Searching Sterile Neutrinos at $e^- p$ Colliders: Promising Signatures

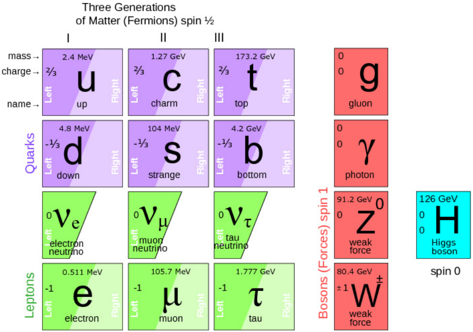
Oliver Fischer

Karlsuhe Institute of Technology
Institut für Kernphysik

September the 11th 2017, CERN

See chapter 5 in [1612.02728] and also [1709.00880]

Motivation for sterile neutrinos



- Neutrino oscillations are evidence for new physics.
- Sterile neutrinos for type I seesaw mechanism.

The Seesaw Mechanism

- Naïve $(1\ \nu_L,\ 1\ \nu_R)$ version: $m_\nu = \frac{1}{2} \frac{v_{\rm EW}^2 |y_\nu|^2}{M_R}$
- More realistic example, the $(2\ \nu_L,\ 2\ \nu_R)$ version:

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ 0 & \mathcal{O}(y_\nu) \end{pmatrix}, \qquad M_N = \begin{pmatrix} M_R & 0 \\ 0 & M_R(1+\varepsilon) \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = \frac{v_{\rm EW}^2 \mathcal{O}(y_\nu^2)}{M_R}(1-\varepsilon)$$

$\Rightarrow$ Knowledge of m_{ν_i} implies a relation between y_ν and M_R.

Lowscale Seesaw

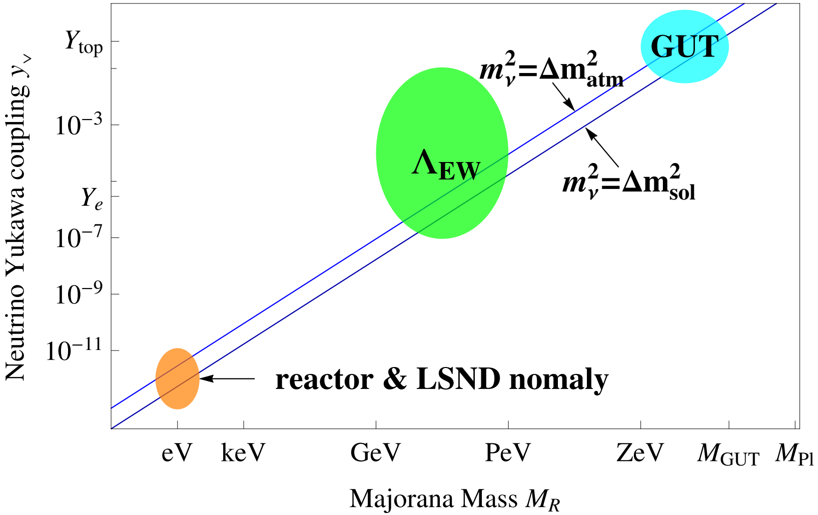
- Specific structures of the Yukawa and mass matrices can be realised by symmetries (no fine tuning).
- A $(2\ \nu_L,\ 2\ \nu_R)$ example:

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \qquad \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\mathrm{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

$\Rightarrow$ $y_\nu \sim \mathcal{O}(1)$ and $M_R \sim v_{\mathrm{EW}}$ possible!

The Big Picture



The Symmetry Protected Seesaw Scenario

Benchmark model, defined in Antusch, OF; JHEP **1505** (2015) 053

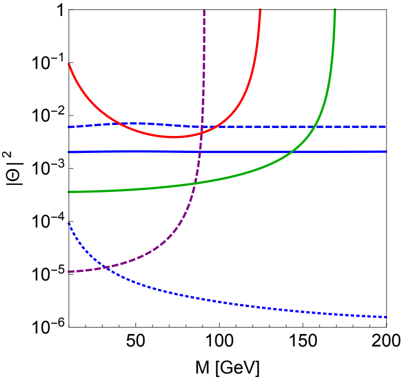
- Collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry, such that

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

- Further "decoupled" sterile neutrinos included.
- Active-sterile mixing: $\theta_\alpha = y_{\nu_\alpha} \frac{v_{\mathrm{EW}}}{\sqrt{2}}$, $\theta^2 \equiv \sum_\alpha |\theta_\alpha|^2$
- The mass matrix:

$$\mathcal{M}_\nu = -\frac{1}{2} \begin{pmatrix} 0 & \frac{y_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{2}} & 0 \\ \frac{y_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{2}} & 0 & M \\ 0 & M & 0 \end{pmatrix} + \text{ H.c.}$$

Present constraints including direct searches



Antusch, OF; JHEP **1505** (2015) 053

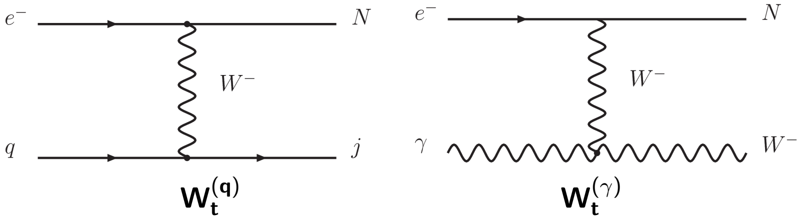
- Z pole search: limits from Z branching ratios .

