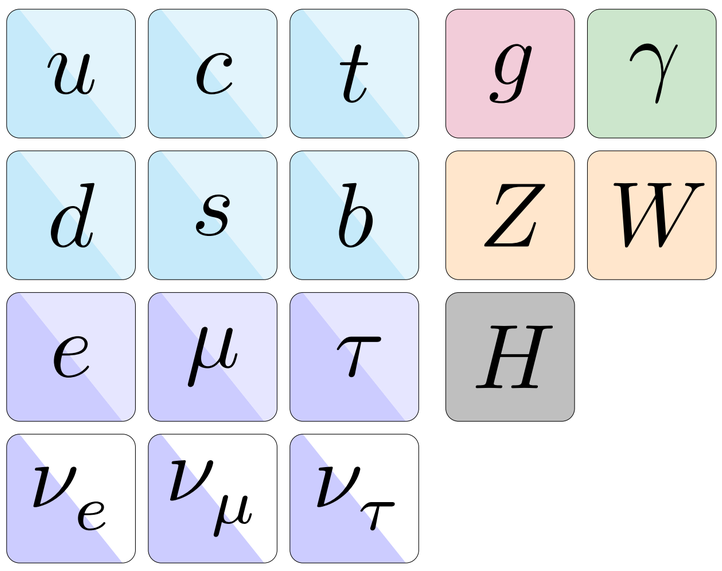
Lepton number violation: From the **longest standing puzzle** in particle physics to **heavy neutrino-antineutrino oscillations**.

Heavy Neutrino-Antineutrino Oscillations

Bruno M. S. Oliveira in collaboration with Stefan Antusch, Jan Hajer, and Filipe Rafael Joaquim

The Missing Neutrinos and The Seesaw Mechanism



Theory:
No right-chiral neutrinos
⇓
Neutrinos are **massless**

Experiment:
Neutrino flavour oscillations
⇓
Neutrinos are **massive**

Solution:
Add (at least two) **right-chiral** neutrinos
⇓
Sterile under the Standard Model's gauge group
⇓

Dirac masses (M_D):
Left- and right-chiral fields

Majorana masses (M_M):
Right-chiral fields

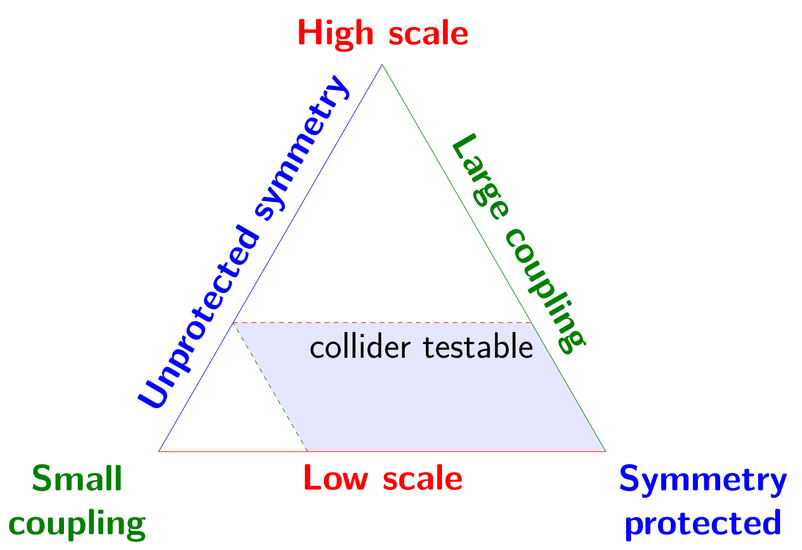
From the generic mass Lagrangian...

