Proposal of benchmarks for the complex and real singlet models

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WG3: Extended scalars benchmarking

with Raul Costa, Margarete Mühlleitner and Rui Santos

Outline

1. Singlet models
2. The CxSM
   - Dark Phase
   - Broken phase
3. The RxSM – Broken phase

Singlets & the Higgs portal (see note for references!)

How?

- Scalar sector prone to coupling to hidden sectors!
  Only SM singlets with dimension < 4 are: $H^\dagger H\,,\ B_{\mu\nu}\,, HL$

$$V = V_{SM}(H^\dagger H) + H^\dagger H \times \mathcal{O}_\delta^{(2)}(\phi_i) + V_{New}(\phi_i)$$

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- Couplings to SM through mixing (dilutes higgs couplings):

$$\text{Higgs fluctuation} \leftarrow h = \sum_a \kappa_a H_a \, , \; \sum_a |\kappa_a|^2 = 1$$

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Why?

- Simple parametrization of DM
- V_{eff} @ $T \neq 0$ can be compatible with EW-Baryogenesis
- Improve stability of SM @ high energies

CxSM – dark matter AND new visible scalars

SM plus $\mathbb{S} = (S + iA)/\sqrt{2}$, with residual $\mathbb{Z}_2$ symmetry $A \to -A$ after ~~$U(1)$~~ symmetry by soft terms (in parenthesis)

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4} (H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |\mathbb{S}|^2 + \frac{b_2}{2} |\mathbb{S}|^2 + \frac{d_2}{4} |\mathbb{S}|^4 + \left(\frac{b_1}{4} \mathbb{S}^2 + a_1 \mathbb{S} + c.c. \right)$$

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- $\mathbb{Z}_2$ phase ($v_S \neq 0, v_A = 0$): 2 scalars mix + 1 dark

$$\begin{pmatrix} h_1 \\ h_2 \\ A \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ s \\ A \end{pmatrix}$$

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- $\not{\mathbb{Z}}_2$ phase ($v_S \neq 0, v_A \neq 0$): 3 scalars mix

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} R_{1h} & R_{1S} & R_{1A} \\ R_{2h} & R_{2S} & R_{2A} \\ R_{3h} & R_{3S} & R_{3A} \end{pmatrix} \begin{pmatrix} h \\ s \\ a \end{pmatrix}$$

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- Many OBSs related to SM up to κ_a factors (Ex. $\frac{\sigma_a}{\sigma_{SM}} \propto \kappa_a^2$)

RxSM – dark matter OR new visible scalar

SM plus S, with $\mathbb{Z}_2$ symmetry $S \to -S$

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

Lots of literature (see note). See also T. Robens talk next!

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$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- $\mathbb{Z}_2$ phase ($v_S = 0$): 1 Higgs + 1 dark

$$\begin{pmatrix} h_1 \\ S \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- We ignore dark phase!

Lots of literature (see note). See also T. Robens talk next!

Scan conditions – PHENO TESTS [arXiv:1411.4048]

Phenomenological constraints imposed using ScannerS:

scanners.hepforge.org

- Electroweak precision observables – STU
- Collider data (LEP, Tevatron, LHC) HiggsBounds/Signals
- Dark matter relic density below Planck measurement & bounds from LUX on σ_{SI} (micrOMEGAs)

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$\Rightarrow$ **Decay widths – adaptation of HDECAY$\rightarrow$ sHDECAY.**

`www.itp.kit.edu/~maggie/sHDECAY/`

- EW corrections consistently off
- CxSM and also RxSM

$\Rightarrow$ **We also turned EW off for 13 TeV** $\sigma(gg \rightarrow h_i)$

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We define global signal rate for direct channels

$$\mu_i = R_{ih}^2 \sum_{X_{\mathrm{SM}}} \mathrm{BR}(h_i \rightarrow X_{\mathrm{SM}})$$

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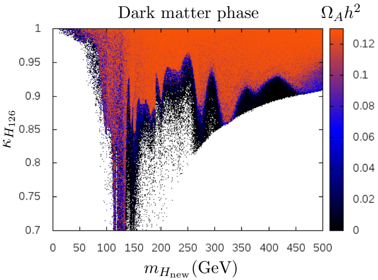
Theoretical motivation & LHC7+8 [arXiv:1411.4048]



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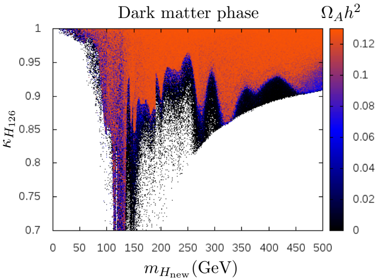

