Two-loop stability of singlet extensions of the SM with dark matter

Marco O. P. Sampaio

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Based on: arXiv:1411.4048 with Raul Costa, António Morais and Rui Santos
http://scanners.hepforge.org
Outline

1. Singlet models & Why?

2. Radiative corrections & RGEs

3. Results & The Pheno
Singlets & the Higgs portal

How?

- Scalar sector prone to coupling to hidden sectors!

Only SM singlets with dimension $< 4$ are: $H^H, B_{\mu\nu}, HL$

\[ V = V_{SM}(H^H) + H^H \times \mathcal{O}_\delta^{(2)}(\phi_i) + V_{New}(\phi_i) \]
Singlets & the Higgs portal

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

  Higgs fluctuation $\leftarrow h = \sum_a \kappa_a H_a$, $\sum_a |\kappa_a|^2 = 1$
Singlets & the Higgs portal

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\]

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  Higgs fluctuation \( \leftrightarrow h = \sum_a \kappa_a H_a \), \( \sum_a |\kappa_a|^2 = 1 \)

Why?

- Simple (& natural?) parametrization of DM
- \( V_{\text{eff}} @ T \neq 0 \) can be compatible with EW-Baryogenesis
- Improve stability of SM @ high energies (?)
A minimal model with dark matter & new visible scalar

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

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4} (H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H|S|^2 + \frac{b_2}{2} |S|^2 + \frac{d_2}{4} |S|^4 + \left( \frac{b_1}{4} S^2 + a_1 S + \text{c.c.} \right)$$
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- $\mathbb{Z}_2$ phase ($v_S \neq 0, v_A = 0$): 2 Higgs mix + 1 dark

$$\begin{pmatrix} H_{126} \\ H_{\text{new}} \\ H_{\text{DM}} \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ s \\ A \end{pmatrix}$$
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H_{126} \\
H_{\text{new}} \\
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\end{pmatrix} =
\begin{pmatrix}
\cos \alpha & -\sin \alpha & 0 \\
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0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
h \\
s \\
A
\end{pmatrix}
\]

- \( \mathbb{Z}_2 \) phase (\( v_S \neq 0, v_A \neq 0 \)): 3 Higgs mix

\[
\begin{pmatrix}
H_{126} \\
H_{\text{light}} \\
H_{\text{Heavy}}
\end{pmatrix} =
\begin{pmatrix}
R_{1h} & R_{1S} & R_{1A} \\
R_{2h} & R_{2S} & R_{2A} \\
R_{3h} & R_{3S} & R_{3A}
\end{pmatrix}
\begin{pmatrix}
h \\
s \\
a
\end{pmatrix}
\]
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$$\begin{pmatrix} H_{126} \\ H_{\text{light}} \\ H_{\text{Heavy}} \end{pmatrix} = \begin{pmatrix} \kappa_{126} & R_{1S} & R_{1A} \\ \kappa_{\text{light}} & R_{2S} & R_{2A} \\ \kappa_{\text{Heavy}} & R_{3S} & R_{3A} \end{pmatrix} \begin{pmatrix} h \\ S \\ A \end{pmatrix}$$

- Many OBSs related to SM up to $\kappa_a$ factors (Ex. $\frac{\sigma_{a}}{\sigma_{SM}} \propto \kappa_{a}^2$)
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The effective potential and the RGEs

Previous global scan studies → mostly tree level
V. Barger, P. Langacker, M. McCaskey, M. Ramsey-Musolf, G Shaughnessy, PRD79 (2009) 015018
M. Gonderinger, H. Lim, M. Ramsey-Musolf, PRD86 (2012) 043511 (1-loop & special points)
R. Coimbra, MOPS, R. Santos, EPJ C73 (2013) 2428
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Radiative corrections \( (\varepsilon \equiv \hbar/(4\pi)^2, \ t \equiv \log \mu) \):

\[
\Lambda + \text{\includegraphics[width=0.15\textwidth]{circle}} + \text{\includegraphics[width=0.15\textwidth]{square}} + \ldots
\]

\[
\begin{align*}
V_{\text{eff}} &= V^{(0)} + \varepsilon V^{(1)} + \varepsilon^2 V^{(2)} + \ldots \\
&\vdots
\end{align*}
\]