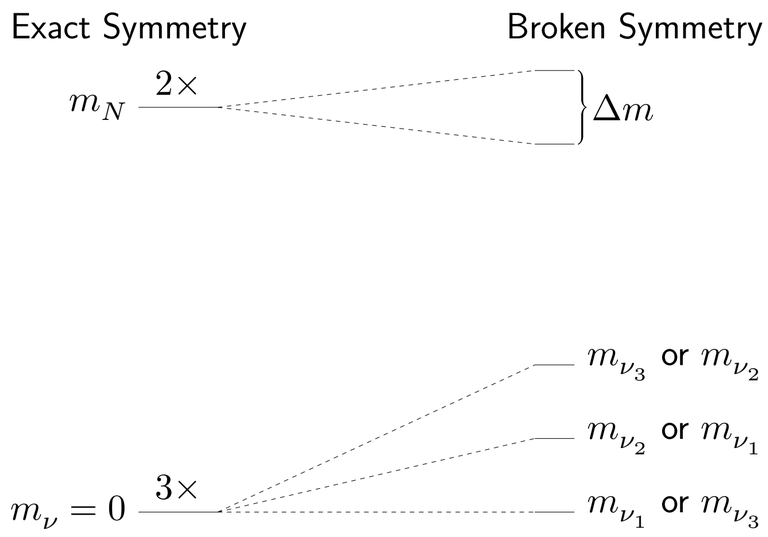
$$\mathcal{L}^{\nu}_{\text{mass}} = -\frac{1}{2}\left(\overline{\nu_L}\ \overline{\nu^c_R}\right)\begin{pmatrix} 0 & M_D^T \\ M_D & M_M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix} \xrightarrow{M_M \gg M_D}$$

...to the Type I Seesaw Mechanism

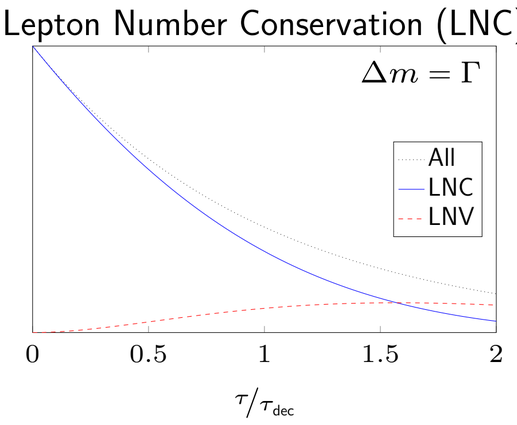
$$M_n \simeq M_M \qquad M_\nu \simeq \frac{M_D \otimes M_D}{M_M}$$

Symmetry Protection and Neutrino-Antineutrino Oscillations

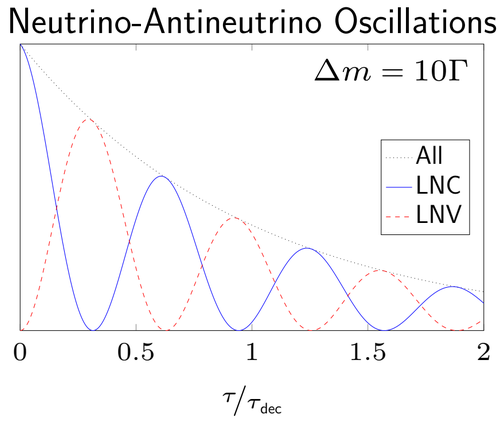




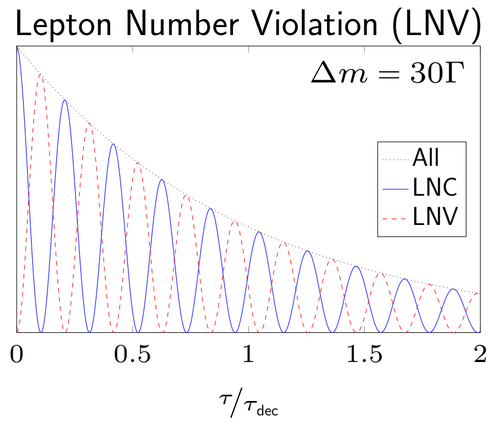
$\Delta m = 0$
⇓
Pure **Dirac** neutrino-antineutrino
⇓
Lepton Number Conservation (LNC)



$0 < \Delta m \ll m_M$
⇓
Pseudo-Dirac neutrino-antineutrino
⇓
Neutrino-Antineutrino Oscillations

