# Dark matter in the MSSM and its singlet extension (postprint)

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## Abstract

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## Full Text

## Preamble

**Dark Matter in the MSSM and Its Singlet Extension**

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## Abstract

We briefly review the supersymmetric explanation for cosmic dark matter. Although the neutralino in the minimal supersymmetric model (MSSM), the next-to-minimal supersymmetric model (NMSSM), and the nearly minimal supersymmetric model (nMSSM) can naturally explain the dark matter relic density, the PAMELA result can hardly be explained in these popular models.

In the general singlet extension of the MSSM, both the PAMELA result and the relic density can be explained by the singlino-like neutralino. Such singlino-like neutralinos annihilate into singlet-like Higgs bosons, which are light enough to decay dominantly to muons or electrons, and the annihilation cross section can be greatly enhanced by the Sommerfeld effect via exchange of a light CP-even singlet-like Higgs boson. In this scenario, in order to meet the stringent LEP constraints, the SM-like Higgs boson tends to decay into singlet Higgs pairs instead of $b\bar{b}$ and consequently will give a multi-muon signal $h_{SM} \to aa \to 4\mu$ or $h_{SM} \to hh \to 4a \to 8\mu$ at the LHC.

## Introduction

The cosmic dark matter relic density measured by WMAP [?], $0.0945 < \Omega h^2 < 0.1287$, can be naturally explained by the thermal production of WIMPs (weakly interacting massive particles). The neutralino (assumed to be the lightest supersymmetric particle) in the minimal supersymmetric model (MSSM) is a good candidate for a WIMP. Indeed, the two events recently reported by CDMSII [?] can also be naturally explained by such a WIMP [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. Thus both the relic density measured by WMAP and the two events observed by CDMSII can be perfectly explained by the neutralino in the MSSM.

However, the excess of cosmic ray positrons in the energy range 10–100 GeV observed by PAMELA [?] is difficult to explain by the neutralino in the popular MSSM. To explain the PAMELA excess through WIMP annihilation, the WIMP must annihilate dominantly into leptons since PAMELA has observed no excess of antiprotons [?] (though this conclusion may not be robust due to significant astrophysical uncertainties associated with their propagation [?]). Meanwhile, the WIMP annihilation rate must be greatly enhanced (for instance, by the Sommerfeld effect of a new force [?]) relative to the rate required by the relic density if dark matter was produced thermally in the early universe. These two requirements cannot be satisfied in the MSSM because there is no new force in the neutralino dark matter sector to induce Sommerfeld enhancement, and the neutralino dark matter annihilates primarily into final states consisting of heavy quarks or gauge and/or Higgs bosons [?, ?, ?, ?, ?] (so if it predicts a positron excess, it must simultaneously produce an antiproton excess).

It should be noted that if supersymmetry is realized in nature, the MSSM may not be the most favored model. Indeed, since the MSSM suffers from the mu-problem and the little hierarchy problem, some non-minimal supersymmetric models may be equally or better motivated. Among these, the most intensively studied are extensions of the MSSM by introducing a singlet Higgs superfield. If we do not impose any discrete symmetry to forbid some terms in the superpotential, the model is the general singlet extension of the MSSM. If we impose a discrete symmetry, we obtain specific singlet extensions such as the next-to-minimal supersymmetric standard model (NMSSM) [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?] and the nearly minimal supersymmetric standard model (nMSSM) [?, ?, ?, ?, ?, ?, ?, ?, ?]. As shown by recent studies [?, ?], the nMSSM and NMSSM are unlikely to explain the PAMELA result due to the tight parameter space constrained by various current experiments, while the general singlet extension of the MSSM can do so perfectly. In the general singlet extension of the MSSM, the singlino-like neutralino (the lightest supersymmetric particle) serves as dark matter, annihilating into light singlet-like Higgs bosons. Since the interaction between the singlino-like neutralino and singlet-like Higgs bosons is not suppressed and is typically of weak strength, the relic density can be naturally obtained just as in the MSSM. At the same time, the singlet-like Higgs bosons, which are not strongly coupled to electroweak symmetry breaking, can be light enough to be kinematically allowed to decay dominantly into muons or electrons. The Sommerfeld enhancement needed to explain the PAMELA result can be induced by exchange of the light CP-even singlet-like Higgs boson.

