Physics Letters B ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Can we discover a light singlet-like NMSSM Higgs boson at the LHC?

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A R T I C L E I N F O

Article history:
Received 4 December 2017
Received in revised form 9 April 2018
Accepted 30 April 2018
Available online xxxx
Editor: L. Rolandi

Keywords:
Supersymmetry
Higgs boson
NMSSM
Higgs boson branching ratios
LHC benchmark points

A B S T R A C T

In the next-to minimal supersymmetric standard model (NMSSM) one additional singlet-like Higgs boson with small couplings to standard model (SM) particles is introduced. Although the mass can be well below the discovered 125 GeV Higgs boson mass its small couplings may make a discovery at the LHC difficult. We use a novel scanning technique to efficiently scan the whole parameter space and determine the range of cross sections and branching ratios for the light singlet-like Higgs boson below 125 GeV. This allows to determine the perspectives for the future discovery potential at the LHC. Specific LHC benchmark points are selected representing the salient NMSSM features.

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1. Introduction

Supersymmetry (SUSY) predicts a light Higgs boson with a mass below 130 GeV (for reviews see [1–3]) which is compatible with the discovered Higgs-like boson with SM-like couplings and a mass of 125 GeV [4,5]. In addition to the SM-like Higgs boson a second singlet-like Higgs boson is predicted in the next-to-minimal supersymmetric standard model (NMSSM) [6]. This additional Higgs boson couples only weakly to SM particles because of its large singlet content. So the decay modes for the singlet-like Higgs boson differ from the well-known decays of the SM Higgs boson. In addition, the singlet-like couplings lead to a small production cross section.

The introduction of an additional Higgs singlet S in the NMSSM yields more parameters in the Higgs sector for the interactions between the singlet and the Higgs doublets and the singlet self interaction. Even if one considers the well-motivated subspace with unified masses and couplings at the GUT scale the additional particles and their interactions lead to a large parameter space. To cope with this large parameter space and especially the large correlations between the parameters, we use a novel scanning technique to obtain the expected range of cross sections and branching ratios of the light singlet-like Higgs boson. This method was previously used for the heavy Higgs boson [7] and will be shortly described in Sect. 3. In this letter we apply this method, which allows for an efficient scanning of the whole parameter space with a complete coverage, to the light singlet-like Higgs boson and determine the cross sections and branching ratios over the whole parameter space, thus complementing previous studies using methods not guaranteeing complete coverage [8–25]. The singlet-like Higgs boson can be the lightest Higgs boson H_1 implying it has a mass below 125 GeV, although scenarios, where the SM-like Higgs boson is the lightest one, are also possible. However, since a singlet-like Higgs boson has by definition small couplings to SM-like particles we concentrate on $m_{H1} < 125$ GeV, where the phase-space and correspondingly, the cross section can still be large despite the small couplings. An interesting possibility is the fact that the slight excess of a Higgs-like signal seen at 98 GeV at the LEP originates from the H_1 Higgs boson as discussed in Ref. [26] after the Higgs boson discovery or even before [27]. After a short summary of the Higgs sector in the NMSSM we summarize the fit strategy to sample the 6D parameter space based on the 3D neutral Higgs boson mass space. We find two regions for the couplings of the singlet-like Higgs boson to itself (called κ) and to the other Higgs bosons (called λ), namely regions with large (small) values of λ and κ, which are called Region I (II), respectively. The Higgs singlet production has been studied before in Ref. [28] as well using also the distinction between these two regions with the focus on $\gamma\gamma$ final state. With our novel scanning technique yielding complete coverage we can study in detail

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https://doi.org/10.1016/j.physletb.2018.04.067
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the branching ratios of all channels and discover large differences between the two Regions. We conclude by showing the branching ratios and cross sections times branching ratios as function of the Higgs boson mass for the most promising discovery channels like $\tau\tau, \gamma\gamma, Z\gamma, ZZ, WW, \tilde{\chi}_0^1\tilde{\chi}_0^1$ and A_1A_1. We select benchmark points in 4 bins of the Higgs boson mass m_{H1} in both, Regions I and II, for each of the most promising discovery channels. These benchmark points, as detailed in the supplemental material, can be used to simulate the discovery channels and its background more precisely in order to get a quantitative determination of the discovery potential.

2. NMSSM Higgs sector

We focus on the well-motivated semi-constrained NMSSM, as described in Ref. [6] and use the corresponding code NMSSM-Tools 5.2.0 [29] to calculate the SUSY mass spectrum, Higgs boson masses and branching ratios from the NMSSM parameters. The Higgs production cross sections are calculated with SusHi [30–38].

Within the NMSSM the Higgs fields consist of the two Higgs doublets (H_u, H_d), which appear in the MSSM as well, but in addition, the NMSSM has an additional complex Higgs singlet S. Furthermore, we have the GUT scale parameters of the constrained minimal supersymmetric standard model (CMSSM): m_0, $m_{1/2}$ and A_0, where $m_0(m_{1/2})$ are the common mass scales of the spin 0(1/2) SUSY particles at the GUT scale and A_0 is the trilinear coupling of the CMSSM Higgs sector at the GUT scale. In total, the semi-constrained NMSSM has nine free parameters:

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \mu_{eff}. \quad (1)$$

Here $\tan\beta$ corresponds to the ratio of the vevs of the Higgs doublets, i.e. $\tan\beta \equiv v_u/v_d$, λ represents the coupling between the Higgs singlet and doublets $(\lambda S H_u \cdot H_d)$, κ the self-coupling of the singlet $(\kappa S^3/3)$; A_λ and A_κ are the corresponding trilinear soft breaking terms, μ_{eff} represents an effective Higgs mixing parameter and is related to the vev of the singlet s via the coupling λ, i.e. $\mu_{eff} \equiv \lambda s$. Therefore, μ_{eff} is naturally of the order of the electroweak scale [39,40], thus avoiding the μ-problem [6]. The latter six parameters in Eq. (1) form the 6D parameter space of the NMSSM Higgs sector. A_0 is highly correlated with A_λ and A_κ in the semi-constrained NMSSM, so fixing it would restrict the range of A_λ and A_κ severely. Therefore, A_0 is allowed to vary as well.

