Heavy neutrino-antineutrino oscillations at the HL-LHC

to appear soon

Jan Hajer

in collaboration with Stefan Antusch and Johannes Rosskopp

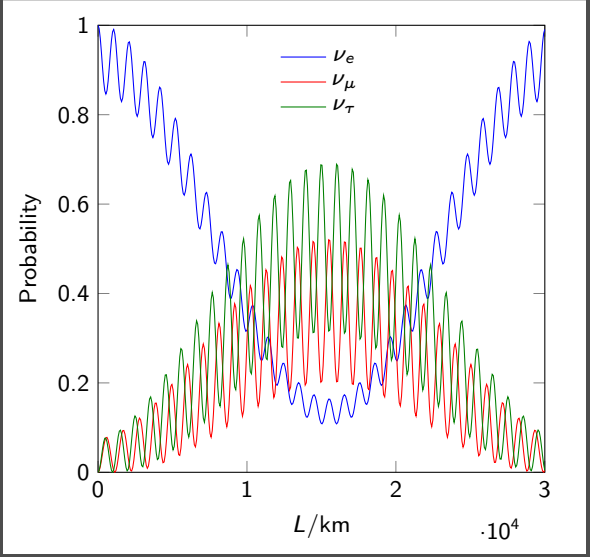
Centro de Física Teórica de Partículas, Instituto Superior Técnico, Universidade de Lisboa

FLASY 2022
9th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

FCT Fundação para a Ciência e a Tecnologia

Neutrino masses

SM neutrino ν flavour oscillations



Explained by

small SM neutrino masses m_ν

Generated by

right-chiral (sterile) neutrinos N

Dirac mass

$$\mathcal{L}_D = -m_D \overline{\nu} N\,, \quad m_D = vy$$

Majorana mass

$$\mathcal{L}_M = -\frac{1}{2} M_M \overline{N^c} N$$

Majorana mass vanishes only if

lepton-number L is conserved

Neutrino oscillation pattern requires

at least two massive neutrinos

Majorana contribution causes

neutrinoless double β decay

Coupling parameter

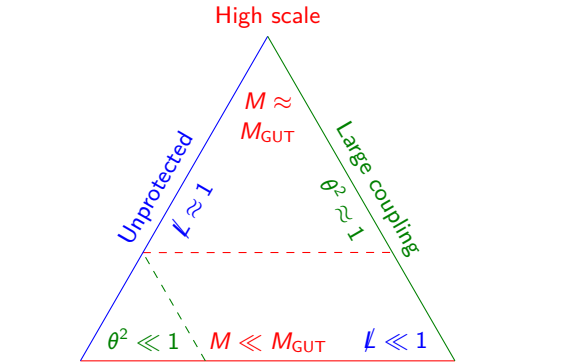
$$\theta = m_D / M_M$$

Seesaws

Neutrino mass matrix from two sterile neutrinos

$$m_\nu^{ij} \propto \frac{m_{D,1}^i m_{D,1}^j}{M_1} + \frac{m_{D,2}^i m_{D,2}^j}{M_2}$$

