Golden channels for heavy neutrino searches at the FCC

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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 ($\nu_R$) in the SM.
- Observation of neutrino oscillations requires at least two of the light neutrinos to be massive.

⇒ Extra terms in the Lagrangian density due to adding $\nu_R$:

$$\mathcal{L}_N = - (Y_\nu)_{i\alpha} \bar{\nu}_R \phi^\dagger L^\alpha - \frac{1}{2} \nu_i \bar{\nu}_R M_{ij} (\nu_j)^c + \text{H.c.}$$

- $\nu$ Yukawa matrix
- sterile $\nu$ mass matrix
The seesaw mechanism

- Naive \((1 \, \nu_L, 1 \, \nu_R)\) version: \(m_\nu = \frac{1}{2} \frac{v_{EW}^2 |y_\nu|^2}{M_R}\)

- More realistic example, the \((2 \, \nu_L, 2 \, \nu_R)\) version:

\[
Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ 0 & \mathcal{O}(y_\nu) \end{pmatrix}, \quad M = \begin{pmatrix} M_R & 0 \\ 0 & M_R(1 + \epsilon) \end{pmatrix}
\]

\[M_R \gg y_\nu v_{EW} \quad \Rightarrow \quad m_{\nu_i} = \frac{v_{EW}^2 \mathcal{O}(y_\nu^2)}{M_R}(1 + \epsilon)\]

\(\Rightarrow\) Knowledge of \(m_{\nu_i}\) implies a relation between \(y_\nu\) and \(M_R\).

\(\Rightarrow\) In general not very promising to observe at collider experiments:

\[M_R \sim 10^2 \text{ GeV} \Rightarrow y_\nu \sim \mathcal{O}(10^{-6})\]
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:

\[
Y_\nu = \begin{pmatrix} O(y_\nu) & 0 \\ O(y_\nu) & 0 \end{pmatrix}, \quad \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}
\]

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

\Rightarrow \text{In general: no fixed relation between } y_\nu \text{ and } M_R.

\Rightarrow \text{Large } y_\nu \text{ are compatible with neutrino oscillations.}

\Rightarrow \text{Allows for testable effects at collider experiments.}
Neutrino parameters landscape

EW scale sterile neutrino models (often similar to latter example)

$\Lambda_{EW}$

$m^2_{\nu} = \Delta m^2_{\text{atm}}$

$m^2_{\nu} = \Delta m^2_{\text{sol}}$

reactor & LSND anomaly
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

$$\mathcal{L}_N = -\frac{1}{2} N_R^1 M (N_R^2)^c - y_{\nu_\alpha} N_R^1 \phi^\dagger L^\alpha + \text{H.c.}$$
Assumption: collider phenomenology dominated by two sterile neutrinos $N_i$ with protective symmetry, such that

$$\mathcal{L}_N = -\frac{1}{2} \overline{N}^\dagger_R M (N^R_R)^c - y_{\nu\alpha} \overline{N}^\dagger_R \phi^\dagger L^\alpha + \text{H.c.} + \ldots$$

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

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

Additional sterile $\nu$ 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 $O(\varepsilon)$ terms), $M$ and $y_{\nu_\alpha}$ ($\alpha = e, \mu, \tau$) are free parameters (not constrained by $m_\nu$).

- Specific models have correlation among the $y_{\nu_\alpha}$.

Strategy of the SPSS: study how to measure the $y_{\nu_\alpha}$ independently in order to test such correlations!
The active-sterile mixing parameter: \( \theta_\alpha = \frac{y^*_\alpha v_{EW}}{\sqrt{2}M} \)

SPSS Parameters:
- \( M \) and \( y_{\nu_\alpha} (\alpha = e, \mu, \tau) \) or
- \( M \) and \( \theta_\alpha (\alpha = e, \mu, \tau) \)
Symmetry Protected Seesaw Scenario

A benchmark model for collider searches with EW scale sterile neutrinos

- The active-sterile mixing parameter: \( \theta_\alpha = \frac{y_{\nu_\alpha} v_{\text{EW}}}{\sqrt{2}M} \)

**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 \( \theta_\alpha \)

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

Sterile \( \nu \) mix with active ones
Symmetry Protected Seesaw Scenario

A benchmark model for collider searches with EW scale sterile neutrinos

- The active-sterile mixing parameter: \( \theta_{\alpha} = \frac{y_{\nu_{\alpha}} v_{EW}}{\sqrt{2} M} \)

