Light Chargino Effects onto $H \rightarrow \gamma\gamma$ in the MSSM$^\dagger$

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We analyse the implications of light charginos on the Higgs boson signal strength via gluon-gluon fusion and di-photon decay in the Minimal Supersymmetric Standard Model (MSSM) at the Large Hadron Collider (LHC). 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 non-universal Higgs and gaugino masses. In contrast, effects due to light charged Higgs bosons, that we also have investigated, are generically negligible in the $\gamma\gamma$ decay, though they may affect the $bb$ rate, hence the total width.

$^\dagger$We dedicate this work to the lasting memory of Ahmed Elsayed.

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 highest precision are $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow 4l$ and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$, where $l$ denotes a lepton (electron and/or muon) and $\nu$ 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]:

\begin{align}
\mu_{\gamma\gamma} &= 1.65 \pm 0.35, \\
\mu_{ZZ} &= 1.7 \pm 0.5, \\
\mu_{WW} &= 1.01 \pm 0.31.
\end{align}

From the CMS collaboration one has instead [5–8]:

\begin{align}
\mu_{\gamma\gamma} &= 0.78 \pm 0.28, \\
\mu_{ZZ} &= 0.91^{+0.3}_{-0.24}, \\
\mu_{WW} &= 0.76 \pm 0.21.
\end{align}

These results indicate suppression or enhancement in the di-photon mode, with respect to the Standard Model (SM), with more than 2$\sigma$ deviation either way, a trend which could then be a very important signal for possible new physics Beyond the SM (BSM) [3,10] such as the MSSM [11–28] (also the constrained version [29–34]), Next-to-MSSM [35–42] and (B-L)SSM [43–46].

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 $\alpha$, 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 (VEVs) of the two Higgs doublets pertaining to this minimal realisation 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 [17,18], owing to SUSY states entering the one- and two-loop corrections to it. Therefore, in some sense, the new LHC results are in favour of a low energy SUSY scenario, indeed (possibly) the MSSM. The signal strength of the di-photon channel, $H \rightarrow \gamma\gamma$, relative to the SM expectation, in terms of production cross section ($\sigma$) and decay Branching Ratio (BR), is defined as

\begin{equation}
\mu_{\gamma\gamma} = \frac{\sigma(pp \rightarrow h \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow h \rightarrow \gamma\gamma)^{\text{SM}}} \frac{\text{BR}(h \rightarrow \gamma\gamma)}{\text{BR}(h \rightarrow \gamma\gamma)^{\text{SM}}} = \frac{\Gamma(h \rightarrow gg)}{\Gamma(h \rightarrow gg)^{\text{SM}}} \frac{\Gamma_{\text{tot}}}{\Gamma_{\text{tot}}^{\text{SM}}} = \kappa_g \kappa_{\text{tot}}^{-1}\kappa_{\gamma\gamma}. \tag{3}
\end{equation}

In the MSSM, the $H \rightarrow \gamma\gamma$ 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 $H \rightarrow \gamma\gamma$ is given by
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

$$\mathcal{L} = g_N \tilde{\chi}_i^++ (C_{ij}^L P_L + C_{ij}^R P_R) \tilde{\chi}_j^+ h + h.c.$$  \hspace{1cm} (9)
from this plot, such couplings can reach their maximum values and become of order \( O(\pm 1) \) if \( \tan \beta \) is very small, close to 1, and \( \mu \approx M_2 \). 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, \( M_{\chi^\pm_1} \), with \( m_h \approx 125 \text{ GeV} \). We scan over the following expanse of parameter space (using CPSuperH (version 2.3) [53, 54]): \( 1.1 < \tan \beta < 5, \text{ 100 GeV} < \mu < 300 \text{ GeV} \) and \( 100 \text{ GeV} < M_2 < 300 \text{ GeV} \). Other dimensionful SUSY parameters are fixed to be of order few TeV so that all other possible SUSY effects onto \( H \rightarrow \gamma\gamma \) are essentially negligible. As can be seen from this figure, in order to have a significant chargino contribution to \( \kappa_{\gamma\gamma} \), quite a light chargino mass (\( M_{\chi^\pm_1} \approx 104 \text{ GeV} \)), around the LEP limit, is required [55, 59]. 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 \( M_2 \), \( \mu \) and \( \tan \beta \) and light charginos require small \( M_2 \) and \( \mu \), 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 \( m_0 \). In order to overcome this contradiction, a departure from the constrained MSSM is necessary. In particular, one has to consider non-universal gaugino masses so that \( M_2 \) can be much smaller than \( M_3 \). In addition, a non-universal Higgs mass is also crucial to guarantee small values of the \( \mu \) parameter. Therefore, the following set of soft SUSY breaking terms at high scale are favoured for this analysis:

\[
m_{H_1}^2 = m_0^2 (1 + d_1),
\]
\[
m_{H_2}^2 = m_0^2 (1 + d_2),
\]
\[
m_{q,l}^2 = m_0^2,
\]

in addition to

\[
M_1 \lesssim M_2 \ll M_3,
\]
\[
A_0 \lesssim O(1 \text{ TeV}).
\]

