NLO electroweak corrections to $H \to h\,h$ in the singlet extension

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based on
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D. Lopez-Val, TR (PRD 90 (2014) 114018)
F. Bojarski, G. Chalons, D. Lopez-Val, TR (JHEP 1602 (2016) 147)

[TR (arXiv:1908.10809)]

and work in progress...

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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, 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: Classical Lagrangian

$$\boxed{\mathscr{L}_{\mathbf{xSM}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{fermions}} + \mathscr{L}_{\text{Yukawa}} + \mathscr{L}_{\text{scalar}} + \mathscr{L}_{\mathbf{GF}} + \mathscr{L}_{\mathbf{ghost}}}$$

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

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

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

Singlet extension: free parameters in the potential

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

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

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

- rewrite as

$$\mathbf{m_h},\, \mathbf{m_H},\, \sin\alpha,\, \mathbf{v},\, \tan\beta$$

- **fixed**, **free**

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

- physical states ($m_h < m_H$):

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

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

- SM-like couplings of **light/ heavy** Higgs:

  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

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

Constraints on the model [1908.10809]

- **strongest constraints:**

$$m_H \gtrsim 850\,\mathrm{GeV} \quad : \quad \textbf{perturbativity of couplings}$$

$$m_H \in [650; 850]\mathrm{GeV} \quad : \quad m_W \textbf{ @ NLO}$$

$$m_H \in [125; 650]\mathrm{GeV} \quad : \quad \textbf{experimental searches/signal strength}$$

$$m_h \lesssim 120\,\mathrm{GeV} \quad : \quad \textbf{SM-like Higgs coupling rates } (+\,\mathrm{LEP})$$

$\Rightarrow \kappa \leq 0.06$ for all masses considered here

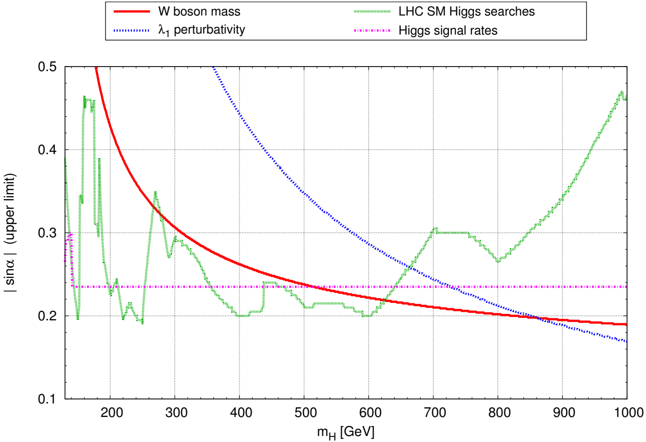
$$\Gamma_{\mathbf{tot}} \lesssim 0.02\, m_H$$

⇒ Highly (??) suppressed, narrow(er) heavy scalars ⇐

⇒ new (easier ?) strategies needed wrt searches for SM-like Higgs bosons in this mass range ⇐

[width studies (from $\sim$ 2015): cf. Maina ; Kauer, O'Brien; Kauer, O'Brien, Vryonidou; Ballestrero, Maina; Dawson, Lewis; Martin; Jung, Yoon, Song; Djouadi, Ellis, [Popov], Quevillon; Carena, Liu, Riembau; Kauer, Lind, Maierhöfer, Song; ...]

Combined limits on $|\sin\alpha|$ [1908.10809]



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]

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

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

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

Renormalization: SM inheritance

- S: **singlet under SM gauge group**

$\Rightarrow$ in the electroweak gauge sector: **follow SM prescriptions***

- scalar sector: counterterms for

$$\boxed{T_{h,H};\ [v];\ v_s;\ m^2_{h,H};\ Z_{h,H,hH,Hh};\ m^2_{hH}}$$

$\Rightarrow$ 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...

$$\boxed{\begin{aligned} v_s^0 &\longrightarrow v_s + \delta v_s, \\ T_i^0 &\longrightarrow T_i + \delta T_i, \\ \mathcal{M}^2_{hH} &\longrightarrow \mathcal{M}^2_{hH} + \delta\mathcal{M}^2_{hH} \end{aligned}}$$

where $\delta\mathcal{M}^2_{hH} = \begin{pmatrix} \delta m_h^2 & \delta m_{hH}^2 \\ \delta m_{hH}^2 & \delta m_H^2 \end{pmatrix}$

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

$+$ renormalization re electroweak scheme (e.g. δe, δm_W^2, δm_Z^2)