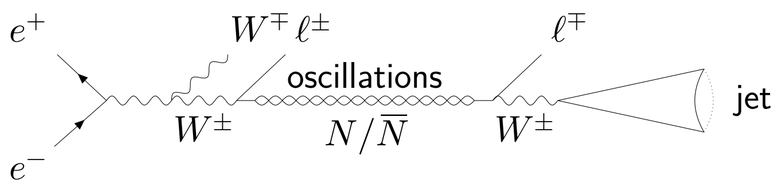


$\Delta m \sim m_N$
⇓
Independent **Majorana** pair
⇓
Lepton Number Violation (LNV)

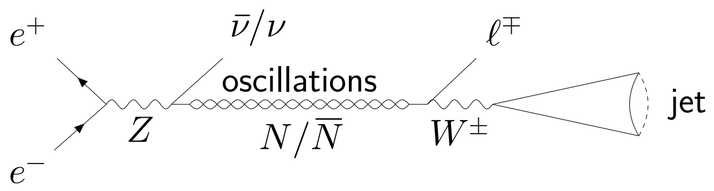


Resolving Oscillations at Collider Experiments

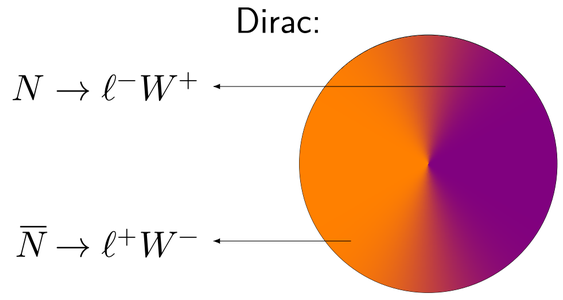
Reconstruct oscillations between LNC and LNV:



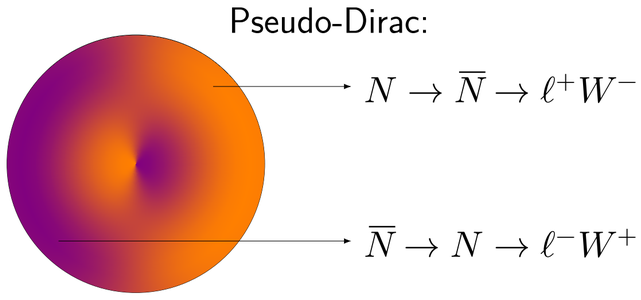
Reconstruct oscillations in observables:



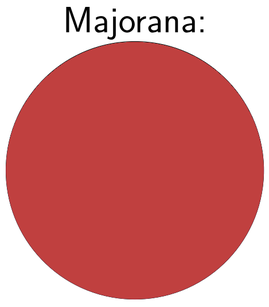
Dirac:



Pseudo-Dirac:



Majorana:

