SUSY Higgs at the LHC:
Effects of light charginos and neutralinos.

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Abstract

In view of the latest LEP data we consider the effects of charginos and neutralinos on the two-photon and $b\bar{b}$ signatures of the Higgs at the LHC. Assuming the usual GUT inspired relation between M_1 and M_2 we show that there are only small regions with moderate $\tan\beta$ and large stop mixings that may be dangerous. Pathological models not excluded by LEP which have degeneracy between the sneutrino and the chargino are however a real danger because of large branching fraction of the Higgs into invisibles. We have also studied models where the gaugino masses are not unified at the GUT scale. We take $M_1 = M_2/10$ as an example where large reductions in the signal at the LHC can occur. However we argue that such models with a very light neutralino LSP may give a too large relic density unless the sleptons are light. We then combine this cosmological constraint with neutralino production with light sfermions to further reduce the parameter space that precludes observability of the Higgs at the LHC. We still find regions of parameter space where the drops in the usual Higgs signals at the LHC can be drastic. Nonetheless, in such scenarios where Higgs may escape detection we show that one should be able to produce all charginos and neutralinos. Although the heavier of these could cascade into the Higgs, the rates are not too high and the Higgs may not always be recovered this way.

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1 Introduction

Uncovering the mechanism of symmetry breaking is one of the major tasks of the high energy colliders. Most prominent is the search for the Higgs particle. Within the standard model, $\mathcal{SM}$, this scalar particle poses the problem of naturalness and its mass is a free parameter. Current data[1] seem to indicate a preference for a light Higgs with a mass that can nicely fit within a supersymmetric version of the $\mathcal{SM}$. In fact an intermediate mass Higgs, IMH, is one of the most robust prediction of SUSY, since one does not have strict predictions on the large array of the other masses and parameters in this model. Another, perhaps circumstantial, evidence of SUSY is the successful unification of the gauge couplings at some high scale. Add to this the fact that the neutralino can provide a good dark matter candidate explains the popularity of the model. Even so the search for the lightest Higgs is not so easy. LEP2 where the Higgs signature is easiest may unfortunately be some $20-30$ GeV short to be able to cover the full range of the minimal SUSY lightest Higgs mass. Searches at the Tevatron need very good background rejection and in any case need to upgrade the present luminosities quite significantly. At the LHC, most analyses have relied extensively on the two-photon decay of the IMH either in the dominant inclusive channel through $gg \to h \to \gamma\gamma$ or in associated production. Only recently has it been shown that associated production of the Higgs with tops with the former decaying into $b\bar{b}$ can improve the discovery of the Higgs, albeit in the region $m_h < 120$GeV[2]. Unfortunately, until recently[2], most simulations for Higgs searches have in effect decoupled the rest of the supersymmetric spectrum from the Higgs sector, like in the much advertised ATLAS/CMS $M_A - \tan\beta$ plane[2, 3].

This assumption of a very heavy SUSY spectrum can not be well justified. First, naturalness arguments require that at least some of the SUSY masses be below $1TeV$ or even much less. Second, it has been known[4, 5] that relaxing this assumption can have some very important consequences on the Higgs search at the LHC. This is not surprising considering the fact that the most important production channel $gg \to h$ is loop induced as is the main discovery channel $h \to \gamma\gamma$. One of the most dramatic effect is that of a light stop with large mixing which drastically reduces the production rate[4, 6]. Fortunately, when this happens, a careful analysis[7] shows that the Higgs signal can be rescued in a variety of channels that become enhanced or that open up precisely for the same reason that the normal inclusive channel drops, so that in a sense there is a complementarity. For instance with all other sparticles but the stops heavy, one can show that whenever the production rate in the inclusive channel drops, the branching ratio into two photons increases with the consequence that associated Wh/Zh and $t\bar{t}h$ where the Higgs decays into two photons becomes a very efficient means of tracking the Higgs.

Moreover associated $\tilde{t}_1\tilde{t}_1 h$ production[7, 8, 9] becomes important through the cascade of the heavier stop $\tilde{t}_2$, $\tilde{t}_2 \rightarrow \tilde{t}_1 h$. At the same time since the $hb\bar{b}$ coupling is hardly affected $t\bar{t}h$ production could play an important role. Similar sort of complementarity has also been pointed out in supersymmetric scenarios where the coupling $hb\bar{b}$ can be made very small[10].

In our investigation of the effects of light stops with large mixing, all other particles but the stops were assumed rather heavy. It is then important to ask how the overall picture changes had we allowed other sparticles to be relatively light. Considering that the present LEP and Tevatron data precludes the decay of the lightest Higgs into sfermions, the effect of the latter on the properties of the lightest Higgs can only be felt through loops. These effects can therefore be considered as a special case of the stop that we studied at some length and apart from the sbottom at large $\tan\beta$ the effects will be marginal. One can then concentrate on the spin-half gaugino-higgsino sector. In order to extract the salient features that may have an important impact on the Higgs search at the LHC, we leave out in this study the added effects of a light stop. Compared to the analysis with the stop, this sector does not affect inclusive production nor the usual associated production mechanisms. The effect will be limited to the Higgs decay. First, if the charginos are not too heavy they can contribute at the loop level. We find however, by imposing the present limits on their masses, that this effect is quite small. On the other hand we show that the main effect is due to the possible decay of the Higgs into the lightest neutralino. This is especially true if one relaxes the usual so-called unification condition between the two gaugino components of the LSP neutralino. Although at LEP an invisible Higgs is not so much of a problem[11], since it can be easily tagged through the recoiling Z, it is a different matter at the LHC. Few studies have attempted to dig out such an invisible (not necessarily supersymmetric) Higgs at the LHC, in the associated $Zh, (Wh)$[12, 13] channel. Even with rather optimistic rejection efficiencies the backgrounds seem too overwhelming. It has also been suggested [14] to use associated $t\bar{t}h$ production but this requires very good b-tagging efficiencies and a good normalisation of the backgrounds. Recently Ref. [15] looked at how to hunt for an invisible Higgs at the Tevatron. For $m_h > 100$GeV a 5σ discovery requires a luminosity in excess of 30fb^{-1}.

Compared to the effects of the stop or a vanishing $hb\bar{b}$, where a sort of compensation occurs in other channels, the opening up of the invisible decay reduces all other channels including the branching ratio in $b\bar{b}$. Previous studies[16, 17] have mainly concentrated if not on a mSUGRA scenario then on a scenario based on the mSUGRA inspired relation between the electroweak gaugino masses, M_1, M_2. Moreover LEP searches and limits refer essentially to the latter paradigm. In the course of this analysis we had to re-interpret the LEP data in the light of more general scenarios. We therefore had to take recourse to various limits on cross sections rather than absolute limits on some physical parameters quoted in the literature. We have also tried to see whether new mechanisms come to the rescue of the Higgs search at the LHC when the invisible channel becomes substantial and reduces the usual signal significantly. Much like in our analysis of the stop[7] where we found that the Higgs could be produced through the decay of the heavier stop into the lighter one, we inquired whether a similar cascade decay from the heavier neutralino or charginos to their lighter companions can take place. This is known to occur for instance for some mSUGRA points[18, 2], but its rate is found not to be substantial when an important branching ratio into invisibles occurs. Even if it were substantial it would be difficult to reconstruct the Higgs since again at the end of the chain the Higgs will decay predominantly invisibly.

Considering the dire effects of a large invisible branching ratio occurring for rather light neutralinos, we have investigated the astrophysical consequences of such scenarios, specifically the contribution of such light neutralinos on the relic density. We find that these models require rather light slepton masses. In turn, with such light sleptons, neutralino production at LEP2 provides much restrictive constraints than the chargino cross sections. Taking into account the latter constraints helps rescue some of the Higgs signals.

The paper is organised as follows. In the next section we introduce our notation for the chargino-neutralino sector and make some qualitative remarks concerning the coupling of the lightest Higgs as well as that of the Z to this sector. This will help understand some of the features of our results. In section 2 we review the experimental constraint and discuss how these are to be interpreted within a general supersymmetric model. Section 3 presents the results for Higgs detection at the LHC within the assumption of the GUT relation for the gaugino masses. Section 4 analyses the “pathological” cases with a sneutrino almost degenerate with the chargino, leading to lower bounds on the chargino mass. Section 5 analyses how the picture changes when one relaxes the GUT inspired gaugino masses constraint and the impact of the astrophysical constraints on the models that may jeopardise the Higgs search at the LHC. Section 6 summarises our analysis.

2 The physical parameters and the constraints

2.1 Physical parameters

When discussing the physics of charginos and neutralinos it is best to start by defining one’s notations and conventions. All our parameters are defined at the electroweak scale.

The chargino mass matrix in the gaugino-higgsino basis is defined as

$$\begin{pmatrix} M_2 & \sqrt{2}M_W\cos\beta \\ \sqrt{2}M_W\sin\beta & \mu \end{pmatrix} \tag{2.1}$$

where M_2 is the soft SUSY breaking mass term for the $SU(2)$ gaugino while μ is the so-called higgsino mass parameter whereas $\tan\beta$ is the ratio of the vacuum expectation values for the up and down Higgs fields.

Likewise the neutralino mass matrix is defined as

$$\begin{pmatrix} M_1 & 0 & -M_Z\sin\theta_W\cos\beta & M_Z\sin\theta_W\sin\beta \\ 0 & M_2 & M_Z\cos\theta_W\cos\beta & -M_Z\cos\theta_W\sin\beta \\ -M_Z\sin\theta_W\cos\beta & M_Z\cos\theta_W\cos\beta & 0 & -\mu \\ M_Z\sin\theta_W\sin\beta & -M_Z\cos\theta_W\sin\beta & -\mu & 0 \end{pmatrix} \tag{2.2}$$

where the first entry M_1 (corresponding to the bino component) is the $U(1)$ gaugino mass. The oft-used gaugino mass unification condition corresponds to the assumption

$$M_1 = \frac{5}{3}\tan^2\theta_W M_2 \simeq M_2/2 \tag{2.3}$$

Then constraints from the charginos alone can be easily translated into constraints on the neutralino sector. Relaxing Eq. 2.3, or removing any relation between M_1 and M_2 means that one needs further observables specific to the neutralino sector.

The other parameters that appear in our analysis emerge from the Higgs sector. We base our study on the results and prescription of [19] for the improved two-loop calculations based on the effective Lagrangian[3]. The parameters here are, apart from the ubiquitous $\tan\beta$, the mass of the pseudo-scalar Higgs, M_A, A_t the trilinear mixing parameter in the stop sector, as well as M_S a supersymmetric scale that may be associated to the scale in the stop sector. Since we want to delimit the problem compared to our previous study on the stop effects, we will set the stop masses (and all other squarks) to 1TeV. We will also be working in the decoupling limit of large M_A that we also set at 1TeV. The lightest Higgs mass is then larger than if we had taken a lower M_A. As we will see the most important effect that results in small branching ratio for the two-photon width is when the invisible decay opens. This occurs if one has enough phase space and therefore if the mass of the Higgs is made as large as possible. Thus for a given $\tan\beta$ the effect is maximal for what is called maximal mixing: $A_t \sim \sqrt{6}M_S$ in the implementation

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[3] There is now a two-loop diagrammatic calculation[20] which is in good agreement with an updated version of the two-loop effective Lagrangian approach [21, 22].

of [19]. One would also think that one should make $\tan\beta$ large, however this parameter also controls the masses of the neutralinos and for the configuration of interest, those leading to the largest drops in the two-photon signal, one needs to keep $\tan\beta$ as low as possible to have the lightest neutralino as light as possible.

In principle we would have liked to decouple all other sparticles, specifically sfermions as stated in the introduction. However sleptons (in particular selectrons and sneutrinos) masses determine also the cross sections and the decay signature of the charginos and the neutralinos. Therefore, allowing for smaller sfermions masses does not so much directly affect the two-photon width but can relax quite a bit some of the limits on the chargino-neutralino sector which in turn affect the Higgs search. We thus allow for this kind of indirect dependence on the sfermion mass.

Often, especially in the case of neutralinos, LEP analyses set *absolute* bounds on masses. Ideally, since one is using bounds that are essentially set from the couplings of neutralinos to gauge bosons, to translate to couplings of these neutralinos and charginos to the Higgs, one needs to have access to the full parameter space $\mu, \tan\beta, M_1, M_2$. Thus absolute bounds are only indicative and it is much more informative to reinterpret the data. In the case of limits set solely from the chargino data, the re-interpretation is quite straightforward since no assumption on the parameters in Eq. 2.1 is made and the limits ensue from $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$. Limits on the neutralinos are a bit more involved. To make some of these points clearer and to help understand some of our results it is worth reviewing the couplings to neutralinos.

2.2 Couplings of Neutralinos to the Higgs and Z

The width of the lightest Higgs to the lightest neutralinos writes[16]

$$\Gamma(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0) = \frac{G_F M_W m_h}{2\sqrt{2}\pi}\,(1 - 4m^2_{\tilde{\chi}_1^0}/m_h^2)^{3/2}\,|C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}|^2 \tag{2.4}$$

where[23]

$$\begin{aligned} C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} &= (O_{12}^N - \tan\theta_W O_{11}^N)(\sin\alpha\, O_{13}^N \;+\; \cos\alpha\, O_{14}^N) \\ &\simeq (O_{12}^N - \tan\theta_W O_{11}^N)(\sin\beta\, O_{14}^N \;-\; \cos\beta\, O_{13}^N) \end{aligned} \tag{2.5}$$

O_{ij}^N are the elements of the orthogonal (we assume $\mathcal{CP}$ conservation) matrix which diagonalizes the neutralino mass matrix. α is the angle that enters the diagonalization of the CP-even neutral Higgses which in the decoupling (large M_A and ignoring radiative corrections) is trivially related to the angle β. $|O_{1j}^N|^2$ defines the composition of the lightest neutralino $\tilde{\chi}_1^0$. For instance $|O_{11}^N|^2$ is the bino purity and $|O_{11}^N|^2 + |O_{12}^N|^2$ is the gaugino purity. It is clear then, apart from phase space, that the LSP has to be a mixture of gaugino and higgsino in order to have a large enough coupling to the Higgs. The same applies for the diagonal coupling of the charginos ($h\chi_i^- \chi_i^+$).

