Higgs Production through Sterile Neutrinos

Work in progress

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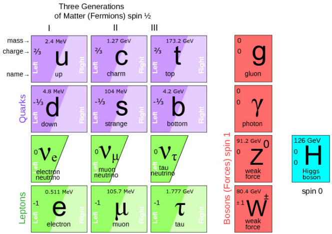
Motivation for sterile neutrinos

- Neutrino oscillations require *at least* two massive light/active SM neutrinos.
- One of the most attractive ways to introduce massive neutrinos is the addition of gauge singlet fermions – "sterile neutrinos".
- Symmetry protected seesaw allows for (sub) TeV masses **and** large active-sterile neutrino mixings.



Courtesy Marco Drewes

⇒ Observable effects via non-unitarity of the leptonic mixing matrix and direct tests at colliders.

Low scale seesaw scenario

- Assumption: collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry, such that

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

- The leptonic mixing matrix to leading order in the active-sterile mixing parameters:

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu 1} & \mathcal{N}_{\mu 2} & \mathcal{N}_{\mu 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau 1} & \mathcal{N}_{\tau 2} & \mathcal{N}_{\tau 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\mathrm{i}}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

Interactions between heavy neutrinos and the SM

- **Charged current** (CC):

$$j^{\pm}_{\mu} = \frac{g}{2}\,\theta_{\alpha}\,\bar{\ell}_{\alpha}\,\gamma_{\mu}\,(-\mathrm{i}N_1 + N_2)$$

- **Neutral current** (NC):

$$j^{0}_{\mu} = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_{\mu}\,N_2 \,+ (\bar{\nu}_i\,\gamma_{\mu}\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_{\mu}\,\xi_{\alpha 2}\,N_2 \,+\, \text{H.c})\right]$$

- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\text{Yukawa}} = \sum_{i=1}^{3} \xi_{\alpha 2}\,\frac{\sqrt{2}\,M}{v_{\text{EW}}}\nu_i\phi^0\left(\overline{N}_1 + \overline{N}_2\right)$$

- With the mixing parameters: $\xi_{\alpha 1} = (-\mathrm{i})\,\mathcal{N}^{*}_{\alpha\beta}\,\frac{\theta_{\beta}}{\sqrt{2}}$, $\xi_{\alpha 2} = \mathrm{i}\,\xi_{\alpha 1}$

Non-unitarity of the PMNS matrix

- Input parameters affected: Fermi constant, $\sin\theta_W$
- Effective field theory treatment for energies below M.
- Described by Minimal Unitarity Violation (MUV) scheme. Antusch *et al.* (2006).
- Weak currents with active neutrinos:

$$\left(J^{\mu,\pm}\right)_{\alpha i} = \ell_\alpha \gamma^\mu \nu_i \mathcal{N}_{\alpha i}\,, \qquad \left(J^{\mu,0}\right)_{ij} = \nu_i \gamma^\mu \nu_j \left(\mathcal{N}^\dagger \mathcal{N}\right)_{ij}$$

- $\mathcal{N}\mathcal{N}^\dagger \neq 1$

$\Rightarrow$ Allows for indirect tests of leptonic mixing (electroweak precision observables)

Present indirect constraints on leptonic mixing

Antusch and Fischer; arXiv:1407.6607 (2014)

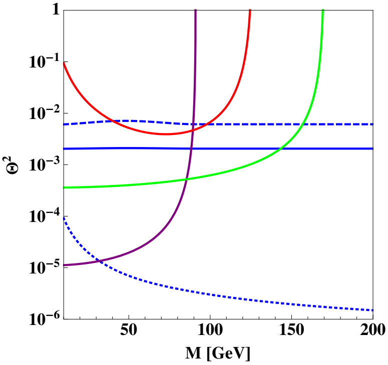
- Analysis includes 34 precision observables:
  EWPO, lepton universality, charged lepton flavour violation, CKM unitarity
- Highest posterior density intervals at 90% Bayesian C.L.:

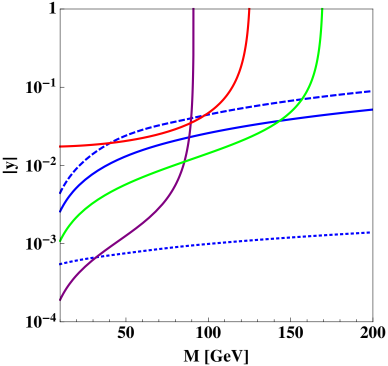
-0.0021	$\leq \varepsilon_{ee} \leq$	-0.0002	$\lvert\varepsilon_{e\mu}\rvert$	$<$	1.0×10^{-5}
-0.0004	$\leq \varepsilon_{\mu\mu} \leq$	0	$\lvert\varepsilon_{e\tau}\rvert$	$<$	2.1×10^{-3}
-0.0053	$\leq \varepsilon_{\tau\tau} \leq$	0	$\lvert\varepsilon_{\mu\tau}\rvert$	$<$	8.0×10^{-4}

! Indication for non-zero mixing with the electron neutrino.

