Updated constraints for the Real Higgs Singlet Extension of the Standard Model

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based on recent work with
T. Stefaniak (EPJC 75 (2015) 3,105, Eur.Phys.J. C76 (2016) no.5, 268, work in progress), A. Ilnicka, T. Stefaniak (Mod.Phys.Lett. A33 (2018) no.10n11, 1830007)

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WG3 extended scalars subgroup open meeting

24.10.18

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 ($m_h < m_H$):

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

SM phenomenology in three lines

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

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

relative BRs stay the same

additional channel $H \to h\,h$

Bounds

G.M. Pruna, TR, PRD 88 (2013) 115012;
D. Lopez-Val, TR, PRD 90 (2014) 114018;
TR, T. Stefaniak, EPJC75 (2015)3, 104; EPJC76 (2016)5, 268
A. Ilnicka, TR, T. Stefaniak, Mod.Phys.Lett. A33 (2018) no.10n11, 1830007

Theoretical and experimental constraints on the model

our studies: $m_{h,H} = 125.09\,\mathrm{GeV},\ 0\,\mathrm{GeV} \leq m_{H,h} \leq 1\,\mathrm{TeV}$

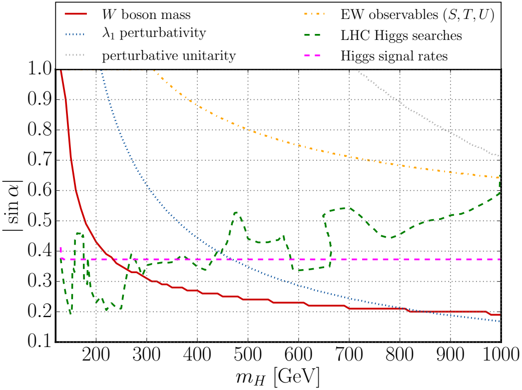
1. limits from **perturbative unitarity**
2. limits from EW precision observables through $S,\ T,\ U$
3. special: **limits from W-boson mass** as precision observable
4. **perturbativity** of the couplings (up to certain scales*)
5. **vacuum stability and minimum condition** (up to certain scales*)
6. **collider limits** using HiggsBounds
7. measurement of **light Higgs signal rates** using HiggsSignals

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

(*): only for $m_h = 125.09\,\mathrm{GeV}$

Combined limits on $|\sin\alpha|$

(A. Ilnicka, TR, T. Stefaniak, Mod.Phys.Lett. A33 (2018) no.10n11, 1830007)



m_W still strongest constraint for $m_H \gtrsim 300\,\mathrm{GeV}$;

$\Rightarrow$ strong improvement: direct searches (ZZ @ 13 TeV) $\Leftarrow$

Newest update

- in HiggsSignals: use Run I combination, Run II results, simplified template cross sections
- with this:

signal strength strongest constraint
(nearly everywhere)

$$\textbf{for } m_h = 125\,\mathrm{GeV}\textbf{:}\ |\sin\alpha| \leq 0.22$$

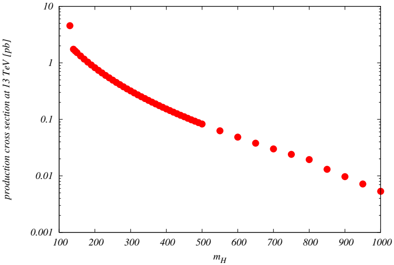
$$\textbf{for } m_H = 125\mathrm{GeV}\textbf{:}\ |\sin\alpha| \geq 0.972$$

LEP stronger: around $m_h \sim 70 - 80$ GeV, perturbativity stronger: $> 800\mathrm{GeV}$

Direct production cross sections

m_h	$\sigma_{gg}^{13\,\mathrm{TeV}}$	m_h	$\sigma_{gg}^{13\,\mathrm{TeV}}$
120	3.46	60	9.41
110	2.75	50	12.6
100	3.36	40	17.8
90	4.63	30	27.1
80	5.72	20	46.5
70	7.26	10	105

