Search for SUSY and Higgs particles

W. de Boer

Institut für Experimentelle Kernphysik,
University of Karlsruhe
Postfach 6980, D-76128 Karlsruhe, Germany

Abstract

An overview of hints for new physics outside the Standard Model and the status of sparticle and Higgs searches is given. The present limits on Higgs bosons of about 90 GeV as well as the $b \rightarrow s \gamma$ rate and cosmological constraints severely restrict the available parameter space of the MSSM.

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1 Introduction

Interest in supersymmetry, the symmetry between fermions and bosons, originated from the fact, that it is a non-trivial extension of the Poincaré group, which now includes internal quantum numbers of particles, thus paving the way for a unification of strong, electromagnetic and weak interactions with gravity. In addition, supersymmetry removed the ultraviolet divergencies that plagued the Standard Model (SM). Details about these developments in the 1970s can be found in many reviews[1].

Interest in supersymmetry became a big boost in the 1990s after precise measurements of the gauge couplings at LEP, which showed that gauge coupling unification, the prerequisite for Grand Unified Theories (GUT), is only possible in the supersymmetric extension of the SM, not in the SM itself[2]. However, the price to be paid for this symmetry is a doubling of the particle spectrum[1]: for each fermion (boson) of the SM one needs to introduce an additional boson (fermion) with the same quantum numbers. In addition, two Higgs doublets instead of one doublet are required. This minimal supersymmetric extension is called the Minimal Supersymmetric Standard Model (MSSM).

Supersymmetry cannot be an exact symmetry in nature as the superpartners must be heavier than the SM ones: none of the predicted spin 0 partners of the quarks and leptons, the so-called squarks and sleptons, nor the spin 1/2 partners of the gauge bosons, the photino, zino, wino and gluino, have been observed so far. It should be noted that some of the higgsinos and gauginos have the same quantum numbers, such as spin and electric charge, thus allowing mixing between the mass and interaction eigenstates: the mixed states of the wino and charged higgsino are usually called chargino whilst the mixed states of the photino, zino and two neutral higgsinos are the so-called neutralinos. The detailed properties of the mass mixing matrices and mass relations can be found in standard reviews[1].

In addition to gauge unification at a scale $m_{\text{GUT}} \approx 10^{16}$ GeV, the Yukawa couplings of the $b$-quark and $\tau$-lepton turned out to unify at the same scale in the MSSM, as expected in practically all GUT’s, since the quarks with charge ($-1/3$) and leptons belong to the same representation of any group containing the well-known $SU(3) \otimes SU(2) \otimes U(1)$ from the SM as subgroups[1].

After the discovery of the heavy top quark the Higgs mechanism has a natural explanation in the MSSM because of the large radiative corrections from the Yukawa couplings to the Higgs potential, which can easily introduce a non-trivial minimum due to the difference between the running of the masses of the two Higgs doublets[1]. Therefore, the electroweak symmetry breaking need not be introduced ad hoc, as in the SM, but its origin is the heavy top quark, thus linking intimately the $Z^0$ mass and the top mass. This link only functions for $140 < m_t < 200$ GeV and therefore the experimental top mass is exactly in the range required by the MSSM.

Furthermore, the coupling in the Higgs potential is not arbitrary, as in the SM, but constrained by the gauge couplings. This allows the prediction that the Higgs mass will be below 130 GeV (preferentially even below 100 GeV). Such a low Higgs mass is indeed preferred by the
electroweak precision data\cite{3}, as will be discussed in Section 2. The direct observation of a Higgs mass in the predicted range would certainly provide another big boost for the MSSM, although its ultimate verification can only come from the direct proof of the existence of sparticles.

During recent years’ several deviations from the SM have been suggested as hints of supersymmetry. Although none of the few sigma deviations themselves were convincing, it has been argued that most of them pointed to the same region of the MSSM parameter space\cite{4}. However, most of these ‘hints’ have faded away during the last year, as will be discussed in the next Section.

