

Electroweak Renormalization of the Higgs Singlet Extension

Tania Robens

based on

D. Lopez-Val, TR (PRD 90 (2014) 114018)
F. Bojarski, G. Chalons, D. Lopez-Val, TR (JHEP 1602 (2016) 147)
[TR, T. Stefaniak (Eur.Phys.J. C76 (2016) no.5, 268)]

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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)
- **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: Classical Lagrangian

$$\mathcal{L}_{xSM} = \mathcal{L}_{gauge} + \mathcal{L}_{fermions} + \mathcal{L}_{Yukawa} + \mathcal{L}_{scalar} + \mathcal{L}_{GF} + \mathcal{L}_{ghost}$$

$$\mathcal{L}_{scalar} = (\mathcal{D}^\mu \Phi)^\dagger \mathcal{D}_\mu \Phi + \partial^\mu S \partial_\mu S - \mathcal{V}(\Phi, S)$$

$$\mathcal{V}(\Phi, S) = \mu^2 \Phi^\dagger \Phi + \lambda_1 |\Phi^\dagger \Phi|^2 + \mu_s^2 S^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2 .$$

- \mathcal{L}_{gauge} , $\mathcal{L}_{fermions}$, \mathcal{L}_{Yukawa} as in SM
- BRST invariance $\Rightarrow \delta_{BRST} \mathcal{L}_{GF} = -\delta_{BRST} \mathcal{L}_{ghost}$
- more later...

Singlet extension: free parameters in the potential

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

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

$$\lambda_1, \lambda_2, \lambda_3, v, v_s$$

- rewrite as

$$m_h, m_H, \sin \alpha, v, \tan \beta$$

- fixed, free**

$$\sin \alpha: \text{mixing angle}, \tan \beta = \left(\frac{v}{v_s} \right)^{-1}$$

- physical states ($m_h < m_H$):

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

Phenomenology (in the following: focus on $m_h \sim 125 \text{ GeV}$)

- 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

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

Constraints on the model

- **strongest constraints:**

- $m_H \gtrsim 800 \text{ GeV}$: **perturbativity of couplings**
- $m_H \in [270; 800] \text{ GeV}$: $m_W @ \text{NLO}$
- $m_H \in [175; 270] \text{ GeV}$: **experimental searches**
- $m_H \in [120; 175] \text{ GeV}$: **signal strength**
- $m_h \lesssim 120 \text{ GeV}$: **SM-like Higgs coupling rates (+ 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

[width studies (~ 2015): cf. Maina ; Kauer, O'Brien; Kauer, O'Brien, Vryonidou; Ballestrero, Maina; Dawson,

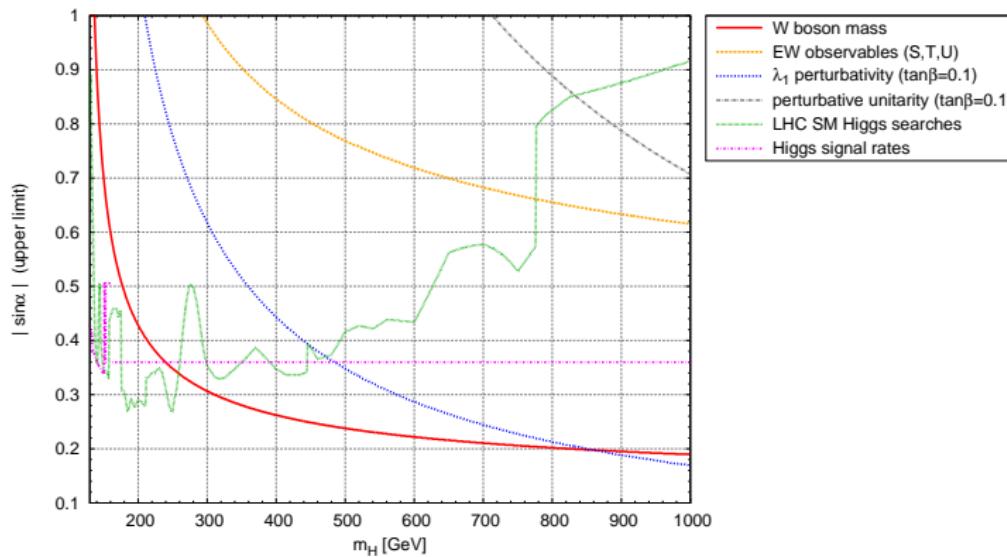
Lewis; ...]

