Two-Higgs Doublet Model with Scalar Singlet Dark Matter

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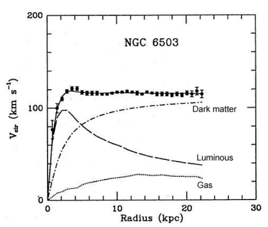
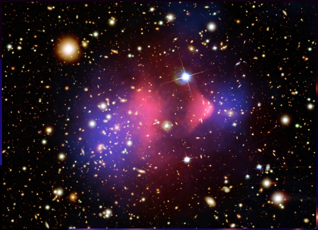
Outline:

- Motivation
- 2HDMS Model
- Constraints on parameter space
- Summary

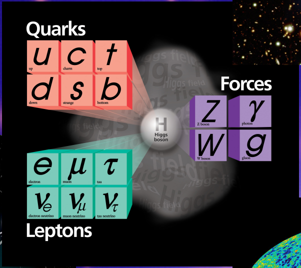
2HDM: B. Dumont, J. Gunion, S. Kraml, Y. Jiang, arXiv:1405.3584 (see talk by J.F. Gunion)

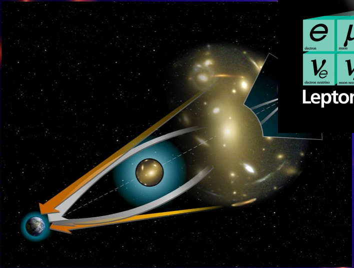
2HDMS: A.D., B. Grządkowski, J. Gunion, Y. Jiang, in preparation

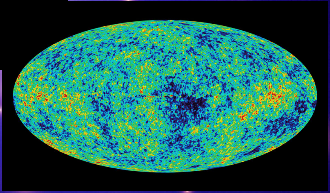




Bullet Cluster

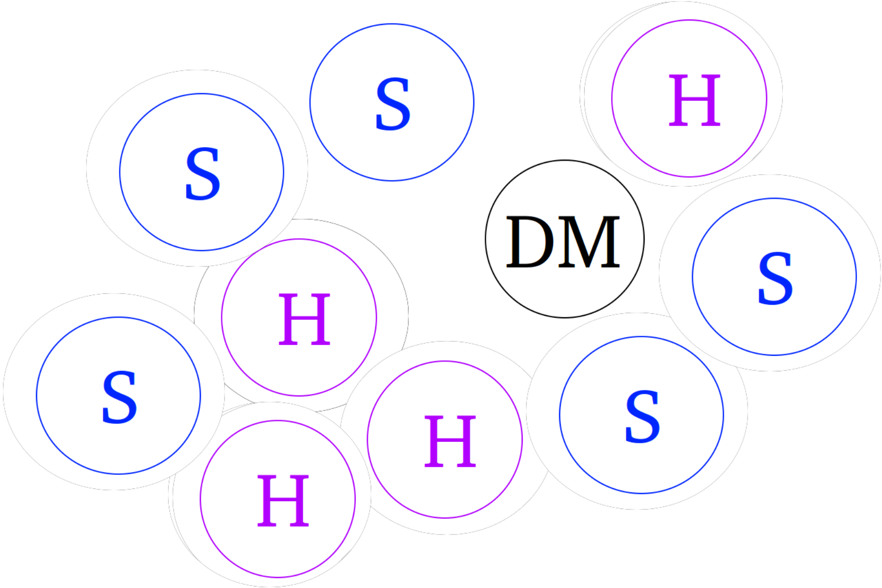






WMAP/Planck

Galaxy Cluster - dark matter


S
H
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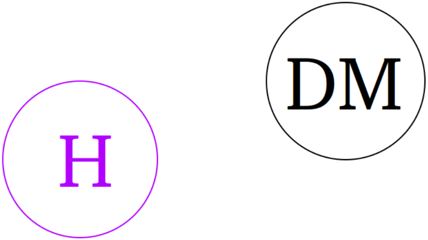
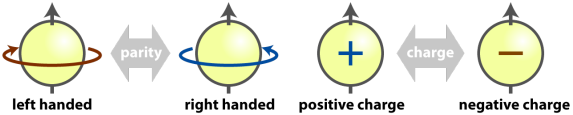
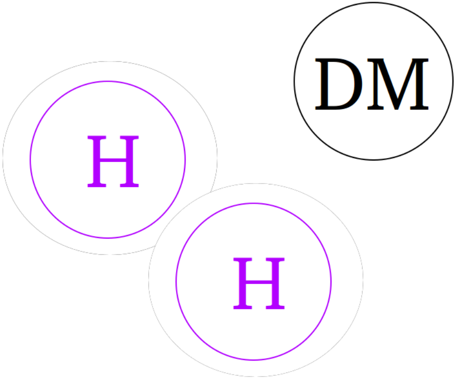

H
DM

CP violation!





