Phenomenology of non-universal gaugino masses in supersymmetric SU(5) GUT

Jari Laamanen

Helsinki Institute of Physics

Helsinki, Finland

Work by K. Huitu, J. Laamanen, P. N. Pandita and S. Roy

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Motivation

The large number of free parameters in the Standard Model motivates GUTs. Supersymmetry is introduced to solve the technical aspects of the gauge hierarchy problem (quadratic divergences). Also the apparent unification of the gauge couplings hints for GUTs.

- The phenomenology of SUSY models depends heavily on the compositions of the particles
- In SUSY the lightest supersymmetric particle (LSP) has a special role (dark matter, usually stable...)
- In most of the models the lightest neutralino χ_1^0 is the LSP

It is also important to study the Higgs sector and it is interesting to see how those are connected to the neutralino sector.

In the global SU(5) SUSY there are three different degenerate vacua corresponding

$$SU(5), \quad SU(4) \times U(1) \text{ and } SU(3) \times SU(2) \times U(1)$$

One needs gravitational effects to get the vev that gives $SU(3) \times SU(2) \times U(1)$ to be the global minimum $\longrightarrow$ need SUGRA

Non-universal gauginos in SUSY $SU(5)$

The Lagrangian can be written in terms of two fundamental functions, the Kähler potential $G(\Phi_i, \Phi^*{}_i)$ and the gauge kinetic function $f_{ab}(\Phi)$. The Lagrangian for the coupling of gauge kinetic function to the gauge field strength (W^a) can be written

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

where the gauge kinetic function is

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

The Φ^s and the Φ^n are the gauge singlet and the gauge non-singlet chiral superfields, respectively.

If the auxiliary part F_Φ of a chiral superfield Φ gets a VEV $\langle F_\Phi \rangle$, then gaugino masses arise from the coupling of $f_{ab}(\Phi)$ with the field strength superfield W^a

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

where $\lambda^{a,b}$ are gaugino fields. Since the gauge kinetic function transforms as a symmetric product of two adjoint representations, Φ and F_Φ can belong to any of the (irreducible) representations appearing in the symmetric product of the two **24** dimensional representations of $SU(5)$:

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

Only the component of F_Φ that leaves the SM group $SU(3) \times SU(2) \times U(1)$ invariant should acquire a vev, in which case

$$\langle F_\Phi \rangle_{ab} = c_a \delta_{ab}.$$

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 c_a.

Below are the ratios of resulting gaugino masses at tree-level as they arise when F_Φ belongs to various representations of $SU(5)$.

Table 1: Ratios of the gaugino masses at the GUT scale in the normalization $M_3(GUT)$ = 1, and at the electroweak scale in the normalization $M_3(EW)$ = 1 at the 1-loop level.

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

Note:

- We assume that the dominant component of gaugino masses comes from one of the non-singlet F-component, i.e. the singlet component vev is small enough. In that case the relations of the gaugino masses at the GUT-scale are defined by the group theoretical factors c_a.
- Assume the unification of gauge couplings ($\alpha_3^G = \alpha_2^G = \alpha_1^G = \alpha^G$ $(\approx 1/25)$) at the grand unification scale (the corrections are of the order $\mathcal{O}(M_X/M_P) \sim \mathcal{O}(1/100)$).

Properties of Neutralinos

Neutralinos are combinations of gauginos and higgsinos, so their properties vary with respect to the chosen representation (relevant parameters: M_1, M_2 and M_3, the Higgs mixing parameter μ and $\tan\beta$)