In Fig. 1 we show the strength $C^2_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$ assuming the GUT unification condition between M_1 and M_2 for $\tan\beta = 5$ and $\tan\beta = 15$. One should note that the coupling is much larger for positive values of μ. The largest effect (peak) occurs for small values of μ and M_2 which however are ruled out by LEP data on the chargino mass. Note also, by comparing the $\tan\beta = 5$ and $\tan\beta = 15$ case in Fig. 1, that especially for $\mu > 0$, as $\tan\beta$ increases the Higgs coupling to the LSP gets smaller. At the same time the neutralino LSP gets heavier. Thus large $\tan\beta$ values corresponding to higher Higgs masses will not lead to the largest $h \to \tilde{\chi}_1^0\tilde{\chi}_1^0$. Similar behaviour is also observed for the coupling of the chargino to Higgs, the largest coupling sits in the $\mu > 0$ and small M_2 region. However, it turns out that the effect of charginos in the loop never becomes very large.
As seen in Fig. 2 for the case with $M_1 = M_2/10$, the same kind of behaviour persists: $\mu > 0$ and moderate $\tan\beta$ lead to stronger couplings. On the other hand, the constraints on M_2, M_1, μ which are derived for instance from neutralino production are more sensitive to the higgsino component of the neutralino. Indeed the Z coupling to these writes

$$Z^* \to \chi_i^0 \chi_j^0 \propto (O_{i3}^N O_{j3}^N - \, O_{i4}^N O_{j4}^N)^2 \tag{2.6}$$

Chargino production in e^+e^- is not as much critically dependent on the amount of mixing since both the wino and (charged) higgsino components couple to the Z and the photon. Some interference with the t-channel sneutrino exchange may occur in the case of a wino component (*i.e.* $|\mu| \ll M_2$), therefore the kinematic limit can be reached quite easily, except the situation where the signature of the chargino leads to almost invisible decay products.

2.3 Accelerator Constraints

This brings us to how we have set the constraints.

- Higgs mass:

In the scenarios we are considering with large M_A and large stop masses the ZZh coupling is essentially SM-like and LEP2 limits on the mass of the SM Higgs apply with little change even for an invisible Higgs. In any case, as discussed earlier, to make the chargino-neutralino effect most dramatic we will always try to maximise the Higgs mass independently of $\tan\beta$ by choosing an appropriate A_t. The LEP2 mass limit are thus always evaded. For $M_1 = M_2/10$ we stick to $\tan\beta = 5$, considering there is always

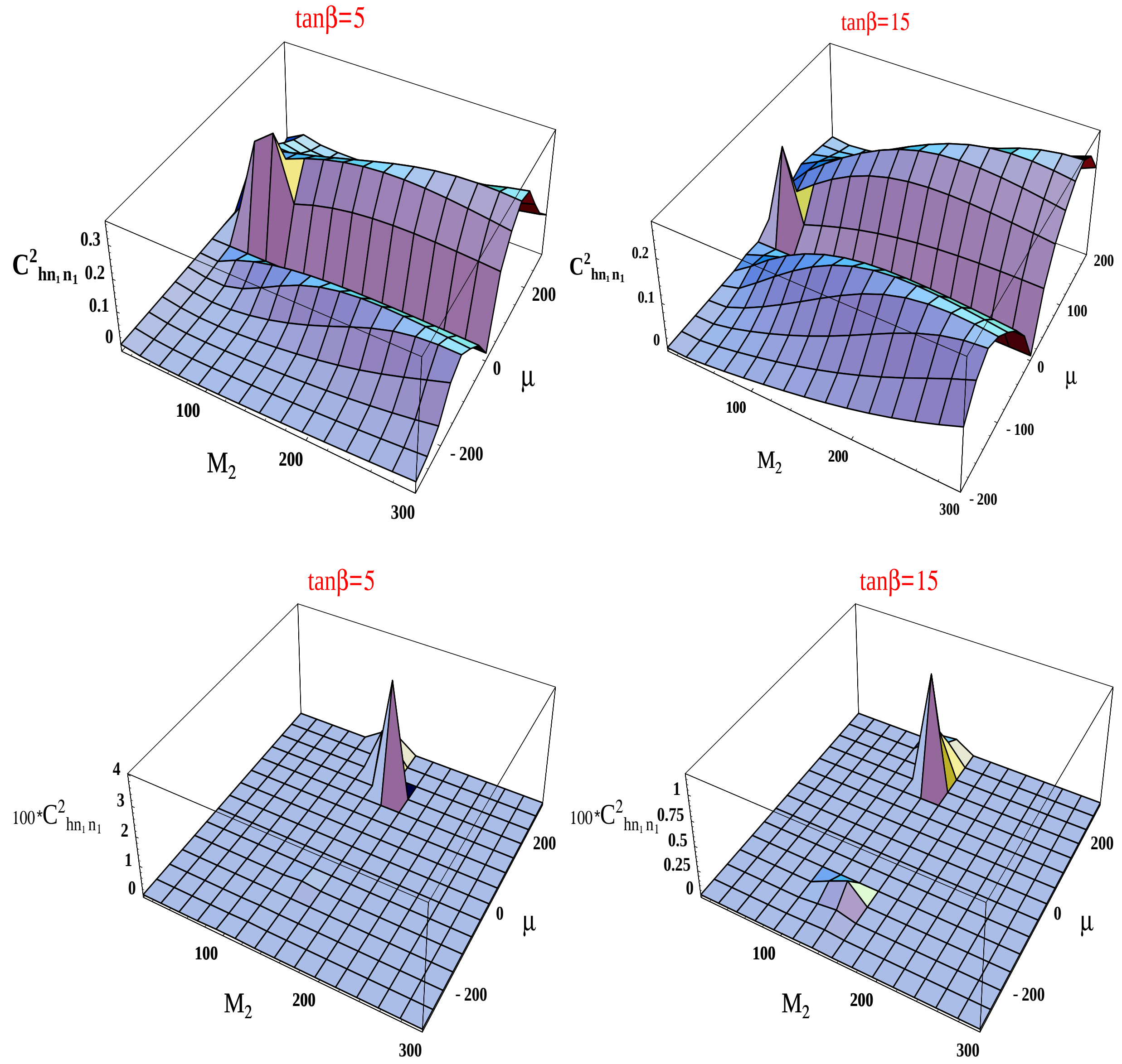

Figure 1: *Strength of the lightest Higgs coupling to* $\tilde{\chi}_1^0\tilde{\chi}_1^0$ *for* $\tan\beta = 5$ *and* $\tan\beta = 15$. *In the second set (bottom) of figures we have imposed* $m_{\tilde{\chi}_1^+} > 94.5 GeV$ *(the current limit on the lightest chargino) and* $m_{\tilde{\chi}_1^0} < 65 GeV$ *(this corresponds to the threshold for the lightest Higgs with a maximum mass of about* $130 GeV$ *to decay into the LSP neutralino). Here* $C_{hn_1n_1} \equiv C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$.

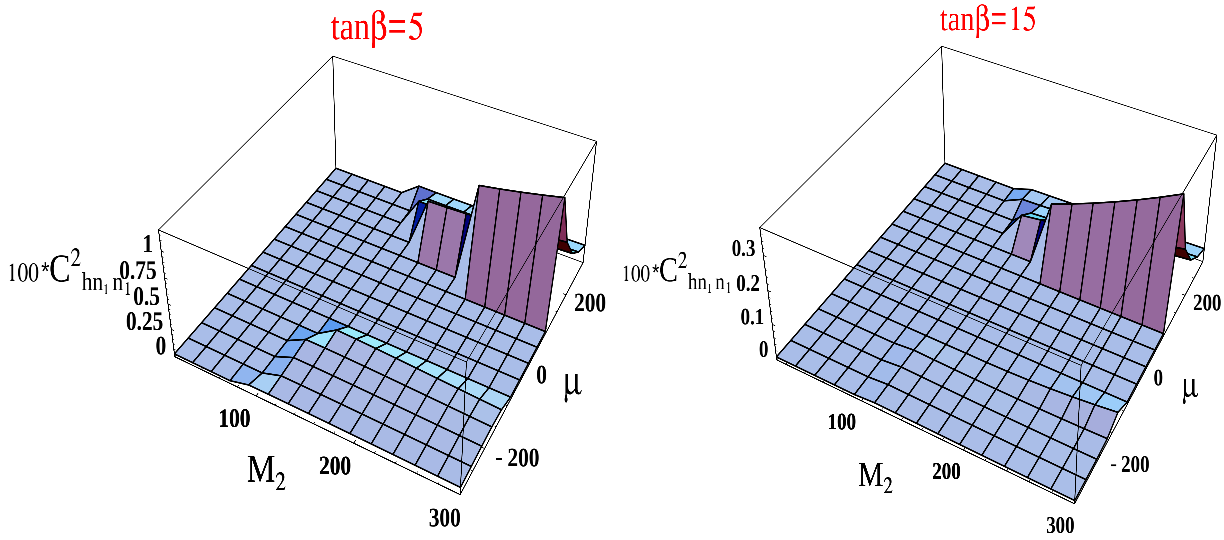

Figure 2: *Strength of the lightest Higgs coupling to* $\tilde{\chi}_1^0\tilde{\chi}_1^0$ *for* $\tan\beta = 5$ *and* $\tan\beta = 15$ *in the case* $M_1 = M_2/10$ *. As in Fig. 1, we have imposed* $m_{\tilde{\chi}_1^+} > 94.5 GeV$ *and* $m_{\tilde{\chi}_1^0} < 65 GeV$*.*

enough phase space for $h \to \tilde{\chi}_1^0\tilde{\chi}_1^0$, it is sufficient to discuss the case with $A_t = 0$. For the canonical unification case, the effect of maximising the Higgs mass through A_t is crucial.

- Chargino cross section:

Typically when no sparticle is degenerate with the chargino, the lower limit on the chargino mass reaches the LEP2 kinematic limit independently of the exact composition of the chargino and does not depend much on the sneutrino mass as explained earlier. Latest LEP data give [24],

$$m_{\chi_1^+} \geq 94.5 GeV. \tag{2.7}$$

Very recent combined preliminary data[1] suggest $m_{\chi_1^+} \geq 100.5 GeV$. We will also comment on how our results can change by imposing this latter limit.

Degeneracy with the LSP

Even when slepton masses can be large, in which case the chargino cross section is larger, the chargino mass constraint weakens by a few GeV when the lightest chargino and neutralino are almost degenerate[24]. The $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 f\bar{f}'$ decay leads to soft “visible” products that are difficult to detect . Recent LEP data has greatly improved the limits in this small $\Delta M_{\tilde{\chi}_1^+ - \tilde{\chi}_1^0}$ mass difference region. However within the assumption of gaugino mass unification the highly degenerate case with a light chargino/neutralino occurs in the region $\mu \ll M_2, M_2 \geq 2$ TeV. In this region the light (and degenerate) neutralino and chargino are almost purely Higgsino and therefore as seen from Eq. 2.5 do not couple strongly to the Higgs. Their effect on the Higgs invisible width as well as indirectly on the two-photon width is negligible. We will not consider this case.

Degeneracy with a light sneutrino:

There is another degeneracy which is of more concern to us. It occurs for small slepton masses that are almost degenerate with the chargino, rendering the dominant two-body decay mode $\chi^+ \rightarrow \tilde{\nu} l^+$ undetectable (the three flavours of sneutrinos are also degenerate). When this occurs, for $\Delta_{\rm deg} = m_{\tilde{\chi}_1^+} - m_{\tilde{\nu}_e} < 3GeV$, neutralino production is also of no use since the neutralinos will also decay into invisible sneutrinos. Since SU(2) relates the mass of the sneutrinos to that of the left selectrons, the search for the latter will then set a limit on the charginos in this scenario. The explorable mass of the selectron is a few GeV from the LEP2 kinematical limit. In fact the LEP Collaborations make a stronger assumption to relate the mass of the sneutrinos to those of the selectrons. Left and right sleptons masses are calculated according to a mSUGRA scenario by taking a common scalar mass, m_0, defined at the GUT scale. This gives

$$\begin{aligned}
m^2_{\tilde{e}_R} &= m_0^2 \;+\; 0.15 M^2_{1/2} \;-\; \sin^2\theta_W D_z \\
m^2_{\tilde{e}_L} &= m_0^2 \;+\; 0.52 M^2_{1/2} \;-\; (.5 - \sin^2\theta_W) D_z \\
m^2_{\tilde{\nu}_e} &= m_0^2 \;+\; 0.52 M^2_{1/2} \;+\; D_z/2 \qquad \text{with} \\
D_z &= M_Z^2 \cos(2\beta)
\end{aligned} \tag{2.8}$$

where $M_{1/2}$ is the common gaugino mass at the GUT scale also, which we can relate to the $SU(2)$ gaugino mass as $M_2 \sim 0.825 M_{1/2}$. With these assumptions, $m_{\tilde{e}_R}$ gives the best limit. One thus arrives at a limit[24]

$$m_{\chi_1^+} \simeq m_{\tilde{\nu}_e} \geq 70GeV (\tan\beta = 5). \tag{2.9}$$

The above reduction in the chargino mass limit compared to Eq. 2.7 will have dramatic effects on the Higgs two-photon width. In this very contrived scenario the conclusions we will reach differ significantly from the general case. This very contrived scenario will be discussed separately in section 4.

