Measuring lepton number violation via heavy neutrino-antineutrino oscillations

based on work together with Stefan Antusch and Bruno Oliveira

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Physics studies — Muon collider

FCT Fundação para a Ciência e a Tecnologia

COMPETE

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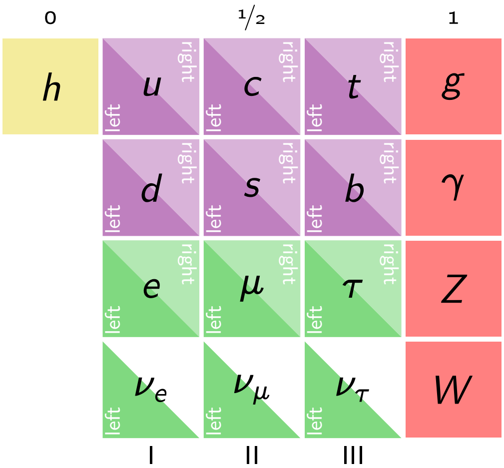
Funded by the European Union

Standard Model neutrinos

Standard Model particle content



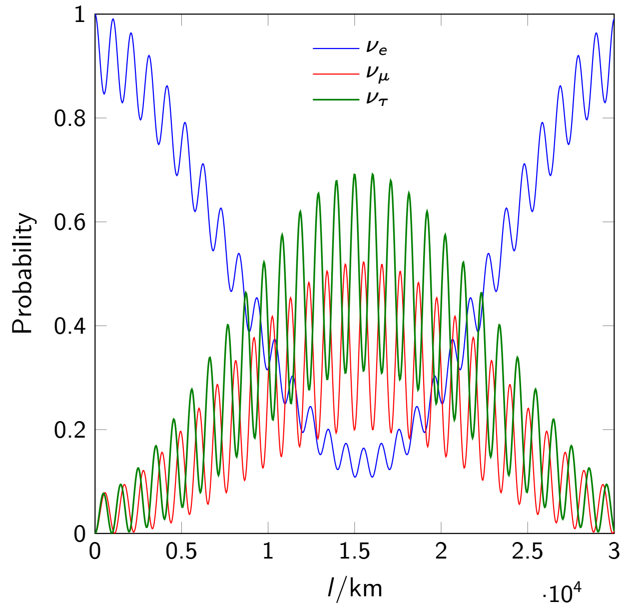
Neutrinos ν_α stand out

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

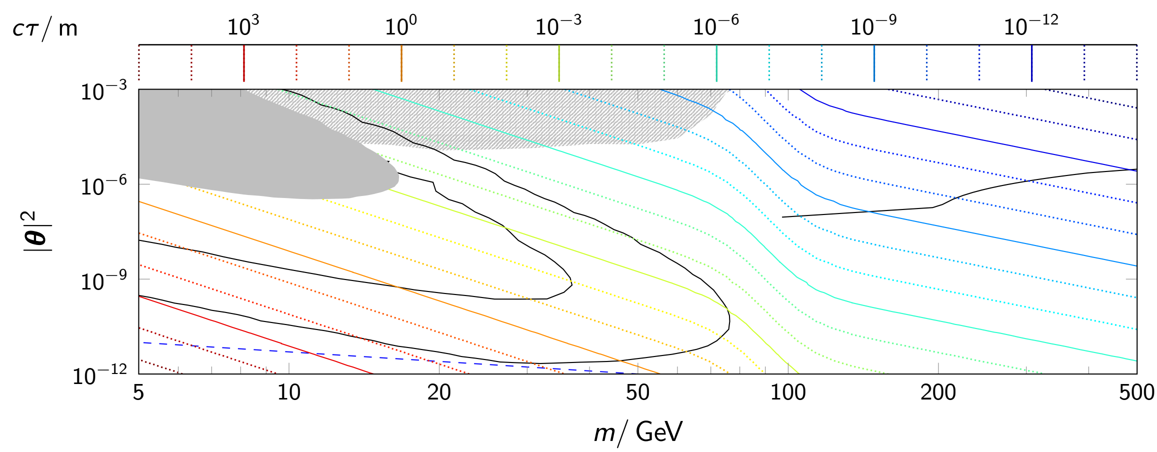
Simplest model

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

- No massive light neutrino
- No LNV

Majorana

- Single massive light neutrino
- Generated mass is correct for small coupling or GUT scale
- Decay width wrong by factor of 2

