Golden channels for heavy neutrino searches at the FCC

Eros Cazzato

e.cazzato@unibas.ch

S. Antusch & O. Fischer

University of Basel, Switzerland

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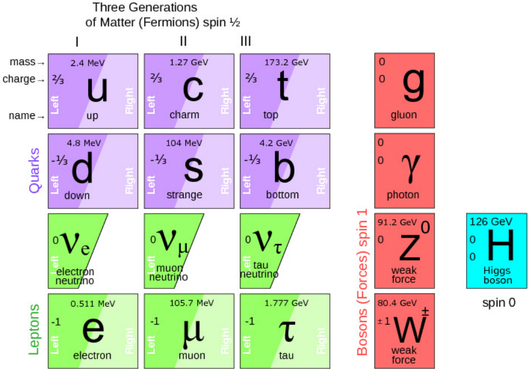
based on arXiv:1612.02728
and references therein

Where to best look for heavy neutrinos?

http://belhene.deviantart.com/

Motivation for sterile (= right-chiral) neutrinos

- There are no right-chiral neutrinos (ν_R) in the SM.
- Observation of neutrino oscillations requires *at least* two of the light neutrinos to be massive.



Shaposhnikov et al.

⇒ Extra terms in the Lagrangian density due to adding ν_R:

$$\mathscr{L}_N = -\underbrace{(Y_\nu)_{i\alpha}}_{\nu\text{ Yukawa matrix}}\overline{\nu_R^i}\tilde{\phi}^\dagger L^\alpha - \frac{1}{2}\overline{\nu_R^i}\underbrace{M_{ij}}_{\text{sterile }\nu\text{ mass matrix}}(\nu_R^j)^c + \text{H.c.}$$

The seesaw mechanism

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

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

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

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

$\Rightarrow$ 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

- Specific structure of the Yukawa and mass matrices can be realised by symmetries, e.g. approximate "lepton number"-like symmetry.
- A $(2\ \nu_L,\ 2\ \nu_R)$ example:

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

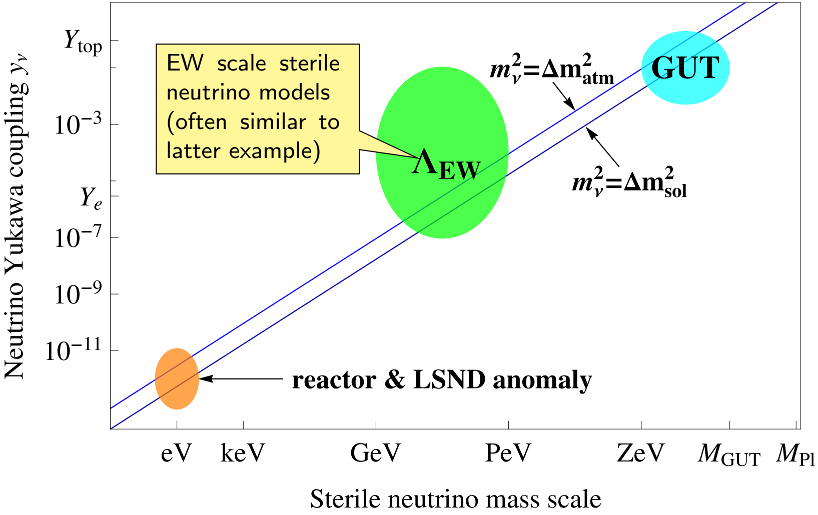
$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\mathrm{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

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

⇒ Large y_ν are compatible with neutrino oscillations.

⇒ Allows for testable effects at collider experiments.

Neutrino parameters landscape



Symmetry Protected Seesaw Scenario

A benchmark model for collider searches with EW scale sterile neutrinos

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

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

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Additional sterile ν can exist but have no effects ("decoupled") at colliders, which can be realised e.g. by giving lepton number=0.

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Additional sterile ν can exist but have no effects ("decoupled") at colliders, which can be realised e.g. by giving lepton number=0.

$\Rightarrow$ In the symmetric limit (i.e. without $\mathcal{O}(\varepsilon)$ terms), M and $y_{\nu_\alpha} (\alpha = e, \mu, \tau)$ are free parameters (not constrained by m_ν).

- Specific models have correlation among the y_{ν_α}.

Strategy of the SPSS: study how to measure the y_{ν_α} independently in order to test such correlations!

