

Heavy neutrino-antineutrino oscillations at colliders

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Standard Model neutrinos

Standard Model (SM) particle content

0	1/2			1
h	u <small>right</small> <small>left</small>	c <small>right</small> <small>left</small>	t <small>right</small> <small>left</small>	g
	d <small>right</small> <small>left</small>	s <small>right</small> <small>left</small>	b <small>right</small> <small>left</small>	γ
	e <small>right</small> <small>left</small>	μ <small>right</small> <small>left</small>	τ <small>right</small> <small>left</small>	Z
	ν_e <small>left</small>	ν_μ <small>left</small>	ν_τ <small>left</small>	W
	I	II	III	

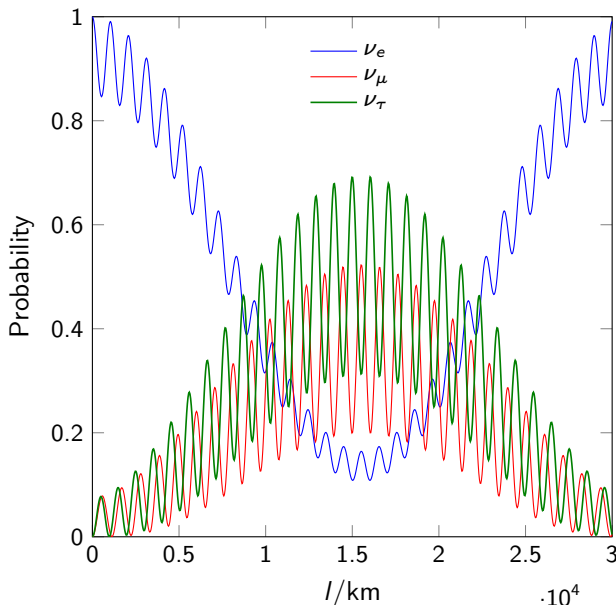
Neutrinos ν_α stand out

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

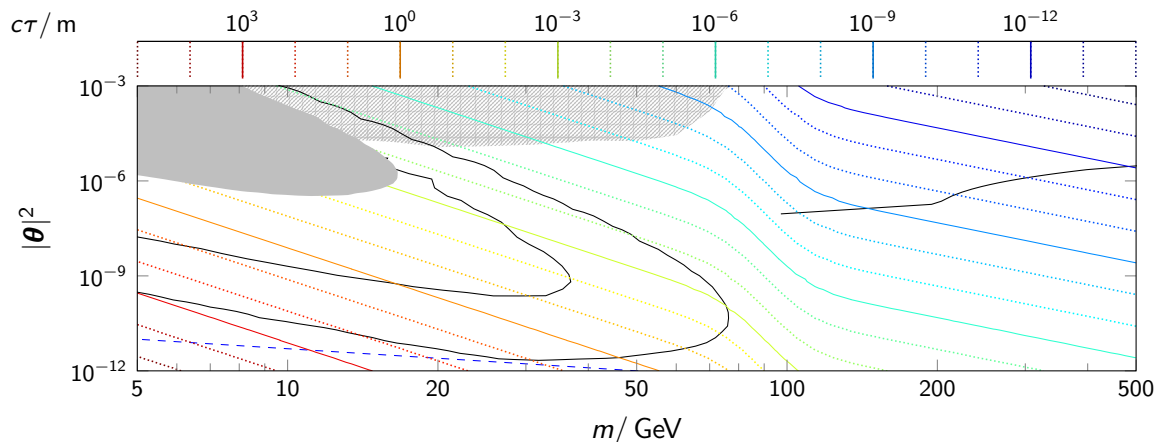
Simplest model

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

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

Seesaw mass

$$M_\nu = m_M \theta \otimes \theta$$



Dirac

- ⚡ No massive light neutrino
- ⚡ No LNV

Majorana

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

Seesaw model regimes

Dirac mass

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

Majorana mass

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

Coupling strength is determined by

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

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

