Searches for Sterile Neutrinos at Future electron-proton Colliders

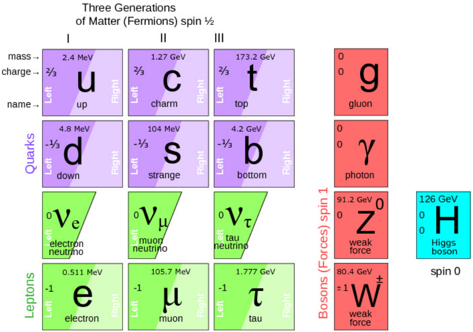
Oliver Fischer

University of Basel, Switzerland

May the 4th 2017, video conference

Based on S. Antusch, E. Cazzato, OF, 1612.02728

Motivation for sterile neutrinos



- Neutrino oscillations are evidence for new physics.
  $\Rightarrow$ *At least* two light neutrinos are massive.
- Sterile neutrinos for type I seesaw mechanism.

The Seesaw Mechanism

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

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

$$\Rightarrow m_{\nu_i} = \frac{v_{\mathrm{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R}(1+\varepsilon\delta_{i2})$$

$\Rightarrow$ 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:

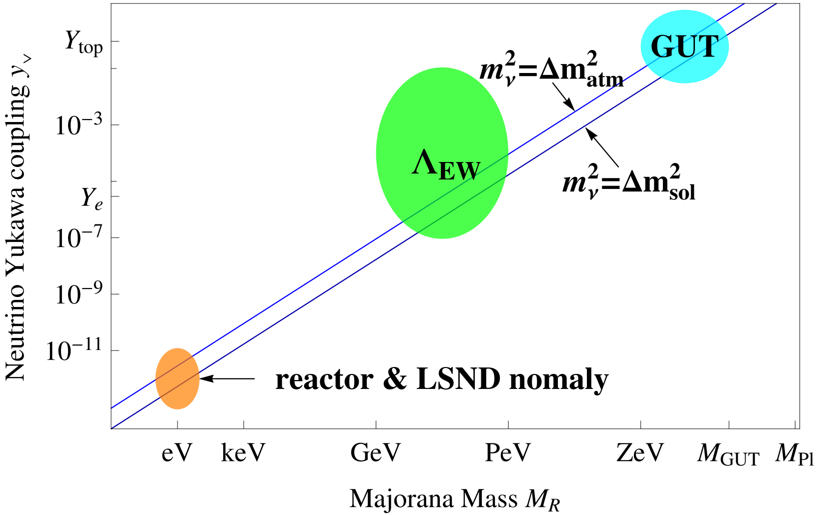
$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \qquad \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

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

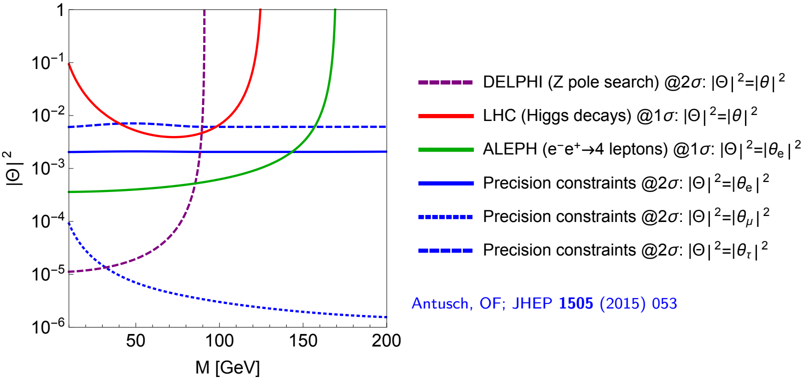
$\Rightarrow$ In general: no fixed relation between y_ν and M_R.

$\Rightarrow$ Large y_ν are compatible with neutrino oscillations.

The Big Picture



Present constraints



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

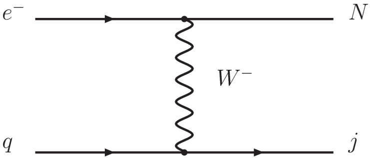
- Z pole search: limits from Z branching ratios .

