Phenomenlogy of Non-Universal Gaugino Masses and Implications for Higgs Boson Decays

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Introduction

- In the experimental search for supersymmetry (SUSY) the lightest supersymmetric particle (LSP) will play a crucial role since the heavier supersymmetric particles will decay into it.

- In SUSY models with R-parity conservation, the lightest supersymmetric particle is absolutely stable. In most of the supersymmetric models the lightest neutralino ($\tilde{\chi}_1^0$), a admixture of gauginos and higgsinos, is the LSP.

- From the point of view of experimental discovery of supersymmetry at colliders, the LSP is the final product of the cascade decay of a SUSY particle.

- We will assume that the LSP is the lightest neutralino, and that it escapes the collider experiments undetected. The cascade chain will typically also contain other neutralinos ($\tilde{\chi}_j^0$, $j = 2, 3, 4$) as well as charginos ($\tilde{\chi}_i^{\pm}$, $i = 1, 2$).

- The charginos are an admixture of charged gauginos and charged higgsinos. The composition and mass of the neutralinos and charginos will play a key role in the search for supersymmetric particles. These properties determine also the time-scale of their decays.

- Although most of the phenomenological studies involving neutralinos and charginos have been performed with universal gaugino masses at the grand unification scale, there is no compelling theoretical reason for such a choice.

- Gaugino masses follow from higher dimensional interaction terms which involve gauginos and auxiliary parts of chiral superfields in a given supersymmetric model.

- If the auxiliary field of one of the GUT nonsinglet chiral superfields obtains a vacuum expectation value (VEV), then the gaugino masses are not universal at the grand unification scale.

- Moreover, nonuniversal soft supersymmetry gaugino masses are a necessary feature in some of the supersymmetric models, e.g. in anomaly mediated supersymmetry breaking models the gaugino masses are not unified.

- The phenomenology of supersymmetric models depends crucially on the composition of neutralinos and charginos. Experimental signals for supersymmetry can change with changes in the composition of neutralinos and charginos that may arise because of the changes in the boundary conditions at the GUT scale.

- In particular, the study of the implications of the nonuniversal gaugino masses for the phenomenology of neutral Higgs bosons is important.

- The cascade decays of the SUSY particles may be a major source of the Higgs bosons. This method of producing the Higgs bosons does not depend on the value of $\tan\beta$.

- This method of producing Higgs bosons may help to cover a larger parameter space as compared to the more conventional methods.

- The gauginos also play an important role in the decays of Higgs bosons when they are kinematically allowed to decay to the second lightest neutralino pair, which in turn may decay to the lightest neutralinos and two leptons.

- Such a signal seems to be relatively easy to discover at the LHC. The Higgs boson production via cascade decays and their detection has been studied in CMS detector simulations at LHC in the case of minimal supersymmetric standard model (MSSM) with universal gaugino masses.

- Here we discuss the lightest neutralino properties when the gaugino masses are nonuniversal.

Gaugino Masses in GUTS

- The masses and the compositions of neutralinos and charginos are determined by the soft SUSY breaking gaugino masses M_1, M_2, and M_3, the Higgs mixing parameter μ, and $\tan\beta$.

- In the simplest SUSY models $M_1 = M_2 = M_3$ at the GUT scale. However, in SUSY models with an underlying GUT gauge group, the gaugino masses need not be equal at the GUT scale.

- We will consider the nonuniversality of gaugino masses as it arises in the simplest of the SUSY GUTS, namely supersymmetric $SU(5)$ grand unified theory.

- In SUSY GUTS, non-universal gaugino masses are generated by a non-singlet chiral superfield Φ^n that appears in the gauge kinetic function $f(\Phi)$ which is function of the chiral singlet (Φ^s) and non-singlet (Φ^n) superfields in the theory.

