Survey of (and update on) the Higgs singlet extension

Tania Robens

based on

G.M. Pruna, TR (PRD 88 (2013) 115012)
TR, T. Stefaniak, work in progress
TU Dresden

Workshop of LHC Higgs Cross Section Working Group
CERN
13.6.2014
Higgs Singlet extension (aka The Higgs portal)

**The model**

- **Singlet extension:**
  - simplest extension of the SM Higgs sector
- **add an additional real scalar**, singlet under SM gauge groups
  (many people worked on this, standard Ref: Schabinger, Wells, ’05)
- here: no hidden sector interactions
- **Singlet acquires VeV**
- physical states related via **mixing angle** $\sin \alpha$ ($m_h < m_H$):

\[
\begin{pmatrix}
  h \\
  H
\end{pmatrix} =
\begin{pmatrix}
  \cos \alpha & -\sin \alpha \\
  \sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
  \tilde{h} \\
  h'
\end{pmatrix},
\]

- 5 parameters

\[m_h, m_H, \sin \alpha, v, \tan \beta = \frac{v}{x}\]

- **2 fixed, 3 free**, $(m_h \parallel m_H) = 125.7 \text{ GeV}$
Potential

\[ V = -m^2 H^\dagger H - \mu^2 \chi^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 \chi^4 + \lambda_3 H^\dagger H \chi^2 , \]
Phenomenology (in the following: focus on $m_h \sim 126 \text{ GeV}$)

- SM-like couplings of **light/ heavy** Higgs: 
  
  rescaled by $\sin \alpha$, $\cos \alpha$

- in addition: **new physics channel**: $H \rightarrow h\ h$

  $$\Gamma_{\text{tot}}(H) = \sin^2 \alpha \Gamma_{\text{SM}}(H) + \Gamma_{H\rightarrow hh},$$

- **SM like decays** parametrized by

  $$\kappa \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{\text{BSM}}}{\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}} = \frac{\sin^4 \alpha \Gamma_{\text{tot,SM}}}{\Gamma_{\text{tot}}}$$

- **new physics channel** parametrized by

  $$\kappa' \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{H\rightarrow hh}}{\sigma_{\text{SM}}} = \frac{\sin^2 \alpha \Gamma_{H\rightarrow hh}}{\Gamma_{\text{tot}}}$$
Theoretical and experimental constraints on the model

**our studies:** $m_{h,H} = 125.7 \text{ GeV}$, $0 \text{ GeV} \leq m_{H,h} \leq 1 \text{ TeV}$

we considered

1. limits from **perturbative unitarity**
2. **perturbativity** of the couplings (up to certain scales*)
3. **vacuum stability and minimum condition** (up to certain scales*)
4. corrections to $m_W$ at NLO $\implies$ !! NEW !! $\Leftarrow$
5. **collider limits** using HiggsBounds
6. measurement of **light Higgs signal rates** using HiggsSignals

(*): only for $m_h = 125.7 \text{ GeV}$
Results

- **Strongest constraints:**
  
  $m_H \gtrsim 800 \text{ GeV}$ : perturbativity of couplings
  
  $m_H \in [200; 800] \text{ GeV}$ : $m_W$ @ NLO
  
  $m_H \in [130; 200] \text{ GeV}$ : experimental searches
  
  $m_h \lesssim 120 \text{ GeV}$ : SM-like Higgs coupling rates ($\pm$ LEP)

  $\Rightarrow \kappa \leq 0.25$ for all masses considered here

  $\Gamma_{\text{tot}} \lesssim 0.02 \times m_H$

  $\Rightarrow$ Highly (??) suppressed, narrow(er) heavy scalars $\Leftarrow$

  $\Rightarrow$ new (easier ?) strategies needed wrt searches for SM-like Higgs bosons in this mass range $\Leftarrow$

  $\Rightarrow$ (partially) already correctly treated in experimental searches (variation of $\Gamma$ by hand...)$\Leftarrow$
NLO corrections to $m_W$ (D. Lopez-Val, TR, arXiv:1406.1043)

Contribution to $m_W$ for different Higgs masses

$m_h = 125.7$ GeV
$m_H = 125.7$ GeV

$\Rightarrow \text{low } m_h \text{ bring } m_{W}^{\text{NLO}} \text{ close to } m_{W}^{\text{exp}} \iff$
Combined limits on $|\sin \alpha|$ !! PRELIMINARY !!