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

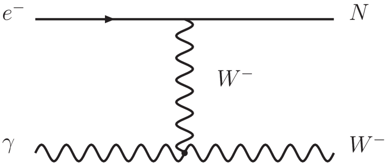
- Higgs decays: Best constraints from $h \to \gamma\gamma$.
- Direct Search: $\delta\sigma_{\rm SM}^{WW} = 0.011_{stat} + 0.007_{syst}$

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

Heavy neutrino production at electron-proton colliders



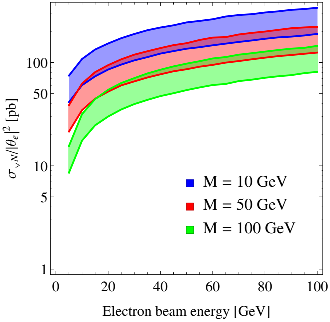
$\mathbf{W_t^{(q)}}$



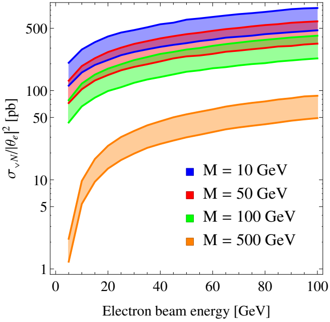
$\mathbf{W_t^{(\gamma)}}$

- 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.

Production cross section



LHeC



FCC-eh

For 60 GeV as benchmark for the electron beam E_e:

- $\sigma_{\nu N}$ 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).

Signal channels from $\mathbf{W}_t^{(q)}$

Name	Final State	$\lvert\theta_\alpha\rvert$ Dependency	LFV
lepton-trijet	$jjj\ell_\alpha^-$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓
jet-dilepton	$j\ell_\alpha^-\ell_\beta^+\nu$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}$	✓
trijet	$jjj\nu$	$\lvert\theta_e\rvert^2$	$\times$
monojet	$j\nu\nu\nu$	$\lvert\theta_e\rvert^2$	$\times$

- LFV (and LNV) signature for $\alpha \neq e$, $\beta \neq \alpha$, and $\gamma \neq \alpha, \beta$
- Unambiguous LNV final states, e.g. e^+jjj.

$\star$ LNV not expected when $M > m_W$.

Signal channels from $\mathbf{W}_t^{(\gamma)}$

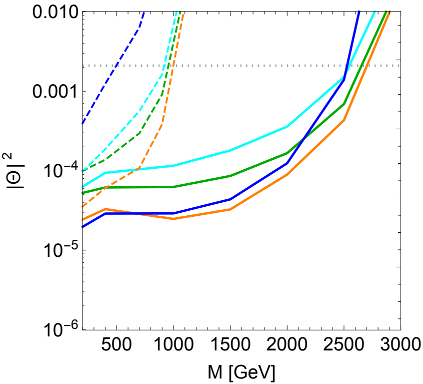
Name	Final State	$\lvert\theta_\alpha\rvert$ Dependency	LFV
lepton-quadrijet	$jjjj\ell_\alpha^-$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓
dilepton-dijet	$\ell_\alpha^-\ell_\beta^+\nu jj$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}$	✓
trilepton	$\ell_\alpha^-\ell_\beta^-\ell_\gamma^+\nu\nu$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}$	✓
quadrijet	$jjjj\nu$	$\lvert\theta_e\rvert^2$	×
electron-di-b-jet	$e^- b\bar{b}\nu\nu$	$\lvert\theta_e\rvert^2$	×
dijet	$jj\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×
monolepton	$\ell_\alpha^-\nu\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

- Additional signatures of LFV/LNV.
- Cross section suppressed by the small PDF of the photon.
- More efficient at higher center-of-mass energies.

Caveat:

- ⋆ For the following "first look" we confined ourselves to the parton level.
- ⋆ The analysis on the reconstructed level is about to begin.

