SCALAR SINGLET S AT PRESENT AND FUTURE COLLIDERS

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Abstract

A scalar singlet, coupled to the other particles only through its mixing with the Higgs boson, appears in several motivated extensions of the Standard Model. The prospects for the discovery of a generic singlet at the various stages of the LHC, as well as at future high-energy colliders, are studied, and the reach of direct searches is compared with the precision attainable with Higgs couplings measurements. The results are then applied to the NMSSM and Twin Higgs.

1 Introduction

Is the Higgs boson recently found by the ATLAS and CMS experiments the only scalar particle, or are there other Higgs-like states around the Fermi scale? This question is of fundamental importance for particle physics, and motivates a detailed study of the phenomenology of additional scalars, as well as the prospects for their discovery at the LHC and future colliders.\(^1\)

The simplest example of an extended Higgs sector is realised adding just a real scalar field, singlet under all the known gauge groups, to the Standard Model (SM). Despite its great simplicity, this scenario is of considerable physical relevance, since it can easily arise in many of the most natural extensions of the SM – e.g. the Next-to-Minimal Supersymmetric SM (NMSSM), Twin Higgs, some Composite Higgs models.

In general, such a singlet will mix with the Higgs boson. As a consequence, both physical scalar states are coupled to SM particles, hence they can both be produced at colliders and be observed by means of their visible decays. In the following, after briefly reviewing the main
properties of a generic singlet-like scalar, I shall present the constraints on the existence of such a particle that arise from both direct searches and Higgs couplings precision measurements.

2 General properties

Let us call $h$ and $\phi$ the two neutral, CP-even propagating degrees of freedom, with masses $m_h = 125.1$ GeV and $m_\phi$. They are related to the Higgs and singlet gauge eigenstates via a mixing angle $\gamma$.

In a weakly interacting theory, the couplings of $h$ and $\phi$ are just the ones of a standard Higgs boson with the same mass, rescaled by a universal factor of $c_\gamma$ or $s_\gamma$, respectively. As a consequence, their signal strengths $\mu_{h,\phi}$ are

$$\mu_h = \mu_{\text{SM}}(m_h) \times c_\gamma^2,$$

$$\mu_{\phi\rightarrow VV,ff} = \mu_{\text{SM}}(m_\phi) \times s_\gamma^2 \times (1 - \text{BR}_{\phi\rightarrow hh}),$$

$$\mu_{\phi\rightarrow hh} = \sigma_{\text{SM}}(m_\phi) \times s_\gamma^2 \times \text{BR}_{\phi\rightarrow hh},$$

where $\mu_{\text{SM}}(m)$ is the corresponding signal strength of a SM Higgs with mass $m$, and BR$_{\phi\rightarrow hh}$ is the branching ratio of $\phi$ into two 125 GeV Higgs bosons. The phenomenology of the Higgs system is therefore completely described by three parameters: $m_\phi$, $s_\gamma$, and BR$_{\phi\rightarrow hh}$. The second state $\phi$ behaves like a heavy SM Higgs boson, with reduced couplings and an additional decay width into hh.

Notice that the mixing angle $\gamma$ and $m_\phi$ are not independent quantities, since the former has to vanish when the mass tends to infinity. Indeed,

$$\sin^2 \gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2},$$

where $M_{hh}$ is the first diagonal entry of the mass matrix of the scalar system before diagonalisation, which is proportional to the electroweak scale.

In the limit of large $m_\phi$, the Goldstone boson equivalence theorem sets the relations

$$\text{BR}_{\phi\rightarrow hh} = \text{BR}_{\phi\rightarrow ZZ} = \frac{1}{2} \text{BR}_{\phi\rightarrow WW}.$$ 

The exact formulae for the $hhh$ and $\phi hh$ couplings are reported in reference 1).

2.1 Higgs couplings

The measurement of the Higgs signal strengths provides a constraint on the mixing angle $\gamma$ through eq. (1). At present, a global fit to 8 TeV LHC data constrain it to be $s_\gamma^2 < 0.23$ at 95% C.L. 2). Projections for the reach of future hadron and lepton colliders 3) are listed in Table 1.

Large modifications to the triple Higgs coupling can arise in some regions of the parameter space, even if the deviation in the signal strengths is moderate. Future collider experiments, and even the LHC, could in principle be sensitive to these modifications. More details about Higgs couplings can be found in 1).
3 Direct searches

The main decay channels of a heavy singlet are into a pair of $W$ and $Z$ vector bosons, or into a pair of Higgs bosons, if kinematically allowed.

