Neutralinos of the U(1)-extended MSSM: from colliders to cosmology

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

1. Introduction

Recent astrophysical observations showing the existence of a substantial amount of non-relativistic and non-baryonic dark matter (DM) seem to make supersymmetric (SUSY) extension of the standard model 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 DM. On the other hand, the minimal extension (MSSM) 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. Moreover, current collider and DM data make the parameter space of the constrained MSSM strongly restricted. Both problems can be relaxed postulating an additional $\mathrm{U}_X(1)$ gauge symmetry [1]. Such a U(1)-extended MSSM (USSM) can be considered as an effective low-energy approximation of a more complete E_6SSM model [2], with other E_6SSM fields assumed heavy.

The USSM contains a chiral superfield $\hat{S}$ and an Abelian gauge superfield B' in addition to the MSSM superfields. Thus the MSSM particle spectrum is extended by a new CP-even Higgs boson S, a gauge bozon Z' and two neutral –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 [3] and in cosmology-related processes [4, 5]. To illustrate this we consider a physically interesting scenario with higgsino and gaugino mass parameters of the order $M_{\mathrm{SUSY}} \sim \mathcal{O}(10^3\ \mathrm{GeV})$ while the interaction between the new states and the MSSM fields is of the order of the EW scale, $v \sim \mathcal{O}(10^2\ \mathrm{GeV})$.

2. The neutralino sector of the USSM

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 [3].

Since the $\tilde{S}$ mass term is forbidden by the $\mathrm{U}_X(1)$ gauge symmetry and the $\tilde{S}$-$\tilde{B}'$ mixing term is controlled by the Z' mass (constrained to be of order 1 TeV), the 2x2 $\tilde{S}$-$\tilde{B}'$ mass matrix is of the see-saw type. With increasing $\tilde{B}'$ soft mass term M_1', one of the eigenstates of the 2x2 submatrix can become light and contribute significantly to the MSSM neutralinos, in particular the lightest one which can get a significant admixture of the singlino state. An interesting pattern of neutralino mixing is observed with M_1' taken to be independent[1]. For the numerical values we take the MSSM gaugino unification relation $M_1 = (5/3)\tan^2\theta_W M_2 \approx 0.5 M_2 = 0.75$ TeV, unified couplings $g_X = g_Y$, $\mu = \lambda v_s/\sqrt{2} = 0.3$ 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 E_6SSM assignment for the $\mathrm{U}_X(1)$ charges [3].

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 $\tilde{\chi}^0_{1'}, \tilde{\chi}^0_{2'}$, MSSM higgsinos $\tilde{\chi}^0_{3'}, \tilde{\chi}^0_{4'}$, and maximally mixed $\mathrm{U}_X(1)$ gaugino and singlino states, $\tilde{\chi}^0_{5'}, \tilde{\chi}^0_{6'}$. 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 $\tilde{\chi}^0_{6'}$ and $\tilde{\chi}^0_{2'}$ states, and at $M_1' \approx 2.68$ TeV for $\tilde{\chi}^0_{4'}$ and $\tilde{\chi}^0_{5'}$. For higher M_1' the $\tilde{\chi}^0_{5'}$ approaches the singlino state and becomes the LSP.

3. Collider phenomenology

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, $\tilde{u}_R \to u\tilde{\chi}^0_6 \to uZ_1\tilde{\chi}^0_5 \to uZ_1\ell\tilde{\ell}_R \to uZ_1\ell\ell\tilde{\chi}^0_1$, 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 $\tilde{\chi}^0_2, \tilde{\chi}^0_3 \to \tilde{\chi}^0_1 + \gamma, \tilde{\chi}^0_3 \to \tilde{\chi}^0_2 + \gamma$ become non-negligible. Since the decay photon will be very soft, these decays will be invisible making the decay chains apparently shorter. In addition there are significant changes to the production cross-sections at an e^+e^- collider compared with the MSSM [3].

4. USSM implications for dark matter

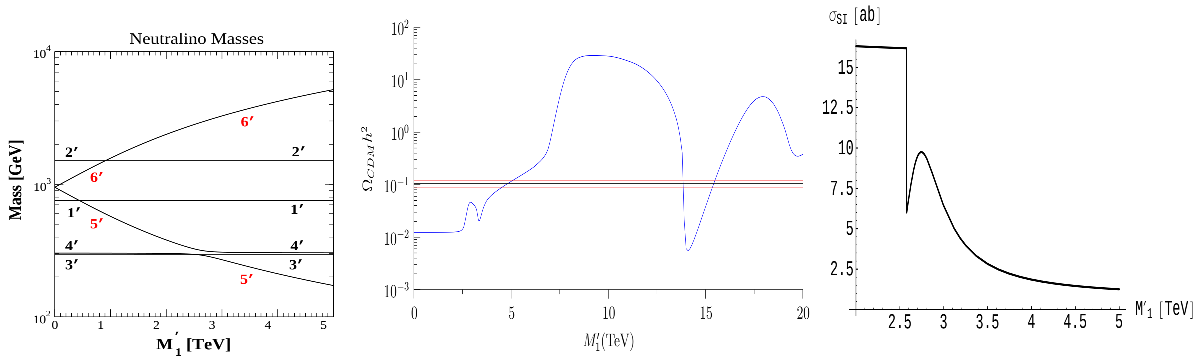

Figure 1. *The M_1' dependence of (left) the neutralino masses [3], (center) the predicted relic density of DM, and (right) the elastic spin-independent LSP-^{73}Ge cross section [5].*

[1] For a mechanism of generating non-universal U(1) gaugino masses, see e.g. [6].

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 Fig.1 (center) it is shown as a function of M_1' [5]. For small M_1' the LSP is almost a pure MSSM higgsino with $m_{\tilde{\chi}_1^0} \sim 300$ GeV and 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.1 (center) [5]). 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, $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_1 h_1$. 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.1 (right) [5] for the ^{73}Ge nucleus. 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.1 (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.

5. 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 be significantly 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 $\tilde{S}\tilde{B}' \to S^* \to hh$.

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