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Enhanced Higgs associated production with a top quark pair in the NMSSM with light singlets

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ABSTRACT: Precision measurements of the 125 GeV Higgs resonance recently discovered at the LHC have determined that its properties are similar to the ones of the Standard Model (SM) Higgs boson. However, the current uncertainties in the determination of the Higgs boson couplings leave room for significant deviations from the SM expectations. In fact, if one assumes no correlation between the top-quark and gluon couplings to the Higgs, the current global fit to the Higgs data lead to central values of the Higgs couplings to the bottom-quark and the top-quark that are about 2σ away from the SM predictions. In a previous work, we showed that such a scenario could be realized in the Next to Minimal Supersymmetric extension of the SM (NMSSM), for heavy singlets and light MSSM-like Higgs bosons and scalar top quarks, but for couplings that ruined the perturbative consistency of the theory up to the GUT scale. In this work we show that a perturbative consistent scenario, for somewhat heavier stops, may be obtained in the presence of light singlets. An interesting bonus of this scenario is the possibility of explaining an excess of events observed in CP-even Higgs searches at LEP2.

KEYWORDS: Beyond Standard Model, Higgs Physics, Supersymmetric Standard Model

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1 Introduction

After the discovery of a 125 GeV resonance in July 2012 [1, 2], the LHC collaborations have established that its properties are close to the ones of the SM Higgs boson, namely a neutral CP-even scalar. The ratio of the observed Higgs production cross section to the SM predicted values differs from one by just a few tens of percent in most final state channels [3]. This indicates that the couplings to third generation fermions and vector gauge bosons are roughly consistent with their SM predicted values. The measurement of the Higgs production rate in association with top quarks in multilepton channels, however, shows central values that are significantly above the SM expectations [4–8]. Moreover, the search for Higgs bosons produced in association with weak gauge bosons and decaying into bottom quarks have revealed values that tend to be significantly smaller than the SM predicted values. In fact, if one ignores the correlation between the top-quark and gluon couplings to the Higgs, the best fit to the Higgs couplings leads to central values of the Higgs couplings to bottom-quarks and top-quarks that are 2σ away from the SM predicted values, as shown by the recent analysis of the Higgs data by the CMS and ATLAS collaborations [3]. Although these channels are statistically limited, as reflected by the fact that no Higgs discovery may be established in the $t\bar{t}h$ channel at this point, it is worthwhile to analyze if such deviations from the SM predictions may be realized in any realistic low energy extension of the SM.

As has been shown in ref. [9], a Higgs with enhanced couplings to the top quark and suppressed couplings to the bottom quark may be easily obtained in two Higgs doublet models (2HDM), for values of $\tan\beta$, the ratio of vacuum expectation value, close to one. The trouble with these models is that the coupling of the Higgs to gluons is in first approximation proportional to the Higgs coupling to the top quark and therefore one would expect enhanced gluon fusion production rates too, what is in conflict with experiment. In addition, the bottom coupling suppression would lead to a reduction of the width of the

Higgs decay into bottom quarks, and to a subsequent enhancement of the branching ratios of the Higgs decay into vector gauge bosons.

A consistent solution to this problem may be obtained in the presence of additional light color degrees of freedom, with significant couplings to the Higgs and that may lead to contributions to the gluon coupling that compensates the top-quark ones.¹ A particular example is the case of low-energy supersymmetry [12], in which these new colored particles are just given by the stops, the superpartners of the top quark. It was demonstrated that if the lightest stop mass is of the order of a few hundred GeV and the stop mixing parameters are large, the Higgs rates may be brought to agreement with the experimentally observed ones [9]. This solution cannot be realized in the Minimal Supersymmetric extension of the SM (MSSM) since it is difficult to obtain the right Higgs mass for such small values of $\tan\beta$ and the stop masses and, in addition, the Higgs mixing effects in this model lead to an enhancement of the Higgs bottom coupling and a suppression of the top one, that is the opposite as the tendency indicated by data.

In ref. [9] it was shown that this problem may be fixed in the simplest extension of the MSSM, with the addition of a singlet superfield, namely the NMSSM [13]. In such a case, the same coupling λ that enhances the Higgs mass modifies the CP-even Higgs mixing, leading to couplings of the Higgs consistent with the observed ones. It was shown that, for heavy singlets, the required values of λ , the superpotential coupling of the singlet to the Higgs doublet superfields, were $\lambda > 0.7$, what leads to the breakdown of the perturbative consistency of the theory below the GUT scale. In this article, we shall show that an alternative solution can be obtained for the case of light singlets. In such a case, the values of λ can be lower than 0.7 and a perturbative consistent solution can be found. In addition, although this is not a requirement of this scenario, we shall demonstrate that values of the masses and couplings to vector bosons of the (predominantly singlet) lightest CP-even Higgs, consistent with the ones required to explain an observed excess in the LEP2 Higgs search data [14], can be obtained in this scenario.

The possibility of a $t\bar{t}h$ coupling enhancement was also studied in the context of models with vector-like top quark partners that mix with the top quark [15]. The $t\bar{t}h$ production excess is mainly driven by the multi-lepton channel and is one of several excesses in searches in final states consisting of bottom quarks and many leptons [16–18]. Such excesses were also explained in models with standard Higgs sector by introducing new scalar or fermion particles [19–21].

This article is organized as follow. In section 2 we review the conditions to obtain an enhancement of the Higgs-top-quark coupling in the presence of light singlets. In section 3 we present the NMSSM realization and in section 4 we present a numerical analysis of the Higgs production rates in this scenario. In section 5 we analyze the phenomenology of the non-standard Higgs bosons. We reserve section 6 for our conclusions.

¹The degeneracy in the gluon fusion production cross-section between the top quark and New Physics contributions can be broken by studying production of a boosted Higgs with a jet, see e.g. [10, 11].

