Heavy neutrino-antineutrino oscillations

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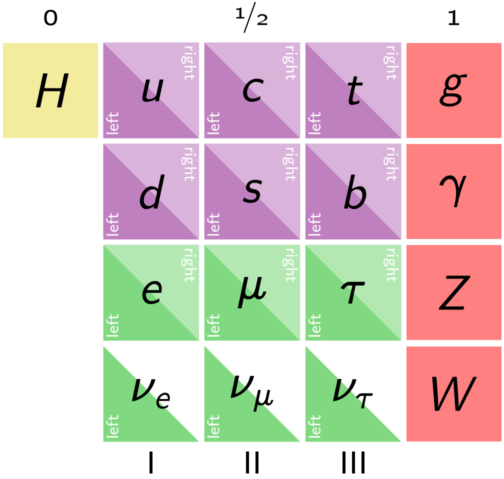
Standard Model (SM) neutrinos

SM particle content



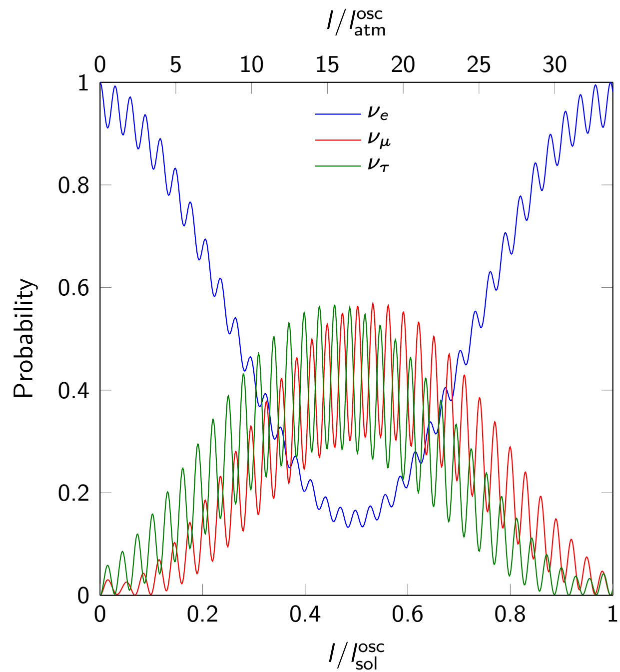
Neutrinos ν_α stand out

purely left-chiral and massless

Right-chiral or sterile Neutrinos

- neutral under SM symmetries
- allow mass term and explain oscillations

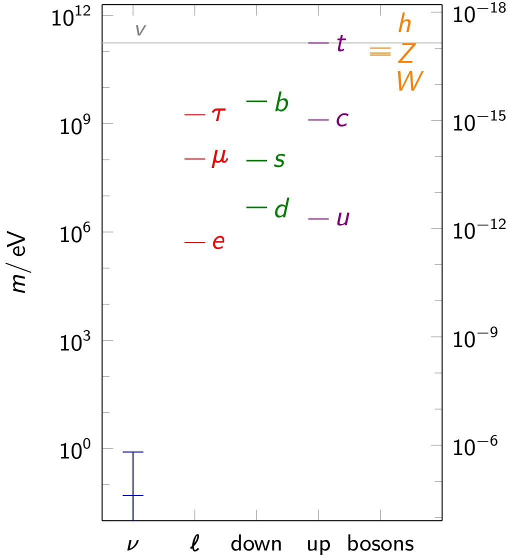
Observed neutrino flavour oscillations



Flavour oscillations are not explained within the SM

Flavour puzzle

Particle masses



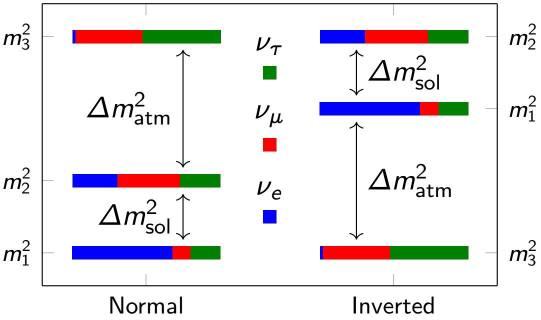
Neutrinos are

- not massless
- much lighter than other particles

Not all neutrino properties are well measured

- Lightest neutrino can still be massless
- Mass hierarchy is not known
- Angles and phases have large uncertainties

