SUSY Dark Matter: Direct Searches vs. Collider Experiments

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Abstract. The lightest neutralino in supersymmetric models with conserved R-parity is an attractive candidate for non-luminous matter in the universe. If relic neutralinos are indeed present as dark matter in our galaxy, they can be directly detected in scattering experiments. This could serve as an independent search channel for supersymmetry complementary to collider experiments. I compare the sensitivity of direct detection experiments with the reach for supersymmetry at collider facilities in the framework of the minimal supergravity model.

1. Introduction

Low energy supersymmetry (SUSY) is one of the possible ways nature may have chosen to avoid the well-known problem of naturalness occuring in the Higgs sector of the Standard Model (SM) of particle physics. The simplest supersymmetrized extension of the Standard Model, the Minimal Supersymmetric Standard model (MSSM) [1], introduces superpartners to all SM particles in order to control ultraviolet properties of the theory. Global supersymmetry is subsequently explicitly broken by a collection of soft-breaking terms preserving the UV behavior of the model. In addition, the MSSM conserves R-parity, a symmetry introducing a multiplicative R quantum number equal to +1 for ordinary particles and −1 for their superpartners. This symmetry of the MSSM Lagrangian then ensures that

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the lightest supersymmetric particle (LSP) is stable. In order to avoid easy
detection, the LSP has to be charge and color neutral, and interacts only
weakly with the rest of the particle spectrum. The lightest neutralino \( \tilde{Z}_1 \)
is strongly favored to be the LSP in the MSSM and, due to its favorable
properties, it is also an excellent cold dark matter candidate. If indeed
some or all of dark matter consists of relic neutralinos decoupled from the
thermal equilibrium with other particles in the early stages of the universe,
their direct detection could provide us with an independent signal for su-
persymmetry complementary to standard collider experiment searches.

In order to illustrate the general situation, it is useful to consider the
specific framework of the minimal supergravity (mSUGRA) model \[2\]. This
model assumes that the MSSM and its spectrum arises as a low energy
effective theory from \( N = 1 \) supergravity. SUSY is broken in the hidden
sector of the model at energy scale \( M \sim 10^{10} \) GeV and the information
of SUSY breaking is then gravitationally transmitted to the observable
sector inducing soft SUSY breaking terms at the \( M_{GUT} \) scale. These soft
breaking terms are typically in the range of a few hundred GeV up to a
TeV and in the minimal version of the model they consist of a universal set
of GUT scale parameters: a common scalar mass \( m_0 \), a common trilinear
and bilinear couplings \( A_0 \) and \( B_0 \), and a common gaugino mass \( m_{1/2} \). All
the soft breaking parameters are evolved from the GUT scale down to the
electroweak scale by solving the relevant set of coupled renormalization
group equations and the particle spectrum is calculated. The electroweak
symmetry is broken radiatively as one of the Higgs mass parameters is
driven negative in the process of renormalization group evolution and as
a consequence the B parameter together with the absolute value of the
Higgs parameter in the superpotential \( |\mu| \) can be traded for the ratio of the
vacuum expectation values of the two neutral Higgs fields \( \tan \beta \) and \( M_Z \).

The resulting parameter set

\[
m_0, m_{1/2}, A_0, \tan \beta, \text{sgn}(\mu)
\]

substantially reduces the number of supersymmetric parameters.

2. Direct detection of neutralinos

The relic abundance of neutralinos in mSUGRA models depends on the
particular set of parameters and the superpartner spectrum \[3\]. It can be
very small with \( \Omega h^2 < 10^{-3} \) especially if the total mass of two neutrali-
nos is close to the mass of \( Z^0 \) or the light neutral Higgs boson so that
an s-channel resonance occurs in the neutralino annihilation cross section
effectively wiping out the relic density. Generally, however, there tends
to be a significant region of parameter space for relatively small values of
Figure 1. Feynman diagrams contributing to the scalar part of the effective Lagrangian.

