Scotogenic Model: Phenomenological Constraints and Mono-Higgs Search

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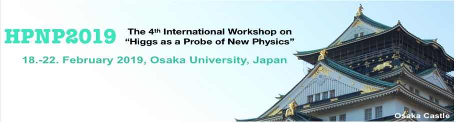


In collaboration with: A. Arhrib, A. Jueid, K. McDonald & S. Nasri.
Based on: JHEP1606(2016)182, PRD97(2018)095012, arXiv:1811.00490 [hep-ph].

Outline

Introduction

- After the Higgs dicovery $m_h = 125.09\ GeV$, there are still unanswered questions: DM, ν-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 & experiemental constraints should be fulfilled: vaccum stabilty, 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 Ma2006 (SSm), and (2) a scale invariant scotogenic model (SI-Sm). Some collider signatures are investigated.

Scotogenic Models with Majorana DM

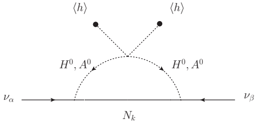
Here the SM is extended by an inert scalar doublet Φ and three singlet Majorana fermions $N_i \sim (1,1,0)$, with new Yukawa interactions [Ma2006]:

$$\begin{aligned}\mathcal{L} &\supset \{h_{ij}\bar{L}_i\epsilon\Phi N_j + \frac{1}{2}M_i\bar{N}_i^C N_i + h.c.\} - \mu_2^2|\Phi|^2 \\ &+ \frac{\lambda_2}{6}|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \frac{\lambda_4}{2}|H^\dagger\Phi|^2 + \frac{\lambda_5}{4}\left[(H^\dagger\Phi)^2 + h.c.\right],\end{aligned}$$

The tree-level masses are given by:

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

These interactions lead to the one-loop neutrino mass diagram



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

Scotogenic Models with Majorana DM

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

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

- The parameters λ_H, λ_S and λ_{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 $\ell_\alpha \to \ell_\beta + \gamma$ and $\ell_\alpha \to \ell_\beta \ell_\beta \ell_\beta$. (both models)
- Electroweak precision tests, (ΔS, ΔT). (both models)
- The Higgs decay channel $h \to \gamma\gamma$. (both models)
- Higgs invisible decay; $h_1 \to N_i N_k, h_2 h_2$. (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

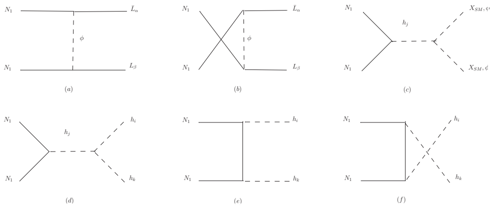
In both models, the lightest RH neutrino N_1 is the DM candidate, and it has the following annihilation channels:

SSm:

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

SI-Sm:

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



At the freeze-out, the relic density is given

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

and the thermally averaged annihilation cross section is estimated as in (Jungman et al. Phys. Rept. 267 (1996) 195).

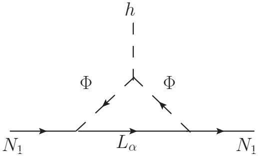
Dark Matter: direct detection

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

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

Here, $M_{\mathcal{N}}$ is the nucleon mass and $M_{\mathcal{B}}$ 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:

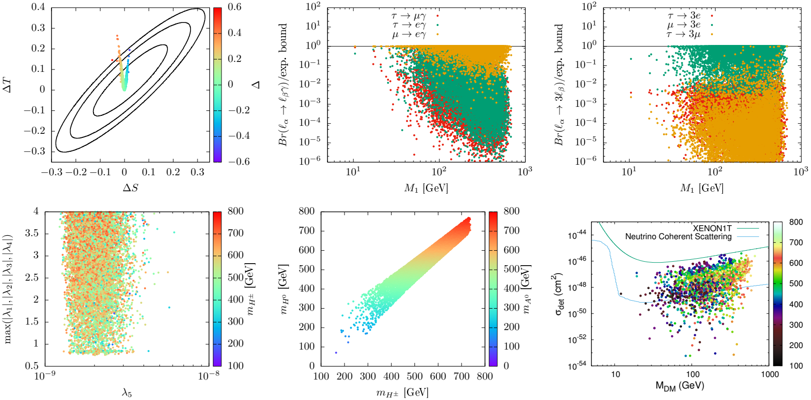
SSm:



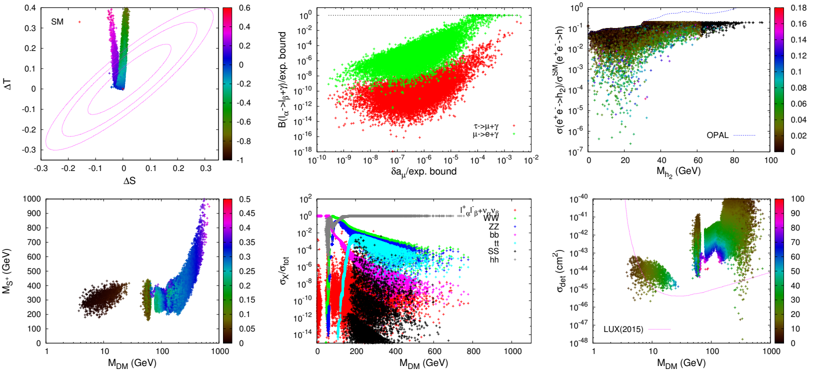
SI − Sm:

$$c_{hNN} \sim y_i \ \sin\theta \ \cos\theta$$

Parameters Space: SSm



Parameters Space: SI-Sm

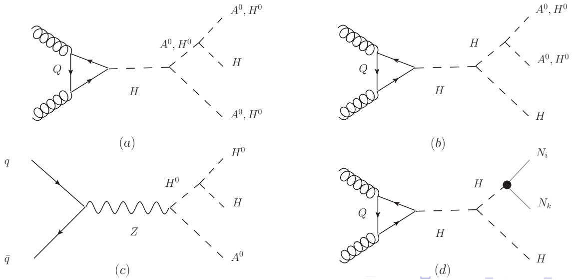


Mono-Higgs signature

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 $pp \to H + (E_{miss} = H^0, A^0, N_i)$.

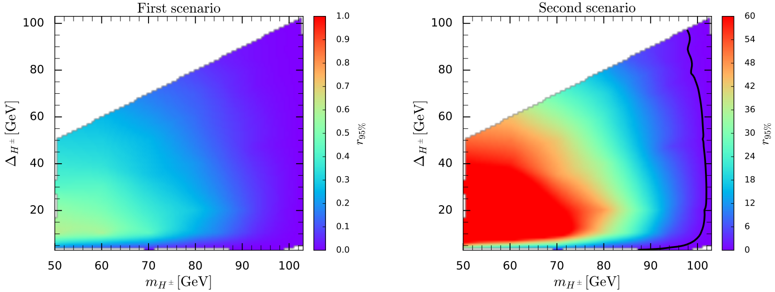


Mono-Higgs signature

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 $A^0 \to H^0 Z \to H^0 \ell\ell$ is forbidden.



Mono-Higgs signature

LHC constraints

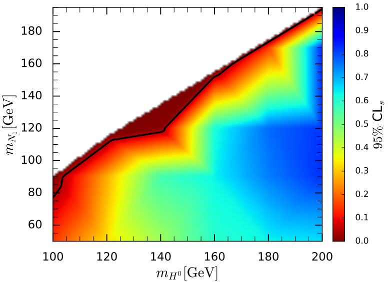
We consider

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

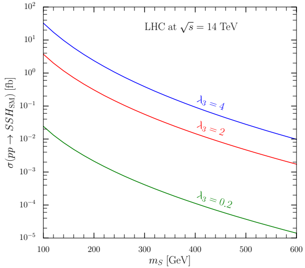
$$h_{ij}/10^{-2} = \begin{pmatrix} -60.86 - i0.20 & -0.30 - i0.80 & 14.49 - i0.75 \\ 25.14 - i0.57 & -1.12 - i2.49 & 40.87 + i0.24 \\ 3.70 + i0.62 & 1.10 + i3.88 & -44.20 + i0.14 \end{pmatrix}$$