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

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

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

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

Parameters: mass eigenstates and couplings

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

- 10 parameters in the potential, various basis possible

General Basis:

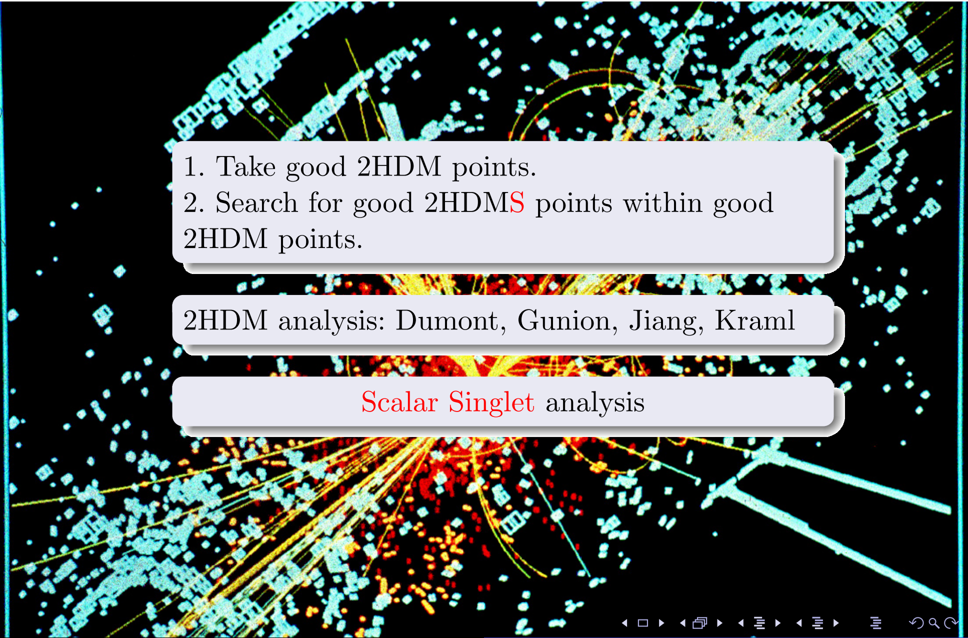
- $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$
- m_{12}^2, $\text{tg}\,\beta$
- m_S, κ_1, κ_2

Physical Basis:

- $m_h, m_H, m_A, m_{H^{\pm}}, \sin\alpha$
- m_{12}^2, $\text{tg}\,\beta$
- m_S, λ_h, λ_H

- 2 types of Yukawa interaction

Strategy

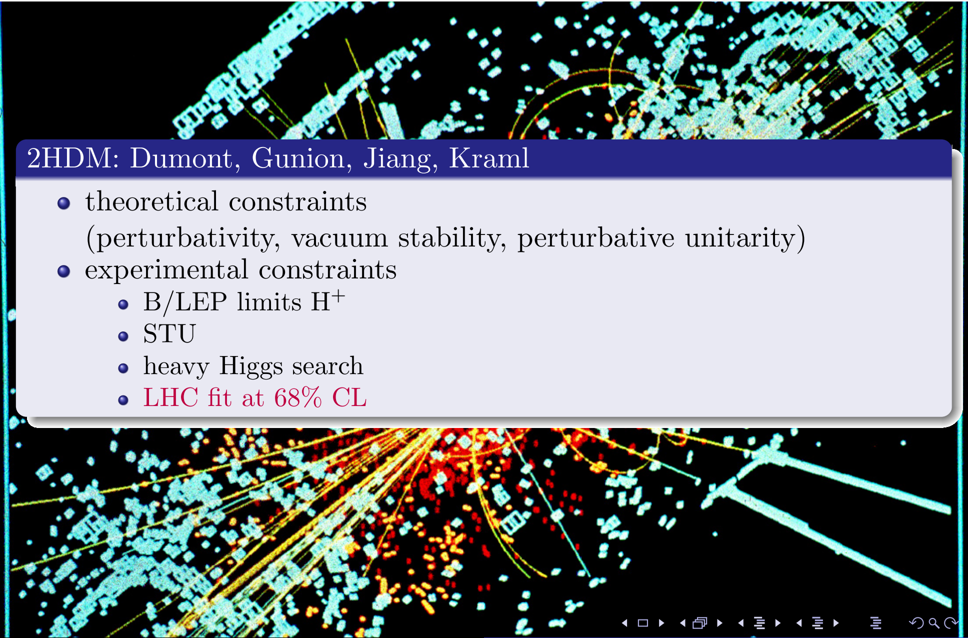


1. Take good 2HDM points.
2. Search for good 2HDMS points within good 2HDM points.

2HDM analysis: Dumont, Gunion, Jiang, Kraml

Scalar Singlet analysis

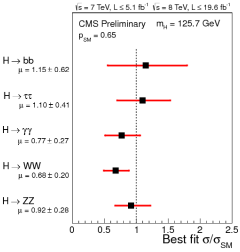
Strategy

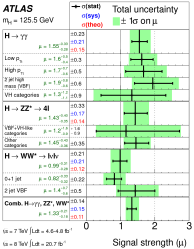


2HDM: Dumont, Gunion, Jiang, Kraml

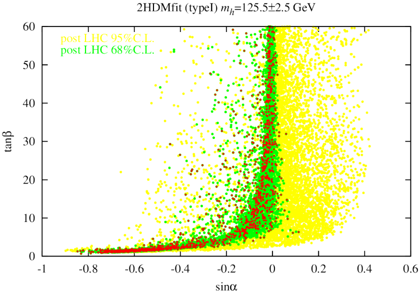
- theoretical constraints
  (perturbativity, vacuum stability, perturbative unitarity)
- experimental constraints
  - B/LEP limits H^+
  - STU
  - heavy Higgs search
  - LHC fit at 68% CL

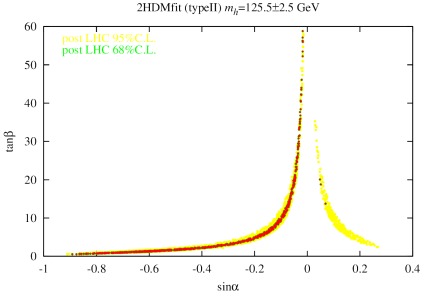
Higgs @ LHC - Higgs signal strengths fit





$m_h \sim 125$ GeV





Strategy

Take good 2HDM points.