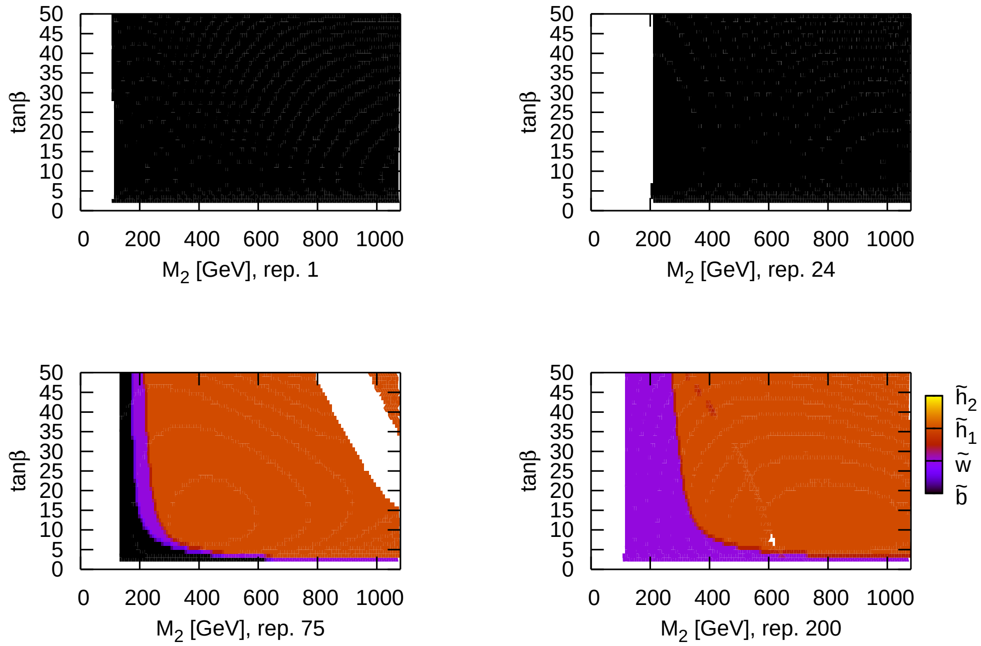


Figure 1: Main component of the lightest neutralino in different representations of $SU(5)$ for a common universal scalar mass $m_0 = 1$ TeV given at the GUT scale. The value of M_2 is calculated and plotted at the electroweak scale.

Upper limits of $m_{\chi_1^0}$ and $m_{\chi_2^0}$

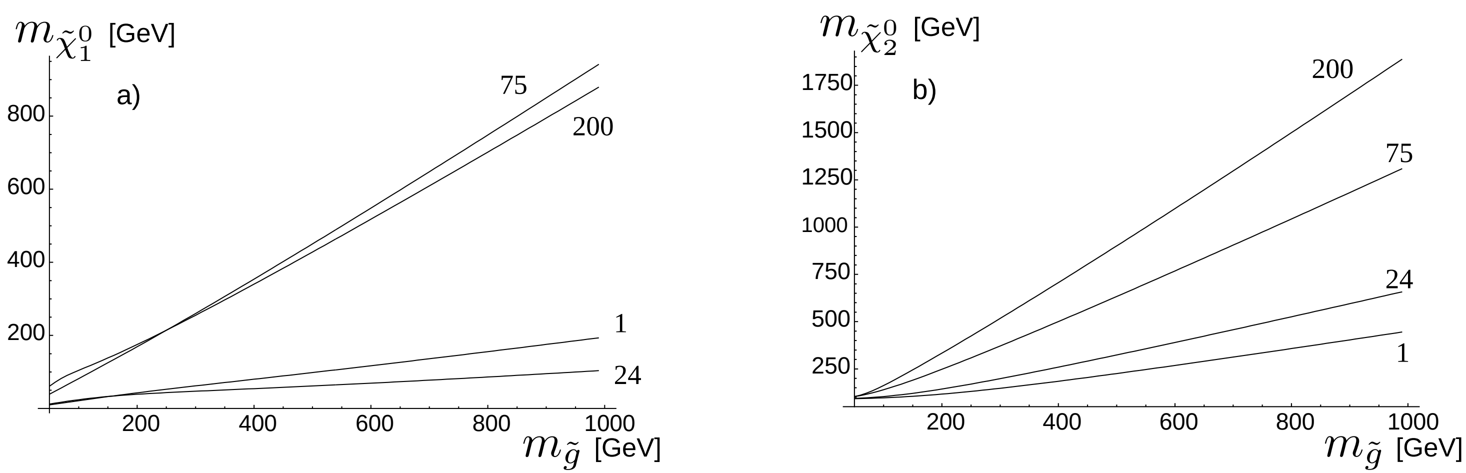


Figure 2: The upper bound for (a) the lightest neutralino mass and (b) for the second lightest neutralino mass for different representations.

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

The above limit comes from the structure of the neutralino mass matrix.