- *Neutralino Production and decays*:

LEP2 also provides a constraint on the mass of the neutralino LSP from the search for a pair of neutralinos, specifically $e^+e^- \rightarrow \chi_i^0 \chi_j^0$. This constraint is relevant for the small (μ, M_2) and also when we relax the unification condition. We have implemented the neutralino constraint by comparing the crosssection for neutralino production with the tables containing the upper limit on the production cross-section for $\chi_1^0 \chi_j^0$ obtained by the L3 collaboration at $\sqrt{s} = 189GeV$[25]. These tables give an upper limit on the cross-section for the full range of kinematically accessible $\tilde{\chi}_1^0 + \tilde{\chi}_2^0$ masses. The limits depend in a non-trivial manner on the masses of the produced particles. Moreover the limits are slightly different depending on whether one assumes purely hadronic final states from the decay of the heavier neutralino or whether one assumes leptonic final states. [4] Under the same assumptions we have also used these tables for setting the upper limit on $\tilde{\chi}_1^0\tilde{\chi}_3^0$ production. In all models where gaugino mass unification is imposed, the virtual Z decay mode, $\chi_{2,3}^0 \rightarrow \tilde{\chi}_1^0 Z^*$, constitutes the main decay mode when the neutralinos are light enough to be accessible at LEP2. In models where the gaugino mass unification is relaxed and very light neutralinos exist, as will be discussed in section "no-unification", other decay channels may open up, for example $\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 h$. The analysis, and hence the derived constraints, is made more complicated if one allows for light sleptons as will be suggested by cosmology in these models. Though light sleptons enhance the neutralino cross section quite significantly, in the case of left sleptons the efficiency is degraded because the branching ratio of the heavier neutralino into invisible (through a three body or even two-body $\tilde{\chi}_2^0 \rightarrow \nu\tilde{\nu}^*$) may be important.

As just discussed one also needs to take into account the various branching ratios of the neutralinos and charginos. These were also needed when considering production of neutralinos and charginos at the LHC. We have taken into account all two-body and three-body decay modes of gauginos , including fermionic and bosonic final states, $\chi_j^0 \rightarrow \chi_i^0 Z, \chi_i^0 h, \chi^\pm W^\mp, \tilde{l}l$ and $\chi_j^+ \rightarrow \chi_i^+ Z, \chi_1^+ h, \chi_j^0 W^+, \tilde{l}l, \tilde{\nu}\nu$. The analytical formulas were checked against the outputs of programs for automatic calculations such as `GRACE` [26] and `COMPHEP`[27] . For channels involving a Higgs boson, the radiatively corrected Higgs mass as well as the Higgs couplings, $\sin\alpha$, following the same implementation as in [28] were used.

- *Invisible width of the Z and single photon cross section at LEP2*:

In the case were we lift the unification condition that leads to rather small neutralino masses which are kinematically accessed through Z decays we have imposed the limits on the invisible width of the Z[29]:

$$\Gamma_{\rm inv}^Z \equiv \Gamma(Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0) < 3MeV \tag{2.10}$$

In view of the limits on the single photon cross section which can translate into limits on $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma)$, with cuts on the photon such that $E_\gamma > 5GeV$ and $\theta_{\rm beam-\gamma} > 10^0$, we used $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma) < .1pb$ at $\sqrt{s} = 189GeV$. In fact L3 gives a limit of $.3pb$[30],

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[4] The combination of the various selections, the leptonic and hadronic ones, is an *a priori* optimisation using Monte Carlo signal and background events. This optimisation procedure is defined to maximise the signal efficiency (including the leptonic and hadronic branching ratios) and minimise the background contamination. This consists in the minimisation of κ, expressed mathematically by: $\kappa = \Sigma_{n=0}^{\infty} k(b)_n P(b,n)/\epsilon$, where $k(b)_n$ is the 95% confidence level Bayesian upper limit, $P(b,n)$ is the Poisson distribution for n events with an expected background of b events, and ϵ is the signal efficiency including the branching ratios.

foreseeing that similar analysis will be performed for the other collaborations and the results will be combined we conservatively took .1pb. However this constraint turned out not to be of much help.

2.4 Cosmological Constraints

Scenarios with $M_1 = M_2/10$ have very light neutralino LSP into which the Higgs can decay, suppressing quite strongly its visible modes. Accelerator limits still allow for such a possibility. However, it has been known that a very light neutralino LSP can contribute quite substantially to the relic density if all sfermions are light. In the last few years constraints on the cosmological parameters that enter the calculation of the relic density have improved substantially. Various observations[31] suggest to take as a benchmark $\Omega_\chi h_0^2 < .3$ where we identify Ω_χ with the fraction of the critical energy density provided by neutralinos. h_0 is the Hubble constant in units of 100 km sec^{-1} Mpc^{-1}. This constraint is quite consistent with limits on the age of the Universe[32], the measurements of h_0 [33], the measurements of the lower multipole moment power spectrum from CMB data and the determination of Ω_{matter} from rich clusters, see [31] for reviews. It also, *independently*, supports data from type Ia supernovae[34] indicative of a cosmological constant. For illustrative purposes and to show how sensitive one is to this constrain we will also consider a higher value, $\Omega_\chi h_0^2 < .6$ that may be entertained if one relies on some mild assumptions based on the age of the Universe and the CMB result only[35]. In this scenario the calculation of the relic density is rather simple since one only has to take into account annihilations into the lightest fermions. Keeping with our analysis, we required all squarks to be heavy but allowed the sleptons to be light. To calculate the relic abundance we have relied on a code whose characteristics are outlined in [36]. To help with the discussion we will also give an approximate formula that agrees better than 30% with the results of the full calculation.

2.5 LHC Observables

The principal observables we are interested in are those related to the Higgs production and decay. Since we are only considering the effects of non-coloured particles and are in a regime of large M_A, all the usual production mechanisms (inclusive direct production through gluon-gluon as well as the associated production $W(Z)h$ and $t\bar{t}h$) are hardly affected compared to a SM Higgs with the same mass. Contrary to the indirect effects of light stops and/or sbottoms, the main effects we study in this paper affect only decays of the Higgs. The main signature into photons is affected both by the indirect loop effects of light enough charginos (and in some cases sleptons) and by the possible opening up of the

Higgs decay into neutralinos. When the latter is open it leads to the most drastic effects reducing both the branching into photons as well as into $b\bar{b}$, hence posing a problem even for the search in $t\bar{t}h$ with $h \to b\bar{b}$. To quantify the changes of the branching ratios we define, as in [7], the ratio of the Higgs branching ratio into photons normalised to that of the SM, defined for the *same value of the Higgs mass*:

$$R_{\gamma\gamma} = \frac{BR^{SUSY}(h \to \gamma\gamma)}{BR^{SM}(h \to \gamma\gamma)} \tag{2.11}$$

Likewise for the branching ratio into $b\bar{b}$

$$R_{b\bar{b}} = \frac{BR^{SUSY}(h \to b\bar{b})}{BR^{SM}(h \to b\bar{b})} \tag{2.12}$$

The latter signature for the Higgs has only recently been analysed within a full ATLAS simulation and found to be very useful for associated $t\bar{t}h$ production, but only for $m_h <$ 120GeV[2]. With 100fb^{-1} the significance for a $\mathcal{SM}$ Higgs with $m_h = 100$GeV is 6.4 but drops to only 3.9 for $m_h = 120$GeV. Since this is the range of Higgs masses that will interest us, we will consider a drop corresponding to $R_{b\bar{b}} = .7$ to mean a loss of this signal.

As concerns the two-photon signal, we take $R_{\gamma\gamma} < .6$ as a benchmark for this range of Higgs masses. This is somehow a middle-of-the-road value between the significances given by ATLAS[2] and the more optimistic CMS simulations[3].

For the computation of the various branching ratios of the Higgs and its couplings we rely on `HDECAY`[28] in which the Higgs masses are determined following the two-loop renormalisation group approach[19].

Since appreciable effects in the Higgs search occur for relatively light spectra, this means that the light particles should also be produced at an appreciable rate at the LHC even though they are electroweak processes. We have calculated, at leading order, all associated chargino and neutralino cross sections.

$$pp \to \chi_i^{\pm}\chi_j^0 \qquad i = 1, 2\ ;\ j = 1, 2, 3, 4 \tag{2.13}$$

Neutralino pair production[5] $pp \to \chi_j^0\chi_k^0$ is much smaller with the heavy squark masses that we assume. These processes have been calculated with the help of `CompHEP`[27]. For the structure function we use CTEQ4M at a scale, $Q^2 = \hat{s}/4$.

It is also possible for the heaviest of these neutralinos to cascade into the lighter ones and the lightest Higgs. We have therefore calculated all branching ratios for all the charginos and neutralinos. In principle other means of neutralino/chargino production are possible through cascade decays of heavy squarks, if these are not too heavy to be produced at the LHC.

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[5] K-factors for these processes have been computed in [37].

3 Gauginos masses unified à la GUT

3.1 The available parameter space

In the case of no-degeneracy of the lightest chargino with the sneutrino, the constraint comes essentially from the chargino cross section. With heavy sleptons, neutralino production does not constrain the parameter space any further. Therefore the $\tan\beta$ independent limit Eq. 2.7 applies. All these limits map into the $M_2 - \mu$ parameter space for a specific $\tan\beta$. The available parameter space for $\tan\beta = 5, 30$ is shown in Fig. 3

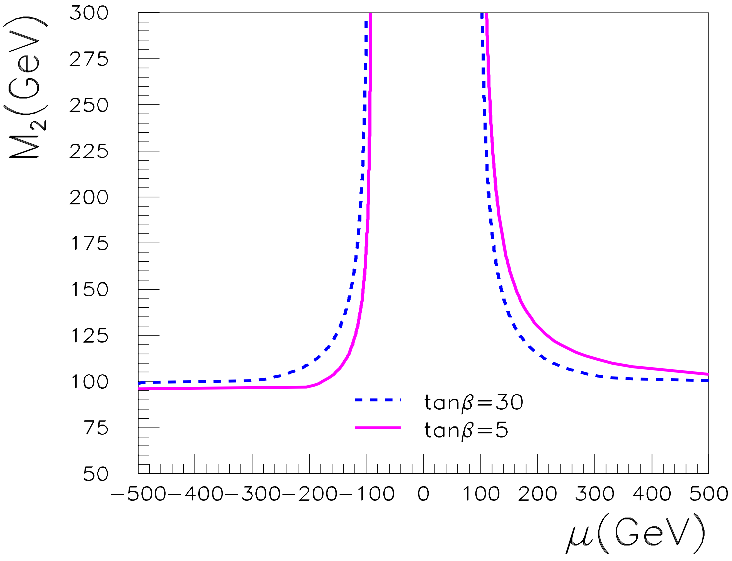

Figure 3: *LEP2 excluded region (inside the branch) in the* $M_2 - \mu$ *parameter space for* $\tan\beta = 5$ *and* $\tan\beta = 30$ *from* $m_{\chi_1^+} \geq 94.5 GeV$.

The absolute limit on the lightest neutralino for $\tan\beta = 5$ turns out to be:

$$m_{\tilde{\chi}_1^0} \geq 47.5 GeV (\tan\beta = 5). \tag{3.14}$$

Therefore in the non degenerate case there is a very small window for the Higgs to decay into neutralinos. For the lower limit on the neutralino mass the reduction factor brought about by the β^3 P-wave factor in Eq. 2.4 factor amounts to about .1, for $m_h = 109$GeV.

3.2 The A_t $\tan\beta$ dependence

The above mass of the Higgs for $\tan\beta = 5$ corresponds to a mixing angle in the stop sector $A_t = 0$. Obviously to maximise the effect of the neutralinos through the opening up of the Higgs decay into neutralino one should increase the mass of the Higgs. We have already taken $M_A = M_S = m_{\tilde{t}} = m_{\tilde{g}} = 1TeV$. We can therefore increase A_t and $\tan\beta$. However increasing $\tan\beta$ also increases the neutralino masses and reduces the $h\tilde{\chi}_1^0\tilde{\chi}_1^0$ couplings as we discussed earlier. Scanning over $\mu(> 0)$, M_2 and $\tan\beta$ we show, Fig. 4, the extremal variation of the $R_{\gamma\gamma}$ as a function of $\tan\beta$ for maximal mixing and taking the available constraints into account. We see that the maximum drop is for $\tan\beta \sim 5$. Below this value of $\tan\beta$ the Higgs mass is small compared to the neutralino threshold, while above this value the LSP gets heavier "quicker" than does the Higgs. Moreover the Higgs coupling to the LSP gets weaker as $\tan\beta$ increases. On the other hand the increase $R_{\gamma\gamma} > 1$ grows with smaller $\tan\beta$, but this is mainly due to the loop effects of the charginos. Also, as expected, the variation with A_t affects essentially the maximal reduction curve.

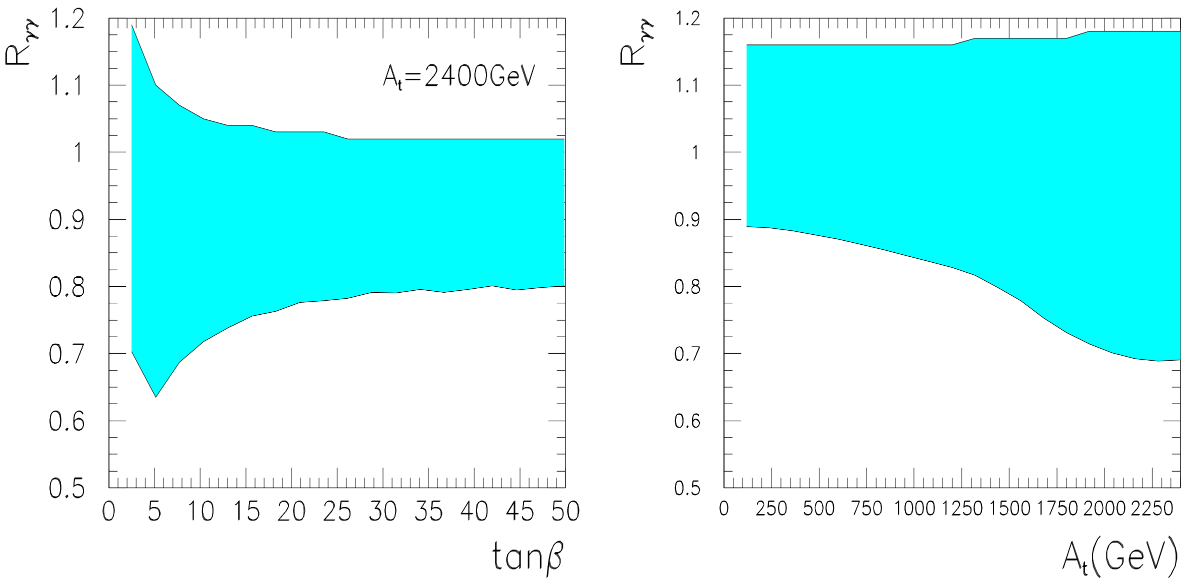

Figure 4: $R_{\gamma\gamma}$ *(shaded area) as a function of a)* $\tan\beta$ *for* $A_t = 2.4$ *TeV, b)*A_t *for* $\tan\beta = 2.5 - 50$.

