Natural Multi-Higgs Model with Dark Matter

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Outline

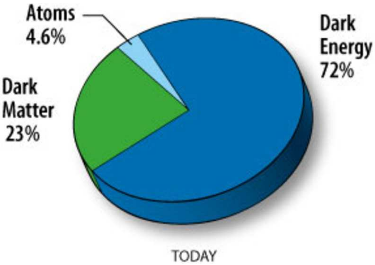
What is really out there? And of what is it all made?

- WMAP and dark matter
- Gravitational lensing

Comparing the visible and baryonic as well as total matter density lead to:

$$\Omega_{\text{visible}} < \Omega_b < \Omega$$

It follows the fact that there must be both baryonic and non-baryonic dark matter in the universe.



Dark matter candidates are usually split into two categories;

Baryonic, MACHOs:

- Brown Dwarfs, Neutron Stars
- Black Holes

Non-Baryonic, WIMPs:

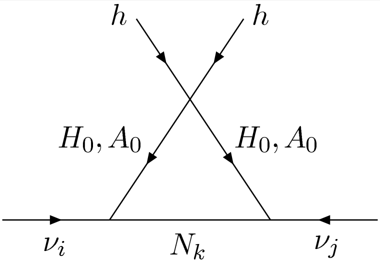
- Hot dark matter
  - Massive neutrinos
- Cold dark matter
  - Spin $\frac{1}{2}$ supersymmetric fields. The most acclaimed one is neutralino.
  - Spin 1, the lightest Klauze-Klein gauge bososn, KK-photon.
  - Spin 0 particles, the SM plus an extra scalar, IDM.

Scalar dark matter model:

- The central density profile of structure is not flat.
- In the prediction of a non-observed amount of small structure

It is assumed that the dark matter is made of a light spinless particle known as scalar dark matter, SDM. It requires the existence of a fundamental scalar field, spinless boson as a dark matter candidate.

To explain mass mechanism for the neutrinos



Scalar dark matter model:

$$\Phi_1(x) = \begin{pmatrix} \phi^+(x) \\ \frac{v+h(x)+i\sigma(x)}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2(x) = \begin{pmatrix} H^+(x) \\ \frac{H^0(x)+iA^0(x)}{\sqrt{2}} \end{pmatrix}$$

$$\Phi_2 \xrightarrow{Z_2} -\Phi_2$$

Scalar vacuum:

$$\langle\Phi_1(x)\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \langle\Phi_2(x)\rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- Considering light S, Higgs could be heavy without contradicting the LEP precision measurments.

Allowed regions:

- Low regime, $M_{H_0} \lesssim M_W$
- Middle regime, $M_W \lesssim M_{H_0} \lesssim M_h$
- Heavy regime, $M_{H_0} \gtrsim M_W$

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Natural Multi-Higgs Model with CP violation and dark matter

IDM2

- The 2HDM, non inert, sector;

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ (v_1 + \eta_1 + i\chi_1)/\sqrt{2} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ (v_2 + \eta_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

- $$\eta = \begin{pmatrix} \eta^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}.$$

- $$V(\Phi_1, \Phi_2, \eta) = V_{12}(\Phi_1, \Phi_2) + V_3(\eta) + V_{123}(\Phi_1, \Phi_2, \eta)$$

- $$Z_2' : \quad \Phi_1 \to -\Phi_1 \quad \text{and} \quad u_R \to -u_R$$

- $$Z_2 : \quad \eta \to -\eta$$

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Unbroken Z_2, then no mixing in mass terms between $\Phi_{1,2}$ and η.

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- $$V_{12}(\Phi_1,\Phi_2) = -\frac{1}{2}\{m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]\} + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

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$$+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

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$$\begin{aligned} V_{123}(\Phi_1, \Phi_2, \eta) = {} & \lambda_{1133}(\Phi_1^\dagger \Phi_1)(\eta^\dagger \eta) + \lambda_{2233}(\Phi_2^\dagger \Phi_2)(\eta^\dagger \eta) \\ & + \lambda_{1331}(\Phi_1^\dagger \eta)(\eta^\dagger \Phi_1) + \lambda_{2332}(\Phi_2^\dagger \eta)(\eta^\dagger \Phi_2) \\ & + \frac{1}{2}\left[\lambda_{1313}(\Phi_1^\dagger \eta)^2 + \text{h.c.}\right] + \frac{1}{2}\left[\lambda_{2323}(\Phi_2^\dagger \eta)^2 + \text{h.c.}\right] \end{aligned}$$

Dark democracy:

$$\lambda_a \equiv \lambda_{1133} = \lambda_{2233}$$
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The masses can be written as:

$$M^2_{\eta^\pm} = m^2_\eta + \frac{1}{2}\lambda_a v^2$$
$$M^2_S = m^2_\eta + \frac{1}{2}(\lambda_a + \lambda_b + \lambda_c)v^2 = M^2_{\eta^\pm} + \frac{1}{2}(\lambda_b + \lambda_c)v^2$$
$$M^2_A = m^2_\eta + \frac{1}{2}(\lambda_a + \lambda_b - \lambda_c)v^2 = M^2_{\eta^\pm} + \frac{1}{2}(\lambda_b - \lambda_c)v^2$$