Seesaw model regimes

Dirac mass

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

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

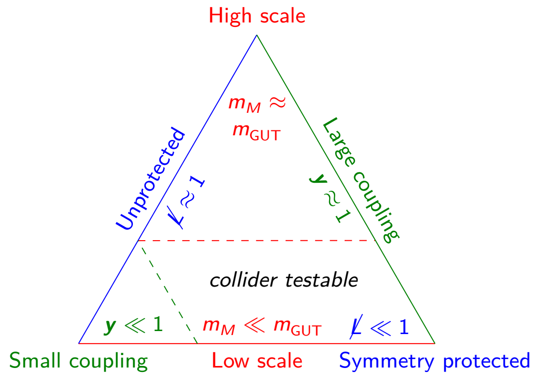
Neutrino oscillation pattern requires

at least two massive neutrinos

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

Particle content of benchmark model candidates

Number of Majorana degrees of freedom (DOFs)

DOF	Particles	Properties	
1	Majorana	One massive light neutrino	↯
2	Dirac	No massive light neutrino	↯
	pseudo-Dirac	Minimal linear seesaw / pSPSS	✓
	2 Majorana	Light neutrinos too heavy	↯
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 possible number of parameters

Minimal set of parameters for single pseudo-Dirac

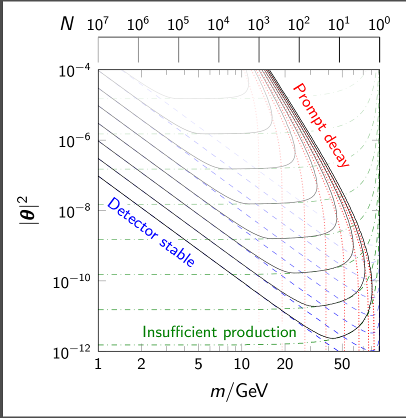
- Mass m
- Coupling vector $\boldsymbol{\theta}$
- Mass splitting Δm

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

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

Since they are pseudo-Dirac they oscillate

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

Collider signature: Decaying oscillations

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

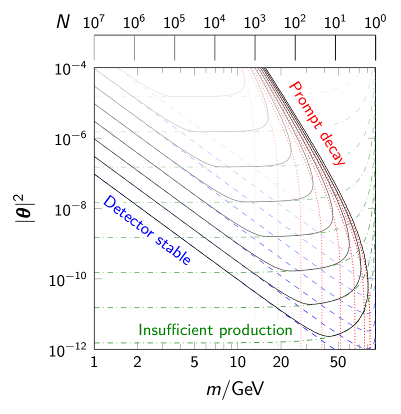
Time-integrated oscillations

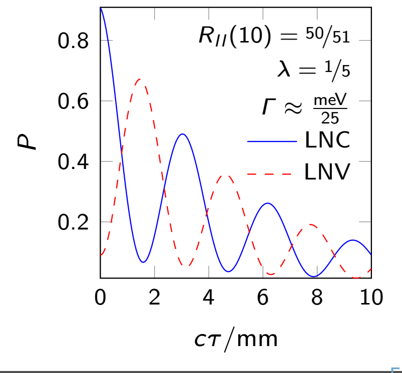
[2307.06208]

