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R. Arnowitt
Harvard University

A. H. Chamseddine
Northeastern University

Pran Nath
Northeastern University

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Low mass neutralino dark matter in the minimal supersymmetric standard model with constraints from $B_s \to \mu^+\mu^-$ and Higgs boson search limits

Daniel Feldman,[1] Zuowei Liu,[2] and Pran Nath[3]

[1]*Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, Michigan 48109, USA*
[2]*C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[3]*Department of Physics, Northeastern University, Boston, Massachusetts 02115, USA*

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An analysis of spin independent neutralino-proton cross sections $\sigma_{\rm SI}(\chi p)$ that includes this low mass region is given. The analysis is done in minimal supersymmetric standard model (MSSM) with radiative electroweak symmetry breaking (REWSB). It is found that cross sections as large as 10^{-40} cm^2 can be accommodated in MSSM within the REWSB framework. However, inclusion of sparticle mass limits from current experiments, as well as lower limits on the Higgs searches from the Tevatron, and the current experimental upper limit on $B_s \to \mu^+\mu^-$ significantly limit the allowed parameter space reducing $\sigma_{\rm SI}(\chi p)$ to lie below $\sim 10^{-41}$ cm^2 or even lower for neutralino masses around 10 GeV. These cross sections are an order of magnitude lower than the cross sections needed to explain the reported data in the recent dark matter experiments in the low neutralino mass region.

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I. INTRODUCTION

Recent experimental results on the direct detection of dark matter [1–3] have made very significant progress in increasing the sensitivity of detectors to probe the spin independent scattering cross sections of WIMPs off target nuclei. Specifically, the most recent five tower CDMS II result [4] has reached the sensitivity of 3.8×10^{-44} cm^2 at a mass of 70 GeV. These results have received attention in supersymmmetric models of cold dark matter [5].

More recently CoGeNT [6] has reported results that show some overlap with the parameter space where DAMA sees an excess of events [7]. In the context of the minimal supersymmetric standard model (MSSM), with electroweak symmetry broken radiatively, it is interesting to ask whether neutralino dark matter can give rise to detectable events in the region where CoGeNT/DAMA see an excess. The reported excess occurs in the low mass region with neutralino mass as low as 5–10 GeV. Indeed light neutralinos with masses $O(10)$ GeV have been entertained by several authors within the MSSM framework [8–11] and light dark matter using different frameworks has also been investigated [12–14].

In this brief note we investigate the neutralino low mass region in MSSM under the Tevatron constraints from Higgs searches and on $B_s \to \mu^+\mu^-$. For the analysis here we choose the framework of radiative breaking of the electroweak symmetry with the aim of finding the parameter space of soft breaking that can generate spin independent neutralino-proton cross sections, which can lie in the range $(10^{-40}$–$10^{-41})$ cm^2 needed to get compatibility with the data in the low neutralino mass experiments. The large spin independent neutralino-proton cross sections of size $O(10^{-40})$ cm^2 arise via t-channel Higgs exchange for large $\tan\beta$, which is typically required to be as large as 50 or larger. (Squark exchange in the s channel can also produce competitive results if the lower limit on the masses is relaxed below the current experimental limits as will be evident in the discussion given in Sec II.) However, the large $\tan\beta$ region is precisely the region where the $B_s \to \mu^+\mu^-$ becomes large [15]. It is known that the $B_s \to \mu^+\mu^-$ branching ratio has a $\tan\beta$ dependence, which grows as powers of $\tan\beta$ (the growth can vary from $\tan^2\beta$ to $\tan^6\beta$ depending on the part of the parameter space one is in). For this reason the $B_s \to \mu^+\mu^-$ experimental limits produce a very strong constraint in regions of the parameter space where $\tan\beta$ gets large, which is what is needed to get a large spin independent neutralino-proton cross section. We give now details of the analysis including the constraints from mass limits [16] and from the $B_s \to \mu^+\mu^-$ branching ratio.

