Dark Matter, Neutrino Mass, Gravitational Waves via Singlet Scalars

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Outline

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Model: Motivation & Description

- 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, enlarging spacetime, or exotic ideas (SUSY, HPGB) .. 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.
- Here, our model : Scotogenic model with Majorana DM: IDM $+ 3\ N_i$.

Model: Motivation & Description

Schotogenic Model with Majorana DM:

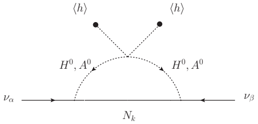
Here, the SM is extended by an inert scalar doublet Φ and three singlet Majorana fermions $N_i \sim (1,1,0)$, with new Yukawa interactions [Ma2006]:

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

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



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

Theoretical & Experiemental Constraints

- Gauge bosons decay widths:

  $$\mathrm{m}_{H^0}+m_{A^0}>M_Z\ ,\ m_{H^\pm}+m_{A^0}>M_W,\ 2m_{H^\pm}>M_Z\ ,\ m_{H^\pm}+m_{H^0}>M_W.$$

- LFV processes:

  $$Br(\ell_\alpha\to\ell_\beta+\gamma)=\frac{3\alpha\upsilon^4}{32\pi m_{H^\pm}^4}\left|\sum_{i=1}^{3}h_{\beta i}^{*}h_{\alpha i}F\left(M_i^2/m_{H^\pm}^2\right)\right|^2,\ (1)$$

  We considered also the constraints on $B(\ell_\alpha\to\ell_\beta\ell_\beta\ell_\beta)$.

- EW precision tests: the oblique parameters can be written as

  $$\Delta T=\frac{1}{16\pi s_{\mathrm{w}}^2M_W^2}\left\{F\left(m_{H^0}^2,m_{H^\pm}^2\right)+F\left(m_{A^0}^2,m_{H^\pm}^2\right)-F\left(m_{H^0}^2,m_{A^0}^2\right)\right\},$$

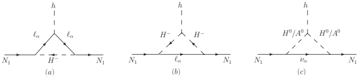
  $$\Delta S=\frac{1}{24\pi}\left\{\left(2s_{\mathrm{w}}^2-1\right)^2G\left(m_{H^\pm}^2,m_{H^\pm}^2,M_Z^2\right)+G\left(m_{H^0}^2,m_{A^0}^2,M_Z^2\right)+\ln\left(\frac{m_{H^0}^2m_{A^0}^2}{m_{H^\pm}^4}\right)\right\},$$

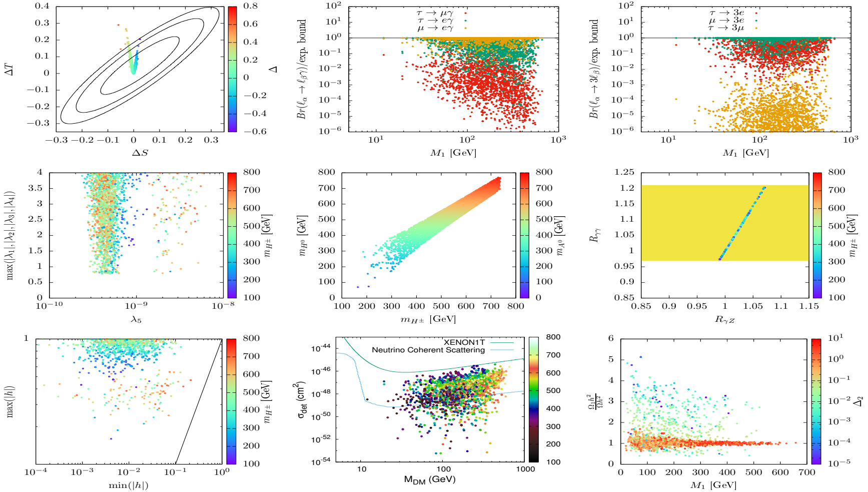
- The ratio $R_{\gamma\gamma}$: ATLAS and CMS collaborations: $R_{\gamma\gamma} := \mathcal{B}(h \to \gamma\gamma)/\mathcal{B}(h \to \gamma\gamma)^{SM} = 1.09 \pm 0.12$, then in our model, we have

$$R_{\gamma\gamma} = \left| 1 + \frac{\lambda_3 \upsilon^2}{2 m_{H^\pm}^2} \frac{A_0^{\gamma\gamma}\left(\frac{m_h^2}{4 m_{H^\pm}^2}\right)}{A_1^{\gamma\gamma}\left(\frac{m_h^2}{4 M_W^2}\right) + N_c Q_t^2 A_{1/2}^{\gamma\gamma}\left(\frac{m_h^2}{4 m_t^2}\right)} \right|^2, \qquad (2)$$