Heavy Higgs Detection

For the heavy Higgses H^0, A the decays to SUSY particles can be important or even dominant We study first the chain $pp \rightarrow (H^0, A) \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l + invisible$ where l is an electron or a muon (τ's may decay to pions etc.)

- Higgs decays to sleptons are suppressed because of the small coupling proportional to m_l
- Decay to χ_2^0 gives a clear 4-lepton signal if (left) sleptons are not lighter than χ_2^0

Let's first look at the decay $H^0, A^0 \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ and after that the decay $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$

PART I: Decay of $H^0, A^0 \longrightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_2$ (1, 75 and 200)

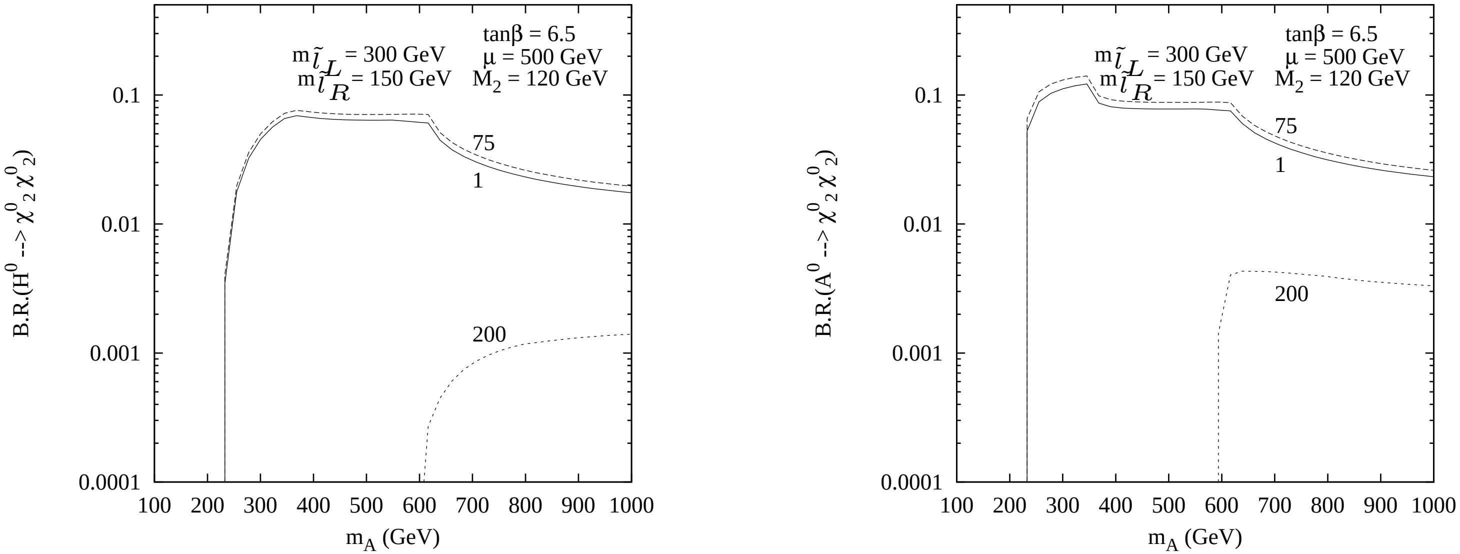


Figure 3: The branching ratio of $H^0, A^0 \longrightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_2$ as a function of m_A for three different $SU(5)$ representations for (a) H^0 and (b) A^0.

- H^0 has more possibilities to decay to SM particles $\longrightarrow$ smaller BR to sparticles
- The **24** representation produces too light $\tilde{\chi}^0_1$ compared to the experimental limit

PART II: Decay $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$ (1, 75 and 200)

