Precision physics in the singlet extension

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based on [recent] work with

G.M. Pruna (PRD 88 (2013) 115012); D. Lopez-Val (PRD 90 (2014) 114018);
T. Stefaniak (EPJC 75 (2015) 3,105, Eur.Phys.J. C76 (2016) no.5, 268);
F. Bojarski, G. Chalons, D. Lopez-Val (JHEP 1602 (2016) 147);
S. Dawson, I.M.Lewis, T.Stefaniak, M. Sullivan (arXiv:1910.00012)

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After Higgs discovery: Open questions

Higgs discovery in 2012 $\Rightarrow$ last building block discovered

? Any remaining questions ?

- Why is the SM the way it is ??
  $\Rightarrow$ search for **underlying principles/ symmetries**
- find **explanations for observations not described by the SM**
  $\Rightarrow$ e.g. dark matter, flavour structure, ...
- ad hoc approach: Test **which other models still comply with experimental and theoretical precision**

for all: **Search for Physics beyond the SM (BSM)**

$\Longrightarrow$ **main test ground for this: particle colliders** $\Longleftarrow$

⇒ see whether I can extend Higgs sector ⇐

- ... accomodating for all **limits from theory and experiment**
- ... and how I would **look for this at present or future colliders**

  (or elsewhere)

introduce physics beyond the SM (BSM)

take minimal approach

add 1 additional scalar

obtain theory with 3 additional free parameters

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)

⇒ 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

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

- 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 as in SM for m_H

additional channel $H \to h\,h$

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

Theoretical and experimental constraints on the model

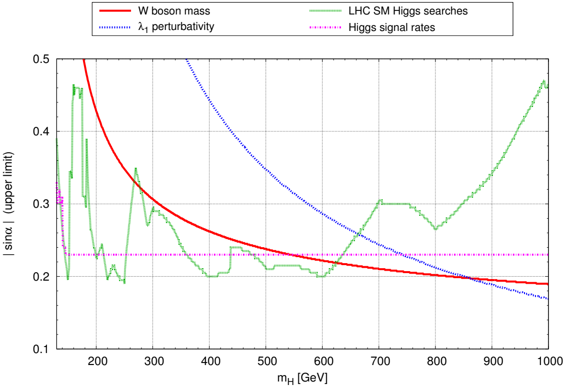
our studies: $m_{h,H} = 125.09\,\mathrm{GeV},\ 0\,\mathrm{GeV} \leq m_{H,h} \leq 1\,\mathrm{TeV}$

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

Current status: generic combination of constraints



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

(TR, PoS LHCP2019 (2019) 138)

! experimental constraints from LHC start to dominate !

NLO corrections to m_W

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

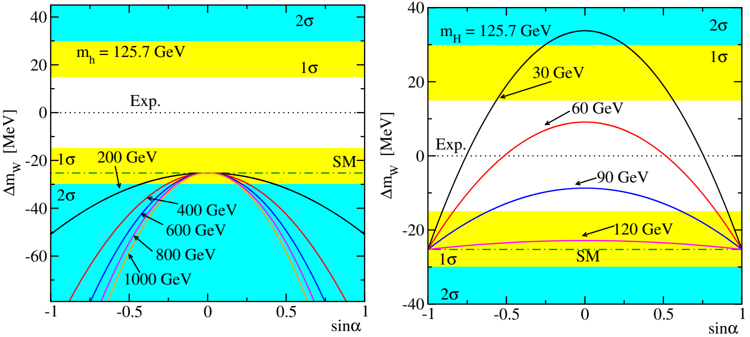
- electroweak fits: fit $\mathcal{O}(20)$ parameters, constraining S, T, U
- idea here: single out m_W, measured with error $\sim\, 10^{-4}$
- **setup renormalization for Higgs and Gauge boson masses**
- EW gauge and matter sector: on-shell scheme
- Higgs sector: several choices, currently a mixture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



$m_h \;=\; 125.7\,\text{GeV}$ $\qquad$ $m_H \;=\; 125.7\,\text{GeV}$

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

Full renormalization: Classical Lagrangian

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

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

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

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

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]

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

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

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

Renormalization: SM inheritance

- S: **singline 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

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**

  [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; ...]

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

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

- **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 !!**

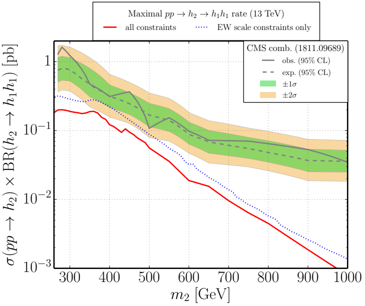
- **improved onshell**

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

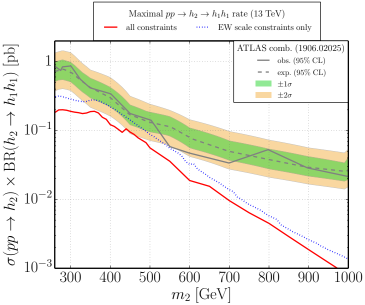
[similar result e.g. in Baro, Boudjema, Phys. Rev. D80 (2009) 076010; ...]