This said, let us however not forget that especially in the two-photon signal at the LHC the significance increases with increasing Higgs mass. One can already conclude on the basis of Fig. 4 and our benchmark $R_{\gamma\gamma} > .6$, that critical regions are for moderate $\tan\beta$, $\tan\beta \sim 5$, and maximal stop mixing.

3.3 The case with $A_t = 0$ and $\tan\beta = 5$

We now go into more detail and choose $\tan\beta = 5$ in the case of no mixing. The results are summarised in Fig. 5.

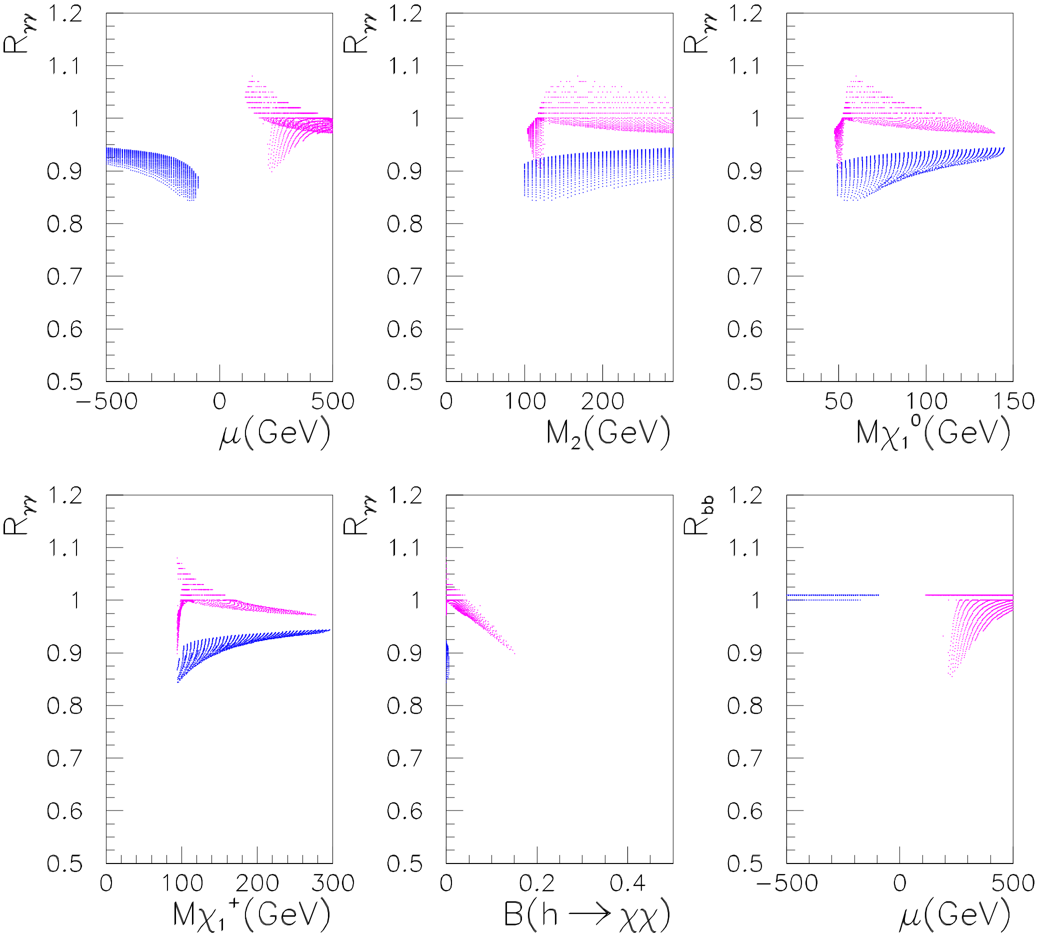

Figure 5: *Variation of $R_{\gamma\gamma}$ and $R_{b\bar{b}}$ vs μ, M_2, $m_{\chi_1^+}$, $m_{\tilde{\chi}_1^0}$ and $Br(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$. Also shown, last frame, the variation of $R_{b\bar{b}}$ with μ. All plots are for $\tan\beta = 5$, $M_2 = 50 - 300 GeV$, $\mu = 100 - 500 GeV$ and $A_t = 0$.*

First of all note that in this scenario the ratio $R_{\gamma\gamma}$ can vary at most by 15% and that this can lead to either a slight increase or a slight decrease. Contrary to what we will see for other scenarios, the largest drop occurs for *negative* values of μ and is due to the contribution of the light charginos in the two-photon width (see also the dependence with $m_{\tilde{\chi}_1^+}$ and M_2). The sign of μ is also that of the interference between the dominant W loop and the chargino loop contribution. A decrease for positive μ is strongly correlated with the opening up of the little window for $h \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$. The latter channel leads to a branching ratio which is at most some 20%. When this occurs (only for positive μ) it will affect also the branching into $b\bar{b}$ and thus the channel $t\bar{t}h \rightarrow t\bar{t}b\bar{b}$. However with our benchmark for observability of the Higgs in this channel, $R_{b\bar{b}} > .7$, the Higgs should still be observed in this channel.

At this stage one can conclude that the effect of light charginos/neutralinos, especially in view of the theoretical uncertainty (higher order QCD corrections) in predicting the signal, is very modest. Furthermore the small window for Higgs decaying into LSP will be almost closed, at least at $\tan\beta = 5$, with an increase of a few GeV on the lower limit on charginos.

3.4 The case with maximal A_t and $\tan\beta = 5$

Increasing the mass of the Higgs through as large A_t as possible for the same value of $\tan\beta$ changes the picture quite substantially. With our implementation of the corrections to the Higgs mass the increase is about 10GeV and leaves enough room for $h \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ in the small $\mu - M_2$ region. In this case the two-photon rate and the $h \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ branching ratios are well correlated as shown (Fig. 6a), the result of a scan over the parameters $M_2 = 50 - 300$ GeV, $\mu = 100 - 500$ GeV for $\tan\beta = 5$ in the maximal mixing case, $A_t = 2.4$ TeV. A scan over a wider range, $M_2 \leq 2$ TeV and $|\mu| \leq 1$ TeV, was also performed. The points for larger values of $M_2 - \mu$ all cluster around $R_{\gamma\gamma} \approx 1$ allowing for only a few percent fluctuations. The Higgs branching ratio into neutralinos can reach as much as 40%, leading to a reduction of $R_{\gamma\gamma}$and $R_{b\bar{b}}$ of about 60%. This means that there might be problems with Higgs detection especially in the $t\bar{t}h$ channel. The contour plots of constant $h \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ in the $M_2 - \mu$ plane are displayed in Fig. 6b). It is only in a small region $M_2 \leq 160$ GeV and $\mu \leq 400$ GeV that $h \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ exceeds 10%.

As the results presented here depend critically on the minimum allowed value for the mass of the lightest chargino and neutralino, see Fig. 6c-d), it is interesting to enquire about the consequence of an improved lower limit of the chargino masses in the last runs of LEP2. We have therefore imposed the constraint $m_{\tilde{\chi}_1^+} \geq 100$ GeV. As the maximum reduction occurs for the lightest allowed value for the chargino mass, an increase of just

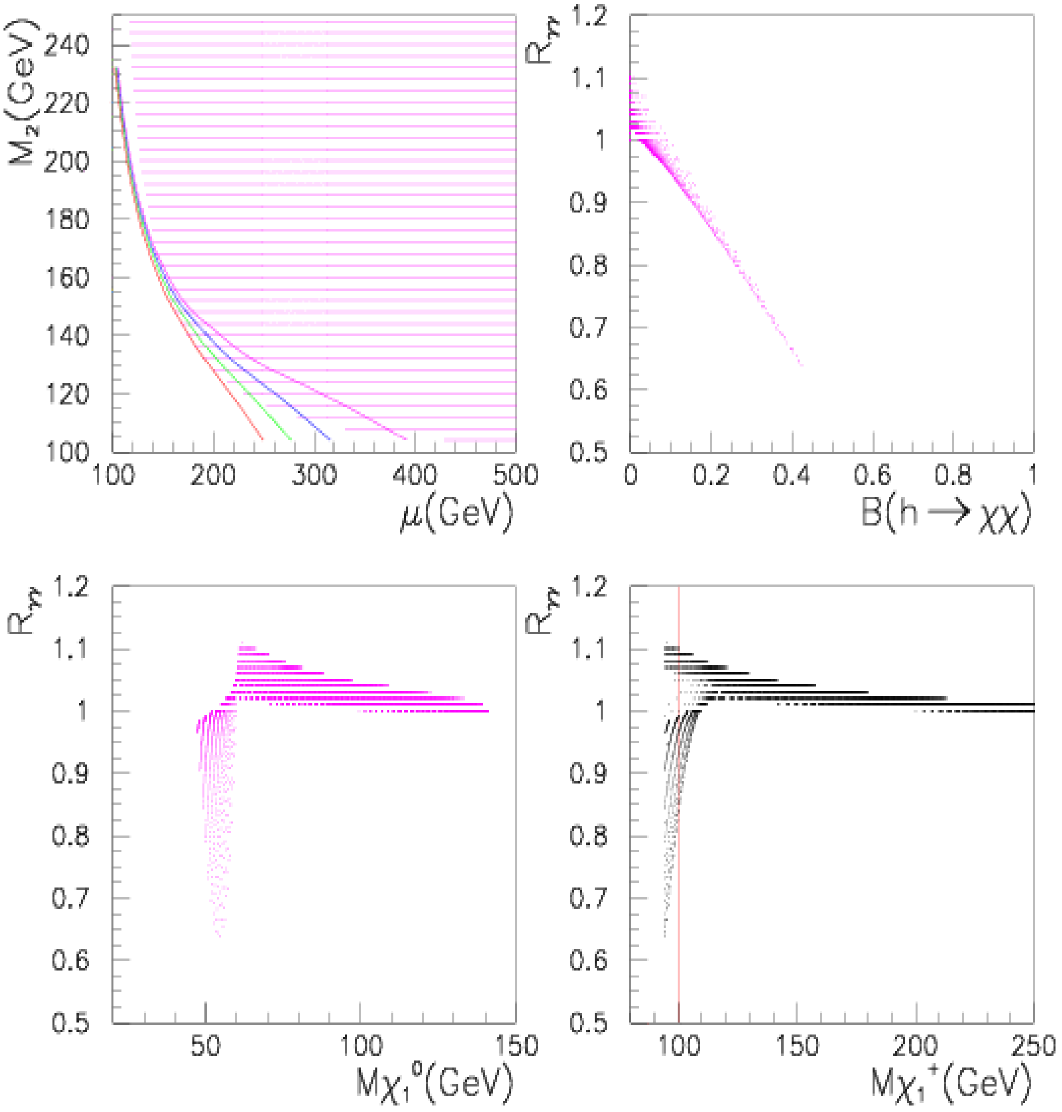

Figure 6: *a) Contour plot of* $Br(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 0.1, 0.2, 0.3, 0.4$ *(from right to left respectively) in the* $M_2 - \mu$ *plane. The shaded area is the allowed region.b) Correlation between* $R_{\gamma\gamma}$*and* $Br(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ *c) Variation of* $R_{\gamma\gamma}$ *with the mass of the LSP* $M_{\chi_1^0}$ *and d) mass of the chargino* $M_{\chi_1^+}$*. The vertical line corresponds to* $m_{\tilde{\chi}_1^+} = 100 GeV$*. All plots are for* $\tan\beta = 5$, $M_2 = 50 - 300 GeV$, $\mu = 100 - 500 GeV$ *and* $A_t = 2.4 TeV$.

a few GeV's has a drastic effect. The reduction in $R_{\gamma\gamma}$ is no longer more than 80%. In conclusion, the effect of gauginos/higgsinos on the crucial branching ratio of the Higgs, when one assumes the unification condition and no degeneracy, will only be marginal at the LHC if LEP2 does not observe any charginos or neutralinos before the end of its final run.

3.5 Associated chargino and neutralino production at the LHC

In our previous study of the effects of light stops[7] on the Higgs search at the LHC, reduction in the usual two photon signals was due essentially to a drop in the main production mechanism through gluons and occurred when the stops developed strong couplings to the Higgs. When this occurs, as a lever, one has large production of stops as well as associated stop Higgs production, thus recovering a new mechanism for Higgs. In the present case uncovering a new effective Higgs production mechanism will be more complicated. First the effects are due to weakly interacting particles whose cross sections at the LHC are smaller than those for stops. Also since the largest drops are when the branching ratio of the Higgs into invisible is appreciable, this means that even if one triggers Higgs production through charginos and neutralinos , the reconstruction of the Higgs will be more difficult. Nevertheless one should enquire how large any additional production mechanism, if any, can get. In the present scenario with a common gaugino mass at the GUT scale and no (accidental) degeneracy between the chargino and the sneutrinos, $R_{\gamma\gamma}$ (and $R_{b\bar{b}}$) being at worst .6 (for maximal mixing), the Higgs should be discovered in the usual channels. Moreover since the $Br(h \rightarrow b\bar{b})$ does not drop below about .6, we could use this signature in the cascade decay of the heavier neutralinos and charginos into Higgs.

