Low scale type II seesaw: present constraints and prospect for displaced vertex signature

based on S. Antusch, O. Fischer, A. Hammad, and C. Scherb,

arxiv: 1811.03476

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Outline

1. Type II Seesaw
2. Non-Collider Constraints
3. Collider Signatures
4. Analysis for a Benchmark Point
Type II Seesaw
Scalar sector:

\[ \Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \Delta^+ \\ \frac{\Delta^0}{\sqrt{2}} \\ \Delta^+ \end{pmatrix} \]

\[ \mathcal{L} \supset (D_\mu \Phi)\dagger(D^\mu \Phi) + Tr((D_\mu \Delta)\dagger(D^\mu \Delta)) - V(\Phi, \Delta) - \mathcal{L}_{Yukawa} \]

\[ V(\Phi, \Delta) = -\mu^2 \Phi^\dagger \Phi + M_T^2 Tr(\Delta^\dagger \Delta) + \frac{\lambda}{4} |\Phi^\dagger \Phi|^2 + \lambda_{HT} \Phi^\dagger \Phi Tr(\Delta^\dagger \Delta) + \lambda_T(Tr(\Delta^\dagger \Delta))^2 + \lambda'_T Tr((\Delta^\dagger \Delta)^2) + \lambda'_{HT} \Phi^\dagger \Delta \Delta^\dagger \Phi + (\kappa \Phi^\dagger i\sigma^2 \Delta^\dagger \Phi + h.c.) \quad (1) \]

\[ \mathcal{L}_{Yukawa} = Y_\Delta i\sigma^2 \overline{c} \Delta l + h.c. \quad (2) \]
Masses for the Neutrinos

SSB:

\[
\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix}, \quad \langle \Delta \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ \nu_T & 0 \end{pmatrix}
\]

\[
\mathcal{L}_{Yukawa} = Y_\Delta \frac{\nu_T}{\sqrt{2}} \bar{\nu}^c \nu + h.c.
\]

Seesaw Relation:

\[
\nu_T = \frac{\kappa \nu^2}{\sqrt{2} M_T^2}
\]

Neutrino Masses:

\[
m_\nu = Y_\Delta \sqrt{2} \nu_T = Y_\Delta \frac{\kappa \nu^2}{M_T^2}
\]

\[
(Y_\Delta)_{ij} = \frac{1}{\sqrt{2} \nu_T} U^{\dagger}_{PMNS} m_{\nu}^{diag} U_{PMNS}
\]

Normal hierarchy, \( \delta_{CP} = 0 \)
Masses for the Scalars

- seven physical scalar bosons: $H^{\pm\pm}, H^\pm, h, H$ and $A^0$

\[
m_{H^{\pm\pm}}^2 = \frac{\kappa v^2}{\sqrt{2} v_T} + \frac{\lambda'_{HT} v^2}{2} + \lambda' T v^2_T
\]

\[
m_{H^\pm}^2 = \frac{\kappa v^2}{\sqrt{2} v_T} - \frac{\lambda'_{HT} v^2}{4} - \frac{\lambda'_{HT} v^2_T}{2} + \sqrt{2} \kappa v_T
\]

\[
m_h^2 = \frac{1}{2} (A + C - \sqrt{(A - C)^2 + 4B^2})
\]

\[
m_H^2 = \frac{1}{2} (A + C + \sqrt{(A - C)^2 + 4B^2})
\]

\[
m_{A^0}^2 = \frac{\kappa v^2}{\sqrt{2} v_T} + 2\sqrt{2} \kappa v_T
\]

with $A = -\frac{\lambda}{2} v^2$, $B = -(\lambda_{HT} + \lambda'_{HT})v_T v - \sqrt{2} \kappa v$ and

