Two-Higgs Doublet Models with Scalar Singlet 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

2HDM: B. Dumont, J. Gunion, S. Kraml, Y. Jiang, arXiv:1405.3584

2HDMS: A. Drozd, B. Grzadkowski, J. F. Gunion and Y. Jiang, ”Extending two-Higgs-doublet models by a singlet scalar field - the Case for Dark Matter”, 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

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

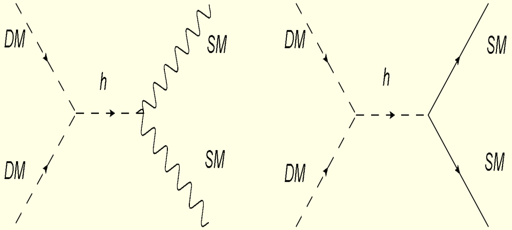
EWSB: Z_2' unbroken $\to$ NO VEV FOR S

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

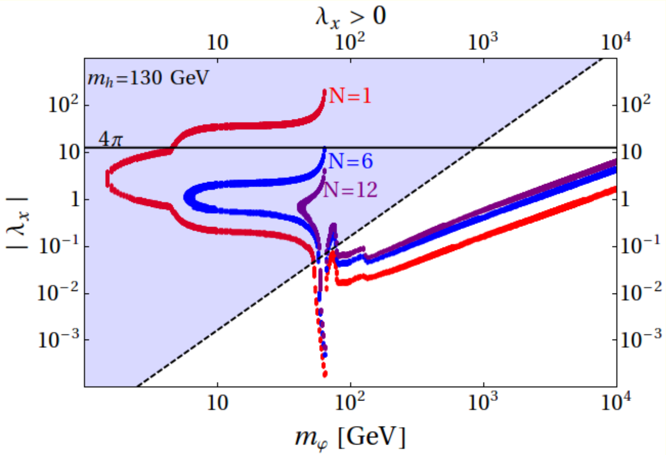
Motivations

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



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

Strategy

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

- 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:

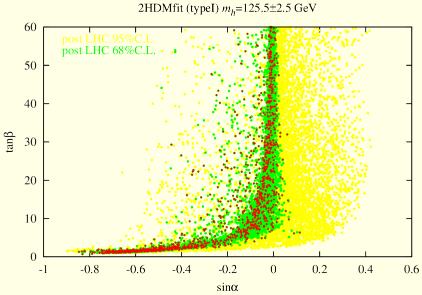
- $m_h, m_H, m_A, m_{H^{\pm}}, sin\alpha$
- m_{12}^2, $\tan\beta$
- $m_S, \lambda_h, \lambda_H$

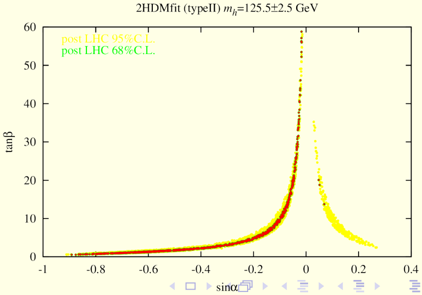
- 2 types of Yukawa interaction

Strategy

2HDM: Dumont, Gunion, Jiang, Kraml

- theoretical constraints
  (perturbativity, vacuum stability, perturbative unitarity)
- experimental constraints
  - B/LEP limits H^+
  - STU
  - heavy Higgs search
  - LHC fit at 68% CL





Strategy

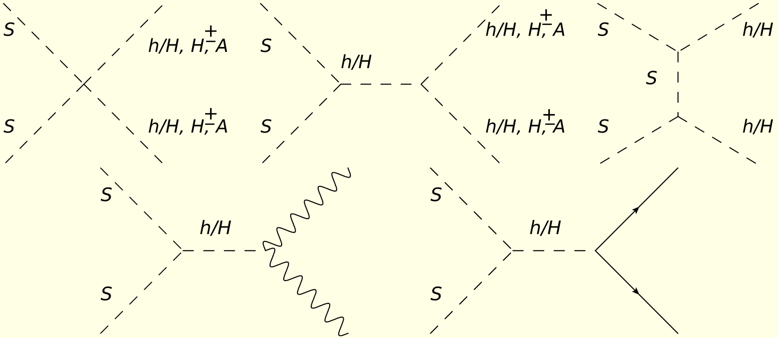
2HDM

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)
- with $BR(h \to DM, DM) < 10\%$
- WMAP/Planck
- direct DM detection