- If the auxiliary part F_Φ of a chiral superfield Φ in $f(\Phi)$ gets a VEV, then gaugino masses arise from the coupling of $f(\Phi)$ with the field strength superfield W^a:

$$\mathcal{L}_{g.k.} = \int d^2\theta f_{ab}(\Phi) W^a W^b + h.c.,$$

$$f_{ab}(\Phi) = f_0(\Phi^s)\delta_{ab} + \sum_n f_n(\Phi^s) \frac{\Phi^n_{ab}}{M_P} + \cdots,$$

- Here $f_0(\Phi^s)$ and $f_n(\Phi^s)$ are functions of gauge singlet superfields Φ^s, and M_P is some large scale. When F_Φ gets a VEV $\langle F_\Phi \rangle$, this interaction gives rise to gaugino masses ($\lambda^{a,b}$ are gaugino fields):

$$\mathcal{L}_{g.k.} \supset \frac{\langle F_\Phi \rangle_{ab}}{M_P} \lambda^a \lambda^b + h.c.$$

- Since the gauginos belong to the adjoint representation of $SU(5)$, Φ and F_Φ can belong to any of the representations appearing in the symmetric product of the two **24** dimensional representations of $SU(5)$:

$$(\mathbf{24} \otimes \mathbf{24})_{Symm} = \mathbf{1} \oplus \mathbf{24} \oplus \mathbf{75} \oplus \mathbf{200}.$$

- In the minimal case Φ and F_Φ are assumed to be in the singlet representation of $SU(5)$, which implies equal gaugino masses at the GUT scale.

- However, Φ can belong to any of the non-singlet representations **24**, **75**, and **200** of $SU(5)$, in which case these gaugino masses are unequal but related to one another via the representation invariants.

- Because of the renormalization group (RG) evolution we have at any scale (at the one-loop level)

$$
\begin{aligned}
M_1 &= \frac{5}{3}\frac{\alpha}{\cos^2\theta_W}\left(\frac{M_1(\mathrm{GUT})}{\alpha_1(\mathrm{GUT})}\right), \\
M_2 &= \frac{\alpha}{\sin^2\theta_W}\left(\frac{M_2(\mathrm{GUT})}{\alpha_2(\mathrm{GUT})}\right), \\
M_3 &= \alpha_3\left(\frac{M_3(\mathrm{GUT})}{\alpha_3(\mathrm{GUT})}\right).
\end{aligned}
$$

- For the **24** dimensional representation

$$\frac{M_1}{M_3} = -\frac{1}{2\alpha_3}\left(\frac{5}{3}\frac{\alpha}{\cos^2\theta_W}\right),$$
$$\frac{M_2}{M_3} = -\frac{3}{2\alpha_3}\left(\frac{\alpha}{\sin^2\theta_W}\right).$$

- For the **75** dimensional representation

$$\frac{M_1}{M_3} = -5\left(\frac{5}{3}\frac{\alpha}{\cos^2\theta_W}\right)\left(\frac{1}{\alpha_3}\right),$$
$$\frac{M_2}{M_3} = 3\left(\frac{\alpha}{\sin^2\theta_W}\right)\left(\frac{1}{\alpha_3}\right),$$