Neutrino mass hierarchy $\Delta m^2_{\text{sol}} \ll \Delta m^2_{\text{atm}}$



Model building work

- Explanation for flavour structure
- Mass generation mechanism

Seesaw mechanism

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

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

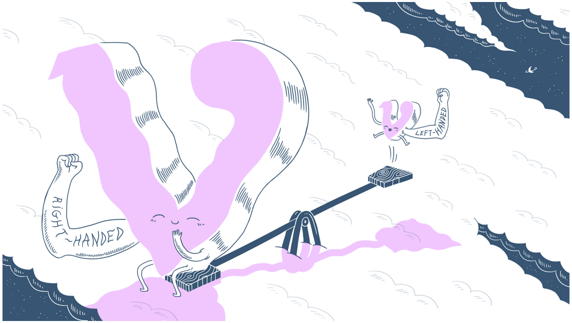
Tiny neutrino masses are ensured for

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

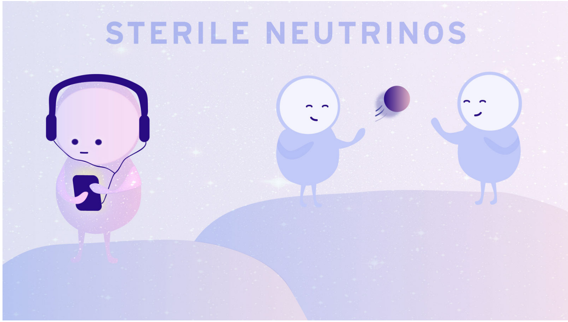
Sterile neutrinos/Heavy neutral leptons

- Inaccessibly heavy or
- Tiny interactions

[SymmetryMagazine]

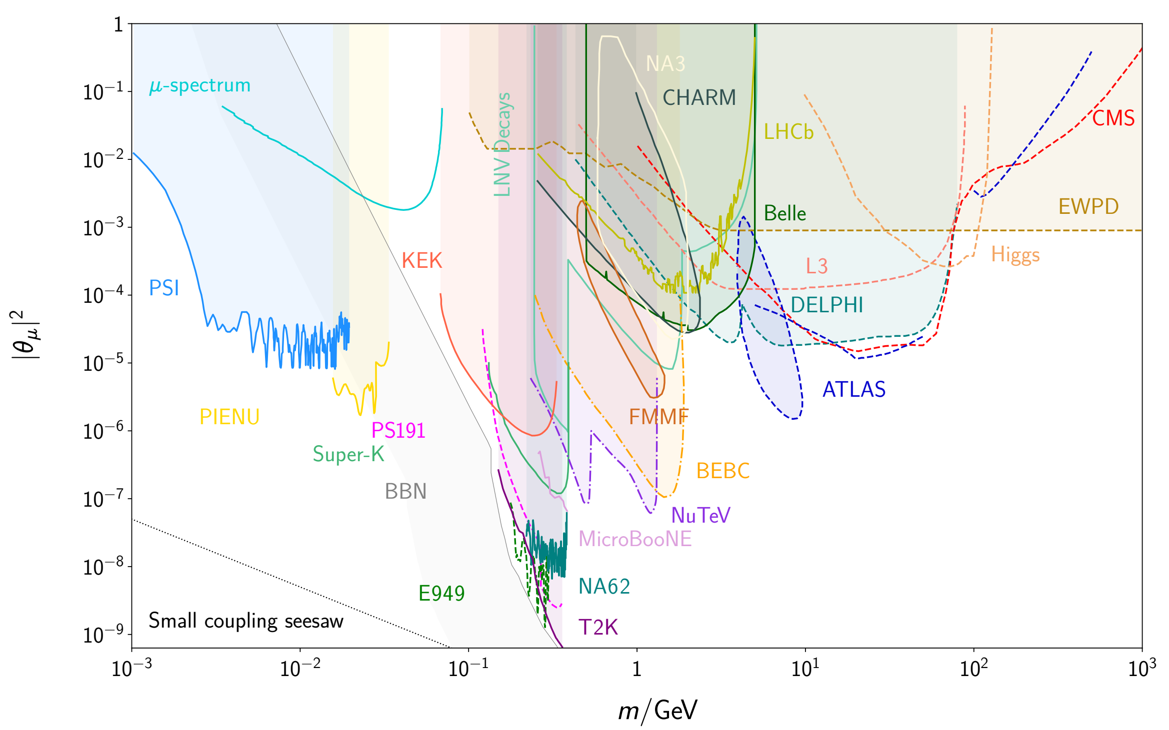


[SymmetryMagazine]