II. AN MSSM ANALYSIS WITH REWSB

The excess reported in DAMA and CoGeNT experiments requires a relatively large $\sigma_{\rm SI}(\chi p)$, i.e.,

$$\sigma_{\rm SI}(\chi p) \sim 10^{-40}\ {\rm cm}^2, \qquad m_{\rm WIMP} \sim (5\text{–}10)\ {\rm GeV}. \quad (1)$$

We discuss now the possibility whether cross sections of the above size can arise in MSSM. The elastic spin independent cross section, $\sigma_{\rm SI}(\chi p)$, in the MSSM is controlled dominantly by the Higgs exchange and by the squark exchange depending on the relative lightness of the scalars. For the Higgs or the squark exchange diagrams the cross section is maximized for large $\tan\beta$ and $\sigma_{\rm SI}(\chi p)$ scales as [17]

$$\sigma_{\rm SI}(\chi p)_{\rm max} \sim \frac{(g_Y g_2)^2 |n_{11} n_{1,[4,3]}|^2}{4\pi M_W^2} \frac{[1, \tan^2\beta]}{m_S^4} F_p, \quad (2)$$

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$$[S = h, (S = \tilde{q} \quad \text{or} \quad H)]. \tag{3}$$

Here $(n_{11=\tilde{B}}, n_{12=\tilde{W}}, n_{13=\tilde{H}_1}, n_{14=\tilde{H}_2})$ stand for the bino, wino, and Higgsino components of the neutralino and F_p depends on the neutralino couplings to the proton. The sensitivity of $\sigma_{\rm SI}(\chi p)$ to MSSM parameters enters essentially via the Higgs/squark masses and via the eigencomponents n_{11}, n_{13}, etc., of the neutralino wave function. In the analysis of radiative breaking of the electroweak symmetry we assume the MSSM parameter space with nonuniversalities in the gaugino masses. Equation (2) is an approximate form, and in the analysis we have used the full form for $\sigma_{\rm SI}(\chi p)$. Thus implementing micrOMEGAs and SuSpect [18] we scan the parameter space consistent with radiative electroweak symmetry breaking (REWSB) and with grand unified theory (GUT) scale unification in the ranges $m_0 \leq 500$ GeV, $m_{1/2} \leq 200$ GeV, $|A_0/m_0| \leq 4$, the latter guided by constraints on charge and color breaking, with $\tan\beta \in (45, 60)$. We take the sign of μ to be positive and take the top quark mass to be 171 GeV. In the gaugino sector we assume $M_a/m_{1/2} = (1 + \Delta_a)$, for $a = 1, 2, 3$ where $\Delta_1 \in (-1, 0)$ and $\Delta_{2,3} \in (0, 1)$, where the ranges are guided in part by the restriction that the lightest chargino $\chi^{\pm}$ mass should be greater than 100 GeV. Beyond this, we require the lightest CP even Higgs to have a mass of 100 GeV or larger, and we require the squark and gluino mass to be larger than 300 GeV. To account for theoretical uncertainties in the large $\tan\beta$ region, we take a broad range around the WMAP [19] value of the neutralino relic density so that $\Omega h^2 \in [0.08, 0.15]$.

An analysis of the $\sigma_{\rm SI}(\chi p)$ under the constraints of radiative electroweak symmetry breaking but without the imposition of any sparticle mass limits is given in Fig. 1. Here one finds that the allowed parameter space does encompass the regions where CoGeNT and DAMA/LIBRA see excess events. However, in the analysis of Fig. 1 we have not imposed any sparticle mass limits or the $B_s \to \mu^+\mu^-$ branching ratio constraint. In Fig. 2 we give an analysis of $\sigma_{\rm SI}(\chi p)$ as a function of the neutralino mass with inclusion of the experimental sparticle mass limits. The points within the boxes are those that satisfy the relic density while the small circles do not. One finds that the maximal $\sigma_{\rm SI}(\chi p)$ in the allowed parameter space is an order of magnitude below the CoGeNT region while some of the points in the allowed parameter space do lie in the DAMA/LIBRA region. Next, in the left panel of Fig. 3 we give a plot of $\sigma_{\rm SI}(\chi p)$ vs the CP even Higgs mass M_H. Here we exhibit the parameter space constrained by the Tevatron data on the Higgs searches. Inclusion of this constraint reduces the size of $\sigma_{\rm SI}(\chi p)$ to be no greater than $\sim 5 \times 10^{-42}$ cm^2. We note that in the analysis of both Fig. 2 and the left panel of Fig. 3 we have not included the $B_s \to \mu^+\mu^-$ constraint. We will see below that inclusion of the $B_s \to \mu^+\mu^-$ constraint further reduces the maximally allowed size of $\sigma_{\rm SI}(\chi p)$.

