Double Higgs final states in Singlet Extensions of the SM

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The RxSM (real singlet extension of the SM)

RxSM: real singlet field is added to the SM content.

For simplicity: potential invariant under the Z_2 symmetry:

$$\Phi_S \rightarrow -\Phi_S$$

Singlet does not couple to the other SM fields except via mixing

Most general potential:

$$V = \frac{m^2}{2}|\Phi|^2 + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + \frac{m_S^2}{2}|\Phi_S|^2 + \frac{\lambda_S}{4!}\Phi_S^4 + \frac{\lambda_{HS}}{2}(\Phi^\dagger\Phi)\Phi_S^2$$

with the fields defined as

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \rho + i\eta) \end{pmatrix} \qquad \Phi_S = v_S + \rho_S$$

If a VEV is present there is mixing between the two CP-even states

There are now two distinct models that can occur.

The RxSM (real singlet extension of the SM)

a) No singlet VEV: the Z_2 symmetry is exact ⟶ dark matter candidate from singlet.
Mass eigenstates:

$$\begin{pmatrix} h_{SM} \\ DM \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \rho \\ \rho_s \end{pmatrix}$$

RxSM (DM phase)

Model: SM plus a DM candidate that only couples to the Higgs boson. Not discussed here.

b) Non-zero singlet VEV: the Z_2 symmetry is broken ⟶ scalar from the doublet mixes with the one from the singlet.
Mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \rho \\ \rho_s \end{pmatrix}$$

RxSM (Broken phase)

one of the scalars is the 125 GeV Higgs.

All couplings to fermions, gauge bosons modified by the same factor:
cosα or sinα, depending on which of the scalars is chosen to be the 125 GeV one.

The CxSM (complex singlet extension of the SM)

CxSM: complex singlet field added to the SM content.
For simplicity the potential is invariant under a U(1) symmetry:

$$\Phi_S \to e^{i\theta}\Phi_S$$

softly broken by dimension one and two terms and is invariant under the residual symmetry

$$\Phi_S \to \Phi_S^*$$

Singlet does not couple to the other SM fields except via mixing.

Potential:

$$V = \frac{m^2}{2}|\Phi|^2 + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + \frac{b_2}{2}|\Phi_S|^2 + \frac{d_2}{4}(\Phi_S^\dagger\Phi_S)^2 + \frac{\lambda_{HS}}{2}(\Phi^\dagger\Phi)(\Phi_S^\dagger\Phi_S) + \left[\frac{b_1}{4}\Phi_S^2 + a_1\Phi_S + c.c.\right]$$

with the fields defined as

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \rho + i\eta) \end{pmatrix} \qquad \Phi_S = v_S + \rho_S + i(v_A + \eta_S)$$

There are now two distinct models that can occur (not considering models with two dark matter candidates).

The CxSM (complex singlet extension of the SM)

a) Only real part of the singlet acquires a VEV ⟶ a DM candidate and two mixing scalars

Mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \\ DM \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha & 0 \\ s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \rho \\ \rho_s \\ \eta_S \end{pmatrix}$$

CxSM (DM phase)

Model: SM plus a DM candidate plus a scalar. Couplings to fermions, gauge bosons modified by the same factor (either cosα or sinα). One of the scalars is the 125 GeV one.

b) Both the real and the imaginary part of the singlet acquire VEVs ⟶ Z_2 symmetry is broken and all three scalars mix.

