Can we distinguish between h^{SM} and h^0 in split supersymmetry?

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We investigate the possibility to distinguish between the Standard Model Higgs boson and the lightest Higgs boson in Split Supersymmetry. We point out that the best way to distinguish between these two Higgs bosons is through the decay into two photons. It is shown that there are large differences of several percent between the predictions for $\Gamma(h \to \gamma\gamma)$ in the two models, making possible the discrimination at future photon-photon colliders. Once the charginos are discovered at the next generation of collider experiments, the well defined predictions for the Higgs decay into two photons will become a cross check to identify the light Higgs boson in Split Supersymmetry.

I. INTRODUCTION

Despite the great success of the Standard Model (SM), the mechanism for electroweak symmetry breaking remains to be tested in experiments. There are many reasons to believe there is physics beyond the SM. In particular, the Minimal Supersymmetric Standard Model (MSSM) is one of the best motived theories where it is possible to describe the cold dark matter in the Universe and where the unification of the gauge couplings is achieved. In low energy supersymmetry it is assumed that the SUSY breaking scale is at TeV following the naturalness criterion.

Recently, Arkani-Hamed and Dimopoulos [1], have noticed that gauge coupling unification can be achieved in a supersymmetric model where all scalars, except for one Higgs doublet, are very heavy. Most of the unpleasant aspects of low energy supersymmetry, such as excessive flavour and CP violation, very fast dimension 5 proton decay, and tight constraints on the Higgs mass, are eliminated. At the same time, there is a candidate to describe the cold dark matter in the Universe. Several phenomenological studies in this scenario, now called split supersymmetry, have been performed [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18].

It is expected that the Higgs boson will be discovered in the next generation of collider experiments. Therefore, one of the main issues in Higgs boson physics is the identification of observable useful to distinguish between the SM Higgs h^{SM} and the lightest Higgs in possible extensions of the SM. There are several studies devoted to this very important issue in the context of the MSSM

[19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

As we mention before we hope at future collider experiments we will discover at least a neutral particle with spin zero, the Higgs boson, and the lightest supersymmetric particles, the neutralinos and charginos. Since in Split supersymmetry the interactions of the lightest Higgs boson with the SM fermions are the same as the interactions of the SM Higgs, through the decays into two SM fermions it is not possible to make the identification of the Higgs. Therefore we have to use the decays at one loop, where the effect of virtual particles present in Split SUSY is relevant. In this Letter we investigate this issue and we argue that the way to address it is studying the decays of the Higgs boson into two photons. We show several numerical examples where it is possible to appreciate large differences between the decay rates in the SM and in Split supersymmetry.

II. DISTINGUISHING BETWEEN h^{SM} AND h^0 IN SPLIT SUSY

In order to identify the Higgs boson at future colliders the predictions of all its decay rates have to match with their measurements. This is the case of SM Higgs boson h^{SM} or the lightest Higgs boson h^0 of the supersymmetric extension of the standard model.

It is particularly difficult to distinguish between the SM Higgs boson and the MSSM lightest Higgs boson in the decoupling limit [31]. This is precisely what happens in Split Supersymmetry, where all scalars are very heavy except for one Higgs doublet and for the neutralinos and charginos which are all light. Therefore, in split supersymmetry we expect that at future colliders the lightest Higgs boson will be discovered together with charginos and neutralinos. However, their discovery is not enough to claim that the observed Higgs corresponds to the SPLIT SUSY light Higgs, since we have to measure its couplings with a good precision.

In the context of the MSSM there are studies about the possibility to distinguish between different Higgses through the couplings Hgg [19], $HZ\gamma$ [20, 21, 22] and $H\gamma\gamma$ [23, 24, 25, 26, 27]. Also the quantity $B(H \to b\bar{b})/B(H \to \tau^+\tau^-)$ has been studied extensively [28, 29, 30].