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

Viable seesaw models

Symmetry protected

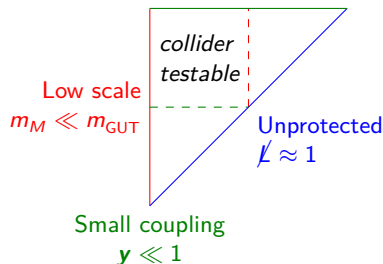
$$\lambda \ll 1$$

Large coupling

$$\mathbf{y} \approx 1$$

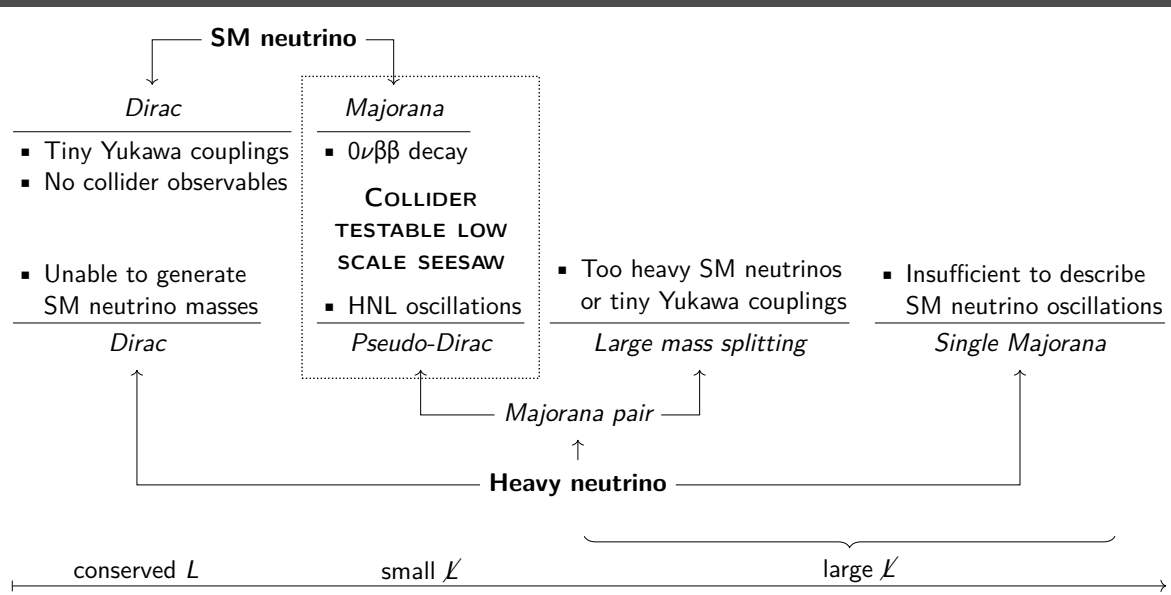
High scale

$$m_M \approx m_{\text{GUT}}$$



Neutrino masses are small for

- small \mathbf{y}
- large m_M
- symmetry protected cancellation



Single Majorana and Dirac HNLs are

- not predicted by detectable seesaw models

Unique phenomenology of pseudo-Dirac HNLs

- Heavy neutrino-antineutrino oscillations ($N\bar{N}Os$)
- $0 < R_{II} = \frac{M_{LNV}}{M_{LNC}} < 1$
- Governed by mass splitting Δm

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

Exact limit

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

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

$$\mathcal{L}_{\text{SPSS}}^L = -y_2 \tilde{H}^\dagger \bar{\ell} N_2^c - \mu'_M \bar{N}_1 N_1^c - \mu_M \bar{N}_2 N_2^c + \text{h.c.}$$

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

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

Symmetric limit

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

Mild symmetry breaking

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

Large symmetry breaking

$$M_n^{L \gg 0} = \begin{pmatrix} 0 & \mathbf{m}_D & \hat{\mathbf{m}}_D \\ \mathbf{m}_D^T & \hat{\mathbf{m}}'_M & m_M \\ \hat{\mathbf{m}}_D^T & m_M & \hat{\mathbf{m}}_M \end{pmatrix}$$

