Renormalization Group Analysis of the xSM model and implementation in the ScannerS Tool

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Centro de Física Teórica e Computacional

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Outline

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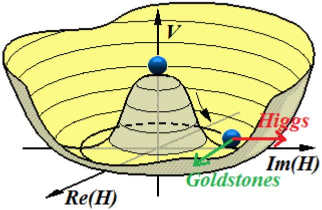
Motivation

The Standard Model $\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\overline{\psi} \not{D} \psi + h.c. - \overline{\psi}_i \left(y_l\right)_{ij} \psi_j \phi + h.c. + \left(D^\mu H\right)^\dagger \left(D_\mu H\right) - V\left(H^\dagger H\right)$$



- $V\left(H^\dagger H\right) = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4} (H^\dagger H)^4$
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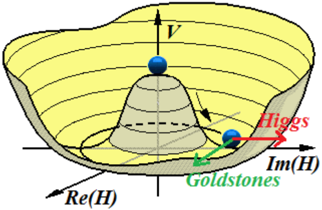

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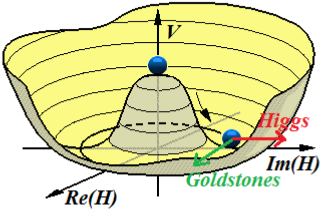

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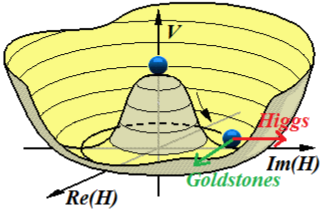

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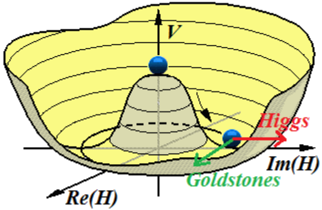

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- Charge quantization
- Fermion masses and mixings
- Hard to reconcile with the theory of General Relativity

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- $\kappa_j \equiv \dfrac{\lambda^{(p)}_{H_j}}{\lambda^{(p)}_{h_{SM}}}$
  - $\lambda^{(p)}_{h_{SM}}$ Coupling of particle p to the SM Higgs
  - $\lambda^{(p)}_{H_j}$ Coupling of particle p to the new scalar

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- **V_{eff} is scale invariant**

What is our aim?

Investigate the stability of the xSM model with energy/RG scale μ

- Use the scale invariance of the **effective potential** to derive the RGEs
- Apply stability constraints to the RG evolved couplings using **ScannerS** (bottom-up approach)
- For each generated point, determine the scale up to where V_{xSM} is stable

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Renormalization Group Equations (RGEs)

- Generic loop expansion of V_{eff}

$$V_{eff} = \sum_{n=0}^{+\infty} \varepsilon^n V^{(n)} (L, v_i, \mu) \ , \quad \varepsilon = \frac{\hbar}{16\pi^2}$$

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- 1-loop $\longrightarrow$ truncate to first order $n = 1$

$$V_{eff} = V^{(0)} + \frac{\hbar}{16\pi^2} V^{(1)} + \mathcal{O}(\hbar^2)$$

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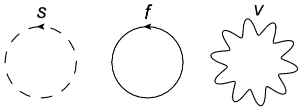

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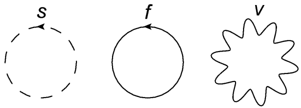

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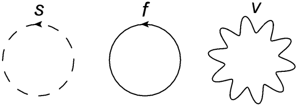

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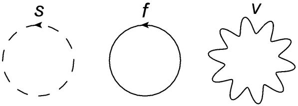

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- Ongoing work: **Full two-loop RGEs for xSM**

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Outline

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Theoretical Constraints

- Check boundedness from below of the scalar potential (all scales)
- **Check perturbative unitarity in** $2 \to 2$ **processes** (all scales)

$$|\lambda| \leq 16\pi \,, |d2| \leq 16\pi \,, |\delta_2| \leq 16\pi \,, \left| \frac{3}{2}\lambda + d_2 \pm \sqrt{\left(\frac{3}{2}\lambda + d_2\right)^2 + d_2^2} \right| \leq 16\pi$$

