Simulation of LNV via heavy neutrino-antineutrino oscillations

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Searching for long-lived particles at the LHC and beyond:
Twelfth workshop of the LLP Community
Neutrinos $\nu_\alpha$ stand out

purely left-chiral and massless
Neutrinos $\nu_\alpha$ stand out purely left-chiral and massless

Right-chiral or sterile Neutrinos neutral under SM symmetries

Flavour oscillations are explained by right-chiral neutrinos allowing mass terms
Dirac mass
\[
\mathcal{L}_D = -m_D \bar{\nu} \alpha N + \text{h.c.}, \quad m_D = \nu y
\]

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

Coupling strength is determined by
\[
\theta = \frac{m_D}{m_M}
\]

Majorana mass vanishes if lepton-number \( L \) is conserved

Majorana mass introduces lepton number violation (LNV)

Neutrino oscillation pattern requires at least two massive neutrinos

Neutrino mass matrix from two sterile neutrinos
\[
M_\nu = \frac{m_D^{(1)} \otimes m_D^{(1)}}{m_M^{(1)}} + \frac{m_D^{(2)} \otimes m_D^{(2)}}{m_M^{(2)}}
\]

Viable seesaw models

Neutrino masses are small for
\begin{itemize}
  \item small \( y \)
  \item large \( m_M \)
  \item symmetry protected cancellation
\end{itemize}
Are HNLs Majoran or Dirac Fermions?

HNL oscillations

Pseudo-Dirac

- Too heavy SM neutrinos or tiny Yukawa couplings
- Large mass splitting

Majorana

- 0νββ decay

Collider

Testable low scale seesaw

- Insufficient to describe SM neutrino oscillations

Dirac

- Unable to generate SM neutrino masses
- Tiny Yukawa couplings
- No collider observables

Single Majorana and Dirac HNLs are

- not predicted by low-scale seesaw models

Unique phenomenology of pseudo-Dirac HNLs

- Heavy neutrino-antineutrino oscillations
- $0 < R_{II} = \frac{N_{LNV}}{N_{LNC}} < 1$
Symmetry protected seesaw scenario (SPSS)

Symmetric limit

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

Lepton number-like symmetry

generalises accidental SM lepton number \( L \)

Neutrino mass matrix

contains seesaw information

Symmetric limit

\[ M_n^L = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\top & 0 & m_M \\ 0 & m_M & 0 \end{pmatrix} \]

- Massless neutrinos \( M_\nu = 0 \)
- Dirac HNL

Symmetry protected \( \nu y_2 \approx \mu M \approx \mu_M^' \ll m_M \)

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

One simple choice of charges

<table>
<thead>
<tr>
<th>( \ell )</th>
<th>( N_1 )</th>
<th>( N_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L )</td>
<td>+1</td>
<td>−1</td>
</tr>
</tbody>
</table>

Other new fields

further terms in Lagrangian

Basis

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

Dirac masses

\[ m_D = y_1 \nu, \quad \mu_D = y_2 \nu \]

Large symmetry breaking

\[ M_n^{L''} \gg 0 = \begin{pmatrix} 0 & m_D & m_M \\ m_D^\top & \mu_M^' & m_M \\ \mu_D^\top & m_M & \mu_M \end{pmatrix} \]

- Large \( \Delta m \) Majorana pair
- Requires large \( m_M \) or tiny \( \theta \)

- Pseudo-Dirac HNL
  (small \( \Delta m \) Majorana pair)
- Phenomenology governed by small parameters \( \mu \)
Special cases captured by the symmetry protected seesaw

<table>
<thead>
<tr>
<th>Cases</th>
<th>Linear seesaw $\mu_D$</th>
<th>Inverse seesaw $\mu_M$</th>
<th>Seesaw independent $\mu'_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_n =$</td>
<td>$\begin{pmatrix} 0 &amp; m_D &amp; \mu_D \ m_D^T &amp; 0 &amp; m_M \ \mu_D^T &amp; m_M &amp; 0 \end{pmatrix}$</td>
<td>$\begin{pmatrix} 0 &amp; m_D &amp; 0 \ m_D^T &amp; 0 &amp; m_M \ 0 &amp; m_M &amp; \mu_M \end{pmatrix}$</td>
<td>$\begin{pmatrix} 0 &amp; m_D &amp; 0 \ m_D^T &amp; \mu_M &amp; m_M \ 0 &amp; m_M &amp; 0 \end{pmatrix}$</td>
</tr>
<tr>
<td>$M_\nu =$</td>
<td>$\mu_D \otimes \theta$</td>
<td>$\mu_M \theta \otimes \theta$</td>
<td>0 (at tree level)</td>
</tr>
<tr>
<td>$\Delta m =$</td>
<td>$\Delta m_\nu$</td>
<td>$m_\nu</td>
<td>\theta</td>
</tr>
</tbody>
</table>

