Light Scalar Dark Matter and Higgs Physics

Bohdan Grzadkowski
University of Warsaw

"Astroparticle Physics in Poland 2015"
May 12^{th}, 2015, Warsaw

Outline:

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

- A. Drozd, BG, 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, 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:

$$\mathcal{L}_Y^{(q)} = \bar{Q}_L \tilde{\Gamma} u_R \tilde{H} + \bar{Q}_L \Gamma d_R H + \text{H.c.}$$

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)
  - V. Silveira, A. Zee, "Scalar Phantoms", Phys. Lett. B161, 136 (1985), . . .
  - A. Drozd, BG, J. Wudka, "Multi-Scalar-Singlet Extension of the Standard Model - the Case for Dark Matter and an Invisible Higgs Boson", JHEP 1204 (2012) 006, JHEP 1411 (2014) 130
- 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)
  - BG, P. Osland, "Tempered Two-Higgs-Doublet Model", Phys.Rev. D82 (2010) 125026
  - A. Drozd, BG, 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
  - C. Bonilla, D. Sokolowska, J. Lorenzo Diaz-Cruz, M. Krawczyk, N. Darvishi, "IDMS: Inert Dark Matter Model with a complex singlet", e-Print: arXiv:1412.8730
- Extra two Higgs doublets (DM and new sources of CP violation)
  - BG, O.M. Ogreid, P. Osland, "Natural Multi-Higgs Model with Dark Matter and CP Violation" Phys.Rev. D80 (2009) 055013
  - 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: $Z_2 : H_1 \to -H_1$, other scalar fields Z_2-even
$Z_2' : S \to -S$, other fields Z_2'-even

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

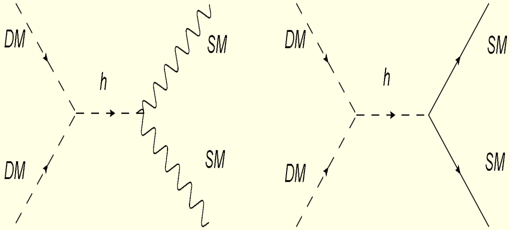
EWSB: Z_2' unbroken $\to$ NO VEV FOR S $\to$ NO MIXING WITH $H_{1,2}$