Strategy

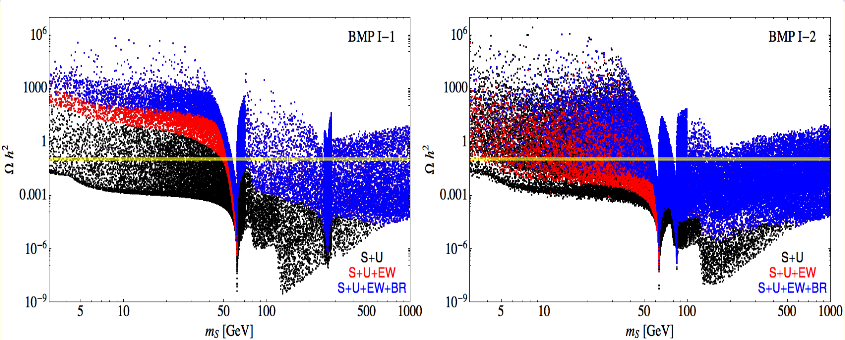


Calculation of DM relic abundance Ω:

MicrOmegas by G. Belanger, F. Boudjema, A. Pukhov, A. Semenov, arXiv:0803.2360

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

Resulting Constraints on the parameter space

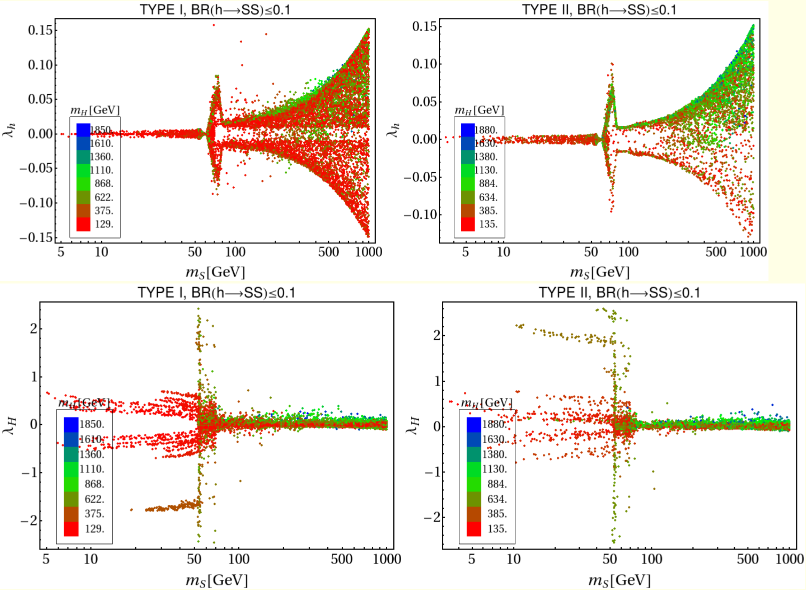


#	$\tan\beta$	$\sin\alpha$	m_{12}^2	m_h	m_H	m_A	$m_{H^\pm}$
I-1	1.586	-0.587	$+5621$	123.71	534.25	645.13	549.25
I-2	1.346	-0.663	-2236	126.49	168.01	560.92	556.94

