

Light scalar dark matter by double Higgs portal

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"Portorož 2015"

Particle Phenomenology from the Early Universe to High Energy Colliders
April 7th, 2015, Portorož, Slovenia

Outline:

- 2HDMS Model
- Motivations
- Strategy
- Resulting Constraints on the parameter space
- Direct DM detection constraints
- Summary

- A. Drozd, B. G., J. F. Gunion and Y. Jiang, "Extending two-Higgs-doublet models by a singlet scalar field - the Case for Dark Matter", JHEP 1411 (2014) 105, arXiv:1408.2106.
- A. Drozd, B. G., J. F. Gunion and Y. Jiang, "Light Higgs portal DM obeying all experimental constraints, the role of isospin violation", in progress

2HDM_S model

2HDM_S - 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

$$\begin{aligned} \mathcal{V} = & m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - [m_{12}^2 H_1^\dagger H_2 + \text{h.c.}] + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 \\ & + \lambda_3 (H_1^\dagger H_1) (H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2) (H_2^\dagger H_1) + \left\{ \frac{\lambda_5}{2} (H_1^\dagger H_2)^2 + \text{h.c.} \right\} \\ & + \frac{m_0^2}{2} S^2 + \frac{\lambda_S}{4!} S^4 + \kappa_1 S^2 (H_1^\dagger H_1) + \kappa_2 S^2 (H_2^\dagger H_2) \end{aligned}$$

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

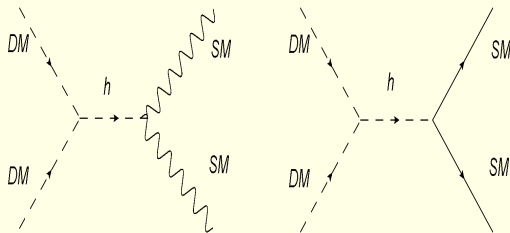
$$H_{1,2} = \begin{pmatrix} \varphi_{1,2}^+ \\ (v_{1,2} + \rho_{1,2} + i\eta_{1,2})/\sqrt{2} \end{pmatrix} \quad \tan \beta \equiv \frac{v_2}{v_1}, \quad v_1^2 + v_2^2 = (246 \text{ GeV})^2$$

Literature

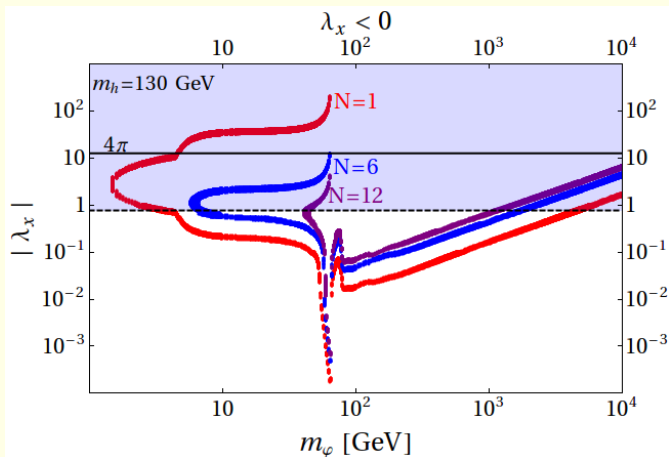
- X.-G. He, T. Li, X.-Q. Li, J. Tandean and H.-C. Tsai, *Constraints on scalar dark matter from direct experimental searches*, Phys. Rev. D 79 (2009) 023521 [arXiv:0811.0658].
- B. G. and P. Osland, *Tempered two-Higgs-doublet model*, Phys. Rev. D 82 (2010) 125026 [arXiv:0910.4068].
- A. Badin and A. A. Petrov, *Searching for light Dark Matter in heavy meson decays*, Phys. Rev. D 82 (2010) 034005 [arXiv:1005.1277 [hep-ph]].
- M.S. Boucenna and S. Profumo, *Direct and indirect singlet scalar dark matter detection in the lepton-specific two-Higgs-doublet model*, Phys. Rev. D 84 (2011) 055011 [arXiv:1106.3368].
- X.-G. He, B. Ren and J. Tandean, *Hints of standard model Higgs boson at the LHC and light dark matter searches*, Phys. Rev. D 85 (2012) 093019 [arXiv:1112.6364].
- Y. Bai, V. Barger, L.L. Everett and G. Shaughnessy, *Two-Higgs-doublet-portal dark-matter model: LHC data and Fermi-LAT 135 GeV line*, Phys. Rev. D 88 (2013) 015008 [arXiv:1212.5604].
- X.-G. He and J. Tandean, *Low-mass dark-matter hint from CDMS II, Higgs boson at the LHC and darkon models*, Phys. Rev. D 88 (2013) 013020 [arXiv:1304.6058].
- Y. Cai and T. Li, *Singlet dark matter in a type-II two Higgs doublet model*, Phys. Rev. D 88 (2013) 115004 [arXiv:1308.5346].
- L. Wang, *A simplified 2HDM with a scalar dark matter and the galactic center gamma-ray excess*, arXiv:1406.3598.
- C.-Y. Chen, M. Freid and M. Sher, *The next-to-minimal two Higgs doublet model*, Phys. Rev. D 89 (2014) 075009 [arXiv:1312.3949].

