PROCEEDINGS OF SCIENCE

The Higgs singlet extension at LHC Run 2

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We discuss the current status of theoretical and experimental constraints on the real Higgs singlet extension of the Standard Model. For the second neutral (non-standard) Higgs boson the mass range up to 1 TeV accessible at past and current collider experiments is considered. We furthermore discuss electroweak corrections to the $H \rightarrow hh$ partial decay width within this model.

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1. The model

In this work we consider the simplest extension of the Standard Model (SM) Higgs sector, where an additional real scalar field is added [1, 2, 3]. The model contains a complex $SU(2)_L$ doublet, in the following denoted by Φ, and a real scalar S which is a singlet under the SM gauge group. The most general renormalizable Lagrangian compatible with an additional Z_2 symmetry is then given by $\mathscr{L}_s = (D^\mu\Phi)^\dagger D_\mu\Phi + \partial^\mu S \partial_\mu S - V(\Phi,S)$, with the scalar potential

$$V(\Phi,S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger\Phi S^2. \tag{1.1}$$

In the unitary gauge, the Higgs fields are given by $\Phi \equiv \begin{pmatrix} 0 & \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}^T$, $S \equiv \frac{h'+v_s}{\sqrt{2}}$, with v, v_s denoting the non-zero vacuum expectation values of the doublet and singlet. Physically, the above potential leads to a mixing between the gauge eigenstates, related via the mixing angle α according to $h = c_\alpha \tilde{h} - s_\alpha h'$, $H = s_\alpha \tilde{h} + c_\alpha h'$, where we used the shorthand notation $s_\alpha\,(c_\alpha) \equiv \sin\alpha\,(\cos\alpha)$. We here use the convention that $m_h \leq m_H$, and choose as input parameters m_h, m_H, $\sin\alpha$, v, $\tan\beta \equiv \frac{v}{v_s}$, where $v \sim 246\,\text{GeV}$. In addition, one of the scalar masses is fixed to $\sim 125\,\text{GeV}$, where we distinguish between the *high-mass* ($m_h \sim m_{h,\text{SM}}$) and *low-mass* ($m_H \sim m_{h,\text{SM}}$) scenario. The above mixing also leads to the familiar rescaling of the SM-like Higgs couplings at tree level by $\sin\alpha$ ($\cos\alpha$) for h(H), with respect to the couplings for a SM Higgs boson of that mass.

2. Parameter constraints and predictions at the LHC Run 2

We refer the reader to [4, 5, 6] for a detailed discussion of the individual constraints. Vacuum stability, perturbative unitarity, perturbativity of the couplings, agreement with electroweak precision observables have been explicitly discussed in the above references; constraints from the W-boson mass measurement follow [7]. In [6], previous results were updated especially with regard to the latest LHC limits and Higgs signal strength measurements [8], using the public tools `HiggsBounds` (version 4.3.1) [9, 10, 11] and `HiggsSignals` (version 1.4.0) [12]. A summary of all constraints on the maximal mixing angle $\sin\alpha$ is shown in Fig. 1. Production cross-sections for the 14 TeV LHC, after all constraints have been taken into account, are shown in Fig. 2 for the high-mass range. Specific benchmarks for all mass ranges have been presented in [6][1].

3. Renormalization

The complete electroweak renormalization of the singlet model has been presented in [14], and we refer the reader to this reference for explicit details. Here we only want to point to two major features of our scheme setup.

Non-linear gauge fixing We use a non-linear gauge fixing, specified by

$$\mathscr{L}_{GF} = -\frac{1}{\xi_W} F^+ F^- - \frac{1}{2\xi_Z}|F^Z|^2 - \frac{1}{2\xi_A}|F^A|^2, \tag{3.1}$$

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[1] See also [13].

