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Higgs boson decays into $\gamma\gamma$ and $Z\gamma$ in the MSSM and the B-L supersymmetric SM

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We calculate Higgs decay rates into $\gamma\gamma$ and $Z\gamma$ in the minimal supersymmetric Standard Model and (B-L) supersymmetric Standard Model by allowing for contributions from light staus ($\tilde{\tau}$s) and charginos ($\tilde{\chi}^{\pm}$s). We show that sizable departures are possible from the Standard Model predictions for the 125 GeV state and that they are testable during Run 2 at the Large Hadron Collider. Furthermore, we illustrate how a second light scalar Higgs signal in either or both of these decay modes can be accessed at the CERN machine rather promptly within the (B-L) supersymmetric Standard Model, a possibility instead precluded to the minimal supersymmetric Standard Model, owing to the much larger mass of its heavy scalar state.

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The strongest experimental evidence of Higgs boson discovery at the LHC emerged from its decay channels into $\gamma\gamma$ and ZZ. Although these decays are at present largely consistent with the Standard Model (SM) predictions, one finds that the signal strength of the diphoton decay mode is larger than the SM expectation by an $\approx 2\sigma$ deviation [1,2]. While this effect may well be compatible with the SM, the difference calls for close scrutiny, as a Higgs decay into diphotons is a loop-mediated process, thus subject to beyond the SM (BSM) effects entering at the same perturbative level as the SM ones. Hence, it may well be regarded as a possible hint of new physics. In addition, both ATLAS [3] and CMS [4] reported upper bounds for the $Z\gamma$ decay rate, which are 1 order of magnitude larger than the SM expectation, thereby not eliminating the possibility of deviations from the SM in this channel either. Indeed, just like $\gamma\gamma$, also $Z\gamma$ is induced by loops wherein BSM particles may enter alongside the SM ones. Therefore, both such decay channels are key to understanding the nature of the SM-like Higgs boson discovered at CERN in July 2012, and they will be analyzed very thoroughly in the second LHC run.

A common feature of the $\gamma\gamma$ and $Z\gamma$ decay modes is that they are both primarily mediated by W-boson and t-quark loops, which are of opposite sign and with the former dominanting the latter, so that, upon accounting for the dominance of the $h \to WW$ decay starting from $\approx$160 GeV, one finds that the corresponding branching ratios (BRs) tend to be largest below the WW threshold, say, around 130 and 150 GeV, respectively. Another peculiarity of these two decay modes is that any contribution to the $\gamma\gamma$ channel will affect the $Z\gamma$ one as well. The opposite case is not true, though? For example, scenarios with a Z' boson which can mix with the Z state of the SM would affect the latter but not the former. A spectacular situation which would definitely hint at new physics is, for example, the one where the SM-like Higgs decay rate into $Z\gamma$ is measured to be larger than the one in $\gamma\gamma$. Recall in fact that for the Higgs boson of the SM with a 125 GeV mass one has that $\Gamma(h \to \gamma\gamma) > \Gamma(h \to Z\gamma)$. Needless to say, the discovery of another Higgs boson signal, in $\gamma\gamma$, $Z\gamma$, or otherwise, would be clear evidence for a BSM nature of electroweak symmetry breaking (EWSB).

Among models of supersymmetry (SUSY), a theory well placed as the prime candidate for BSM physics, two are of interest here. First, the minimal supersymmetric Standard Model (MSSM), which contains two CP-even neutral Higgs bosons: h, the SM-like Higgs, and H, a much heavier state. Second, the (B-L) supersymmetric Standard Model (BLSSM), which is an extension of the MSSM obtained via enlarging its gauge group by a $U(1)_{B\text{-}L}$ and is one of the best motivated nonminimal SUSY models as it accounts for nonzero neutrino masses. The Higgs sector of the BLSSM consists of two Higgs doublets and two Higgs singlets [(B-L) charged]. Therefore, one finds that the physical CP-even neutral Higgs bosons are four, h, H, h', and H', where the first two are MSSM-like and the last two are the truly BLSSM ones. Of relevance in the choice of these two benchmark SUSY scenarios is that, owing to the fact that they have the same quantum numbers and $U(1)_Y$ and $U(1)_{B\text{-}L}$ are not orthogonal, the Z boson of the SM and the Z' of the BLSSM mix (and, not less importantly, so do their SUSY counterparts), a phenomenological aspect of course missing in the MSSM.