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

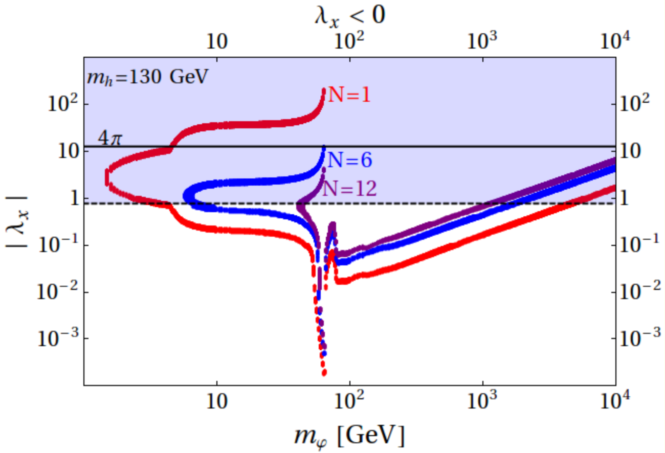
Motivations

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



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

A. Drozd, BG 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

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

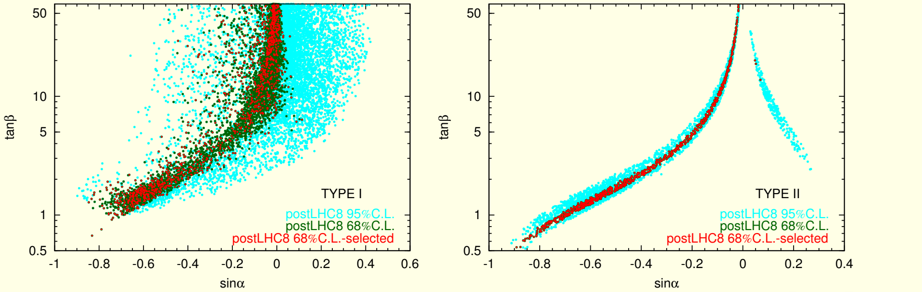
- 2 types of Yukawa interaction

	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
  - LHC fit at 68% CL



Strategy

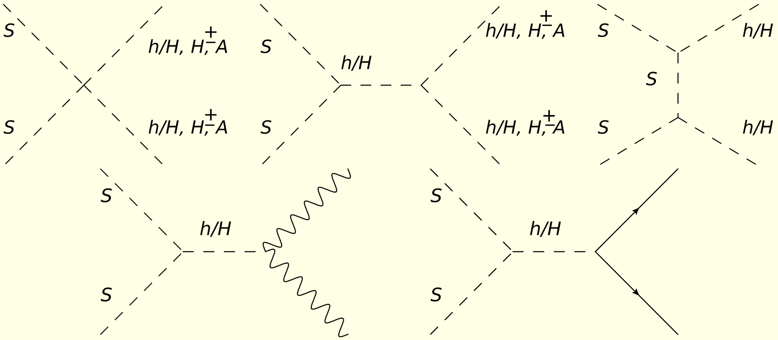
2HDM

Take good 2HDM points

Scalar Singlet parameter scan:

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

Strategy

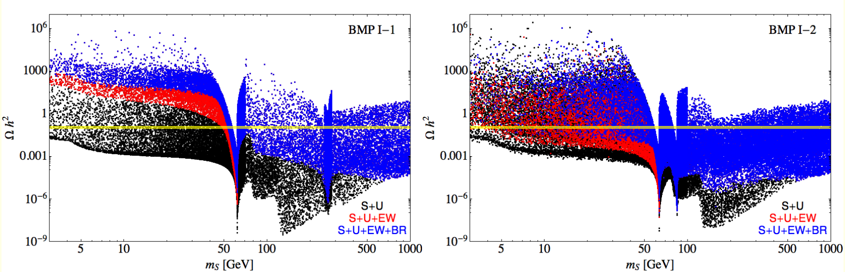


Calculation of DM relic abundance Ω:

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

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

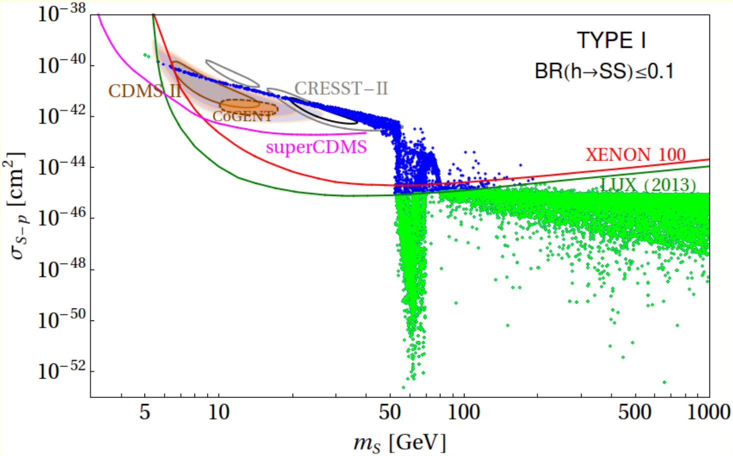
Resulting Constraints on the parameter space

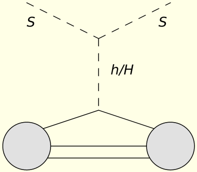


#	$\tan\beta$	$\sin\alpha$	m_{12}^2	m_h	m_H	m_A	$m_{H^\pm}$
I-1	1.586	-0.587	$+5621$	123.71	534.25	645.13	549.25
I-2	1.346	-0.663	-2236	126.49	168.01	560.92	556.94

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

Direct DM detection constraints





Direct DM detection constraints

TYPE II - isospin violation

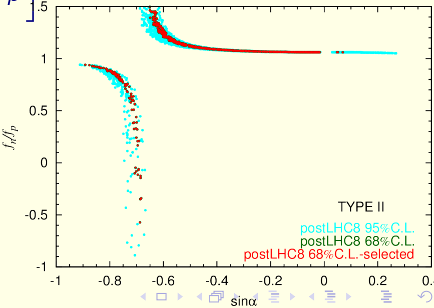
$$\sigma_{DM-N} = \frac{4\mu_{Z_A}^2}{\pi} f_p^2 \left[Z + \frac{f_n}{f_p}(A-Z) \right]^2$$

