SUSY Dark Matter In Light Of CDMS/XENON Limits Postprint

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Preamble

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Abstract

In this talk we briefly review the current CDMS/XENON constraints on the neutralino dark matter in three popular supersymmetric models: the minimal (MSSM), the next-to-minimal (NMSSM) and the nearly minimal (nMSSM). The constraints from the dark matter relic density and various collider experiments are also taken into account. The conclusion is that for each model the current CDMS/XENON limits can readily exclude a large part of the parameter space allowed by other constraints and the future SuperCDMS or XENON100 can cover most of the allowed parameter space. The implication for the Higgs search at the LHC is also discussed. It is found that in the currently allowed parameter space the MSSM charged Higgs boson is quite unlikely to be discovered at the LHC while the neutral Higgs bosons H and A may be accessible at the LHC in the parameter space with a large µ parameter.

Introduction

Low-energy supersymmetry (SUSY) represents the mainstream approach to physics beyond the Standard Model and is often called the standard theory for non-standard physics. In addition to solving the fine-tuning problem and ensuring gauge coupling unification, SUSY models with R-parity also provide a welcome byproduct—cosmic dark matter. The lightest supersymmetric particle, usually assumed to be the lightest neutralino (though the gravitino may also qualify), serves as a natural candidate for cosmic cold dark matter. Such a neutralino constitutes a perfect Weakly Interacting Massive Particle (WIMP) and likely falls within the sensitivity reach of direct detection experiments like CDMS [**?**] and XENON [**?**].

Current results from CDMS and XENON have established limits on the strength of dark matter-nucleon scattering [**?**, **?**]. These limits translate into constraints on the SUSY parameter space under the assumption that neutralinos compose the cosmic dark matter. Recently, our studies [**?**, **?**] (for earlier work see, e.g., [**?**]) performed scans over the SUSY parameter space considering the new CDMS/XENON limits together with constraints from dark matter relic density and various collider experiments, including searches for Higgs bosons and superparticles, precision electroweak measurements, and the muon anomalous magnetic moment. For comparison, we examined several SUSY models: the minimal (MSSM), next-to-minimal (NMSSM) [**?**], and nearly minimal (nMSSM) [**?**].

Meanwhile, the Large Hadron Collider at CERN will intensively hunt for SUSY particles, including neutralino dark matter and SUSY Higgs bosons. SUSY predicts at least five Higgs bosons: in addition to the SM-like Higgs boson $h_{\rm SM}$, there are the neutral Higgs bosons H and A and the charged Higgs bosons $H^{\pm}$. Within a given SUSY framework, dark matter search experiments like CDMS or XENON and Higgs boson searches at the LHC become correlated, and their interplay enables deep probes of SUSY. Focusing on MSSM Higgs bosons, we studied their observability at the LHC [**?**] within the parameter space allowed by current dark matter and collider constraints.

We note that this mini-review does not discuss SUSY explanations for the PAMELA cosmic ray anomaly [**?**], which remains subject to large uncertainties and could also be explained astrophysically by pulsars. Typically, the MSSM, NMSSM, or nMSSM struggle to provide satisfactory explanations for such anomalies (the final states of neutralino dark matter annihilation produce excessive antiprotons, and generating the large boost factor for the annihilation rate through elegant Sommerfeld enhancement proves difficult) [**?**, **?**], while some general singlet extensions may offer plausible explanations [**?**, **?**, **?**] albeit with some tension with CDMS limits [**?**].

This review is organized as follows. In Sec.~II we recapitulate the three SUSY models: MSSM, NMSSM, and nMSSM. Section~III discusses the current CDMS/XENON constraints on each model’ s parameter space and their implications for MSSM Higgs searches at the LHC. Finally, Sec.~IV presents a summary.

SUSY Models

The MSSM contains the minimal particle content and thus represents the most economical realization of supersymmetry. To date, this model has been studied most intensively. However, it suffers from the so-called μ-problem and the little hierarchy problem. For this reason, singlet extensions like the NMSSM and nMSSM have recently attracted considerable attention. In both the NMSSM and nMSSM, the superpotential does not contain the μ-term; instead, μ is generated by the non-zero vacuum expectation value of a newly introduced singlet field. The little hierarchy problem can also be alleviated since the tree-level upper bound on the SM-like Higgs boson mass increases, and the stop need not be excessively heavy to generate large quantum corrections for the Higgs mass. Meanwhile, the LEP II lower bound of 114 GeV on the SM-like Higgs boson is somewhat relaxed since this Higgs boson contains singlet admixture and its coupling to the Z-boson is weakened.