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$$\lambda_a = \frac{2}{v^2}\left(M^2_{\eta^\pm} - m^2_\eta\right)$$
$$\lambda_b = \frac{1}{v^2}\left(M^2_S + M^2_A - 2M^2_{\eta^\pm}\right)$$
$$\lambda_c = \frac{1}{v^2}\left(M^2_S - M^2_A\right)$$

Theoretical constraints:

- CP violation

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  - Not imposing CP conservation on the neutral Higgs sector
  - Basis-independent approach of Gunion and Haber

$$\Im J_1 = -\frac{v_1^2 v_2^2}{v^4}(\lambda_1 - \lambda_2)\Im\lambda_5$$

$$\Im J_2 = -\frac{v_1^2 v_2^2}{v^8}[\left((\lambda_1 - \lambda_3 - \lambda_4)^2 - |\lambda_5|^2\right) v_1^4 + 2(\lambda_1 - \lambda_2)\Re\lambda_5 v_1^2 v_2^2 - \left((\lambda_2 - \lambda_3 - \lambda_4)^2 - |\lambda_5|^2\right) v_2^4]\Im\lambda_5$$

$$\Im J_3 = \frac{v_1^2 v_2^2}{v^4}(\lambda_1 - \lambda_2)(\lambda_1 + \lambda_2 + 2\lambda_4)\Im\lambda_5$$

  - $\Im\lambda_5 \neq 0$ with $\lambda_1 = \lambda_2$ and $v_1 = v_2$

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  The potential should be bounded from below.

$$V(\Phi_1, \Phi_2, \eta) = V_{12}(\Phi_1, \Phi_2) + V_3(\eta) + V_{123}(\Phi_1, \Phi_2, \eta)$$

  $V_{12}(\Phi_1, \Phi_2)$, $V_3(\eta)$ and $V_{123}(\Phi_1, \Phi_2, \eta)$ are required to satisfy positivity individually.

- For simple case of dark democracy

$$\lambda_a \geq \max(0, -2\lambda_b, -\lambda_b \pm \lambda_c)$$

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- Unitarity and perturbativity.
- The little hierarchy.

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Experimental constraints:

Charged Higgs sector

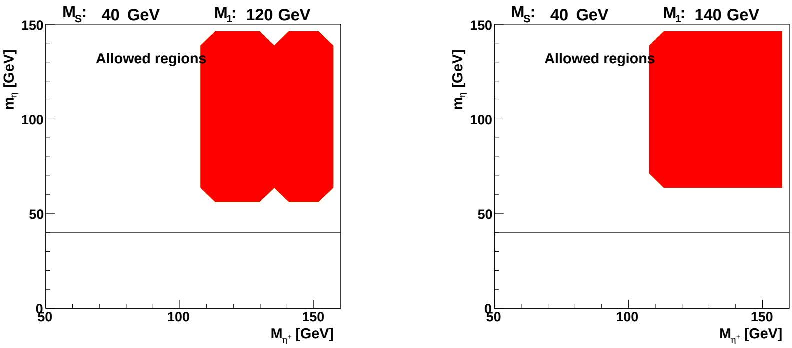
- $B \longrightarrow X_s\gamma$: Low values of $\tan\beta$ and low $M_\pm$.
- $B_0 - \bar{B}_0$ mixing.
- $B \longrightarrow \tau\bar{\nu}_\tau X$.
- $B \longrightarrow D\tau\bar{\nu}_\tau$.

Neutral-Higgs sector

- LEP2
- Bounds stemming from the **T** and **S** parameters measurements
- Electron electric dipole moment

Dark matter

$$\Omega h^2 = 0.1131 \pm 0.0034$$


M_S: 40 GeV
M_1: 120 GeV
Allowed regions
m_η [GeV]
$M_{\eta^\pm}$ [GeV]
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M_1: 140 GeV
Allowed regions
m_η [GeV]
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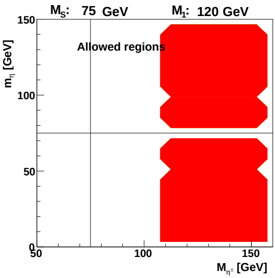
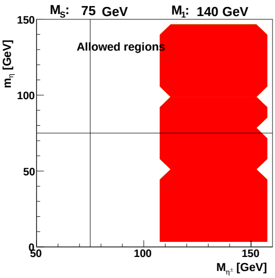
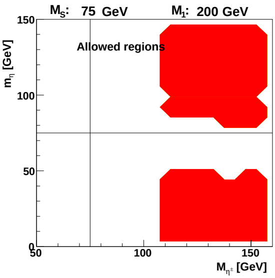
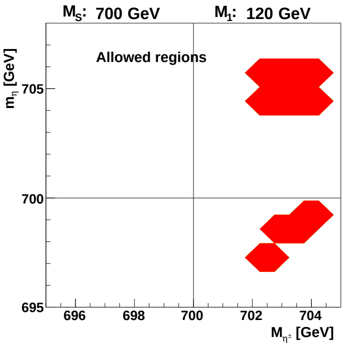
Constraints