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- Check that the minimum we chose is **global** (low scale only)
- Compare with EW precision observables S, T, U (low scale only)

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Experimental Constraints

Collider searches for SM Higgs boson

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Collider searches for SM Higgs boson

- Experiments provide exclusion limits on various signal strengths μ_i normalized to the SM
- Cross sections σ and decay widths Γ for the new scalars are rescaled by κ_i^2

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- Use HDECAY to calculate $\Gamma(h_{SM} \to X_{SM})$
- Provide Γ for each scalar to HiggsBounds and HiggsSignals
  - exclude points with μ_i above limits
  - exclude points beyond 3σ

Dark Matter searches

- $\Omega_{cdm}h^2 = 0.1196 \pm 0.0031$ (WMAP)
- LUX bounds
- micrOMEGAS (v2.4.5) to calculate relic density $\Omega_A h^2$ and exclude a point if above WMAP bounds
- Calculate σ_{scaled} for SI WIMP-nucleon scattering
- Reject point if $\sigma_{scaled} > \sigma_{LUX}$ with $\sigma_{scaled} = \sigma_A \dfrac{\Omega_A h^2}{0.1196}$

Input Parameters

Broken phase inputs

- Fixed input parameters: $v = 246\ \mathrm{GeV}$, $m_h = 125.7\ \mathrm{GeV}$
- Free parameters: $v_A, v_S, m_{H_{1,2}} \in [0\,,500]\ \mathrm{GeV}$, $\kappa_{1,2,3} \in [0\,,1]$
- Our convention $\rightarrow m_{H_{1,2}} \equiv m_{H_{light\,,heavy}}$

Dark Matter phase inputs

- Fixed input parameters: $v_A = 0\ \mathrm{GeV}$
- Free parameters: $a_1 \in \left[-10^8\,,0\right]\ \mathrm{GeV}^3$, $\phi \in [0\,,1]$
- Our convention $\rightarrow m_{H_{1,2}} \equiv m_{H_{DM\,,new}}$

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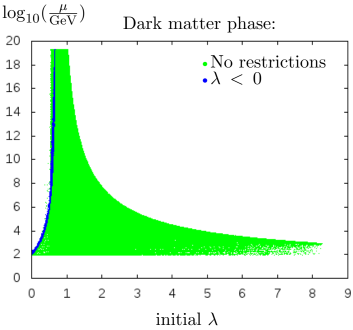
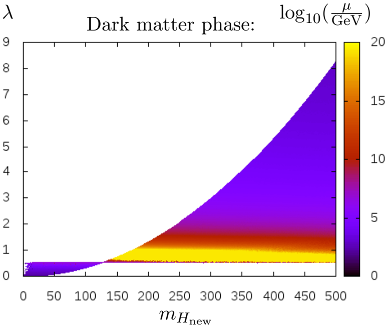
Outline

Dark Matter Phase: Theoretical tests only





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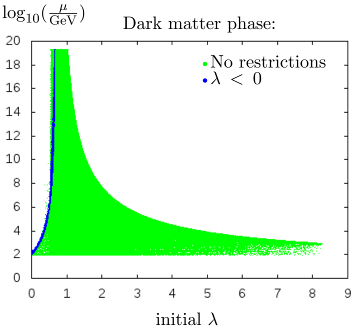
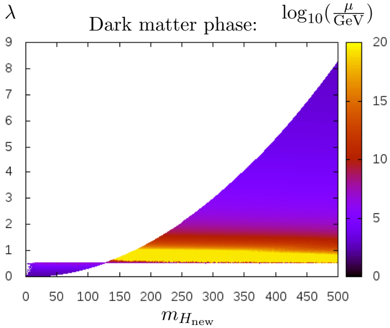
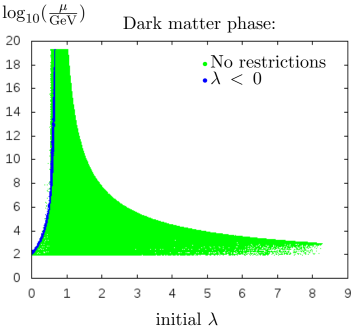
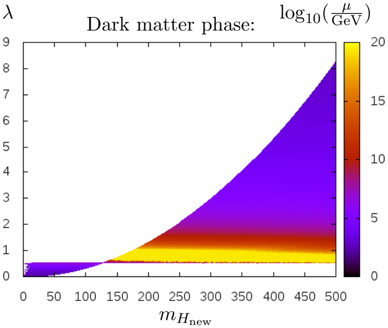




