Theoretical and experimental constraints on the Real Higgs Singlet extension of the Standard Model

Tania Robens

.
based on
.

G.M. Pruna, TR (PRD 88 (2013) 115012)
D. Lopez-Val, TR (arXiv:1406.1043)

TR, T. Stefaniak, work in progress

TU Dresden

Hamburg Workshop on Higgs Physics
Preparing on Higgs Boson Studies with Future LHC data
DESY Hamburg, Hamburg, Germany

24.10.2014

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)

$\Rightarrow$ 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 ($m_h < m_H$):

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

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. limits from EW precision observables through $S,\ T,\ U$
3. **perturbativity** of the couplings (up to certain scales*)
4. **vacuum stability and minimum condition** (up to certain scales*)
5. **collider limits** using HiggsBounds
6. measurement of **light Higgs signal rates** using HiggsSignals

(debatable: minimization up to arbitrary scales, $\Rightarrow$ perturbative unitarity to arbitrary high scales [these are common procedures though in the SM case])

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

Results

- **strongest constraints:**

$$
\begin{aligned}
m_H &\gtrsim 800\,\mathrm{GeV} &:& \quad \textbf{perturbativity of couplings} \\
m_H &\in [200;800]\mathrm{GeV} &:& \quad m_W \textbf{ @ NLO} \\
m_H &\in [130;200]\mathrm{GeV} &:& \quad \textbf{experimental searches} \\
m_h &\lesssim 120\,\mathrm{GeV} &:& \quad \textbf{SM-like Higgs coupling rates } (+\text{ LEP})
\end{aligned}
$$

$\Rightarrow \kappa \leq 0.25$ 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...)** $\Leftarrow$

Comments on constraints - 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 ?

$\Rightarrow$ check at relative low scale (cf next slide)

$\Rightarrow$ 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 ($\sim 10^8\,\mathrm{GeV}$)
- 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...)

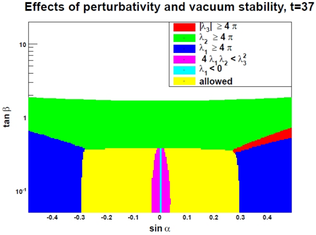
- RGEs for this model well-known (cf eg Schabinger, Wells)
- decoupling ($\lambda_3 = 0$): recover SM case
- in our setup: $\mu_{\text{SM,break}} \sim 6.3 \times 10^{10}\,\text{GeV}$
  (remark: just simple NLO running)
- **we took:** $\mu_R \sim 1.2 \times 10^{11}\,\text{GeV}$

  (higher scales $\Longleftrightarrow$ stronger constraints)

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

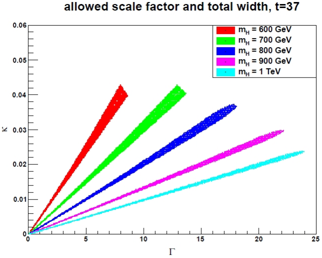
$\Rightarrow$ disregard constraints from running in this case

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



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

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



limits on $\kappa,\ \Gamma$ 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)

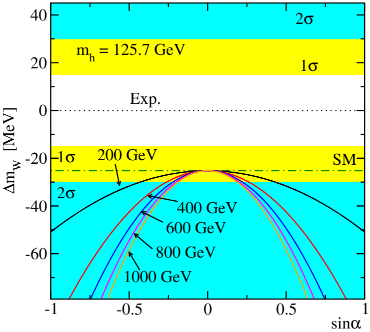
NLO corrections to m_W (D. Lopez-Val, TR, arXiv:1406.1043)

- electroweak fits: fit $\mathcal{O}(20)$ parameters, constraining S, T, U
- idea here: single out m_W, measured with error $\sim 10^{-5}$
- **setup renormalization for Higgs and Gauge boson masses**
- EW gauge and matter sector: on-shell scheme
- Higgs sector: several choices, currently a mixture of onshell/ $\overline{MS}$

