Updated Constraints on the Higgs Singlet Extension of the SM

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based on

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G.M. Pruna, TR (PRD 88 (2013) 115012)
D. Lopez-Val, TR (arXiv:1406.1043)
TR, T. Stefaniak, work in progress

TU Dresden

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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)
- $\Rightarrow$ potential (H doublet, χ real singlet)

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

- collider phenomenology studied by many authors: Schabinger, Wells; Patt, Wilczek; 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 $m_h \sim 126\,\text{GeV}$)

- SM-like couplings of **light/ heavy** Higgs:
  $$\textbf{rescaled by } \sin\alpha, \cos\alpha$$

- in addition: **new physics channel:** $H \to h\,h$

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

- **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

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

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:**

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

$\Rightarrow \kappa \leq 0.25$ for all masses considered here

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

$\Rightarrow$ **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 (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)

Perturbativity of couplings

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

Tania Robens   Update on Singlet   SUSY 2014, 21.7.2014

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 (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 ($\sim 10^8 \, \text{GeV}$)
- 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 $m_H \geq 600\,\mathrm{GeV}$

Effects of perturbativity and vacuum stability, t=37
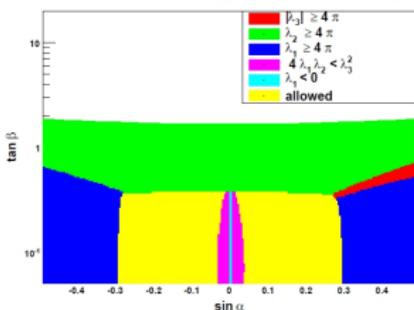
Limits in $\sin\alpha$, $\tan\beta$ plane,

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

$\Longrightarrow$

allowed scale factor and total width, t=37
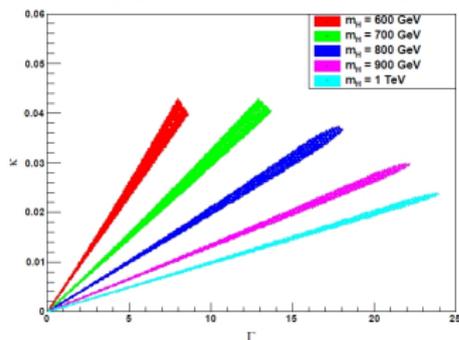
limits on κ, Γ plane from all constraints

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)

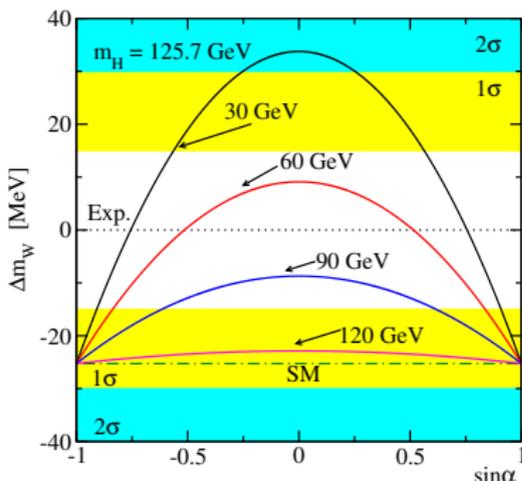# NLO corrections to m_W (D. Lopez-Val, TR, arXiv:1406.1043)

- idea: replace electroweak tests using S, T, U by m_W

  (includes calculation of $\Delta\rho$,...)
- **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)

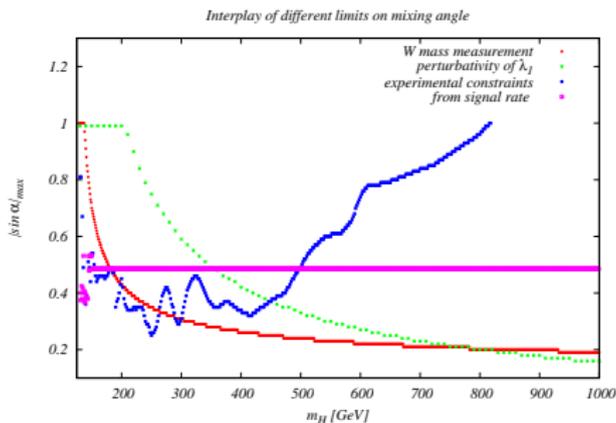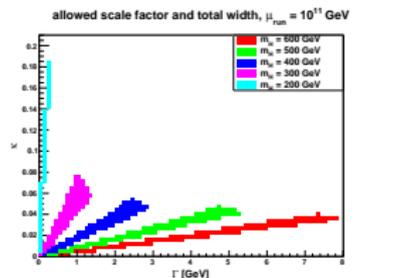## Contribution to m_W for different Higgs masses
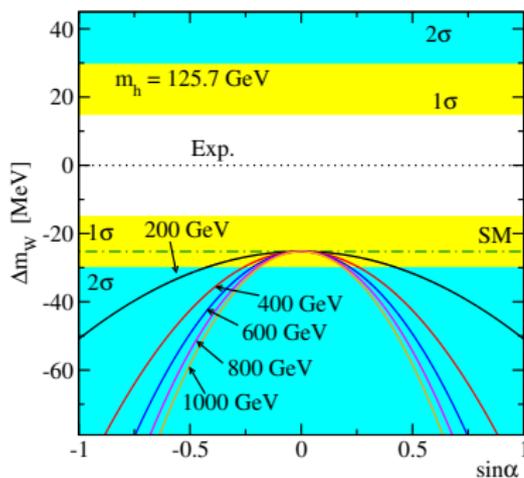
$m_h = 125.7\,\mathrm{GeV}$ $m_H = 125.7\,\mathrm{GeV}$

