Long-lived Particles and Heavy Neutral Leptons: Theory/Pheno Perspective

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Long-Lived Particles can travel macroscopic distances before decaying

**LLP in the SM**

Their presence comes from conserved symmetries, feebly couplings, heavy mediators/hierarchy of mass scales, small phase space.

\[
\Gamma \sim L^2 \left( \frac{\Delta m}{\Lambda} \right)^n \Delta m
\]

\[
c\tau = \Gamma^{-\frac{1}{2}}
\]

Image by B.Shuve.
Long-Lived Particles are predicted in many beyond the Standard Model theories

**LLP in BSM** can arise from many well motivated classes of theories

**Why?** We need BSM to explain matter/antimatter asymmetry, dark matter and neutrino masses. Need to invest in a dedicated long-lived particle (LLP) program at colliders/experiments!

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Umbrella theories predicting Long-Lived Particles (LLP)

- **SUSY**
  - Multiple LLP with SM gauge charges
- **Higgs Portal**
  - LLP predominantly coupled to the Higgs
- **Dark Matter**
  - Non-SUSY, hidden sector DM. Can come from LLP decay
- **Gauge Portal**
  - New vector mediators can produce LLP
- **Heavy Neutral Leptons**
  - Right-handed singlet fermions or sterile neutrinos can be LLP

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See also MATHUSLA physics case motivating models, D. Curtin et al, [arXiv:1806.07396](https://arxiv.org/abs/1806.07396)

SM image @ CERN, ATLAS web

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HNL LLP Motivation

**Known**

- Neutrino oscillations therefore neutrinos in the SM have mass

![Neutrino Oscillations](image)

**Unknown**

- Neutrino Mass Mechanism involving HNL (i.e. seesaw mechanism, inverse seesaw, ...)
- Specific BSM Model of neutrino mass generation (i.e. new interactions of HNL beyond Yukawa ones?)
- HNL nature (Dirac or Majorana)
- HNL mass scale


An answer for neutrino mass generation mechanism


Could also explain Dark Matter and Baryon Asymmetry


Images by @symmetrymagazine
Seesaw Mechanism(s)
- Predicts HNLs
- HNLs mix with SM neutrinos
- Can be realised in many BSM models

Minimal Type I Seesaw

\[ \mathcal{L}_{\text{mass}} = \frac{1}{2} \left( \nu^c_N N^c_R \right) M_{\nu} \left( \nu_N \right) + h.c \]

\[ M_{\nu} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \]

\[ M_N \gg m_D \quad m_{\nu} \approx -m_D \cdot M_N^{-1} \cdot m_D^T \]

\[ m_N \approx M_N \]

\[ V_{EN} = m_D \cdot M_N^{-1} \Rightarrow V_{EN} \sim m_{\nu}/M_N \]

\[ V_{EN} = m_D \cdot M_N^{-1} \Rightarrow V_{EN}^2 \sim m_{\nu}/M_N \]

Is not the only possibility ...

i.e. Inverse Seesaw

\[ (\nu_L, N^c_R, S_L) \]

\[ M_{\nu} = \begin{pmatrix} 0 & m_D^T & \epsilon^T \\ m_D & M & M_N \end{pmatrix} \]

\[ m \ll M_N \quad \text{Inverse seesaw} \rightarrow V_{EN}^2 \sim m_{\nu}/M_N \]

Pheno approach: consider HNL mass and mixing as independent parameters
Rich collider phenomenology across different masses
See reviews
Y. Cai, T. Han, Tong Li, R. Ruiz, Front.in Phys. 6 (2018) 40, arXiv:1711.02180

HNL LLP Motivation

\[ \Gamma \sim G_F^2 m_N^5 |\text{V}e|^2 \]

Small mixing and \( \sim \text{GeV scale} \) result in LLP!

HNL discovery potential with a variety of LLP signatures!

Adapted from G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)

Adapted from Heather Russel
HNL LLP Phenomenology in Minimal Type I seesaw

HNL mixes with SM neutrino. Large lifetime due to off-shell decay

“HNL optimized” displaced strategies/proposals that build up on experimental LLP-LHC searches not really designed for HNLs (apologies if I missed your work!)

