

Dark Matter in the USSM

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We discuss the neutralino dark matter within classes of extended supersymmetric models, referred to as the USSM, containing one additional SM singlet Higgs plus an extra Z^0 , together with their superpartners the singlino and bino'.

1 Introduction

Models with additional $U(1)$ gauge group provide an elegant solution to the problem of the minimal supersymmetric standard model (MSSM). The Higgs/Higgsino mass term $\hat{H}_1\hat{H}_2$ of the MSSM is replaced by $\hat{S}\hat{H}_1\hat{H}_2$ (with a dimensionless coupling λ), where the additional superfield \hat{S} is a singlet under the Standard Model (SM). The vacuum expectation value $\langle S \rangle$ then not only dynamically generates a SUSY Higgs/Higgsino mass near the weak scale as required but also results in an increased Higgs boson mass upper bound which in turn gives a welcome reduction in electroweak fine tuning. Moreover, by gauging the Abelian $U(1)_X$ symmetry arising from the $\hat{S}\hat{H}_1\hat{H}_2$ term the troublesome axion is avoided via the Higgs mechanism resulting in a massive Z^0 gauge boson [1]. The essential additional elements of such a scenario then consist of two extra superfields relative to those of the MSSM, namely the singlet superfield \hat{S} and the $U(1)_X$ gauge superfield B^0 . The USSM is then defined as a model with the MSSM superfields plus these two additional superfields at the TeV scale. Since it does not include other superfields necessary for cancellation of the fermionic $U(1)_X$ gauge anomalies, it has to be considered as a truncation of a complete model. For example, identifying the Abelian gauge group as a subgroup of E_6 with complete 27 dimensional representations of matter down to the TeV scale solves the anomaly problem, while requiring further the right-handed neutrinos to be singlets under $U(1)_X$ (for a see-saw mechanism) defines the theory uniquely as the E_6 SSM [2].

For the USSM we adopt the charge assignment under the extra $U(1)_X$ as in the E_6 SSM and study the physics and cosmology in this simplified setting to learn about crucial features which will be relevant to any complete model involving an additional $U(1)_X$ gauge group and a singlet. This talk, which updates the preliminary results presented previously [3], is based on the recent comprehensive analysis of neutralino dark matter in the USSM in [4], where full details (and an extensive list of references) can be found.

2 The USSM model

Compared to the MSSM the particle spectrum is extended by a new CP-even Higgs boson S , a gauge boson Z^0 and two neutralinos: a singlino \tilde{S} and a bino' \tilde{B}^0 . Other sectors are not enlarged but the sfermion scalar potential receives additional D-terms.

With two additional degrees of freedom the neutralino sector cannot be solved analytically any more. However, since the original MSSM and the new degrees of freedom are coupled weakly, an approximate analytical solution can be found following a two-step diagonalization procedure [5]. First – the 4×4 MSSM and the new 2×2 singlino-bino' sectors are separately diagonalised; second – a block-diagonalization provides approximate solutions. Since $U(1)_X$ forbids the singlino mass term (in contrast to the NMSSM) the mini-see-saw structure of the singlino-bino' mass matrix implies a singlino-dominated lightest neutralino in the limit of large bino' mass. Figure 1 shows the neutralino mass spectrum as a function of the soft bino' mass parameter M_1^0 in a GUT-scale unifying scenario $M_1^0 = M_1 = M_2 = 2$, where $M_1; M_2$ are the $U(1); SU(2)$ mass parameters respectively; $\tan \beta = 5$, other parameters are chosen so that the effective $\mu = 600$ GeV, the heavy $M_{Z_2} = 950$ GeV, and the pseudoscalar Higgs mass $m_A = 500$ GeV.

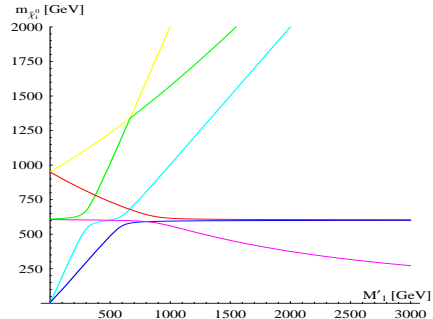


Figure 1: Neutralino mass spectrum.