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

Combined limits on $|\sin\alpha|$

(D. Lopez-Val, TR, arXiv:1406.1043, and TR, T. Stefaniak, to appear)

Interplay of different limits on mixing angle

- W mass measurement
- perturbativity of λ_I
- experimental constraints
- from signal rate

several bounds on $|\sin\alpha|$

allowed scale factor and total width, $\mu_{run} = 10^{11}$ GeV

- $m_H = 600$ GeV
- $m_H = 500$ GeV
- $m_H = 400$ GeV
- $m_H = 300$ GeV
- $m_H = 200$ GeV

limits on κ, Γ plane from all constraints

m_W, perturbativity, LHC direct searches, Higgs Signal strength

Limits in numbers; high mass scenario

$m_H[\mathrm{GeV}]$	$|\sin\alpha|$	source upper limit	$(\tan\beta)_{\mathsf{max}}$
1000	[0.020; 0.16]	λ_1 perturbativity	0.21
800	[0.028; 0.20]	m_W at NLO/ λ_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

- $\sin\alpha_{\mathsf{min}}$ always from **vacuum stability**
- $\tan\beta_{\mathsf{max}}$ always from **perturbativity of** λ_2
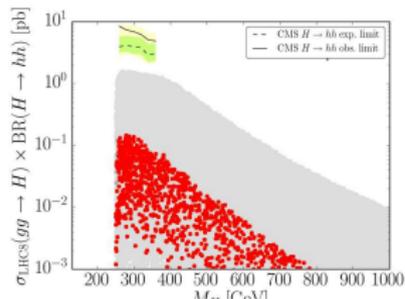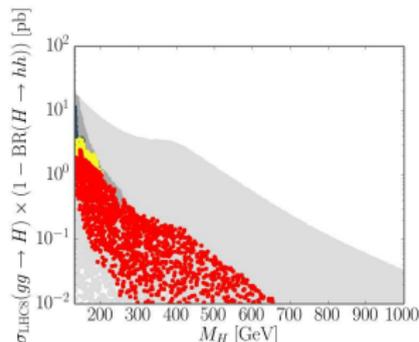
Results from generic scans and predictions for LHC 14

(TR, T. Stefaniak, in preparation)

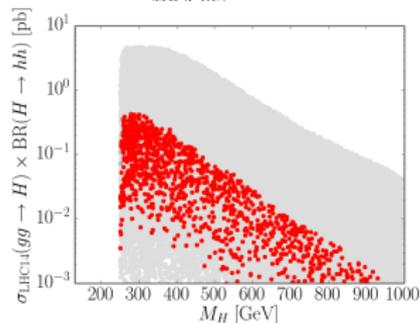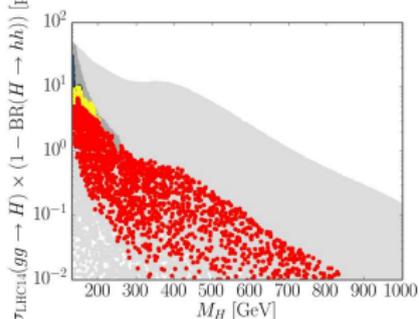1 σ, 2 σ, allowed

SM like decays

BSM decay to hh

Could we have seen them ??

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

$\mathbf{m_H}\,[\mathrm{GeV}]$	κ_{max}	#**gg** $\sim$	κ'_{max}	#**gg** $\sim$
200	0.18	$\mathbf{3 \times 10^4}$	0	0
300	0.076	$\mathbf{6 \times 10^3}$	0.038	$\mathbf{3 \times 10^3}$
400	0.053	$\mathbf{4 \times 10^3}$	0.021	$\mathbf{1 \times 10^3}$
500	0.047	$\mathbf{1 \times 10^3}$	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 $m_H \lesssim 600\,\mathrm{GeV}$, may could already have been produced
which are not excluded by current searches !!**

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 $\sigma_{gg \to h}$**

$m_h[\mathrm{GeV}]$	$|\sin\alpha|_{\text{min, exp}}$	$|\sin\alpha|_{\text{min, }2\sigma}$	$(\tan\beta)_{\text{max}}$	$\#gg \sim$
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)

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

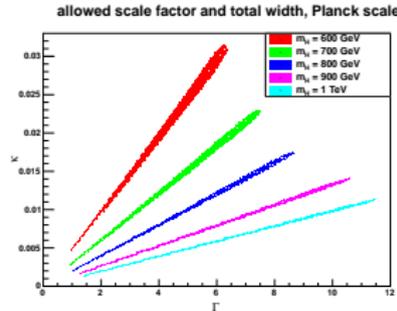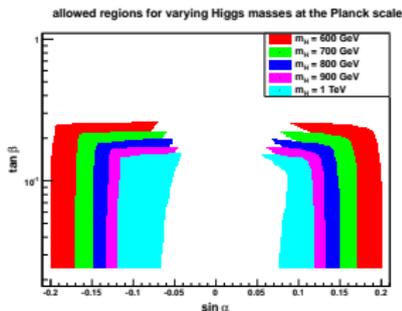$$m_h^2 = \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 xv)^2}, \quad (1)$$

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

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

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

Limits at Planck scale

assume that the model is valid up to $\mu_{run} \sim 10^{19}\,\mathrm{GeV}$
(not always well motivated)

- naturally: **parameter space more restricted**
- translates to $\kappa \lesssim 0.03$ **for** $m_H = 600\,\mathrm{GeV}$ (25 % decrease)
- now: μ no longer relevant, only constraint from perturbativity of $\lambda_1,\ \lambda_2$

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 $H \rightarrow h\,h$

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

$$H \rightarrow h\,h \rightarrow ...$$

- **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...)