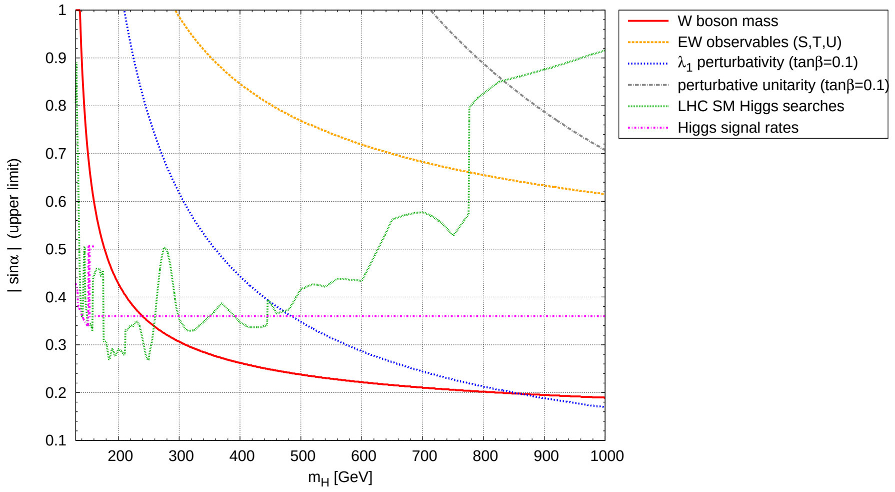
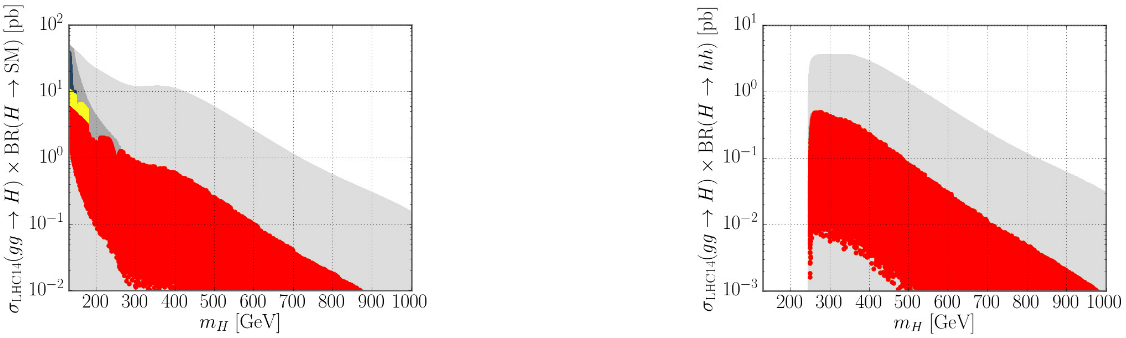


Figure 1: Maximal allowed values for $|\sin\alpha|$ in the high mass region, $m_H \in [130, 1000]$ GeV, from NLO calculations of the W boson mass (*red, solid*) [7], electroweak precision observables (EWPOs) tested via the oblique parameters S, T and U (*orange, dashed*), perturbativity of the RG-evolved coupling λ_1 (*blue, dotted*), evaluated for an exemplary choice $\tan\beta = 0.1$, perturbative unitarity (*grey, dash-dotted*), direct LHC Higgs searches (*green, dashed*), and the Higgs signal strength (*magenta, dash-dotted*). Taken from [6].



(a) Heavy Higgs signal rate with SM particles in the final state for the LHC at 14 TeV.

(b) Heavy Higgs signal rate with light Higgs bosons in the final state for the LHC at 14 TeV.

Figure 2: Production cross-sections at a 14 TeV LHC, for a heavy Higgs H decaying into SM particles *(left)* or hh final states *(right)*; for the latter, electroweak corrections have not been included. Cross sections stem from a simple rescaling of production cross sections presented in [13]. Red and yellow regions correspond to agreement with the Higgs signal strength measurements at the 1σ and 2σ level, respectively, blue points comply with direct experimental searches but do not agree with the Higgs signal strength within 2σ. Taken from [6].