Renormalization conditions

$\Longrightarrow$ **Our choices** $\Longleftarrow$

- Tadpoles: $\delta T = -T$ $[\hat{T}=0]$ $\Rightarrow$ stay in ew minimum
- $\delta v_s = 0$ (not fixed by any measurement) **!!! choice !!!**

  [no UV-divergence ! ; see e.g. Sperling, Stöckinger, Voigt, '13]
- $\delta m_{h,H}$, $\delta Z_{H,h}$: on-shell
- difficult part **off-diagonal terms** m^2_{hH}, δZ_{hH} **!!**
- "naive" choice $\Rightarrow$ can lead to **gauge-parameter dependent physical results** $\Rightarrow$ next slides...

  [many similar discussions in recent years; e.g.: Krause, Lorenz, Mühlleitner, Santos, Ziesche; Denner, Jenniches, Lang, Sturm; Kanemura, Kikuchi, Sakurai, Yagyu; Krause, Lopez-Val, Mühlleitner, Santos; Denner, Dittmaier, Lang; ...]

  [see also talks by F. Domingo and L. Fritz]

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

Always: $\boxed{\textbf{Re}\,\hat{\Sigma}_{hH}(m_h^2) = 0;\ \textbf{Re}\,\hat{\Sigma}_{hH}(m_H^2) = 0}$

- **Onshell scheme**: $\delta Z_{hH} = \delta Z_{Hh}$

$\Rightarrow$ **drawback:** predictions remain **gauge-parameter dependent !!**

- **Mixed $\overline{\text{MS}}$/on-shell:** fix δm^2_{hH} through **UV-divergence of** λ_2

$\Rightarrow$ **drawback:** corrections $\sim \sin^{-1}\alpha,\ \cos^{-1}\alpha$, **can get large !!**

- **improved onshell**

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

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

$\Rightarrow$ **drawback: NONE !!**

... and in numbers...

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

	$\delta\Gamma^{\text{1-loop}}_{H\to hh}$ [GeV]		
Scheme	$\Delta = 0$, $\{\text{nlgs}\} = 0$	$\Delta = 10^7$, $\{\text{nlgs}\} = 0$	$\Delta = 10^7$, $\{\text{nlgs}\} = 10$
OS	$+4.2633488\mathbf{8} \times 10^{-3}$	$+4.2633488\mathbf{6} \times 10^{-3}$	$-5.27015844 \times 10^{3}$
Mixed $\overline{\text{MS}}$/OS	$+6.846750\mathbf{6} \times 10^{-3}$	$+6.846750\mathbf{4} \times 10^{-3}$	$+6.846750\mathbf{0} \times 10^{-3}$
Improved OS	$+3.939356\mathbf{9} \times 10^{-3}$	$+3.939356\mathbf{8} \times 10^{-3}$	$+3.93935\mathbf{56} \times 10^{-3}$

$\delta\Gamma^{\text{1-loop}}_{H\to hh}$

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

δm^2_{hH}

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

First application: NLO corrections to m_W

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

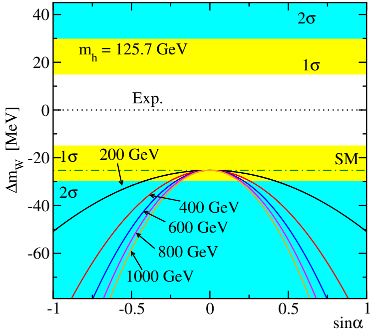
- electroweak fits: fit $\mathcal{O}\,(20)$ parameters, constraining $S,\,T,\,U$
- idea here: single out m_W, measured with error $\sim\,10^{-5}$
- first step on the road to full renormalization
- requires recursive solution for m_W

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

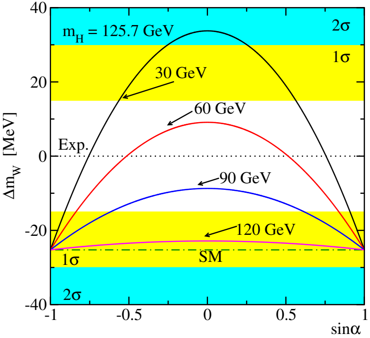
First application: NLO corrections to m_W