- And for **200** dimensional representation

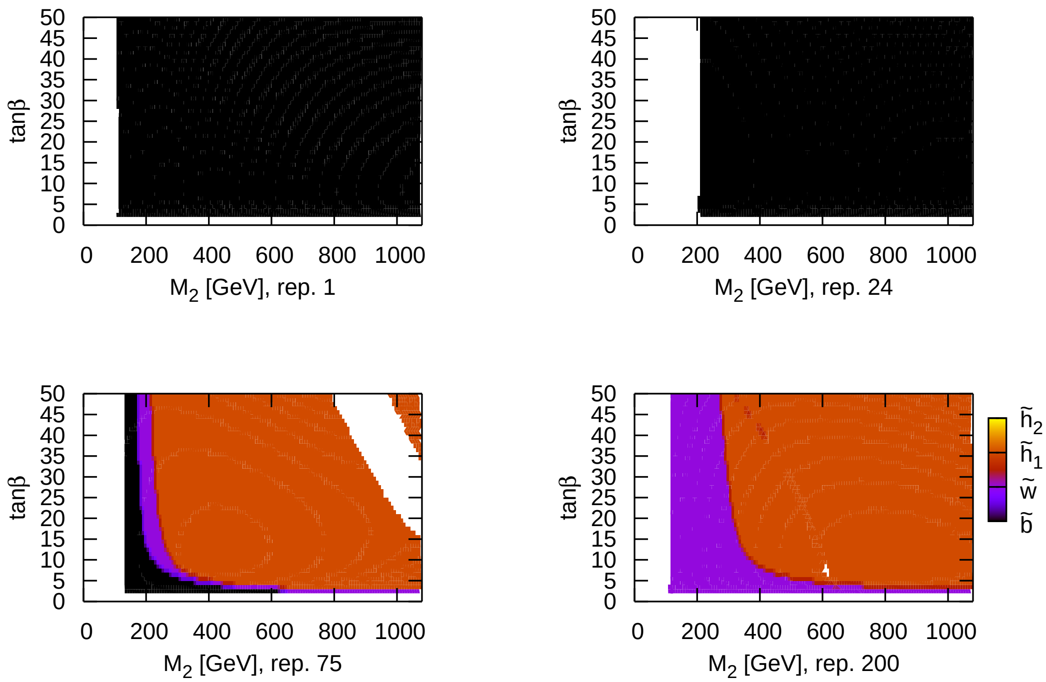
$$\frac{M_1}{M_3} = 10\left(\frac{5}{3}\frac{\alpha}{\cos^2\theta_W}\right)\left(\frac{1}{\alpha_3}\right),$$
$$\frac{M_2}{M_3} = 2\left(\frac{\alpha}{\sin^2\theta_W}\right)\left(\frac{1}{\alpha_3}\right).$$

- After RG evolution, at EW scale, $M_1 < M_2$ for the singlet representation, $|M_1| < |M_2|$ for the **24** and **75** representation, and $M_1 > M_2$ for **200** dimensional representation. Two-loop effects increase the M_1/M_2-ratio.

- The ratios of the gaugino masses:

F_Φ	M_1^G	M_2^G	M_3^G	M_1^{EW}	M_2^{EW}	M_3^{EW}
1	1	1	1	0.14	0.29	1
24	-0.5	-1.5	1	-0.07	-0.43	1
75	-5	3	1	-0.72	0.87	1
200	10	2	1	1.44	0.58	1

- The main component of the lightest neutralino in different representations of $SU(5)$



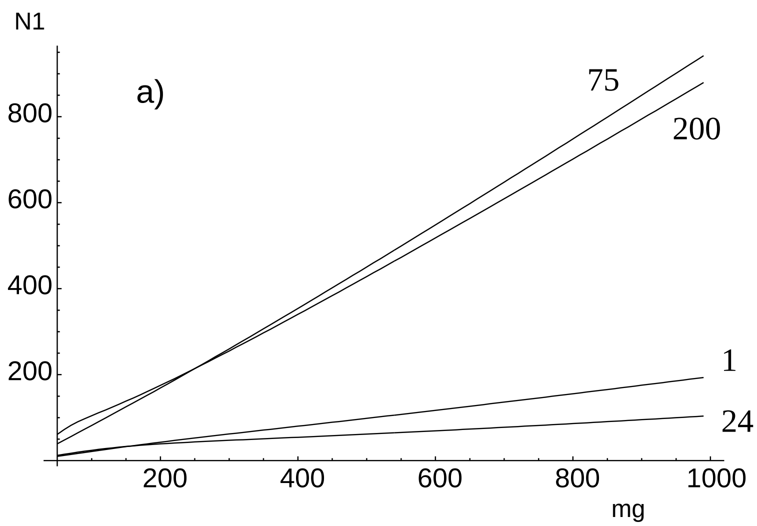
- For singlet rep., the dominant component is always the bino. This is also true for the **24** dimensional rep.

- For the **75** dimensional representation, we have several possibilities. For the value of the soft parameter $m_0 = 1$ TeV, one has a bino LSP for small values of M_2, a wino LSP for slightly larger values of M_2, and a higgsino LSP for $M_2 \gtrsim 300$ GeV, all for a value of $\tan\beta \gtrsim 10$. There exists a band of discontinuity in the $(M_2, \tan\beta)$-parameter space. For these values of parameters the lighter chargino mass becomes too light. The lower end of the M_2 range is restricted in this case by the experimental limit on the gluino mass.

