Heavy neutrino-antineutrino oscillations at the FCC-*ee*

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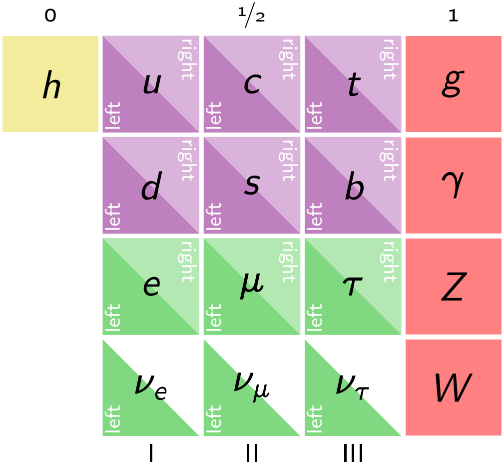
Standard Model neutrinos

Standard Model (SM) particle content



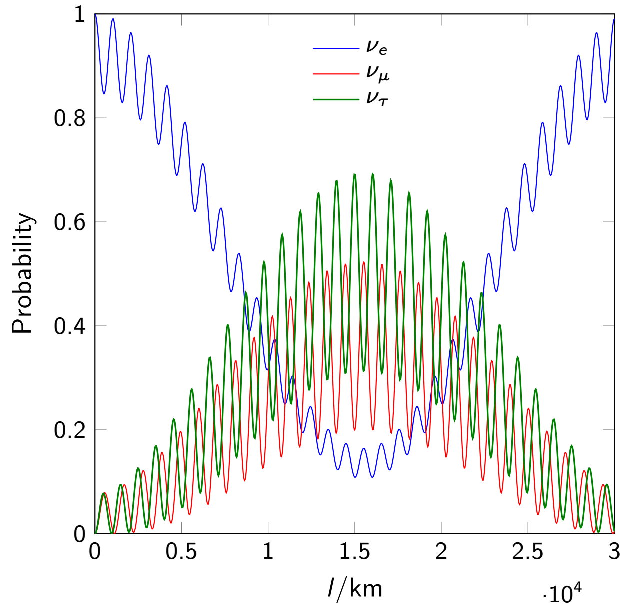
Neutrinos ν_α stand out

purely left-chiral and massless

Right-chiral or sterile Neutrinos

neutral under SM symmetries

Observed neutrino flavour oscillations



Flavour oscillations are explained by

right-chiral neutrinos allowing mass terms

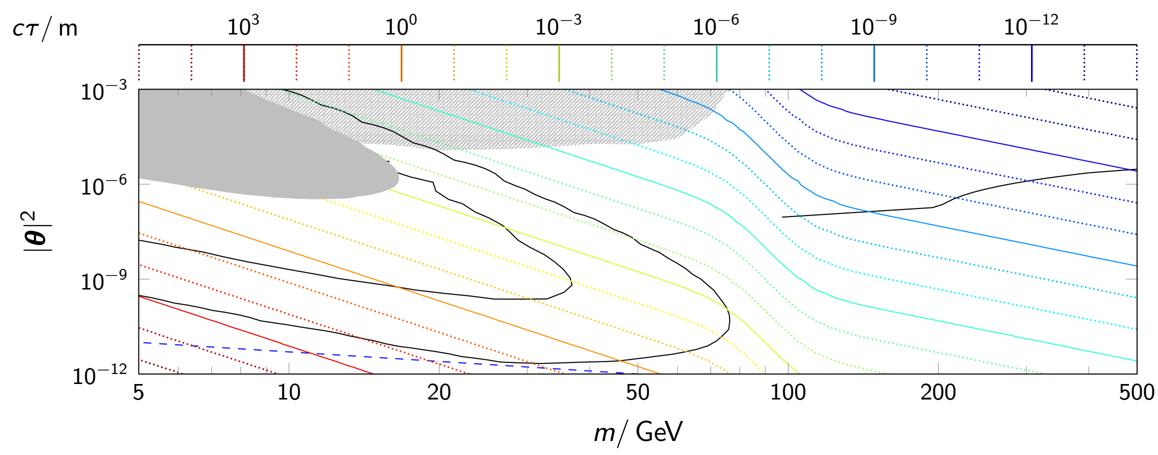
Simplest model

Interactions of a Majorana or Dirac heavy neutral lepton (HNL)