2 Enhanced tth coupling with a light singlet

In order to enhance the associated production of h with a top quark pair (which we shall denote tth) in a model with two Higgs doublets the 125 GeV Higgs eigenstate must have a non-negligible component in the non-SM-like doublet. In type-II 2HDM the CP-even Higgs couplings to fermions and gauge bosons (normalized to the SM values) are determined by the values of the CP-even Higgs mixing angle α and $\tan\beta$, the ratio of the two Higgs doublet vacuum expectation values in the following way:

$$c_t = \frac{\cos\alpha}{\sin\beta} = \sin(\beta - \alpha) [1 + \cot\beta \cot(\beta - \alpha)] , \quad (2.1)$$

$$c_b = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta - \alpha) [1 - \tan\beta \cos(\beta - \alpha)] , \quad (2.2)$$

$$c_V = \sin(\beta - \alpha) , \quad (2.3)$$

where $c_i = g_{hii}/g_{hii}^{\text{SM}}$ denotes the ratio of the Higgs coupling to the i particle normalized to its SM value. Enhanced tth is obtained for low $\tan\beta$ and sizeable $\cot(\beta - \alpha) > 0$. In a pure 2HDM, in which the coupling of the Higgs bosons to gluons is induced by loops of third generation quarks, enhanced tth is inevitably correlated with enhanced Higgs production in the gluon fusion channel, which is phenomenologically unacceptable. One can avoid this correlation if there exist additional light colored states, such as stops, that give negative contribution to the effective Higgs coupling to gluons [9]. It was demonstrated in ref. [9] that in such a case enhancement of the tth signal of the Higgs decaying to gauge bosons can be larger than in the SM by a factor of two without violation of any experimental constraints. Moreover, it was shown in ref. [9] that this can be also realized in the NMSSM with heavy singlets, which effectively corresponds to a type-II 2HDM, with relatively light highly-mixed stops. The stop contributions modify the effective Higgs coupling to gluons and photons in the following way, see e.g. refs. [22, 23]:

$$\frac{c_g}{c_g^{\text{SM}}} = \frac{c_\gamma}{c_\gamma^{\text{SM}}} = c_t + \frac{m_t^2}{4} \left[c_t \left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} \right) - \frac{\tilde{X}_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right] , \quad (2.4)$$

where $\tilde{X}_t^2 \equiv X_t \left(A_t \frac{\cos\alpha}{\sin\beta} + \mu \frac{\sin\alpha}{\sin\beta} \right)$ with the stop mixing parameter given by $X_t \equiv A_t - \mu/\tan\beta$ (note: in the decoupling limit $\tilde{X}_t^2 = X_t^2$). It should be clear from the above formula that significant reduction of the Higgs coupling to gluons is possible only for light enough stops. At the ICHEP 2016 conference, the LHC collaborations presented new constraints on the lightest stop mass, which are quite strong in simplified models in which the mass difference between the stop and the lightest supersymmetric particle is large [24–28]. However, the constraints are still relatively weak for small mass splitting between the stop and the LSP. In order to avoid constraints on light sbottoms it is preferred that the lightest stop is mostly right-handed. The limit is especially weak if the lightest stop decays mainly to charm and neutralino. For such topology a lightest stop as light as about 260 GeV is allowed if the stop-LSP mass splitting is above about 20 GeV (but not large enough to make the stop decays to charm and neutralino subdominant) [29–32].

Another important requirement to induce a large tth enhancement in the NMSSM with heavy singlets is that the value of $\lambda \gtrsim 0.8$ [9]. Such large values of λ lead to a Landau pole below the Grand Unification (GUT) scale, $M_{\text{GUT}} \simeq 2 \cdot 10^{16}$ GeV. In the following, we will show that smaller values of λ are possible if the singlets are light.

If in addition to the CP-even Higgs bosons proceeding from the two Higgs doublets also a singlet is light, in order to determine non-SM doublet component of the 125 GeV Higgs one needs to consider three-by-three Higgs mass matrix (in the Higgs basis):²

$$\hat{M}^2 = \begin{pmatrix} \hat{M}_{hh}^2 & \hat{M}_{hH}^2 & \hat{M}_{hs}^2 \\ \hat{M}_{hH}^2 & \hat{M}_{HH}^2 & \hat{M}_{Hs}^2 \\ \hat{M}_{hs}^2 & \hat{M}_{Hs}^2 & \hat{M}_{ss}^2 \end{pmatrix}. \quad (2.5)$$

Since the singlet does not couple to SM particles, the couplings of the 125 GeV are still given by eqs. (2.1)–(2.3) but the effective $\cot(\beta - \alpha)$ depends now also on the mixing of the singlet with the Higgs doublets:

$$\cot(\beta - \alpha) = \frac{(m_h^2 - \hat{M}_{hh}^2) \hat{M}_{Hs}^2 + \hat{M}_{hs}^2 \hat{M}_{hH}^2}{(\hat{M}_{HH}^2 - m_h^2) \hat{M}_{hs}^2 - \hat{M}_{Hs}^2 \hat{M}_{hH}^2}. \quad (2.6)$$

In the above the effective $\sin(\beta - \alpha)$ and $-\cos(\beta - \alpha)$ are defined as the \hat{h} and \hat{H} components of h , respectively. We see that it is possible to generate non-zero $\cot(\beta - \alpha)$ even for $\hat{M}_{hH}^2 = 0$. This feature is particularly important in the context of the NMSSM since for the most interesting values of $\lambda \approx 0.65$ (which give a large positive correction to the Higgs mass but do not generate the Landau pole below the GUT scale) $\hat{M}_{hH}^2 \approx 0$ which is known as the NMSSM alignment limit [33, 34]. Notice also that in the limit $\hat{M}_{hH}^2 = 0$, tth is enhanced for $\hat{M}_{hs}^2 \hat{M}_{Hs}^2 > 0$ (< 0) if the singlet-like scalar is lighter (heavier) than 125 GeV. This is because in this limit mixing of the Higgs with lighter (heavier) singlet-like scalar pushes up (down) the Higgs mass so $(m_h^2 - \hat{M}_{hh}^2)$ is positive (negative) [35–37]. It is also interesting to note that in principle large $\cot(\beta - \alpha)$ may be also obtained for very heavy non-SM Higgs doublet if $|\hat{M}_{Hs}^2|$ is large enough.