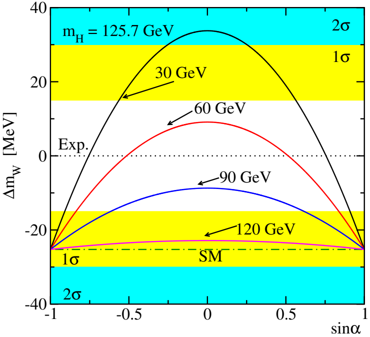
  (in this case: $\delta\lambda$ only enter at 2-loop $\Longrightarrow$ not relevant here)
- first step on the road to full renormalization

NLO corrections to m_W (D. Lopez-Val, TR, arXiv:1406.1043)

Contribution to m_W for different Higgs masses



$m_h = 125.7\,\text{GeV}$

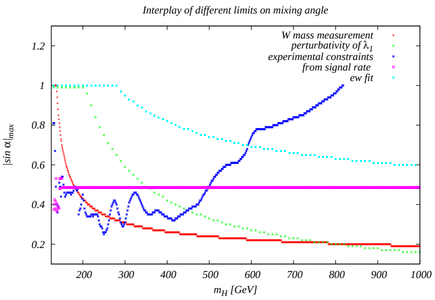


$m_H = 125.7\,\text{GeV}$

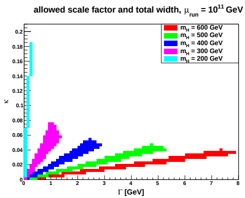
$\Longrightarrow$ low m_h bring m_W^{NLO} close to m_W^{exp} $\Longleftarrow$

Combined limits on $|\sin\alpha|$

(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

m_W, perturbativity, LHC direct searches, Higgs Signal strength, EW fit

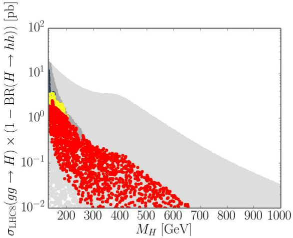
Results from generic scans and predictions for LHC 14

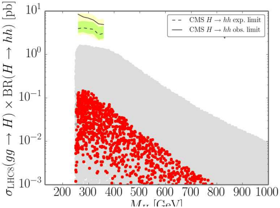
(TR, T. Stefaniak, in preparation)

1 σ, 2 σ, allowed

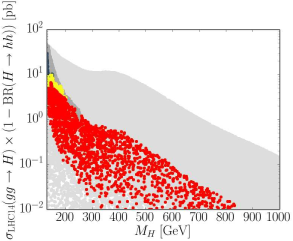
SM like decays | BSM decay to *hh*

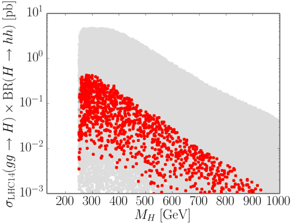
limits





pred.





Could we have seen them ??

all numbers below: $\sqrt{S_{\text{hadr}}} = 8\,\text{TeV},\ \int \mathcal{L} = 23\,\text{fb}^{-1}$

m_H [GeV]	κ_{max}	#gg ∼	κ'_{max}	#gg ∼
200	0.18	**3×10^4**	0	0
300	0.076	**6×10^3**	0.038	**3×10^3**
400	0.053	**4×10^3**	0.021	**1×10^3**
500	0.047	**1×10^3**	0.015	**440**
600	0.039	**470**	0.012	140
700	0.035	180	0.010	50
800	0.033	80	0.009	20
900	0.027	40	0.007	10
1000	0.021	15	0.005	4

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

for $m_H \lesssim 600\,\text{GeV}$, may could already have been produced which are not excluded by current searches !!

Summary

- Singlet extension: **simplest extension of the SM Higgs sector**, easily identified with one of the benchmark scenarios of the HHXWG (cf. also YR3, Snowmass report)
- constraints on **maximal mixing** from m_W **at NLO** ($m_H \in [200\,\mathrm{GeV}; 800\,\mathrm{GeV}]$), **experimental searches and fits** ($m_{H,h} \leq 200\,\mathrm{GeV}$) and/ or **running couplings** ($m_H \geq 800\,\mathrm{GeV}$)
- **quite narrow widths wrt SM-like Higgses** in this mass range $\Rightarrow$ **better theoretical handle**
- quite large suppression from current experimental/ theoretical constraints

!!! still, large numbers could have been produced already !!!