$$\mathcal{L}_N = -\frac{m_W}{v}\overline{N}\boldsymbol{\theta}^*\gamma^\mu e W_\mu^+ - \frac{m_Z}{\sqrt{2}v}\overline{N}\boldsymbol{\theta}^*\gamma^\mu \nu Z_\mu - \frac{m}{\sqrt{2}v}\boldsymbol{\theta} h \overline{\nu} N + \text{H.c.}$$

Seesaw mass

$$M_\nu = m_M \boldsymbol{\theta} \otimes \boldsymbol{\theta}$$



Dirac

- ϟ No massive light neutrino
- ϟ No LNV

Majorana

- ϟ Single massive light neutrino
- ϟ Only tiny couplings or GUT scale generates correct ν mass
- ϟ Decay width wrong by factor of 2

Seesaw model regimes

Dirac mass

$$\mathcal{L}_D = -m_D \bar{\nu} N + \text{h.c.}\,, \qquad \boldsymbol{m}_D = v \boldsymbol{y}$$

Majorana mass

$$\mathcal{L}_M = -\frac{1}{2} m_M \overline{N} N^c + \text{h.c.}$$

Coupling strength is determined by

$$\boldsymbol{\theta} = \boldsymbol{m}_D / m_M$$

Majorana mass introduces

Lepton number violation (LNV)

Majorana mass vanishes if

lepton-number L is conserved

Neutrino oscillation pattern requires

at least two massive neutrinos

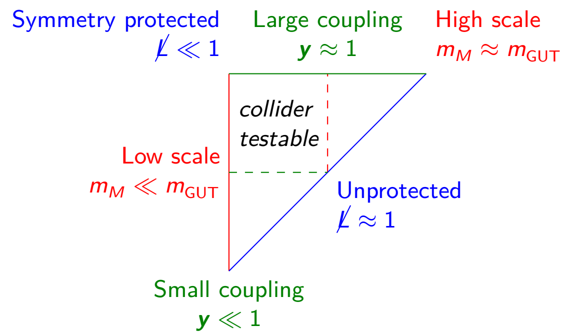
Collider-testable low-scale seesaw models

predict pseudo-Dirac HNLs

Neutrino mass matrix from two sterile neutrinos

$$M_\nu = \frac{\boldsymbol{m}_D^{(1)} \otimes \boldsymbol{m}_D^{(1)}}{m_M^{(1)}} + \frac{\boldsymbol{m}_D^{(2)} \otimes \boldsymbol{m}_D^{(2)}}{m_M^{(2)}}$$

Viable seesaw models



Neutrino masses are small for

- small $\boldsymbol{y}$
- large m_M
- symmetry protected cancellation

Single pseudo-Dirac symmetry protected seesaw scenario (SPSS) [2210.10738]

Exact limit

$$\mathcal{L}^{L}_{\text{SPSS}} = -m_M \overline{N}_1 N_2^c - y_1 \widetilde{H}^\dagger \bar{\ell} N_1^c + \text{h.c.}$$

Small breaking terms $v y_2 \approx \mu_M \approx \mu'_M \ll m_M$

$$\mathcal{L}^{\not{L}}_{\text{SPSS}} = -y_2 \widetilde{H}^\dagger \bar{\ell} N_2^c - \mu'_M \overline{N}_1 N_1^c - \mu_M \overline{N}_2 N_2^c + \text{h.c.}$$