3 NMSSM realization

Let us now focus on tth enhancement in the general NMSSM for which the MSSM superpotential is supplemented by:

$$W_{\text{NMSSM}} = \lambda S H_u H_d + \xi_F S + \mu' S^2/2 + \kappa S^3/3. \quad (3.1)$$

²The Higgs basis $(\hat{h}, \hat{H}, \hat{s})$ is defined as $\hat{h} = H_d \cos \beta + H_u \sin \beta$, $\hat{H} = H_d \sin \beta - H_u \cos \beta$ and $\hat{s} = S$. In this basis the \hat{h} field has exactly the same couplings to the gauge bosons and fermions as the SM Higgs field. The field \hat{H} is a non-SM-like doublet which does not couple to the gauge bosons and its couplings to the down and up fermions are the SM Higgs ones rescaled by $\tan \beta$ and $-\cot \beta$, respectively. The mass eigenstates are denoted as s, h, H , with the understanding that h is the SM-like Higgs.

and the soft terms are given by

$$-\mathcal{L}_{\text{soft}} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \left(A_\lambda \lambda H_u H_d S + \frac{1}{3} A_\kappa \kappa S^3 + m_3^2 H_u H_d + \frac{1}{2} m_S'^2 S^2 + \xi_S S + \text{h.c.} \right), \quad (3.2)$$

where S is a SM-singlet superfield which scalar component acquires vacuum expectation value v_s . The first term is the source of the effective higgsino mass parameter, $\mu_{\text{eff}} \equiv \lambda v_s$ (we drop the subscript “eff” in the rest of the paper and we set explicitly the MSSM μ -term to zero by shifting the value of S , what amounts to a simple redefinition of some of the parameters).

The off-diagonal terms of the tree-level Higgs mass matrix in the Higgs basis in the general NMSSM are given by:

$$\hat{M}_{hH}^2 = \frac{1}{2} (M_Z^2 - \lambda^2 v^2) \sin 4\beta, \quad (3.3)$$

$$\hat{M}_{hs}^2 = \lambda v (2\mu - \Lambda \sin 2\beta), \quad (3.4)$$

$$\hat{M}_{Hs}^2 = \lambda v \Lambda \cos 2\beta. \quad (3.5)$$

where $\Lambda \equiv A_\lambda + \mu' + 2\kappa v_s$, $v \approx 174$ GeV, and we have ignored loop-corrections that are generically small and have a minor phenomenological impact in the region of parameters relevant for this work [33, 34]. The diagonal mass in the SM-like Higgs component is given by:

$$\hat{M}_{hh}^2 = M_Z^2 \cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta) + \Delta_{\text{loop}}, \quad (3.6)$$

where Δ_{loop} parameterizes loop corrections which are dominated by stops.

The explicit form of the remaining diagonal entries of the Higgs mass matrix, that can be found e.g. in ref. [37], is not relevant for our discussion, since in the general NMSSM there is enough freedom in the parameter space to set them to arbitrary values.

Eq. (3.6) implies that for small values of $\tan \beta$ the Higgs mass of 125 GeV can be accommodated only for relatively large $\lambda \gtrsim 0.5$ unless stops are heavy. On the other hand, avoiding a Landau pole below the GUT scale sets requires $\lambda \lesssim 0.7$ (for $\kappa \ll \lambda$) with the upper bound getting stronger as $\tan \beta$ decreases. For this range of λ the lack of a Landau pole below the GUT scale for the top Yukawa coupling requires also $\tan \beta \gtrsim 1.5$. As a result, in this range of parameters $\hat{M}_{hH}^2 \approx 0$ so using eqs. (3.4)–(3.5) together with eq. (2.6) one obtains the following approximate formula for the effective $\cot(\beta - \alpha)$:

$$\cot(\beta - \alpha) \approx \frac{(m_h^2 - \hat{M}_{hh}^2) \lambda v \Lambda \cos 2\beta}{(\hat{M}_{HH}^2 - m_h^2) \hat{M}_{hs}^2} \approx \text{sgn} \left(\frac{\Lambda \sin 2\beta - 2\mu}{m_h - m_s} \right) \bar{g}_s \frac{\lambda v \Lambda \cos 2\beta}{\hat{M}_{HH}^2 - m_h^2}, \quad (3.7)$$

where \bar{g}_s is the s coupling to the Z boson normalized to the corresponding coupling of the SM Higgs with the same mass. In the approximation made on the very right hand side of the above equation we assumed $\bar{g}_s^2 \ll 1$ which is justified since the Higgs-singlet mixing must be relatively small to comply with constraints from the LHC and LEP. Smallness of the Higgs-singlet mixing requires $|\hat{M}_{hs}^2| \ll m_h^2 + m_s^2$ which is fulfilled when

$$\Lambda \approx \frac{2\mu}{\sin 2\beta}, \quad (3.8)$$

and implies in particular that $\mu\Lambda$ must be positive. We should stress, however, that the above condition should not be satisfied exactly because otherwise $\cot(\beta - \alpha)$ would vanish. Using the above condition together with eq. (3.7) one obtains an approximate formula for the effective $\cot(\beta - \alpha)$ as a function of μ , namely

$$\cot(\beta - \alpha) \approx \text{sgn}\left(\frac{\Lambda \sin 2\beta - 2\mu}{m_h - m_s}\right) \bar{g}_s \frac{\lambda v \mu \cot 2\beta}{\hat{M}_{HH}^2 - m_h^2}. \quad (3.9)$$

In order to enhance tth signal one has to also guarantee that $\cot(\beta - \alpha) > 0$ which happens if the following condition is fulfilled:

$$|\Lambda| > \frac{2|\mu|}{\sin 2\beta} \quad \left(|\Lambda| < \frac{2|\mu|}{\sin 2\beta} \right) \quad (3.10)$$

for $m_s < m_h$ ($m_s > m_h$).

