Scotogenic Model: Phenomenological Constraints and Mono-Higgs Search

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Introduction

• After the Higgs discovery $m_h = 125.09$ GeV, there are still unanswered questions: DM, $\nu$-mass, EW scale origin, Strong CP pb, Dark energy, BAU, Inflation ... etc.

• Neutrino oscillation data & Dark Matter and other problems require SM extension: larger gauge symmetry (LR, SU(5) etc), adding extra fields to SM .. etc.

• Small neutrino mass can be addressed via seesaw mechanism(s) or via radiative models.

• In radiative $\nu - DM$ models (SM+extra fields), many theoretical & experimental constraints should be fulfilled: vacuum stability, unitarity, perturbativity, EWPT, LFV, $h \to \gamma\gamma$, relic density, direct detection ... etc.

• Two $\nu - DM$ models models where DM candidate is a Majorana singlet are presented: (1) Standard scotogenic (SSm), and (2) a scale invariant scotogenic model (SI-Sm). Some collider signatures are investigated.
Scotogenic Models with Majorana DM

Here the SM is extended by an inert scalar doublet $\Phi$ and three singlet Majorana fermions $N_i \sim (1, 1, 0)$, with new Yukawa interactions $[\text{Ma2006}]$:

$$\mathcal{L} \supset \{ h_{ij} \bar{L}_i \epsilon \Phi N_j + \frac{1}{2} M_i \bar{N}_i^C N_i + h.c. \} - \mu_2^2 |\Phi|^2$$

$$+ \frac{\lambda_2}{6} |\Phi|^4 + \lambda_3 |H|^2 |\Phi|^2 + \frac{\lambda_4}{2} |H^\dagger \Phi|^2 + \frac{\lambda_5}{4} \left[(H^\dagger \Phi)^2 + h.c. \right],$$

The tree-level masses are given by:

$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2} \lambda_3 \nu^2, \quad m_{H^0, A^0}^2 = m_{H^\pm}^2 + \frac{1}{4} (\lambda_4 \pm \lambda_5) \nu^2.$$ 

These interactions lead to the one-loop neutrino mass diagram

$$\left(\mathcal{M}_\nu\right)_{\alpha \beta} = \sum_k \frac{h_{\alpha k} h_{\beta k} M_k}{16\pi^2} \left[ \frac{m_{H^0}^2}{m_{H^0}^2 - M_k^2} \ln \frac{m_{H^0}^2}{M_k^2} - \frac{m_{A^0}^2}{m_{A^0}^2 - M_k^2} \ln \frac{m_{A^0}^2}{M_k^2} \right].$$
Scotogenic Models with Majorana DM

This model (SI-Sm) is a scale invariant generalization of the scotogenic model, where a new real singlet scalar \( S \sim (1, 1, 0) \) is added in order to assist radiative EWSB,

\[
\mathcal{L} \supset -\frac{y_i}{2} S \overline{N_i^c} N_i - \left\{ \frac{\lambda_S}{4} S^4 + \frac{\lambda_{SH}}{2} S^2 |H|^2 + \frac{\lambda_S\Phi}{2} S^2 |\Phi|^2 \right\}.
\]

- The parameters \( \lambda_H, \lambda_S \) and \( \lambda_{SH} \) are eliminated in favor of tadpole conditions and the Higgs mass \( h_1 \).
- In this setup, we have \( \lambda_{SH} < 0 \), and therefore the EWSB gets broken radiatively \( \langle h \rangle \equiv v \neq 0 \) and \( \langle S \rangle \equiv x \neq 0 \), then all the fields get masses including \( \{h, S\} \Rightarrow \{h_1 = Higgs, h_2 = Dilaton\} \).
- Radiative corrections (especially the interactions of \( \lambda_{H\Phi} \) and \( \lambda_{S\Phi} \)) dictate EWSB and the values of \( m_{h_1,2} \) and the tiny mixing \( \sin \theta \).
Experiemental Constraints

Due to new fields & interactions, we have to consider the following constraints:

- Vacuum stability, unitarity, perturbativity, decay width of $W$ ($m_W < m_{H^\pm} + m_{H^0}$, $m_{H^\pm} + m_{A^0}$) and $Z$ ($m_Z < m_{H^0} + m_{A^0}$, $2m_{H^\pm}$) etc. (both models)
- LFV, mainly $\ell_\alpha \rightarrow \ell_\beta + \gamma$ and $\ell_\alpha \rightarrow \ell_\beta \ell_\beta \ell_\beta$. (both models)
- Electroweak precision tests, ( $\Delta S$, $\Delta T$). (both models)
- The Higgs decay channel $h \rightarrow \gamma \gamma$. (both models)
- Higgs invisible decay; $h_1 \rightarrow N_iN_k$, $h_2h_2$. (only SI-Sm)
- OPAL (LEP) constraints on the dilation production. (only SI-Sm)
- Constraints on the Higgs-dilation mixing due to gauge couplings measurements. (only SI-Sm)
Dark Matter: relic density

In both models, the lightest RH neutrino $N_1$ is the DM candidate, and it has the following annihilation channels:

**SSm:**

$N_1 N_1 \rightarrow \ell^- \ell^+ , \nu_\alpha \bar{\nu}_\beta$.

**SI-Sm:**

$N_1 N_1 \rightarrow \ell^- \ell^+ , \nu_\alpha \bar{\nu}_\beta , b \bar{b} , t \bar{t} , W^+ W^-, ZZ, \Phi \Phi, h_i h_k$.