Furthermore, due to the gauge kinetic mixing between $U(1)_Y$ and $U(1)_{B\text{-}L}$, a tree-level mixing between the $SU(2)$ (H_u, H_d) and $U(1)_{B\text{-}L}$ (χ_1, χ_2) scalar states is induced. In this case, the squared mass matrix of the BLSSM CP-even neutral Higgses at tree level is 4×4, with the off-diagonal entries proportional to the gauge coupling mixing [5]. The MSSM-like Higgs boson h is the lightest Higgs state, with mass $\sim$125 GeV. The second-lightest Higgs state can become the B-L Higgs boson h', with mass $\gtrsim$135 GeV

[5]. The large mixing in the CP-even Higgs mass matrix enables the h' to couple to the SM (and MSSM) (s)particles. Therefore, similarly to $h \to \gamma\gamma$ and $Z\gamma$, the BLSSM h' also decays these ways via W-boson loops, top-quark loops, light-stau loops, and chargino loops. Note that contributions from squarks are negligible, owing to the fact that in our parameter space they are rather heavy, with masses of $\mathcal{O}(2\ \text{TeV})$. Therefore, the BLSSM offers another Higgs state which can have significant decays into $\gamma\gamma$ and $Z\gamma$, in addition to ZZ, so that it may even explain a possible second Higgs peak at ≈140 GeV in the CMS samples of $\gamma\gamma$ and ZZ [5].

In previous analyses [6–9], the role that light $\tilde{\tau}$ and $\tilde{\chi}^{\pm}$ effects can have in the diphoton decay rates in the MSSM was emphasized. We revisit here those analyses by also including an investigation of the $Z\gamma$ channel in the MSSM. Furthermore, we contrast these results with what instead emerges in the BLSSM. The aim is to assess whether significant differences may occur between the MSSM and BLSSM in the $\gamma\gamma$ and/or $Z\gamma$ decay channels with respect to the SM and indeed between each other. Finally, we also intend to establish the LHC scope in accessing one or the other of these two modes when the decaying object is the lightest genuinely BLSSM Higgs state.

As intimated, just like for the case of the $h \to \gamma\gamma$ decay (whose formulas can be found in Refs. [6,7,10]), in the MSSM, a significant effect on the decay width of $h \to Z\gamma$ may be obtained through the exchange of a light $\tilde{\tau}$ and/or light $\tilde{\chi}^{\pm}$. For this mode, the partial decay width is given by Ref. [11],

$$\Gamma(h \to Z\gamma) = \frac{G_F^2 \alpha^2 M_W^2 m_h^3}{64\pi^4}\left(1 - \frac{M_Z^2}{m_h^2}\right)^3 \times |A_t + A_W + A_{\chi^{\pm}} + A_{\tilde{\tau}}|^2, \quad (1)$$

where G_F is the Fermi constant. The SM form factors A_t and A_W are obtained from the loops mediated by the t quark and W boson, respectively. The explicit form of $A_{t,W}$ can be found in Ref. [12]. The SUSY form factor $A_{\tilde{\tau}}$ is given by

$$A_{\tilde{\tau}} = \frac{4v^2}{c_W s_W M_{\tilde{\tau}}^2} \sum_{ij} g_{h\tilde{\tau}_i\tilde{\tau}_j} g_{Z\tilde{\tau}_i\tilde{\tau}_j} C_2(M_{\tilde{\tau}_i}, M_{\tilde{\tau}_j}, M_{\tilde{\tau}_j}), \quad (2)$$

where $g_{Z\tilde{\tau}_i\tilde{\tau}_j}$ and $g_{h\tilde{\tau}_i\tilde{\tau}_j}$ are the couplings of the Z and h bosons to $\tilde{\tau}$s, respectively. Now, the $\tilde{\tau}$ mass matrix can have a large mixing if A_τ or $\mu \tan\beta$ is large enough. Therefore, one of the eigenvalues, say, $M_{\tilde{\tau}_1}$, can be as light as 100 GeV. In the decoupling limit, where $M_A \gg M_Z$, $\sin\alpha \sim -\cos\beta$, and $\cos\alpha \sim -\sin\beta$, the Higgs coupling to the lightest $\tilde{\tau}$, normalized by $v/\sqrt{2}$, with v the SM Higgs vacuum expectation value, is

$$g_{h\tilde{\tau}_1\tilde{\tau}_1} = \cos 2\beta\left(-\frac{1}{2}\cos^2\theta_{\tilde{\tau}} + \sin^2\theta_W \cos 2\theta_{\tilde{\tau}}\right) + \frac{M_\tau^2}{M_Z^2} + \frac{M_\tau(A_\tau - \mu\tan\beta)}{2M_Z^2}\sin 2\theta_{\tilde{\tau}}. \quad (3)$$