- Dark matter relic density: In this model, we have 2 annihilation channels $N_1 N_1 \to \ell^+ \ell^-, \nu\bar{\nu}$. We followed Jungman1995 to estimate the relic density and the freezze out. Also, the co-annihilation effect $N_1 N_{2,3}$ is considered since Majorana mass degeneracy is favored.
- Dark matter direct detection:

$$\sigma_{det}(N_1 + \mathcal{N} \to N_1 + \mathcal{N}) = \frac{\tilde{y}_{hN_1N_1}^2 (m_{\mathcal{N}} - \frac{7}{9} m_{\mathcal{B}}) m_{\mathcal{N}}^2 M_1^2}{4\pi \upsilon^2 m_h^4 (m_{\mathcal{N}} + M_1)^2},$$



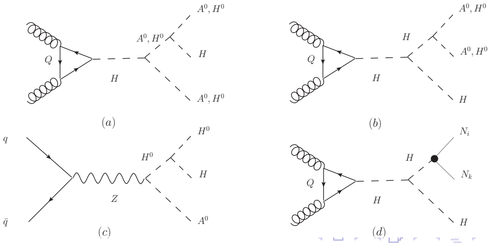

ΔT
ΔS
Δ
$\tau \to \mu\gamma$
$\tau \to e\gamma$
$\mu \to e\gamma$
$Br(\ell_\alpha \to \ell_\beta\gamma)$/exp. bound
M_1 [GeV]
$\tau \to 3e$
$\mu \to 3e$
$\tau \to 3\mu$
$Br(\ell_\alpha \to 3\ell_\beta)$/exp. bound
M_1 [GeV]
$\max(|\lambda_1|, |\lambda_2|, |\lambda_3|, |\lambda_4|)$
λ_5
$m_{H^\pm}$ [GeV]
m_{H^0} [GeV]
$m_{H^\pm}$ [GeV]
m_{A^0} [GeV]
$R_{\gamma\gamma}$
$R_{\gamma Z}$
$m_{H^\pm}$ [GeV]
max(|h|)
min(|h|)
$m_{H^\pm}$ [GeV]
XENON1T
Neutrino Coherent Scattering
σ_{det} (cm^2)
M_{DM} (GeV)
$\frac{\Omega_1 h^2}{\Omega h^2}$
M_1 [GeV]
Δ_2

Mono-Higgs signature

- We have interesting signatures such as:

Process	Decay mode	signature
$pp, e^+e^- \to H^\pm H^\mp$	$H^\pm \to W^\pm H^0/A^0 \to q_1\bar{q}_2N_1\nu_\ell,\ H^\mp \to W^\mp H^0/A^0 \to q_3\bar{q}_4N_1\bar{\nu}_\ell$	$4\ \text{jets} + \not{E}_T$
	$H^\pm \to W^\pm H^0/A^0 \to \ell^\pm\nu_\ell N_1\nu_\ell,\ H^\mp \to W^\mp H^0/A^0 \to q_3\bar{q}_4N_1\bar{\nu}_\ell$	$1\ell + 2\ \text{jets} + \not{E}_T$
	$H^\pm \to W^\pm H^0/A^0 \to \ell_1^\pm\nu_\ell N_1\nu_\ell,\ H^\mp \to W^\mp H^0/A^0 \to \ell_2^\mp\bar{\nu}_\ell N_1\nu_\ell$	$2\ell + \not{E}_T$
	$H^\pm \to W^\pm H^0/A^0 \to \ell_1^\pm\nu_\ell N_1\nu_\ell,\ H^\mp \to \ell_2^\mp N_1$	$2\ell + \not{E}_T$
	$H^\pm \to W^\pm H^0/A^0 \to q_1\bar{q}_2N_1\nu_\ell,\ H^\mp \to \ell^\mp N_1$	$1\ell + 2\ \text{jets} + \not{E}_T$
$pp, e^+e^- \to H^\pm H^0/A^0$	$H^\pm \to W^\pm H^0/A^0 \to q_1\bar{q}_2N_1\nu_\ell,\ H^0 \to N_1\nu_\ell$	$1\ell + 2\ \text{jets} + \not{E}_T$
	$H^\pm \to W^\pm H^0/A^0 \to \ell_1^\pm\nu_\ell N_1\nu_\ell,\ H^0 \to N_1\nu_\ell$	$1\ell + \not{E}_T$
$pp, e^+e^- \to H^0H^0$	$H^0 \to N_1\nu_\ell$	$\not{E}_T +$ ISR (mono-jet, mono-γ)
$e^+e^- \to N_1N_1\gamma$	stable final state	$\not{E}_T + \gamma$