Since the reduction in the usual inclusive two photon channel always occurs in the small (M_2, μ) region, all gauginos are relatively light and therefore have reasonable production rates. In fact as Fig. 7 shows, the rates are more than reasonable in the parameter space that leads to the largest drops. For instance, with $M_2 = 140$GeV, the cross section $\tilde{\chi}_2^0\chi_1^+$ is about 6pb and is mildly dependent on μ, while production of $\tilde{\chi}_4^0\chi_2^+$, is some 100fb (with $m_{\tilde{\chi}_4^0} \sim 250$GeV) when $R_{\gamma\gamma} = .6$, and decreases quickly with increasing μ (where however $R_{\gamma\gamma}$ increases). With the first process, considering the rather large cross section, it should be possible through measurements of the masses and some of the signatures of $\tilde{\chi}_2^0$ and χ_2^+ to get some information on the parameters of the neutralinos and charginos[6], we would then know that one might have some difficulty with the Higgs signal in the inclusive channel. As for the latter process, it has more chance to trigger light Higgs than the

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[6] See for instance [38].

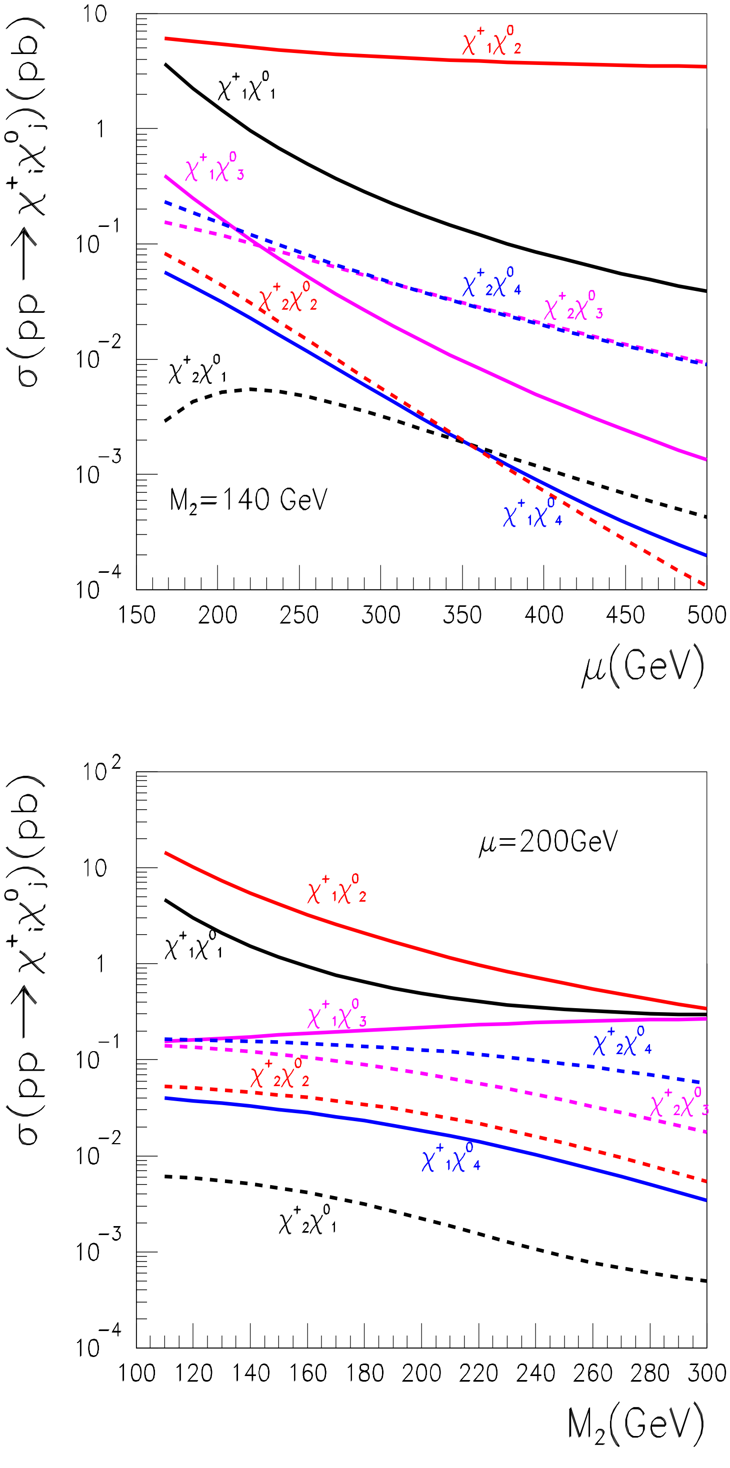

Figure 7: *Associated Production of chargino and neutralino at the LHC at LO a) as a function of* μ *for* $M_2 = 140 GeV$. *b) as a function of* M_2 *for* $\mu = 200 GeV$. *In the case of gaugino mass unification without degeneracy with the sneutrinos, the LEP limit means that for* $M_2 = 140 GeV$, $\mu > 176 GeV$ *and for* $\mu = 200 GeV$, $M_2 > 130 GeV$. *In the case of degeneracy with the sneutrinos all points in the figure are valid .*

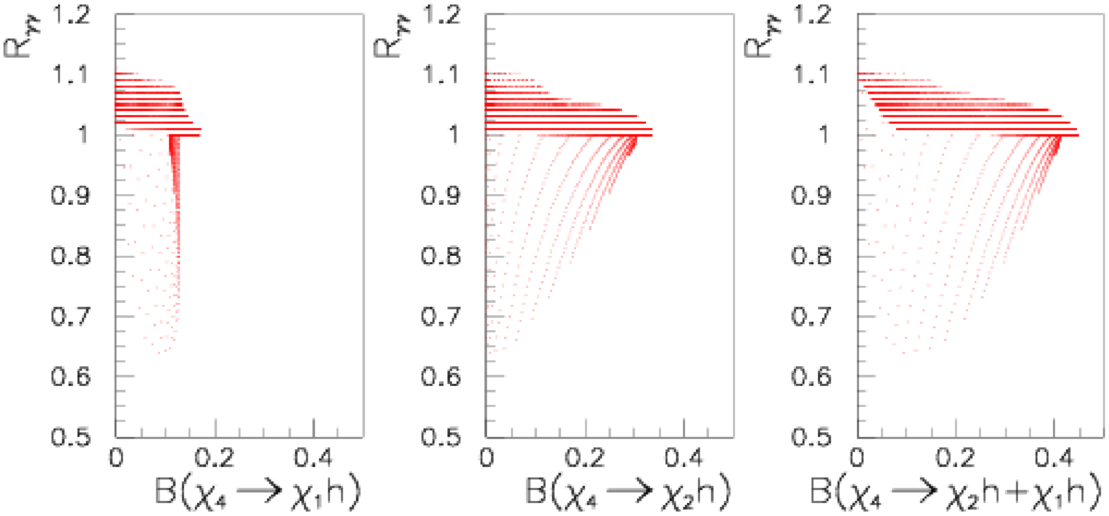

Figure 8: *Branching ratio of* $\tilde{\chi}_4^0$ *into* h *for* $\tan\beta = 5$, $A_t = 2400 GeV$. *The scan over* M_2 *and* μ *is as in Fig. 5.*

former. Since in our scenario there isn't enough phase space for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$. The following modes are potentially interesting: $\chi_4^0 \to \chi_{1,2}^0 h$ and $\chi_2^+ \to \chi_1^+ h$. For the former one obtains as much as 25% branching ratio for $\tilde{\chi}_4^0 \to h +$ anything when $R_{\gamma\gamma}$is lowest , see Fig . 8. Much higher branching are of course possible, but they occur for higher values of $m_{\tilde{\chi}_4^0}$ where there is no danger for Higgs discovery in the usual modes. Less effective and not always open is the mode $\chi_3^0 \to \chi_{1,2}^0 h$ where the branching never exceeds a few per-cent.

We are now in a position of folding the different branching ratios for the heavier neutralinos and chargino into Higgs (h) with the corresponding cross sections to obtain the yield of Higgs in these channels. As advertised, for the parameters of interest, we see from Fig. 9 that the largest cross sections originate from the decays of the heaviest neutralino $\tilde{\chi}_4^0$ while the chargino helps also. Still, the yield is quite modest, about 20fb. It rests to see whether a full simulation with a reduced branching ratio of h into b's can dig out the Higgs signal from such cascade decays. We should make another remark. In [18], where $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ and $h \to b\bar{b}$ is advocated, the neutralinos themselves are produced through cascade decays of gluinos and squarks which can have large cross sections. In our case we have taken these to be as heavy as 1TeV and thus their cross section is rather modest. For instance gluino pair production at the LHC with this mass is about .2pb. However, without much effect on the decoupling scenario we have assumed, if we had taken $m_{\tilde{g}} = 500$GeV, which by the way corresponds to a situation where the gaugino mass unification extends also to M_3, the gluino cross section jumps to about 20pb. So many gluinos could, therefore, through cascade decays provide an additional source of Higgs.

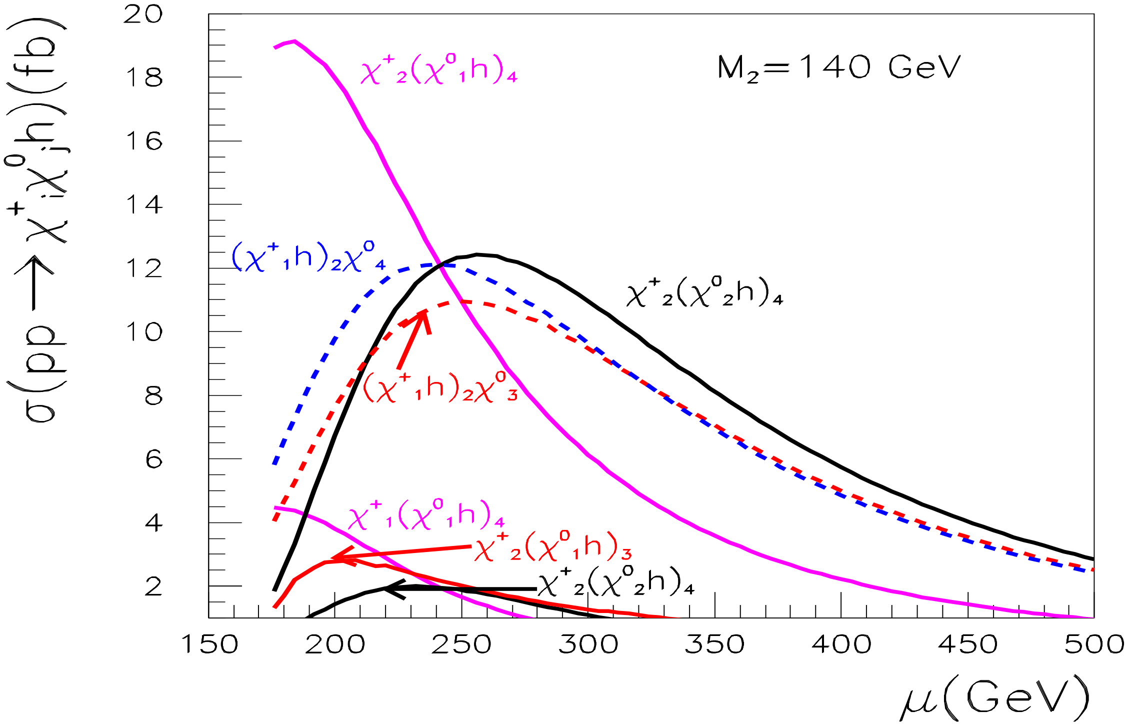

Figure 9: *Higgs yield through charginos and neutralinos decays as a function of* μ. $M_2 = 140 GeV$ *and* $\tan\beta = 5$ *and maximal mixing. The subscript for the parentheses* $(\quad)_j$ *indicates the parent neutralino or chargino.*

4 Gauginos masses unified à la GUT degenerate with sleptons

In the so-called sneutrino-degenerate case where charginos can be as low as 70GeV, the absolute lower limit on the neutralino LSP mass:

$$m_{\chi_0} \geq 34.5 GeV (\tan\beta = 5). \tag{4.15}$$

This lower bound rises by roughly 1GeV for $\tan\beta = 2.5$ and never goes below 34GeV for larger values of $\tan\beta$. We will only study the case with A_t maximum.