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M_1: 120 GeV
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695
700
705
696
698
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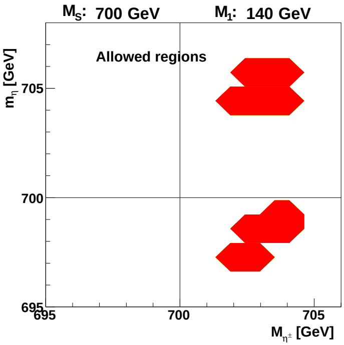
702
704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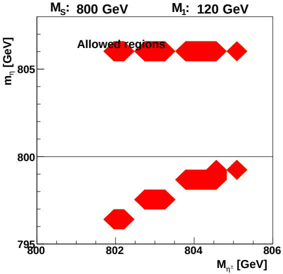
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800
795
800
802
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806
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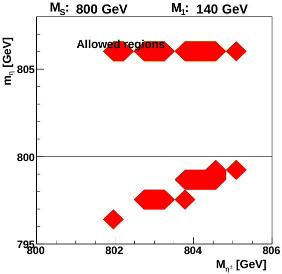
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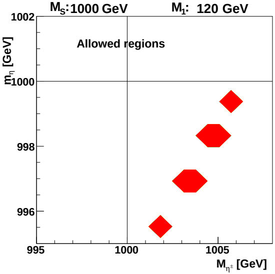
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995
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The decay of DM is forbidden by the conservation of some quantum numbers.

For different dark profiles:

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$M_s = 40\ Gev$	$SS \longrightarrow b\bar{b}$	$SS \longrightarrow b\bar{b}$
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$M_s = 700\ Gev$	$SS \longrightarrow W^+W^-/ZZ$	$SS \longrightarrow W^+W^-/ZZ$
	$\eta_+\eta_- \longrightarrow W^+W^-$	$\eta_+\eta_- \longrightarrow W^+W^-$
$M_s = 800\ Gev$	$SS \longrightarrow W^+W^-/ZZ$	$SS \longrightarrow W^+W^-/ZZ$
	$\eta_+\eta_- \longrightarrow W^+W^-$	$\eta_+\eta_- \longrightarrow W^+W^-$
$M_s = 1000\ Gev$	$SS \longrightarrow W^+W^-$	$SS \longrightarrow W^+W^-$
$M_s = 2\ Tev$		

	$mh_1 = 200Gev$
$M_s = 75\ Gev$	$SS \longrightarrow W^+W^-$

The decay of DM is forbidden by the conservation of some quantum numbers.

For different dark profiles:

	$mh_1 = 120Gev$	$mh_1 = 140Gev$
$M_s = 40\ Gev$	$SS \longrightarrow b\bar{b}$	$SS \longrightarrow b\bar{b}$
$M_s = 75\ Gev$	$SS \longrightarrow W^+W^-$	$SS \longrightarrow W^+W^-$
$M_s = 700\ Gev$	$SS \longrightarrow W^+W^-/ZZ$	$SS \longrightarrow W^+W^-/ZZ$
	$\eta_+\eta_- \longrightarrow W^+W^-$	$\eta_+\eta_- \longrightarrow W^+W^-$
$M_s = 800\ Gev$	$SS \longrightarrow W^+W^-/ZZ$	$SS \longrightarrow W^+W^-/ZZ$
	$\eta_+\eta_- \longrightarrow W^+W^-$	$\eta_+\eta_- \longrightarrow W^+W^-$
$M_s = 1000\ Gev$	$SS \longrightarrow W^+W^-$	$SS \longrightarrow W^+W^-$
$M_s = 2\ Tev$		

	$mh_1 = 200Gev$
$M_s = 75\ Gev$	$SS \longrightarrow W^+W^-$

Summary:

- We have explored an extension of the IDM by replacing the SM Higgs doublet sector by a THDM.
- The inert sector of IDM2 has 4 scalars, and 3 ordinary neutral scalars and an accompanying pair of charged ones.
- In order to guarantee stability of the DM candidate we impose an extra symmetry.
- Adopting the code microMEGAs, all relevant theoretical and experimental constraints have been checked and solutions have been found both for light as well as heavy DM particles .
- The splitting between the masses of the charged and neutral scalars turn out to be small in order to reproduce the right amount of the DM.
- In the the case of heavier DM the splitting is tiny implying nearly vanishing contribution to the T parameter.
- In this approach the little hierarchy problem is softened by increasing the Higgs boson masses, this is possible mainly through the 2HDM sector alone.

The work is in progress.

Thank you!