Constraints of dark matter direct detection experiments on the MSSM and implications for LHC Higgs search (Postprint)

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Full Text

Constraints from Dark Matter Direct Detection Experiments on the MSSM and Implications for LHC Higgs Searches

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Abstract

Assuming the lightest neutralino solely composes the cosmic dark matter, we examine the constraints from the CDMS-II and XENON100 dark matter direct searches on the parameter space of the MSSM Higgs sector. We find that the current CDMS-II/XENON100 limits can exclude some of the parameter space that survives the constraints from the dark matter relic density and various collider experiments. We also find that in the currently allowed parameter space, the charged Higgs boson is hardly accessible at the LHC for an integrated luminosity of 30 fb ^{1}, while the neutral non-SM Higgs bosons (H,A) may be accessible in some allowed regions characterized by a large .

The future XENON100 experiment (with 6000 kg-days exposure) will significantly tighten the parameter space in case of non-observation of dark matter, further shrinking the likelihood of discovering the non-SM Higgs bosons at the LHC.

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Introduction

The existence of non-baryonic cold dark matter (DM) has been established by cosmological observations [**?**]. Weakly interacting massive particles (WIMPs) are natural candidates for DM, among which the lightest neutralino χ_1^0 in the Minimal Supersymmetric Standard Model (MSSM) has been most extensively studied [**?**]. The most convincing detection method for neutralino DM is through underground direct detection experiments like CDMS and XENON, which search for neutralino-nucleon (χN) scattering in a low-background environment [**?**], [**?**]. Recently, both CDMS-II and XENON100 reported their search results [**?**], [**?**], which immediately stimulated theoretical works [**?**], [**?**]. On the theoretical side, great efforts have been made to improve the accuracy of predictions for the χN scattering rate [**?**], [**?**]. For example, it has long been known that hadronic uncertainty, especially the strange quark content in a nucleon, can affect the rate by almost one order of magnitude and therefore significantly impacts the interpretation of experimental DM searches [**?**]. This problem was recently better addressed by lattice simulations, which found that the strange quark content is much smaller than previously thought, leading to a significant reduction in the uncertainty [**?**].

In light of these experimental and theoretical advances in DM studies, we reinvestigate χN scattering and use the recent CDMS-II/XENON limits to constrain the MSSM parameter space. Unlike most recent studies that attempt to explain the two possible DM events reported by CDMS-II, we use the CDMS-II 90% upper limit on the spin-independent (SI) χN scattering cross section. In addition to direct detection limits from CDMS-II and XENON100, we also consider constraints from the DM relic density and various collider experiments. We first perform a scan over the MSSM parameter space incorporating these constraints, then investigate χN scattering in the surviving parameter space to demonstrate the further constraints imposed by CDMS-II/XENON. Given the extreme importance of Higgs searches at the LHC and the strong correlation between χN scattering and the Higgs sector, our study focuses on the MSSM Higgs sector.

χN Scattering in the MSSM

For the sensitivity of current DM direct detection experiments, it is sufficient to consider only the spin-independent interactions between χ_1^0 and nucleons (denoted by f_p for proton and f_n for neutron [**?**]) when calculating the scattering rate. In the MSSM, these interactions are induced by exchanging squarks or neutral Higgs bosons at tree level [?], [?]. For moderately light Higgs bosons, the Higgs exchange contribution is dominant, and f_p is approximated by [?] (similarly for f_n):

$$f_p = \sum_{q=u,d,s} m_p f_{Tq}^{(p)} \frac{f_q}{m_q} + \frac{2}{27} f_{TG}^{(p)} \sum_{q=c,b,t} \frac{f_q}{m_q}$$

where $f_{Tq}^{(p)}$ denotes the fraction of the proton mass contributed by light quark q, while $f_{TG}^{(p)} = 1 - \sum_{q=u,d,s} f_{Tq}^{(p)}$ is the heavy quark contribution through gluon exchange. f_q is the coefficient of the effective scalar operator given by [?]:

$$f_q = \frac{m_q}{4m_W} \left[C_h^{\chi\chi} C_h^{qq} + C_H^{\chi\chi} C_H^{qq}\right]$$

with C standing for the corresponding Yukawa couplings. The χ_1^0-nucleus scattering rate is then given by [?]:

$$\sigma_{SI} = \frac{4}{\pi} \left(\frac{m_{\chi_1^0} m_T}{m_{\chi_1^0} + m_T}\right)^2 \left[n_p f_p + n_n f_n\right]^2$$

where m_T is the mass of the target nucleus and n_p (n_n) is the number of protons (neutrons) in the target nucleus.