2HDMs

- An attempt to provide both extra CP violation *and* DM candidate - 2HDMs 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



$$BR(h \rightarrow SS) \propto \lambda_x^2 \quad \text{for} \quad V(H, S) = \dots + \lambda_x H^\dagger H S^2$$

A. Drozd, B.G. and J. Wudka, "Multi-scalar-singlet extension of the Standard Model - the case for dark matter and an invisible higgs boson", JHEP 1204 (2012) 006, arXiv:1112.2582

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

$$V_S = \frac{1}{2} m_S^2 S^2 + \lambda_h v h S^2 + \lambda_H v H S^2 + \dots$$

- 10 parameters in the potential, various basis possible

General Basis:

- $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$
- $m_{12}^2, \tan \beta$
- m_S, κ_1, κ_2

Physical Basis:

- $m_h, m_H, m_A, m_{H^\pm}, \sin \alpha$
- $m_{12}^2, \tan \beta$
- $m_S, \lambda_h, \lambda_H$

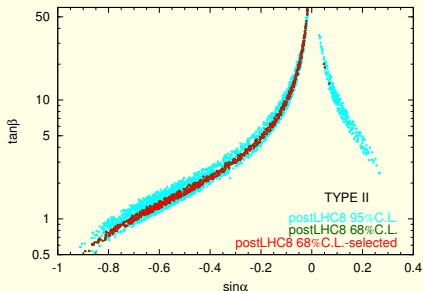
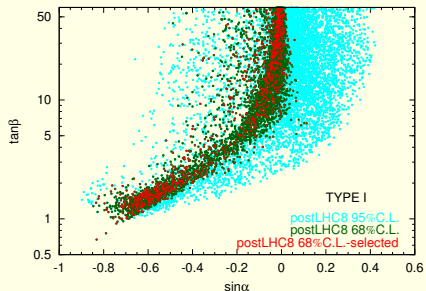
- 2 types of Yukawa interaction

	Type I and II	Type I		Type II	
Higgs	C_V	C_U	C_D	C_U	C_D
h	$\sin(\beta - \alpha)$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$
H	$\cos(\beta - \alpha)$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$
A	0	$\cot \beta$	$-\cot \beta$	$\cot \beta$	$\tan \beta$

Strategy

B. Dumont, J. F. Gunion, Y. Jiang and S. Kraml, "Constraints on and future prospects for Two-Higgs-Doublet Models in light of the LHC Higgs signal", Phys. Rev. D **90**, 035021 (2014), arXiv:1405.3584

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



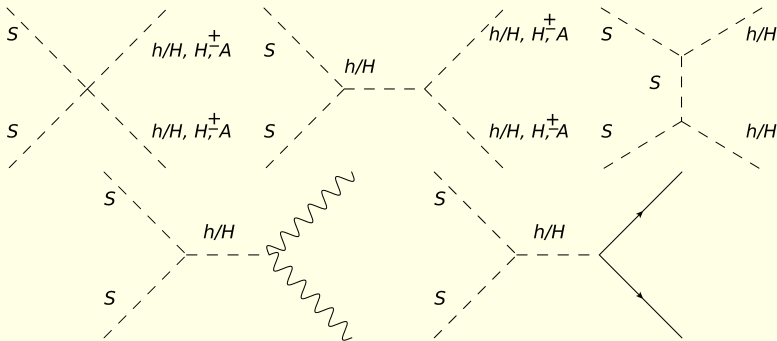
2HDM

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 ($\langle S \rangle = 0$),
- $BR(h \rightarrow SS) < 10\%$,
- WMAP/Planck,
- direct DM detection.

Strategy

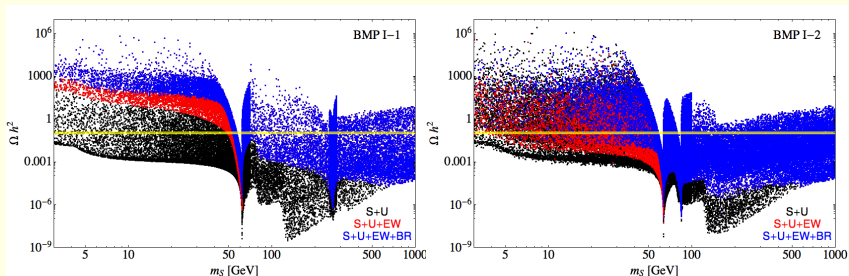


Calculation of DM relic abundance Ω :

