Benchmark scenarios and resonant decays in singlet models at the LHC run 2

Marco Sampaio & R. Costa & M. Mühlleitner & R. Santos

universidade de aveiro

Gr@v
gravitation.web.ua.pt

Karlsruhe Institute of Technology

CFTC
Centro de Física Teórica e Computacional

ISEL
INSTITUTO SUPERIOR
DE ENGENHARIA DE LISBOA

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MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

Outline

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- Improve stability of SM @ high energies

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- Help explain the baryon asymmetry of the Universe

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- Rich phenomenology with Higgs-to-Higgs decays

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LHC run 2 $\rightarrow$ start probing Higgs self couplings
$\Rightarrow$ opportunity also to probe extended Higgs sectors

CxSM: minimal model with dark matter + new Higgs(s)

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SM plus $\mathbb{S} = (S + iA)/\sqrt{2}$, with residual $\mathbb{Z}_2$ symmetry $A \to -A$

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

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

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

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

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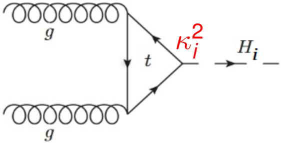
New Higgs production and decays

In singlet models, various LO (in EW corrections) observables, related to SM by a factor of κ^2:

- **Production cross sections:**

$$\sigma_i = \kappa_i^2 \sigma_{SM}$$



- **Decay widths to SM particles:**

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- **Total decay width:**

$$\Gamma_i^{total} = \kappa_i^2 \Gamma_{SM}^{total} + \sum_{jk} \Gamma_{i \to jk}$$

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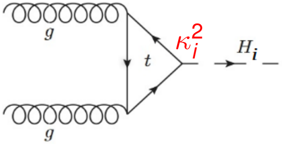

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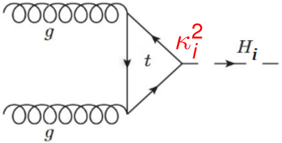

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Some remarks on the NMSSM

In the NMSSM a singlet superfield ($\hat{S}$) is introduced to (dynamically) solve the μ-problem. Then

$$(H_1, H_2, H_3)^T = \mathcal{R}^S(h_d, h_u, h_s)^T$$

$$(A_1, A_2, G)^T = \mathcal{R}^P\mathcal{R}^G(a_d, a_u, a_s)^T$$

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Why compare with NMSSM?

- Singlet creates a 3×3 CP-even sector
- CP-odd sector introduces more cases
- Constrained by SUSY relations but more parameters

$$\begin{array}{lllllllll}
A_2 & \to & A_1 + H_1 \,, & A_2 & \to & A_1 + H_2 & & & \\
H_{2,3} & \to & H_1 + H_1 \,, & H_3 & \to & H_1 + H_2 \,, & H_3 & \to & H_2 H_2 \\
H_{1,2,3} & \to & A_1 A_1 \,. & & & & & &
\end{array}$$

Phenomenological constraints

A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun., 108:56-74, 1998.

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Pheno constraints (CxSM & RxSM) imposed in ScannerS:

scanners.hepforge.org

- Electroweak precision observables – STU
- Collider bounds (LEP, Tevatron, LHC) HiggsBounds
- Used ATLAS+CMS global signal rate $\mu_{h_{125}} = 1.09 \pm 0.11$
- Dark matter relic density below Planck measurement & bounds from LUX on σ_{SI} (micrOMEGAs)

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NMSSM: Similar constraints imposed. Used a sample from

S.F. King, M. Muhlleitner, R. Nevzorov, K. Walz, Phys.Rev., D90(9):095014, 2014

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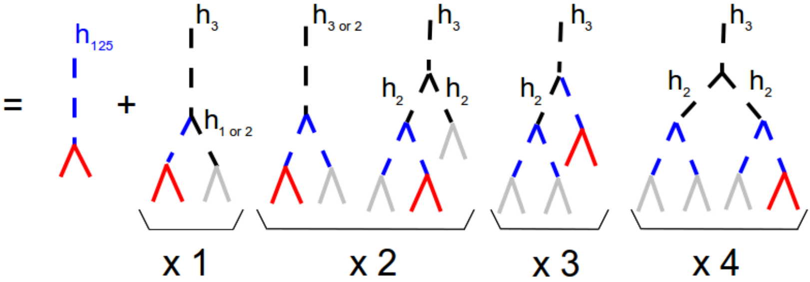
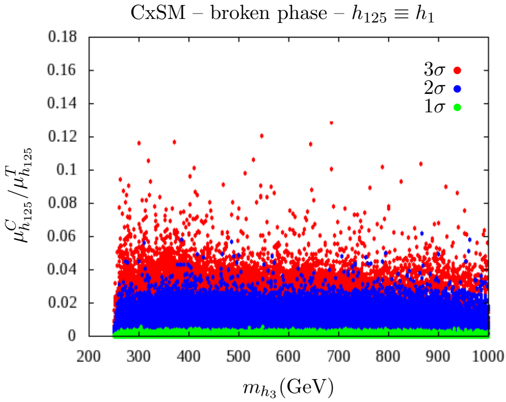
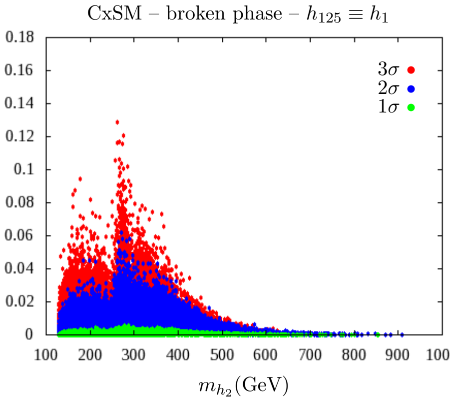
Chain decay contributions to the signal strength