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

Contribution to m_W for different Higgs masses



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

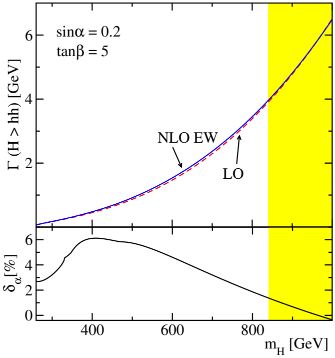


$m_H = 125.7\,\mathrm{GeV}$

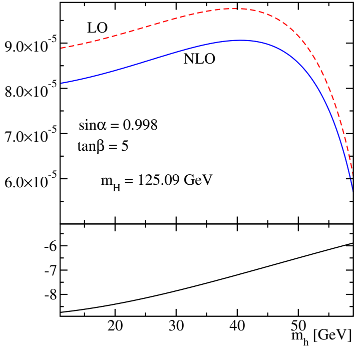
$\Longrightarrow$ low m_h bring m_W^{NLO} close to m_W^{exp} $\Longleftarrow$

Renormalization: numerical results

all results here for $\Gamma_{H \to h\, h}$



$m_h = 125\,\mathrm{GeV}$

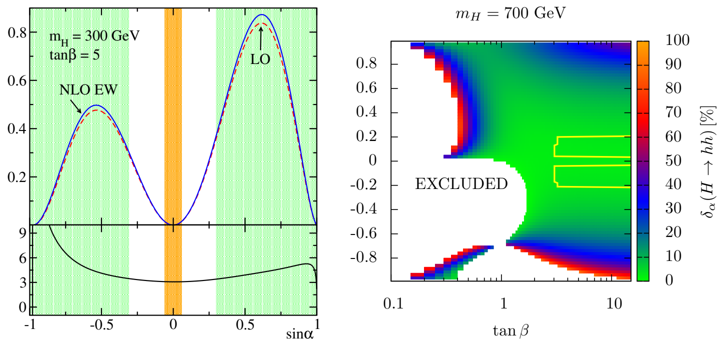


$m_H = 125\,\mathrm{GeV}$

"typical" size of corrections

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

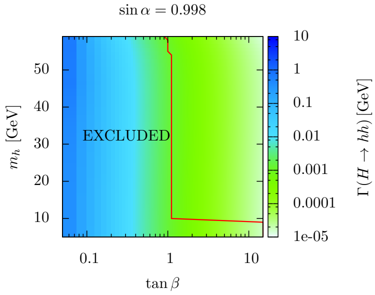
all results here for $\Gamma_{H \to h\,h}$

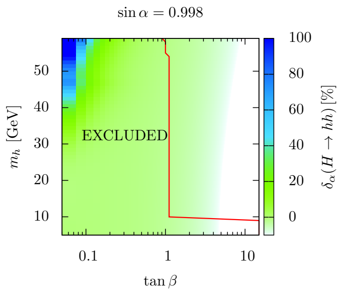


exlusions (left): m_W, vacuum stability ;
white space (right): corrections $> 100\,\%$

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

all results here for $\Gamma_{H\to h\,h}$





exlusions: signal strength, LEP searches

Results for benchmarks (BR max)

high mass region					low mass region				
	m_H[GeV]	$\lvert\sin\alpha\rvert$	$BR^{H\to h\,h}$	$\tan\beta$		m_h[GeV]	$\lvert\sin\alpha\rvert$	$BR^{H\to h\,h}$	$\tan\beta$
BHM1	300	0.31	0.34	3.71	BLM1	60	0.9997	0.26	0.29
BHM2	400	0.27	0.32	1.72	BLM2	50	0.9998	0.26	0.31
BHM3	500	0.24	0.27	2.17	BLM3	40	0.9998	0.26	0.32
BHM4	600	0.23	0.25	2.70	BLM4	30	0.9998	0.26	0.32
BHM5	700	0.21	0.24	3.23	BLM5	20	0.9998	0.26	0.31
BHM6	800	0.21	0.23	4.00	BLM6	10	0.9998	0.26	0.30

	$\Gamma^{\rm LO}_{H\to hh}$	$\Gamma^{\rm NLO}_{H\to hh}$	δ_α [%]	δ_{G_F} [%]	Γ_H		$\Gamma^{\rm LO}_{H\to hh}$	$\Gamma^{\rm NLO}_{H\to hh}$	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

$\Longrightarrow$ **"typical" corrections between** .2 **and** 20 % $\Longleftarrow$

[$\tan\beta$ defined in G_F scheme]

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, Dihiggs white paper, ...)