From these formulas, we can infer when the scattering cross section is large. Equation (2) indicates that this occurs only when $C_S^{\chi\chi}$ and/or C_S^{qq} (where S stands for a Higgs boson) become enhanced. Since the potential enhancement of C_H^{dd} by $\tan\beta$ is well known, we here analyze only the behavior of $C_S^{\chi\chi}$ with variation of SUSY parameters. For a bino-like χ_1^0 encountered in this work, this coupling is generated through bino-higgsino mixing [?], so a large $C_S^{\chi\chi}$ requires large mixing, which means a small μ. To make this statement clearer, one may consider the limit $M_1 \ll M_2, \mu$, where M_1, M_2, and μ denote respectively the masses of bino, wino, and higgsino. After diagonalizing the neutralino mass matrix perturbatively, one obtains [?]:

$$C_h^{\chi\chi} \simeq C_H^{\chi\chi} \simeq -\frac{m_Z \sin\theta_W \tan\beta}{M_1 + \mu \sin 2\beta} \left(1 - \frac{\mu^2}{M_1^2 + \mu^2 + 2M_1 \mu \sin 2\beta}\right)$$

Thus both couplings become large when μ approaches M_1 from above.

In our numerical calculations for the scattering rate, we consider all known contributions, including QCD corrections, SUSY-QCD corrections [?], as well as contributions from higher-dimensional operators [?]. Note that the SUSY-QCD corrections are not negligible because they may sizably reduce the scattering rate by suppressing C_S^{qq} [?], [?]. In our calculations we take $f_{Tu}^{(p)} = 0.023$, $f_{Td}^{(p)} = 0.034$,

$f_{Ts}^{(p)} = 0.020$, $f_{Tu}^{(n)} = 0.019$, $f_{Td}^{(n)} = 0.041$, and $f_{Ts}^{(n)} = 0.020$. Note that the value of f_{Ts} we choose is much smaller than that used in most previous studies. This small value comes from recent lattice simulations [?], and it can reduce the scattering rate significantly.

Numerical Results

We make several assumptions to reduce the number of free parameters before performing our scan. First, we note that the first two generation squarks may be heavier than about 400 GeV from Tevatron experiments [?], and thus their effects on scattering should be unimportant in the presence of light Higgs bosons. Therefore, for the first two generation squarks we fix the soft masses and trilinear parameters to 1 TeV. We have checked that our conclusions are not affected by this specific choice. Second, since the third generation squarks affect the Higgs sector significantly, we allow all relevant soft parameters to vary freely. However, to simplify our analysis, we assume $m_{\tilde{D}_3} = m_{\tilde{U}_3}$ and $A_b = A_t$, which is well motivated by the mSUGRA model with large $\tan\beta$. Third, although slepton masses do not directly affect the χN scattering rate, they can affect the allowed range of $\tan\beta$ via the muon $g{-}2$ constraint. To avoid a tight constraint on $\tan\beta$, we assume a universal soft parameter $m_{\tilde{\ell}}$ and vary it in our scan. Finally, we use the grand unification relation $3M_1/5\alpha_1 = M_2/\alpha_2 = M_3/\alpha_3$ for the gaugino masses.

With these assumptions, the remaining free parameters are scanned in the ranges: $1 \le \tan\beta \le 80$, 80 GeV $\le m_A \le$ 300 GeV, 30 GeV $\le M_1 \le$ 500 GeV, 100 GeV $\le \mu, m_{\tilde{\ell}}, m_{\tilde{Q}_3}, m_{\tilde{U}_3} \le$ 1 TeV, and -3 TeV $< A_t \le$ 3 TeV. In our scan, we consider the following constraints as done in [?]: (1) Direct bounds on sparticle and Higgs masses from LEP and Tevatron experiments. (2) LEP II searches for Higgs bosons, including various Higgs production channels. (3) LEP I and LEP II constraints on neutralino and chargino productions. (4) Constraints (2σ) from precision electroweak observables plus R_b [?], and also constraints from B-physics observables such as $B \to X_s\gamma$, $B_s \to \mu^+\mu^-$, $B^+ \to \tau^+\nu_\tau$, and the mass differences ΔM_d and ΔM_s. (5) The muon $g-2$ constraint [?] (we require the MSSM contribution to explain the deviation at the 2σ level). (6) We require χ_1^0 to account for the WMAP-measured dark matter relic density at the 2σ level [?]. The samples surviving these constraints are then used as input for calculating the χN scattering rate. Note that most of these constraints have been encoded in NMSSMTools [?]. We extended the code to the MSSM case, particularly writing code for the χN scattering rate to improve scan efficiency.