4.1 Results

Relaxing the chargino mass by some 20GeV has quite impressive effects that result in dramatic drops, see Fig. 10. The branching fraction into invisibles can be as large as 90%. For these situations clearly the Higgs would be difficult to hunt at the LHC in both the two-photon and (associated) $b\bar{b}$ channels. As seen for $R_{\gamma\gamma} vs\ m_{\tilde{\chi}_1^+}$, there is an immediate fall for $m_{\tilde{\chi}_1^+} < 100$GeV. But then this should be compensated by the production of plenty

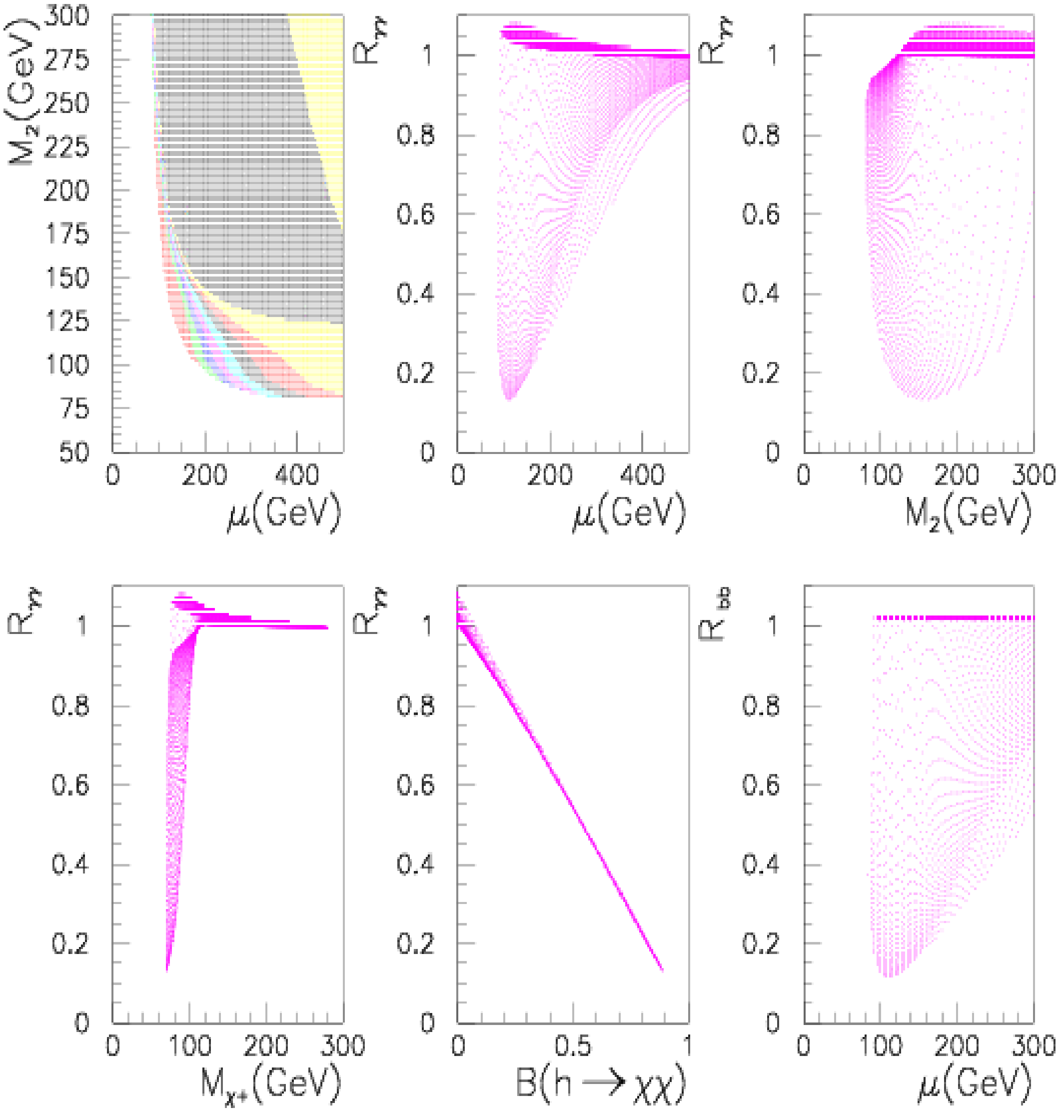

Figure 10: *Results in the degenerate scenario with* $\tan\beta = 5$ *and maximal* A_t*. In all plots the scans are over* $M_2 = 50 - 300\,GeV$*,* $\mu = 100 - 500\,GeV$*. From left to right and top to bottom (a) Density plot for* $R_{\gamma\gamma}$*in the allowed* $M_2 - \mu$ *plane. The different shadings correspond to* $.3 < R_{\gamma\gamma} < 1.1$ *from left to right. (b) Variation of* $R_{\gamma\gamma}$*with* μ *(c) with* M_2 *(d) with the mass of the chargino* $M_{\chi_1^+}$*. (e) Correlation between* $R_{\gamma\gamma}$*and the branching of* h *into LSP. (f) Variation of* $R_{b\bar{b}}$ *with* μ*.*

of charginos and sleptons while some of the heavier neutralinos and chargino should still be visible. As indicated by Fig. 7, in this situation all charginos and all neutralinos will be produced with cross sections exceeding 100fb. χ_1^+ has a cross section in excess of 10pb!. These processes can trigger Higgs production. However, because of the decays into light sleptons the rates are modest as seen in Fig. 11. In fact, the largest rates occur when the Higgs has the largest branching into invisible. These modes will probably not help much.

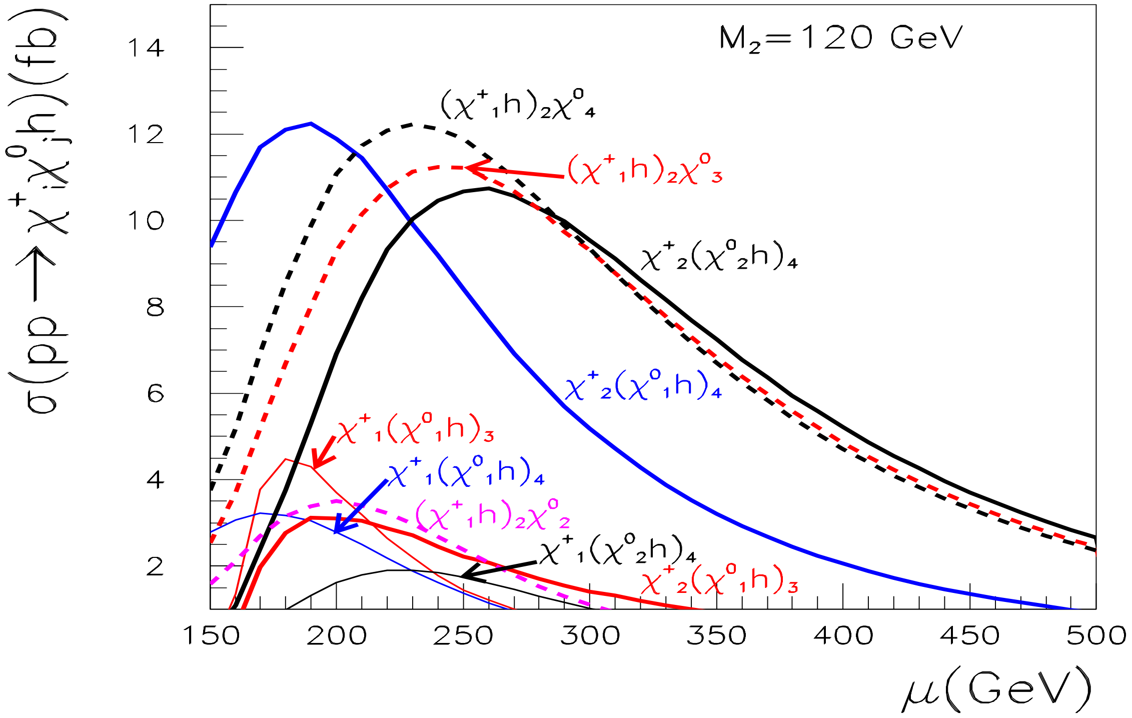

Figure 11: *As in Fig. 9 but in the case of a chargino degenerate with the sneutrino and* $M_2 = 120 GeV$.

5 Relaxing the gaugino mass unification

As we have seen, having light neutralinos can very much jeopardise the Higgs discovery at the LHC. However in the canonical model with $M_1 \simeq M_2/2$ and no pathological degeneracy the effect is never a threat. Basically this is because the almost model independent limit on the chargino translates into values of M_2 (hence M_1) and μ large enough that the neutralinos are not so light that they contribute significantly a large invisible Higgs width. On the other hand if M_1 were made much smaller than M_2, one could make $m_{\tilde{\chi}_1^0}$ small enough without running into conflict with the chargino mass limits. The LSP could then be very light and almost bino. To make it couple to the Higgs though one still needs some higgsino component and thus μ should not be too large. Largest couplings will be for smallest values of μ which are however, again, constrained by the chargino mass limit for instance. To investigate such scenarios we have studied the case with

$$M_1 = r\ M_2 \quad \text{with} \quad r = 0.1 \tag{5.16}$$

and have limited ourselves to the case with $\tan\beta = 5$.

Models with $r > 1$ would not affect the Higgs phenomenology at the LHC, since their lightest neutralino should be of the order of the lightest chargino. LEP data already excludes such a neutralino to contribute to the invisible width of the Higgs and therefore the situation is much more favourable to what we have just studied assuming the usual GUT relation.

It is important to stress that the kind of models we investigate in this section are quite plausible. The GUT-scale relation which equates all the gaugino masses at high scale need not be valid in a more general scheme of SUSY breaking. In fact even within SUGRA this relation need not necessarily hold since it requires the kinetic terms for the gauge superfields to be the most simple and minimal possible (diagonal and equal). One can easily arrange for a departure from equality by allowing for more general forms for the kinetic terms[39]. In superstring models, although dilaton dominated manifestations lead to universal gaugino masses, moduli-dominated or a mixture of moduli and dilaton fields lead also to non universality of the gaugino masses[40] and may or may not (multi-modulii[41]) lead to universal scalar masses. The recent so-called anomaly-mediated SUSY breaking mechanisms[42] are also characterised by non-universal gaugino masses, though most models in the literature lead rather to $r > 1$ which is of no concern for the Higgs search.

With $r = 1/10$ the main feature is that the neutralino mass spectrum is quite different. Most importantly LSP have masses in the range $\sim 10 - 20$GeV for the cases of interest. Since there is plenty of phase space for the decay of the lightest Higgs into such neutralinos we will only consider $A_t = 0$ for the stop mixing.

5.1 The available parameter space

In the case of heavy sleptons we find that the $\mu - M_2$ allowed parameter space is still determined from the chargino mass limit through $e^+e^- \rightarrow \chi_1^+\chi_1^-$ production. Neutralino pair production $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0\tilde{\chi}_3^0$, although kinematically possible do not squeeze the parameter space further. The contour plot, see Fig. 12, is therefore essentially the same as the one with the GUT relation. Since cosmological arguments will drive us to consider

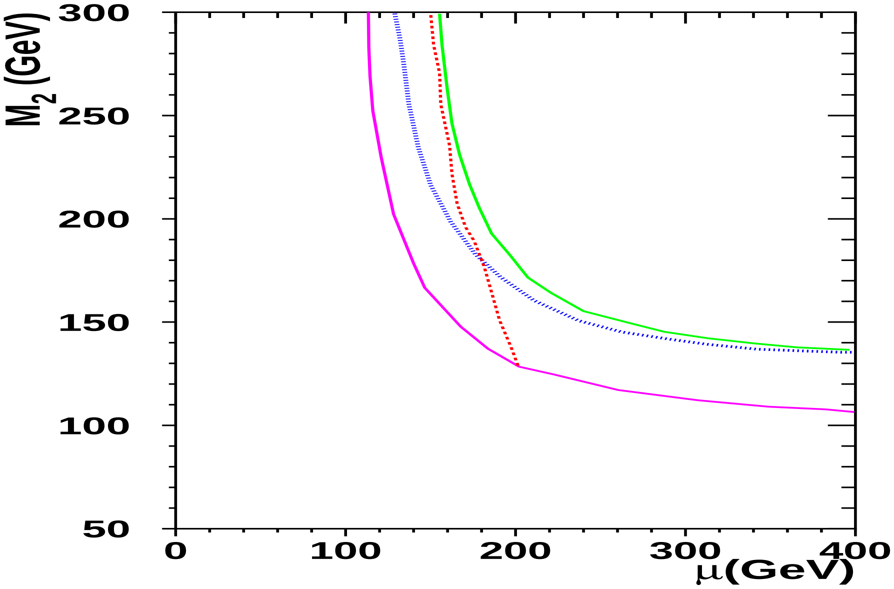

Figure 12: *LEP2 allowed region in the* $M_2 - \mu$ *parameter space in the case* $M_1 = M_2/10$ *for* $\tan\beta = 5$ *and* $\mu > 0$. *The inside curve corresponds to the case where all sleptons are heavy (*$1TeV$*) and is derived essentially from the chargino cross section. The dashed curve is for* $m_{\tilde{e}_R} = 100GeV$ *and* $m_{\tilde{e}_L} = 1TeV$*, the dotted curve is with* $m_{\tilde{e}_L} = 150GeV$ *and* $m_{\tilde{e}_R} = 1TeV$*, the outer curve is for* $m_{\tilde{e}_L} = 150GeV$ *and* $m_{\tilde{e}_R} = 100GeV$*. The limits in the case of light sleptons are derived from data on neutralino production, see text.*

light sleptons masses, we show on the same figure, Fig. 12, how the $\mu - M_2$ parameter space is squeezed in this case. The squeezing comes from limits on $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0\tilde{\chi}_3^0$ cross sections properly folded with branching ratios where two-body and three-body decays involving the relatively light sleptons play an important role. In fact, while light sleptons generally enhance the neutralino cross sections, this enhancement can be counterbalanced by the fact that a non negligible branching ratio into invisible neutrinos can occur with small enough left selectrons. In all cases the leptonic final state signature can be enhanced at the expense of the hadronic signature which usually have a better efficiency. To illustrate this, we have considered three cases: i) $m_{\tilde{e}_R} = 100$GeV with large $m_{\tilde{e}_L}$, ii) $m_{\tilde{e}_L} = 150$GeV with large $m_{\tilde{e}_R}$ iii)$m_{\tilde{e}_R} = 100, m_{\tilde{e}_L} = 150$GeV. One sees that, with a very mild M_2 dependence, light right selectrons eliminate smallest $|\mu|$ values that are otherwise still allowed by chargino searches. That $\tilde{e}_R$ do not cut on M_2 values can be understood on the basis that they do not have any $SU(2)$ charge. Since smallest values of μ are the ones that enhance $h \to \tilde{\chi}_1^0\tilde{\chi}_1^0$ these limits are important. With light left selectrons the gain with respect to the chargino limit is appreciable and occurs across all M_2 values, more so for the smallest M_2 values. When both left and right selectrons are relatively light, one carves out an important region, although this region does not cover all the available neutralino phase space.

5.2 Heavy sleptons

The main message is that there are some dangerous reductions in the branching ratios of the Higgs both into photons and into $b\bar{b}$ which can be only a 1/5th of what they are in the $\mathcal{SM}$, see Fig. 13 . These drops are due essentially to a large branching ratio of the Higgs into invisibles. The most dramatic reductions occur for chargino masses at the edge of the LEP2 limits, however even for chargino masses as high as 200GeV the drop can reach 60%. In these configurations the lightest chargino and $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ have a large higgsino component. This explains why, in the $M_2 - \mu$ plane the decrease in the ratios is strongly dependent on μ.