Symmetry Protected Seesaw Scenario

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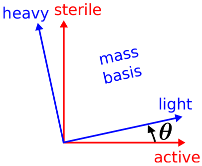

- The active-sterile mixing parameter: $\theta_\alpha = \frac{y^*_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{2}M}$

> SPSS Parameters:
> M and $y_{\nu_\alpha}(\alpha = e, \mu, \tau)$ or
> M and $\theta_\alpha(\alpha = e, \mu, \tau)$

Symmetry Protected Seesaw Scenario

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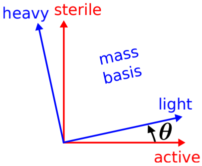

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SPSS Parameters:
M and $y_{\nu_\alpha}(\alpha = e, \mu, \tau)$ or
M and $\theta_\alpha(\alpha = e, \mu, \tau)$

- The leptonic mixing matrix to leading order in θ_α

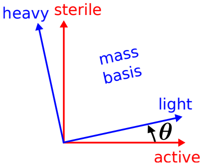
Mixing matrix of the light ν $\equiv U_{\text{PMNS}}$

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu1} & \mathcal{N}_{\mu2} & \mathcal{N}_{\mu3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau1} & \mathcal{N}_{\tau2} & \mathcal{N}_{\tau3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta^*_e & -\theta^*_\mu & -\theta^*_\tau & -\frac{\mathrm{i}}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

Sterile ν mix with active ones

Symmetry Protected Seesaw Scenario

A benchmark model for collider searches with EW scale sterile neutrinos



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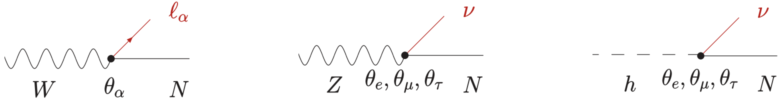
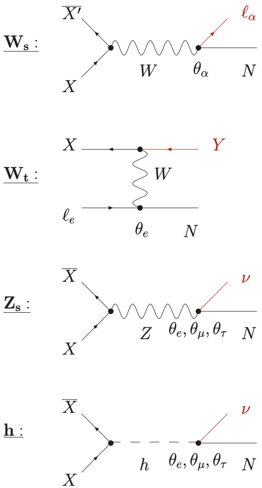
Sterile ν mix with active ones

$\Rightarrow$ Heavy ν (mass eigenstates) participate in weak interaction processes:



Systematic assessment of heavy neutrino signatures at colliders

Production



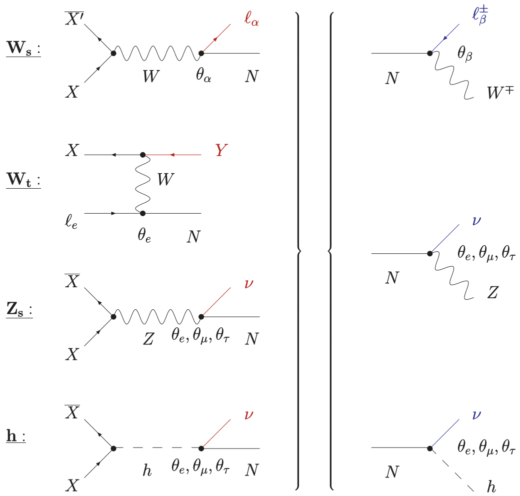
Different production channels for collider types:

	e^-e^+	pp	e^-p
$\mathbf{W_s}$	×	✓+LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ +LNV/LFV
$\mathbf{Z_s}$	✓	✓	×
$\mathbf{h}$	(✓)	(✓)	(✓)

At leading order!

Systematic assessment of heavy neutrino signatures at colliders

Production | Decay



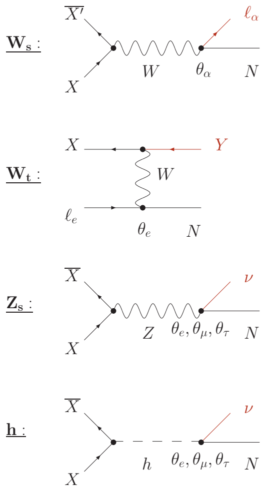
Inclusion of decay channels gives processes with different dependencies on the active-sterile mixing angles.