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

Charged lepton ratio

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





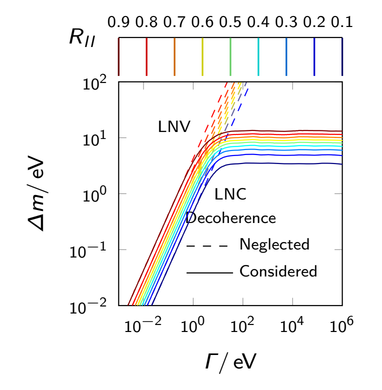
Problems measuring R_{ll}

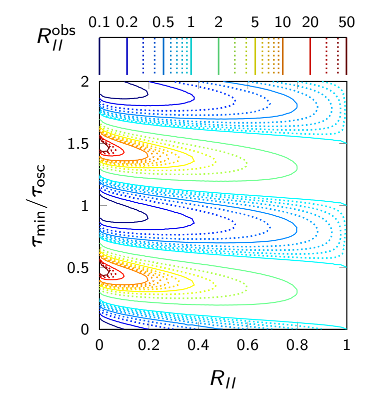
Integration limits correspond to [2210.10738]

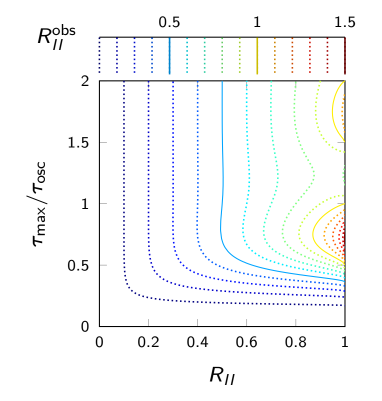
- Minimal distance cut
- Maximal measurable vertex distance

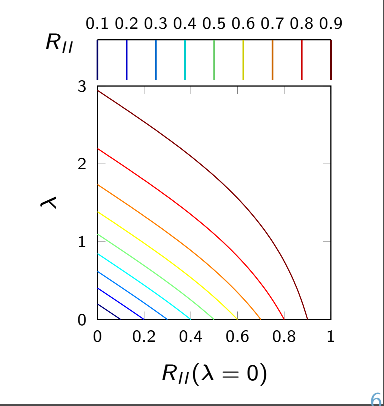
Decoherence [2307.06208]

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



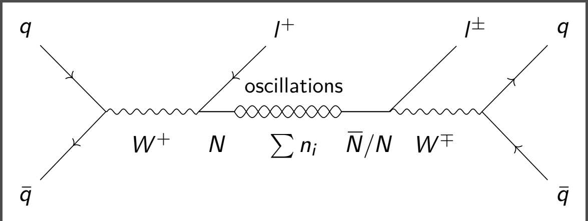






Measuring LNV at the HL-LHC

[2212.00562; pSPSS]



LNV is measured
by comparing the charges of the two leptons

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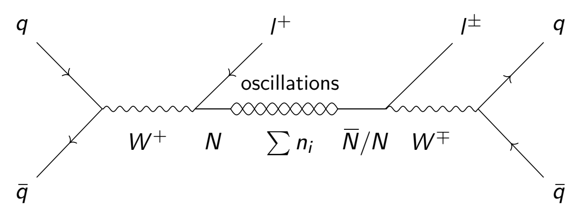