As long as the origin of the breaking of supersymmetry is not known, one has to search for direct signs of SUSY in very diversified ways. Among the models obtaining most attention for direct searches with the present colliders are:

- **The $R_p$ scenarios.**
  In the SM the decay of a quark into a lighter quark plus lepton is effectively suppressed by angular momentum conservation since all have spin 1/2. However, in SUSY this is not the case, so quarks can e.g. decay into a lepton and a squark, leading to Baryon- and Lepton-number violation, and consequently to proton decay, if no precautions are taken. To avoid such B- and L-violating interactions one usually assumes that the multiplicative quantum number $R_p = (-1)^{3B+L+2S}$ is conserved. This R-parity is +1 for SM particles and −1 for SUSY particles. As a result of $R_p$ conservation, sparticles have to be produced in pairs and the decay products of any SUSY particle ($R_p = 1$) must contain another SUSY particle, thus for kinematical reasons the lightest SUSY particle cannot decay anymore and must therefore be stable. These properties define it as the perfect candidate for the dark matter in our universe, provided it is neutral too, which is the case in many scenarios. The non-interacting stable LSP leads to the famous missing energy signatures for supersymmetry. If R-parity is broken, there is no missing energy and momentum, but the SUSY signature would consist of events with many jets and/or multiple leptons\cite{5}.

- **The gauge mediated scenario.**
  In the gauge mediated scenario the breaking of supersymmetry is caused by gauge interactions. Since the breaking is proportional to the gauge couplings, one expects the SUSY masses to be proportional to the gauge couplings times a breaking scale, i.e. $M_{\tilde{B}} \approx (\alpha_1/4\pi)\Lambda^2_{\text{SUSY}}$. For SUSY masses in the 100 GeV to 1 TeV range, the breaking scale $\Lambda^2_{\text{SUSY}}$ has to be of the order of $10^2 - 10^3$ TeV. In such scenarios the gravitino $M_{\tilde{G}} \approx (\Lambda^2_{\text{SUSY}}/M_{\text{Pl}})$ is of the order of a few eV, which implies that it is the LSP, but it is too light to be a candidate for cold dark matter.

  The sparticles can decay into a gravitino plus a photon. The famous CDF event\cite{6} with two isolated charged particles and two photons was the perfect candidate for such a scenario (see Section 2) and consequently many searches, both at LEP and the Tevatron, concentrated on final states with isolated photons, albeit without success so far\cite{6,7,8}.

- **The supergravity inspired scenario.**
If the symmetry breaking is due to flavour blind gravitational interactions, one usually assumes a common mass \( m_0 \) for the scalars and one \( m_{1/2} \) for the spin 1/2 gauginos at the GUT scale. Owing to radiative corrections the masses become different at the electroweak scale, but in a well defined manner given by Renormalization Group Equations (RGE).

Space does not permit all scenarios to be covered exhaustively. I will concentrate on the supergravity inspired scenario, which is the most interesting one for cosmology, since it provides a very natural candidate for dark matter for a large region of parameter space, as will be discussed in Section 5.

The status of the present sparticle and Higgs searches will be summarized in Sections 3 and 4, respectively. The present limits severely constrain the parameter space of the MSSM, as will be discussed in Section 5.

2 Hints for SUSY?

In this section, we discuss the status of several deviations from the SM which have been suggested as possible hints of supersymmetry.

2.1 The CDF \( ee\gamma\gamma \not{E}_t \) event.

Several years ago, the CDF collaboration found an interesting event with two isolated electrons and two isolated energetic photons plus missing energy[6]. Since the probability from SM backgrounds (mainly radiative W-pair production) was low \( \approx 10^{-6} \), the origin might be selectron pair production with each selectron decaying into an electron plus an unstable photino-like neutralino. The latter one can decay either into a photon plus Higgsino-like LSP[9] or a photon plus a light gravitino[10]. A light gravitino is expected in gauge-mediated supersymmetry-breaking scenarios, the Higgsino-like LSP in supergravity inspired scenarios with a small Higgs mixing parameter \( \mu \).

Recently, the CDF Collaboration reanalysed and published the event[6]. They concluded that after the final detector alignment one of the tracks, previously defined as an electron, did not align up with the electromagnetic cluster anymore. In addition, the invariant mass between track and cluster was above the \( \tau \) mass, so the initial lepton interpretation is doubtful.