Tania Robens

Singlet@NLO

Combined limits on $|\sin \alpha|$

(TR, T. Stefaniak, Eur.Phys.J. C76 (2016) no.5, 268)



several bounds on $|\sin \alpha|$

m_W , perturbativity, LHC direct searches, Higgs Signal strength

Renormalization: gauge fixing

Our choice: **non-linear gauge fixing !!**

- reason: want to check **gauge-parameter dependence for physical processes**
- implementation: **SLOOPs** [Boudjema ea, '05; Baro ea, '07-'09]

$$\mathcal{L}_{GF} = -\frac{1}{\xi_W} F^+ F^- - \frac{1}{2\xi_Z} |F^Z|^2 - \frac{1}{2\xi_A} |F^A|^2$$

$$\begin{aligned} F^\pm &= \left(\partial_\mu \mp ie\tilde{\alpha} A_\mu \mp ig \cos \theta_W \tilde{\beta} Z_\mu \right) W^\mu + \\ &\quad \pm i\xi_W \frac{g}{2} \left(v + \tilde{\delta}_1 h + \tilde{\delta}_2 H \pm i\tilde{\kappa} G^0 \right) G^+ \\ F^Z &= \partial_\mu Z^\mu + \xi_Z \frac{g}{2 \cos \theta_W} \left(v + \tilde{\epsilon}_1 h + \tilde{\epsilon}_2 H \right) G^0 \\ F^A &= \partial_\mu A^\mu . \end{aligned}$$

- $\tilde{\alpha}, \tilde{\beta}, \dots$: **non-linear gauge-fixing parameters**
- $\tilde{\alpha} = \tilde{\beta} = \dots = 0, \xi = 1 \Rightarrow$ back to t'Hooft-Feynman gauge



Renormalization: SM inheritance

- S : singlet under SM gauge group
 - ⇒ in the electroweak gauge sector: follow SM prescriptions*
- parameter count in the scalar sector: 11 counterterms
 - ⇒ renormalize

$$T_{h,H}; v; v_s; m_{h,H}^2; Z_{h,H,hH,Hh}; m_{hH}^2$$

- ⇒ need to be determined by suitable renormalization conditions

* performed in 2 different electroweak schemes:

α_{em} : $\alpha_{em}(0)$, m_W , m_Z as input;

G_F : $\alpha_{em}(0)$, G_F , m_z as input, related via Δr

... and in more detail...

$$\begin{aligned} v_i^0 &\rightarrow v_i + \delta v_i, \\ T_i^0 &\rightarrow T_i + \delta T_i, \\ \mathcal{M}_\phi^2 &\rightarrow \mathcal{M}_\phi^2 + \delta \mathcal{M}_\phi^2 \end{aligned}$$

$$\text{where } \delta \mathcal{M}_{hH}^2 = U(\alpha) \cdot \delta \mathcal{M}_{\phi_h, \phi_s}^2 \cdot U(-\alpha) = \begin{pmatrix} \delta m_h^2 & \delta m_{hH}^2 \\ \delta m_{hH}^2 & \delta m_H^2 \end{pmatrix}$$

$$\begin{pmatrix} h \\ H \end{pmatrix}^0 \rightarrow \begin{pmatrix} 1 + \frac{1}{2}\delta Z_h & \frac{1}{2}\delta Z_{hH} \\ \frac{1}{2}\delta Z_{Hh} & 1 + \frac{1}{2}\delta Z_H \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

NO mixing angle renormalization

Renormalization conditions

⇒ Our choices ⇐

- Tadpoles: $\delta T = -T$ [$\hat{T}=0$]
- v : as in SM, on-shell (ie through ew gauge sector)
- $\delta v_s = 0$ (not fixed by any measurement) !!! choice !!!
[no UV-divergence ! ; Sperling, Stöckinnger, Voigt, '13]
- $\delta m_{h,H}$, $\delta Z_{H,h}$: on-shell
- difficult part off-diagonal terms m_{hH}^2 , δZ_{hH} !!
- "naive" choice ⇒ can lead to gauge-parameter dependent physical results ⇒ next slides...