- Ferminonic DM implies that $\lambda_{L,A} = \lambda_3 + \lambda_4 \pm \lambda_5$ are not subject of either relic density or direct detection, and since $A^0(H^0) \to N_i\nu_\alpha$, then they behaves as DARK scalars at colliders.

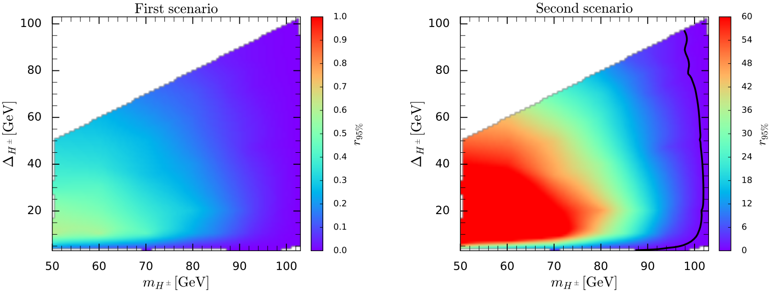


Mono-Higgs signature

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

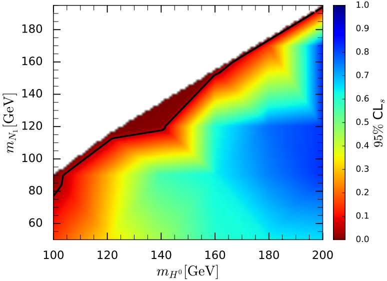
We consider

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

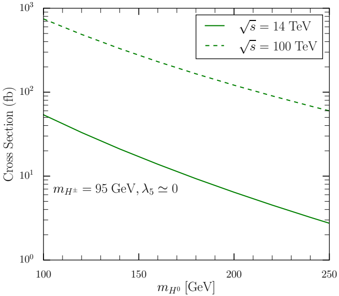
$$h_{ij}/10^{-2} = \begin{pmatrix} -60.86 - i0.20 & -0.30 - i0.80 & 14.49 - i0.75 \\ 25.14 - i0.57 & -1.12 - i2.49 & 40.87 + i0.24 \\ 3.70 + i0.62 & 1.10 + i3.88 & -44.20 + i0.14 \end{pmatrix}$$

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 $H \to \gamma\gamma$ at the LHC for $m_{H^0} = 100$ GeV for 3 ab^{-1}.

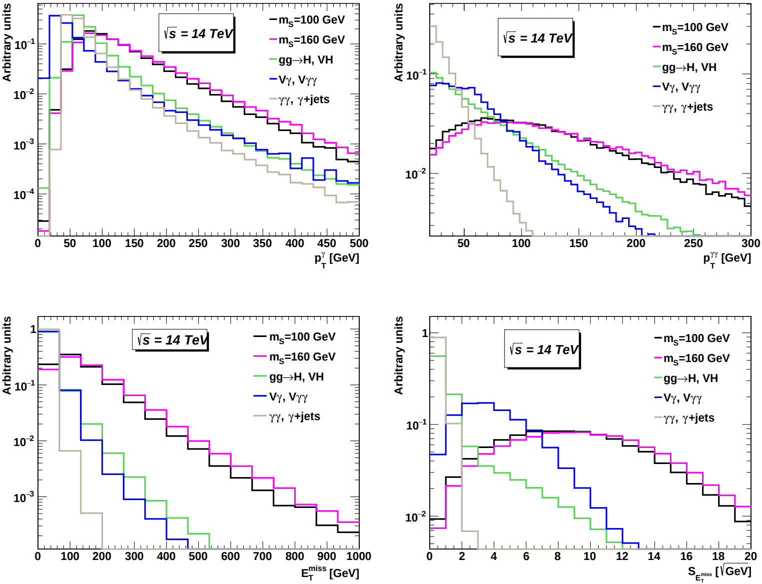
Cuts	SM Higgs	$V\gamma\gamma, V\gamma$	$\gamma\gamma$+jets	Signal	S/B
Initial events	322359	128432167	24030000	365	2.4×10^{-6}
2 Photons	168005	2548352	6837913	218	2.3×10^{-5}
Photon PT	150570	1177335	6317283	189	2.5×10^{-5}
Ratio Tag	135720	830147	5582001	168	2.6×10^{-5}
Invariant Mass	135492	174358	2066511	166	6.9×10^{-5}
ATLAS Signal Region	98	151	0	89	0.35
Final Selection	29	5	0	32	0.94