$$
\begin{aligned}
\mu^{T}_{h_{125}} &\equiv \mu_{h_{125}} + \mu^{\mathrm{C}}_{h_{125}} \\
&= \frac{\sigma_{\mathrm{New}}(h_{125})\mathrm{BR}_{\mathrm{New}}(h_{125}\to X_{\mathrm{SM}})}{\sigma_{\mathrm{SM}}(h_{125})\mathrm{BR}_{\mathrm{SM}}(h_{125}\to X_{\mathrm{SM}})} + \sum_i \frac{\sigma_{\mathrm{New}}(h_i)}{\sigma_{\mathrm{SM}}(h_{125})} N_{h_i,h_{125}} \frac{\mathrm{BR}_{\mathrm{New}}(h_{125}\to X_{\mathrm{SM}})}{\mathrm{BR}_{\mathrm{SM}}(h_{125}\to X_{\mathrm{SM}})}
\end{aligned}
$$



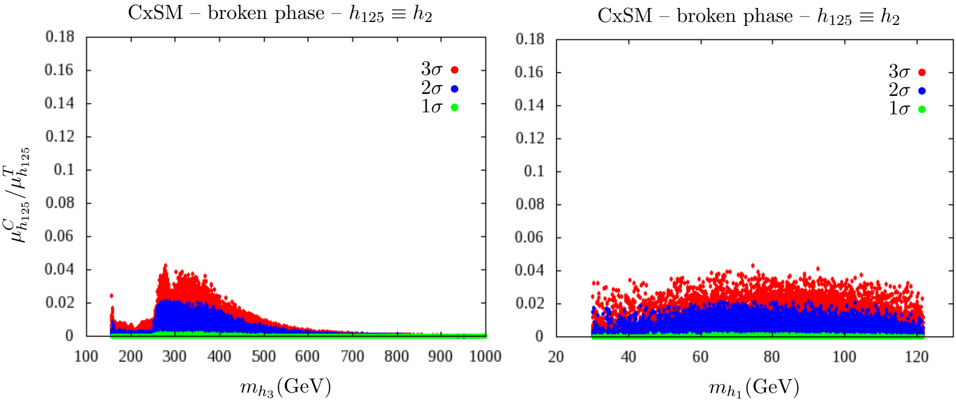
Large chain decays @ LHC2: **CxSM-broken** $h_1 \equiv h_{125}$





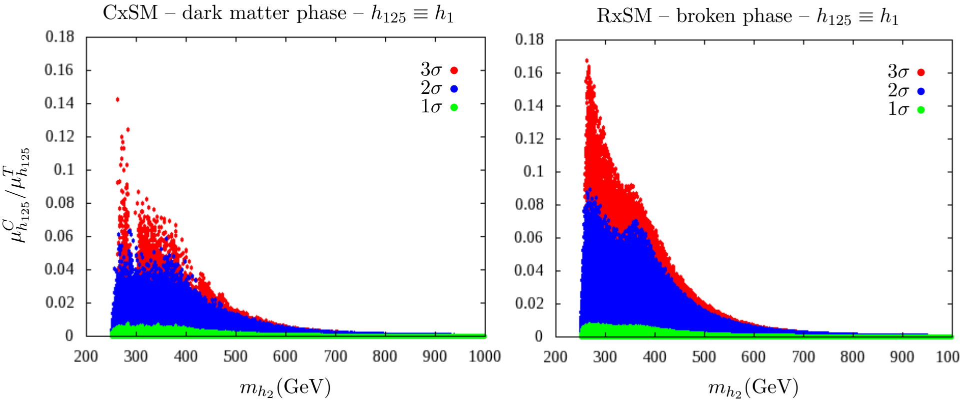
- Tail on the right due to STU
- LHC Run 1 still allows scenarios with large chain decays
- Up to $\sim$ 6% ($\sim$ 12%) at 2σ (3σ)

Large chain decays @ LHC2: **CxSM-broken** $h_2 \equiv h_{125}$



- LHC Run 1 allows scenarios with smaller chain decays
- But still up to $\sim$ 2% ($\sim$ 6%) for the 2σ (3σ)
- Due to one less channel contributing + different kinematics