5.3 Cosmological constraint

Considering these large reductions and the fact that the LSP is very light, $10 - 20$GeV, we investigated whether the most dramatic scenarios are not in conflict with a too large relic density[7]. One knows that for a very light LSP bino the annihilation cross section is dominated by sfermions with largest hypercharge, that is right sleptons[44, 45]. This calls for light (right) sfermions. As a rule of thumb, with all sfermions heavy but the three right sleptons, an approximate requirement is

$$m^2_{\tilde{l}_R} < 10^3 \sqrt{(\Omega_\chi h^2)_{\rm max}} \times m_{\tilde{\chi}_1^0}. \tag{5.17}$$

with all masses expressed in GeV.

In our case the LSP is not a pure bino, the bino purity is around 90% for the worst case scenarios, otherwise it would not couple to the Higgs. We have therefore relied on a full calculation. We assumed all squarks heavy and took a common mass for the SUSY breaking sfermion mass terms of both left and right sleptons of all three generations, m_0, defined at the GUT scale, thus assuming unification for the scalar masses. As for the gaugino masses to obtain $M_1 = M_2/10$ at the electroweak scale one needs $\bar{M}_1 \simeq \bar{M}_2/5$ at the GUT scale. $\bar{M}_2$ is the $SU(2)$ gaugino mass at the GUT scale which again relates to M_2 at the electroweak scale as $M_2 \sim 0.825\bar{M}_2$. This scheme leads to almost no running of the right slepton mass, since the contribution from the running is of order M_1^2, while left sleptons have an added M_2^2 contribution and would then be “much heavier”. Indeed neglecting Yukawa couplings one may write

$$\begin{aligned} m^2_{\tilde{e}_R} &= \bar{m}_0^2 + 0.006\bar{M}_2^2 - \sin^2\theta_W D_z \\ m^2_{\tilde{e}_L} &= \bar{m}_0^2 + 0.48\bar{M}_2^2 - (.5 - \sin^2\theta_W) D_z \\ m^2_{\tilde{\nu}_e} &= \bar{m}_0^2 + 0.48\bar{M}_2^2 + D_z/2 \end{aligned} \tag{5.18}$$

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[7] Cosmological consequences of non-unified gaugino masses have been investigated in [43] but not from the perspective followed in this paper.

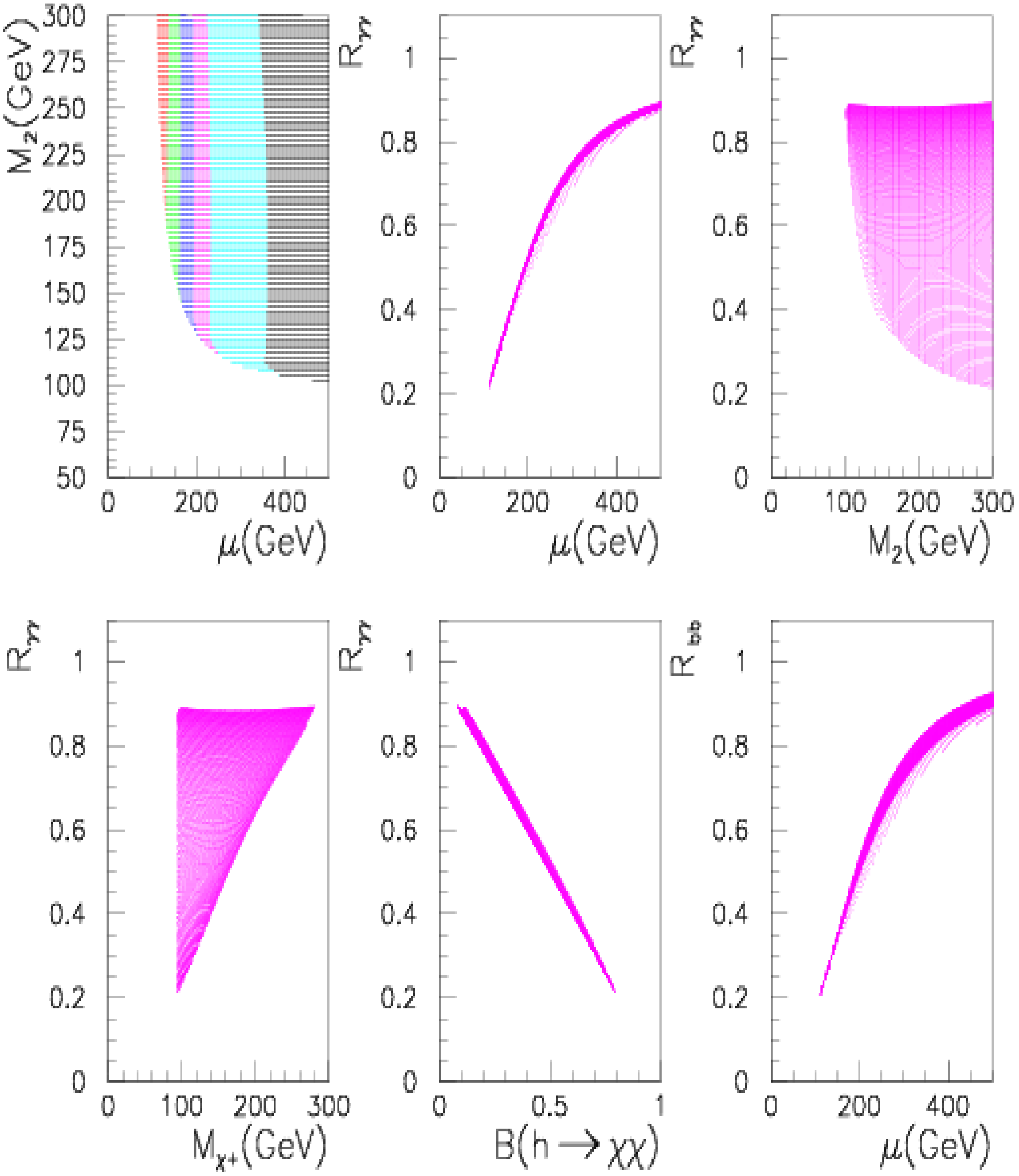

Figure 13: *Effects of neutralinos from* $M_1 = M_2/10$ *with* $\tan\beta = 5$ *and* $A_t = 0$ *with heavy selectrons. In all the plots, scans are over* $M_2 = 50 - 300\,GeV$, $\mu = 100 - 500\,GeV$. *From left to right and top to bottom a) Density plot for* $R_{\gamma\gamma}$ *in the allowed* $M_2 - \mu$ *plane. The different shadings correspond to* $.3 < R_{\gamma\gamma} < .4$ *(left band) to* $.8 < R_{\gamma\gamma} < .9$ *(right band). b) Variation of* $R_{\gamma\gamma}$ *with* μ *c) with* M_2 *d) with the mass of the chargino* $M_{\chi_1^+}$. *e) Correlation between* $R_{\gamma\gamma}$ *and the branching into LSP. f) Variation of* $R_{b\bar{b}}$ *with* μ.

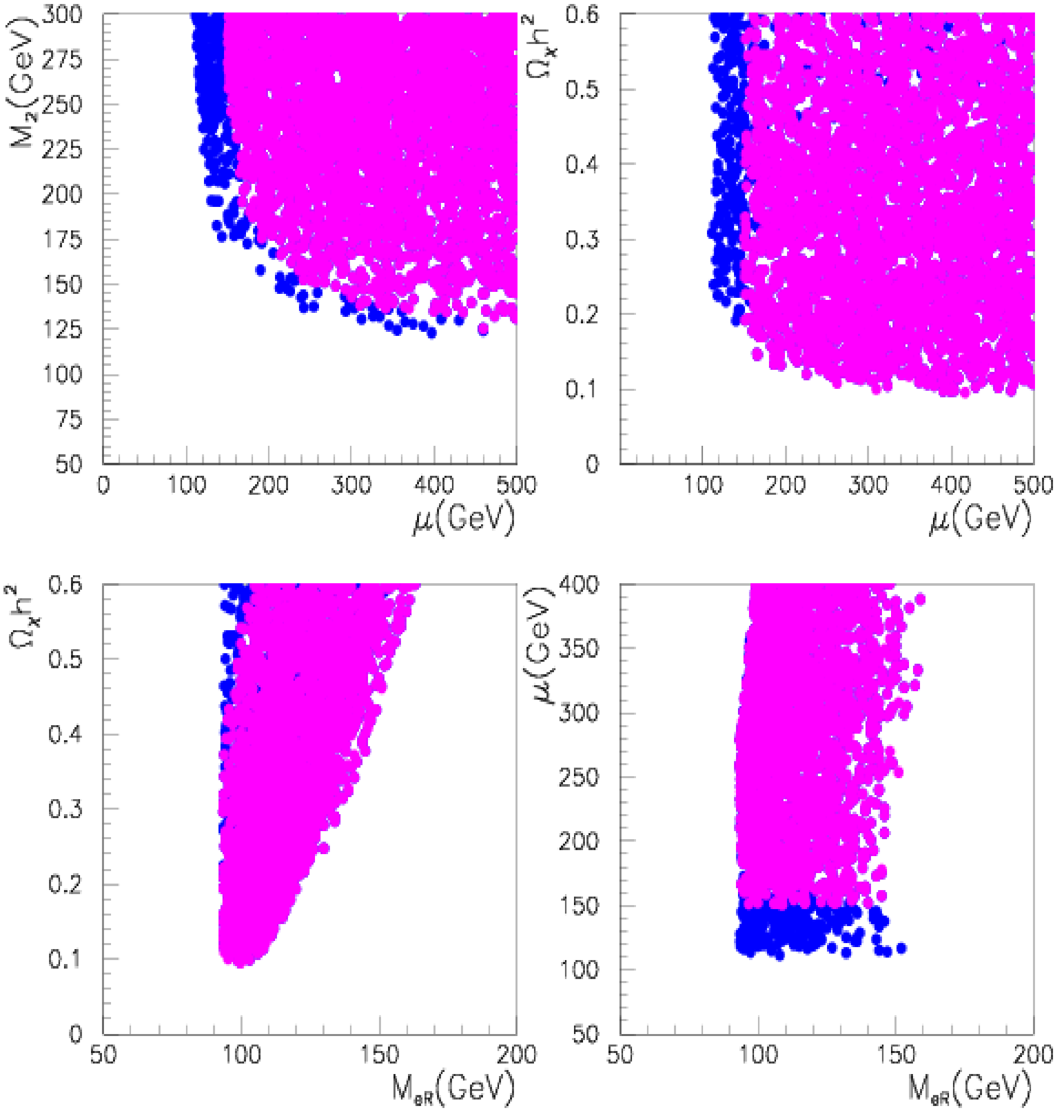

Figure 14: *All points that pass the constraint* $\Omega_\chi h^2 < .6$ *in the case* $M_1 = M_2/10$ *with* $\tan\beta = 5$ *and* $A_t = 0$. *In these plots, scans are over* $M_2 = 50{-}300\,GeV$, $\mu = 100{-}500\,GeV$ *and* $m_0 = 50 - 1000\,GeV$. *From left to right and top to bottom a) Allowed region in the* $M_2 - \mu$ *plane. b)* $\Omega_\chi h^2$ *vs* μ *c)* $m_{\tilde{e}_R}$ *d) Scatter plot of* μ *vs* $m_{\tilde{e}_R}$. *The grey areas represent the allowed parameter space after including the constraints from neutralino cross sections at* $\sqrt{s} = 189\,GeV$ *while the extra dark area does not include the constraint on neutralino production.*

Note in passing that Eq. 5.18 can be extended to squarks and if we take $M_3 = r_3 M_2 \quad r_3 > 1$ at the GUT scale one could make the squarks "naturally heavy" as we have assumed. Note also in this respect that had we not taken the squarks, specifically the stops, sufficiently heavy we would not have had large enough radiative corrections to the Higgs mass and would have been in conflict with the LEP2 constraint on the Higgs mass. Since the limit on the relic density in these scenarios with $M_1 = M_2/10$ constrain essentially the right slepton mass, this means that one has an almost direct limit on m_0.

Putting all this together the parameter space still allowed by requiring that the relic density be such that $\Omega_\chi h^2 < .3$ and by taking into account all accelerator constraints listed in section 2 is shown in Fig. 14. The most important message is that sleptons must be lighter than about 140GeV. The approximate rule of thumb given by Eq. 5.17 is therefore quite good and explains the various behaviours of Fig. 14. Had we imposed a lower $\Omega_\chi h^2$, $\Omega_\chi h^2 < .2$ would have meant $m_{\tilde{e}_R} < 125$GeV. Even with the very mild constraint $\Omega_\chi h^2 < .6$ right selectron masses are below 160GeV. The same figure also shows the effect of not taking into account the constraint from the LEP2 neutralino cross sections. As expected the latter cut on smallest μ values (and also a bit on smaller M_2 values), that not only allow accessible $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ but also cut on the amount of the higgsino component in $\tilde{\chi}_1^0$ and thus on the contribution of $\tilde{\chi}_1^0$ to the invisible decay of h. We therefore see that a combination of LEP2 neutralino cross sections with improved constraints from the relic density are important.

5.4 Light Sleptons

We now allow for light sleptons with masses such that $m_{\tilde{l}} > 90$GeV but take into account all cosmological and accelerator constraints. The masses are calculated according to Eq. 5.18. Although one has reduced the $\mu - M_2$ parameter space somehow one has also allowed for light sleptons that indirectly contribute to $h \to \gamma\gamma$ beside the light charginos. Right and left charged sleptons of equal masses contribute almost equally and interfere destructively with the dominant W loop hence reducing the width $h \to \gamma\gamma$. Once again large drops are possible with reduction factor as small as .3 in both the branching ratio of the Higgs into photons and $b\bar{b}$.

The loop effects of the sleptons are rather marginal compared to the effect of the opening up of the neutralino channels. They account for some $10 - 15\%$ drop as can be seen when $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ is closed and by comparing with the heavy slepton case.