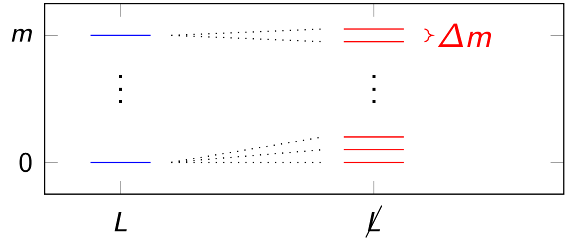
Lepton number-like symmetry

generalises accidental SM lepton number L

One simple choice of charges

	ℓ	N_1	N_2
L	$+1$	-1	$+1$

Mass splitting induced by symmetry breaking



Symmetric limit

$$M_n^L = \begin{pmatrix} 0 & \boldsymbol{m}_D & 0 \\ \boldsymbol{m}_D^\mathsf{T} & 0 & m_M \\ 0 & m_M & 0 \end{pmatrix}$$

- Massless neutrinos $M_\nu = 0$
- Dirac HNL

Mild symmetry breaking

$$M_n^{\not{L} \ll 1} = \begin{pmatrix} 0 & \boldsymbol{m}_D & \boldsymbol{\mu}_D \\ \boldsymbol{m}_D^\mathsf{T} & \mu'_M & m_M \\ \boldsymbol{\mu}_D^\mathsf{T} & m_M & \mu_M \end{pmatrix}$$

- Pseudo-Dirac HNL (small Δm Majorana pair)
- Phenomenology governed by small parameters μ

Large symmetry breaking

$$M_n^{\not{L} \gg 0} = \begin{pmatrix} 0 & \boldsymbol{m}_D & \widehat{\boldsymbol{m}}_D \\ \boldsymbol{m}_D^\mathsf{T} & \widehat{m}'_M & m_M \\ \widehat{\boldsymbol{m}}_D^\mathsf{T} & m_M & \widehat{m}_M \end{pmatrix}$$

- Large Δm Majorana pair
- Requires large m_M or tiny $\boldsymbol{\theta}$

Particle content of benchmark model candidates

Number of Majorana degrees of freedom (DOFs)

DOF	Particles	Properties	
1	Majorana	One massive light neutrino	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	...	

Good benchmark model

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

Minimal 'single pseudo-Dirac' parameter set

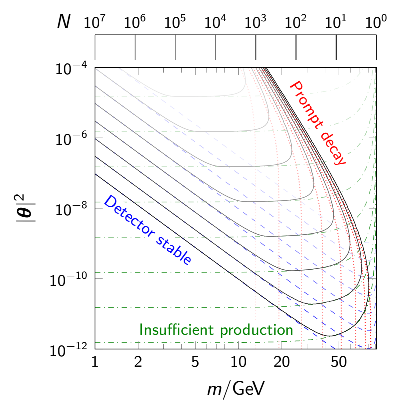
- Mass m
- Coupling vector $\boldsymbol{\theta}$
- Mass splitting Δm

Decaying oscillations

[2210.10738]

HNLs can be long-lived particles

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



Decaying oscillations

[2210.10738]

HNLs can be long-lived particles

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

Since they are pseudo-Dirac they oscillate

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

Collider signature: Decaying oscillations

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

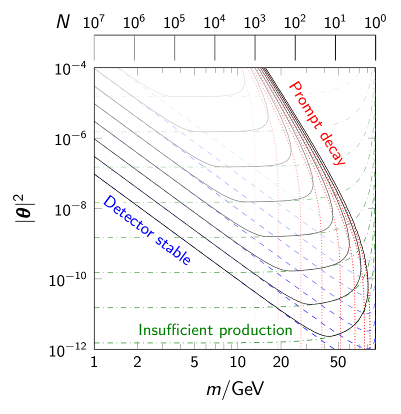
Time-integrated oscillations

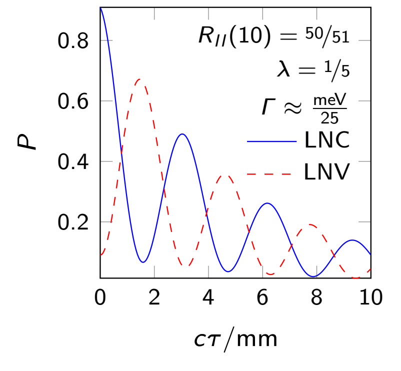
[2307.06208]