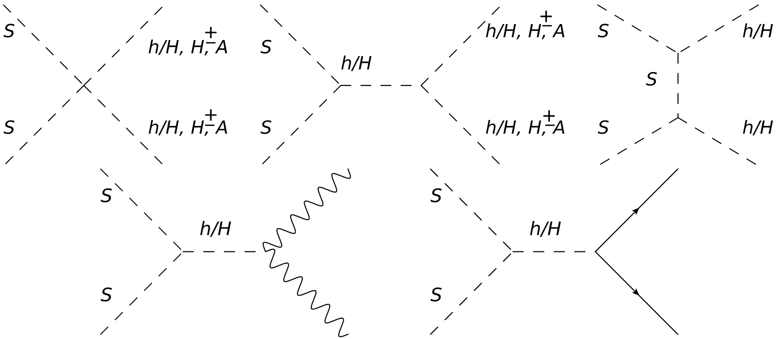
Scalar Singlet parameter search:

- $m_S \in [1\ \text{GeV}, 1\ \text{TeV}]$
- $\lambda_h, \lambda_H \in [-4\pi, 4\pi]$

S:

- theoretical constraints
  (perturbativity, vacuum stability, perturbative unitarity, EWSB)
- $BR(h \to SS)^{LIMIT} = 10\%$
- WMAP/Planck
- direct DM detection

2HDMS - interactions of DM with 2HDM

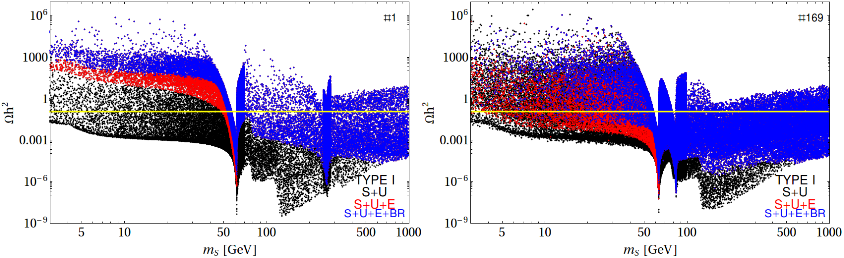


Calculation of DM relic abundance Ω:

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

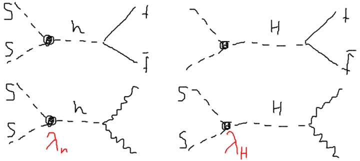
$$\Omega^{\rm WMAP/Planck} = 0.1187 \pm 0.0017$$

2HDM + S space scan

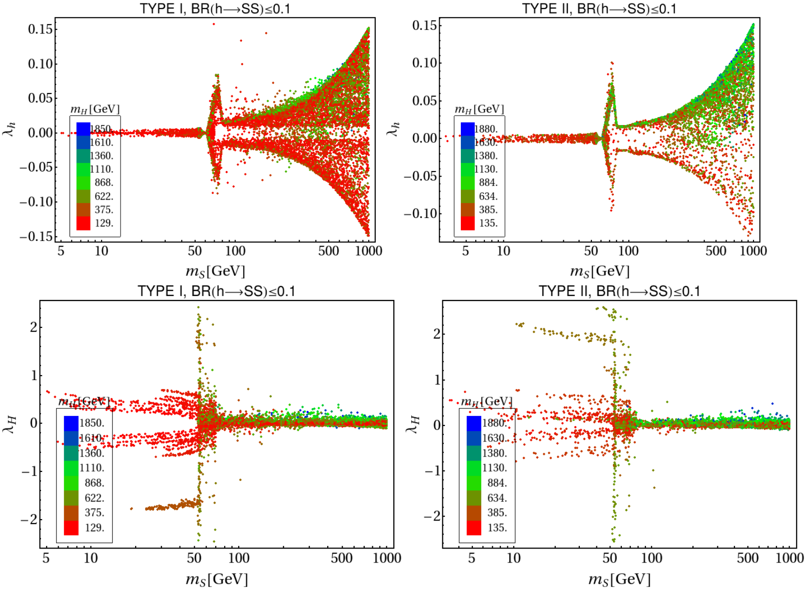


$$\mathrm{BR}(h \to SS) = ???$$

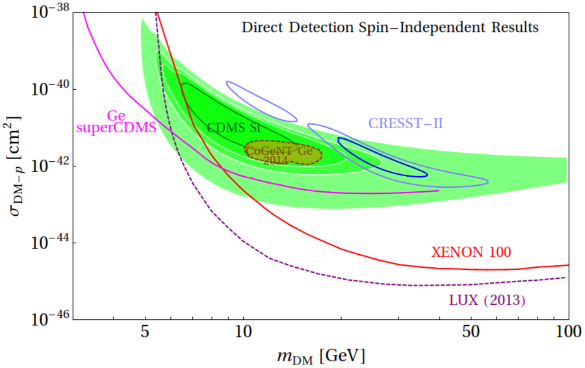
- Ω_{DM} requires suffiently strong SM - DM coupling
- search λ_h, λ_H give appropriate $\mathrm{BR}(h \to SS)$ i Ω_{DM}
- H responsible for DM production!