$C = \frac{\kappa v^2}{\sqrt{2} v_T} - 2(\lambda_T + \lambda'_T) v_T^2$
Non-Collider Constraints
\[ \rho = \frac{m_W^2}{\cos \theta_W m_Z^2} \]

\[ \rho = 1 + \frac{2v_T^2}{v^2} = 1 + \delta \rho \]

\[ \delta \rho = -\frac{|\kappa|^2 \sqrt{2}}{M_T^4 G_F} \]

\[ \Rightarrow v_T < 2.1 \text{ GeV} \]

\[ \Gamma_Z < 2\text{MeV at 95 \% CL} \]

\[ \Rightarrow m_{H^{\pm \pm}} > 42.9 \text{ GeV} \]
can mediate LFV processes like $l_i \rightarrow l_j \gamma$ and $l_i \rightarrow \bar{l}_k l_m l_n$:

$l_i \rightarrow \bar{l}_k l_m l_n$ proportional to $| (Y_\Delta)_{mn} (Y_\Delta)_{ki} |^2 / m_{H_{\pm \pm}}^2$

strongest bound from $Br(\mu \rightarrow \bar{e}ee) < 10^{-12}$ (SINDRUM, 1988)
- measured and predicted value vary about $3\sigma$
- charged scalars contribute to anomalous magnetic moment of muon

\[
| (Y_{\Delta})_{ij} (Y_{\Delta})_{ij} |^2 / m_{H^{\pm\pm}}^2
\]
- contribution from $H^\pm$: $g_{hH^\pm H^\mp} \approx \frac{v^2}{m_{H^\pm}^2} (\lambda_{HT} + \frac{1}{2} \lambda'_{HT})$

- contribution from $H^{\pm\pm}$: $g_{hH^{\pm\pm} H^{\pm\mp}} \approx \frac{v^2}{m_{H^{\pm\pm}}^2} \lambda_{HT}$
Collider Signatures
Production Modes

- focus on $H^{\pm\pm}$
- searches for $H^\pm$ also exist, but are weaker

- cross sections for $\nu_T = 0.1$ GeV, $\lambda'_{HT} = 0$
possible decay channels: $H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$, $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ and $H^{\pm\pm} \rightarrow H^{\pm}W^{\pm}$

for $\lambda_{HT}' \sim 0$: $H^{\pm\pm} \rightarrow H^{\pm}W^{\pm}$ kinematically forbidden

for $\nu_T \gtrsim 10^{-4}$ GeV $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ dominant

for $\nu_T \lesssim 10^{-4}$ GeV and $m_{H^{\pm\pm}} < 160$ GeV: all decay modes small $\Rightarrow$ small decay width $\Rightarrow$ large lifetimes
Lifetime

\[
m_{H^+} = 130 \text{ GeV}
\]

\[
\Gamma = \frac{1}{m_{H^+}} \Gamma_H
\]

\[
\Gamma_{WW} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{TT} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{tot} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{u} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{WW} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{TT} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{tot} = 10^{-10} \text{ GeV}
\]

\[
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\[
\Gamma_{WW} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{TT} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{tot} = 10^{-10} \text{ GeV}
\]

\[
\Gamma_{u} = 10^{-10} \text{ GeV}
\]
searches for $H^{\pm\pm} \rightarrow \ell_i^{\pm} \ell_j^{\pm}$ have been done at LHC, LEP and Tevatron

stringenst bounds arise from LHC measurements, excluding $m_{H^{\pm\pm}} \lesssim 600$ GeV (arxiv:1710.09748, CMS-PAS-HIG-16-036)

prompt is defined as (arxiv: 1412.0237)

$$|z_0 \times \sin \theta| < 1 \text{ mm}$$

$$|d_0| < 0.2 \text{ mm}$$

searches for $H^{\pm\pm} \rightarrow W^\pm W^\pm$ have been done at LHC, excluding the region $200 \leq m_{H^{\pm\pm}} \leq 220$ GeV and $\nu_T \gtrsim 3 \times 10^{-4}$ GeV (arxiv: 1808.01899)
- In the from prompt searches excluded region non-prompt decays happen
- Only events fulfilling the promptness criteria