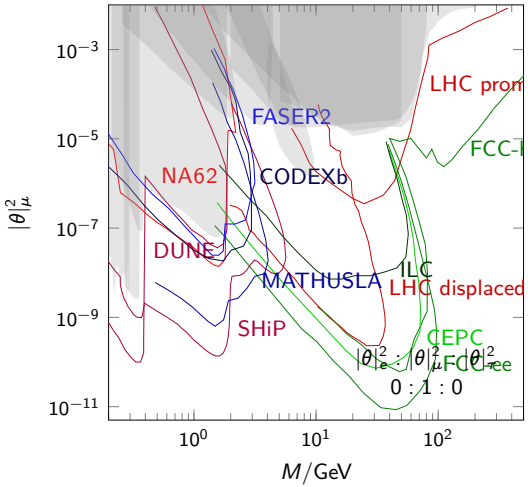
Viable seesaw models



Neutrino masses are small for

- small m_D
- large M
- symmetry ensuring cancellation

Heavy neutral leptons (HNLs) at experiments



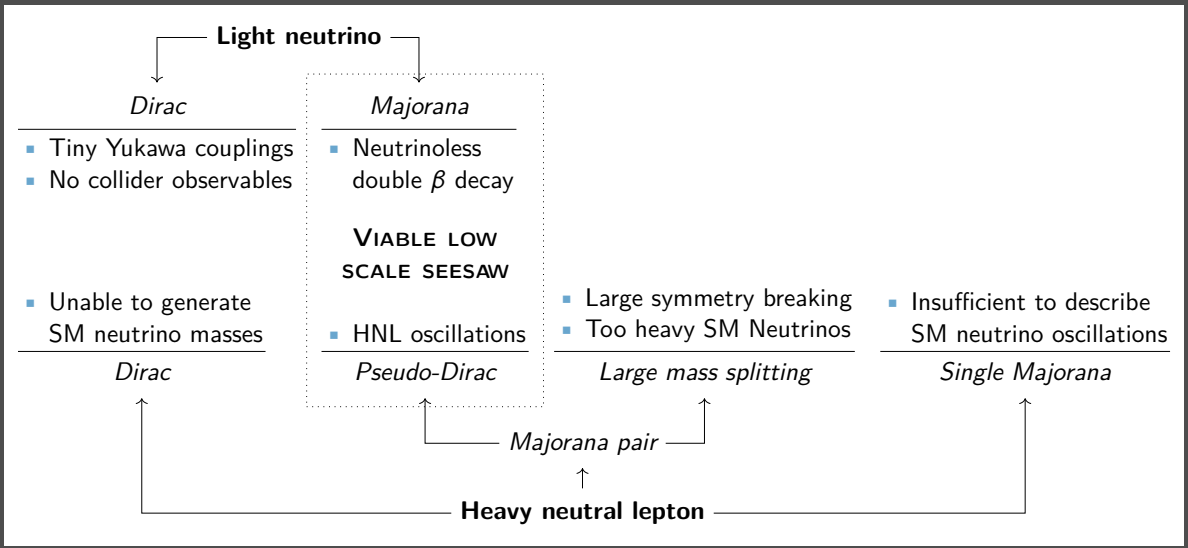
Lepton number-like symmetry ensures

- small neutrino masses
- small mass splitting between heavy neutrinos

Prediction: pseudo-Dirac HNL

Almost mass degenerate pair of Majorana HNLs

Are HNLs Majoran or Dirac Fermions?



Neither Majorana nor Dirac HNLs are

- expected to be found at colliders
- insufficient benchmark points

pseudo-Dirac HNLs have unique phenomenology

- Varying $R_{ll} = \frac{N_{\text{LNV}}}{N_{\text{LNC}}}$
- Oscillations between mass eigenstates

