The search for sterile neutrinos at Future Circular Colliders

Eros Cazzato

S. Antusch & O. Fischer

University of Basel, Switzerland

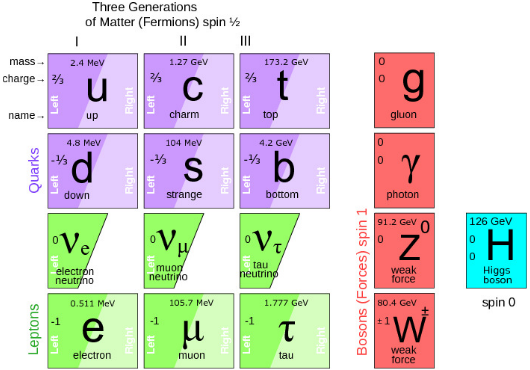
based on arXiv:1612.02728
and references therein

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.

$\Rightarrow$ 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:

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

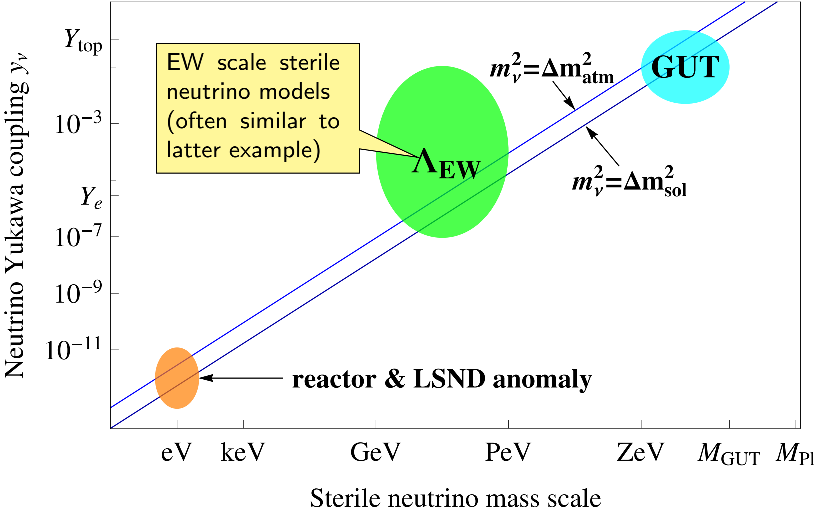
$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\mathrm{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

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

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

$\Rightarrow$ 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.

- 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!

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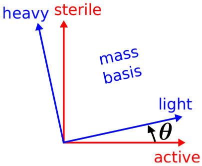
A benchmark model for collider searches with EW scale sterile neutrinos



- 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 $\theta_\alpha (\alpha = e, \mu, \tau)$

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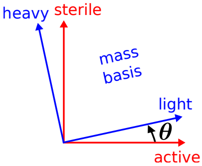

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SPSS Parameters:
M and $y_{\nu_\alpha} (\alpha = e, \mu, \tau)$ or
M and $\theta_\alpha (\alpha = e, \mu, \tau)$

- The leptonic mixing matrix to leading order in θ_α

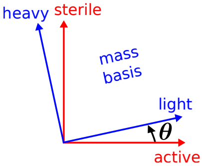
Mixing matrix of the light ν $\equiv U_{\mathrm{PMNS}}$

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

Sterile ν mix with active ones

Symmetry Protected Seesaw Scenario

A benchmark model for collider searches with EW scale sterile neutrinos



- 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 $\theta_\alpha (\alpha = e, \mu, \tau)$

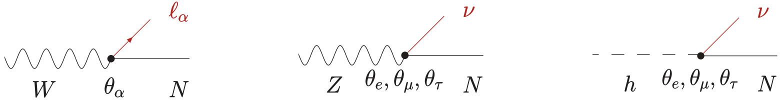
- The leptonic mixing matrix to leading order in θ_α

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

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

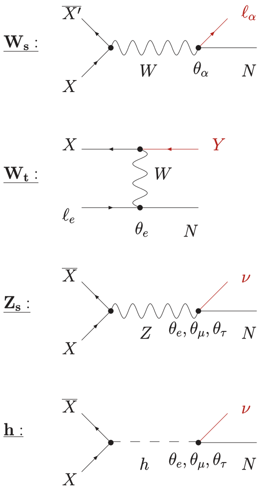
> Sterile ν mix with active ones

$\Rightarrow$ 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!