$m_0$ and $m_{1/2}$ where $\Omega h^2$ lies within the cosmologically interesting interval between 0.01 and 1. Heavy spectra, with the exception of the resonance cases, tend to produce values of $\Omega h^2 > 1$ which would lead to universe less than 10 billion years old. The best way to confirm the existence of ambient relic neutralinos, at least in our vicinity, would be to devise a detecting method capable of providing a recognizable experimental signature. The most straightforward method of direct detection relies on direct measurement of the neutralino scattering off the nuclei in a detector. The main ingredients in the calculation of direct detection rates include the neutralino-quark elastic scattering amplitude, related by the crossing symmetry to the $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}$ annihilation process contributing to the relic density calculation, and the amplitude for neutralino scattering on gluons proceeding through one-loop diagrams. The parton level amplitudes then have to be properly convoluted with quark and gluon distribution functions.
in nucleons and a nuclear model must be specified for a particular detector nucleus to account for structure effects.

The effective elastic scattering Lagrangian can generally be divided into two parts

\[ \mathcal{L}^{\text{eff}}_{\text{elastic}} = \mathcal{L}^{\text{eff}}_{\text{scalar}} + \mathcal{L}^{\text{eff}}_{\text{spin}}. \]  

The scalar Lagrangian receives contributions from neutralino-quark interaction via squarks and Higgs bosons exchange, and from neutralino-gluon interactions at one-loop level involving quarks, squarks and the Higgses in the loop diagrams. The parton level Lagrangian includes all effective couplings obtained from the matching between the full MSSM and the effective theory at scale \( Q \) (typically \( \sim m_{\tilde{Z}_1} \)) and can be converted into an effective neutralino-nucleon Lagrangian

\[ \mathcal{L}^{\text{eff}}_{\text{scalar}} = f_p \bar{\chi} \tilde{\Psi}_p \chi \bar{\Psi}_p + f_n \bar{\chi} \tilde{\Psi}_n \chi \bar{\Psi}_n. \]  

Effective couplings \( f_p \) and \( f_n \) contain all the relevant information about physics above scale \( Q \) and about nucleonic parton structure. The differential cross section for a neutralino scattering off a nucleus \( X_A \) with mass \( m_A \) is then expressed as

\[ \frac{d\sigma^{\text{scalar}}}{d|\vec{q}|^2} = \frac{1}{\pi v^2} [Zf_p + (A - Z)f_n]^2 F^2(Q_r), \]  

where \( \vec{q} = \frac{m_A m_{\tilde{Z}_1}}{m_A + m_{\tilde{Z}_1}} \vec{v} \) is the transferred momentum, \( Q_r = \frac{|\vec{q}|^2}{2m_A} \) and \( F^2(Q_r) \) is the scalar nuclear form factor. It is obvious from Eqn. (3) that the scalar interaction cross section increases quadratically with increasing mass of the target nucleus.

Analogously, interaction between the neutralino and nucleon spins is described by a spin-dependent nucleon level Lagrangian

\[ \mathcal{L}^{\text{eff}}_{\text{spin}} = 2\sqrt{2}(\bar{\chi}\gamma^\mu \gamma_5 \chi \tilde{\Psi}_p s_\mu \Psi_p + a_n \bar{\chi}\gamma^\mu \gamma_5 \chi \tilde{\Psi}_n s_\mu \Psi_n), \]  

explicitly involving the nucleon spin vectors \( s_\mu \). Coefficients \( a_p \) and \( a_n \) depend on the nucleonic spin factors parametrizing the nucleonic spin matrix elements and on the MSSM parameters entering through the parton level effective couplings. For a nucleus with total angular momentum \( J \), the spin interaction differential cross section takes the form

\[ \frac{d\sigma^{\text{spin}}}{d|\vec{q}|^2} = \frac{8}{\pi v^2} \Lambda^2 J(J + 1) \frac{S(|\vec{q}|)}{S(0)}, \]  

where \( \frac{S(|\vec{q}|)}{S(0)} \) is the nuclear spin form factor normalized to 1 for pointlike particles, and \( \Lambda = \frac{J}{4}[a_p \langle S_p \rangle + a_n \langle S_n \rangle] \). The quantities \( \langle S_p \rangle \) and \( \langle S_n \rangle \)
Figure 2. Feynman diagrams contributing to the spin dependent part of the effective Lagrangian.

represent the expectation value of the proton (neutron) group spin content in the nucleus.