The CDF data give the following upper limit from the process $B_s \to \mu^+\mu^-$ [20]

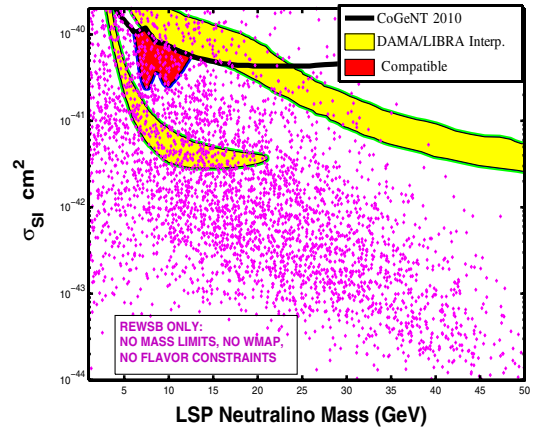

FIG. 1 (color online). A display of the spin independent neutralino-proton cross section $\sigma_{\rm SI}(\chi p)$ as a function of LSP mass with inclusion of REWSB constraints. The sparticle mass limits, WMAP constraints, and flavor constraints are not imposed. The analysis of this figure should be compared with the analysis of Fig. 2, which shows the large reduction in the parameter space when sparticle mass and WMAP constraint are imposed (see Bottino *et al.* [11]).

$$\mathcal{B}r(B_s \to \mu^+\mu^-) < (5.8/4.7) \times 10^{-8} \quad (95/90\% \text{ C.L.}). \tag{4}$$

We will see that these limits are quite constraining at large $\tan\beta$ specifically for regions where the spin independent cross sections get large. $B_s \to \mu^+\mu^-$ has a leading $\tan^6\beta$ dependence, which is further modified by loop corrections [15,21] so that

$$B_s \to \mu^+\mu^- \sim 1.92 \times 10^{-6} (\tan\beta)^6 (M_A/\text{GeV})^{-4} \times \frac{(16\pi^2\epsilon_Y)^2}{(1 + (\epsilon_0 + y_t^2\epsilon_Y)\tan\beta)^2(1 + \epsilon_0\tan\beta)^2}, \tag{5}$$

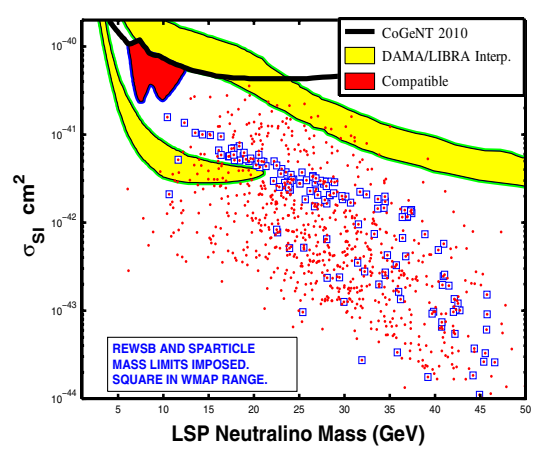

FIG. 2 (color online). A display of the spin independent neutralino-proton cross section $\sigma_{\rm SI}(\chi p)$ in MSSM with the inclusion of REWSB and mass limit constraints. The tagged boxed points accommodate the WMAP results (see text) while the untagged ones do not. Shown also are the CoGeNT limits [6].