S. Martin, PRD65 (2002) 116003
The effective potential and the RGEs

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V_{\text{eff}} &= V^{(0)} + \varepsilon V^{(1)} + \varepsilon^2 V^{(2)} + \ldots \\
\frac{dV_{\text{eff}}}{dt} &= 0 \\
\frac{dL}{dt} &= \varepsilon \beta_L^{(1)} + \varepsilon^2 \beta_L^{(2)} + \ldots
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$$\begin{align*}
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V_{\text{eff}} &= V^{(0)} + \varepsilon V^{(1)} + \varepsilon^2 V^{(2)} + \ldots \\
G_{ij}^{-1} &= \Pi_{ij}^{(0)} + \varepsilon \Pi_{ij}^{(1)} + \varepsilon^2 \Pi_{ij}^{(2)} + \ldots \\
\frac{dV_{\text{eff}}}{dt} &= 0 \\
\frac{dL}{dt} &= \varepsilon \beta_L^{(1)} + \varepsilon^2 \beta_L^{(2)} + \ldots
\end{align*}$$

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M. Machacek, M. Vaughn Nucl.Phys. B222 (1983) 83
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**Radiative corrections** ($\varepsilon \equiv \hbar/(4\pi)^2$, $t \equiv \log \mu$):

\[
\begin{align*}
\Lambda + & \quad \includegraphics[width=0.5\textwidth]{potential}\quad + \ldots \\
V_{\text{eff}} = & \quad V^{(0)} + \varepsilon V^{(1)} + \varepsilon^2 V^{(2)} + \ldots \quad \frac{dv_{\text{eff}}}{dt} = 0 \\
G_{ij}^{-1} = & \quad \Pi^{(0)}_{ij} + \varepsilon \Pi^{(1)}_{ij} + \varepsilon^2 \Pi^{(2)}_{ij} + \ldots \quad \frac{dL}{dt} = \varepsilon \beta^{(1)}_L + \varepsilon^2 \beta^{(2)}_L + \ldots \\
& \quad \includegraphics[width=0.5\textwidth]{potential2} + \ldots \\
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\]

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\]

\[
\boxed{\frac{dL}{dt}} = \varepsilon \beta_L^{(1)} + \varepsilon^2 \beta_L^{(2)} + \ldots
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\[
\boxed{\frac{1}{v_i} \frac{dv_i}{dt}} = \varepsilon \gamma_i^{(1)} + \varepsilon^2 \gamma_i^{(2)} + \ldots
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- Got general scalar RGEs @ 2-loop  
  R. Costa, A. Morais, MOPS, R. Santos 1411.4048
  + combined SM contributions (checked with SARAH)

- **Checked** special limits
  
  **2HDM @ 1-loop** – P.M. Ferreira, D.R.T. Jones JHEP 0908 (2009) 069
  **U(n) Complex singlets @ 2-loops** – C. Tamarit, PRD90 (2014) 5, 055024
Stability conditions under RGE evolution

**Initial data** @ $\mu = M_Z$ need $\{L, v_i\}$ relating to input $m_i^2$
Stability conditions under RGE evolution

Initial data @ $\mu = M_Z$ need $\{L, v_i\}$ relating to input $m_i^2$, but

$$L(M_Z) = L^{(0)}$$

& $\beta_L = \varepsilon \beta_L^{(1)}$

- 0-loop input relations $\Rightarrow$ 1-loop accuracy RGEs

SM seems to be metastable @ 2-loops!