The differential detection rate is calculated by summing the scalar and spin interaction contributions and convoluting them with the local neutralino relic density $\rho_{\tilde{Z}_1}$

$$
\frac{dR}{dQ_r} = \frac{4}{\sqrt{\pi^3 m_{\tilde{Z}_1} v_0}} T(Q_r) \left\{ [Z f_p + (A - Z) f_n]^2 F^2(Q_r) + 8\Lambda^2 J(J+1) \frac{S(|\vec{q}|)}{S(0)} \right\},
$$

where $v_0 \sim 220 \text{ km/s}$ is the circular speed of the Sun around the center of our galaxy and

$$
T(Q_r) = \frac{\sqrt{\pi v_0}}{2} \int_{v_{\text{min}}}^{\infty} \frac{f_{\tilde{Z}_1}(v)}{v} dv
$$

integrates over the neutralino velocity distribution. In order to obtain the total detection rate, the differential rate in Eqn. (6) has to be integrated over the relevant interval of $Q_r$ ranging typically from zero up to about 100 keV.

It is important to realize that many of the quantities entering the detection rate calculation, particularly those related to the nucleonic matrix elements of the scalar and spin operators, are affected by a fair amount of uncertainty as they come from experiment. This uncertainty is even bigger for the nucleonic spin structure constant. Similarly, the nuclear form factors are subject to the assumptions of a particular nuclear model and their reliability depends on the degree to which that model accommodates nuclear experimental data. But the most significant source of uncertainty in the detection rate calculation is associated with the value of the
local neutralino relic density. Here the results depend on particular galactic formation models and the error margin can be easily as large as a factor of two or more. It is therefore necessary to view the numerical results with these limitations in mind.

I will discuss here numerical results obtained for a particular case of a $^{73}\text{Ge}$ detector. This isotope is suitable since it is a relatively heavy element with mass $m_{^{73}\text{Ge}} = 67.93\text{ GeV}$ and a non-zero total spin $J = \frac{9}{2}$. Both the scalar interaction and the spin interaction therefore contribute to the elastic scattering cross section. In fact, in some parts of the mSUGRA parameter space, particularly for $\mu < 0$ and moderate values of $\tan \beta$ ($\tan \beta \sim 4 - 10$), the spin dependent contribution is quite comparable in magnitude with the coherent scalar part. This goes against the standard view that for sufficiently heavy nuclei the spin dependent component is always significantly smaller than the scalar part. Another reason for choosing $^{73}\text{Ge}$ is the fact that the nuclear properties of this isotope have been studied and model calculations of the necessary form factors and expectation values are available in the literature.

Qualitative behavior of the detection rate as a function of the mSUGRA parameters can be understood based on an analysis of the general formulas tracking down the processes contributing most to the scattering cross section within the particular framework of minimal supergravity. First of all, Eqn. (6) suggests that the detection rate is inversely proportional to the lightest neutralino mass $m_{\tilde{\chi}^0_1}$. Since the lightest neutralino is almost a pure bino (albeit with non-vanishing wino and higgsino admixtures), its mass scales with the universal gaugino mass parameter $m_{1/2}$ and so the rate is a decreasing function of $m_{1/2}$. It turns out that the dominant part of the neutralino-nucleus scattering amplitude comes from the $t$-channel heavy Higgs boson exchange between the quarks and neutralinos. The Higgs exchange contribution to the $f_N$ coupling is

$$f^{(H)}_N = m_N \sum_{q=u,d,s} f^{(N)}_{Tq} \sum_{j=1,2} \frac{c_{Z}^{(j)} c_{q}^{(j)}}{m_{H_j}^2}, \quad (8)$$

where $f^{(N)}_{Tq}$ is a phenomenological constant. The CP-even Higgs couplings are

$$c_{Z}^{(1)} = \frac{1}{2}(g_N^2 - g_N^L)(N_{\ell 3} \sin \alpha + N_{\ell 4} \cos \alpha) \quad (9)$$

for the lighter Higgs and

$$c_{Z}^{(2)} = \frac{1}{2}(g_N^2 - g_N^L)(N_{\ell 3} \sin \alpha - N_{\ell 4} \cos \alpha) \quad (10)$$
Figure 3. Illustration of the $^{73}$Ge detection rate $\tan \beta$ dependence for a particular choice of mSUGRA parameters $m_0 = 150$ GeV, $m_1/2 = 200$ GeV and $A_0 = 150$ GeV, and both signs of $\mu$.

