos\alpha) = (1 \mp a\cos\alpha)/2\,, \qquad a = \sigma_1/\sigma_0\,,$$



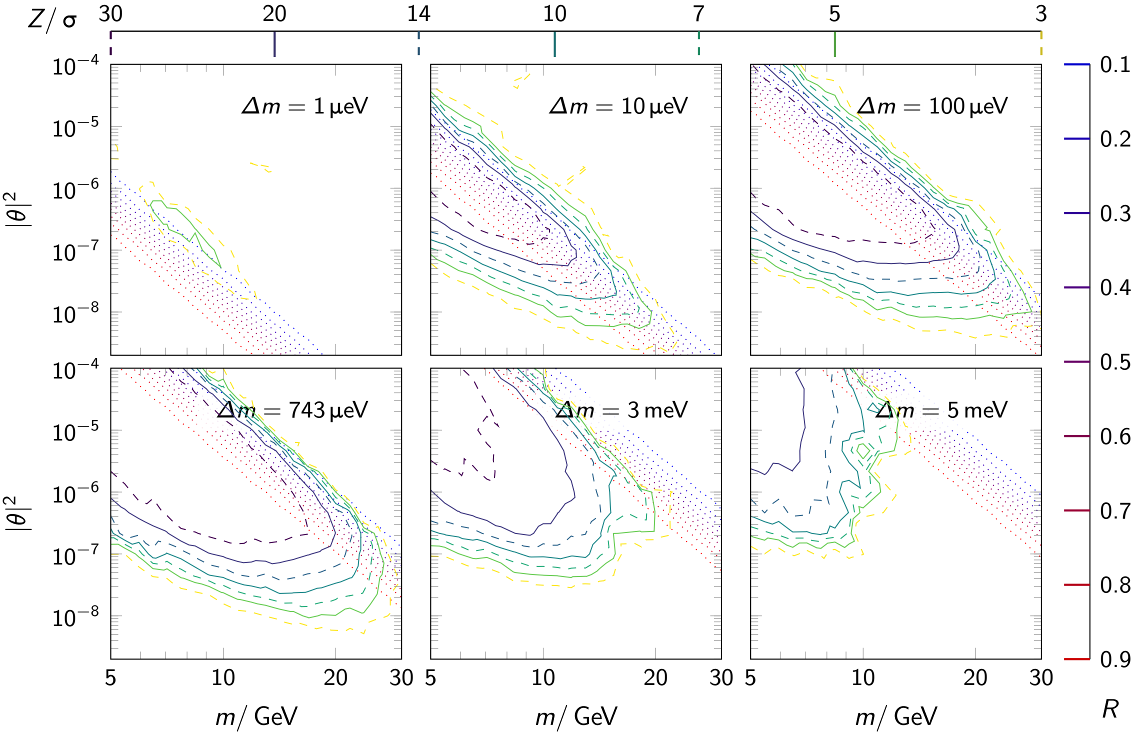
LNV in distributions at future lepton colliders

[To appear]

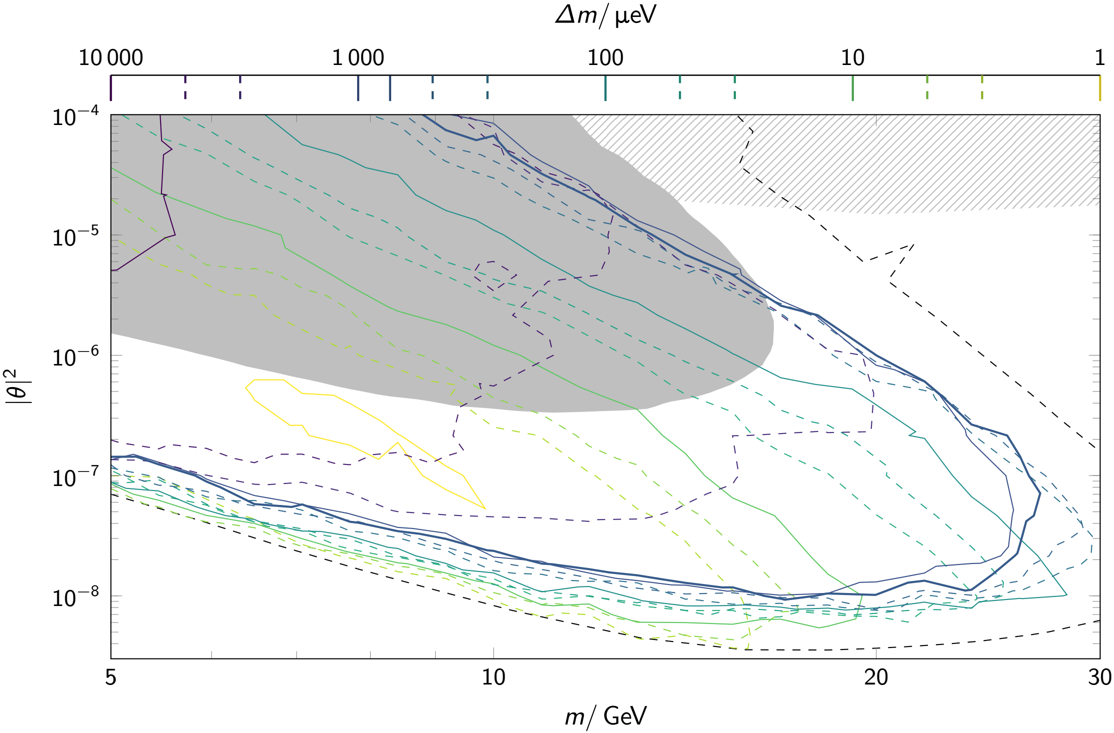
Opening angle asymmetry is sensitive to LNV