$\sqrt{s} = 14$ TeV

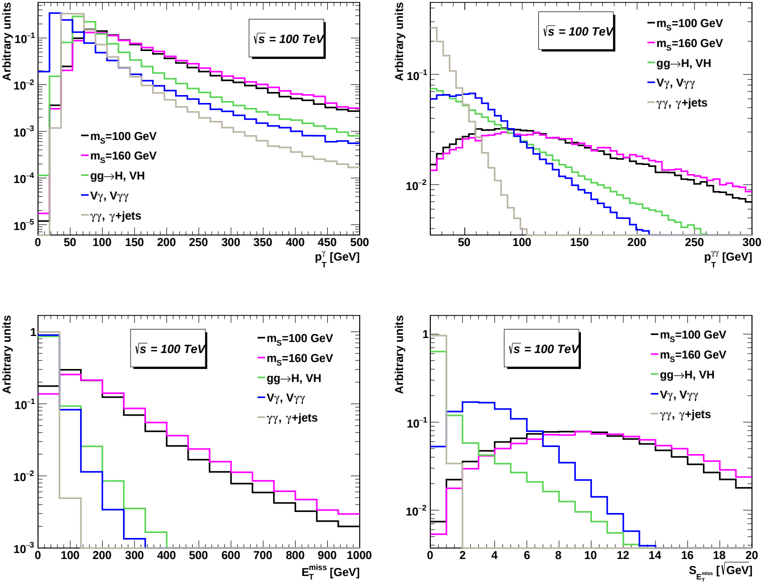
Cuts	SM Higgs	$V\gamma\gamma, V\gamma$	$\gamma\gamma$+jets	Signal	S/B
Initial events	5885817	1192995664	252090000	5147	3.5×10^{-6}
2 Photons	2597337	18298491	73202377	2287	2.4×10^{-5}
Photon PT	2272845	8405387	67325991	1941	2.5×10^{-5}
Ratio Tag	2051298	6134810	59189681	1753	2.6×10^{-5}
Invariant Mass	2048497	1228567	21714801	1741	6.9×10^{-5}
ATLAS Signal Region	4882	1889	0	1036	0.15
Final Selection	2215	315	0	612	0.24

$\sqrt{s} = 100$ TeV

Mono-Higgs signature



Mono-Higgs signature



Gravitational Waves from a Strong EW Phase Transition

EW Phase Transition

In 1967, Sakharov criteria:
- B violation
- C CP violation
- Out-of-equilibrium

In the SM (KRS):
- B+L anomaly
- CKM matrix
- Strong first order Phase transition

- In the SM, $\upsilon_c/T_c > 1$ implies m_h less than 45 GeV!!.
- Knowing that $\upsilon_c/T_c \sim 1/\lambda$, the quartic coupling can be relaxed to smaller value due to extra radiative contributions to the Higgs mass

$$\lambda = \frac{3m_h^2}{\upsilon^2} - \frac{3}{32\pi^2}\sum_{i=all} n_i\alpha_i^2 log\frac{\mu_i^2 + \frac{1}{2}\alpha_i\upsilon^2}{m_h^2},$$

Then large masses of the scalar multiplet members $\mu_i^2 + \frac{1}{2}\alpha_i\upsilon^2$ can put λ to smaller values, which makes the EWPT strongly first order.