  Abreu *et al.* Z.Phys. C74 (1997) 57-71

- Higgs decays: Best constraints from $h \to \gamma\gamma$.
- Direct Search: $\delta\sigma^{WW}_{\mathrm{SM}} = 0.011_{stat} + 0.007_{syst}$

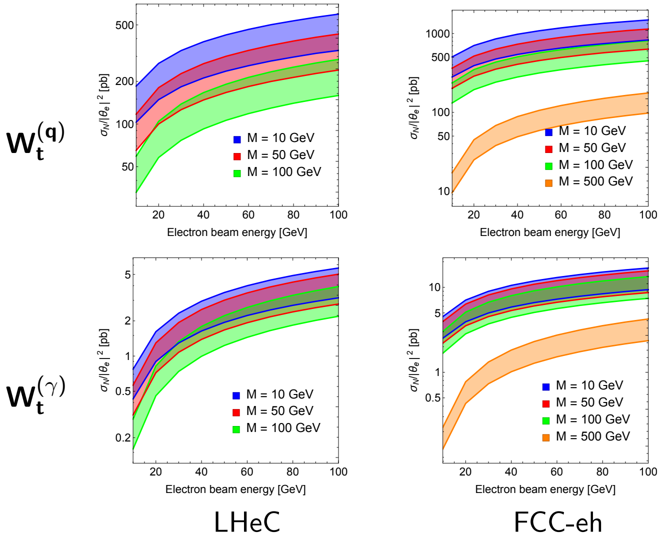
  OPAL collaboration, Abbiendi **et al.** (2007)

Heavy neutrino production at electron-proton colliders

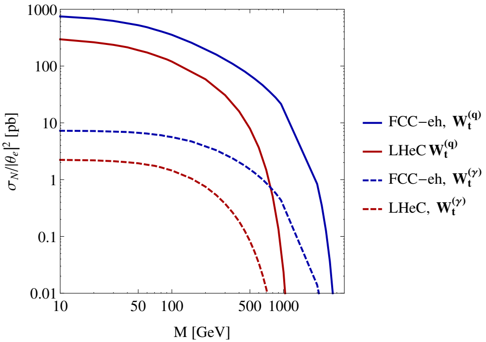


- Leading order production of heavy neutrino mass eigenstate.
- $\mathbf{W_t^{(q)}}$: dominant at lower center-of-mass energies.
- $\mathbf{W_t^{(\gamma)}}$: relevant for larger masses & large energies.

Production cross sections, variation with beam energy



Benchmark: 60 GeV electron beam, unpolarised



- σ_N increase of $\sim 30\%$ for $E_e \to 100$ GeV.
- Increased by $\sim 80\%$ when including polarisation.
- Consider 1 ab^{-1} (for FCC-eh and LHeC).

Most promising signature: lepton-trijet ($\ell_\alpha jjj$)

- No SM background at parton level.
- Sensitive to the combination of active-sterile mixing $\frac{|\theta_e \theta_\alpha|^2}{\theta^2}$
- Unambiguous signal for lepton flavor violation (LFV) for $\ell_\alpha = \mu^-, \tau^-$.
- Unambiguous signal for lepton number violation (LNV) for $\ell_\alpha = e^+, \mu^+, \tau^+$.
- *Note: LNV is absent in the SPSS.*

Other useful signatures

(There are many more!)

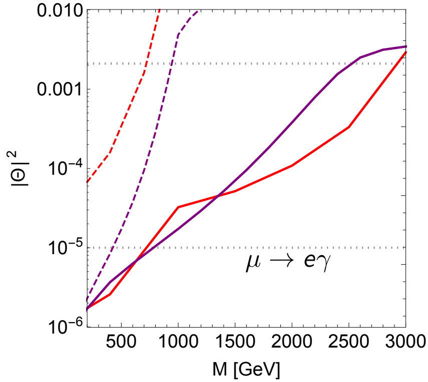
Jet-dilepton ($\mathbf{W_t^{(q)}}$):

- Final state: $j\ell_\alpha^- \ell_\beta^+ \nu$)
- Sensitive to $\frac{|\theta_e \theta_\alpha|^2}{\theta^2}$
- LFV: $\tau^- \mu^+ j\nu$ and $\tau^+ \mu^- j\nu$