The superpotentials of these models are given by

$$\begin{aligned}
W_{\mathrm{MSSM}} &= W_F + \mu \hat{H}_u \cdot \hat{H}_d, \\
W_{\mathrm{NMSSM}} &= W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \frac{\kappa}{3} \hat{S}^3, \\
W_{\mathrm{nMSSM}} &= W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \xi_F M_n^2 \hat{S},
\end{aligned}$$

with

$$W_F = Y_u \hat{Q} \cdot \hat{H}_u \hat{U} - Y_d \hat{Q} \cdot \hat{H}_d \hat{D} - Y_e \hat{L} \cdot \hat{H}_d \hat{E},$$

where $\hat{Q}$, $\hat{U}$, and $\hat{D}$ are the squark superfields, $\hat{L}$ and $\hat{E}$ are the slepton superfields, $\hat{H}_u$ and $\hat{H}_d$ are the Higgs doublet superfields, λ, κ, and ξ_F are dimensionless coefficients, and μ and M_n are parameters with mass dimension.

In the MSSM we have the SM-like Higgs boson h_{SM}, the heavy neutral CP-even Higgs boson H, the CP-odd Higgs boson A, and the charged Higgs bosons $H^{\pm}$. In the NMSSM and nMSSM, we have one additional CP-even Higgs boson and one additional CP-odd Higgs boson. Because the lightest CP-even Higgs boson and the lightest CP-odd Higgs boson may be dominated by singlet components, they can evade experimental constraints and thus be very light (sometimes called the light dark Higgs).

The neutralinos are mixtures of neutral gauginos and neutral Higgsinos. While there are four neutralinos in the MSSM, the NMSSM and nMSSM each have five neutralinos. The lightest neutralino is usually assumed to be the lightest supersymmetric particle (LSP). Due to R-parity conservation, this LSP is stable. Since it interacts weakly and its mass is typically around the weak scale (a light LSP at the GeV scale may also be possible, see, e.g., [**?**]), it constitutes a perfect

WIMP and serves as the dark matter particle. The neutralino mass matrices in these models are given by

For the MSSM:

$$\begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

For the NMSSM:

$$\begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta & 0 \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta & 0 \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu & -\lambda v_d \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 & -\lambda v_u \\ 0 & 0 & -\lambda v_d & -\lambda v_u & 2\kappa s \end{pmatrix}$$

For the nMSSM:

$$\begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta & 0 \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta & 0 \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu & -\lambda v_d \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 & -\lambda v_u \\ 0 & 0 & -\lambda v_d & -\lambda v_u & 0 \end{pmatrix}$$

Here M_1 and M_2 are the $U(1)$ and $SU(2)$ gaugino masses, $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, $s_\beta = \sin\beta$ and $c_\beta = \cos\beta$ with $\tan\beta \equiv v_u/v_d$.

The properties of the neutralino LSP are determined by its composition. In the MSSM with the GUT relation $M_2 \approx 2M_1$, the LSP may be bino-like or Higgsino-like (without the GUT relation it may also be wino-like). Since LSP-nucleon scattering is dominated by Higgs boson exchange (for heavy squarks), a bino-like neutralino scatters very weakly with nucleons and thus proves difficult to detect at CDMS/XENON. In the NMSSM, throughout most of the parameter space the neutralino LSP closely resembles the MSSM case [**?**], though some parameter space corners exist where the neutralino LSP is singlino-like and can be very light [**?**]. In the nMSSM, due to the zero diagonal element for the singlino in the mass matrix, the singlino is always very light and thus the neutralino LSP is singlino-like. Consequently, the neutralino LSP properties in the nMSSM differ considerably from those in the MSSM or NMSSM.

