Can SUSY be found at the Tevatron Run II?

A. Lipniacka
Stockholm University, Stockholm Center for Physics, Astronomy and Biotechnology, Fysikum, S - 106 91 Stockholm, Sweden

Abstract

Searches for SUSY particles are the main physics focus of the ongoing Run IIa of the Tevatron. LEP results have constrained heavily the Minimal Supersymmetric Standard Model. In this paper the results obtained at LEP and the Tevatron Run I are analysed within two consistent scenarios: the gravity-mediated MSSM framework and the minimal SUGRA scenario. In these frameworks limits much beyond the kinematic reach of LEP are set, and the allowed mass range for particles which are not directly observable at LEP is explored. These results can be used to evaluate searches at the Tevatron Run II. Both R-parity conserving and violating scenarios are considered. Model-dependence and coverage of LEP results is discussed in view of searches at the Tevatron Run II, and a conservative review of some of the other constraints is given. Consequences of the light Higgs boson of the Minimal Supersymmetric Standard Model with mass close to 114-117 GeV/$c^2$ and branching ratio to $b\bar{b}$ consistent with the one expected in the Standard Model are examined.

Presented at the Fourth Nordic Workshop for the LHC Physics, Stockholm 2001.
1 Introduction

Supersymmetry (SUSY) is believed to be one of the most attractive scenarios for physics beyond the Standard Model. In the last few years around 150 papers on experimental searches for SUSY were published, out of which around 100 were related to the LEP results and close to 30 to the Tevatron results. This large number of papers reflects perhaps as well the large number of free parameters relevant to SUSY models at the presently explored energy scale. LEP and Tevatron are complementary from the experimental point of view: LEP has lower energy reach, but it is better suited to explore corners of SUSY models in a relatively assumption independent way, while the Tevatron can discover SUSY provided the Nature has chosen a version of the model with favourable signatures. For this reason perhaps, LEP and Tevatron results are rarely analysed in a consistent framework, and usually models used to interpret LEP results are less constrained.

In this paper the results obtained by LEP experiments and these of the Tevatron Run I are analysed within two consistent scenarios: the gravity-mediated constrained MSSM framework and the minimal SUGRA scenario. In these frameworks, limits much beyond LEP’s kinematic reach can be set, and the allowed mass range for particles which are not directly observable at LEP (sneutrino and gluino) can be explored. This has direct consequences for designing the searches at the Tevatron.

In the Minimal Supersymmetric extension of the Standard Model (MSSM) \[1\], each Standard Model particle has a supersymmetric partner with the same couplings and with spin differing by $\hbar/2$. Large corrections to the Higgs mass from interactions involving virtual particles (heavy quarks in particular) are partially cancelled due to their superpartners. If they are lighter than 1-10 TeV\(^2\), this solves the so called hierarchy problem \[2\]. Moreover, supersymmetric particles modify the energy dependence of the electromagnetic, weak and strong coupling constants, and help them to unify at the scale of around \(10^{15}\) GeV\(\text{[3]}\).

The Higgs sector of the MSSM has to be extended to two complex Higgs doublets \(H_1, H_2\) responsible for giving masses to the up and down-type fermions. Five physical Higgs boson mass states remain after the Electroweak Symmetry breaking. The lightest scalar neutral Higgs boson \(h^0\) and the heavier pseudoscalar neutral Higgs boson \(A\) are of interest for this paper. On the tree level, masses of the Higgs bosons depend on just two parameters, which can be chosen as tan\(\beta\), the ratio of vacuum expectation values of the two Higgs doublets, and \(m_A\). In particular \(m_h < m_Z \ast |\cos 2\beta| \text{[4]}\), however due to radiative corrections mentioned above (which depend on the top quark mass, and on the mass terms of the superpartners of heavy quarks), the upper limit on the mass of the lightest Higgs boson grows to \(m_h < \sim 135 \text{ GeV}/c^2 \text{[4, 5]}\).

If \(m_A > 150 \text{ GeV}/c^2\) the lightest supersymmetric Higgs boson resembles very much the one of the Standard Model. Precise electroweak measurements \[3\] suggest that the Higgs boson is relatively light \[4\], \(m_h = 88^{+53}_{-36}\text{ GeV}/c^2\), well in the range of the MSSM prediction. Searches for the Standard Model like Higgs boson at LEP \[4, 5\] set a lower limit for \(m_h, m_h > 114.1 \text{ GeV}/c^2\) (if \(\tan \beta < 6\), or \(m_A > 120 \text{ GeV}/c^2\)), constraining heavily the MSSM. The 2.1\(\sigma\) “excess” observed at LEP \[4\] of events compatible with production of the Standard Model Higgs boson with \(m_h \sim 114 - 117 \text{ GeV}/c^2\), together with the EW uncertainty.

\[1\] For \(m_A > m_Z, m_{h_0}^{(\text{tree})} \sim m_Z \ast |\cos 2\beta|/(1+ m_Z^2/m_A^2)\), and for \(\tan \beta > 10, m_{h_0}^{(\text{tree})} \sim m_Z \ast |\cos 2\beta|\)

\[2\] The central value moves to \(\sim 110 \text{ GeV}/c^2\) if a different ansatz for hadronic corrections to the fine structure constant is used
constraints, makes low $m_{h}$, just above the reach of LEP, quite probable. The Run II of the Tevatron should cover the whole mass range allowed for $m_{h}$ in the MSSM, providing a definite answer to whether the MSSM is a valid extension of the Standard Model [10, 11].

The MSSM provides a phenomenologically interesting wealth of superpartners of the Standard Model particles. Supersymmetric partners of gauge and Higgs bosons (gauginos and higgsinos) mix to realize four neutral mass states, neutralinos, $\tilde{\chi}_{1}^{0}$, and four charged mass states, charginos, $\tilde{\chi}_{1}^{\pm}$, $\tilde{\chi}_{2}^{\pm}$. Supersymmetric partners of left-handed and right-handed fermions, “right-handed” and “left-handed” scalar quarks (squarks) and scalar leptons (sleptons) can mix. This leads to the off-diagonal “left-right” terms in their mass matrices and induces an additional mass splitting between the lighter and the heavier state.

While the Higgs sector is well constrained in the MSSM, very little can be said about the superpartners mass spectrum unless one makes some additional assumptions. Experimental searches at LEP and the Tevatron (discussed in more detail in section 5) constrain the lightest chargino and the sfermions to be heavier than $\sim 100 \text{ GeV}/c^{2}$, except for pathological mass configurations which are discussed later. The Supersymmetry has thus to be broken. The pattern of the sparticle mass spectrum depends primarily on the mechanism of its breaking.

In the models with gravity mediated supersymmetry breaking which will be discussed in this paper, the lightest neutralino ($\tilde{\chi}_{1}^{0}$) is usually the Lightest Supersymmetric Particle (LSP). If R-parity $^{3}$ is conserved the LSP does not decay, and it is an ideal cold dark matter candidate $^{12}$. R-parity conservation was introduced to suppress baryon and lepton number violating terms in the MSSM Lagrangian and thus to prevent the proton from decaying. However it is not the only and perhaps not the best $^{13}$ way to achieve this aim. Constraints on models with broken R-parity will be only briefly discussed in this paper along with a detailed discussion of R-parity conserving models.

Experimental searches motivated by the MSSM with R-parity conservation and gravity-mediated supersymmetry breaking exploit features of the model independent of further assumptions, like the strength of superpartner couplings to the gauge bosons, pair-production of sparticles, and the missing energy and momentum signature due to escaping LSPs in the final state. The same is to a large extent true for searches in the MSSM with R-parity violation, except that single sparticle production and complicated decays of the LSP have to be taken into account.

However, to cover “pathological” situations with final states which cannot be efficiently detected or situations where the production cross-sections are low, or finally to achieve more predictivity and set limits on masses of the sparticles which are not directly observable (e.g. the LSP in the R-parity conserving model), additional model assumptions have to be made. In this paper two “flavours” of such constraining assumptions are discussed (see section 2): the constrained MSSM with non-universal Higgs parameters (CMSSM with nUHP), which is often used to interpret LEP results, and an even more constrained minimal SUGRA scenario (mSUGRA) $^{4}$, often used to interpret Tevatron results and for

---

$^{3}$R-parity is a multiplicative quantum number defined as $R = (-1)^{3(B-L)+2S}$ where $B$, $L$ and $S$ are the baryon number, the lepton number and the spin of the particle, respectively. SM particles have $R = +1$ while their SUSY partners have $R = -1$.

$^{4}$ The definition of mSUGRA used in this paper corresponds to what is called CMSSM with universal Higgs masses in [14, 15, 16].
benchmark searches at future colliders [15]. It is shown in section 5 that in both models LEP results can be used to exclude sparticles much beyond the kinematic limit of LEP. Perspectives to find sparticles at the Tevatron are discussed in section 6.

2 The models: CMSSM with nUHP and mSUGRA

To make the MSSM more predictive, the unification of some parameters at a high mass scale typical of Grand Unified Theories (GUT) can be assumed. In this section, approximate relations between the model parameters and the superpartner masses which are important to understand the experimental limits will be quoted without explanations. For a more complete information see e.g. [1].

2.1 CMSSM with nUHP

As well as the already mentioned tan \( \beta \) and \( m_A \), the following parameters are relevant in the constrained MSSM with non-universal Higgs parameters:

- \( \mu \), the Higgs mass parameter,

- \( M_1, M_2, M_3 \), the \( U(1) \times SU(2) \times SU(3) \) gaugino masses at the electroweak (EW) scale. Gaugino mass unification at the GUT scale is assumed, with a common gaugino mass of \( m_{1/2} \). The resulting relation between \( M_1 \) and \( M_2 \) is \( M_1 = \frac{5}{3} tan^2 \theta_W M_2 \sim 0.5 M_2 \),

- \( m_{\tilde{t}} \), the sfermion masses. Under the assumption of sfermion mass unification, \( m_0 \) is the common sfermion mass at the GUT scale,

- the trilinear couplings \( A_f \) determining the mixing in the sfermion families. The third family trilinear couplings are the most relevant ones, \( A_\tau, A_b, A_t \).

Gaugino mass unification leads to \( m_{1/2} \approx 1.2 M_2 \) and to the following approximate relations between \( m_{\tilde{\chi}^\pm_1}, m_{\tilde{\chi}^0_1} \) and the gluino mass \( (m_3) \):

- in the region where \( \tilde{\chi}^0_1 \) and \( \tilde{\chi}^\pm_1 \) are gauginos (\( |\mu| >> M_1 \)), \( m_{\tilde{\chi}^\pm_1} \approx m_{\tilde{\chi}^0_2} \approx 2 m_{\tilde{\chi}^0_1} \), \( m_3 \approx 3.2 m_{\tilde{\chi}^\pm_1} \) and \( m_{\tilde{\chi}^\pm_1} \approx M_2 \),

- in the higgsino region (\( |\mu| << M_1 \)), \( m_{\tilde{\chi}^\pm_1} \approx m_{\tilde{\chi}^0_2} \approx m_{\tilde{\chi}^0_1} \approx |\mu| \).

