Non-universal gaugino masses and implications on the dark matter and Higgs searches

Katri Huitu¹, Jari Laamanen²,¹, and Sourav Roy³

¹ Helsinki Institute of Physics and High Energy Physics Division, Department of Physical Sciences, PL 64, FIN-00014, University of Helsinki, Finland
² Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany
³ Department of Theoretical Physics and Centre for Theoretical Sciences, Indian Association for the Cultivation of Science, 2A & 2B Raja S.C. Mullick Road, Kolkata 700 032, India

Abstract. Non-universal boundary conditions in grand unified theories can lead to non-universal gaugino masses at the unification scale. In R-parity preserving theories the lightest supersymmetric particle is a natural candidate for the dark matter. We have studied the composition of the lightest neutralino in non-universal gaugino mass cases from the SU(5), and implications on the dark matter. In the representations of SU(5) thermal relic density agreeing with WMAP is found. The possibility to observe the neutral MSSM Higgs bosons (h/H/A) at the LHC via neutralino cascades when the lightest neutralino is dark matter, is discussed for the representation 24, and the connection to dark matter is established.

PACS. 12.60.Jv Supersymmetric models – 95.35.+d Dark matter

1 Introduction

Most of the phenomenological studies involving neutralinos have been performed with universal gaugino masses at the grand unification scale. However, there is no compelling theoretical reason for such a choice. This talk is based on the reference [1], where the non-universal gauginos arising from SU(5) are considered.

In grand unified supersymmetric models, which include an SU(5) grand unified model, non-universal gaugino masses are generated by a nonsinglet chiral superfield \( \Phi^a \) that appears linearly in the gauge kinetic function \( f(\Phi) \) [2,3]. The function \( f(\Phi) \) is an analytic function of the chiral superfields \( \Phi \) in the theory. It should be noted that the chiral superfields \( \Phi \) consist of a set of gauge singlet superfields \( \Phi^a \) and gauge nonsinglet superfields \( \Phi^a \), respectively, under the grand unified group. If the auxiliary part \( F_\Phi \) of a chiral superfield \( \Phi \) in the \( f(\Phi) \) gets a vev, then gaugino masses arise from the coupling of \( f(\Phi) \) with the field strength superfield \( W^a \). The Lagrangian for the coupling of gauge kinetic function with the gauge field strength is written as

\[
L_{gk} = \int d^2 \theta f_{ab}(\Phi) W^a W^b + \text{h.c.}, \tag{1}
\]

where a and b are group indices [for example, \( a, b = 1,2, \ldots, 24 \) for SU(5)], and repeated indices are summed over. The gauge kinetic function \( f_{ab}(\Phi) \) is

\[
f_{ab}(\Phi) = f_0(\Phi^s) \delta_{ab} + \sum_n f_n(\Phi^s) \frac{\Phi^{a,b}}{M_P} + \cdots, \tag{2}
\]

where \( \Phi^s \) and \( \Phi^a \) are the singlet and nonsinglet chiral superfields, respectively. Here \( f_0(\Phi^s) \) and \( f_n(\Phi^s) \) are functions of gauge singlet superfields \( \Phi^s \), and \( M_P \) is some large scale. When \( F_\Phi \) gets a vev \( \langle F_\Phi \rangle \), the interaction (1) gives rise to gaugino masses:

\[
L_{gk} \supset \frac{\langle F_\Phi \rangle_{ab}}{M_P} \lambda^a \lambda^b + \text{h.c.}, \tag{3}
\]

where \( \lambda^a, \lambda^b \) are gaugino fields. The U(1), SU(2), and SU(3) gauginos are denoted by \( \lambda_1, \lambda_2, \) and \( \lambda_3 \), respectively.

Since the gauginos belong to the adjoint representation of the gauge group, in the case of SU(5) for example, \( \Phi \) and \( F_\Phi \) can belong to any of the following representations appearing in the symmetric product of the two 24 dimensional representations of SU(5):

\[
(24 \otimes 24)_{\text{Symm}} = 1 + 24 \oplus 75 \oplus 200. \tag{4}
\]

