The Search for Sterile Neutrinos at Future Circular Colliders

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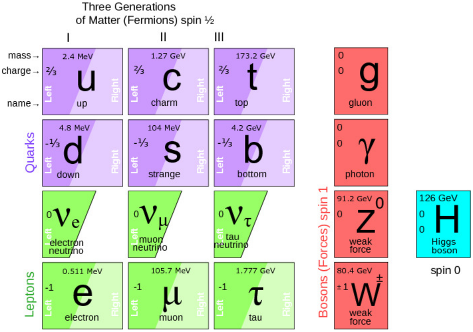
Motivation for Sterile Neutrinos



- Neutrino oscillations are evidence for new physics.
  $\Rightarrow$ *At least* two light neutrinos massive.
- Mass generation mechanism requires an extension of the SM.
- Elegant and economic: sterile (or right-handed) neutrinos.
- Many studies on collider phenomenology.

Sterile Neutrinos at colliders

Incomplete author list:

Abada, Abazajian, Acero, Adhikari, Agarwalla, Aguilar-Arevalo, Aguilar-Saavedra, Akhmedov, Albright, Antusch, Aoki, Arguelles-Balantekin, Asaka, Atre, Basso, Biggio, Blanchet, Blondel, Blum, Bonivento, Bonnet, Borah, Boyanovsky, Boyarsky, Cely, Chen, Cheung, Das, delAguilar, DeRomeri, Dev, Dijkstra, Drewes, Egede, Fan, Ferro-Luzzi, Franceschini, Gariazzo, Gavela, Giunti, Goddard, Golutvin, Gorbunov, Gorbunov, Graverini, Hall, Hambye, Han, He, Hernandez, Hernandez, Hoang, Hung, Ibarra, Jacobsson, Kamat, Kanemura, Kartavtsev, King, Kopp, Laveder, Lello, Lindner, Ma, Merle, Michaels, Mohapatra, Molinaro, Monteil, Murakami, Murase, Nemevsek, Okada, Orloff, Panman, Pascoli, Petcov, Pinner, Pittau, Reece, Rodejohann, Schwetz-Mangold, Serra, Seto, Shaposhnikov, Smirnov, Sun, Tait, Tandean, Teixeira, Tenchini, Timiryasov, Tsai, van der Bij, Vicente, Wang, Weiland, Yanagida, Zhang, ...

... and others.

Appologies to those who are not on the list!

Symmetry Protected Seesaw Scenario

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

Similar to e.g.: Mohapatra, Valle (1986); Malinsky, Romao Valle (2005); Shaposhnikov (2007);

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

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

- Further "decoupled" sterile neutrinos may exist.
- The leptonic mixing matrix to leading order in the active-sterile mixing parameters θ_α:

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

Present Constraints

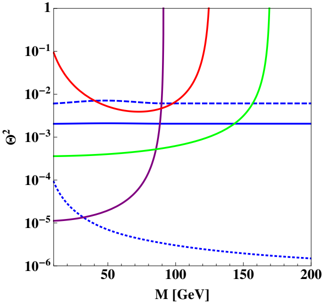
Global fit to precision data:

- Electroweak Precision Observables (mainly LEP).
- Non-universality observables (decays of μ, τ, π, K).
- Rare charged lepton flavour violating decays.
- CKM unitarity tests.
- Low energy measurements of the weak mixing angle.

Direct Searches:

- Z pole searches at LEP I.
- Four fermion final states at LEP II.
- Higgs boson branching rations at the LHC.
- Many beam-dump experiments at lower energies.

Present Constraints: Summary Plot

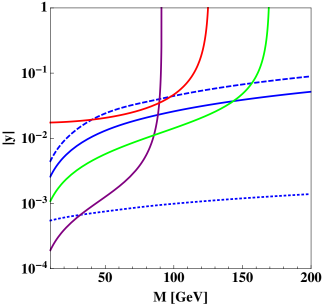


Direct searches

🟪 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)

