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Light chargino effects onto $H \to \gamma\gamma$ in the MSSM

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We analyze the implications of light charginos on the Higgs boson signal strength via gluon-gluon fusion and diphoton decay in the minimal supersymmetric standard model (MSSM) at the Large Hadron Collider. We show that enhancements are possible with a rate up to 25%. We also prove that they are possible for a high scale constrained version of the MSSM with nonuniversal Higgs and gaugino masses. In contrast, effects due to light charged Higgs bosons, which we also have investigated, are generically negligible in the $\gamma\gamma$ decay, though they may affect the $b\bar{b}$ rate, and hence the total width.

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The most recent results reported by ATLAS [1–4] and CMS [5–8] confirmed a Higgs boson discovery with a mass of order 125 GeV. The decay channels investigated experimentally with the highest precision are $H \to \gamma\gamma$, $H \to ZZ^{(*)} \to 4l$ and $H \to WW^{(*)} \to l\nu l\nu$, where l denotes a lepton (electron and/or muon) and ν its associated neutrino. The data analyses in these channels are based on an integrated luminosity of 4.7 fb^{-1} at $\sqrt{s} = 7$ TeV plus 13 fb^{-1} at $\sqrt{s} = 8$ TeV (ATLAS) and 5.1 fb^{-1} at $\sqrt{s} = 7$ TeV plus 19.6 fb^{-1} at $\sqrt{s} = 8$ TeV (CMS). The results reported by ATLAS for the signal strengths of these channels are given by [1–4]

$$\mu_{\gamma\gamma} = 1.65 \pm 0.35,$$
$$\mu_{ZZ} = 1.7 \pm 0.5,$$
$$\mu_{WW} = 1.01 \pm 0.31. \quad (1)$$

From the CMS Collaboration one has instead [5–8]

$$\mu_{\gamma\gamma} = 0.78 \pm 0.28,$$
$$\mu_{zz} = 0.91^{+0.3}_{-0.24},$$
$$\mu_{ww} = 0.76 \pm 0.21. \quad (2)$$

These results indicate suppression or enhancement in the diphoton mode, with respect to the Standard Model (SM), with more than 2σ deviation either way, a trend that could then be a very important signal for possible new physics beyond the SM [9,10] such as the minimal supersymmetric standard model (MSSM) [11–29] (also the constrained version [30–35]), next-to-MSSM [36–44] and (B-L)SSM [45–48].

In the MSSM, the Higgs sector consists of five scalar Higgs bosons: two CP-even neutral ones, h, H (with increasing mass, $m_h < m_H$), a pseudoscalar one, A, and a pair of charged ones, $H^{\pm}$. The mixing between the two CP-even neutral Higgs bosons is defined by the mixing angle α, which is a derived parameter. In fact, in the MSSM at the tree level, all Higgs sector observables can be defined in terms of only two input parameters, i.e., the ratio of the vacuum expectation values of the two Higgs doublets pertaining to this minimal realization of supersymmetry (SUSY), denoted by $\tan\beta$, and any of the Higgs boson masses, e.g., m_h.

However, in the MSSM in higher orders, genuine SUSY effects affect observables from the Higgs sector. In particular, the mass of the lightest CP-even neutral MSSM Higgs state, h, typically the SM-like Higgs, is predicted to be less than 135 GeV [49,50], owing to SUSY states entering the one- and two-loop corrections to it. Therefore, in some sense, the new LHC results are in favor of a low energy SUSY scenario, indeed (possibly) the MSSM. The signal strength of the diphoton channel, $H \to \gamma\gamma$, relative to the SM expectation, in terms of the production cross section (σ) and decay branching ratio (BR), is defined as