G. Degrassi et al, JHEP 1208 (2012) 098
Stability conditions under RGE evolution

Initial data @ \( \mu = M_Z \) need \( \{L, v_i\} \) relating to input \( m_i^2 \), but

\[
L(M_Z) = L^{(0)} + \varepsilon L^{(1)}(m^2_i, v_i) + \ldots \quad \text{&} \quad \beta_L = \varepsilon \beta_L^{(1)} + \varepsilon^2 \beta_L^{(2)} + \ldots
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- 0-loop input relations \( \Rightarrow \) 1-loop accuracy RGEs
- 1-loop input relations \( \Rightarrow \) 2-loop accuracy RGEs

Used 2-loop \( \leftarrow \) check robustness under small corrections

Stability conditions (imposed also in evolution):
- Boundedness from below: \( \lambda > 0 \wedge d_2 > 0 \wedge \delta_2 > -\sqrt{\lambda d_2^2} \)
- Perturbative unitarity:
  \[ |\lambda|, |d_2|, |\delta_2|, \mid \frac{3}{2} \lambda + d_2 \pm \sqrt{(\frac{3}{2} \lambda + d_2)^2 + d_2^2} \mid \leq 16\pi \]

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Phenomenological constraints imposed in *ScannerS*:

- Electroweak precision observables – STU
- Collider data (LEP, Tevatron, LHC) HiggsBounds/Signals
- Dark matter relic density below Planck measurement & bounds from LUX on $\sigma_{SI}$ (micrOMEGAs)
RGE stability bands – NO PHENO!

Dark matter phase $m_{H_{\text{new}}} (\text{GeV})$

$\lambda$

$\log_{10}(\frac{\mu}{\text{GeV}})$

Vacuum stability consequences

Broken phase $m_{H_{\text{light}}} (\text{GeV})$

$\kappa_{H_{126}}$

$\log_{10}(\frac{\mu}{\text{GeV}})$

Lower bound on new visible scalar mass

If new Higgs found lighter than $\simeq 140$ GeV, dark matter phase disfavoured! Lower bound for heaviest new visible scalar mass
RGE stability bands – NO PHENO!

**Vacuum stability consequences**

**Broken phase**

If new Higgs found lighter than $\sim 140$ GeV
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Combination with Pheno – Dark matter phase

Known (126 GeV) Higgs coupling vs new mass

All points (3σ) $m_{H_{\text{new}}} < 2m_{\text{DM}}$:

- 3σ
- 2σ
- 1σ

Stable models + saturate relic dens.

Combination with Pheno – Dark matter phase

Dark matter phase

$m_{H_{\text{new}}} (\text{GeV})$

$\kappa_{H_{126}}$

$|vS\delta^2| (\text{GeV})$

$\log_{10}(\mu \text{ GeV})$
Combination with Pheno – Dark matter phase

Known (126 GeV) Higgs coupling vs new mass

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- 1σ

Dark matter phase

\( m_{H_{\text{new}}} \) (GeV)

\( \kappa H_{126} \)

\( \log_{10}(\frac{\mu}{\text{GeV}}) \)

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Combination with Pheno – Dark matter phase

**Dark matter phase**

Known (126 GeV) Higgs coupling vs new mass

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$m_{H_{\text{new}}} < 2m_{\text{DM}}$

3σ, 2σ, 1σ

Dark matter phase

$m_{H_{\text{new}}} (\text{GeV})$

$\kappa_{H_{126}}$

Log 10 ($\mu$ GeV)

Stable models + saturate relic dens.
Conclusions

1. Obtained 2-loop RGEs of minimal complex singlet model with dark matter

2. Found impact of imposing stability up to GUT/Planck scale:
   - Stability bands in both phases
   - A new mixing heavy scalar ($\gtrsim 140$ GeV) in the spectrum
   - New light mixing scalar ($\lesssim 140$ GeV) disfavours dark phase

3. Combined with collider/dark phenomenology and found:
   - LHC & RGEs $\Rightarrow$ stabilizer Higgs, $m_{H_{\text{new}}} \gtrsim 170$ GeV
   - Imposing “completeness” implies $m_{DM} \gtrsim 50$ GeV

