Review on Sterile Neutrinos

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Neutrino oscillations & the Standard Model

- No right-handed neutrinos in the Standard Model (SM).
- No mass matrix, no mixing of the neutrino flavour states.
  \[ \Rightarrow \text{Neutrino oscillations are evidence of physics beyond the SM.} \]
Lowscale seesaw

Benchmark model, defined in Antusch, OF; JHEP 1505 (2015) 053
Similar to e.g.: Mohapatra, Valle (1986); Malinsky, Romao Valle (2005); Shaposhnikov (2007);

- Lowscale seesaw Lagrangian, two sterile neutrinos $N_i$ with protective symmetry:

$$\mathcal{L}_N = -\frac{1}{2} \overline{N}_R^1 M (N_R^2)^c - y_{\nu \alpha} \overline{N}_R^1 \tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

- The mass matrix after electroweak symmetry breaking:

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

- Perturbations $\Rightarrow m_\nu$ and HNL mass splitting ($\Delta M$)
- $m'_D$: Linear seesaw, $\Delta M^{NO} = 0.0416$ eV, $\Delta M^{IO} = 0.000753$ eV
- $\mu$: inverse seesaw, $\Delta M \sim \frac{m_{\nu i}}{|\theta|^2}$. 
Heavy neutrino interactions

- Heavy neutrinos are mostly sterile, interactions via mixing.
- **Charged current (CC):**
  \[ j_{\mu}^\pm = \frac{g}{2} \theta_\alpha \bar{\ell}_\alpha \gamma_\mu N \]

- **Neutral current (NC):**
  \[ j_{\mu}^0 = \bar{\nu}_\alpha \gamma_\mu \theta_\alpha N \]

- Higgs boson **Yukawa** interaction:
  \[ L_{\text{Yukawa}} = \sum_{\alpha=e,\mu,\tau} \theta_\alpha \frac{\sqrt{2}}{v_{\text{EW}}} M \nu_\alpha \phi^0 N \]

- Simplification: light neutrino mass eigenstates \( \equiv \nu_e, \nu_\mu, \nu_\tau \)
Traditionally searched for via Lepton Number Violating signatures

e.g. $\mu^\pm \mu^\pm + J$ at pp (SS dimuons) or $e^+ + J$ at ep

However...
Lepton number violation and $\Delta M$

- With $m'_D = \mu = 0$, no LNV in this class of models.
- $R_{\ell\ell}$ (LNV/LNC) function of $\Delta M$ and $\Gamma_N$.
- For mass splitting $\sim$ decay width, $R_{\ell\ell} \in [0, 1]$.
- Zero mass splitting $\Rightarrow$ zero LNV.
Parameter space with LNV

The colored bands separate parameterspace w/ and w/o LNV.

Upper contour: $R_{\ell\ell} = 0.1$, lower contour: $R_{\ell\ell} = 0.9$

$\Rightarrow$ No LNV for $M > 100$ GeV!
Interlude: Searching for $N$ with $M > 100$ GeV

\[ e^- \rightarrow N \]
\[ q \rightarrow W^- \]
\[ j \rightarrow j \]