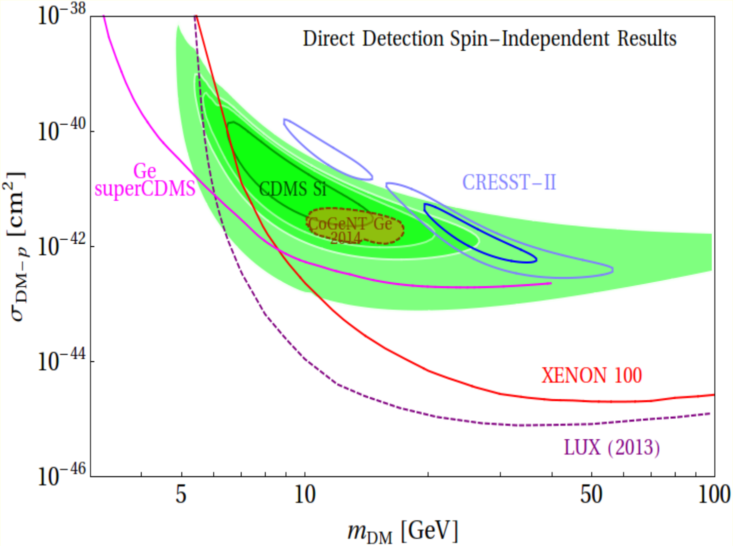
$$BR(h \to SS) = ???$$

- Ω_{DM} requires sufficiently strong SM - DM coupling
- search λ_h, λ_H give appropriate $BR(h \to SS)$ i Ω_{DM}
- H responsible for DM production!

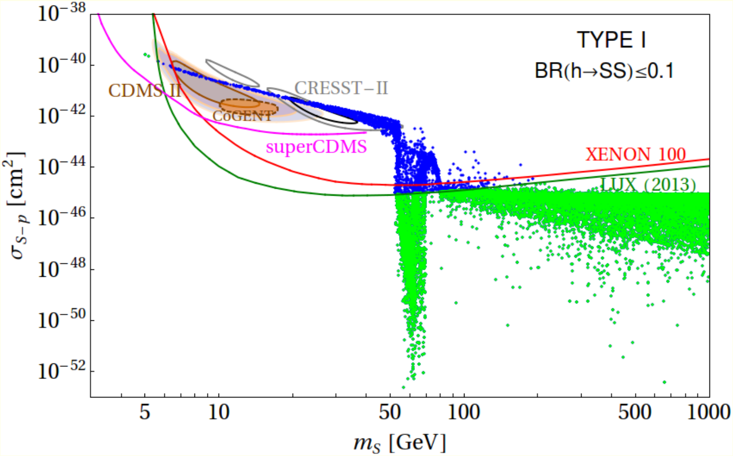
Resulting Constraints on the parameter space

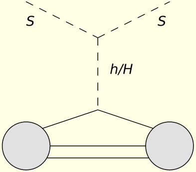


Direct DM detection constraints



Direct DM detection constraints





Direct DM detection constraints

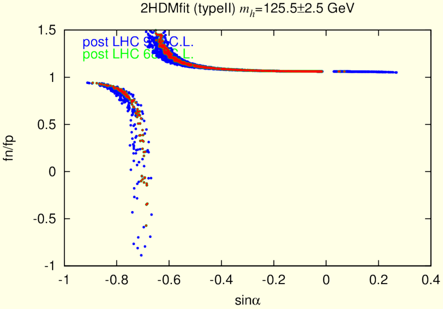
TYPE II

$$\sigma_{DM-N} = \frac{4\mu_{Z_A}^2}{\pi} f_p^2 \left[Z + \frac{f_n}{f_p}(A-Z)\right]^2$$
$$BR(h \to SS) \le 0.1 \Rightarrow \lambda_h < 0.015$$

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

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

	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

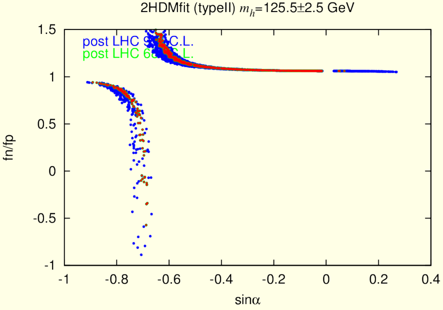
TYPE II

$$\sigma_{DM-N} = \frac{4\mu^2_{Z_A}}{\pi} f_p^2 \left[Z + \frac{f_n}{f_p}(A - Z) \right]^2 \qquad \sigma^{EXP}_{DM-p} \geq \sigma^{THEO}_{DM-p}\, \Theta^{EXP}(f_n, f_p)$$

