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Extended Higgs Sector: 2HDM, MSSM and NMSSM

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Abstract. We review some aspects of Higgs phenomenology within the Two Higgs Model (2HDM), Minimal Supersymmetric Standard Model (MSSM) and Next–to–Minimal Supersymmetric Standard Model (NMSSM).

INTRODUCTION

Nowadays there are compelling indications that a new particle with a mass around $\sim$ 125 GeV discovered at the LHC in 2012 is consistent with the Standard Model (SM) Higgs boson. At the moment, the measured signal strengths into $\gamma\gamma$, WW, ZZ channels favour the interpretation of the observed particle as a neutral scalar state with spin-0. Nevertheless in order to assess its nature thoroughly more data is needed. The more detailed analysis of the signal strengths in different channels can in principle reveal discrepancies from the predictions of the SM that would provide a smoking gun signal of the new physics. Indeed, there are serious reasons to believe that the SM with the minimal Higgs content is not the ultimate theoretical structure responsible for electroweak (EW) symmetry breaking since it is unable to address many fundamental questions. For example, one can expect that at ultra–high energies the SM gets embedded in an underlying theory that provides a framework for unification of all interactions including gravity. Such underlying theory should also explain the weakness of gravitational force at low energies as compared with the strong and EW interactions. However, if the SM is embedded in a more fundamental theory characterized by the Planck scale $M_{Pl} \approx 10^{19}$ GeV, then the SM Higgs mechanism suffers from a stability crisis. In other words because of the quadratical scale dependence of the radiative corrections , the Higgs boson tends to acquire a mass of order of M_{Pl}. Practically all extensions of the SM predict more complicated Higgs sector leading to the presence of other neutral and/or charged Higgs bosons. An observation of any of such new states provides another possible smoking gun indication of the new physics.

Low–scale supersymmetry (SUSY) stabilizes the scale hierarchy. The Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) involves two Higgs doublets. The inclusion of the superfields associated with the second Higgs doublet allows to achieve anomaly cancellation and induce masses for all quarks and leptons. In the MSSM there exists an upper limit on the lightest Higgs boson mass of about 130 – 135 GeV (see *e.g.* [1] and references therein). Thus the MSSM can be consistent with a 125 – 126 GeV SM-like Higgs boson. The local version of SUSY (supergravity) leads to a partial unification of the SM gauge interactions with gravity near the Planck scale. When SUSY partners of ordinary particles have TeV scale masses the lightest SUSY particle in the MSSM can be stable and play the role of dark matter. The unification of gauge coupling constants, which takes place in the MSSM and its simplest extensions at high energies, makes possible the incorporation of the EW and strong gauge interactions within Grand Unified Theories (GUTs) [2] based on simple gauge groups such as $SU(5)$, $SO(10)$ or E_6 that permits to explain the peculiar assignment of $U(1)_Y$ charges postulated in the SM and to address the observed mass hierarchy of quarks and leptons.

TWO HIGGS DOUBLET EXTENSION OF THE SM

As has been already mentioned in the Introduction, SUSY extensions of the SM contain two Higgs doublets. Both doublets may survive down to the EW scale. The most general renormalizable $SU(2)_W \times U(1)_Y$ gauge invariant potential of the two Higgs doublet model (2HDM) is given by [3]

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \tag{1}$$

$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right](\Phi_1^\dagger\Phi_2) + h.c.\right\}.$$

It is easy to see that the number of couplings in the 2HDM potential compared with the SM grows from two to ten. Furthermore, four of them m_3^2, λ_5, λ_6 and λ_7 can be complex, inducing CP–violation in the Higgs sector. At the physical minimum of the scalar potential (1) the Higgs fields Φ_1 and Φ_2 develop vacuum expectation values (VEVs) v_1 and v_2 respectively. When CP is conserved one can use the following parametrisation for Φ_1 and Φ_2

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\,\eta_a)/\sqrt{2} \end{pmatrix}, \qquad a = 1,2\,. \tag{2}$$

The non–zero VEVs v_1 and v_2 break the $SU(2)_W\times U(1)_Y$ gauge symmetry to $U(1)_{em}$ associated with electromagnetism. The combination of the Higgs VEVs $v = \sqrt{v_1^2 + v_2^2}$ is fixed by the Fermi scale, i.e. $v = 246\,\text{GeV}$. On the other hand the ratio of the Higgs VEVs remains arbitrary. Hence it is convenient to introduce $\tan\beta = v_2/v_1$.