Lepton-Higgs ($\mathbf{W_t^{(\gamma)}}$):

- Flavor democratic lepton (i.e. e^-, μ^-, τ^-) from the W^-
- Sensitive to $|\theta_e|^2$
- We checked $e^- b\bar{b}\nu\nu$; very good sensitivity at FCC-eh for LFC
- May involve a hard jet with very small P_t

Sensitivity of sigantures with LFV



$\ell_\alpha^- jjj$ ($\alpha=\mu,\tau$): $|\Theta|^2=|\theta_\alpha\theta_\tau|^2/|\theta|^2$

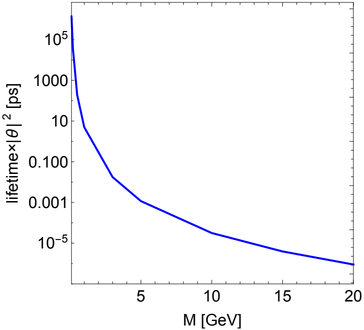
$\tau^-\mu^+ j\nu$: $|\Theta|^2=|\theta_e\theta_\tau|^2/|\theta|^2$

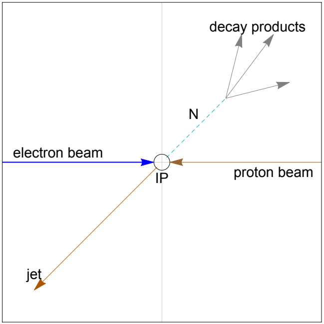
Dashed lines denote the LHeC

Antusch, OF; [1709.00880]

- Upper bound on $|\theta_e\theta_\mu|$ from $\mu \to e\gamma$ (MEG)
- Upper bound on $|\theta_e\theta_\tau|$ from precision data
- Requires $|\theta_\alpha| \gtrsim |\theta_e|$ for sizeable branching ratios

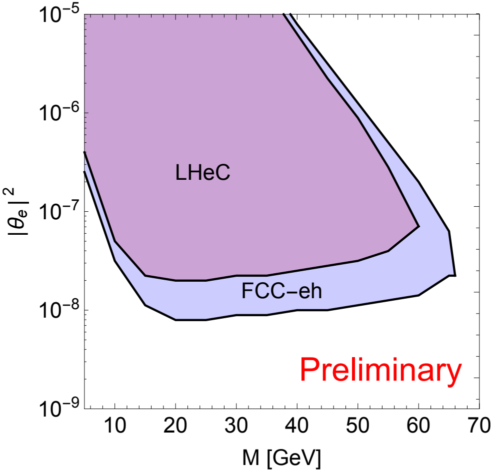
Displaced vertex searches





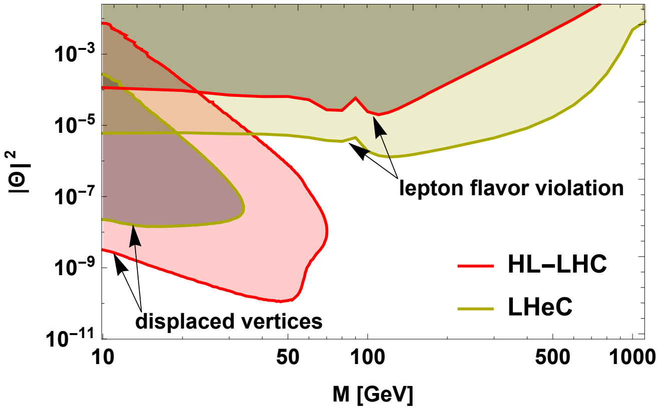
- $M < m_W$ and $|\theta|^2 < 10^{-5}$ leads to macroscopic lifetimes
- Interaction point from recoiling jet with high precision
- Secondary vertex with "large" displacement unique signal
- "Large": a few times tracking resolution (8 μm).

Possible sensitivities of displaced vertex searches



- Analysis analogous to Antusch, Cazzato, OF; [1706.05990].
- Consider decays in the tracker only.

Synergy and Complementarity (Example: LHeC and HL-LHC.)



***ep* collisions provide an excellent opportunity for testing the origin of neutrino masses!**

Conclusions

- Sterile neutrinos are well motivated extensions of the SM.
- Symmetry protected seesaw scenarios allow for electroweak scale sterile neutrino masses and $\mathcal{O}(1)$ active-sterile mixings.
- Present constraints: active-sterile mixing $|\theta|^2 \leq 10^{-3}$.

- Electron-proton colliders produce heavy neutrinos via $|\theta_e|$.
- Most sensitive searches for sterile neutrinos with masses
  - below m_W via displaced vertices
  - above $\mathcal{O}(100)$ GeV via lepton-flavour violating signatures.
- Great prospects at testing sterile neutrinos!

$\Rightarrow$ It seems like a wasted opportunity not to upgrade a *pp* collider with an electron beam!

Antusch, OF; [1709.00880]

Thank you for your attention.