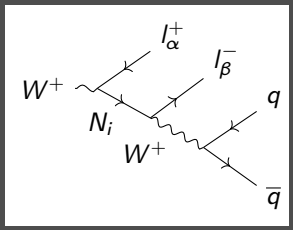
Oscillations

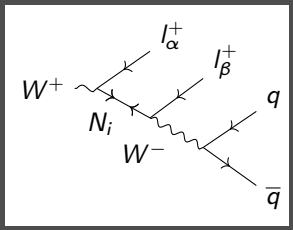
Oscillations

between LNC and LNV decays

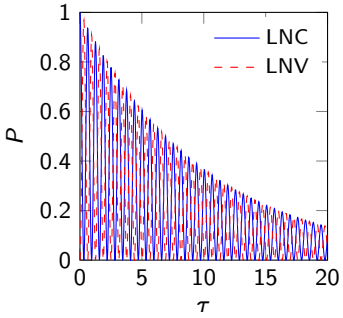
Mass splitting ΔM

governs size of oscillations at leading order



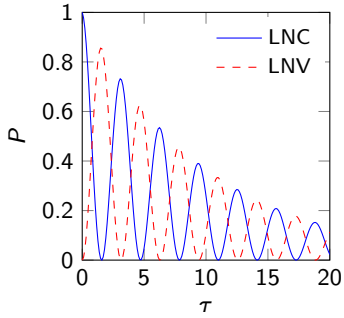


Short oscillation length



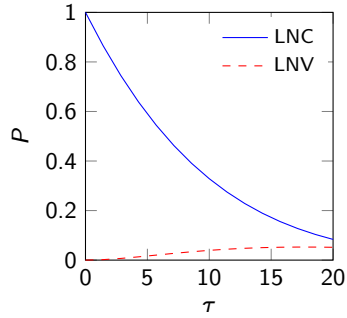
- Oscillations not resolvable
- Integrated effect $R_{ll} = N_{\text{LNV}}/N_{\text{LNC}} \approx 1$
- Majorana limit

Intermediate oscillation length



- $\Delta M/\Gamma \approx \mathcal{O}(1)$
- Oscillations measurable

Long oscillation length



- LNV contribution not detectable
- LNV strongly suppressed
- Dirac limit

Symmetry protected seesaw

Symmetric limit

$$\mathcal{L}^{\text{sym}}_{\text{SPSS}} = -\overline{N_1^c} M_{\text{maj}} N_2 - \widetilde{H}^\dagger \overline{N_1^c} \ell_a y_{a1} + \text{h.c.}\,,$$

In the symmetry protected limit $y_{a2} \ll 1$

$$\Delta\mathcal{L}^{y\ll 1}_{\text{SPSS}} = -\widetilde{H}^\dagger \overline{N_2^c} \ell_a y_{a2} + \text{h.c.} + \ldots\,,$$

Neutrino mass matrix

contains seesaw information

Basis

(ν, N_4, N_5)

Other new fields

contribute further terms

Symmetric limit

$$M_\nu^{\text{sym}} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^{\mathsf{T}} & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

- Massless neutrinos
- Dirac HNL

Mild symmetry breaking

$$M_\nu^{\text{SPSS}} = \begin{pmatrix} 0 & m_D & \mu \\ m_D^{\mathsf{T}} & \mu'' & M \\ \mu^{\mathsf{T}} & M & \mu' \end{pmatrix}$$

- pseudo-Dirac HNL
- phenomenology governed by small parameters μ

Large symmetry breaking

$$M_\nu^{\text{generic}} = \begin{pmatrix} 0 & m_D & m'_D \\ m_D^{\mathsf{T}} & M'' & M \\ m_D'^{\mathsf{T}} & M & M' \end{pmatrix}$$

- 2 Majorana HNLs with large ΔM
- Large M or tiny m_D

Consequences of small parameters μ, μ', μ''

Generic seesaw

All μ's are nonzero

Neutrinos

light and proportional the μ's

Special cases

Linear seesaw μ

$$M_\nu = \begin{pmatrix} 0 & m_D & \mu \\ m_D^\mathsf{T} & 0 & M \\ \mu^\mathsf{T} & M & 0 \end{pmatrix}$$

$$m_\nu \propto \mu^\mathsf{T} \frac{m_D}{M}$$

$$\Delta M = \Delta m_\nu$$

Inverse seesaw μ'

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\mathsf{T} & 0 & M \\ 0 & M & \mu' \end{pmatrix}$$

$$m_\nu \propto \mu' \frac{m_D^\mathsf{T} m_D}{M^2}$$

$$\Delta M = \frac{m_\nu}{|\theta^2|}$$

Seesaw independent term μ''

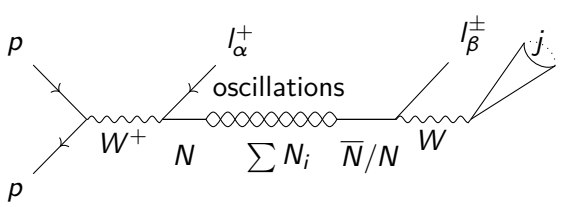
$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\mathsf{T} & \mu'' & M \\ 0 & M & 0 \end{pmatrix}$$