$\Longrightarrow$ STAY TUNED $\Longleftarrow$

Appendix

Coupling and mass relations

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

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

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

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

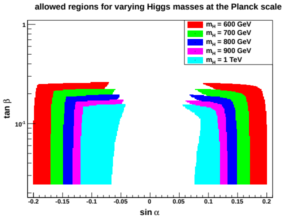
Limits in numbers; high mass scenario

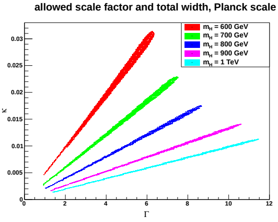
m_H[GeV]	$\vert\sin\alpha\vert$	source upper limit	$(\tan\beta)_{max}$
1000	[0.020; 0.16]	$\lambda_1$perturbativity	0.21
800	[0.028; 0.20]	m_W at NLO/ $\lambda_1$perturbativity	0.26
600	[0.038; 0.22]	m_W at NLO	0.36
400	[0.057; 0.26]	m_W at NLO	0.54
200	[0.092; 0.43]	m_W at NLO	1.08
180	[0.10; 0.44]	126 GeV signal strength	1.20
160	[0.12; 0.44]	126 GeV signal strength	1.34
140	[0.17; 0.36]	$h \to \ell^+\ell^-\ell^+\ell^-$	1.54

- $\sin\alpha_{min}$ always from **vacuum stability**
- $\tan\beta_{max}$ always from **perturbativity of λ_2**

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

mainly ruled out by LEP and/ or χ^2 fit from HiggsSignals
however, *still* large number produced due to large $\sigma_{gg \to h}$

$m_h[\mathrm{GeV}]$	$\lvert\sin\alpha\rvert_{\text{min, exp}}$	$\lvert\sin\alpha\rvert_{\text{min, }2\sigma}$	$(\tan\beta)_{\max}$	$\#gg \sim$
110	0.82	0.89	9.2	10^5
100	0.86	$--$	10.1	10^5
90	0.91	$--$	11.2	10^5
80	0.98	$--$	12.6	10^4
70	0.99	$--$	14.4	10^4
60	0.98	$\gtrsim 0.99$	16.8	10^4
50	0.99	$\gtrsim 0.99$	20.2	10^4
40	0.99	$\gtrsim 0.99$	25.2	10^4

Table: 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)

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)

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...)

Comments on constraints (1) - Perturbativity issues

Perturbative unitarity:

- tests combined system of all (relevant) $2 \rightarrow 2$ scattering amplitudes for $s \rightarrow \infty$
- we considered:

$$WW, ZZ, HH, Hh, hh \rightarrow WW, ZZ, HH, Hh, hh$$

- 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

(Literature: Lee/ Quigg/ Thacker, Phys. Rev. D 16, 1519 (1977))

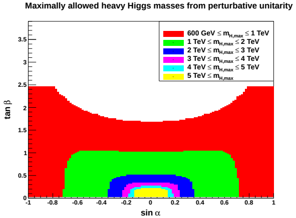
(in the end: all "beaten" by perturbativity of running couplings)

Comments on constraints (1) - Perturbativity issues

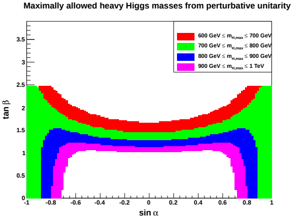
- we tested: **maximal m_H** from PU

  $\Longrightarrow$ **strongest constraints from $H\,H \rightarrow H\,H$** $\Longleftarrow$

- rule of thumb (exact for $\alpha = 0$): $\tan^2\beta \leq \frac{16\,\pi\,v^2}{3\,m_H^2}$



Limits in $\sin\alpha$, $\tan\beta$ plane, maximally allowed m_H from PU



Limits in $\sin\alpha$, $\tan\beta$ plane, maximally allowed $m_H \leq 1\,\mathrm{TeV}$ from PU