![Graph](image-url)
Search for Long-lived $H^{±±}$

- searches for HSCPs have been done at LHC, Tevatron and LEP
- in most analyses particles are assumed to decay outside the detector
- probability for decays in a certain range
  \[ P(x_1, x_2) = e^{-\frac{x_1}{x_{lab}}} - e^{-\frac{x_2}{x_{lab}}} \]
- tracker-only analysis for doubly charged fermion-like particles (arxiv:1609.08382)
- significant number of events inside the tracker

- tracker-only analysis of charged scalars would be desirable
Analysis for a Benchmark Point
- benchmark point: $v_T = 5 \times 10^{-4}$ GeV, $m_{H^{\pm\pm}} = 130$ GeV, $\lambda'_{HT} = 0$, $cT \approx 1$ cm
- LHC with 13 TeV, 100 fb$^{-1}$
- HL-LHC with 14 TeV, 3000 fb$^{-1}$
- FCC-hh with 100 TeV, 20 ab$^{-1}$
<table>
<thead>
<tr>
<th>Cuts</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected events (detector level)</td>
<td>280</td>
<td>10640</td>
<td>345323</td>
</tr>
<tr>
<td>Two same sign muons</td>
<td>220</td>
<td>8135</td>
<td>244050</td>
</tr>
<tr>
<td>$P_T(\mu) &gt; 25$ GeV &amp; $</td>
<td>\eta(\mu)</td>
<td>&lt; 2.5$ &amp; $\Delta R(\mu, \mu) &gt; 0.2$</td>
<td>180</td>
</tr>
<tr>
<td>$110$ GeV $&lt; m_{H\pm\pm} &lt; 150$ GeV</td>
<td>175</td>
<td>6332</td>
<td>203586</td>
</tr>
<tr>
<td>$L_{xy} &gt; 8$ mm</td>
<td>76</td>
<td>2749</td>
<td>105864</td>
</tr>
<tr>
<td>$d_0 &gt; 4$ mm</td>
<td>13.6</td>
<td>467</td>
<td>31759</td>
</tr>
</tbody>
</table>
- minimal model for neutrino masses with interesting phenomenology
- wide part of well motivated parameter space is unconstrained
- no searches for the displaced same-sign dilepton signature
- already in the current data \( \sim 13 \) events could be found
- collider searches would be desirable
Backup Slides
bounds from $\mu \rightarrow e\gamma$, $\mu \rightarrow \bar{e}ee$ and muon anomalous magnetic moment
mean Lorentz factor from simulations and probability for decays outside the detector (after $\sim 11$ m)
Collider Constraints

taken from arxiv: 1901.05269
\[ \Gamma(H^{\pm\pm} \rightarrow W^\pm W^{\pm*} \rightarrow W^\pm f \bar{f}') = \frac{g^6 v_T^2 m_{H^{\pm\pm}}}{6144 \pi^3 m_{W^\pm}^2} \left( 3 + N_C \sum_{q,q'} |V_{q,q'}|^2 \right) \frac{F\left( \frac{m_{W^\pm}^2}{m_{H^{\pm\pm}}^2} \right)}{F\left( \frac{m_{W^\pm}^2}{m_{H^{\pm\pm}}^2} \right)} \]

\[ \Gamma(H^{\pm\pm} \rightarrow l_i^\pm l_j^\pm) = \frac{|Y_{\Delta ij}|^2}{4\pi (1 + \delta_{ij})} m_{H^{\pm\pm}} \]

\[ F(x) = 47x^2 - 60x + 15 - \frac{2}{x} - 3(4x^2 - 6x + 1) \log x + \frac{6(20x^2 - 8x + 1)}{\sqrt{4x - 1}} \arccos\left( \frac{3x - 1}{2x^{3/2}} \right) \]
Plots before Cuts

- Track $d_0$ [mm]
  - Events / mm
  - FCC-hh
  - HL-LHC
  - LHC

- Track $P_T$ [GeV]
  - Events / GeV
  - FCC-hh
  - HL-LHC
  - LHC

- M($\mu\mu$) [GeV]
  - Events / GeV
  - FCC-hh
  - HL-LHC
  - LHC

- Track $L_{xy}$ [mm]
  - Events / mm
  - FCC-hh
  - HL-LHC
  - LHC