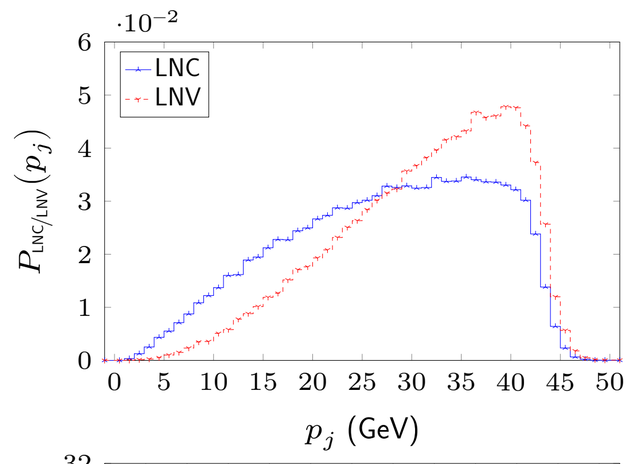


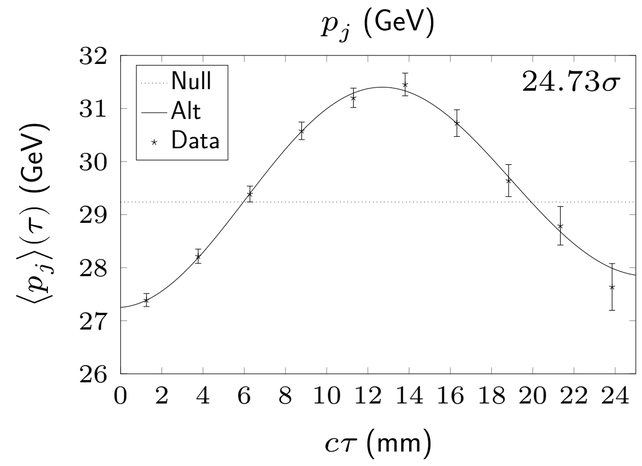
Phenomenological Symmetry Protected Seesaw Scenario

Standard Model with two Majorana neutrinos
⇓
Six additional parameters:

$$\underbrace{m_M \qquad (\theta_e, \theta_\mu, \theta_\tau)}_{\text{Exact Symmetry}} + \underbrace{\Delta m \qquad \lambda}_{\text{Broken Symmetry}}$$

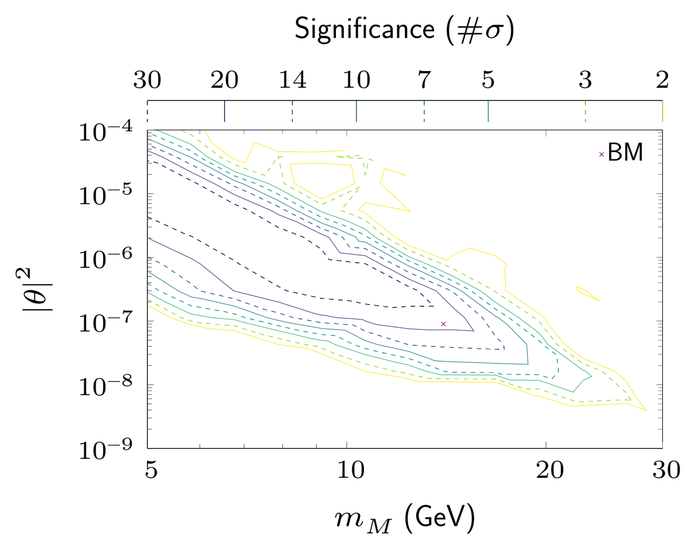
Full Monte Carlo **simulation** and **analysis**
⇓
Assess resolution of **oscillations in observables**

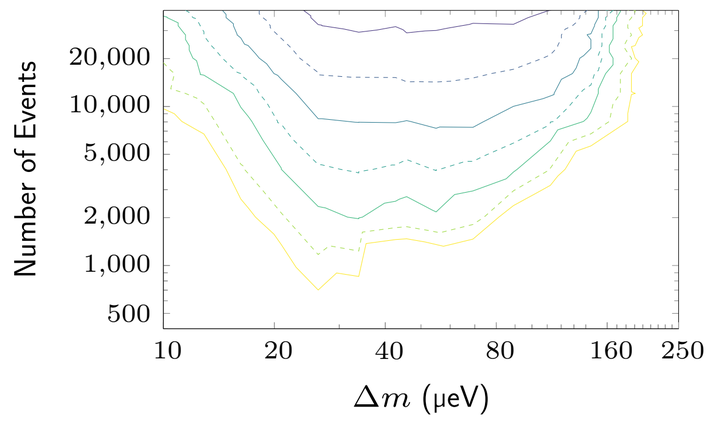




Significance of oscillations depends on

⇓	⇓
Number of events (m_M and $\lvert\theta\rvert^2$)	Oscillations and decay (Δm and $\Gamma \leftrightarrow m_M, \lvert\theta\rvert^2$)





HL-LHC ($W^\pm \to N/\overline{N}\,\ell^\pm$)
⇓
Lepton number violation
⇓
Neutrino-antineutrino oscillations

FCC-ee ($Z \to N/\overline{N}\,\overline{\nu}/\nu$)
⇓
Neutrino-antineutrino oscillations
⇓
Lepton number violation

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