Resolving Heavy Neutral Lepton oscillations at the intensity frontier

(*Based on* Coherent Oscillations of Heavy Neutral Leptons, *soon on arXiv*)

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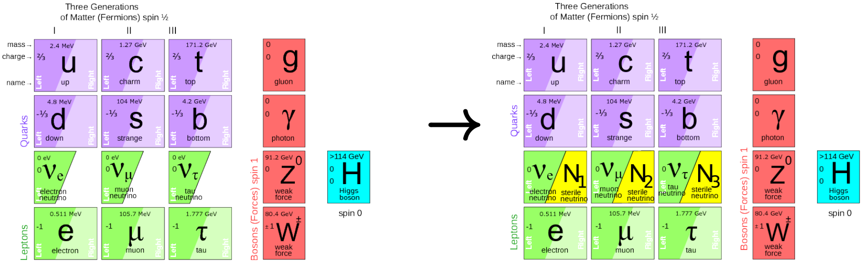
centre for particle physics
Discovery

Why Heavy Neutral Leptons?

The SM is tremendously successful at explaining collider results, but...

1. Predicts massless neutrinos, but we know at least 2 are massive.
2. Not enough CP-violation to account for the observed BAU.
3. Does not provide a (particle type) Dark Matter candidate.
4. Its particle content hints at singlet (sterile), "right-handed"[1] counterparts to neutrinos $\rightarrow N^{\dagger}$.



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[1] Since HNLs are sterile under $SU(2)_L$, it does not make much sense to associate them with a specific chirality, but this denomination remains common.

Massive neutrinos

- The SM allows two types[2] of masses terms for neutrinos[3] [4]:
  1. Dirac: $m_D(\nu N + N^\dagger \nu^\dagger)$.
  2. Majorana (for the singlets): $\frac{M_R}{2}(NN + N^\dagger N^\dagger)$.
- For three generations and multiple HNLs[5]:
  1. $(m_D)_{\alpha I}\nu_\alpha N_I + \text{h.c.} \overset{\text{def}}{=} \nu^T m_D N + \text{h.c.}$
  2. $(M_R)_{IJ} N_I N_J + \text{h.c.} \overset{\text{def}}{=} N^T M_R N + \text{h.c.}$
- In general, both terms can be present:
  - → Dirac-Majorana mass term (here in matrix form):

$$\mathcal{L}_{\text{D+M}} = \begin{pmatrix} \nu^T & N^T \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} + \text{h.c.}$$

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[2] Including only the existing representations of the SM gauge groups.

[3] Everything here is in two-component spinor formalism (see Dreiner, Haber, and Martin 2010 for a review), using the $(\frac{1}{2}, 0)$ representation.

[4] For convenience, we define the left-handed HNLs $N_a = \varepsilon_{ab}(N^{\dagger\dot{a}})^\dagger$.

[5] The number of HNLs is not constrained by anything, but we often postulate one HNL per generation.

The Type-I Seesaw mechanism

(Minkowski 1977; Gell-Mann, Ramond, and Slansky 1979; Mohapatra and Senjanović 1980; Yanagida 1980)

- Diagonalize mass matrix with an orthogonal field rotation[6].

$$\mathcal{L}_{\mathrm{D+M}} = \frac{m_i}{2}(n_i n_i + n_i^\dagger n_i^\dagger)$$

- Singular values are the physical *Majorana* masses.
- Mixing between flavor states ν_α and mass eigenstates n_i:

$$\nu_\alpha = \mathcal{U}_{\alpha i} n_i = U^{\mathrm{PMNS}}_{\alpha i} \nu_i + \Theta_{\alpha I} N_I$$

→ *Sterile* neutrinos can still interact through (small) mixing!

- Approximate block diagonalization leads to:

$$\hat{M}_{\mathrm{light}} \cong -m_D^T (M_R)^{-1} m_D$$
$$\hat{M}_{\mathrm{heavy}} \cong M_R$$

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[6] Takagi factorization.

Seesaw models

Different choices of parameters lead to different phenomenologies.