Furthermore, if one of the SUSY interpretations was correct, one would expect more events from other SUSY processes in the inclusive \( \gamma\gamma \) sample, i.e. without the requirement of lepton tagging. None were found by CDF in the full data sample of about 90 pb\(^{-1}\). This search was used to set upper limits on chargino production[6]. A similar search by D0 was used to set limits on squark production[8].

2.2 HERA anomalies

From the 1994–1996 data, both H1 and ZEUS reported anomalies in the high \( Q^2 \) region[11]. The clustering of the H1 events at an invariant mass around 200 GeV led to speculations about the
2.3 ALEPH 4-jet anomaly

ALEPH discovered a splendid signal during their Higgs search in four jets\cite{12}, when no b-tagging was required, as shown in Fig. 1. Possible MSSM interpretations included the pair production of left and right handed selectrons\cite{13} or charginos\cite{14}. However, the results were not confirmed by the other experiments. A working group of the four experiments concluded that all experiments had a similar efficiency for 4 jets, so it was unclear why it only showed up in one experiment. Finally, the LEPC Committee decided to have a new run at 135 GeV, where the bulk of the ALEPH signal had accumulated. However, after two weeks of running the total accumulated luminosity of 24 pb\(^{-1}\) from the four experiments did not show any signal (see Fig. 1), and therefore this \(\approx 7 - 10 \sigma\) ALEPH anomaly should only be remembered as an anomaly, not new physics.
2.4 Electroweak precision measurements

The MSSM can describe Electroweak Precision Measurements (EPM) at least as well as the SM, as demonstrated in Fig. 2. These results are an update from Ref. [15] with the summer 1998 data, as compiled by the Electroweak Working Group [3]. The famous deviation in $R_b = \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})}$ has gradually come down from a 3.5 $\sigma$ deviation a few years ago, to a 1.4 $\sigma$ effect at present. The better agreement in the MSSM for this variable mainly stems from chargino-stop corrections to the b-quark production vertex, although this requires light stop and chargino masses. The improvement with the present exclusion limits for stops and charginos above 90 GeV (see Section 3) is small.

Another interesting result from electroweak fits is the fact that they point to a low Higgs mass [3], as is apparent from the $\chi^2$ distribution in Fig. 2. However, the discrepancy between LEP and SLC on $\sin^2 \theta_W$ is still a dominant source of uncertainty in the Higgs mass: $\sin^2 \theta_W = 0.23101 \pm 0.00031$ from SLC [16] corresponds to a Higgs mass of $m_H = 17^{+27}_{-8}$ GeV, while the LEP value of $\sin^2 \theta_W = 0.23183 \pm 0.00021$ corresponds to $m_H = 176^{+120}_{-76}$ GeV. The combined value is $m_H = 100^{+72}_{-45}$ GeV. If the combined fit is performed with the requirement that the Higgs mass has to be above 90 GeV, the SLC data get less weight, thus leading to a higher upper limit on the Higgs mass [17, 18].
Figure 3: Excluded right-handed stop and stau masses as a function of the LSP mass. For the stop the excluded region by the D0 Collaboration is shown as well as the pessimistic case of a mixing angle of $56^\circ$ between left- and right-handed stops, which minimizes the coupling to the $Z^0$ boson. For the stau the expected limit, based on the expected number of events instead of the observed number of events, is also shown.

3 Search for SUSY particles

As mentioned in the introduction, we restrict ourselves here to the supergravity inspired scenarios with common mass scales at the GUT scale and a stable LSP. In these scenarios, the signature is the missing energy and momentum. However, backgrounds from $\gamma\gamma$, $W e\nu_e$, $Zee$, $WW$ and $ZZ$ production have to be suppressed by suitable cuts on variables like visible energy, visible mass, thrust, etc. Typically, the number of candidates after the cuts can be reduced to a few events. Up to now, the number of candidates is consistent with the background, so one can set only upper limits on the SUSY cross sections for a given mass, or alternatively, these cross section limits can be transformed into mass limits. These limits depend on the LSP mass, since it defines the amount of missing energy, which is an important criteria to separate the signal from the background (assuming that enough energy is seen in the detector to trigger the event). If the mass difference $\Delta M$ between the LSP and the SUSY sparticle mass is at least 15 GeV, the background is usually no problem. If $\Delta M$ becomes smaller, the visible energy rapidly decreases and the background, especially the $\gamma\gamma$ background, rapidly increases. If $\Delta M$ becomes only a few GeV, the lifetime of the sparticles can become so long that they decay inside or even outside the detector, thus forming kinks in the charged tracks or resembling stable charged particles. The results of such scenarios have been summarized by the SUSY Working Group[7].
Therefore, it is useful to give upper limits on the cross sections in a plane of the sparticle mass versus the LSP mass. Such plots are shown in Fig. 3 for stops and staus, which are expected to be the lightest sfermions due to the negative corrections from the Yukawa couplings. These preliminary plots were prepared by the SUSY Working Group[7].

