SUSY spectrum constraints on direct dark matter detection

V.A. Bednyakov\textsuperscript{1} and H.V. Klapdor-Kleingrothaus

Max-Planck-Institut für Kernphysik,
Postfach 103980, D-69029, Heidelberg, Germany

Abstract

We perform an investigation of the MSSM parameter space at the Fermi scale taking into account available accelerator, non-accelerator and cosmological constraints. Extra assumptions about upper bounds for some of the SUSY particles are also imposed. We show that a non-observation of the SUSY dark matter candidates with a high-accuracy dark matter detector, such as $^{73}$Ge, under above-mentioned assumptions can exclude large domains of the MSSM parameter space and, for instance, can make especially desirable collider search for light SUSY charged Higgs boson.

As already well-known \cite{1, 2, 3}, a direct dark matter search for neutralinos, lightest SUSY particles (LSP), is complimentary to high energy searches for SUSY with colliders. The direct dark matter search is able to give information which is not available from collider physics.

It has been found, that future-possible SUSY spectrum restrictions from colliders, especially such as upper mass bounds for some of the SUSY particles, can strongly enforce the importance of the direct dark matter detection experiments. The main point is that this hypothetical information leads to some important restrictions of the expected event rates for direct dark matter detection. In some cases the restriction is a clear lower limit for this rate. Another obvious example of such restriction is an upper bound for the LSP, which appears only due to the fact that all sfermions and gauginos are not lighter than the LSP. Thus, these high-energy bounds bring in restrictions on the parameter space which can result in a lower limit for the expected rate. Such effect is obtained mostly when the sfermion masses are restricted, but the effect appeared quite strongly especially in the Higgs sector of the MSSM \cite{3}.

The question — to what extent the accelerator searches are able to affect future prospects for direct dark matter search provided the dark matter particle candidate is LSP — was investigated comprehensively in the minimal supergravity SUSY models \cite{2, 4, 5, 6}. In this paper we explore the MSSM parameter space at the weak scale in the most phenomenological way, relaxing completely any constraints following from the unification assumption. On the other side we hold all restrictions from the age of the Universe, accelerator SUSY searches, rare FCNC $b \rightarrow s\gamma$ decay, etc \cite{7, 8, 9}.

The MSSM parameter space in our approach is determined by entries of the mass matrices of neutralinos, charginos, Higgs bosons, sleptons and squarks. To specify the parameter space we give all relevant mass matrices below. The one-generation

\textsuperscript{1}Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, Moscow region, 141980 Dubna, Russia. E-mail: bedny@msun.jinr.ru
squark and slepton mass matrices (using the notation of the third family) are given by \[1\]

\[
\begin{align*}
M_l^2 &= \begin{bmatrix}
M_Q^2 + m_l^2 + m_Z^2 \left( \frac{1}{2} - \frac{2 s_W^2}{3} \right) \cos 2\beta & m_t(A_t - \mu \cot \beta) \\
m_t(A_t - \mu \cot \beta) & M_U^2 + m_l^2 + m_Z^2 s_W^2 \cos 2\beta
\end{bmatrix}, \\
M_b^2 &= \begin{bmatrix}
M_Q^2 + m_b^2 - m_Z^2 \left( \frac{1}{2} - \frac{2 s_W^2}{3} \right) \cos 2\beta & m_b(A_b - \mu \tan \beta) \\
m_b(A_b - \mu \tan \beta) & M_D^2 + m_b^2 - m_Z^2 s_W^2 \cos 2\beta
\end{bmatrix}, \\
M_{\tilde{t}}^2 &= M_L^2 + \frac{1}{2} m_Z^2 \cos 2\beta,
\end{align*}
\]

where \( s_W^2 \equiv \sin^2 \theta_W \) and \( \tan \beta \equiv \langle H_2^0 \rangle / \langle H_1^0 \rangle \). In the \( \tilde{W}^+ - \tilde{H}^+ \) basis, the chargino mass matrix is

\[
X = \begin{pmatrix}
M_2 & \sqrt{2} m_W \sin \beta \\
\sqrt{2} m_W \cos \beta & \mu
\end{pmatrix}.
\]