Large chain decays @ LHC2: **CxSM-dark vs RxSM**



- Models much more similar
- LHC Run 1 allows scenarios with even larger chain decays
- Up to $\sim 7\% - 9\%$ ($\sim 15\% - 17\%$) for the 2σ (3σ)

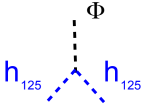
Outline

The Four cases

Aim: Find differences between NMSSM & CxSM-broken

1. $\Phi \to h_{125} + h_{125}$

   Example: $h_3 \to h_1 + h_1$, $h_1 \equiv h_{125}$; $(\ldots)$



2. $\Phi \to h_{125} + \varphi$

   Example: $h_3 \to h_{125} + h_2$; $A_2 \to h_{125} + A_1$; $(\ldots)$

3. $h_{125} \to \varphi_i + \varphi_j$

   Example: $h_3 \equiv h_{125} \to h_1 + h_1$; $(\ldots)$

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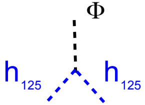

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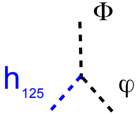

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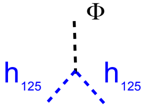

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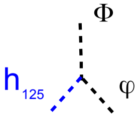

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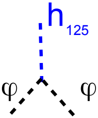

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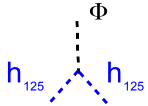

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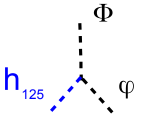

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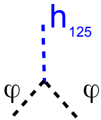

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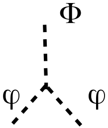
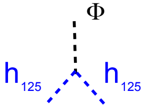


The Four cases

Aim: Find differences between NMSSM & CxSM-broken

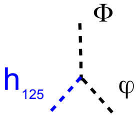
1. $\underline{\Phi \to h_{125} + h_{125}}$

   Example: $h_3 \to h_1 + h_1$, $h_1 \equiv h_{125}$; $(\ldots)$
   Inconclusive



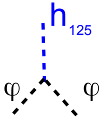
2. $\underline{\Phi \to h_{125} + \varphi}$

   Example: $h_3 \to h_{125} + h_2$; $A_2 \to h_{125} + A_1$; $(\ldots)$
   Interesting case!



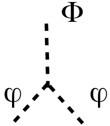
3. $\underline{h_{125} \to \varphi_i + \varphi_j}$

   Example: $h_3 \equiv h_{125} \to h_1 + h_1$; $(\ldots)$
   Inconclusive



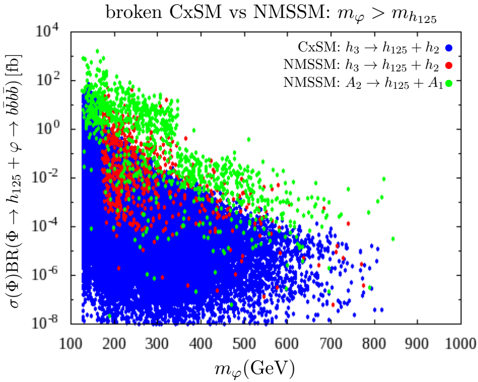
4. $\underline{\Phi \to \varphi + \varphi}$

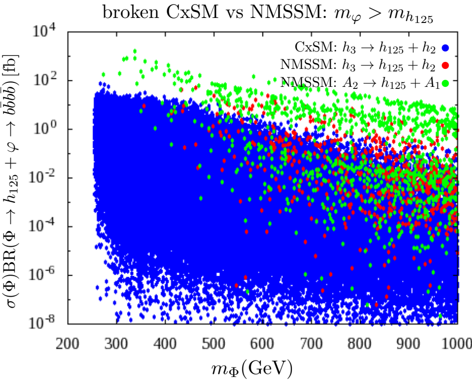
   Example: $h_3 \to h_1 + h_1$, $h_2 \equiv h_{125}$; $(\ldots)$
   Inconclusive



Strategy for plots: Focus on (representative) $4b$ final state

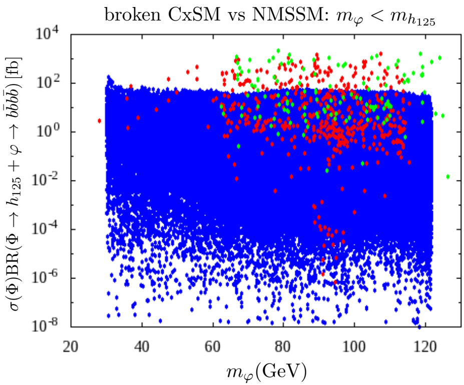
CxSM-broken vs NMSSM: Case 2 & $h_1 \equiv h_{125}$