Benchmark models

<table>
<thead>
<tr>
<th>Seesaw</th>
<th>Hierarchy</th>
<th>$\Delta m_\nu$</th>
<th>BM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>Normal</td>
<td>$42.3 \text{ meV}$</td>
<td>$\Delta m_\nu = 42.3 \text{ meV}$</td>
</tr>
<tr>
<td></td>
<td>Inverted</td>
<td>$748 \mu\text{eV}$</td>
<td>$\Delta m_\nu = 748 \mu\text{eV}$</td>
</tr>
<tr>
<td>Inverse</td>
<td></td>
<td></td>
<td>$m_\nu = 1 \text{ meV}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$m_\nu = 10 \text{ meV}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$m_\nu = 100 \text{ meV}$</td>
</tr>
</tbody>
</table>

Generic seesaw

All small parameter $\mu$ are nonzero
Heavy neutrino-antineutrino oscillations

Oscillations
between LNC and LNV decays

Oscillation length
governed by mass splitting \( \Delta m \)

Oscillations not resolvable
Large \( R_{ll} \)
‘Majorana’ limit

Oscillations potentially measurable
Pseudo-Dirac character crucial

Damping due to decoherence

governed by \( \lambda \)

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

Short oscillation length

\( R_{ll}(100) = \frac{500}{501} \)
\( \lambda = \frac{1}{5} \)
\( \Gamma = \frac{\text{meV}}{25} \)
LNC
LNV

Intermediate oscillation length

\( R_{ll}(10) = \frac{50}{51} \)
\( \lambda = \frac{1}{5} \)
\( \Gamma = \frac{\text{meV}}{25} \)
LNC
LNV

Long oscillation length

\( R_{ll}(1) = \frac{1}{3} \)
\( \lambda = \frac{1}{5} \)
\( \Gamma = \frac{\text{meV}}{25} \)
LNC
LNV

LNV strongly suppressed
Small \( R_{ll} \)
‘Dirac’ limit
Software implementation of the phenomenological SPSS

Mass splitting

\[ m_{4/5} = m_M (1 + |\theta|^2/2) \mp \Delta m/2 \]

Phenomenological SPSS (pSPSS) adds

\( \Delta m \) Heavy neutrino-antineutrino oscillations

\( \lambda \) Decoherence damping

FeynRules model file

Pseudo-Dirac HNLs in the pSPSS

Available online

feynrules.irmp.ucl.ac.be/wiki/pSPSS

Parameter

<table>
<thead>
<tr>
<th>BLOCK PSPSS #</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1.0000000e+02 # mmaj</td>
<td></td>
</tr>
<tr>
<td>2 1.0000000e-12 # deltam</td>
<td></td>
</tr>
<tr>
<td>3 0.0000000e+00 # theta1</td>
<td></td>
</tr>
<tr>
<td>4 1.0000000e-03 # theta2</td>
<td></td>
</tr>
<tr>
<td>5 0.0000000e+00 # theta3</td>
<td></td>
</tr>
<tr>
<td>6 0.0000000e+00 # damping</td>
<td></td>
</tr>
</tbody>
</table>

Oscillations implemented in MadGraph

```python
mass_splitting = param_card.get_value('PSPSS', 2)
damping = param_card.get_value('PSPSS', 6)
for event in lhe:
    leptonnumber = 0
    write_event = True
    for particle in event:
        if particle.status == 1:
            if particle.pid in [11, 13, 15]:
                leptonnumber += 1
            elif particle.pid in [-11, -13, -15]:
                leptonnumber -= 1
    for particle in event:
        id = particle.pid
        width = param_card['decay'].get(abs(id)).value
        if width:
            if id in [8000011, 8000012]:
                tau0 = random.expovariate(width / cst)
                if 0.5 * (1 + math.exp(-damping)*math.cos(mass_splitting * tau0 / cst)) >= random.random():
                    write_event = (leptonnumber == 0)
                else:
                    write_event = (leptonnumber != 0)
            vtim = tau0 * c
        else:
            vtim = c * random.expovariate(width / cst)
        if vtim > threshold:
            particle.vtim = vtim
            # write this modify event
            if write_event:
                output.write(str(event))
                output.write('</LesHouchesEvents>
')
        output.write(output.close())
```

Detailed description: [2210.10738]
Monte Carlo Simulation

HL-LHC event number with $\mathcal{L} = 3 \text{ ab}^{-1}$

<table>
<thead>
<tr>
<th>$N$</th>
<th>$10^3$</th>
<th>$10^2$</th>
<th>$10^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_BMs$</td>
<td>$5\times10^{-10}$</td>
<td>$2\times10^{-9}$</td>
<td>$1\times10^{-8}$</td>
</tr>
<tr>
<td>$5\times10^{-7}$</td>
<td>$10^{-6}$</td>
<td>$10^{-5}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$m=\text{GeV}$</td>
<td>$\mid$</td>
<td>$\mid$</td>
<td>$\mid$</td>
</tr>
</tbody>
</table>

Integrate oscillations from origin to infinity

$$R_{ll} = \frac{N_{\text{LN}}}{N_{\text{LNC}}} = \frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2}.$$ 

$R_{ll}$ simulation vs. calculation

- analytic
- $R_{ll}(1) = \frac{1}{3}$
- $R_{ll}(10) = \frac{50}{51}$
- $R_{ll}(100) = \frac{500}{501}$
- MC