for the heavier Higgs, where $\alpha$ is the Higgs mixing angle. The quark coefficients are evaluated as

$$c_q^{(i)} = \frac{g}{2m_W} r_q^{(i)}$$

with

$$r_u^{(1)} = -\frac{\sin \alpha}{\sin \beta}, \quad r_u^{(2)} = -\frac{\cos \alpha}{\sin \beta}$$

for the up type quarks and

$$r_d^{(1)} = -\frac{\cos \alpha}{\cos \beta}, \quad r_d^{(2)} = \frac{\sin \alpha}{\cos \beta}$$

for the down type quarks. The contribution from the light Higgs goes through zero for $\mu < 0$ as the coupling in Eqn. (9) changes sign for $\tan \beta \sim 7$.
3 – 4 and the rate for the $\mu < 0$ is therefore systematically smaller than for $\mu > 0$. Moreover, the Higgs couplings to the down type quarks are enhanced by a $\tan \beta$ factor and therefore the total detection rate has a tendency to grow substantially with increasing $\tan \beta$ as shown in Fig. 3. Variation of $A_0$ can also alter the resulting detection rate which generally increases with $A_0$ increasing from negative to positive values. It is necessary to keep that in mind when analyzing the mSUGRA results.

3. Collider signals

Searches for SUSY signals in various channels is one of the major tasks at collider experiments. The implications of mSUGRA for both $e^+e^-$ and hadron colliders have been studied and experimental reaches for individual channels as well as the integrated discovery potential have been worked out. If a signal for supersymmetry is discovered, $e^+e^-$ colliders give a better chance of disentangling the signal and determining the actual SUSY parameters, especially if the electron beam is polarized. The possibility of precise determination of the center of mass energy is also an important factor distinguishing the $e^+e^-$ colliders from the hadron machines.

For the purposes of comparison between expected SUSY reaches at colliders and possible direct detection rates in $^{73}$Ge, I consider four major collider projects, either currently in operation or planned for the near future.

**LEP2** is an $e^+e^-$ machine operating at CERN with non-polarized beams. The target center of mass energy considered here for SUSY searches was chosen at 190 GeV while the operating energy for the current run is 189 GeV. In the calculations, an integrated luminosity of 300 fb$^{-1}$ was used as a benchmark for the SUSY production processes.

**Tevatron** is a $p\bar{p}$ collider operating at $\sqrt{s} = 1.8$ TeV and two major upgrades affecting the SUSY searches are planned for this collider. The Main Injector (MI) upgrade will increase the energy to 2 TeV and the integrated luminosity will reach 1 – 2 fb$^{-1}$, so these values were used in the analysis of MI’s potential for discovering SUSY. The second upgrade, TeV33, will possibly increase the luminosity up to 25 fb$^{-1}$ and will further enhance the reach for SUSY at the Tevatron.

**LHC**, or the Large Hadron Collider, will collide protons with protons at the center of mass energy of 14 TeV. All evaluations of the LHC production capabilities in the SUSY channels mentioned in this talk assume an integrated luminosity of 10 fb$^{-1}$.

**NLC** - the Next Linear Collider - is a project of a linear $e^+e^-$ collider, possibly with polarized beams, whose energy at the first stage of operation would be set at 500 GeV and the luminosity might reach 20 fb$^{-1}$. 

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3.1. $e^+e^-$ collider signals

**Charginos.** The $e^+e^- \rightarrow \tilde{W}_1\tilde{W}_1$ chargino production signal occurs in the multi-jet+$E_T$ channel, the mixed jets+$\ell+E_T$ channel and the leptonic $\ell\ell'$+$E_T$ channel observable both at LEP2 and the NLC. Here and in further text electron or muon are meant by leptons. The production usually has a large cross section and consequently the regions where charginos become observable almost coincides with the kinematical limit. Only regions of small $m_0$ allowing the decay mode $\tilde{W}_1 \rightarrow \tilde{\nu}\ell$ to turn on producing soft leptons are an exception to this rule. The lightest charginos are gauginos and therefore the regions of their observability lie below contours of approximately constant $m_{1/2}$.

