

Dark Matter in the U(1) Extended SUSY

D. Jarecka¹, J. Kalinowski^{1*}, S.F. King² and J.P. Roberts¹

1- Physics Department, University of Warsaw
Hoza 69, 00-681 Warsaw, Poland

2- Department of Physics and Astronomy, University of Southampton
Highfield, Southampton, SO17 1BJ, United Kingdom

The neutralino sector of the U(1) extended SUSY is presented and some collider and cosmology-related phenomenology discussed.

1 Introduction

Supersymmetry (SUSY) has been considered to be the best candidate beyond the standard model (SM) from a viewpoint of both the hierarchy problem and the gauge coupling unification. Recent astrophysical observations showing the existence of a substantial amount of non-relativistic and non-baryonic dark matter seem to make SUSY even more promising. The lightest SUSY particle (LSP) of R-parity conserving models, in most cases the lightest neutralino, can serve as a good candidate for Dark Matter (DM).

The parameter space of the constrained MSSM, however, is strongly restricted by the requirement of matching the precise measurement of the DM relic density as measured by the WMAP. The MSSM also suffers from a naturalness problem (the so-called μ problem): why the dimensionful parameter μ of the supersymmetric Higgs mass term $\mu \hat{H}_1 \hat{H}_2$ has to be of EW scale. This problem can be solved in the next-to-MSSM (NMSSM) by promoting the μ parameter to a new singlet superfield S coupled to Higgs doublets, $\lambda \hat{S} \hat{H}_1 \hat{H}_2$ [1]. This triple-Higgs coupling term also helps to push up the mass of the lightest CP-even Higgs boson, relaxing the fine-tuning necessary to comply with the LEP bounds. Postulating an additional $U_X(1)$ gauge symmetry [2] avoids a massless axion, or domain wall problems of the NMSSM. Such a U(1)-extended MSSM (USSM) can be considered as an effective low-energy approximation of a more complete E_6 SSM model [3], with other E_6 SSM fields assumed heavy.

In addition to the MSSM superfields, the USSM contains a chiral superfield $\hat{S}$ and an Abelian gauge superfield B' . Thus the MSSM particle spectrum is extended by a new CP-even Higgs boson S , a gauge boson Z' and two neutral $\tilde{\text{inos}}$: a singlino $\tilde{S}$ and a bino' $\tilde{B}'$; other sectors are not enlarged. As a result the phenomenology of the neutralino sector can be significantly modified both at colliders [4] and in cosmology-related processes [5, 6]. To illustrate this we consider a physically interesting scenario with higgsino and gaugino mass parameters of the order $M_{\text{SUSY}} \sim \mathcal{O}(10^3 \text{ GeV})$, and we take the interaction between the singlino and the MSSM fields to be of the order of the EW scale, $v \sim \mathcal{O}(10^2 \text{ GeV})$.

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2 The neutralino sector of the USSM

We assume the MSSM gaugino unification relation $M_1 = (5/3) \tan^2 \theta_W M_2 \approx 0.5 M_2$ and unified couplings $g_X = g_Y$, but M'_1 will be taken as independent^a to investigate the impact of new states as a function of M'_1 . For the numerical values we take $M_2 = 1.5$ TeV, $\mu = \lambda v_s / \sqrt{2} = 0.3$ TeV, $m_s = g_X v_s = 1.2$ TeV, $\tan \beta = 5$, $M_A = 0.5$ TeV, neglect (small) $\tilde{B}-\tilde{B}'$ mixing, and adopt the E₆SSM assignment for the $U_X(1)$ charges [4].

Unlike the 4x4 MSSM case, the full 6x6 neutralino mass matrix cannot be diagonalised analytically. However, since the mixing between the new and MSSM states is small $\mathcal{O}(v)$ compared to M_{SUSY} , one can perform first the diagonalisation of the 4x4 MSSM and the 2x2 $\tilde{S}-\tilde{B}'$ submatrices separately. Then the perturbative expansion of the block-diagonalisation in v/M_{SUSY} provides an excellent approximation to masses and mixings [4].

