Higgs production from sterile neutrinos at the FCC-ee

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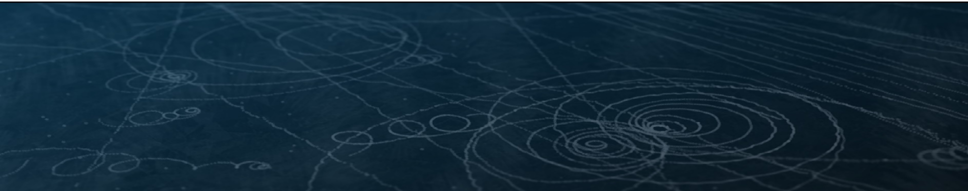
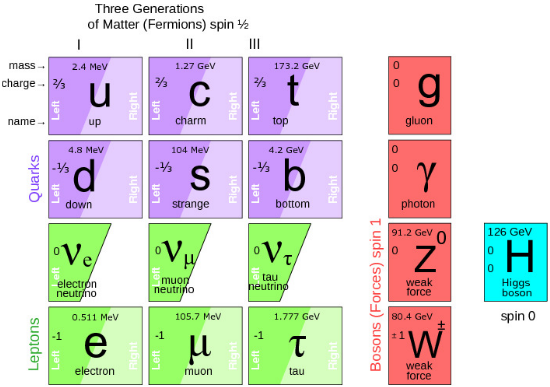


Motivation for Sterile Neutrinos



- Observation of neutrino oscillations requires *at least* two of the light neutrinos to be massive.
- Neutrino masses can be accounted for efficiently by right-handed or “sterile neutrinos”.

The Seesaw Mechanism

- Naive $(1\ \nu_L,\ 1\ \nu_R)$ 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:

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

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

⇒ Knowledge of m_{ν_i} implies a relation between y_ν and M_R.

⇒ In general not very promising to observe at collider experiments:
$M_R \sim 10^2$ GeV $\Rightarrow y_\nu \sim \mathcal{O}(10^{-6})$

Lowscale Seesaw

- Different realisation which uses a specific structure of the Yukawa and mass matrices that can be realised by symmetries (no fine tuning), e.g. approximate "lepton-number-like" symmetry.
- A $(2\ \nu_L,\ 2\ \nu_R)$ example:

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

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

⇒ In general: no fixed relation between y_ν and M_R.

⇒ Large y_ν are compatible with neutrino oscillations.

⇒ Enters promising region for testable effects at collider experiments.

Symmetry Protected Seesaw Scenario

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

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

- The active-sterile mixing parameter: $\theta_\alpha = \frac{y_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{2}M}$
- The leptonic mixing matrix to leading order in θ_α

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

⇒ Heavy neutrino mass eigenstates interact with weak gauge bosons $\propto \theta_\alpha$

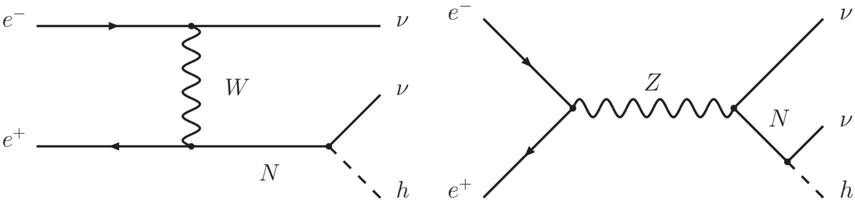
- With EW scale M, y_{ν_α} constrained to at most $\mathcal{O}(10^{-2})$

⇒ Enabled Higgs production through sterile neutrinos at the FCC-ee.

Resonant Mono-Higgs from Sterile Neutrinos

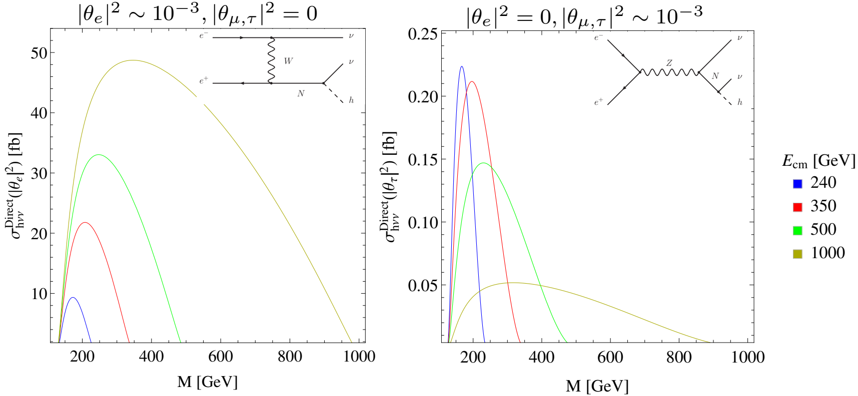
based on arXiv:1512.06035

- Mono-Higgs = Higgs plus missing energy



- Generally: $\sigma_{h\nu\nu} = \sigma_{h\nu\nu}^{\text{SM}} + \sigma_{h\nu\nu}^{\text{Non-U}} + \sigma_{h\nu\nu}^{\text{Direct}}$.
- $\sigma_{h\nu\nu}^{\text{SM}}$: Higgs Strahlung and WW fusion.
- $\sigma_{h\nu\nu}^{\text{Direct}}$: resonantly enhanced contribution from on-shell production of heavy neutrinos.
  - W-exchange process only sensitive to y_{ν_e}.
  - Z-exchange process produces all flavours.
- $\sigma_{h\nu\nu}^{\text{Non-U}}$: indirect effect from the PMNS matrix.