**Neutralinos.** Production of the lightest and second lightest neutralino $e^+e^- \rightarrow \tilde{Z}_1\tilde{Z}_2$ can materialize in the detector as a $\ell\ell+E_T$ or a jets+$E_T$ signal depending on the decay mode of $Z_2$. Neutralino signals can in some cases extend beyond the reach of the chargino channel since $\tilde{Z}_1\tilde{Z}_2$ production can be allowed when the production of charginos is disallowed because of kinematical constraints. Usually this enhancement occurs in the region of smaller $m_0$ and typically is not very big.

**Sleptons.** In $e^+e^-$ collisions, selectron production is preferred over production of other sleptons due to the presence of additional $t$-channel exchange diagrams. Selectron production results in a clean $e^+e^-+E_T$ signal with a substantial acollinearity allowing to distinguish it from the background SM processes. The selectron signal adds to the SUSY reach mainly in the small $m_0$ region where sleptons are light.

3.2. Hadron collider signals

**Gluinos and squarks.** Production of squarks and gluinos typically results in a jets+$E_T$ signature although the details of the expected signal depend on the particle spectrum and the subsequent decay cascade may also lead to the presence of one or more isolated leptons in the event.

**Chargino-neutralino.** Production of $\tilde{W}_1\tilde{Z}_2$ pairs in hadronic collisions yields a very strong and distinct signal with 3 leptons+$E_T$ and no hadronic activity. This signal is particularly important for Tevatron SUSY searches where it provides a substantial increase of the discovery potential. Additional topologies include jets+3 leptons+$E_T$ and jets+2 opposite sign leptons+$E_T$ where the two leptons come from the neutralino decay and the chargino decays hadronically.

**Sleptons.** The $\tilde{e}^+\tilde{e}^-$ production at the LHC manifests itself through a clean signal including an opposite sign same flavor dilepton+$E_T$.

Generally speaking, SUSY signals which are to be expected at hadron colliders consist of $m$ jets+$n$ leptons+$E_T$ and their potential depends on the details of the particular mSUGRA model.
3.3. Large tan $\beta$

The large tan $\beta$ ($\sim 30$) edge of the mSUGRA parameter space is quite different - as far as collider signals are concerned - from the regions with low or moderate values of tan $\beta$. As tan $\beta$ increases, the $\tau$ lepton and bottom quark Yukawa couplings also increase and become comparable to the top Yukawa coupling and the gauge couplings. The lightest $\tau$ slepton and bottom squark are significantly lighter than their first two generation partners. As a result, gluino, chargino and neutralino decays into $\tau$ leptons and bottom quarks are enhanced thus obscuring some of the SUSY signals. Especially the reach via signatures with isolated leptons is substantially limited although some extra sensitivity can be gained by using $b$-tagging. This situation is very important for the Tevatron SUSY reaches since it greatly reduces (or even wipes out) the SUSY regions reachable in the large tan $\beta$ regime at this machine. The LHC sensitivity, on the other hand, is not very much affected. The large production rate helps to overcome the decreased number of produced hard isolated leptons and for heavier sparticle spectra decay channels into on-shell W’s and Higgses open up producing hard leptons and ensuring that SUSY will still be observed through some of the channels.

4. Comparison of detection rates with collider reaches

The results for tan $\beta = 2$ are summarized in Fig. 3. For all parameter sets $A_0$ was set to zero. The SUSY reaches for all four considered experimental facilities are shown together with solid lines indicating the contours of constant detection rate in $\Omega h^2$. The region to the right of the contour of $\Omega h^2 = 1$ is excluded since larger values of $\Omega h^2$ require too young a universe. The reaches for LEP2 and the NLC display the two regions corresponding to the chargino signal limit scaling with $m_{1/2}$ and to the slepton signal responsible for the bulge appearing at the left edge of the contour. The contours do not include the LEP2 and NLC sensitivity to Higgs bosons. Frame a indicates that in the $\mu < 0$ case the largest detection rates favor smaller values of $m_{1/2} \sim 150$ GeV, and $m_0 < 200$ GeV. Even though this region lies within the reach of both LEP2 and the Tevatron Main Injector upgrade, the actual rates are few $\times 10^{-3}$ events/kg/day, far below any realistic detection experiment sensitivity ($0.1 - 1$ events/kg/day). It is obvious that the LHC signal from slepton production (and even more so the jets+$E_T$ signal which covers the whole allowed region of parameter space) and the NLC cumulative reach would cover regions with extremely small detection rates of the order of $10^{-4}$ events/kg/day or less.