The upper limits on the cross section can be transferred into lower limits on the sparticle masses, which are indicated in Table 4 together with typical expected masses in the Constrained MSSM (CMSSM), which will be discussed in Section 5. These limits are only valid for a sufficiently large $\Delta M$, since if the LSP mass is close to the sfermion mass, the visible energy in the detector is too small. This can be observed from the small unexcluded regions close to the diagonal in Fig. 3. Note that these regions are much larger for hadron colliders, as shown by the D0 exclusion plot in Fig. 3.

LSP production yields only invisible final states, except for initial state radiation. Nevertheless, LSP mass limits can be obtained, if one assumes unified gaugino masses at the GUT scale, which yield mass relations between neutralinos and charginos at low energies (see left-hand side of Fig. 4). Using these assumptions, L3 finds a lower limit of 25.9 GeV for the LSP mass for low tan $\beta$ and any value of $m_0$ allowed by the slepton limits[19]. For high values of tan $\beta$ and $m_0$ the LSP limit is about half the chargino limit, which follows directly from the evolution of the masses by the RGE. For large $m_0$ the sneutrinos are heavy and the chargino cross sections is not decreased by the negative interference from the t-channel sneutrino exchange. Other experiments have performed similar analysis with similar results[20].
4 Search for Higgs bosons

In the SM there is only one Higgs boson with an arbitrary mass. Since the decay amplitudes are proportional to the fermion mass, the branching ratios are predominantly to heavy fermions: $\approx 84\%$ to $b\bar{b}$ pairs and $\approx 6\%$ to $\tau\tau$ pairs. Higgs production occurs mainly via Higgs Bremsstrahlung: $e^+e^- \rightarrow hZ$ with a cross section of the order of a few tenths of a pb. The Higgs boson can therefore be searched for in the final states indicated in Fig. 5. Note that the large fraction of events with b-quarks leads to very distinct event signatures, which is apparent from a nice candidate, shown in Fig. 6.

In the MSSM there are five Higgs bosons: two charged ($H^\pm$), one heavy neutral (H), one light neutral (h), and one neutral pseudoscalar (A). In addition to the SM Higgs bremsstrahlung, one can have hA production, if it is kinematically allowed. This process leads to the final states shown on the right-hand side of Fig. 5. All these channels have been searched for, but no signal above the expected background from SM processes has been found. Consequently, one has to conclude that Higgs bosons are most likely too heavy to be produced at present centre-of-mass energies. From a preliminary combination of the 1997 data of the four LEP experiments at 183 GeV one finds that the SM Higgs mass has to be above 90.1 GeV\cite{21}. For the MSSM the lightest Higgs mass, obtained from the diagonalization of the mass matrices, is a function of $m_A$ and $\tan \beta = v_2/v_1$, the ratio of the vacuum expectation values of the neutral components of the two Higgs doublets\cite{1}. Consequently, the lower limit on the Higgs mass depends on $\tan \beta$ and $m_A$. This dependence on three variables is difficult to depict. Therefore one usually shows the excluded regions in the two-dimensional $(m_h, \tan \beta)$ and $(m_A, \tan \beta)$ planes, whilst varying the third parameter ($0.5 < \tan \beta < 50$ and $0 < m_A < 2$ TeV). The results are shown in Fig. 7. At low $\tan \beta$ the $m_h$ limit is close to the SM one, but at high $\tan \beta$ the limit is approximately 10 GeV lower; the $m_A$ limit for any $\tan \beta$ is about 82 GeV. In special cases (region when $m_h \approx m_A \approx 78$ GeV) the limits are reduced by a few GeV, as found by special
Figure 6: DELPHI Higgs candidate in the $b\bar{b}qq$ channel. Note the large secondary vertex, characteristic of the decay of a $B$-meson, in the blown up version of the vertex region on the right-hand side. The invariant masses of the quark pairs are 89 and 91 GeV, respectively, so the event is consistent with a ZZ candidate.