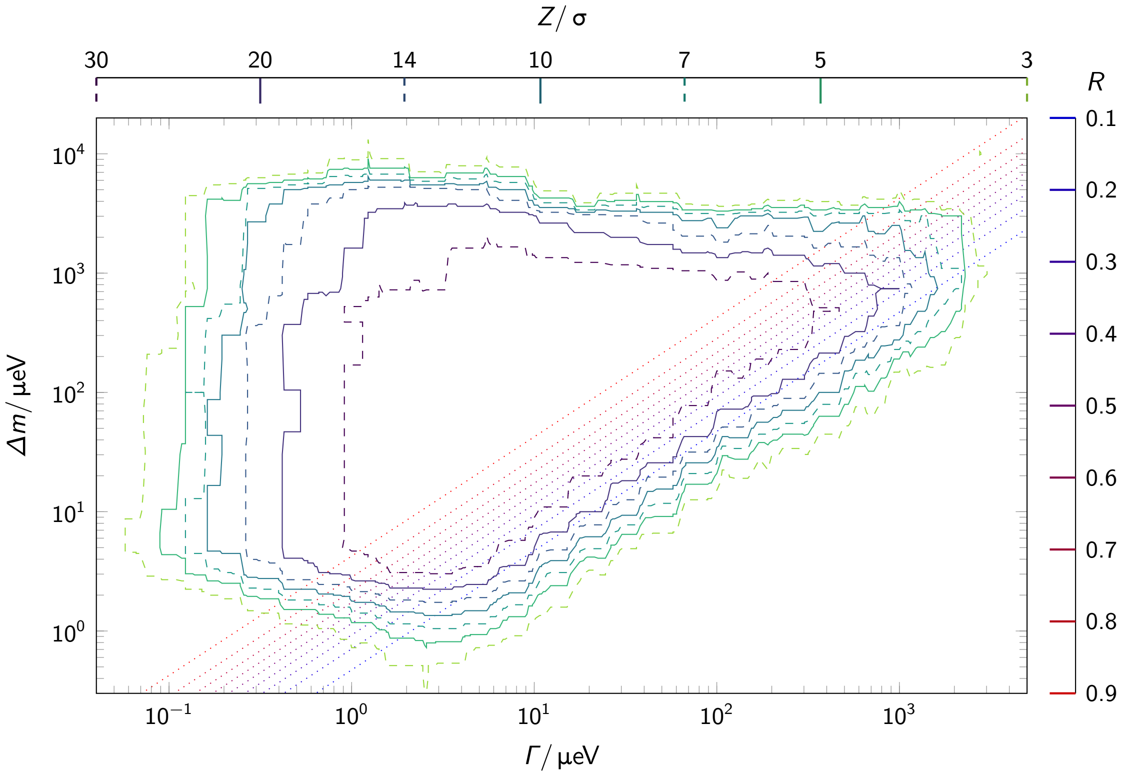
Significance for different mass splittings