The relations between chargino, neutralino and gluino masses and \( |\mu| \) and \( M_2 \) are affected by radiative corrections of the order of 2%-20% [17]. However, only the relative relations between chargino, neutralino and gluino masses are important from the experimental point of view, and here the corrections are much smaller. For example, the relation \( m_{\tilde{\chi}^\pm_1}/m_{\tilde{\chi}^0_1} \approx 2 \) in the gaugino region, which is usually exploited to set a limit on the LSP mass, receives the corrections only of the order of 2%; and the ratio \( m_3/m_{\tilde{\chi}^\pm_1} \approx 3.2 \) receives corrections of the order of 6%. Thus, for example, the limit [28] on the chargino mass of 103.5 GeV/c² set by LEP (valid for \( m_\nu > 300 \text{ GeV/c}^2 \), \( m_{\tilde{\ell}_R} > m_{\tilde{\chi}^\pm_1} \), and for \( M_2 \lesssim 200 \text{ GeV/c}^2 \)) can be safely translated to \( m_{\tilde{\chi}^0_1} \gtrsim 51 \text{ GeV/c}^2 \).
and $m_3 \gtrsim 310 \text{ GeV/c}^2$.

If the sleptons are heavy the chargino mass limit excludes regions in $(M_2, |\mu|)$ plane (see e.g. [13]). For $\tan \beta \gtrsim 2$ $|\mu| \lesssim 100 \text{ GeV/c}^2$ is excluded up to very high values of $M_2$ (of the order of 1000 GeV/c$^2$ or more) while $M_2 \lesssim 100 \text{ GeV/c}^2$ is excluded for $|\mu| \gtrsim 100 \text{ GeV/c}^2$.

Electroweak symmetry imposes the following relation between the masses of the superpartners of the left-handed electron ($\tilde{e}_L$) and of the neutrino ($\tilde{\nu}$),

1) $m_{\tilde{e}_L}^2 = m_{\tilde{\nu}}^2 + m_W^2 |\cos 2\beta|.$

The assumption of sfermion mass unification relates masses of the “left-handed” ($m_L$) and the “right-handed” ($m_R$) “light” sfermions, “light” squark masses, and the gaugino mass parameter $M_2$. For example:

2) $m_{\tilde{\nu}}^2 = m_0^2 + 0.77 M_Z^2 - 0.5 m_Z^2 |\cos 2\beta|$
3) $m_{\tilde{e}_L}^2 = m_0^2 + 0.77 M_Z^2 + (0.5 - \sin^2 \theta_W) m_Z^2 |\cos 2\beta|$
4) $m_{\tilde{\tau}}^2 = m_0^2 + 0.22 M_Z^2 + \sin^2 \theta_W m_Z^2 |\cos 2\beta|$
5) $m_{\tilde{q}_{3L}} = m_0^2 + 9 M_Z^2 + (0.5 - 1/3 \sin^2 \theta_W) m_Z^2 |\cos 2\beta|$

Thus, for example, $m_{\tilde{q}_{3L}} \gtrsim 310 \text{ GeV/c}^2$, if $m_{\tilde{\chi}_1^\pm} \gtrsim 103.5 \text{ GeV/c}^2$.

Mixing between left and right states (present for superpartners of heavy fermions) gives rise to off-diagonal “left-right” mixing terms in their mass matrices, which lead to a mass splitting between the lighter and the heavier state. At the EW scale these terms are proportional to $m_t(A_t - \mu \tan \beta)$, $m_b(A_b - \mu \tan \beta)$ and $m_t(A_t - \mu / \tan \beta)$ for $\tilde{\tau}, \tilde{b}$ and $\tilde{t}$, respectively, where $A_t, A_b, A_t$ are free parameters. Therefore, for large $\mu$ this can give light stau and sbottom states if $\tan \beta$ is large, or a light stop for small $\tan \beta$.

For large $m_A$, the lightest Higgs boson mass depends primarily on $\tan \beta$, $m_{top}$ and the mixing in the stop sector $X_t$ (expressed here as $X_t = A_t - \mu / \tan \beta$), and this dependence is maintained whether any additional constraints on the MSSM are imposed or not. The top quark mass is presently known with the uncertainty (1σ) of around 5 GeV/c$^2$ [13], and the resulting uncertainty of the lightest Higgs boson mass calculation is around 6.5 GeV/c$^2$, as $\Delta m_{h_1} / m_{h_0} \simeq 2 \Delta m_{top} / m_{top}$. It was shown in [1] that for a given $\tan \beta$ and top mass, the maximal $m_{h_0}$ occurs for $X_t / m_{SUSY} = \sqrt{6}$. Another, slightly lower maximum occurs for $X_t / m_{SUSY} = -\sqrt{6}$. $m_{SUSY}$ is typically taken to be of the order of the gluino mass, or of the diagonal terms in the squark mass matrices, and $m_{h_0}$ grows with $m_{SUSY}$.

It should be noted that the off-diagonal terms in mass matrices of the third family sparticles cannot be too big compared to the diagonal terms, in order for a real solution for sparticle masses to exist. As diagonal terms grow with $m_0$ and $M_2$, for every given value of the off-diagonal term a lower limit is set on the corresponding combination of $m_0$ and $M_2$.

\footnote{To avoid “tachyonic” mass solutions we must have:}

\[ m_{ll} + m_{rr} > \sqrt{(m_{ll} - m_{rr})^2 + 4 * m_{lr}^2} \]

where $m_{lr}$ is the off-diagonal mixing term, and $m_{ll}, m_{rr}$ are the diagonal mass terms. For example, for the stop we have $m_{lr} = m_{top} X_t$ and,
2.2 mSUGRA

In the minimal SUGRA model not only the sfermion masses, but also the Higgs masses $m_{H_1}$ and $m_{H_2}$, are assumed to unify to the common $m_0$ at the GUT scale. Then $m_{H_2}^2$ becomes negative at the EW scale in most of the parameter space, thus ensuring EW symmetry breaking.

The additional requirements of the unification of the trilinear couplings to a common $A_0$ and the correct reproduction of the EW symmetry scale, which fixes the absolute value of $\mu$, defines the minimal gravity-broken MSSM (mSUGRA). The value of $\mu^2$ can be determined minimising the Higgs potential and requiring the right value of $m_Z$. At tree level [1]:

$$6) \mu^2 = -1/2m_Z^2 + \frac{m_0^2 - m_{H_2}^2 tan^2\beta}{tan^2\beta - 1}$$

$$7) m_{H_1}^2 \simeq m_0^2 + 0.5m_{1/2}^2, \ m_{H_2}^2 \simeq -(0.275m_0^2 + 3.3m_{1/2}^2)$$

The parameter set is then reduced to $m_{1/2}, m_0, tan\beta, A_0$ and the sign of $\mu$.

In addition to the mass relations listed in the previous subsection, $m_A$ can be related to $m_{1/2}$ ($M_2$), $m_0$ and Yukawa coupling of the top quark. The stop mixing parameter can be expressed (approximately) as $A_t = 0.25A_0 - 2m_{1/2}$ [1]. The lightest Higgs mass can thus be related to $m_{1/2}$ ($M_2$), and the experimental limit on it can be used to set limits on the masses of (for example) the lightest chargino and the lightest neutralino dependent on $tan\beta, A_0$ and $m_{top}$.

3 LEP and Tevatron results

In years 1995-2000, the Aleph, DELPHI, L3 and OPAL experiments at LEP collected an integrated luminosity of more than 2000 pb$^{-1}$ at centre-of-mass energies ranging from 130 GeV to 208 GeV. These data have been analysed to search for the sfermions, charginos, neutralinos and Higgs bosons predicted by supersymmetric models [7, 18, 20, 21, 22, 23, 24, 25].

Extensive searches for supersymmetry and Higgs were performed at the Run I of the Tevatron with luminosity of around 100 pb$^{-1}$ [26, 27]. LEP and Tevatron results used in this note are discussed below.

3.1 Searches for $h^0$ production

The Standard Model Higgs boson is produced via the Bjorken “higgsstrahlung” process, $e^+e^- \rightarrow Z^\ast \rightarrow hZ$. Higgs searches (both in the Standard Model and the MSSM) are primarily sensitive to the Bjorken process with $h \rightarrow b\bar{b}$. Thus, the 95% CL lower limit on the SM Higgs mass of $m_h > 114.1$ GeV/c$^2$ set by LEP [8] corresponds approximately to the limit $\sigma(ee \rightarrow hZ) \times BR(h \rightarrow b\bar{b}) \leq 0.07$ pb at $\sqrt{s}=207$ GeV. This value can be used to set a conservative h$^0$ mass limit in the MSSM. It follows that the SM mass limit

\[ m_{h^0} \simeq m_0^2 + 9M_2^2 + m_{top}^2 + m_Z^2 cos2\beta(0.5 - 2/3 sin^2\theta_W) \]

\[ m_{h^0} \simeq m_0^2 + 8.3M_2^2 + m_{top}^2 + 2/3m_Z^2 cos2\beta sin^2\theta_W \]

For an example value of $X_t = \sqrt{6}$ TeV/c$^2$, the condition above sets a lower limit on a combination of $m_0^2$ and $M_2^2$: $m_0^2 + 8.5M_2^2 > 0.39$ TeV/c$^2$. Thus, if $m_0 < 300$ GeV/c$^2$ we must have $M_2 > 190$ GeV/c$^2$.

For low $\tan\beta$, $m_A^2 \simeq m_0^2 + 3m_{1/2}^2 - m_Z^2$. As $m_{h^0}$ grows with $m_A$ and $A_t$ (see section [1]), Higgs searches can be used to set a limit on $m_{1/2}$ ($M_2$) which depends on $\tan\beta, A_0,$ and $m_{top}$. 

---

$m_{h^0}$ is the mass of the Higgs boson, $m_0$ is the scalar mass parameter, $M_2$ is the gaugino mass parameter, $m_{top}$ is the top quark mass, $m_Z$ is the Z boson mass, $\theta_W$ is the weak mixing angle.
holds in the MSSM if $\tan \beta < 6$ and/or $m_A > 120 \text{ GeV}/c^2$ (where $e^+e^- \rightarrow Z^* \rightarrow h^0Z$ and $h^0 \rightarrow b\bar{b}$ dominate), unless there are supersymmetric particles to which $h^0$ decays or which enhance other branching-ratios via virtual loops. For $h^0 \rightarrow \chi_1^0 \chi_1^0$ (or $h^0$ decaying to other experimentally invisible final states) there exist a limit $m_h > 114.4 \text{ GeV}/c^2$ set by LEP.