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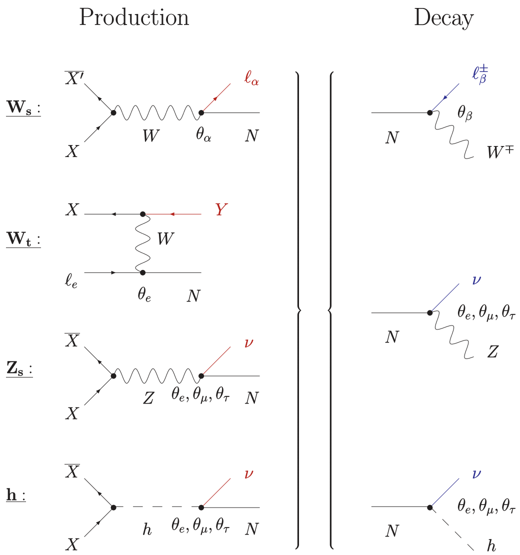


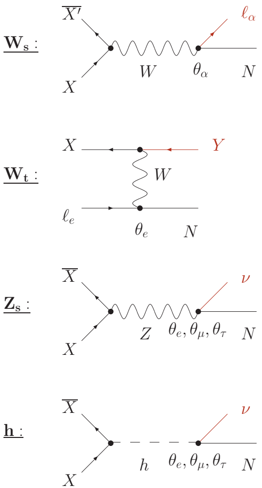
Inclusion of decay channels gives processes with different dependencies on the active-sterile mixing angles.

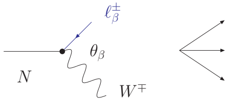
Production channel	Decay channel: W	Decay channel: $Z(h)$
$\mathbf{W_s}$	$\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\lvert\theta\rvert^2}$	$\lvert\theta_\alpha\rvert^2$
$\mathbf{W_t}$	$\frac{\lvert\theta_e\theta_\beta\rvert^2}{\lvert\theta\rvert^2}$	$\lvert\theta_e\rvert^2$
$\mathbf{Z_s(h)}$	$\lvert\theta_\beta\rvert^2$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

$\lvert\theta\rvert^2 = \sum \lvert\theta_\alpha\rvert^2$

Systematic assessment of heavy neutrino signatures at colliders

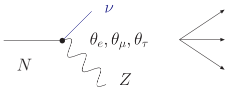
Production | Decay | Final States





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

At leading order!



- $\mathbf{pp}$: $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu \nu \nu$
- $\mathbf{e^-e^+, e^-p}$: $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu \nu \nu$
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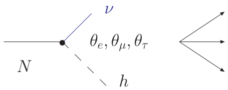

- $\mathbf{pp}$: $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu VV$
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- $\mathbf{e^-e^+, pp}$: $\nu \nu jj$, $\nu \nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu \nu VV$

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, it is difficult to measure LNV since they escape detection. Unambiguous signal of LNV possible if no light ν in the final state.
- Unambiguous signals of LNV:
  @pp : same-sign dilepton $\leftrightarrow \ell_\alpha^\pm \ell_\alpha^\pm jj$
  @e^-p : $\ell_\alpha^+ jjj$

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Lepton-number violating signatures are suppressed by the protective "lepton number"-like symmetry.

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Remarks on LFV:

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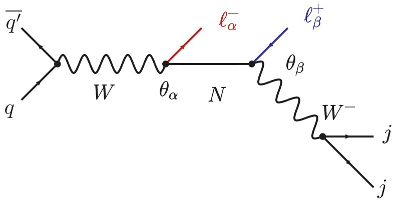
  @pp : dilepton-dijet $\longleftrightarrow$ $\ell_\alpha^\mp \ell_\beta^\pm jj$
  with e.g. $\alpha = e$ and $\beta = \mu$



@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 : $j\ell_\mu^- \ell_e^+ \nu$
- BKGs from processes with additional light ν

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$\mathbf{W_s}$	×	✓+LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ +LNV/LFV
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$\mathbf{h}$	(✓)	(✓)	(✓)

Lepton-number violating signatures are suppressed by the protective "lepton number"-like symmetry.

Unambigous signals of LFV possible (with no SM background at parton level). Very promising for future searches since BKG only from processes with additional light ν in the final state.

