Extending 2HDM by a singlet scalar field - the case for dark matter -

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Outline:

- 2HDMS Model
- Motivations
- Strategy
- Resulting Constraints on the parameter space
- Direct DM detection constraints
- New Higgs physics at the LHC?
- 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.

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: $Z_2 : H_1 \to -H_1$, other scalar fields Z_2-even
$Z_2' : S \to -S$, other fields Z_2'-even

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

EWSB: Z_2' unbroken $\to$ NO VEV FOR S $\to$ NO MIXING WITH $H_{1,2}$

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

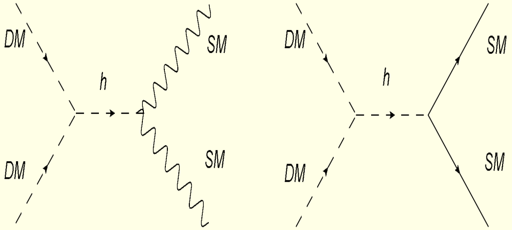
Literature

- 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].
- 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].

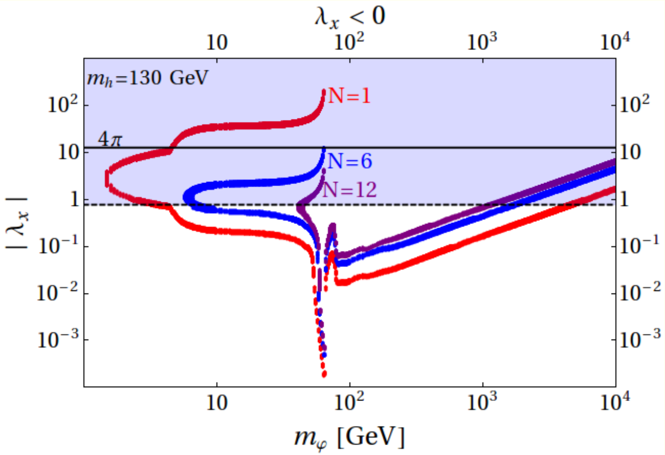
Motivations

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



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

Strategy

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}^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, λ_h, λ_H

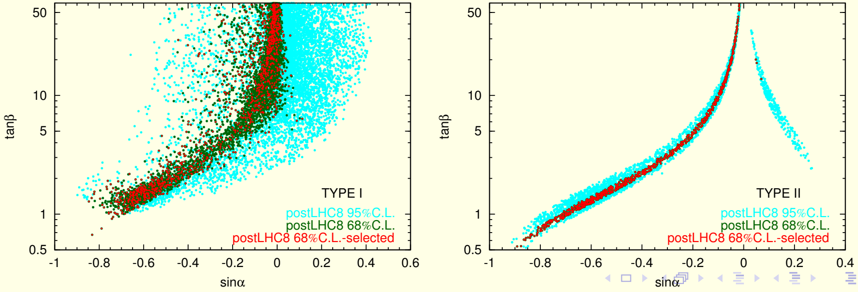
- 2 types of Yukawa interaction

	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
  - heavy Higgs searches
  - LHC fit at 68% CL



Strategy

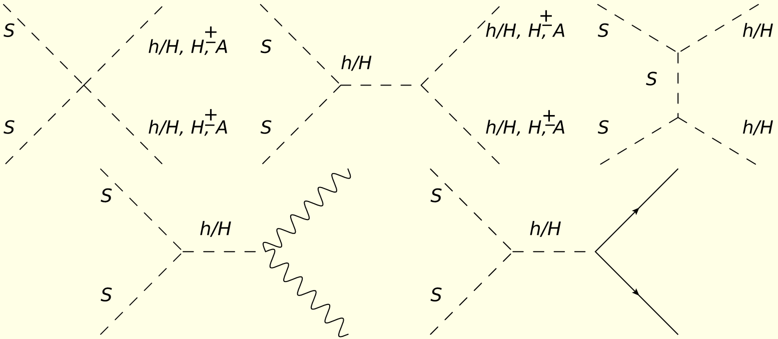
2HDM

Take good 2HDM points

Scalar Singlet parameter scan:

- $m_S \in$ [1 GeV, 1 TeV],
- λ_h, $\lambda_H \in$ [-4π, 4π],
- theoretical constraints: perturbativity, vacuum stability, perturbative unitarity, EWSB ($\langle S \rangle = 0$),
- $BR(h \to SS) < 10\%$,
- WMAP/Planck,
- direct DM detection.