In this Letter we study the possibility to identify the light Higgs in split supersymmetry [1]. Since in this case all sfermions and Higgs bosons, except for the lightest one, are very heavy it is not possible to use the quantity $B(H \to b\bar{b})/B(H \to \tau^+\tau^-)$ nor the coupling Hgg. The $Hb\bar{b}$ and $H\tau\tau$ couplings are equal at tree level in the SM and in SPLIT SUSY. There are not differences at one-loop, since all squarks or sleptons in the loops are very heavy. In the case of Hgg coupling, this is a one-loop induced coupling with quark contributions being common to both the SM and SPLIT-SUSY, and with the difference being the squark contributions, which are negligible. The two other possibilities are to use the couplings $HZ\gamma$ and $H\gamma\gamma$. However, it is not possible to use the first one since we know that the $B(h \to Z\gamma)$ is very small and it will be very difficult to determine it with a very good precision [32]. Therefore we concentrate on the possibility to use the coupling $H\gamma\gamma$ for our study. The decay $h \to \gamma\gamma$ can be observed at the LHC but with an error larger than 10% [33, 34, 35]. At electron-positron colliders there is the additional possibility of photon-photon collisions, where the rate $\gamma\gamma \to h \to b\bar{b}$ can be measured with a 2% precision [36, 37, 38, 39]. This combined with a measurement of $B(h \to b\bar{b})$ with a 2.4% [35], gives a determination of $B(h \to \gamma\gamma)$ with a $\sim 2\%$ error.

The decay rate $\Gamma(h \to \gamma\,\gamma)$ is given by [40]:

$$\Gamma(h \to \gamma\,\gamma) = \frac{\alpha^2 g^2}{1024\pi^3}\frac{m_h^3}{m_W^2}\left|\sum_i A_i\right|^2 \tag{1}$$

where α is the fine structure constant, g is the $SU(2)$ gauge coupling constant, m_W is the W boson mass, and m_h is the Higgs boson mass. There is an amplitude A_i for each charged particle inside the loop, and depends on a loop function F whose form varies according to the spin of the particle in the loop.

In Split Supersymmetry the relevant contributions are:

$$A_W = C_W F_1(\tau_W) \tag{2}$$

$$A_f = N_C^f\, Q_f^2\, C_f\, F_{1/2}(\tau_f) \tag{3}$$

$$A_{\tilde{\chi}^\pm} = C_{\tilde{\chi}^\pm}\frac{M_W}{M_{\tilde{\chi}^\pm}}F_{1/2}(\tau_{\tilde{\chi}^\pm}) \tag{4}$$

where A_W, A_f, $A_{\tilde{\chi}^\pm}$ are the amplitudes for the contributions with W bosons, fermions, and charginos inside the loop, respectively. The parameter $\tau_i = 4m_i^2/m_h^2$, where m_i is the mass of the particle inside the loop, and m_h is the Higgs mass. $N_C = 3$ for quarks and squarks, while $N_C = 1$ for leptons and sleptons, and Q_f is the electric charge of the fermion f. The couplings of the lightest Higgs to the internal particles are given by:

$$C_{f=u,c,t} = 1, \quad C_{f=d,s,b,e,\mu,\tau} = 1, \quad C_W = 1, \tag{5}$$

$$C_{\tilde{\chi}_i^\pm} = 2(S_{ii}\sin\beta + Q_{ii}\cos\beta) \tag{6}$$

with $S_{ij} = U_{i1}V_{j2}/\sqrt{2}$ and $Q_{ij} = U_{i2}V_{j1}/\sqrt{2}$. The matrices U and V are the matrices which diagonalize the chargino mass matrix. The loop functions F_0, $F_{1/2}$ and F_1 can be found in [40].

In Split supersymmetry, the Higgs couplings to fermions and W bosons are SM-like, giving contributions which are equal in both models. Therefore, the chargino contribution will determinate the difference between the decays into two photons in the SM and split SUSY.