Resonant Mono-Higgs-Production Cross Section



$|\theta_e|^2 \sim 10^{-3}, |\theta_{\mu,\tau}|^2 = 0$

$|\theta_e|^2 = 0, |\theta_{\mu,\tau}|^2 \sim 10^{-3}$

Antusch, Cazzato, Fischer, arXiv:1512.06035 (2015)

- Using present upper bounds at 68% Bayesian confidence level.

⇒ Resonant mono-Higgs production mostly sensitive to $|\theta_e|$.

- $\sigma^{\text{SM}}_{h\nu\nu} \sim 54$ fb for $\sqrt{s}$ of 240 and 350 GeV

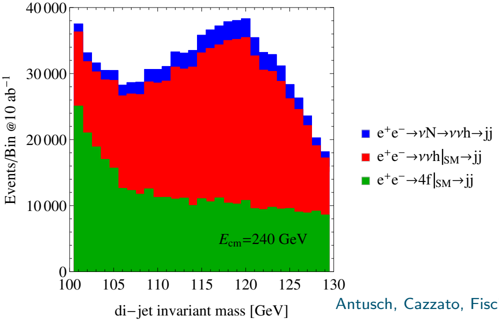
Software Framework

- Event simulation: WHIZARD 2.2.7
- Showering: PYTHIA 6.427
- Reconstruction: Delphes 3.2.0 (ILD card)
- Anaylsis: Madanalysis5

⇒ Mono-Higgs search channel: di-jet + missing energy

The Higgs Peak:

$|y_{\nu_e}| = {\color{red}0.036}$ & $M = 152\ GeV\ \ at\ 240\ GeV\ \ for\ 10\ ab^{-1}$



Antusch, Cazzato, Fischer, arXiv:1512.06035 (2015)

Our cuts (not fully optimised):

- Pre selection: $N_j = 2, N_\ell = 0,\ 110 < M_{jj} < 125$ GeV
- For the example: $P_{jj} > 70,\ \not{E}_T > 15$ GeV

Event counts: (starting with pre selection)

BKG	548k	$\rightarrow$	18k
$\sigma_{h\nu\nu}^{\rm Direct}$	15k	$\rightarrow$	4.8k

$$\Rightarrow \boxed{\frac{S}{\sqrt{S+B}} \simeq 30}$$

Contamination of SM Parameters

- Higgs properties obtained by applying “standard cuts” on the Higgs event sample at lepton colliders:

$\sqrt{s}$	240 GeV	350 GeV
Missing Mass [GeV]	$80 \leq M_{\text{miss}} \leq 140$	$50 \leq M_{\text{miss}} \leq 240$
Transverse P [GeV]	$20 \leq P_T \leq 70$	$10 \leq P_T \leq 140$
Longitudinal P [GeV]	$\|P_L\| < 60$	$\|P_L\| < 130$
Maximum P [GeV]	$\|P\| < 30$	$\|P\| < 60$
Di-jet Mass [GeV]	$100 \leq M_{jj} \leq 130$	$100 \leq M_{jj} \leq 130$
Angle (jets) [Rad]	$\alpha > 1.38$	$\alpha > 1.38$