[Figure 2: see original paper] shows the same as Figure 1, but displaying $\tan\beta$ and μ versus m_{H^+} for $f_{Ts} = 0.02$. The future XENON100 limits will shrink the currently allowed regions, and in particular set a bound $m_{H^+} \gtrsim 165$ GeV. Around this lower bound, the value of μ is quite large ($\simeq 1$ TeV), leading to fine-tuning in the MSSM due to the relation $m_{H_u}^2 + m_{H_d}^2 + 2\mu^2$ [?]. In our following discussions, we focus only on samples that satisfy the current CDMS-II/XENON limits.

In Figure 3 [Figure 3: see original paper], we project the surviving samples onto the $\tan\beta$-μ and $\tan\beta_{\text{eff}}$-m_{H^+} planes, where $\tan\beta_{\text{eff}} \equiv \tan\beta/(1+\Delta_b)$ with Δ_b denoting the SUSY radiative corrections to the bottom quark mass [**?**]. As expected, large $\tan\beta$ must be accompanied by large μ to suppress the scattering rate, and this tendency becomes more apparent for samples that further satisfy the future XENON100 limit. We note that in this case–i.e., large $\tan\beta$ together with large μ–Δ_b should be large [**?**], so that $\tan\beta_{\text{eff}}$ is significantly smaller than $\tan\beta$. This speculation is verified by Figure 3 and by our results for Δ_b, which show Δ_b larger than 30% for $\tan\beta \geq 40$.

Implications for LHC Higgs Searches

The above results show that the CDMS-II/XENON limits have set upper bounds on $\tan\beta_{\text{eff}}$. Since LHC searches for non-SM Higgs bosons typically require large $\tan\beta_{\text{eff}}$ to enhance the signal rate [**?**]-[**?**], such upper bounds on $\tan\beta_{\text{eff}}$ may have important implications for LHC searches for non-SM Higgs bosons.

We first consider the LHC search for the charged Higgs boson. For a charged Higgs heavier than the top quark, the main channel is $gg/gb \to t[b]H^+$ with H^+ subsequently decaying to $\tau^+\nu_\tau$ [**?**]. In Figure 4 [Figure 4: see original paper], we show the rate of this channel in the allowed parameter space, where the model-independent 5σ discovery sensitivity is obtained by the ATLAS collaboration for 30 fb ^{1} integrated luminosity [**?**]. In calculating the signal rate, we used the effective Lagrangian method to incorporate important SUSY corrections. Our results show that for more than 99% of the surviving samples, the rate is smaller than the discovery sensitivity, meaning that the LHC is unlikely to discover H^+. Our results also indicate that future XENON100 limits (in case of non-observation of DM) will further tighten the parameter space, making the discovery of H^+ unlikely even with higher luminosity. For a charged Higgs lighter than the top quark, the LHC search can instead utilize top pair production with one top decaying into a charged Higgs [**?**]. Like the heavy charged Higgs case, our results indicate that for more than 99% of surviving samples, the signal is below the 5σ discovery sensitivity obtained by the ATLAS collaboration due to $\text{Br}(t \to H^+ b) < 10^{-2}$. The small branching ratio of $t \to H^+ b$ arises because $\tan\beta$ is around 10 for $m_{H^+} \leq 150$ GeV (see Figure 1), and for such values of $\tan\beta$ there is strong cancellation between different terms in the amplitude for this decay.

Now we turn to the LHC search for the non-SM neutral Higgs bosons H and A, for which both ATLAS and CMS collaborations utilize the channels $gg \to H(A)$ or $b\bar{b}H(A)$ with $H(A)$ decaying to τ leptons [**?**]-[**?**]. Unlike the charged Higgs search, for which model-independent discovery sensitivity can be obtained, the analysis for neutral Higgs boson searches is performed in certain SUSY scenarios. Here we consider the $m_h^{\max}$ scenario with the following fixed parameters: $M_{\text{SUSY}} = 1$ TeV, $M_2 = 200$ GeV, $m_{\tilde{g}} = 800$ GeV, and $X_t = A_t - \mu\cot\beta = 2$ TeV.

To show the μ dependence of the constraints, we choose several representative values of μ and scan the remaining free parameters in the ranges: $1 \leq \tan\beta \leq 80$, 80 GeV $\leq m_A, m_{\tilde{\ell}} \leq 0.8$ TeV, and 30 GeV $\leq M_1 \leq 500$ GeV.