First look: lepton-flavour-conserving signatures



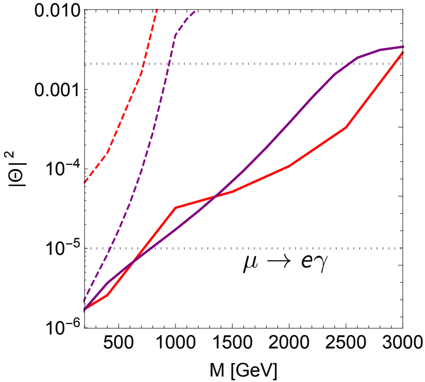
- $e^- jjj$: $|\Theta|^2 = |\theta_e|^4/|\theta|^2$
- νjjj: $|\Theta|^2 = |\theta_e|^2$
- $j\nu\nu\nu$: $|\Theta|^2 = |\theta_e|^2$
- $e^-\nu\nu bb$: $|\Theta|^2 = |\theta_e|^2$

Dashed lines denote the LHeC

Antusch, Cazzato, OF; [1612.02728]

- Sensitive to $|\theta_e|$ or $|\theta_e| \times \mathrm{Br}(N \to e^- W^+)$.
- Here: "Conservative" sensitivity for $|\theta_\alpha| \ll |\theta_e|$.
- For $|\theta_\alpha| \sim |\theta_e|$ LFV is *expected*.

Lepton-flavour-violating signatures

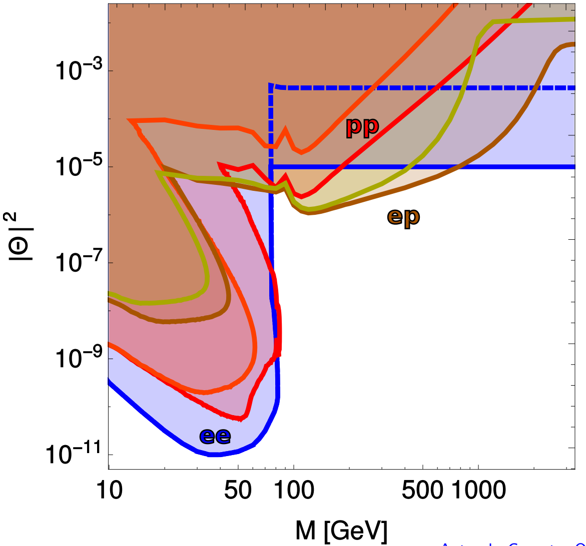


Dashed lines denote the LHeC

Antusch, Cazzato, OF; [1612.02728]

- Very sensitive tests of combinations $|\theta_e \theta_\alpha|$.
- Upper bounds:
  $|\theta_e \theta_\mu|$ from $\mu \to e\gamma$ (MEG); $|\theta_e \theta_\tau|$ from precision data.
- Requires $|\theta_\alpha| \gtrsim |\theta_e|$ for sizeable branching ratios.

Synergy and Complementarity with other colliders



Antusch, Cazzato, OF; [1612.02728]

Conclusions & outlook

- Sterile neutrinos are well motivated extensions of the SM.
- Symmetry protected seesaw scenarios allow for electroweak scale sterile neutrino masses and large active-sterile mixings.
- Most sensitive searches for sterile neutrinos with masses above $\mathcal{O}(100)$ GeV via lepton-flavour violating signatures.
- Sensitivities for direct searches more promising than LHC/FCC-hh.
- Outlook (to-do list):
  - Sensitivity of LFV-LNC signatures on the reconstructed level including all relevant backgrounds.
  - Similarly for promising LFC-LNC signatures (e.g. boosted lepton-'Higgs')
  - Searches via displaced vertices.
  - Searches via LNV for $M < m_W$.

Thank you for your attention.