Strategy

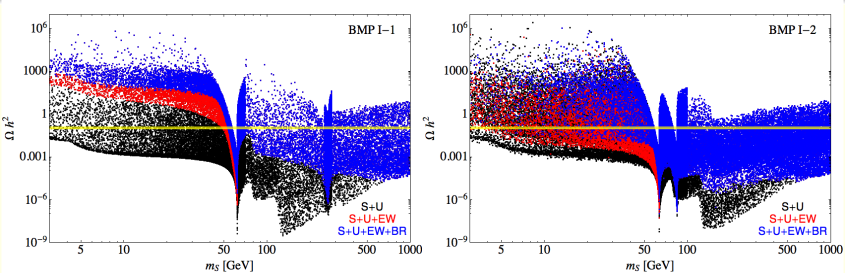


Calculation of DM relic abundance Ω:

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

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

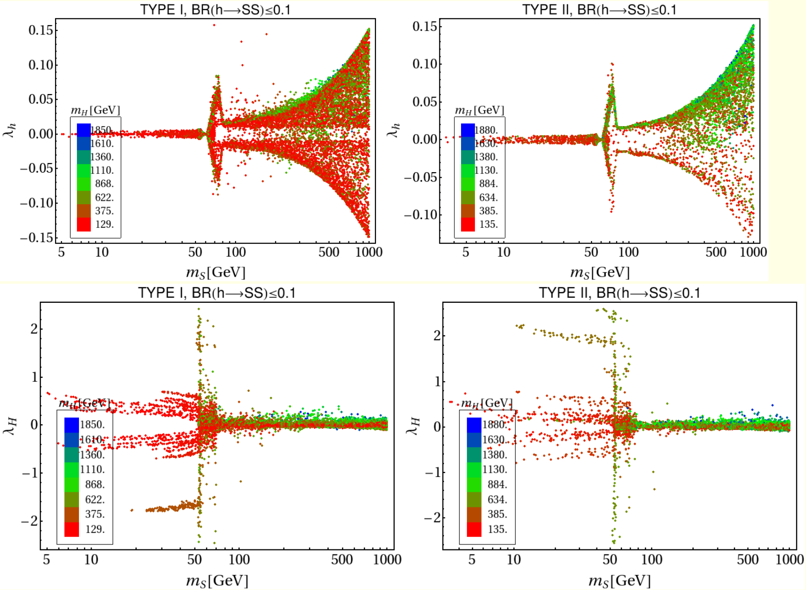
Resulting Constraints on the parameter space



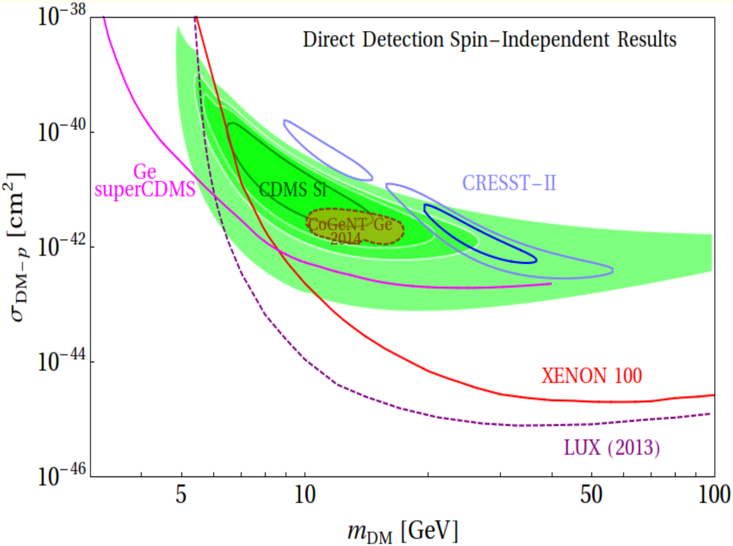
#	$\tan\beta$	$\sin\alpha$	m_{12}^2	m_h	m_H	m_A	$m_{H^\pm}$
I-1	1.586	-0.587	$+5621$	123.71	534.25	645.13	549.25
I-2	1.346	-0.663	-2236	126.49	168.01	560.92	556.94

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

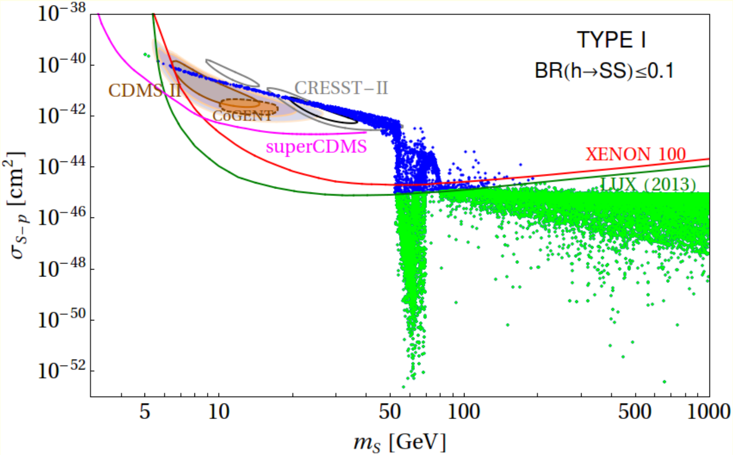
Resulting Constraints on the parameter space