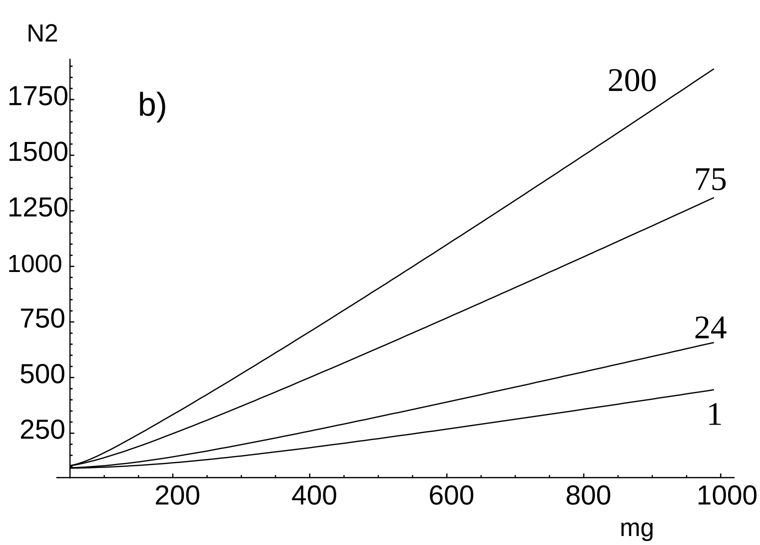
- For the **200** dimensional representation the LSP is either a wino or a higgsino, depending on the values of M_2 and $\tan\beta$.

- An upper bound on the mass of the lightest neutralino ($\tilde{\chi}_1^0$):

$$M_{\tilde{\chi}_1^0}^2 \leq \frac{1}{2}\left(M_1^2 + M_2^2 + M_Z^2 - \sqrt{(M_1^2 - M_2^2)^2 + M_Z^4 - 2(M_1^2 - M_2^2)M_Z^2 \cos 2\theta_W}\right)$$

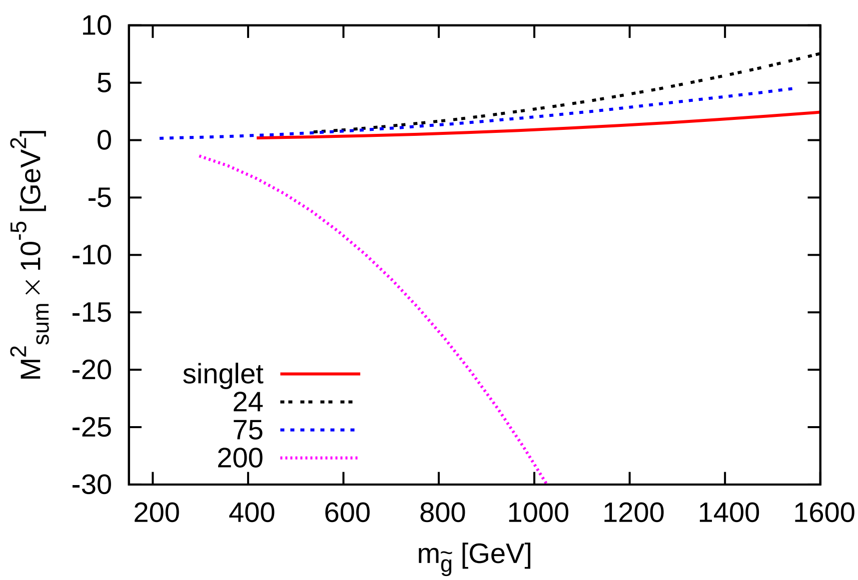


- The upper bound on the mass of the second lightest neutralino ($\tilde{\chi}_2^0$):



