Higgs Singlet extension in the light of the LHC discovery

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based on

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G.M. Pruna, TR (arXiv:1303.1150)

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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**: no dark matter candidate

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 ($m_h < m_H$):

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

SM phenomenology in three lines

Question 1:
Modfication for SM-like final states at tree level ?

In case we neglect the new *Hhh* coupling:

- light/ heavy Higgs non-singlet component $\sim \cos\alpha / \sin\alpha$

⇒ for light/ heavy Higgs: every SM-like coupling is **rescaled by** $\cos\alpha / \sin\alpha$

⇒ this alone would lead to **"global"** $\cos^4\alpha / \sin^4\alpha$ $(\cos^2\alpha / \sin^2\alpha)$ for full production and decay (production or decay)

- **BRs stay the same**

Non SM-like phenomenology

- in addition: **new physics channel:**

$$H \rightarrow h\,h$$

- effect:

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

needs to be included for SM like decays

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

- breakdown:

$$\sigma_{\text{prod}} = \sin^2\alpha \times \sigma_{\text{prod,SM}},\; \text{BR}_{H\rightarrow\ldots} = \sin^2\alpha\,\frac{\Gamma_{\text{tot, SM}}}{\Gamma_{\text{tot}}} \times \text{BR}^{\text{SM}}_{H\rightarrow\ldots}$$

$\Rightarrow$ **sufficient for tree level rescaling** $\Leftarrow$

Theoretical and experimental constraints on the model

our study: $m_h = 125\,\mathrm{GeV},\ 600\,\mathrm{GeV} \leq m_H \leq 1\,\mathrm{TeV}$

we considered

1. limits from **perturbative unitarity**
2. limits from EW precision observables through $S,\ T,\ U$ (with a small caveat...)
3. **perturbativity** of the couplings (up to certain scales)
4. **vacuum stability and minimum condition** (up to certain scales)
5. measurement of **light Higgs signal strength**

(debatable: minimization up to arbitrary scales, ⇒ perturbative unitarity to arbitrary high scales...)

(these are common procedures though in the SM case)

Results (for details, cf arXiv: 1303.1150)

- **strongest constraints:**

$$m_H \lesssim 700\,\mathrm{GeV} \quad : \quad \textbf{light Higgs coupling strength}$$
$$m_H \gtrsim 700\,\mathrm{GeV} \quad : \quad \textbf{perturbativity of couplings}$$

$\Rightarrow$ $\kappa \leq 0.04$ for all masses considered here

$\Rightarrow$ in addition: smallish values for $\Gamma_{H \to h\, h}\,(\leq 5\,\mathrm{GeV})$

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

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

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

(note: $\Gamma_{\text{tot}} \lesssim 0.08\, m_H$ from signal strength limit only)

Treatment of light Higgs coupling strength μ

- assume **no** (weaker: negligible) hidden sector interactions for the light Higgs
- in this case **(LO treatment, NO fit !!!)**

$$\cos^2\alpha \equiv \mu$$

with μ: coupling strength
(this assumes parton-level-like definition of μ)

- **we took** *(Phys.Lett., B716:1–29, 2012;Phys.Lett., B716:30–61, 201)*

$$\mu_{\text{ATLAS}} = 1.4 \pm 0.3,\ \mu_{\text{CMS}} = 0.87 \pm 0.23$$
$$\overline{\mu} = 1.14 \pm 0.19,\ \cos^2\alpha \geq 0.95$$
$$\Rightarrow \sin\alpha \leq \mathbf{0.23}$$

(errors: one σ, SM-like Higgs hypothesis)

- (aside: first studies presented at EPS13: test $\sin\alpha \geq 0.44$)

Comments on other 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)
  (more sopisticated methods to unitarize theories: Argand circle, ...
  $\Rightarrow$ WS in DD 09/13)

Perturbativity of couplings

- make sure that no coupling $\geq 4\,\pi$ ("typical" loop prefactor$^{-0.5}$)
- at ew scale: perturbative unitarity stronger

Comments on other constraints (2) - EW precision data

S, T, U

- oblique parameters (Peskin, Takeuchi '92; Hagiwara ea. '94)
- parametrize deviations from SM in electroweak sector
- here: neglected contributions from $H \rightarrow hh$
  (aside: OK ?? $\Rightarrow$ depends on renormalization scheme)
- anyways: all "beaten" by μ restriction on $\sin\alpha$ $\Rightarrow$ not relevant
  (should be redone using full theory though)

Comments on other constraints (3) - 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 (...like SUSY, this model can never be excluded...)
- perturbativity of couplings severely restricts parameter space, even for low scales