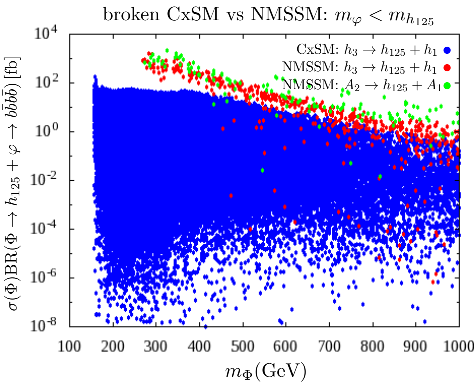




- NMSSM points can go up by up to 2 orders of magnitude compared to CxSM-broken
- This also happens in the next-to-lightest scenario

CxSM-broken vs NMSSM: Case 2 & $h_2 \equiv h_{125}$





- NMSSM points can go up by up to 2 orders of magnitude compared to CxSM-broken
- This also happens in the next-to-lightest scenario

Outline

Remarks on benchmarks – Properties

Leading principles (whenever possible!):

- Cover kinematically interesting situations
- Maximize the visiblility of the new scalars (i.e. maximize chain decay cross-sections)
- Stability up to a large cutoff scale
- In CxSM-dark, $\Omega_A h^2$ explains Planck measurement

Points submitted to “WG3: Extended scalars benchmarking” for YR4.

https://indico.cern.ch/event/443289/

Remarks on benchmarks – **CxSM-broken**

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
m_{h_1} (GeV)	125	125	57.8	86.8	33.2
m_{h_2} (GeV)	261	228	125	125	65.0
m_{h_3} (GeV)	450	311	299	292	125
...	...	...	...	...	...
$\mu^C_{h125}/\mu^T_{h125}$	0.0127	0.0407	0.0128	0.0104	0
μ_{h_1}	0.836	0.771	0.0362	0.0958	0.00767
$\sigma_1 \equiv \sigma(gg \to h_1)$	36.1 [pb]	33.3 [pb]	6.42 [pb]	8.03 [pb]	4.61 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	7.03 [pb]	6.49 [pb]	0.314 [fb]	9.35 [fb]	$<$ 0.01 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	880 [fb]	812 [fb]	0.0969 [fb]	2.22 [fb]	$<$ 0.01 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	22.2 [pb]	20.5 [pb]	5.56 [pb]	6.72 [pb]	4.06 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	2.13 [pb]	1.97 [pb]	455 [fb]	599 [fb]	297 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	77.9 [fb]	71.9 [fb]	2.61 [fb]	8.29 [fb]	0.568 [fb]
μ_{h_2}	0.0752	0.0759	0.784	0.785	0.0106
$\sigma_2 \equiv \sigma(gg \to h_2)$	1.01 [pb]	1.11 [pb]	35.1 [pb]	33.9 [pb]	1.51 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	618 [fb]	784 [fb]	6.55 [pb]	6.62 [pb]	0.167 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	265 [fb]	319 [fb]	819 [fb]	828 [fb]	0.0499 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.932 [fb]	1.86 [fb]	20.9 [pb]	20.9 [pb]	1.30 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.103 [fb]	0.201 [fb]	2.01 [pb]	2.00 [pb]	109 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0189 [fb]	0.0373 [fb]	73.1 [fb]	73.2 [fb]	0.791 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1h_1)$	122 [fb]	0	1.25 [pb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1h_1 \to bbbb)$	46.2 [fb]	0	936 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1h_1 \to bb\tau\tau)$	8.86 [fb]	0	153 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1h_1 \to bbWW)$	29.2 [fb]	0	0.106 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1h_1 \to bb\gamma\gamma)$	0.324 [fb]	0	0.878 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1h_1 \to \tau\tau\tau\tau)$	0.425 [fb]	0	6.28 [fb]	0	0