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

Charged lepton ratio

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





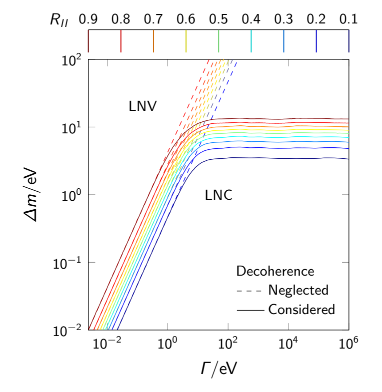
Problems measuring R_{ll}

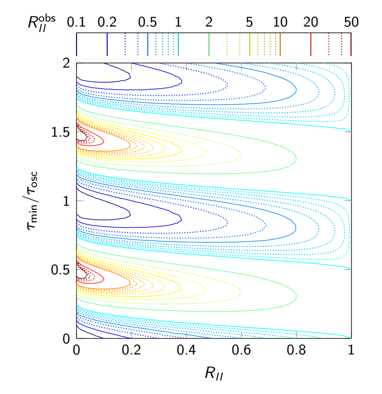
Integration limits correspond to [2210.10738]

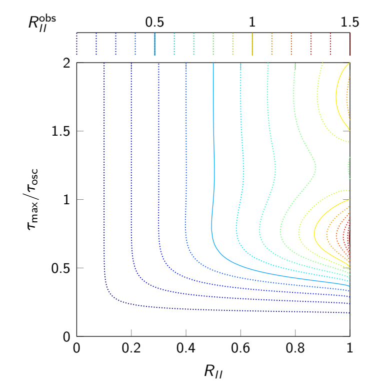
- Minimal distance cut
- Maximal measurable vertex distance

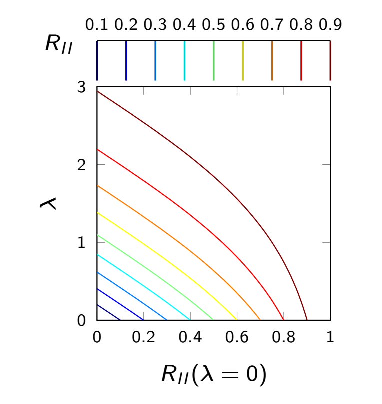
Decoherence [2307.06208]

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









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

Oscillations

between LNC and LNV processes

Damping due to decoherence

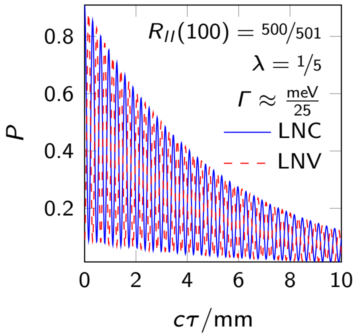
governed by λ

Oscillation length

governed by mass splitting Δm

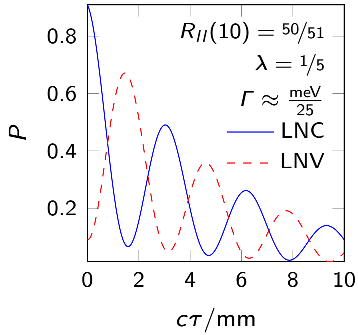
$$P_{\text{osc}}^{\text{LNC/LNV}}(\tau) = \frac{1 \pm \cos(\Delta m \tau)\exp(-\lambda)}{2}$$

Short oscillation length



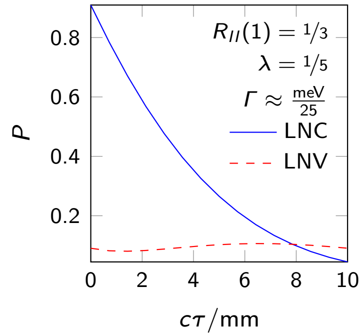
- Oscillations not resolvable
- Large R_{ll}
- 'Majorana BM'-like