GWs from a Strong EW Phase Transition

The relevant quantities, here, are

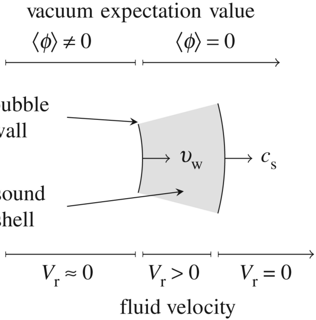
$$\alpha = \frac{\epsilon(T_t)}{\rho_{\rm rad}(T_t)}, \quad \tilde{\beta} = \frac{\beta}{H_T} = T_t \frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Bigg|_{T=T_t},$$

$$\Omega_{\rm GW} h^2 = \Omega_\phi h^2 + \Omega_{\rm sw} h^2 + \Omega_{\rm tur} h^2,$$

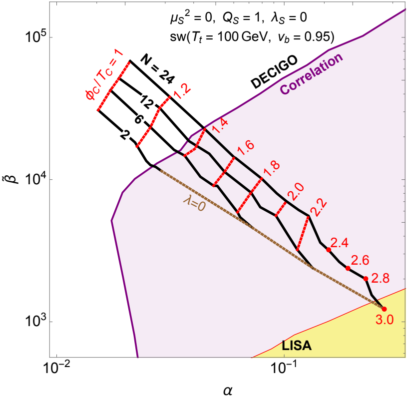
$$\Omega_{\rm sw}(f) h^2 = \widetilde{\Omega}_{\rm sw} h^2 \times (f/\tilde{f}_{\rm sw})^3 \left(\frac{7}{4+3(f/\tilde{f}_{\rm sw})^2}\right)^{7/2},$$

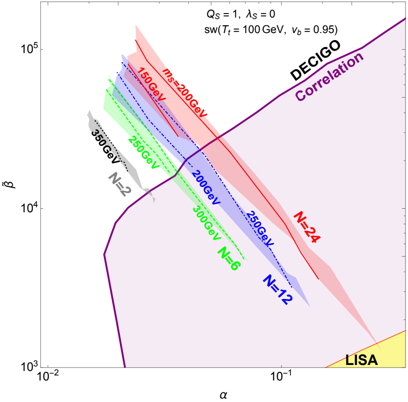
$$\widetilde{\Omega}_{\rm sw} h^2 \simeq 2.65\times 10^{-6} v_b \tilde{\beta}^{-1}\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{1/3},$$

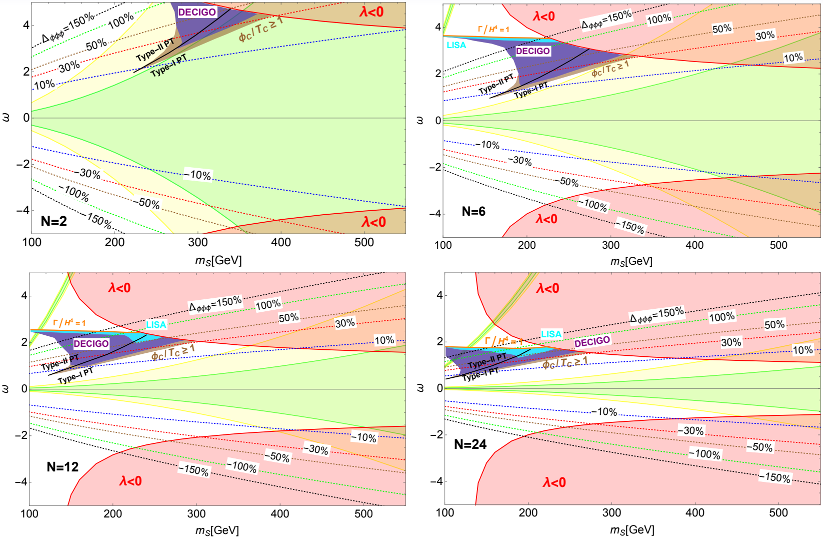
$$\tilde{f}_{\rm sw} \simeq 1.9\times 10^{-5}{\rm Hz}\frac{1}{v_b}\tilde{\beta}\left(\frac{T_t}{100{\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}.$$



Here, we consider a generic SM extension by a sacalar with a multiplicity $N = 2, 6, 12, 24$, mass m_S and a coupling to the Higgs doublet ω. This analysis is valid for our model, as well for many scalars endented SM models.






N=2
N=6
N=12
N=24
λ<0
DECIGO
LISA
Γ/H⁴=1
Type–II PT
Type–I PT
φc/Tc ≥ 1
Δφφφ=150%
100%
50%
30%
10%
−10%
−30%
−50%
−100%
−150%
ω
mS[GeV]
100
200
300
400
500
4
2
0
−2
−4

Conclusion

The model

- explains neutrino oscillation data.
- is not in conflict with different experiemental constraints such as LFV.
- provides a Majorana DM candidate at different mass ranges in agreement with different constraints.
- could lead to detectable GWs from a strong first order phase transition.
- provides intersting signatures at both leptonic and hadronic colliders.

Thank you for your attention.