scans over the SUSY parameters, so that lower limits at 95% C.L. are[21]:

$$m_h > 77 \text{ GeV}; \ m_A > 78 \text{ GeV}.$$  

5 Constraints from low energy data and cosmology

In the gravity inspired scenario, the breaking of supersymmetry occurs via universal gravitational interactions, which leads to universal masses at the GUT scale. These common masses at the GUT scale completely determine the low-energy SUSY spectrum from the known radiative corrections, which lead to running masses as depicted in Fig. [4].

There are nine free parameters (at the GUT scale) in this minimal scenario: the GUT scale $m_{\text{GUT}}$ and the unified gauge coupling $\alpha_{\text{GUT}}$, the Yukawa couplings of the third generation $Y_{t}^{0}, Y_{b}^{0}, Y_{\tau}^{0}$ (those of the other generations are small, $b - \tau$ unification presupposes $Y_{b}^{0} = Y_{\tau}^{0}$), the common masses for spin 0 and spin 1/2 sparticles, called $m_0$ and $m_{1/2}$, respectively, the Higgs mixing parameter $\mu$, and the trilinear couplings $A^0$. The superscript denotes the GUT scale value. These GUT scale parameters are constrained by the low-energy data: the running of the gauge couplings determines $m_{\text{GUT}}$ and $\alpha_{\text{GUT}}$, the masses of the third generation quarks and leptons determine the Yukawa couplings, $b - \tau$ Yukawa unification yields the preferred value for $\tan \beta$ and electroweak symmetry breaking determines the absolute value of $\mu$. The trilinear couplings play a minor role, mainly in the $b \rightarrow s\gamma$ rate and the mixing in the stop sector. Of course, all parameters are correlated, so they can only be determined in a common fit to the data. Since the mass parameters $m_0, m_{1/2}$ are strongly correlated, such a fit was performed for all values between 100 GeV and 1 TeV in steps of 100 GeV[22].
Only three values of \(\tan \beta\) give an acceptable \(\chi^2\) fit for \(m_t = 174\) GeV, if the Yukawa couplings are constrained by \(Y^0_b = Y^0_\tau\) (see Fig. 8). The large \(\tan \beta\) solutions have the unique feature of a possible triple Yukawa unification: all three Yukawa couplings are driven to an approximate fixed point, as shown on the r.h.s. of Fig. 8. These low-energy values of the Yukawa couplings yield approximately the correct masses of the leptons and quarks of the third generation for \(\tan \beta = 64\). The difference between the two solutions at high \(\tan \beta\), corresponding to opposite signs of \(\mu\), stems from finite loop corrections to the bottom quark mass involving squark-gluino and stop-chargino loops. These corrections are small for low \(\tan \beta\) solutions, but can become as high as 10–20\% for the high \(\tan \beta\) values\(^{23}\), since the dominant corrections are proportional to \(\mu \tan \beta\). Consequently, they change sign for different signs of \(\mu\).

In Fig. 8 the total \(\chi^2\) distribution is shown as a function of \(m_0\) and \(m_{1/2}\) for the three values of \(\tan \beta\) determined above from \(b - \tau\) unification. The areas at low \(m_0\) and high \(m_{1/2}\) are excluded by the LSP constraint, since in this case the lightest \(\tilde{\tau}\) can become the LSP. If R-parity is conserved, a charged LSP is not allowed, since the vacuum would be filled with charged relics from the Big Bang.

