Di-scalar final states in the Z_2 symmetric singlet extension

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based on recent work with
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(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),
S. Dawson, I. Lewis, T. Stefaniak, M. Sullivan (Dihiggs White Paper, to appear),
A.Papefstathiou, J. Zurita (work in progress)

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HH Subgroup Meeting

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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)

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

- 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

$$\text{VeVs:}\;\; H \equiv \left(\begin{array}{c} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{array} \right),\; \chi \equiv \frac{h'+x}{\sqrt{2}}.$$

- 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 ($m_h < m_H$):

$$\left(\begin{array}{c} \mathbf{h} \\ \mathbf{H} \end{array} \right) = \left(\begin{array}{cc} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{array} \right) \left(\begin{array}{c} \tilde{h} \\ h' \end{array} \right),$$

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 $H \rightarrow h\,h$

parameters: $m_{H/h}, \sin\alpha, \tan\beta$

note: $\tan\beta$ can be replaced by Γ_H^{tot} or $\mathrm{BR}_{H\rightarrow h\,h}$

Theoretical and experimental constraints on the model

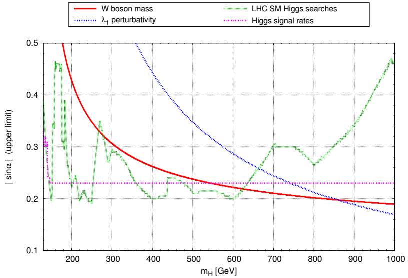
our studies: $m_{h,H} = 125.09\,\mathrm{GeV},\ 0\,\mathrm{GeV} \leq m_{H,h} \leq 1\,\mathrm{TeV}$

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

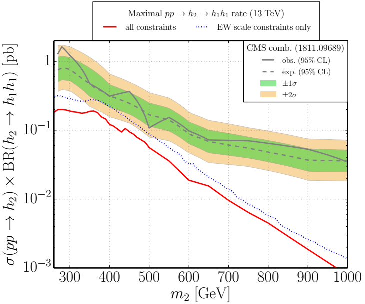
(*): only for $m_h = 125.09\,\mathrm{GeV}$

Current status



[example for fixed $\tan\beta$; SM : $\sin\alpha = 0$]

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



(S. Dawson, I. Lewis, TR, T. Stefaniak, M. Sullivan, contribution to Dihiggs White paper, to appear)

! experimental constraints from LHC start to dominate !

$H \rightarrow h\,h$ branching ratios

- **production: rescale σ_{gg} for SM-like Higgs of m_H by $\sin^2\alpha$**

  (first approximation)

m_H[GeV]	$\vert\sin\alpha\vert_{\max}$	$BR^{H\to hh}_{\max}$	$BR^{H\to hh}_{\max,\,EW}$	m_H[GeV]	$\vert\sin\alpha\vert_{\max}$	$BR^{H\to hh}_{\max}$	$BR^{H\to hh}_{\max,\,EW}$
260	0.22	0.32	0.54	470	0.22	0.28	0.42
265	0.22	0.35	0.57	520	0.21	0.27	0.39
280	0.22	0.39	0.60	590	0.20	0.26	0.36
290	0.22	0.40	0.61	665	0.21	0.26	0.35
305	0.22	0.40	0.60	770	0.20	0.25	0.33
325	0.22	0.40	0.59	875	0.19	0.25	0.32
345	0.22	0.39	0.56	920	0.18	0.25	0.31
365	0.22	0.36	0.53	980	0.17	0.25	0.31
395	0.20	0.33	0.49	1000	0.16	0.25	0.31

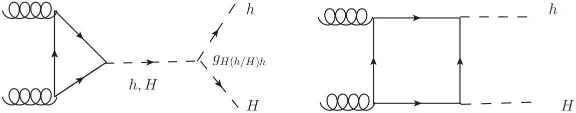
Minimal and maximal branching ratios for $H \rightarrow h\,h$

- **Low mass benchmarks:** $m_H \sim 125\,\mathrm{GeV}$

  Resonant production times decay $\sim 3.4\,\mathrm{pb}$, for $m_h \leq m_H/2$

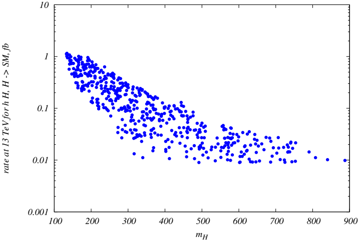
  h typically decays to $b\bar{b}$ (or $c\,\bar{c}$, $\tau\tau$)