Interplay of different limits on mixing angle; PRELIMINARY

W mass measurement
perturbativity of $\lambda_1$
experimental constraints
from signal rate (no fit)

Interplay of different limits on mixing angle; PRELIMINARY

allowed scale factor and total width, $\mu_{nn} = 10^{11}$ GeV

limits on $\kappa$, $\Gamma$ plane from all constraints

several bounds on $|\sin \alpha|$
Results from generic scans and predictions for LHC 14
(TR, T. Stefaniak, in preparation)

$1 \sigma$, $2 \sigma$, allowed

SM like decays

BSM decay to $hh$

Limits

Pred.

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Summary

- Singlet extension: **simplest extension of the SM Higgs sector** (cf. also YR3, Snowmass report)
- constraints on parameter space: $m_W$, experiment, signal strength of light Higgs, perturbativity of the couplings
- quite narrow widths wrt SM-like Higgses
- did **not** talk about $m_h \leq 120 \text{ GeV} \Rightarrow$ quite interesting results

⇒ Happy to contribute to WG activities ⇐

⇒ STAY TUNED ⇐

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Appendix
The model

Higgs Singlet extension (aka The Higgs portal)

**The model**

- Singlet extension: simplest extension of the SM Higgs sector
- add an additional scalar, singlet under SM gauge groups
  (further reduction of terms: impose additional symmetries)
  ⇒ potential ($H$ doublet, $\chi$ real singlet)

\[
V = -m^2 H^\dagger H - \mu^2 \chi^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 \chi^4 + \lambda_3 H^\dagger H \chi^2,
\]

- collider phenomenology studied by many authors: Schabinger, Wells; Patt, Wilzcek; Barger ea; Bhattacharyya ea; Bock ea; Fox ea; Englert ea; Batell ea; Bertolini/ McCullough; ...
- our approach: **minimal**: no hidden sector interactions
- equally: **Singlet acquires VeV**
Singlet extension: free parameters in the potential

\[ H \equiv \begin{pmatrix} 0 \\ \tilde{h} + v \\ \sqrt{2} \end{pmatrix}, \quad \chi \equiv \frac{h' + x}{\sqrt{2}}. \]

- potential: **5 free parameters**: 3 couplings, 2 VeVs

\[ \lambda_1, \lambda_2, \lambda_3, v, x \]

- rewrite as

\[ m_h, m_H, \sin \alpha, v, \tan \beta \]

- **fixed, free**

\[ \sin \alpha: \text{mixing angle, } \tan \beta = \frac{v}{\chi} \]

- physical states \((m_h < m_H)\):

\[
\begin{pmatrix}
 h \\
 H
\end{pmatrix} =
\begin{pmatrix}
 \cos \alpha & -\sin \alpha \\
 \sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
 \tilde{h} \\
 h'
\end{pmatrix},
\]
Comments on constraints (1) - Perturbativity issues

**Perturbative unitarity:**

- tests combined system of all (relevant) $2 \to 2$ scattering amplitudes for $s \to \infty$
- makes sure that the largest eigenvalue for the "0"-mode partial wave of the diagonlized system $\leq 0.5$
- "crude" check that unitarity is not violated
  (in the end: all "beaten" by perturbativity of running couplings)

**Perturbativity of couplings**

- make sure that no coupling $\geq 4\pi$ ("typical" loop prefactor$^{-0.5}$)
- at ew scale: perturbative unitarity stronger
Comments on constraints (2) - running couplings and vacuum

**Vacuum stability and perturbativity of couplings at arbitrary scales**

- clear: vacuum should be stable for large scales
- unclear: do we need ew-like breaking everywhere? perturbativity?

⇒ check at relative low scale (cf next slide)
⇒ bottom line: small mixings excluded from stability for larger scales (for $m_H \leq 1\text{ TeV}$ !! for the model-builders...)