Remarks on benchmarks – **CxSM-broken**

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
μ_{h_3}	0.0558	0.0791	0.0788	0.0491	0.863
$\sigma_3 \equiv \sigma(gg \to h_3)$	520 [fb]	1.46 [pb]	1.48 [pb]	1.20 [pb]	42.4 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to WW)$	201 [fb]	518 [fb]	536 [fb]	343 [fb]	7.26 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to ZZ)$	95.1 [fb]	232 [fb]	238 [fb]	151 [fb]	909 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to bb)$	0.0638 [fb]	0.450 [fb]	0.525 [fb]	0.362 [fb]	23.0 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \tau\tau)$	<0.01 [fb]	0.0513 [fb]	0.0594 [fb]	0.0408 [fb]	2.20 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \gamma\gamma)$	<0.01 [fb]	<0.01 [fb]	0.0105 [fb]	<0.01 [fb]	80.4 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$	44.4 [fb]	706 [fb]	438 [fb]	427 [fb]	4.37 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbbb)$	16.8 [fb]	268 [fb]	329 [fb]	300 [fb]	3.38 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	3.23 [fb]	51.4 [fb]	53.8 [fb]	53.4 [fb]	496 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbWW)$	10.7 [fb]	170 [fb]	0.0372 [fb]	0.833 [fb]	<0.01 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\gamma\gamma)$	0.118 [fb]	1.88 [fb]	0.308 [fb]	0.739 [fb]	0.946 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.155 [fb]	2.47 [fb]	2.20 [fb]	2.38 [fb]	18.2 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2)$	107 [fb]	0	89.0 [fb]	207 [fb]	770 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbbb)$	0.0608 [fb]	0	45.9 [fb]	107 [fb]	583 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bb\tau\tau)$	0.0126 [fb]	0	8.16 [fb]	19.7 [fb]	91.6 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbWW)$	40.4 [fb]	0	14.4 [fb]	33.9 [fb]	0.0759 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bb\gamma\gamma)$	<0.01 [fb]	0	0.182 [fb]	0.505 [fb]	0.437 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to \tau\tau\tau\tau)$	<0.01 [fb]	0	0.360 [fb]	0.912 [fb]	3.58 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2)$	0	0	183 [fb]	75.2 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bbbb)$	0	0	64.7 [fb]	28.5 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bb\tau\tau)$	0	0	12.4 [fb]	5.48 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bbWW)$	0	0	40.6 [fb]	18.1 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bb\gamma\gamma)$	0	0	0.453 [fb]	0.20 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to \tau\tau\tau\tau)$	0	0	0.596 [fb]	0.263 [fb]	0
$\log_{10}\left(\frac{\mu}{\mathrm{GeV}}\right)$	9.40	6.05	19.3	15.7	6.64

Remarks on benchmarks – **CxSM-dark**

	CxSM.D1	CxSM.D2	CxSM.D3	CxSM.D4
$\star\ m_{h_1}$ (GeV)	125	125	56.1	121
$\star\ m_{h_2}$ (GeV)	335	341	125	125
$\star\ m_A$ (GeV)	52.5	94.0	139	52.0
...	...	...	...	...
$\mu^C_{h_{125}}/\mu^T_{h_{125}}$	0.0190	0.0235	0	0
μ_{h_1}	0.804	0.837	0.00404	0.0444
$\sigma_1 \equiv \sigma(gg \to h_1)$	34.7 [pb]	36.2 [pb]	759 [fb]	2.03 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.87 [pb]	7.05 [pb]	0.0302 [fb]	4.82 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	609 [fb]	881 [fb]	< 0.01 [fb]	0.563 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	15.4 [pb]	22.3 [pb]	658 [fb]	23.0 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.48 [pb]	2.14 [pb]	53.6 [fb]	2.19 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	53.9 [fb]	78.1 [fb]	0.288 [fb]	0.0725 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to AA)$	9.75 [pb]	0	0	2.00 [pb]
μ_{h_2}	0.138	0.108	0.723	0.841
$\sigma_2 \equiv \sigma(gg \to h_2)$	1.83 [pb]	1.55 [pb]	43 [pb]	41.3 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	886 [fb]	704 [fb]	6.09 [pb]	7.08 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	402 [fb]	320 [fb]	762 [fb]	886 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.620 [fb]	0.468 [fb]	19.2 [pb]	22.4 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.0717 [fb]	0.0543 [fb]	1.85 [pb]	2.15 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0121 [fb]	< 0.01 [fb]	67.4 [fb]	78.5 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	337 [fb]	436 [fb]	11.8 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	66.2 [fb]	165 [fb]	8.86 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	12.7 [fb]	31.7 [fb]	1.44 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	41.9 [fb]	105 [fb]	0.814 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	0.464 [fb]	1.16 [fb]	7.76 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.609 [fb]	1.52 [fb]	58.7 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to AA)$	207 [fb]	91.1 [fb]	0	4.93 [pb]
$\Omega_A h^2$	0.118	0.123	0.116	0.125
$\log_{10}\left(\frac{\mu}{\mathrm{GeV}}\right)$	14.9	17.1	6.69	6.69

Remarks on benchmarks – **RxSM-dark**

	RxSM.B1	RxSM.B2	RxSM.B3	RxSM.B4
m_{h_1} (GeV)	125	125	55.3	92.4
m_{h_2} (GeV)	265	173	125	125
...	...	...	...	...
$\mu^C_{h_{125}}/\mu^T_{h_{125}}$	0.0509	0	0	0
μ_{h_1}	0.827	0.831	0.0376	0.163
$\sigma_1 \equiv \sigma(gg \to h_1)$	35.7 [pb]	35.9 [pb]	7.26 [pb]	12.2 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	6.96 [pb]	6.99 [pb]	0.260 [fb]	32.3 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	871 [fb]	875 [fb]	0.0808 [fb]	5.62 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	22.0 [pb]	22.1 [pb]	6.30 [pb]	10.1 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	2.11 [pb]	2.12 [pb]	511 [fb]	911 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	77.2 [fb]	77.5 [fb]	2.67 [fb]	14.6 [fb]
μ_{h_2}	0.0888	0.169	0.863	0.837
$\sigma_2 \equiv \sigma(gg \to h_2)$	1.97 [pb]	4.06 [pb]	41.6 [pb]	36.2 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	709 [fb]	3.90 [pb]	7.26 [pb]	7.05 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	305 [fb]	112 [fb]	909 [fb]	882 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	1.01 [fb]	34.2 [fb]	23.0 [pb]	22.3 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.112 [fb]	3.48 [fb]	2.20 [pb]	2.14 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0204 [fb]	0.583 [fb]	80.5 [fb]	78.1 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	959 [fb]	0	4.29 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	364 [fb]	0	3.23 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	69.9 [fb]	0	525 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	230 [fb]	0	0.267 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	2.55 [fb]	0	2.74 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	3.35 [fb]	0	21.3 [fb]	0

