Multicomponent dark matter, neutrinos and high scale validity

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Based on the works:

(i) arXiv :2009.01262,
(ii) JCAP 04 (2020) 013,
(iii) PHYSICAL REVIEW D 100, 055027 (2019)

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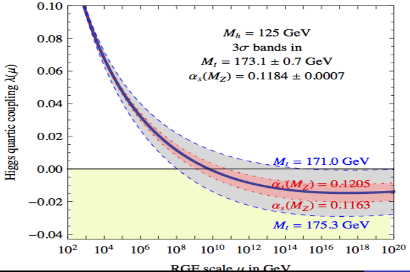
A. Here we address two of the most important aspects of present day particle physics and cosmology:

- **Dark matter** $\longrightarrow$ requires beyond the Standard Model fields [*e.g.* Scalar / fermion/ boson].
- **Neutrino mass** $\longrightarrow$ [most popular one: type-I seesaw: requires additional SM singlet RH neutrinos.]

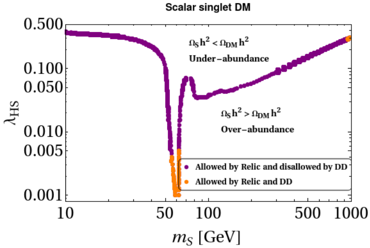
B. These BSM fields: affects the EW vacuum stability at high scale.

$$\beta_\lambda^{\rm SM} = 24\lambda^2 + \frac{3}{4}g_1^2 g_2^2 - 3g_1^2\lambda + \frac{3}{8}g_1^4 - 9g_2^2\lambda + \frac{9}{8}g_2^4 + 12y_t^2\lambda - 6y_t^4.$$

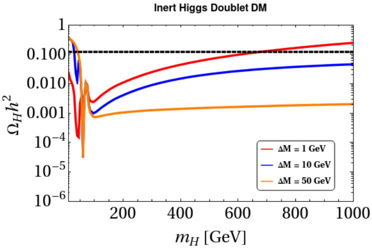


I. an additional scalar can alter the situation towards stability.

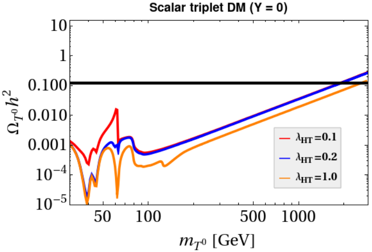
II. On the other hand, additional fermion having coupling with the SM Higgs can make it worse.


Scalar singlet DM
0.500
0.100
0.050
0.010
0.005
0.001
λ_{HS}
$\Omega_S h^2 < \Omega_{DM} h^2$
Under−abundance
$\Omega_S h^2 > \Omega_{DM} h^2$
Over−abundance
Allowed by Relic and disallowed by DD
Allowed by Relic and DD
10
50
100
500
1000
m_S [GeV]

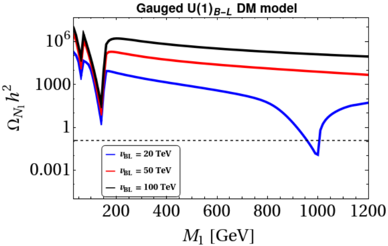
(a)


Inert Higgs Doublet DM
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
$\Omega_H h^2$
ΔM = 1 GeV
ΔM = 10 GeV
ΔM = 50 GeV
200
400
600
800
1000
m_H [GeV]

(b)


Scalar triplet DM (Y = 0)
10
1
0.100
0.010
0.001
10^{-4}
10^{-5}
$\Omega_{T^0} h^2$
λ_{HT}=0.1
λ_{HT}=0.2
λ_{HT}=1.0
50
100
500
1000
m_{T^0} [GeV]

(c)


Gauged U(1)$_{B-L}$ DM model
10^6
1000
1
0.001
$\Omega_{N_1} h^2$
v_{BL} = 20 TeV
v_{BL} = 50 TeV
v_{BL} = 100 TeV
200
400
600
800
1000
1200
M_1 [GeV]

(d)

Motivation

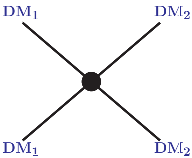
Lack of precise information of DM quantum numbers

↓ **Proposal**

Multicomponent DM

Introduction of multicomponent DM:

- Opens up the new **DM-DM interaction**.



- DM-DM interaction influences the relic, however do not contribute to DD. Hence an evade stringent constraints coming from the direct search experiments.