1. "Traditional Type-I Seesaw":
   - $m_D \sim v$ (natural Yukawas), $M_R \sim 10^{15}$ GeV.
   - $m_\nu \sim \frac{m_D^2}{M_R}$: the larger M_R, the smaller $m_\nu \to$ *seesaw*.
   - Leads to observed ν masses: $\hat{M}_\nu \sim 10^{-2}$ eV.
2. $\nu\mathrm{MSM}$ (Asaka and Shaposhnikov 2005):
   - Some variants can explain neutrino masses, BAU and Dark Matter.
   - Complete the SM with 2 nearly-degenerate HNLs $N_{1,2}$.[7]
   - Include all renormalizable terms allowed by the SM symmetries.
   - $m_D = -\frac{v}{\sqrt{2}} Y^\nu_{\alpha I}$ and $M_R \sim v$.
   - Neutrinos masses are small because Yukawas are small...
   - ... or new symmetry: approximate lepton number conservation.
3. And more (radiative seesaw, ...)

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[7] And optionally add a DM candidate.

Why HNL oscillations?

- In the $\nu\mathrm{MSM}$, BAU is produced through the ARS mechanism (Akhmedov, Rubakov, and Smirnov 1998):
  1. CP-violating oscillations between $N_{1,2}$ produce a lepton *flavor* asymmetry.
  2. Difference between couplings leads to a lepton *number* asymmetry.
  3. This lepton number asymmetry is partially processed into a *baryon* number asymmetry by sphalerons.
- If the physical splitting δM is small enough, HNL oscillations can produce the observed Dark Matter abundance (Shaposhnikov 2008).

Can we resolve oscillations and measure δM?

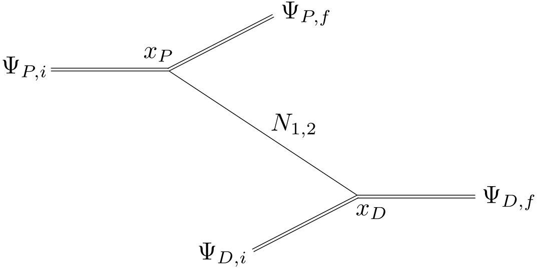
We need an accurate model of HNL oscillations to answer this question.

$\longrightarrow$ *External wave packet model*

External wave packet model I

Sachs 1963; Giunti, Kim, and Lee 1993; Beuthe 2003; Akhmedov and Kopp 2010; Akhmedov and Smirnov 2011; Akhmedov, Hernandez, and Smirnov 2012

1. **External:**
   - Compute the amplitude for the whole process, including the HNL production and its decay.



   - Keep the phase factor $e^{-iq_I\cdot(x_D-x_P)}$ with each internal line.
   - Sum the partial amplitudes:

$$\mathcal{P}(\Psi_i \to \Psi_f) = \left|\mathcal{A}(\Psi_i \to \Psi_f)\right|^2 = |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + 2\,\mathrm{Re}\left(\mathcal{A}_1^* \mathcal{A}_2\right)$$

External wave packet model II

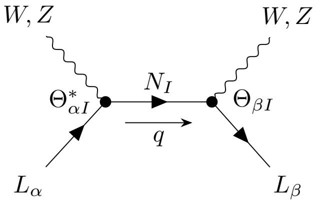
2. **Wave packet:**
   - Both the initial and final states have associated wave packets. For example, for a HNL produced in a semileptonic decay $H \to H' l_\alpha N$, then decaying to as $N \to H'' l_\beta$:

$$|\psi_I\rangle = \int \mathrm{d}\Omega_p \, \psi_I(\mathbf{p}) \, |H(\mathbf{p})\rangle$$

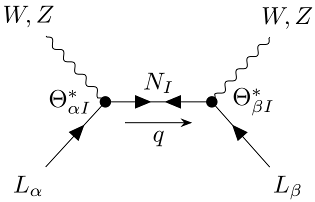
$$|\psi_F\rangle = \int \mathrm{d}\Omega_{k_1} \mathrm{d}\Omega_{k_2} \mathrm{d}\Omega_{k_3} \mathrm{d}\Omega_{k_4} \, \psi_F(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) \cdot \left| H'(\mathbf{k}_1), l_\alpha(\mathbf{k}_2), H''(\mathbf{k}_3), l_\beta(\mathbf{k}_4) \right\rangle$$

   - Interaction vertices are *localized*: no integration over $x_{P,D}$.
   - Necessary to have overlap between initial and final states while conserving momentum at *each* vertex (see Cohen, Glashow, and Ligeti 2009).
   - If it is possible to tell the HNLs apart with a sufficiently precise measurement of the external momenta or of the propagation time (due to dispersion), then decoherence occurs.