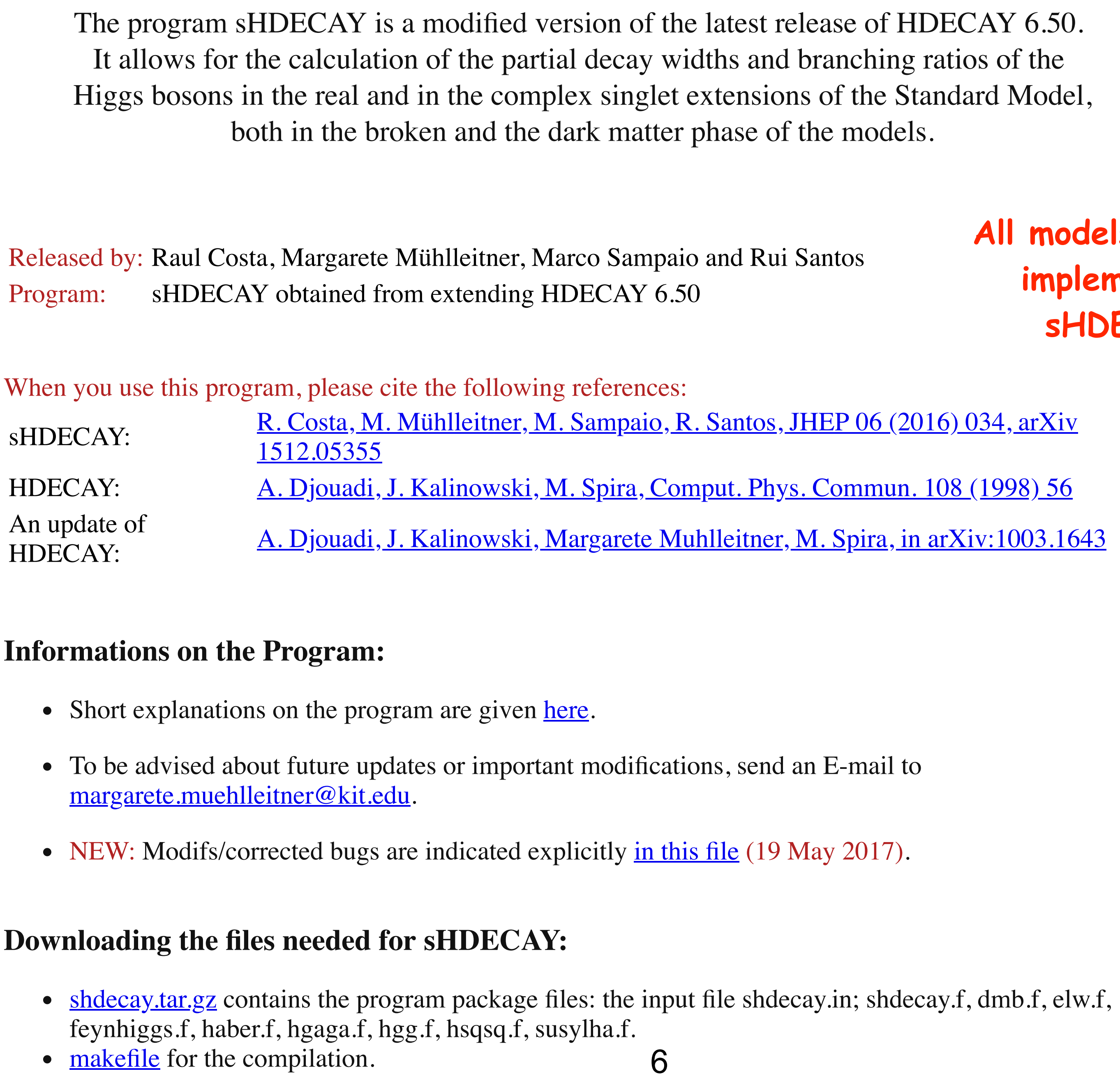
Mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} \begin{pmatrix} \rho \\ \rho_s \\ \eta_S \end{pmatrix}$$

CxSM (broken phase)

No DM particle but the coupling modifier is the same for all particles. However, it now depends on more than one angle. One of the scalars is the 125 GeV one.

sHDECAY



The program sHDECAY is a modified version of the latest release of HDECAY 6.50.
It allows for the calculation of the partial decay widths and branching ratios of the
Higgs bosons in the real and in the complex singlet extensions of the Standard Model,
both in the broken and the dark matter phase of the models.