The mass spectrum is shown in Fig.1 (left) as a function of M'_1 . For small M'_1 the eigenstates (denoted by numbers with primes) are almost pure MSSM $U(1)$ and $SU(2)$ gauginos $\tilde{\chi}_{1'}^0, \tilde{\chi}_{2'}^0$, MSSM higgsinos $\tilde{\chi}_{3'}^0, \tilde{\chi}_{4'}^0$, and maximally mixed $U_X(1)$ gaugino and singlino states, $\tilde{\chi}_{5'}^0, \tilde{\chi}_{6'}^0$. When M'_1 is shifted to higher values, the mass eigenvalues in the new sector move apart, generating strong cross-over patterns whenever a (signed) mass from the new block comes close to one of the (signed) MSSM masses. This happens at $M'_1 \approx 0.91$ TeV for $\tilde{\chi}_{6'}^0$, and $\tilde{\chi}_{2'}^0$ states, and at $M'_1 \approx 2.68$ TeV for $\tilde{\chi}_{4'}^0$ and $\tilde{\chi}_{5'}^0$. For higher M'_1 the $\tilde{\chi}_{5'}^0$ approaches the singlino state and becomes the LSP.

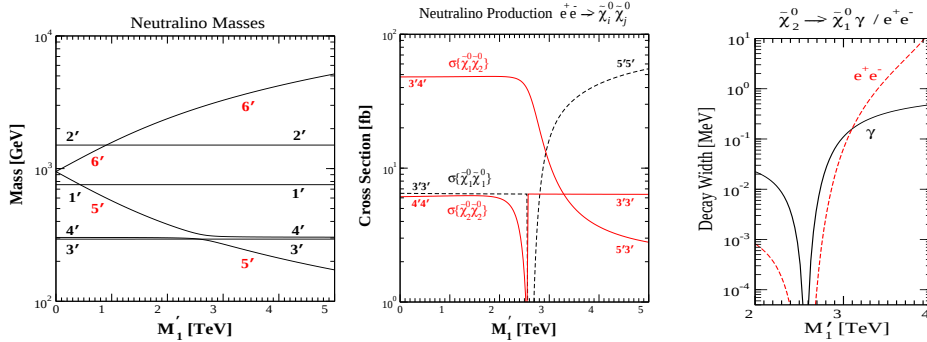


Figure 1: The M'_1 evolution of (left) neutralino masses, (center) production cross sections for $\tilde{\chi}_1^0 \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ pairs in e^+e^- collisions, and (right) partial decay widths of $\tilde{\chi}_2^0$ (from [4]).

At an e^+e^- collider the production processes $e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$ are generated by s -channel Z_1 and Z_2 exchanges (mass-eigenstates of Z and Z'), and t - and u -channel $\tilde{e}_{L,R}$ exchanges.^b In our scenario $M_{Z_2} = 949$ GeV, the ZZ' mixing angle $\theta_{ZZ'} = 3.3 \times 10^{-3}$, and $m_{\tilde{e}_{R,L}} = 701$ GeV. The M'_1 dependence of the production cross sections for the three pairings of the two lightest neutralinos, $\{11\}$, $\{12\}$ and $\{22\}$, is shown in Fig.1 (center) for $\sqrt{s} = 800$ GeV. For small M'_1 the presence of Z_2 has little influence on $\sigma\{\tilde{\chi}_1^0 \tilde{\chi}_2^0\}$ which is of similar size as in the MSSM for mixed higgsino pairs. However it significantly enhances diagonal higgsino pairs $\sigma\{\tilde{\chi}_1^0 \tilde{\chi}_1^0\}$ and $\sigma\{\tilde{\chi}_2^0 \tilde{\chi}_2^0\}$ compared with the MSSM, even though the light neutralino

^aFor a mechanism of generating non-universal $U(1)$ gaugino masses, see e.g. [7].

^bThe numbering without primes refers to mass eigenstates ordered according to ascending masses.

masses are nearly identical in the two models. At and beyond the cross-over with singlino, $M'_1 \approx 2.68$ TeV, dramatic changes set in for pairs involving the lightest neutralino.

At the LHC the neutralinos will be analyzed primarily in cascade decays of squarks or gluinos. In the USSM the cascade chains may be extended compared with the MSSM by an additional step due to the presence of two new neutralino states, for example, $\tilde{u}_R \rightarrow u\tilde{\chi}_6^0 \rightarrow uZ_1\tilde{\chi}_5^0 \rightarrow uZ_1\ell\tilde{\ell}_R \rightarrow uZ_1\ell\ell\tilde{\chi}_1^0$, with partial decay widths significantly modified by the singlino and bino' admixtures. Also the presence of additional Higgs boson will influence the decay chains. Moreover, in the cross-over zones the gaps between the masses of the eigenstates become very small suppressing standard decay channels and, as a result, enhancing radiative decays of neutralinos. These decays are particularly important in the cross-over at $M'_1 \simeq 2.6$, where the radiative modes $\tilde{\chi}_2^0, \tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 + \gamma, \tilde{\chi}_3^0 \rightarrow \tilde{\chi}_2^0 + \gamma$ become non-negligible, see Fig.1 (right). Since the photon will be very soft, these decays will be invisible making the decay chains apparently shorter.