With a large $\tilde{\tau}$ mixing, $\sin 2\theta_{\tilde{\tau}} \simeq 1$, $\tan\beta > 50$, and $\mu \sim$ TeV, one finds that $g_{h\tilde{\tau}_1\tilde{\tau}_1} \simeq \frac{M_\tau \mu \tan\beta}{2M_Z^2}$. Therefore, the sign of the $\tilde{\tau}$ contribution depends on the sign of μ. Finally, the loop function $C_2(M_{\tilde{\tau}_i}, M_{\tilde{\tau}_j}, M_{\tilde{\tau}_j})$ is again given in Ref. [12].

As mentioned, also the $\tilde{\chi}^{\pm}$s can mediate $h \to Z\gamma$, and they, too, can be light, $\mathcal{O}(100)$ GeV. The $\tilde{\chi}^{\pm}$ form factor $A_{\chi^{\pm}_{ij}}$ is given by

$$A_{\chi^{\pm}_{ij}} = -2\sqrt{2}M_Z^2 \cot_W \sum_{ij} \frac{M_W}{M_{\chi^{\pm}_{ij}}} g_{Z\chi_i^+\chi_j^-} g_{h\chi_i^+\chi_j^-} \times f(M_{\chi_i^{\pm}}, M_{\chi_j^{\pm}}, M_{\chi^{\pm}_{ij}}), \quad (4)$$

where $g_{Z\chi_i^+\chi_j^-}$ and $g_{h\chi_i^+\chi_j^-}$ are the couplings of the Z and h to $\tilde{\chi}^{\pm}$s, respectively. Note that, due to the vector and axial interactions of the Z boson, both diagonal and off-diagonal couplings of $\tilde{\chi}^{\pm}$s can contribute to the $h \to Z\gamma$ decay. The couplings of the Higgs boson h with $\tilde{\chi}^{\pm}$s are given by $g_{h\chi_i^+\chi_j^-} = C_{ij}^L P_L + C_{ij}^R P_R$, where

$$C_{ij}^L = \frac{1}{\sqrt{2}sw}[-\sin\alpha V_{j1} U_{i2} + \cos\alpha V_{j2} U_{i1}], \quad (5)$$

$$C_{ij}^R = \frac{1}{\sqrt{2}sw}[-\sin\alpha V_{i1} U_{j2} + \cos\alpha V_{i2} U_{j1}]. \quad (6)$$

These couplings can reach their maximum values and become of $\mathcal{O}(\pm 1)$ if $\tan\beta$ is very small, close to 1, and $\mu \simeq M_2$. In Ref. [7], it was emphasized that the Higgs couplings to $\tilde{\chi}^{\pm}$s can be negative, and hence the $\tilde{\chi}^{\pm}$ can give a constructive interference with the W boson that may lead to a possible enhancement for $\gamma\gamma$. In $Z\gamma$, too, the relative sign of $g_{Z\tilde{\chi}_i^+\tilde{\chi}_j^-}$ and $g_{h\tilde{\chi}_i^+\tilde{\chi}_j^-}$ is important for enhancing (or suppressing) the effective signal strength of the $hZ\gamma$ coupling. Finally, the loop functions $f(x_1, x_2, x_3)$ can be found in Ref. [13].