The relic density constraint excludes \(m_0 > 350\) GeV for small \(\tan \beta\), as discussed previously\(^{23}\). For large \(\tan \beta\) the Higgsino mixture of the LSP allows a fast enough decay via s-channel \(Z^0\) exchange, which means the requirement \(\Omega h^2 \leq 1\) is easily fulfilled. The combined requirements of the correct \(b \to s \gamma\) rate and \(b - \tau\) unification exclude a large region of parameter space for large \(\tan \beta\), as shown by the contours in the lower part of that figure\(^{22}\).
Figure 8: Left: The top quark mass as a function of $\tan \beta$ (top) for values of $m_0, m_{1/2} \approx 1\text{TeV}$ after requiring $b - \tau$ unification. The curve is hardly different for lower SUSY masses. The middle part shows the corresponding values of the Yukawa couplings at the GUT scale and the lower part the $\chi^2$ values. If the top constraint ($m_t = 174 \pm 5$, horizontal band) is not applied, all values of $\tan \beta$ between 1.2 and 70 are allowed, but if the top mass is constrained to the experimental value, only the regions $\tan \beta = 1.65 \pm 0.3$, $\tan \beta \sim 35$, and $\tan \beta \sim 64$ are allowed. Right: The running of the Yukawa couplings when $Y_t = Y_b = Y_\tau$ at the GUT scale ($SO(10)$ type solution). One can clearly see the approach to the three different fixed points, i.e. the value at low energy is largely independent of the GUT scale value. Consequently the GUT scale values can be chosen to be equal (triple unification). The fixed point values at low energy yield correct masses for bottom and tau for $\tan \beta \approx 64$; the fixed point of the top mass yields $m_t^2 \equiv (4\pi)^2 Y_t v^2 \sin^2 \beta = 184\text{GeV}$, which is about 2$\sigma$ above the experimental value. At low $\tan \beta$ only $Y_t$ is large (see left-hand side), in which case also $Y_t$ shows an infrared fixed point behaviour.

One observes $\chi^2$ minima at $m_0, m_{1/2}$ around (200,500), (1000,900), and (800,600) for the different $\tan \beta$ values, respectively, as indicated by the stars.

Note that the squarks and gluinos are typically above 1 TeV for the high $\tan \beta$ solutions. Furthermore, the minimal $\chi^2$ values are not excellent for high $\tan \beta$: for $\tan \beta = 64$ $\chi^2_{min} = 6.1$ from the fitted top mass ($m_t = 189\text{GeV}$), while for $\tan \beta = 35$ $\chi^2_{min} = 4.3$ from $b \to s\gamma$. All other $\chi^2$ contributions are negligible. For $\tan \beta = 1.65$ $\chi^2_{min} = 1.7$, basically from the $BR(b \to s\gamma)$ constraint alone.

Apart from the heavy spectra for large $\tan \beta$, one has the problem that the Born level Higgs masses are strongly negative, as expected from the fast running of the soft mass terms of the two Higgs doublets, $m_1^2$ and $m_2^2$, which receive negative radiative corrections proportional to the Yukawa couplings (see the running of $m_2^2$ in Fig. 4).

For low $\tan \beta$ the present limit on the lightest Higgs mass severely constrains the parameter
Figure 9: The $\chi^2$-distribution for the low and high $\tan \beta$ solutions. The different shades in the projections indicate steps of $\Delta \chi^2 = 4$, so basically only the light shaded region is allowed. The stars indicate the optimum solution. Contours enclose domains excluded by the particular constraints used in the analysis. From Ref. [22].

space in Fig. 10, which shows the excluded regions in the $(m_0, m_{1/2})$ plane for different signs of $\mu$. As mentioned in the introduction the SM Higgs limit of 90.1 GeV is also valid for the low $\tan \beta$ scenario ($\tan \beta < 4$) of the MSSM. As shown in Fig. 10, this limit rules out the $\mu < 0$ solution. However, this figure assumes $m_t = 175$ GeV. The top mass dependence of the Higgs mass is slightly steeper than linear in this range. Adding about one $\sigma$ to the top mass, i.e. $m_t = 180$ GeV, implies that for the contours in Fig. 11 one should add 6 GeV to the numbers shown. Even in this case the $\mu < 0$ solution is excluded for a large region of parameter space. Only the small allowed region with $m_{1/2} > 700$ GeV is not yet excluded for $m_t = 180$ GeV. Note that in this region the squarks are well above 1 TeV, and therefore the cancellation of the quadratic divergencies in the Higgs masses, which is only perfect if sparticles and particles have the same masses, starts to become worrying. For $m_0 = 1000, m_{1/2} = 1000$, which corresponds
\[
\tan \beta = 1.65, \mu < 0 \quad \tan \beta = 1.65, \mu > 0
\]