[similar recent discussions in the context of 2HDMs: Krause, Lorenz, Mühlleitner, Santos, Ziesche, 1605.04853; Denner, Jenniches, Lang, Sturm, 1607.07352]

Different choices for mixed terms $\delta Z_{Hh, hH}$, δm_{hH}^2

Always:

$$\text{Re } \hat{\Sigma}_{hH}(m_h^2) = 0; \text{Re } \hat{\Sigma}_{hH}(m_H^2) = 0$$

- **Onshell scheme:** $\delta Z_{hH} = \delta Z_{Hh}$
 \Rightarrow **drawback:** predictions remain **gauge-parameter dependent !!**
- **Mixed $\overline{\text{MS}}$ /on-shell:** fix δm_{hH}^2 through **UV-divergence of λ_2**
 \Rightarrow **drawback:** corrections $\sim \sin^{-1} \alpha, \cos^{-1} \alpha$, **can get large !!**
- **improved onshell**

$$\delta m_{hH}^2 = \text{Re } \Sigma_{hH}(p_*^2) \Big|_{\xi_W = \xi_Z = 1, \tilde{\delta}_i = 0}, \quad p_*^2 = \frac{m_h^2 + m_H^2}{2}$$

[similar result e.g. in Baro, Boudjema, Phys. Rev. D80 (2009) 076010; ...]

- \Rightarrow **drawback: NONE !!**

... and in numbers...

NLO corrections to $H \rightarrow hh$ decay, gauge-parameter dependence

Scheme	$\delta\Gamma_{H \rightarrow hh}^{1\text{-loop}}$ [GeV]		
	$\Delta = 0, \{\text{nlgs}\} = 0$	$\Delta = 10^7, \{\text{nlgs}\} = 0$	$\Delta = 10^7, \{\text{nlgs}\} = 10$
OS	$+4.26334888 \times 10^{-3}$	$+4.26334886 \times 10^{-3}$	-5.27015844×10^3
Mixed $\overline{\text{MS}}/\text{OS}$	$+6.8467506 \times 10^{-3}$	$+6.8467504 \times 10^{-3}$	$+6.8467500 \times 10^{-3}$
Improved OS	$+3.9393569 \times 10^{-3}$	$+3.9393568 \times 10^{-3}$	$+3.9393556 \times 10^{-3}$

$$\delta\Gamma_{H \rightarrow hh}^{1\text{-loop}}$$

$\delta m_{hH}^2 ^\infty$	$\{\text{nlgs}\} = 0$	$\{\text{nlgs}\} = 10$	$\delta m_{hH}^2 ^\text{fin}$	$\{\text{nlgs}\} = 0$	$\{\text{nlgs}\} = 10$
OS	-5.80×10^2	-9.44×10^2	OS	$+5.75 \times 10^3$	$+8.80 \times 10^3$
Mixed $\overline{\text{MS}}/\text{OS}$	-5.80×10^2	-5.80×10^2	Mixed $\overline{\text{MS}}/\text{OS}$	-2.48×10^2	-2.48×10^2
Improved OS	-5.80×10^2	-5.80×10^2	Improved OS	$+5.72 \times 10^3$	$+5.72 \times 10^3$

$$\delta m_{hH}^2$$

Δ : UV-divergence; $\{\text{nlgs}\}$: non-linear gauge fixing parameters

First application: NLO corrections to m_W

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

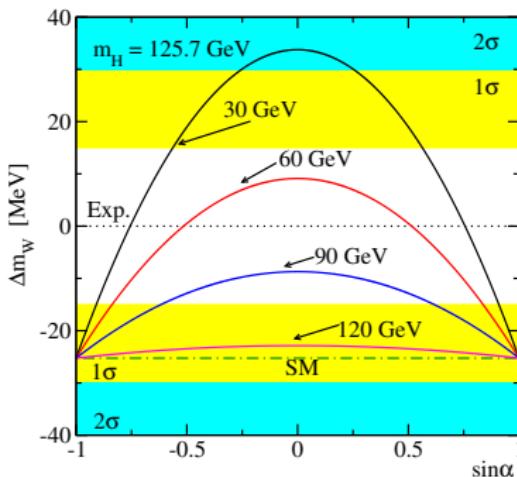
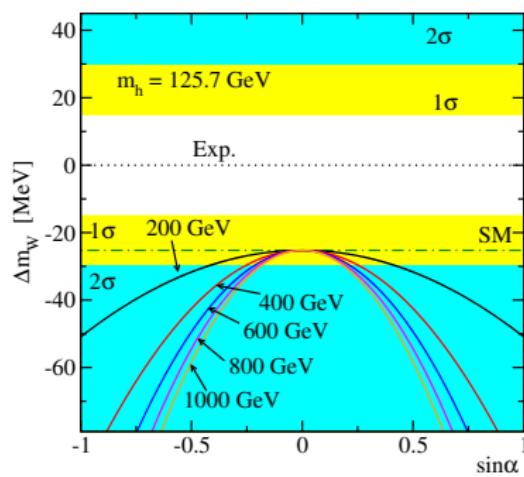
- electroweak fits: fit $\mathcal{O}(20)$ parameters, constraining S, T, U
- idea here: single out m_W , measured with error $\sim 10^{-5}$
- first step on the road to full renormalization
- requires recursive solution for m_W

