Light Scalar Dark Matter and Higgs Physics

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Outline:

- Introduction
- 2HDM$_S$ Model
- Motivations
- Strategy
- Resulting Constraints on the parameter space
- Direct DM detection constraints
- Summary


- A. Drozd, BG, J. F. Gunion and Y. Jiang, "Light Higgs portal DM obeying all experimental constraints, the role of isospin violation", in progress
Introduction

The role of the Higgs field in the Standard Model

- Generation of masses (minimal model for spontaneous gauge symmetry breaking, Higgs mechanism)
- Renormalizability - Unitarity

Experimental problems of the Standard Model

- Baryon asymmetry (too weak CP violation)
- Absence of Dark Matter (DM)

The SM scalar potential:

\[ V(H) = m^2 H^\dagger H + \frac{\lambda}{2} (H^\dagger H)^2 \]

The SM Yukawa couplings:

\[ \mathcal{L}^{(q)}_Y = \bar{Q}_L \tilde{\Gamma} u_R \tilde{H} + \bar{Q}_L \Gamma d_R H + \text{H.c.} \]
Extended scalar sector offers solutions to the problems of the Standard Model

- **Extra real/complex scalar gauge singlet** (DM, no new sources of CP violation)

- **Extra Higgs doublet** (DM and no new sources of CP violation or no DM and new sources of CP violation)
  - N. G. Deshpande and E. Ma, "Pattern of Symmetry Breaking with Two Higgs Doublets", Phys. Rev. D 18, 2574 (1978), ...
  - M. Krawczyk, D. Sokolowska, P. Swaczyna, B. Swiezewska, "Constraining Inert Dark Matter by $R_{\gamma\gamma}$ and WMAP data", JHEP 1309 (2013) 055

- **Extra Higgs doublet together with a real/complex scalar singlet** (DM and new sources of CP violation)

- **Extra two Higgs doublets** (DM and new sources of CP violation)
  - BG, O.M. Ogreid, P. Osland, A. Pukhov, M. Purmohammadi, "Exploring the CP-Violating Inert-Doublet Model” JHEP 1106 (2011) 003
2HDMS model

2HDMS - Yukawa Interactions

- Type I (only $H_2$ couples to fermions)
- Type II ($H_2$ couples to up-type fermions, $H_1$ other)

Symmetry: $Z_2 : H_1 \rightarrow -H_1$, other scalar fields $Z_2$-even

$Z'_2 : S \rightarrow -S$, other fields $Z'_2$-even

$$V = m^2_{11} H^\dagger_1 H_1 + m^2_{22} H^\dagger_2 H_2 - \left[ m^2_{12} H^\dagger_1 H_2 + \text{h.c.} \right] + \frac{\lambda_1}{2} (H^\dagger_1 H_1)^2 + \frac{\lambda_2}{2} (H^\dagger_2 H_2)^2$$

$$+ \lambda_3 (H^\dagger_1 H_1) (H^\dagger_2 H_2) + \lambda_4 (H^\dagger_1 H_2) (H^\dagger_2 H_1) + \left\{ \frac{\lambda_5}{2} (H^\dagger_1 H_2)^2 + \text{h.c.} \right\}$$

$$+ \frac{m^2_0}{2} S^2 + \frac{\lambda_s}{4!} S^4 + \kappa_1 S^2 (H^\dagger_1 H_1) + \kappa_2 S^2 (H^\dagger_2 H_2)$$

EWSB: $Z'_2$ unbroken $\rightarrow$ NO VEV FOR $S \rightarrow$ NO MIXING WITH $H_{1,2}$

$$H_{1,2} = \left( \begin{array}{c} \varphi_{1,2}^+ \\ (\nu_{1,2} + \rho_{1,2} + i \eta_{1,2})/\sqrt{2} \end{array} \right)$$

$$\tan \beta \equiv \frac{\nu_2}{\nu_1}, \quad \nu_1^2 + \nu_2^2 = (246 \text{ GeV})^2$$
Motivations

**2HDMS**

- An attempt to provide both extra CP violation *and* DM candidate - 2HDM minimal model,
- 2HDM provides an interesting "low-mass" new physics accessible at the LHC,
- To have a chance for $M_{DM} < m_h/2$
Motivations

BR(h → SS) ∝ \lambda_x^2 \quad \text{for} \quad V(H, S) = \cdots + \lambda_x H^\dagger HS^2

5 mass eigenstates: \( h, H, A, H^\pm, S \)

\[
V_S = \frac{1}{2} m_S^2 S^2 + \lambda_h v h S^2 + \lambda_H v H S^2 + \cdots 
\]

- 10 parameters in the potential, various basis possible

**General Basis:**
- \( \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \)
- \( m_{12}, \tan \beta \)
- \( m_S, \kappa_1, \kappa_2 \)

**Physical Basis:**
- \( m_h, m_H, m_A, m_{H^\pm}, \sin \alpha \)
- \( m_{12}^2, \tan \beta \)
- \( m_S, \lambda_h, \lambda_H \)