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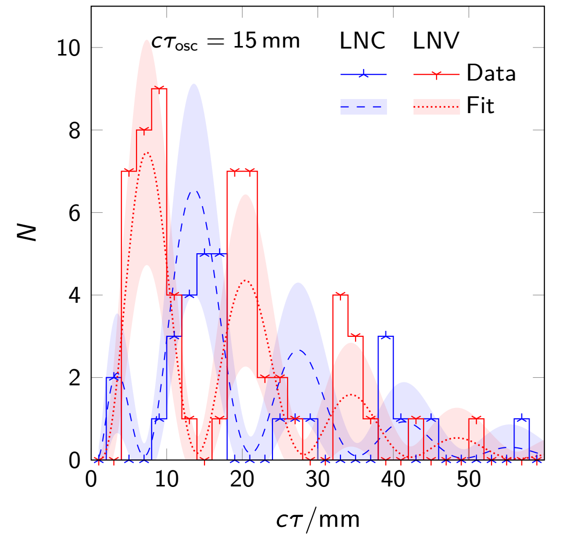
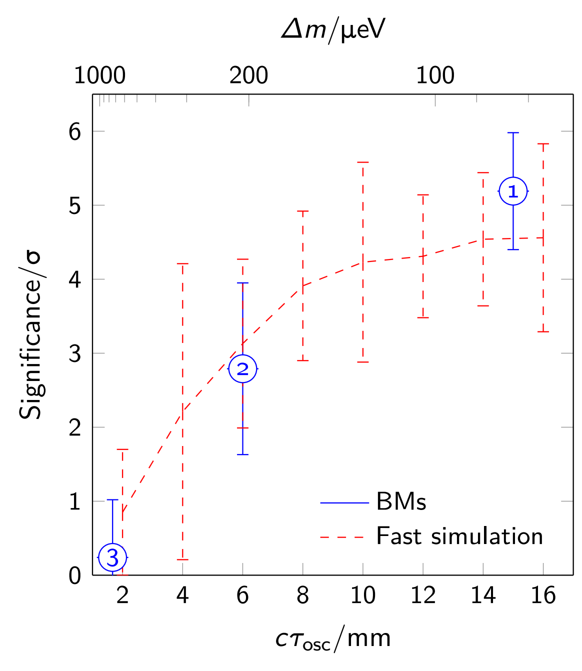
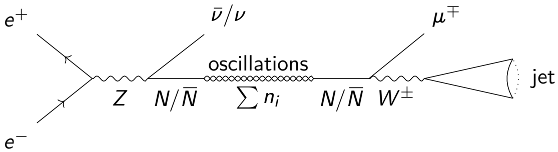




At the Z-pole of the FCC-ee

[2105.06576]



LNV cannot be measured using two different charges

One can still measure angular distributions

Angular dependent probability

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

Probability for HNLs

$$P^{M/D}(\cos\theta) = \frac{3}{4}\frac{m_Z^2 f^{M/D}(\theta) + m^2\sin^2\theta}{2m_Z^2 + m^2}$$

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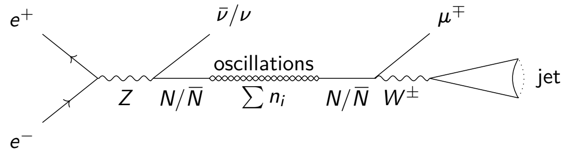

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Z-boson polarisation due to P-violation

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

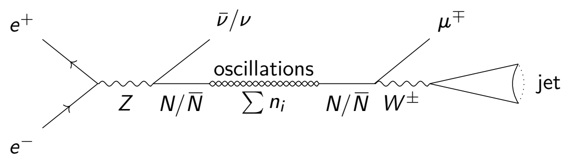
$$\gamma_L = \frac{g_L^2}{g_L^2 + g_R^2}, \qquad \gamma_R = \frac{g_R^2}{g_L^2 + g_R^2}$$

couplings of the charged leptons to the Z boson

$$g_L = 1 - 2\sin^2\theta_W, \qquad g_R = 2\sin^2\theta_W$$

At the Z-pole of the FCC-ee

[2105.06576]



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Majorana

$$f^M(\theta) = 1 + \cos^2\theta$$

Dirac

$$f^D_{N/\overline{N}}(\theta) = \gamma_{R/L}(1-\cos\theta)^2 + \gamma_{L/R}(1+\cos\theta)^2$$

Symmetric charge distribution

$$P^M_{l^-}(\cos\theta) = P^M_{l^+}(\cos\theta) = \frac{1}{2}P^M(\cos\theta)$$

Asymmetric charge distribution

$$P^D_{l^\mp}(\cos\theta) = P^D_{N/\overline{N}}(\cos\theta)$$

Forward-backward asymmetry (FBA)

(Anti-)symmetrised Dirac HNL probability

$$P_N^{\pm}(\cos\theta) := \frac{P_N^D(\cos\theta) \pm P_{\overline{N}}^D(\cos\theta)}{2},$$

Symmetrization corresponds to Majorana

$$P_N^{+}(\cos\theta) = P^M(\cos\theta)$$

Asymmetric contribution contains polarisation

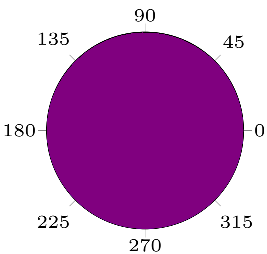
$$P_N^{-}(\cos\theta) = \frac{3}{2}\frac{m_Z^2}{2m_Z^2 + m^2}\Delta\gamma\cos\theta$$