$$m_W^2 = \frac{1}{2} m_Z^2 \left[1 + \sqrt{1 - \frac{4\pi\alpha_{\text{em}}}{\sqrt{2} G_F m_Z^2} [1 + \Delta r(m_W^2)]} \right]$$

First application: NLO corrections to m_W

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

Contribution to m_W for different Higgs masses



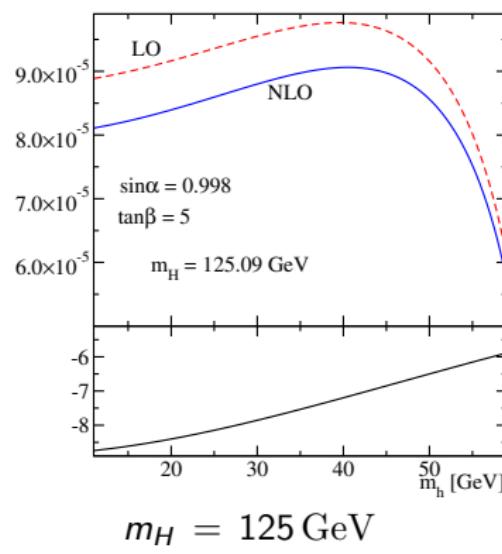
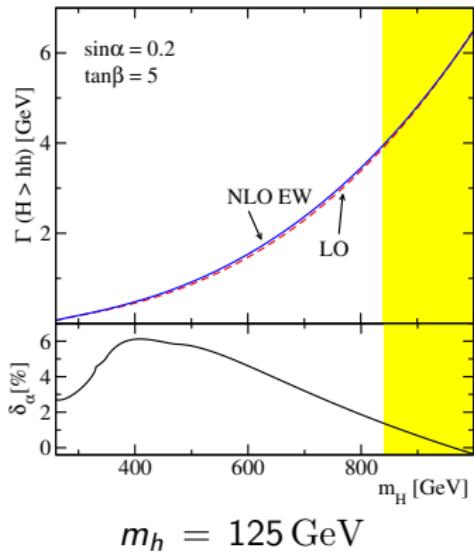
$$m_h = 125.7 \text{ GeV}$$

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

⇒ low m_h bring m_W^{NLO} close to m_W^{exp} ⇐

Renormalization: numerical results

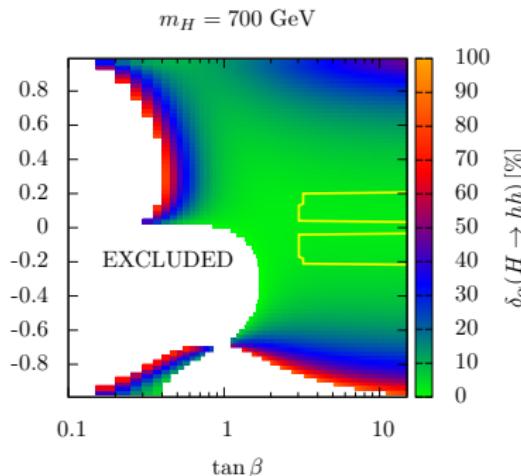
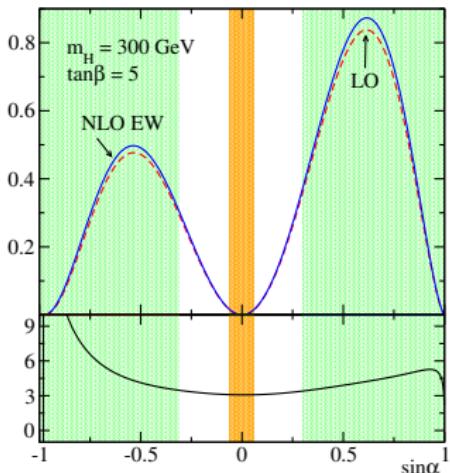
all results here for $\Gamma_{H \rightarrow hh}$