Two unitary \( 2 \times 2 \) matrices \( U \) and \( V \) are required to diagonalize the chargino mass-squared matrix \( \mathcal{M}_{\tilde{\chi}^+}^2 = V X^T X V^{-1} = U^* X X^T (U^*)^{-1} \). The two mass eigenstates are denoted by \( \tilde{\chi}_1^+ \) and \( \tilde{\chi}_2^+ \). In the \( \tilde{B} - \tilde{W}^3 - \tilde{H}_1^0 - \tilde{H}_2^0 \) basis, the neutralino Majorana mass matrix is

\[
Y = \begin{pmatrix}
M_1 & 0 & -m_Z c_b s_W & m_Z s_b s_W \\
0 & M_2 & m_Z c_b c_W & -m_Z s_b c_W \\
-m_Z c_b s_W & m_Z c_b c_W & 0 & -\mu \\
m_Z s_b s_W & -m_Z s_b c_W & -\mu & 0
\end{pmatrix},
\]

where \( s_\beta = \sin \beta, c_\beta = \cos \beta, \) etc. A \( 4 \times 4 \) unitary matrix \( Z \) is required to diagonalize the neutralino mass matrix \( \mathcal{M}_{\tilde{\chi}^0} = Z^T Y Z^{-1} \) where the diagonal elements of \( \mathcal{M}_{\tilde{\chi}^0} \) can be either positive or negative. The CP-even Higgs mass matrix has the form \[10\]

\[
\frac{1}{2} \left( \frac{\partial^2 V}{\partial \psi_i \partial \psi_j} \right)_{v_1, v_2} \equiv \begin{pmatrix}
H_{11} & H_{12} \\
H_{12} & H_{22}
\end{pmatrix} = \frac{1}{2} \begin{pmatrix}
\tan \beta & -1 \\
-1 & \cot \beta
\end{pmatrix} M_A^2 \sin 2\beta + \frac{1}{2} \begin{pmatrix}
\cot \beta & -1 \\
-1 & \tan \beta
\end{pmatrix} m_Z^2 \sin 2\beta + \omega \begin{pmatrix}
\Delta_{11} & \Delta_{12} \\
\Delta_{12} & \Delta_{22}
\end{pmatrix},
\]

where \( \omega = \frac{3 g_2^2}{16 \pi^2 m_W} \) and:

\[
H_{11} = \frac{\sin 2\beta}{2} \left( \frac{m_Z^2}{\tan \beta} + M_A^2 \tan \beta \right) + \omega \Delta_{11},
\]
\[
H_{22} = \frac{\sin 2\beta}{2} \left( m_Z^2 \tan \beta + \frac{M_A^2}{\tan \beta} \right) + \omega \Delta_{22},
\]
\[
H_{12} = H_{21}^* = -\frac{\sin 2\beta}{2} \left( m_Z^2 + M_A^2 \right) + \omega \Delta_{12}.
\]
The mixing angle \( \alpha_H \) is obtained from

\[
\sin 2\alpha_H = \frac{2H_{12}^2}{m_{H_1^0}^2 - m_{H_2^0}^2}, \quad \cos 2\alpha_H = \frac{H_{11}^2 - H_{22}^2}{m_{H_1^0}^2 - m_{H_2^0}^2}.
\]

The mass of the charged Higgs boson is given by \( m_{CH}^2 = m_{W}^2 + M_A^2 + \omega \Delta_{ch} \).

Therefore free parameters are: \( \tan \beta \) is the ratio of neutral Higgs boson vacuum expectation values, \( \mu \) is the bilinear Higgs parameter of the superpotential, \( M_1, M_2 \) are soft gaugino masses, \( M_A \) is the CP-odd Higgs mass, \( m_{L}^2, m_{Q}^2, m_{U}^2, m_{D}^2 \) are squared squark mass parameters for the 1st and 2nd generation, \( m_{L_E}^2, m_{E}^2 \) are squared slepton mass parameters for the 1st and 2nd generation, \( m_{Q_3}^2, m_{T}^2, m_{B}^2 \) are squared 3rd generation squark mass parameters, \( m_{L_A}^2, m_{A}^2 \) are squared 3rd generation slepton mass parameters and \( A_t, A_b, A_\tau \) are soft trilinear couplings for the 3rd generation. With these parameters one completely determines the SUSY spectrum and the MSSM coupling constants at the Fermi scale.