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 SM

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

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

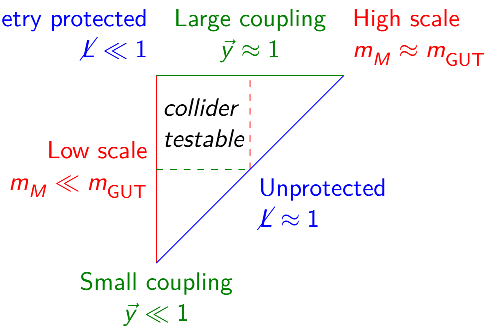
Symmetry L conserved

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

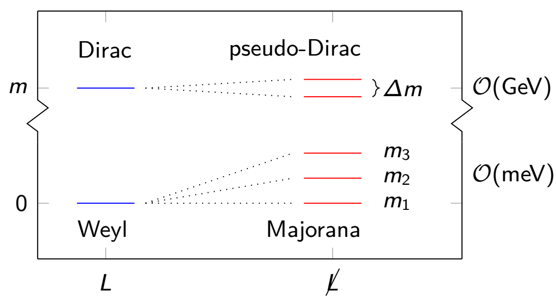
Small symmetry breaking $\not{L}$

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

Viable seesaw limits



Breaking induced neutrino mass splitting



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

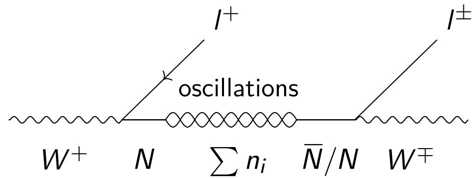
Oscillations between events that are

- lepton number conserving (LNC) $l^\pm l^\mp$
- lepton number violating (LNV) $l^\pm l^\pm$

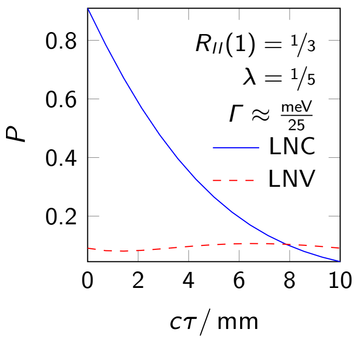
Oscillation frequency governed by Δm

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

Oscillating mass eigenstates n_i

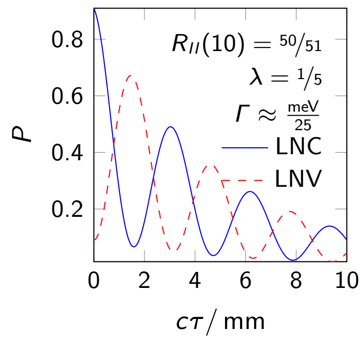


Slow oscillation



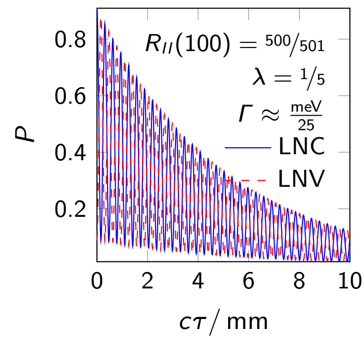
- Mostly LNC
- ‘Dirac BM’-like

Intermediate oscillation



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

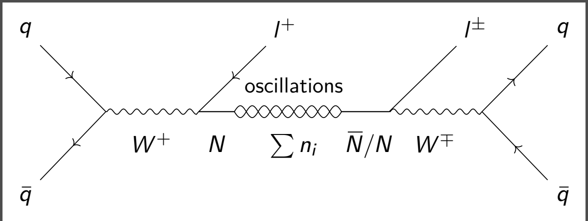
Fast oscillation



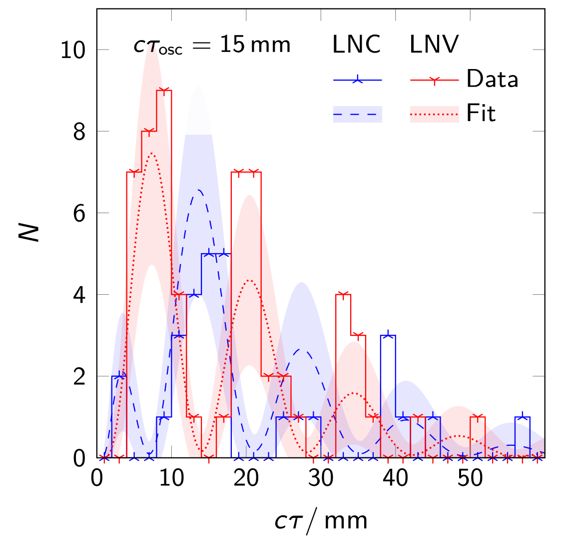
- Unresolvable
- LNV as frequent as LNC
- ‘Majorana BM’-like