Intermediate oscillation length



- Oscillations potentially measurable
- Pseudo-Dirac character crucial

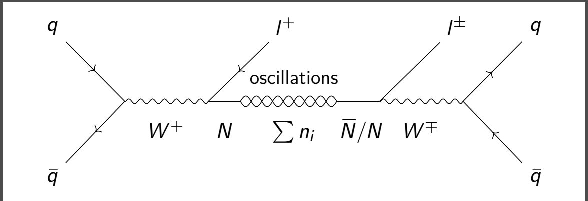
Long oscillation length



- LNV strongly suppressed
- Small R_{ll}
- 'Dirac-BM'-like

Measuring LNV at the HL-LHC

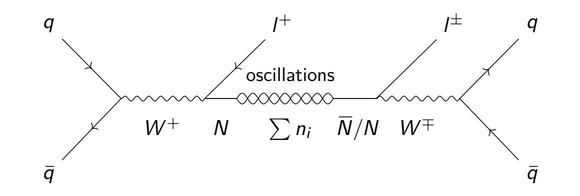
[2212.00562; pSPSS]



LNV is measured by comparing the charges of the two leptons

Measuring LNV at the HL-LHC

[2212.00562; pSPSS]



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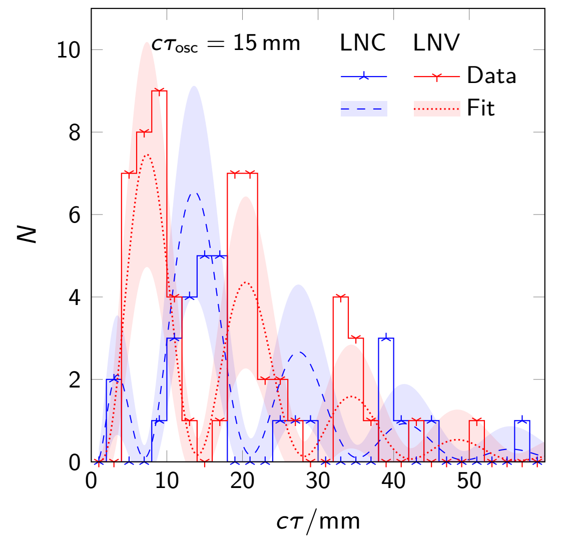
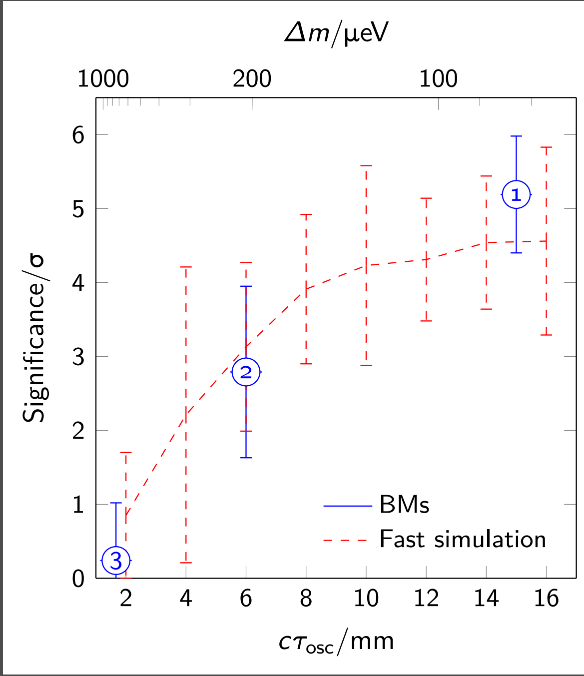
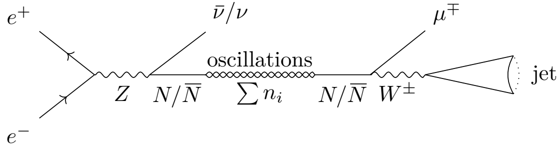




At the Z-pole of the FCC-ee

[2105.06576]

Single charged lepton



Angular dependent probability

$$P(\cos\theta) := \frac{1}{\sigma}\frac{d\sigma(\cos\theta)}{d\cos\theta}$$

Measurement

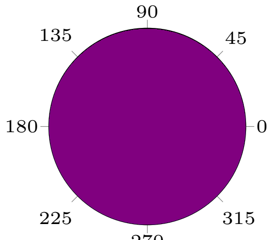
- LNV cannot be measured using two charges
- One can still measure angular distributions

