Review on Sterile Neutrinos

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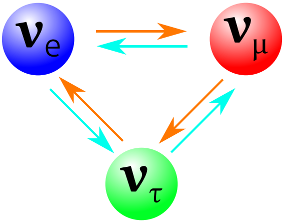
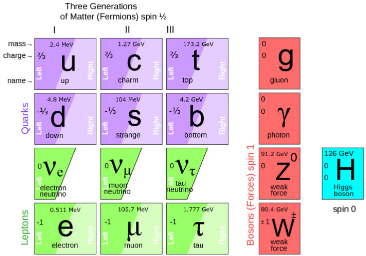
Neutrino oscillations & the Standard Model





courtsy M. Shaposhnikov

- No right-handed neutrinos in the Standard Model (SM).
- No mass matrix, no mixing of the neutrino flavour states.

⇒ 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:

$$\mathscr{L}_N = -\frac{1}{2}\overline{N_R^1} M (N_R^2)^c - y_{\nu_\alpha} \overline{N_R^1} \widetilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

- 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 ⇒ m_ν and HNL mass splitting (ΔM)
- m_D': Linear seesaw, $\Delta M^{\mathrm{NO}} = 0.0416\,\mathrm{eV}$, $\Delta M^{\mathrm{IO}} = 0.000753\,\mathrm{eV}$
- μ: 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):

$$j^{\pm}_{\mu} = \frac{g}{2}\,\theta_\alpha\,\bar{\ell}_\alpha\,\gamma_\mu N$$

- **Neutral current** (NC):

$$j^{0}_{\mu} = \bar{\nu}_\alpha\,\gamma_\mu\,\theta_\alpha\,N$$

- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\rm Yukawa} = \sum_{\alpha=e,\mu,\tau} \theta_\alpha \frac{\sqrt{2}\,M}{v_{\rm EW}} \nu_\alpha \phi^0 \overline{N}$$

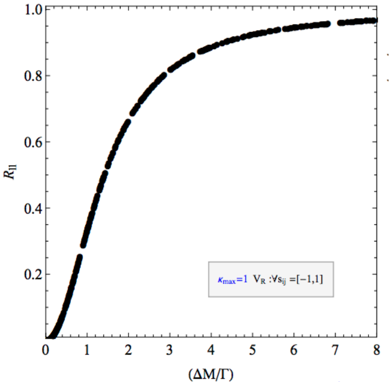
- Simplification: light neutrino mass eigenstates $\equiv \nu_e, \nu_\mu, \nu_\tau$

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...

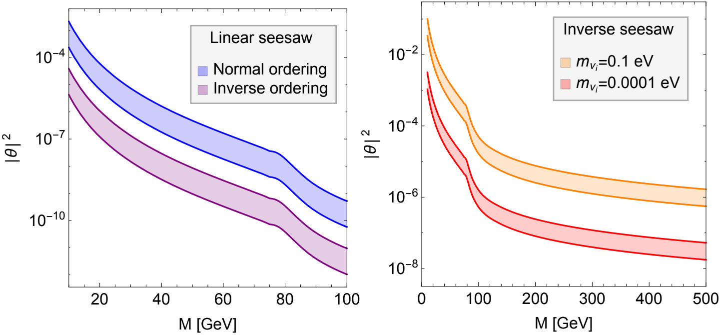
Lepton number violation and ΔM



Anamiati, Hirsch, Nardi; 1607.05641

- With $m'_D = \mu = 0$, no LNV in this class of models.
- $R_{\ell\ell}$ (=LNV/LNC) function of ΔM and Γ_N.
- For mass splitting ∼ decay width, $R_{\ell\ell} \in [0, 1]$.
- Zero mass splitting ⇒ zero LNV.

Parameter space with LNV



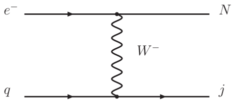
Antusch et al.; [1709.03797]

$$R_{\ell\ell} = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}$$

- 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

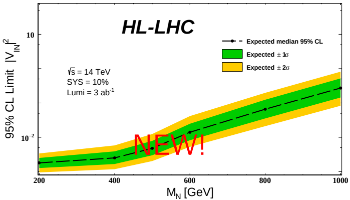


Name	Final State	Channel [production,decay]	$\lvert\theta_\alpha\rvert$ dependency	LNV/LFV
lepton-trijet	$jjj\ell_\alpha$	$[\mathbf{W_t}^{(q)}, W]$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓/✓
jet-dilepton	$j\ell_\alpha^\pm\ell_\beta^\mp\nu$	$[\mathbf{W_t}^{(q)}, \{W, Z(h)\}]$	$\left\{\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}, \lvert\theta_e\rvert^{2(*)}\right\}$	×/✓
trijet	$jjj\nu$	$[\mathbf{W_t}^{(q)}, Z(h)]$	$\lvert\theta_e\rvert^2$	×
monojet	$j\nu\nu$	$[\mathbf{W_t}^{(q)}, Z]$	$\lvert\theta_e\rvert^2$	×