Figure 10: Contours of the Higgs mass (solid lines) in the \(m_0, m_{1/2}\) plane (above) and the Higgs masses (below) for both signs of \(\mu\) for the low \(\tan \beta\) solution \(\tan \beta = 1.65\) for \(m_t = 175\) GeV. The lightly shaded areas correspond to the region allowed by the relic density constraint (see Fig. 9).

To squarks masses of about 2 TeV\(^2\), one finds for the upper limit on the Higgs mass in the low \(\tan \beta\) scenario:

\[
m_h^{\text{max}} = 97 \pm 6 \text{ GeV},
\]

where the error is dominated by the uncertainty from the top mass. If one requires the squarks to be below 1 TeV, these upper limits are reduced by 4 GeV.

This CMSSM number agrees well with the value from Casas et al.: \(m_h = 97 \pm 2\) GeV\(^2\). In both analyses the Renormalization Group Equations are used to determine the trilinear coupling at low energies and \(\mu\) from electroweak symmetry breaking (EWSB), so the mixing in the stop sector is fixed, once the sign of \(\mu\) is choosen. Furthermore, in both cases solutions close to the infrared fixed point are considered, which are required in the CMSSM by EWSB. The error on the upper limit quoted above is larger than the one from Casas et al., as they did not consider the error on the top mass.

For high \(\tan \beta\) the upper limit on the Higgs mass in the CMSSM is:

\[
m_h^{\text{max}} = 120 \pm 2 \text{ GeV}.
\]

\(^2\)Explicit analytical expressions for the sparticle masses as a function of the SUSY parameters can be found in Ref. 24.
Table 1: Values of the fitted SUSY parameters (upper part) and corresponding SUSY masses (lower part) for low and high tan β solutions. The experimental 95% C.L. lower limits on the sparticle masses in the last column assume the conservative case of right-handed sfermions being lighter than the left-handed. The gluino and lightest neutralino limits assume gauge mass unification at the GUT scale, so they follow in the CMSSM basically from the chargino limit, since the mass ratios of the chargino and LSP are completely determined by the running masses (see Fig. 4). These mass ratios depend slightly on tan β, as can be seen from the numerical values in the Table. The neutral Higgs limit of 90 GeV assumes a large m_A, which is the case in the CMSSM (see the last row).

The error from the top mass is small in this case, as the high tan β fits prefer top masses around 190 GeV.

6 Summary

Present search limits are starting to constrain the parameter space of the Constrained Minimal Supersymmetric Model (CMSSM) considerably. The preferred and allowed region of parameter space is the low tan β region with a positive Higgs mixing parameter, since the present Higgs limit of 90.1 GeV excludes the µ < 0 solution. The high tan β scenarios have serious finetuning problems, as all Yukawa couplings are large, which causes the Higgs masses at tree level to be strongly negative (typically –1 TeV), so the radiative corrections have to be positive and very large to offset this large negative ‘starting’ value. Furthermore, the solutions with minimal χ² require squarks above 1 TeV, which causes an additional finetuning problem because of the non-cancellation of the quadratic divergencies to the Higgs masses.

In summary, supersymmetry is still the leading candidate for physics beyond the SM, as it provides as a GUT a natural explanation for:

- the different strengths of the strong and electroweak interactions;
• the non-integer electric quark charges;
• the different mass scales for quarks and leptons;
• radiative electroweak symmetry breaking, thus linking the heavy top mass and $Z^0$ mass;
• the large amount of cold dark matter in the universe, if R-parity is conserved.

In addition, the supersymmetric extension of the SM describes the low-energy electroweak precision data as well as the SM. Do alternative theories exist? For the individual items, ‘yes’, but there is no known theory, which can explain all these observations at the same time!

Einstein, when asked what he would think if his General Theory of Relativity would not be confirmed by experiment, used to answer: ‘The Almighty Lord missed a most wonderful opportunity’. I think the same is true for supersymmetry.

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