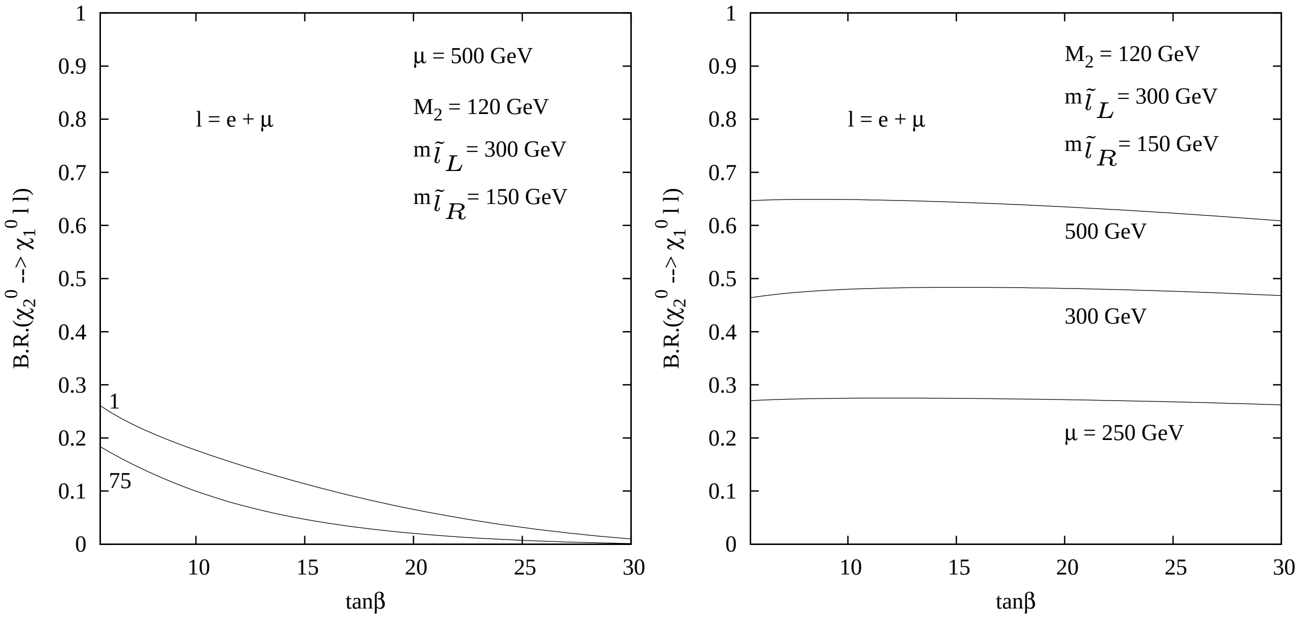


Figure 4: Branching ratio as a function of $\tan\beta$, in the case of a) $m_{\tilde{l}} > m_{\tilde{\chi}_2^0}$ and for the representations **1** and **75** and for μ = 500 GeV and b) $m_{\tilde{l}_R} < m_{\tilde{\chi}_2^0}$ and for the representation **200**.

- For **1** and **75** the BR decreases due to the increase of BR($\chi_2^0 \rightarrow \chi_1^0 \tau^+ \tau^-$) which has larger Yukawa coupling
- **200** case depends strongly on μ (as μ increases χ_2^0 becomes more bino-like thus enhancing $\chi_2^0 \rightarrow \tilde{l}_R l$ that eventually leads to $\tilde{l}_R \rightarrow \chi_1^0 l$)