The signal strength of $h \to Z\gamma$, relative to the SM expectation, in terms of the production cross section (σ) and decay BR, is defined as

$$\mu_{Z\gamma} = \frac{\sigma(pp \to h \to Z\gamma)}{\sigma(pp \to h \to Z\gamma)^{\text{SM}}} = \frac{\sigma(pp \to h)}{\sigma(pp \to h)^{\text{SM}}} \frac{\text{BR}(h \to Z\gamma)}{\text{BR}(h \to Z\gamma)^{\text{SM}}} = \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)^{\text{SM}}} \frac{\Gamma_{\text{tot}}^{\text{SM}}}{\Gamma_{\text{tot}}} \frac{\Gamma(h \to Z\gamma)}{\Gamma(h \to Z\gamma)^{\text{SM}}}. \quad (7)$$

(A similar expression holds for $\gamma\gamma$.) In computing $\mu_{\gamma\gamma}$ and $\mu_{Z\gamma}$, we have used SARAH [14,15] and SPheno [16,17] to build the model. Then, we linked it with CPsuperH [11,18] to compute the numerical values of the Higgs decays in all channels.

In Fig. 1, we display the results of the signal strengths of $h \to \gamma\gamma$ and $Z\gamma$ as a function of the lightest $\tilde{\tau}$ [19] and $\tilde{\chi}^{\pm}$ masses for $m_h \simeq 125\,\mathrm{GeV}$. For the $\tilde{\chi}^{\pm}$ plot, we scan over the following parameter space: $1.1 \leq \tan\beta \leq 5$, $100\,\mathrm{GeV} < \mu < 300\,\mathrm{GeV}$, and $100\ \mathrm{GeV} < M_2 < 300\ \mathrm{GeV}$. For the $\tilde{\tau}$ plot, we randomize over the following parameter ranges: $5 \leq \tan\beta \leq 50$, $250\,\mathrm{GeV} \leq m_{L_3,E_3} \leq 500\,\mathrm{GeV}$, $500\,\mathrm{GeV} < \mu < 2000\,\mathrm{GeV}$, and $M_1 = M_2 = M_3 = 3000\,\mathrm{GeV}$. Other dimensionful SUSY parameters are fixed to be of order few TeV so that all other possible SUSY effects on $\mu_{\gamma\gamma}$ and $\mu_{Z\gamma}$ are essentially negligible. As can be seen from the plots, the $\tilde{\tau}$ contribution may lead to a limited enhancement for the signal strength of $\mu_{Z\gamma}$, 1.1, or so, unlike the case of $\mu_{\gamma\gamma}$, which can be increased up to 1.6 at $M_{\tilde{\tau}} \sim 100\,\mathrm{GeV}$. Curiously, it can happen, for large $\tilde{\tau}$ masses, that $\Gamma(h \to \gamma\gamma) < \Gamma(h \to Z\gamma)$. The $\tilde{\chi}^{\pm}$s instead contribute to $\mu_{\gamma\gamma}$ and $\mu_{Z\gamma}$ equally, and both modes can be enhanced up to 1.2.

Now, we consider the decay of the MSSM heavy Higgs, which has a mass of order $m_H \sim (m_A^2 + \sin^2 2\beta M_Z^2)^{1/2}$ and coupling with W gauge bosons equal to $g_{HWW} = -2M_Z^2/M_A^2 \tan^2\beta$. It is clear that, for large $\tan\beta$ and $m_A \gg M_Z$ (as required for compliance with LHC data), the coupling g_{HWW} will have to be very small. Therefore, the main contribution to $H \to \gamma\gamma$ and $Z\gamma$ through W exchange is significantly suppressed, and hence one expects the corresponding decay rates to be much smaller than those of the SM-like Higgs, finally recalling the relative dominance of $H \to WW$ (as $m_H > 2M_W$). This conclusion is confirmed by Fig. 2, where we display the signal strength (again normalized to the SM rates for $m_h = 125$ GeV) of $H \to \gamma\gamma$ and $Z\gamma$ as a function of m_H. In the presence of light $\tilde{\tau}$s, the $H \to \gamma\gamma$ strength is larger than the $H \to Z\gamma$ one throughout the entire H mass interval considered (we trace this effect back as being due to very large values of $\tan\beta$). In contrast, it is remarkable that, for a light $\tilde{\chi}^{\pm}$ yielding an enhancement occurring for $\tan\beta < 5$, $Z\gamma$ is generally more sizable than $\gamma\gamma$. Altogether though, the signal strengths of $H \to Z\gamma$ and $H \to \gamma\gamma$ are much smaller than 1, so probing these channels will be rather difficult.