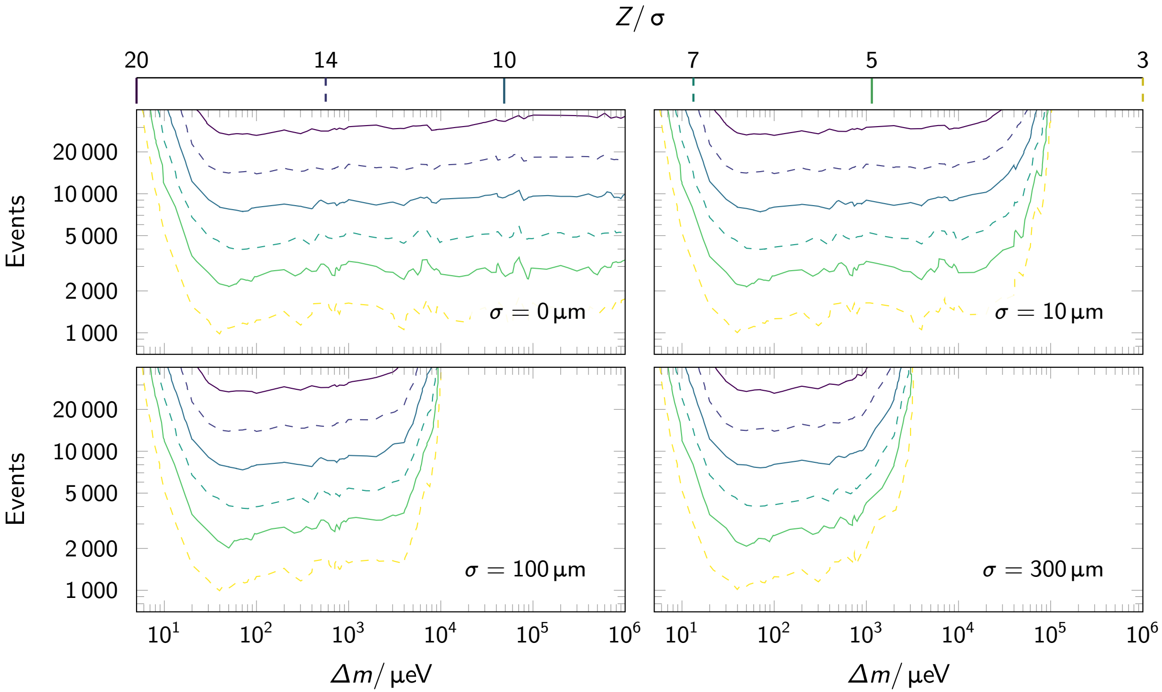
5 σ discovery reach



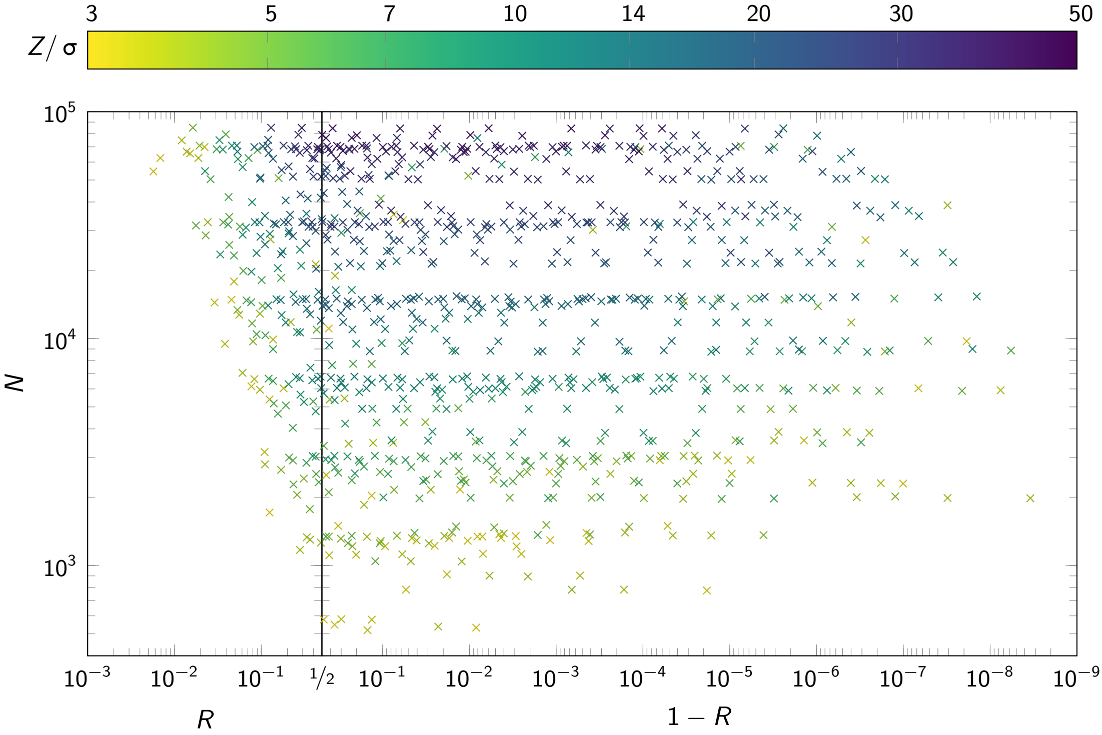
Maximal significance



Significance dependents on the vertex reconstruction error



Testable values of the LNV ratio



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`

[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'.

[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'