- Run from $\mu = M_z$ to $M_{Pl} \sim 10^{19}$ GeV

Dark Matter Phase: Theoretical tests only





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- Perturbative unitarity conditions dominant
- Blue layer → V becomes UFB

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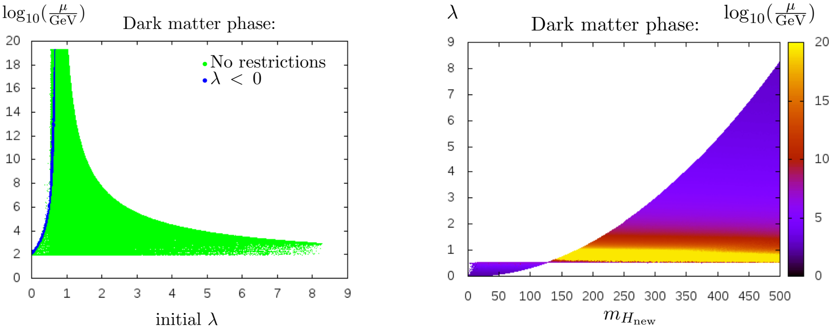

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- Blue layer $\rightarrow$ V becomes UFB
- Narrow range $0.5 \lesssim \lambda \lesssim 1.0$ survives to large scales
- **Favours a new visible particle with mass $\mathbf{m_{H_{new}}} \gtrsim$ 140 GeV** if we insist in RG stability

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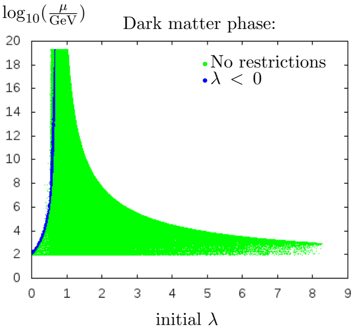

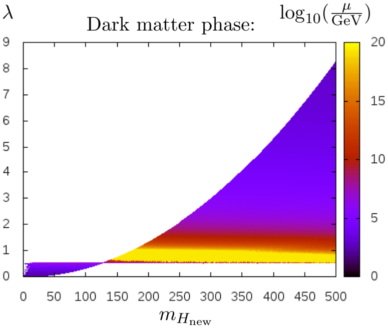

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- Minimum conditions + Higgs mass

$$\lambda = \frac{1}{v^2}\left[m^2_{H_{\rm new}} + m^2_{H_{126}} \pm \sqrt{(m^2_{H_{\rm new}} - m^2_{H_{126}}) - (v_s\delta_2)^2}\right]$$

- No mixing limit ($v_s \rightarrow 0$) we obtain $\lambda = 2m^2_{H_{\rm new}}/v^2$ or $\lambda = 2m^2_{H_{126}}/v^2$