Released by:	Raul Costa, Margarete Mühlleitner, Marco Sampaio and Rui Santos
Program:	sHDECAY obtained from extending HDECAY 6.50

When you use this program, please cite the following references:

sHDECAY:	R. Costa, M. Mühlleitner, M. Sampaio, R. Santos, JHEP 06 (2016) 034, arXiv 1512.05355
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput. Phys. Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to margarete.muehlleitner@kit.edu.
- NEW: Modifs/corrected bugs are indicated explicitly in this file (19 May 2017).

Downloading the files needed for sHDECAY:

- shdecay.tar.gz contains the program package files: the input file shdecay.in; shdecay.f, dmb.f, elw.f, feynhiggs.f, haber.f, hgaga.f, hgg.f, hsqsq.f, susylha.f.
- makefile for the compilation.

All models described are implemented in the sHDECAY code.

Constraints

- Points generated with ScannerS requiring

Coimbra, Sampaio, Santos, EPJC73 (2013) 2428

  - $m_{h_{SM}}$ =125.09 GeV (others 5 GeV away)
  - absolute minimum
  - boundedness from below
  - that perturbative unitarity holds
  - S,T and U

- DM abundance in agreement with the Planck collaboration measurement. Relic density calculated with MicrOmegas.

Bélanger, Boudjema, Goudelis, Pukhov, Zaldivár, CPC231 (2018) 173

- The Higgs rates are checked with HiggsSignals

Bechtle, Heinemeyer, Stal, Stefaniak, Weiglein, EPJC74 no. 2, (2014) 2711

- The Higgs exclusion limits stemming from experiments at the LEP, Tevatron and LHC are checked with HiggsBounds

Bechtle, Brein, Heinemeyer, Stal, Stefaniak, Weiglein, Williams, EPJC74 no. 3, (2014) 2693

Benchmark points and comparison between models

Benchmarks for the RxSM (broken phase)

	RxSM.B1	RxSM.B2	RxSM.B3	RxSM.B4
$\star\ m_1$ (GeV)	125.4	125.4	36.283	117.19
$\star\ m_2$ (GeV)	279.65	176.3	125.4	125.4
$\star\ \alpha$	-0.54065	-0.46964	1.4272	-0.97629
$\star\ v_S$ (GeV)	209.97	995.11	357.45	84.837
λ	1.0648	0.62253	0.50904	0.49815
λ_{HS}	0.53333	0.025292	-0.023182	0.044269
λ_S	4.1955	0.084633	0.037835	5.9845
m^2 (GeV^2)	-55789	-43916	-12468	-15419
m_S^2 (GeV^2)	-46994	-14735	-103	-8520.6
μ_{h_1}	0.735	0.795	0.0205	0.314
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	23.2 [pb]	25.1 [pb]	7.26 [pb]	11.2 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.62 [pb]	5 [pb]	0.0162 [fb]	1.07 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	581 [fb]	629 [fb]	$<$ 0.01 [fb]	115 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	14.2 [pb]	15.3 [pb]	6.38 [pb]	8 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.36 [pb]	1.47 [pb]	475 [fb]	758 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	50.1 [fb]	54.2 [fb]	1.08 [fb]	22.7 [fb]
μ_{h_2}	0.148	0.205	0.66	0.686
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	2.09 [pb]	3.48 [pb]	30.9 [pb]	21.6 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	810 [fb]	3.31 [pb]	4.15 [pb]	4.32 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	354 [fb]	130 [fb]	522 [fb]	543 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.972 [fb]	24.6 [fb]	12.7 [pb]	13.2 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.109 [fb]	2.52 [fb]	1.22 [pb]	1.27 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0196 [fb]	0.429 [fb]	45 [fb]	46.8 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	920 [fb]	0	10.1 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	344 [fb]	0	7.79 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	66.1 [fb]	0	1.16 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	225 [fb]	0	0.0395 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	2.43 [fb]	0	2.63 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	3.17 [fb]	0	43.2 [fb]	0

RxSM.B1: - SM-like Higgs is the lightest of the two scalars
- decay $h_2 \to h_1 h_1$ is allowed
- cross sections are all above about 3 fb for the presented final states, Higgs decays taken into account

RxSM.B3: - SM-like Higgs is the heaviest of the two scalars
- point chosen such that the new h_1 can be found both directly or in the decay $h_2 \to h_1 h_1$.

