
Sterile neutrino and singlet Higgs signatures at colliders

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OUTLINE

- Singlet Higgs + sterile neutrino models have many motivations: dark matter, baryogenesis, neutrino masses.
- Bounds on the Higgs sector are relaxed compared to the SM.
- Collider signatures depend on the sterile neutrino mass:
  - Light neutrinos appear as missing energy.
  - Intermediate neutrinos decay with macroscopically displaced vertex with lepton number violation.
  - Heavy neutrinos decay promptly with lepton number violation.
Motivations

- A $\sim$keV sterile neutrino can be dark matter and explain pulsar kicks [Alex Kusenko’s talk].
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Motivations

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- Singlet Higgs allows for the possibility of a 1st order phase transition, making EW baryogenesis possible [Petraki, Kusenko (2008)].
- Neutrinos have mass.
Neutrino masses

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\[ L = L_{SM} + i\bar{N}_a \phi N_a - y_{aa} \epsilon^{ij} H_i \left( \bar{L}_a \right)_j N_a - \frac{M_a}{2} \bar{N}_a^c N_a + \text{h.c.} \]
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- Thus active and sterile neutrinos mass mix via:
  
  \[ \hat{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_a \end{pmatrix} \]
Seesaw mechanism

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- Where does this new scale \( M_a \) come from?
Singlet extended Higgs sector

- Suppose that, like all other SM fermion masses, the RH Majorana mass comes from the Higgs mechanism:
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- DM keV neutrinos will not be produced at colliders.
- Can we find evidence of sterile neutrinos at a collider?
How to produce sterile neutrinos at a collider
Gauge structure of the SM

\[ SU(3) \cap SU(1) \cap SU(2) \]
Gauge structure of the SM
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$\begin{array}{c}
N_a \\
\begin{array}{ccc}
\text{SU}(3) & & \\
\text{SU}(1) & & \text{SU}(2)
\end{array}
\end{array}$
Gauge structure of the SM

- SU(3)
- SU(2)
- SU(1)

$N_a$

Dirac mass
Gauge structure of the SM

$N_a$  $S$

Mass mixing and coupling

SU(3)  SU(1)  SU(2)

d  u  e

$Q$

$W$

$\gamma$

$H$

$Z$
Gauge structure of the SM

Mass mixing and coupling

Yukawa term
Gauge structure of the SM

Yukawa term

Large yukawa couplings + large singlet-doublet Higgs mixing = sterile neutrinos produced at a collider.
Higgs mixing and couplings

- Singlet and doublet Higgses mix:

\[
\begin{pmatrix}
H_1 \\
H_2
\end{pmatrix} = \begin{pmatrix}
\cos \phi_{HS} & \sin \phi_{HS} \\
-\sin \phi_{HS} & \cos \phi_{HS}
\end{pmatrix}
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h \\
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- Where the mixing angle is determined by scalar potential.
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- Where the mixing angle is determined by scalar potential.
- We adopt the convention \( M_{H_2} > M_{H_1} \).
- The couplings to SM and sterile neutrinos now given by:

<table>
<thead>
<tr>
<th></th>
<th>Light Higgs ((H_1))</th>
<th>Heavy Higgs ((H_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs-Neutrino coupling</td>
<td>(g_{1NN} = -if_a \sin \phi_{HS})</td>
<td>(g_{2NN} = -if_a \cos \phi_{HS})</td>
</tr>
<tr>
<td>Higgs-SM coupling</td>
<td>(g_{1SM} = g_{SM} \cos \phi_{HS})</td>
<td>(g_{2SM} = g_{SM} \sin \phi_{HS})</td>
</tr>
</tbody>
</table>
Higgs branching fractions

- With modified Higgs-SM couplings and the introduction of sterile neutrino mode, BR are altered as

- **Light Higgs:**

  \[ Br(H_1 \rightarrow SM) = \frac{g_{1SM}^2 Br(h \rightarrow SM) \Gamma_h}{g_{1SM}^2 \Gamma_h + \Gamma(H_1 \rightarrow N_a N_a)} \]

- **Heavy Higgs:**

  \[ Br(H_2 \rightarrow SM) = \frac{g_{1SM}^2 Br(h \rightarrow SM) \Gamma_h}{g_{1SM}^2 \Gamma_h + \Gamma(H_2 \rightarrow N_a N_a) + \Gamma(H_2 \rightarrow H_1H_1)} \]
Mass mixing determines bounds

1. Small $\sin \phi_{HS}$: $H_1 \approx h$, $H_2 \approx S$.
   - Light Higgs is mostly doublet obeys SM LEP bound.
   - Heavy Higgs is mostly singlet weakened EWPO bound.