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

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

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

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

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

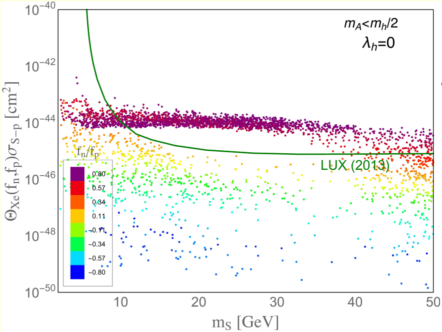
$$\sigma_{DM-p}^{EXP} \geq \sigma_{DM-p}^{THEO}\,\Theta(f_n, f_p)$$

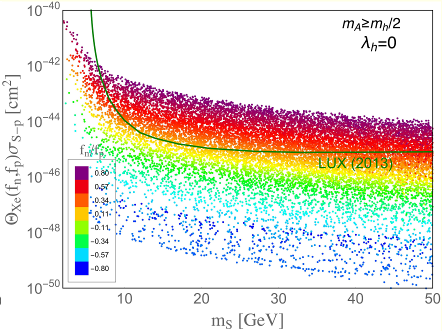
$$\Theta(f_n, f_p) = \left[\frac{Z}{A} + \frac{f_n}{f_p}\left(1 - \frac{Z}{A}\right)\right]^2$$

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

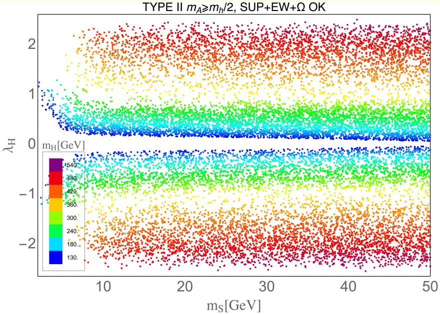
Type II, $m_h \simeq 125$ GeV and $\lambda_h \simeq 0$

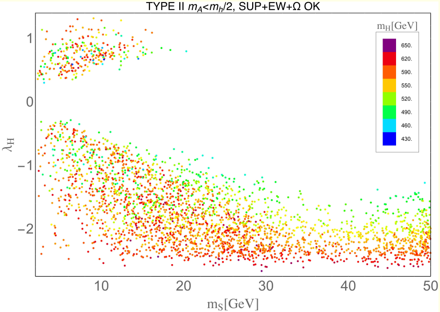




Direct DM detection constraints

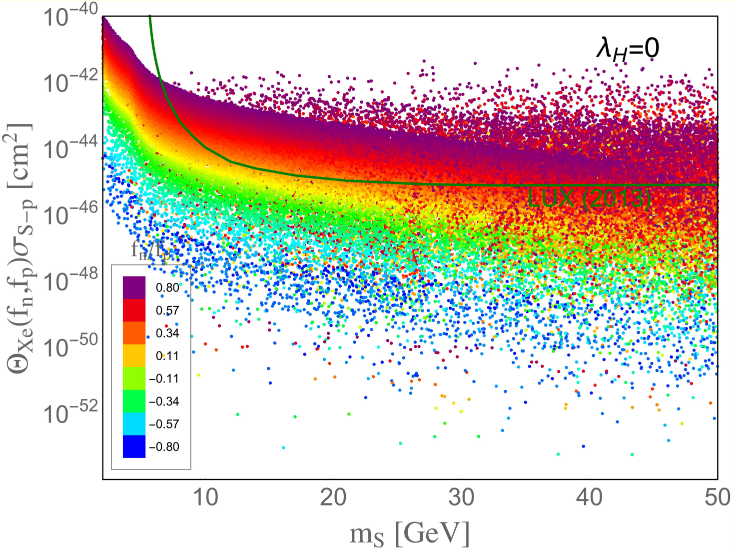
Type II, $m_h \simeq 125$ GeV and $\lambda_h \simeq 0$





Direct DM detection constraints

Type II, $m_H \simeq 125$ GeV and $\lambda_H \simeq 0$



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 $BR[h(H) \to SS] \ll 1$
  - 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 $BR(H \to SS) \sim 1$ or $BR(h \to SS) \sim 1$
  - $(tan\beta, sin\alpha)$ fixed ($h(H)$ Yukawa's MS like)
  - $m_{H^\pm} \gtrsim 320$ GeV
  - A and $H^\pm$ interactions have to be investigated