Precision physics in the singlet extension

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based on [recent] work with
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2 Singlet extension: Model and bounds

3 Singlet extension: full renormalization

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After Higgs discovery: Open questions

Higgs discovery in 2012 ⇒ last building block discovered

? Any remaining questions?

- Why is the SM the way it is??
  ⇒ search for underlying principles/ symmetries
- find explanations for observations not described by the SM
  ⇒ 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)

⇒ main test ground for this: particle colliders ←
⇒ 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, $\chi$ real singlet)

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

- 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

\[ \text{VeVs: } H \equiv \begin{pmatrix} 0 \\ \tilde{h} + v \\ \sqrt{2} \end{pmatrix}, \quad \chi \equiv \frac{h' + x}{\sqrt{2}}. \]

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

\[ \lambda_1, \lambda_2, \lambda_3, v, x \]

• rewrite as

\[ m_h, m_H, \sin \alpha, v, \tan \beta \]

• fixed, free

\[ \sin \alpha: \text{mixing angle}, \tan \beta = \frac{v}{x} \]

• physical states \( m_h < m_H \):

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

parameters: $m_H/h, \sin \alpha, \tan \beta$
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\(^\ast\))
5. **vacuum stability and minimum condition** (up to certain scales\(^\ast\))
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])

\(^\ast\): only for \( m_h = 125.09 \text{ GeV} \)
Current status: generic combination of constraints

![Graph showing constraints]

\[ |\sin \alpha| \text{ (upper limit)} \]

W boson mass, LHC SM Higgs searches, \( \lambda_1 \) perturbativity, Higgs signal rates

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


! 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 $\implies$ not relevant here)

$\implies$ first step on the road to full renormalization $\implies$
NLO corrections to $m_W$

**Contribution to $m_W$ for different Higgs masses**

$m_h = 125.7$ GeV

$\Delta m_W [\text{MeV}]$

$\sin \alpha$

$m_W^{\text{NLO}}$ close to $m_W^{\text{exp}}$
**Full renormalization: Classical Lagrangian**

\[ \mathcal{L}_{\text{xSM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{fermions}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{ghost}} \]

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

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

- \( \mathcal{L}_{\text{gauge}}, \mathcal{L}_{\text{fermions}}, \mathcal{L}_{\text{Yukawa}} \) as in SM
- BRST invariance \( \Rightarrow \delta_{\text{BRST}} \mathcal{L}_{\text{GF}} = -\delta_{\text{BRST}} \mathcal{L}_{\text{ghost}} \)
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]

\[
\mathcal{L}_{GF} = -\frac{1}{\xi_W} F^+ F^- - \frac{1}{2\xi_Z} |F_Z|^2 - \frac{1}{2\xi_A} |F_A|^2
\]

\[
F^\pm = \left( \partial_\mu \mp ie\tilde{\alpha} A_\mu \mp ig \cos \theta_W \tilde{\beta} Z_\mu \right) W^{\mu \pm} \\
\pm i\xi_W \frac{g}{2} \left( v + \tilde{\delta}_1 h + \tilde{\delta}_2 H \pm i\tilde{\kappa} G^0 \right) G^+ \\
F_Z = \partial_\mu Z^\mu + \xi_Z \frac{g}{2 \cos \theta_W} \left( v + \tilde{\varepsilon}_1 h + \tilde{\varepsilon}_2 H \right) G^0 \\
F_A = \partial_\mu A^\mu.
\]

- \(\tilde{\alpha}, \tilde{\beta}, ... : \) **non-linear gauge-fixing parameters**
- \(\tilde{\alpha} = \tilde{\beta} = ... = 0, \xi = 1 \Rightarrow \) back to t’Hooft-Feynman gauge
Renormalization: SM inheritance

- \( S \): singlet under SM gauge group
  - in the electroweak gauge sector: follow SM prescriptions
- scalar sector: counterterms for
  
  \[
  T_{h,H}; [v]; v_s; m_{h,H}^2; Z_{h,H,hH,Hh}; m_{hH}^2
  \]

- need to be determined by suitable renormalization conditions

* performed in 2 different electroweak schemes:
  \( \alpha_{em} : \alpha_{em}(0), m_W, m_z \) as input;
  \( G_F : \alpha_{em}(0), G_F, m_z \) as input, related via \( \Delta r \)
Renormalization conditions

⇒ Our choices ⇐

- 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 $m_{hH}^2, \delta Z_{hH}$ !
- ”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 $\delta Z_{Hh, hH}, \delta m_{hH}^2$

Always: \[ \text{Re} \hat{\Sigma}_{hH}(m_h^2) = 0; \text{Re} \hat{\Sigma}_{hH}(m_H^2) = 0 \]

- **Onshell scheme**: $\delta Z_{hH} = \delta Z_{Hh}$
  \[ \Rightarrow \text{drawback: predictions remain gauge-parameter dependent} !! \]

- **Mixed MS/on-shell**: fix $\delta m_{hH}^2$ through \textbf{UV-divergence of $\lambda_2$}
  \[ \Rightarrow \text{drawback: corrections } \sim \sin^{-1} \alpha, \cos^{-1} \alpha, \text{can get large} !! \]