"typical" size of corrections

Renormalization: numerical results, $m_h = 125 \text{ GeV}$

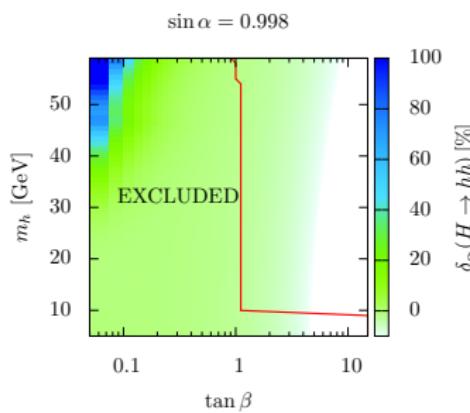
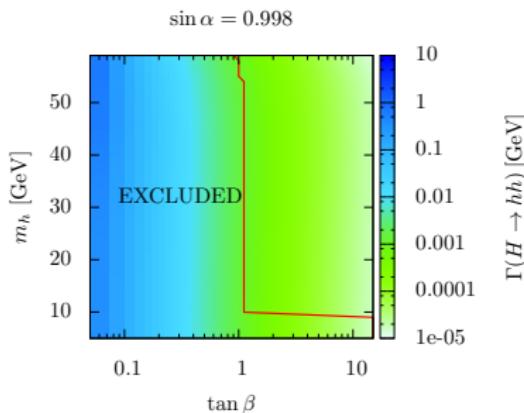
all results here for $\Gamma_{H \rightarrow hh}$



exclusions (left): m_W , vacuum stability ;
 white space (right): corrections $> 100\%$

Renormalization: numerical results, $m_H = 125 \text{ GeV}$

all results here for $\Gamma_{H \rightarrow hh}$



exclusions: signal strength, LEP searches

Results for benchmarks (BR max)

high mass region				low mass region			
	m_H [GeV]	$ \sin \alpha $	$BR^{H \rightarrow h h}$		m_h [GeV]	$ \sin \alpha $	$BR^{H \rightarrow h h}$
BHM1	300	0.31	0.34	3.71	BLM1	60	0.9997
BHM2	400	0.27	0.32	1.72	BLM2	50	0.9998
BHM3	500	0.24	0.27	2.17	BLM3	40	0.9998
BHM4	600	0.23	0.25	2.70	BLM4	30	0.9998
BHM5	700	0.21	0.24	3.23	BLM5	20	0.9998
BHM6	800	0.21	0.23	4.00	BLM6	10	0.9998

	$\Gamma_{H \rightarrow hh}^{\text{LO}}$	$\Gamma_{H \rightarrow hh}^{\text{NLO}}$	δ_α [%]	δ_{G_F} [%]	Γ_H		$\Gamma_{H \rightarrow hh}^{\text{LO}}$	$\Gamma_{H \rightarrow hh}^{\text{NLO}}$	δ_α [%]	δ_{G_F} [%]	Γ_H
BHM1	0.399	0.413	3.411	3.291	1.210	BLM1	1.426	1.536	7.765	7.763	5.506
BHM2	0.963	1.026	6.485	6.272	3.092	BLM2	1.439	1.472	2.305	2.304	5.520
BHM3	1.383	1.463	5.803	5.604	5.299	BLM3	1.423	1.432	0.586	0.586	5.504
BHM4	2.067	2.161	4.520	4.361	8.574	BLM4	1.419	1.415	-0.272	-0.272	5.500
BHM5	2.637	2.717	3.027	2.918	11.413	BLM5	1.431	1.425	-0.445	-0.445	5.512
BHM6	3.798	3.867	1.826	1.759	17.204	BLM6	1.427	1.421	-0.438	-0.438	5.508

⇒ "typical" corrections between .2 and 20 % ⇐

Summary

- Singlet extension: **simplest extension of the SM Higgs sector**, easily identified with one of the benchmark scenarios of the HHXWG (cf. also YR3,4, Snowmass report)
 - ⇒ **complete NLO ew treatment**
 - ⇒ **comparison of different schemes**
 - ⇒ "typical" corrections $\sim 10\%$

⇒ STAY TUNED ⇐

Appendix

Coupling and mass relations

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

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

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

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

Theoretical and experimental constraints on the model

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

- 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 and ATLAS-CONF-2015-044 [signal strength combination]