A dark matter (DM) event is elastic scattering of a relic DM neutralino from a target nucleus producing a nuclear recoil which can be detected by a suitable detector. The differential event rate in respect to the recoil energy is the subject of experimental measurements. The rate depends on the distribution of the DM neutralinos in the solar vicinity and the cross section of neutralino-nucleus elastic scattering.
In our analysis we use the so-called total event rate \( R \) which is integrated over recoil energies, and which is useful for searching for domains with extreme rates. We follow our paper [11], where one can find all relevant formulas and astrophysical parameters. To calculate the event rate we use for the relic neutralino mass density and for the escape neutralino velocity commonly accepted values 0.3 GeV/cm\(^3\) and 600 km/s, respectively. Their experimental variations can slightly change \( R \) but leave the dependence of \( R \) on the MSSM parameters (Fig. 1 and 2) unaffected. To compare our results with sensitivities of different dark matter experiments we calculate also the total cross section for relic neutralino elastic scattering on the nucleon.

The present lifetime of the Universe implies an upper limit on the expansion rate and correspondingly on the total relic abundance. One finds [12] that the contribution of each relic particle species \( \chi \) has to obey \( \Omega_\chi h^2_0 < 1 \), where \( h_0 \) is the Hubble constant and the relic density parameter \( \Omega_\chi = \rho_\chi / \rho_c \) is the ratio of the relic neutralino mass density \( \rho_\chi \) to the critical one \( \rho_c = 1.88 \times 10^{-29} h^2_0 \text{g cm}^{-3} \). Assuming that the neutralinos form a dominant part of the dark matter in the Universe one obtains a lower limit on the neutralino relic density. We restrict our analysis with the cosmological constraint

\[
0.025 < \Omega_\chi h^2_0 < 1 \quad [1, 7, 11].
\]

We calculate \( \Omega_\chi h^2_0 \) following the standard procedure on the basis of the approximate formula [13, 14]. We take into account all channels of the \( \chi - \chi \) annihilation. Since the neutralinos are mixtures of gauginos and higgsinos, the annihilation can occur both, via s-channel exchange of the \( Z^0 \) and Higgs bosons and t-channel exchange of a scalar particle, like a selectron [15]. This constrains the parameter space [9, 13, 16].

Another stringent constraint is imposed by the branching ratio of \( b \rightarrow s\gamma \) decay, measured by the CLEO collaboration to be \( 1.0 \times 10^{-4} < B(b \rightarrow s\gamma) < 4.2 \times 10^{-4} \). In the MSSM this flavor changing neutral current process receives contributions from \( H^\pm - t, \tilde{\chi}^\pm - \tilde{t} \) and \( \tilde{g} - \tilde{q} \) loops in addition to the standard model \( W - t \) loop. These also strongly restrict the parameter space [17].

The masses of the supersymmetric particles are constrained by the results from the high energy colliders LEP at CERN and Tevatron at Fermilab. This imposes relevant constraints on the parameter space of the MSSM. We use the following experimental restrictions for the SUSY particle spectrum in the MSSM [15]:

- \( M_{\tilde{\chi}^+_1} \geq 65 \text{ GeV} \) for the light chargino,
- \( M_{\tilde{\chi}^0_1} \geq 99 \text{ GeV} \) for the heavy chargino,
- \( M_{\tilde{\chi}^0_{1,2,3}} \geq 45, 76, 127 \text{ GeV} \) for non-LSP neutralinos, respectively;
- \( M_\rho \geq 43 \text{ GeV} \) for sneutrinos,
- \( M_{\tilde{\ell}_R} \geq 70 \text{ GeV} \) for selectrons,
- \( M_{\tilde{\tau}_1} \geq 210 \text{ GeV} \) for squarks,
- \( M_{\tilde{q}} \geq 85 \text{ GeV} \) for light top-squark,
- \( M_{H^0} \geq 79 \text{ GeV} \) for neutral Higgs bosons,
- \( M_{\tilde{\chi}_H} \geq 70 \text{ GeV} \) for charged Higgs boson.