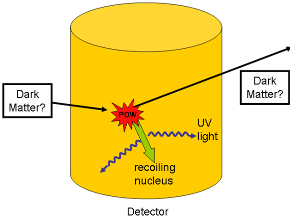


$\lambda_h(m_S), \lambda_H(m_S)$

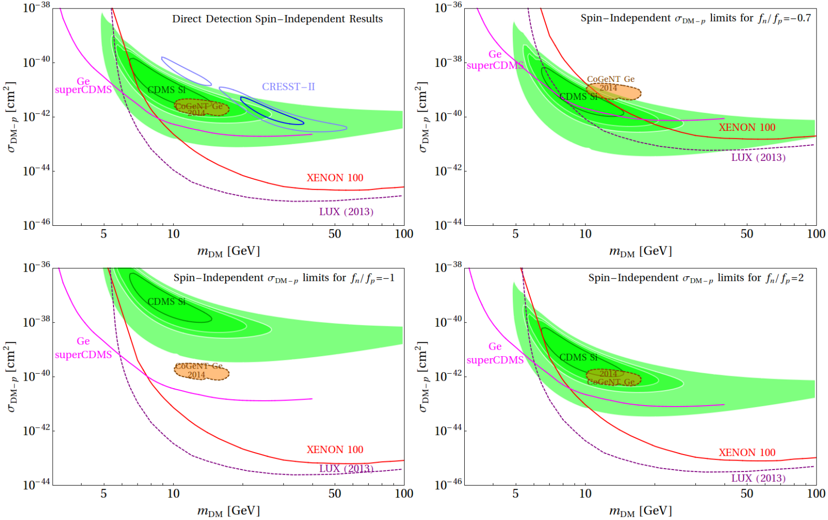


DM Direct Detection

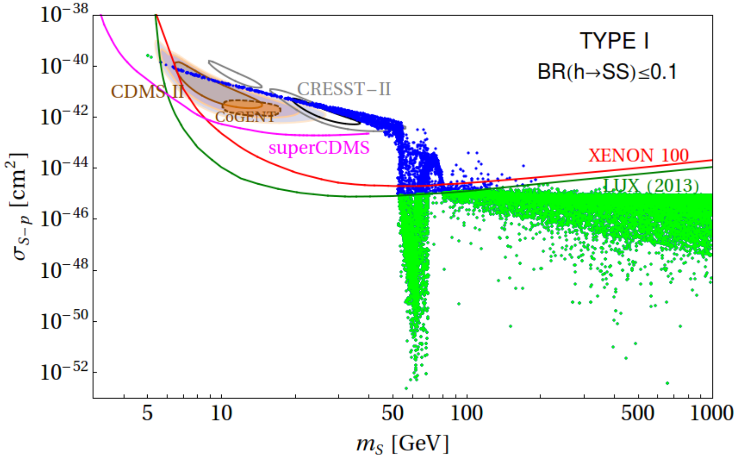


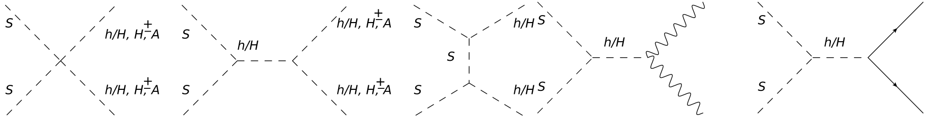


DM Direct Detection



Direct Detection - full scan results - isospin-conserving



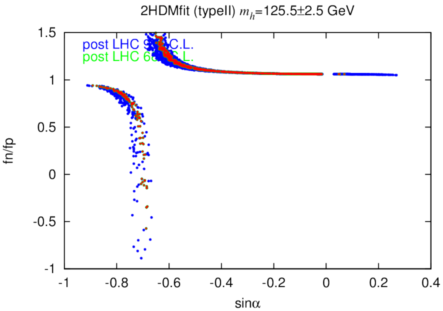


$$\sigma_{\mathrm{DM-N}} = \frac{4\mu_A^2}{\pi}\left(\mathrm{f_p Z} + \mathrm{f_n}(\mathrm{A}-\mathrm{Z})\right)^2 \qquad \mathrm{BR}(\mathrm{h}\to\mathrm{SS}) \leqslant 0.1 \Rightarrow \lambda_\mathrm{h} < 0.015$$

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

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

	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 Detection - IVDM

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

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

Tabela: 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	$\cos\alpha / \sin\beta$	$\cos\alpha / \sin\beta$
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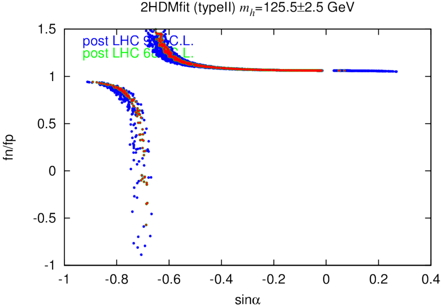
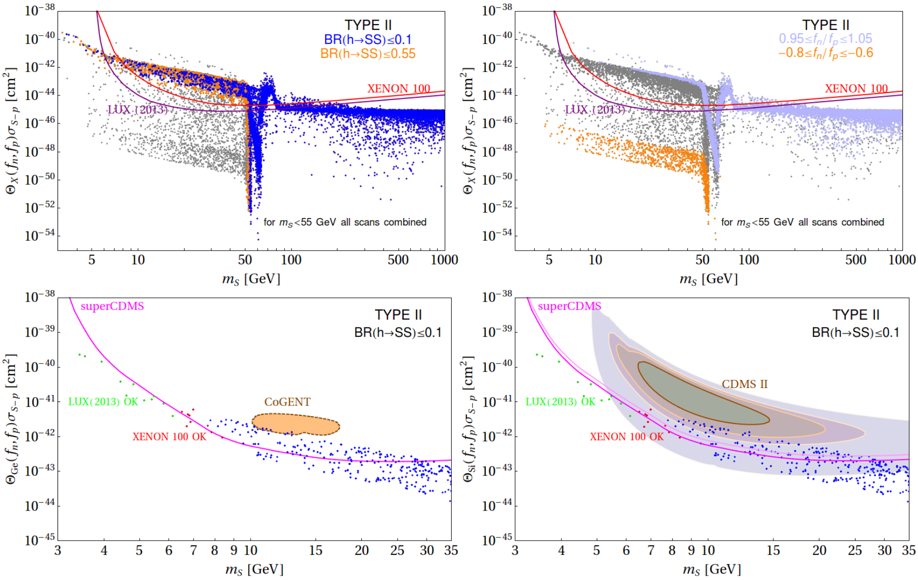
ξ_H^d	$\sin\alpha / \sin\beta$	$\cos\alpha / \cos\beta$