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)}{\sigma(pp \to h \to \gamma\gamma)^{\rm SM}} = \frac{\sigma(pp \to h)}{\sigma(pp \to h)^{\rm SM}} \frac{\text{BR}(h \to \gamma\gamma)}{\text{BR}(h \to \gamma\gamma)^{\rm SM}}$$
$$= \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)^{\rm SM}} \frac{\Gamma_{\rm tot}^{\rm SM}}{\Gamma_{\rm tot}} \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)^{\rm SM}} = \kappa_{gg} \kappa_{\rm tot}^{-1} \kappa_{\gamma\gamma}. \quad (3)$$

In the MSSM, the $H \to \gamma\gamma$ decay can be mediated at one loop by the $W^{\pm}$ boson, top quark, light squarks (in particular sbottoms and stops), light sleptons (in particular staus), charginos and charged Higgs boson. Therefore, in such a model, the decay rate of $H \to \gamma\gamma$ is given by

$$\Gamma(h\to\gamma\gamma)=\frac{G_F\alpha^2M_h^3}{128\sqrt{2}\pi^3}\bigg|\sum_f N_cQ_f^2g_{hff}A_{1/2}^h(\tau_f)+g_{hVV}A_1^h(\tau_W)+\frac{M_W^2\lambda_{hH^+H^-}}{2c_W^2M_{H^\pm}^2}A_0^h(\tau_{H^\pm})$$
$$+\sum_{\tilde\chi_i^\pm}\frac{2M_W}{m_{\tilde\chi_i^\pm}}g_{h\tilde\chi_i^+\tilde\chi_i^-}A_{1/2}^h(\tau_{\tilde\chi_i^\pm})+\sum_{\tilde f_i}\frac{g_{h\tilde f_i\tilde f_i}}{m_{\tilde f_i}^2}N_cQ_{\tilde f_i}^2A_0^h(\tau_{\tilde f_i})\bigg|^2, \quad (4)$$

where G_F is the Fermi constant, V, f, and $\tilde f$ refer to vector, fermion, and scalar particles, respectively, entering a triangle diagram. The dimensionless parameter τ_i is defined as $\tau_i=M_h^2/4M_i^2$ with $i=f,W,H^\pm,\tilde\chi^\pm,\tilde f$, and the loop functions $A_{0,1/2,1}$ can be found in [17,49]. In Ref. [51] a comprehensive analysis for the generic MSSM effects on the Higgs decay to diphotons, Higgs production via gluon-gluon fusion and total Higgs decay width was presented. In particular, it was focused on the specific effects of light stops, sbottoms and/or staus [52–54]. In this article, we complete that analysis by revisiting the chargino and charged Higgs boson effects onto, essentially, the $H\to\gamma\gamma$ decay rate. In fact, recall that neither $H^\pm$ nor $\tilde\chi_i^\pm$ ($i=1$, 2) states can enter the Higgs production mode (via gg fusion) and notice that their contribution to the total Higgs boson width is subleading, as $m_h<2M_{\tilde\chi_i^\pm}$, $2m_{H^\pm}$. Therefore, in this case, one finds that $\mu_{\gamma\gamma}=\kappa_{\gamma\gamma}$.

It is worth noting that the ratio among the loop functions of a vector, fermion and scalar for masses of order $\mathcal{O}(100)$ GeV is about 8∶1.5∶0.4. Therefore, it is clear that charged Higgs boson effects onto $\Gamma(h\to\gamma\gamma)$ are quite limited unless one can obtain a huge coupling with the SM-like Higgs via the vertex hH^+H^-. In contrast, chargino effects can be relevant and lead to a significant enhancement of $\Gamma(h\to\gamma\gamma)$.