In our numerical analysis the parameters of the MSSM are randomly varied at the Fermi scale in the intervals given below:

\[
\begin{align*}
-1000 \text{ GeV} & < M_1 < 1000 \text{ GeV} \\
-2000 \text{ GeV} & < M_2 < 2000 \text{ GeV} \\
1 & < \tan \beta < 50 \\
-2000 \text{ GeV} & < \mu < 2000 \text{ GeV} \\
60 \text{ GeV} & < M_A < 1000 \text{ GeV} \\
10 \text{ GeV}^2 & < m_{Q_1}^2 < 1000000 \text{ GeV}^2 \\
10 \text{ GeV}^2 & < m_{Q_2}^2 < 1000000 \text{ GeV}^2 \\
10 \text{ GeV}^2 & < m_{Q_3}^2 < 1000000 \text{ GeV}^2 \\
-2000 \text{ GeV} & < A_t < 2000 \text{ GeV}.
\end{align*}
\]
For each parameter some number, between 0 and 1, was defined by the random generator from the CERN Library. With this number and lower and upper bounds given above the random value of the MSSM parameter was calculated by means of linear function. We stopped running when the lower border of the rate $R$ stopped move down and only density of points continued to increase. In our main scan we have tested about $10^8$ models. and only about $10^5$ models passed all constraints.

For simplicity, for other sfermion mass parameters we used the relations $m_{\tilde{U}_{1,2}}^2 = m_{\tilde{Q}_{1,2}}^2$, $m_{\tilde{D}_{1,2}}^2 = m_{\tilde{E}_{1,2}}^2$, $m_{\tilde{Q}}^2 = m_{\tilde{Q}_{3}}^2$, $m_{\tilde{B}}^2 = m_{\tilde{E}_{3}}^2$, $m_{\tilde{T}}^2 = m_{\tilde{L}}^2$, and $A_b$ and $A_\tau$ are fixed to be zero. We consider the domain of the MSSM parameter space, in which we perform our scans, as quite spread and natural. Any extra expansion of it like, for example, using $-10$ TeV $< M_2 <$ 10 TeV, etc, of course, can be possible, but should be considered as quite unnatural in the framework of the idea of SUSY.

Some of results of the main (without extra constraints) scan are presented in

Figure 1: Total event rate in $^{73}$Ge versus MSSM parameters $M_2$, $\tan \beta$, $\mu$, $M_A$, $m_{\tilde{Q}_{1,2}}^2$ (labeled as "sq2") and $m_{\tilde{L}}^2$ (as "sl2").
Figure 2: Total event rate in $^{73}$Ge versus masses of squarks, sleptons, light chargino (practically the same scatter plot one obtains for next-to-lsp neutralino), heavy chargino, light CP-even neutral Higgs boson and charged Higgs boson (the same is for heavy Higgs boson).

Figs. 1–3 as scatter plots. The main feature we paying our attention to is the presence of a lower bound for the total event rate $R$. An absolute minimum value of about $10^{-6}$ events/day/kg in a $^{73}$Ge detector is obtained in the above-mentioned domain of the MSSM parameter space. There is a clear growth (up to one order of magnitude) of the lower bound only with $\tan \beta$ (Fig. 1). In all other cases there is a decrease of the lower bound, the decrease is most sharp with $|\mu|$, $M_A$ (about 5 orders of magnitude) and $M_{Q_{1,2}}^2$ (Fig. 1) and with squark mass $M_q$, heavy chargino mass $M_{\tilde{\chi}_1^+}$ and charged Higgs boson mass $M_{\text{CH}}$ (Fig. 2).

Figure 3 (upper panel) gives expectations for the total event rate $R$ obtained by means of scanning the parameter space at the Fermi scale without any extra limitations on the SUSY particle spectrum. There is a lower bound, which decreases with mass of the LSP and reaches an absolute minimum of about $10^{-6}$ events/day/kg in a
Figure 3: Total event rate in $^{73}\text{Ge}$ in events/day/kg (upper panel) and cross section of scalar elastic scattering of LSP (WIMP) off neutron in GeV$^{-2}$ (lower panel) versus mass of LSP (in GeV).