We now turn to the CP-even Higgs bosons of the BLSSM. Recall that the h and H states of the BLSSM are essentially the same as in the MSSM. Furthermore, as

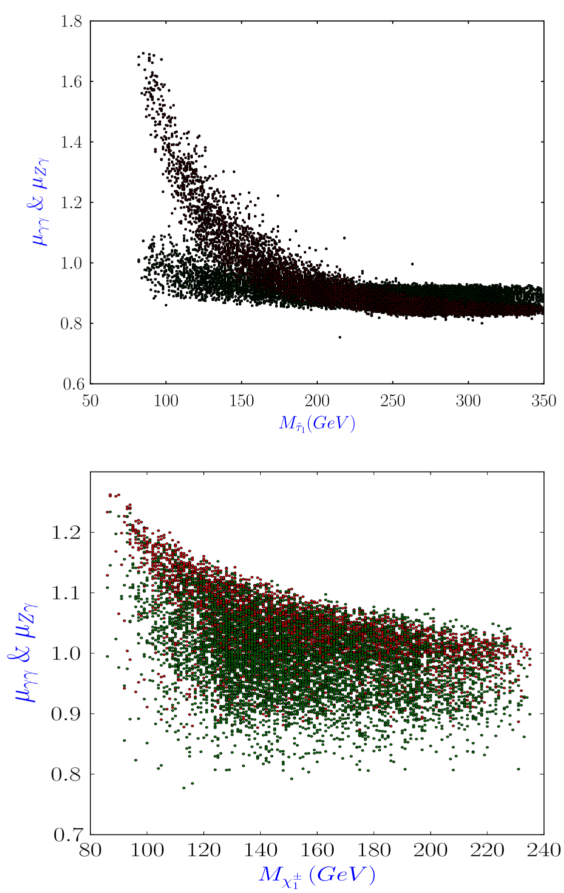

FIG. 1 (color online). Signal strength of $h \to \gamma\gamma$ (red) and $Z\gamma$ (green) vs the lightest stau (top panel) and chargino (bottom panel) mass.

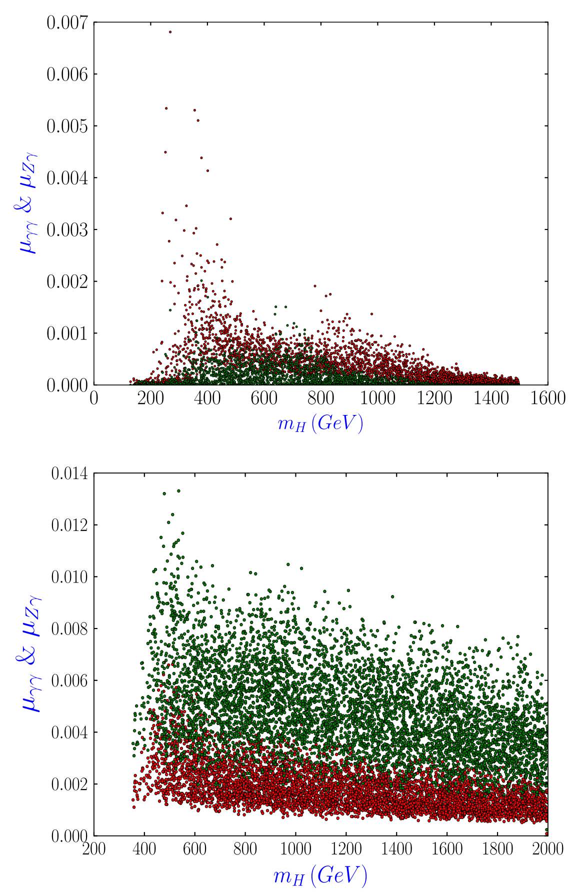

FIG. 2 (color online). Signal strength of $H \to \gamma\gamma$ (red) and $Z\gamma$ (green) vs the H mass for the light $\tilde{\tau}$ (top) and light $\tilde{\chi}^{\pm}$ (bottom) scenario.