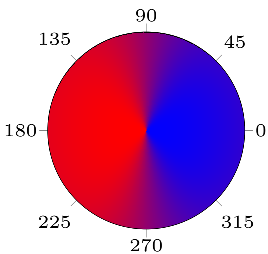
Forward backward symmetric

$$S^{\mathrm{FB}} := P_N^{+}(\pm 1) = \frac{3}{2}\frac{m_Z^2}{2m_Z^2 + m^2}$$

Forward backward asymmetry [2105.06576]

$$A_{N/\overline{N}}^{\mathrm{FB}} := P_N^{-}(\pm 1) = \pm S^{\mathrm{FB}}\Delta\gamma$$





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

Probability to measure an (anti-)lepton

$$P_{l^\mp}(\tau, \cos\theta) = P_{\nu l}^{\text{LNC}}(\tau) P_{N/\overline{N}}(\cos\theta) + P_{\nu l}^{\text{LNV}}(\tau) P_{\overline{N}/N}(\cos\theta)$$

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

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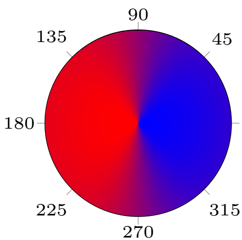
Probability to measure an (anti-)lepton

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

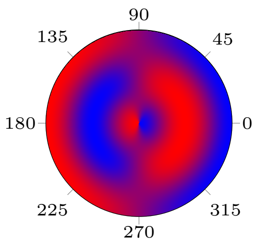
Oscillation probability difference

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

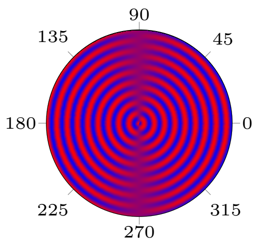
‘Dirac BM’-like



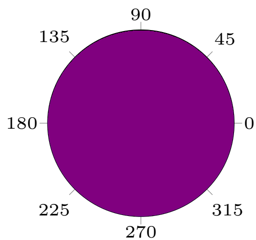
Slow oscillation



Fast oscillation



‘Majorana BM’-like



Time integrated observable

Time integrated probability

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

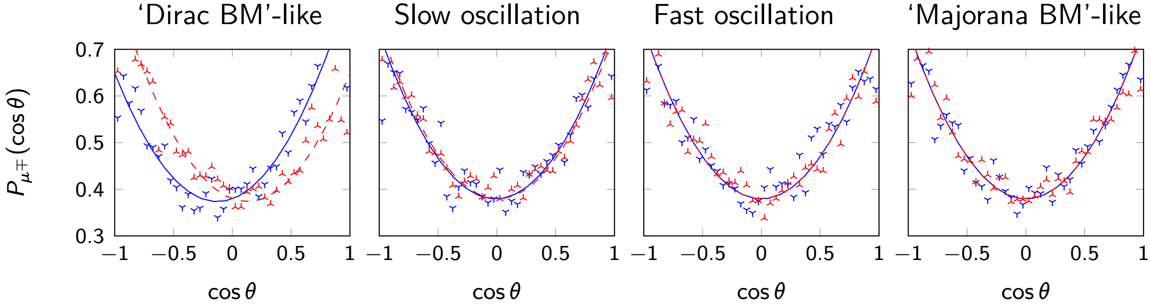
$$P_{l\mp}(\cos\theta) = P_N^+(\cos\theta) \pm P_N^-(\cos\theta)\Delta P_{\nu l}$$

Difference of time-integrated probabilities

$$\Delta P_{\nu l} := \int_0^\infty P_{\nu l}^{\text{LNC}}(\tau) - P_{\nu l}^{\text{LNV}}(\tau)\, d\tau$$