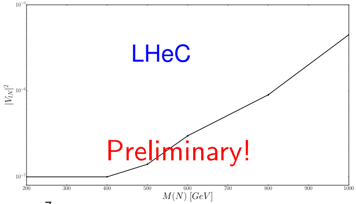
lepton-quadrijet	$jjjj\ell_\alpha$	$[\mathbf{W_t}^{(\gamma)}, W]$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓/✓
dilepton-dijet	$\ell_\alpha\ell_\beta\nu jj$	$[\mathbf{W_t}^{(\gamma)}, \{W, Z(h)\}]$	$\left\{\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}, \lvert\theta_e\rvert^{2(*)}\right\}$	×/✓
trilepton	$\ell_\alpha^-\ell_\beta^-\ell_\gamma^+\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, \{W, Z(h)\}]$	$\left\{\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}, \lvert\theta_e\rvert^{2(*)}\right\}$	×/✓
quadrijet	$jjjj\nu$	$[\mathbf{W_t}^{(\gamma)}, Z(h)]$	$\lvert\theta_e\rvert^2$	×
lepton-dijet	$\ell_\alpha^- jj\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z(h)]$	$\lvert\theta_e\rvert^2$	×
dijet	$jj\nu\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z]$	$\lvert\theta_e\rvert^2$	×
monolepton	$\ell_\alpha^-\nu\nu\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z]$	$\lvert\theta_e\rvert^2$	×

see Antusch et al.; [1612.02728]

Lepton flavor violation



Antusch et al.; [1805.11400]

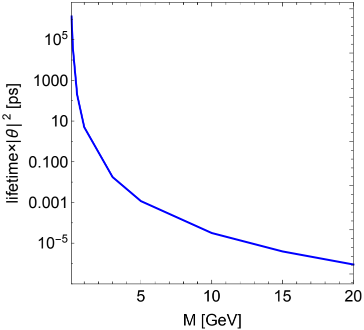


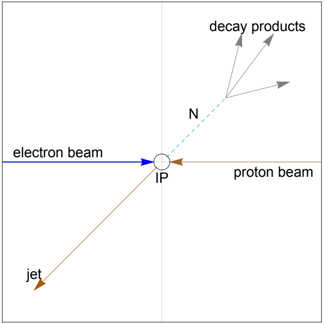
10^{-7}

- 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 τs for ep.
- Preliminary results for LHeC improve sensitivity significantly.

Now: new phenomena from N with $M < m_W$

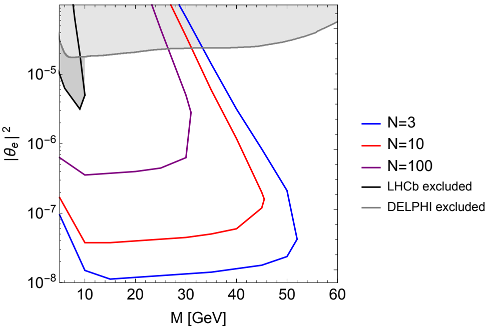
Displaced vertex searches





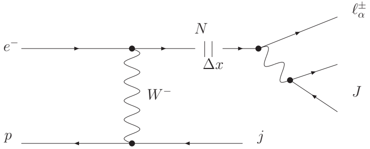
- $M < m_W$ and $|\theta|^2 < 10^{-5}$ leads to macroscopic lifetimes
- Interaction point from recoiling jet with high precision
- Secondary vertex with "large" displacement unique signal
- "Large": a few times tracking resolution (8 μm).

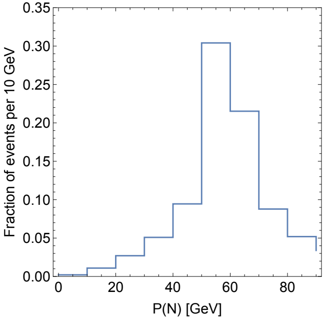
Sensitivities at the LHeC



- 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.

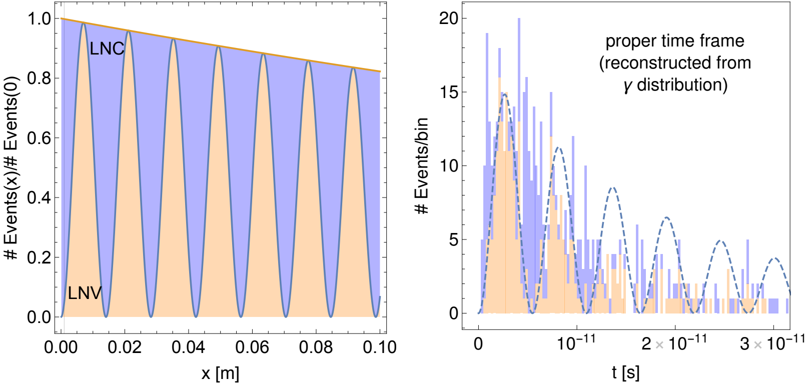
Heavy neutrino oscillations





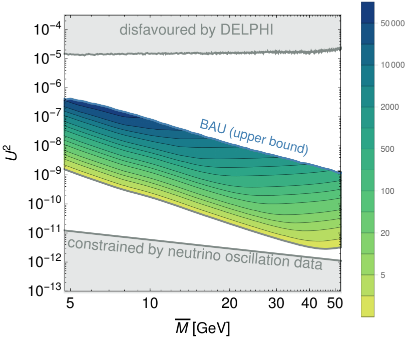
- Final lepton can be ℓ^+ due to Δx-dependent interference.
- Interference with oscillation length dependent on theory.
- Example: $\lambda_{\text{osc}}^{\text{lin,IO}} = 3.29 \cdot 10^{-3}\sqrt{\gamma^2 - 1}\,\text{m}$.
- Lorentz boosts make this oscillation more visible.

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



Antusch, Cazzato, Drewes, Fischer, Garbrecht, Gueter, Klaric; 1710.03744

- Active-sterile mixing angles θ_α fixed by the light neutrino data.
- Ratios of θ_α measurable at LHeC with high accuracy.
- Test minimal type I seesaw hypothesis.
- Together with ΔM 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.

$\Rightarrow$ LHeC physics case + Baryon Asymmetry of the Universe.

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

Antusch, OF; [1709.00880]