Cross section for the total process $pp \longrightarrow 4l$ + invisible

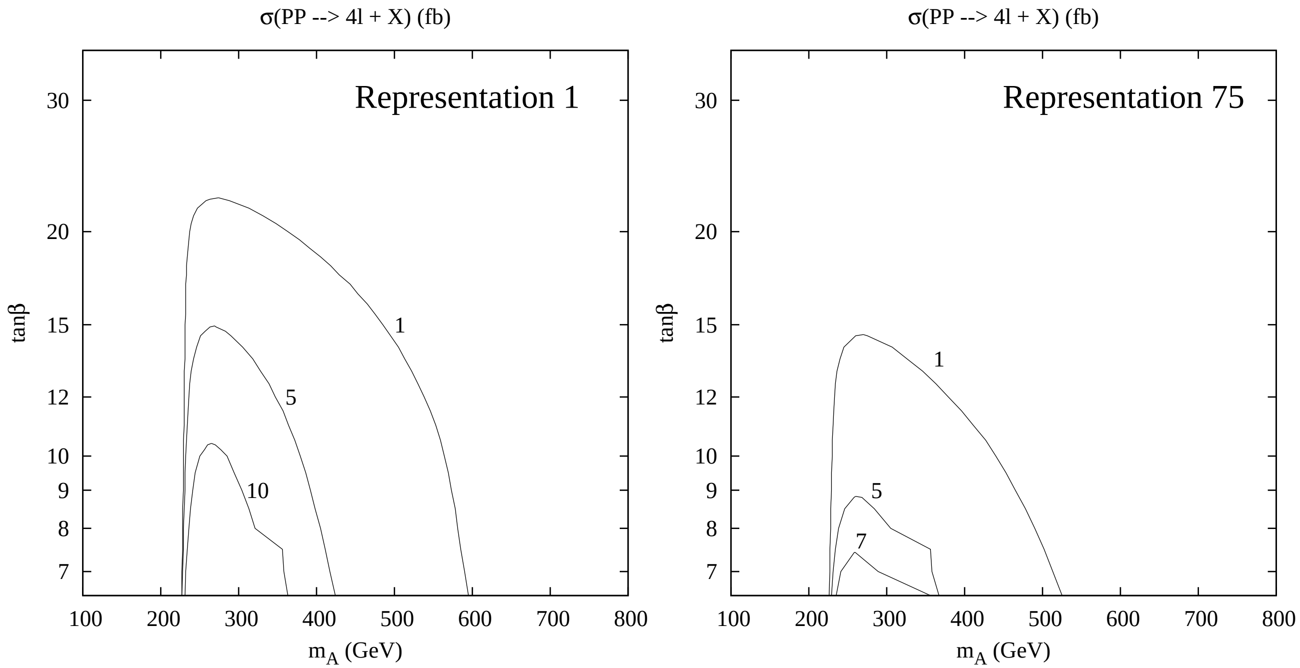


Figure 5: Contours of $\sigma(pp \longrightarrow H^0, A^0 \longrightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \longrightarrow 4l + X)$ in fb, where $l = e^{\pm}$ or $\mu^{\pm}$ and X represents invisible final state particles in (a) singlet (b) representation **75** ($m_{\tilde{l}_L} = 300, m_{\tilde{l}_R} = 150, m_{\tilde{q}} = 1000, \mu = 500, M_2 = 120$ q [GeV], $\sqrt{s}$ = 14 TeV)

- With the same number of events a smaller region in the $(m_A, \tan\beta)$-region can be covered in the **75** representation than in **1**
- For large $\tan\beta$ the four lepton signal is very small, since BR($H^0/A^0 \longrightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0$) is decreasing
- For **200** the total cross section is less than 1 fb

Chain II: Higgs production in the cascade

$$\tilde{q}, \tilde{g} \longrightarrow \tilde{\chi}_2^0 \longrightarrow h(H^0, A^0)\tilde{\chi}_1^0$$

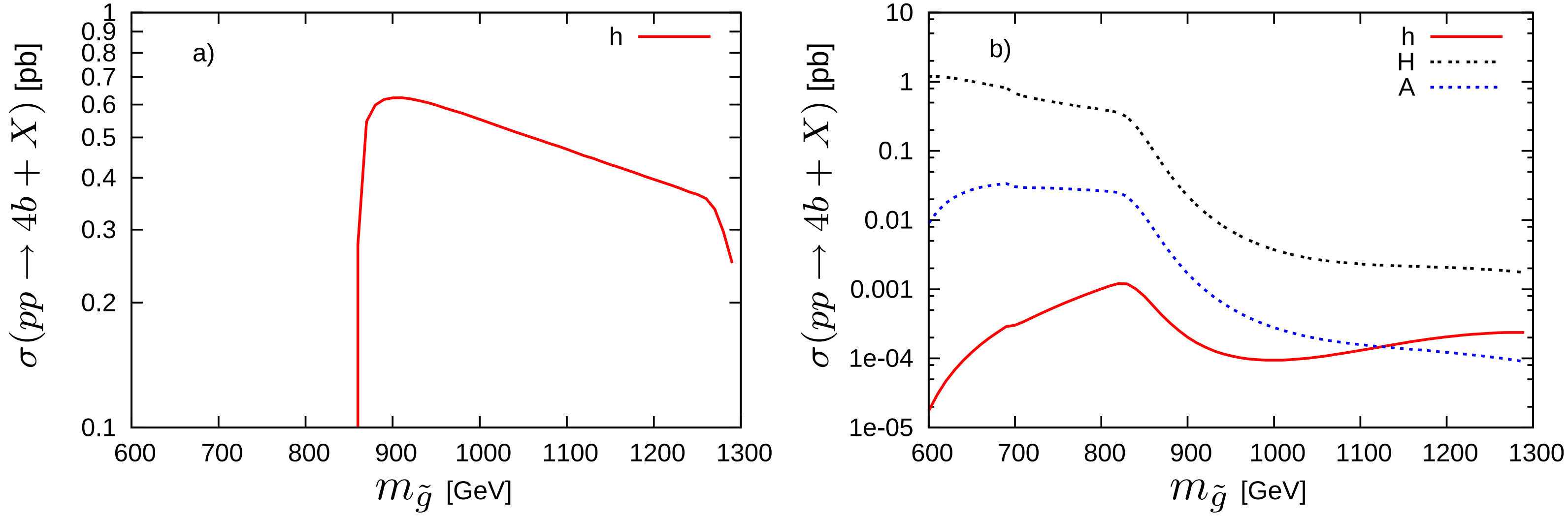
If squarks and gluinos are light enough to be produced ($pp \longrightarrow \tilde{q}\tilde{q}', \tilde{g}\tilde{g}, \tilde{g}\tilde{q}$), then their production cross section will be large at a hadron collider. Thus, the decay chain