Numerical Results and Discussions

Our study incorporates the following experimental constraints: (1) Direct bounds on sparticle and Higgs masses from LEP and Tevatron experiments; (2) LEP II Higgs boson searches in various channels; (3) LEP I and LEP II constraints on neutralino and chargino production; (4) Indirect constraints from precision electroweak observables and various B-decay processes and mixings; (5) The muon anomalous magnetic moment constraint, requiring SUSY effects to account for the discrepancy at the 2σ level; (6) Dark matter constraints from the WMAP relic density measurement (2σ). For the CDMS II/XENON100 direct detection exclusion limits (90% C.L.) on the scattering cross section, we display results both with and without such limits. In addition to these experimental constraints, we also require stability of the Higgs potential, meaning the physical vacuum with non-vanishing Higgs scalar vevs must be lower than any local minima.

In our scan, the soft breaking parameters are assumed to be below 1 TeV, and the parameter λ at the weak scale is assumed to be less than approximately 0.7 to ensure perturbativity up to the grand unification scale. To reduce the number of relevant soft parameters, we adopt the so-called $m_h^{\max}$ scenario with soft masses for the third-generation squarks: $M_{Q_3} = M_{U_3} = M_{D_3} = 800$ GeV, and $X_t = A_t - \mu \cot\beta = -1600$ GeV.

The parameter space surviving these constraints is plotted in Fig.~1 of [**?**]. This figure demonstrates that for each model, the CDMS-II/XENON100 limits can exclude a large portion of the parameter space allowed by other constraints, and future experiments such as SuperCDMS (25 kg) or XENON100 (6000 kg-days) can cover most of the remaining allowed parameter space. Nevertheless, some fraction of the allowed parameter space lies beyond the future sensitivity of SuperCDMS or XENON100, requiring much larger detectors or greater exposure to fully cover the allowed parameter space of these SUSY models. The figure also reveals that in the nMSSM the LSP can be as light as several GeV, whereas for the MSSM and NMSSM the LSP mass has a lower bound of 50 GeV arising from the assumed GUT relation $M_1 \approx 0.5 M_2$ (plus the chargino lower bound of 103.5 GeV). Without such a GUT relation, a lighter LSP would be allowed. The similarity between the allowed parameter spaces of the MSSM and NMSSM stems from the fact that throughout most of the parameter space, the LSP in both models is bino-like. The distinctive nature of the nMSSM parameter space arises because the LSP is singlino-like in this model.

The properties of the neutralino LSP in the allowed parameter space are shown in Fig.~2 of [**?**]. The figure indicates that in the absence of dark matter detection, CDMS/XENON constraints push the neutralino LSP to be more bino-like in the MSSM and NMSSM, while more singlino-like in the nMSSM. This behavior is easily understood because a more bino-like or singlino-like LSP scatters more feebly with nucleons, making it more difficult to detect at CDMS/XENON.

The charged Higgs boson mass range is shown in Fig.~7 of [**?**]. The figure demonstrates that in the absence of dark matter detection, CDMS/XENON constraints push the charged Higgs boson mass upward for both the MSSM and NMSSM. For the MSSM, we studied the charged Higgs signal at the LHC via $gg/gb \to t[b]H^+$ with H^+ subsequently decaying to $\tau^+\nu_\tau$ [**?**]. As shown in Fig.~4 of [**?**], only a few surviving points lie above the 5σ discovery sensitivity projected by the ATLAS collaboration for 30 fb^{-1} integrated luminosity. Thus, the likelihood of discovering the charged Higgs boson at the LHC is very small.

For the MSSM neutral Higgs bosons H and A at the LHC, we consider the channels $gg \to H(A)$ or $b\bar{b}H(A)$ with $H(A)$ decaying to tau leptons. The results appear in Fig.~5 of [**?**]. The figure shows that in the allowed parameter space with large μ, the neutral Higgs bosons H and A are quite likely observable at the LHC. This can be understood because for larger μ parameters, the neutralino LSP becomes more bino-like and scatters more feebly with nucleons, thereby weakening the CDMS/XENON constraints.

Finally, for the light Higgs bosons in the NMSSM, recent studies [**?**] have shown that they may exhibit interesting signals at the LHC, such as enhanced di-photon signals. Such enhanced di-photon signatures could help distinguish the NMSSM from the MSSM.