Benchmarks for the CxSM (DM phase)

	CxSM.D1	CxSM.D2	CxSM.D3
$\star\ m_1$ (GeV)	125.4	125.4	49.116
$\star\ m_2$ (GeV)	456.57	339.77	125.4
$\star\ m_A$ (GeV)	52.98	77.022	65.054
$\star\ \alpha$	-0.39506	-0.50029	1.4617
$\star\ v_S$ (GeV)	766.84	553.5	341.32
λ	1.4606	1.2757	0.51357
δ_2	0.7252	0.61592	-0.034278
d_2	0.58451	0.55	0.042823
m^2 (GeV^2)	-2.575×10^5	-1.3302×10^5	-13571
b_2 (GeV^2)	-1.8298×10^5	-88740	2852.4
b_1 (GeV^2)	5245.8	2315.6	-4156.4
$\star\ a_1$ (GeV^3)	-4.3665×10^6	-3.2282×10^6	-18263
$\Omega_A h^2$	0.115	0.116	0.115
μ_{h_1}	0.852	0.77	0.0118
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	26.9 [pb]	24.3 [pb]	2.14 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.59 [pb]	4.84 [pb]	0.0346 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	577 [fb]	609 [fb]	0.011 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	14.1 [pb]	14.9 [pb]	1.87 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.35 [pb]	1.43 [pb]	148 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	49.7 [fb]	52.5 [fb]	0.608 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to AA)$	3.84 [pb]	0	0
μ_{h_2}	0.0977	0.135	0.743
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	698 [fb]	1.6 [pb]	31.2 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	251 [fb]	642 [fb]	4.67 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	119 [fb]	292 [fb]	587 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.0764 [fb]	0.432 [fb]	14.3 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	$<$ 0.01 [fb]	0.0501 [fb]	1.38 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	$<$ 0.01 [fb]	$<$ 0.01 [fb]	50.6 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	155 [fb]	429 [fb]	7.74 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	42.7 [fb]	160 [fb]	5.89 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	8.19 [fb]	30.8 [fb]	932 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	27.8 [fb]	105 [fb]	0.218 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	0.302 [fb]	1.13 [fb]	3.83 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.393 [fb]	1.48 [fb]	36.9 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to AA)$	0.0822 [pb]	0.233 [pb]	0

CxSM.D1, CxSM.D2: - SM-like Higgs is the lightest scalar

- large invisible decay cross sections chosen, but also a large decay $h_2 \to h_1h_1$
- large cross sections for direct production of h_2 , so that the $h_2 \to h_1h_1$ decay complementary to direct discovery.

CxSM.D3: - no invisible decays

- SM-like Higgs is the heaviest visible scalar. -
- indirect discovery of h_1 through $h_2 \to h_1h_1$ possible due to its large cross section, with bbbb and bbττ final states.

Benchmarks for the CxSM (broken phase)

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
⋆ m_1 (GeV)	125.4	125.4	57.34	98.12	41.61
m_2 (GeV)	258.9	230.8	125.4	125.4	69.51
⋆ m_3 (GeV)	462.4	271.3	345.5	255.2	125.4
⋆ α_1	-0.04867	0.03148	-1.071	-0.7888	-1.169
⋆ α_2	0.4739	-0.5707	1.126	0.7717	1.24
⋆ α_3	-0.4763	-0.3888	-0.005447	-0.1945	1.044
⋆ v_S (GeV)	42.03	11.53	412.6	107.9	250.9
v_A (GeV)	110.3	92.86	257.8	168.9	559.3
λ	1.584	1.041	1.127	0.6614	0.504
δ_2	-4.807	2.167	-0.6748	-0.6795	-0.03074
d_2	24.37	12.67	0.7469	2.606	0.01501
m^2 (GeV^2)	-1.455×10^4	-4.103×10^4	4.569×10^4	-6395	-9502
b_2 (GeV^2)	5.491×10^4	-6.562×10^4	-5.208×10^4	-1.371×10^4	2302
b_1 (GeV^2)	7.89×10^4	5.556×10^4	1.585×10^4	1.806×10^4	4191
a_1 (GeV^3)	-2.345×10^6	-4.531×10^5	-4.624×10^6	-1.378×10^6	-7.434×10^5