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

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

- Large Δm Majorana pair
- Requires large m_M or tiny θ

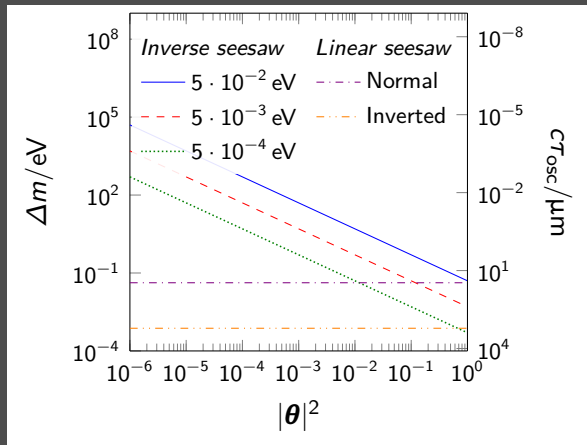
	Linear seesaw μ_D	Inverse seesaw μ_M	Seesaw independent μ'_M
$M_n =$	$\begin{pmatrix} 0 & \mathbf{m}_D & \mu_D \\ \mathbf{m}_D^T & 0 & m_M \\ \mu_D^T & m_M & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \mathbf{m}_D & 0 \\ \mathbf{m}_D^T & 0 & m_M \\ 0 & m_M & \mu_M \end{pmatrix}$	$\begin{pmatrix} 0 & \mathbf{m}_D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

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



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	✓
3	2 Majorana	Light neutrinos too heavy	⚡
	pseudo-Dirac + Majorana	ν MSM (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

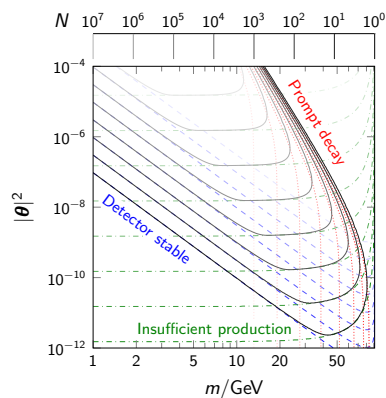
- Reproduces neutrino mass scale
- Captures dominant collider effects
- Minimal number of parameters

Minimal 'single pseudo-Dirac' parameter set

- Mass m
- Coupling vector θ
- Mass splitting Δm

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

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

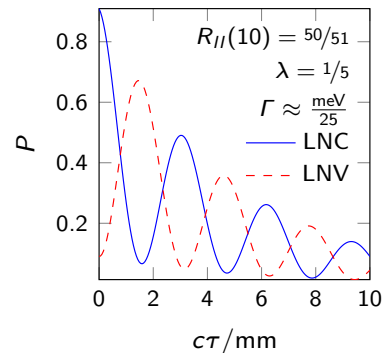
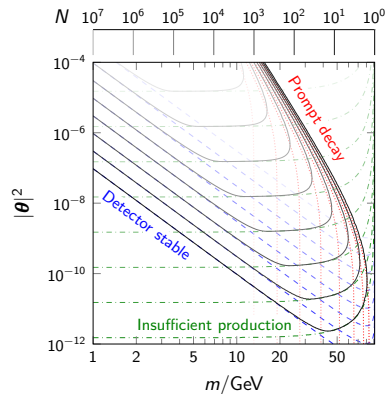
Time-integrated oscillations

[2307.06208]

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

Charged lepton ratio

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



Problems measuring R_{II}

Integration limits correspond to

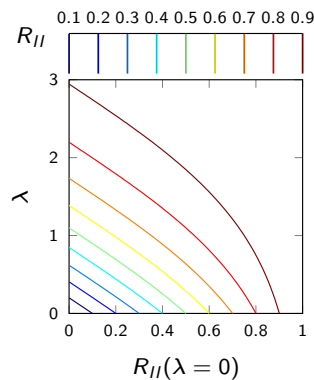
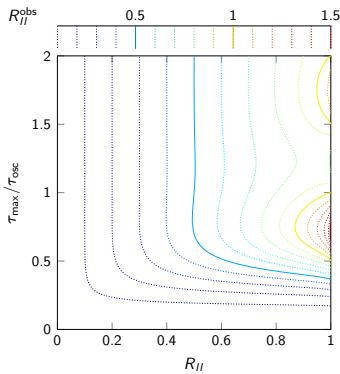
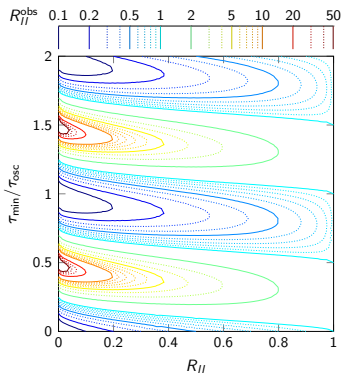
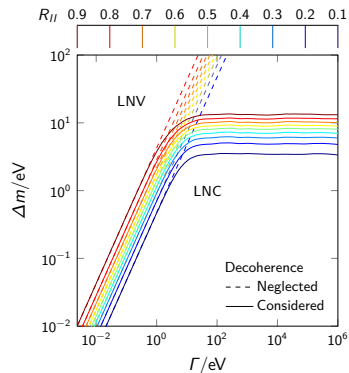
[2210.10738]