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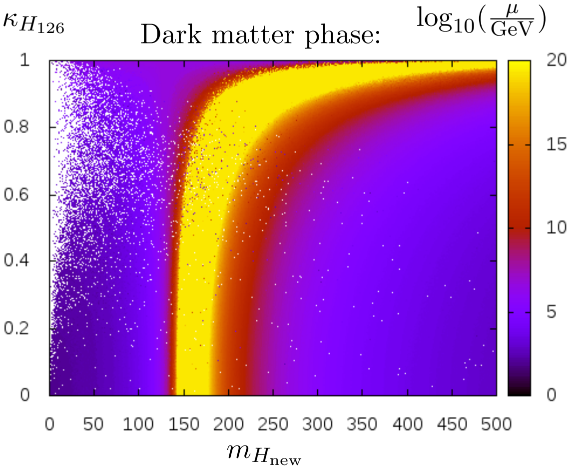
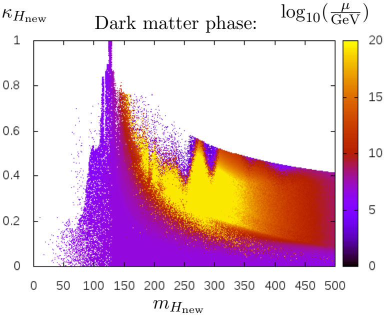
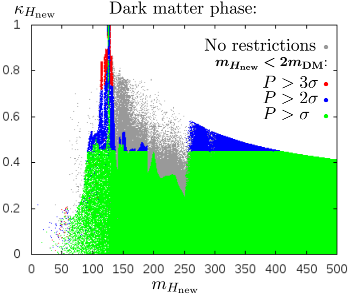
Dark Matter Phase: Theoretical tests



Dark Matter Phase: Phenomenological tests





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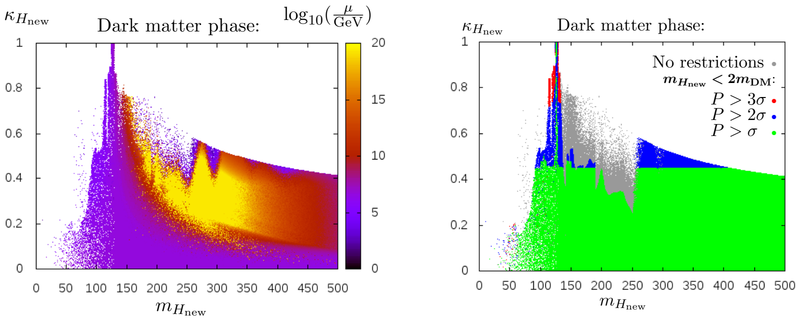

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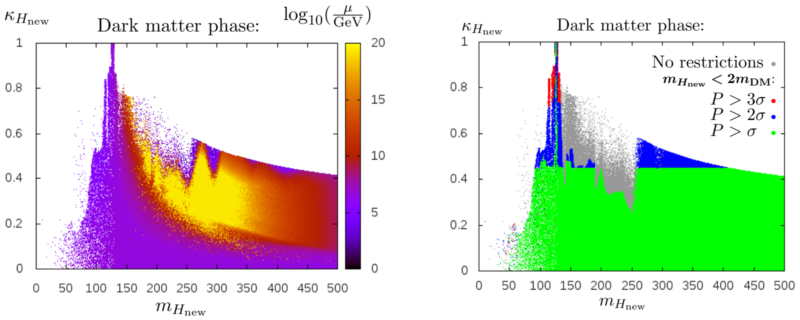

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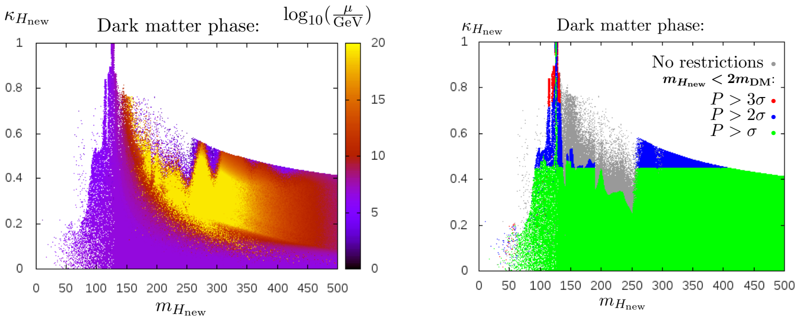