- For the four different representations of $SU(5)$, we have the sum rules

$$
\begin{aligned}
M^2_{sum} &\equiv 2\sum M^2_{\tilde{\chi}_i^\pm} - \sum M^2_{\tilde{\chi}_i^0} \\
&= (\alpha_2^2 - \alpha_1^2)\frac{M^2_{\tilde{g}}}{\alpha_3^2} + 4m_W^2 - 2m_Z^2, \quad \mathbf{1}, \\
&= (\frac{9}{4}\alpha_2^2 - \frac{1}{4}\alpha_1^2)\frac{M^2_{\tilde{g}}}{\alpha_3^2} + 4m_W^2 - 2m_Z^2, \quad \mathbf{24}, \\
&= (9\alpha_2^2 - 25\alpha_1^2)\frac{M^2_{\tilde{g}}}{\alpha_3^2} + 4m_W^2 - 2m_Z^2, \quad \mathbf{75}, \\
&= (4\alpha_2^2 - 100\alpha_1^2)\frac{M^2_{\tilde{g}}}{\alpha_3^2} + 4m_W^2 - 2m_Z^2, \quad \mathbf{200}.
\end{aligned}
$$



Implications for Higgs Physics

- It is possible that for heavy Higgs bosons H^0, A^0 and $H^\pm$ the decays to supersymmetric particles are important or even dominant.

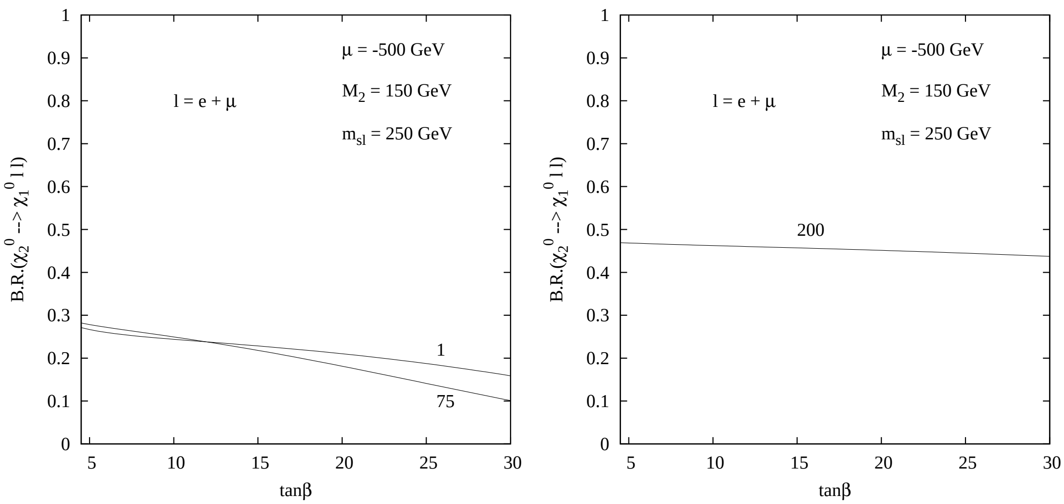
- The decay of heavy Higgs bosons to the second lightest neutralinos ($\tilde{\chi}_2^0$) is promising because of the clear four lepton signal:

$$
\begin{aligned}
H^0, A^0 &\rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0, \\
\tilde{\chi}_2^0 &\rightarrow \tilde{\chi}_1^0 l^+ l^-, \;\; l = e, \mu
\end{aligned}
$$

- The decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 l^+ l^-$ depends on the parameters M_2, M_1, μ, and $\tan\beta$, and also on the slepton masses $m_{\tilde{l}}$. Hence it depends on the $SU(5)$ representation that is used in the gauge kinetic function.

- As long as the direct decay of $\tilde{\chi}_2^0$ into $\tilde{\chi}_1^0 + Z^0$ is suppressed and the sleptons are heavier than the $\tilde{\chi}_2^0$, three body decays of $\tilde{\chi}_2^0$ into charged leptons and $\tilde{\chi}_1^0$ will be significant.

- We show the branching ratio of the three body decay for different representation of $SU(5)$ as a function of $\tan\beta$:



- Due to the choice of M_2 value, $\tilde{\chi}_2^0$ for the singlet representation is predominantly a wino, and $\tilde{\chi}_1^0$ is a bino-dominated state. The decay of $\tilde{\chi}_2^0$ into $\tilde{\chi}_1^0$ and a Z^0 is kinematically disallowed.