━ $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

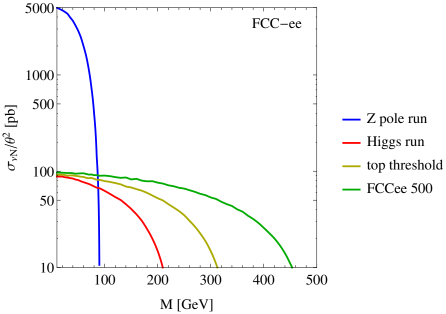
┅ $|y|=|y_{\nu_\mu}|$, $\Theta^2=|\theta_\mu|^2$

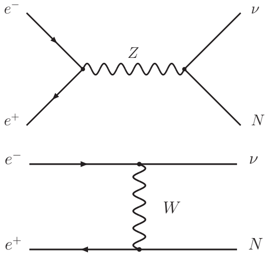
╍ $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$

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

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

Heavy Neutrino Production at the FCC-ee





- At the Z pole run: efficient production via s-channel Z boson.
- At higher energies: t-channel W boson exchange.
- Higher center-of-mass energies ⇒ enhanced mass reach and logarithimic growth of the production cross section.

Search Strategies for heavy neutrinos at the FCC-ee

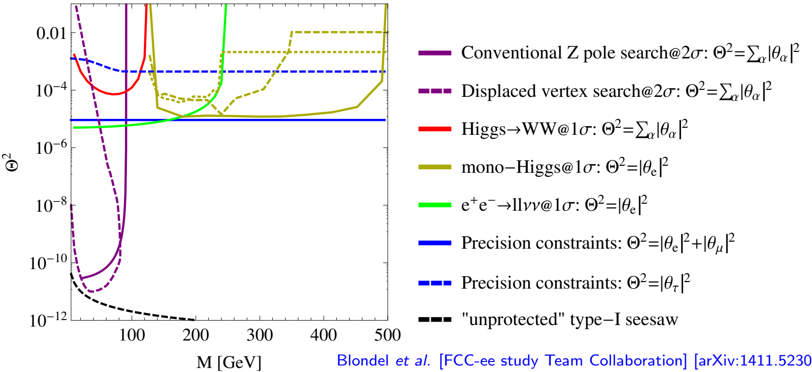
Modi operandi:

- 🟦 Z pole run: $\sqrt{s} = m_Z$, 100 ab^{-1}
- 🟨 Higgs run: $\sqrt{s} = 240$ GeV, 10 ab^{-1}
- 🟥 Top threshold scan: $\sqrt{s} = 350$ GeV, 3.5 ab^{-1}
- 🟩 High energy run: $\sqrt{s} = 500$ GeV, 1.0 ab^{-1}

Signatures:

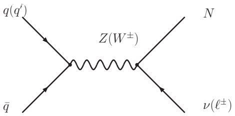
- Electroweak Precision Observables: 🟦.
- Lepton flavour violating Z decays: 🟦.
- "Long-lived" heavy neutrinos with displaced vertices 🟦 (🟨).
- Higgs production cross section and decays: 🟨 (🟥 🟩).
- WW-like signatures: $\ell^{\pm}jj$ and $\ell^{+}\ell^{-}$ plus $\not{E}$: 🟨 🟥 🟩.

Prospects of Sensitivity at the FCC-ee: Update

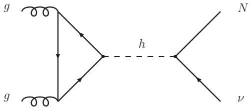


Blondel *et al.* [FCC-ee study Team Collaboration] [arXiv:1411.5230]
Antusch, OF; JHEP **1505** (2015) 053
Antusch, Cazzato, OF; [arXiv:1512.06035]
Antusch, Cazzato, OF; [arXiv:1604.02420]

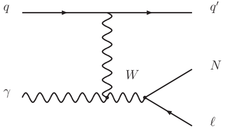
Heavy Neutrino Production at hadron colliders



Drell-Yan



Gluon fusion



$W\gamma$ fusion

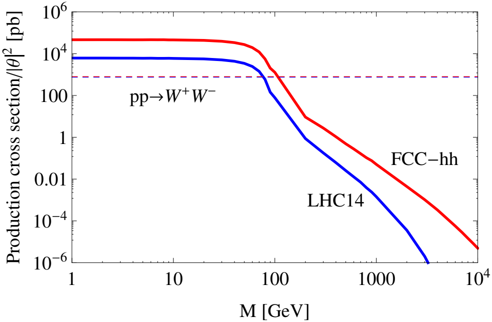
Search strategies:

- Displaced vertices
- Lepton-Number-Violation
- Lepton-Flavour-Violation ($H \to \mu\tau$ excess?)
- Boosted mono-Higgs, or mono-Z bosons (ATLAS 3σ excess?).