Boltzmann Equation:

$$\frac{dy_1}{dx} = \frac{-1}{x^2}\Big[\langle\sigma v_{11\to XX}\rangle\left(y_1^2-(y_1^{EQ})^2\right) + \langle\sigma v_{11\to 22}\rangle\left(y_1^2-\frac{(y_1^{EQ})^2}{(y_2^{EQ})^2}y_2^2\right)\Theta(m_1-m_2)$$
$$-\langle\sigma v_{22\to 11}\rangle\left(y_2^2-\frac{(y_2^{EQ})^2}{(y_1^{EQ})^2}y_1^2\right)\Theta(m_2-m_1)\Big],$$
$$\frac{dy_2}{dx} = \frac{-1}{x^2}\Big[\langle\sigma v_{22\to XX}\rangle\left(y_2^2-(y_2^{EQ})^2\right) + \langle\sigma v_{22\to 11}\rangle\left(y_2^2-\frac{(y_2^{EQ})^2}{(y_1^{EQ})^2}y_1^2\right)\Theta(m_2-m_1)$$
$$-\langle\sigma v_{11\to 22}\rangle\left(y_1^2-\frac{(y_1^{EQ})^2}{(y_2^{EQ})^2}y_2^2\right)\Theta(m_1-m_2)\Big].$$

Here, $y_i = 0.264 M_{\rm Pl}\sqrt{g_*}\mu Y_i$ with $Y_i = \frac{n_i}{s}$, $x = \frac{\mu}{T}$, $\mu = \frac{m_1 m_2}{m_1+m_2}$

Relic density:

$$\Omega_i h^2 = \frac{854.45\times 10^{-13}}{\sqrt{g_*}}\frac{m_i}{\mu}y_i\left(\frac{\mu}{m_i}x_\infty\right), \quad \Omega_{Tot}h^2 = \Omega_1 h^2 + \Omega_2 h^2$$

Direct detection: The *effective* SI-DD cross sections:

$$\sigma_{i,eff}^{SI} = \frac{\Omega_i}{\Omega_{Tot}}\sigma_i^{SI}$$

Our Goal

The questions on can ask is, can multicomponent DM

- Provide a solution for a scalar singlet model which is allowed by DD in the sub-TeV range?
- Provide a DM candidate in the $m_W - 500$ GeV range for a Inert Higgs doublet (IHD) DM scenario?
- Provide a DM candidate below 1.8 TeV for a scalar triplet ($Y = 0$) DM scenario?
- Provide a DM candidate in the region apart from the resonance regions in a gauged $U(1)_{\mathrm{B-L}}$ scenario?

Some possibilities of a multicomponent DM framework:

- 2 Scalar singlet [JCAP 04 (2017)043]
- Scalar singlet + Inert doublet [JHEP 03 (2020) 090]
- Scalar singlet + Scalar Triplet [arXiv:2009.01262]
- Two inert doublets [Phys.Rev.D 100 (2019) 5, 055027]
- Inert doublet in a gauged $U(1)_{\mathrm{B-L}}$ model [JCAP 04 (2020) 013]

Our Proposal

Consider a **multicomponent scenario** with a focus on sub-TeV range of scalar singlet DM and a below 1.8 TeV range of scalar triplet DM ($Y = 0$).

Proposal : a hybrid with scalar singlet + scalar triplet!

DM: Scalar singlet and neutral component of the scalar triplet . [DM-DM conversion would be important]

Stability of the Higgs vacuum: Higgs portal couplings of scalar singlet and scalar triplet $\rightarrow$ can make the EW vacuum stable.

Extension of the SM by: $Z_2 \times Z_2'$

Particle	$SU(2)$	$U(1)_Y$	Z_2	Z_2'
H	2	$\frac{1}{2}$	$+$	$+$
T	3	0	-	$+$
S	1	0	$+$	-

$$V_H = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2,$$

$$V_T = \frac{M_T^2}{2} tr[T^2] + \frac{\lambda_T}{4!}(tr[T^2])^2,$$

$$V_S = \frac{M_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4,$$

$$V_{\rm int} = \frac{\lambda_{HT}}{2}(H^\dagger H) tr[T^2] + \frac{\lambda_{HS}}{2}(H^\dagger H) S^2 + \frac{\kappa}{4} tr[T^2] S^2$$

The scalar fields are then parametrised as

$$H = \begin{pmatrix} w^+ \\ \frac{1}{\sqrt{2}}(v + h + iz) \end{pmatrix}, \qquad T = \begin{pmatrix} \frac{1}{\sqrt{2}}T^0 & -T^+ \\ -T^- & -\frac{1}{\sqrt{2}}T^0 \end{pmatrix}, \quad S \; .$$

