Properties of the Lightest Neutralino in MSSM Extensions

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Abstract. We study neutralino sectors in extensions of the MSSM that dynamically generate the $\mu$-term. The extra neutralino states are superpartners of the Higgs singlets and/or additional gauge bosons. The extended models may have distinct lightest neutralino properties which can have important influences on their phenomenology. We consider constraints on the lightest neutralino from LEP, Tevatron, and $(g-2)_\mu$ measurements and the relic density of the dark matter. The lightest neutralino can be extremely light and/or dominated by its singlino component, which does not couple directly to SM particles except Higgs doublets.

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INTRODUCTION

Extensive studies of the Minimal version of the Supersymmetric SM (MSSM) show that its lightest neutralino has the right ranges of mass and interaction strength to be a good cold dark matter (CDM) candidate [2]. Although the MSSM may be the optimal low energy Supersymmetric model with minimal extension of the fields and symmetry, the model may not fully describe the TeV scale physics. It is important to see if other versions of the Supersymmetric SM can also give acceptable CDM.

We consider various extended MSSM models that resolve the $\mu$-problem [3] and compare their lightest neutralino properties to that of the MSSM. In these beyond-MSSM models, at least one Higgs singlet is commonly present and generates an effective $\mu$ parameter when the associated symmetry is broken at the EW or TeV scale. Because of the superpartners of the Higgs singlets or the extra gauge boson, the neutralino sector in these models may be significantly different from that of the MSSM. We investigate the mass and the coupling of the lightest neutralino of each model allowed by the model parameters and the experimental data.

MODELS

The extended MSSM models that we consider are the Next-to-Minimal Supersymmetric SM (NMSSM) [4], the Minimal Non-minimal Supersymmetric SM (MNSSM) a.k.a. the nearly Minimal Supersymmetric SM (nMSSM) [5], the $U(1)'$-extended Minimal Supersymmetric SM (UMSSM) [6], and the $U(1)'$-extended Supersymmetric SM with a secluded $U(1)'$-breaking sector (S-model) [7]. All of these extended models prevent the $\mu$-term ($\mu H_1 H_2$) and allow an effective $\mu$-term ($SH_1 H_2$) through a vacuum expectation value (VEV) $\langle S \rangle$ of a Higgs singlet associated with a new symmetry.

The NMSSM assumes a discrete symmetry $Z_3$ to avoid the $\mu$-term, but allows an $S^3$ term in the superpotential. The NMSSM is one of the simplest extensions of the MSSM, but the $Z_3$ symmetry predicts domain walls which are not observed [8]. The nMSSM was devised to avoid the domain wall problem while maintaining a discrete symmetry. The term $\alpha S$ in the nMSSM is a loop-generated tadpole term that breaks the discrete symmetry. The UMSSM uses an Abelian gauge symmetry instead of a discrete symmetry and thus is free from the domain wall problem. The new gauge symmetry introduces a new gauge boson $Z'$. The S-model was introduced to resolve tension between the EW scale $\mu_{\text{eff}}$ and the heavy $Z'$ (up to multi-TeV scale). It is basically the extension of the UMSSM with 3 additional Higgs singlets to provide additional contributions to the $Z'$ mass while keeping $\mu_{\text{eff}} = h_s \langle S \rangle$ at the EW scale.

The models are listed in Table 1 with adopted symmetries, superpotentials of Higgses, and the Higgs and neutralinos. The other parts of the superpotentials are the Yukawa terms of the MSSM and possible extra terms related to the exotic chiral fields in the $U(1)'$ models needed to cancel anomalies. In the $U(1)'$-extended model, the addition of one Higgs singlet does not give an additional CP odd Higgs since a goldstone boson is absorbed to the longitudinal mode of the massive $U(1)'$ gauge boson, $Z'$.

For easy comparisons, we use the common notation of

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1 Proceedings for PASCOS 2005 (Gyeongju, Korea) talk given by H.S. Lee. For a full paper by the authors, see Ref. [1]
$h_\mu$ for the coefficient of the $SH_1H_2$ term in each model. In every model the dynamically generated effective $\mu$ parameter is given by

$$\mu_{\text{eff}} = h_\mu \langle S \rangle$$

and therefore the VEV of the Higgs singlet or the symmetry breaking scale needs to be at the EW/TeV scale.