MicrOmegas by G. Belanger, F. Boudjema, A. Pukhov, A. Semenov, Comput.Phys.Commun. 180 (2009) 747-767, arXiv:0803.2360

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

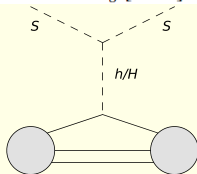
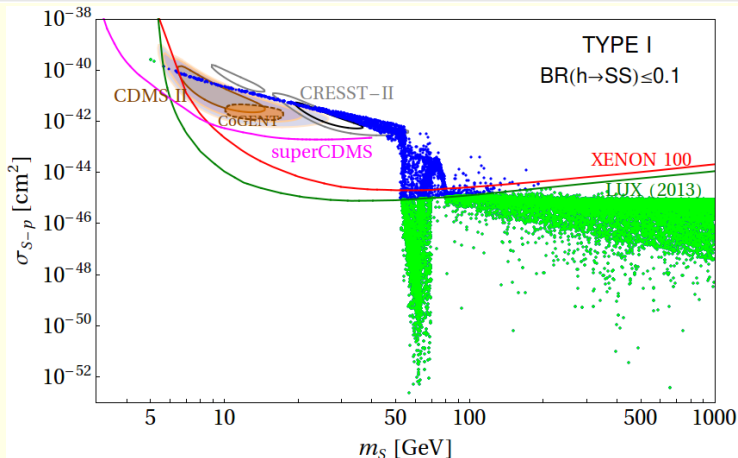
Resulting Constraints on the parameter space



#	$\tan \beta$	$\sin \alpha$	m_{12}^2	m_h	m_H	m_A	m_{H^\pm}
I-1	1.586	-0.587	+5621	123.71	534.25	645.13	549.25
I-2	1.346	-0.663	-2236	126.49	168.01	560.92	556.94

- small λ_h required by $BR(h \rightarrow SS) < 10\%$,
- substantial λ_H needed for Ω_{DM} ,
- m_H can not be too large,
- h fits LHC data!

Direct DM detection constraints



Direct DM detection constraints

TYPE II - isospin violation

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

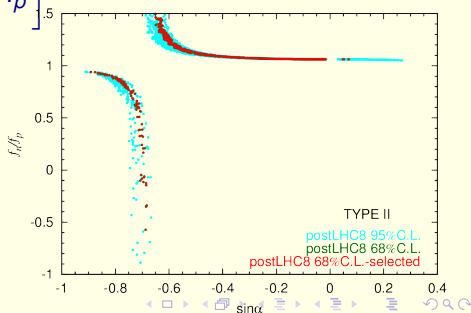
$$BR(h \rightarrow SS) \leq 0.1 \Rightarrow \lambda_h < 0.015$$

$$\frac{f_n}{f_p} = \frac{m_n \sum_q \left[\left(\frac{\lambda_h}{\lambda_H} C_q^h + \left(\frac{m_h}{m_H} \right)^2 C_q^H \right) f_n^q \right]}{m_p \sum_q \left[\left(\frac{\lambda_h}{\lambda_H} C_q^h + \left(\frac{m_h}{m_H} \right)^2 C_q^H \right) f_p^q \right]} \rightarrow \frac{m_n \sum_q C_q^H f_n^q}{m_p \sum_q C_q^H f_p^q} \quad (\text{S - indep.})$$

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:

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

	Type I	Type II
C_U^h	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$
C_U^H	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$
C_D^h	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$
C_D^H	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$



Direct DM detection constraints

TYPE II - isospin violation

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

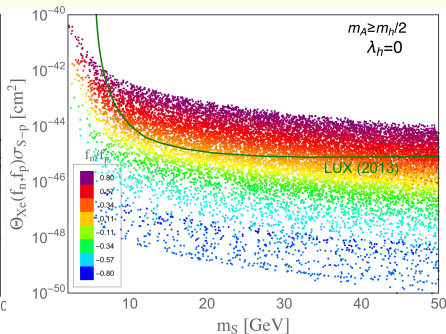
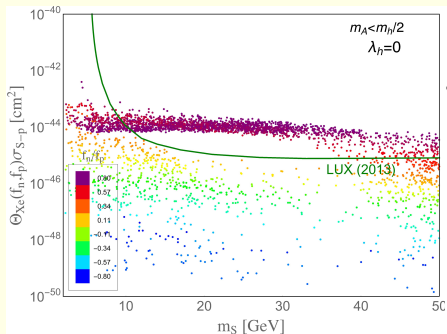
$$\sigma_{DM-p}^{EXP} \geq \sigma_{DM-p}^{THEO} \Theta(f_n, f_p)$$