After the EWSB, the masses of the scalar particles are given as

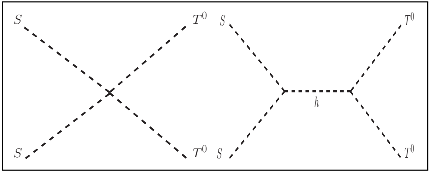
$$\begin{aligned} m_h^2 &= 2\lambda_H v^2 \\ m_{T^0,T^\pm}^2 &= M_T^2 + \frac{\lambda_{HT}}{2} v^2 \\ m_S^2 &= M_S^2 + \frac{\lambda_{HS}}{2} v^2 \; . \end{aligned}$$

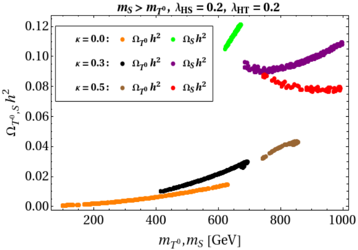
A small mass difference of **166 MeV** between the charged and the neutral scalars can be generated at 1-loop

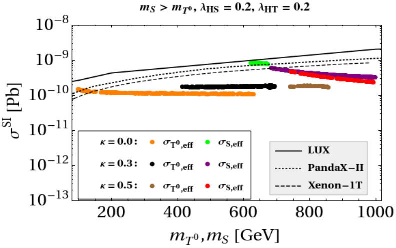
$$\Delta m = (m_{T^\pm} - m_{T^0})_{1-loop} = \frac{\alpha m_{T^0}}{4\pi}\left[f\left(\frac{M_W}{m_{T^0}}\right) - c_W^2 f\left(\frac{M_Z}{m_{T^0}}\right)\right].$$

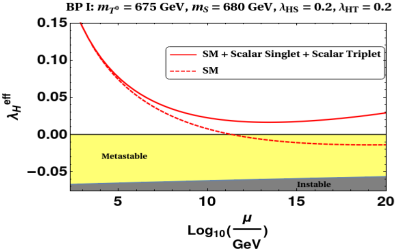
This makes the T^0 a viable DM candidate.

DM-DM conversion ($m_S > m_T$):









$$\beta_{\lambda_H} = \beta^{SM}_{\lambda_H} + \frac{3}{2}\lambda^2_{HT} + \frac{1}{2}\lambda^2_{HS}$$

The next question we ask is

Can multicomponent provide DM in the mass range $m_W - 500$ GeV of IHD?

↓ **Yes**[1]**!!**

Proposal : a hybrid with 2 IHDs!

DM: Lightest neutral component of both the IHDs .
[DM-DM conversion would be important]

Neutrino mass: Together with the RHNs, $\nu-$ masses can be generated at 1-loop.

[1] A similar analysis with one singlet and one IHD can be found in JHEP 03 (2020) 090

Extension of the SM: $SU(2)_L \times U(1)_Y \times \mathbb{Z}_2 \times \mathbb{Z}_2'$

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$\mathbb{Z}_2$	$\mathbb{Z}_2{}'$
η_1	$(1,\ 2,\ \frac{1}{2})$	-	+
η_2	$(1,\ 2,\ \frac{1}{2})$	+	-
N_1	$(1,\ 1{,}0)$	-	+
N_2	$(1,\ 1{,}0)$	+	-

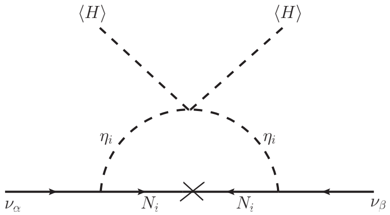
Lagrangian

$$-\mathcal{L}^{\rm new} = Y_{\alpha 1}\bar{L}_\alpha \tilde{\eta}_1 N_1 + Y_{\alpha 2}\bar{L}_\alpha \tilde{\eta}_2 N_2 + \frac{1}{2}M_1 \bar{N}_1^c N_1 + \frac{1}{2}M_2 \bar{N}_2^c N_2 + h.c,$$

Scalar potential

$$\begin{aligned} V_{\rm int} \quad = \quad & \lambda_3 (H^\dagger H)(\eta_1^\dagger \eta_1) + \lambda_4 (H^\dagger \eta_1)(\eta_1^\dagger H) + \frac{\lambda_5}{2}\left[(H^\dagger \eta_1)^2 + (\eta_1^\dagger H)^2\right] \\ & + \tilde{\lambda}_3 (H^\dagger H)(\eta_2^\dagger \eta_2) + \tilde{\lambda}_4 (H^\dagger \eta_2)(\eta_2^\dagger H) + \frac{\tilde{\lambda}_5}{2}\left[(H^\dagger \eta_2)^2 + (\eta_2^\dagger H)^2\right] \\ & + \lambda_3' (\eta_1^\dagger \eta_1)(\eta_2^\dagger \eta_2) + \lambda_4' (\eta_1^\dagger \eta_2)(\eta_2^\dagger \eta_1) + \frac{\lambda_5'}{2}\left[(\eta_1^\dagger \eta_2)^2 + (\eta_2^\dagger \eta_1)^2\right]. \end{aligned}$$