In the minimal case (which is the simplest one too), \( \Phi \) and \( F_\Phi \) are assumed to be in the singlet representation of SU(5). This corresponds to equal gaugino masses at the grand unified theory (GUT) scale. However, \( \Phi \) can belong to any of the nonsinglet representations 24, 75, and 200 of SU(5). In that case, the gaugino masses are unequal but related to one another via the representation invariants. It should be kept in mind that an arbitrary combination of these different representations is also allowed but we shall study the case of each representation separately. As we shall discuss later, the 24 dimensional representation is the most interesting one.
Table 1. Ratios of gaugino masses at the GUT scale in the normalization $M_2$(GUT) = 1 and at the electroweak scale in the normalization $M_3$(EW) = 1 at the one-loop level.

| $F_\phi$ | $M_1^2$ | $M_2^2$ | $M_3^2$ | $M_1^{2N}$ | $M_2^{2N}$ | $M_3^{2N}$ |
|---------|---------|---------|---------|-----------|-----------|-----------|
| 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         |

in the context of our present investigation. In Table 1 we display the ratios of resulting gaugino masses at tree level as they arise when $F_\phi$ belongs to various representations of SU(5). Clearly, the nonsinglet representations have characteristic mass relationships for the gauginos at the GUT scale. The resulting relations at the electroweak scale, using the renormalization group evolution at the one-loop level are also displayed.

The phenomenology of supersymmetric models depends crucially on the compositions of neutralinos and charginos. In addition to the laboratory studies, relevant input is obtained from the dark matter searches. The WMAP satellite has put precise limits on the relic density. Supersymmetric theories which preserve R-parity contain a natural candidate for the cold dark matter particle. If the lightest neutralino is the lightest supersymmetric particle (LSP), it can provide the appropriate relic density.

2 Dark matter in SU(5) representations

In many supergravity type models the lightest neutralino is bino-like, which often leads to too high thermal relic density, as compared to the limits provided by the WMAP experiment \cite{4}. The non-universal gaugino masses change this considerably. When the gaugino masses are not universal at the GUT scale, the resulting neutralino composition changes from the usual universal gaugino mass case \cite{5}.

2.1 Representation 1

In Fig. 1 the area of preferred thermal relic density in the representation 1 is plotted for a set of (GUT scale) parameters for the reference. For the chosen parameters the WMAP preferred regions are found near the $M_2$ (i.e. $m_{1/2}$ in universal gaugino mass language) and $m_0$ axes. The dark shaded areas represent larger relic density than the lighter areas. wmap denoted filling is the WMAP preferred region, lep shows an area, where the experimental mass limits are not met, rge shows an area where there is no radiative EWSB, and lsp the area where neutralino is not the LSP. For the relic density, we use here the WMAP combined three year limits \cite{4}.

\[
\Omega_{CDM}h^2 = 0.11054^{+0.00976}_{-0.00956} \quad (2\sigma).
\]

The area enclosed by the bsg contour is disallowed by $b \to s\gamma$ constraint. For the particle masses, the following limits are applied \cite{6}: $m_{\tilde{\tau}_R} > 99.4$ or 100.5 GeV depending if the lightest neutralino mass is below or above 40 GeV, $m_{\tilde{\mu}_R} > 95$ GeV, $m_{\tilde{\tau}_1} > 80.5$ to 88 GeV depending on the lightest neutralino mass (from 10 to 75 GeV), $m_{\nu_e} > 43$ GeV, and $m_{\chi_{\pm}} > 73.1$ to 103 GeV depending on the sneutrino masses (from 45 to 425 GeV). The curve $m_h = 114$ GeV is depicted in the figure (line denoted by $h$). For the shown parameter region, when otherwise experimentally allowed, Higgs is always heavier than 91 GeV, which is the Higgs mass limit in MSSM for $\tan \beta \geq 10$ assuming maximal top mixing \cite{7}. We have used the two sigma world average of $BR(b \to s\gamma) = (355 \pm 24^{+9}_{-10}) \times 10^{-6}$ for the branching fraction \cite{8}. The preferred relic density area is quite constrained, and often the neutralino relic density is overclosing the Universe.

2.2 Representation 24 – large relic density

The amount of thermal relic density in the representation 24 is presented in Fig. 2 for a set of GUT scale parameters. The most striking feature in Fig. 2 is the

\[
\Omega_{CDM}h^2 = 0.11054^{+0.00976}_{-0.00956} \quad (2\sigma).
\]

valley of the low relic density area around $M_2 \sim -300$
GeV. The minimum occurs at the Z peak providing an efficient annihilation of the neutralinos to quarks. Outside of the valley the relic density rises, overclosing the universe. In the representation 24 the lightest neutralino is very bino-like, and the WMAP preferred region tends to be quite narrow. Many values of $m_0$ are allowed, but only for specified $m_2$. The Higgs mass is always greater than 91 GeV for these parameters. Higgsino component can be increased by increasing tan$\beta$. This results in a larger higgsino component in the lightest neutralino, which then annihilates more efficiently.