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

J. L. Feng, J. Kumar, D. Marfatia and D. Sanford, "Isospin-Violating Dark Matter", Phys. Lett. B **703**, 124 (2011) [arXiv:1102.4331]

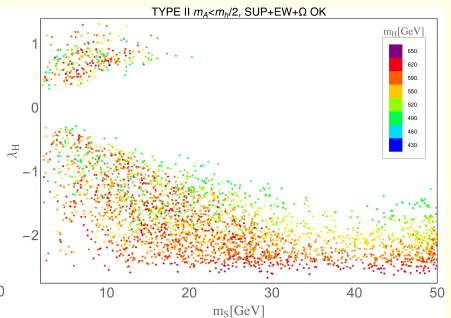
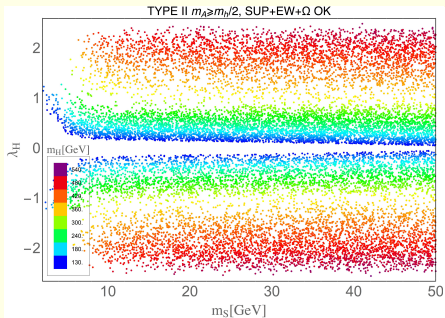
Direct DM detection constraints

Type II, $m_h \simeq 125$ GeV and $\lambda_h \simeq 0$



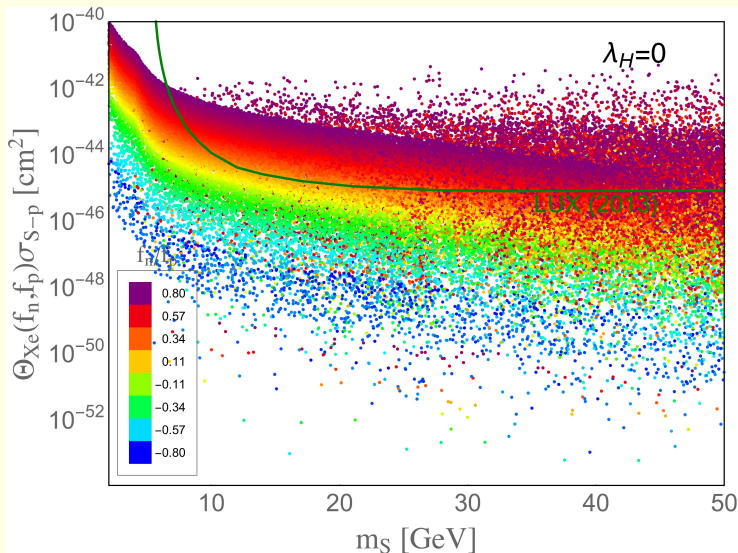
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Direct DM detection constraints

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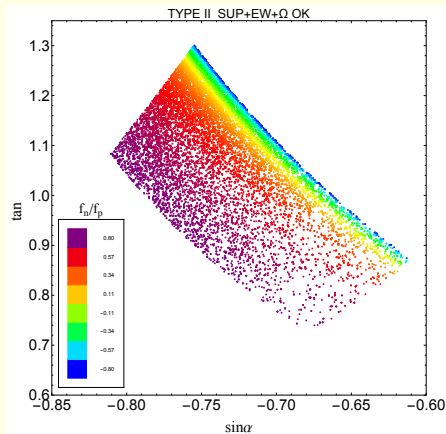


Conclusions

- 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

Direct DM detection constraints

$$m_h \simeq 125 \text{ GeV} \quad \lambda_h \simeq 0$$



Theoretical constraints - Vacuum stability

2HDM Tree Level Vacuum Stability Constraints

- $\lambda_1, \lambda_2 > 0$
- $\lambda_3 > -\sqrt{\lambda_1 \lambda_2}$
- $\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}$
- $\lambda_3 > -\sqrt{\lambda_1 \lambda_2}$

Scalar Singlet Tree Level Vacuum Stability Constraints

- $\lambda_S > 0$
- $\kappa_1 > -\sqrt{\frac{1}{12} \lambda_1 \lambda_S}$
- $\kappa_2 > -\sqrt{\frac{1}{12} \lambda_2 \lambda_S}$
- if $\kappa_1 < 0$ or $\kappa_2 < 0$ then
 - $-2\kappa_1 \kappa_2 + \frac{1}{6} \lambda_S \lambda_3 > -\sqrt{4(\frac{1}{12} \lambda_1 \lambda_S - \kappa_1^2)(\frac{1}{12} \lambda_2 \lambda_S - \kappa_2^2)}$
 - $-2\kappa_1 \kappa_2 + \frac{1}{6} \lambda_S (\lambda_3 + \lambda_4 - |\lambda_5|) > -\sqrt{4(\frac{1}{12} \lambda_1 \lambda_S - \kappa_1^2)(\frac{1}{12} \lambda_2 \lambda_S - \kappa_2^2)}$