An update on the two singlet Dark Matter model

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The Two-singlet Model

- Model : SM + Two singlets (S_1 & S_2)
- Imposed $Z_2 \times Z_2'$ symmetry
- SM : even under both Z_2 & Z_2' symmetry and the rest transform as,

$$\boxed{\begin{aligned} S_1 \xrightarrow{Z_2} -S_1,\ S_1 \xrightarrow{Z_2'} S_1, \\ S_2 \xrightarrow{Z_2} S_2,\ S_2 \xrightarrow{Z_2'} -S_2 \end{aligned}}$$

- Z_2 symmetry : broken spontaneously
- Z_2' symmetry : unbroken and ensures the stability of S_2 (Dark matter candidate)
- Scalar Lagrangian of the model :

$$\boxed{\mathcal{L}_s = (D^\mu \Phi)^\dagger D_\mu \Phi + \frac{1}{2}\partial^\mu S_1 \partial_\mu S_1 + \frac{1}{2}\partial^\mu S_2 \partial_\mu S_2 - V(\Phi, S_1, S_2)}$$

The Two-singlet Model

- Scalar Potential :

$$V = -\frac{m_0^2}{2}(\Phi^\dagger\Phi) - \frac{m_1^2}{2}S_1^2 + \frac{m_2^2}{2}S_2^2 + \frac{\lambda_0}{4}(\Phi^\dagger\Phi)^2 + \frac{\lambda_1}{4}S_1^4 + \frac{\lambda_2}{4}S_2^4 + \lambda_{01}(\Phi^\dagger\Phi)S_1^2 + \lambda_{02}(\Phi^\dagger\Phi)S_2^2 + \lambda_{12}S_1^2S_2^2$$

- After symmetry breaking,

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_0 + h_0 \end{pmatrix}; \qquad S_1 = v_1 + h_1$$

- Mass matrix for the scalar sector :

$$\mathcal{M}_s = \begin{pmatrix} h_0 & h_1 \end{pmatrix} \begin{pmatrix} \frac{\lambda_0 v_0^2}{4} & \lambda_{01} v_0 v_1 \\ \lambda_{01} v_0 v_1 & \lambda_1 v_1^2 \end{pmatrix} \begin{pmatrix} h_0 \\ h_1 \end{pmatrix} + \frac{1}{2}(m_2^2 + \lambda_{02} v_0^2 + 2\lambda_{12} v_1^2) S_2^2$$

The Two-singlet Model

- Mass eigenstates h and H and the mixing angle α

$$\tan 2\alpha = \frac{2\lambda_{01} v_0 v_1}{\frac{\lambda_0 v_0^2}{4} - \lambda_1 v_1^2}$$

- Quartic self-couplings λ_0 and λ_1 :

$$\lambda_0 = \frac{2}{v_0^2}\left(\frac{m_h^2 + m_H^2}{2} + \sqrt{\frac{(m_h^2 - m_H^2)^2}{4} - 4\lambda_{01}^2 v_0^2 v_1^2}\right),$$

$$\lambda_1 = \frac{1}{2v_1^2}\left(\frac{m_h^2 + m_H^2}{2} - \sqrt{\frac{(m_h^2 - m_H^2)^2}{4} - 4\lambda_{01}^2 v_0^2 v_1^2}\right)$$

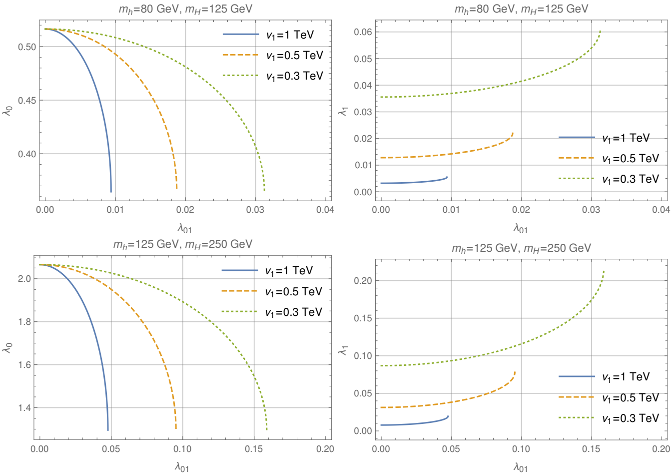
Constraints

- All theoretical and experimental constraints to be imposed upon the parameter space
- Analyze and scan the parameter space of the couplings $(\lambda_{01}, \lambda_{02}, \lambda_{12})$ and put bounds on their values from various constraints
- Two choices: (i) fixing the lighter scalar : SM Higgs and $m_H = 250$ GeV and (ii) choosing the heavier scalar : SM Higgs and $m_h = 80$ GeV.