For $m_A \leq 1000 \text{ GeV}/c^2$, $A_t - \mu/\tan \beta = \sqrt{6} \text{ TeV}/c^2$ (the maximal $m_{h^0}$ scenario used in [8]), and $m_{\text{top}} = 174.3 \text{ GeV}/c^2$, the $\tan \beta$ range, $0.5 \leq \tan \beta \leq 2.36$, is excluded by the Higgs searches, if there are no supersymmetric particles which affect Higgs decay branching fractions [9].

The possible “evidence” observed at LEP for a SM like Higgs boson with $m_h = 114 - 116$ [8] is based on a 2.1 $\sigma$ excess of $q\bar{q}b\bar{b}$ events compatible with $h^0Z$ production. It can be translated into an approximate preferred region of 0.03 pb $\lesssim \sigma(hZ) \text{ BR}(h \rightarrow b\bar{b}) \lesssim 0.07 \text{ pb}$ at $\sqrt{s} = 207 \text{ GeV}$.

Searches at the Tevatron Run I [26] impose $m_{h^0} > 120 \text{ GeV}/c^2$ for $\tan \beta > 70$, and $m_{h^0} > 110 \text{ GeV}/c^2$ for $\tan \beta > 60$.

### 3.2 Searches for charginos and neutralinos

After the Higgs, charginos were the most important SUSY discovery channel at LEP. Unless there is a light sneutrino [7], the chargino pair production cross-section is predicted to be large if $m_{\chi_i^\pm} < \sqrt{s}/2$. A lower limit on the chargino mass of 103.5 GeV/c$^2$ was set [23], assuming 100% branching fraction to the R-parity conserving decay mode $\chi_1^\pm \rightarrow \chi_1^0W^*$. All R-parity violating modes were studied as well [24, 29, 30], and limits of 102-103 GeV/c$^2$ on the chargino mass were set. If the results of all LEP experiments are combined, the limit will probably reach the kinematic limit of 104 GeV/c$^2$. It should be noted that if R-parity is violated, sneutrino decays lead to visible final states; thus light sneutrinos (and the regions in parameter space where the chargino production cross-section is low) can be directly excluded from the non-observation of sneutrino pair-production [29, 30].

Cross-section limits for chargino pair-production were set. In R-parity conserving scenarios they depend primarily on the difference between the mass of the chargino and an undetectable particle it decays to (e.g. $\chi_1^0$ or $\tilde{\nu}$). Chargino pair production with cross-section larger than 0.1-0.2 pb (corresponding to $\sqrt{s} \sim 205 \text{ GeV}$, the average energy of the year 2000 data) is excluded for $\Delta M > 20 \text{ GeV}/c^2$ [20, 31], where $\Delta M = m_{\chi_i^\pm} - m_{\chi_i^0}$ or $\Delta M = m_{\chi_i^\pm} - m_{\tilde{e}_R}$. If these limits are combined, a chargino production cross-section above 0.05 pb-0.1 pb can be excluded. The limit on chargino mass of $m_{\chi_i^\pm} \gtrsim 100 \text{ GeV}/c^2$ can be set for the light sneutrino as well, as long as $\Delta M \gtrsim 10 \text{ GeV}/c^2$.

If sfermion mass unification is assumed, searches for $\tilde{e}_R$ can be used to set a lower limit on the sneutrino mass, and thus on the chargino mass in the case of a light sneutrino and $\Delta M < 10 \text{ GeV}/c^2$. Moreover, if $\tilde{\nu}$ and $\tilde{e}_R$ are light, neutralino production in the gaugino region is enhanced [8], and neutralino searches set an indirect limit on the sneutrino mass

---

7 for smaller $m_A$, the production of $h^0\phi$ and $h^0 \rightarrow c\bar{c}$ decays start to be important, and the experimental sensitivity degrades

8In the gaugino region the chargino production cross-section can be quite small due to the negative interference between the t-channel sneutrino exchange diagram and the s-channel $Z/\gamma$ exchange diagram. Higgsino-type charginos do not couple to the sneutrino.

9Experimentally observable neutralino production (for example $\chi_1^0\chi_2^0$) has quite large cross-section in the higgsino region as higgsinos couple directly to $Z$. However, in the gaugino region there is no tree-level
in some regions of the parameter space.

In R-parity conserving scenarios, another "blind-spot" in chargino searches arises when the \( \tilde{\tau} \) is light and close in mass to the \( \tilde{\chi}^0_1 \) \([18,32,33]\). Chargino decays \( \tilde{\chi}^\pm_1 \rightarrow \tilde{\tau} \nu \) with \( \tilde{\tau} \rightarrow \tilde{\chi}^0_1 \tau \) then dominate, and lead to an "invisible" final state; but the search for neutralino production can be used \([18,28]\) in this case. If neutralinos decay via light stau states and \( m_\tau \) is close to \( m_{\tilde{\chi}^0_2} \), \( \tilde{\chi}^0_1 \tilde{\chi}^0_2 \) production with \( \chi^0_2 \rightarrow \tau \tau \) and \( \tau \rightarrow \tilde{\chi}^0_1 \tau \) leads to only one \( \tau \) visible in the detector; nevertheless limits on the cross-section times branching ratio are of the order of 0.1-0.4 pb \([31]\). The search for \( \tilde{\chi}^0_1 \tilde{\chi}^0_2 \) in the same region reaches a sensitivity of 0.06 pb \([18]\). In the CMSSM with uHSP, the region in \((M_2, \mu, m_0)\) space where the stau is degenerate in mass with the LSP depends on mixing parameters: \( A_\tau \), and \( A_b, A_t \). It is possible to find configurations of mixing parameters (typically with \(|\mu|\) few times larger than \( M_2 \) and \( m_0 \)) such that the stau is light and close in mass to \( \tilde{\chi}^0_1 \) while the selectrons are heavy, rendering the neutralino cross-section small. However, the chargino production cross-section is large in this case, and this region can be explored by the search for \( \tilde{\chi}^\pm_1 \tilde{\chi}^\pm_1 \gamma \) production \([18,32,33]\) where the photon arises from initial state radiation and is detected together with a few low energy tracks originating from \( \tilde{\chi}^0_2 \rightarrow \tau \tau \) and \( \tau \rightarrow \tilde{\chi}^0_1 \tau \) decay chain.

In mSUGRA, \(|\mu|^2\) is in the range 3.3 \( m^2_{\tilde{\chi}^0_1} - 0.5m^2_Z < \mu^2 < m^2_0 + 3.8m^2_{\tilde{\chi}^0_1/2} \) for tan\( \beta > 2 \) and and light stau cannot be degenerate with neutralino for large \( m_0 \). Thus neutralino searches set a limit on the chargino mass for small \( m_{\tilde{\tau}_1} - m_{\tilde{\chi}^0_1} \) which is close to the one obtained for heavy sleptons (around 103 GeV/c^2).

It is perhaps worth mentioning that, because in the higgsino region \((M_1 >> |\mu|)\) the \( \tilde{\chi}^0_1 \tilde{\chi}^0_2 \) production cross-sections at LEP are large, \( \tilde{\chi}^0_1 \tilde{\chi}^0_2 \) production can be excluded nearly up to the kinematic limit as long as \( m_{\tilde{\chi}^0_1} \) is not too close to \( m_{\tilde{\chi}^0_2} \) \((M_2 \approx 1500 \text{ GeV/c}^2 \) in the constrained MSSM). For 200 < \( M_2 < 1500 \text{ GeV/c}^2 \) a lower limit on the LSP mass of 70 GeV/c^2 was set by DELPHI \([12]\), using the data collected at \( \sqrt{s} = 189 \text{ GeV} \). In the constrained MSSM the mass difference between the lightest chargino and the lightest neutralino is less than 3 GeV/c^2 for \( M_2 \approx 1500 \text{ GeV/c}^2 \). A lower limit on the \( m_{\tilde{\chi}^0_1} \) of around 86 GeV/c^2 was set in this region by L3 Collaboration,\([21]\), implying a similar lower limit on the mass of the lightest neutralino.

### 3.3 Searches for Sleptons and Squarks

Pair-produced selectrons and muons with the typical decay modes, \( \tilde{\ell} \rightarrow \tilde{\chi}^0_1 \ell \), have been searched for by all LEP collaborations. These searches exclude slepton pair production with a cross-section above (0.02-0.1) pb depending on the neutralino mass and on the slepton mass, assuming 100% branching fraction to the above decay mode. With this assumptions, right-handed smuons (selectrons) lighter than around 96 (99) GeV/c^2 can be excluded, provided \( m_{\tilde{\mu}_R} - m_{\tilde{\chi}^0_1} \approx 20 \text{ GeV/c}^2 \) and that the selectron pair production cross-section is as for tan\( \beta = 2, \mu = -200 \). For the minimal coupling to \( Z/\gamma \) and sufficiently large \( \Delta M = m_{\tilde{\tau}_1} - m_{\tilde{\chi}^0_1} > 15 \text{ GeV/c}^2 \), \( m_{\tilde{\tau}_1} < 85 \text{ GeV/c}^2 \) can be excluded, while the lower limit on the mass of the stable stau is close to 87 GeV/c^2.

The results of the LEP combined searches for sbottom (\( \tilde{b} \)) and stop (\( \tilde{t} \)) are used in this paper. The typical decay modes \( \tilde{t} \rightarrow \tilde{\chi}^0_1 c \) and \( \tilde{b} \rightarrow \tilde{\chi}^0_1 b \) have been searched for. These searches exclude squark pair production with a cross-section above (0.05-0.1) pb coupling of \( \tilde{\chi}^0_1 \) to Z, and e^+e^- → \( \tilde{\chi}^0_1 \tilde{\chi}^0_2 \) can only be mediated via t-channel selectron exchange.
depending on the neutralino and on the squark masses, assuming 100% branching fraction to the above decay modes. For the minimal coupling to $Z/\gamma$ and for $\Delta M = m_t(m_b) - m_{\tilde{\chi}_1^0} > 15 \text{ GeV}/c^2$, the $\tilde{t}(\tilde{b})$ with mass below 95 (93) GeV/$c^2$ is then excluded \[28\].

The CDF Run I searches exclude a stop quark lighter than 115 GeV/$c^2$, if $m_{\tilde{\chi}_1^0}$<50 GeV/$c^2$. However, searches at LEP exclude $m_{\tilde{\chi}_1^0}$<50 GeV/$c^2$ in most of the parameter space (see section 5). If CDF and LEP results on the sbottom searches are combined, a $\tilde{b}_1$ lighter than 140 GeV/$c^2$ can be excluded for $m_{\tilde{\chi}_1^0}$<60 GeV/$c^2$ and $\Delta M = m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0} > 7 \text{ GeV}/c^2$ \[28, 27\].

4 Other experimental constraints

Other experimental constraints which can be used to evaluate SUSY models are the measurements of the $b\rightarrow s\gamma$ decay rate (via $B\rightarrow X_s\gamma$ decay), the measurement of the muon magnetic moment ($g-2$) and, in R-parity conserving scenarios, the relict abundance of the LSP given by the model. These constraints are discussed briefly below.