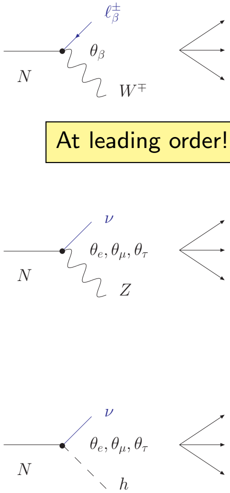
		Decay channel	
		W	$Z(h)$
Production channel	$\mathbf{W_s}$	$\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\lvert\theta\rvert^2}$	$\lvert\theta_\alpha\rvert^2$
	$\mathbf{W_t}$	$\frac{\lvert\theta_e\theta_\beta\rvert^2}{\lvert\theta\rvert^2}$	$\lvert\theta_e\rvert^2$
	$\mathbf{Z_s(h)}$	$\lvert\theta_\beta\rvert^2$	$\lvert\theta\rvert^2$

$|\theta|^2 = \sum |\theta_\alpha|^2$

Systematic assessment of heavy neutrino signatures at colliders

Production | Decay | Final States





At leading order!

- $\mathbf{pp}$: $\ell_\alpha \ell_\beta^\pm jj$, $\ell_\alpha \ell_\beta^\pm \ell_\gamma^\mp \nu$
- $\mathbf{e^-e^+, e^-p}$: $Y \ell_\beta^\pm jj$, $Y \ell_\beta^\pm \ell_\gamma^\mp \nu$
- $\mathbf{e^-e^+, pp}$: $\nu \ell_\beta^\pm jj$, $\nu \ell_\beta^\pm \ell_\gamma^\mp \nu$

- $\mathbf{pp}$: $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu\nu\nu$
- $\mathbf{e^-e^+, e^-p}$: $Y \nu jj$, $Y \nu \ell_\beta^\pm \ell_\beta^\mp$, $Y \nu\nu\nu$
- $\mathbf{e^-e^+, pp}$: $\nu\nu jj$, $\nu\nu \ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu\nu\nu$

- $\mathbf{pp}$: $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu VV$
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- $\mathbf{e^-e^+, pp}$: $\nu\nu jj$, $\nu\nu \ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu VV$

Systematic assessment of heavy neutrino signatures at colliders

	e^-e^+	pp	e^-p
$\mathbf{W_s}$	$\times$	$\checkmark$ + LNV/LFV	$\times$
$\mathbf{W_t}$	$\checkmark$	$\times$	$\checkmark$ +LNV/LFV
$\mathbf{Z_s}$	$\checkmark$	$\checkmark$	$\times$
$\mathbf{h}$	$(\checkmark)$	$(\checkmark)$	$(\checkmark)$

Remarks on LNV:

- When light ν are in the final states, difficult to measure LNV since they escape detection. Unambiguous signal of LNV if no light ν in the final state:
- Example on unambiguous signals of LNV: @pp : same-sign dilepton @e^-p : $\ell_\alpha^+ jjj$

Systematic assessment of heavy neutrino signatures at colliders

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Lepton-number violating signatures (with no SM background at parton level) however in the SPSS suppressed by the protective "lepton number"-like symmetry.

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$\mathbf{W_s}$	×	✓+ LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ + LNV/LFV
$\mathbf{Z_s}$	✓	✓	×
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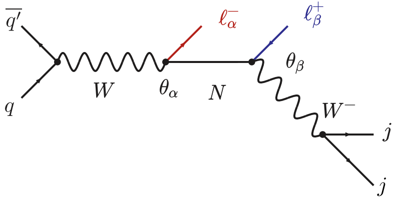
  with e.g. $\alpha = e$ and $\beta = \mu$



@e^-p : lepton-trijet $\longleftrightarrow$ $\ell_\alpha^- jjj$ with $\alpha \neq e$

- Unambiguous signals for LFV (at the parton level) with light ν in the final state possible:
  @pp: $\ell_e \ell_\mu \ell_\tau \nu$ @e^-p : $j\ell_\mu^- \ell_e^+ \nu$

Systematic assessment of heavy neutrino signatures at colliders

	e^-e^+	pp	e^-p
$\mathbf{W_s}$	×	✓+LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ +LNV/LFV
$\mathbf{Z_s}$	✓	✓	×
$\mathbf{h}$	(✓)	(✓)	(✓)

Lepton-number violating signatures (with no SM background at parton level) however in the SPSS suppressed by the protective "lepton number"-like symmetry.

Lepton-flavour violating (and lepton-number conserving) signatures possible (with no SM background at parton level). Very promising for future searches.