In the MSSM, the chargino mass matrix is given by

$$\mathcal{M}_C=\begin{bmatrix} M_2 & \sqrt{2}M_Ws_\beta \\ \sqrt{2}M_Wc_\beta & -\mu\end{bmatrix}, \quad (5)$$

where M_2 is the soft SUSY-breaking mass of the gaugino partner of the $W^\pm$ gauge boson, the wino $\tilde W^\pm$, μ is the Higgs mixing parameter and $s_\beta\equiv\sin\beta$, $c_\beta\equiv\cos\beta$. The chargino mass matrix can be diagonalized by two unitary matrices U and V, where $U=\mathcal{O}_-$ and $V=\mathcal{O}_+$ or $\sigma_3\mathcal{O}_+$ if $\det\mathcal{M}_C>0$ or $\det\mathcal{M}_C<0$, respectively. $\mathcal{O}_\pm$ are rotation matrices with angles $\phi_\pm$ defined by

$$\tan 2\phi_-=2\sqrt{2}M_W\frac{-\mu\sin\beta+M_2\cos\beta}{M_2^2-\mu^2-2M_W^2\cos 2\beta}, \quad (6)$$

$$\tan 2\phi_+=2\sqrt{2}M_W\frac{-\mu\cos\beta+M_2\sin\beta}{M_2^2-\mu^2-2M_W^2\cos 2\beta}. \quad (7)$$

The matrix $\mathcal{M}_C$ has two eigenstates, $\tilde\chi_1^\pm$ and $\tilde\chi_2^\pm$ (the charginos), with the following mass eigenvalues:

$$M_{2,1}^2=\frac{1}{2}(M_2^2+\mu^2+2M_W^2)\pm\sqrt{(M_2^2-\mu^2)^2+4M_W^4\cos^2 2\beta+4M_W^2(M_2^2+\mu^2-2M_2\mu\sin 2\beta)}). \quad (8)$$

The lightest chargino $\tilde\chi_1^\pm$ is often of order M_Z and has the characteristic of being the lightest charged SUSY particle.

The interactions of the lightest neutral MSSM Higgs boson with SM-like couplings, h, with the charginos are given by

$$\mathcal{L}=g\tilde\chi_i^+(C_{ij}^LP_L+C_{ij}^RP_R)\tilde\chi_j^+h+\text{H.c.}, \quad (9)$$

where the $C_{ij}^{L,R}$'s are given by

$$C_{ij}^L=\frac{1}{\sqrt{2}sw}[-\sin\alpha V_{j1}U_{i2}+\cos\alpha V_{j2}U_{i1}], \quad (10)$$

$$C_{ij}^R=\frac{1}{\sqrt{2}sw}[-\sin\alpha V_{i1}U_{j2}+\cos\alpha V_{i2}U_{j1}]. \quad (11)$$

In Fig. 1 we display these couplings as a function of $\tan\beta$ for different values of μ and M_2. As can be seen from this plot, such couplings can reach their maximum values and

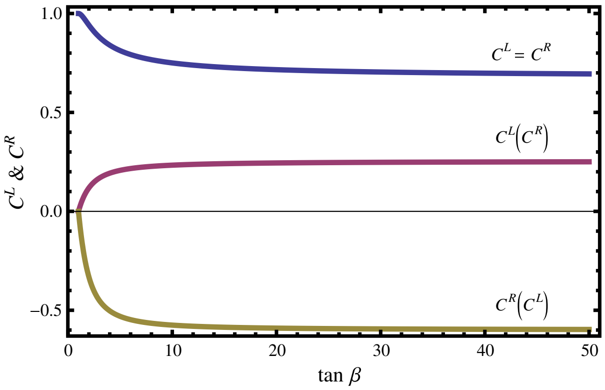

FIG. 1 (color online). Chargino-Higgs couplings C_L and C_R versus $\tan\beta$ for $\mu = M_2 = 200$ GeV (green line), $M_2 = 2\mu = 300$ (red line for C_L and blue line for C_R) and $\mu = 2M_2 = 300$ GeV (red line for C_R and blue line for C_L).

become of order $\mathcal{O}(\pm 1)$ if $\tan\beta$ is very small, close to 1, and $\mu \simeq M_2$. It is also remarkable that, if $\mu > M_2$ ($\mu < M_2$), the coupling $C_R(C_L)$ flips its sign, which leads to destructive interference between the chargino contributions. From this plot, it is clear that the Higgs coupling to charginos can be negative; hence the chargino can give a constructive interference with the $W^\pm$ boson that may lead to a possible enhancement for $\kappa_{\gamma\gamma}$ and $\mu_{\gamma\gamma}$.