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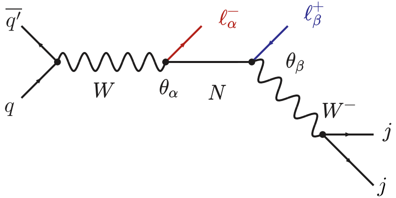

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- BKGs from processes with additional light ν

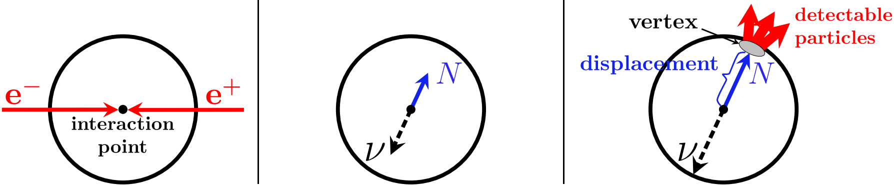
Systematic assessment of heavy neutrino signatures at colliders

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.

No SM background, very promising!

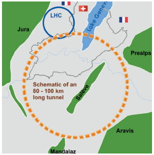
$\mathbf{t = 0}$	$\mathbf{0 < t <}$ **lifetime of** $\boldsymbol{N}$	**lifetime of** $\boldsymbol{N} \mathbf{< t}$
electron-positron collision	production of N and propagation	decay of N into detectable particles



Heavy neutrinos at proton-proton colliders

Large Hadron Collider (LHC):

- 27km ring
- $\sqrt{s}$ =14 TeV



Future Circular Collider (FCC-hh):

- 100km ring
- $\sqrt{s}$ =100 TeV

Heavy ν signatures at pp colliders to 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	$\nu\nu jj$	$\lvert\theta\rvert^2$	×

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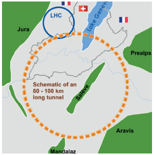

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Heavy ν signatures at pp colliders to leading order:

pp colliders can test all flavour combinations

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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	$\nu\nu jj$	$\lvert\theta\rvert^2$	×

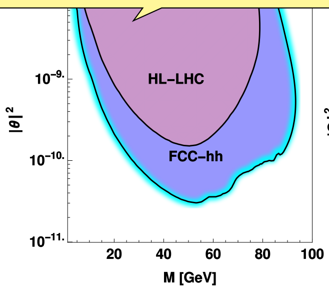
"Same sign dileptons" most studied signature, in SPSS suppressed by the protective "lepton number"-like symmetry.

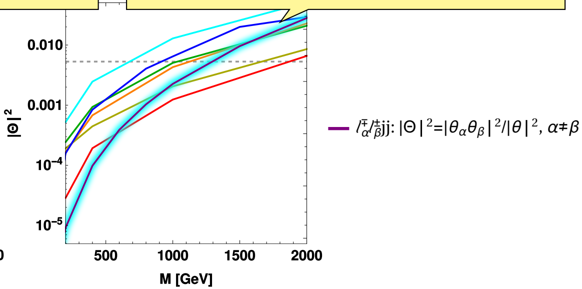
Unambiguous signals for LFV (with no SM background at the parton level).

"First looks" at FCC-hh sensitivities

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

First looks at 1σ sensitivities from heavy ν signatures at the parton level.





The golden channels of the FCC-hh:

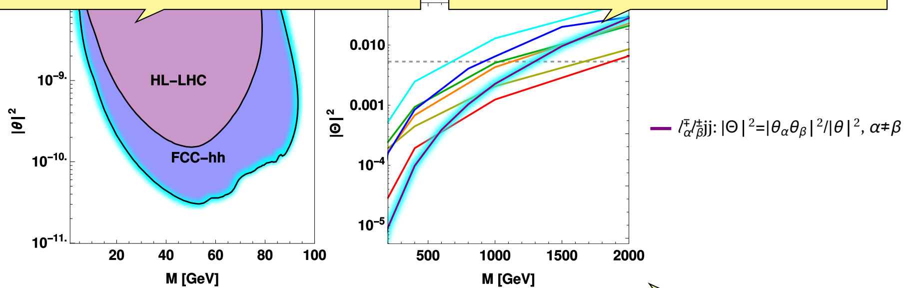
- For $M < 100$ GeV: *Displaced vertex search*
- For $M > 100$ GeV: *LFV signatures*

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

“First looks” at FCC-hh sensitivities

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

First looks at 1σ sensitivities from heavy ν signatures at the parton level.