Initially the Higgs sector of the two Higgs doublet extension of the SM involves eight degrees of freedom. Three of them become massless Goldstone modes which are swallowed by the $W^\pm$ and Z gauge bosons. As a consequence the $W^\pm$ and Z bosons gain masses $M_W = g_2 v/2$ and $M_Z = \bar{g}v/2$ where $\bar{g} = \sqrt{g_2^2 + g_1^2}$ while g_2 and g_1 are the gauge couplings of the $SU(2)_W$ and $U(1)_Y$ interactions. When CP is conserved the remaining five physical degrees of freedom form two charged, one CP–odd and two CP-even Higgs states.

The Yukawa interactions of the Higgs doublets Φ_1 and Φ_2 with quarks and leptons may generate non–diagonal flavour transitions. In order to avoid flavor changing neutral currents (FCNC) one applies Glashow-Weinberg-Paschos condition: all fermions with the same quantum numbers couple to the same Higgs multiplet [4, 5]. The common way to realize the GWP condition is to impose a certain protecting custodial Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) that forbids potentially dangerous couplings of the Higgs fields to quarks and leptons.

Such a custodial symmetry implies that the Higgs couplings λ_6 and λ_7 vanish. This symmetry also requires the down-type quarks to couple to just one Higgs doublet, Φ_1 say, while the up-type quarks couple either to the same Higgs doublet Φ_1 (Type I) or to the second Higgs doublet Φ_2 (Type II) but not both. In addition the right down-type lepton may couple to the first or second Higgs doublet oppositely to the right down-type quarks leading to the models of Type 3 (Lepton-specific) or Type 4 (Flipped) [6]. The custodial Z_2 symmetry also forbids the mixing term $m_{12}^2(\Phi_1^\dagger\Phi_2)$ in the Higgs potential (1). However usually a soft violation of the Z_2 symmetry by dimension–two terms is allowed, since it does not induce Higgs–mediated tree–level FCNC.

There are many scenarios in 2HDM parameter space still allowed by all the measurements and constrains, in particular, by the Higgs coupling measurements. As an example one can mention recently refreshed [7] so called alignment without decoupling scenario, in which the other Higgs scalars with masses not significantly larger than m_h are not decoupled.

HIGGS SECTOR OF THE MSSM

At the tree level the couplings of the Higgs doublets in the MSSM are basically the same as in the 2HDM of type II. Nevertheless the structure of the tree level Higgs potential is considerably simpler in the MSSM than in the 2HDM of type II. Since the Lagrangian of SUSY models is fully determined by the structure of the gauge interactions and by the superpotential of the model under consideration the quartic Higgs couplings are not independent parameters. In the MSSM the quartic part of the Higgs potential is set by the contribution of D–terms. Therefore at the tree level the quartic Higgs couplings are given by

$$\lambda_1 = \lambda_2 = \frac{\bar{g}^2}{4}, \qquad \lambda_3 = \frac{g_2^2 - g'^2}{4}, \qquad \lambda_4 = -\frac{g_2^2}{2}, \qquad \lambda_5 = \lambda_6 = \lambda_7 = 0\,. \tag{3}$$