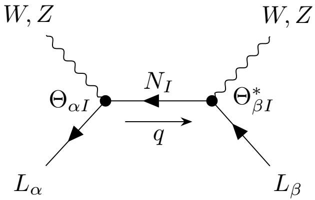
Propagators for Majorana particles



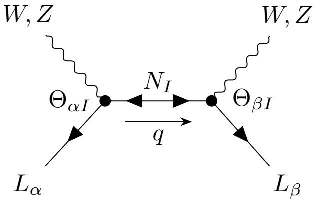
(a) $L \to L$



(b) $L \to R$



(c) $R \to R$



(d) $R \to L$

Coherent cross-section

- For the coherent cross-section, the extra phases $e^{-iq_I\cdot(x_D-x_P)}$ coming from on-shell propagators are relevant.
- If we integrate wave packets[8] over 3-momentum $\mathbf{q}$, then for each eigenstate the energy is $E_I=\sqrt{M_I^2+\mathbf{q}^2}$.
- In the ultra-relativistic limit: $q_I\cdot(x_D-x_P)\cong\frac{M_I^2}{2|\mathbf{q}|}L$.
- Squaring the amplitude and including self-energy corrections $M_I^2\to M_I^2-iM_I\Gamma_I$, we can express the (differential) coherent cross-section in terms of the incoherent one:

$$(d\sigma_{\mathrm{coh}})^{\pm\pm}_{\alpha\beta}=\frac{\left|\sum_I\Theta^{\mp}_{\alpha I}\Theta^{\pm}_{\beta I}e^{-i\frac{M_I^2}{2E}L-\frac{\Gamma_I}{2}\tau}\right|^2}{\sum_J|\Theta_{\alpha J}|^2|\Theta_{\beta J}|^2e^{-\Gamma_J\tau}}(d\sigma_{\mathrm{inc}})^{\pm\pm}_{\alpha\beta}$$

where we have defined $\Theta^-\overset{\mathrm{def}}{=}\Theta$ and $\Theta^+\overset{\mathrm{def}}{=}\Theta^*$.

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8. There is neither fixed E nor fixed $\mathbf{q}$, but rather overlap between wave packets.

Quasi-Dirac limit

- Current facilities can only probe HNLs with large ("unnatural") mixing with flavor fields.
- In the large-couplings limit, 2 HNLs form a quasi-Dirac pair[9], i.e. $\Theta_{\alpha 2} = \pm i \Theta_{\alpha 1}$.
- A new symmetry, leading to *approximate* lepton-number conservation, can be postulated to produce nearly-degenerate HNLs with large couplings while avoiding fine-tuning (Shaposhnikov 2007).
- The maximal mixing between the two HNLs leads to LNC-LNV oscillations (Anamiati, Hirsch, and Nardi 2016; Antusch, Cazzato, and Fischer 2017).

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[9] This is easily seen from the Casas-Ibarra parameterization, and more generally this is a consequence of the argument from Kersten and Smirnov 2007.

LNC-LNV asymmetry

1. Long-lived HNLs at colliders:
    - Displaced vertex.
    - Primary and secondary leptons may have opposite (LNC) or same sign (LNV), and in general they can have different flavors.
    - LNC-LNV asymmetry oscillates as a function of $\tau = \sqrt{(x_D - x_P)^2}$.
2. Short-lived HNLs at colliders:
    - Integrated LNC-LNV asymmetry R_{ll} can tell us whether $\delta M \lesseqgtr \Gamma$.
3. Beam-dump experiments:
    - Primary lepton usually inside the target → not visible.
    - HNLs produced in the decay of heavy mesons: D, D_s, B, B_c...
    - Beam-dump experiments typically produce equal amounts of anti-mesons.