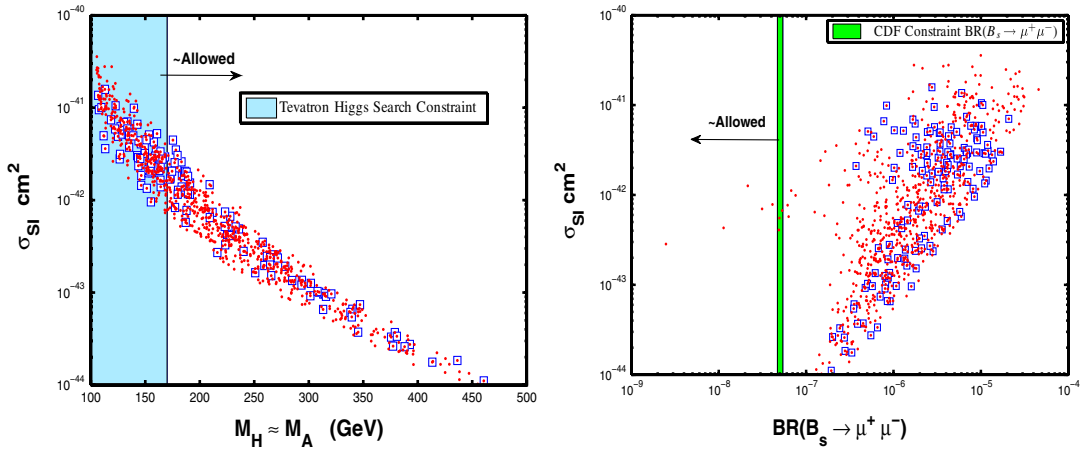

FIG. 3 (color online). Left: An exhibition of the spin independent neutralino-proton cross section $\sigma_{\rm SI}(\chi p)$ in MSSM as a function of the CP even Higgs mass M_H. The blue band is the approximate range of Higgs mass disallowed by Tevatron searches. The analysis shows that the reach of the spin independent cross section is strongly constrained by the mass of the Higgses [24,25]. Right: Spin independent cross section correlated to the branching ratio $B_s \to \mu^+\mu^-$. The region of maximal $\sigma_{\rm SI}(\chi p)$ is inconsistent with constraints from CDF data on $B_s \to \mu^+\mu^-$ [20]. The models shown have large $\tan\beta$ and light scalars (see left panel and Sec. II for the full parameter space).

where ϵ_0 and ϵ_Y are loop corrections [Eq. (5) is an approximate form for $B_s \to \mu^+\mu^-$ and in the analysis we have used the full form]. Equation (5) exhibits the fact that a light SUSY Higgs boson and a large $\tan\beta$ tend to enhance the $B_s \to \mu^+\mu^-$ branching ratio, which is subject to strong Tevatron limits. These Tevatron constraints are exhibited in the right panel of Fig. 3. Here the allowed region of the parameter space consistent with the upper limit on $B_s \to \mu^+\mu^-$ does not fall within the region consistent with the region where CoGeNT or DAMA are sensitive to $\sigma_{\rm SI}(\chi p)$. As is easily seen, very few parameter points lie in this region consistent with the $B_s \to \mu^+\mu^-$ constraint and relatively large $\sigma_{\rm SI}(\chi p)$, and those that fall in the region consistent with the $B_s \to \mu^+\mu^-$ constraint have $\sigma_{\rm SI}(\chi p)$, which does not exceed $\sim 5 \times 10^{-42}$ cm^2.