- 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

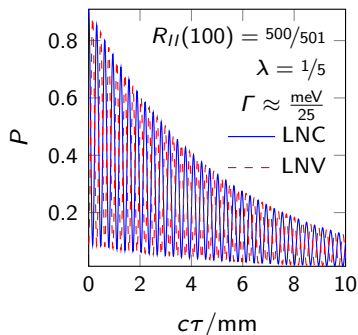
governed by λ

Oscillation length

governed by mass splitting Δm

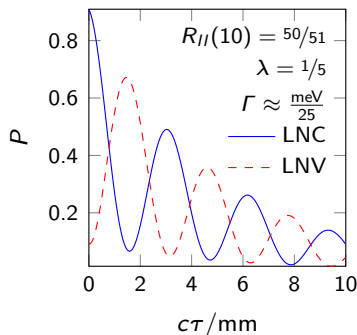
$$P_{\text{osc}}^{\text{LNC/LNV}}(\tau) = \frac{1 \pm \cos(\Delta m \tau) \exp(-\lambda)}{2}$$

Short oscillation length



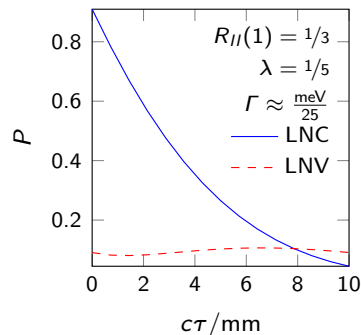
- Oscillations not resolvable
- Large R_{II}
- 'Majorana BM'-like

Intermediate oscillation length

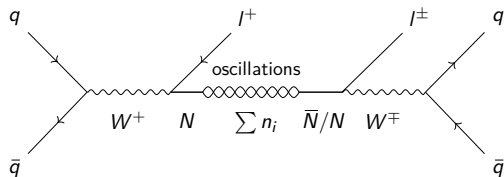


- Oscillations potentially measurable
- Pseudo-Dirac character crucial

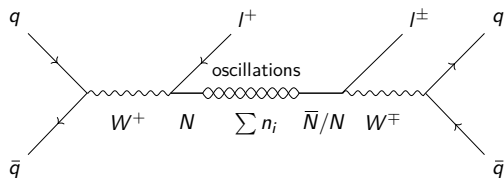
Long oscillation length



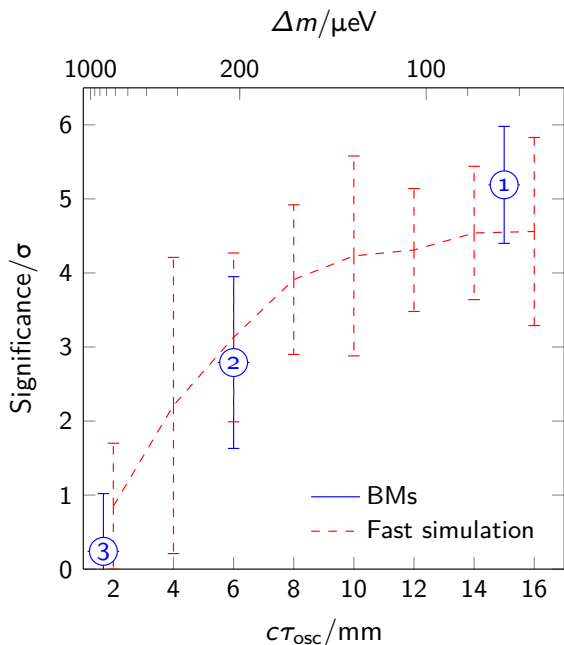
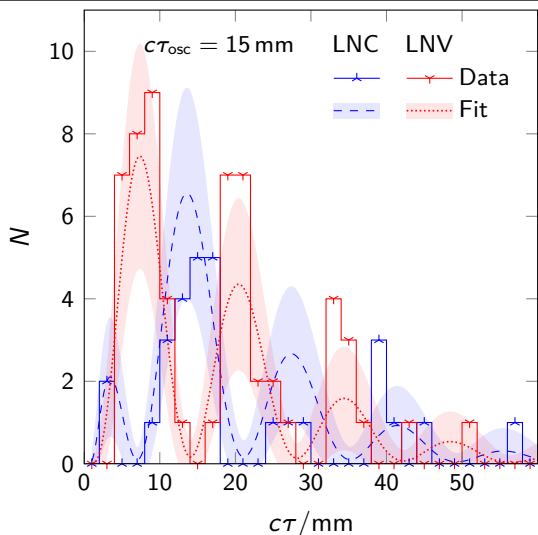
- LNV strongly suppressed
- Small R_{II}
- 'Dirac-BM'-like