2.3 Representation 75 – large higgsino component

In Fig. 3 the area of preferred thermal relic density in the representation 75 is plotted for one set of (GUT scale) parameters. Since the higgsino component in the representation 75 is large $^5$, the resulting relic density is low, and most of the parameter space is not overclosed by the WMAP limits. Also the co-annihilations with the lightest chargino reduces the relic density, since the lightest neutralino and chargino are nearly mass degenerate in the higher $M_2$ part of the parameter space. This is also seen in the Fig. 3 at high $m_0$, where the lightest chargino becomes the LSP for specific $M_2$ values. At the low $m_0$ region the LSP can be the lighter stop. In the low $M_2$ region the EWSB condition pushes the value of $\mu$ high, which in turn decreases the higgsino component in the lightest neutralino, making it mostly a bino. The lightest neutralino and chargino are not degenerate anymore, and the relic density increases in low $M_2$ area. This enables the emergence of the WMAP preferred region in the parameter space. The second lightest neutralino can annihilate also directly into gauge bosons in this parameter region. Again, increasing tan$\beta$ enhances the higgsino component leading to lower relic densities in general.

2.4 Note for representation 200

In the representation 200 the lightest neutralino and chargino are almost degenerate, so the co-annihilations reduce the relic density substantially. Also the Higgsino mixing is large, and, more importantly, bino component is very small. Therefore, the resulting relic density is tiny. In contrast to the 75 dimensional case, the value of the $\mu$ parameter decreases with decreasing $M_2$, so the bino component does not get very large. The parameter space suitable for finding partial neutralino dark matter can be extended both in $m_0$ and in $M_2$ beyond 1 TeV for both signs of $\mu$, but neutralino in this representation can never be the only source of dark matter.

It is also possible to have contributions from many representations simultaneously. In any point of the parameter space, WMAP limits can be reached by suitably combining representations. For an example, see [1].

3 Higgses from cascades

If the squarks and gluinos are light enough, their production cross sections are large at the LHC. The light neutralinos $\tilde{\chi}_{1,2}$ are typical decay products of $\tilde{g}$ and $\tilde{q}$. The neutral Higgs bosons can be produced in the decay of $\tilde{\chi}_2$, if the mass difference between $\tilde{X}_2$ and $\tilde{\chi}_1$ is large enough. As the production rate is largely independent on the value of tan$\beta$, these production channels have been found particularly interesting at the LHC to cover the difficult region of low and medium tan$\beta$ values $^9$.

A possible way to look for the Higgs bosons is through the cascade

$$pp \rightarrow \tilde{q}\tilde{q}/\tilde{q}\tilde{g}/\tilde{g}\tilde{g} \rightarrow \tilde{\chi}_2^0 + X$$

$$\rightarrow \tilde{\chi}_1^0 h/H/A + X \rightarrow \tilde{\chi}_1^0 b\bar{b} + X. \quad (6)$$

In Fig. 4 the cross section for the process $pp \rightarrow H + \tilde{\chi}_1^0 + X \rightarrow b\bar{b} + \tilde{\chi}_1^0 + X$ in the $(m_A, \tan\beta)$ (upper) and $(m_{\tilde{A}}, m_{3/2})$ (lower) planes for the heavier neutral Higgs scalar are plotted. The solid (green) fill denotes the WMAP preferred relic density region. Also the Higgs 114 GeV mass contour is plotted with the contours of constant cross section (larger $m_A$ values correspond to larger $m_h$). The values of the parameters are $\mu = +700$ GeV, $m_q = 600$ GeV, $m_{\tilde{g}} = 350$ GeV, and the trilinear coupling for the top sector is chosen to be $A_t = 800$ GeV. In the $(m_A, \tan\beta)$ plane the gluino mass is chosen as $m_{\tilde{g}} = 770$ GeV, and in the $(m_A, m_{3/2})$ plane tan$\beta = 10$. The choice of $m_{\tilde{g}} > m_q$ means that every gluino decays to a quark and the corresponding squark pair ($q\tilde{q}$).