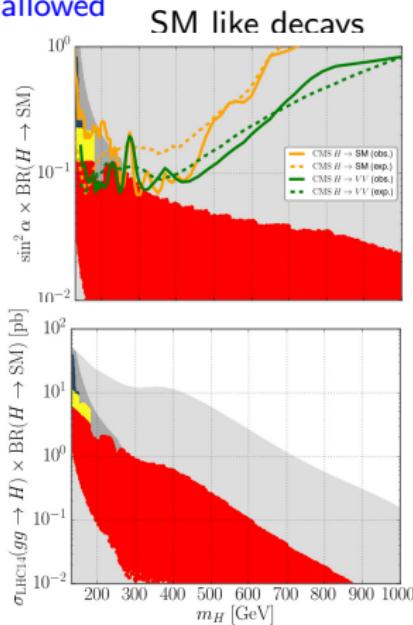
(debatable: minimization up to arbitrary scales, \Rightarrow perturbative unitarity to arbitrary high scales [these are common procedures though in the SM case])

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

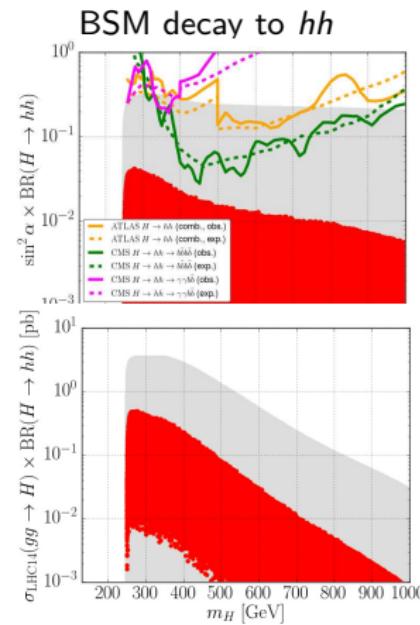
Results from generic scans and predictions for LHC 14 (TR, T. Stefaniak, arXiv:1601.07880)

1 σ , 2 σ , allowed

limits



pred.



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

$$H \rightarrow h h \rightarrow \dots$$

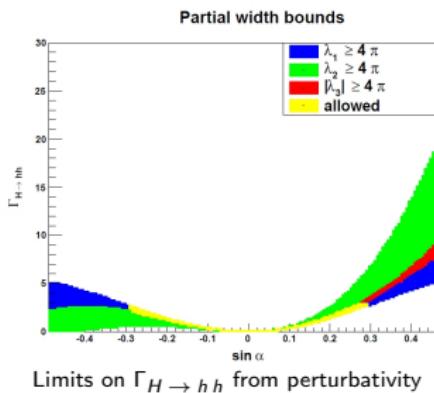
- **widely discussed in the literature**
(for recent work, cf Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam, Sanz; Cooper, Konstantinidis, Lambourne, Wardrobe; ...)
- **HOWEVER** in our scan, **WW always dominant**
⇒ **would go for this first**
(but mb more than 1 group is interested...)

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:** $4\lambda_1\lambda_2 - \lambda_3^2 > 0$
- ⇒ need (2), can debate about (1), (3) at all scales ⇐

Limits on $\kappa, \Gamma_{\text{tot}}$

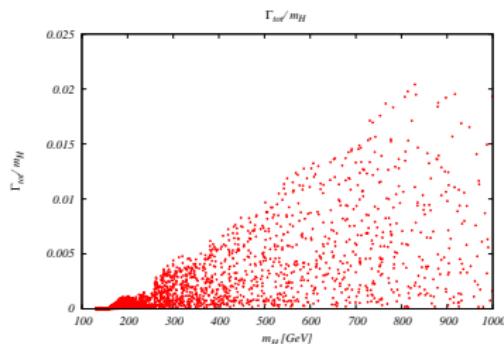
limits on $\Gamma_{H \rightarrow hh}$, $m_H = 600 \text{ GeV}$



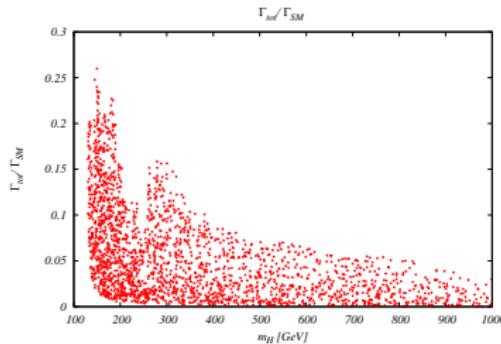
- constraint from μ on $\sin \alpha$: $\Gamma_{H \rightarrow hh}$ already small ($\lesssim 0.08 m_H$)
- running of couplings: even stronger constraints

Interim comment on total width

- Total width greatly reduced



width over mass



suppression factor of width