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

The active-sterile mixing parameter:

\[
\begin{align*}
U &= \begin{pmatrix}
N_{e1} & N_{e2} & N_{e3} & -\frac{i}{\sqrt{2}} \theta_e & \frac{1}{\sqrt{2}} \theta_e \\
N_{\mu1} & N_{\mu2} & N_{\mu3} & -\frac{i}{\sqrt{2}} \theta_\mu & \frac{1}{\sqrt{2}} \theta_\mu \\
N_{\tau1} & N_{\tau2} & N_{\tau3} & -\frac{i}{\sqrt{2}} \theta_\tau & \frac{1}{\sqrt{2}} \theta_\tau \\
0 & 0 & 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \left(1 - \frac{\theta_e^2}{2}\right) \\
-\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{i}{\sqrt{2}} \left(1 - \frac{\theta_e^2}{2}\right) & \frac{1}{\sqrt{2}} \left(1 - \frac{\theta_e^2}{2}\right)
\end{pmatrix}
\end{align*}
\]

Heavy \( \nu \) (mass eigenstates) participate in weak interaction processes:

- \( W \) or \( Z \) \( \theta_\alpha N \)
- \( h \) \( \theta_\alpha N \)

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Golden channels for heavy neutrinos
CERN, 18 January 2017
Systematic assessment of heavy neutrino signatures at colliders

Different production channels for collider types:

<table>
<thead>
<tr>
<th></th>
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<tr>
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At leading order!
Systematic assessment of heavy neutrino signatures at colliders

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

<table>
<thead>
<tr>
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<th>Decay channel</th>
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<tr>
<td>$W_s$</td>
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$|\theta|^2 = \sum |\theta_\alpha|^2$
Systematic assessment of heavy neutrino signatures at colliders

Production

\[ \begin{align*}
W_s: & \quad X \xrightarrow{\ell_{\alpha}} W \xrightarrow{\theta_{\alpha}} N \\
W_t: & \quad X \xrightarrow{Y} W \xrightarrow{\ell_{\epsilon}} \theta_{\epsilon} N \\
Z_s: & \quad X \xrightarrow{\nu} Z \xrightarrow{\theta_{\epsilon, \theta_{\mu}, \theta_{\tau}}} N \\
h: & \quad X \xrightarrow{\nu} h \xrightarrow{\theta_{\epsilon, \theta_{\mu}, \theta_{\tau}}} N 
\end{align*} \]

Decay

\[ \begin{align*}
\ell_\alpha \rightarrow \ell_\beta \theta_{\beta} N \\
\ell_\beta \rightarrow \gamma W \theta_{\beta} N \\
\nu \rightarrow \gamma Z \theta_{\beta} N \\
\nu \rightarrow h \theta_{\beta} N
\end{align*} \]

Final States

\[ \begin{align*}
pp & : \ell_\alpha \ell_\beta jj, \ell_\alpha \ell_\beta \ell_\gamma \nu \\
e^-e^+, e^-p & : Y \ell_\beta jj, Y \ell_\beta \ell_\gamma \nu \\
e^-e^+, pp & : \nu \ell_\beta jj, \nu \ell_\beta \ell_\gamma \nu \\
pp & : \ell_\alpha \nu jj, \ell_\alpha \nu \ell_\beta \ell_\beta, \ell_\alpha \nu \nu \nu \\
e^-e^+, e^-p & : Y \nu jj, Y \nu \ell_\beta \ell_\beta, Y \nu \nu \nu \\
e^-e^+, pp & : \nu \nu jj, \nu \nu \ell_\beta \ell_\beta, \nu \nu \nu \nu \\
pp & : \ell_\alpha \nu jj, \ell_\alpha \nu \ell_\beta \ell_\beta, \ell_\alpha \nu \nu VV \\
e^-e^+, e^-p & : Y \nu jj, Y \nu \ell_\beta \ell_\beta, Y \nu \nu VV \\
e^-e^+, pp & : \nu \nu jj, \nu \nu \ell_\beta \ell_\beta, \nu \nu \nu VV
\end{align*} \]
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Remarks on LNV:

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

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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.
Systematic assessment of heavy neutrino signatures at colliders

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- Example on unambiguous signals of LNV:
  - @$pp$ : same-sign dilepton $\leftrightarrow \ell_\alpha \ell_\beta jj$
  - @$e^- p$ : lepton-trijet $\leftrightarrow j_\alpha j jj$

Remarks on LFV:

- Example on unambiguous signals of LFV: $\checkmark$,$pp$ : dilepton-dijet $\leftrightarrow \ell_\alpha \ell_\beta \pm j j$
  - with e.g. $\alpha = e$ and $\beta = \mu$

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

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

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- When light $\nu$ are in the final states, difficult to measure LNV since they escape detection. Unambiguous signal of LNV if no light $\nu$ in the final state:
- Example on unambiguous signals of LNV:
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Remarks on LFV:
- Example on unambiguous signals of LFV:
  - $@pp$ : dilepton-dijet $\leftrightarrow \ell^+_{\alpha} \ell^{\pm}_{\beta} jj$ with $e.g. \alpha = e$ and $\beta = \mu$
- Example on unambiguous signals of LFV:
  - $@e^-p$ : lepton-trijet $\leftrightarrow \ell^-_{\alpha} jjj$ with $\alpha \neq e$
- Unambiguous signals for LFV (at the parton level) with light $\nu$ in the final state possible:
  - $@pp$: $\ell_e \ell_\mu \ell_\tau \nu$
  - $@e^-p$: $j \ell^-_\mu \ell^+_e \nu$