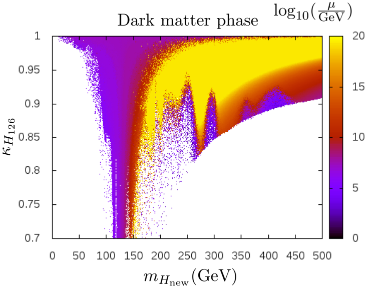

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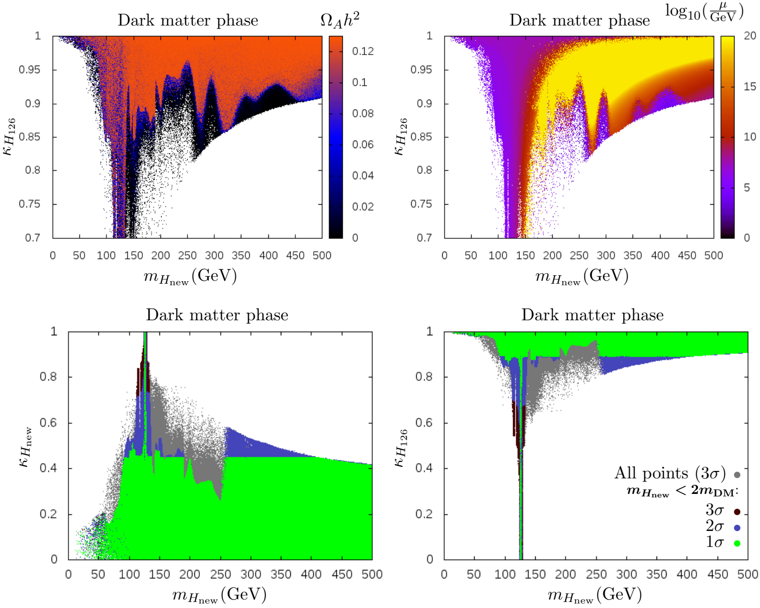
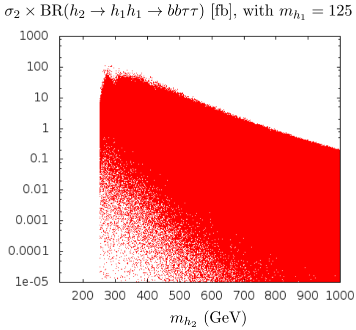
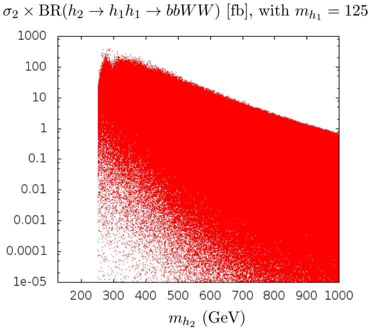


Cross-sections at LHC13





Suggested Benchmarks – CxSM Dark

	CxSM.D1	CxSM.D2	CxSM.D3
⋆ m_1 (GeV)	125.4	125.4	49.116
⋆ m_2 (GeV)	456.57	339.77	125.4
⋆ m_A (GeV)	52.98	77.022	65.054
⋆ α	-0.39506	-0.50029	1.4617
$\Omega_A h^2$	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
$\mu_{\text{stability}}$ (GeV)	10^{12}	10^{14}	10^{8}

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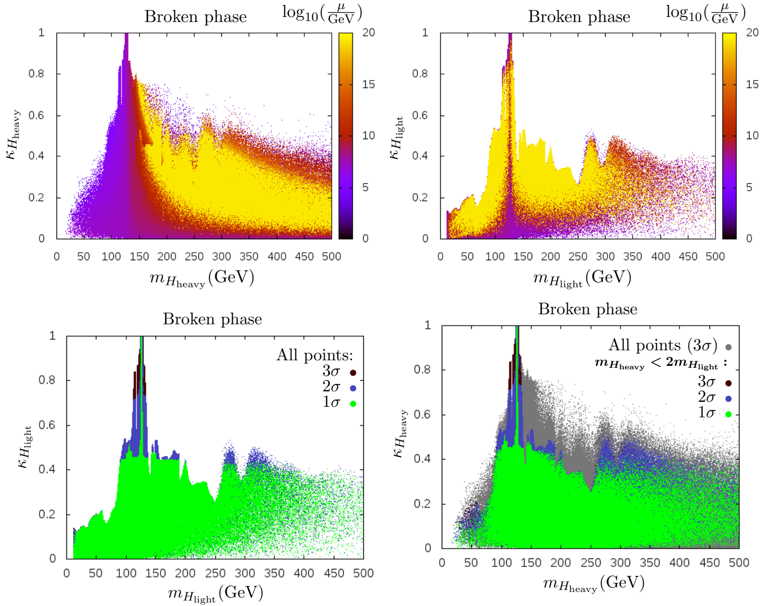
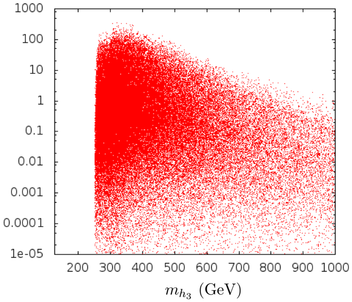
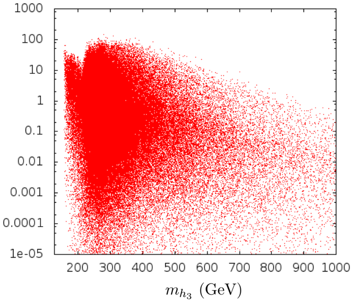