In this review, we recapitulate recent studies on the dark matter explanation in supersymmetric models. In Sec. II we discuss the MSSM. In Sec. III we discuss the NMSSM and nMSSM. In Sec. IV we focus on the general singlet extension of the MSSM. Finally, a summary is given in Sec. V.

## II. Neutralino Dark Matter in the MSSM

The MSSM is the most economical realization of supersymmetry, with minimal particle content. Among the four neutralinos (mixtures of neutral gauginos and neutral Higgsinos), the lightest is usually assumed to be the lightest supersymmetric particle (LSP). Under the assumption of R-parity conservation, the neutralino LSP is stable. Since it has weak interactions and its mass is around the weak scale, it is a perfect WIMP. The neutralino LSP mainly annihilates into final states consisting of heavy quarks or gauge and/or Higgs bosons, as shown in Fig. 1.

With current experimental constraints from precision electroweak measurements, direct searches for sparticles and Higgs bosons, stability of the Higgs potential, and the muon $g-2$ measurement, a scan over the parameter space (see the last reference in [**?**]) found that a large portion of the parameter space can yield the required dark matter relic density. When we project the allowed parameter space onto the plane of $\tan\beta$ versus $\mu$, the result is shown in Fig. 2. In constrained versions of the MSSM such as mSUGRA, the parameter space allowed by the dark matter relic density requirement is usually displayed in the plane of $m_0$ versus $m_{1/2}$, showing that several regions can give the required dark matter relic density [**?**].

[Figure 1: see original paper] Feynman diagrams of the main annihilation channels of the neutralino LSP in the MSSM.

[Figure 2: see original paper] The shaded regions are allowed by the cosmic dark matter relic density at $2\sigma$ level plus other experimental constraints in the MSSM, taken from the last reference in [**?**].

Although both the neutralino LSP in the MSSM and constrained MSSM can naturally explain the dark matter relic density, the PAMELA result cannot be explained. As shown in Fig. 1, the annihilation final states consist of heavy quarks or gauge bosons, and therefore if the model predicts a positron excess, it must simultaneously lead to an antiproton excess. Furthermore, there exist no light scalar or gauge bosons to induce Sommerfeld enhancement.

## III. Neutralino Dark Matter in the NMSSM and nMSSM

Both the NMSSM and nMSSM extend the MSSM by adding a singlet Higgs superfield $\hat{S}$. The difference between the two models lies in their superpotential terms. The NMSSM contains a trilinear singlet term $\kappa\hat{S}^3$, which is replaced in the nMSSM by a tadpole term $\xi_F M^2$. Neither model has a $\mu$ term in the superpotential; instead, such a term is dynamically generated through the coupling between the two Higgs doublets and the newly introduced singlet Higgs field, which develops a vacuum expectation value of order the SUSY breaking scale. Thus the $\mu$ problem is solved in both models. The little hierarchy problem can also be alleviated because, on one hand, the LEP II lower bound on the mass of the SM-like Higgs boson $h$ is relaxed by the suppressed $ZZh$ coupling and/or by the suppressed visible decay $h \to b\bar{b}$, while on the other hand the tree-level upper bound on the Higgs boson mass $m_h$ is pushed up.

[Figure 3: see original paper] The shaded regions are allowed by the cosmic dark matter relic density at $2\sigma$ level plus other experimental constraints in the NMSSM and nMSSM, taken respectively from the last reference in [**?**] and [**?**].