Running these soft terms from the Grand Unification Theory (GUT) scale down to the SUSY scale \( \sim \sqrt{m_{\tilde{t}_1} m_{\tilde{b}_2}} \) and imposing the electroweak breaking conditions, one finds that the \( \mu \)-parameter is given by

\[
\mu^2 = \frac{m_{H_2}^2 - m_{H_2}^2 \tan^2 \beta}{1 - \tan^2 \beta} - \frac{M_{\tilde{q}}^2}{2}.
\]

One can easily show that \( \mu \) is strongly dependent upon the value of \( d_1 \) and \( d_2 \) and that for \( d_1 < d_2 \) a light \( \mu \sim O(100 \text{ GeV}) \) is achieved, so that we obtain different values for \( m_{H_1} \) and \( m_{H_2} \) in correspondence to a small \( \mu \). In Fig. 3 we display the results for \( \mu_{\gamma\gamma} \) versus \( \mu \) for \( m_0 \sim A_0 \sim 1 \text{ TeV} \) and \( 500 \leq M_3 \leq 1100 \) (so that \( m_h \approx 125 \text{ GeV} \)), \( 3 \leq \tan \beta \leq 30 \), \( 0 \leq d_2 \leq 5 \) and \( 150 \text{ GeV} < M_2 < 250 \text{ GeV} \). This figure confirms that a quite small \( \mu \) is obtainable in this class of SUSY models and the signal strength in \( \gamma\gamma \) is significantly enhanced for these values. In Fig. 4 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 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 behaviour 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 $h \rightarrow \gamma \gamma$ decay, so we do not produce the corresponding formulae. However, we do present here an interesting plot, highlighting the key role of the $H^\pm$ mass entering the $hbb$ coupling squared (but not the effective $h\gamma\gamma$ one), see Fig. 4 wherein $\kappa_{bb} \equiv \Gamma(h \rightarrow bb)/\Gamma(h \rightarrow b\bar{b})_{SM}$ (also recall that $\Gamma_{tot} \approx \Gamma(h \rightarrow b\bar{b})$). In this figure, using again CPsuperH (version 2.3) [53, 54], we assume that 100 GeV $< m_{H^\pm} < 1000$ GeV, $\mu \sim M_2 \approx 2000$ GeV (so that chargino effects are completely decoupled). In fact, owing to the mass relation between the charged and pseudoscalar Higgs bosons, i.e., $m_{H^\pm}^2 = m_A^2 + m_{W^\pm}^2$ (at tree level), this argument can be recast in terms of $m_A$. The point is that the MSSM rescaling factor of the $hbb$ coupling (at tree level) is $\sin \alpha/\cos \beta$ and that the $\alpha$ and $\beta$ angles are related via the well-known (tree level) formula

$$\tan 2\alpha = \tan 2\beta \frac{m_{H^\pm}^2 - m_{W^\pm}^2 + m_Z^2}{m_{H^\pm}^2 - m_{W^\pm}^2 - m_Z^2},$$

(18)

so that there exists a strong correlation between $\kappa_{bb}^{-1}$ and $m_{H^\pm}$: in particular, the smaller $m_{H^\pm}$ (or $m_A$) the smaller $\kappa_{bb}^{-1}$. This is well exemplified by noting that the edge of the distribution of green points in Fig. 4 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 $\kappa_{bb}$ 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 realised 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 realisation, including in its constrained version, so long that non-universal gaugino and Higgs masses are allowed. Light charginos can increase significantly the $h\gamma\gamma$ (effective) coupling whereas light charged Higgs bosons can sizeably increase the $hbb$ 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 $h \rightarrow b\bar{b}$ partial decay width is very close to the total one. Finally notice that such $\chi_{\pm}^\pm$ and $H^\pm$ effects are normally realised on non-overlapping regions of parameter space, so that they would not appear simultaneously.

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