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.
Remarks on Displaced Vertex signature:

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

$t = 0$

- Electron-positron collision

$0 < t < \text{lifetime of } N$

- Production of $N$ and propagation

_lifetime of $N < t$

- Decay of $N$ into detectable particles

![Diagram showing the interaction point, electron-positron collision, and displaced vertex with particle decay to detectable particles.](image)
Heavy neutrinos at the FCC-hh

production channel:
\( Z_s \propto |\theta|^2 \)
\( (W_s \propto |\theta_\alpha|^2) \)

Signatures of heavy \( \nu \) for \( pp \) colliders at leading order

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

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| trilepton\((*)\) | \( \ell_\alpha \ell_\beta \ell_\gamma \nu \) | \( \frac{|\theta_\alpha \theta_\beta|^2}{\theta^2} \) | ×/✓     |
| lepton-dijet    | \( \ell_\alpha \nu jj \) | \( |\theta_\alpha|^2 \) | ×       |
| dilepton\((*)\) | \( \ell_\alpha \ell_\beta \nu \nu \) | \( |\theta_\alpha|^2 \) | ×       |
| mono-lepton     | \( \ell_\alpha \nu \nu \nu \) | \( |\theta_\alpha|^2 \) | ×       |
| dijet           | \( \nu \nu jj \) | \( |\theta|^2 \) | ×       |

“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 $\nu$ 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
  - Unambiguous signal for LFV (at the parton level):
    e.g. dilepton-dijet $\ell^+_\alpha \ell^-_\beta jj$ with $\alpha = e$ and $\beta = \mu$

No SM background, very promising!
“First looks” at FCC-hh sensitivities

Displaced vertex search $2\sigma$ sensitivity. Displacements of 1mm - 1m as background free.

Presented first looks for the $1\sigma$ sensitivities of heavy $\nu$ 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;
“First looks” at FCC-hh sensitivities

Displaced vertex search $2\sigma$ sensitivity. Displacements of 1mm - 1m as background-free.

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

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

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 $\nu$. 
Heavy neutrinos at the FCC-eh

Production channel: \( W_t \propto |\theta_e|^2 \)

Signatures of heavy neutrinos for \( e^-p \) colliders at leading order

| Name           | Final State | \(|\theta_\alpha|\) dependency | LNV/LFV   |
|----------------|-------------|-------------------------------|-----------|
| lepton-trijet  | jjj\(\ell_\alpha\) | \(\frac{|\theta_e \theta_\alpha|^2}{\theta^2}\) | ✓/✓       |
| jet-dilepton\( (*)\) | j\(\ell_\alpha^\pm \ell_\beta^\mp \nu\) | \(\frac{|\theta_e \theta_\alpha|^2}{\theta^2}\) | ×/✓       |
| trijet         | jjj\(\nu\)  | \(|\theta_e|^2\)          | ×         |
| monojet        | j\(\nu\nu\nu\) | \(|\theta_e|^2\)          | ×         |
Signatures of heavy $\nu$ for $e^- p$ colliders at leading order

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

$e^+jjj$ 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 $2\sigma$ sensitivity. Displacements of 1mm - 1m as backgroundfree.

Presented first looks for the $1\sigma$ sensitivities of heavy $\nu$ 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 $\nu$ $|\theta_e \theta_\tau|^2/|\theta|^2 \sim 10^{-6}$ reachable

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

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Heavy neutrinos at the FCC-ee

| 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

Signatures of heavy $\nu$ for $e^- e^+$ colliders at leading order

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

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

production channel: $Z_S \propto |\theta|^2$

production channel: $W_t \propto |\theta_e|^2$

Modify $WW$ production

Modifies mono-$Z$, mono-$h$ production

Eros Cazzato (University of Basel)  Golden channels for heavy neutrinos  CERN, 18 January 2017
More heavy neutrino signatures at the FCC-ee

- Indirect searches via EW precision data
  - Mixing matrix of the 3 active $\nu$ ($U_{\text{PMNS}}$) 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
  - Heavy $\nu$ 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.

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

No SM background, very promising!
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:
- $110 \text{ ab}^{-1}$ for $\sqrt{s} = 90$ GeV;
- $5 \text{ ab}^{-1}$ for $\sqrt{s} = 240$ GeV;
- $1.5 \text{ ab}^{-1}$ 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

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

FCC-hh able to test all flavour combinations.

Good sensitivity reach from FCC-hh & FCC-eh.
Where to best look for heavy neutrinos?

http://belhene.deviantart.com/