$Y_{\alpha i}\bar{L}_{\alpha}\tilde{\eta}_i N_i$: ν-mass generation at 1-loop



$$(m^\nu)_{\alpha\beta} = \sum_{i=1,2} Y_{\alpha i}Y_{\beta i}\frac{M_i}{32\pi^2}\left[\frac{m^2_{H_i}}{m^2_{H_i}-M_i^2}\ln\frac{m^2_{H_i}}{M_i^2} - \frac{m^2_{A_i}}{m^2_{A_i}-M_i^2}\ln\frac{m^2_{A_i}}{M_i^2}\right],$$

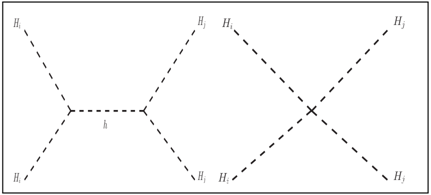
With $Y = U_{\text{PMNS}}\sqrt{m_\nu^{diag}}R^\dagger\sqrt{\Lambda^{-1}}$ [CI parameterization[2]]
where

$$m_\nu^{diag} = dia(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}),\ R = \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \end{pmatrix} \text{ and } RR^T = 1.$$

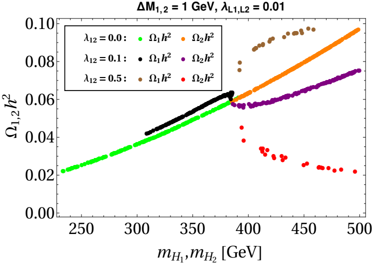
[2] Nucl.Phys. B618 (2001) 171-204

DM Phenomenology

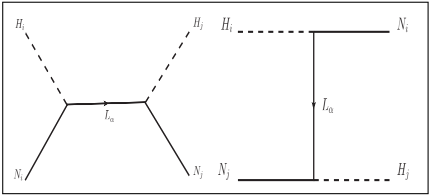
DM-DM conversion ($m_{H_2} > m_{H_1}$, $\lambda_3', \lambda_4', \lambda_5' = \lambda_{12}$ **and without** $Y_{\alpha i}$)



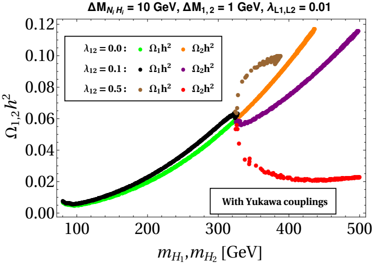
$\longrightarrow$



DM-DM conversion (with $Y_{\alpha i}$ **and** $M_i - m_{H_i} = 10$ **GeV)**



$\longrightarrow$



And finally,

Can multicomponent provide DM candidate in a gauged $U(1)_{\rm B-L}$ scenario apart from the region near resonances ?

$\downarrow$ **Yes, but one needs to pay a price!!**

Proposal : a hybrid with Gauged $\mathrm{U(1)_{B-L}} + \mathrm{IHD}$!

DM: Lightest neutral component of the IHD and the lightest RHN . [DM-DM conversion would be important]

Neutrino mass:RHNs together with the IHD, $\nu-$ masses can be generated at 1-loop.

High scale validity: The fate of EW vacuum will now depend on the choice of DM conversion coupling.

Model (JCAP 04 (2020) 013), [SB,NC,RR,AS]

- Extension of the SM by
  - Gauged $U(1)_{B-L}$
  - Two discrete symmetries: $\mathbb{Z}_2 \times \mathbb{Z}_2'$
- Charges of the particle under different symmetry groups

Field	$SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$	$\mathbb{Z}_2$	$\mathbb{Z}_2{}'$
ϕ_2	$(2,\ \frac{1}{2})$	0	-	-
N_1	(1, 0)	-1	-	$+$
N_2, N_3	(1, 0)	-1	-	-
S	(1, 0)	2	$+$	$+$

$$\begin{aligned}\mathcal{L}_{new} \quad &= \quad i\bar{N}\not{D}N + |D_\mu \phi_1|^2 + |D_\mu S|^2 + \frac{1}{4}(Z_{BL})_{\mu\nu}(Z_{BL})^{\mu\nu} \\ &\quad -\zeta_{i\alpha}\bar{L}_{Li}\tilde{\phi}_2 N_\alpha - y_{\alpha\beta}\bar{N}^c_\alpha N^c_\beta S - y_{11}\bar{N}^c_1 N^c_1 S - V(\phi_1, S)\end{aligned}$$