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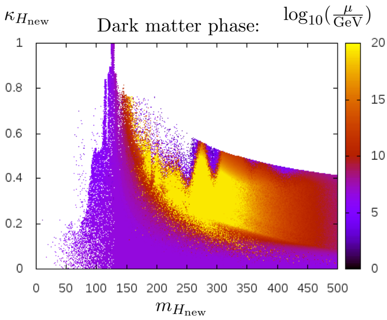

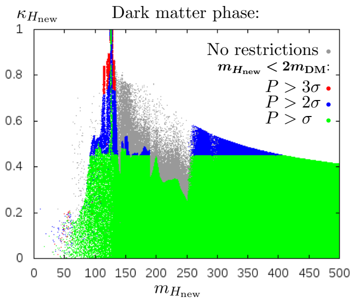

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- Grey points $\rightarrow P > 3\sigma$ and new particle decays to DM

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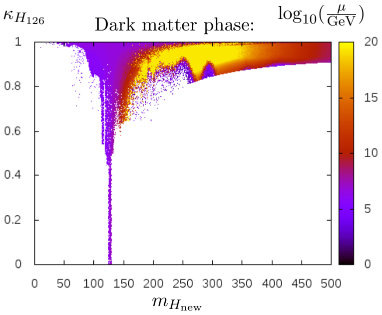
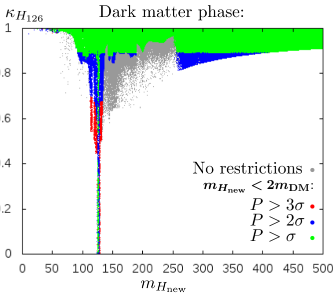
Dark Matter Phase: Phenomenological tests





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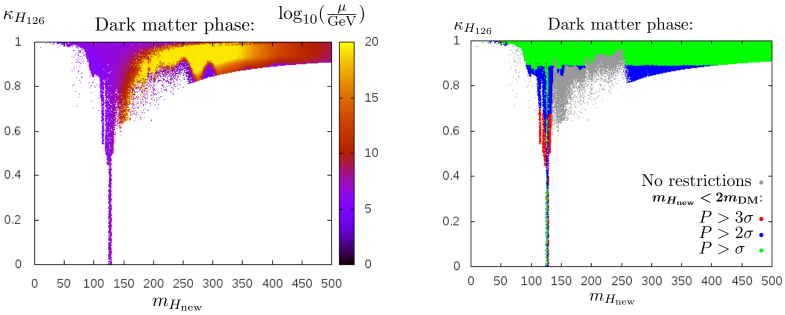

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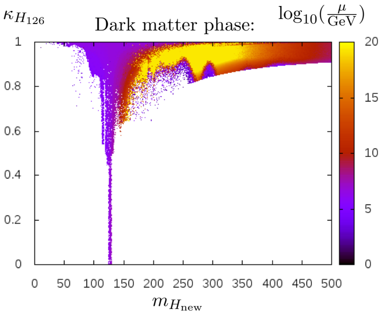

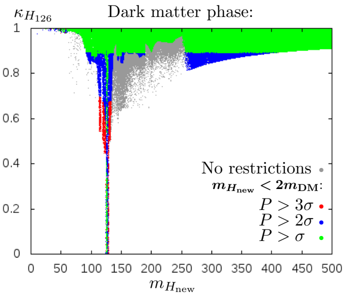

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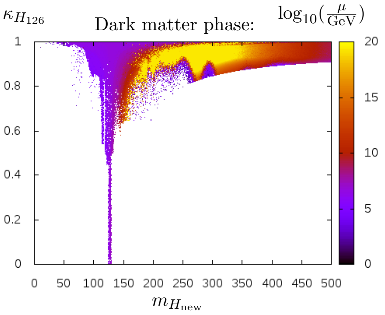