- arbitrary large $m_H$ can cure this !! cf Lebedev; Elias-Miro ea.

Out of collider range though ($\sim 10^8 \text{ GeV}$) 

(...like SUSY, this model can never be excluded...)

- perturbativity of couplings severely restricts parameter space, even for low scales
Question: at which scale did we require perturbativity?

**Answer:** ”just above” the SM breakdown

(other answers equally valid...)

- RGEs for this model well-known (cf eg Schabinger, Wells)
- decoupling ($\lambda_3 = 0$): recover SM case
- in our setup: $\mu_{\text{SM, break}} \sim 6.3 \times 10^{10} \text{GeV}$
  (remark: just simple NLO running)
- **we took:** $\mu_R \sim 1.2 \times 10^{11} \text{GeV}$
  (higher scales $\leftrightarrow$ stronger constraints)

- **obvious:** for $m_H = 125.7 \text{GeV}$, breakdown “immediate”
  when going to $\mu_{\text{run}} > \nu$

$\Rightarrow$ disregard constraints from running in this case
Comments on constraints

Limits for $m_H \geq 600$ GeV

$m_H = 600$ GeV including all bounds

for $\sin \alpha \leq 0.23$: only $\lambda_2$ running important

(sideremark: here, $1 \sigma$ constraint on mixing from $\mu$; relaxed and improved in newer work, just as an example here)
Could we have seen them ?? **YES !!**

(at least they could have been produced...)

**all numbers below:** $\sqrt{S_{\text{hadr}}} = 7\text{TeV}, \int \mathcal{L} = 25\text{fb}^{-1}$

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\kappa_{\text{max}}$</th>
<th>$#\text{gg} \sim$</th>
<th>$#\text{VBF} \sim$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.04</td>
<td>330</td>
<td>60</td>
</tr>
<tr>
<td>700</td>
<td>0.04</td>
<td>130</td>
<td>40</td>
</tr>
<tr>
<td>800</td>
<td>0.04</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>900</td>
<td>0.03</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>1000</td>
<td>0.025</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

maximal number of events from production $\times$ decay to SM-like final states (running conditions at low scale)

(cross sections from "Handbook of LHC Higgs Cross sections I", Dittmaier ea)

for specific final state, multiply with SM-like BR (LO approx)

$$\Rightarrow \text{Model awaits discovery !!}$$ (optimist) $\leftarrow$

(or at least limits...) (pessimist)

(cf. e.g. CMS-PAS-HIG-13-008, CMS-PAS-HIG-13-014, ...)

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Comments on constraints

Limits at Planck scale

assume that the model is valid up to $\mu_{\text{run}} \sim 10^{19}$ GeV
(not always well motivated)

- naturally: parameter space more restricted
- translates to $\kappa \lesssim 0.03$ for $m_H = 600$ GeV (25% decrease)
- now: $\mu$ no longer relevant, only constraint from perturbativity of $\lambda_1, \lambda_2$
New physics channel

What about $H \rightarrow hh$ ??

all numbers below: $\sqrt{S_{\text{hadr}}} = 7\text{TeV}$, $\int \mathcal{L} = 25 \text{fb}^{-1}$,

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>$\kappa'_{\text{max}}$</th>
<th>#gg $\sim$</th>
<th>#VBF $\sim$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.013</td>
<td>110</td>
<td>20</td>
</tr>
<tr>
<td>700</td>
<td>0.012</td>
<td>40</td>
<td>11</td>
</tr>
<tr>
<td>800</td>
<td>0.010</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>900</td>
<td>0.007</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>1000</td>
<td>0.005</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

maximal number of events from $H \rightarrow hh$ \begin{equation*} \kappa' = \frac{\sigma_{\text{BSM}}^{hh}}{\sigma_{H,\text{prod}}} \end{equation*}

(cross sections from ”Handbook of LHC Higgs Cross sections I”, Dittmaier ea)

for specific final state, multiply with SM-like BR for $m_h$

”naively”: many b-jets with $m_{bb} \sim 125$ GeV, or $bb\gamma\gamma$, or...