III. RESULTS

In order to quantify the difference between the decay rate of the SM Higgs and the lightest Higgs into two photons in split supersymmetry we define the following quantity:

$$\delta = \frac{\Gamma^{Split}(h^0 \to \gamma\gamma) - \Gamma(h^{SM} \to \gamma\gamma)}{\Gamma(h^{SM} \to \gamma\gamma)} \tag{7}$$

We calculate this quantity using the above formulas for different values of the relevant parameters, which are the Higgs mass, the higgsino mass parameter μ, the $SU(2)$ gaugino mass M_2, and $\tan\beta$. We take $m_h = 120$ GeV and consider it as an independent parameter. Notice that in the case of split supersymmetry, since we accept the fine-tuning and we integrate out all superheavy scalars, the Higgs mass basically does not change when we vary the rest of the parameters. The loops corrections with charginos and neutralinos are not very important, see for example [9].

In Figure 1 we see how this quantity changes as a function of the parameter μ, for given values of M_2 and $\tan\beta$. Note that it is possible to achieve differences up to 6% when the chargino contribution is large. As this difference is achieved, the branching ratio of the decay into two photons is of the order of 10^{-3}. We impose the experimental bound $m_{\tilde{\chi}_1^+} > 103$ GeV, which limits the curves at low values of μ. As the magnitude of the parameter μ increases the chargino masses increase also, the heavier faster than the lightest. In general, larger chargino masses produce smaller contributions to $h \to \gamma\gamma$ and thus the parameter δ decreases. For a similar reason, curves defined by larger values of the gaugino mass M_2 have smaller δ. These curves are defined by $M_2 = 150$ GeV (red crosses), $M_2 = 200$ GeV (blue x's), and $M_2 = 250$ GeV (green circles). Two different values of $\tan\beta$ are considered in this figure, $\tan\beta = 10$ and 50 with the smaller value giving larger δ. Another interesting point to notice in this figure is the correlation between the sign of μ (actually, the sign of μM_2 since we work with $M_2 > 0$) and the sign of δ.

In Fig. 2 we show the variation of δ as a function of M_2 for $\tan\beta = 10$ and $\mu = 150$, 250, and 350 GeV. It is clear that when M_2 is increased our quantity decreases since the chargino contributions are less important, due to their larger mass. The three curves are limited at low M_2 by the experimental lower bound on the chargino mass described before. At the other extreme