2. Maximal mixing: $H_{1,2} = \frac{1}{\sqrt{2}} (h \pm S)$.
   - Light Higgs is mixed weakened LEP bound.
   - Heavy Higgs is mixed weakened EWPO bound.

3. Large $\sin \phi_{HS}$: $H_1 \approx S$, $H_2 \approx h$.
   - Light Higgs is mostly singlet weakened LEP bound.
   - Heavy Higgs is mostly doublet obeys SM EWPO bound.
How to evade the LEP bound

- A SM Higgs is ruled out at 95% CL for $M_h < 114.4 \text{GeV}$.
  - Assumes SM production cross section and SM branching ratios.
- However LEP has non-SM bounds, constrained by the parameter:

\[
\xi^2(H_i \rightarrow X_{SM}) = \left( \frac{\sigma(e^+e^- \rightarrow ZH_i)}{\sigma(e^+e^- \rightarrow Zh_{SM})} \right) \times \frac{\text{Br}(H_i \rightarrow X_{SM})}{\text{Br}(h_{SM} \rightarrow X_{SM})}
\]

- Reduced HZZ coupling and/or reduced SM branching fractions weakens the LEP bound.
LEP bounds are generically relaxed

Maximal mixing reduces LEP bound to $M_{H_1} \sim 45\,\text{GeV}$

$\sin \phi_{HS} = 1/\sqrt{2}$, $M_N = 20\,\text{GeV}$
Electroweak precision observable (EWPO) bounds

- Radiative corrections to the W and Z boson propagators from the scalar sector imply a weakening of EWPO constraints.
- Maximal mixing reduces the EWPO upper bound on the heaviest Higgs to $M_{H_2} \leq 220$ GeV.

[Barger et al. (2007), Profumo, Ramsey-Musolf, Shaughnessy (2007)]
Light Higgs branching ratios

\[
\sin \phi_{HS} = \frac{1}{\sqrt{2}} \quad M_{N_2} = 20\text{GeV} \quad \langle S \rangle = 200\text{GeV}
\]

\[\text{Br}(H_1 \rightarrow \text{ii}) \]

![Graph showing branching ratios as a function of \(M_{H_1}\).]
Sterile neutrino decays

Lepton number violation in all modes.
Displaced vertices

Intermediate neutrino masses $50 \text{GeV} \leq M_{N_2} \leq 150 \text{GeV}$ decay displaced from production region.
Light neutrinos appear as missing energy

\[ qq \rightarrow qqVV \rightarrow qqH \rightarrow qq + \text{inv} \]

- Neutrinos with \( \leq 50\text{GeV} \) decay outside the detector, and appear as missing energy.
- Discoverability of invisibly decaying Higgs assessed in [Eboli, Zeppenfield (2000)].
- When \( Br(H_i \rightarrow N_2N_2) \approx 100\% \), and the Higgs is produced via weak boson fusion appropriate cuts on the correlation of the forward jets allow for a 5\( \sigma \) detection.
Summary

- Extended singlet sector relaxes both direct LEP and indirect EWPO bounds on Higgs masses.
  - Viable models have large NN branching fractions.

- Collider signatures depend on the sterile neutrino mass:
  - Light neutrinos appear as missing energy.
  - Intermediate neutrinos decay with macroscopically displaced vertex with lepton number violation.
  - Heavy neutrinos decay promptly with lepton number violation.
Extra slides
Heavy higgs decays

![Graph showing the decay modes of H2, including bb, NN, gg, TT, cc, WW, ZZ, and tt. The graph displays the BR(H2→ii) against MH2[GeV].]
Sterile neutrino decays

\[ \text{Br}(N_2 \rightarrow ii) \]

Missing energy

Displaced vertices

Prompt decays

Lepton number violation in all modes.
Extended Higgs sector

- The real singlet field has mass mixings and couplings to SM Higgs:

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- For example:
Suppose that, like all other SM fermion masses, the RH Majorana mass comes from the Higgs mechanism:

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Most general potential (assuming no new symmetries):

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Kusenko (2006) has shown that a keV sterile neutrino can be DM and explain pulsar kicks.

Petraki and Kusenko (2008) have shown that S decays can be dominant production mechanism of DM and the presence of S allows for a 1\textsuperscript{st} order EWPT.
Review

- Constraints on the Higgs boson properties from the hep-ph/9703412