Hh production (A. Papaefstathiou, TR, J. Zurita, in preparation)

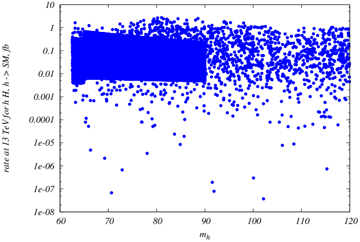


[implemented into Herwig7.1]

Cross sections at 13 TeV [fb]



$m_h \sim 125$ GeV



$m_H \sim 125$ GeV

hH Benchmark points

BP	m_H [GeV]	$\sigma_{hH} \times \text{BR}_{H \to SM}$ [fb]	σ_{hhh} [fb]
1	134	1.15	0
2	166	1.0	0
3	202	0.79	0
4	262	0.45	0.18
5	293	0.31	0.12
6	260	0.10	0.03
7	304	0.10	0.05
8	280	0.37	0.24
9	301	0.25	0.16

$m_h \sim 125\,\text{GeV}$

BP	m_h [GeV]	$\sigma_{hH} \times \text{BR}_{h \to SM}$ [fb]
1	81.03	11.57
2	94.03	1.86
3	63.12	1.64
4	90.78	1.16
5	102.53	1.14
6	99.57	1.11
7	116.48	1.04
8	77.48	0.91

$m_H \sim 125\,\text{GeV}$

BP 1-5: large σ_{Hh}
BP 6,7: σ_{hh} suppressed
BP 8,9: large σ_{hhh}

all BPs: large σ_{hH}

BP 6-8: reduced σ_{hh}

[(nearly) all points: outside of "resonance" region]

References

- Pruna, M. G., and Robens, T., *The Higgs Singlet extension parameter space in the light of the LHC discovery*, arXiv:1303.1150 [hep-ph], Phys. Rev. D 88, 115012 (2013)
- Lopez-Val, D. and Robens, T., *Delta r and the W-boson mass in the Singlet Extension of the Standard Model*, arXiv:1406.1043 [hep-ph], Phys. Rev. D 90, 114018
- T. Robens, T. Stefaniak, *Status of the Higgs Singlet Extension of the Standard Model after LHC Run 1*, arXiv:1501.02234, EPJC (2015) 75:105

BPs Robens, T., and Stefaniak, T., *LHC Benchmark Scenarios for the Real Higgs Singlet Extension of the Standard Model*, arXiv:1601.07880, Eur.Phys.J. C76 (2016) no.5, 268

BPs The LHC Higgs Cross Section Working Group Collaboration (D. de Florian et al.), *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, arXiv:1610.07922

- Ilnicka, A., Robens, T., and Stefaniak, T., *Constraining Extended Scalar Sectors at the LHC and beyond*, arXiv:1803.03594, Mod.Phys.Lett. A33 (2018) no.10n11, 1830007

BPs Robens, T., and Stefaniak, T., *Updated constraints for the Real Higgs Singlet Extension of the Standard Model*, submitted to the Higgs Cross Section Working Group, October 2018

BPs Dawson, S., Lewis, I., Robens, T., Stefaniak, T., and Sullivan, M., *Spin-0 models*, contribution to DiHiggs White paper (to appear), February 2019

BPs Papaefstathiou, A., Robens, T., Stefaniak, T., and Zurita, J., *WG benchmarks, Z_2 symmetric model*, submitted to Higgs Cross Section Working Group, April 2019

- Papaefstathiou, A., Robens, T., and Zurita, J., work in progress

Many BPs around $\Rightarrow$ please use them !