Z-boson polarisation due to P-violation

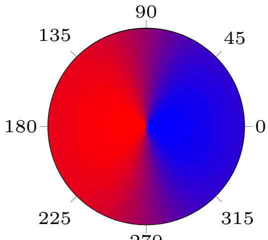
$$P_Z = -\Delta\gamma, \qquad \Delta\gamma = \gamma_L - \gamma_R \approx 0.1494$$

$$\gamma_L = \frac{g_L^2}{g_L^2 + g_R^2}, \qquad \gamma_R = \frac{g_R^2}{g_L^2 + g_R^2}$$

Majorana



Dirac



LNV corresponds to symmetric distribution → Not possible to measure LNV

Oscillating pseudo-Dirac HNLs

[2308.07297]

What about pseudo-Dirac HNL?

Majorana and Dirac HNLs can only be considered as limiting cases of the pseudo-Dirac HNL

l^- from non-oscillating N or from oscillating $\overline{N}$ (similar for l^+)

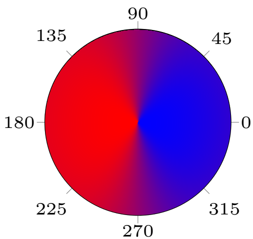
Probability to measure an (anti-)lepton

$$P_{l^\mp}(\tau, \cos\theta) = P_{\text{decay}}(\tau)\left[P_N^+(\cos\theta) \pm P_N^-(\cos\theta)\Delta P_{\text{osc}}(\tau)\right]$$