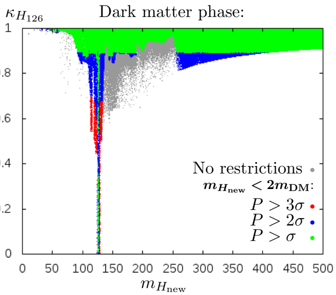

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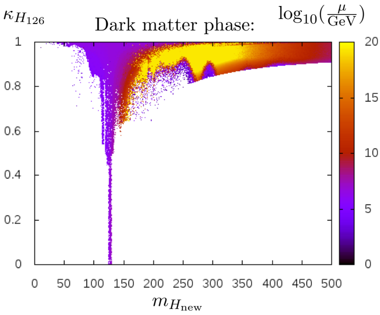
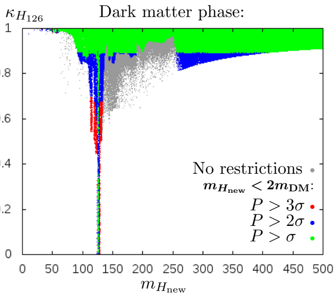
Dark Matter Phase: Phenomenological tests





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- **For both $\kappa_{H_{new}}$ and $\kappa_{H_{126}}$ most of the points within 2σ**
- **If not at the decoupling limit ($\kappa_{H_{new}} \rightarrow 0$ and $\kappa_{H_{126}} \rightarrow 1$) region may be probed at the 14 TeV LHC runs**

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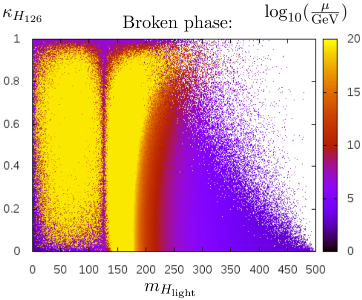
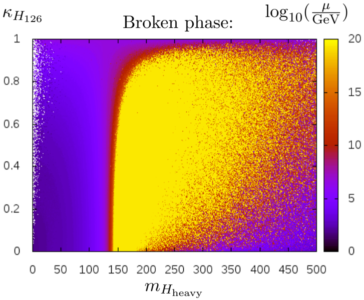
Outline

Broken Phase: Theoretical tests





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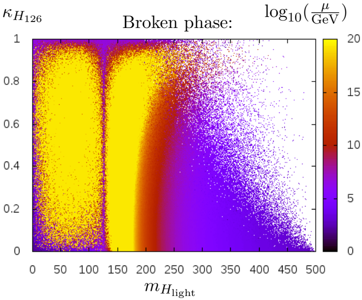
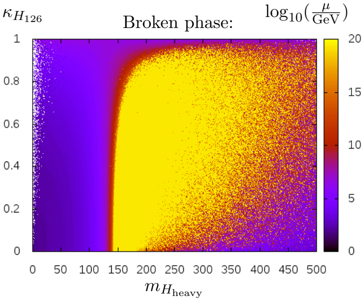
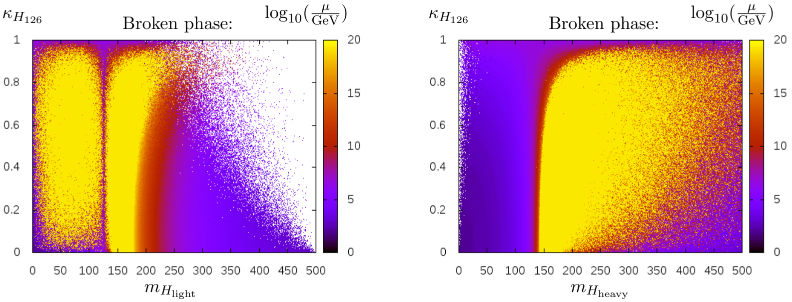




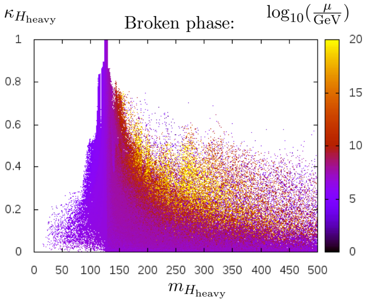
- Three states mixing

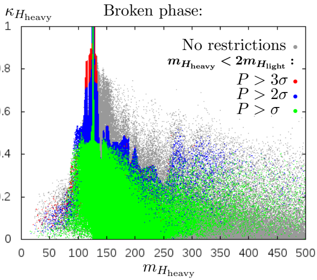
Broken Phase: Theoretical tests



- Three states mixing
- New heavy particle predicted to be $m_{H_{heavy}} \gtrsim 140\ \mathrm{GeV}$ if we insist in RG stability