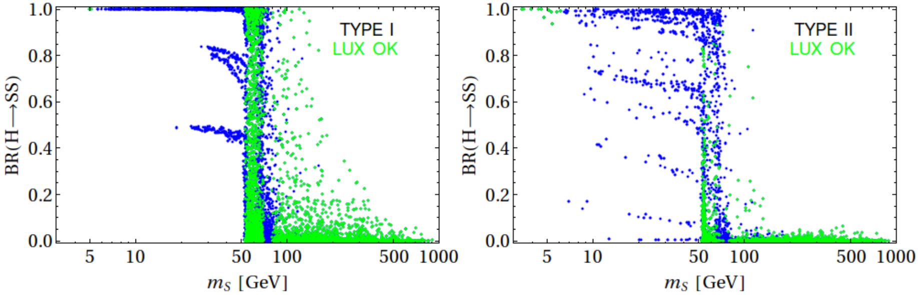


Direct Detection - full scan results - IVDM



New Higgs physics?

H→SS decay - invisible H!



Conclusions:

- 2HDM is allowed by current collider limits (see talk by J.F. Gunion)
- Scalar Singlet 2HDM extension provides a DM candidate and an opportunity for extra CP-violation

- 2HDMS is allowed by current collider and Ω limits
- LUX requires $m_S > 50\,\mathrm{GeV}$ or $m_S < 7\,\mathrm{GeV}$ ($m_S < 9\,\mathrm{GeV}$ for XENON)
- CDMS Si reqiures $|\lambda_h| < 0.05$, $|\lambda_H| > 0.1$, and implies large $BR(H \to SS)$).
- A fit of 2HDMS to LUX, superCDMS and CDMS Si is only possible within 99% CL for CDMS, for TYPE II model, $m_s \sim 5 - 6.5$ GeV. For those points $BR(H \to SS) > 93\%$

Thank you for your attention!

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Extra Slides

International PhD Projects Programme (MPD) - Grants for Innovations

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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

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

Decoupling limit of 2HDM

$\mathrm{m_h^2} \to \mathrm{o(v^2)}$
$\mathrm{m^2_{A,H,H^\pm}} \to \mathrm{o(|m^2_{12}|)}$
$\cos(\beta - \alpha) \to \mathrm{o(v^2/m^2_{12})}$

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

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

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

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

Model Type	point #	$\tan\beta$	$\sin\alpha$	m_{12}^2	m_h	m_H	m_A	$m_{H^\pm}$
Type I	1	1.586	-0.587	5621	123.71	534.25	645.13	549.25
Type II	1	0.969	-0.721	1.251×10^5	127.96	678.98	600.36	563.18
Type I	169	1.346	-0.663	-2236	126.49	168.01	560.92	556.94
Type II	22	2.092	-0.4096	-1.264×10^4	125.89	137.86	451.33	398.76

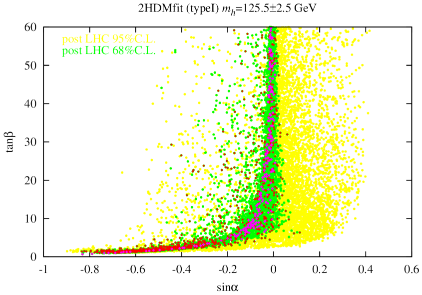
TABLE II: 2HDM parameters for the plots of Figs. 5 and 6. Masses in GeV; m_{12}^2 in GeV^2.

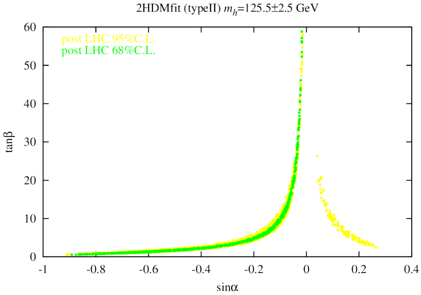
2HDM project (Dumont, Gunion, Jiang, Kraml)

2HDM Input:

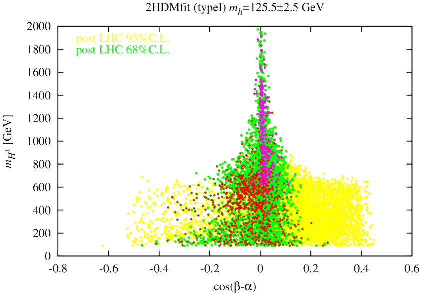
- Yukawa type I/II
- $\mathrm{m_h} \in$ [123 GeV, 128 GeV]
- $\mathrm{m_H} \in$ [128 GeV, 2 TeV], $\mathrm{m_A} \in$ [5 GeV, 2 TeV]
- $\mathrm{m_{H^\pm}} \in$ [*, 2 TeV]
- $\sin\alpha \in [-\pi/2, \pi/2]$, $\mathrm{tg}\,\beta \in [5,60]$, $\mathrm{m}_{12}^2 \in [-(2\mathrm{TeV})^2,(2\mathrm{TeV})^2]$