Drawbacks:

- QCD backgrounds necessitate large integrated luminosities.
- Suppressed production cross section for large M.

Heavy Neutrino Production in hadronic Collisions

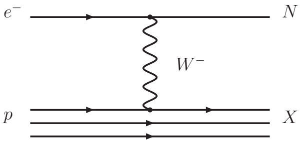


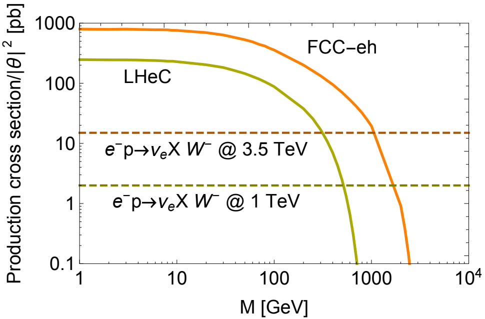
- In hadron-hadron collisions: $|\theta|^2 = \sum_\alpha |\theta_\alpha|^2$.
- SM Backgrounds:
  $p\,p \to W^+W^-$: 750 pb @ LHC14, 800 pb @ FCC-hh
  $p\,p \to Z\,Z$:10 pb @ LHC14, 125 pb @ FCC-hh
- Global fit prefers $|\theta_e|^2 \sim 10^{-3}$ at 2 to 3 σ.

Antusch, OF; JHEP **1410** (2014) 094.

Basso, OF, van der Bij; Europhys. Lett. **105** (2014) no.1, 11001

Heavy Neutrino Production in electron-proton Collisions





- The Large Hadron electron Collider: $\sqrt{s}$ up to 1.0 TeV.
- The Future Circular electron proton Collider: $\sqrt{s} = 3.5$ TeV.
- Heavy neutrino produced via the charged current.
- Electron-hadron collisions are sensitive to $|\theta_e|$.
- SM Background:
  $e^- \, p \to \nu_e \, X \, W^-$: ~ 3 pb @ LHeC3.5, 33 pb @ FCC-eh

Summary and 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.
- Heavy neutrinos can be searched for via ...
  - ... their decay products (direct searches).
  - ... modifications of SM processes (indirect searches).
- Future lepton colliders:
  - ⋆ Electroweak precision observables.
  - ⋆ Z pole searches (conventional and displaced vertices).
  - ⋆ Mono-Higgs production and Higgs decays.
  - ⋆ WW-like signatures
- Future hadron colliders:
  - ⋆ Drell-Yan production, rapid “drop off” for lage M.
  - ⋆ flavour democratic, Discovery via LNV, LFV, mono-Z.
- Future electron-proton colliders provide significant gain in mass reach and fairly “stable” production cross sections.

⇒ The FCCs provide great prospects for discovering the origin of neutrino masses.

Thank you for your attention.

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

Next: Important processes to search for sterile neutrinos at present and future colliders

Backup II - 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 III - 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 IV - CKM unitarity constraint

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

$$|V_{ij}^{th}|^2 = |V_{ij}^{exp}|^2 (1 + f^{\text{process}}(\varepsilon_{\alpha\alpha})) ,$$

$$|V_{ud}^{th}|^2 = |V_{ud}^{exp,\beta}|^2 (NN^\dagger)_{\mu\mu} .$$

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	$f^{\text{process}}(\varepsilon)$	$\lvert V_{us}\rvert$
$\frac{B(\tau\to K\nu)}{B(\tau\to\pi\nu)}$	$\varepsilon_{\mu\mu}$	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 V - 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}	$\varepsilon_{\mu e} \geq 2.4 \times 10^{-6}$
$R_{\mu e}^{Ti}$	$1.5 \times 10^{-5}\|\varepsilon_{\mu e}\|^2$	2×10^{-18}	$\varepsilon_{\mu e} \geq 3.6 \times 10^{-7}$

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