- **improved onshell**
  \[
  \delta m_{hH}^2 = \text{Re} \Sigma_{hH}(p_*^2) \bigg|_{\xi_W=\xi_Z=1, \delta_i=0}, \quad p_*^2 = \frac{m_h^2 + m_H^2}{2}
  \]

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

  \[ \Rightarrow \text{drawback: NONE} !! \]
DiHiggs final states [current status]

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

Renormalization: numerical results

**all results here for** $\Gamma_H \rightarrow hh$

$m_h = 125 \text{ GeV}$

"typical" size of corrections
Renormalization: numerical results, $m_h = 125$ GeV

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

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

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Singlet precision

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Summary and Outlook

- current status: **no new physics discovery at LHC**
- ⇒ important for search: good understanding of SM background
- ⇒ also important: higher order corrections in new physics models
  - if needed (e.g. $m_h$ in SUSY)
  - for loop-induced processes (e.g. $h \rightarrow gg, \gamma\gamma, ...$)
  - ... 
- recent 5 years: **renewed interest in renormalization of mixing gauge-mass eigenstates**
- currently highly active field


⇒ Stay Tuned ←
Appendix
\[ \sin \alpha \quad (\text{upper limit}) \]

\[ m_H \text{ [GeV]} \]

- **W boson mass**
- **LHC SM Higgs searches**
- **\( \lambda_1 \) perturbativity**
- **Higgs signal rates**

- \( \leq 153 \text{ GeV} : h_2 \to ZZ \text{ Run II [arXiv:1804.01939]}\)
- \([153 - 183 \text{ GeV}] : \text{SM-like decays to VV, Run I [CMS-PAS-HIG-13-003], Run II [1712.06386], Run I combination [CMS-PAS-HIG-17-045]}\)
- \([183 - 438 \text{ GeV}] : h_2 \to ZZ \text{ Run II [arXiv:1804.01939]}\)
- \([438 - 990 \text{ GeV}] : h_2 \to VV, \text{combination Run II [arXiv:1808.02380]}\)
- \( > 990 \text{ GeV}: \text{VBF mode to VV, combination Run II [arXiv:1808.02380]}\)
Zoom into exclusion regions [very rough draft]

Exclusion bounds from direct searches, all 36 fb$^{-1}$, fixed tan $\beta$

- CMS ZZ final states, JHEP 1806 (2018) 127

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Parameter count

- gauge eigenbasis:
  \[ \lambda_{1,2,3}, v, v_s, \mu^2, \mu_s^2, g_1, g_2 \]

- can be rewritten:
  \[ T_h, H, m_h^2, m_H^2, m_{hH}^2, \tan \beta \equiv \frac{v_s}{v}, m_W^2, m_Z^2, v \]
  ew scheme

- minimization: \( T_i = 0 \)

- \( h, H \) mass-eigenstates: \( m_{hH}^2 = 0 \)
\( \delta \alpha \) and \( \delta m_{hH}^2 \); \( \text{Re} \hat{\Sigma}_{hH}(p^2) \)

can also renormalize mixing angle, such that

\[
\alpha^0 = \alpha + \delta \alpha
\]

Connection to \( \delta m_{hH}^2 \)

\[
\delta \alpha = \frac{1}{m_H^2 - m_h^2} \delta m_{hH}^2
\]

\[
\text{Re} \hat{\Sigma}_{hH}(p^2) = \text{Re} \Sigma_{hH}(p^2) + \frac{1}{2} \delta Z_{hH}(p^2 - m_h^2) + \frac{1}{2} \delta Z_{Hh}(p^2 - m_H^2) - \delta m_{hH}^2
\]
... and in more detail...

\[ \nu_s^0 \rightarrow \nu_s + \delta \nu_s, \]
\[ T_i^0 \rightarrow T_i + \delta T_i, \]
\[ \mathcal{M}_{hH}^2 \rightarrow \mathcal{M}_{hH}^2 + \delta \mathcal{M}_{hH}^2 \]

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

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

+ renormalization re electroweak scheme (e.g. \( \delta e, \delta m_W^2, \delta m_Z^2 \))
... and in numbers...

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

<table>
<thead>
<tr>
<th>Scheme</th>
<th>$\Delta = 0, {\text{nlgs}} = 0$</th>
<th>$\Delta = 10^7, {\text{nlgs}} = 0$</th>
<th>$\Delta = 10^7, {\text{nlgs}} = 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>$+4.2633488 \times 10^{-3}$</td>
<td>$+4.2633486 \times 10^{-3}$</td>
<td>$-5.27015844 \times 10^{-3}$</td>
</tr>
<tr>
<td>Mixed $\overline{\text{MS}}$/OS</td>
<td>$+6.8467506 \times 10^{-3}$</td>
<td>$+6.8467504 \times 10^{-3}$</td>
<td>$+6.8467500 \times 10^{-3}$</td>
</tr>
<tr>
<td>Improved OS</td>
<td>$+3.9393569 \times 10^{-3}$</td>
<td>$+3.9393568 \times 10^{-3}$</td>
<td>$+3.9393556 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

$\delta m_{hh}^2$ : UV-divergence; $\{\text{ngls}\}$ : non-linear gauge fixing parameters