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

The golden channels of the FCC-hh:

- For $M < 100$ GeV: *Displaced vertex search*
- For $M > 100$ GeV: *LFV signatures*

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

Heavy neutrinos at electron-proton colliders

Large Hadron electron Collider (LHeC):

- Crossing LHC beam with e^- beam
- $\sqrt{s} = 1.0$ TeV

Future Circular Collider (FCC-eh):

- Crossing FCC-hh beam with e^- beam
- $\sqrt{s} = 3.5$ TeV

Heavy ν signatures at $e^- p$ colliders to 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	$j\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

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Future Circular Collider (FCC-eh):

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- $\sqrt{s} = 3.5$ TeV

Heavy ν signatures at $e^- p$ colliders to leading order:

always $|\theta_e|^2$ invovled due to production

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	$j\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

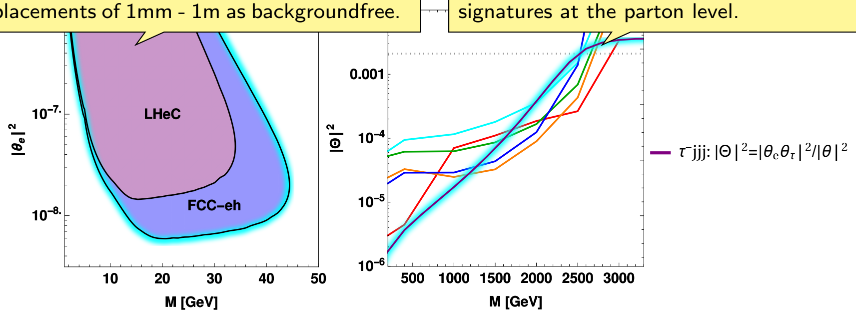
e^+jjj as unambiguous signal of LNV, in SPSS suppressed by the protective "lepton number"-like symmetry.

$\ell_\alpha^- jjj$ 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.

First looks at 1σ sensitivities from heavy ν signatures at the parton level.



The golden channels of the FCC-eh:

- For $M < M_W$: *Displaced vertex searches*
- For $M > M_W$: *LFV signatures*

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

Heavy neutrinos at electron-positron colliders

Large Electron Positron Collider (LEP):

- 27km ring

Future Circular Collider (FCC-ee):

- 100km ring
- high precision: 110 ab^{-1} of data at $\sqrt{s} = 90$ GeV

Heavy ν signatures at e^-e^+ colliders to 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	$\nu\nu\nu\nu$	$\|\theta\|^2$	$\|\theta_e\|^2$

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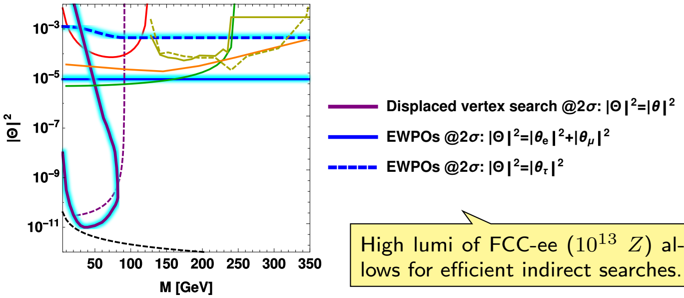
Heavy ν signatures at e^-e^+ colliders to leading order:

Always one light ν in the final state, no unambiguous LNV and LFV signature.

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

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



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

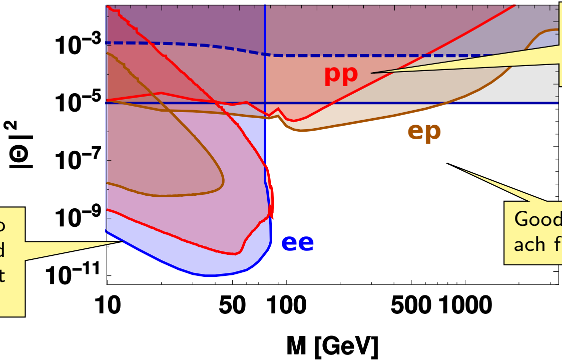
The golden channels of the FCC-ee:

- 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:
  - pp: LFV signatures and displaced vertex search
  - ep: LFV signatures and displaced vertex search
  - e^+e^-: Indirect search via EWPO and displaced vertex search



pp able to test all flavour combinations.

Good sensitivity reach from pp & ep.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at e^+e^-.

Where to best look for heavy neutrinos?

http://belhene.deviantart.com/