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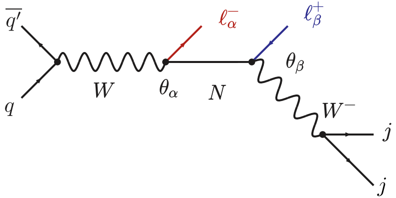

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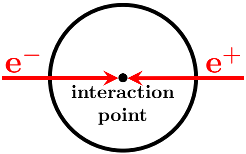
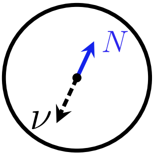
Systematic assessment of heavy neutrino signatures at colliders

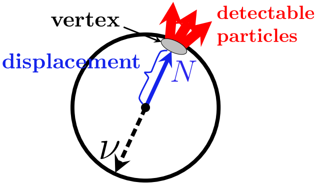
Remarks on Displaced Vertex signature:

- Heavy ν with $M < M_W$ and small mixing $|\theta|^2$ may be "long-lived" .
- Visible displacement of the secondary vertex from the interaction point.

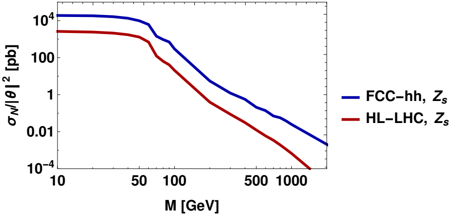
$\mathbf{t = 0}$	$\mathbf{0 < t <}$ **lifetime of** $\boldsymbol{N}$	**lifetime of** $\boldsymbol{N} <$ **t**
electron-positron collision	production of N and propagation	decay of N into detectable particles



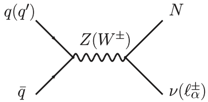




Heavy neutrinos at the FCC-hh



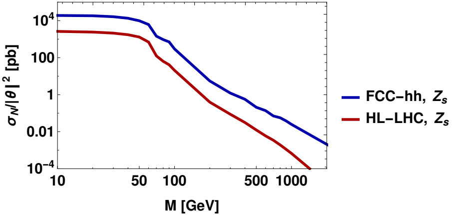
production channel:
$\mathbf{Z_s} \propto |\theta|^2$
$(\mathbf{W_s} \propto |\theta_\alpha|^2)$



Signatures of heavy ν for pp colliders at leading order

Name	Final State	$\lvert\theta_\alpha\rvert$ dependency	LNV/LFV
dilepton-dijet	$\ell_\alpha \ell_\beta jj$	$\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\theta^2}$	✓/✓
trilepton$^{(*)}$	$\ell_\alpha \ell_\beta \ell_\gamma \nu$	$\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\theta^2}$	×/✓
lepton-dijet	$\ell_\alpha \nu jj$	$\lvert\theta_\alpha\rvert^2$	×
dilepton$^{(*)}$	$\ell_\alpha \ell_\beta \nu\nu$	$\lvert\theta_\alpha\rvert^2$	×
mono-lepton	$\ell_\alpha \nu\nu\nu$	$\lvert\theta_\alpha\rvert^2$	×
dijet	$\nu\nu jj$	$\lvert\theta\rvert^2$	×

Heavy neutrinos at the FCC-hh



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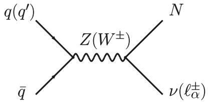

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mono-lepton	$\ell_\alpha \nu\nu\nu$	$\lvert\theta_\alpha\rvert^2$	×
dijet	$\nu\nu jj$	$\lvert\theta\rvert^2$	×

"Same sign dileptons" most studied signature, in SPSS suppressed by the protective "lepton number"-like symmetry.

Unambiguous signals for LFV (with no SM background at the parton level).

Modifies mono-Z, mono-h production

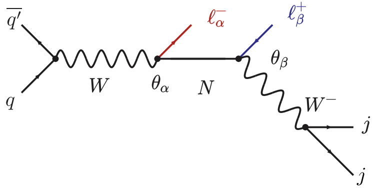
More heavy neutrino signatures at the FCC-hh

- Indirect searches via h branching ratios
  - △ Extra decay channels modify the h total width and branching ratios.
- Displaced vertex searches
  - △ Heavy ν with $M < M_W$ and small mixing $|\theta|^2$ may be "long-lived"
  - △ Visible displacement of the secondary vertex from the interaction point.

No SM background, very promising!