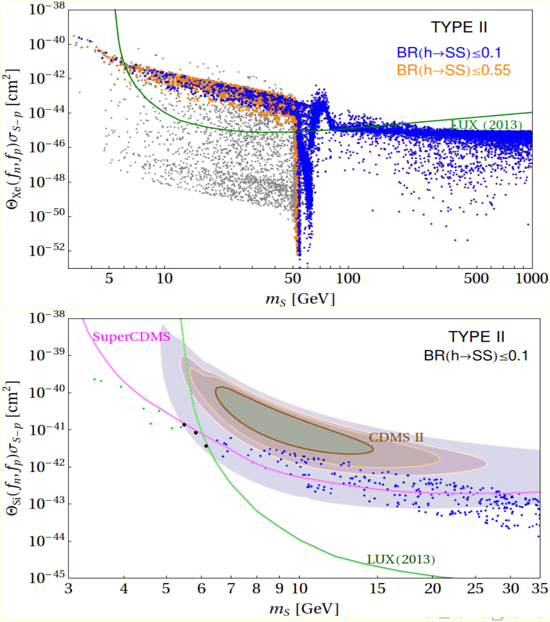
$$\Theta^{EXP}(f_n, f_p) = \sum_I \mu_I \left(\frac{Z_I}{A_I} + \frac{f_n}{f_p} \frac{A_I - Z_I}{A_I} \right)^2$$

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: $\mathcal{L}^{Yukawa} = \frac{m_q}{v} \xi^q_h \bar{q} q h + \frac{m_q}{v} \xi^q_H \bar{q} q H$

	Type I	Type II
ξ^u_h	$\cos\alpha / \sin\beta$	$\cos\alpha / \sin\beta$
ξ^d_h	$\cos\alpha / \sin\beta$	$-\sin\alpha / \cos\beta$
ξ^u_H	$\sin\alpha / \sin\beta$	$\sin\alpha / \sin\beta$
ξ^d_H	$\sin\alpha / \sin\beta$	$\cos\alpha / \cos\beta$



Direct DM detection constraints



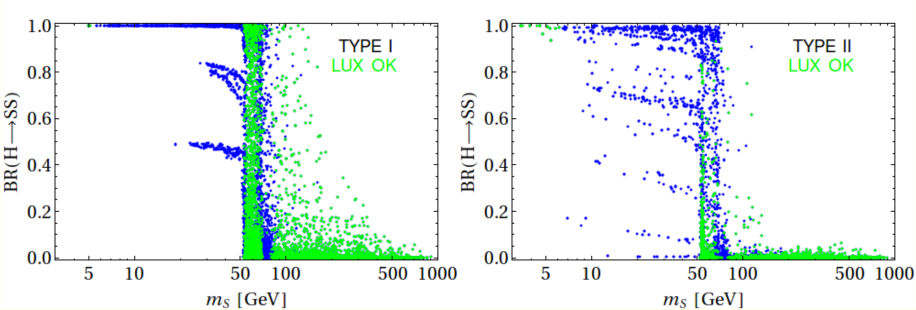
Direct DM detection constraints

$\tan\beta$	$\sin\alpha$	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
- 2HDMS is allowed by current collider and Ω limits
- 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 $BR(H \to SS) \gtrsim 90\%$

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

Decoupling limit of 2HDM

$m_h^2 \to \mathcal{O}(v^2)$
$m_{A,H,H^\pm}^2 \to \mathcal{O}(|m_{12}^2|)$
$cos(\beta - \alpha) \to \mathcal{O}(v^2/m_{12}^2)$

$$m_A^2 = \frac{m_{12}^2}{s_\beta c_\beta} - \frac{1}{2}v^2(2\lambda_5 + \lambda_6 t_\beta^{-1} + \lambda_7 t_\beta)\,,$$
$$m_{H^\pm}^2 = m_{A^0}^2 + \frac{1}{2}v^2(\lambda_5 - \lambda_4)\,.$$

$$\mathcal{M}^2 \equiv m_{A^0}^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \mathcal{B}^2\,,$$

$$\mathcal{B}^2 \equiv v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 & (\lambda_3+\lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 \\ (\lambda_3+\lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 & \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 \end{pmatrix}$$