The neutral components from the two Higgs doublets and singlet mix to form three physical CP-even scalar bosons and two physical CP-odd pseudo-scalar bosons. The elements of the corresponding mass matrices at tree level are given in Ref. [41]. The mass eigenstates of the neutral Higgs bosons are determined by the diagonalization of the mass matrix, so the scalar Higgs bosons H_i, where the index i increases with increasing mass, are mixtures of the CP-even weak eigenstates H_d, H_u and S

$$H_i = S_{i1}H_d + S_{i2}H_u + S_{i3}S, \quad (2)$$

where S_{ij} with $i, j = 1, 2, 3$ are the elements of the Higgs mixing matrix. For the lightest Higgs boson with $i = 1$ the value of S_{13} is usually close to 1, which implies small couplings of H_1 to SM particles as will be discussed below. The Higgs couplings to quarks and leptons of the third generation are crucial for the allowed range of branching ratios and given by:

$$H_i t_L t_R^c : -\frac{h_t}{\sqrt{2}} S_{i2} \qquad h_t = \frac{m_t}{v \sin\beta},$$
$$H_i b_L b_R^c : \frac{h_b}{\sqrt{2}} S_{i1} \qquad h_b = \frac{m_b}{v \cos\beta}, \quad (3)$$
$$H_i \tau_L \tau_R^c : \frac{h_\tau}{\sqrt{2}} S_{i1} \qquad h_\tau = \frac{m_\tau}{v \cos\beta},$$

where h_t, h_b and h_τ are the corresponding Yukawa couplings. The relation includes the quark and lepton masses m_t, m_b and m_τ and $v^2 = v_u^2 + v_d^2$. The couplings to fermions of the first and second generation are analogous to Eq. (3) with different quark and lepton masses.

3. Analysis

The branching ratios and cross sections of the light Higgs boson have been determined for two different regions, since a certain Higgs mass combination is not unique, as can be easily seen already from the approximate expression for the 125 GeV Higgs boson [6]:

$$M_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}} + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2}(\lambda - \kappa \sin 2\beta)^2. \quad (4)$$

The first tree level term can become at most M_Z^2 for large $\tan\beta$. The difference between M_Z and 125 GeV has to originate mainly from the logarithmic stop mass corrections $\Delta_{\tilde{t}}$. The two remaining terms originate from the mixing with the singlet of the NMSSM at tree level and become large for large values of the couplings λ and κ and small $\tan\beta$. As mentioned before, this region we call *Region I*. However, there exists another solution to Eq. (4) with small values of λ, κ and large values of $\tan\beta$. This we call *Region II* (also mentioned before), which can be obtained by a trade-off between the first two terms and last two terms. So Region II with its small couplings λ and κ is in some sense closer to the MSSM although the singlet-like Higgs and its corresponding singlino-like LSP yield additional physics, like the possibility of double Higgs production and an LSP hardly coupling to matter. In both regions the radiative corrections from stop loops can be small with stop masses around the TeV scale. Quantitatively, Region I is defined by $\lambda > 0.3$, $\tan\beta < 10$ and Region II by $\lambda < 0.1$, $\tan\beta < 30$. These upper and lower limits for λ and $\tan\beta$ were suggested by the χ^2 distribution of Fig. 1 in Ref. [7]. The limit for $\tan\beta$ in Region II allows additionally to be consistent with the results from B-physics.

For each set of the 6 parameters in the Higgs sector the 6 Higgs boson masses are completely determined: 3 scalar Higgs masses m_{H_i}, 2 pseudo-scalar Higgs masses m_{A_i} and the charged Higgs boson mass $m_{H^\pm}$. The masses of A_2, H_3 and $H^\pm$ are of the order of M_A, if $M_A >> M_Z$. Then only one of the masses is needed. Furthermore, either H_1 or H_2 has to be the observed Higgs boson with a mass of 125 GeV, so there are only 3 free neutral Higgs boson masses in the NMSSM, i.e. a 3D parameter space, e.g. m_{A_1}, m_{H_1} and $m_{H_3} \approx m_{A_2} \approx m_{H^\pm}$. We choose $m_{H_2} = 125$ GeV, so $m_{H_1} < 125$ GeV. Instead of scanning over the 6D parameter space of the couplings to determine the range of Higgs boson masses, as was done by other groups in the (N)MSSM, see e.g. Ref. [20,42,43], one can invert the problem and scan the 3D parameter space of the Higgs boson masses. For each combination of Higgs boson masses one finds a single set in the 6D parameter space of the Higgs parameters. This is graphically illustrated in Fig. 1. The transition of the 3D to 6D parameter space can be done by a Minuit [44] fit with the constraints given in the lower box of Fig. 1. The connection between the upper and lower box is obtained from NMSSMTools 5.2.0. Note that the fit is free to determine the optimum values of the parameters from the top box in Fig. 1 within the corresponding range of Regions I and II for each combination of Higgs boson masses. The χ^2 function to be minimized includes the following contributions

Please cite this article in press as: C. Beskidt et al., Can we discover a light singlet-like NMSSM Higgs boson at the LHC?, Phys. Lett. B (2018), https://doi.org/10.1016/j.physletb.2018.04.067

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