3 Results

The presence of new singlino and bino' states greatly modifies the phenomenology of the neutralino sector both at colliders and in cosmology-related processes. It is informative to consider the general form of the interactions that arise from the singlino and bino' components of the lightest neutralino before presenting our numerical results.

The interactions of the bino' component, which is always subdominant due to the see-saw structure of the neutralino mass matrix, closely mirror those of the bino component, except for the different coupling constant and charges under the new $U(1)_X$. On the other hand, the $\hat{S}\hat{H}_u\hat{H}_d$ term in the superpotential gives rise to a new type of neutralino coupling: the lightest neutralino with significant singlino and higgsino components will couple strongly to Higgs bosons with a significant H_u or H_d component, usually the lighter Higgs bosons, $H_{1,2}$ and A in the spectrum. Moreover, the absence of the singlet cubic term S^3 , in contrast to the NMSSM, implies that the singlino-dominated LSP needs an admixture of MSSM higgsinos to annihilate through s-channel Higgs bosons. Since the singlino component does not interact with the $SU(2)$ or $U(1)_Y$ gauginos or with fermions, a significant singlino component in the lightest neutralino will suppress couplings to W or Z_1 bosons and to fermions.

3.1 Relic density

The differences between the MSSM relic density calculation and the USSM calculation arise through the extension of the particle spectrum and through the new interactions that are introduced. We have implemented all new interactions into the micrOMEGAs [6] code which takes full account of all annihilation and coannihilation processes and calculates their effect whenever they are relevant.

Figure 2 shows the relic density as a function of M_1^0 . Ignoring initially the resonance effects, a general trend in the relic density from a large value at low M_1^0 , down to a lower value at around $M_1^0 = 0.75$ TeV and then back to larger values at high M_1^0 is easily understood as this follows the evolution of the LSP from bino through higgsino to singlino, see Figure 1.

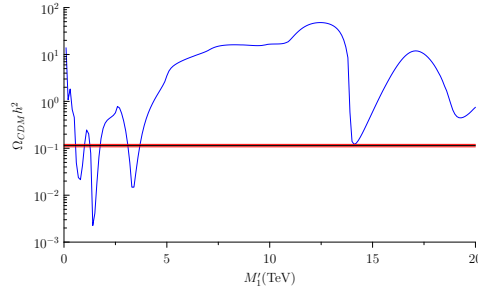


Figure 2: The relic density across varying M_1^0

Beyond this general behavior there are interesting resonance structures as the LSP mass first increases with the M_1^0 increase reaching a maximum of 560 GeV at M_1^0

800 GeV and then falls down crossing all possible s-channel resonances twice. Starting from $M_1^0 = 0$ we first arrive at a little dip in the relic density around $M_1^0 = 250$ GeV due to the s-channel $H_2=A$ resonance, and a little wiggle around $M_1^0 = 500$ GeV due to $Z_2=H_3$ as the LSP has not yet developed an appreciable singlino component. The first appreciable dip in the relic density occurs around $M_1^0 = 0.8$ TeV where $\Omega_{CDM} h^2$ drops to 0.02. Here the LSP has a strong higgsino component which enhances the annihilation via the s-channel $Z_2=H_3$ resonances considerably. Increasing M_1^0 further, the LSP mass increases, going over resonance (hence local maximum in the relic density), until it reaches its maximum of 590 GeV at $M_1^0 = 800$ GeV. From now on the LSP mass decreases and its nature becomes singlino-dominated. Around $M_1^0 = 1.5$ TeV it once again hits the $Z_2=H_3$ resonance. However, this time the LSP is predominantly singlino. Although pure singlino neutralinos do not couple to the singlet Higgs, so the H_3 resonance is subdominant, they couple strongly to the Z^0 and annihilate very efficiently. As a result, the relic density drops to 2×10^{-3} . The kink at $M_1^0 = 2.5$ TeV develops as the LSP mass drops below threshold for production of H_{1A} in the final state. Increasing M_1^0 further we find a pseudoscalar Higgs resonance at $M_1^0 = 3.5$ TeV, the top threshold at $M_1^0 = 5$ TeV, the light Higgs threshold at $M_1^0 = 11$ TeV, the light Higgs resonance at $M_1^0 = 14$ TeV and the Z resonance at $M_1^0 = 19$ TeV.