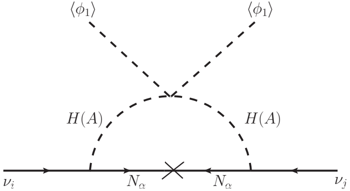
where $D_\mu = \partial_\mu - ig\frac{\tau}{2}W_\mu - i\frac{g'}{2}B_\mu - ig_{BL}Q(Z_{BL})_\mu$

$$\begin{aligned} V(\phi_1,\phi_2,S) &= -\mu_1^2\phi_1^\dagger\phi_1+\mu_2^2\phi_2^\dagger\phi_2-\mu_S^2|S|^2 \\ &+\lambda_1(\phi_1^\dagger\phi_1)^2+\frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2+\lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) \\ &+\lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)+\frac{\lambda_5}{2}\left[(\phi_1^\dagger\phi_2)^2+(\phi_2^\dagger\phi_1)^2\right] \\ &+\lambda_6(\phi_1^\dagger\phi_1)|S|^2+\lambda_7(\phi_2^\dagger\phi_2)|S|^2+\lambda_8|S|^4 \end{aligned}$$

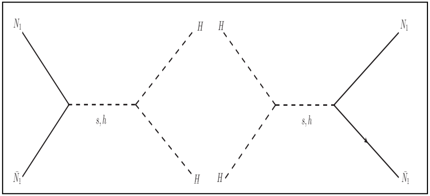
After EWSB, $\langle\phi_1\rangle = v$, $\langle S\rangle = v_{BL}$, $\langle\phi_2\rangle = 0$ and ϕ_h mixes with ϕ_s

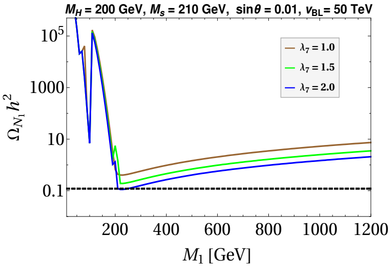
$$\begin{pmatrix}\phi_h\\ \phi_s\end{pmatrix} = \begin{pmatrix}c_\theta & s_\theta\\ -s_\theta & c_\theta\end{pmatrix}\begin{pmatrix}h\\ s\end{pmatrix}$$

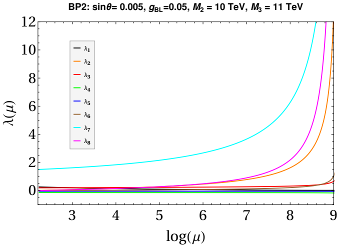
Neutrino mass: $\zeta_{i\alpha}\overline{L}_{Li}\tilde{\phi}_2 N_\alpha$, with $\alpha = 2,3$

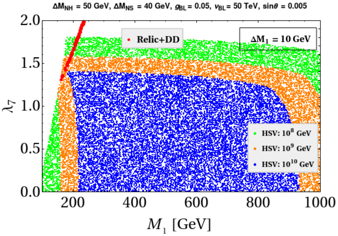


DM-DM conversion :









$$\beta_{\lambda_7} = 6\lambda_2\lambda_7 + 4\lambda_3\lambda_6 + 2\lambda_4\lambda_6 + 4\lambda_7^2 + 8\lambda_7\lambda_8 + 4\lambda_7 \mathrm{Tr}[y^\dagger y] - 24\lambda_7 g_{BL}^2,$$

Conclusions

- Multicomponent DM models can evade ever tightening bound on the direct detection (DD) rates while enlarging relic density allowed parameter space.
- The proposed scenarios opens up an attractive possibility of DM-DM conversion, a phenomenon that goes on to become the main theme of these studies.
- Conversion processes can lead to the desired relic density for:
  - Scalar singlet plus scalar triplet scenario in the sub-TeV mass regime.
  - IHD DM scenario in the mass range $m_W - 500$ GeV.
  - Gauged $U(1)_{\mathrm{B-L}}$ model apart from the near resonance regions.
- The multicomponent scenarios discussed above can generate neutrino mass and at the same time can also modify the fate of EW vacuum.
- Multicomponent DM studies can also open up an interesting collider prospects (lighter DM masses are allowed).