$$\tilde{q}, \tilde{g} \rightarrow \tilde{\chi}_2^0 + X \rightarrow \tilde{\chi}_1^0 h(H^0, A^0) + X \rightarrow \tilde{\chi}_1^0 b\bar{b} + X$$

will be an important source to look for Higgs bosons at LHC in the final state $b\bar{b}b\bar{b} + X$. Here we study the part of the parameter space for which $m_{\tilde{g}} > m_{\tilde{q}}$. Then every gluino decays to a quark and the corresponding squark.

Cross section $pp \longrightarrow b\bar{b}b\bar{b} + X$ at LHC through the decay chain

$$\tilde{q}, \tilde{g} \longrightarrow \tilde{\chi}_2^0 \longrightarrow \tilde{\chi}_1^0 h(H^0, A^0) \longrightarrow \tilde{\chi}_1^0 b\bar{b} + X$$



In the case of singlet representation [Fig. (a)]

- Only the decay through the light Higgs boson h is kinematically possible. The light Higgs channel opens, when the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ mass difference is large enough.
- The production cross section of squarks decreases as gluino mass increases.

In the case of **24** dimensional representation [Fig. (b)]

- All the Higgs channels available.
- As gluino mass increases, the decay branching ratio of $\tilde{\chi}_2^0 \longrightarrow h, H^0, A^0 + \tilde{\chi}_1^0$ decreases.

Note about the 75 and 200 in the cascade

$$\tilde{q}, \tilde{g} \rightarrow \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h(H^0, A^0) \rightarrow \tilde{\chi}_1^0 b\bar{b} + X$$

- In the **75** dimensional representation the mass difference of the two lightest neutralinos are generally too small in order for $\tilde{\chi}_2^0$ to decay into Higgs bosons
- For the **200** dimensional representation, the mass difference of the two lightest neutralinos depends on the squark masses. Requiring the lightest neutralino to be the LSP, and for experimentally viable Higgs boson mass, the mass difference of the two lightest neutralinos is relatively small, and the total cross section resulting from the decay chain remains below the detection level.

Conclusion

- The ratios of the lightest neutralino masses changes significantly with the representation
- Depending on the region of the parameter space, the Higgs decay $h(H^0, A^0) \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ may be observable in any representation. However the region in which $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$ is large, and it is possible for Higgs bosons to decay to the second lightest neutralinos, is rather limited in any of these models.
- Interestingly, for the production of the Higgs bosons via the decay chain including $\tilde{\chi}_2^0 \rightarrow h(H^0, A^0)\tilde{\chi}_1^0$, in addition to the singlet, we found relevant region of the parameter space only for the representation **24**. Also the fact that colRa all the neutral Higgs channels are open in the **24** case distinguishes it from the singlet case, where only the light Higgs channel is available.

Generally it is important to realize that the detection modes (e.g. of Higgses) depend strongly on the parameters of the model. Thus the investigation of non-minimal models is of a great importance.