In Fig. 2 we display the results for $\kappa_{\gamma\gamma}$ as a function of the lightest chargino mass, $M_{\tilde{\chi}_1^+}$, with $m_h \simeq 125$ GeV. We scan over the following expanse of parameter space [using CPsuperH (version 2.3) [55,56]]: $1.1 < \tan\beta < 5$, $100\ \text{GeV} < \mu < 300$ GeV and $100\ \text{GeV} < M_2 < 300$ GeV. Other dimensionful SUSY parameters are fixed to be of order few TeV so that all other possible SUSY effects onto $H \to \gamma\gamma$ are essentially negligible. As can be seen from this figure, to have a significant chargino contribution to $\kappa_{\gamma\gamma}$, quite a light chargino mass

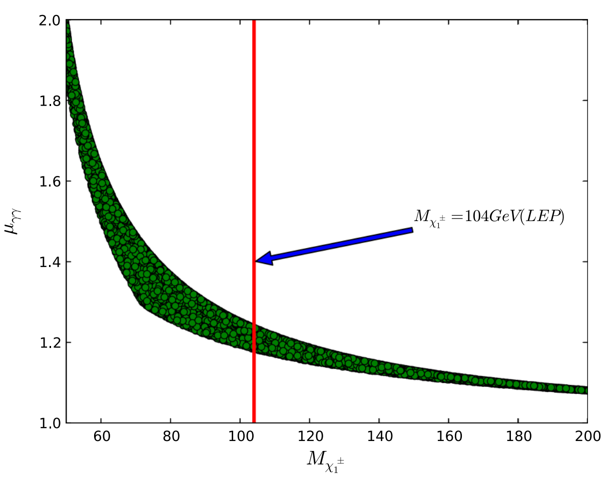

FIG. 2 (color online). Signal strength of the diphoton channel as a function of the lightest chargino mass for $1.1 < \tan\beta < 5$, $100\ \text{GeV} < \mu < 500$ GeV and $100\ \text{GeV} < M_2 < 500$ GeV.

($M_{\tilde{\chi}_1^+} \sim 104$ GeV), around the large electron-positron collider limit, is required [57–61]. Precisely at this limiting value, one finds that the Higgs signal strength is enhanced by about 25%.

As shown, the chargino mass is determined by M_2, μ and $\tan\beta$ and light charginos require small M_2 and μ, which implies that $M_{1/2}$ and m_0 (in the case of a constrained MSSM, wherein the former/latter represents the universal fermion/scalar mass) should be quite small. However, a Higgs mass of order 125 GeV requires quite a large stop mass $m_{\tilde{t}_1}$ and trilinear term A_t, which leads to a very large $M_{1/2}$ and m_0. To overcome this contradiction, a departure from the constrained MSSM is necessary. In particular, one has to consider nonuniversal gaugino masses so that M_2 can be much smaller than M_3. In addition, a nonuniversal Higgs mass is also crucial to guarantee small values of the μ parameter. Therefore, the following set of soft SUSY breaking terms at high scale are favored for this analysis:

$$m_{H_1}^2 = m_0^2(1 + d_1), \tag{12}$$

$$m_{H_2}^2 = m_0^2(1 + d_2), \tag{13}$$

$$m_{\tilde{q},\tilde{l}}^2 = m_0^2, \tag{14}$$

in addition to

$$M_1 \lesssim M_2 \ll M_3, \tag{15}$$

$$A_0 \gtrsim \mathcal{O}(1\ \text{TeV}). \tag{16}$$

Running these soft terms from the grand unification theory scale down to the SUSY scale $\sim\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ and imposing the electroweak breaking conditions, one finds that the μ parameter is given by

$$\mu^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{1 - \tan^2\beta} - \frac{M_Z^2}{2}. \tag{17}$$