Backup Slides

IHD parameters

$$
\begin{aligned}
m_{H_1}^2 &= \mu_1^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2, \\
m_{A_1}^2 &= \mu_1^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2, \\
m_{\eta_1^+}^2 &= \mu_1^2 + \frac{1}{2}\lambda_3 v^2, \\
m_{H_2}^2 &= \mu_2^2 + \frac{1}{2}(\tilde{\lambda_3} + \tilde{\lambda_4} + \tilde{\lambda_5})v^2, \\
m_{A_2}^2 &= \mu_2^2 + \frac{1}{2}(\tilde{\lambda_3} + \tilde{\lambda_4} - \tilde{\lambda_5})v^2, \\
m_{\eta_2^+}^2 &= \mu_2^2 + \frac{1}{2}\tilde{\lambda_3} v^2.
\end{aligned}
$$

Annihilation channels

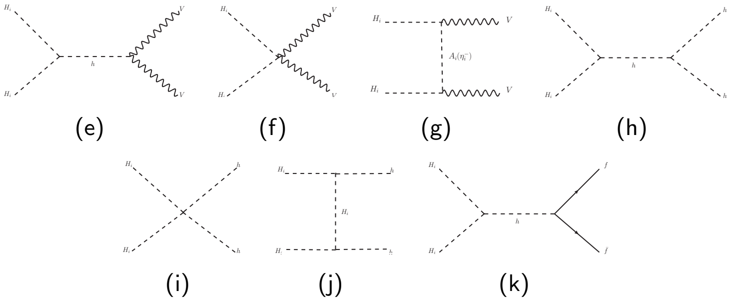


Figure: Annihilation channels

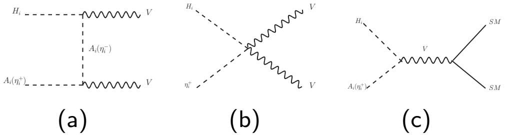


Figure: Coannihilation Channels

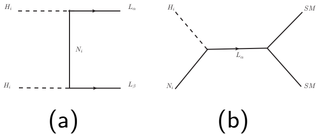
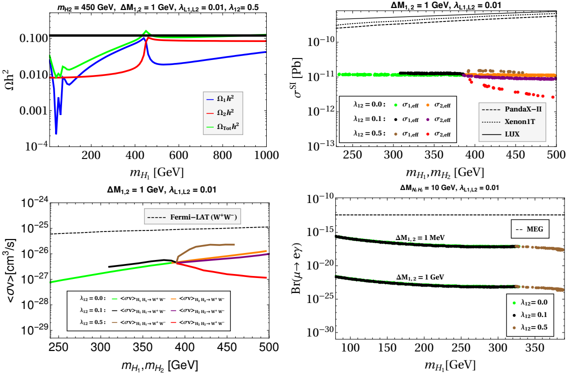
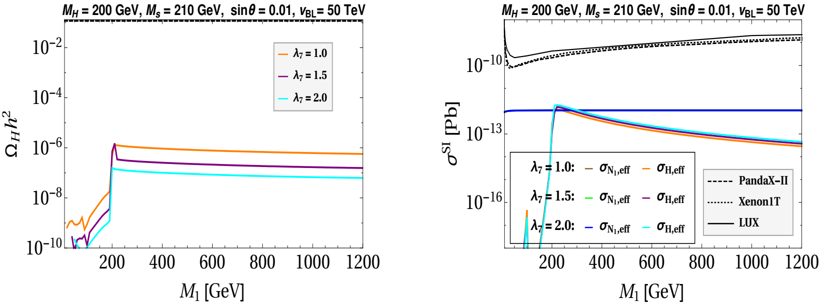


Figure: (Co)annihilation channels in presence of singlet neutral fermions



BP	m_{H_1} [GeV]	m_{H_2} [GeV]	$\Omega_1 h^2$	$\Omega_2 h^2$
Without Yukawa interactions	250	492	0.026	0.095
With Yukawa interactions	250	380	0.033	0.085

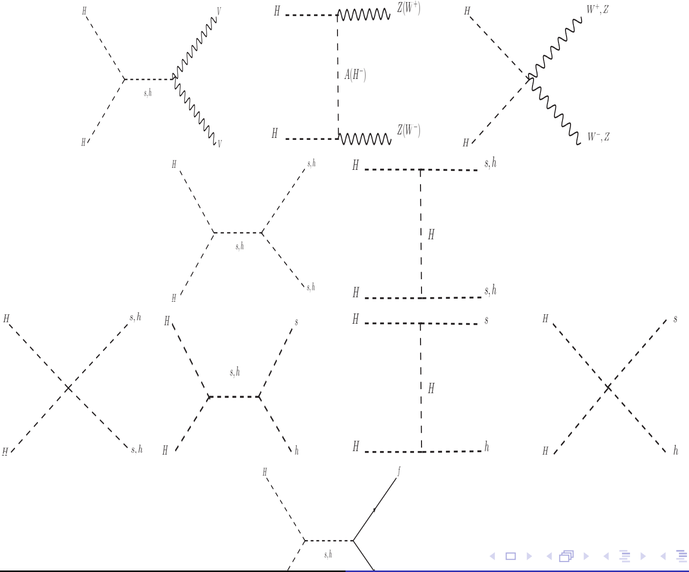
Table: In producing the above values, we considered: $\lambda_{L_1} = \lambda_{L_2} = 0.01$ and $\lambda_{12} = 0$