3 USSM implications for dark matter

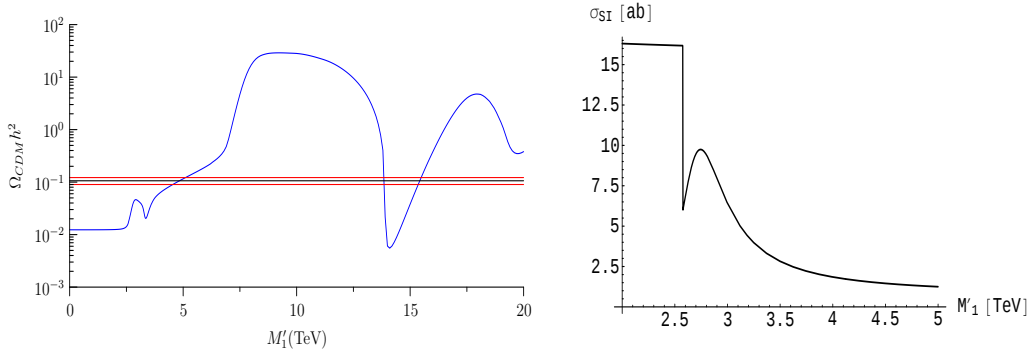


Figure 2: The M'_1 dependence of (left) the predicted relic density of DM, and (right) the elastic spin-independent LSP- ^{73}Ge cross section. We restrict the right hand plot to 5 TeV as there are no new features above this energy.

If the lightest neutralino (LSP) is expected to be the source of the relic abundance of dark matter in the universe, the predicted relic density depends on the LSP composition. In the left panel of Fig.2 it is shown as a function of M'_1 [6]. For small M'_1 the LSP is almost an MSSM higgsino and for a mass ~ 300 GeV the predicted value falls below the WMAP result. As M'_1 increases, the singlino admixture increases suppressing the LSP annihilation cross section and the predicted relic density increases. The singlino LSP predominantly annihilates via an off-shell s-channel singlet Higgs, which decays to two light Higgs bosons. As M'_1 increases, the LSP mass decreases and at $M'_1 \approx 3.3$ TeV it reaches $m_{\tilde{\chi}_1^0} \approx 250$ GeV making the resonant annihilation via the heavy Higgs boson efficient enough to lower the relic density. Further increase of M'_1 switches off the heavy Higgs resonance and eventually the WMAP value is met (shown as a horizontal band in Fig.2 (left) [6]). Around $M'_1 = 7.5$ TeV the LSP becomes lighter than the light Higgs. This switches off the annihilation via an off-shell singlet Higgs, $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h_1 h_1$, normally the dominant annihilation mode of a singlino

LSP. As a result the relic density rises sharply. Further increasing M'_1 decreases the LSP mass until it matches the resonant annihilation channels of the light Higgs (at around 14 TeV) and Z boson (at around 20 TeV). In both cases this results in a significant dip in the relic density.

The singlino nature of the LSP is also of importance for direct DM searches. It has a strong impact on the elastic spin-independent scattering off the nuclei, e.g. as shown in Fig.2 (right) [6] for the ^{73}Ge nucleus (the numerical codes have been developed in [8]). For small M'_1 the two lightest neutralinos (3' and 4' in Fig.1) are almost pure maximally mixed MSSM higgsinos. When M'_1 increases, the mixing with singlino lowers $m_{4'}$ so that at $M'_1 \approx 2.6$ TeV the state 4' becomes the LSP. Since the higgsino mixing angles are such that the elastic scattering of the state 4' is almost two orders of magnitude smaller than for the state 3', it explains a sudden drop seen in Fig.2 (right). At the same time the singlino and bino' admixture of the LSP increases, which explains a local maximum around 2.8 TeV. As the singlino component (the state 5') of the LSP becomes dominant for higher M'_1 values, the elastic cross section becomes smaller and smaller.

4 Summary

The U(1) extended MSSM provides an elegant way of solving the μ problem. As the neutralino sector is extended, the collider phenomenology can significantly be altered and new scenarios for matching the WMAP constraint can be realised. One example, in contrast to the NMSSM, is that the USSM contains regions in which predominantly singlino dark matter can fit the WMAP relic density measurement without the need for coannihilation, or resonant s-channel annihilation processes, where the LSP annihilates via $\tilde{S}\tilde{B}' \rightarrow S^* \rightarrow hh$.

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