Both the ATLAS and CMS collaborations provide a combined limit from all the $WW$ and $ZZ$ channels\(^4\), with the strongest bound always coming from searches in the $4\ell$ and $2\ell2\nu$ final states. In the di-Higgs channel, the main constraint comes from the $4b$ final state\(^5\). All these searches are already sensitive to cross-sections smaller than the ones for a SM Higgs at the same mass, and exceed the reach of Higgs coupling measurements for low enough $m_\phi$.

Projections for future colliders have been obtained in\(^1\), rescaling the expected limits from the 8 TeV LHC with the parton luminosities of the backgrounds, following the procedure presented in\(^6\). The colliders that have been considered are: the 8 TeV, 13 TeV, and 14 TeV LHC, its high-luminosity upgrade, a possible 33 TeV energy upgrade, and a futuristic 100 TeV FCC-hh.

Figure 1 shows the present and extrapolated limits on the $\mu_{\phi\to ZZ}$ (left) and $\mu_{\phi\to hh}$ (right). In the left panel, the $s^2_\gamma$ exclusion from Higgs couplings is also superimposed, assuming a 100% branching ratio into vectors.

| $pp$   | LHC8 | LHC14 | HL-LHC | HE-LHC | FCC-hh |
|--------|------|-------|--------|--------|--------|
| $s^2_\gamma$ | 0.2  | 0.08–0.12 | 0.04–0.08 | ?      | ?      |
| $|\Delta g_{hhh}/g_{hhh}^{SM}|$ | 0.5  | 0.2   | 0.08   | 0.1–0.2 | 0.1–0.2 |

Table 1: Current and expected precisions on Higgs couplings\(^3\).
Figure 2: Comparison between the combined reach of direct searches and Higgs coupling measurements, in the plane $m_{φ} - M_{hh}$. BR$_{φ→hh}$ has been fixed to 0.25 for simplicity. Left: region relevant for the LHC. Right: projections for future colliders. The notation for the lines is the same as in Figure 1.

$m_{φ} - M_{hh}$ plane, and for BR$_{φ→hh} = 1/4$. The direct exclusion is dominated by $φ → VV$.

4 Explicit models

4.1 Supersymmetry

The Higgs sector of the NMSSM $^7$ contains the two usual doublets $H_{u,d}$, plus a singlet scalar $S$, coupled through a Yukawa interaction $λH_uH_dS$ in the superpotential. An extra contribution to the Higgs mass is generated at tree-level by $λ$, and reduces the size of the radiative correction needed to obtain 125 GeV. At the same time, the fine-tuning of the electroweak scale $v$ is reduced.

In the decoupling limit for the heavy doublet, the CP-even states are the SM Higgs and the singlet, and can be matched to the previous scenario via $^8$)

$$M_{hh}^2 = m_Z^2 c_{2β}^2 + v^2 λ^2 s_{2β}^2 + Δ^2,$$

where $Δ$ is the radiative correction and $tan β = v_u/v_d$. Figure 3 (left) shows the current exclusions and projections from both direct searches and Higgs couplings, in the plane $m_{φ} - tan β$, for fixed values of $λ = 1$ and $Δ = 70$ GeV.

4.2 Twin Higgs

In Twin Higgs models $^9$, a naturally light Higgs is obtained without the presence of coloured particles close to the TeV scale. This is achieved introducing a copy of the SM field content and gauge symmetries, $SM_A × SM_B$. The Higgs potential has an approximate global $SO(8)$
symmetry, which is spontaneously broken at a scale $f$, and the Higgs $h = H_A \cos \gamma + H_B \sin \gamma$ is a Goldstone boson of this breaking. Quadratic “divergences” in the Higgs mass cancel between the A and B sectors, while all the new Twin particles are SM singlets.

The phenomenology of the “radial mode” $\sigma = H_B \cos \gamma - H_A \sin \gamma$ is described by eq. (2), (3). The mixing angle is proportional to $v/f$, and one has

$$M_{hh}^2 = \frac{v^2}{f^2} (m_\sigma^2 + m_h^2).$$

The only difference with respect to the previous cases is the presence of an invisible width into $W_B$ and $Z_B$ bosons. Figure 3 (right) illustrates the present and future constraints in the plane $m_\sigma - f$, which are the only two free parameters of the model. One can see that direct searches for the radial mode are the most powerful probe for a Twin Higgs scenario, at least for not too large values of $m_\sigma$ and $f$.

5 Conclusions

Searches for scalar singlets at colliders can be an important probe for the extended Higgs sectors of many physically motivated models, and complementary to the measurement of Higgs couplings. By means of only three parameters that determine the phenomenology in a completely general way, the reach of future colliders in the relevant $VV$ and $hh$ channels has been studied. On the other hand, already the second run of the LHC can efficiently explore this scenario, and will provide valuable information in the near future.
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