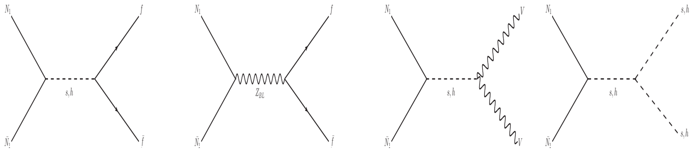
M_H = 200 GeV, M_s = 210 GeV, sinθ = 0.01, v_{BL}= 50 TeV
$\lambda_7 = 1.0$
$\lambda_7 = 1.5$
$\lambda_7 = 2.0$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$\Omega_H h^2$
200 400 600 800 1000 1200
M_1 [GeV]
M_H = 200 GeV, M_s = 210 GeV, sinθ = 0.01, v_{BL}= 50 TeV
10^{-10}
10^{-13}
10^{-16}
σ^{SI} [Pb]
$\lambda_7 = 1.0$: $\sigma_{N_1,eff}$ $\sigma_{H,eff}$
$\lambda_7 = 1.5$: $\sigma_{N_1,eff}$ $\sigma_{H,eff}$
$\lambda_7 = 2.0$: $\sigma_{N_1,eff}$ $\sigma_{H,eff}$
PandaX-II
Xenon1T
LUX
200 400 600 800 1000 1200
M_1 [GeV]

Feynman Diagrams: U(1)B-L

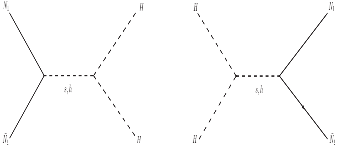
Annihilation and co-annihilation processes for *H*

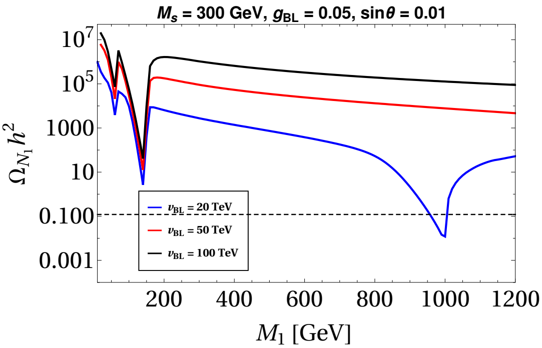


Annihilation processes for N_1



$N_1 - H$ conversion proceses





- Correct relic $\Omega_{N_1} h^2 \simeq 0.11$ is only obtained in the vicinity of the resonance dip.
- Annihilation of N_1 are **gauge driven**: $\Omega_{N_1} h^2 \propto v_{BL}^4$
- Here, $M_{Z_{BL}} = 2 g_{BL} v_{BL} = 2$ TeV for $v_{BL} = 20$ TeV, the resonance dip corresponding to $M_{Z_{BL}}$ is visible.

The **masses of the IHD component** after the symmetry breaking:

$$\begin{aligned} M_H^2 &= \mu_2^2 + \frac{1}{2}\lambda_L v^2 + \frac{1}{2}\lambda_7 v_{BL}^2, \\ M_A^2 &= \mu_2^2 + \frac{1}{2}\lambda_L v^2 + \frac{1}{2}\lambda_7 v_{BL}^2, \\ M_{H^+}^2 &= \mu_2^2 + \frac{1}{2}\lambda_3 v^2 + \frac{1}{2}\lambda_7 v_{BL}^2. \end{aligned}$$

where $\lambda_L = \lambda_3 + \lambda_4 + \lambda_5$.

Masses of the 3 RHNs will be given as:

$$M_N = \sqrt{2}\ v_{BL} \begin{pmatrix} y_{11} & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{23} & y_{33} \end{pmatrix}.$$

We take $y_{23} = 0$ for simplicity for the rest of the analysis, in which case M_N is diagonal with entries $M_i = \sqrt{2}\ y_{ii} v_{BL}$.

