Survey of (and update on) the Higgs singlet extension

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.

based on

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G.M. Pruna, TR (PRD 88 (2013) 115012)
D. Lopez-Val, TR, arXiv:1406.1043
TR, T. Stefaniak, work in progress

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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** x
- physical states related via **mixing angle** $\sin\alpha$ $(m_h < m_H)$:

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

- 5 parameters

$$\mathbf{m_h},\ \mathbf{m_H},\ \sin\alpha,\ \mathbf{v},\ \tan\beta = \frac{\mathbf{v}}{\mathbf{x}}$$

- **2 fixed**, **3 free**, $(m_h\,||\,m_H) = 125.7\,\mathrm{GeV}$

Potential

$$\mathbf{V} = -\mathbf{m}^2\mathbf{H}^\dagger\mathbf{H} - \mu^2\,\chi^2 + \lambda_1(\mathbf{H}^\dagger\mathbf{H})^2 + \lambda_2\,\chi^4 + \lambda_3\mathbf{H}^\dagger\mathbf{H}\,\chi^2,$$

Phenomenology (in the following: focus on $m_h \sim 126\,\mathrm{GeV}$)

- SM-like couplings of **light/ heavy** Higgs:

  rescaled by $\sin\alpha$, $\cos\alpha$
- in addition: **new physics channel:** $H \rightarrow h\,h$

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

- **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

$$\kappa' \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{H\rightarrow h\,h}}{\sigma_{\text{SM}}} = \frac{\sin^2\alpha\,\Gamma_{H\rightarrow h\,h}}{\Gamma_{\text{tot}}}$$

Theoretical and experimental constraints on the model

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

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 $\Longrightarrow$!! NEW !! $\Longleftarrow$**
5. **collider limits** using HiggsBounds
6. measurement of **light Higgs signal rates** using HiggsSignals

(*): only for $m_h = 125.7\,\mathrm{GeV}$

Results

- **strongest constraints:**

$$m_H \gtrsim 800\,\mathrm{GeV} \quad : \quad \text{perturbativity of couplings}$$

$$m_H \in [200;800]\mathrm{GeV} \quad : \quad m_W \text{ @ NLO}$$

$$m_H \in [130;200]\mathrm{GeV} \quad : \quad \text{experimental searches}$$

$$m_h \lesssim 120\,\mathrm{GeV} \quad : \quad \text{SM-like Higgs coupling rates } (+\text{ LEP})$$

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

$$\Gamma_{\mathbf{tot}} \lesssim 0.02\, m_H$$

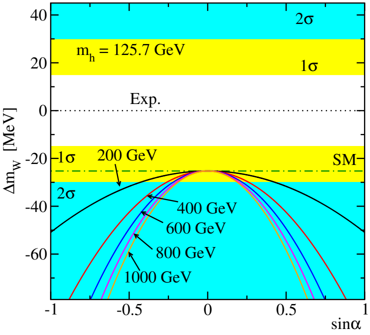
$\Rightarrow$ **Highly (??) suppressed, narrow(er) heavy scalars** $\Leftarrow$

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

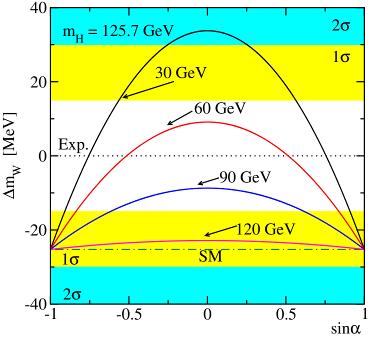
$\Rightarrow$ **(partially) already correctly treated in experimental searches (variation of Γ by hand...)** $\Leftarrow$

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

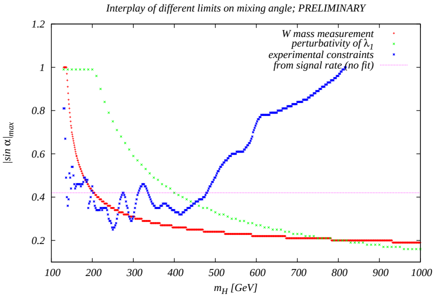


$m_H = 125.7$ GeV

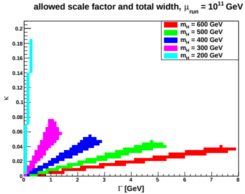
$\Longrightarrow$ **low m_h bring m_W^{NLO} close to m_W^{exp}** $\Longleftarrow$

Combined limits on $|\sin\alpha|$!! PRELIMINARY !!