- We see from the figure that for higher values of $\tan\beta$ this branching ratio decreases since the branching ratio $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$ increases with $\tan\beta$ due to a larger Yukawa coupling.

- For the values of parameters chosen, the lightest neutralino mass is below the experimental lower limit for the **24** dimensional representation.

- For the **75** representation, $\tilde{\chi}_2^0$ is wino-dominated and $\tilde{\chi}_1^0$ is bino-dominated as in the singlet case. However, the mass difference between the $\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$ is much smaller compared to the singlet case. In the low $\tan\beta$ region the branching ratio for these two different representations are very close though the branching ratio for the **75** representation is slightly larger. This is due to the fact that BR($\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 q\bar{q}$) is slightly larger in the singlet case as compared to the case of **75** dimensional representation. The leptonic branching ratio is then almost equally distributed among the available channels. However, for large $\tan\beta$ the branching ratio in the $\tilde{\chi}_1^0 \tau^+\tau^-$ channel is larger for the **75** case than for the singlet case. For large $\tan\beta$ this makes the branching ratio in the $\tilde{\chi}_1^0 l^+ l^-$ channel smaller for the case of **75** dimensional representation. We also note that in the case of **75** dimensional representation the partial decay width of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \nu\bar{\nu}$ is larger than the partial decay width of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-$ in the large $\tan\beta$ region. On the other hand, in the singlet case the partial decay width of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \nu\bar{\nu}$ is always smaller than that of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-$.

- Decay of heavy Higgs bosons into a pair of neutralinos: $H^0, A \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$

- The decay widths and branching ratios depend on the ratio of M_1 and M_2, and other MSSM parameters.

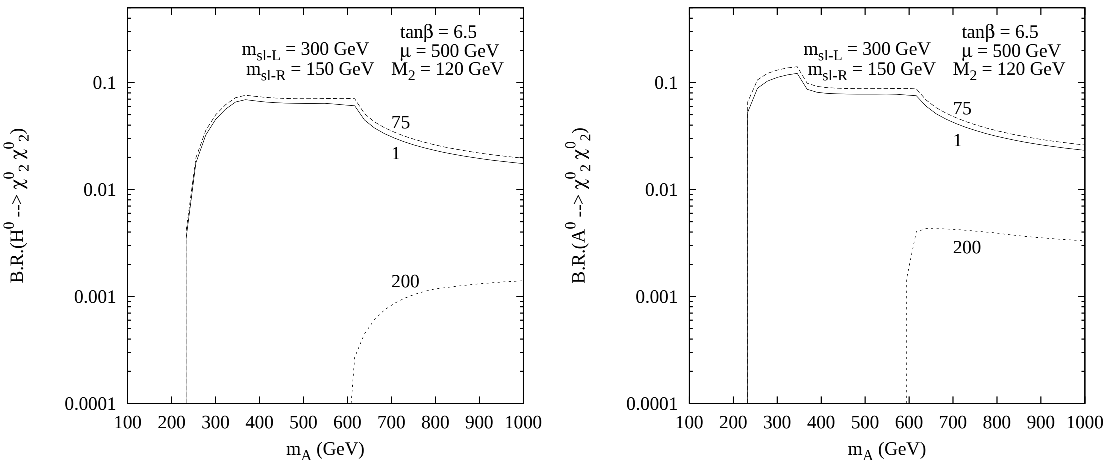
- The coupling of the heavy Higgs bosons H^0, A^0 to a pair of neutralinos is given by (P_L, P_R are projection operators):

$$
\begin{aligned}
H^0 \tilde{\chi}_i^0 \tilde{\chi}_j^0 &: \quad -ig(A_L P_L + A_R P_R), \\
A^0 \tilde{\chi}_i^0 \tilde{\chi}_j^0 &: \quad -g(B_L P_L - B_R P_R)
\end{aligned}
$$