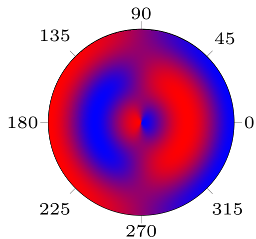
Oscillation probability difference

$$\Delta P_{\text{osc}}(\tau) = \cos(\Delta m \tau)$$

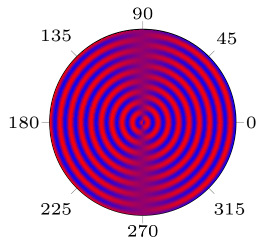
‘Dirac BM’-like



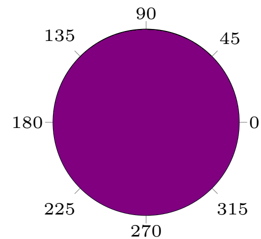
Slow oscillation



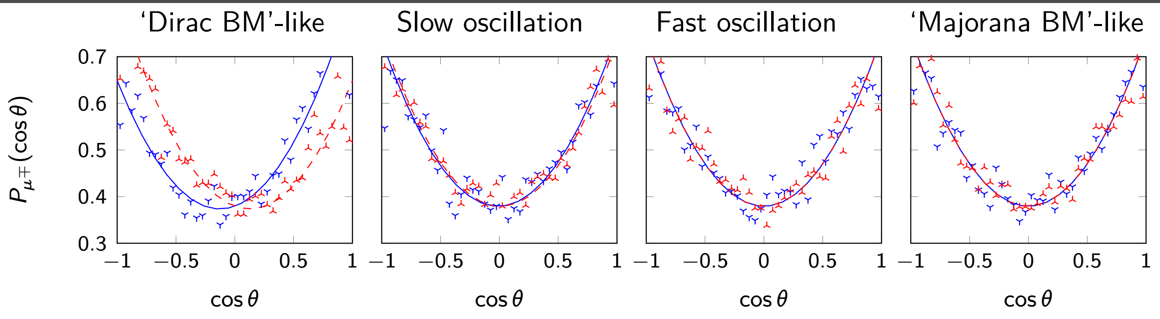
Fast oscillation



‘Majorana BM’-like



Time and angular integrated observable

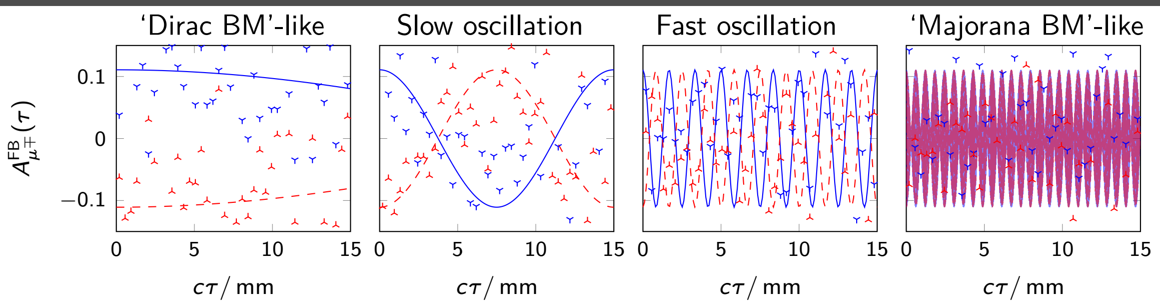


Time integrated probability

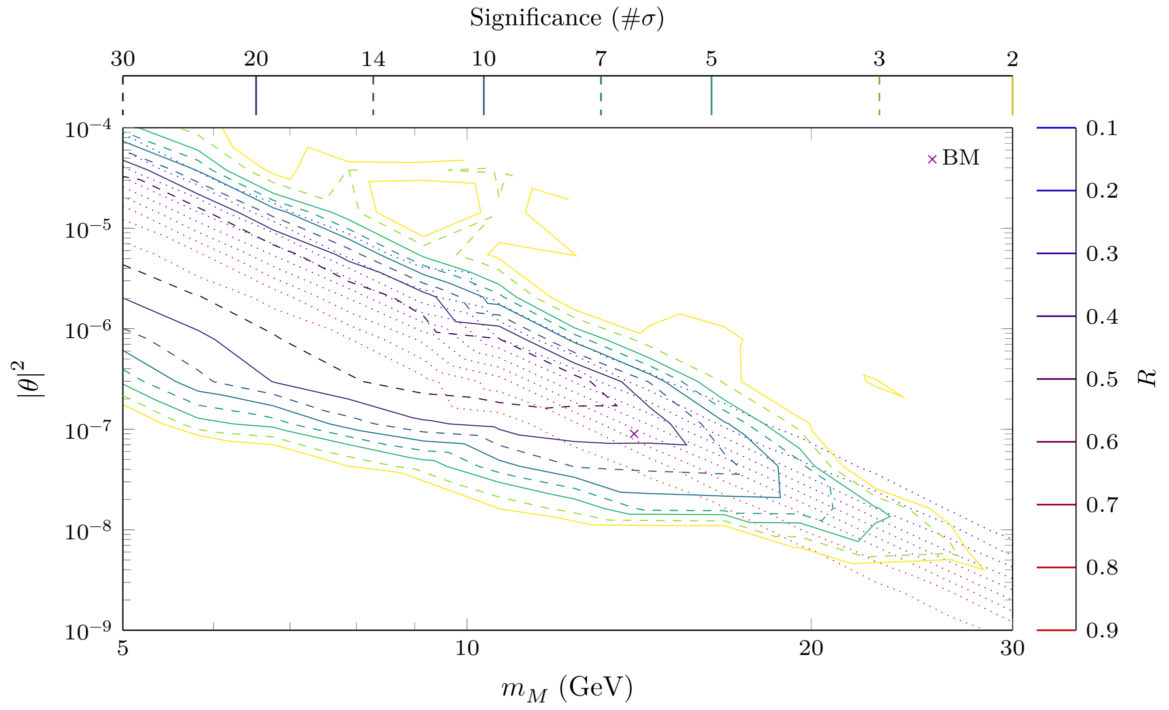
$$P_{l\mp}(\cos\theta) := \int_0^\infty P_{l\mp}(\tau, \cos\theta)\, d\tau$$

Angular integrated probability

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



$N\bar{N}$Os discovery reach at the FCC-*ee* (preliminary)