(D. Lopez-Val, TR, arXiv:1406.1043, and TR, T. Stefaniak, to appear)



several bounds on $|\sin\alpha|$



limits on κ, Γ plane from all constraints

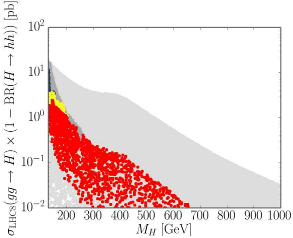
Results from generic scans and predictions for LHC 14

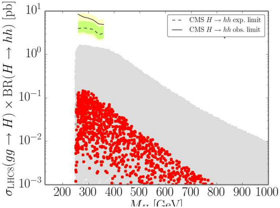
(TR, T. Stefaniak, in preparation)

1 σ, 2 σ, allowed

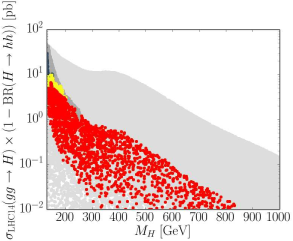
SM like decays | BSM decay to *hh*

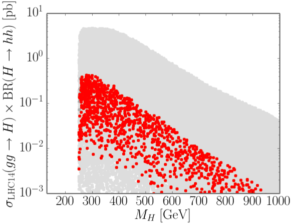
limits





pred.





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 $m_h \leq 120\,\mathrm{GeV}$ $\Rightarrow$ quite interesting results

$\Longrightarrow$ **Happy to contribute to WG activities** $\Longleftarrow$

$\Longrightarrow$ **STAY TUNED** $\Longleftarrow$

Appendix

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, χ real singlet)

$$\mathbf{V} = -\mathbf{m}^2\mathbf{H}^\dagger\mathbf{H} - \mu^2\,\chi^2 + \lambda_1(\mathbf{H}^\dagger\mathbf{H})^2 + \lambda_2\,\chi^4 + \lambda_3\mathbf{H}^\dagger\mathbf{H}\,\chi^2,$$

- 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

$$\text{VeVs: } H \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix},\ \chi \equiv \frac{h'+x}{\sqrt{2}}.$$

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

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ v,\ x$$

- rewrite as

$$\mathbf{m_h},\ \mathbf{m_H},\ \sin\alpha,\ \mathbf{v},\ \tan\beta$$

- **fixed**, **free**

$$\sin\alpha\text{: mixing angle, } \tan\beta = \frac{v}{x}$$

- physical states ($m_h < m_H$):

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

Comments on constraints (1) - Perturbativity issues

Perturbative unitarity:

- tests combined system of all (relevant) $2 \rightarrow 2$ scattering amplitudes for $s \rightarrow \infty$
- makes sure that the largest eigenvalue for the "0"-mode partial wave of the diagnolized system ≤ 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 $m_H \leq 1\,\mathrm{TeV}$!! for the model-builders...)

- arbitrary large m_H can cure this !! cf Lebedev; Elias-Miro ea. Out of collider range though ($\sim 10^8\,\mathrm{GeV}$)

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

- perturbativity of couplings severely restricts parameter space, even for low scales

RGE running in more detail

Question: at which scale did we require perturbativity ?
Answer: "just above" the SM breakdown
(other answers equally valid...)

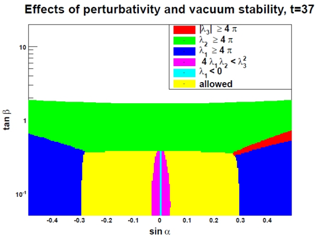
- RGEs for this model well-known (cf eg Schabinger, Wells)
- decoupling ($\lambda_3 = 0$): recover SM case
- in our setup: $\mu_{\text{SM,break}} \sim 6.3 \times 10^{10}\,\text{GeV}$
  (remark: just simple NLO running)
- **we took:** $\mu_R \sim 1.2 \times 10^{11}\,\text{GeV}$

  (higher scales $\Longleftrightarrow$ stronger constraints)