Cross-sections at LHC13

$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbWW)$ [fb], with $m_{h_1} = 125$



$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbWW)$ [fb], with $m_{h_2} = 125$



Suggested Benchmarks – CxSM Broken

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
$\star\ m_1$ (GeV)	125.4	125.4	57.34	98.12	41.61
m_2 (GeV)	258.9	230.8	125.4	125.4	69.51
$\star\ m_3$ (GeV)	462.4	271.3	345.5	255.2	125.4
$\star\ \alpha_1$	-0.04867	0.03148	-1.071	-0.7888	-1.169
$\star\ \alpha_2$	0.4739	-0.5707	1.126	0.7717	1.24
$\star\ \alpha_3$	-0.4763	-0.3888	-0.005447	-0.1945	1.044
μ_{h_1}	0.79	0.707	0.0426	0.255	0.0161
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	24.9 [pb]	22.3 [pb]	5.67 [pb]	12.5 [pb]	4.19 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.97 [pb]	4.45 [pb]	0.262 [fb]	87.4 [fb]	0.0226 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	625 [fb]	560 [fb]	0.0807 [fb]	10 [fb]	$<$ 0.01 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	15.2 [pb]	13.6 [pb]	4.91 [pb]	10.2 [pb]	3.67 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.46 [pb]	1.31 [pb]	401 [fb]	936 [fb]	281 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	53.8 [fb]	48.2 [fb]	2.26 [fb]	17.4 [fb]	0.831 [fb]
μ_{h_2}	0.0636	0.0547	0.768	0.626	0.0205
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	559 [fb]	577 [fb]	24.4 [pb]	19.7 [pb]	1.88 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	390 [fb]	408 [fb]	4.87 [pb]	3.95 [pb]	0.342 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	167 [fb]	167 [fb]	613 [fb]	497 [fb]	0.0998 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.601 [fb]	0.928 [fb]	14.8 [pb]	12.1 [pb]	1.61 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.0663 [fb]	0.1 [fb]	1.42 [pb]	1.16 [pb]	137 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0122 [fb]	0.0186 [fb]	52.4 [fb]	42.7 [fb]	1.15 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	0.0467 [fb]	0	195 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.0175 [fb]	0	146 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	$<$ 0.01 [fb]	0	23.9 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	0.0114 [fb]	0	0.0156 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	0	0.134 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	$<$ 0.01 [fb]	0	0.976 [fb]	0	0

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$\star\ m_1$ (GeV)	125.4	125.4	57.34	98.12	41.61
m_2 (GeV)	258.9	230.8	125.4	125.4	69.51
$\star\ m_3$ (GeV)	462.4	271.3	345.5	255.2	125.4
μ_{h_3}	0.0774	0.0868	0.111	0.0273	0.777
$\sigma_3 \equiv \sigma(gg \to h_3)$ 13 TeV	659 [fb]	1.95 [pb]	1.31 [pb]	1.07 [pb]	30.4 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to WW)$	189 [fb]	496 [fb]	537 [fb]	172 [fb]	4.89 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to ZZ)$	89.7 [fb]	215 [fb]	245 [fb]	73.2 [fb]	615 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to bb)$	0.0558 [fb]	0.656 [fb]	0.345 [fb]	0.277 [fb]	15 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \tau\tau)$	$<$ 0.01 [fb]	0.073 [fb]	0.0401 [fb]	0.0305 [fb]	1.44 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \gamma\gamma)$	$<$ 0.01 [fb]	0.0133 [fb]	$<$ 0.01 [fb]	$<$ 0.01 [fb]	53 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$	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
$\mu_{\text{RGE stability}}$ (GeV)	10^4	10^5	10^{16}	10^9	10^7

Outline

1. Singlet models

2. The CxSM
   - Dark Phase
   - Broken phase

3. The RxSM – Broken phase

Suggested Benchmarks – RxSM Broken

	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
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

Conclusions

- We have chosen benchmarks trying to cover many kinematically different situations
- Imposed correct relic density when dark matter present
- Some points can improve the stability of the SM
- Attempted to maximise Higgs-to-Higgs decays
- In some cases, it might be possible to find new heavy scalar in $h_3 \to h_1 h_2$ in broken phase of CxSM