Physics Letters B 694 (2010) 44–53

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measuring hidden Higgs and strongly-interacting Higgs scenarios

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ARTICLE INFO

Article history:
Received 2 August 2010
Received in revised form 8 September 2010
Accepted 15 September 2010
Available online 18 September 2010
Editor: G.F. Giudice

Keywords:
Higgs boson
Beyond Standard Model
LHC

ABSTRACT

Higgs couplings can be affected by physics beyond the Standard Model. We study modifications through interactions with a hidden sector and in specific composite Higgs models accessible at the LHC. Both scenarios give rise to congruent patterns of universal, or partially universal, shifts. In addition, Higgs decays to the hidden sector may lead to invisible decay modes which we also exploit. Experimental bounds on such potential modifications will measure the concordance of an observed Higgs boson with the Standard Model.

1. Introduction

Embedding the Standard Model [SM] into an extended theory will, in general, modify the couplings predicted in the minimal Higgs sector of the Standard Model [1,2]. Thus, measuring the Higgs couplings at the LHC [3,4] will shed light on potential scenarios beyond the Standard Model. In two well-motivated models the analysis is particularly transparent:

First, theories beyond the Standard Model may include a hidden sector. The Higgs field offers an attractive candidate for opening the portal to such a hidden sector [5–8]. The coupling between the SM-singlet Higgs mass term and the corresponding SM-neutral Higgs term in the hidden sector leads to an interaction which transfers the renormalizability from the Standard Model to the extended theory.

Second, interpreting the Higgs particle as composite pseudo-Goldstone boson generated by new strong interactions is clearly a well-motivated scenario [9–12]. The strong interactions will induce deviations from the properties predicted for a minimal point-like Higgs particle so that the Higgs profile may signal dynamical structures beyond the Standard Model.

If the Standard Model Higgs field couples to a hidden Higgs sector, the couplings to the other Standard Model particles are modified universally; in addition, decays into the hidden sector may generate an invisible decay mode and thereby affect the total width. In strong interaction models where the Higgs boson emerges as a pseudo-Goldstone boson all the Higgs couplings, cross sections and partial widths, may be altered universally or following a simple fermion *vs* boson pattern. Moreover, this scenario does not predict any novel invisible decays. The set of these characteristics will allow us to discriminate between the two scenarios.

In general, depending on the operator basis chosen [13–17], some $\mathcal{O}(10)$ free parameters may affect the measured production and decay rates at the LHC. A universal [or partially universal] modification of the Higgs couplings tremendously simplifies the complexity of any experimental analysis to the measurement of just one, or two, new parameters. Furthermore, setting bounds on universal deviations from the Standard Model Higgs couplings measures the degree of concordance between the observed Higgs boson and the Standard Model in a particularly transparent form.

In the two scenarios introduced above, the twin width-ratios of the Higgs boson are modified by a parameter κ:

$$\frac{\Gamma_p \Gamma_d}{\Gamma_{\rm tot}} = \kappa \left(\frac{\Gamma_p \Gamma_d}{\Gamma_{\rm tot}} \right)^{\rm SM}. \tag{1}$$

The partial widths refer to the production channel p and the decay mode d, either exclusively or summing over sets of initial or final states. These ratios are measured, at the Born level, directly by the product of production cross section times decay branching ratio of the process $p \to Higgs \to d$ in the narrow width approximation. In the hidden sector the parameter κ is universal; in the strong

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2010.09.032

interaction scenario we consider it may take different values for Higgs couplings to vector bosons or fermions [12].

For a hidden sector the decay label d includes invisible Higgs decays, *i.e.* the partial width Γ_{hid}. This second parameter can be measured via the invisible branching ratio BR_{inv}. It is well known [18–21] that the determination of BR_{inv} at hadron colliders is quite demanding, even through it naturally appears in many extensions of the Standard Model, like four lepton generations or supersymmetry [8].

In the present study we will show, adopting the tools of SFitter, at which level κ as well as Γ_{hid}, if present, can be determined at the LHC.

The measurements of κ and BR_{inv} do not require the estimate of the total width appearing in the denominator of Eq. (1). Nevertheless, estimating Γ_{tot} will provide us with consistency checks on our theoretical ansatz. One way is to simply identify the total Higgs width with the sum of all partial widths, with or without invisible channels [4]. The non-observed partial widths are fixed to the Standard Model value scaled by the same global factor applied to the observed partial widths. This method relies strongly on the recent resurrection of the $H \to b\bar{b}$ channel based on fat jet searches [22,23]. An alternative way to construct an upper limit to the Higgs width — to be combined with the lower limit from all observed partial widths — would be motivated by the unitarization of $WW \to WW$ scattering. The Standard Model Higgs state saturates this unitarization, so modulo quantum corrections the relation $g_{WWH} \lesssim g^{\text{SM}}_{WWH}$ becomes an upper bound to the Higgs width [3]. We cannot use such an additional constraint because the observed scalar state in our models overlaps only partly with the state related to electroweak symmetry breaking.

Extracting Higgs parameters from LHC data [3,4] forces us to pay attention to the different uncertainties affecting the rate measurements and their comparison to theory predictions for Higgs production [24,25] and decay [26,27]. For typical luminosities around 30 fb^{-1} statistical uncertainties will be the limiting factor for example in weak-boson-fusion or Higgs-strahlung channels. Simulating these statistical uncertainties we use Poisson statistics. Experimental systematic errors, as long as they are related to measured properties of the detector, are expected to be dominantly Gaussian. We include flat theory errors based on the Rfit profile-likelihood construction [28,29].