! $> 3\sigma$ when neglecting $\sin^{\ell,\mathrm{had}}_{eft}$ Basso, Fischer, v.d. Bij; arXiv:1310.2057 (2013).

Combination of present bounds





Direct searches

- Delphi (Z pole searches) @2σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- LHC (Higgs decays*) @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- Aleph ($e^+e^- \to 4$ leptons) @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

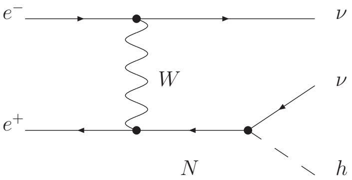
Other (global fit)

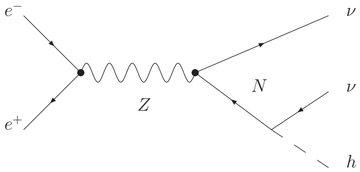
- $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$
- $|y|=|y_{\nu_\mu}|$, $\Theta^2=|\theta_\mu|^2$
- $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$

Antusch, Fischer; arXiv:1502.05915 (2015)

$*$ Currently dominated by $h \to \gamma\gamma$.

Sterile-neutrino induced "Higgs plus nothing" events

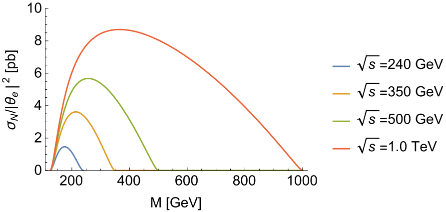




- Interference with SM-background strongly suppressed.
- W-exchange process effective at larger centre-of-mass energies, but sensitive only to y_{ν_e}.
- s-channel production (Z boson) produces all flavours.

Comparing center-of-mass energies for y_{ν_e}

- $\sqrt{s} = 240$ GeV: 12 ab^{-1}
  0.6 ab^{-1}/IP/a
  2 Interaction points
  10 years
- $\sqrt{s} = 350$ GeV: 3.6 ab^{-1}
  0.18 ab^{-1}/IP/annum
  2 Interaction points
  10 years (?)



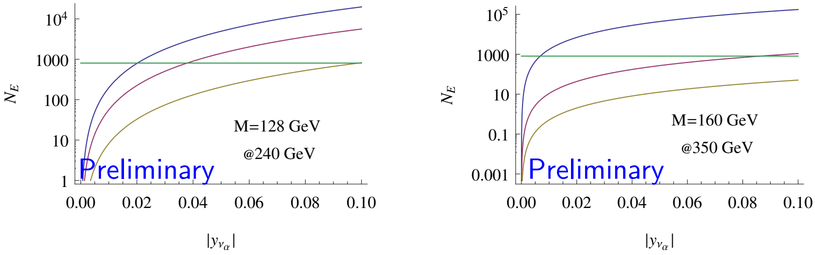
$\Rightarrow$ Reduction from luminosity is (at least partly) compensated by gain in production cross section.

! Higher center-of-mass energy is sensitive to larger masses.

$\star$ $\sqrt{s} \geq 500$ GeV: FCC-ee, ILC/CLIC, Muon collider

Number of "Higgs plus nothing" events from N-decays

– Here: Parton level only –

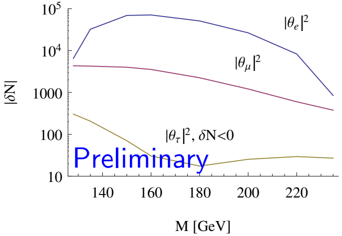


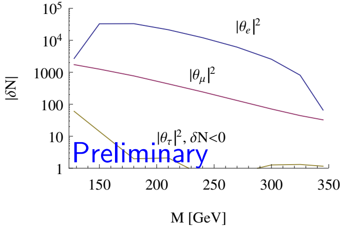
- Number of additional events grows quadratically with y_{ν_α}.
- Dominant: y_{ν_e} due to t-channel W-boson exchange.
- Suppressed: y_{ν_τ}, due to cancellation between s-channel production and non-unitarity effects.