THANK YOU!
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THANK YOU!
BACKUP
| Scan parameter | Dark matter phase | Broken phase |
|----------------|------------------|--------------|
|                | Min | Max | Min | Max |
| $m_h$ (GeV)    | 124.7 | 127.1 | 124.7 | 127.1 |
| $m_{s_1}$ (Gev) |      |      |      |      |
| -Theoretical   | 0   | 1000 | 0   | 1000 |
| -Phenomenological | 12 | 1000 | 12 | 1000 |
| $m_{s_2}$ (Gev) |      |      |      |      |
| -Theoretical   | 0   | 1000 | 0   | 1000 |
| -Phenomenological | 6  | 1000 | 12 | 1000 |
| $\nu_h$ (GeV)  | 246 | 246 | 246 | 246 |
| $\nu_S$ (GeV)  | 0   | 1000 | 0   | 1000 |
| $\nu_A$ (GeV)  | 0   | 0   | 0   | 1000 |
| $a_1$ (GeV$^3$) | $-10^8$ | 0 | n/a |
Combination with Pheno – Dark matter phase

**New visible Higgs coupling vs mass**

**Known (126 GeV) Higgs coupling vs new mass**

All points (3σ) $m_{H_{\text{new}}} < 2m_{\text{DM}}$:
- $3\sigma$
- $2\sigma$
- $1\sigma$
Combination with Pheno – Dark matter phase

New visible Higgs coupling vs mass

Known (126 GeV) Higgs coupling vs new mass

All points (3σ)

\( m_{H_{\text{new}}} < 2m_{\text{DM}}: \)

\( 3\sigma \)

\( 2\sigma \)

\( 1\sigma \)

Stable models + saturate relic dens.

All 3σ points combined with RGEs

\( \log_{10}\left( \frac{\mu}{\text{GeV}} \right) \)
Combination with Pheno – Dark matter phase

**New visible Higgs coupling vs mass**

**Known (126 GeV) Higgs coupling vs new mass**

$m_{H_{\text{new}}} < 2m_{\text{DM}}$: 
3σ, 2σ, 1σ

**Stable models + saturate relic dens.**

**All 3σ points combined with RGEs**

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Combination with Pheno – Broken phase

$\kappa_{H}$ vs $m_{H_{\text{heavy}}}$

$|m_{H_{\text{light}}}-m_{H_{126}}| > 5$:

- $3\sigma$
- $2\sigma$
- $1\sigma$
Combination with Pheno – Broken phase

$\kappa_{H_{\text{heavy}}}$

$m_{H_{\text{heavy}}}$ < $2m_{H_{\text{light}}}$:

All points (3σ)

$m_{H_{\text{light}}} - m_{H_{126}}$ > 5:

All points (3σ)

$\kappa_{H_{126}}$

$m_{H_{\text{light}}}$ (GeV)

$m_{H_{\text{heavy}}}$ (GeV)

$\kappa_{H_{\text{light}}}$

$m_{H_{\text{light}}}$ (GeV)

$m_{H_{\text{heavy}}}$ (GeV)
Combination with Pheno – Broken phase

\[\kappa_{H_{\text{heavy}}} \quad \log_{10}\left(\frac{\mu}{\text{GeV}}\right)\]

\[m_{H_{\text{heavy}}} \quad (\text{GeV})\]

\[\kappa_{H_{126}} \quad \log_{10}\left(\frac{\mu}{\text{GeV}}\right)\]

\[m_{H_{\text{heavy}}} \quad (\text{GeV})\]

\[\kappa_{H_{\text{light}}} \quad \log_{10}\left(\frac{\mu}{\text{GeV}}\right)\]

\[m_{H_{\text{light}}} \quad (\text{GeV})\]
Error measure

Dark matter phase

$\log_{10}(\mu \text{GeV})$

$\delta_{12}^\lambda(\%)$

$\Delta_{12}(\%)$

initial $\lambda$

$\log_{10}(\mu \text{GeV})$

$\Delta_{12}(\%)$
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.  

\[
\frac{dn_A}{dt} + 3H n_A = - \left< \sigma_A | v | \right> \left( n_A^2 - (n_A^{EQ})^2 \right)
\]