Is a function of decay width and mass splitting

$$\Delta P_{\nu l} = \frac{\Gamma^2}{\Gamma^2 + \Delta m^2}$$



Charged lepton ratio

$$R_l(\cos\theta) := \frac{P_{l-}(\cos\theta)}{P_{l+}(\cos\theta)}$$

has the form

$$R_l(\cos\theta) = 1 + 2\frac{P_N^-(\cos\theta)}{P_N^+(\cos\theta)\Delta P_{\nu l}^{-1} - P_N^-(\cos\theta)},$$

Angular-integrated distributions

Angular integrated probability

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

Forward-backward probability

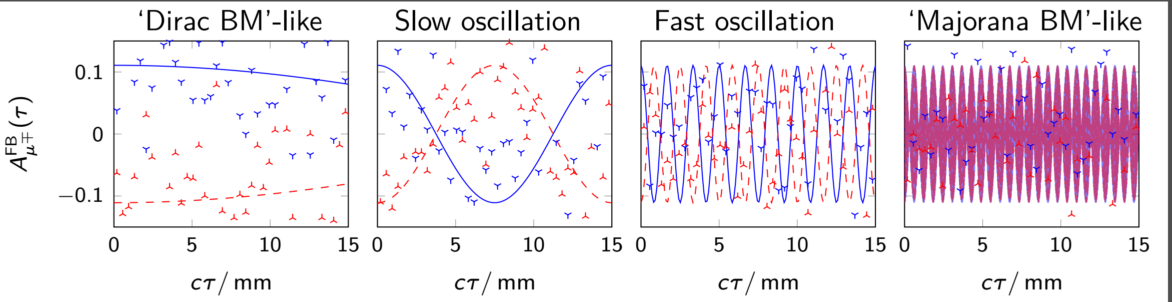
$$P_{l\mp}^{[\pi/2,0]}(\tau) = P_{l\pm}^{[\pi,\pi/2]}(\tau) = \frac{1 + A_{l\mp}^{\mathrm{FB}}(\tau)}{2} P_{\mathrm{decay}}(\tau)$$

Time dependent FBAs

$$A_{l\mp}^{\mathrm{FB}}(\tau) = A_{N/\overline{N}}^{\mathrm{FB}} \Delta P_{\mathrm{osc}}(\tau)$$

Limit recovers non-oscillating result

$$A_{l\mp}^{\mathrm{FB}}(\tau = 0) = A_{N/\overline{N}}^{\mathrm{FB}}$$



Forward lepton ratio

$$R_l^{[\pi/2,0]}(\tau) = \frac{P_{l-}^{[\pi/2,0]}(\tau)}{P_{l+}^{[\pi/2,0]}(\tau)} = \frac{1 + A_{l-}^{\mathrm{FB}}(\tau)}{1 + A_{l+}^{\mathrm{FB}}(\tau)}$$

Backward lepton ratio

$$R_l^{[\pi,\pi/2]}(\tau) = \frac{P_{l-}^{[\pi,\pi/2]}(\tau)}{P_{l+}^{[\pi,\pi/2]}(\tau)} = \frac{1 - A_{l-}^{\mathrm{FB}}(\tau)}{1 - A_{l+}^{\mathrm{FB}}(\tau)}$$

Combined observable

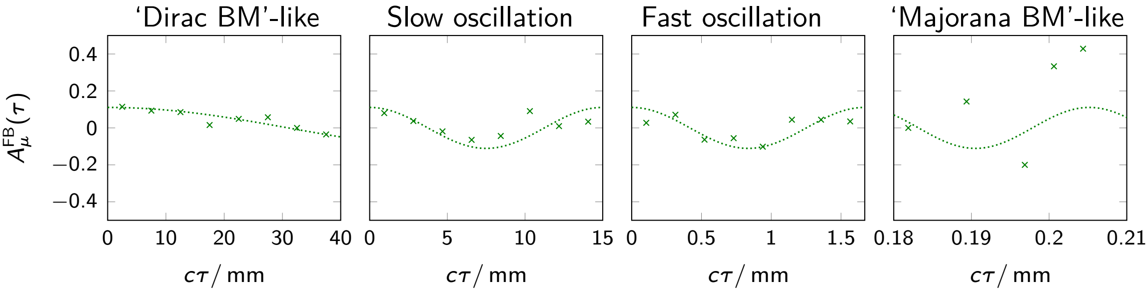
Combined lepton FBA

$$A_l^{\mathrm{FB}}(\tau) := \frac{A_{l^-}^{\mathrm{FB}}(\tau) - A_{l^+}^{\mathrm{FB}}(\tau)}{2}$$