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

$\Rightarrow$ disregard constraints from running in this case

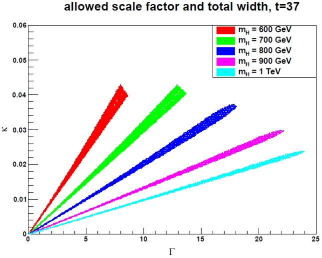
Limits for $m_H \geq 600\,\mathrm{GeV}$



Limits in $\sin\alpha$, $\tan\beta$ plane,

$m_H = 600\,\mathrm{GeV}$ including all bounds

$\Longrightarrow$



limits on κ, Γ plane from all constraints

for $\sin\alpha \leq 0.23$: only λ_2 **running important**

(sideremark: here, 1 σ constraint on mixing from μ; 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: $\sqrt{S_{\text{hadr}}} = 7\text{TeV}, \int \mathcal{L} = 25\,\text{fb}^{-1}$

m_H [GeV]	$\kappa_{\max}$	$\#gg \sim$	#VBF $\sim$
600	0.04	330	60
700	0.04	130	40
800	0.04	60	20
900	0.03	20	12
1000	0.025	8	7

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)

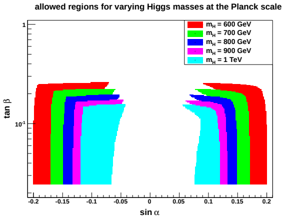
$\Longrightarrow$ Model awaits discovery !! (optimist) $\Longleftarrow$

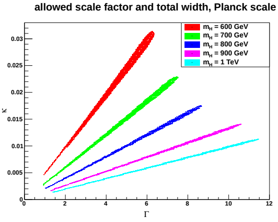
(or at least limits...) (pessimist)

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

Limits at Planck scale

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



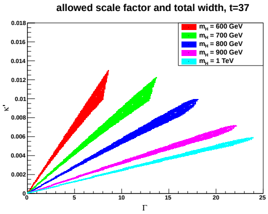


- naturally: **parameter space more restricted**
- translates to $\kappa \lesssim 0.03$ **for** $m_H = 600\,\text{GeV}$ (25 % decrease)
- now: μ no longer relevant, only constraint from perturbativity of λ_1, λ_2

What about $H \rightarrow h\,h$??

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

m_H [GeV]	κ'_{max}	$\#gg \sim$	$\#\text{VBF} \sim$
600	0.013	110	20
700	0.012	40	11
800	0.010	14	6
900	0.007	4	3
1000	0.005	2	1



maximal number of events from $H \rightarrow h\,h$ $\left(\kappa' = \frac{\sigma_{hh}^{\text{BSM}}}{\sigma_{H,\text{prod}}}\right)$

(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 $m_{bb} \sim 125\,\text{GeV}$, or $bb\,\gamma\,\gamma$, or...

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

What about the "inverse" scenario, ie. $m_H = 125.7\,\mathrm{GeV}$

mainly ruled out by LEP and/ or χ^2 fit from HiggsSignals

$m_H[\mathrm{GeV}]$	$\lvert\sin\alpha\rvert_{\text{min, exp}}$	$\lvert\sin\alpha\rvert_{\text{min, }2\sigma}$	$(\tan\beta)_{\max}$
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 $m_h \gtrsim 60\,\mathrm{GeV}$, $\tan\beta$ irrelevant for collider observables)

Higher order corrections in the Singlet extension (1) - QCD

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

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

- remember: every SM-like coupling is **rescaled by** $\sin\alpha$

$\Rightarrow$ every $(\alpha_s, y_i, ...)$ with heavy Higgs $\Rightarrow$ $(\alpha_s, y_i, ...) \times \sin^2\alpha$

$\Rightarrow$ **naive approach:**
higher order (differential/ non-differential) **K-factors remain the same**, only tree level production/ decay needs rescaling

$\Rightarrow$ would lead to same scaling with κ**, ...** as tree level, with (differential) higher order K-factors as in SM

Higher order corrections in the Singlet extension (2b) - EW

Some comments re full NLO treatment...

- SM-sector: contributions from new heavy Higgs to finite part of gauge Boson propagators

$\Rightarrow$ influences renormalization of m_W, m_Z

- other (possibly important) effects: **one-loop contribution to**

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

$\Rightarrow$ could lead to modifications in $t\,\bar{t}$ production
(remember: production suppressed by $\sin^2\alpha$,
$\sigma \lesssim 0.(0)1\,\mathrm{pb}$ 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

$$\mathbf{H \rightarrow W\,W}$$

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

$\Rightarrow$ 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

$$m_h^2 = \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \quad (1)$$

$$m_H^2 = \lambda_1 v^2 + \lambda_2 x^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \quad (2)$$

$$\sin 2\alpha = \frac{\lambda_3 x v}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}, \quad (3)$$

$$\cos 2\alpha = \frac{\lambda_2 x^2 - \lambda_1 v^2}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}. \quad (4)$$

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)