Barger et al. PRD79 (2009) 015018
The origin of the lower bound on the mass of the new heavy scalar is related to the local minimum conditions:

\[
\lambda = \frac{m_{H_{new}}^2 + m_{H_{126}}^2}{v^2} \pm \sqrt{\left[ \frac{m_{H_{new}}^2 - m_{H_{126}}^2}{v^2} \right]^2 - \left( \frac{v_{S} \delta_2}{v} \right)^2}.
\]

In the limiting case of no mixing \((v_{S} \rightarrow 0)\) we obtain \(\lambda = 2m_{H_{new}}^2/v^2\) or \(\lambda = 2m_{H_{126}}^2/v^2\). Furthermore

\[
\kappa_{H_{126}}^2 = \frac{1}{2} \left[ 1 \pm \sqrt{\left( \frac{m_{H_{new}}^2 - m_{H_{126}}^2}{v^2} \right)^2 - \left( \frac{v v_{S} \delta_2}{v} \right)^2} \right].
\]

The upper boundary of the stability band matches the plus sign case. Noting that in the stability region \(m_{H_{new}}^2 - m_{H_{126}}^2 > 0\), then \(\kappa_{H_{126}}^2 = 1\) is only possible when \(m_{H_{new}}^2 \rightarrow +\infty\).
Tree level unitarity module

\( (\ldots, |\Phi_i\rangle, \ldots) \equiv \left( \frac{1}{\sqrt{2!}} |\phi_1\phi_1\rangle, \ldots, \frac{1}{\sqrt{2!}} |\phi_N\phi_N\rangle, |\phi_1\phi_2\rangle, \ldots, |\phi_{N-1}\phi_N\rangle \right) \)

**Tree level unitarity in** \(2 \rightarrow 2\) **high energy scattering:**

\[ |\Phi_i\rangle \times |\Phi_j\rangle, \]

Lee, Quigg, Thacker; PRD16, Vol.5 (1977)

In SM, the 2-particle states are \(w^+w^-, hh, zz, hz\) ⇒ constrains quartic coupling \(\lambda\), ⇒ \(m_h^2 < 700\) GeV

In BSM ⇒ bounds on combinations of quartic \(\lambda a_4\)

Reduces to finding eigenvalues of \(a_4(0)\) numerically ⇒ fast!
(\ldots, \left| \Phi_i \right\rangle, \ldots) \equiv \left( \frac{1}{\sqrt{2}} \left| \phi_1 \phi_1 \right\rangle, \ldots, \frac{1}{\sqrt{2}} \left| \phi_N \phi_N \right\rangle, \left| \phi_1 \phi_2 \right\rangle, \ldots, \left| \phi_{N-1} \phi_N \right\rangle \right)

Tree level unitarity in $2 \rightarrow 2$ high energy scattering:

$$\left| \Phi_i \right\rangle \times \left| \Phi_j \right\rangle, \Re \left\{ a_{ij}^{(0)} \right\} < \frac{1}{2}, \quad a_{ij}^{(0)} = \frac{\left\langle \Phi_i \left| i T_{ij}^{(0)} \right| \Phi_j \right\rangle}{16\pi} \sim \sum a_4 \cdots \lambda a_4$$

Lee, Quigg, Thacker; PRD16, Vol.5 (1977)
Tree level unitarity module

\[(\ldots, |\Phi_i\rangle, \ldots) \equiv \left( \frac{1}{\sqrt{2!}} |\phi_1\phi_1\rangle, \ldots, \frac{1}{\sqrt{2!}} |\phi_N\phi_N\rangle, |\phi_1\phi_2\rangle, \ldots, |\phi_{N-1}\phi_N\rangle \right)\]

Tree level unitarity in $2 \rightarrow 2$ high energy scattering:

\[|\Phi_i\rangle \times |\Phi_j\rangle, \Re \{a_{ij}^{(0)}\} < \frac{1}{2}, a_{ij}^{(0)} = \frac{\langle \Phi_i | iT^{(0)} | \Phi_j \rangle}{16\pi} \sim \sum a_4 \ldots \lambda a_4\]

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- In SM, the 2-particle states are $w^+w^-, hh, zz, hz$
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