As a consequence in these relations the masses and couplings of the Higgs states can be parametrised in terms of the mass of the pseudoscalar Higgs boson m_A and $\tan\beta$ only. The dependence of Higgs boson masses as a function of m_A at various $\tan\beta$ including loop corrections is shown explicitely in [8]. In particular, the analytic expressions for the masses of the charged and CP–even Higgs eigenstates takes the form

$$m^2_{H^\pm} = m_A^2 + M_W^2\,, \qquad m^2_{h,H} = \frac{1}{2}\left(M_{11}^2 + M_{22}^2 \mp \sqrt{(M_{22}^2 - M_{11}^2)^2 + 4M_{12}^4}\right), \tag{4}$$

where

$$M_{11}^2 = M_Z^2 \cos^2 2\beta\,, \qquad M_{12}^2 = -\frac{1}{2}M_Z^2 \sin 4\beta\,, \qquad M_{22}^2 = m_A^2 + M_Z^2 \sin^2 2\beta\,.$$

The qualitative pattern of the Higgs spectrum depends very strongly on m_A. With increasing m_A the masses of all the Higgs particles grow. At very large values of m_A ($m_A^2 \gg v^2$), the lightest Higgs boson mass approaches its theoretical upper limit $\sqrt{M_{11}^2}$, while the heaviest CP–even, CP–odd and charged states are almost degenerate around m_A. Thus at the tree–level m_h is always less than $M_Z \cos 2\beta$. When the Higgs spectrum is rather hierarchical, i.e. $m_A^2 \gg v^2$, the couplings of the lightest CP–even Higgs state are almost the same as the ones of the Higgs boson within the SM.

The inclusion of loop corrections raises the mass of the SM–like Higgs boson in the MSSM. In the simplest SUSY extensions of the SM the dominant contribution to m_h comes from the loops involving the top–quark and its superpartners because of their large Yukawa coupling h_t. When SUSY breaking scale M_S is considerably larger than M_Z and the masses of the superpartners of the top quark $m_{t_1} \simeq m_{t_2} \simeq M_S \gg v$ the contribution of the one–loop corrections to m_h^2 in the leading approximation can be written as

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2, \qquad \Delta m_h^2 \simeq \frac{3m_t^4}{2\pi^2 v^2}\left[\frac{X_t^2}{M_S^2}\left(1 - \frac{1}{12}\frac{X_t^2}{M_S^2}\right) + \ln\left(\frac{M_S^2}{m_t^2}\right)\right], \tag{5}$$

where X_t is a stop mixing parameter and m_t is the running top quark mass . From Equation (5) it follows that the sufficiently large loop corrections to the SM–like Higgs mass can be obtained only if $M_S \gg m_t$ and the ratio $|X_t/M_S|$ is also large. The contribution of the one–loop corrections (5) attains its maximal value for $X_t^2 = 6\,M_S^2$. This is the so–called maximal mixing scenario. Simple estimations show that in order to raise the mass of the SM–like Higgs state to 125 GeV we need at large values of $\tan\beta$ a total loop contribution of $\Delta m_h^2 \simeq (85\,\mathrm{GeV})^2$ which is nearly as large as the value of the tree level mass. So large contribution of loop corrections to m_h implies that stops are substantially heavier than M_Z. As a consequence a tuning at least of order 1% in the MSSM is required to ensure the stabilisation of the EW scale. The value 125 GeV is somewhat smaller than the upper limit on the lightest Higgs mass one can achieve in the maximal mixing scenario. Scenarios with relaxed values for X_t called m_h^{mod+} and m_h^{mod+} where formulated and worked out in [9] and intensively used in experimental analyses [10, 11]. Simple approxiative formulas for relations between the Higgs masses including corrections are given recently in [12] assuming the the mass of the lightest Higgs fixed at 125 GeV. The approximation is valid for rather low $\tan\beta$. Corresponding scenario called hMSSM has been also considered in experimental searches (see [11]).