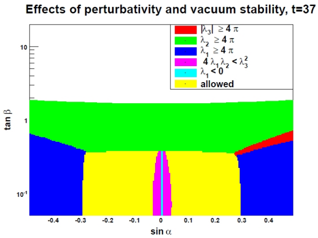
RGE running in more detail

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: $\mu_{\text{SM,break}} \sim 1.6 \times 10^{16}\,\text{GeV}$
  (remark: just simple NLO running)
- **we took:** $\mu_R \sim 2.6 \times 10^{16}\,\text{GeV}$

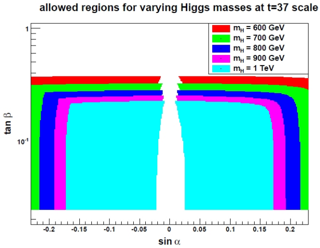
(higher scales $\Longleftrightarrow$ stronger constraints)

Limits on $\sin\alpha$, $\tan\beta$, $\mu_{\text{run}} \sim 2.6 \times 10^{16}\,\text{GeV}$



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

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



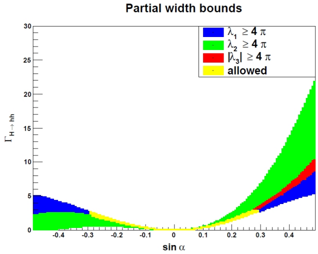
Limits in $\sin\alpha$, $\tan\beta$ plane, varying m_H

including all bounds

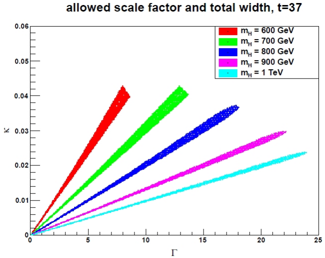
for $\sin\alpha \leq 0.23$: only λ_2 **running important**

Limits on κ, Γ_{tot}, $\mu_{\text{run}} \sim 2.6 \times 10^{16}\,\mathrm{GeV}$

translation to collider observables κ, Γ_{tot}



Limits on $\Gamma_{H \to h h}$ from perturbativity

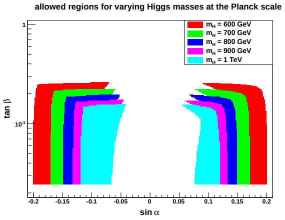


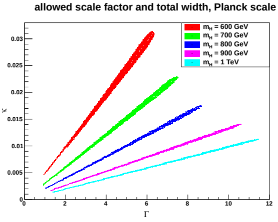
limits on κ, Γ plane from all constraints

- constraint from μ on $\sin\alpha$: $\Gamma_{H \to h h}$ already small ($\lesssim 0.08\, m_H$)
- running of couplings: even stronger constraints

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

Could we have seen them ?? YES !!

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

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

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, ...)

One more word about $H \to h\,h$

- all above: **focuses on SM-like decays**
- **viable alternative:** search for

$$H \to h\,h \to \ldots$$

- **widely discussed in the literature**
  (for recent work, cf Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam, Sanz; Cooper, Konstantinidis, Lambourne, Wardrope; ...)
- **HOWEVER** in our scan, WW **always dominant**

$\Rightarrow$ **would go for this first**
(but mb more than 1 group is interested...)

$H \rightarrow h\,h$: parametrization

- remember:

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

- define κ' **in analogy to** κ as

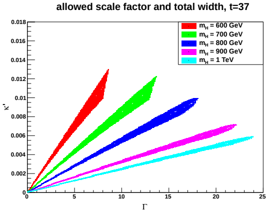
$$\kappa' \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{H\rightarrow h\,h}}{\sigma_{\text{SM}}} = \frac{\sin^2\alpha\,\Gamma_{H\rightarrow h\,h}}{\Gamma_{\text{tot}}}$$

(then obviously $\kappa + \kappa' = \sin^2\alpha$)

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 @ $8\,\text{TeV}$)

Summary

- Singlet extension: **simplest extension of the SM Higgs sector**, easily identified with one of the benchmark scenarios of the HHXWG (cf. also YR3)
- constraints on parameter space: **signal strength of light Higgs, perturbativity of the couplings**
- **quite narrow widths wrt SM-like Higgses** in this mass range
  $\Rightarrow$ **better theoretical handle**
- quite low (??) production cross sections due to small mixings
- currently tested (as presented at EPS13): $\sin\alpha \geq 0.44$; severely restricted from μ measurements for light Higgs

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

Appendix

Coupling and mass relations

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

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

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

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

Other tree-level effects...