$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$	3.75 [fb]	1.24 [pb]	280 [fb]	415 [fb]	5.47 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbbb)$	1.4 [fb]	464 [fb]	210 [fb]	279 [fb]	4.2 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	0.269 [fb]	89 [fb]	34.4 [fb]	51 [fb]	643 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbWW)$	0.915 [fb]	302 [fb]	0.0224 [fb]	4.76 [fb]	0.0518 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	3.28 [fb]	0.193 [fb]	0.948 [fb]	1.9 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.0129 [fb]	4.27 [fb]	1.41 [fb]	2.33 [fb]	24.6 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2)$	307 [fb]	0	83.5 [fb]	408 [fb]	401 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbbb)$	0.202 [fb]	0	43.8 [fb]	204 [fb]	301 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bb\tau\tau)$	0.0417 [fb]	0	7.78 [fb]	38.3 [fb]	48.7 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbWW)$	131 [fb]	0	14.4 [fb]	68.7 [fb]	0.0657 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	0	0.175 [fb]	1.07 [fb]	0.284 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to \tau\tau\tau\tau)$	$<$ 0.01 [fb]	0	0.344 [fb]	1.79 [fb]	1.96 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2)$	0	0	151 [fb]	0.318 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bbbb)$	0	0	55.5 [fb]	0.119 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bb\tau\tau)$	0	0	10.6 [fb]	0.0228 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bbWW)$	0	0	36.6 [fb]	0.0776 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bb\gamma\gamma)$	0	0	0.393 [fb]	$<$ 0.01 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to \tau\tau\tau\tau)$	0	0	0.511 [fb]	$<$ 0.01 [fb]	0

CxSM.B1, CxSM.B2: SM- like Higgs is the lightest
CxSM.B3, CxSM.B4: next to lightest
CxSM.B5: heaviest

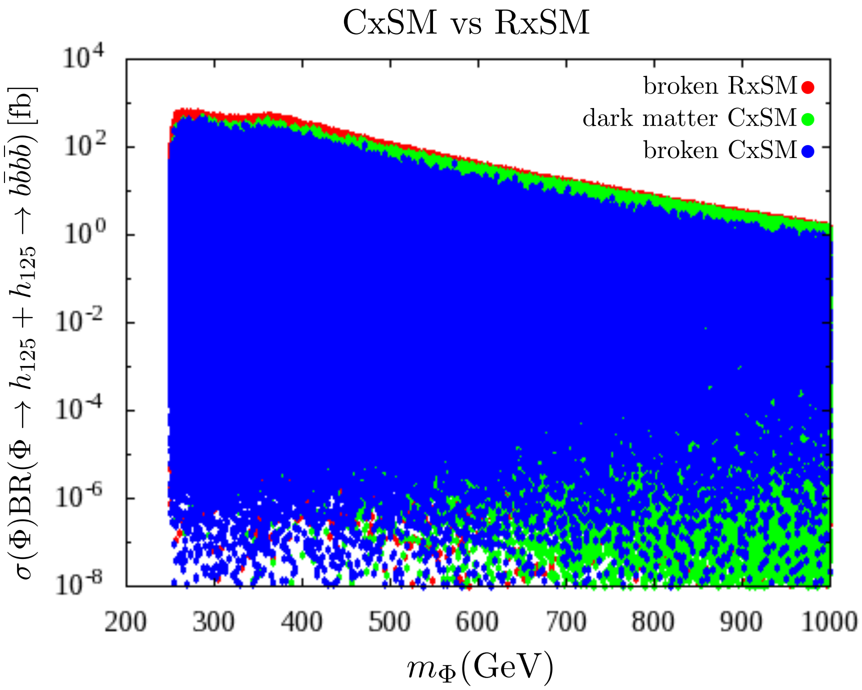
CxSM.B3: model remains stable up the GUT (10^{16} GeV) scale, since the new heavy scalar stabilises the theory