Production cross sections at 13 TeV, gg, in pb
$m_H \;=\; 125\,\mathrm{GeV}$



Production cross sections at 13 TeV, gg, in pb
$m_h \;=\; 125\,\mathrm{GeV}$

$H \to h\,h$ branching ratios

m_H[GeV]	$\lvert\sin\alpha\rvert_{max}$	$BR_{min}^{H\to hh}$	$BR_{max}^{H\to hh}$	m_H[GeV]	$\lvert\sin\alpha\rvert_{max}$	$BR_{min}^{H\to hh}$	$BR_{max}^{H\to hh}$
260	0.22	0.17	0.32	470	0.22	0.23	0.29
270	0.22	0.22	0.37	520	0.22	0.20	0.27
280	0.22	0.23	0.39	590	0.22	0.20	0.26
290	0.22	0.24	0.40	670	0.22	0.20	0.26
310	0.22	0.25	0.40	770	0.22	0.22	0.24
330	0.22	0.25	0.39	880	0.19	0.22	0.25
350	0.22	0.25	0.38	920	0.18	0.22	0.25
370	0.22	0.24	0.36	980	0.17	0.23	0.25
400	0.22	0.22	0.32	1000	0.16	0.23	0.25

Minimal and maximal branching ratios for $H \to h\,h$

Appendix

Coupling and mass relations

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

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

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

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

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), **Whizard** (J. Reuter), **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)
- higher orders: would need to be implemented in respective tools (I am not aware of any at the moment)

NLO corrections to m_W

[D. Lopez-Val, TR, (PRD 90 (2014) 114018)]

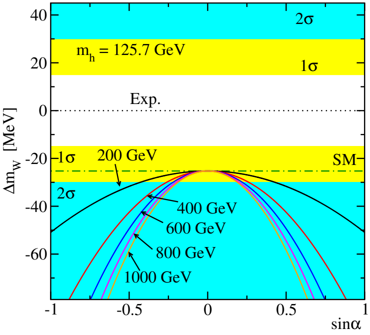
- electroweak fits: fit $\mathcal{O}(20)$ parameters, constraining S, T, U
- idea here: single out m_W, measured with error $\sim 10^{-4}$
- **setup renormalization for Higgs and Gauge boson masses**
- EW gauge and matter sector: on-shell scheme
- Higgs sector: several choices, currently a mixture of onshell/ $\overline{MS}$

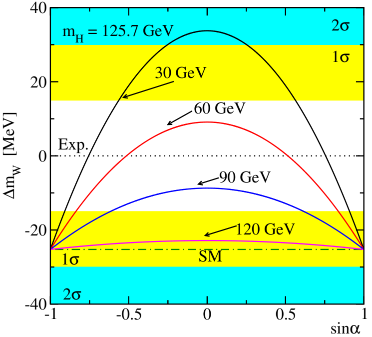
  (in this case: $\delta\lambda$ only enter at 2-loop $\Longrightarrow$ not relevant here)

$\Longrightarrow$ **first step on the road to full renormalization** $\Longleftarrow$

NLO corrections to m_W

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}** $\Longleftarrow$

Results

- **strongest constraints:**

$$
\begin{aligned}
m_H &\gtrsim 800\,\mathrm{GeV} &:&\quad \textbf{perturbativity of couplings}\\
m_H &\in [270;800]\mathrm{GeV} &:&\quad m_W\ \textbf{@ NLO}\\
m_H &\in [125;800]\mathrm{GeV} &:&\quad \textbf{experimental searches/ signal strength}\\
m_h &\lesssim 120\,\mathrm{GeV} &:&\quad \textbf{SM-like Higgs coupling rates}\ (+\ \mathrm{LEP})
\end{aligned}
$$

$\Rightarrow \kappa \leq 0.25$ 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 $\Leftarrow$

[width studies ($\sim$ 2015): cf. Maina ; Kauer, O'Brien; Kauer, O'Brien, Vryonidou; Ballestrero, Maina; Dawson, Lewis; ...]

Comments on constraints (1) - Perturbativity issues

Perturbative unitarity:

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

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

- 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 (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

⇒ 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

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 $\Longleftarrow$