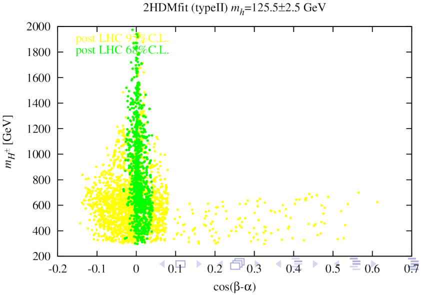
2HDM preliminiary results Dumont, Gunion, Jiang, Kraml

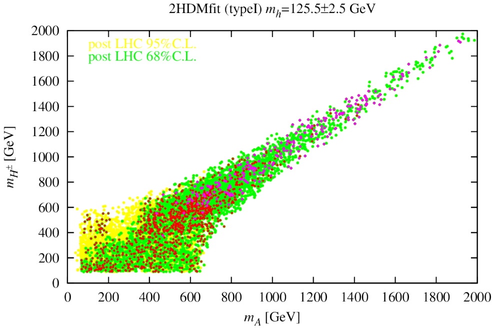


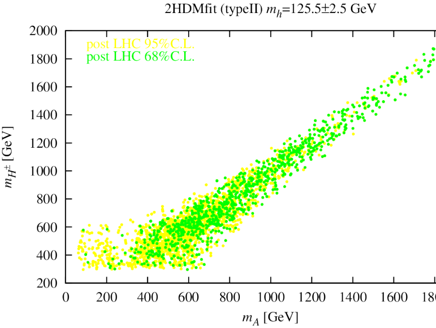


SM limit for the h in case of type I/II: $\alpha = \beta - \pi/2$






2HDMfit (typeI) m_h=125.5±2.5 GeV
post LHC 95%C.L.
post LHC 68%C.L.
$m_{H^\pm}$ [GeV]
m_A [GeV]


2HDMfit (typeII) m_h=125.5±2.5 GeV
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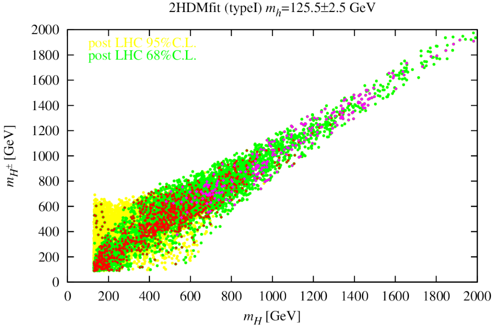
post LHC 68%C.L.
$m_{H^\pm}$ [GeV]
m_A [GeV]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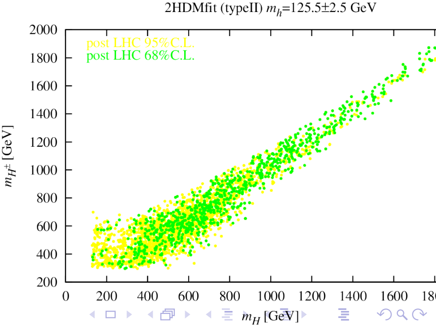
post LHC 68%C.L.
$m_{H^\pm}$ [GeV]
m_H [GeV]


2HDMfit (typeII) m_h=125.5±2.5 GeV
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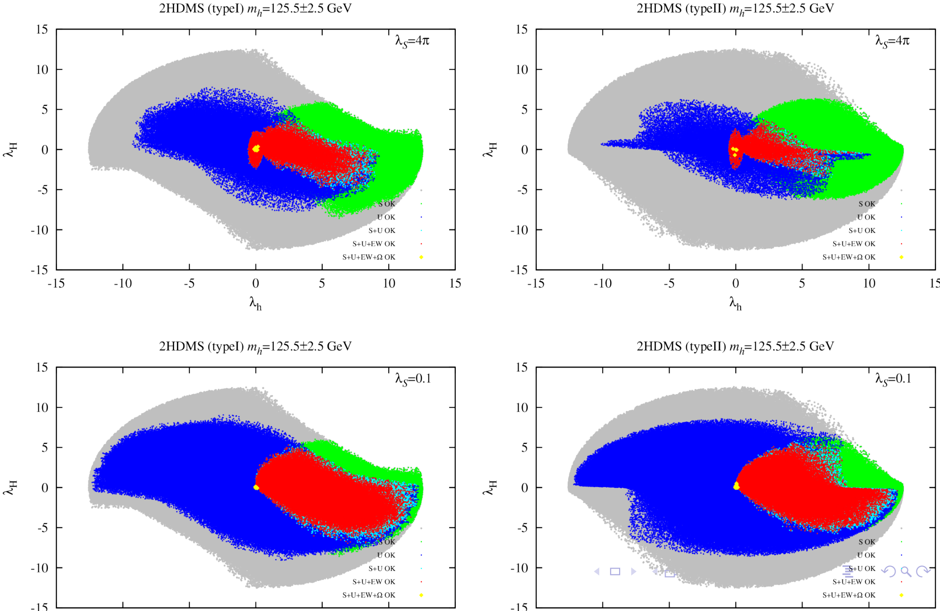
post LHC 68%C.L.
$m_{H^\pm}$ [GeV]
m_H [GeV]