Appendix

BP	m_H [GeV]	$\sin\alpha$	$\tan\beta$	$\sigma_{hH} \times \text{BR}_{H\rightarrow SM}$ [fb]	σ_{hhh} [fb]	σ_{hh} [fb]	$\text{BR}_{H\rightarrow hh}$	$\text{BR}^{max}_{H\rightarrow SM}$
1	134	-0.23	0.03	1.15	0	11.3	0	0.42 (bb)
2	166	0.23	0.84	1.0	0	11.21	0	0.96 (WW)
3	202	0.22	0.05	0.79	0	11.1	0	0.74 (WW)
4	262	0.23	0.29	0.45	0.18	61.9	0.28	0.50 (WW)
5	293	-0.23	0.44	0.31	0.12	54.0	0.28	0.50 (WW)
6	260	-0.10	0.74	0.10	0.03	21.6	0.23	0.54 (WW)
7	304	-0.13	0.09	0.10	0.05	28.6	0.34	0.46 (WW)
8	280	0.23	0.83	0.37	0.24	74.3	0.39	0.43 (WW)
9	301	0.2	0.6	0.25	0.16	56.7	0.39	0.42 (WW)

$m_h \sim 125\,\text{GeV}$

BP	m_h [GeV]	$\sin\alpha$	$\tan\beta$	$\sigma_{hH} \times \text{BR}_{h\rightarrow SM}$ [fb]	σ_{hh} [fb]	$\text{BR}_{h\rightarrow b\bar{b}}$
1	81.03	-0.975	11.57	2.76	12.57	0.82
2	94.03	-0.9759	9.95	1.86	8.96	0.80
3	63.12	-0.985	12.35	1.64	10.54	0.85
4	90.78	-0.9737	7.013	1.16	4.27	0.81
5	102.53	-0.979	9.59	1.14	7.24	0.78
6	99.57	-0.973	7.16	1.11	4.42	0.79
7	116.48	-0.971	7.07	1.04	4.17	0.69
8	77.48	-0.980	7.41	0.91	4.28	0.84

$m_H \sim 125\,\text{GeV}$

Coupling and mass relations

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

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

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

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

NLO corrections to m_W

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

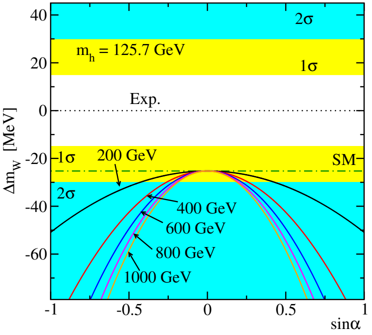
- electroweak fits: fit $\mathcal{O}(20)$ parameters, constraining S, T, U
- idea here: single out m_W, measured with error $\sim 10^{-4}$
- **setup renormalization for Higgs and Gauge boson masses**
- EW gauge and matter sector: on-shell scheme
- Higgs sector: several choices, currently a mixture of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

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

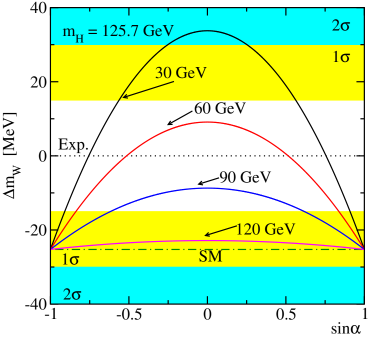
$\Longrightarrow$ **first step on the road to full renormalization** $\Longleftarrow$

NLO corrections to m_W

Contribution to m_W for different Higgs masses



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



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

⟹ low m_h bring m_W^{NLO} close to m_W^{exp} ⟸

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 (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

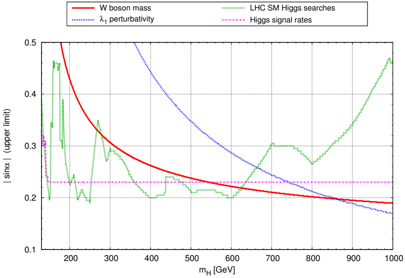
⇒ bottom line: small mixings excluded from stability for larger scales (for $m_H \leq 1\,\text{TeV}$!! for the model-builders...)

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



- $\leq 153\,\text{GeV}$: $h_2 \rightarrow Z\,Z$ Run II [arXiv:1804.01939]
- $[153 - 183\,\text{GeV}]$: SM-like decays to VV, Run I [CMS-PAS-HIG-13-003], Run II [1712.06386], Run I combination [CMS-PAS-HIG-17-045]
- $[183 - 438\,\text{GeV}]$: $h_2 \rightarrow Z\,Z$ Run II [arXiv:1804.01939]
- $[438 - 990\,\text{GeV}]$: $h_2 \rightarrow V\,V$, combination Run II [arXiv:1808.02380]
- $> 990\,\text{GeV}$: VBF mode to VV, combination Run II [arXiv:1808.02380]