Choice of parameters

- We have the following free parameters in our set-up:

$$M_1,\ M_2,\ M_3,\ M_H,\ M_A,\ M_{H^+},\ M_s,\ \theta, \lambda_L, \lambda_7,\ g_{BL}, v_{BL}$$

- Dependent parameters in the set-up:

$$\begin{aligned}
\mu_2^2 &= M_H^2 - \frac{1}{2}\lambda_L v^2 - \frac{1}{2}\lambda_7 v_{BL}^2, \\
\lambda_1 &= \frac{(M_h^2 c_\theta^2 + M_S^2 s_\theta^2)}{v^2}, \\
\lambda_3 &= \lambda_L + \frac{2(M_{H^+}^2 - M_H^2)}{v^2}, \\
\lambda_4 &= \frac{M_H^2 + M_A^2 - 2M_{H^+}^2}{v^2}, \\
\lambda_5 &= \frac{(M_H^2 - M_A^2)}{v^2}, \\
\lambda_6 &= \frac{(M_S^2 - M_h^2) s_\theta c_\theta}{v v_{BL}}, \\
\lambda_8 &= \frac{(M_h^2 s_\theta^2 + M_S^2 c_\theta^2)}{2 v_{BL}^2} \\
y_{ii} &= \frac{M_{ii}}{\sqrt{2} v_{BL}}.
\end{aligned}$$

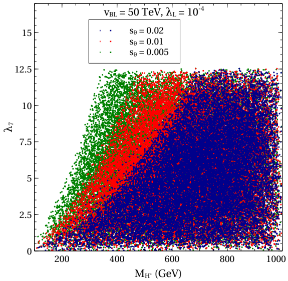


Figure: Parameter space in the $\lambda_7 - M_{H^+}$ plane allowed by the $\mu_{\gamma\gamma}$ constraint

Scalar interations:

$$\lambda_{HHh} = (\lambda_3 + \lambda_4 + \lambda_5) v c_\theta - \lambda_7 v_{BL} s_\theta , \tag{4a}$$

$$\lambda_{HHs} = (\lambda_3 + \lambda_4 + \lambda_5) v s_\theta + \lambda_7 v_{BL} c_\theta , \tag{4b}$$

$$\lambda_{AAh} = (\lambda_3 + \lambda_4 - \lambda_5) v c_\theta - \lambda_7 v_{BL} s_\theta , \tag{4c}$$

$$\lambda_{AAs} = (\lambda_3 + \lambda_4 - \lambda_5) v s_\theta + \lambda_7 v_{BL} c_\theta , \tag{4d}$$

$$\lambda_{H^+H^-h} = \lambda_3 v c_\theta - \lambda_7 v_{BL} s_\theta , \tag{4e}$$

$$\lambda_{H^+H^-s} = \lambda_3 v s_\theta + \lambda_7 v_{BL} c_\theta . \tag{4f}$$

Yukawa interations:

$$y_{hN_1N_1} = -\frac{1}{\sqrt{2}} y_{11} s_\theta \,, \tag{5a}$$

$$y_{sN_1N_1} = \frac{1}{\sqrt{2}} y_{11} c_\theta \,, \tag{5b}$$

$$y_{hff} = \frac{M_f}{v} c_\theta \,, \tag{5c}$$

$$y_{sff} = \frac{M_f}{v} s_\theta \text{ where } f \text{ is a SM fermion.} \tag{5d}$$

Gauge interations:

$$g_{hVV} = \frac{2M_V^2}{v} c_\theta \,, \tag{6a}$$

$$g_{sVV} = \frac{2M_V^2}{v} s_\theta \text{ where } V = W^+, Z \tag{6b}$$

$$g_{hZ_{BL}Z_{BL}} = -\frac{2M_V^2}{v_{BL}} s_\theta \,, \tag{6c}$$

$$g_{sZ_{BL}Z_{BL}} = \frac{2M_V^2}{v_{BL}} c_\theta \,. \tag{6d}$$

- **LHC diphoton signal strength**:
  - Measured Higgs signal strength at LHC gives constraint on $\sin\theta \leq 0.36$[3].
  - The presence of H^+ will alter the decay width of $h \to \gamma\gamma$ through **one loop**[4]

$$\mathcal{M}_{h\to\gamma\gamma} = \frac{4}{3} c_\theta A_f\left(\frac{M_h^2}{4M_t^2}\right) + c_\theta A_V\left(\frac{M_h^2}{4M_W^2}\right) + \frac{\lambda_{hH^+H^-} v}{2M_{H^+}^2} A_S\left(\frac{M_h^2}{4M_{H^+}^2}\right),$$

$$\Gamma_{h\to\gamma\gamma} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3}|\mathcal{M}_{h\to\gamma\gamma}|^2.$$

where A_f, A_V and A_S are the loop functions. [ref]
The latest $\mu_{\gamma\gamma}$ values from 13 TeV LHC read [ref]

$$\mu_{\gamma\gamma} = 0.99^{+0.14}_{-0.14} \text{ (ATLAS)}, \quad = 1.18^{+0.17}_{-0.14} \text{ (CMS)}.$$

[3] Eur.Phys.J. C76 (2016) no.5, 268
[4] Phys.Rev. D85 (2012) 095021