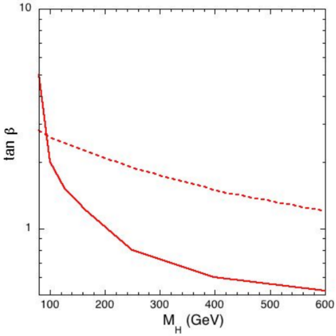
Theoretical constraints

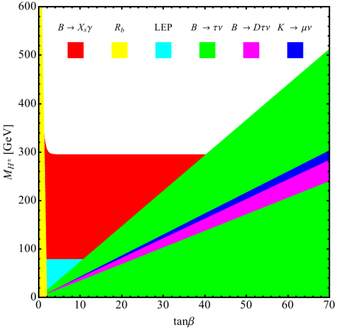


2HDM constraints by Dumont, Gunion, Jiang, Kraml

Experimental Constraints:

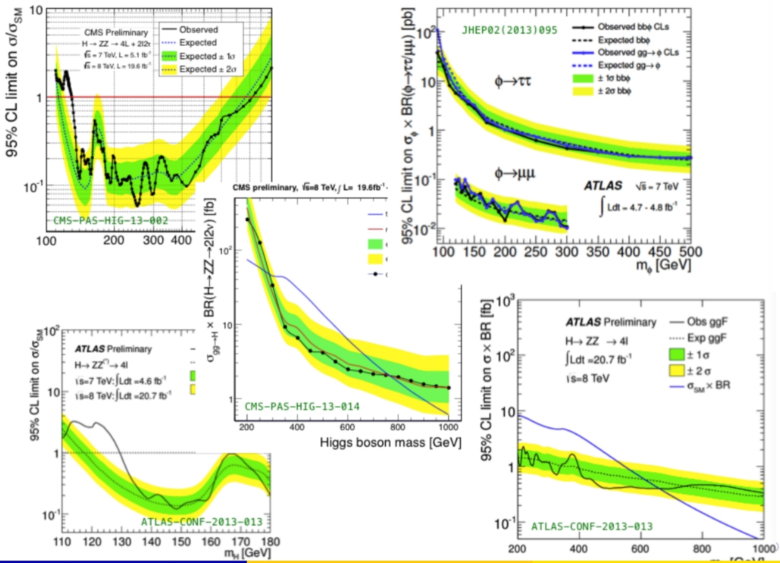
- precision electroweak data: S,T,U constraints
- bounds in the $(m_{H^\pm}, \mathrm{tg}\,\beta)$ plane from various B-physics constraints for the type I/II (0805.2141, 1006.0470, 0912.0267)

