

Higgs Singlet extension in the light of the LHC discovery

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based on

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 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

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

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

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

- rewrite as

$$\mathbf{m}_h, \mathbf{m}_H, \sin \alpha, \mathbf{v}, \tan \beta$$

- 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:

Modification 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**



Tree level: rescaling wrt Standard Model

Non SM-like phenomenology

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

$$H \rightarrow hh$$

- effect:

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

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:

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

\Rightarrow sufficient for tree level rescaling \Leftarrow

Theoretical and experimental constraints on the model

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

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, \Rightarrow perturbative unitarity to arbitrary high scales...)

(these are common procedures though in the SM case)

Results (for details, cf arXiv: 1303.1150)

- strongest constraints:**

$$m_H \lesssim 700 \text{ GeV} : \text{light Higgs coupling strength}$$

$$m_H \lesssim 700 \text{ GeV} : \text{perturbativity of couplings}$$

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

⇒ in addition: smallish values for $\Gamma_{H \rightarrow hh} (\leq 5 \text{ GeV})$

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

⇒ **Highly (??) suppressed, narrow(er) heavy scalars** ⇐

⇒ **new (easier ?) strategies needed wrt searches for SM-like Higgs bosons in this mass range** ⇐

(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*)

$$\mu_{\text{ATLAS}} = 1.4 \pm 0.3, \mu_{\text{CMS}} = 0.87 \pm 0.23$$

$$\bar{\mu} = 1.14 \pm 0.19, \cos^2 \alpha \geq 0.95$$

$$\Rightarrow \sin \alpha \leq \mathbf{0.23}$$

(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 diagonalized system ≤ 0.5
- "crude" check that unitarity is not violated
(in the end: all "beaten" by perturbativity of running couplings)
(more sophisticated 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) - 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 (...like SUSY, this model can never be excluded...)
 - perturbativity of couplings severely restricts parameter space, even for low scales

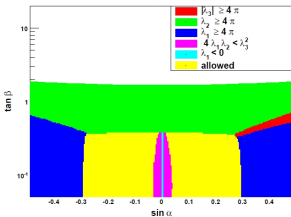
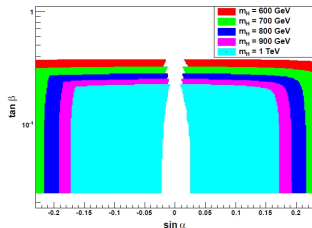
RGE running in more detail

Question: at which scale did we require perturbativity ?

Answer: "just above" the SM breakdown

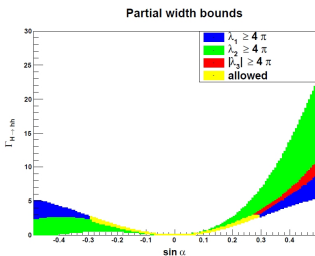
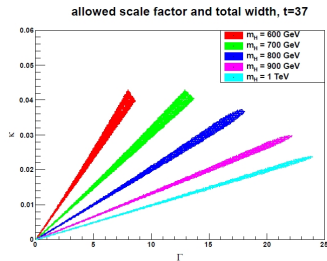
(other answers equally valid...)

- RGEs for this model **well-known** (cf eg Schabinger, Wells)
- **decoupling** ($\lambda_3 = 0$): **recover SM** case
- in our setup: $\mu_{SM,break} \sim 1.6 \times 10^{16}$ GeV
(remark: just simple NLO running)
- **we took:** $\mu_R \sim 2.6 \times 10^{16}$ GeV
(higher scales \iff stronger constraints)

Limits on $\sin \alpha$, $\tan \beta$, $\mu_{\text{run}} \sim 2.6 \times 10^{16}$ GeVEffects of perturbativity and vacuum stability, $t=37$ Limits in $\sin \alpha$, $\tan \beta$ plane, $m_H = 600$ GeV including all boundsallowed regions for varying Higgs masses at $t=37$ scaleLimits 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} , $\mu_{\text{run}} \sim 2.6 \times 10^{16} \text{ GeV}$ translation to collider observables κ , Γ_{tot} Limits on $\Gamma_{H \rightarrow hh}$ from perturbativitylimits on κ , Γ plane from all constraints

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

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]	κ_{max}	$\#gg \sim$	$\#\text{VBF} \sim$
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)

\implies Model awaits discovery !! (optimist) \longleftarrow

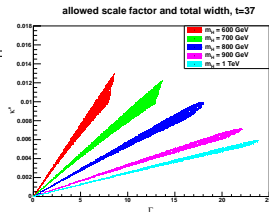
(or at least limits...) (pessimist)

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

What about $H \rightarrow hh$??