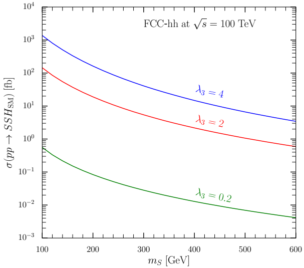
Analysis	Experiment	Luminosity (fb^{-1})	Reference
*atlas_conf*_2016_050	ATLAS	13.3	ATLAS:2016ljb
*atlas_conf*_2016_066	ATLAS	13.3	ATLAS:2016fks
*atlas_conf*_2016_076	ATLAS	13.3	ATLAS:2016xcm
*atlas_conf*_2017_060	ATLAS	36.1	ATLAS:2017dnw
*atlas*_1704_03848	ATLAS	36.1	Aaboud:2017dor
*atlas*_1709_04183	ATLAS	36.1	Aaboud:2017ayj
*atlas*_1712_02332	ATLAS	36.1	Aaboud:2017vwy
*atlas*_1712_08119	ATLAS	36.1	Aaboud:2017leg
*atlas*_1802_03158	ATLAS	36.1	Aaboud:2018doq
*cms_sus*_16_025	CMS	12.9	CMS:2016zvj
*cms_sus*_16_039	CMS	35.6	Sirunyan:2017lae
*cms_sus*_16_048	CMS	35.9	Sirunyan:2018iwl

ATLAS and CMS searches that were used to constraint the model using CheckMate.



Mono-Higgs signature





Cut flow for $H \to \gamma\gamma$ final state at the LHC for $m_{H^0} = 100$ GeV for 3 ab^{-1} of luminosity.

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

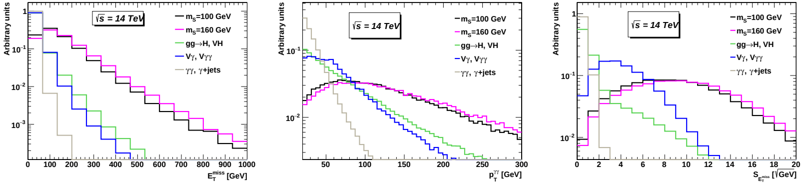
$\sqrt{s} = 14$ TeV

Cuts	$gg \to H$	$W^\pm H$	ZH	$Z\gamma\gamma$	BP1	S/B
Initial events	5.825×10^6	37785	22032	804000	38276	0.0057
lepton veto	2572710	11133	7425	574184	17530	0.0055
$p_T^\gamma > 40$ GeV	2443692	10456	6978	180455	14268	0.0054
$115 < m_{\gamma\gamma}/\text{GeV} < 135$	2438864	10361	6934	14560	14192	0.0030
$E_T^{miss} > 200$ GeV	4959	189	322	1274	7417	1.0997
$E_T^{miss} > 600$ GeV	37	1	4	6	615	12.8125

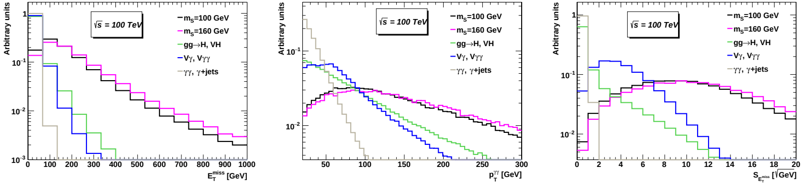
$\sqrt{s} = 100$ TeV

Mono-Higgs signature

14 *TeV*



100 *TeV*



$$S_{E_T^{miss}} = \frac{E^{miss}}{\sqrt{\sum_i E_{T,i}^{vis}}} > 7$$

Conclusion

- Both ν-mass & DM can be addressed in scotogenic models without being in coflict with different constraints: LFV, $h \to \gamma\gamma$, $h \to inv$, EWPT .. etc.
- In scotogenic models, Ωh^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 phenomenolgy different than the IHDM does exist.
- Possible probe of this scenrio at HL-LHC and at future 100 TeV colliders.

Thank you for your attention.