Eq. (3.9) confirms the intuitive expectation that large tth enhancement prefers relatively light MSSM-like Higgs bosons. However, it also shows that large $|\mu|$ is preferred and that H does not have to be very light if $|\mu|$ is large enough. The importance of $|\mu|$ can be seen from table 1 where several benchmark points with large tth enhancement are presented. We shall define the theoretically predicted signal strengths modifiers as:

$$R_i^j \equiv \frac{\sigma^j \times \text{BR}(h \rightarrow i)}{\sigma^{j\text{SM}} \times \text{BR}^{\text{SM}}(h \rightarrow i)}, \quad (3.11)$$

and we shall distinguish the theoretical predictions for the signal strengths from the corresponding LHC measurements, that we define in the conventional way as μ_i^j . Comparing points P3 and P4 we see that similar tth enhancement is possible for $M_A = 300$ GeV and $\mu = 500$ GeV as for $M_A = 400$ GeV and $\mu = 650$ GeV with comparable Higgs-singlet mixing. Eq. (3.9) also implies that the effective $|\cot(\beta - \alpha)|$ increases with $\tan\beta$. This is the reason why points P1 and P3 have similar values of R_{VV}^{tth} in spite of the fact that P3 features smaller Higgs-singlet mixing and the value of μ while the value of M_A is the same.

Another interesting feature of this scenario is that light singlet-like scalar can explain the LEP2 excess [14]. Indeed, the LEP2 experiments observed an excess of $b\bar{b}$ events, produced in association with a Z gauge boson, with an invariant mass in the vicinity of 98 GeV and a signal strength of about one tenth of the one of the SM Higgs with the same mass. Phenomenological aspects of the NMSSM with singlet-like scalar explaining the LEP2 excess were studied e.g. in refs. [41–43] while in refs. [44, 45] it was shown that this excess can be explained in a UV complete NMSSM model based on gauge mediated SUSY breaking [46]. However, none of those works links the LEP2 excess to the tth enhancement. In table 1 we give a value for the prediction of this signal strength:

$$\xi_{b\bar{b}}^{\text{LEP}} \equiv \bar{g}_s^2 \times \frac{\text{BR}(s \rightarrow b\bar{b})}{\text{BR}(h^{\text{SM}} \rightarrow b\bar{b})}, \quad (3.12)$$

Note that the SM normalized $s\bar{b}b$ coupling in the present scenario is enhanced with respect to the corresponding sZZ coupling so $\xi_{b\bar{b}}^{\text{LEP}} > \bar{g}_s^2$. We see that point P1 fits very well the LEP2 excess since it features $m_s \approx 98$ GeV and $\xi_{b\bar{b}}^{\text{LEP}} \approx 0.1$. Point P2 also has $m_s \approx$

	P1	P2	P3	P4
λ	0.5	0.52	0.5	0.52
$\tan \beta$	1.6	1.6	2	2
m_{Q_3}	800	800	800	800
m_{U_3}	240	250	235	200
A_t	-1500	-1500	-1550	-1480
μ	550	650	500	650
μ'	310	350	235	250
M_A	300	300	300	400
M_P	244	308	297	305
A_λ	810	963	908	1305
m_s	98	98	88	84
m_h	124.9	125.6	124.9	126.3
m_H	303	336	355	414
m_{H^\pm}	217	199	224	317
m_a	108	94	105	87
m_A	311	358	359	434
$m_{\tilde{\chi}_1^0}$	235	235	235	235
$m_{\tilde{t}_1}$	272	277	276	275
$m_{\tilde{t}_2}$	946	951	945	948
R_{VV}^{tth}	1.60	1.62	1.60	1.60
$R_{\gamma\gamma}^{\text{tth}}$	1.83	1.85	1.80	1.78
R_{VV}^{gg}	1.02	1.00	1.04	1.04
$R_{\gamma\gamma}^{\text{gg}}$	1.16	1.15	1.16	1.16
$R_{VV}^{\text{VBF/VH}}$	1.32	1.34	1.41	1.39
$R_{\gamma\gamma}^{\text{VBF/VH}}$	1.51	1.54	1.58	1.55
$R_{\tau\tau}^{\text{VBF/VH}}$	0.72	0.76	0.77	0.73
ξ_{bb}^{LEP}	0.10	0.06	0.04	0.06
\bar{g}_s	0.30	0.24	0.20	0.24

Table 1. List of benchmark points obtained with `NMSSMTools` 5.0.0 [38, 39]. All masses are in GeV. All points satisfy all experimental constraints from the Higgs signal strength measurements, as well as from direct searches for Higgs bosons, checked with `HiggsBounds` 4.3.1 [40], and stops. The gluino and the remaining soft sfermion masses are set to 2 TeV, $M_2 = 1$ TeV, $M_1 = -235$ GeV. All the remaining A -terms are set to 1.5 TeV, while $\kappa = A_\kappa = m_3^2 = m_{\tilde{G}}^2 = 0$. The remaining parameters are calculated with `NMSSMTools` using EWSB conditions and the values of μ , M_A (diagonal mass of MSSM-like pseudoscalar) and M_P (diagonal mass of singlet-like pseudoscalar).

98 GeV but smaller Higgs-singlet mixing, hence also ξ_{bb}^{LEP} , than P1 so in order to have tth enhancement of similar size $|\mu|$ is larger in P2 than in P1.