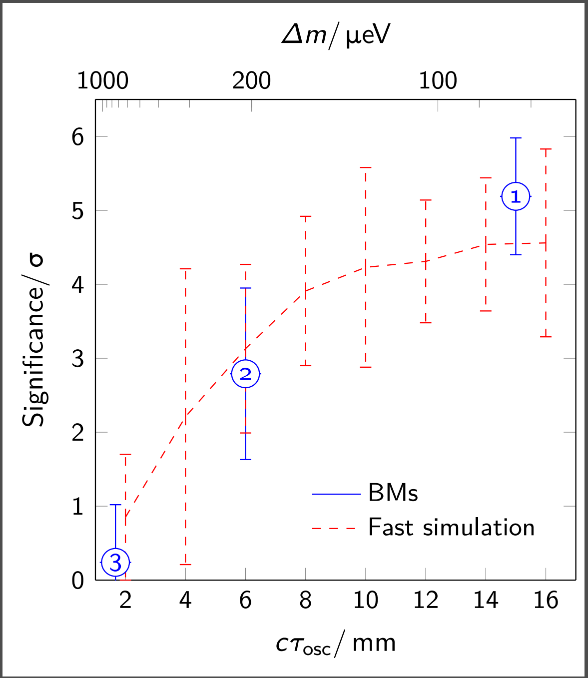
Measuring LNV at the HL-LHC

[pSPSS, 2212.00562]

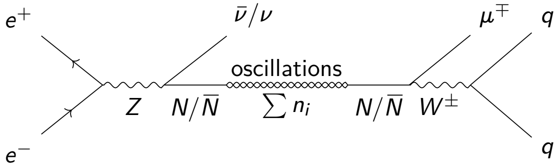


Lepton number violation (LNV) is measured by comparing the charges of the two leptons





Single charged lepton



Measurement

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

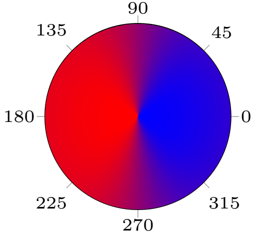
Angular dependent probability

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

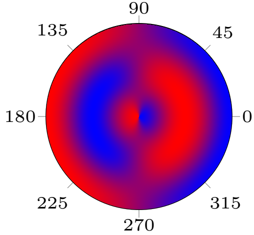
Probability of measuring charged leptons

- 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^+)

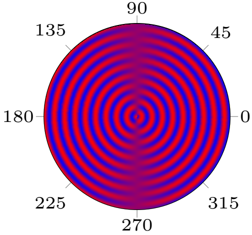
'Dirac BM'-like



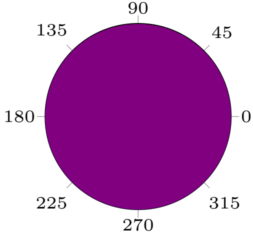
Slow oscillation



Fast oscillation



'Majorana BM'-like



Open question

Potential projects

- Detection potential at muon collider
- Decoherence at future colliders
- Loop contributions to neutrino masses
- ...

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Oscillating particles in quantum field theory (QFT)

[2307.06208]

Inadequate frameworks for oscillating relativistic particles

- Quantum mechanics
- Plane-wave QFT

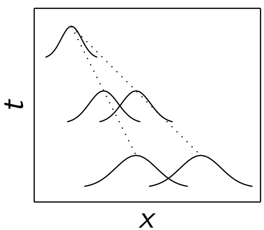
QFT with external wave packets

- 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

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

Decoherence



Result can be expressed with

effective damping parameter λ

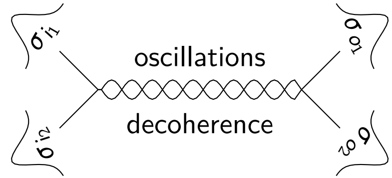
Damped oscillations

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

LNV can be

drastically enhanced

Width of external wave packets σ



Impact on $N\overline{N}$Os