| Name         | Final State | Channel [production,decay] | $|\theta_\alpha|_\text{dependency}$ | LNV/LFV |
|--------------|-------------|-----------------------------|-----------------------------------|---------|
| lepton-trijet| $jjj\ell_\alpha$ | $[W_t^{(q)}, W]$ | $\frac{|\theta_e \theta_\alpha|^2}{\theta_\alpha^2}$ | $\checkmark / \checkmark$ |
| jet-dilepton | $j\ell_\alpha \ell_\beta \nu \nu$ | $[W_t^{(q)}, \{W, Z(h)\}]$ | $\left\{ \frac{|\theta_e \theta_\alpha|^2}{\theta_\alpha^2}, |\theta_\alpha|^2 \right\}$ | $\times / \checkmark$ |
| trijet       | $jjj\nu$    | $[W_t^{(q)}, Z(h)]$ | $|\theta_\alpha|^2$ | $\times$ |
| monojet      | $j\nu\nu\nu$ | $[W_t^{(q)}, Z]$ | $|\theta_\alpha|^2$ | $\times$ |
| lepton-quadrijet | $jjjj\ell_\alpha$ | $[W_t^{(\gamma)}, W]$ | $\frac{|\theta_e \theta_\alpha|^2}{\theta_\alpha^2}$ | $\checkmark / \checkmark$ |
| dilepton-dijet | $\ell_\alpha \ell_\beta \nu \ell_\gamma \nu$ | $[W_t^{(\gamma)}, \{W, Z(h)\}]$ | $\left\{ \frac{|\theta_e \theta_\alpha|^2}{\theta_\alpha^2}, |\theta_\alpha|^2 \right\}$ | $\times / \checkmark$ |
| trilepton    | $\ell_\alpha \ell_\beta \ell_\gamma \nu \nu$ | $[W_t^{(\gamma)}, \{W, Z(h)\}]$ | $\left\{ \frac{|\theta_e \theta_\alpha|^2}{\theta_\alpha^2}, |\theta_\alpha|^2 \right\}$ | $\times / \checkmark$ |
| quadrijet    | $jjjj\nu$    | $[W_t^{(\gamma)}, Z(h)]$ | $|\theta_\alpha|^2$ | $\times$ |
| lepton-dijet | $\ell_\alpha jj\nu\nu$ | $[W_t^{(\gamma)}, Z(h)]$ | $|\theta_\alpha|^2$ | $\times$ |
| dijet        | $jj\nu\nu\nu$ | $[W_t^{(\gamma)}, Z]$ | $|\theta_\alpha|^2$ | $\times$ |
| mono-lepton  | $\ell_\alpha \nu\nu\nu\nu$ | $[W_t^{(\gamma)}, Z]$ | $|\theta_\alpha|^2$ | $\times$ |

see Antusch et al.; [1612.02728]
Lepton flavor violation

Antusch et al.; [1805.11400]

- LHC search: $e^\pm \mu^\mp + J$
- LHeC search: $\mu^- + J$ or $\tau^- + J$
- Include many bkgs for pp, and $(\mu\nu\nu + J)$, + single $\tau$s for ep.
- Preliminary results for LHeC improve sensitivity significantly.
Now: new phenomena from $N$ with $M < m_W$
Displaced vertex searches

- $M < m_W$ and $|\theta|^2 < 10^{-5}$ leads to macroscopic lifetimes
- Interaction point from recoiling jet with high precision
- Secondary vertex with “large” displacement unique signal
- “Large”: a few times tracking resolution (8 $\mu$m).
Present bounds by LHCb and DELPHI.
Large numbers of displaced $N$ decays possible.
In principle this parameter space can be probed by LHC.
LHeC complementary: testing electron and tau flavor.
Heavy neutrino oscillations

- Final lepton can be $\ell^+$ due to $\Delta x$-dependent interference.
- Interference with oscillation length dependent on theory.
- Example: $\lambda_{\text{osc}}^{\text{lin,IO}} = 3.29 \times 10^{-3} \sqrt{\gamma^2 - 1}$ m.
- Lorentz boosts make this oscillation more visible.
Oscillation, a theorist’s take

- Left: distribution of events as a function of displacement.
- Right: Monte Carlo simulation with 500 events, assuming a reconstruction error of 10%.
- Both assume a mass of 7 GeV and mixing close to existing bounds.
Why we should care

Active-sterile mixing angles $\theta_\alpha$ fixed by the light neutrino data.

Ratios of $\theta_\alpha$ measurable at LHeC with high accuracy.

Test minimal type I seesaw hypothesis.

Together with $\Delta M$ also tests the compatibility with leptogenesis.
Conclusions

▶ Sterile neutrinos are well motivated extensions of the SM.
▶ Present constraints allow for abundant production at LHeC.
▶ Most sensitive searches for sterile neutrinos with masses
  - below $m_W$ via displaced vertices
  - above $\mathcal{O}(100)$ GeV via lepton-flavour violating signatures.
▶ Studying heavy neutrino Oscillations to gain insight into leptogenesis and the neutrino mass mechanism.

⇒ LHeC physics case + Baryon Asymmetry of the Universe.

**Personal opinion:**
Not upgrading LHC with an electron beam = wasted opportunity!

Antusch, OF; [1709.00880]