      $\Longrightarrow$ We cannot reliably use the LNC-LNV asymmetry here![10]

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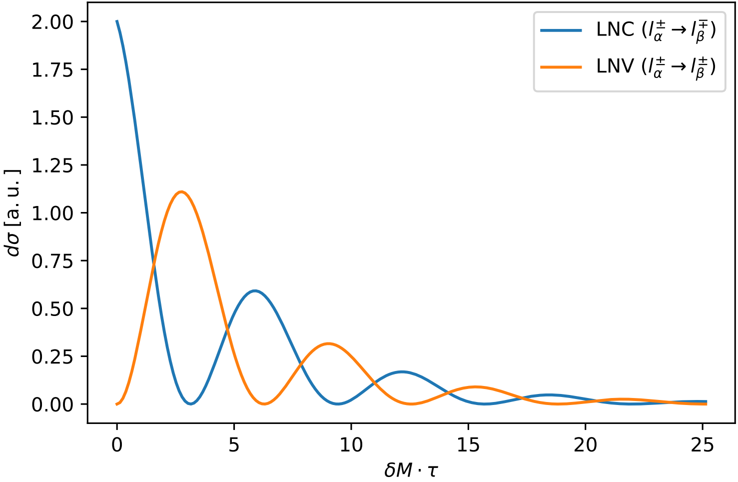
[10] We can in principle see HNL disappearance close to the seesaw bound (lowest possible couplings), but no experiment is sensitive to this region yet.

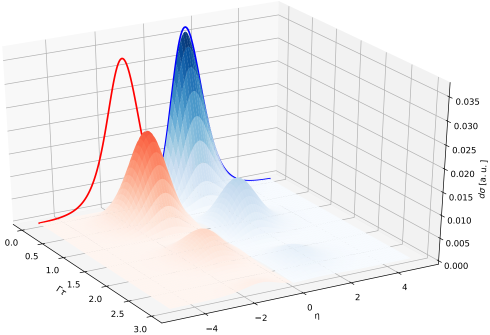
LNC-LNV asymmetry



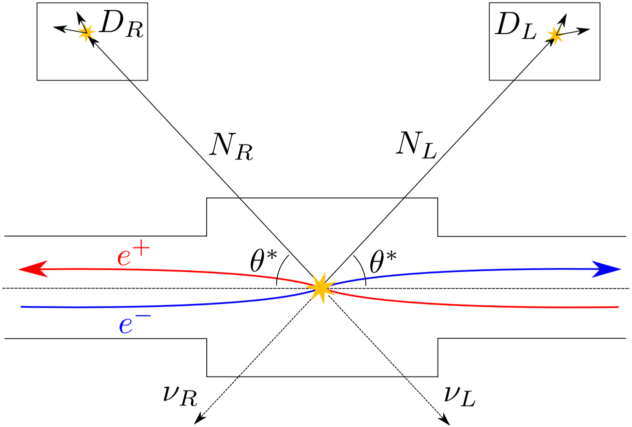
Angular distribution

Here, we generalize results from Hernández, Jones-Pérez, and Suárez-Navarro 2018.

- Prompt HNLs produced at an e^+e^- collider, along with light ν.
- Bin HNL candidate events by secondary lepton charge and flavor, as well as HNL proper lifetime τ and pseudorapidity η.
- Conservation of total spin will lead to non-trivial correlations between these parameters. For a secondary l_β^-:



Detecting small-δM oscillations at e^+e^- colliders



- Opposite, non-trivial charge asymmetries in both detectors would indicate that HNLs have oscillated.
- A similar effect might be used to break the accidental symmetry at beam-dump experiments.

Conclusion

- HNLs are a primary target for future intensity frontier facilities.
- Observing their oscillations and measuring δM would put strong constraints on BAU / leptogenesis.
- There are several ways to detect their oscillations, using charge asymmetries and kinematics.
- HNL oscillations are best studied using scattering theory.
- When studying displaced vertices, the phases of on-shell propagators should be kept in the calculations, otherwise only the integrated effect of oscillations is visible.
- Oscillations must be allowed for in displaced vertex searches.

Questions?

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