Even though it is an interesting possibility that this scenario can simultaneously explain the tth enhancement and the LEP2 excess, we should emphasize that our scenario does not require to have the singlet-like scalar mass to be close to the one necessary to explain the LEP excess. It is the size of the Higgs-singlet mixing rather than m_s which controls the magnitude of the tth enhancement as can be seen from benchmarks P3 and P4 that feature m_s far away from the one consistent with the LEP excess. It is noteworthy that m_s can be as small as about 85 GeV (or even smaller if $|\mu|$ is larger than in benchmark P4) without inducing a conflict with stringent LEP constraints.

4 Higgs signal rates

All benchmark points presented in table 1 are compatible with the combination of the run-I Higgs signal measurements [3] at least at the 2σ level. Nevertheless, there are some potential tensions of this scenario with recent run II data that will be probed with future LHC measurements. Let us now discuss these deviations and how they depend on the model parameters in some more detail. Let us start with the $\gamma\gamma$ decay channel in the gluon fusion production mode. All benchmarks were chosen to have $R_{\gamma\gamma}^{\text{gg}} \approx 1.15$ by appropriate adjustment of the stop sector parameters. This is very close to the central value of the ATLAS and CMS combination of the Run-I data which yields $\mu_{\gamma\gamma}^{\text{gg}} = 1.10_{-0.22}^{+0.23}$ [3]. Preliminary results of Run II indicate that both experiments observed some suppression of this signal strength: $\mu_{\gamma\gamma}^{\text{gg}} = 0.59_{-0.28}^{+0.29}$ for ATLAS [47] and $\mu_{\gamma\gamma}^{\text{gg}} = 0.77_{-0.23}^{+0.25}$ for CMS [48] so the 2σ upper bound from ATLAS Run II on $R_{\gamma\gamma}^{\text{gg}}$ is about 1.17. By the end of this year the LHC is expected to deliver a few times more data than analysed for ICHEP2016 so the discrepancy between the Run-I and Run-II results should be clarified relatively soon.

While the mechanism that we propose may generate some tension with the Run-II measurement of $\mu_{\gamma\gamma}^{\text{gg}}$ the fit to the Run-II results for $h \rightarrow \gamma\gamma$ in the VBF production mode is significantly improved. Indeed, the ATLAS Run-II result is $\mu_{\gamma\gamma}^{\text{VBF}} = 2.24_{-0.71}^{+0.80}$ which is almost 2σ above the SM prediction. It can be seen from the benchmark table that in the present scenario it is generically brought to 1σ agreement with the ATLAS result. Moreover, the prediction is very close to the central value of the Run-II CMS result of $\mu_{\gamma\gamma}^{\text{VBF}} = 1.61_{-0.8}^{+0.9}$.

As already emphasized, the present scenario features also suppressed Higgs coupling to down-type fermions. This is in very good agreement with very weak signal of the Higgs decaying into $b\bar{b}$ observed in both Run I and Run II of the LHC. On the other hand, the Higgs decays to $\tau\tau$ in the VBF production mode (gluon fusion is far less sensitive in this decay channel) has been observed to be relatively close to the SM prediction. Nevertheless, due to the large uncertainties, values of $R_{\tau\tau}^{\text{VBF/VH}}$ as small as about 0.4 (0.8) are consistent with current data at 2σ (1σ) level [3]. We can see from table 1 that $R_{\tau\tau}^{\text{VBF/VH}}$ is in the range between 0.7 and 0.8 for R_{VV}^{tth} of about 1.6. Larger values of $R_{\tau\tau}^{\text{VBF/VH}}$ keeping the same value of R_{VV}^{tth} are obtained for smaller Higgs-singlet mixing which is evident from comparison of benchmark P1 with the other ones. Needless to say that $R_{\tau\tau}^{\text{VBF/VH}}$ also deviates less from the SM prediction when R_{VV}^{tth} is smaller. It is also interesting to note

that a given value of R_{VV}^{tth} fitting the LEP2 excess fixes $R_{\tau\tau}^{\text{VBF/VH}}$ (up to small variations from $\tan\beta$ dependence), e.g. $R_{VV}^{\text{tth}} \approx 1.6$ implies $R_{\tau\tau}^{\text{VBF/VH}} \approx 0.7$ as for benchmark P1. Such indirect cross-check is particularly important since in this scenario the CP-even singlet s decays are predominantly into $b\bar{b}$ final states.

Let us also note that the larger $\tan\beta$ is the more enhancement of R_{VV}^{tth} comes from suppressed $\text{BR}(h \rightarrow b\bar{b})$ which results in closer values for signal rates in tth and VBF/VH production modes. Therefore, if the excess in the tth channel persists, information about $\tan\beta$ may be also extracted from future Higgs precision measurements.

We should also comment that all benchmarks presented in table 1 feature rather large values of $|X_t|$ with $|X_t|/m_{\tilde{t}_2}$ around two. Such values are needed to keep the gluon fusion signal rates close to SM predictions when the tth signals are enhanced. It is known from MSSM studies that too large values of $|A_t|$ may lead to color and/or charge breaking global minima [49]. Indeed, all the benchmarks in table 1 feature unphysical global minima. Whether these benchmarks are phenomenologically viable depends on the lifetime of the metastable EW vacuum. It was recently shown that constraints on $|A_t|$ from stability of the EW vacuum are overestimated by analytical formulae, presented e.g. in ref. [49], if one admits as a viable solution sufficiently long-lived metastable EW vacua [50–52]. It was also emphasized in ref. [52] that it is essentially impossible to have a simple universal phenomenological formula that may reliably estimate whether a given point in the MSSM parameter space leads to destabilization of the EW vacuum and a dedicated study is necessary. Moreover, the MSSM analyses considered only moderate and large $\tan\beta$, which is not our case. Last but not least, the NMSSM scalar potential has a richer structure than the MSSM one. Studies of color and charge breaking vacua in the scale-invariant NMSSM have been performed in the past but they either consider NMSSM specific directions [53, 54] in field space or give a simple generalizations of the MSSM analytical formulae [55] which do not account for the fact that EW vacuum may be metastable and long-lived. It is beyond the scope of the present paper to investigate the conditions for metastability of the EW vacuum in the general NMSSM and we leave a dedicated study of this issue for future work. Nevertheless, we expect that for a given value of the lightest stop mass there exist an upper bound on $|X_t|/m_{\tilde{t}_2}$ which could be translated to an upper bound on possible tth enhancement after taking into account the Higgs measurements in the gluon fusion production modes.