Major constraints :

- Vacuum stability
- Collider constraints
- LHC Higgs searches

Vacuum Stability : Bound on coupling λ_{01}



Bound on λ_{01} : (Top/Bottom left) Due to positivity constraints on λ_0 for v_1: 1 TeV, 0.5 TeV and 0.3 TeV and that on λ_1 (Top/Bottom right) for the $m_H = 125 (m_h = 125)$ GeV case for the same set of v_1 values.

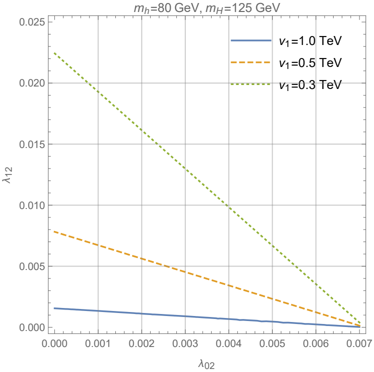
Collider Constraints

Branching Ratio (BR) of the Higgs invisible decays:

$$\mathrm{BR}_{h\to inv} = \frac{\Gamma_{h\to inv}}{\Gamma_{h\to SM} + \Gamma_{h\to inv}}$$

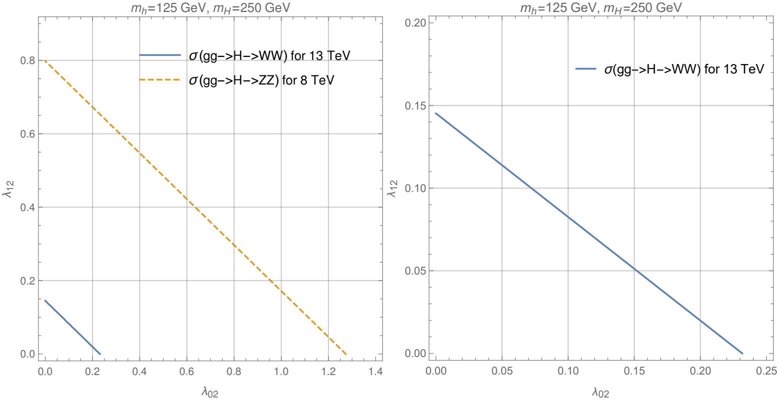
- Case 1 : $m_H = 125$ GeV with both h and S_2 lighter, both decays $H \to hh$ and $H \to S_2 S_2$ to be considered
- Case 2 : $m_h = 125$ GeV, only the decay $h \to S_2 S_2$ is relevant
- Fixing $\lambda_{01} = 0.008$ (0.04) for $m_H = 80$ GeV (250 GeV) : consistent with Vacuum stability

Bound on coupling λ_{12}



Contours of BR=11% for $v_1 = 1$ TeV, 0.5 TeV and 0.3 TeV for $m_H = 125$ GeV (left) and $m_h = 125$ GeV case (right). The allowed region for the $m_h = 125$ GeV case on the right is the band between the corresponding lines.

LHC Higgs searches



Allowed regions in the $\lambda_{02} - \lambda_{12}$ parameter space : from searches for the heavy scalar H at the LHC in the diboson channel $gg \to H \to WW/ZZ$ with the gauge bosons decaying either leptonically or hadronically (left) and a magnified view of the 13 TeV constraints (right).