In both models the neutralino LSP has a large singlino component (the fermion component of $\hat{S}$), which serves as the dark matter particle and can explain the dark matter relic density measured by WMAP. With current experimental constraints from precision electroweak measurements, direct searches for sparticles and Higgs bosons, stability of the Higgs potential, and the muon $g-2$ measurement, scans over the parameter space were performed for the NMSSM (see the last reference in [**?**]) and the nMSSM (see the last reference in [**?**]). It was found that in both models there exists a large portion of the parameter space that can yield the required dark matter relic density. Some results from these scans are shown in Fig. 3.

As evident from Fig. 3, the neutralino LSP in the parameter space allowed by the dark matter relic density cannot explain the PAMELA result. In the NMSSM, the lightest CP-even Higgs boson cannot be light enough to induce Sommerfeld enhancement (the neutralino may explain either the relic density or PAMELA, but not both via Sommerfeld enhancement [**?**]), while in the nMSSM the neutralino mass is constrained to a narrow range.

## IV. Dark Matter in the General Singlet Extension of the MSSM

In the general singlet extension of the MSSM, the Higgs superpotential contains both the $\mu$ term and all possible terms involving the singlet superfield. Therefore this model can only solve the little hierarchy problem but suffers from the $\mu$ problem. The dark matter candidate is the singlino-like neutralino LSP, which annihilates into light singlet-like Higgs bosons $h$ (CP-even) or $a$ (CP-odd), as shown in Fig. 4. The relic density can be naturally obtained from the weak interaction between the singlino and singlet Higgs bosons. Due to the vast parameter space, the singlet-like Higgs bosons $h$ and $a$ can be light enough to be kinematically allowed to decay dominantly into muons or electrons, as shown in the left panel of Fig. 5. The Sommerfeld enhancement can be induced by exchange of the light singlet Higgs boson $h$, and for a sufficiently light $h$ such an enhancement can be quite large, as shown in the right panel of Fig. 5.

[Figure 4: see original paper] Feynman diagrams for the singlino-like neutralino dark matter annihilation where Sommerfeld enhancement is induced by exchanging a light CP-even Higgs boson $h$.

With muon final states from neutralino annihilation and the large Sommerfeld enhancement induced by a light $h$, the PAMELA result can be explained in this model [**?**, **?**]. A scan showed [**?**] that in the allowed parameter space, the SM-like Higgs boson $h_{SM}$ tends to decay into singlet Higgs pairs $aa$ or $hh$ instead of $b\bar{b}$. Consequently, the $h_{SM}$ produced at the LHC will give a multi-muon signal: $h_{SM} \to aa \to 4\mu$ or $h_{SM} \to hh \to 4a \to 8\mu$.

[Figure 5: see original paper] Left panel: Scatter plots showing the decay branching ratios $a \to \mu^+\mu^-$ (muon), $a \to gg$ (gluon), and $a \to s\bar{s}$ (s-quark). Right panel: Scatter plots showing the Sommerfeld enhancement factor induced by $h$. These results are taken from the second reference in [**?**].

### V. Conclusion

We have briefly reviewed the supersymmetric explanation for cosmic dark matter. The neutralino in the MSSM, NMSSM, and nMSSM can naturally explain the dark matter relic density, but can hardly explain the PAMELA result. In the general singlet extension of the MSSM, both the PAMELA result and the relic density can be explained simultaneously by the singlino-like neutralino, which annihilates into singlet-like Higgs bosons. These singlet-like Higgs bosons are light enough to decay dominantly to muons or electrons, and the annihilation cross section can be greatly enhanced by the Sommerfeld effect via exchange of a light CP-even singlet-like Higgs boson. In this scenario, in order to satisfy the stringent LEP constraints, the SM-like Higgs boson tends to decay into singlet Higgs pairs instead of $b\bar{b}$ and consequently will give a multi-muon signal $h_{SM} \to aa \to 4\mu$ or $h_{SM} \to hh \to 4a \to 8\mu$ at the LHC.

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