Maximum "Higgs plus nothing" events from N-decays

Using present upper bounds at 68% C.L. (arXiv: 1502.05915):

$$|y_{\nu_e}| = 0.042\frac{\sqrt{2}M}{v_{\rm EW}}, \qquad |y_{\nu_\tau}| = 0.065\frac{\sqrt{2}M}{v_{\rm EW}}, \qquad |y_{\nu_\mu}| = 0.015\frac{\sqrt{2}M}{v_{\rm EW}}.$$





Up to $\mathcal{O}(10^5)$ additional events possible.

- $\sqrt{s} = 240$ GeV: 12 ab^{-1} $\Rightarrow 6.5 \times 10^5$ $\nu\nu h|_{\rm SM}$ events
- $\sqrt{s} = 350$ GeV: 3.6 ab^{-1} $\Rightarrow 1.9 \times 10^5$ $\nu\nu h|_{\rm SM}$ events

Finding a "Higgs plus nothing" event at 240 GeV

– Here: fully reconstructed events –

- WHIZARD 2.2.7 $\oplus$ PYTHIA 6.427 $\oplus$ Delphes 3.2.0
- Detector: delphes card for CMS
- Backgrounds: (misidentified)
  $2b\bar{b}$, $(e^+e^-/u\bar{u}/d\bar{d}/s\bar{s}/c\bar{c}) \times b\bar{b}$, $(u\bar{u}/d\bar{d}/s\bar{s}/c\bar{c}) \times \tau^+\tau^-$
- Standard model "signal":
  Higgs strahlung $\oplus$ $Z \to \nu\bar{\nu}$ & W-boson fusion
- Cuts used in Ono and Miyamoto; arXiv: 1202.4955:

$$80 < M_{\text{miss}} < 140, \qquad 20 < P_T < 70, \qquad |P_L| < 60,$$

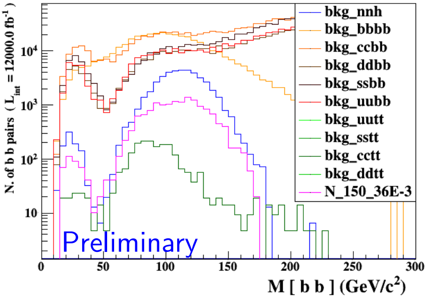
$$P_{\text{max}} < 30, \qquad N_{\text{chd}} > 10.$$

- Feedback welcome!

Example: $|y_{\nu_e}| = 0.036$ & $M = 150$ GeV, $N \to$ all

Our cuts (not optimised):

$N_j = 2,\ N_\ell = 0,$
$\not{E}_T < 38,\ P < 40,$
$M(jj) < 130,$
$100 < M(bb) < 130,$
$38 < P(jj) < 80,$
$40 < P(bb) < 70,$
$\Delta R < 2.7$

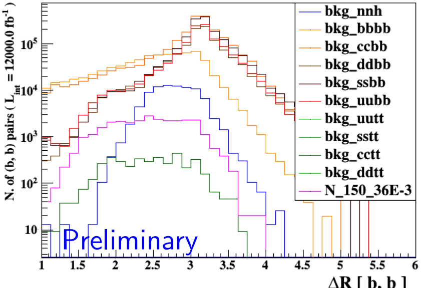


Event counts:

$\text{BKG}|_{\text{SM}}$ 2.2M $\to$ 88k

$\nu\nu h|_{\text{SM}}$ 648k $\to$ 66k

$\nu\nu h|_{N}$ 504k $\to$ 31k

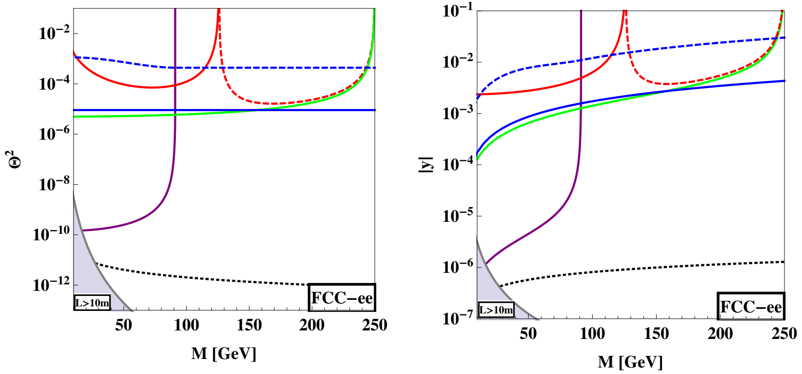


Summary and conclusions

- Sterile neutrinos are well motivated extensions of the SM.
- Symmetry protected scenarios allow for large Yukawa couplings and masses in the interesting range.
- $\sqrt{s} =$ **350 GeV is almost as sensitive as 240 GeV.**
- **Higher center-of-mass energies lead to increased production cross sections.**
- Realistic example: Up to 31k additional events in the $\sim$ 154k "Higgs plus nothing" events.
  - ⋆ **Important for understanding the data.**
  - ⋆ **Complementarity** to other searches for sterile Neutrinos.
  - ⋆ Infer sterile neutrino properties.
- For other search channels, see: Antusch, Fischer; arXiv:1502.05915 (2015)

Thank you for your attention.

Backup I: Prospects of Sensitivity at the FCC-ee



Direct searches

- Z pole search @2σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- Higgs → WW @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- $e^+e^-\to h + ME_{(T)}$ @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$
- $e^+e^-\to l\nu l\nu^*$ @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

Other

- Precision constraints: $|y|=\sqrt{|y_{\nu_e}|^2+|y_{\nu_\mu}|^2}$, $\Theta^2=|\theta_e|^2+|\theta_\mu|^2$
- Precision constraints: $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$
- ”Unprotected” type−I seesaw

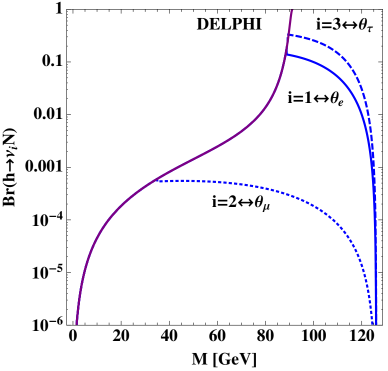
Antusch, Fischer; arXiv:1502.05915 (2015)

∗ Preliminary estimate using statistical uncertainty only.

Backup II: Higgs Boson Branching Ratio into Neutrinos

- From "indirect" tests and Delphi.
- $\mathcal{O}(1)$ branching ratio possible.

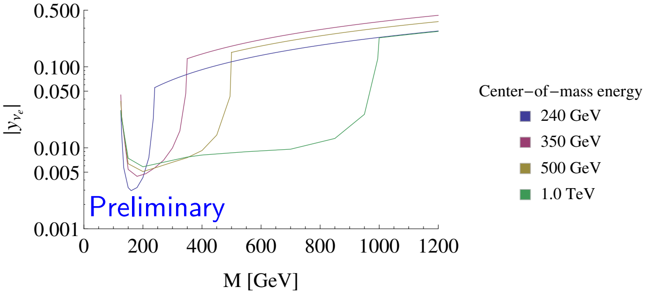
$\Rightarrow$ Possible effect on Higgs decay rates into Standard Model particles.



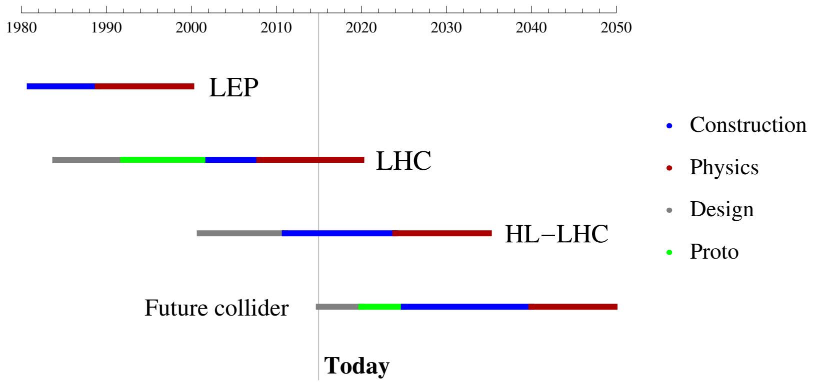
Antusch, Fischer; arXiv:1502.05915 (2015)

Backup III: Sensitivity of Higgs-Production to $|y_{\nu_e}|$

– Parton level only –



Backup IVa: High Energy Physics Time Scales



Backup IVb: High Energy Physics Time Scales