NATURAL NMSSM HIGGS BOSONS

In the simplest extension of the MSSM, the Next–to–Minimal Supersymmetric Standard Model (NMSSM), the superpotential is invariant with respect to the discrete transformations $\Phi_i \to e^{2\pi i/3}\Phi_i$ of the Z_3 group (for recent review see [13]). The term $\mu(H_u H_d)$ does not meet this requirement. Therefore it is replaced in the superpotential by

$$W_H = \lambda S (H_1 H_2) + \frac{1}{3}\kappa S^3\,, \tag{6}$$

where S is an additional superfield which is a singlet with respect to $SU(2)_W$ and $U(1)_Y$ gauge transformations. A spontaneous breakdown of the $SU(2)_W \times U(1)_Y$ symmetry gives rise to the non–zero VEV of singlet field $< S >= s/\sqrt{2}$ and an effective μ parameter is generated ($\mu_{eff} = \lambda s/\sqrt{2}$).

The NMSSM Higgs potential can be written as a sum

$$V = V_F + V_D + V_{soft} + \Delta V\,, \tag{7}$$

$$V_F = \lambda^2|S|^2(|H_1|^2 + |H_2|^2) + \lambda^2|(H_1 H_2)|^2 + \lambda\kappa\left[S^{*2}(H_1 H_2) + h.c.\right] + \kappa^2|S|^4\,, \tag{8}$$

$$V_D = \frac{g_2^2}{8}\left(H_1^+\sigma_a H_1 + H_2^+\sigma_a H_2\right)^2 + \frac{g'^2}{8}\left(|H_1|^2 - |H_2|^2\right)^2\,, \tag{9}$$

$$V_{soft} = m_1^2|H_1|^2 + m_2^2|H_2|^2 + m_S^2|S|^2 + \left[\lambda A_\lambda S(H_1 H_2) + \frac{\kappa}{3}A_\kappa S^3 + h.c.\right]. \tag{10}$$

At the tree level the Higgs potential (7) is described by the sum of the first three terms. V_F and V_D are the F and D terms. Their structure is fixed by the superpotential (6) and the EW gauge interactions. The soft SUSY breaking terms are collected in V_{soft}. The set of soft SUSY breaking parameters involves soft masses m_1^2, m_2^2, m_S^2 and trilinear couplings A_κ, A_λ. The last term in Eq. (7), ΔV, corresponds to the contribution of loop corrections.

At the physical vacuum of the Higgs potential (7) H_1, H_2 and S acquire non-zero VEVs. The equations for the extrema of the full Higgs boson effective potential (7), i.e.

$$\frac{\partial V}{\partial s} = 0\,, \qquad \frac{\partial V}{\partial v_1} = 0\,, \qquad \frac{\partial V}{\partial v_2} = 0\,, \tag{11}$$

can be used to express soft scalar masses m_S^2, m_1^2, and m_2^2 in terms of other parameters and Higgs VEVs. As a result at the tree-level, the spectrum of the NMSSM Higgs bosons and their couplings can be parametrised in terms of the six parameters: $\lambda, \kappa, \tan\beta, A_\kappa$, A_λ and μ_{eff}. Relations between masses of neutral Higgs states are shown in [14].

It is well known that the fine-tuning of the MSSM could be ameliorated in the NMSSM. The theoretical upper bound on the mass of the lightest Higgs boson in this SUSY model is given by

$$m_h^2 \approx M_Z^2\cos^2 2\beta + \frac{\lambda^2 v^2}{2}\sin^2 2\beta + \Delta m_h^2. \tag{12}$$

Contrary to the MSSM, for $\lambda v > M_Z$, the tree-level contributions to m_h are maximized for moderate values of $\tan\beta$. For example, setting $\lambda = 0.6$ and $\tan\beta = 2$, these tree-level contributions raise the Higgs boson mass to about 100 GeV requiring $\Delta m_h^2 \simeq (75\,\mathrm{GeV})^2$ in order to match the 125 GeV Higgs mass value [15]. Thus with a 125 GeV Higgs boson, due to the fine-tuning of the MSSM, the NMSSM has emerged as a more natural alternative.