$m_\nu = 0$ at tree level

$$\Delta M \propto \mu''$$

Heavy neutrino oscillations at the LHC

Production, oscillation, and decay



Process

- Production of interaction eigenstates N or $\overline{N}$
- Mass splitting induced ΔM oscillations between N_4 and N_5
- LNC decay into l^- or LNV decay into l^+

Idea

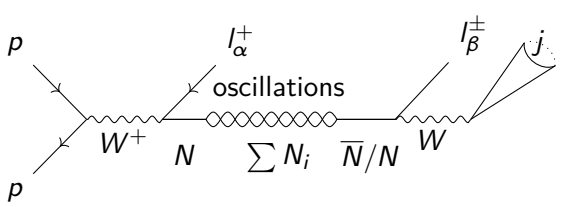
Observe heavy neutrino oscillations in long-lived decays

Simulation

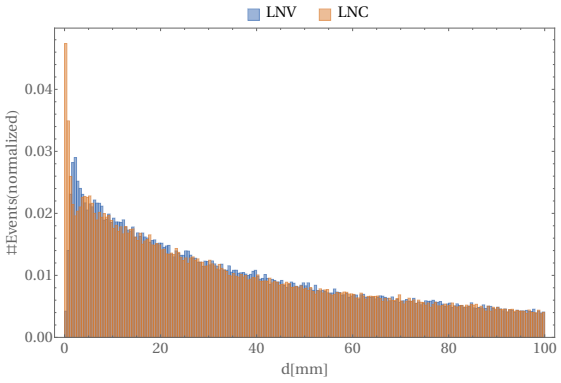
- Model implementation in FeynRules
- Event generation in MadGraph
- CMS Detector simulation in Delphes

Heavy neutrino oscillations at the LHC

Production, oscillation, and decay



Lab frame



Process

- Production of interaction eigenstates N or $\overline{N}$
- Mass splitting induced ΔM oscillations between N_4 and N_5
- LNC decay into l^- or LNV decay into l^+

Idea

Observe heavy neutrino oscillations in long-lived decays

Simulation

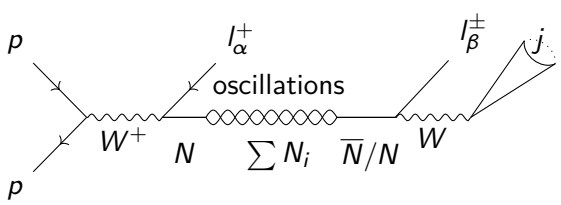
- Model implementation in FeynRules
- Event generation in MadGraph
- CMS Detector simulation in Delphes

Observations

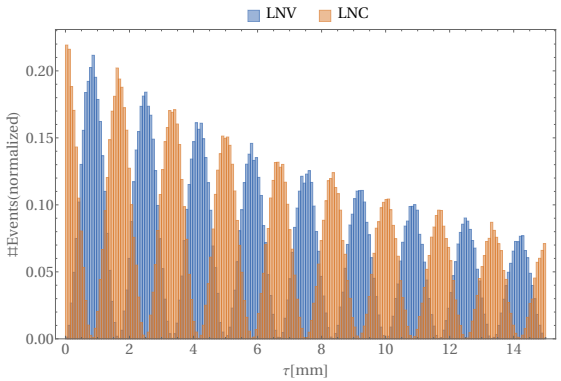
- No oscillations in the lab frame

Heavy neutrino oscillations at the LHC

Production, oscillation, and decay



Proper time frame



Process

- Production of interaction eigenstates N or $\overline{N}$
- Mass splitting induced ΔM oscillations between N_4 and N_5
- LNC decay into l^- or LNV decay into l^+