Conclusion

Current collider experiments and dark matter relic density measurements stringently constrain the SUSY parameter space. The CDMS II and XENON100 limits further shrink the allowed parameter space and push the neutralino dark matter to be bino-like in the MSSM and NMSSM. The future sensitivity of SuperCDMS or XENON100 can cover most of the allowed parameter space for each model, and in the absence of dark matter detection, the neutralino dark matter will become more bino-like in the MSSM and NMSSM while more singlino-like in the nMSSM. In the currently allowed parameter space, the MSSM charged Higgs boson is quite unlikely to be discovered at the LHC, whereas the neutral Higgs bosons H and A may be accessible at the LHC in parameter space regions with large μ parameter.

Note added: While this manuscript was being prepared, additional studies on light SUSY dark matter appeared on arXiv [**?**].

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References

[1] Z. Ahmed et al., arXiv:0912.3592.
[2] E. Aprile et al., arXiv:1005.0380.
[3] J. Cao et al., JHEP 1007, 044 (2010).
[4] J. Cao et al., Phys. Rev. D 82, 051701 (2010).
[5] J. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Rev. D 71, 095007 (2005).
[6] J. R. Ellis et al., Phys. Rev. D 39, 844 (1989); M. Drees, Int. J. Mod. Phys.

A4, 3635 (1989); S. F. King and P. L. White, Phys. Rev. D 52, 4183 (1995); B. Ananthanarayan and P.N. Pandita, Phys. Lett. B 353, 70 (1995); B. A. Dobrescu and K. T. Matchev, JHEP 0009, 031 (2000); V. Barger, P. Langacker, H.-S. Lee and G. Shaughnessy, Phys. Rev. D 73, 115010 (2006); R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005); G. Hiller, Phys. Rev. D 70, 034018 (2004); F. Domingo and U. Ellwanger, JHEP 0712, 090 (2007); Z. Heng et al., Phys. Rev. D 77, 095012 (2008); R. N. Hodgkinson and A. Pilaftsis, Phys. Rev. D 76, 015007 (2007); W. Wang, Z. Xiong and J. M. Yang, Phys. Lett. B 680, 167 (2009); J. Cao and J. M. Yang, JHEP 0812, 006 (2008); Phys. Rev. D 78, 115001 (2008).

[7] C. Panagiotakopoulos and K. Tamvakis, Phys. Lett. B 446, 224 (1999); C. Panagiotakopoulos and A. Pilaftsis, Phys. Rev. D 63, 055003 (2001); A. Dedes et al., Phys. Rev. D 63, 055009 (2001); J. Cao, H. E. Logan and J. M. Yang, Phys. Rev. D 79, 091701 (2009); J. Cao, Z. Heng and J. M. Yang, JHEP 1011, 110 (2010).

[8] O. Adriani et al., PAMELA Collaboration, Nature 458, 607 (2009).

[9] D. Hooper and T. M. P. Tait, Phys. Rev. D 80, 055028 (2009).

[10] W. Wang, Z. Xiong, J. M. Yang and L.-X. Yu, JHEP 0911, 053 (2009).

[11] J. M. Yang, Mod. Phys. Lett. A25 (2010) 976.

[12] C. Arina, F.-X. Josse-Michaux and N. Sahu, Phys. Lett. B 691 (2010) 219.

[13] P. Grajek et al., Phys. Rev. D 79 (2009) 043506.

[14] Y. Bai, M. Carena and J. Lykken, Phys. Rev. D 80 (2009) 055004.

[15] See, e.g., D. A. Vasquez et al., arXiv:1009.4380 [hep-ph]; P. Draper et al., arXiv:1009.3963 [hep-ph]; J. F. Gunion, A. V. Belikov and D. Hooper, arXiv:1009.2555 [hep-ph]; A. V. Belikov, J. F. Gunion, D. Hooper and T. Tait, arXiv:1009.0549 [hep-ph].

[16] U. Ellwanger, arXiv:1012.1201 [hep-ph]; M. Almarashi and S. Moretti, arXiv:1011.6547 [hep-ph].

[17] See, e.g., N. Fornengo, S. Scopel and A. Bottino, arXiv:1011.4743 [hep-ph]; Z. Kang et al., JCAP 1101, 028 (2011).