A possible discrepancy with the Standard Model was recently reported in the $g-2$ experiment \[34\], suggesting a presence of sparticles \[15, 35, 36\] lighter than a few hundreds of GeV/$c^2$'s. However, the experimental results are still very fresh and need a cross-check with more statistics.

In the constrained MSSM, the SUSY contribution to $B\rightarrow X_s\gamma$ depends primarily on the charged Higgs-top quark loops and chargino-stop quark loops. The result obtained by the CLEO collaboration, $B\rightarrow X_s\gamma = (3.21\pm0.43\pm0.27^{+0.18}_{-0.10})\times10^{-4}$ \[37\], is compatible with the recent result of BELLE $B\rightarrow X_s\gamma = (3.34\pm0.50^{+0.34+0.26}_{-0.37-0.28})\times10^{-4}$ \[38\] and compatible with the next-to-leading order SM prediction including non-perturbative effects, $B\rightarrow X_s\gamma = (3.71\pm0.31)\times10^{-4}$ \[39\]. Thus the overall SUSY contribution (which can be either positive or negative) has to be small. A relatively conservative estimate of the allowed range for the SUSY contribution would be to use weighted (with the statistical errors) average of BELLE and CLEO results and to treat systematic errors and theory errors as fully correlated. The experimental result is then $B\rightarrow X_s\gamma = (3.27\pm1.15(2.5\sigma)\pm0.27\pm0.2)\times10^{-4}$. Using 2.5 $\sigma$ (95% confidence level) statistical error and assuming that the systematic and theory errors can induce a correlated shift of the result, one arrives at a conservative allowed range for the discrepancy between the theoretical (SM+MSSM) and the experimental value (EX); $-2\times10^{-4} \leq (\text{MSSM+SM})-\text{EX} \leq 2\times10^{-4}$.

In the constrained MSSM, SUSY contribution is small for a large $m_A$ (and thus large $m_{H^\pm}$ as $M_{H^\pm}^2=M_W^2+M_A^2$), and in the gaugino region for the chargino where the chargino-stop coupling is smaller. For example, the charged Higgs-top contribution is below $0.25(1)\times10^{-4}$ for $m_A > 1000(250)$ GeV/$c^2$ and low tan $\beta$ \[10, 11\]. The chargino-stop contribution in the gaugino region ($M_2 < 0.2\mu$) is of the order of $0.25 \times10^{-4}$ for $m_{\tilde{\chi}_1^\pm} = m_t = 300$ GeV/$c^2$ and of the order of $2 \times10^{-4}$ for $m_{\tilde{\chi}_1^\pm} = m_t = 100$ GeV/$c^2$, close to the experimental lower mass limit. The charged Higgs-top contribution always adds to the SM one, whereas there can be a destructive interference between the SM and the chargino-stop contribution. Both contributions grow at large tan $\beta$. The charged Higgs-top contribution contains tan $\beta$ dependent NLO terms. The chargino-stop contribution grows with $\sim A_t\mu\tan \beta$ for high values of tan $\beta$ already in the leading order. It was shown...
in [11] that there is a cancelation between the leading and next-to-leading order terms for
$A_t > 0$ and $\mu > 0$ and the chargino-stop contribution is never very large. For example,
for $A_t = \mu = 500$ GeV, $m_\tilde{t} = 250$ GeV/$c^2$ and tan $\beta < 40$ the chargino-stop contribution 
is smaller than $0.25 \times 10^{-4}$. For $A_t = -\mu = -500$ GeV and tan $\beta = 20(40)$ it is however of
the order of 2(4) and, if $A_t \mu < 0$, can be partially cancelled by the charged Higgs-stop
contribution. Thus if $A_t < 0$, the positive $\mu$ is favoured and for tan $\beta > 20$ one must have either
$\tilde{t}_1$ or $\tilde{\chi}^+_1$ heavier than $\sim 250$ GeV/$c^2$ or $m_{H^\pm}(m_A)$ of the order of $250(200)$ GeV/$c^2$.

In mSUGRA $A_t \simeq 0.25 A_0 - 2 m_{1/2}$, thus it is negative unless one considers large and
positive $A_0$ values. As $M_2, \mu, m_{H^\pm}, A_t$, and the stop and the chargino masses are related,
the $B \rightarrow X_s \gamma$ measurements can be used to exclude regions of ($m_{1/2}(M_2); m_0$) space.
This was discussed in e.g. [15, 16] for $A_0 = 0$. Somewhat less conservative estimate of
the allowed experimental range of $B \rightarrow X_s \gamma$ was used there than suggested in this paper.

At tan $\beta < 10$, there is essentially no constraints for $\mu > 0$ and $m_{\tilde{\chi}^\pm_1} \gtrsim 100$ GeV/$c^2$,
whereas either a heavy chargino or a squark is required if $\mu < 0$. For tan $\beta > 20(35)$, the
limit of $\sim 200(300)$ GeV/$c^2$ is set for $m_{1/2}$ if $m_0 \lesssim 600$ GeV/$c^2$. This corresponds to
a lower limit on the diagonal terms in the squark mass matrix (or on the masses of the
superpartners of light quarks) of the order of 600-700 GeV/$c^2$. However, the sbottom
squark can still be made lighter via mixing. The bounds mentioned above cannot have
an interpretation of limits at 95% level. For that, a more sophisticated estimate of the
allowed range of the experimental value should be employed, and SUSY contribution to
$B \rightarrow X_s \gamma$ should be calculated for $A_0$ values other than 0 [19].

If R-parity is conserved, the Universe could be filled with the neutralino relict of the
Big Bang. The relict LSP density ($\Omega_{LSP} h^2$) is governed by their annihilation rate at
decoupling time [12]. If the annihilation rate was too small we could have enough LSP
Dark Matter to have collapsed the Universe by now. The annihilation rate is proportional
to the neutralino self-interaction cross-section and to the interaction cross-section between
LSPs and other supersymmetric particles (co-annihilation) which are suitably close in
mass (see e.g. [18]).

For higgsino type neutralinos, the self-interaction can be mediated by the Z and the
cross-sections are large enough to keep $\Omega_{LSP} h^2 < 0.3$, as long as $m_{\tilde{\chi}^0_1} \lesssim 10$ TeV/$c^2$.

For gaugino-like neutralinos the cross-sections are smaller, and the tree-level interaction
process has to be mediated by sfermions or Higgs bosons. The annihilation rate is
roughly inversely proportional to the neutralino and the slepton mass scale, if one neglects
the resonant annihilation $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow H$ [13] or $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow A$ [14] or the resonant co-annihilation
$\tilde{\chi}^0_1 \tilde{\tau}_1$ [13]. Except for $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow A (H)$, which can occur for high $m_{A(H)}$ when the width of
$A (H)$ is large, other resonant annihilation conditions imply a slightly fine tuned mass
relation between $\tilde{\chi}^0_1$ and $\tilde{\tau}_1$.

If one ignores the resonant annihilation channels mentioned above, $\Omega_{LSP} h^2 < 0.3$ imposes
$m_0 \lesssim 500$ GeV/$c^2$ and $M_2 \lesssim 600$ GeV/$c^2$ for tan $\beta < 50$, and $m_0 \lesssim 150(200)$ GeV/$c^2$
and $M_2 \lesssim 300$ GeV/$c^2$ for tan $\beta < 10(20)$. This implies an upper limit on the LSP
mass of 150-300 GeV/$c^2$ depending on tan $\beta$ and, for example, on the $m_{\tilde{g}}$ mass of 200-
600 GeV/$c^2$, if the lightest neutralino is a gaugino. This is typically the case in mSUGRA,

10 Such an analysis, employing $B \rightarrow X_s \gamma$ g-2, and Higgs constraints was performed in [33]. The
conclusions will change however if present CLEO [47] results, which bring the experimental average
closer to the SM result, are used.
Neutralino dark matter has received a lot of attention in the literature (see for example [16] and references therein). To set constraints on SUSY models it is often required that the LSP relict density should provide all the non-baryonic dark matter for which experimental evidence exists. This implies a lower bound on $\Omega_{\text{LSP}} h^2$. However, such a bound cannot be regarded as an experimental constraint, as there may be other suitable sources of the non-baryonic dark matter.

5 Limits

The searches described in the previous section were used to set limits on sparticles masses in the CMSSM with non universal Higgs parameters and in mSUGRA. Whenever available, combined LEP cross-section limits and mass limits were used. These concern chargino, slepton and squark searches. For the neutralino cascade decays via stau which were searched for so far only by DELPHI and ALEPH [18, 33, 42, 43], it was assumed that other LEP collaborations can reach a similar sensitivity. It was also assumed that $\sigma(h Z) \text{BR}(h \rightarrow b\bar{b}) \lesssim 0.07 \text{ pb}$, in accordance with the results of searches for the Higgs boson production. $m_{\text{top}} = 174.3 \text{ GeV}/c^2$ was used, the dependence of results on this value is discussed further.

Limits presented in this section are valid in the R-parity conserving scenario and in all R-parity violating scenarios where a chargino limit of 103 GeV/$c^2$ or more can be set by LEP experiments, as discussed below.

5.1 Limits in the CMSSM with nUHP

Higgs boson searches and chargino searches set limits in this scenario. ”Holes” which arise in chargino searches in the R-parity conserving scenario are covered by selectron, neutralino, Higgs and squark searches. All limits presented in this section are for $m_A=1000 \text{ GeV}/c^2$. This choice is conservative from the point of view of the experimental limit set at low and moderate $\tan \beta$ because the $h^0$ mass grows with $m_A$. Although for $92 < m_A < 120 \text{ GeV}/c^2$ and $\tan \beta > 6$ the limit on $m_{h^0}$ degrades to 91-110 GeV/$c^2$, this is not expected to affect significantly any of the results presented in this section. High value of $m_A$ ensures that the SUSY contribution to $b \rightarrow s \gamma$ is small, at least for $A_t > 0$, in agreement with the present experimental value [37, 38, 40, 41](see section 4).

The following range of parameters was studied: $-2000 \leq \mu \leq 2000 \text{ GeV}/c^2$, $0 \leq M_2 \leq 2000 \text{ GeV}/c^2$, $0 \leq m_0 \leq 1000 \text{ GeV}/c^2$, $3 \leq \tan \beta \leq 60$, $0 \leq A_t \leq 500 \text{ GeV}/c^2$, $A_t = A_b = 0$.