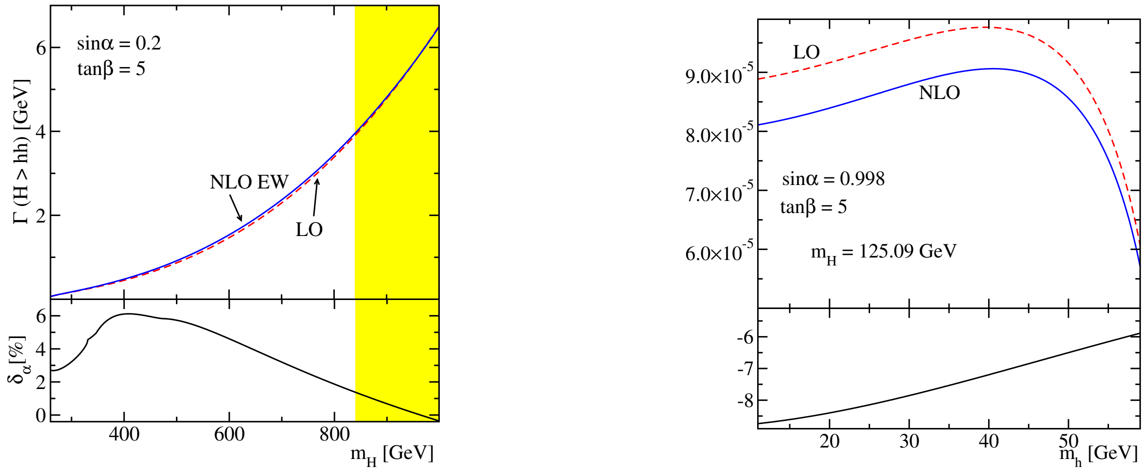
where the functions F depend non-linearly on the Higgs and gauge fields and are given by Eqns. (21)-(23) of [14]. The gauge-fixing terms explicitly depend on the non-linear gauge-fixing quantities $\tilde{\delta}_i$. We perform our implementation of the singlet model using SLOOPS (see e.g. [15, 16]).

Gauge-parameter independent physical results We have studied different schemes and explicitly tested gauge-fixing parameter dependence. An improved On-shell prescription leads to gauge-parameter independent predictions for the one-loop corrections to $\Gamma_{H\to hh}$:

$$\delta m_{hH}^2 = \mathrm{Re}\,\Sigma_{hH}(p_*^2)\big|_{\xi_W=\xi_Z=1,\tilde{\delta}_i=0} \quad \text{with} \quad p_*^2 = \frac{m_h^2+m_H^2}{2}\,, \tag{3.2}$$

This prescription coincides with the discussion in [16] in the context of supersymmetry, and can also be related to the so-called pinch technique (see e.g. [17]).

We rely on two independent implementations of the model[2]. Once all present constraints on the model are included, we find mild NLO corrections, typically of few percent, and with theoretical uncertainties on the per mille level. Sample results for the one-loop eletroweak corrections to the decay width $\Gamma_{H\to hh}$ are displayed in Fig. 3.



(a) $m_h = 125.09$GeV (b) $m_H = 125.09$GeV

Figure 3: NLO corrections to the $H \to hh$ partial decay width, for fixed $\sin\alpha$, $\tan\beta$ values and m_h *(left)* or m_H *(right)* being the 125 GeV resonance measured at the LHC, as a function of the second scalar mass. We display the total decay width for $H \to hh$, as well as the *relative* correction in the α_{em} input scheme for the electroweak parameters (see [14] for details). The yellow region is excluded by perturbativity of the couplings. *Note:* $\tan\beta$ is defined as $\frac{v_s}{v}$ in this case, in contrast to the definitions given above. Taken from [14].

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[2] See [14] for a complete description of the computational setup.

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