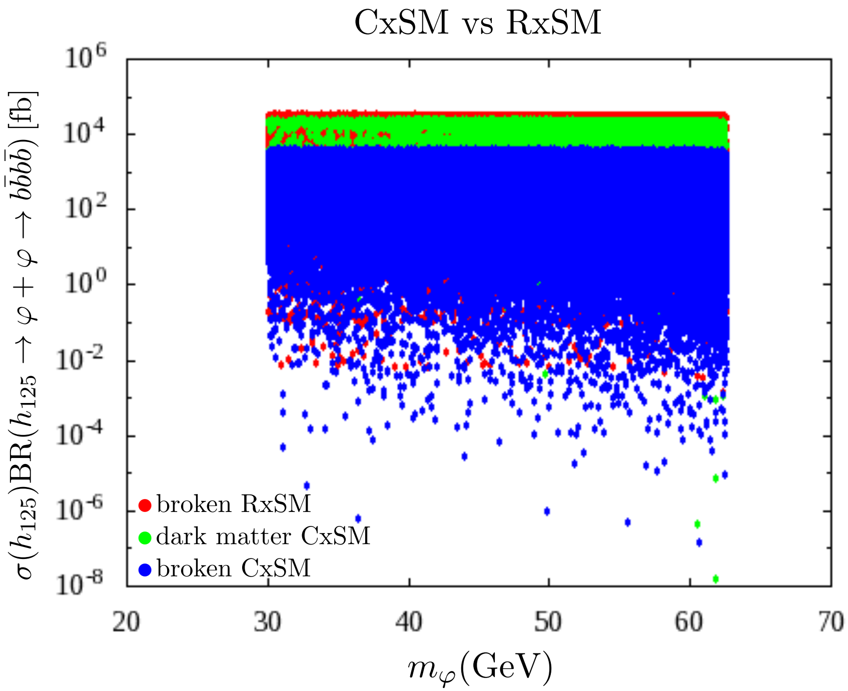
Most points were chosen such that the cross-section for the channel $h_3 \to h_2 h_1$ is relatively large (most notably CxSM.B1, CxSM.B4, CxSM.B5), so that discovery of h_3 through decays proceeding through this channel can compete with the direct decay of h_3 (see CxSM.B1, CxSM.B4).

Note that in this very simple model we can have the decay of a scalar to two other scalars with different masses.