- 2 types of Yukawa interaction

<table>
<thead>
<tr>
<th>Higgs</th>
<th>Type I and II</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_V )</td>
<td>( C_U )</td>
<td>( C_D )</td>
</tr>
<tr>
<td>( h )</td>
<td>( \sin(\beta - \alpha) )</td>
<td>( \cos \alpha / \sin \beta )</td>
<td>( \cos \alpha / \sin \beta )</td>
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</tr>
<tr>
<td>( A )</td>
<td>0</td>
<td>( \cot \beta )</td>
<td>( -\cot \beta )</td>
</tr>
</tbody>
</table>

- theoretical constraints: perturbativity, vacuum stability, perturbative unitarity
- experimental constraints
  - B/LEP limits $H^+$
  - S,T,U
  - LHC fit at 68% CL
2HDM
Take good 2HDM points

Scalar Singlet parameter scan:
- \( m_S \in [1 \text{ GeV, } 1 \text{ TeV}] \),
- \( \lambda_h, \lambda_H \in [-4\pi, 4\pi] \),
- theoretical constraints: perturbativity, vacuum stability, perturbative unitarity, EWSB (\( \langle S \rangle = 0 \)),
- \( BR(h \to SS) < 10\% \),
- WMAP/Planck,
- direct DM detection.
Calculation of DM relic abundance $\Omega$:

$\Omega^{WMAP/Planck} = 0.1187 \pm 0.0017$

Resulting Constraints on the parameter space

\begin{align*}
\tan \beta & = 1.586, \\
\sin \alpha & = -0.587, \\
m_1^2 & = +5621, \\
m_h & = 123.71, \\
m_H & = 534.25, \\
m_A & = 645.13, \\
m_{H^\pm} & = 549.25
\end{align*}

- $h$ fits LHC data
- small $\lambda_h$ required by $\text{BR}(h \to SS) < 10\%$
- substantial $\lambda_H$ needed for $\Omega_{DM}$
- $m_H$ can not be too large

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**TYPE II - isospin violation**

\[
\sigma_{DM-N} = \frac{4\mu^2 Z_A}{\pi} f_p^2 \left[ Z + \frac{f_n}{f_p} (A - Z) \right]^2
\]

\[
BR(h \rightarrow SS) \leq 0.1 \Rightarrow \lambda_h < 0.015
\]

\[
f_n \frac{f_n}{f_p} = \frac{m_n}{m_p} \sum_q \left[ \left( \frac{\lambda_h}{\lambda_H} C_q^h + \left( \frac{m_h}{m_H} \right)^2 C_q^H \right) f_q^n \right] \sum_q \left[ \left( \frac{\lambda_h}{\lambda_H} C_q^h + \left( \frac{m_h}{m_H} \right)^2 C_q^H \right) f_q^p \right]
\]

\[
\frac{m_n}{m_p} \sum_q C_q^H f_q^n \frac{f_q^n}{f_q^p} \Rightarrow \lambda_h < 0.015
\]

**Table:** Yukawa couplings of up and down type quarks to light and heavy Higgs bosons $h, H$ in Type I/II models. The Yukawa Lagrangian is normalised as follows:

\[
\mathcal{L}_{Yukawa} = \frac{m_q}{v} C_q^h \bar{q} q h + \frac{m_q}{v} C_q^H \bar{q} q H
\]

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<td>$C_U^h$</td>
<td>$\cos \alpha / \sin \beta$</td>
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</tr>
<tr>
<td>$C_D^h$</td>
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Direct DM detection constraints

TYPE II - isospin violation

\[ \sigma_{DM-N} = \frac{4 \mu_Z^2}{\pi} f_p A^2 \left[ \frac{Z}{A} + \frac{f_n}{f_p} \left(1 - \frac{Z}{A}\right) \right]^2 \]

\[ \sigma_{DM-p}^{EXP} \geq \sigma_{DM-p}^{THEO} \Theta(f_n, f_p) \]

\[ \Theta(f_n, f_p) = \left[ \frac{Z}{A} + \frac{f_n}{f_p} \left(1 - \frac{Z}{A}\right) \right]^2 \]

Direct DM detection constraints

Type II, $m_h \sim 125$ GeV and $\lambda_h \sim 0$
Type II, $m_h \sim 125$ GeV and $\lambda_h \sim 0$
Direct DM detection constraints

Type II, \( m_H \approx 125 \text{ GeV} \) and \( \lambda_H \approx 0 \)
Conclusions

- 2HDM is allowed by current collider limits, even in the non-decoupling regime
- 2HDMS provides a viable DM candidate and an opportunity for extra CP-violation
- $\Omega_{DM}h^2$ and LUX requirements are met for $m_{DM} \lesssim 50$ GeV within the Type II 2HDMS if
  - $h(H)$ is the state observed at the LHC
  - $\lambda_h(\lambda_H) \ll 1$ then $BR[h(H) \rightarrow SS] \ll 1$
  - $H, h$ responsible for DM annihilation with $\lambda_H(\lambda_h) \sim 1$
  - LUX limit satisfied by isospin violation: $f_n/f_p < 1$ (or by resonance in the case of $m_H = 125$ GeV)
- LHC prospects for the Type II 2HDMS with isospin violation:
  - $H(h)$ invisible, as $BR(H \rightarrow SS) \sim 1$ or $BR(h \rightarrow SS) \sim 1$
  - $(\tan \beta, \sin \alpha)$ fixed (h(H) Yukawa’s MS like)
  - $m_{H^\pm} \gtrsim 320$ GeV
  - $A$ and $H^\pm$ interactions have to be investigated