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

m_H [GeV]	κ'_{max}	#gg \sim	#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 $H \rightarrow hh$ ($\kappa' = \frac{\sigma_{hh}^{\text{BSM}}}{\sigma_{H,\text{prod}}}$)

(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 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
⇒ **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

⇒ **STAY TUNED** ⇐

Appendix

Coupling and mass relations

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

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

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

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

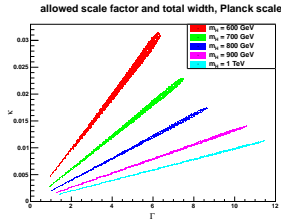
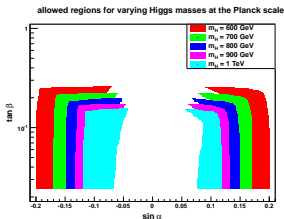
Comments on other constraints (2) - EW precision data

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)

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: μ no longer relevant, only constraint from perturbativity of λ_1, λ_2

$H \rightarrow hh$: parametrization

- remember:

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

- define κ' **in analogy to** κ as

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

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

One more word about $H \rightarrow hh$

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

$$H \rightarrow hh \rightarrow \dots$$

- **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**
- ⇒ **would go for this first**
(but mb more than 1 group is interested...)

Other tree-level effects...

- in principle:

$$H \rightarrow WW \quad (5)$$

could be mimicked by

$$H \rightarrow hh \rightarrow WW\gamma\gamma \quad (6)$$

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

- **maximal allowed scenario:**

$$BR_{hh} \sim 0.25, BR_{WW} \sim 0.45$$

- (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 w/o higher orders
 \Rightarrow can this be **transferred to BSM ??**

- remember: every SM-like coupling is **rescaled by $\sin \alpha$**
- \Rightarrow every (α_s, y_i, \dots) with heavy Higgs $\Rightarrow (\alpha_s, y_i, \dots) \times \sin^2 \alpha$
- \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, \dots as tree level, with (differential) higher order K-factors as in SM

Including higher order corrections: principle

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

- previous slide: ignored $H \rightarrow hh$ contributions
- ⇒ valid for strong corrections
- left out: corrections with h running in the loop (vertex, propagator,...)
- BR can be $\sim 25\%$
- ⇒ current status (at least for me): **effects/ changes from including these not clear, in principle full calculation (including renormalization) needed to check**
- ⇒ **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
- ⇒ 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**

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

- ⇒ could lead to modifications in $t \bar{t}$ production
(remember: production suppressed by $\sin^2 \alpha$,
 $\sigma \lesssim 0.(0)1 \text{ pb}$ for (7) 14 TeV)

Including higher order corrections: principle

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

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

⇒ 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, $\mathcal{O}(10\%)$

⇒ more accurate calculation needed...

Including higher order corrections: principle

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

- along similar lines: loop contributions to

$$H \rightarrow WW$$

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

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

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

Including higher order corrections: principle

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

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

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

⇒ **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...**

- ⇒ in this spirit: **simple rescaling of tree-level by κ** , together with **SM-like QCD K-factor**, should work as a first guess...
- ⇒ could be done with **factorized production** × **decay**
- ⇒ should be **doable with standard tools**
(as long as they dont assume broad widths)

If you insist on NLO from BSM...

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

⇒ need calculations here

- for a generic coupling g_{SM} and $H \rightarrow X_{\text{SM}} X_{\text{SM}}^*$

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

$$\times (\text{your favourite loop approximation})$$

(x depends on dimensions of couplings)

Numbers used in loop approximation

small $\sin \alpha$, m_h limit

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

$$\mu \sim -\sin \alpha \frac{m_H^2}{2v}$$

running couplings and β s

$$y_t(125 \text{ GeV}) = 0.95, y_t(600 \text{ GeV}) = 0.88,$$

$$\beta_t = 0.82, \beta_h = 0.91$$

Perturbativity of couplings λ_2, λ_3 :

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