Backup I - EWPO

Experimental results and SM predictions for the EWPO, and the modification*, to first order in the "non-unitarity" parameters $\varepsilon_{\alpha\alpha} = \theta^*_\alpha \theta_\beta$. (formulae for $M \gg m_Z$)

Prediction in MUV	SM Prediction	Experiment
$[R_\ell]_{\rm SM}\,(1 - 0.15(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\rm SM}\,(1 + 0.03(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\rm SM}\,(1 - 0.06(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$\left[\sigma^0_{had}\right]_{\rm SM}\,(1 - 0.25(\varepsilon_{ee} + \varepsilon_{\mu\mu}) - 0.27\varepsilon_\tau)/\text{nb}$	41.470(15)	41.541(37)
$[R_{inv}]_{\rm SM}\,(1 + 0.75(\varepsilon_{ee} + \varepsilon_{\mu\mu}) + 0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\rm SM}(1 - 0.11(\varepsilon_{ee} + \varepsilon_{\mu\mu}))/\text{GeV}$	80.359(11)	80.385(15)
$[\Gamma_{\rm lept}]_{\rm SM}(1 - 0.59(\varepsilon_{ee} + \varepsilon_{\mu\mu}))/\text{MeV}$	83.966(12)	83.984(86)
$[(s^{\ell,{\rm lep}}_{W,{\rm eff}})^2]_{\rm SM}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,{\rm had}}_{W,{\rm eff}})^2]_{\rm SM}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23222(27)

* Minimal Unitarity Violation scheme: Antusch *et al.*; JHEP **0610** (2006) 084.

Backup II - lepton universality

Modification due to sterile neutrinos (formulae for $M \gg m_Z$):

$$R_{\alpha\beta} = \sqrt{\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}} \simeq 1 + \frac{1}{2}\left(\varepsilon_{\alpha\alpha} - \varepsilon_{\beta\beta}\right) .$$

	Process	Bound
$R^{\ell}_{\mu e}$	$\frac{\Gamma(\tau \to \nu_\tau \mu \bar{\nu}_\mu)}{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}$	1.0018(14)
$R^{\ell}_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)}$	1.0006(21)
$R^{W}_{e\mu}$	$\frac{\Gamma(W \to e \bar{\nu}_e)}{\Gamma(W \to \mu \bar{\nu}_\mu)}$	1.0085(93)
$R^{W}_{\tau\mu}$	$\frac{\Gamma(W \to \tau \bar{\nu}_\tau)}{\Gamma(W \to \mu \bar{\nu}_e)}$	1.032(11)

	Process	Bound
$R^{\pi}_{\mu e}$	$\frac{\Gamma(\pi \to \mu \bar{\nu}_\mu)}{\Gamma(\pi \to e \bar{\nu}_e)}$	1.0021(16)
$R^{\pi}_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau \pi)}{\Gamma(\pi \to \mu \bar{\nu}_\mu)}$	0.9956(31)
$R^{K}_{\tau\mu}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to \mu \bar{\nu}_\mu)}$	0.9852(72)
$R^{K}_{\tau e}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to e \bar{\nu}_e)}$	1.018(42)

Backup III - CKM unitarity constraint

Current world averages: $V_{ud} = 0.97427(15)$, $V_{ub} = 0.00351(15)$

$$|V_{ij}^{th}|^2 = |V_{ij}^{exp}|^2(1 + f^{\rm process}(\varepsilon_{\alpha\alpha})) \; ,$$
$$|V_{ud}^{th}|^2 = |V_{ud}^{exp,\beta}|^2(NN^\dagger)_{\mu\mu} \; .$$

For the kaon decay processes we have:

$$|V_{us}^{th}|^2 = |V_{us}^{exp,K\to e}|^2(NN^\dagger)_{\mu\mu} \; ,$$
$$|V_{us}^{th}|^2 = |V_{us}^{exp,K\to \mu}|^2(NN^\dagger)_{ee} \; .$$

Process	$V_{us}f_+(0)$
$K_L \to \pi e \nu$	0.2163(6)
$K_L \to \pi \mu \nu$	0.2166(6)
$K_S \to \pi e \nu$	0.2155(13)
$K^\pm \to \pi e \nu$	0.2160(11)
$K^\pm \to \pi \mu \nu$	0.2158(14)
Average	0.2163(5)

Processes involving tau leptons:

Process	$f^{\rm process}(\varepsilon)$	$\lvert V_{us}\rvert$
$\frac{B(\tau\to K\nu)}{B(\tau\to\pi\nu)}$	$\varepsilon_{\mu\mu}$	0.2262(13)
$\tau \to K\nu$	$\varepsilon_{ee} + \varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}$	0.2214(22)
$\tau \to \ell, \tau \to s$	$0.2\varepsilon_{ee} - 0.9\varepsilon_{\mu\mu} - 0.2\varepsilon_{\tau\tau}$	0.2173(22)

Backup IV - lepton flavour violation

- Present experimental limits at 90% C.L.:

Process	MUV Prediction	Bound	Constraint on $|\varepsilon_{\alpha\beta}|$
$\mu \to e\gamma$	$2.4 \times 10^{-3}|\varepsilon_{\mu e}|^2$	5.7×10^{-13}	$\varepsilon_{\mu e} < 1.5 \times 10^{-5}$
$\tau \to e\gamma$	$4.3 \times 10^{-4}|\varepsilon_{\tau e}|^2$	1.5×10^{-8}	$\varepsilon_{\tau e} < 5.9 \times 10^{-3}$
$\tau \to \mu\gamma$	$4.1 \times 10^{-4}|\varepsilon_{\tau\mu}|^2$	1.8×10^{-8}	$\varepsilon_{\tau\mu} < 6.6 \times 10^{-3}$

- Estimated sensitivities of planned experiments at 90% C.L.:

Process	MUV Prediction	Bound	Sensitivity
$Br_{\tau e}$	$4.3 \times 10^{-4}|\varepsilon_{\tau e}|^2$	10^{-9}	$\varepsilon_{\tau e} \geq 1.5 \times 10^{-3}$
$Br_{\tau\mu}$	$4.1 \times 10^{-4}|\varepsilon_{\tau\mu}|^2$	10^{-9}	$\varepsilon_{\tau\mu} \geq 1.6 \times 10^{-3}$
$Br_{\mu eee}$	$1.8 \times 10^{-5}|\varepsilon_{\mu e}|^2$	10^{-16}	$\varepsilon_{\mu e} \geq 2.4 \times 10^{-6}$
$R^{Ti}_{\mu e}$	$1.5 \times 10^{-5}|\varepsilon_{\mu e}|^2$	2×10^{-18}	$\varepsilon_{\mu e} \geq 3.6 \times 10^{-7}$

$\Rightarrow R^{Ti}_{\mu e}$ yields a sensitivity to m_{ν_R} up to 0.3 PeV.

Backup V - 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 may exist.
- Active-sterile mixing parameters:

$$\theta_\alpha = y_{\nu_\alpha} \frac{v_{\mathrm{EW}}}{\sqrt{2}}, \; \theta^2 \equiv \sum_\alpha |\theta_\alpha|^2$$

- The leptonic mixing matrix to leading order in θ_α:

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

Backup VI - Heavy neutrino interactions

- **Charged current** (CC):

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

- **Neutral current** (NC):

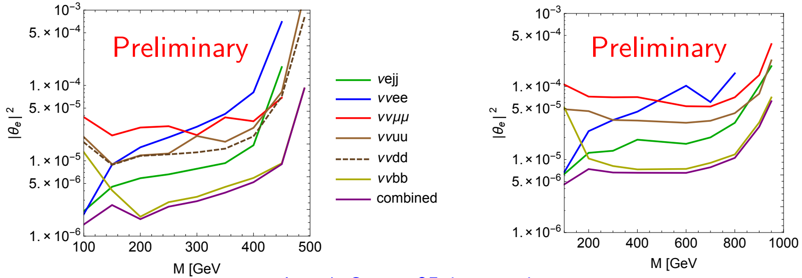
$$j_\mu^0 = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_\mu\,N_2\,+(\bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 2}\,N_2\,+\,\mathrm{H.c})\right]$$

- Higgs boson **Yukawa** interaction:

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

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

ILC direct searches



Antusch, Cazzato, OF; *in preparation*

- Operation scenario G-20, with 4 ab^{-1} at $\sqrt{s} = 500$ GeV.
- Using 1 ab^{-1} at $\sqrt{s} = 1.0$ TeV.
- Displaced vertex searches possible for $M < m_W$.