$$
\begin{aligned}
A_L &= Q''^{*}_{ji} \cos\alpha - S''^{*}_{ji} \sin\alpha, \\
A_R &= Q''_{ij} \cos\alpha - S''_{ij} \sin\alpha, \\
B_L &= Q''^{*}_{ji} \sin\beta - S''^{*}_{ji} \cos\beta, \\
B_R &= Q''_{ij} \sin\beta - S''_{ij} \cos\beta.
\end{aligned}
$$

$$
\begin{aligned}
Q''_{ij} &= \frac{1}{2}[Z_{i3}(Z_{j2} - Z_{j1} \tan\theta_W) + Z_{j3}(Z_{i2} - Z_{i1} \tan\theta_W)]\epsilon_i, \\
S''_{ij} &= \frac{1}{2}[Z_{i4}(Z_{j2} - Z_{j1} \tan\theta_W) + Z_{j4}(Z_{i2} - Z_{i1} \tan\theta_W)]\epsilon_i.
\end{aligned}
$$

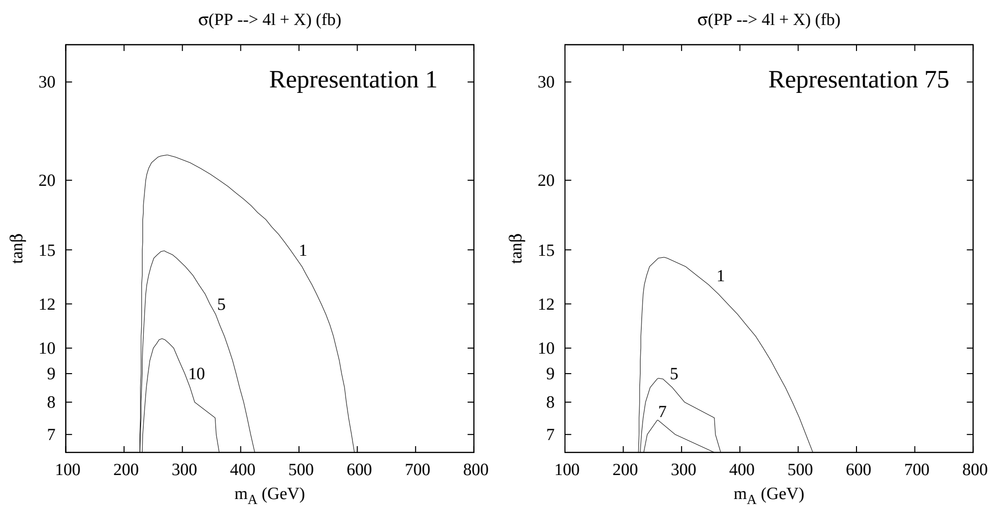
- Dependence of branching ratios BR($H^0, A^0 \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$) on m_A for a particular choice of MSSM parameters.



- For $m_A < 350$GeV, the branching ratio of the decay of A^0 is larger than that of the decay of the heavy Higgs scalar H^0 for the reps. 1 and 75. This is due to the fact that for H^0 the total decay width is large due to the increase in the number of available channels to the SM particles, which leads to a smaller branching ratio to sparticles.

- In the case of **200** dimensional rep. the threshold opens up for heavier m_A, and once again the branching ratio of A^0 is larger than that of H^0.

- Signal Cross Section and the total event rate in the four lepton channel at the LHC with $\sqrt{s} = 14$ TeV for the 1 and 75 reps.



- For the singlet representation, we see that for $\tan\beta$ up to ≈ 10, and $m_A \sim$ 250-350 GeV the total $4l$ cross section can reach up to 10 fb, which corresponds to 1000 signal events (without any cuts) for integrated luminosity of 100fb^{-1}.

- For the 75 dimensional rep., a much smaller region in the $(m_A, \tan\beta)$ plane can be probed in this case with the same number of events.

- The four lepton signal is very small for large values of $\tan\beta$ due to the suppression of the branching ratio B.R.($H^0/A^0 \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0$).

- There are two types of backgrounds, namely, the SM processes, and SUSY processes. The main SM background comes from Z^0Z^0 and $t\bar{t}$ production.

- The $t\bar{t}$ background can be eliminated to a large extent by requiring four isolated leptons with $p_l^T > 10$ GeV. Demanding a missing transverse energy of 20 GeV and an explicit Z^0 veto can reduce the background from Z^0Z^0.