5 Non-SM-like Higgs phenomenology

The phenomenology of non-SM-like Higgs bosons is significantly different from that in the case of heavy singlet discussed in ref. [9]. Both, light and heavy singlet scenarios feature heavy doublet-like Higgs bosons in the range of several hundred GeV but their dominant decay channels are totally different. In the heavy singlet case H and A have large branching ratio for decay into a pair of lightest neutralinos and $H \rightarrow hh$ decay is also very frequent if kinematically accessible. In contrast, in the light singlet scenario H/A decay products in dominant channels involve light singlet-like (pseudo)scalars, as can be seen from table 3. The main decay mode for A is as and Zs . $\text{BR}(A \rightarrow H^\pm W^\mp)$ may also be large if this decay channel is kinematically open. The main decay channels for H involve aa , aZ and

sometimes ss and $H^\pm W^\mp$. The only existing analysis that may probe the sector of heavy neutral Higgses is the CMS search for $A \rightarrow Zs$ or $H \rightarrow Za$ with Z decaying leptonically and the lighter pseudo(scalar) decaying to $b\bar{b}$. Branching ratios of $A \rightarrow Zs$ and $H \rightarrow Za$ vary between 10 and 40 % [58, 59]. The upper limits on the 13 TeV cross-section for $llb\bar{b}$ production in this topology are between 0.1 and 1 pb (depending on the masses of the heavy and light Higgs bosons) with 2.3 fb^{-1} of 13 TeV CMS data. This is at least factor of few above the prediction for this cross-section for the benchmark points presented in table 3. Therefore, with $\mathcal{O}(50) \text{ fb}^{-1}$ it may be possible to probe some of the parameter space that predicts tth enhancement but for a generic point in parameter space this would require much more data. Searches for double Higgs production in $b\bar{b}b\bar{b}$ final state may be more powerful to test this model provided that the experimental collaborations will relax the assumption that the products of heavy resonance decay have mass of 125 GeV as it is assumed in existing analyses [60, 61]. It is also noteworthy that $H \rightarrow hh$ decays are negligible in the light singlet scenario which is due to the fact that the correct Higgs mass requires $\lambda \approx 0.5$ for which Hhh coupling is strongly suppressed due to approximate alignment in the $\hat{h} - \hat{H}$ sector [33, 34].

The charged Higgs is also relatively light. It is typically not far above $H^\pm \rightarrow tb$ threshold while the ATLAS Run-II results for charged Higgs search in $t\bar{b}$ decay mode are available only for $m_{H^\pm} > 300 \text{ GeV}$ with the strongest upper bound on $\tan\beta$ in type-II 2HDM with $\text{BR}(H^\pm \rightarrow tb) = 100\%$ of about 1.7 for $m_{H^\pm} = 300 \text{ GeV}$ [62]. While the charged Higgs production cross-section in our model is expected to be similar as in the type-II 2HDM, $\text{BR}(H^\pm \rightarrow tb)$ is much less than 100 % since charged Higgs often decays to W^+a and W^+s which weakens the bound on $\tan\beta$ significantly. This is the reason why benchmark P4 which features $m_{H^\pm} > 300 \text{ GeV}$ comfortably satisfies current constraints. Nevertheless, future searches for charged Higgs in $t\bar{b}$ decay mode may probe important part of the model parameter space, especially if they are extended to masses below 300 GeV. While there are difficulties in reliable computation of the charged Higgs production cross-section for masses close to the top quark mass, some progress has been made on this front recently [63], so comparing the experimental results with theoretical predictions may be easier now. Moreover, it was argued in ref. [64] that the NMSSM charged Higgs decaying to W^+a could be efficiently probed in searches for events with missing transverse momentum, b-jets, leptons and/or taus.

As already emphasized, the crucial feature that allows for significant tth enhancement is large mixing between singlet scalar and MSSM-like doublet scalar. This generically implies also large mixing in the pseudoscalar sector. Indeed, for benchmarks presented in tables 1–3 this mixing is close to maximal. One consequence of this is large gluon-fusion production cross-section for lighter pseudoscalar, as seen from table 3. Direct production of a may be discovered at the LHC in the $\tau\tau$ decay channel which contributes about 10 % to total decay width of a (the remaining 90 % of a decays are to $b\bar{b}$ but this decay channel is extremely difficult to observe in the gluon-fusion production mode at the LHC). On the other hand, CMS $\tau\tau$ search extends down to masses of about 90 GeV, so it covers an interesting part of parameter space of the model including benchmarks P1-P3. The current upper limit on $\sigma(gga) \times \text{BR}(a \rightarrow \tau\tau)$ from the 13 TeV CMS search with 2.3 fb^{-1} of data [65] is about 40 pb for the mass close to 100 GeV with the limit improving rather quickly for masses above

	P5	P6
λ	0.48	0.5
$\tan \beta$	1.6	2
κ	0.48	0.48
m_{Q_3}	800	800
m_{U_3}	195	190
A_t	-1400	-1450
μ	700	700
A_λ	-15	223
A_κ	-3678	-3431
ξ_S	-10^9	-10^9
m_3^2	$-4.9 \cdot 10^5$	$-6.1 \cdot 10^5$
$m_S'^2$	0	$-3.64 \cdot 10^6$
m_s	98	90
m_h	125.1	125.5
m_H	325	405
m_{H^\pm}	246	271
m_a	2834	107
m_A	248	442
$m_{\tilde{\chi}_1^0}$	235	234
$m_{\tilde{t}_1}$	271	277
$m_{\tilde{t}_2}$	950	949
R_{VV}^{tth}	1.59	1.59
$R_{\gamma\gamma}^{\text{tth}}$	1.81	1.76
R_{VV}^{gg}	1.03	1.05
$R_{\gamma\gamma}^{\text{gg}}$	1.17	1.16
$R_{VV}^{\text{VBF/VH}}$	1.31	1.40
$R_{\gamma\gamma}^{\text{VBF/VH}}$	1.49	1.56
$R_{\tau\tau}^{\text{VBF/VH}}$	0.71	0.77
ξ_{bb}^{LEP}	0.11	0.04
\bar{g}_s	0.32	0.20