For the three neutral scalar Higgses, the cross section is largest for the $H$ Higgs production. The stripe of WMAP preferred relic density passes through the large cross section area. For the $A$ production, the cross section is somewhat smaller, while for the $h$ pro-
production it is substantially smaller for the WMAP preferred area. In the \((m_A, \tan \beta)\) plane the near-horizontal WMAP stripe around \(\tan \beta = 8\) (beginning at \(m_A = 130\) GeV, \(\tan \beta = 13\)) corresponds to the closing of the Higgs resonance in the LSP annihilation: in the region below that line the lightest neutralino mass is more than half of the light Higgs boson mass. Therefore the annihilation never occurs at the resonance. Heavier \(A\) corresponds to the larger relic density. The relic density is lowest in between the two relic density stripes, the minimum occurring at the \(A\)-peak.

In the \((m_A, m_\tilde{g})\) plane the large \(H\) production cross section is again passed by the preferred relic density stripe. The Higgs 114 GeV limit divides the parameter space in two (vertical line in the lower plot of Fig. 4) it should be kept in mind, though, that for the tan \(\beta = 10\) used here the actual Higgs boson mass limit can be as low as around 90 GeV). Also here the relic density is the lowest in between the two relic density stripes. The horizontal kink in the relic density stripe around \(m_\tilde{g} \sim 770\) GeV corresponds to the closing of the Higgs resonance in the LSP annihilation: in contrast to the \((m_A, \tan \beta)\)-figure, the Higgs resonance is open below that line due to the decreasing of the lightest neutralino mass. The \(A\) production cross section is slightly smaller than for \(H\), while \(h\) production is the one with the lowest cross section. For comparison, representation \(1\) gives only the lightest Higgs channel.

4 Summary

We studied the dark matter allowed regions in the SU(5) GUT representations, of which all but the singlet lead to non-universal gaugino masses. The WMAP preferred relic density regions were quite distinct for different representations, which leads to a suggestion that combinations of different representations can give observed dark matter for otherwise experimentally allowed parameter values.

Production of the neutral Higgs bosons in the SUSY cascades with \(b\bar{b}\) decay modes was studied. In the \(24\) dimensional representation the main decay modes are to heavy Higgs bosons, whereas in the \(1\) dimensional representation only the lighter scalar channel is kinematically possible (with the parameter choice we have used). We especially concentrated on the representation \(24\), since there the Higgs signal from the neutralino decay is interesting and different from the usual universal singlet model. It is important to realize that there is no automatically theoretical preference for the gaugino masses to be unified.

This work was supported by the Academy of Finland (project 115032). The work of J.L. is partially supported by the Bundesministerium für Bildung und Forschung, Berlin-Bonn.

References

1. K. Huitu, R. Kinnunen, J. Laamanen, S. Lehti, S. Roy, and T. Salmiinen. Search for Higgs bosons in SUSY cascades in CMS and dark matter with non-universal gaugino masses. To appear, 2007.
2. J. R. Ellis, K. Enqvist, D. V. Nanopoulos, and K. Tamvakis. Gaugino masses and grand unification. Phys. Lett., B155:381, 1985.
3. M. Drees. Phenomenological consequences of N=1 supergravity theories with nonminimal kinetic energy terms for vector superfields. Phys. Lett., B158:409, 1985.
4. D. N. Spergel et al. Wilkinson microwave anisotropy probe (WMAP) three year results: Implications for cosmology. astro-ph/0603449, 2006.
5. K. Huitu, J. Laamanen, P. N. Pandita, and S. Roy. Phenomenology of non-universal gaugino masses in supersymmetric grand unified theories. Phys. Rev., D72:055013, 2005.
6. G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov. micrOMEGAs2.0: A program to calculate the relic density of dark matter in a generic model. Comput. Phys. Commun., 176:367–382, 2007.
7. LEP Higgs Working Group. Search for charged Higgs bosons: Preliminary combined results using LEP data collected at energies up to 209 GeV. hep-ex/0107031, 2001.
8. E. Barberio et al. Averages of b-hadron properties at the end of 2006. Heavy Flavor Averaging Group (HFAG), arXiv:0704.3575 [hep-ex], 2007.
9. A. Datta, A. Djouadi, M. Guchait, and F. Moortgat. Detection of MSSM Higgs bosons from supersymmetric particle cascade decays at the LHC. Nucl. Phys., B681:31–64, 2004.