- The background from SUSY processes can come from squark/gluino production or sneutrino pair production. The events coming from squark/gluino production can be eliminated by requiring soft jets with $E_T < 100$ GeV and $E_T^{miss} < 130$ GeV.

- The background coming from sneutrino pair production is more difficult to handle. However, it could possibly be distinguished due to the fact that it has larger E_T^{miss} and larger p_l^T compared to the signal.

- After using all these cuts the percentage of four lepton signal surviving is approximately about 60%.

- Higgs production in the cascade

$$\tilde{q}, \tilde{g} \to \tilde{\chi}_2^0 \to h\tilde{\chi}_1^0.$$

- If squarks and gluinos are light enough to be produced ($pp \to \tilde{q}\tilde{q}', \tilde{g}\tilde{g}, \tilde{g}\tilde{q}$), then their production cross section will be large at a hadron collider.

- Thus, the decay chain

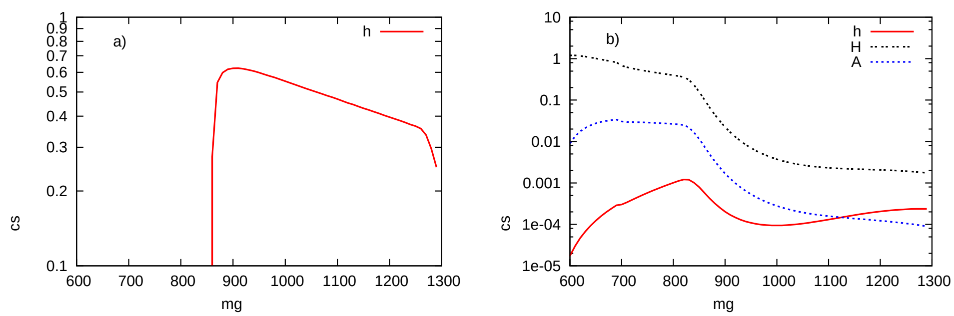
$$\begin{aligned} \tilde{q}, \tilde{g} \to \tilde{\chi}_2^0 + X &\to \tilde{\chi}_1^0 h(H^0, A^0) + X \\ &\to \tilde{\chi}_1^0 b\bar{b} + X \end{aligned}$$

will be an important source to look for Higgs bosons at LHC in the final state $b\bar{b}b\bar{b}$ + X.

- It was found that for suitable values of the parameters, the signal for all of the neutral Higgs bosons was clearly above the background. Discovery potential for A^0 and H^0 extended to 200 GeV, independent of the values of $\tan\beta$.

- The cross section as a function of the gluino mass for the 1 and 24 dimensional rep.

- Parameters: $\tan\beta = 10, m_A = 200$ GeV, $\mu = +500$ GeV, $m_{\tilde{q}} = 600$ GeV and $m_{\tilde{l}} = 350$ GeV as input values. In this case only decay through the light Higgs boson h^0 is kinematically possible. The mass difference of the two lightest neutralinos is too small to produce heavier Higgs bosons H^0 and A^0.



- For 24 dimensional rep. the composition and masses of the neutralinos are different from the universal case. Now all the Higgs channels are available. We see that the CP-even neutral Higgs H^0-channel gives the largest cross section. As gluino mass increases, the decay branching ratio of $\tilde{\chi}_2^0 \rightarrow h, H^0, A^0 + \tilde{\chi}_1^0$ decreases.

Summary

- We have studied the consequences of gaugino mass nonuniversality in SUSY GUTS for the neutralino masses and mass relations, as well as particular Higgs production and decay processes.

- Upper bounds for masses of neutralinos. Sum rules for neutralino and Chargino masses. These have significant dependence on the representation of the underlying gauge group.

- The decay of the second lightest neutralino to two leptons and the lightest neutralino very much depends on the mass difference between the lightets and the second lightest neutralino, which in turn depends on the representation. This is also true for the production of Higgs bosons in the decay of the second lightest neutralino.

- Implications of nonuniversality for the Higgs phenomenolgy.