The case of $\mu > 0$, (shown in frame b), is different in that the region with largest rates predicts rates $\sim 0.1$ events/kg/day, close to the current
Figure 4. Direct detection rate $R$ in events/kg/day in a $^{73}$Ge detector for $\tan \beta = 2$, a) $\mu < 0$ and b) $\mu > 0$. Added are SUSY reach contours for LEP2, Tevatron MI, LHC slepton signal and NLC. The regions labelled by TH are excluded by theoretical considerations while the EX regions are excluded by collider searches for SUSY particles.

experimental limits. However, regions with relatively large detection rates also yield small neutralino relic density unless they lie in the vicinity of a neutralino annihilation pole [6]. Therefore, should SUSY be discovered by the LHC in the slepton channel or the multi-jet+$E_T$ channel in the segment of the parameter space favoring larger relic density, direct dark matter detection experiments would face decreased detection rates. The triangular region of Tevatron MI reach for $m_0 < 200 \text{ GeV}$ comes mainly from the $\tilde{W}_1 \tilde{Z}_2$ trilepton signal and covers a wide range of relic density values. The
region below the $10^{-2}$ events/kg/day contour could then possibly be open to competition between the Tevatron MI searches and neutralino direct detection experiments with corresponding sensitivity.

Increasing the value of $\tan \beta$, Fig. 5 displays the results of the calculation for $\tan \beta = 10$. The situation in frame b is similar to the $\tan \beta = 2$ case but one has to realize that the detection contours here are shifted towards larger values of $m_{1/2}$. For $\mu < 0$ we see a significant increase in the detection rate. This is due to the fact that the effective contribution from the Higgs bosons exchange, which dominates the scalar cross section as quark-squark couplings are suppressed by chiral symmetry and large squark masses, increases with $\tan \beta$. Also, the Tevatron MI trilepton signal in both frames covers only part of the region with detection rates larger.
Figure 6. Same as Fig. 4, except for $\tan \beta = 35$. Shown are SUSY reach contours for the Tevatron MI and TeV33 upgrades, and for the cumulative LHC search.

than $10^{-2}$ events/kg/day. In addition to the region where the direct detection experiments will be competing against the Tevatron signal there is also a region with $m_0 > 150$ GeV where direct detection could be the only chance of observing a supersymmetric signal before the LHC comes into operation. Existence of this region is mostly due to the presence of the neutralino annihilation poles which increase the annihilation cross section and decrease the relic density in their vicinity. For this value of $\tan \beta$ too, the LHC and the NLC will cover the mSUGRA parameter space up to regions yielding very small detection rates of the order of $10^{-4}$ events/kg/day.

Finally, Fig. 6 shows the detection rate contours and collider reaches
for the case of \( \tan \beta = 35 \). Since the region of cosmologically interesting relic density \( \Omega h^2 \) has grown considerably compared to previous two plots the scale in this plot is also expanded. The first thing to be noted is the fact that detection rates for small values of \( m_{1/2} \) can be larger than 1 event/kg/day. Unfortunately, this occurs in the region where the relic density is uninterestingly small, not even large enough to provide a sufficient amount of relic neutralinos to explain the rotation curves of galaxies. However, big enough detection rates can be achieved for values of \( m_{1/2} \) up to 300 GeV with corresponding relic density values much more interesting from the cosmological point of view and reaching up to \( \Omega h^2 \approx 0.5 \). SUSY discovery potential contours for both upgrades of the Tevatron, the Main Injector and TeV33, are plotted. The MI reach is very tiny and covers only a part of the region with detection rates above 1 event/kg/day. The TeV33 upgrade improves the situation but still large pieces of the parameter space available to detectors with sensitivities better than \( 10^{-2} \) event/kg/day remain out of reach for the Tevatron. This is even more interesting since the uncovered regions generally yield larger relic densities. Therefore in the large \( \tan \beta \) regime the direct detection experiments stand a good chance of being unchallenged in the search for SUSY until the LHC becomes operational. The cumulative reach of the LHC from the jets+\( E_T \) and jets+\( \ell+E_T \) signals will cover the rest of the parameter space where detection rates are too small for direct experiments.