Comparison between the RxSM and the two phases of the CxSM

Blue points: CxSM-broken; green: CxSM-dark; red: RxSM-broken





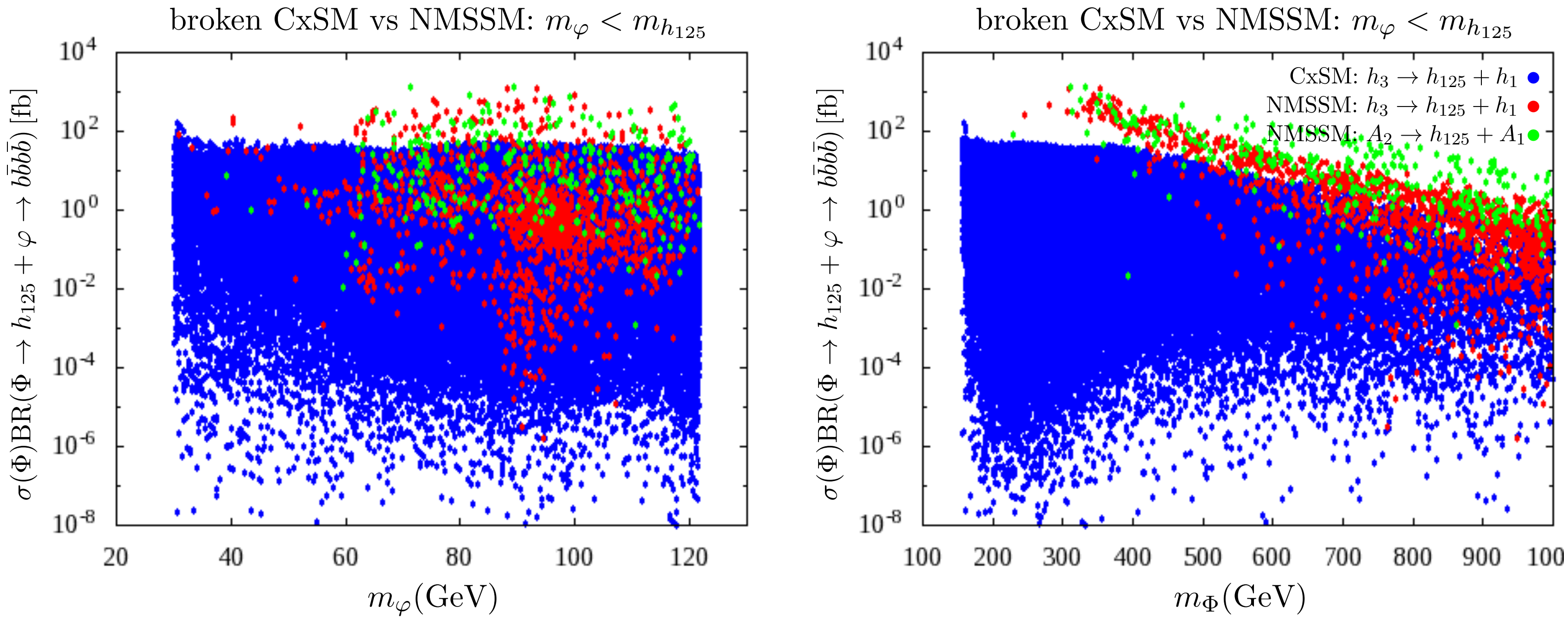
Left: Heavier Higgs $\Phi \rightarrow h_{125}\, h_{125} \rightarrow 4b$
(Φ heavier non-SM Higgs; φ lighter non-SM Higgs)

Right: Heavier Higgs $h_{125} \rightarrow \varphi\varphi$
production through gluon fusion at 13 TeV

- Maximum rates in RxSM- broken > CxSM rates; DM CxSM maximum rates not much smaller, CxSM-broken maximum rates one order of magnitude below maximum RxSM rates
- Larger rates for models w/ two-by-two mixing (CxSM-dark and RxSM) due to different vacuum structure; larger rates can be traced back to BR($h_{125} \to \varphi + \varphi$) (differs from model to model, in its allowed parameter space for the new scalar couplings of the theory)

Comparison between the NMSSM and the broken phase of the CxSM

blue (CxSM-broken); red points (NMSSM): $\Phi \equiv h_3$, $h_{125} \equiv h_2$ and $\varphi \equiv h_1$; green points (NMSSM): $\Phi \equiv A_2$, $h_{125} \equiv h_{1,2}$ and $\varphi \equiv A_1$.