Table 2. List of benchmark points that avoid unphysical global minimum. Unspecified MSSM-like parameters are the same as in table 1 while $\mu' = \xi_F = 0$. All dimensionful parameters are in GeV except for ξ_S in GeV^3 and m_3^2 and $m_S'^2$ in GeV^2 .

	P1	P2	P3	P4	P5	P6
BR($H \rightarrow t\bar{t}$)	0	0	0.01	0.07	0	0.17
BR($H \rightarrow ss$)	0.32	j0.01	0.05	0.28	0.72	0.01
BR($H \rightarrow aa$)	0.31	0.66	0.39	0.12	0	0.81
BR($H \rightarrow aZ$)	0.22	0.19	0.35	0.38	0	0.12
BR($H \rightarrow hs$)	0.11	j0.01	j0.01	0.11	0.24	j0.01
BR($H \rightarrow H^\pm W^\mp$)	0.01	0.13	0.19	0.03	0	0.05
BR($A \rightarrow t\bar{t}$)	0	0.14	0.13	0.18	0	0.06
BR($A \rightarrow as$)	0.66	0.39	0.32	0.35	0	0.61
BR($A \rightarrow Zs$)	0.22	0.23	0.33	0.32	0.95	0.14
BR($A \rightarrow ah$)	0.08	j0.01	j0.01	0.05	0	0.07
BR($A \rightarrow H^\pm W^\mp$)	0.04	0.24	0.20	0.08	0	0.12
BR($H^+ \rightarrow t\bar{b}$)	0.58	0.43	0.34	0.29	0.70	0.30
BR($H^+ \rightarrow W^+a$)	0.19	0.34	0.27	0.38	0	0.34
BR($H^+ \rightarrow W^+s$)	0.23	0.23	0.39	0.32	0.29	0.36
$\sigma(ggH)$ [pb]	2.4	1.6	1.2	1.4	2.7	1.2
$\sigma(ggA)$ [pb]	4.9	5.2	4.0	2.2	11.9	1.3
$\sigma(gga)$ [pb]	24.3	40.4	18.7	19.2	10^{-9}	17.7
$\sigma(ggs)$ [pb]	4.6	10.6	10.3	7.1	3.9	9.8
$\Omega_{\text{th}} h^2$	0.08	0.09	0.07	0.06	0.08	0.07
$\sigma_{\text{SI}}^{\text{p}}$ [pb]	$3.8 \cdot 10^{-10}$	$3 \cdot 10^{-10}$	$8.4 \cdot 10^{-10}$	$4.3 \cdot 10^{-10}$	$2.5 \cdot 10^{-10}$	$3.8 \cdot 10^{-10}$

Table 3. Branching ratios and gluon-fusion production cross-sections (calculated with SuShi 1.6.0 [56, 57]) for non-SM-like Higgs bosons for benchmark points presented in tables 1 and 2. Thermal relic abundance $\Omega_{\text{th}} h^2$ of the LSP and SI LSP-proton scattering cross-section $\sigma_{\text{SI}}^{\text{p}}$ are also given.

about 120 GeV. Therefore, the limit is an order of magnitude above the benchmark predictions so while some of the parameter space may be probed with 300 fb^{-1} , as exemplified by P2, vast of the parameter space will require high-luminosity LHC to be covered.

Weaker constraints for a ditau resonance with mass about 100 GeV are also the reason why it is hard to probe the production of the 98 GeV singlet scalar explaining the LEP excess. For benchmark P1 which fits the LEP excess the cross-section for $\tau\tau$ from decay of s produced in gluon fusion is about 100 times smaller than the CMS upper limit so it might not be probed even at high-luminosity LHC. It is interesting to note that the benchmark P2 has larger gluon-fusion production cross-section of s than P1 by more than a factor of two even though s has much smaller \hat{h} component than in P1. This is mainly because \hat{h} and \hat{H} components of s give opposite sign contributions to s coupling to top quarks, which is the main source of effective coupling to gluons. It turns out that these contributions have similar magnitude for values of \bar{g}_s that can explain the LEP excess which results in a small s coupling to top quarks, and hence also to gluons. For smaller values of \bar{g}_s this cancellation is less efficient and a larger \hat{H} - \hat{s} mixing is needed to keep the same tth enhancement. In consequence, larger cross-sections for s production via gluon fusion are predicted.

Since scalars, unlike pseudoscalars, couple to weak gauge bosons at tree-level, s can be also produced in VBF or VH modes. These modes have smaller production cross sections but also suffer from less background and for 125 GeV scalars they turn out to be much more sensitive to the gluon-fusion mode both in $b\bar{b}$ and $\tau\tau$ channels. Unfortunately, the LHC collaborations have not looked at these production modes for masses below 100 GeV so currently they cannot test the LEP2 excess. We strongly encourage them to extend their analyses to lower masses.