One can easily show that μ is strongly dependent upon the values of d_1 and d_2 and that for $d_1 \ll d_2$ a light $\mu \sim \mathcal{O}(100\ \text{GeV})$ is achieved, so that we obtain different values for m_{H_1} and m_{H_2} in correspondence to a small μ. In Fig. 4 we display the results for $\mu_{\gamma\gamma}$ versus μ for $m_0 \sim A_0 \sim 1$ TeV and $500 \leq M_3 \leq 1100$ (so that $m_h \approx 125$ GeV), $3 \leq \tan\beta \leq 30$, $0 \leq d_2 \leq 5$ and 150 GeV $150\,\text{GeV} < M_2 < 250$ GeV (some of these scans were done by [62]). This figure confirms that a quite small μ is obtainable in this class of SUSY models, and the signal strength in $\gamma\gamma$ is significantly enhanced for these values. In Fig. 3 we display the results for $\mu_{\gamma\gamma}$ as a function of the difference $\Delta d = d_2 - d_1$. Here, we vary the other parameters in the

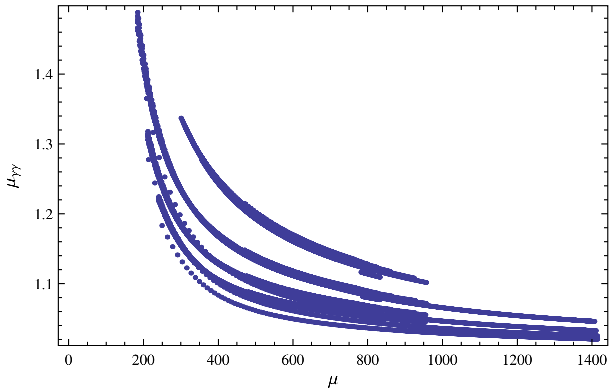

FIG. 3 (color online). Signal strength of the diphoton channel as a function of μ for $3 \leq \tan\beta \leq 30$, $0 \leq d_2 \leq 5$ and 150 GeV $< M_2 <$ 250 GeV.

aforementioned regions. As can be seen from this plot, for $\Delta d > 1$ the signal strength can be enhanced and become larger than one. Also, it may have a resonant behavior in the regions where $\mu \sim M_2$.

Finally, as anticipated, a numerical analysis confirmed that the charged Higgs boson contribution is generally negligible in the $h \to \gamma\gamma$ decay, so we do not produce the corresponding formulas. However, we do present here an interesting plot, highlighting the key role of the $H^{\pm}$ mass entering the $hb\bar{b}$ coupling squared (but not the effective $h\gamma\gamma$ one) (see Fig. 5), wherein $\kappa_{bb} \equiv \Gamma(h \to b\bar{b})/\Gamma(h \to b\bar{b})^{\rm SM}$ [also recall that $\Gamma_{\rm tot} \approx \Gamma(h \to b\bar{b})$]. In this figure, using again CPsuperH (version 2.3) [55,56], we assume that 100 GeV $< m_{H^{\pm}} <$ 1000 GeV, $\mu \sim M_2 \simeq$ 2000 GeV (so that chargino effects are completely decoupled). In fact, owing to the mass relation between the charged and pseudoscalar Higgs bosons, i.e., $m^2_{H^{\pm}} = m^2_A + m^2_{W^{\pm}}$ (at tree level), this argument can be recast in terms of m_A. The point is that the MSSM rescaling factor of the $hb\bar{b}$ coupling (at tree level) is $\sin\alpha/\cos\beta$ and that the α and β angles are related via the well-known (tree level) formula

$$\tan 2\alpha = \tan 2\beta \frac{m^2_{H^{\pm}} - m^2_{W^{\pm}} + m^2_Z}{m^2_{H^{\pm}} - m^2_{W^{\pm}} - m^2_Z}, \quad (18)$$

so that there exists a strong correlation between κ^{-1}_{bb} and $m_{H^{\pm}}$: in particular, the smaller $m_{H^{\pm}}$ (or m_A) the smaller κ^{-1}_{bb}. This is well exemplified by noting that the edge of the distribution of green points in Fig. 5 is nothing but $(\sin\alpha/\cos\beta)^{-2}$, with the spread determined by the actual value of $\tan\beta$ (and subleading loop effects). It is therefore clear the potential that a measurement of κ_{bb} can have in (indirectly) constraining $m_{H^{\pm}}$ (or m_A), even in the region presently compatible with LHC data (above the red line). We find such effects to be generally realized also in the constrained version of the MSSM.