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

DiHiggs final states [current status]



(S. Dawson, I. Lewis, TR, T. Stefaniak, M. Sullivan, contribution to arXiv:1910.00012, Dihiggs White paper)

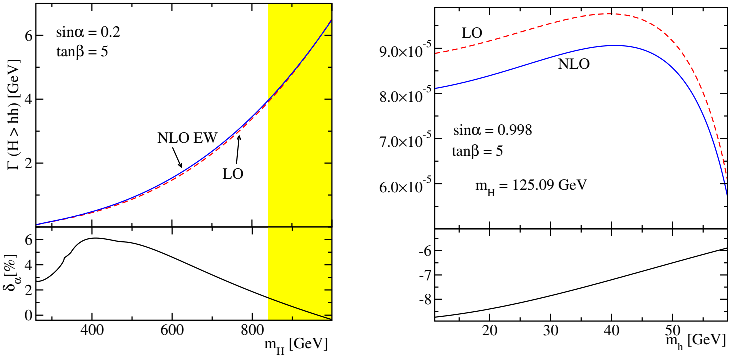


(TR, T. Stefaniak)

- $|\sin\alpha| \leq 0.24$ from signal strength
- $\tan\beta$ constraints mainly from RGE running (perturbativity)/ perturbative unitarity

Renormalization: numerical results

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

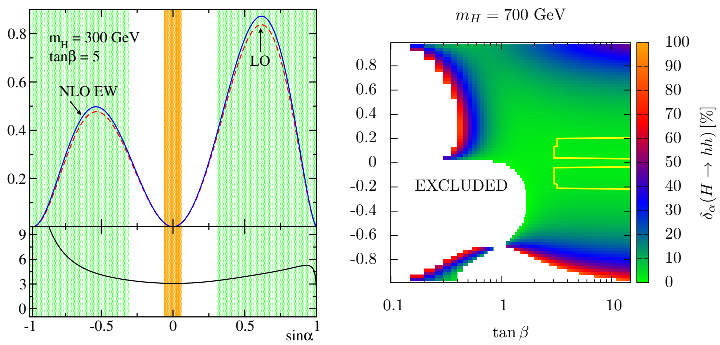


$m_h = 125\,\mathrm{GeV}$ $\quad$ $m_H = 125\,\mathrm{GeV}$

"typical" size of corrections

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

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



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

Summary and Outlook

- current status: **no new physics discovery at LHC**

$\Rightarrow$ important for search: good understanding of SM background

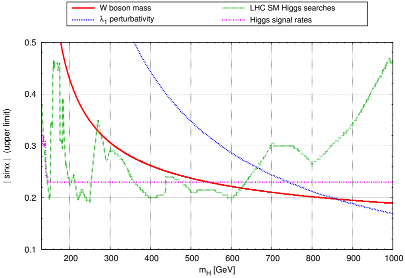
$\Rightarrow$ also important: higher order corrections in new physics models

  - if needed (e.g. m_h in SUSY)
  - for loop-induced processes (e.g. $h \to gg, \gamma\gamma, ...$)
  - ...

- recent 5 years: **renewed interest in renormalization of mixing gauge-mass eigenstates**
- currently highly active field

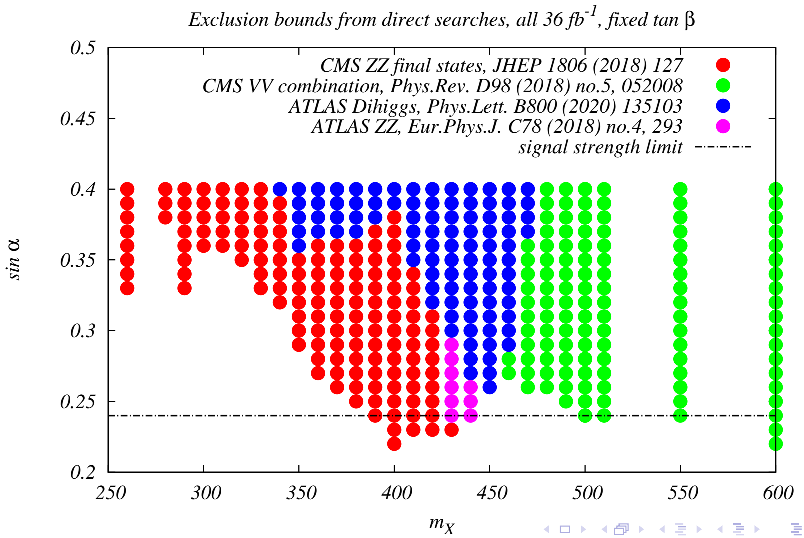
$\Longrightarrow$ **Stay Tuned** $\Longleftarrow$

Appendix



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

Zoom into exclusion regions [very rough draft]



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}; $\mathrm{Re}\,\hat{\Sigma}_{hH}(p^2)$

can also renormalize mixing angle, such that

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

Connection to δm^2_{hH}

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

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

... and in more detail...

$$v_s^0 \longrightarrow v_s + \delta v_s,$$
$$T_i^0 \longrightarrow T_i + \delta T_i,$$
$$\mathcal{M}_{hH}^2 \longrightarrow \mathcal{M}_{hH}^2 + \delta \mathcal{M}_{hH}^2$$

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

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

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

... and in numbers...

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

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

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

$\delta m^2_{hH}\|^{\infty}$	{nlgs} $= 0$	{nlgs} $= 10$	$\delta m^2_{hH}\|^{\text{fin}}$	{nlgs} $= 0$	{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; {ngls} : non-linear gauge fixing parameters