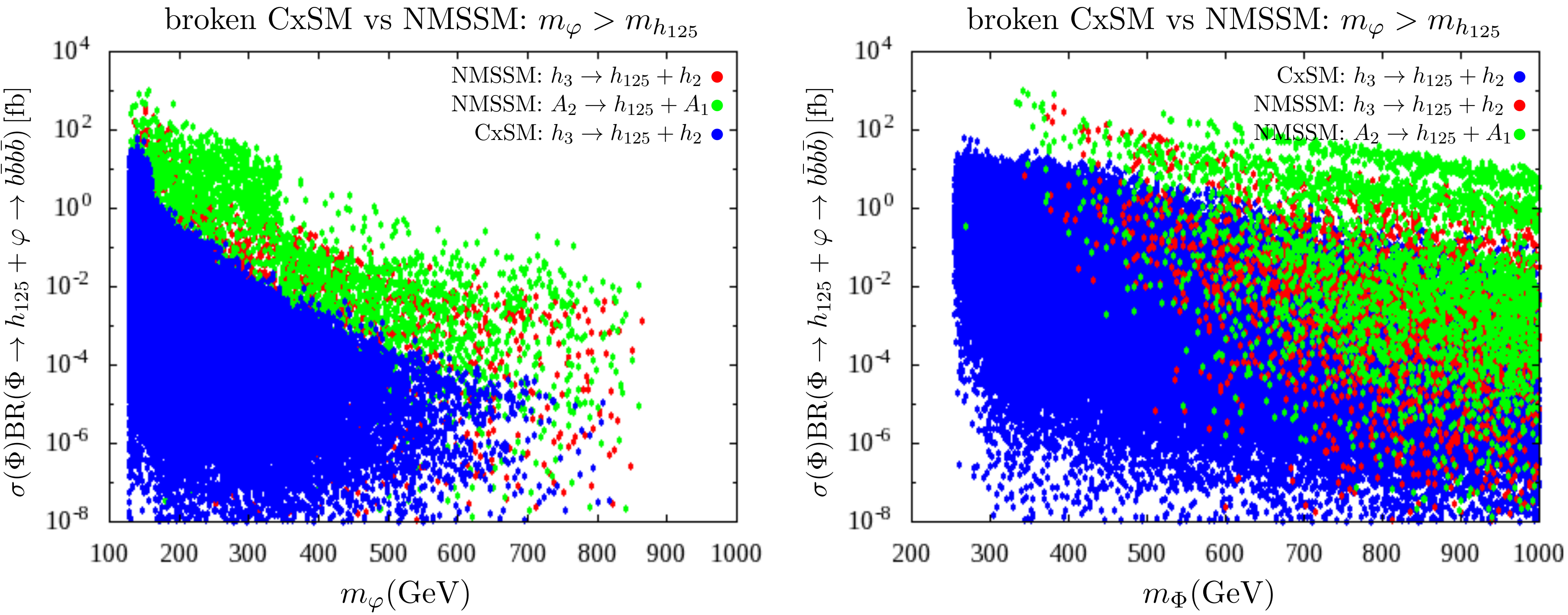
Rates for $\Phi \longrightarrow h_{125}\,\varphi \longrightarrow 4b$, with $m_\varphi < m_{h_{125}}$; left (right): as a function of m_φ (m_Φ).

Maximum NMSSM rates can be enhanced by up to two orders of magnitude compared to CxSM

Observation of a much larger rate than expected in the CxSM-broken in the decay of a heavy Higgs boson into a SM-like Higgs and a lighter Higgs state would hence be a hint to a different model, in this case the NMSSM.

Comparison between the NMSSM and the broken phase of the CxSM

Blue (CxSM-broken); red points (NMSSM): $\Phi \equiv h_3$, $h_{125} \equiv h_1$ and $\varphi \equiv h_2$; green points (NMSSM): $\Phi \equiv A_2$, $h_{125} \equiv h_{1,2}$ and $\varphi \equiv A_1$.



Rates for $\Phi \longrightarrow h_{125}\,\varphi \longrightarrow 4b$, with $m_\varphi > m_{h_{125}}$; left (right): as a function of m_φ (m_Φ)

Same conclusions as for the previous slide in the different mass range.

Conclusions

- Discussion of two of the simplest extensions of the scalar sector of the SM, one with a real singlet and one with a complex singlet.
- Complex singlet - two phases: broken phase with a dark matter candidate and unbroken phase where the three scalars mix.
- Plenty of parameter space in the models where final states with two Higgs either two SM-ones or two light states have large cross sections.
- Although the CxSM is one of the simplest extensions of the SM a decay of a scalar into two different scalars is allowed with large cross sections.
- Comparison between the CxSM and the NMSSM for the above channels: the models could be distinguished based on the rates only, if they are large enough.

BP9 Real and complex singlet benchmarks *[R. Costa, M. Muhlleitner, M.O.P. Sampaio and R. Santos]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/BenchmarksCxSM_and_RxSM.pdf