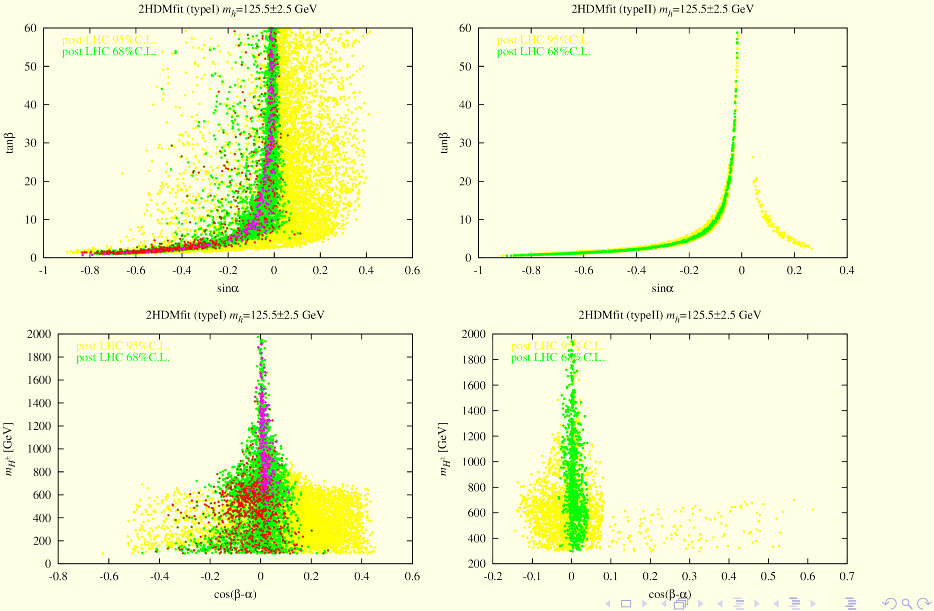
SM-like light Higgs ($\alpha = \beta - \pi/2$)
(Yukawa couplings are like in the SM and VVh as well)
with other scalars heavy

2HDM project (Dumont, Gunion, Jiang, Kraml)

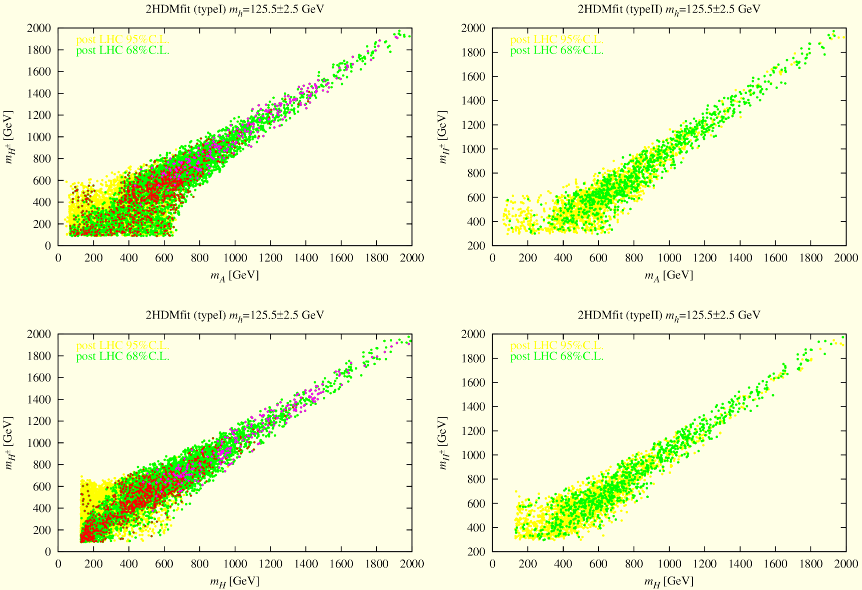
2HDM Input:

- Yukawa type I/II
- $m_h \in$ [123 GeV, 128 GeV]
- $m_H \in$ [128 GeV, 2 TeV], $m_A \in$ [5 GeV, 2 TeV]
- $m_{H^\pm} \in$ [*, 2 TeV]
- $\sin\alpha \in [-\pi/2, \pi/2]$, $\tan\beta \in$ [5,60], $m_{12}^2 \in [-(2\text{TeV})^2,(2\text{TeV})^2]$

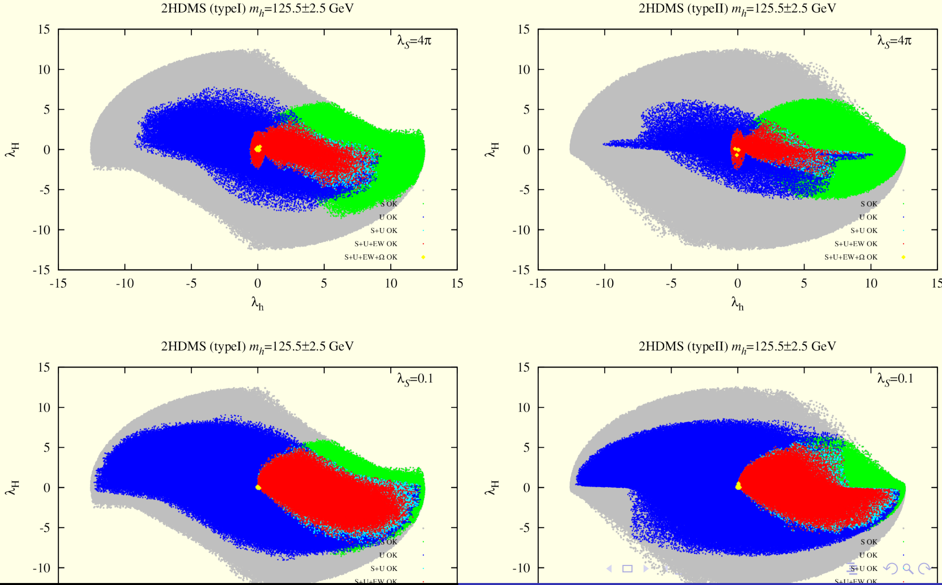
2HDM preliminiary results Dumont, Gunion, Jiang, Kraml



2HDM preliminiary results Dumont, Gunion, Jiang, Kraml

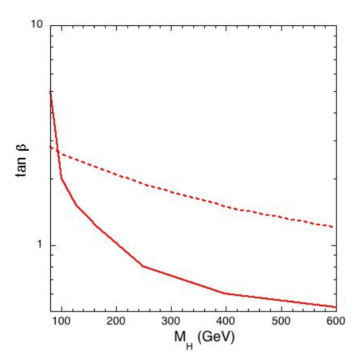


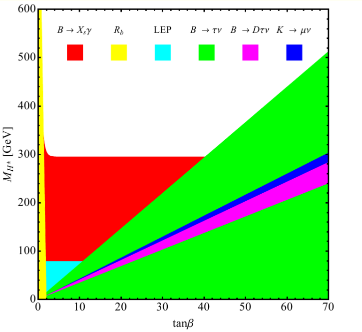
Theoretical constraints



Experimental Constraints:

- precision electroweak data: S,T,U constraints
- bounds in the $(m_{H^\pm}, \tan\beta)$ plane from various B-physics constraints for the type I/II (0805.2141, 1006.0470, 0912.0267)





LEFT: solid line: bounds from $Z \to b\bar{b}$, ϵ_K, Δ_{B_s}; dashed: bounds from $B \to \gamma X_s$
RIGHT: bounds from various B-physics constraints for the typeII model

2HDM constraints by Dumont, Gunion, Jiang, Kraml