In part of our studies ratios of Higgs couplings will play a crucial role. Higher precision in measuring these ratios may naively be expected compared with individual measurements of couplings [3]. For such an improvement the analysis should not be statistics dominated, which it largely is however for an integrated luminosity of 30 fb^{-1}. Moreover, while experimental systematic uncertainties tend to cancel between the same Higgs decays but different production channels, the dominant theory errors are expected to cancel for identical production mechanisms. In line with these arguments we have found that using ratios does not significantly improve the results of Higgs sector analyses [4].

In this study we will show how κ as well as Γ_{hid} can be determined using SFitter. Starting from the completely exclusive likelihood map, SFitter determines the best-fitting point in the Higgs-sector parameter space. While a Bayesian probability analysis of the entire Higgs parameter space at the LHC is spoiled by noise, profile likelihoods can be studied in the vicinity of the best-fitting points [4]. In this analysis we assume that we already know the global structure of the likelihood map, so we can focus on the local properties around the SM-like solution. As it will turn out, alternative solutions can be studied nevertheless, for example with sign switches for some of the Higgs couplings.

Technically, the analysis presented in this Letter is based on the SFitter–Higgs setup. The Higgs production rates include NLO QCD corrections except for the top-quark associated production mode. For the decays we use a modified version of HDECAY [27], which contains both NLO QCD terms and off-shell decays into vector bosons. For a list of all measurements and their different errors we refer to Ref. [4]. Compared to this previous analysis we have updated the numbers for the $H \to b\bar{b}$ channel in associated production with vector bosons from the recent ATLAS study [23], which confirms the previously obtained significances. The event rates for weak-boson-fusion production with decay into invisible states are adopted from Ref. [19]. The central data set is smeared around the theory predictions according to the theoretical error and the experimental errors, taking into account the correlations among the observables. For each of the toy-experiments we determine the best-fit values. This numerical determination of the resulting parameter uncertainties is fitted to Gaussian distributions.

The new technical aspect of the present study is the more refined approach to the hypotheses tested: if we do not measure all Higgs couplings independently but instead test a given model hypothesis, the limits on the extracted model parameters improve significantly. Because this approach requires fewer measurements we now consider Higgs masses between 110 and 200 GeV and find a significant enhancement of the determination power for 30 fb^{-1} of LHC data at a collider energy of 14 TeV.

2. Higgs portal to hidden sector

The Standard Model, or extensions of it, may be connected to a hidden sector. An interesting realization of such a mechanism is provided by specifying the scalar Higgs domains in both sectors as the link between the two sectors [5,6]. To explore the possibility of detecting a hidden sector at the LHC we investigate a scenario in which the Standard Model Higgs sector is coupled to the hidden Higgs sector through quartic interactions. Such a scalar system is technically transparent and may therefore serve as paradigm for generic experimental features that could signal a hidden sector. There are many variants to this specific scenario, *e.g.* a hidden scalar sector without spontaneous symmetry breaking, large ensembles of scalar fields, etc. The scenarios can be disentangled by analyzing a few characteristic observables of the Higgs particles, in particular Higgs couplings. In this Letter we will concentrate on the simplest setup to quantify the potential of experimental analyses at the LHC.

The scenario we will focus on for now is described by the Higgs potential of the Standard Model [s], the isomorphic potential in the hidden sector [h], and the quartic interaction potential coupling the two sectors with strength η_χ, *videlicet*,

$$\mathcal{V} = \mu_s^2|\phi_s|^2 + \lambda_s|\phi_s|^4 + \mu_h^2|\phi_h|^2 + \lambda_h|\phi_h|^4 + \eta_\chi|\phi_s|^2|\phi_h|^2. \quad (2)$$

Expanding the two Higgs fields about their vacuum expectation values $\phi_j \to (v_j + H_j)/\sqrt{2}$ we encounter shifts away from the standard values by the interaction term,

$$v_s^2 = \frac{1}{\lambda_s}\left(-\mu_s^2 - \frac{1}{2}\eta_\chi v_h^2\right) \quad \text{and} \quad v_h^2 = \frac{1}{\lambda_h}\left(-\mu_h^2 - \frac{1}{2}\eta_\chi v_s^2\right). \quad (3)$$

The Higgs states in the SM and the hidden sector will be mixed. Diagonalizing the Higgs mass matrix,

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_s v_s^2 & \eta_\chi v_s v_h \\ \eta_\chi v_s v_h & 2\lambda_h v_h^2 \end{pmatrix}, \quad (4)$$

generates two mass eigenvalues $M_{1,2}$ and the mixing angle χ

$$M_{1,2}^2 = \left(\lambda_s v_s^2 + \lambda_h v_h^2\right) \pm \left[\left(\lambda_s v_s^2 - \lambda_h v_h^2\right)^2 + (\eta_\chi v_s v_h)^2\right]^{1/2},$$
$$\tan 2\chi = \eta_\chi v_s v_h / \left[\lambda_s v_s^2 - \lambda_h v_h^2\right] \quad (5)$$