$^{73}\text{Ge}$ detector in the region of LSP masses 600–700 GeV. The phenomenologically allowed masses of the LSP are spread from about 5 GeV till about 800 GeV. Considering both scatter plots in Fig. 3 one also can conclude that, due to the practical absence of a lower bound for the scalar cross section of WIMP-neutron interaction, the lower bound for the rate is mainly established by the spin-dependent interaction, which in contrast to the scalar interaction is associated with an about 3-order-of-magnitude larger lower bound for WIMP-nucleon cross section.

The existence of the lower bound for the event rate itself and the variation of the bound with the MSSM parameters and masses of the SUSY particles allow us to consider prospects to search for dark matter under special assumptions about restricted values for the above-mentioned parameters and masses. To this end we have performed a number of extra scans taking into account extra limitations on single squark mass ($M_{\text{sq}} < 250, 230$ GeV), light neutral CP-even Higgs boson mass.
Figure 4: Different lower bounds for the total event rate in $^{73}\text{Ge}$ (events/day/kg) versus mass of the LSP (GeV). Here $M_{\text{sq}}, M_{\text{CH}}, M_{\text{Hl}}$ denote masses of the squark, the charged Higgs boson and the light neutral CP-even Higgs boson respectively. Heavy chargino mass is denoted as $M_{\text{ch-os}}$. "Full" corresponds to the lower bound obtained from main (unconstrained) scan, and "Light spectrum" denotes the lower bound for $R$, which is obtained with all sfermion masses lighter than about 300 GeV. The horizontal dotted line represents expected sensitivity for the direct dark matter detection with GENIUS.

$(M_{\text{Hl}} < 80, 100, 120 \text{ GeV})$, charged Higgs boson mass $(M_{\text{CH}} < 150, 200 \text{ GeV})$ and heavy chargino mass $(M_{\text{ch-os}} < 250 \text{ GeV})$. We also considered the situation where masses of all superpartners not exceed 300–400 GeV. All corresponding curves together with the absolute lower bound from the unconstrained scan are depicted in Fig. 4.

A restriction of the single (light) squark mass to be quite small $(M_{\text{sq}} < 230 \text{ GeV})$ as well as another assumption that all sfermions masses not exceed 300–400 GeV, put upper limits on the mass of the LSP and therefore do not permit $R$ to drop very deeply with increasing LSP mass. Furthermore in both cases the lower bound for the rate is established for all allowed masses of the LSP at a level of $10^{-3}$ events/kg/day. This value for the event rate we consider as an optimistic sensitivity expectation for high-accuracy future detectors of dark matter, such as GENIUS [19, 20]. Practically the same lower bound one obtains under the assumption that both charginos are quite light $(M_{\text{ch-os}} < 250 \text{ GeV})$. In this case LSP masses do not exceed 250 GeV and lower rate bound is $2 \div 5 \times 10^{-3}$ events/kg/day.

One can see that the mass of the light neutral CP-even Higgs boson $M_{\text{Hl}}$, perhaps
Figure 5: WIMP-nucleon cross section limits in pb for scalar interactions as function of the WIMP mass in GeV. Filled circles present our calculations with light SUSY spectrum. Filled triangles give the cross section with assumption of $M_{CH} < 200$ GeV.

most easily measurable experimentally due to its smallness, has unfortunately only a very poor restrictive potential. Already for the mass value $M_{H^l} < 80$ GeV, which is practically equal to the experimental border ($M_{H^l}^{exp} = 79$ GeV), the lower bound for the event rate in a detector of $^{73}$Ge is far below $10^{-3}$ events/kg/day. The situation looks most promising when one limits the mass of the charged Higgs boson.