- in principle:

$$\mathbf{H} \rightarrow \mathbf{W\,W} \qquad (5)$$

could be mimicked by

$$\mathbf{H} \rightarrow \mathbf{h\,h} \rightarrow \mathbf{W\,W}\,\gamma\,\gamma \qquad (6)$$

($\gamma\gamma$ escape), if $H \rightarrow h\,h$ is large enough

- **maximal allowed scenario**:

$$\mathrm{BR}_{\mathbf{hh}} \sim \mathbf{0.25},\ \mathrm{BR}_{\mathbf{WW}} \sim \mathbf{0.45}$$

- $(2)/(1) \sim 10^{-4}$, **highly suppressed**

Outlook: Singlet @ NLO

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

(All below are just generic arguments, not based on any calculation)

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

$\Rightarrow$ **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 (2) - EW

- previous slide: ignored $H \rightarrow h\,h$ contributions

$\Rightarrow$ valid for strong corrections

- left out: corrections with h running in the loop (vertex, propagator,...)
- BR can be $\sim 25\,\%$

$\Rightarrow$ current status (at least for me): **effects/ changes from including these not clear, in principle full calculation** (including renormalization) **needed to check**

$\Rightarrow$ **available ??**

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

- Higgs sector itself can be renormalized in on-shell scheme *(thanks to C. Pietsch and D. Lopez-Val for comments)*
- 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 (2c) - EW

A rough estimate...

[(nearly) all below: $\sin\alpha$ small, $m_h^2 \ll m_H^2$]

- coupling $H t\,\bar{t} \sim \frac{y_t(m_H)}{\sqrt{2}} \sin\alpha$
- coupling $H h\, h \sim \frac{m_H^2}{v} \sin\alpha$

$$\frac{\Gamma_{tt}}{\Gamma_{hh}} \sim \frac{y_t^2(m_H)\, N_c}{\left(\frac{m_H^2}{2\,v^2}\right)} \left(\frac{\beta_t}{\beta_h}\right)^3 \lesssim 0.6 \quad \left(\beta_i = \sqrt{1-4\, m_i^2/m_H^2}\right)$$

$\Rightarrow$ contribution via loop (in small mixing limit $\sin\alpha \ll 1$)

$$\sim \left(\frac{y_t(m_h)}{\sqrt{2}}\right)^2 \frac{m_H^2}{v} \sin\alpha$$

could in principle be sizeable, $\mathcal{O}(10\,\%)$

$\Rightarrow$ more accurate calculation needed...

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

- along similar lines: loop contributions to

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

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: $H \longrightarrow g\,g$,...
- probably/ maybe all subdominant wrt "standard" (QCD) NLO effects...

Higher order corrections in the Singlet extension (3) - width and on-shellness

- is the width small enough to neglect "broadness" complications ?
- naive argument: **error**

$$\sim \frac{\Gamma_H}{m_H} \lesssim 2\,\%$$

$\Rightarrow$ **might be OK for a rough estimate**

- alternative: redo cross section calculations eg in complex pole scheme (needed ??) with reduced Γ (how much effort ?? Γ is varied; mb start with a maximal value...)

  (not necessary imho)
- another point: "sideband" complications vanish

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** ($\pm$) (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)

Suggestion

My conclusion:

This is about BSM discovery,
lets worry about precision later...

$\Rightarrow$ in this spirit: **simple rescaling of tree-level by κ**, together with **SM-like QCD K-factor**, should work as a first guess...

$\Rightarrow$ could be done with **factorized production $\times$ decay**

$\Rightarrow$ should be **doable with standard tools** (as long as they dont assume broad widths)

If you insist on NLO from BSM...

- $\sigma \times \mathrm{BR}_{\mathrm{SM}}$ might deviate from simple rescaled κ due to loops including $h\,h$

$\Rightarrow$ need calculations here

- for a generic coupling g_{SM} and $H \longrightarrow X_{\mathrm{SM}}\,X^{*}_{\mathrm{SM}}$

$$\Delta_{\mathrm{NLO,\ rel}} \sim \frac{g^2_{\mathrm{SM}}(m_h)}{g_{\mathrm{SM}}(m_H)}\,\frac{m_H^2}{v} \times (\text{your favourite scale})^x$$
$$\times\,(\text{your favourite loop approximation})$$

(x depends on dimensions of couplings)

Numbers used in loop approximation

small $\sin\alpha$, m_h limit

$$\lambda_1 \sim \frac{m_h^2}{2\,v^2},\ \lambda_2 \sim \frac{m_H^2}{2\,x^2},\ \lambda_3 \sim \frac{m_H^2}{v\,x}\,\sin\alpha$$
$$\mu \sim -\sin\alpha\,\frac{m_H^2}{2\,v}$$

running couplings and βs

$$y_t(125\,\mathrm{GeV}) = 0.95,\ y_t(600\,\mathrm{GeV}) = 0.88,$$
$$\beta_t = 0.82,\ \beta_h = 0.91$$

Perturbativity of couplings λ_2, λ_3 :

$$\tan\beta \leq \frac{4\sqrt{2\,\pi}\,v}{m_H},\ \tan\beta \leq \frac{16\,\pi\,v^2}{\sin\alpha\,m_H^2}$$