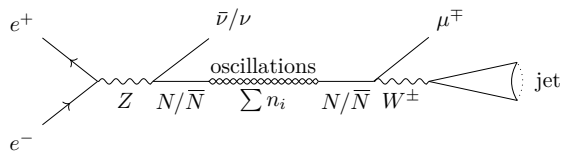
LNV is measured by comparing the charges of the two leptons



LNV is measured by comparing the charges of the two leptons



Single charged lepton



Measurement

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

Z-boson polarisation due to P-violation

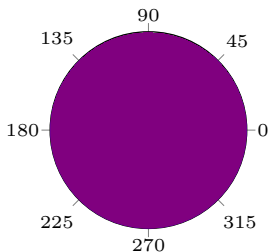
$$P_Z = -\Delta\gamma, \quad \Delta\gamma = \gamma_L - \gamma_R \approx 0.1494$$

Angular dependent probability

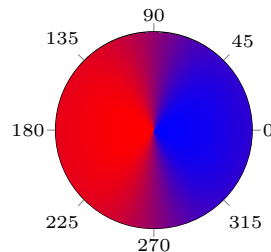
$$P(\cos\theta) := \frac{1}{\sigma} \frac{d\sigma(\cos\theta)}{d\cos\theta}$$

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

Majorana



Dirac



LNV corresponds to symmetric distribution → Not possible to measure LNV

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 \bar{N} (similar for l^+)