Motivated by the fine-tuning consideration it is worth to focus on large values of λ, i.e. $\lambda \gtrsim 0.6$, and the moderate values of $\tan\beta$, i.e. $\tan\beta = 1.5 - 3$, that result in the relatively large values of the top quark Yukawa coupling h_t at low energies. The growth of Yukawa couplings h_t, λ and κ at the EW scale entails the increase of their values at the Grand Unification scale M_X resulting in the appearance of the Landau pole that spoils the applicability of perturbation theory at high energies [16]–[18]. The requirement of validity of perturbation theory up to the scale M_X sets an upper limit on the low energy value of $\lambda(M_Z)$ for each fixed set of $\kappa(M_Z)$ and $h_t(M_t)$ (or $\tan\beta$). In particular, the large value of $\lambda(M_Z) \gtrsim 0.6$ implies that $|\kappa(M_Z)| \lesssim 0.3$ [19].

When $\lambda \gg \kappa$, the Higgs spectrum in the NMSSM has a hierarchical structure and all Higgs matrices can be diagonalised using the perturbation theory [20]-[22]. In this case the heaviest CP–even, CP–odd and charged states are almost degenerate. Their mass scale is set by $\mu_{eff}\tan\beta$ [23]-[25]. Two other CP–even Higgs states and the lightest Higgs pseudoscalar tend to be considerably lighter than the heaviest Higgs bosons. In order to investigate the discovery prospects for the NMSSM Higgs bosons at the High-Energy LHC in this scenario the following part of the parameter space associated with

$$0.6 \le \lambda \le 0.7, \quad -0.3 \le \kappa \le 0.3, \quad 1.5 \le \tan\beta \le 2.5, \quad 100\mathrm{GeV} \le |\mu_{eff}| \le 185\mathrm{GeV}, \tag{13}$$

$$-2\mathrm{TeV} \le A_\lambda, A_\kappa, A_t \le 2\mathrm{TeV}, \quad 100\ \mathrm{GeV} \le M_1 \le 1\ \mathrm{TeV}, \quad 200\ \mathrm{GeV} \le M_2 \le 1\ \mathrm{TeV}, \quad 1.3\ \mathrm{TeV} \le M_3 \le 3\ \mathrm{TeV}$$

was scanned over [26]. In Equation (13) M_1, M_2 and M_3 are the masses of the $U(1)_Y$, $SU(2)_W$ and $SU(3)_C$ gauginos. The value of the effective μ parameter was chosen to be sufficiently low to minimize the fine-tuning. The masses of the first and second generation sfermions as well as the mass of the right-handed sbottom were set to be equal to 3 TeV. All other soft scalar masses were varied from 600 GeV to 3 TeV. It was required that at least one CP–even Higgs state has a mass between 124 GeV and 127 GeV and lead to the signal rates which were consistent with the ones observed by ATLAS and CMS [26]. Only the scenarios that result in the relic dark matter densities which are not larger than $\Omega_c h^2 = 0.1187 \pm 0.0017$ were taken into consideration.

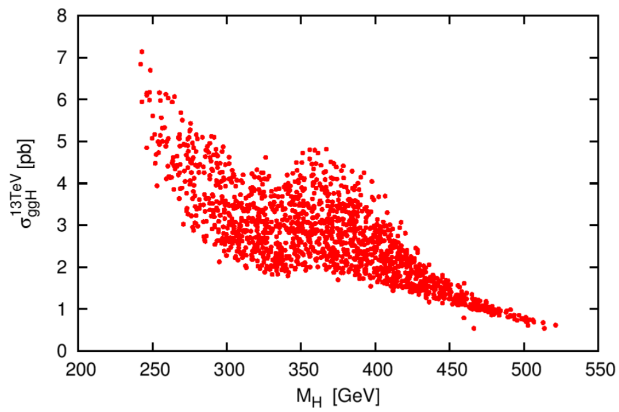

FIGURE 1. The gluon fusion production cross section at $\sqrt{s} = 13$ TeV for H as a function of its mass (see also [26]).