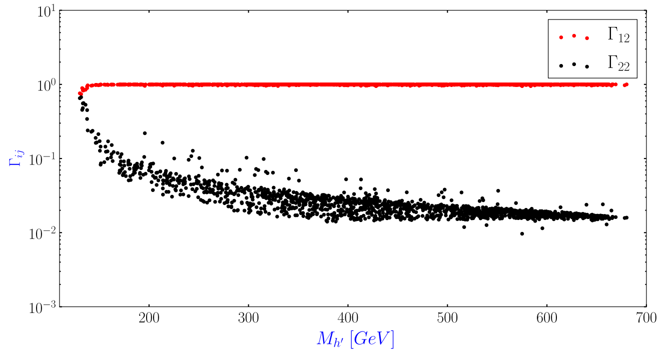

FIG. 3 (color online). Higgs mixing matrix elements vs $M_{h'}$.

shown in Ref. [5], also the genuine BLSSM states, h' and H', show a strong hierarchy, $m_{H'} \gg m_{h'}$, and the h' can be the second-lightest Higgs state, with mass just larger than the SM-like state h; i.e., the CP-even neutral Higgs boson mass matrix can be diagonalized as

$$\Gamma M^2 \Gamma^\dagger = \mathrm{diag}\{m_h^2, m_{h'}^2, m_H^2, m_{H'}^2\}, \tag{8}$$

where Γ is a unitary 4×4 mixing matrix. Thus, the Yukawa coupling of the SM-like Higgs, h, with top quarks is given by $Y_t = -i\frac{m_u \times \Gamma_{12}}{v \sin\beta}$, and the induced Yukawa coupling of the lightest BLSSM Higgs, h', with top quarks is given by $Y_t' = -i\frac{m_u \times \Gamma_{22}}{v \sin\beta}$. In Fig. 3, we show that the mixing matrix element Γ_{12} is close to 1 and almost a constant for all values of $m_{h'}$, while Γ_{22} is significantly suppressed for $m_{h'} \geq 200$ GeV. For $m_h{'} \sim 140$ GeV, Γ_{22} becomes of $\mathcal{O}(0.1)$ and Γ_{21} is slightly decreased. However, this suppression does not affect the top Yukawa coupling Y_t, and we are still able to account for the signal strengths of the SM-like Higgs decay into ZZ or $\gamma\gamma$. The enhancement of Γ_{22} for a light h', which depends on the kinetic mixing $\tilde{g}$, is crucial for explaining the apparent second observed peak induced by the BLSSM Higgs state h'.

Figure 4 shows the signal strengths (normalized to the SM as usual) for the $h' \to \gamma\gamma$ and $Z\gamma$ modes vs $m_{h'}$, again for light $\tilde{\tau}$s and $\tilde{\chi}^{\pm}$s separately. In both cases, the rates generally obtained are significantly higher than for the case of the H state (Fig. 2) so as to favorably conclude that a h' Higgs boson may well be within the reach of the LHC Run 2 for standard luminosities, also thanks to the rather light values that $m_{h'}$ can attain, starting here as low as 135 GeV, thus also greatly enhancing its production rates with respect to the H one (as $m_H \gtrsim 180$ GeV). We find that the $\gamma\gamma$ decay rates are larger than the $Z\gamma$ ones by over an order of magnitude for light $\tilde{\tau}$s if $\tan\beta \sim 40$, whereas in the case of light $\tilde{\chi}^{\pm}$s and low $\tan\beta$ (5 and below), the hierarchy between the two decay modes is inverted as the $Z\gamma$ one is largely dominant over the $\gamma\gamma$ one (even up to 2 orders of magnitude for heavy h's).

From Figs. 2 and 4, it is thus remarkable that for H and h' masses larger than 135 GeV the signal strength $\mu_{Z\gamma}$ can