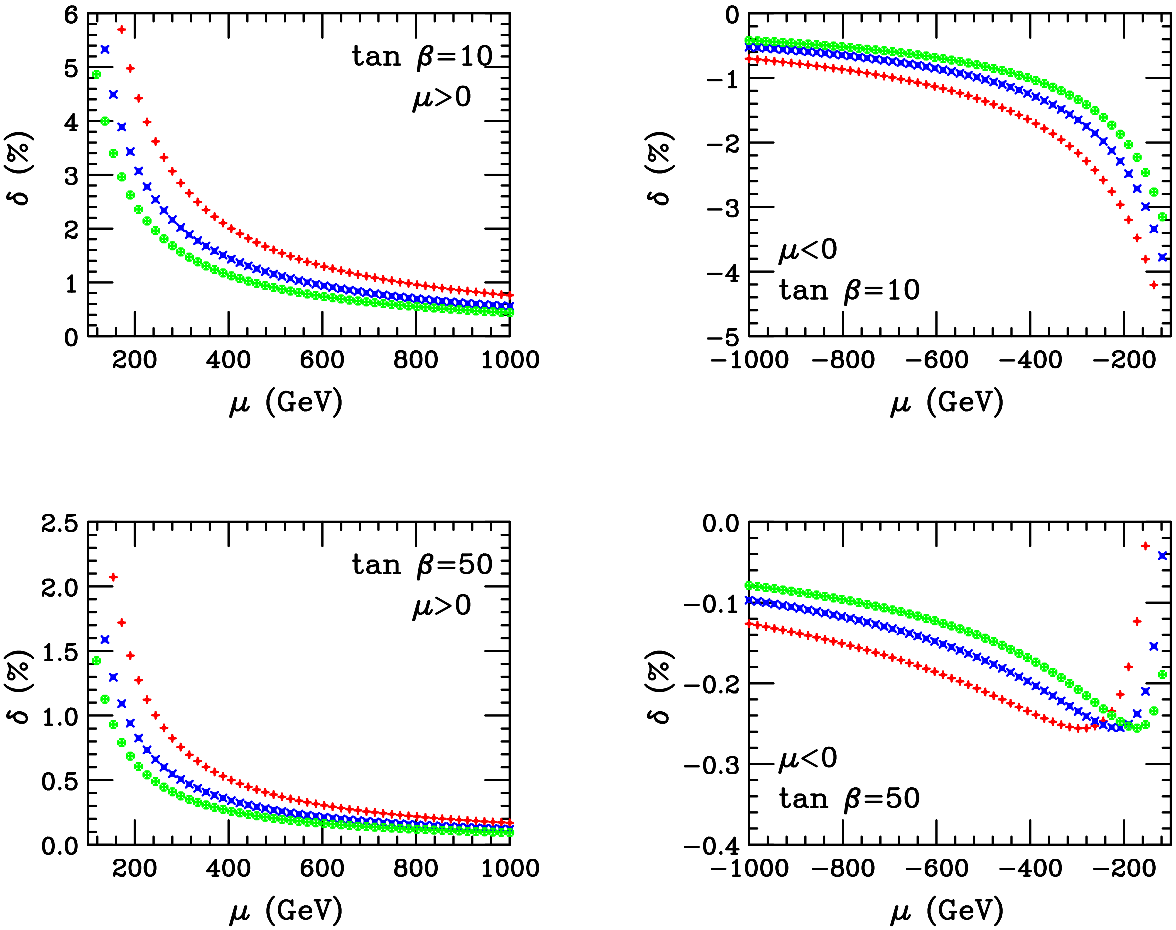

FIG. 1: *Relative difference δ between $\Gamma(h \to \gamma\gamma)$ in the SM and in split supersymmetry as a function of μ for different values of $\tan\beta$ and M_2. Red crosses correspond to $M_2 = 150$ GeV, blue x's to $M_2 = 200$ GeV, and green circles to $M_2 = 250$ GeV. We consider $m_h = 120$ GeV.*

($M_2 = 300$ GeV) the light chargino mass is given by 133, 213, and 262 GeV for $\mu = 150$, 250, and 350 GeV, respectively. Despite these large chargino masses, δ remains above 1% in the whole parameter space shown in the figure.

In Fig. 3 we have the dependence of δ on $\tan\beta$, and plot three curves with increasing values of μ and M_2, as indicated in the figure. In all cases δ decreases with $\tan\beta$ from several percent at low values to less than 1-2% at large values.

The decay rate for $h \to \gamma\gamma$ in the MSSM with the Higgs sector in the decoupling limit was studied in [25, 30]. It was found that contributions from the stop sector are larger when the left-right mixing is large, and that contributions from charginos decrease with $\tan\beta$. At small $\tan\beta$ chargino and stop contributions have opposite signs and a cancellation could occurs. Of course, this cancellation does not happens in Split Supersymmetry, obtaining larger decay rates $\Gamma(h \to \gamma\gamma)$. In