Let us also comment on the fact that in this scenario the LSP may be a good dark matter candidate. In the presented benchmarks the LSP is mainly a Bino, but its thermal relic abundance $\Omega_{\text{th}}h^2$ (computed with `microOMEGAS` [66]) is in agreement with the upper bound on Ωh^2 from Planck measurements [67]. This is because small mass splitting between the LSP and the lightest stop required to satisfy the LHC constraints results in efficient stop co-annihilations. Non-negligible LSP annihilation into final states involving light (pseudo)scalars is another reason for $\Omega_{\text{th}}h^2$ much smaller than generically predicted for Bino-dominated LSP. In fact, for the benchmarks $\Omega_{\text{th}}h^2$ ranges between 0.06 to 0.1 so is somewhat below the central value of 0.12 measured by Planck [67]. Larger values of $\Omega_{\text{th}}h^2$ may be obtained by increasing μ which leads to reduced Higgsino component of the LSP, hence smaller annihilation cross-section. The LSP scattering cross-section on nucleons for all the benchmarks is below the LUX limits [68] but within the future reach of Xenon1T for direct detection via spin-independent (SI) LSP-nucleon interactions [69]. The compatibility with the LUX constraints is the reason for choosing negative value of M_1 in the benchmarks because $\mu M_1 < 0$ allows for some cancellations in the Higgs coupling to LSP which results in smaller SI scattering cross-section [70]. Additional suppression of the SI scattering cross-section may originate from destructive interference between the contributions to the SI scattering amplitude from the Higgs and the light singlet-scalar exchange which are of comparable size if Higgs-singlet mixing is non-negligible as in the present scenario [71]. For somewhat larger $\tan\beta$ SI scattering cross-section could be also suppressed by effects of destructive interference with the amplitude generated by MSSM-like Higgs exchange [72]. Due to small fraction of higgsino component of the LSP, hence small LSP coupling to Z boson, the spin-dependent (SD) scattering cross-section on neutrons is in the range between 10^{-7} and 10^{-6} pb so about three order of magnitude below a recent LUX limit [73]. Limits from the SD scattering cross-section on protons are even weaker.

Since this scenario requires light highly-mixed stops and many additional light Higgs bosons there are non-negligible contributions to B -physics observables. We computed these observables with `NMSSMTools` that follows the calculation of ref. [74], which assumes Minimal Flavor Violation (MFV). For all benchmarks $\text{BR}(b \rightarrow s\gamma)$, $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ and $\text{BR}(B_d \rightarrow \mu^+\mu^-)$ are below the SM prediction while $\text{BR}(B \rightarrow X_s\mu^+\mu^-)$ (in the low dimuon invariant mass region) is above the SM prediction. The $\text{BR}(b \rightarrow s\gamma)$ is in agreement with the experimental central value [75] at the 2σ level for all points apart from P2, while a similar discrepancy with the experiment for $\text{BR}(B \rightarrow X_s\mu^+\mu^-)$ is observed only for P1 and P2 [76]. This proves that it is possible to find points featuring tth enhancement consistent with these observables, even under the Minimal Flavor Violation (MFV) assumption. It should be also emphasized that the predictions for B -physics observables

are sensitive to sources of flavor violation beyond MFV, for example to flavor structure of the down squark parameters via loops with gluinos [77], that have a minor effect in Higgs physics, that is the subject of this work. The only measurement that is in more than 2σ tension with all the benchmarks in the MFV scenario is the combined CMS and LHCb analysis of $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$ decays [78]. However, this is due to the fact that the SM prediction is already 2σ away from the experimental central value. Moreover, in ref. [79] it was specifically demonstrated that $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ and $\text{BR}(B_d \rightarrow \mu^+\mu^-)$ are very sensitive to non-MFV parameters, especially for low $\tan\beta$.

We should also warn the reader that benchmarks P1-P4 presented in table 1 possess unphysical global minimum characterised by vanishing $\langle S \rangle$ and $\langle H_u \rangle$ (or $\langle H_d \rangle$). Such minima have a depth $-2m_{H_d}^4/g^2$ (or $-2m_{H_u}^4/g^2$) and were analysed in the \mathbb{Z}_3 -invariant NMSSM in refs. [53, 54, 80]. It is beyond the scope of the present paper to calculate the lifetime of the metastable EW vacuum for these benchmarks. However, in the general NMSSM there is enough freedom to make the EW vacuum deeper than the above mentioned unphysical minima while preserving characteristic features of benchmarks presented in table 1. For example, large negative ξ_S can make the EW vacuum deeper than the unphysical ones. Such values of ξ_S give positive contribution to the CP-even singlet mass but negative value of κA_κ can keep the singlet light. In table 2 we present benchmarks with the EW vacuum deeper than the unphysical ones. P5 has the same qualitative features as P1 except for heavy CP-odd singlet which results from large negative ξ_S . In consequence, only the CP-even singlet is present in decays of MSSM-like Higgs bosons, as seen from table 3. Nevertheless, the CP-odd singlet can be light also in this case for appropriately chosen positive value of m_S^2 , as exemplified by benchmark P6.

6 Conclusions

The analysis of the Higgs precision measurement data at run I of the LHC have revealed large uncertainties in the coupling of the recently observed Higgs boson to the third generation quarks. In particular, the best fit value of the Higgs coupling to top quarks is more than 2σ above the SM value. Similarly, the best fit of the Higgs coupling to bottom quarks is 2σ below the SM value.

In this article we have investigated the possibility of obtaining such modifications of the third generation couplings within supersymmetric extensions of the Standard Model. In particular we have shown that they may be obtained in the NMSSM for values of the singlet state masses below 125 GeV and values of the heavy CP-even Higgs mass of the order of a few hundred GeV. In addition, in order to get consistency with the observed gluon fusion rates, light stops and relatively large values of the stop mixing parameters are also required. We have discussed the phenomenological implications of this scenario, showing, for instance that it may be also compatible with the observed LEP2 excess in the search for associated production of Higgs bosons with neutral gauge bosons, $e^+e^- \rightarrow hZ$.

This scenario predicts not only deviations of the Higgs rates with respect to the SM values, but also a rich pattern of non-standard Higgs decays, many of which are not covered

by existing LHC searches. It will be also tested in the search for light stops, and therefore may be probed in multiple channels at the LHC in the near future.

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