Conclusions

1. CxSM and RxSM still allow large chain decay scenarios at LHC run 2, which can be up to $\sim 16\%$ of the direct rate
2. The NMSSM can be distinguished from CxSM-broken using $\Phi \to h_{125} + \varphi$ alone.
3. Other channels do not allow to draw a similar conclusion so straightforwardly
4. Benchmark scenarios exist such that:
   - All singlet scalars will be found in the next run
   - Stability up to a high scale
   - Explain dark matter observables (in dark phase)

Conclusions

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   - All singlet scalars will be found in the next run
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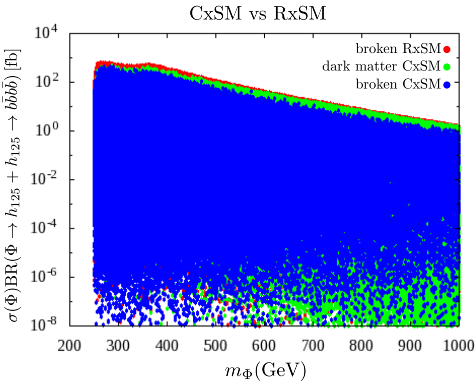
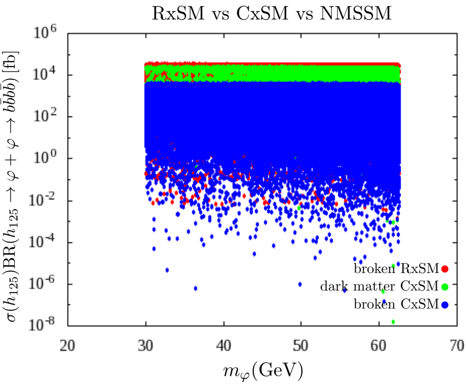
THANK YOU!

BACKUP

Differences among singlet models: **Case 1 vs Case 3**





- Light Higgs $\to$ not much difference (see scale next slides)
- Heavy Higgs $\to$ higher for 2×2 mix, CxSM-dark & RxSM (checked in NMSSM comparison)
- We can focus on CxSM-broken to compare with NMSSM

Scan boxes NMSSM

$$\begin{aligned} -\mathcal{L}_{\text{mass}} &= m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 \\ &+ m_{\tilde{Q}_3}^2 |\tilde{Q}_3^2| + m_{\tilde{t}_R}^2 |\tilde{t}_R^2| + m_{\tilde{b}_R}^2 |\tilde{b}_R^2| + m_{\tilde{L}_3}^2 |\tilde{L}_3^2| + m_{\tilde{\tau}_R}^2 |\tilde{\tau}_R^2| \, . \end{aligned}$$

$$-\mathcal{L}_{\text{tril}} = \lambda A_\lambda H_u H_d S + \frac{1}{3} \kappa A_\kappa S^3 + h_t A_t \tilde{Q}_3 H_u \tilde{t}_R^c - h_b A_b \tilde{Q}_3 H_d \tilde{b}_R^c - h_\tau A_\tau \tilde{L}_3 H_d$$

$$-\mathcal{L}_{\text{gauginos}} = \frac{1}{2} \left[M_1 \tilde{B} \tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a \; + \; \text{h.c.} \right] .$$

$$1 \leq \tan\beta \leq 30 \, , \qquad 0 \leq \lambda \leq 0.7 \, , \qquad -0.7 \leq \kappa \leq 0.7 \, ,$$

$$-2 \text{ TeV} \leq A_\lambda \leq 2 \text{ TeV} \, , \; -2 \text{ TeV} \leq A_\kappa \leq 2 \text{ TeV} \, , \; -1 \text{ TeV} \leq \mu_{\text{eff}} \leq 1 \text{ TeV} \, .$$

$$-2 \text{ TeV} \leq A_U, A_D, A_L \leq 2 \text{ TeV} \, .$$

$$600 \text{ GeV} \leq M_{\tilde{t}_R} = M_{\tilde{Q}_3} \leq 3 \text{ TeV} \, , \; 600 \text{ GeV} \leq M_{\tilde{\tau}_R} = M_{\tilde{L}_3} \leq 3 \text{ TeV}$$