Idea

Observe heavy neutrino oscillations in long-lived decays

Simulation

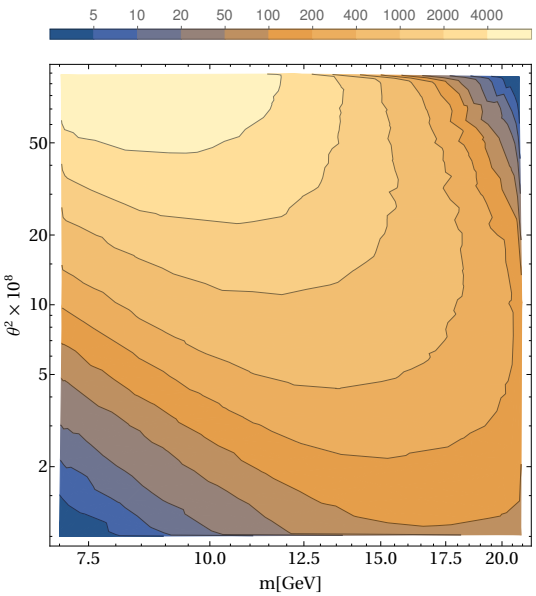
- Model implementation in FeynRules
- Event generation in MadGraph
- CMS Detector simulation in Delphes

Observations

- No oscillations in the lab frame
- Oscillations appear in proper time frame
- It is crucial to reconstruct the boost factor γ
- Only processes without final neutrinos useful

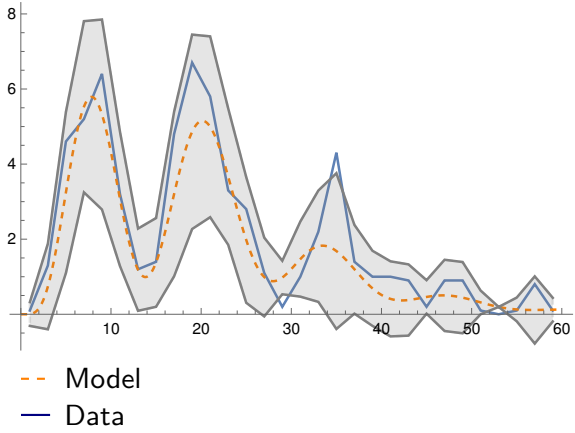
Preliminary results

Event number for semi hadronic decays



Expected pattern for long lived particle searches

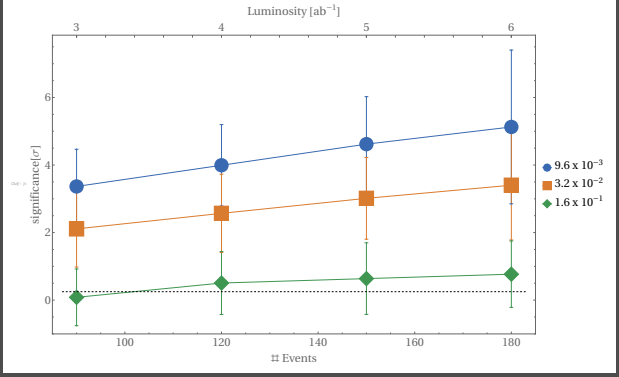
Example of oscillation reconstruction



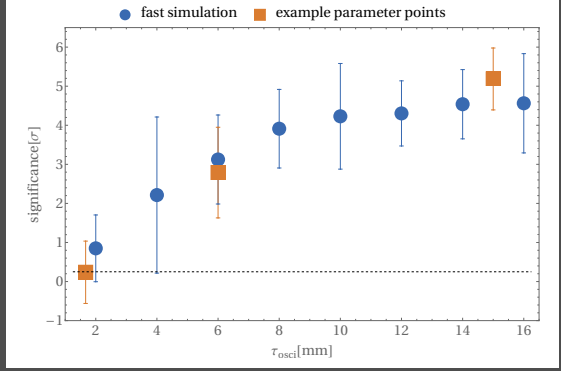
Preliminary results

- Large parts of the accessible parameter space are already excluded by LHC
- HL-LHC can measure some heavy neutrino oscillations with $5\,\sigma$
- Strong dependence on oscillation length

Significance as function of luminosity



Significance as function of oscillation length



Conclusion

- Low scale seesaw model predict pseudo-Dirac HNLs
- pseudo-Dirac HNLs oscillate between LNC and LNV decays
- Displaced HNL oscillations are resolvable at the HL-LHC
- The symmetry protected seesaw captures the relevant physics in a simple model
- Future collider will probe considerable more of the parameter space