$\Delta m/\Gamma$
$R_{ll}$ with finite detector size: $R_{ll}^{\text{obs}}$

$R_{ll}^{\text{obs}}(R_{ll}, \tau_{\max}/\tau_{\text{osc}})$ while $\tau_{\min} \to 0$

$R_{ll}^{\text{obs}}(R_{ll}, \tau_{\min}/\tau_{\text{osc}})$ while $\tau_{\max} \to \infty$
Transition to physical cuts $d_0$, $d_{\text{min}}$, $d_{\text{max}}$

Changes feature but non-trivial pattern remains

[2210.10738]
Heavy neutrino-antineutrino oscillations at the LHC

Production, oscillation, and decay

\[ q \rightarrow l^+ l^\pm q, \quad W^+ N \rightarrow \sum n_i \bar{N}/N W^\mp \]

Idea

Observe heavy neutrino-antineutrino oscillations in long-lived decays

Process

- Production of interaction eigenstates \( N \) or \( \bar{N} \)
- Oscillations between \( n_4 \) and \( n_5 \) due to \( \Delta m \)
- LNC decay into \( l^- \) or LNV decay into \( l^+ \)

Simulation

- Model implementation in FeynRules
- Event generation in MadGraph
- CMS Detector simulation in Delphes
Heavy neutrino-antineutrino oscillations at the LHC

Production, oscillation, and decay

\[ q \xrightarrow{\text{oscillations}} l^+ \sum n_i \xrightarrow{\text{oscillations}} l^\pm \bar{N}/N \xrightarrow{\text{oscillations}} \sum n_i \xrightarrow{\text{oscillations}} l^- \text{ or } l^+ \bar{N} \]

Lab frame

\[ P_{\text{norm}} \]

<table>
<thead>
<tr>
<th>( d/\text{mm} )</th>
<th>0.05</th>
<th>0.1</th>
<th>0.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNV</td>
<td></td>
<td></td>
<td></td>
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Observations after MadGraph

- No oscillations in lab frame
Heavy neutrino-antineutrino oscillations at the LHC

Production, oscillation, and decay

\[ q \rightarrow W^+ N + \sum n_i \bar{N}/N \rightarrow l^+ l^- q \]

Idea

Observe heavy neutrino-antineutrino oscillations in long-lived decays

Process

- Production of interaction eigenstates \( N \) or \( \bar{N} \)
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Simulation

- Model implementation in \texttt{FeynRules}
- Event generation in \texttt{MadGraph}
- CMS Detector simulation in \texttt{Delphes}

Observations after \texttt{MadGraph}

- No oscillations in lab frame
- Oscillations appear in proper time frame
- Crucial to reconstruct Lorentz factor \( \gamma \)
- Depends on final states without neutrinos
Preliminary detector simulation results

BM1 with $c\tau_{osc} = 15$ mm and $Z = 6.66\sigma$

BM3 with $c\tau_{osc} = 1.67$ mm and $Z = 0.67\sigma$

Results

- Large parts of accessible parameter space excluded by LHC
- HL-LHC can measure oscillations in some BMs with 5 $\sigma$
Angular dependence of the transverse impact parameter

<table>
<thead>
<tr>
<th>Transverse impact parameter</th>
<th>Angular dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_0 = \frac{d_T' \wedge p_T'}{p_T'} = \frac{\epsilon_{ij} x'_i p'_j}{p_T'} = \frac{x'_p y' - y'_p x'}{p_T'})</td>
<td>(\sin \phi(N, \mu) = \frac{p_T^N \wedge p_T^\mu}{p_T^N p_T^\mu})</td>
</tr>
</tbody>
</table>

Point with the smallest distance to the z-axis

\(d_T' = (x', y')\)

Transverse momentum at \(d_T'\)

\(p_T' = (p'_x, p'_y)\)

Small B fields and going to secondary vertex

\(d_T' \rightarrow d_T = d_T \frac{p_T^N}{p_T^N}\)

Approximation

\(d_0 \approx d_T \frac{p_T^N \wedge p_T^\mu}{p_T^N p_T^\mu} = d_T \sin \phi(N, \mu)\)

\(d_0\) cuts introduce angular (spin) dependency
Reinterpretation of HNL searches as exclusion on low-scale seesaw models

- **Linear seesaw**
- **Inverse seesaw**
- **Inverted** $10^{-1}$ eV
- **Normal** $10^{-2}$ eV
- **$10^{-3}$ eV**

**Displaced searches**
- Dirac HNLs good approximation when integrating over oscillations

**Prompt LNV searches**
- Majorana HNLs miss a factor of 2
- Model dependency governed by $\Delta m$
- Inconsequential above $R_{ll}$ band
Low-scale seesaw models predict pseudo-Dirac HNLs

Pseudo-Dirac HNLs oscillate between LNC and LNV decays

The symmetry protected seesaw scenario captures the relevant physics in a simple model

We have implemented and published the necessary tools to simulate these oscillations

Displaced HNL oscillations are resolvable at the HL-LHC

Care has to be taken when measuring $R_{ll}$