Limits on the mass of the lightest neutralino

The effect of various searches in the R-parity conserving scenario is illustrated on figure showing the LSP mass limit set by the Higgs and SUSY searches and by the SUSY searches alone, as a function of $\tan \beta$. The mixing in the third family was of the form: $(A_r - \mu \tan \beta, A_b - \mu \tan \beta, A_t - \mu / \tan \beta)$, and plots are shown for two values of $A_t$. The LSP mass limit ranges from 46-51 GeV/$c^2$ depending on the scenario, as discussed below.
Figure 1: The lower limit at 95% confidence level on the mass of the lightest neutralino, \( \tilde{\chi}_0^1 \), as a function of \( \tan \beta \) assuming a stable \( \tilde{\chi}_0^0 \). The dashed and dotted (solid) curves shows limits obtained for \( A_t = 500 \) GeV/\( c^2 \) (\( A_t = 0 \) GeV/\( c^2 \)), and with mixing in the third family of the form: \( (A_\tau - \mu \tan \beta, A_b - \mu \tan \beta, A_t - \mu / \tan \beta, \) with \( A_b = A_\tau = 0 \)). For lines marked “Higgs and SUSY”, constraints both from SUSY and Higgs searches were imposed. Thin dark lines show the limit obtained when a lower limit on the Higgs production cross-section as described in the text was imposed, while for the limit shown with the thicker lighter line, it was assumed that 2.1 \( \sigma \) “excess” observed by LEP represents a real signal and it was required that 0.03 pb \( \lesssim \sigma(hZ) \cdot \text{BR}(h \rightarrow b\bar{b}) \lesssim 0.07 \) pb at \( \sqrt{s} = 207 \) GeV. This condition excludes regions where \( h^0 \) decays to supersymmetric particles or is heavier than 117 GeV. For \( A_t = 0 \), thicker and thinner lines coincide. The dotted line shows the limit in the region where \( m_{\tilde{\tau}_1} - m_{\tilde{\chi}_0^1} > 5 \) GeV/\( c^2 \) was imposed. “SUSY only” lines drop at low \( \tan \beta \) due to a ”hole” in chargino searches when the chargino is close in mass to the sneutrino. This hole is partially covered by selectron and neutralino searches. See the text for more information.
If only the SUSY searches are exploited the limit drops at \( \tan \beta < 10 \) due to the "hole" in chargino searches, where the chargino is close in mass to the sneutrino. The "hole" is partially covered by selectron and neutralino searches, and it is less "deep" for \( A_t = 500 \text{ GeV/c}^2 \) as higher \( m_0 \) is required to avoid the tachyonic stop (section 2.1). It is covered by the Higgs search for \( A_t = 0 \), as higher \( M_2 \) and \( m_0 \) are required to get \( m_{h_{10}} \gtrsim 114 \text{ GeV/c}^2 \). At higher \( \tan \beta \) values this sneutrino hole is covered, because a higher \( m_0 \) is required to get the \( \tau_1 \) heavier than the experimental limit, as the mass splitting between the heavier and the lighter stau grows with \( |A_t - \mu \tan \beta| \). If \( m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0} \) is allowed (the dotted line) the limit drops at high \( \tan \beta \) to 46 \text{ GeV/c}^2, because another hole in chargino and stau searches develops. This "hole" is partially covered by neutralino and "degenerate" chargino searches, but it is not covered by the Higgs searches (unless it is assumed that 2.1 \( \sigma \) observed at LEP represents the real signal and 0.03 \text{ pb} \leq \sigma(h^0Z) \) BR\((h^0 \rightarrow b\bar{b}) \lesssim 0.07 \text{ pb} \) is imposed, which excludes \( h^0 \rightarrow \tilde{\tau}_1 \tilde{\tau}_1 \) which dominates in this region). This limit represents the most conservative scenario and it is maintained even if mixing in all the three families is treated as totally independent and assumed to have an arbitrary \( \mu \) dependence. For other limits the condition \( m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} > 5 \text{ GeV/c}^2 \) was imposed. Radiative corrections according to [17] were applied.

Only the range of \( \tan \beta > 3 \) was analysed, because in the mixing model used in this paper \( \tan \beta < 3 \) is excluded by the Higgs search. Although 2.4(2.0) \( \lesssim \tan \beta < 3 \) for \( m_{\text{top}} = 174.3(179) \text{ GeV/c}^2 \) is allowed for the maximal mixing in the stop sector, a relatively high \( m_0 \) or \( M_2 \) is implied either to avoid a tachyonic stop, or to obtain \( m_{h_{10}} \gtrsim 114 \text{ GeV/c}^2 \).

Thus, the limit \( m_{\tilde{\chi}_1^0} > 46 \text{ GeV/c}^2 \) is valid for \( \tan \beta > 1 \), and essentially independent of the mixing scenario.

If R-parity is violated there are no holes in chargino searches. Both for purely leptonic and purely hadronic R-parity violating terms, the limit \( m_{\tilde{\chi}_1^0} > 50-51 \text{ GeV/c}^2 \) was set by DELPHI [23] for \( \tan \beta > 2 \).

For a mixed leptonic-hadronic (LQ\( \bar{D} \)) R-parity violating term, ALEPH’s limit on the chargino mass at high \( m_0 \) can be translated to \( m_{\tilde{\chi}_1^0} \gtrsim 51 \text{ GeV/c}^2 \) at \( \tan \beta > 2 \). Although the region of the lowest chargino production cross-section is excluded by the \( \tilde{\nu}_e \) and \( \tilde{e}_R \) mass limits of 91 and 93 GeV/c\(^2\) [10] and by the Higgs limit, the cross-section limits from all LEP experiments have to be combined to set a similar mass limit on the lightest chargino (and neutralino) as for purely hadronic and leptonic terms.

The neutralino mass limit is set in the gaugino region, at high \( |\mu| \) values. In the higgsino region \( \chi^{0,\pm}_{12} \chi^{0,\pm}_{12} \) and \( \chi^{+}_1 \chi^{0}_{2} \chi^{0}_{2} \) production cross-sections at LEP are higher and \( m_{\tilde{\chi}_1^0} \) is closer to \( m_{\tilde{\chi}_1^0} \), than in the gaugino region. In the higgsino region \( m_{\tilde{\chi}_1^0} < 86 \text{ GeV/c}^2 \) can be excluded even if \( m_{\tilde{\chi}_1^0} \) is very close or equal to \( m_{\chi_1^0} \) [24]. For \( |\mu| < 0.5 \) \( M_2 \), limits on the cross-sections for \( \chi^{0,\pm}_{12} \chi^{0,\pm}_{12} \) and \( \chi^{+}_1 \chi^{0}_{2} \chi^{0}_{2} \) production set by LEP exclude \( m_{\tilde{\chi}_1^0} < 80 \text{ GeV/c}^2 \).

Limits on the sfermion masses and on the gluino mass

The Higgs mass depends on \( m_{\tilde{t}_1} \) via radiative corrections, so Higgs searches can be used to set a limit on \( m_{\tilde{t}_1} \). Figure 2 shows the allowed range in the \((m_{\tilde{t}_1}, m_{\tilde{b}_1})\) plane resulting from Higgs and SUSY searches, for several values of \( \tan \beta \), and for two example values of \( A_t \). Figure 3 shows a lower limit on \( m_{\tilde{t}_1} \) and \( m_{\tilde{b}_1} \) as a function of \( \tan \beta \). For
Figure 2: Allowed range in \((m_{\tilde{t}_1}, m_{\tilde{b}_1})\) plane at 95\% confidence for several values of \(\tan\beta\), resulting from Higgs and SUSY searches. The darker (lighter) region is for \(A_t = 0\) (\(A_t=500\) GeV/c\(^2\)). The hatched (cross-hatched) region on the lighter (darker) shading is allowed for 0.03 \(\text{pb} \lesssim \sigma(h^0Z)\text{BR}(h^0 \rightarrow b\bar{b}) \lesssim 0.07\) pb.

\(A_t = 500\) GeV/c\(^2\), \(m_{\tilde{t}_1} < 200\) GeV/c\(^2\) is allowed if \(\tan\beta < 20\). If \(A_t=0\) GeV/c\(^2\) one gets \(m_{\tilde{t}_1} \gtrsim 700\) GeV/c\(^2\) for all studied values of \(\tan\beta\). A light sbottom (\(\sim 100\) GeV/c\(^2\)) is allowed for \(\tan\beta \gtrsim 30\), if \(A_t=500\) GeV/c\(^2\). For \(A_t = 0\), one gets \(m_{\tilde{b}_1} > 200\) GeV/c\(^2\) for \(\tan\beta < 50\). If there is a Standard Model like Higgs boson lighter than 117 GeV/c\(^2\), an upper limit of \(\sim 1000\) GeV/c\(^2\) exists on \(m_{\tilde{b}_1}\) and \(m_{\tilde{t}_1}\).

In the CMSSM with nUHP the mass of the lightest Higgs boson is not directly related to \(M_2\) value and (with all the caveats explained before) it is the chargino search which sets the limit on \(M_2\) for \(A_t = 500\), and for \(A_t = 0\) if \(\tan\beta > 10\). For \(A_t = 0\), large \(m_{\rm SUSY}\) is nevertheless required to push \(m_{h^0}\) up, which results in forcing large \(m_0\) for small \(M_2\).

Limits on \(m_{\tilde{g}}, M_2, m_0, m_{\tilde{d}}, m_{\tilde{e}}, m_{\tilde{t}}, m_{\tilde{b}}, m_{\tilde{\ell}_L}\) and \(m_{\tilde{\ell}_R}\) as a function of \(\tan\beta\) are shown on figure 3. As expected, \(m_{\tilde{g}}\) and \(m_{\tilde{d}} \gtrsim 330\) GeV/c\(^2\). At high \(\tan\beta\) higher \(m_0\) is required to avoid the stau becoming the LSP. This is reflected in a rise of the limits.
Figure 3: From left to right, top to bottom: Limits on $m_{\tilde{g}}$ and $M_2$, $m_{\tilde{d}}$ and $m_{\tilde{\nu}}$, $m_{\tilde{t}_1}$ and $m_{\tilde{b}_1}$, $m_{\tilde{e}_R}$, and $m_{\tilde{e}_L}$ as a function of $\tan\beta$, in the CMSSM with non-universal Higgs parameters. Solid (dashed) lines show limits for $A_t = 0$ ($A_t = 500$ GeV/c$^2$).

It should be noted that all limits discussed so far are not expected to depend on the sign of $A_t$.