- LFV signatures
  - △ Unambiguous signal for LFV (at the parton level): e.g. dilepton-dijet $\longleftrightarrow$ $\ell_\alpha^\mp \ell_\beta^\pm jj$ with $\alpha = e$ and $\beta = \mu$

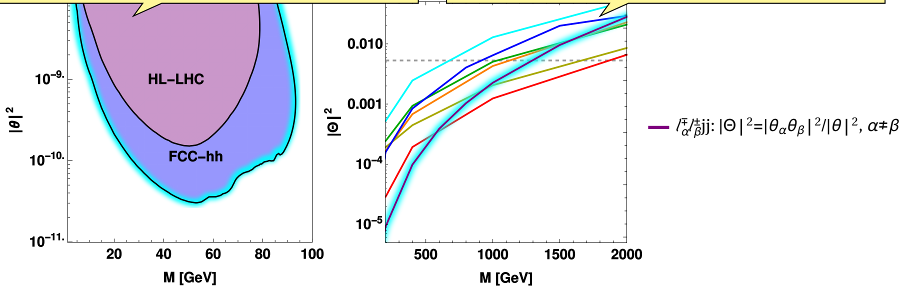
No SM background, very promising!



"First looks" at FCC-hh sensitivities

Displaced vertex search 2σ sensitivity. Displacements of 1mm - 1m as backgroundfree.

Presented first looks for the 1σ sensitivities of heavy ν signatures at the parton level.



The golden channels of the FCC-hh:

- For $M < 100$ GeV: displaced vertex
- For $M > 100$ GeV: LFV signatures
  - △ As unambiguous signal at parton level $|\theta_\alpha \theta_\beta|^2 / |\theta|^2 \sim 10^{-8}$ reachable
  - △ Displayed as estimate with ditop BKG $|\theta_\alpha \theta_\beta|^2 / |\theta|^2 \sim 10^{-5}$ reachable

For the considered physics program: 20 ab^{-1} for $\sqrt{s} = 100$ TeV;

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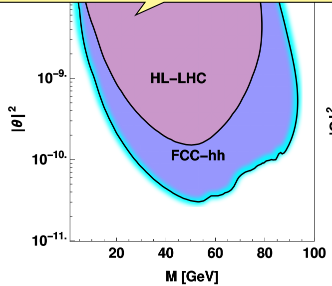

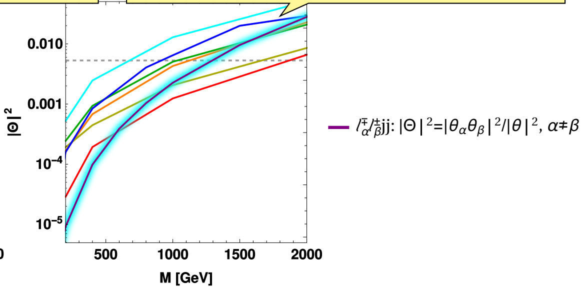

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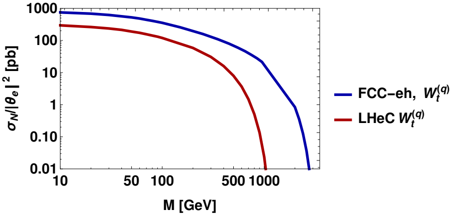
  - △ Displayed as estimate with ditop BKG $|\theta_\alpha \theta_\beta|^2/|\theta|^2 \sim 10^{-5}$ reachable

This is merely a first look, more thorough investigation is required, e.g. LFV signature is being investigated at reconstructed-level.

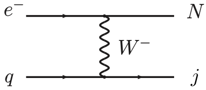
BKGs from final states with additional light ν.

For the considered physics program: 20 ab^{-1} for $\sqrt{s} = 100$ TeV;

Heavy neutrinos at the FCC-eh



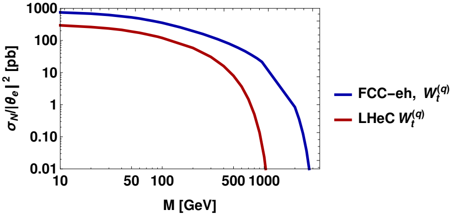
production channel:
$\mathbf{W_t} \propto |\theta_e|^2$



Signatures of heavy ν for $e^- p$ colliders at leading order

Name	Final State	$\lvert\theta_\alpha\rvert$ dependency	LNV/LFV
lepton-trijet	$jjj\ell_\alpha$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓/✓
jet-dilepton$^{(*)}$	$j\ell_\alpha^\pm\ell_\beta^\mp\nu$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	×/✓
trijet	$jjj\nu$	$\lvert\theta_e\rvert^2$	×
monojet	$j\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