The above result is found when fixing $\Sigma_{\pi N} = 55$ MeV with $f_d^p = 0.033$, $f_u^p = 0.023$, $f_s^{p=n} = 0.26$, $f_d^n = 0.042$, $f_u^n = 0.018$, with the hadronic matrix elements $\langle N|m_q \bar{\psi}_q \psi_q|N\rangle = f_q^N M_N$. Of the above quantities, the largest uncertainties in the calculation of $\sigma_{\rm SI}(\chi p)$ arise from variations in the pion-sigma nucleon term, followed by uncertainties in the strange quark contribution (for a recent analysis see [22]). It is useful to illustrate the effects of these uncertainties. In the region of large $\tan\beta$ (the region of interest here where the $\sigma_{\rm SI}(\chi p)$ can be enhanced) for the case of a light neutralino with mass of 7 GeV we find this can lead to an uncertainty as large as a factor of ~ 3 in the $\sigma_{\rm SI}(\chi p)$ over the window $\Sigma_{\pi N} = 64 \pm 8$ MeV. The uncertainty in f_s^p can generally lead to a factor of ~ 2. Taking into account the above, coupled with sparticle mass constraints and the WMAP constraint, we do not find any models that can fall in the Cogent preferred region. It should be noted that the very recent lattice QCD simulations from one group [23] may imply a further uncertainty (which could even lower the cross section). Further detailed analyses on such simulations need to be carried out.

We note that extending the parameter space of the models to include larger scalar masses will suppress $B_s \to \mu^+\mu^-$ and, of course, weaken this constraint. However, heavy scalars will reduce the $\sigma_{\rm SI}(\chi p)$, and it is for this reason we have focused on the parameter space above. We discuss this further below.

III. DISCUSSION AND EXTENSIONS

We now discuss our findings further by extending the set of models. Thus it is also interesting to extend the parameter space to include a larger set of nonuniversalities. As a check on our conclusions, we have carried out an exhaustive scan of high scale supergravity models with nonuniversalities in various sectors. These include nonuniversalities in the gaugino (NUG) masses, nonuniversalities in the Higgs boson (NUH) masses, nonuniversalities in the third generation scalar (NU3) masses, and nonuniversalities in the trilinear couplings (NUA) in the third generation sector A_s, $s = \tilde{\tau}$, $\tilde{b}$, $\tilde{t}$. We utilize Monte Carlo simulations generating several million candidate models for the nonuniversal cases discussed above. Thus in total we investigate NUG, NUA, NUH, and NU3 simulating a total of 4×10^6 candidate models. Specifically the parameter space considered in the Monte Carlo scans are as follows: $0 < m_0/\text{GeV} < 1000$, $1 < \tan\beta < 60$, $169 < m_t/\text{GeV} < 173$, $0 < M_1/\text{GeV} < 1000$, $0 < M_2/\text{GeV} < 1000$, $0 < M_3/\text{GeV} < 1000$, $-5 < A_\tau/m_0 < 5$, $-5 < A_t/m_0 < 5$, $-5 < A_b/m_0 < 5$, $0 < M_{H_u}/\text{GeV} < 1000$, $0 < M_{H_d}/\text{GeV} < 1000$.

Within this rather large parameter space of high scale models and under the constraint of REWSB and other experimental constraints already discussed, our conclu-

sions remain that of Sec. II. We note in passing that in the region of interest the μ parameter typically lies in the range 100–300 GeV and the smaller μ's are associated with significant Higgsino components of the neutralino, which enhance the $\sigma_{\rm SI}$. However, $\sigma_{\rm SI}$ significantly larger than 10^{-42} cm^2 still appear difficult to achieve even with the inclusion of nonuniversalities. Further, one finds that while the REWSB alone allows an LSP (lightest [R parity odd] supersymmetric particle) neutralino as low as even a GeV, the present mass bounds on the supersymmetric particles, along with the $B_s \to \mu^+\mu^-$ and WMAP constraints allow only a 20 GeV LSP in the models discussed in Sec. II. Inclusion of a lower limit on the $\tilde{\tau}$ mass of 98.8 GeV pushes the lower limit on the neutralino mass to about 30 GeV. Finally, we remark that for the LSP neutralino mass in the (20–40) GeV region, in SUGRA models with REWSB, the light neutralino masses are further constrained by direct detection experiments [24]. This constraint was not discussed in the detailed analysis of Ref. [9], which focused on collider bounds and cosmological bounds of light neutralinos. In conclusion, under experimental constraints, it is found that for LSP neutralino masses in the (5–10) GeV range in the MSSM with REWSB, $\sigma_{\rm SI}(\chi p)$ is not in excess of 10^{-41} cm^2 and is significantly lower than that needed to explain an excess in the CoGeNT preferred region.

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