At the freeze-out, the relic density is given as

$$\Omega_{N_1} h^2 \sim \frac{(1.07 \times 10^9) x_F}{\sqrt{g^* M_{pl}} \langle \sigma (N_1 N_1) v_r \rangle},$$

Dark Matter: direct detection

In both models, the lightest RH neutrino $N_1$ couples to the quarks, and the nucleon-DM elastic cross section is given by

$$\sigma_{\text{det}} = c_{hNN}^2 \frac{M_{N'}^2 (M_N - \frac{7}{9} M_B)^2}{\pi (M_{N_1} + M_B)^2} \left[ \frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2} \right]^2.$$

Here, $M_N$ is the nucleon mass and $M_B$ the baryon mass in the chiral limit. This has to be compared with recent results by DD experiments. Here, the $hN_1\bar{N}_1$ coupling is:

**SSm:**

\[ \Phi \]
\[ \Phi \]
\[ h \]
\[ l \]
\[ N_1 \]
\[ L_\alpha \]
\[ N_1 \]

**Sl − Sm:**

\[ c_{hNN} \sim y_i \sin \theta \cos \theta \]
Parameters Space: SSs

\[ \Delta T \]

\[ \Delta S \]

\[ \lambda_5 \]

\[ m_{H^\pm} \]

\[ m_{H^0} \]

\[ \sigma_{\text{det}} \] (cm\(^2\))

\[ M_{\text{DM}} \] (GeV)

\[ \tau \rightarrow \mu \gamma \]

\[ \tau \rightarrow e \gamma \]

\[ \mu \rightarrow e \gamma \]

\[ \tau \rightarrow 3e \]

\[ \tau \rightarrow 3\mu \]

\[ \text{XENON1T Neutrino Coherent Scattering} \]
Parameters Space: SI-Sm
Mono-Higgs signature

Ferminonic DM implies that $\lambda_3 + \lambda_4 \pm \lambda_5$ are not subject of either relic density or direct detection, then different phenomenolgy than IHDM.

We consider (quasi-)degenerate spectrum $\lambda_4 \sim \lambda_5 \sim 0$ for two reasons: (1) this scenario is possible within both two scotogenic models, and (2) it avoids the constraints from collider searches which strongly affect the model in the general case.

We consider the monoHiggs case $pp \rightarrow H + (E_{\text{miss}} = H^0, A^0, N_i)$.
Mono-Higgs signature

In order to see the effect of new Yukawa interactions, we consider two scenarios: (1) $h \sim O(10^{-2})$ and (2) $h \sim O(1)$.

LEP constraints

The following results are obtained due the charginos searches at LEP, and the neutralinos are irrelevant since $A^0 \rightarrow H^0 Z \rightarrow H^0 \ell\ell$ is forbidden.
LHC constraints

We consider

\[ m_{N_2} = m_{N_1} + 1\%, \]
\[ m_{N_3} = m_{N_1} + 2\%. \]

\[
\begin{pmatrix}
-60.86 - i0.20 \\
25.14 - i0.57 \\
3.70 + i0.62
\end{pmatrix},
\begin{pmatrix}
-0.30 - i0.80 \\
-1.12 - i2.49 \\
1.10 + i3.88
\end{pmatrix},
\begin{pmatrix}
14.49 - i0.75 \\
40.87 + i0.24 \\
-44.20 + i0.14
\end{pmatrix}
\]

ATLAS and CMS searches that were used to constraint the model using CheckMate.
Cut flow for $H \rightarrow \gamma\gamma$ final state at the LHC for $m_{H^0} = 100$ GeV for 3 ab$^{-1}$ of luminosity.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$gg \rightarrow H$</th>
<th>$W^\pm H$</th>
<th>$ZH$</th>
<th>$Z\gamma$</th>
<th>BP1</th>
<th>$S/B$</th>
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</thead>
<tbody>
<tr>
<td>Initial events</td>
<td>385000</td>
<td>3486</td>
<td>1569</td>
<td>78000</td>
<td>3194</td>
<td>6.82 $\times$ 10$^{-3}$</td>
</tr>
<tr>
<td>lepton veto</td>
<td>184220</td>
<td>915</td>
<td>711</td>
<td>36099</td>
<td>728</td>
<td>0.0038</td>
</tr>
<tr>
<td>$p_T^\gamma &gt; 30$ GeV</td>
<td>177403</td>
<td>865</td>
<td>679</td>
<td>11976</td>
<td>672</td>
<td>0.0035</td>
</tr>
<tr>
<td>$115 &lt; m_{\gamma\gamma}$/GeV $&lt; 135$</td>
<td>177062</td>
<td>831</td>
<td>676</td>
<td>955</td>
<td>672</td>
<td>0.0037</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 150$ GeV</td>
<td>110</td>
<td>62</td>
<td>104</td>
<td>54</td>
<td>258</td>
<td>0.78</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 350$ GeV</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>40</td>
<td>2.66</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 14$ TeV
Mono-Higgs signature

14 TeV

![Graphs showing mono-Higgs signature at 14 TeV](image)

100 TeV

![Graphs showing mono-Higgs signature at 100 TeV](image)

\[ S_{E_T^{\text{miss}}} = \frac{E_{\text{miss}}^{\text{miss}}}{\sqrt{\sum_i E_{T,i}^{\text{vis}}}} > 7 \]
Conclusion

- Both $\nu$-mass & DM can be addressed in scotogenic models without being in conflict with different constraints: LFV, $h \to \gamma\gamma$, $h \to inv$, EWPT .. etc.
- In scotogenic models, $\Omega h^2$ can be achieved for a significant part of the parameter space, where DD bounds can be easily avoided.
- In the compressed scotogenic scenario $m_{H^\pm} \sim m_{H^0} \sim m_{A^0}$, LEP and LHC exclusions are easily avoided, and rich phenomenology different than the IHDM does exist.
- Possible probe of this scenario at HL-LHC and at future 100 TeV colliders.

Thank you for your attention.