Heavy neutrinos at the FCC-eh



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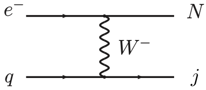

Signatures of heavy ν for $e^- p$ colliders at leading order

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trijet	$jjj\nu$	$\lvert\theta_e\rvert^2$	×
monojet	$j\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

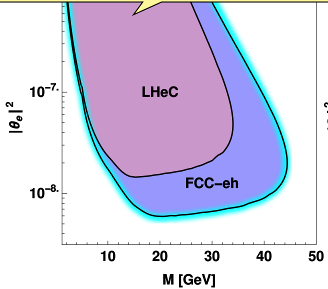
e^+jjj as unambiguous signal of LNV, in SPSS suppressed by the protective "lepton number"-like symmetry.

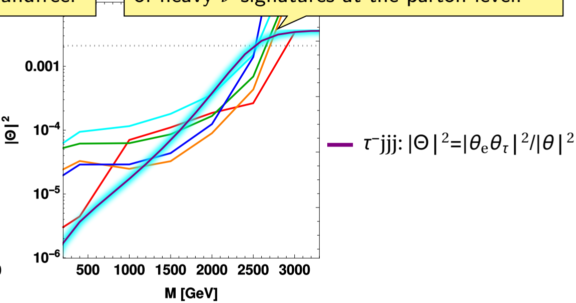
$\ell_\alpha^- jjj$ with $\alpha \neq e$ as unambiguous signal for LFV (with no SM background at the parton level).

“First looks” at FCC-eh sensitivities

Displaced vertex search 2σ sensitivity. Displacements of 1mm - 1m as backgroundfree.

Presented first looks for the 1σ sensitivities of heavy ν signatures at the parton level.



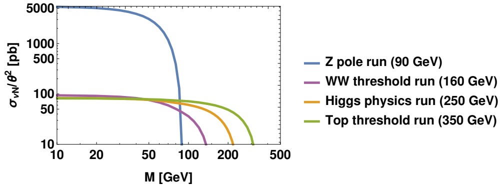


The golden channels of the FCC-eh:

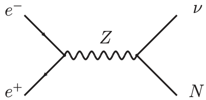
- For $M < M_W$: displaced vertex
- For $M > M_W$: LFV signatures
  - △ As unambiguous signal at parton level $|\theta_e\theta_\tau|^2/|\theta|^2 \sim 10^{-8}$ reachable
  - △ Displayed as estimate with BKGs from final states with additional light ν $|\theta_e\theta_\tau|^2/|\theta|^2 \sim 10^{-6}$ reachable

For the considered physics program: 1 ab^{-1} for $\sqrt{s} = 3.5$ TeV;

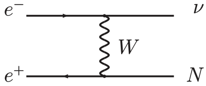
Heavy neutrinos at the FCC-ee



production channel: $\mathbf{Z_s} \propto |\theta|^2$



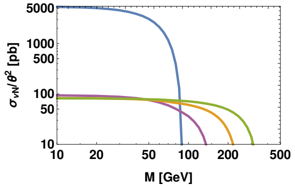
production channel: $\mathbf{W_t} \propto |\theta_e|^2$



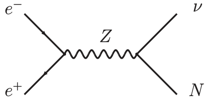
Signatures of heavy ν for e^-e^+ colliders at leading order

Name	Final State	$\|\theta\|$, Z pole	$\|\theta\|$, $\sqrt{s} > m_Z$
lepton-dijet	$\ell_\alpha \nu jj$	$\|\theta_\alpha\|^2$	$\frac{\|\theta_e \theta_\alpha\|^2}{\theta^2}$
mixed flavour dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$\|\theta_\alpha\|^2$	$\frac{\|\theta_e \theta_\alpha\|^2}{\theta^2}$
same flavour dilepton	$\ell_\alpha \ell_\alpha \nu\nu$	$\|\theta\|^2$	$\|\theta_e\|^2$
dijet	$\nu\nu jj$	$\|\theta\|^2$	$\|\theta_e\|^2$
invisible	$\nu\nu\nu\nu$	$\|\theta\|^2$	$\|\theta_e\|^2$

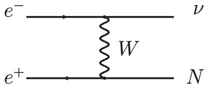
Heavy neutrinos at the FCC-ee



production channel: $\mathbf{Z_s} \propto |\theta|^2$



production channel: $\mathbf{W_t} \propto |\theta_e|^2$



Always one light ν in the final state, no unambiguous LNV signature at the leading order.