$$, M_{\tilde{b}_R} = 3 \text{ TeV} \, , \; M_{\tilde{u}_R, \tilde{c}_R} = M_{\tilde{d}_R, \tilde{s}_R} = M_{\tilde{Q}_{1,2}} = M_{\tilde{e}_R, \tilde{\mu}_R} = M_{\tilde{L}_{1,2}} = 3 \text{ TeV} \, .$$

$$100 \text{ GeV} \leq M_1 \leq 1 \text{ TeV} \, , \; 200 \text{ GeV} \leq M_2 \leq 1 \text{ TeV} \, , \; 1.3 \text{ TeV} \leq M_3 \leq 3 \text{ TeV}$$

Scan boxes CxSM-broken

Input parameter	Broken phase Min	Broken phase Max
$m_{h_{125}}$ (GeV)	125.1	125.1
$m_{h_{\text{other}}}$ (GeV)	30	1000
v (GeV)	246.22	246.22
v_S (GeV)	1	1000
α_1	$-\pi/2$	$\pi/2$
α_2	$-\pi/2$	$\pi/2$
α_3	$-\pi/2$	$\pi/2$

Scan boxes CxSM-dark

Input parameter	Dark phase Min	Dark phase Max
$m_{h_{125}}$ (GeV)	125.1	125.1
$m_{h_{\rm other}}$ (GeV)	30	1000
m_A (GeV)	30	1000
v (GeV)	246.22	246.22
v_S (GeV)	1	1000
α_1	$-\pi/2$	$\pi/2$
$a_1(\mathrm{GeV}^3)$	-10^8	0

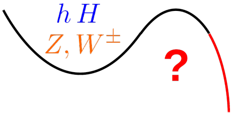
Scan boxes - RxSM

Scan parameter	Broken phase Min	Broken phase Max
$m_{h_{125}}$ (GeV)	125.1	125.1
$m_{h_{(\mathrm{other})}}$ (GeV)	30	1000
v (GeV)	246.22	246.22
v_S (GeV)	1	1000
α	$-\pi/2$	$\pi/2$

Stability conditions under RGE evolution

Stability conditions (imposed also in evolution):

- Boundedness from below: $\lambda > 0 \;\wedge\; d_2 > 0 \;\wedge\; \delta_2 > -\sqrt{\lambda d_2}$



- Perturbative unitarity:

$$\left\{ |\lambda| \,,\; |d_2| \,,\; |\delta_2| \,,\; \left| \frac{3}{2}\lambda + d_2 \pm \sqrt{\left(\frac{3}{2}\lambda + d_2\right)^2 + d_2^2} \right| \right\} \leq 16\pi$$

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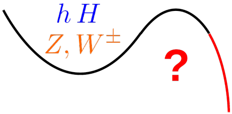

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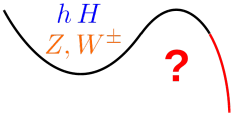

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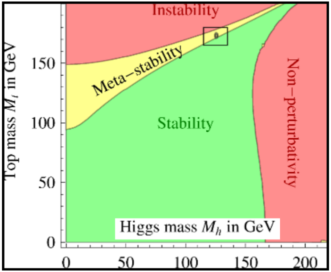
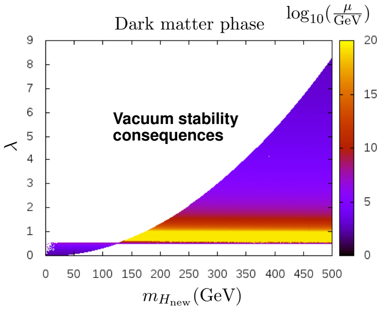
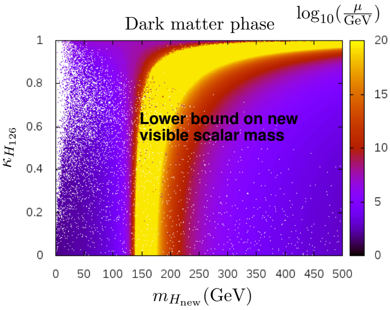
SM seems to be metastable @ 2-loops!