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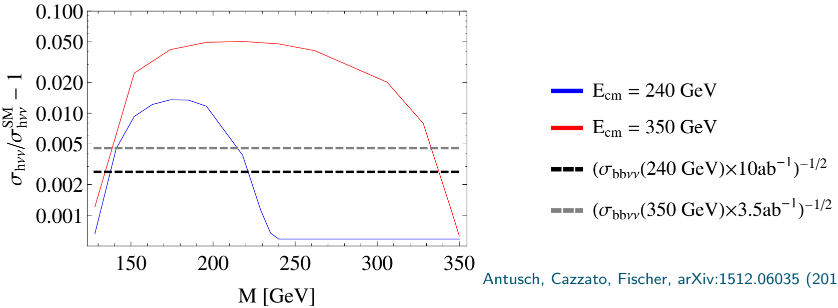
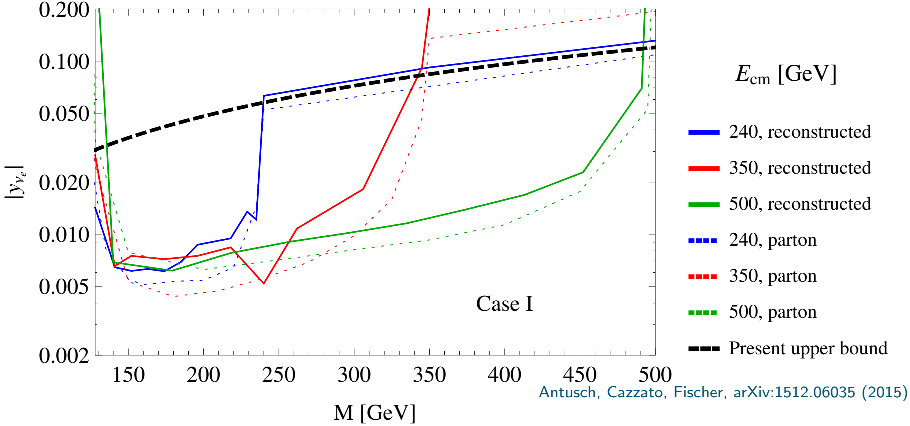
$\Rightarrow$ Contamination of Higgs sample with resonantly produced Higgs events



Antusch, Cazzato, Fischer, arXiv:1512.06035 (2015)

Sensitivity of the Mono-Higgs Channel to Neutrino Mixing at the FCC-ee at 1σ



Antusch, Cazzato, Fischer, arXiv:1512.06035 (2015)

- Considered luminosities:

10 ab^{-1} for 240 GeV	3.5 ab^{-1} for 350 GeV	1 ab^{-1} for 500 GeV

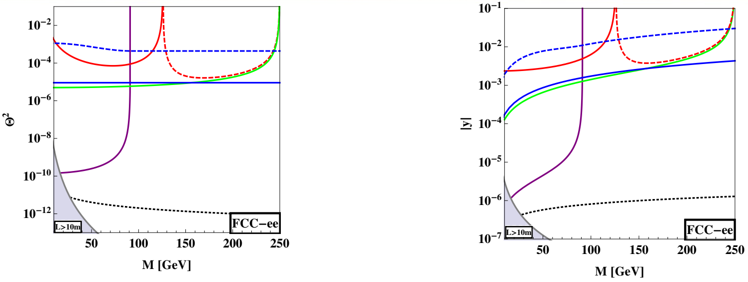
⇒ Reduction in luminosity is partly compensated by gain in production cross section.

Summary and Conclusions

- Symmetry protected seesaw scenarios allow for large neutrino Yukawa couplings and masses in the interesting range.
- **Higher center-of-mass energies lead to increased mono-Higgs production cross sections from sterile neutrinos.**
- $\sqrt{s} =$ **350 GeV is even more sensitive than 240 GeV.**
- A contamination of the Higgs sample with resonantly produced Higgs events can lead to a deviation of the Higgs parameters.
- Sensitivity to $|y_{\nu_e}|$ down to 5×10^{-3} is possible.
  - **Important for understanding the data.**
  - **Complementarity** to other searches for sterile Neutrinos.
- FCC-ee yields valuable information on the neutrino mass mechanism via the mono-Higgs channel.

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: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$

┅ $e^+e^-\rightarrow h + ME_{(T)}$ @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

▬ $e^+e^-\rightarrow l\nu l\nu^*$ @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

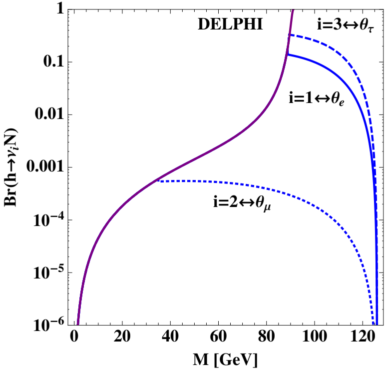
Antusch, Fischer; arXiv:1502.05915 (2015)

∗ 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: Cross Sections for SM Background

Final state	σ^{SM}@240 GeV	σ^{SM}@350 GeV	σ^{SM}@500 GeV
$b\bar{b}\nu\nu$	146.492	134.614	183.594
$c\bar{c}\nu\nu$	88.0172	73.7956	82.7041
$jj\nu\nu$	528.8	463.1	500.3
$b\bar{b}b\bar{b}$	81.2629	47.6152	25.5571
$b\bar{b}c\bar{c}$	146.566	87.6518	51.6446
$b\bar{b}jj$	6820.6	4259.5	2537.8
$b\bar{b}e^+e^-$	2080.87	2500.82	2920.9
$b\bar{b}\tau^+\tau^-$	34.1905	19.7975	11.0619
$c\bar{c}\tau^+\tau^-$	25.2553	15.0695	9.15227
$jj\tau^+\tau^-$	116.0	72.4	37.6
$\tau^+\tau^-\nu\nu$	235.89	163.851	119.989
single top	0.012	63.3	1092
$t\bar{t}$	—	322.	574.

All cross sections in fb.