$\Longrightarrow$ **for realistic $\sin\alpha$ and our m_H range, $\tan\beta \lesssim 8$**

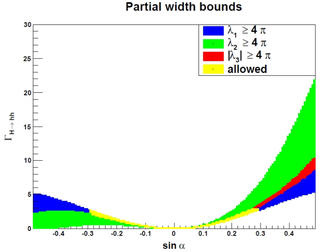
Comments on constraints (2) - running couplings and vacuum

1. **perturbativity:** $|\lambda_{1,2,3}(\mu_{\text{run}})| \leq 4\,\pi$
2. **potential bounded from below:** $\lambda_1, \lambda_2 > 0$
3. **potential has local minimum:** $4\lambda_1\lambda_2 - \lambda_3^2 > 0$

$\Longrightarrow$ need (2), can debate about (1), (3) at all scales $\Longleftarrow$

Limits on κ, Γ_{tot}

limits on $\Gamma_{H\rightarrow hh}$, $m_H = 600\,\mathrm{GeV}$

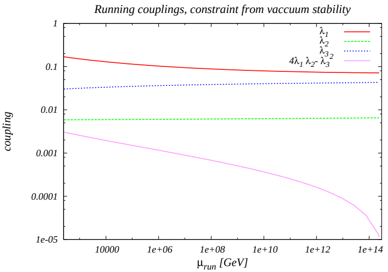


Limits on $\Gamma_{H\rightarrow hh}$ from perturbativity

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

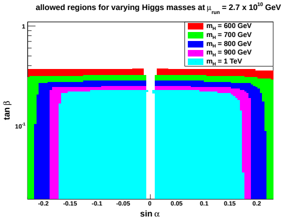
RGE running: a caveat (1)

- important for **collider constraints:** **maximal value of** $|\sin\alpha|$
- important for **vacuum stability:** **minimal value of** $|\sin\alpha|$
- important here: $4\,\lambda_1\,\lambda_2 \;\geq\; \lambda_3^2$
- **sometimes:** this is **(nearly) violated** for running over large scales

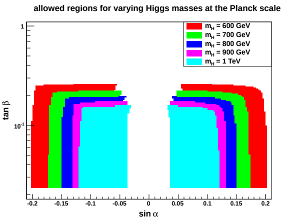


RGE running: a caveat (2)

- $\Rightarrow$ could in principle argue that **higher orders are needed**
- $\Rightarrow$ one possible way to **quantify: neglect this condition**
- $\Rightarrow$ now $|\sin\alpha|_{\min}$ follows from $\lambda_1 \geq 0$.



low scale, third condition neglected



Planck scale, third condition neglected

$\Rightarrow$ back to vacuum stability problem of SM $\Leftarrow$

no important consequences for discovery prospects

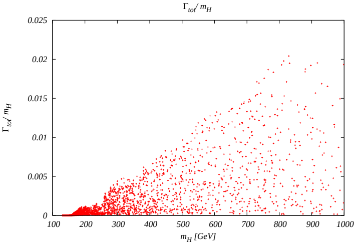
RGE running: variation of input parameters

- especially in sensitive cases, but also otherwise:
  check robustness against input parameters
- here: especially important in decoupling (ie SM-like) case
  (cf. various discussions in the literature...)
- our check:
  vary $\alpha_s(m_Z)$, $y_t(m_t)$ for 1 σ around central values
- main impact: **on vacuum stability,** ie $\lambda_1 > 0$ condition
- **no significant change in $\kappa_{max}(m_H)$, ...**

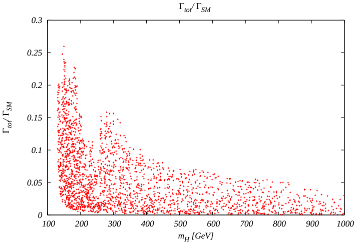
$\Rightarrow$ **not relevant for collider studies** (at this stage...)

Interim comment on total width

- Total width greatly reduced



width over mass



suppression factor of width

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**

- another point: "sideband" complications vanish

$\Rightarrow$ **low-mass case: interference effects ?**
(currently limited from signal strength fits (via Γ_{inv}))