$\Rightarrow$ **complete NLO ew treatment**

$\Rightarrow$ **comparison of different schemes**

$\Rightarrow$ **"typical" corrections** $\sim 10\,\%$

$\Longrightarrow$ **STAY TUNED** $\Longleftarrow$

Appendix

Parameter count

- gauge eigenbasis:

$$\boxed{\lambda_{1,2,3},\ v,\ v_s,\ \mu^2,\ \mu_s^2,\ g_1,\ g_2}$$

- can be rewritten:

$$\boxed{T_{h,H},\ m_h^2,\ m_H^2,\ m_{hH}^2,\ \tan\beta \equiv \frac{v_s}{v},\ \underbrace{m_W^2,\ m_Z^2,\ v}_{\text{ew scheme}}}$$

- minimization: $T_i = 0$
- h, H mass-eigenstates: $m_{hH}^2 = 0$

$\delta\alpha$ and δm^2_{hH}; Re $\hat{\Sigma}_{hH}(p^2)$

can also renormalize mixing angle, such that

$$\alpha^0 = \alpha + \delta\alpha$$

Connection to δm^2_{hH}

$$\delta\alpha = \frac{1}{m_H^2 - m_h^2}\,\delta m^2_{hH}$$

$$\mathrm{Re}\,\hat{\Sigma}_{hH}(p^2) = \mathrm{Re}\,\Sigma_{hH}(p^2) + \frac{1}{2}\delta Z_{hH}(p^2 - m_h^2) + \frac{1}{2}\delta Z_{Hh}(p^2 - m_H^2) - \delta m^2_{hH}$$

Coupling and mass relations

$$
\begin{aligned}
m_h^2 &= \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, & (1)\\
m_H^2 &= \lambda_1 v^2 + \lambda_2 x^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, & (2)
\end{aligned}
$$

$$
\begin{aligned}
\sin 2\alpha &= \frac{\lambda_3 x v}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}, & (3)\\
\cos 2\alpha &= \frac{\lambda_2 x^2 - \lambda_1 v^2}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}. & (4)
\end{aligned}
$$

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 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 $m_h = 125.09\,\mathrm{GeV}$

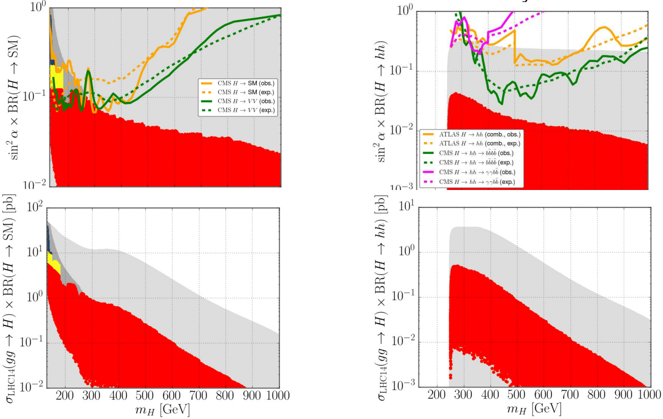
Results from generic scans and predictions for LHC 14 (TR, T. Stefaniak, arXiv:1601.07880)

1 σ, 2 σ, allowed

SM like decays | BSM decay to hh

limits

pred.



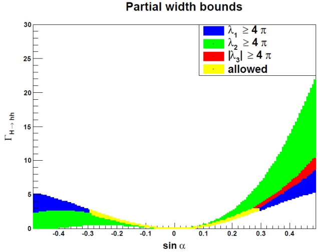
Comments on constraints (2) - running couplings and vacuum

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 $\Gamma_{H\to hh}$, $m_H = 600\,\text{GeV}$

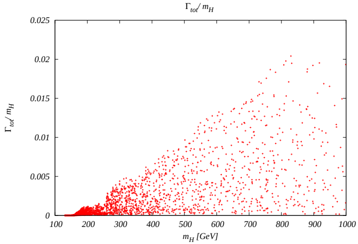


Limits on $\Gamma_{H\to hh}$ from perturbativity

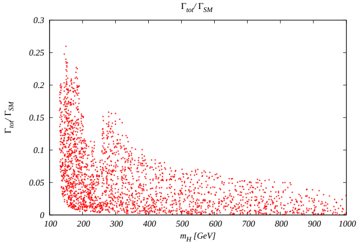
- constraint from μ on $\sin\alpha$: $\Gamma_{H\to hh}$ already small ($\lesssim 0.08\, m_H$)
- running of couplings: even stronger constraints

Interim comment on total width

- Total width greatly reduced



width over mass



suppression factor of width