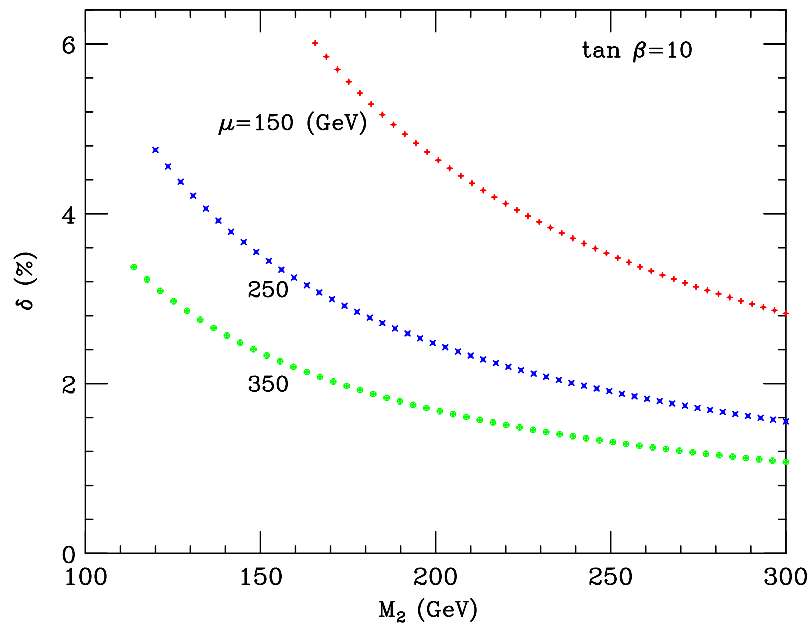

FIG. 2: *Relative difference* δ *between* $\Gamma(h \to \gamma\gamma)$ *in the SM and in split supersymmetry as a function of* M_2*, for* $\tan\beta = 10$ *and different values of* μ*. We consider* $m_h = 120$ *GeV.*

general, smaller decay rates are obtained at large values of $\tan\beta$: chargino contributions are small in both the MSSM and Split SUSY, with the stop contribution adding to the W contribution in the MSSM. Larger decay rates are found in the MSSM at high $\tan\beta$ when the sbottom loops are also important. We hope that the results presented in this section will be useful to understand the possibility to distinguish between the SM Higgs boson and the lightest Higgs boson in Split SUSY.

IV. SUMMARY

In Split Supersymmetry the light Higgs boson couplings to SM particles are identical to the couplings of the SM Higgs boson. We point out that a way to distinguish between them is through the decay into two photons. We show several numerical examples where we appreciate large differences of several percent between the predictions for $\Gamma(h \to \gamma\gamma)$ in the two models, making possible the discrimination at future photon-photon colliders. Once the Higgs boson and the charginos are discovered at the next generation of collider experiments, the well defined predictions for the Higgs decay into two photons will constitute an important cross check to identify the light Higgs boson in Split SUSY.

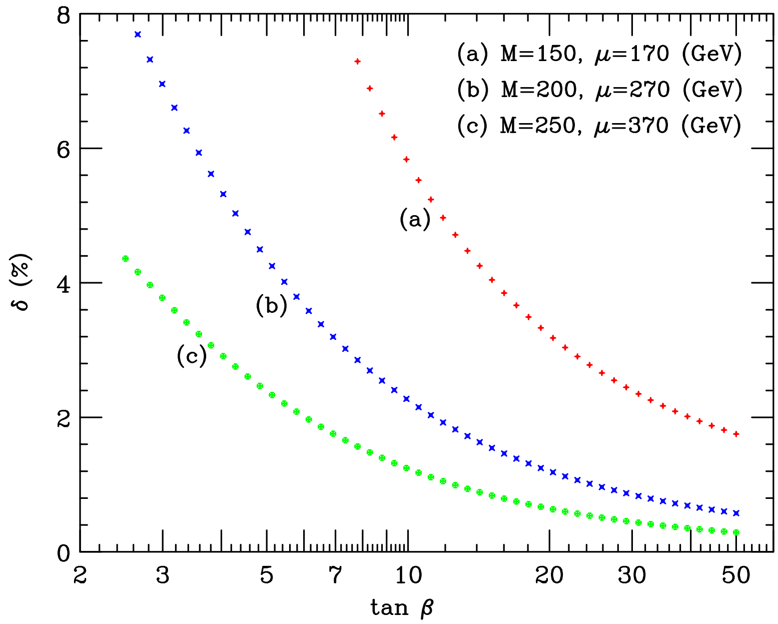

FIG. 3: *Relative difference* δ *between* $\Gamma(h \to \gamma\gamma)$ *in the SM and in split supersymmetry as a function of* $\tan\beta$ *for different values of* μ *and* M_2*. We consider* $m_h = 120$ *GeV.*

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