(e.g. Cooper ea.: $b\bar{b}b\bar{b}$ final state @8 TeV)

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What about the “inverse” scenario, ie. \( m_H = 125.7 \, \text{GeV} \)

cmp{mainly ruled out by LEP and/ or \( \chi^2 \) fit from HiggsSignals}

| \( m_H [\text{GeV}] \) | \( | \sin \alpha |_{\text{min, exp}} \) | \( | \sin \alpha |_{\text{min, 2}\sigma} \) | \( (\tan \beta)_{\text{max}} \) |
|-----------------|-----------------|-----------------|-----------------|
| 110             | 0.82            | 0.89            | 9.2             |
| 100             | 0.86            | ——              | 10.1            |
| 90              | 0.91            | ——              | 11.2            |
| 80              | 0.98            | ——              | 12.6            |
| 70              | 0.99            | ——              | 14.4            |
| 60              | 0.98            | \( \gtrsim 0.99 \) | 16.8            |
| 50              | 0.99            | \( \gtrsim 0.99 \) | 20.2            |
| 40              | 0.99            | \( \gtrsim 0.99 \) | 25.2            |

*Table:* Limits on \( \sin \alpha \) and \( \tan \beta \) in the low mass scenario. Upper limit on \( \tan \beta \) from perturbative unitarity. (—— means no additional constraint)

(side remark: for \( m_h \gtrsim 60 \, \text{GeV} \), \( \tan \beta \) irrelevant for collider observables)

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**Question**: What are the changes in higher order corrections wrt the current (SM-like) description??

**Motivation**: SM-like searches impossible wo higher orders
⇒ can this be transferred to BSM ??

- remember: every SM-like coupling is rescaled by \( \sin \alpha \)
⇒ every \((\alpha_s, y_i, \ldots)\) with heavy Higgs ⇒ \((\alpha_s, y_i, \ldots) \times \sin^2 \alpha\)

⇒ naive approach:
- higher order (differential/ non-differential) K-factors remain the same, only tree level production/ decay needs rescaling
⇒ would lead to same scaling with \( \kappa, \ldots \) as tree level, with (differential) higher order K-factors as in SM
Some comments re full NLO treatment...

- SM-sector: contributions from new heavy Higgs to finite part of gauge Boson propagators
  ⇒ influences renormalization of $m_W, m_Z$
- other (possibly important) effects: one-loop contribution to

$$H \rightarrow t \bar{t}$$

⇒ could lead to modifications in $t \bar{t}$ production

(remember: production suppressed by $\sin^2 \alpha$, $\sigma \lesssim 0.01 \text{ pb}$ for (7) 14 TeV)
Higher order corrections in the Singlet extension (2d) - EW

- $H \rightarrow t \bar{t}$: corrections could be sizeable
- along similar lines: loop contributions to $H \rightarrow W W$

from $H h h$ coupling (for production in VBF and decay)

⇒ probably not as important as decay to tops, but still large(ish)

- also: $H \rightarrow g g$,
- probably/ maybe all subdominant wrt ”standard” (QCD) NLO effects...
Coupling and mass relations

\[ m_h^2 = \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \]  
\[ m_H^2 = \lambda_1 v^2 + \lambda_2 x^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \]  
\[ \sin 2\alpha = \frac{\lambda_3 x v}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}, \]  
\[ \cos 2\alpha = \frac{\lambda_2 x^2 - \lambda_1 v^2}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}. \]
Tools which can do it ?? (incomplete list)

(”it” = LO, NLO, ...)

- LO: any tool talking to FeynRules (in principle)/ LanHep (in practice)
  implemented and run: CompHep (M. Pruna), Sherpa (±) (would need some modification, T. Figy), privately modified codes (??)

- NLO: (mb) a modified version of aMC@NLO (R. Frederix) ?? (production only; might be important for VBF)

- new tool in the MadGraph environment (Artoisenet ea, 06/13): QCD-part of NLO

- complete higher orders: would need to be implemented in respective tools (I am not aware of any at the moment)