### NEUTRALINO MASS MATRICES

With the superpartners of the Higgs singlet ($S$) and the $U(1)'$ gauge boson ($Z'$), the UMSSM has 6 neutralinos (MSSM components + $S + Z'$) and its mass matrix ($M_{\chi^0}$) in the basis of $\{\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S}, \tilde{Z}'\}$ is given by

$$
\begin{pmatrix}
M_1 & 0 & -g_{15}v_1 & g_{15}v_1 & 0 & 0 \\
0 & M_2 & g_{21}v_2 & -g_{21}v_2 & 0 & 0 \\
-g_{15}v_2 & g_{21}v_2 & 0 & -\mu_{\text{eff}} & \mu_{\text{eff}} & \xi_{H_1v_1} \\
g_{15}v_2 & -g_{21}v_2 & -\mu_{\text{eff}} & 0 & -\mu_{\text{eff}} & \xi_{H_2v_2} \\
0 & 0 & -\mu_{\text{eff}} & \mu_{\text{eff}} & 0 & \xi_{S^0} \\
0 & 0 & 0 & 0 & 0 & M_{\chi^0}'
\end{pmatrix}
$$

where $\xi_{\phi} = g_{\phi}Q_\phi$, $\langle S \rangle = \frac{\tilde{S}}{\sqrt{2}}$, and $\langle H_0^0 \rangle = \frac{\tilde{H}_0^0}{\sqrt{2}}$ with $\sqrt{v_1^2 + v_2^2} = v \approx 246$ GeV. The gauge couplings are $g_1 = e/cos\theta_W$ and $g_2 = e/sin\theta_W$. For the $U(1)'$ gauge coupling constant $g_{Z'}$ and the $U(1)'$ charge $Q'$, we use the Grand Unification Theory (GUT) motivated gauge coupling and the $U(1)'$ model charge assignments in our numerical analysis [1]. The $U(1)'$ charges should satisfy

$$Q_{H_1} + Q_{H_2} \neq 0 \quad Q_{H_1} + Q_{H_2} + Q_S = 0$$

in order to replace the $\mu$-term with the effective $\mu$-term dynamically generated by the Higgs singlet $S$.

The first $5 \times 5$ submatrix corresponds to the nMSSM limit (or NMSSM limit in the special case $\kappa = 0$) that can be obtained by taking $M_{\chi^0} \gg \mathcal{O}$(EW). With a $(5,5)$ entry of $\sqrt{2}k_S$ from $S^0$ term in the superpotential, this would be the NMSSM limit.

The first $4 \times 4$ submatrix corresponds to the MSSM limit, which can be obtained by taking $s \gg \mathcal{O}$(EW) on top of the nMSSM limit.

The S-model has 9 neutralinos (UMSSM components + $\tilde{S}_1, \tilde{S}_2, \tilde{S}_3$), and its mass matrix has 3 more columns/rows added to UMSSM neutralino mass matrix. The UMSSM limit can be realized by taking $s_{1,2,3} \gg \mathcal{O}$(EW) with $k_S$ comparable to gauge couplings. However, the most realistic case is for small $\kappa$ and large $s_{1,2,3}$ [7], in which case four of the neutralinos, consisting almost entirely of $\tilde{Z}', \tilde{S}_1, \tilde{S}_2$, and $\tilde{S}_3$, essentially decouple from the other states. Since the full $9 \times 9$ matrix has a number of free parameters, we consider only this decoupling limit when we discuss the light neutralinos, where there are 5 neutralinos with masses and compositions the same as the nMSSM².

### DIRECT CONSTRAINTS

The diagonalization of the neutralino mass matrix is accomplished via a unitary matrix $N$ as

$$N^T M_{\chi^0} N = \text{Diag}(M_{\chi_1^0}, M_{\chi_2^0}, \cdots)$$

The singlino ($\tilde{S}$) composition of the lightest neutralino ($\chi_1^0$) is $|N_{15}|^2$. Here we evaluate the bounds on the lightest neutralino mass ($M_{\chi_1^0}$) and the singlino component ($|N_{15}|^2$) in the MSSM, the NMSSM, the nMSSM (also the decoupling limit of the S-model), and the UMSSM with gaugino mass unification.

We require that the tree-level masses satisfy the direct LEP limits of $M_{\chi_1^0} > 104$ GeV, and $\Gamma_{Z'\rightarrow\chi_1^0\chi_1^0} < 2.3$ MeV (95% C.L.). Bounds from naturalness and perturbativity constraints [7, 10, 11] are also imposed on the couplings of $0.1 \leq h \leq 0.75$ and $\sqrt{h^2 + \kappa^2} \leq 0.75$ (for the NMSSM³). The LEP2 Higgs mass bound of $m_h > 114$ GeV does not apply directly to the extended MSSM mod-

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² The four decoupled neutralinos typically consist of one heavy pair involving the $Z'$ and one linear combination of $S_1, S_2, S_3$ as well as two more states associated with the orthogonal combinations of $S_1, S_2, S_3$. The latter can be light, or even be the lightest neutralino in limiting cases. We do not consider that possibility here.

³ An exact $h_\mu$ bound (and its source) may be a little different depending on models, but we assume a common bound for easy comparison. A lower bound on the NMSSM $|\kappa|$ is fuzzy except that $\kappa \neq 0$ should be satisfied to avoid an unacceptable Peccei-Quinn symmetry. We set $|\kappa| > 0.1$ as a lower bound; results for a smaller $|\kappa|$ can be described by an interpolation of the nMSSM result ($\kappa \rightarrow 0$ limit).
and singlets \[12\]. Where the physical Higgses exist as mixtures of doublets and singlets, we exclude very small VEVs are real and positive. These results are only for positive gaugino masses, but negative gaugino masses do not change these ranges significantly. The mass bound dependence on \(\tan \beta\) is quite sensitive in some models. For example, at \(\tan \beta \approx 1\), the NMSSM and the UMSSM have massless \(\chi_1^0\) while the nMSSM has an upper \(M_{\chi_1^0}\) bound \([1]\); the MSSM violates the LEP2 \(m_h\) constraint at this \(\tan \beta\). The condition for the massless (or very light) neutralinos can be easily satisfied in extended MSSM models without the fine-tuning which is required for the MSSM case \([1]\).