One remark concerning the available parameter space in Figs. (3)-(6) is due here. Various independent constraints, such as from the \( b \to s \gamma \) process \([14]\), from the requirement of no false vacua in the theory \([15]\), from fine tuning \([16]\) etc., limit the extent of the available parameter space, in some cases quite severely. For the sake of brevity these constraints have not been discussed here but have been studied in literature.

5. Impact of CP violating phases

The minimal SUGRA model is parametrized in terms of only four parameters plus one sign and the sparticle spectrum generated starting from this set is therefore highly correlated. By relaxing unification conditions for the scalar soft breaking masses the number of free parameters increases while the gaugino mass unification (inspired by the gauge coupling unification) can still be preserved. These non-universalities are certainly legitimate and their effect on the predicted neutralino relic density and detection rate can be studied \([17]\).

Another important issue which needs to be addressed in connection with the minimal SUGRA parameter set is the question of CP violating phases. The MSSM includes a fairly extensive collection of parameters entering the SUSY breaking sector and many of them are CP violating complex phases.
In the simplest extension of the mSUGRA model, the common gaugino mass \( m_{1/2} \), the common trilinear parameter \( A_0 \), the Higgs mass parameter in the superpotential \( \mu \) and the Higgs bilinear term \( B_0 \) can all be complex. Redefinition of the Higgs fields allows one to eliminate one phase in the Higgs sector and take, for instance, \( B_0 \) to be real. The MSSM possesses one more approximate symmetry, namely the R-symmetry, which is violated by the gaugino mass term and can be used to rotate away the phase of \( m_{1/2} \). As a result, the simplest extension of the mSUGRA framework still observing universality introduces two complex phases \( \varphi_\mu \) and \( \varphi_{A_0} \). Not all values of the phases are allowed by the experimental limits on the electron and neutron dipole moments but, as discussed recently [18], large values of the phase can still be allowed.

The calculation of \( \Omega h^2 \) requires a knowledge of the elements of the neutralino mass matrix, all of which enter into calculating the neutralino annihilation cross section that determines the neutralino relic density. The cross sections depends strongly on the amount of gaugino-higgsino mixing and the resulting relic density can be very different if phases are allowed as parameters in the model. \( \Omega h^2 \) can vary by a factor of a few depending on the phases. Similarly, the neutralino-nucleon scattering cross section can be very sensitive to the presence of complex phases and the limits on neutralino detection need to be re-evaluated in the extended framework [19].

6. Conclusion

The lightest neutralino in supersymmetric models is a very appealing candidate to provide some or all of the cold dark matter (CDM) of the universe. Even in the restrictive framework of the minimal supergravity model with radiative electroweak symmetry breaking one can find regions of parameter space where the neutralino relic density ranges within the cosmologically relevant interval of values. These regions are further restricted by constraints from experimental limits on rare decays, from the requirement of the absence of non-standard global minima in the theory and by other constraints, but typically there are still regions left which are consistent with all constraints and lead to interesting neutralino relic densities. Most of those regions, with the exception of some areas in the vicinity of the neutralino annihilation poles, are also favored by fine tuning considerations.

From the experimental point of view it is interesting that some of these cosmologically favored regions are within the reach of collider experiments at LEP2 and the Tevatron upgrades but certainly most of the relevant parameter space will be covered by searches for SUSY at the LHC and the NLC. Although the collider experiment searches are the main way of looking for SUSY signals in nature, direct detection of ambient neutralinos

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could provide a useful tool for SUSY searches. The neutralino detection rate in direct scattering experiments grows proportionally to \( \tan \beta \) while the experimental reach for SUSY at LEP2 and the Tevatron is decreasing due to decreasing branching ratios for the electron and muon production. In this sense, the direct detection searches are complementary to the collider experiments.

Dark matter detectors reaching a sensitivity of \( R \sim 10^{-2} \) events/kg/day would usually have a better reach in the mSUGRA parameter space than LEP2 would for SUSY particles (excluding the Higgs boson). It would also have a comparable reach with the Tevatron MI or even exceed it in some regions with intermediate values of \( \tan \beta \). In the large \( \tan \beta \) region, the chances of detecting SUSY become much better for direct detection experiments and their reach is even better than the expected reach at the Tev33 Tevatron upgrade. It is therefore possible that in the interesting time period before the LHC becomes operational the first signal for SUSY will come from direct detection experiments.

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