G. Degrassi et al, JHEP 1208 (2012) 098



RGE stability bands – No phenomenology





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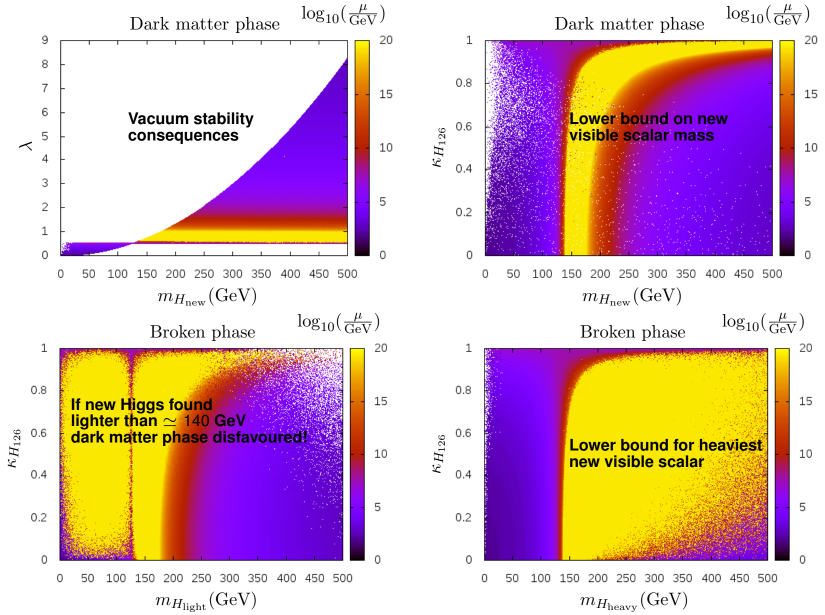
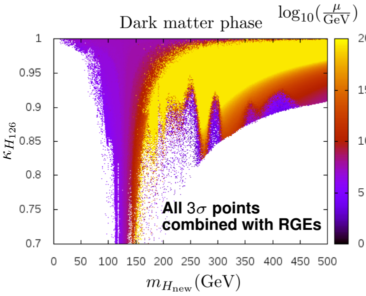
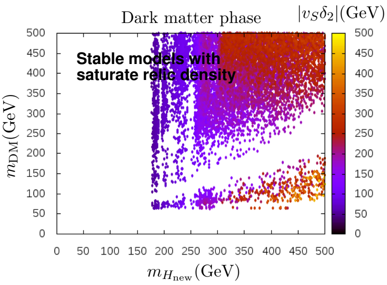
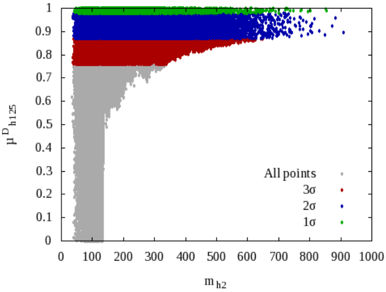


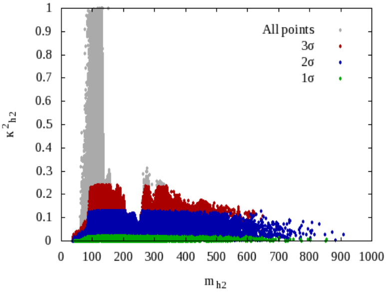
RGE stability – Combined with phenomenology





Results for h_{125} chain production: parameter space





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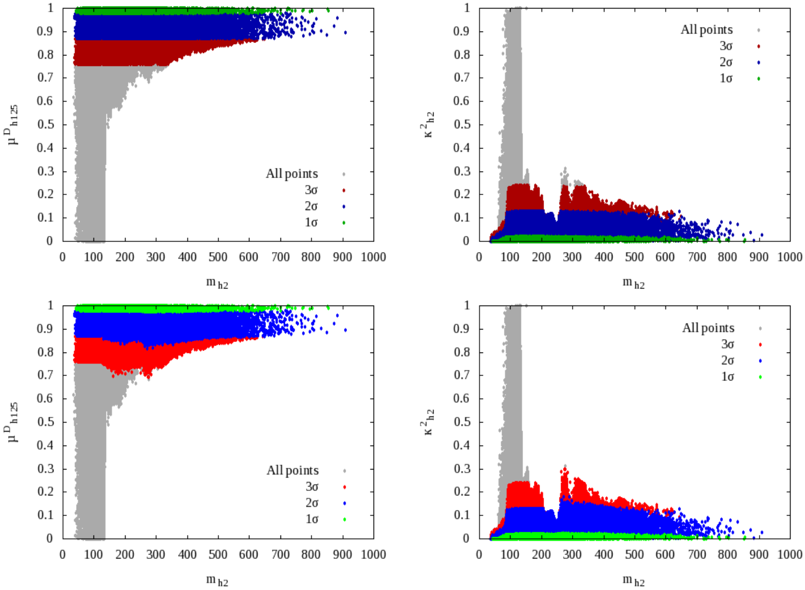

MicrOmegas – relic density & direct detection

Implemented micrOMEGAS interface ⇒ present relic density

Involves:

- Creating LanHep model file
- Link and compile micrOMEGAS routines with ScannerS

Physical idea:

- Only 1 dark A out of equilibrium
- A non-relativistic (CDM)
- relic number density n_A governed by the Boltzmann eq.

$$\frac{dn_A}{dt} + 3H\, n_A = -\langle \sigma_A |v| \rangle \left(n_A^2 - (n_A^{EQ})^2 \right)$$

Barger et al. PRD79 (2009) 015018