has the simple form

$$A_l^{\mathrm{FB}}(\tau) = A_N^{\mathrm{FB}} \Delta P_{\mathrm{osc}}(\tau)$$

Focusing on the first oscillation



Conclusion

- Low-scale seesaw models predict pseudo-Dirac HNLs
- LNV can be measured via heavy neutrino-antineutrino oscillations
- At the Z-pole of the FCC-ee LNV can only be observed in distributions
- Heavy neutrino-antineutrino oscillations appear in these distributions
- Observation of LNV is possible at the FCC-ee

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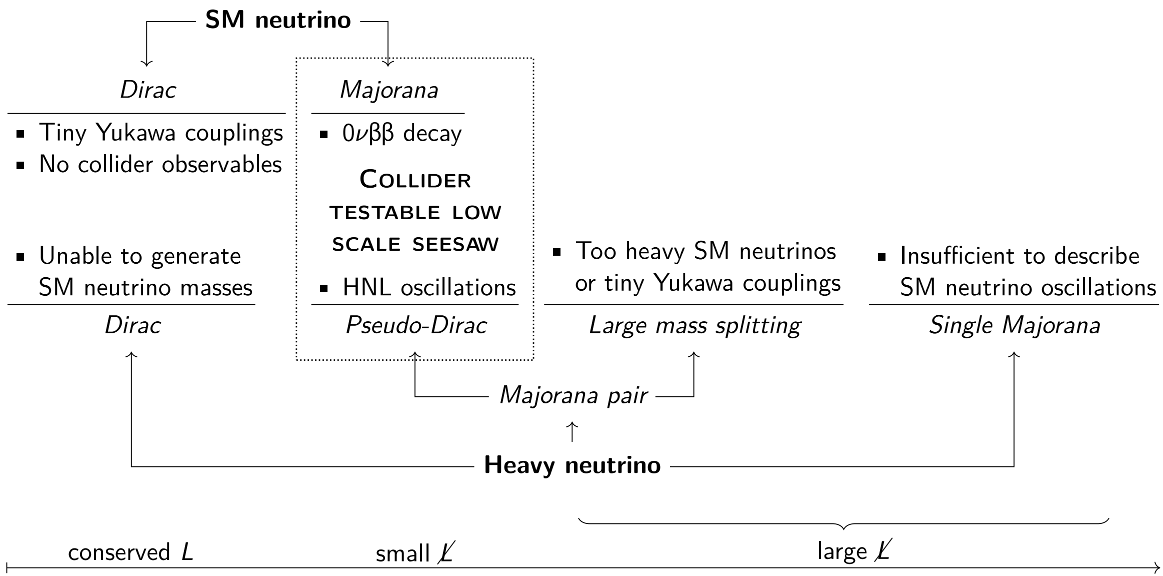
Are HNLs Majoran or Dirac Fermions?

[2210.10738]



Single Majorana and Dirac HNLs are

- not predicted by low-scale seesaw models

Unique phenomenology of pseudo-Dirac HNLs

- Heavy neutrino-antineutrino oscillations
- $0 < R_{ll} = \frac{N_{\mathrm{LNV}}}{N_{\mathrm{LNC}}} < 1$
- Governed by mass splitting Δm

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	$+1$

Other new fields

further terms in Lagrangian

Neutrino mass matrix M_n

contains seesaw information

Basis

$n = (\nu, n_4, n_5)$

Dirac masses

$\boldsymbol{m}_D = \boldsymbol{y}_1 v, \quad \boldsymbol{\mu}_D = \boldsymbol{y}_2 v$

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 $\boldsymbol{\theta}$

Special cases captured by the symmetry protected seesaw

	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