Effect of $b \to s\gamma$ and Dark Matter constraints

As discussed in section 4 for $A_t \geq 0$, $b \to s\gamma$ constraints are not expected to affect any of the limits presented in this section. If $A_t < 0$, positive $\mu$ values are favoured, and for $\tan\beta > 20$ and $A_t \simeq -500$ GeV/c$^2$ either $\tilde{t}_1$ or $\tilde{\chi}_1^\pm$ must be heavier than $\sim 250$ GeV/c$^2$, or $m_{H^\pm}(m_A)$ must be of the order of 250(200) GeV/c$^2$. As Higgs and SUSY searches impose $m_{\tilde{t}_1} > 200$ GeV/c$^2$ for $\tan\beta > 20$, $b \to s\gamma$ constraints do not tighten very much this limit.
In the R-parity conserving scenario, the relict density of dark matter can be used to set upper limits on sparticle masses. If the lightest neutralino is a gaugino, if one ignores slightly fine-tuned possibilities of the neutralino being very close in mass to \( \tilde{\tau} \) or, (much less fine-tuned) to 0.5 \( m_{A,H} \) (resonant annihilation), the condition \( \Omega_{\text{LSP}} \beta < 0.3 \) imposes \( m_0 \leq 500 \text{ GeV}/c^2 \) and \( M_2 \leq 600 \text{ GeV}/c^2 \) for \( \tan \beta < 50 \), and \( m_0 \leq 150(200) \text{ GeV}/c^2 \) and \( M_2 \leq 300 \text{ GeV}/c^2 \) for \( \tan \beta < 10(20) \). This implies an upper limit on the LSP mass of 150-300 \text{ GeV}/c^2 depending on \( \tan \beta \), on \( m_{\tilde{e}_R} \) of 200-600 \text{ GeV}/c^2, on \( m_{\tilde{e}_L} \) of 300-500 \text{ GeV}/c^2, and on \( m_{\tilde{g}} \) of 1000-2000 \text{ GeV}/c^2. For \( \tan \beta < 10 \) a mixing-dependent upper limit of 800-1100 \text{ GeV}/c^2 on the masses of \( t_1 \) and \( \tilde{b}_1 \) is set.

5.2 Limits in the mSUGRA scenario

Limits on the mSUGRA model for \( A_0 = 0 \) were discussed in detail in [13, 16]. The Higgs search plays a major rôle in setting these limits, and the value of \( m_{\tilde{h}_0} \) depends crucially on \( A_t \simeq 0.25 A_0 - 2 m_{1/2} \), as it was noted in for example [44]. Here, \( A_0 \) values in the range of \((-500, 500 \text{ GeV}/c^2)\) are studied. The dependence of the results on the accuracy of the Higgs mass calculations is discussed in the following. The ISASUGRA [13] model was used to calculate the sparticle spectrum and the values of the MSSM parameters at the EW scale, but the radiative corrections of ref. [17] to chargino and neutralino masses were implemented. The calculations of \( m_{\tilde{h}_0} \) of ref. [3] were used, which give \( m_{\tilde{h}_0} \) typically 2-3 \text{ GeV}/c^2 higher than in the ISASUGRA model.

To illustrate the effects of various searches, the corresponding exclusions in the \( m_0 \) and \( m_{1/2} \) plane are plotted on figure for two values of \( \tan \beta \), \( A_0 \) and the sign of \( \mu \). The value of \( m_{\text{top}} = 174.3 \text{ GeV}/c^2 \) was used. Chargino searches set a limit on \( m_{1/2} \) that is nearly independent \( m_0 \) and \( A_0 \). Searches for neutralinos, selectrons and staus help to cover holes in the chargino search at low \( m_0 \) arising in R-parity conserving scenarios. Searches for the Higgs boson set a limit on \( m_{1/2} \) which depends very strongly on \( A_0 \) and \( m_{\text{top}} \). It should be noted that just a 1 \text{ GeV}/c^2 change in the calculated value of the \( h^0 \) mass can move the limit on \( m_{1/2} \) set by the Higgs boson searches by 30-150 \text{ GeV}/c^2 (\( \mu > 0 \)) depending on \( \tan \beta \). For \( A_0 = -500 \text{ GeV}/c^2 \) and \( \mu > 0 \), Higgs searches exclude \( m_{1/2} \) values just about 25 \text{ GeV}/c^2 higher than these excluded by chargino searches already at \( \tan \beta > 5 \).

As remarked in section 4, in mSUGRA \( \mu > 0 \) is favoured due to strong constraints from \( b \rightarrow s \gamma \) on \( \mu < 0 \).

Excluded regions in \( m_{1/2} \) can be translated into limits on \( m_{\tilde{\chi}_1^0} \) and \( m_{\tilde{\chi}_1^\pm} \). Limits on \( m_{\tilde{\chi}_1^0} \) are illustrated on figure 3 for several values of \( A_0 \) and \( m_{\text{top}} \). \( m_{\tilde{\chi}_1^\pm} \) is close to \( 2m_{\tilde{\chi}_1^0} \). For \( A_0 = -500 \text{ GeV}/c^2 \) the Higgs search does not contribute for \( \tan \beta > 10 \) and limit is given by the SUSY searches. However, Higgs searches become more constraining for positive \( A_0 \) values, as long as they lead to an appreciable decrease of the absolute value of \( X_t \simeq 0.25 A_0 - 2 m_{1/2} (1 + \cot \beta) \) for \( m_{1/2} \) values where the chargino limit is no longer effective (\( \simeq 150 \text{ GeV}/c^2 \)). For \( A_0 \) and \( \tan \beta \) values where the Higgs search contributes, the LSP limit can change by 50 \text{ GeV}/c^2 for a 3 \text{ GeV}/c^2 change of the Higgs mass. The \( m_{\tilde{\chi}_1^0} \) limit presented here is in agreement with the conservative “prediction” of the final

---

11 The Higgs mass calculations of [3] used in this paper give values 1-3 \text{ GeV}/c^2 higher than FeynHiggs used for example in [13]. Limits presented here are thus somewhat more conservative. With this conservative Higgs mass calculation \( m_0 = 0 \) is still allowed for \( \tan \beta \simeq 5 \) (see figure 4), as remarked in [6].
Figure 4: Exclusion regions in the mSUGRA scenario from Higgs and SUSY searches at LEP and stop searches at LEP and Tevatron Run I, for two values of \( \tan \beta \) and \( A_0 \). Light shaded vertical bands are excluded by chargino searches, cross-hatched vertical bands are excluded by Higgs searches, and fine cross-hatched areas for plots with \( A_0 = -500 \text{ GeV}/c^2 \) are excluded by stop searches at LEP and Tevatron. Searches for neutralinos, \( \tilde{e}_R \) and \( \tilde{\tau}_1 \) (marked with intermediate shading) complement chargino searches for low \( m_0 \) in R-parity conserving scenarios. In most parity violating scenarios, a similar vertical band is excluded by chargino searches, but “holes” for small \( m_0 \) are absent. Dark hatched shading shows regions where either the \( \tilde{\tau}_1 \) or the \( \tilde{t}_1 \) is the LSP, or the \( \tilde{t}_1 \) is tachyonic.
obtained in the CMSSM scenario. For $A_0 = -500$ GeV/c$^2$, the Higgs limit is not constraining for $\tan \beta > 10$ and $\mu > 0$. At higher $\tan \beta$ there is a limit on $m_0$ set by the requirement that $\tilde{t}_1$ should be heavier than $\chi^0_1$, and limits on the sleptons rise. The Higgs constraint degrades for $\tan \beta > 40$ due to a light $A$ boson being allowed, which results in a decrease of the experimental sensitivity (see section 3.1).

Figure 5 illustrates limits on $m_{\tilde{g}}$, $m_{\tilde{e}}$ and $m_{\tilde{\nu}_R}$. These limits are close to the ones obtained in the CMSSM scenario. For $A_0 = -500$ GeV/c$^2$, the Higgs limit is not constraining for $\tan \beta > 10$ and $\mu > 0$. At higher $\tan \beta$ there is a limit on $m_0$ set by the requirement that $\tilde{t}_1$ should be heavier than $\chi^0_1$, and limits on the sleptons rise. The Higgs constraint degrades for $\tan \beta > 40$ due to a light $A$ boson being allowed, which results in a decrease of the experimental sensitivity (see section 3.1).

Figure 6 shows the allowed range in the $(m_{\tilde{t}_1}, m_{\tilde{b}_1})$ plane resulting from Higgs and SUSY searches in mSUGRA, for several values of $\tan \beta$, and for two example values of $A_0$. For $A_0 = -500$ GeV/c$^2$, $m_{\tilde{t}_1} < 200$ GeV/c$^2$ is marginally allowed for $10 < \tan \beta < 20$. $m_{\tilde{t}_1} \sim 300$ GeV/c$^2$ for $A_0=0$. The lightest sbottom is heavier than 200 GeV/c$^2$ for all the range of $A_0$ and $\tan \beta$ studied. For $\mu > 0$, which is less restricted by $b \rightarrow s\gamma$ constraints, the possible “evidence” for the light $h^0$ sets an upper limit of close to 1000 GeV/c$^2$ on the masses of $\tilde{t}_1$ and $\tilde{b}_1$.

Constraints resulting from the $b \rightarrow s\gamma$ measurement can tighten the above limits on sleptons and squarks at $\tan \beta > 20$, while limits on $m_{\tilde{\chi}^0_1}$, $m_{\tilde{\chi}^\pm_1}$ and $m_{\tilde{g}}$ are not going to be affected as $b \rightarrow s\gamma$ does not constrain $m_{1/2}$ for high $m_0$ (heavy squarks). However, if one applies both $b \rightarrow s\gamma$ limits and an upper limit on $m_0$ for small $m_{1/2}$ resulting from the upper limit on the relic density (R-parity conserving scenario), lower limits on $m_{\tilde{\chi}^0_1}(m_{\tilde{\chi}^\pm_1}) \gtrsim 110(220)$ GeV/c$^2$ and $m_{\tilde{g}} \gtrsim 700$ GeV/c$^2$ will result for $\tan \beta > 20$. Results of [10] and [15] suggest that, at least for $A_0 = 0$, there is little room for spectra which are consistent both with $b \rightarrow s\gamma$ and an upper limit on the relic density for $\tan \beta > 35$, unless resonant neutralino annihilation and co-annihilation are taken into account.

If $b \rightarrow s\gamma$ constraints from [13] are applied, the lower limit on the mass of the $\tilde{t}_1$ ($\tilde{b}_1$) grows to 300 GeV/c$^2$ (450 GeV/c$^2$) for $\tan \beta > 20$. However, these constraints have to be recalculated for $A_0$ values other than 0. In particular, large positive values of $A_0$ (such that $A_t$ is positive at $m_{1/2} \sim 150$ GeV/c$^2$) should be considered, as they weaken $b \rightarrow s\gamma$ constraints [11]. Moreover mass constraints above cannot be interpreted a 95% confidence limits with the present treatment of the experimental and theoretical errors on $b \rightarrow s\gamma$.

It is interesting to note that both the possible “evidence” for the light $h^0$ and “naively” applied dark matter constraints (ignoring the neutralino-stau co-annihilation, and the resonant neutralino annihilation) imply an upper limit of close to 1000 GeV/c$^2$ on the masses of $\tilde{t}_1$ and $\tilde{b}_1$, and an upper limit of 150-250 GeV/c$^2$ on the LSP mass.

6 Searches at the Tevatron Run II and a summary of LEP and Run I limits

Although finding a light $h^0$ at the Tevatron would constitute an interesting suggestion that the MSSM is the right extension of the Standard Model, only the observation of the sparticles can establish its validity.