From Fig. 2 one can conclude that in the charged Higgs boson low-mass region other masses of both CP-even and CP-odd Higgs bosons are also restricted from above. Therefore coupling constants of the scalar neutralino-quark interaction, which contain terms with $\frac{1}{m_{H,k}^2}$-factors, are not suppressed enough and the rate can not decrease significantly. The lower bound of the rate increases when the mass $M_{CH}$ decreases (Fig. 2) and for $M_{CH} < 200$, 150 GeV reaches values of $\sim 10^{-2}$, $\sim 10^{-1}$ events/kg/day, respectively practically for all allowed masses of the LSP. These values can be reached not only with GENIUS ($10^{-2}$ events/kg/day), but also with some other near-future direct dark matter detectors [21]. The fact also is confirmed by Fig. 3 where cross section limits for the WIMP-nucleon scalar interactions for different experiments are presented as functions of the WIMP mass. Light-filled circles in Fig. 3 give the scalar cross sections, calculated under the assumption that the SUSY spectrum is quite light (see Fig. 4). Filled triangles give the cross section, obtained with charged Higgs boson mass restriction $M_{CH} < 200$ GeV.

Therefore if it happened, for instance, that either the SUSY spectrum is indeed light, or the charged Higgs boson mass indeed does not exceed 200 GeV, in both cases at least the GENIUS experiment should detect a dark matter signal. If we consider a
Figure 6: WIMP-nucleon cross section limits in pb for scalar interactions as function of the WIMP mass in GeV. Filled circles present our calculations with light SUSY spectrum and $\tan \beta > 20$. Filled triangles give the same as filled circles, but for $\tan \beta > 40$.

more complicated condition, for example, assuming that the SUSY spectrum is quite light and simultaneously that $\tan \beta$ is quite large, then not only GENIUS, but also CDMS and HDMS \cite{20, 21} will possess very good prospects to detect a dark matter signal. This situation is illustrated in Fig. 6, where besides cross section limits for the WIMP-nucleon scalar interactions for different experiments are given calculations for the case of a light SUSY spectrum with extra assumptions $\tan \beta > 20$ (filled circles) and $\tan \beta > 40$ (filled triangles).

Therefore the obtained correlations between lower limit for the event rate $R$ and some masses of SUSY particles give good prospects for direct dark matter detection with next-generation detectors. The prospects could be very promising if from collider searches one would be able to restrict the mass of the charged Higgs boson at a level of about 200 GeV (light Higgs sector). The observation, due to its importance for dark matter detection, could serve as a source for extra efforts in searching for charged Higgs boson with colliders. Considered together, both these experiments, collider search for charged Higgs and dark matter search for SUSY LSP, become very decisive for a verification of SUSY models.

Otherwise complete non-observation of any dark matter signal with very sensitive dark matter detectors in accordance with Fig. 4–6 would exclude, for example, a SUSY spectrum with masses lighter then 300–400 GeV as well as light SUSY spectrum with large $\tan \beta$ (Fig. 3), charginos with masses smaller then 250 GeV (Fig. 4), charged Higgs boson with $M_{\text{CH}} < 200$ GeV, and therefore any possibility for the entire light Higgs sector in the MSSM (Fig. 5).

The last case is in particular interesting, because if the light charged Higgs boson
is excluded by GENIUS, then either it will be rather unpromising to search it for with colliders, or any positive result of a collider search brings strong contradictions in the MSSM approach to dark matter detections and/or collider SUSY searches.

Finally we would like to comment the following. Unfortunately the MSSM parameter space is huge and to obtain some reliable feeling, concerning, for example, the expected rate of dark matter detection when all relevant experimental and cosmological constraints are taken into account, one has nothing but this statistical numerical method [1, 3, 8, 11, 16].

This method allows lower and upper bounds for any observable to be estimated, and to make conclusions about the prospects for dark matter detection with modern or near-future high-accuracy dark matter detectors. The larger the amount of points which confirms such a conclusion the better. The conclusions we made here are based on hundreds of thousand of points which passed all constraints. Of course, we have no proved protection against peculiar choices of parameters which could lead to some cancellation and to small cross sections even if Higgs masses are small. Nevertheless, the probability of these choices is very small (about 1/100000), otherwise we should already meet them with our random scanning. On the other side, if these peculiar choices exist and one-day would manifest themselves, this would be a very interesting puzzle, because it would be some kind of fine tuning of parameters, which requires strong further development of our understanding of the theory.

The results of this paper may be considered as a good example of the complementarity of modern accelerator and non-accelerator experiments looking for new physical phenomena.

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