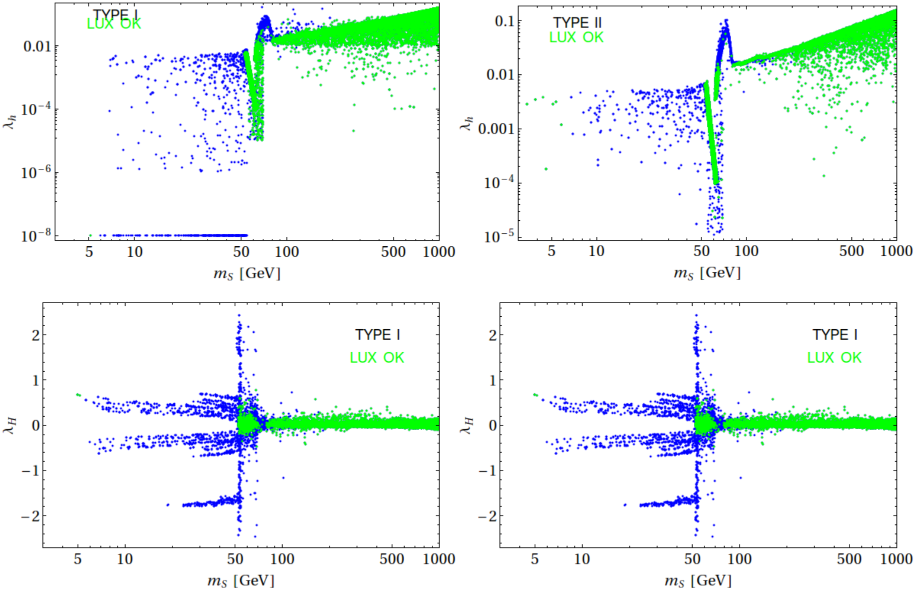


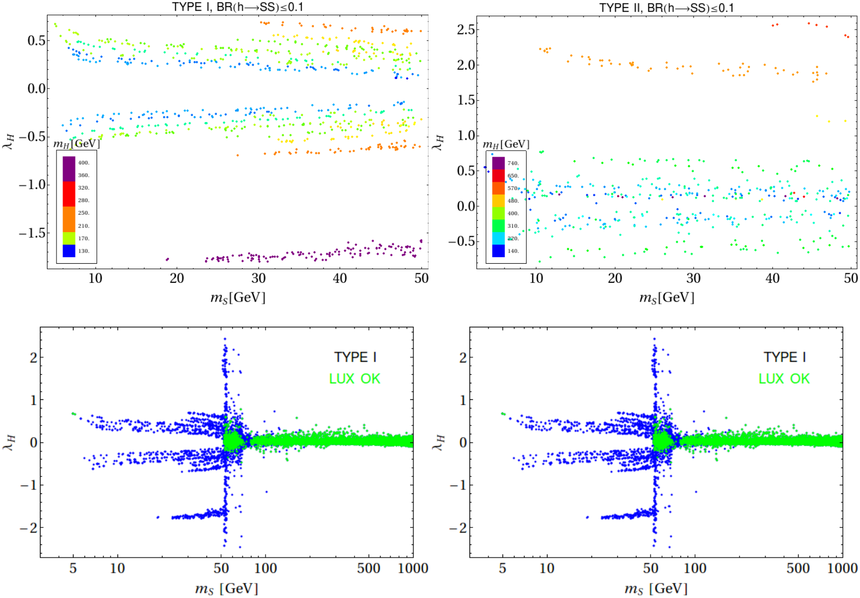


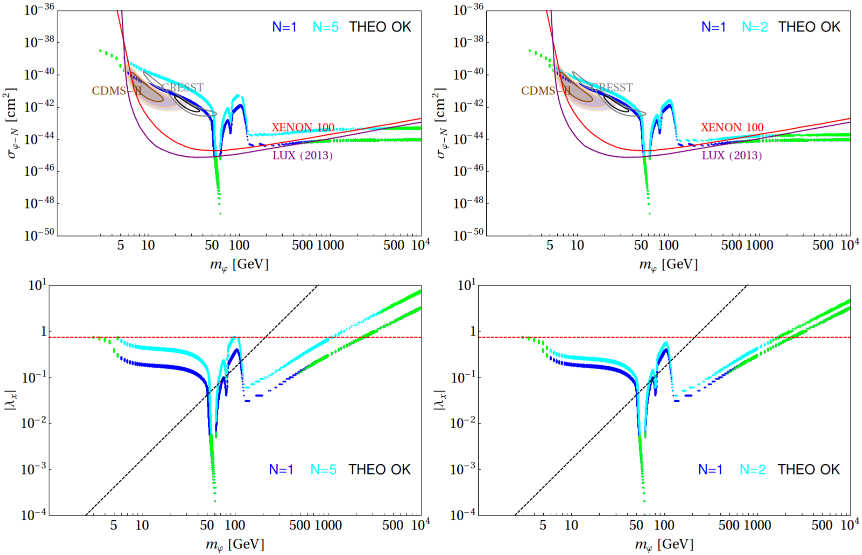
LEFT: solid line: bounds from $Z \to b\bar{b}, \epsilon_K, \Delta_{B_s}$; dashed: bounds from $B \to \gamma X_s$
RIGHT: bounds from various B-physics constraints for the typeII model

Search limits on the heavier Higgs bosons

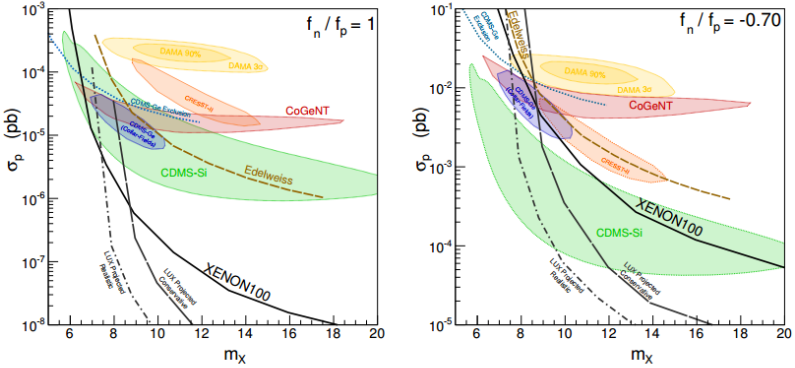



TYPE I
LUX OK
λ_h
0.01
10^{-4}
10^{-6}
10^{-8}
5
10
50
100
500
1000
m_S [GeV]
TYPE II
LUX OK
λ_h
0.1
0.01
0.001
10^{-4}
10^{-5}
5
10
50
100
500
1000
m_S [GeV]
TYPE I
LUX OK
λ_H
2
1
0
−1
−2
5
10
50
100
500
1000
m_S [GeV]
TYPE I
LUX OK
λ_H
2
1
0
−1
−2
5
10
50
100
500
1000
m_S [GeV]


TYPE I, BR(h⟶SS)≤0.1
TYPE II, BR(h⟶SS)≤0.1
λ_H
m_S[GeV]
m_H[GeV]
400.
360.
320.
280.
250.
210.
170.
130.
740.
650.
570.
480.
400.
310.
220.
140.
TYPE I
LUX OK
m_S [GeV]
TYPE I
LUX OK


N=1 N=5 THEO OK
N=1 N=2 THEO OK
CDMS−II
CRESST
XENON 100
LUX (2013)
$\sigma_{\varphi-N}$ [cm^2]
m_φ [GeV]
$|\lambda_x|$

DM Direct Detection



(a) (b)

FIG. 2: Light dark matter experimental results in the (m_X, σ_p) plane for (a) the isospin-invariant case $f_n/f_p = 1$ and (b) the xenophobic case $f_n/f_p = -0.70$ [6]. Plotted are 90% CL ROIs for CoGeNT [8], CRESST [10], CDMS-Si [11], an ROI for an independent analysis of CDMS-Ge data [18], the 90% and 3σ ROIs for DAMA [7] as determined in Refs. [19, 20]. Exclusion contours from CDMS [13], Edelweiss [14], and XENON100 [16, 17] are also shown, as are projected bounds from LUX [21].