Broken Phase: Phenomenological tests





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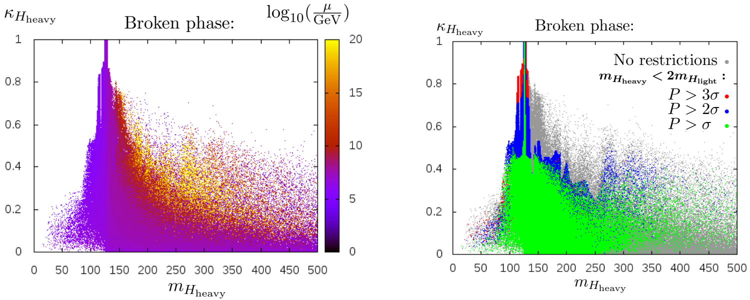

- Harder to find RG stable points with $P > \sigma$ in comparison with the broken phase
- For $\kappa_{H_{heavy}} \sim$ 0.4 and $P > \sigma \rightarrow$ stable up to $\sim 10^{15}$ GeV

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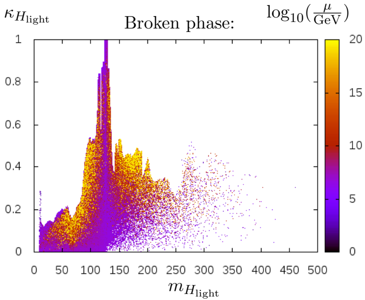

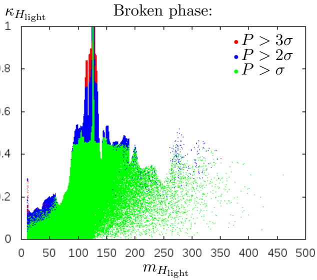

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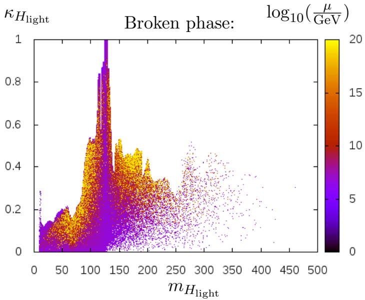

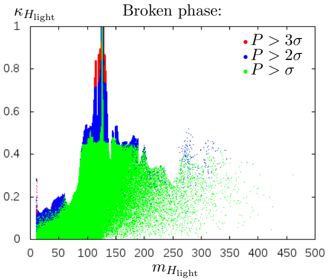

- Coupling
- For $\kappa_{H_{heavy}} \sim$ 0.4 and $P > \sigma$ stable up to $\sim 10^{15}$ GeV

Conclusions

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- Analyzed both the symmetric (Dark Matter) and broken phases
- Studied the low scale and RG stability of the scalar potential
- Imposed collider and Dark Matter phenomenological cuts $\rightarrow$ constraints on the parameter space
- **Plenty of solutions which can be probed at the 14 TeV runs of the LHC**

Decay widths for $H_i \to H_j H_k$ and $H_i \to H_j H_j$

$$
\begin{aligned}
\Gamma\left(H_i \to H_j H_k\right) &= \frac{g_{ijk}^2}{16\pi m_i}\sqrt{1-\frac{\left(m_j+m_k\right)^2}{m_i^2}}\sqrt{1-\frac{\left(m_j-m_k\right)^2}{m_i^2}} \\
\Gamma\left(H_i \to H_j H_j\right) &= \frac{g_{ijj}^2}{32\pi m_i}\sqrt{1-\frac{4m_j^4}{m_i^2}}
\end{aligned}
$$