Several channels of sparticle production in R-parity conserving scenario are considered for Run II of the Tevatron, among them the production of $\tilde{\chi}^0_1\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\tilde{\chi}^0_1$, $\tilde{t}_1\tilde{t}_1$, $\tilde{b}_1\tilde{b}_1$, gluino
Figure 5: The lower limit at 95% confidence level on the mass of the lightest neutralino, $\tilde{\chi}_1^0$, in mSUGRA. The limits for positive $\mu$ (upper plot) and negative $\mu$ (lower plot) are shown. The dashed, solid, and dotted curves show limits obtained for $A_0 = -500$ GeV/$c^2$, $A_0 = 0$ and $A_0 = 300$ GeV/$c^2$, respectively. The thin solid curve on the lower plot shows the limit for $A_0 = 0$ and $m_{top} = 180.0$ GeV/$c^2$. $m_{top} = 174.3$ GeV/$c^2$ for all other curves. The LSP limit degrades in this case down to the one set by chargino searches for $\tan\beta > 15$. Thin solid (dashed) curves on the upper plot show the limit obtained for $A_0 = 0$ GeV/$c^2$ ($A_0 = -500$ GeV/$c^2$) with the calculated $m_{h_0}$ value lowered by 3 GeV/$c^2$ (this corresponds to a rise in the experimental limit). These limits result primarily from chargino and Higgs searches and are also valid in R-parity violating scenarios as long as a kinematic limit on the chargino mass can be set. If $b \rightarrow s\gamma$ and dark matter (R-parity conserving scenario) constraints were used, the lower limit on the LSP mass would rise to $\sim 110$ GeV/$c^2$ for $\tan\beta > 20$. 

$m_{\chi} = 3 GeV/c^2$ for all other curves.
Figure 6: The lower limit at 95% confidence level on the masses $\tilde{g}$, $\tilde{e}_R$ and $\tilde{e}_L$, in mSUGRA. The limits for positive $\mu$ (negative $\mu$) are shown in thin dark (thick light) lines. The dashed (solid) curve shows limits obtained for $A_0 = -500 \text{ GeV}/c^2$ ($A_0 = 0 \text{ GeV}/c^2$). See text for more explanations. These limits result primarily from chargino, $\tilde{e}_R$ and Higgs searches and are also valid in R-parity violating scenario, as long as the kinematic limit on the chargino mass can be set. In R-parity violating scenarios regions, where the $\tilde{e}_R$ limit is effective, and which are not covered by the Higgs search, are covered either by chargino searches or by stop searches, or by the requirement of a non-tachyonic stop. These limits can be tightened for $\tan \beta > 20$, if $b \rightarrow s\gamma$ and dark matter (R-parity conserving scenario) constraints are used (see text).
Figure 7: Allowed range in $(m_{\tilde{t}_1}, m_{\tilde{b}_1})$ plane, at 95\% confidence level for several values of $\tan \beta$, resulting from Higgs and SUSY searches. The darker (lighter) region is for $A_0 = 0$ ($A_0 = -500$ GeV/c$^2$). The hatched (cross-hatched) region on the lighter (darker) shading is allowed for $0.03 \text{ pb} \lesssim \sigma(h^0Z)\text{BR}(h^0 \to bb) \lesssim 0.07 \text{ pb}$. Only the region $\mu > 0$ is shown, as it is less restricted. If $b \to s\gamma$ constraints from [15] are applied, the lower limit on the mass of the $\tilde{t}_1$ ($\tilde{b}_1$) grows to 300 GeV/c$^2$ (450 GeV/c$^2$) for $\tan \beta > 20$ (see text).
and squark production are the most important ones [27, 10]. An approximate reach of Run II with 25 (2) $fb^{-1}$ in the masses of the above sparticles is 150 (110) GeV/$c^2$ for $m_{\tilde{\chi}_{1}^{\pm}}$, 75 (55) GeV/$c^2$ for $m_{\tilde{\chi}_{1}^{0}}$ and 450 (330) GeV/$c^2$ for the gluino mass, provided $m_{0} \lesssim 200$ GeV/$c^2$. The stop, $\tilde{t}_1$, is observable up to 260(180) GeV/$c^2$ and the $\tilde{b}_1$ up to 280(210) GeV/$c^2$.

In R-parity violating scenarios, where the LSP decays to the final states containing leptons (via leptonic $\lambda$ and leptonic-hadronic $\lambda'$ coupling) higher reach was reported for the sparticle pair-production [51]. This is primarily due to the better visibility of the final states. Using all the SUSY production channels and assuming mSUGRA mass relations, gluino with mass below 500-600 GeV/$c^2$ can be excluded at Run IIa ($2fb^{-1}$). Searches for single sparticle production can have a higher kinematic reach, but production cross-sections depend directly on the value of the R-parity violating coupling involved.

LEP and Tevatron Run I searches place relevant limits on the masses of the all above particles.

In the constrained MSSM with non-universal Higgs parameters, the lightest neutralino and the gluino could be in the range of the Tevatron Run II for $\tan \beta > 3$, but only in the high luminosity scenario. For large mixing in the stop sector, the stop lighter than 200 GeV/$c^2$ is allowed for $3 \lesssim \tan \beta \lesssim 20 - 30$, and $b_1$ lighter than 200 GeV/$c^2$ is allowed for $\tan \beta \gtrsim 10$. These squarks could thus be observable in Tevatron Run IIa ($2fb^{-1}$). However, for small mixing they are above the range of the Tevatron.

Light stau $m_{\tilde{\tau}_1} \gtrsim 87$ is not excluded by LEP II constraints, and could be perhaps observable at the Tevatron.

In the mSUGRA scenario, gauginos could be observed at the Tevatron (Run IIb) if $A_0$ is large and $\tan \beta \gtrsim 7$. Gluino can be lighter than 500-600 GeV/$c^2$ for $\mu > 0$, $\tan \beta \gtrsim 7$, thus the R-parity violating SUSY can be observed already at the Run IIa, if the LSP decays give electrons or muons. The stop, $\tilde{t}_1$, can be lighter than 200 GeV/$c^2$ and thus in the range of Run IIa, for large $A_0$ and 10 $\lesssim \tan \beta \lesssim 30$. The sbottom can be somewhat lighter than 300 GeV/$c^2$ for large $A_0$ and 10 $\lesssim \tan \beta \lesssim 40$, thus perhaps in the range of Run IIb. However, if $b \rightarrow s\gamma$ constraints are used, the stop and sbottom are beyond the reach of the Tevatron for $\tan \beta \gtrsim 20$. If both $b \rightarrow s\gamma$ and cosmological constraints are used (R-parity conservation), gauginos (chargino, neutralino, gluino) are beyond the reach of the Tevatron for $\tan \beta \gtrsim 20$. For $7 \lesssim \tan \beta \lesssim 20$ it is still possible to observe gauginos in Run IIb (for large $A_0$) and the possibility of their discovery is enhanced due to the upper limit set on $m_0$ by the relict density of the LSP’s.

Searches for the stop and the sbottom thus seem to be the most promising SUSY discovery channels at Run IIa. Below a few examples of non-excluded sets of CMSSM and mSUGRA parameters corresponding to the light stop or sbottom are given (parameters in GeV/$c^2$ whenever appropriate):

MSSM: $\tan \beta=10$, $m_0 = 154$, $\mu = -1200$, $M_2 = 106$, $A_t = 500$, $A_b = A_{\tau} = 0$, $m_A = 1000$. In this point $m_{\tilde{t}}=198$ and $m_{\tilde{b}}=246$. The stop decays to $\chi_1^{\pm}$ b, and $\chi_1^{\pm} \rightarrow \tau_1\nu$, $m_{\tau_1}=100$ GeV/$c^2$.

MSSM: $\tan \beta=10$, $m_0 = 80$, $\mu = 300$, $M_2 = 133$, $A_t = -800$, $A_b = -800$, $A_{\tau} = -495$, $m_A = 1000$. In this point $m_{\tilde{t}}=194$, and $m_{\tilde{b}}=367$. The stop decays to $\chi_1^{\pm}$ b, and $\chi_1^{\pm} \rightarrow \tau_1\nu$, $m_{\tau_1}=96$ GeV/$c^2$.

MSSM: $\tan \beta=35$, $m_0 = 300$, $\mu = 1519$, $M_2 = 160$, $A_t = 1100$, $A_b = A_{\tau} = 0$, $m_{\tau_1}=100$ GeV/$c^2$. 

\[ m_A = 1000. \] In this point \( m_{\tilde{t}}=374 \) and \( m_{\tilde{b}}=177. \) The sbottom decays to \( \tilde{\chi}_1^0 b \) (80\%), \( \tilde{\chi}_2^0 b \) (20\%) and \( \tilde{\chi}_2^0 \to \tau_1 \tau. \) \( m_{\tilde{\tau}_1} = 100 \text{ GeV}/c^2. \)

mSUGRA: \( \tan \beta = 10, m_0 = 80, m_{1/2} = 160, A_0 = -400, \mu > 0. \) In this point \( m_{\tilde{t}}=176 \) and \( m_{\tilde{b}}=318. \)

mSUGRA: \( \tan \beta = 15, m_0 = 100, m_{1/2} = 180, A_0 = -500, \mu > 0. \) In this point \( m_{\tilde{t}}=186 \) and \( m_{\tilde{b}}=309. \)

In many of these points \( \tilde{\tau}_1 \) is relatively light and final states with \( \tau \)'s are important.

However three-body decays \( \tilde{t}_1 \to b \ell \nu \) are not important for the stop detectable at the Tevatron, due to the high limit on \( m_{\tilde{t}} \) set by LEP (see previous section). For the same reason, the decays \( \tilde{t}_1 \to b \ell \nu \) are only important if \( \tilde{\ell} = \tilde{\tau}_1. \)

In summary, the stop and the sbottom searches are the most promising discovery channels of gravity-mediated SUSY with R-parity conservation. As also pointed out in [47] the final states containing taus should be given a special attention. For \( \mu > 0 \) and \( \tan \beta \simeq 7, \) R-parity violating SUSY can be observed already in Run IIa if the LSP decays give electrons or muons.

It is interesting to note that in the constrained MSSM with non-universal Higgs parameters, the requirement that there is a Standard-Model-like \( h^0 \) with \( m_{h^0} < 117 \text{ GeV}/c^2 \) sets an upper limit of around 1 TeV\(^2/c^2\) on the mass of the lightest stop. A similar limit is set by the requirement that \( \Omega_{\text{LSP}} h^2 < 0.3 \) if the lightest neutralino is a gaugino and the resonant annihilation and resonant co-annihilation are ignored. The mass region \( 50 \lesssim m_{\tilde{\chi}_1^0} \lesssim 300 \text{ GeV}/c^2 \) is preferred. If the lightest neutralino is a higgsino, \( m_{\tilde{\chi}_1^0} > 80 \text{ GeV}/c^2 \) is set by the LEP results, excluding a possibility of the light higgsino Dark Matter (see [48]).