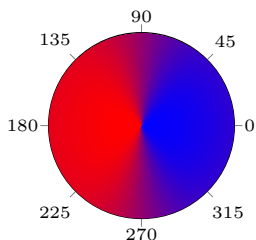
Probability to measure an (anti-)lepton

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

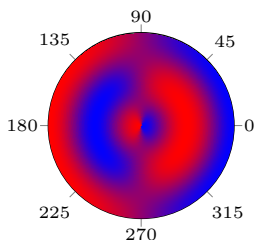
Oscillation probability difference

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

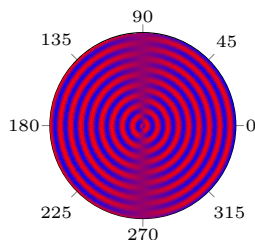
'Dirac BM'-like



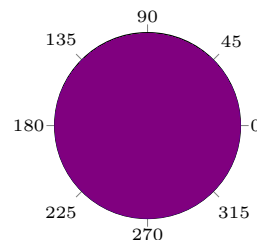
Slow oscillation



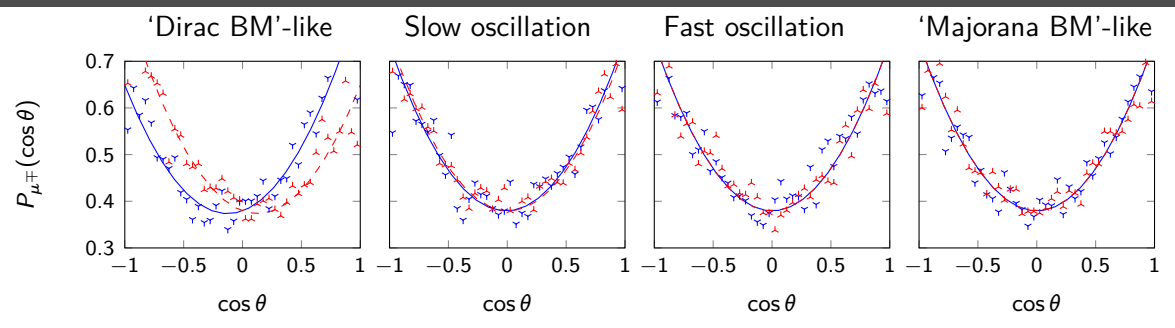
Fast oscillation



'Majorana BM'-like



Time and angular integrated observable

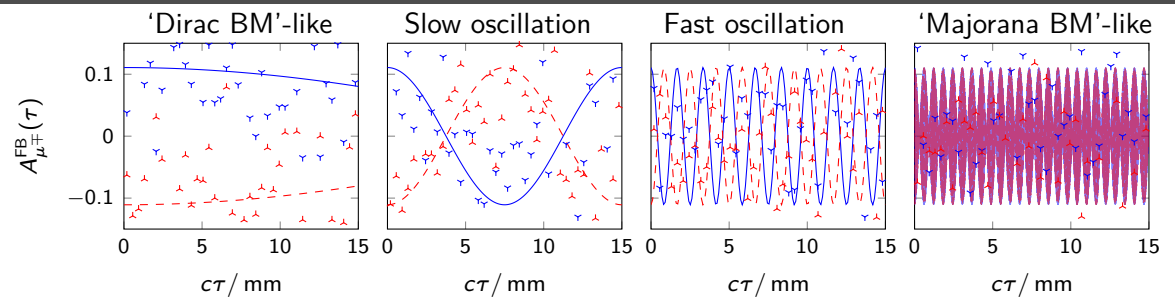


Time integrated probability

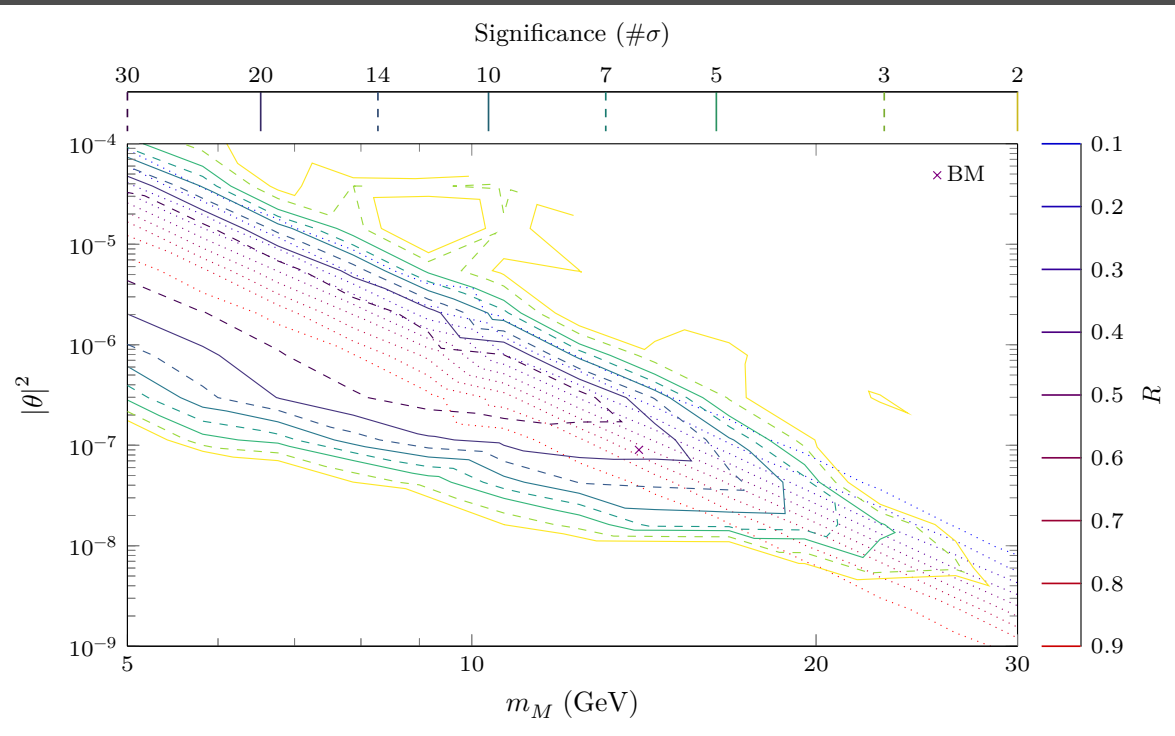
$$P_{I\mp}(\cos\theta) := \int_0^{\infty} P_{I\mp}(\tau, \cos\theta) d\tau$$

Angular integrated probability

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



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



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

References

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