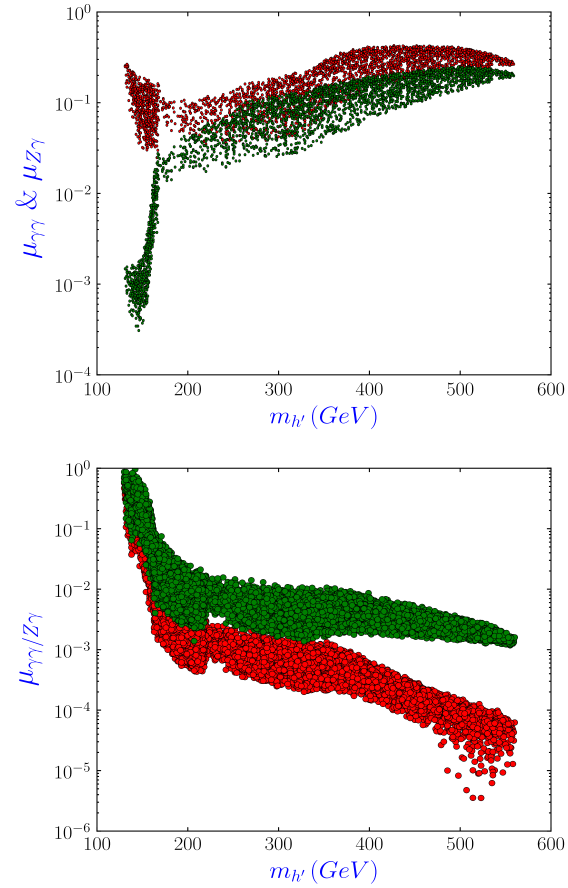

FIG. 4 (color online). Signal strength of $h' \to \gamma\gamma$ (red) and $Z\gamma$ (green) vs the h' mass for the light $\tilde{\tau}$ (top) and light $\tilde{\chi}^{\pm}$ (bottom) scenario.

become larger than $\mu_{\gamma\gamma}$, unlike the expectation of the SM-like Higgs state h. This can be understood as follows. With heavy Higgs bosons, the t-loop function mediating the Higgs decay into $\gamma\gamma$ is increased, while the W-loop function is decreased. Therefore, the net result for $\mu_{\gamma\gamma}$ is to be reduced significantly (up to 3 orders of magnitude) with respect to the h case. In contrast, the enhancement of the t-loop function and reduction of the W-loop one that mediate the Higgs decay to $Z\gamma$ are quite small, and thus the corresponding values for $\mu_{Z\gamma}$ remain of the same order as those for $m_h = 125$ GeV.

In summary, we have shown that a comparative study of the $\gamma\gamma$ and $Z\gamma$ decay channels of the SM-like Higgs boson discovered recently at the LHC may hold the key to unlock the door toward the understanding of its nature, in the ultimate attempt to extract the underlying EWSB mechanism. If the latter is dynamically onset by SUSY and no evidence of sparticle states exists from direct searches, an indirect proof of this paradigm may be obtained by measuring the relative yield of Higgs event rates in the $\gamma\gamma$ and $Z\gamma$ decay modes. On the one hand, a simultaneous enhancement of both with respect to the SM rates may be

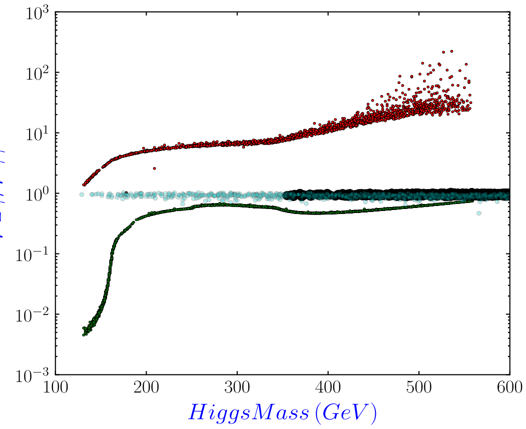

FIG. 5 (color online). Ratio of signal strength, $\mu_{Z\gamma}/\mu_{\gamma\gamma}$, for h' with light $\chi^{\pm}$s (red), h' with light $\tilde{\tau}$s (green), H with light $\chi^{\pm}$s (black), and H with light $\tilde{\tau}$s (blue).

associated with the presence of a light $\tilde{\chi}^{\pm}$. On the other hand, the relative increase of the former with respect to the latter beyond the SM rates may be induced by a light $\tilde{\tau}$. Under these circumstances, in light of a degeneracy existing between the Higgs sectors of the two SUSY realizations, such effects may equally be ascribed to either the MSSM or the BLSSM. What would possibly enable one to split the two SUSY scenarios would be the prompt detection within the BLSSM of a second Higgs signal (the lightest BLSSM state, h') in $\gamma\gamma$ and/or $Z\gamma$, whereas this would not be possible in the MSSM. Finally, the very distinctive hierarchy emerging in the $\gamma\gamma$ and $Z\gamma$ decay widths of the h' may yield information about the structure of the BLSSM sparticle sector, as well illustrated in Fig. 5.

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