Similar conclusions can be drawn in the mSUGRA scenario; the results of [16] and [15] suggest though that (for \( A_0 = 0 \) and \( \tan \beta > 35 \)) there is little room for spectra which are consistent both with \( b \to s \gamma \) and with an upper limit on the relic density, outside the regions allowed by the resonant neutralino annihilation and the resonant neutralino-stau co-annihilation. However, these constraints have to be recalculated for \( A_0 \) values other than 0. In particular, large positive values of \( A_t \) such that \( A_t \) is positive at \( m_{1/2} \gtrsim 150 \text{ GeV}/c^2 \), should be considered, as they weaken \( b \to s \gamma \) constraints [41]. They can allow for lighter sparticles at large \( \tan \beta \), where the LEP Higgs mass limit is less effective in terms of constraints on \( m_{1/2}. \) Moreover the treatment of the experimental and theoretical errors on \( b \to s \gamma \) has to be improved to enable the statistical interpretation of the resulting constraints.

**Acknowledgements**

I would like to thank Wilbur Venus and Janusz Rosiek for reading the manuscript and many useful comments. I would like to thank my DELPHI colleagues for many discussions on this subjects.
References

[1] for a review see e.g. H.E. Haber and G.L. Kane, Phys. Rep. 117 (1985) 75. For useful formulae see: S. Katsanevas and S. Melachroinos in Physics at LEP2, CERN 96-01, Vol. 2, p. 328. S. Katsanevas and P. Morawitz, Comp. Phys. Comm. 122 (1998) 227. Report of SUGRA working group for Run II of the Tevatron, hep-ph/0003154 v1 16 Mar 2000

[2] P. Fayet and S. Ferrara, Phys. Rep. 32 (1977) 249; H.P. Nilles, Phys. Rep. 110 (1984) 1; H.E. Haber and G.L. Kane, Phys. Rep. 117 (1985) 75.

[3] U. Amaldi, W. de Boer and H. Furstenau, Phys. Rep. 260 (1991) 447.

[4] see for example: S. Heinemeyer, W. Hollik and G. Weiglein, “Precise calculations for the neutral Higgs boson masses in the MSSM” hep-ph/9910283.

[5] M. Carena, S. Heinemeyer, C.E.M. Wagner and G. Weiglein, CERN-TH/99-374 and hep-ph/9912223.

[6] Electroweak Review Plenary, Dave Charlton, EPS-HEP Budapest, July 2001, available from http://lepewwg.web.cern.ch/LEPEWWG/misc/ and note LEPEWWG/2001-01.

[7] Delphi Collaboration, Phys. Lett. B 499 (2001) 23.

[8] LEP Higgs Working Group, “Searches for the Neutral Higgs Bosons of the MSSM”, LHWG note 2001-04.

[9] Fabiola Gianotti, EPS 2001, Budapest, available from http://ion.elte.hu/hep2001/scan.html

[10] M. Carena et al., Report of the Tevatron Higgs Working group, hep-ph/0010338

[11] J. R. Ellis, S. Heinemeyer, K. A. Olive and G. Weiglein, Phys. Lett. B 515 (2001) 348

[12] G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. 267,96,195 (19a) and references therein.

[13] Ibanez, Quevedo, JHEP 9910 (1999) 001

[14] J. R. Ellis, T. Falk, G. Ganis and K. A. Olive, Phys. Rev. D 62 (2000) 075010

[15] M. Battaglia et al., Proposed Post-LEP benchmarks for Supersymmetry, hep-ph/0106204

[16] L. Roszkowski, R. Ruiz de Austri and T. Nihei, New Cosmological and Experimental Constraints on CMSSM, hep-ph/0106334 JHEP 0108 (2001) 024 hep-ph/0106334
[17] D. Pierce and A. Papadopoulos, “Radiative corrections to neutralino and chargino masses in the minimal supersymmetric model”, Phys. Rev. D 50 (1994) 565

D. Pierce and A. Papadopoulos, “The Complete radiative corrections to the gaugino and Higgsino masses in the minimal supersymmetric model” Nucl. Phys. B 430 (1994) 278

[18] DELPHI Collaboration, J. Abdallah et al., “Search for supersymmetric particles in $e^+e^-$ collisions up to 208 GeV and interpretation of the results within the MSSM.” DELPHI 2001-085, CONF 513, submitted to EPS2001, Budapest.

[19] Particle Data Group, Review of Particle Properties, D.E Groom et al., The European Physical Journal C15 (2000) 1

[20] OPAL Collaboration, “New Particle Searches in $e^+e^-$ Collision at $\sqrt{s} = 200-209$ GeV”, OPAL Physics Note PN470, submitted to EPS2001, Budapest.

[21] Search for new particles in L3, submitted to Budapest. L3 Collaboration, M. Acciarri et al., “Search for Charginos and Neutralinos in $e^+e^-$ collisions at $\sqrt{(s)} = 192-208$ GeV”, L3 note 2583, Paper contributed to the EPS 2001 conference in Budapest.

[22] ALEPH Collaboration, “Search for Sfermions, Charginos and Neutralinos and the LSP mass limit in the MSSM, with and without Higgs Search Constraints”, Paper contributed to the EPS 2001 conference in Budapest.

[23] Aleph Colaboration, “Observation of an Excess in Search for the Standard Model Higgs Boon in Aleph”, CERN-EP/2000-138

[24] G. Abbiendi et al. [OPAL Collaboration], Higgs boson in e+ e- collisions at $s^{**}(1/2) = 192$-GeV - 209-GeV,” Phys. Lett. B 499 (2001) 38

[25] L3 Collab., P.Achard et al., Submitted to Physics Letters B. CERN-EP/2001-049; July 10, 2001. L3 preprint 239.

[26] M. Roco [CDF and D0 Collaborations], “Higgs searches at the Tevatron: Run 1 results and run 2 prospects,” FERMILAB-CONF-00-203-E, Prepared for 30th International Conference on High-Energy Physics (ICHEP 2000), Osaka, Japan, 27 Jul - 2 Aug 2000

[27] V. Barger, C.E.M Wagner et al., Report of SUGRA working group for Run II of the Tevatron, hep-ph/0003154 v1 16 Mar 2000

[28] Joint LEP2 SUSY Working Group, http://lepsusy.web.cern.ch/lepsusy/
Combined LEP Chargino mass limits, http://lepsusy.web.cern.ch/lepsusy/www/inos_moriond01/, LEPSUSYWG/01-03.1, Combined slepton results, http://alephwww.cern.ch/~ganis/SUSYWG/SLEP/sleptons_2k01.html LEPSUSYWG/01-01.1,
Combined squark results, 
http://lepsusy.web.cern.ch/lepsusy/www/squarks_moriond01/squarks_pub.html.
LEPSUSYWG/01-02.1

[29] R. Barbier, C.Berat, P.Jonsson, V.Poireau [DELPHI Collaboration], “Search for supersymmetry with R-parity violation at $\sqrt{s}=192$ to $208$ GeV “, DELPHI 2001-083 CONF 511, submitted to EPS2001, Budapest.

[30] ALEPH Collaboration, “Search for R-parity violating decays...” ALEPH 2001-012, submitted to EPS2001, Budapest.

[31] T. Alderweireld et al., [DELPHI Collaboration] “Search for AMSB with the DELPHI data”, DELPHI 2001-069 CONF 497, submitted to EPS2001, Budapest.

[32] See for example, DELPHI Coll, P. Abreu et al., “Searches for charginos nearly mass degenerate with the lightest neutralino at centre-of-mass energies up to 202 GeV ”, DELPHI 2000-081 CONF 380, Contributed Paper for ICHEP2000, (Paper 366).

[33] ALEPH Collaboration, “The impact of stau mixing on the mass limit of the lightest neutralino”, ALEPH 2001-068, submitted to EPS2001, Budapest.

[34] H. N. Brown et al. [Muon g-2 Collaboration], Phys. Rev. Lett. 86 (2001) 2227

[35] W. de Boer, M. Huber, C. Sander and D. I. Kazakov, $b \to X/s$ gamma and Higgs limits in the constrained MSSM,” Phys. Lett. B 515 (2001) 283

[36] See for example: M. Byrne, C. Kolda and J. E. Lennon, “Implications of the muon anomalous magnetic moment for supersymmetry,” hep-ph/0108122

[37] CLEO Collaboration, Branching Fraction and Photon Energy Spectrum for $b \to s\gamma$, CLNS 01/1751, hep-ex/0108032

[38] See for example: HongJo Kim, Belle Collaboration, “Non-CP physics at Belle “, Nucl. Instr. and Meth. 462 (2001) 84

[39] See for example, M. Misiak, “Theory of Radiative B Decays”, Acta Physics Polonica B, V32(2001)6

[40] M. Misiak, S. Pokorski and J. Rosiek, “Supersymmetry and FCNC Effects”, hep-ph/9703442. Review Volume “Heavy Flavours”, World Scientific

[41] M. Carena, D. Garcia, U. Nierste and C.E.M Wagner, “$b \to s\gamma$ and supersymmetry with large $\tan \beta$”, hep-ph/0010003.

[42] P. Abreu et al. [DELPHI Collaboration], Phys. Lett. B 489 (2000) 38

[43] DELPHI Coll.,M. Espirito Santo et al., “Limits on the masses of Supersymmetric Particles at $\sqrt{s}$ up to 202 GeV”, DELPHI 2000-087 CONF 386, ICHEP2000, OSAKA.
[44] W. de Boer, M. Huber, A. V. Gladyshev and D. I. Kazakov, Eur. Phys. J. C 20 (2001) 689

[45] H. Baer, F. E. Paige, S. D. Protopopescu and X. Tata, “ISAJET 7.48: A Monte Carlo event generator for p p, anti-p p, and e+ e- reactions ”, hep-ph/0001086

[46] R. Demina, J. D. Lykken, K. T. Matchev and A. Nomerotski, Phys. Rev. D 62 (2000) 035011

[47] A. Djouadi, M. Guchait and Y. Mambrini, high tan beta regime,” Phys. Rev. D 64 (2001) 095014

[48] J. Edsjo, P. Gondolo, Neutralino relic density including coannihilations, Phys. Rev. D56,4,1997 (19,) P. Gondolo and J. Edsjo, Accurate Relic Density Calculation, hep-ph/9804453

[49] J. R. Ellis, T. Falk, G. Ganis, K. A. Olive and M. Srednicki, Phys. Lett. B 510 (2001) 236

[50] J. Ellis, D.V. Nanopoulos, K. A. Olive, Lower limits on on Soft Supersymmetry Breaking Scalar Masses, hep-ph/0109288.

[51] B. Allanach et al., “Searching for R-parity violation at Run-II of the Tevatron,” hep-ph/9906224