Dark matter phenomenology : Direct detection

- Effective lagrangian for nucleon-dark matter interaction :

$$L_{eff} = a_N N\bar{N}S_2^2$$

- Spin independent scattering cross-section :

$$\begin{aligned}\sigma_N^{SI} =& \frac{\mu^2}{4\pi m_{S_2}^2}\Bigg[\frac{\lambda_{HS_2S_2}}{m_H^2}\Bigg(\sum_{q=u,d,s}\frac{m_q}{v_0}\cos\alpha\frac{m_N}{m_q}f_{Tq}^N+\frac{2}{27}f_{TG}^N\sum_{q=c,b,t}\frac{m_q}{v_0}\cos\alpha\frac{m_N}{m_q}\Bigg) \\ & -\frac{\lambda_{hS_2S_2}}{m_h^2}\Bigg(\sum_{q=u,d,s}\frac{m_q}{v_0}\sin\alpha\frac{m_N}{m_q}f_{Tq}^N+\frac{2}{27}f_{TG}^N\sum_{q=c,b,t}\frac{m_q}{v_0}\sin\alpha\frac{m_N}{m_q}\Bigg)\Bigg]^2\end{aligned}$$

where the reduced mass $\mu = \frac{m_N m_{S_2}}{m_N+m_{S_2}}$.

- Assumption of the quark contribution being approximately equal for both the nucleons (i.e., $f_{Tq}^{(n)} \approx f_{Tq}^{(p)} = f_{Tq}^N$)

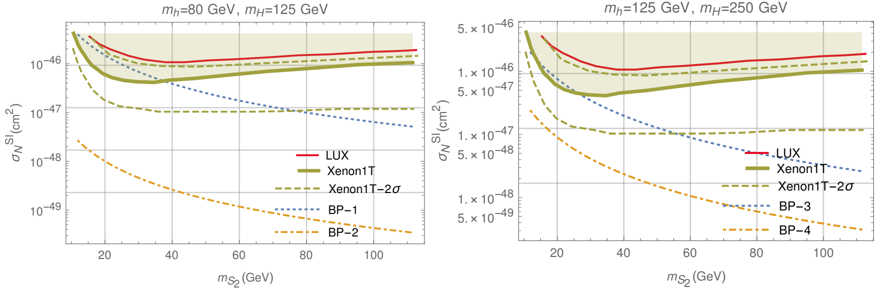
Dark matter phenomenology : Benchmark Points

Benchmark Points :

	Masses (GeV)	λ_{01}	λ_{02}	λ_{12}	$\sigma_N^{SI}(\mathrm{cm}^2)$
BP-1	$m_h = 80,\ m_H = 125$	0.008	0.002	0.0010	3.86×10^{-47}
BP-2	$m_h = 80,\ m_H = 125$	0.008	0.002	0.0005	2.61×10^{-49}
BP-3	$m_h = 125,\ m_H = 250$	0.04	0.010	0.001	1.98×10^{-47}
BP-4	$m_h = 125,\ m_H = 250$	0.04	0.005	0.0006	2.35×10^{-48}

Representative benchmark points shown along with the corresponding spin independent cross-section values for a dark matter mass of 40 GeV and $v_1 = 1000$ GeV.

Dark matter phenomenology : Direct detection



Variation of $\sigma_N^{SI}(\mathrm{cm}^2)$ with m_{S_2}(GeV) for the benchmark points - overlaid on the plots are the constraints from the Xenon-1T and LUX results.

Dark matter phenomenology : Relic abundance

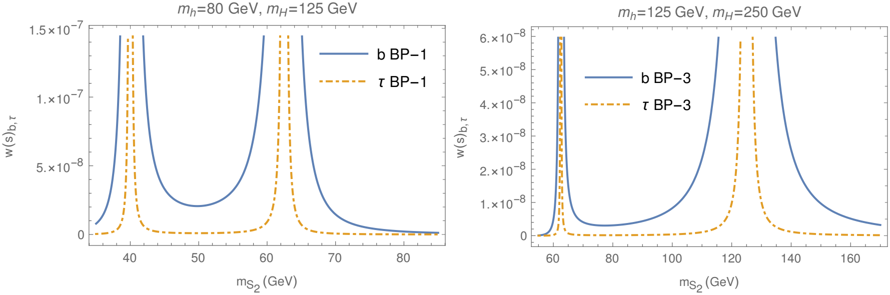
Relic Abundance :

$$\boxed{\Omega h^2 = 1.07 \times 10^9 \frac{x_f}{\sqrt{g^*} m_{pl} \langle \sigma v \rangle}}$$

where $x_f = \frac{m_{S_2}}{T}$, m_{pl} is the Planck mass.