Heavy neutrino mass splitting: $\Delta m = 46\,\mu\text{eV}$

Conclusion

- Observable low-scale seesaw models predict pseudo-Dirac HNLs
- LNV results in heavy neutrino-antineutrino oscillations ($N\overline{N}$Os)
- $N\overline{N}$Os can be resolvable at the LHC
- At the FCC-*ee* Z-pole run $N\overline{N}$Os can be observed in distributions

References

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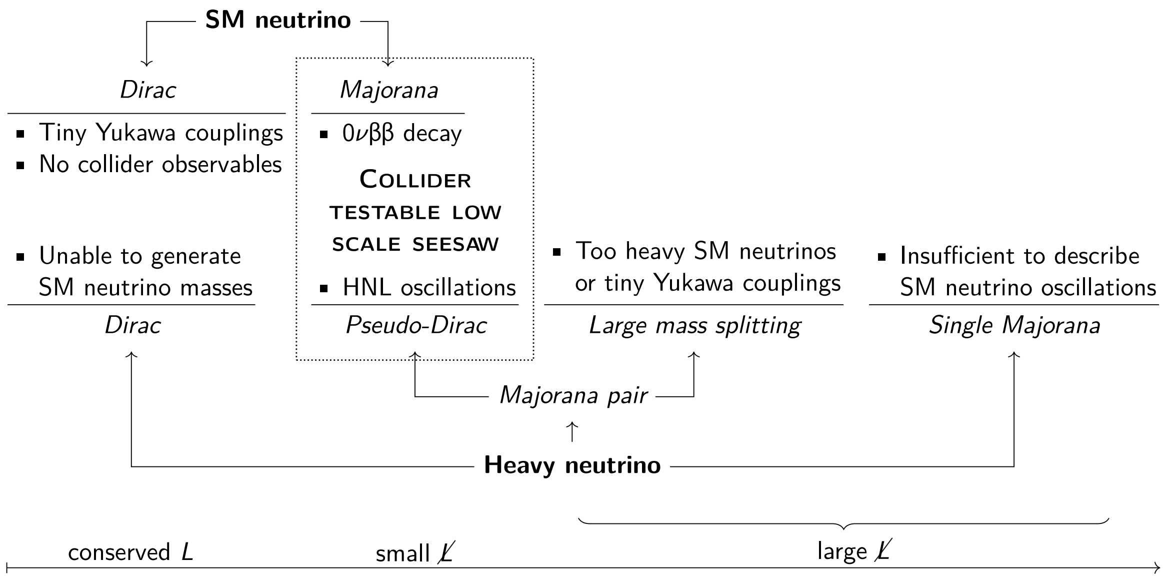
Are HNLs Majoran or Dirac Fermions?

[2210.10738]



Single Majorana and Dirac HNLs are

- not predicted by detectable seesaw models

Unique phenomenology of pseudo-Dirac HNLs

- $N\bar{N}$Os
- $0 < R_{ll} = \frac{N_{\text{LNV}}}{N_{\text{LNC}}} < 1$
- Governed by mass splitting Δm

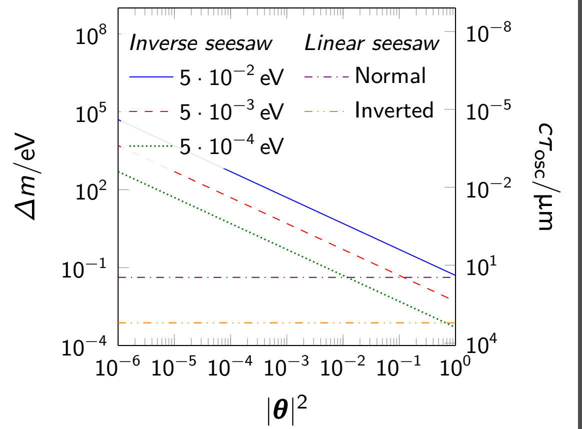
Special cases captured by the symmetry protected seesaw

[2210.10738]

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

Benchmark models

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