In conclusion, we have proven that both chargino and charged Higgs effects induced by the MSSM can affect the LHC data used in the Higgs search over significant regions of the parameter space of such a minimal SUSY realization, including in its constrained version, so long that nonuniversal gaugino and Higgs masses are allowed. Light charginos can increase significantly the $h\gamma\gamma$ (effective) coupling, whereas light charged Higgs bosons can sizably increase the $hb\bar{b}$ one. Whereas the former effect could easily be confirmed or disproved by upcoming LHC data (at higher energy and luminosity) by measuring the $\gamma\gamma$ signal strength, the latter phenomenon may be more difficult to extract via the $b\bar{b}$ signal strength, as the $h \to b\bar{b}$ partial decay width is very close to the total one. Finally notice that such $\tilde{\chi}^{\pm}_i$ and $H^{\pm}$ effects are normally realized on nonoverlapping regions of parameter space, so that they would not appear simultaneously.

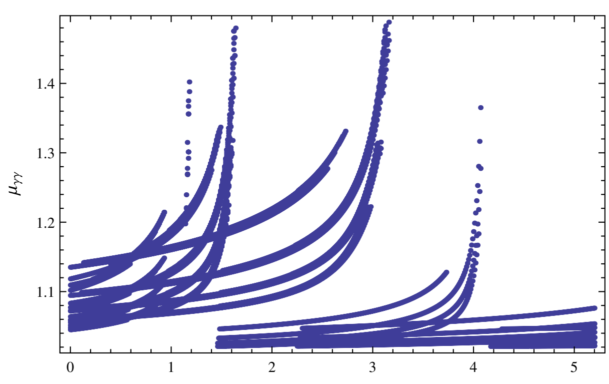

FIG. 4 (color online). Signal strength of the diphoton channel as a function of the difference $\Delta d = d_2 - d_1$ for $3 \leq \tan\beta \leq 30$, $d_1 = -1$, $0 \leq d_2 \leq 5$ and 150 GeV $< M_2 <$ 250 GeV.

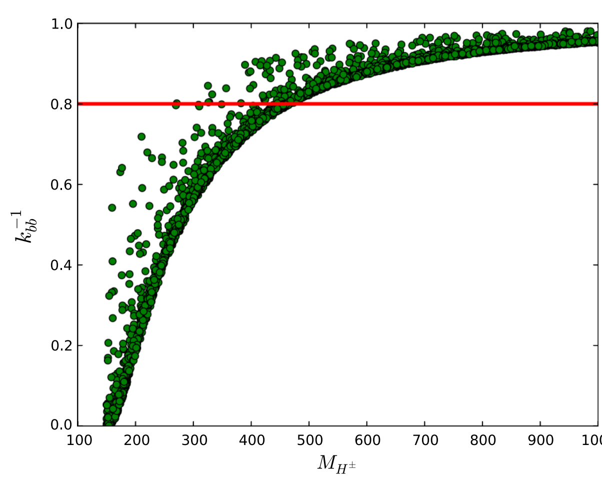

FIG. 5 (color online). $\kappa^{-1}_{bb} \simeq \kappa^{-1}_{\rm tot}$ versus the charged Higgs boson mass. Here, $1.1 < \tan\beta < 50$, $\mu \sim M_2 \simeq$ 2000 GeV and 100 GeV $< m_{H^{\pm}} <$ 1000 GeV. Further, the red line represents the lower limit on κ^{-1}_{bb} roughly compatible with current LHC data.

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