Displaced vertex searches
- HNL decays leptonically and/or semileptonically
- prompt lepton trigger from W decay

Inner Trackers (IT)
- high-mass and displaced track multiplicity DVs in inner tracker to suppress hadronic bkgs.


Muon Systems (MS)
- can access larger displacements (i.e lower HNL masses)
- purely muonic vertices give better sensitivity at low HNL masses (not necessarily limited by invariant mass cut of DV)

M. Drewes, J. Hajer, JHEP 70 (2020)
HNL LLP Phenomenology in Minimal Type I seesaw
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“HNL optimized” displaced strategies/proposals that build up on experimental LLP-LHC searches not really* designed for HNLs (apologies if I missed your work!)

**Displaced lepton searches**
- HNL decays leptonically
- prompt lepton trigger
- At least one displaced track from HNL is a non-isolated lepton
- Can do explicit vertex reconstruction of displaced di-muon/di-electron/emu vertices in ID or MS
- No explicit vertex requirement leads to additional sources of SM bkgs.

M. Drewes, J. Hajer, *JHEP 70 (2020)*
* ATLAS *JHEP 10 (2019)* (first) dedicated HNL displaced search at the LHC

**Displaced lepton-jets**
- Prompt lepton trigger from W decay
- Reconstruct boosted HNL decay as a single displaced $lj$ object
  (with more than one leptonic displaced track concentrated within a cone)

HNL landscape with LLP strategies - apologies if your work is not in this plot!

*electron mixing qualitatively similar, tau sector is far less constrained experimentally!*

e.g., see G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)

With other LHC projections since 2018 — Cottin, Helo, Hirsch (2018)
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Beyond Minimal Type I seesaw

Similar LLP HNL displaced search strategies have been proposed that can be sensitive to non-minimal HNL models with additional production modes via e.g. new gauge bosons ($Z'$, WR), higgs(es).

Can have 1DV or 2 DVs with no additional prompt objects (highlighting a critical need for dedicated displaced triggers)

For Left-Right, see e.g.

For B-L, see e.g.

A systematic way to study such non-minimal HNLs is to apply effective field theory (EFT), with NRO which are suppressed by a new physics scale $\Lambda$

For HNLs in EFT with LLPs at the LHC, see e.g.
Beyond Minimal Type I seesaw

An example for $d = 6$ for the “NRSMEFT”, the EFT of the SM extended with HNLs


$$\mathcal{L}_b > \frac{1}{\Lambda^2} \left( c_{dN} O_{dN} + c_{uN} O_{uN} + c_{QN} O_{QN} \right)$$

Dirac HNL, $c_{\nu N}/\Lambda^2 = 1/(2\text{ TeV})^2$

Majorana HNL, $c_{\nu N}/\Lambda^2 = 1/(2\text{ TeV})^2$

Much larger sensitivities can be achieved with LHC-LLP searches as compared to the Minimal Type I seesaw!
Summary

• HNLs are predicted in (seesaw) mechanisms able to explain the origin of small neutrino masses in the SM, and they can be automatically long-lived particles with masses below the electroweak scale

• In the high-luminosity phase of the LHC, both LHCb and the main detectors ATLAS and CMS can extend existing limits for (or provide discovery of) HNLs using displaced searches. Dedicated detectors can cover complementary regions in HNL mass and mixing space

• Dedicated searches and displaced triggers (able to identify directly the HNL signature) are critical to enhance sensitivity. Experimental searches with different HNL decay signatures i.e. $N \rightarrow e jj$, $N \rightarrow \tau jj$, are desirable to complement existing analyses (existing pheno proposals to test other mixing parameters)

• HNL production in non-minimal models beyond Type I seesaw can lead to enhanced cross-sections (which are not suppressed by the small mixing of the HNLs with the SM neutrinos) leading to a larger sensitivity reach at the HL-LHC

• Displaced searches can provide a clear collider test of many models for neutrino mass generation!