The numerical analysis indicated that in the parameter space under consideration the second lightest CP–even Higgs boson, $H_2 \equiv h$, is SM-like. The heavier CP-even and CP-odd Higgs bosons, $H_3 \equiv H$ and $A_2 \equiv A$, are predominantly a superposition of the components of the Higgs doublets (MSSM-like states). The lightest scalar and pseudoscalar Higgs states, $H_1 \equiv H_s$ and $A_1 \equiv A_s$, are singlet dominated. The almost degenerate heaviest CP-even, CP-odd and charged Higgs states have masses below about 530 GeV, so that they should still be light enough to be observed at the 13 TeV LHC. The H and A gluon fusion production cross sections range between 0.5 pb and a few pb, as shown in Figure 1.

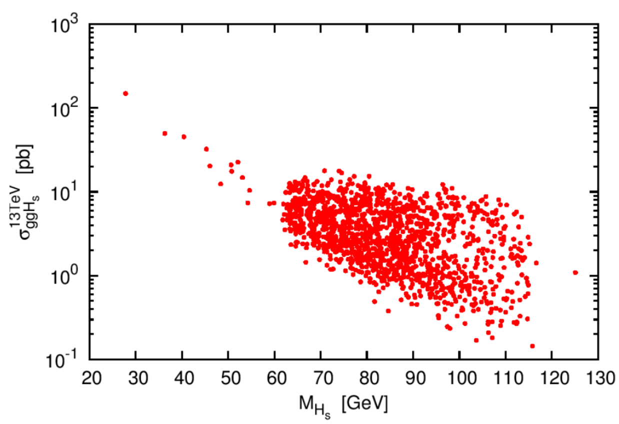

FIGURE 2. The gluon fusion production cross section at $\sqrt{s} = 13$ TeV for H_s as a function of its mass (see also [26]).

Due to the substantial mixing between the SM-like Higgs state and the singlet dominated CP-even state caused by the large value of λ the production cross section of H_s is sufficiently large. The Natural NMSSM scenario discussed here implies the existence of a CP-even Higgs state H_s that has a mass of $62\text{GeV} \lesssim M_{H_s} \lesssim 117\text{GeV}$ and of a CP-odd state A_s with $62\text{GeV} \lesssim M_{A_s} \lesssim 300\text{GeV}$. If masses of H_s and A_s are lower than 62GeV then the SM-like h can decay into these final states and this would reduce signal rates away from the measured values. Figure 2 shows the gluon fusion production cross section for H_s at $\sqrt{s} = 13$ TeV. The lightest pseudoscalar production cross section tend to be an order of magnitude smaller as compared with the one for H_s.

If the light Higgs bosons H_s and A_s are very singlet-like their gluon fusion production rates can be rather small but they may still be produced via the decays of the heaviest Higgs states, because of the large λ value. Indeed, H can decay into pairs H_sH_s, H_sh and A_sA_s resulting in four fermion final state including $(2\tau)(2b)$ and 4τ final state as well as $(2\gamma)(2b)$ final state. Singlet Higgs bosons can be also produced from heavy pseudoscalar A decays into H_sA_s or hA_s. In summary, all Higgs bosons of the Natural NMSSM should in general be accessible at the high-energy LHC (for the detailed analysis, see [26]).

CONCLUDING REMARKS

Higgs-like boson is found at the LHC being in an agreement with the SM Higgs. However a precision of various signal strength measurements is still not good enough leaving many possibilities (points) in parameter space of new models containing extended Higgs sectors, in particular, 2HDM, MSSM, NMMSM, which satisfy all the constrains from EW precision observables, flavor, unitarity, perturbativity, vacuum stability, and searches for dark matter In some scenarios, when one of the Higgs states is 125 GeV CP even scalar boson the other Higgs(es) could be heavier or lighter, or nearly degenerate. Very difficult task is to cover all areas in model parameter spaces and to exclude completely discussed extensions. Well motivated way to proceed is a consideration of benchmark scenarios. Such an approach is under intensive discussion in the framewrok of the BSM Higgs Working Group (Heavy Higgs and Beyond Standard Model subgroup) [27].

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