Signatures of heavy ν for e^-e^+ colliders at leading order

Name	Final State	$\|\theta\|$, Z pole	$\|\theta\|$, $\sqrt{s} > m_Z$
lepton-dijet	$\ell_\alpha \nu j j$	$\|\theta_\alpha\|^2$	$\frac{\|\theta_e \theta_\alpha\|^2}{\theta^2}$
mixed flavour dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$\|\theta_\alpha\|^2$	$\frac{\|\theta_e \theta_\alpha\|^2}{\theta^2}$
same flavour dilepton	$\ell_\alpha \ell_\alpha \nu\nu$	$\|\theta\|^2$	$\|\theta_e\|^2$
dijet	$\nu\nu j j$	$\|\theta\|^2$	$\|\theta_e\|^2$
invisible	$\nu\nu\nu\nu$	$\|\theta\|^2$	$\|\theta_e\|^2$

Modify WW production

Modifies mono-Z, mono-h production

More heavy neutrino signatures at the FCC-ee

- Indirect searches via EW precision data

  High lumi of FCC-ee (10^{13} Z) allows for efficient indirect searches.

  - △ Mixing matrix of the 3 active ν (U_{PMNS}) becomes non-unitary.
  - △ Modification of the weak currents modifies predictions for EWPOs.

- Indirect searches via h branching ratios
  - △ Extra decay channels modify the h total width and branching ratios.

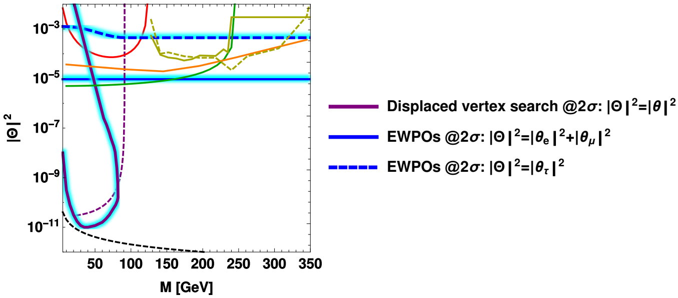
- Displaced vertex searches

  No SM background, very promising!

  - △ Heavy ν with $M < M_W$ and small mixing $|\theta|^2$ may be "long-lived".
  - △ Visible displacement of the secondary vertex from the interaction point.

- LFV signatures
  - △ LFV decays of the Z boson into two charged leptons with different flavour arise at the 1-loop order.

FCC-ee sensitivities to heavy neutrino signatures (available from previous works)



The golden channels of the FCC-ee:

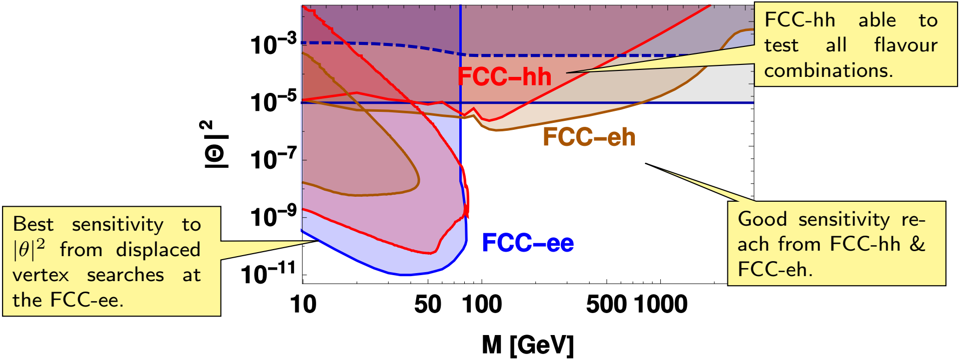
- For $M < M_W$: displaced vertex searches
- For $M > M_W$: indirect searches via EW precision data

For the considered physics program:

110 ab^{-1} for $\sqrt{s} = 90$ GeV; 5 ab^{-1} for $\sqrt{s} = 240$ GeV; 1.5 ab^{-1} for $\sqrt{s} = 350$ GeV

Summary

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search



Where to best look for heavy neutrinos?

http://belhene.deviantart.com/