3.2 Direct detection

Compared to the MSSM, the spin-dependent elastic scattering receives an additional contribution due to a heavy Z_2 gauge boson, while the spin-independent one gets contributions from additional Higgs as well as from interactions generated by the $g_1^0 B^0 (H_i H_i + S S)$ and $H_i (S H_j + H_j S)$ couplings. In Figure 3 the spin-independent as well as spin-dependent elastic cross section of the lightest neutralino on the proton is shown as a function of M_1^0 (restricted to 0-3 TeV, as beyond this range cross sections fall monotonically). Referring to Fig. 1, it is easy to understand the M_1^0 behavior of the cross section. For M_1^0 below 800 GeV, the LSP is mostly a mixture of the MSSM states. It starts as a bino and as M_1^0 approaches 500 GeV, it receives an appreciable admixture of both higgsinos. As a result both σ_{SD} and σ_{SI} first rise and then fall. The fall is due to the diminishing bino component, which reduces the Higgs contribution to σ_{SI} , and increases the cancellation in $c_{34} = \tilde{N}_{13} \tilde{N}_{14}^2$, that controls the Z contribution to σ_{SD} . At $M_1^0 = 800$ GeV the discontinuities reflect crossing of two lightest states since the mixing with singlino forces the second-lightest state to become the lightest. At this point σ_{SI} drops by a factor 3. As the singlino component of the

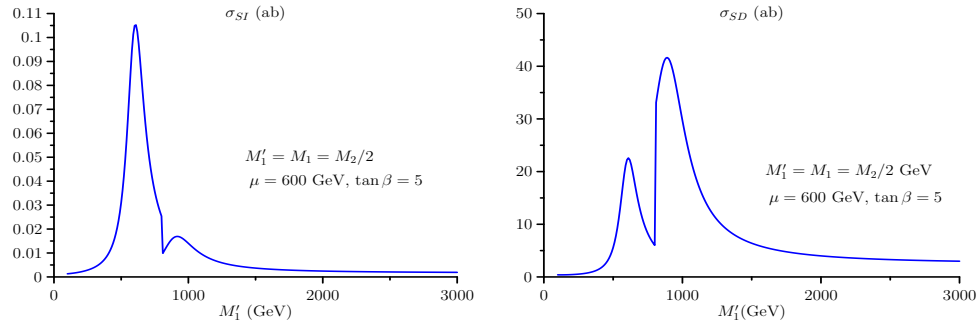


Figure 3: The elastic spin-independent (left) and spin-dependent (right) LSP-proton cross section as a function of M_1^0

LSP increases with M_1^0 the $H_{i1}SH_j$ term becomes responsible for the little rise of the cross section. On the other hand, σ_{SD} jumps by a factor 6 at the discontinuity since the mixing with singlino upsets the cancellation in c_{34} . With further increase of M_1^0 the LSP becomes almost a pure singlino which explains a steady fall of both cross sections.

4 Summary

The USSM, despite its modest additional particle content compared to the MSSM or NMSSM, leads to a surprisingly rich and interesting dark matter phenomenology which distinguishes it from these models. There are many cases where successful relic abundances may be reached, either through a proper balance of the singlino/higgsino mixture, or through a balance of the singlino mass against the mass of a boson that mediates annihilation in the s-channel. The difference in the Higgs spectrum and the singlino interactions results in significant differences in the direct detection predictions as well.

Acknowledgments

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