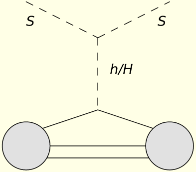


Direct DM detection constraints



Direct DM detection constraints





Direct DM detection constraints

TYPE II - isospin violation

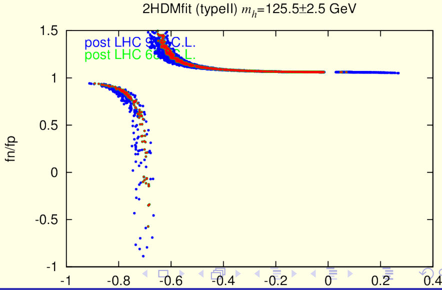
$$\sigma_{DM-N} = \frac{4\mu^2_{Z_A}}{\pi} f_p^2 \left[Z + \frac{f_n}{f_p}(A - Z) \right]^2$$

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

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

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

	Type I	Type II
ξ_h^u	$\cos\alpha / \sin\beta$	$\cos\alpha / \sin\beta$
ξ_h^d	$\cos\alpha / \sin\beta$	$-\sin\alpha / \cos\beta$
ξ_H^u	$\sin\alpha / \sin\beta$	$\sin\alpha / \sin\beta$
ξ_H^d	$\sin\alpha / \sin\beta$	$\cos\alpha / \cos\beta$



Direct DM detection constraints

TYPE II - isospin violation

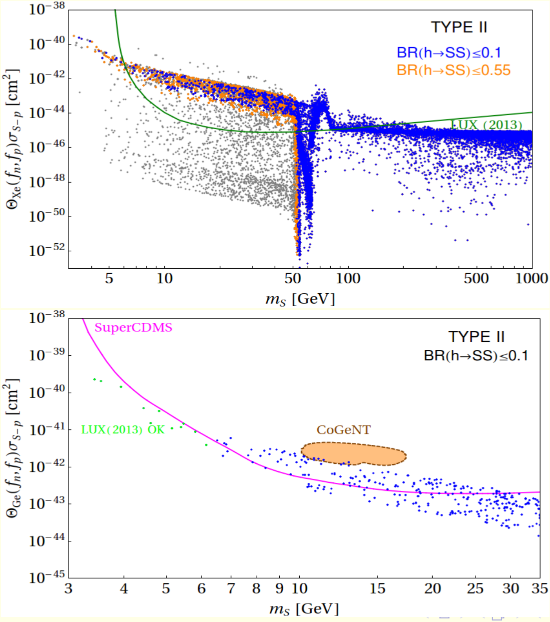
$$\sigma_{DM-N} = \frac{4\mu^2_{Z_A}}{\pi} f_p^2 A^2 \left[\frac{Z}{A} + \frac{f_n}{f_p}\left(1 - \frac{Z}{A}\right)\right]^2$$

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

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

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



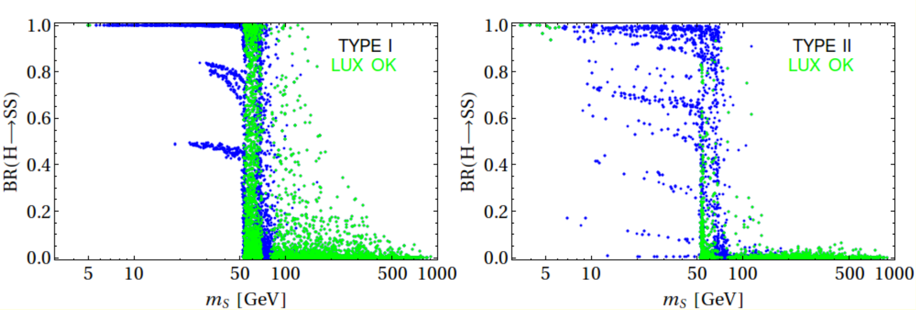
Direct DM detection constraints

$\tan\beta$	$\sin\alpha$	m_H	m_A	$m_{H\pm}$	m_{12}^2	m_S
2.092	-0.41	138	451	399	-12642	3.44; 3.56; 3.95
3.121	-0.282	187	546	571	8943	4.82; 5.48
2.192	-0.394	209	488	503	7518	5.40
1.728	-0.476	177	318	389	9382	5.16
1.789	-0.461	198	420	430	-6594	4.44; 5.15
1.488	-0.528	157	553	576	-10094	4.61
2.375	-0.363	259	260	339	15899	5.83

Table: Summary of the properties of the 2HDM Type II points which make it possible to realize $m_S < 50$ GeV in agreement with within 99% CL for CDMS II imposing the full set of constraints including the LUX and SuperCDMS bounds and. All masses are given in GeV units.

$H \to SS$ decay - invisible H!

$m_H \sim 130 - 200$ GeV



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
- LUX requires $m_S \gtrsim 50$ GeV (TYPE I, II) or together with SuperCDMS $m_S \lesssim 6$ GeV (TYPE II)
- CDMS II reqiures $|\lambda_h| < 0.05$, $|\lambda_H| > 0.1$, and implies large $BR(H \to SS)$ (TYPE I, II)
- A fit of 2HDMS to LUX, superCDMS and CDMS II is only possible within 99% CL for CDMS II, for TYPE II model,then $m_s \sim 3.4 - 5.8$ GeV. For those points $BR(H \to SS) \gtrsim 90\%$