Figure 1(a) shows the \(M_{\chi_1^0}\) dependence on the singlino composition of \(\chi_1^0\), \(|N_{15}|^2\) (and also the \(Z'\)-ino composition \(|N_{16}|^2\) for the UMSSM). The dashed lines are the MSSM bounds. Singlino dominance is typical in the \(\chi_1^0\) of the extended MSSM models. Especially, when \(M_{\chi_1^0}\) is much smaller than the MSSM lower limit\(^6\), \((M_{\chi_1^0} \sim 50\text{ GeV})\), the singlino is always the dominant component.

\(^5\) With \(M_2 = -50 \sim -500\text{ GeV}\), the \(\chi_1^0\) mass ranges are \(M_{\chi_1^0} = 39 \sim 254\text{ GeV (MSSM)}, M_{\chi_1^0} = 0 \sim 254\text{ GeV (NMSSM)}, M_{\chi_1^0} = 0.4 \sim 96\text{ GeV (nMSSM)}, M_{\chi_1^0} = 39 \sim 254\text{ GeV (UMSSM)}\).

\(^6\) The relaxation of the gaugino mass unification requirement would allow the MSSM also to have a very light (bino-dominated) neutralino. For the supernova constraint in this case, see Ref. [13].

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**FIGURE 1.** (a) Scatter plot of the \(\chi_1^0\) singlino composition \(|N_{15}|^2\) versus \(M_{\chi_1^0}\) mass \((M_{\chi_1^0})\) for various models. The crosses represent the \(Z'\)-ino composition \(|N_{16}|^2\) for the UMSSM. The direct constraints are imposed. The upper (lower) UMSSM singlino band corresponds approximately to moderate (large) value of \(s\), with the lightest neutralino being MSSM-like for large \(s\). (b) The allowed mass range of \(\chi_1^0\) after applying direct constraints (model parameters, gaugino mass unification \(M_{\chi} = M_1 \simeq 0.5M_2\), \(M_{\chi}^\prime\), \(\Delta \chi Z'\) and indirect constraints \((g-2)_\mu, \Omega h^2, M_{\chi}^\prime,\text{ domain wall})\). The \(M_{\chi^0}\) bounds in the nMSSM are intended to be illustrative and are not necessarily quantitatively precise.

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4 We exclude very small \(M_2\) or \(\mu\) to avoid very light non-singlino states. These are also excluded by the chargino mass constraints.
DISCUSSION

In the nMSSM (also in the S-model in the decoupling limit), because of the small $\chi'^0_1$ mass, the Z pole is the dominant channel [11, 14]. To obtain an acceptable relic density with only the Z pole annihilation contribution, the lower $M_{\chi'^0_1}$ bound is $M_{\chi'^0_1} \gtrsim 30$ GeV which is allowed for only small tan$\beta$, while the solution for a $2\sigma$ deviation from the SM of $(g-2)_\mu$ favors large tan$\beta$, which allows only small $M_{\chi'^0_1}$. Nonetheless, a common solution was found to exist in this model [15]. We refer to Ref. [16] for the interesting physics associated with the light pseudoscalar Higgs boson including an alternative relic density annihilation channel.

The NMSSM is disfavored by the non-observation of cosmological domain walls predicted by the discrete symmetries of the model. However, there is an approach to interpret the domain wall as the dark energy [17]. Although Supersymmetry at the TeV scale is well-motivated, the MSSM is just one of the possible realizations. In fact, the $\mu$-problem suggests that the MSSM is incomplete. The solution to the $\mu$-problem suggests that an appropriate direction to extend the MSSM is to have an extra Higgs singlet whose VEV gives the effective $\mu$-term of the EW scale. Extensions of the MSSM have extra neutralinos, and the composition of the lightest neutralino involves extra components beyond those of the MSSM. Because of this, both the mass and couplings of the lightest neutralino are modified from the MSSM. The lightest neutralino ($\chi'^0_1$) is interesting both in particle physics (as the LSP) and cosmology (as the CDM), and it is therefore important to study and compare properties of the $\chi'^0_1$ in extended MSSM models.

The properties of the CDM particle, even if it is the lightest neutralino, may be quite different from the MSSM prediction. For instance, it could be extremely light and/or dominated by the singlino, which does not directly couple to SM particles except Higgs doublets. Similar distinctions of models may occur in the Higgs sector. Even if a low energy Supersymmetry is correct, its realization may depend on the model. The measurement of the mass of the lightest neutralino and the determination of its couplings will be particularly useful in testing the MSSM and its extensions at colliders [18].

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