In Figure 5 [Figure 5: see original paper], we show the surviving samples on the m_A versus $\tan\beta$ plane together with the LHC discovery sensitivity for 30 fb ^{1} integrated luminosity. This sensitivity is obtained by the CMS collaboration with $H/A \to \tau^+\tau^- \to \mu^+$+jets topology (semi-leptonic final states) [?], $m = 200$ GeV. Observable Region (LHC, 30 fb ^{1}) sensitivity (1) In obtaining these results we used the package NMSSMTools (version 2.3.1) [?], which uses micrOMEGAs (version 2.2) [?] for calculating the dark matter relic density. However, we extended the package by including more experimental constraints, such as the LEP search for Higgs bosons and $B^+ \to \tau^+\nu_\tau$, so our combined constraint on the parameter space is more stringent. (2) The CDMS-II/XENON constraints are sensitive to the value of μ–i.e., as μ gets larger, the constraints become weaker. The reason is that a larger μ results in a smaller Higgsino component in χ_1^0 and hence suppresses the Higgs-χ_1^0 coupling, which weakens the CDMS-II/XENON constraints. (3) The LHC sensitivity for $\mu = 200$ GeV is taken directly from [?], and for other μ values the curves are obtained by scaling $\tan\beta$ so that the Higgs boson production rate is the same as for $\mu = 200$ GeV. In doing this we used the package FeynHiggs 2.7.1 [?] to calculate the production rate. Note that the μ parameter affects the production rate mainly by changing the $H(A)b\bar{b}$ coupling through loop corrections (Δ_b) which are proportional to $\mu\tan\beta/M_{\mathrm{SUSY}}$ [?]. Therefore, the shift of the LHC sensitivity curve due to variation of μ is not negligible, as shown in Figure 5. (4) Figure 5 shows that for $\mu = 200$ GeV no surviving samples can reach the observable level, while for larger μ values a small fraction of surviving samples can lie within the observable region. Numerically, we find that for $\mu = 400$ GeV, 700 GeV, and 1 TeV, about 8%, 11%, and 7% of surviving samples lie within the observable region, respectively (for $\mu = 1$ TeV about one third of these detectable samples can even survive the future XENON100 limit). The reason for this behavior is that for large μ, although the LHC sensitivity curve is shifted upward, the much weakened CDMS-II/XENON constraints allow some surviving samples to have quite large $\tan\beta$ values (as shown in Figures 3 and 5) so they can reach the LHC sensitivity. (5) Regarding the lower bound of M_A as a function of $\tan\beta$, since both the χN scattering cross section and the Higgs boson production rate are proportional to $\tan^2\beta$ for large $\tan\beta$, one might naively expect the lower bound curve to run parallel with the LHC sensitivity curve. As shown in Figure 5, this is not the case because we considered many experimental constraints that do not all scale as $\tan^2\beta$.

Conclusion

We have seen that if the MSSM is the correct theory, current limits from dark matter and collider experiments already strongly constrain the parameter space, which has important implications for LHC searches for non-SM SUSY Higgs bosons. It turns out that in the currently allowed parameter space, the charged Higgs boson is hardly accessible at the LHC for an integrated luminosity of 30 fb ^{1}, while the neutral non-SM Higgs bosons (H, A) may be accessible in some allowed regions characterized by large μ. The future XENON100 experiment (6000 kg-days exposure) will significantly tighten the parameter space in case of non-observation of dark matter, further shrinking the likelihood of discovering non-SM Higgs bosons at the LHC. Thus, the interplay between dark matter direct detection experiments and LHC Higgs searches will allow for a good test of the MSSM.

Finally, we stress that we obtained the above conclusion by choosing a small $f_{Ts} = 0.02$. If we choose a large f_{Ts}, the scattering rate will be larger, making the limits from current CDMS-II/XENON more stringent. For example, for $f_{Ts} = 0.38$ used in previous studies [**?**], we find that the current CDMS-II/XENON constraints are comparable to the future XENON100 (6000 kg-days) constraints. We also verified that if we relax some assumptions in our scan, such as the grand unification relation for gaugino masses, our findings about LHC Higgs searches remain unchanged. Furthermore, we noted the controversy regarding XENON100 detection efficiency [**?**]. Although our current bounds combine CDMS-II and XENON100, CDMS-II plays the dominant role. If we exclude the current XENON100 limits, our results remain almost unchanged.

Note added: After completing our paper, we noticed that the ATLAS collaboration published an analysis of search sensitivity for neutral non-SM Higgs bosons via semi-leptonic final states [**?**], in which the obtained discovery sensitivity appears better than the CMS result shown in Figure 5. According to this new ATLAS result, more surviving samples in Figure 5 will reach the observable region, so our conclusion about the observability of neutral Higgs bosons remains unchanged.

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Note: Figure translations are in progress. See original paper for figures.