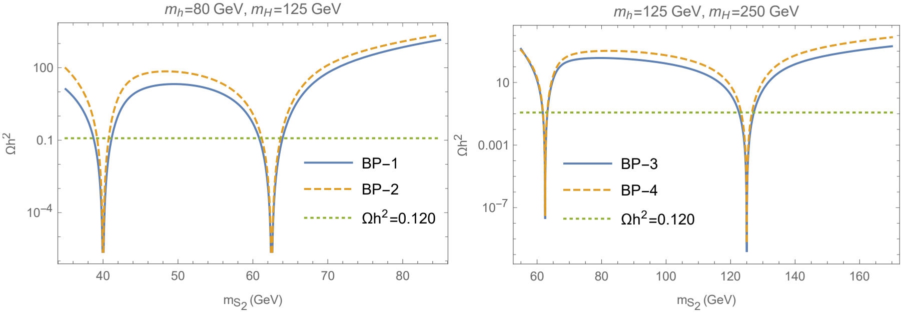
- DM annihilates to SM particles only through scalar portal interactions
- Relevant channels : s-channel diagrams with h and H as propagators and $b\bar{b}$, $\tau\bar{\tau}$, W^+W^-, ZZ, hH, hh and HH as final states
- For DM mass around 40 Gev, dominant contributions to the annihilation cross section will arise from the $b\bar{b}$ and $\tau\bar{\tau}$ channels
- Breit-Wigner resonance : plays an important role in enhancing the velocity averaged cross section of DM-DM annihilation

Dark matter phenomenology : Plot of $w(s)$ vs. m_{S_2}



Plot of $w(s)$ vs. m_{S_2} showing the contribution of $b\overline{b}$ and $\tau\overline{\tau}$ channels. The two resonances correspond to $m_h = 80$ GeV and $m_H = 125$ GeV(left) and $m_h = 125$ GeV and $m_H = 250$ GeV(right)

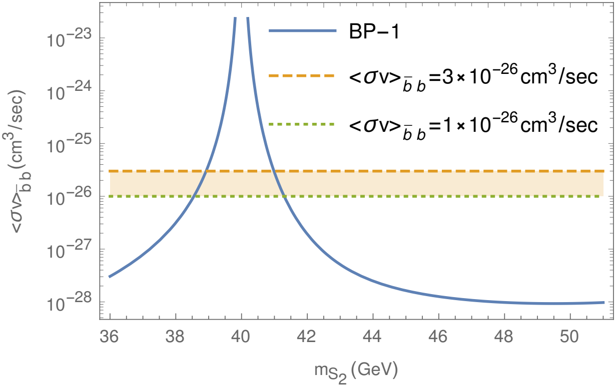
Dark matter phenomenology : Plot of Relic Abundance



Plot of relic abundance as a function of the DM mass. The horizontal dotted line shows the measured value of

$$\Omega h^2 = 0.120 \pm 0.001.$$

Dark matter phenomenology : Gamma ray excess



Enhancement in the $\langle \sigma v \rangle_{b\bar{b}}$ values around resonance, shown here as a function of the dark matter mass.

Conclusion

- we studied a simple scalar extension of the SM with two real singlets S_1 and S_2 with a $Z_2 \times Z_2'$ symmetry
- Z_2' remains unbroken enabling the scalar S_2 to be a viable dark matter candidate
- Coupling λ_{01} is constrained to lie in the $10^{-1} - 10^{-2}$ range, by virtue of vacuum stability
- Direct bounds from the Higgs invisible branching ratios forces $\lambda_{02} \approx 10^{-2} - 10^{-3}$
- Direct detection constraint is relaxed to a great extent by the destructive interference between the two t-channel h and H propagators while the Breit-Wigner resonance helps to get the correct relic abundance
- Two singlet model can also account for the gamma-ray excess for an S_2 in the mass range $36 - 51$ GeV

References

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