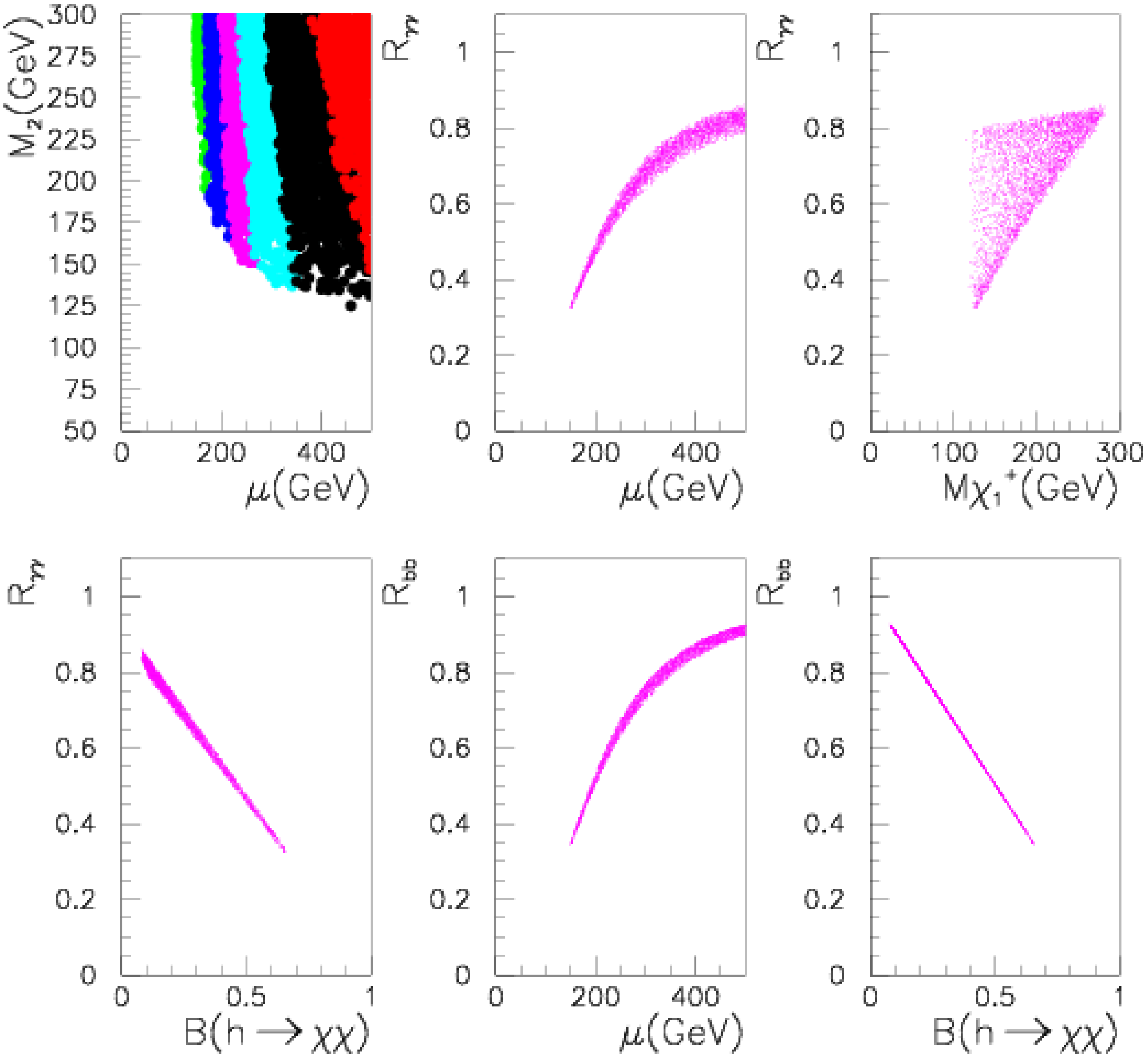

Figure 15: *Effects of neutralinos from* $M_1 = M_2/10$ *with* $\tan\beta = 5$ *and* $A_t = 0$ *with light selectrons. In all plots the scans are over* $M_2 = 50 - 300 GeV$*,* $\mu = 100 - 500 GeV$*. From left to right and top to bottom*
a) Density plot for $R_{\gamma\gamma}$*in the allowed* $M_2 - \mu$ *plane. The different shadings correspond to* $.3 < R_{\gamma\gamma} < .4$ *(left band) to* $.8 < R_{\gamma\gamma} < .9$ *(right band). b) Variation of* $R_{\gamma\gamma}$ *with* μ *c) with the mass of the chargino* $M_{\chi_1^+}$*. d) Correlation between* $R_{\gamma\gamma}$*and the branching into LSP. e) Variation of* $R_{b\bar{b}}$ *with* μ*. f)* $R_{b\bar{b}}$ *vs the branching of the Higgs into the LSP neutralino. .*

5.5 Associated chargino and neutralino production

In cases where there are very large reductions in the usual $b\bar{b}$ and $\gamma\gamma$ signatures of the Higgs, production of charginos and neutralino at the LHC is quite large[8]. Fig. 16 shows that, for values of $\mu - M_2$ where $R_{\gamma\gamma}$ is below .6, all neutralinos and charginos can be produced. For instance with $M_2 = 250$GeV, the cross section for $\tilde{\chi}_4^0\chi_2^+$ is in excess of 100fb while $\tilde{\chi}_2^0\chi_1^+$ is above $1pb$. Therefore early observations of these events, could probably allow the determination of the parameters of the higgsino-gauginos sector "sending an early warning signal" that indicates difficulty in the detection of the Higgs.

If we now look at the (lightest) Higgs that can be produced through cascade decays in these processes, one sees from Fig. 17 that, through essentially $\tilde{\chi}_3^0$ decays, associated Higgs cross sections of about 30fb are possible. Nonetheless, again, it is in these regions with highest yield that the Higgs has a large branching ratio into invisible and would be difficult to track.

6 Conclusions

In a model that assumes the usual common gaugino mass at the GUT scale and where, apart from the charginos and neutralinos, all other supersymmetric particles are heavy, we have shown that current LEP limits on charginos imply that there should be no problem finding the lightest SUSY Higgs at the LHC in the two-photon mode or even $b\bar{b}$ in the associated $t\bar{t}h$ channel. The loop effects of charginos in the two-photon width are small compared to the theoretical uncertainties, they amount to less than about 15% and can either increase or decrease the signal. The LEP data in this scenario mean that the decay of the Higgs into invisibles is almost closed. In scenarios "on the fringe" with a conspiracy between the sneutrino mass and the lightest chargino mass, the Higgs signal can be very much degraded in both the two-photon and the b final states. This is because the (invisible) Higgs decay into light neutralinos may become the main decay mode, suppressing all other signatures. This also occurs in models that do not assume the GUT inspired gaugino mass, specifically those where, at the weak scale, the $U(1)$ gaugino mass is much smaller than the $SU(2)$ gaugino mass. However we point out that limits from the relic density in these types of models require rather light right selectron masses. These in turn contribute quite significantly to the cross section for neutralino production at LEP2 which then constrains the parameter space in the gaugino-higgsino sector where the invisible branching ratio of the Higgs becomes large. Although large reductions in

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[8] Production of light sleptons, as constrained from cosmology in these scenarios, is on the other hand quite modest at the LHC.

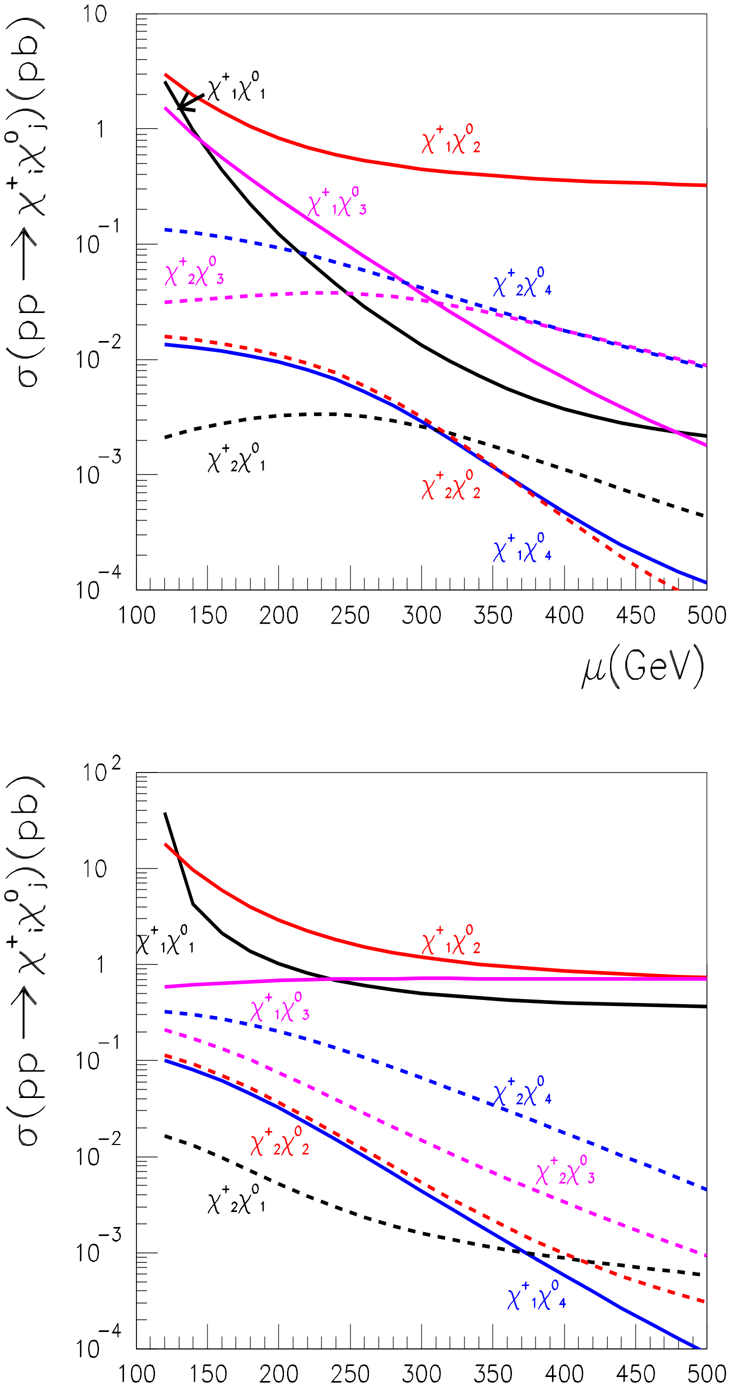

Figure 16: *Associated Production of chargino and neutralino at the LHC at LO for* $M_2 = M_1/10$ *a) as a function of* μ *for* $M_2 = 250\,GeV$. *b) as a function of* M_2 *for* $\mu = 150\,GeV$ *.*

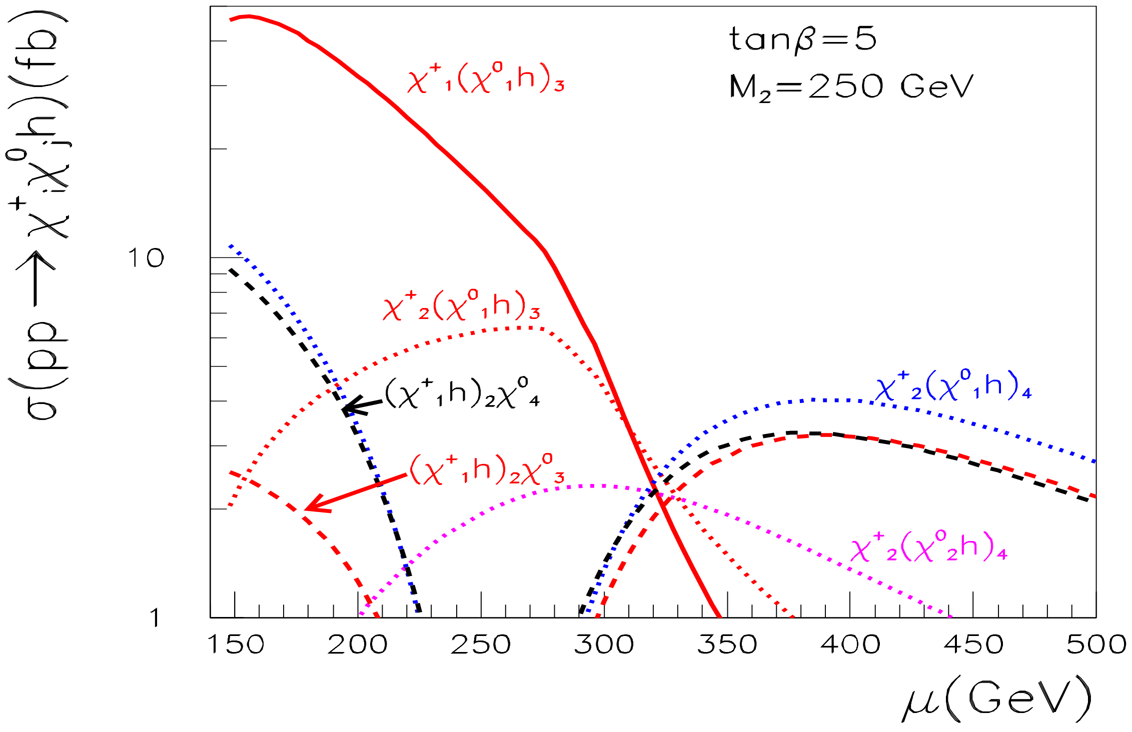

Figure 17: *As in Fig. 9 but with $M_2 = 250 GeV$ and $M_1 = M_2/10$.*

the usual channels are still possible, the combination of LEP2 data and cosmology means that observation of the Higgs signal at the LHC is jeopardised in only a small region of the SUSY parameter space. Moreover, we show that in these scenarios where the drops in the Higgs signals are most dramatic, one is assured of having a quite healthy associated chargino and neutralino cross section at the LHC. Some of the heavier of these particles may even trigger Higgs production through a cascade decay into their lighter partner. It rests to see whether the Higgs can be seen in this new production channels, considering that it will predominantly have an “invisible” signature.

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