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Searching for Higgs bosons of minimal supersymmetry

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Abstract. After a brief introduction, we study the constraints on MSSM the Higgs sector parameters from the non-observation of any Higgs boson signals in experiments at LEP. We also review the range of Higgs boson masses that can be searched for at LEP 200. For the most part, we focus on the prospects for the detection of MSSM Higgs bosons in experiments at hadron supercolliders, assuming that these are too heavy to be discovered at LEP 200. We then show that supersymmetric decays of Higgs bosons can significantly reduce the rates for event topologies usually used for Higgs searches. Finally, we discuss some promising new channels for MSSM Higgs boson detection that become possible if these SUSY decays are allowed.

1. Introduction

The elucidation of the mechanism of electroweak symmetry breaking is one of the foremost challenges confronting particle physicists today. Within the framework of the Standard Model (SM), the breakdown of $SU(2)\times U(1)_Y$ is realised via the vacuum expectation value of a spin zero elementary doublet field which is introduced into the theory for just this reason. One neutral scalar particle with a mass $\lesssim 1$ TeV, the Higgs boson [1], is the relic of this symmetry breaking mechanism. The sensitivity of an elementary scalar field sector to radiative corrections, however, leads to the well known fine-tuning problem. General arguments suggest that this can be avoided if there are new degrees of freedom not present in the SM which manifest themselves at a scale of $\mathcal{O}(1$ TeV). This is the main argument for the construction of hadron supercolliders such as the Large Hadron Collider (LHC) or the Superconducting Super Collider (SSC). If we assume that electroweak symmetry is indeed spontaneously broken by vacuum expectation values of elementary scalar fields [2], we are naturally led to consider models that incorporate supersymmetry (SUSY) [3], a novel symmetry that interrelates properties of bosons and fermions. Supersymmetry provides an elegant solution to the fine tuning problem provided that the SUSY breaking scale is $\mathcal{O}(1$ TeV). The supersymmetric partners of known particles are the new degrees of freedom referred to above, so that they should be accessible at high energy hadron colliders. As reviewed by Nath [4] at this Symposium, the simplest locally supersymmetric grand unified model provides a phenomenologically viable candidate for a grand unified theory. It is remarkable that the predictions of the simplest SUSY SU(5) model, unlike those of its nonsupersymmetric counterpart, are consistent with both the measurements of the gauge couplings at LEP as well as the experimental lower limits on the proton lifetime [4]. These considerations have led to extensive studies of strategies [5] for the identification of supersymmetric particles, both at currently operating colliders such as LEP or the Tevatron as well as at hadron supercolliders which are expected to come into operation at the turn of the century. We will not concern ourselves with sparticle identification in this report, but instead focus on the prospects of detecting the Higgs sector of SUSY models.

The Higgs sector of any supersymmetric model consists of at least two SU(2) doublets to give mass to both $T_3 = \frac{1}{2}$ and $T_3 = -\frac{1}{2}$ fermions [3]. We will work in the framework of the minimal supersymmetric model (MSSM) [3] which we will use as a guide to sparticle masses and mixing angles. The MSSM is the simplest supersymmetric extension of the SM. It contains the minimal number of new particles and interactions consistent with phenomenology, *i.e.* we assume that all the interactions conserve R-parity [6]. Within the MSSM framework, there are five physical spin zero bosons associated with the Higgs sector: these are the light and heavy neutral scalars H_l and H_h, a pseudoscalar, H_p (the terms scalar and pseudoscalar refer to their couplings to matter fermions) and a pair of charged scalars $H^{\pm}$. Depending on their masses, the MSSM Higgs bosons may decay into supersymmetric particles [7] or may even be produced via the cascade decays of sparticles [8] so that a study of Higgs boson signals entails some knowledge of sparticle properties. The sparticles, *i.e.* mass eigenstates of the MSSM, include the gluinos (which being colour octet fermions cannot mix with anything as $SU(3)_C$ is conserved) and the spin zero sfermion partners $\tilde{f}_L$ and $\tilde{f}_R$ of the left- and right-handed fermions (their mixing is proportional to the corresponding fermion mass, and hence, is negligible for all but the top squarks). Finally, the gauginos and Higgsinos with the same electric charge mix once $SU(2)_L \times U(1)_Y$ is broken to form two Dirac charginos $\widetilde{W}_1$ and $\widetilde{W}_2$ ($m_{\widetilde{W}_1} < m_{\widetilde{W}_2}$) and four Majorana neutralinos $\widetilde{Z}_1, \widetilde{Z}_2, \widetilde{Z}_3, \widetilde{Z}_4$ (in order of increasing mass).

Supersymmetry must be broken if it is to be phenomenologically relevant. We can parametrize the effects of SUSY breaking by introducing explicit soft SUSY breaking interactions into the theory. These are interactions that do not lead to the reappearance of quadratic divergences whose cancellation led to the resolution of fine tuning question in the first place. It is sufficient to know that both scalar and gaugino mass terms (which break the degeneracy between matter fermions and sfermions and gauge bosons and gauginos, respectively) are soft. For our purposes, it suffices to include these mass terms, together with the A-parameter for t-quarks that is responsible for $\tilde{t}_L - \tilde{t}_R$ mixing. Motivated by models of supergravity grand unification [4], we will further assume that there is a universal sfermion (gaugino) mass at the unification scale in terms of which the squark and slepton (the electroweak gaugino and gluino) masses relevant for phenomenology at the 100 GeV scale are determined via renormalization group equations. We will not assume any relation between the masses of the Higgs bosons and sfermions. With the assumptions outlined above, the masses and couplings of all the sparticles can be parametrized in terms of just a few parameters which may be taken to be, (*i*) the gluino mass which is assumed to determine the other gaugino masses, (*ii*) the squark mass which determines the slepton masses via a unification condition, (*iii*) the supersymmetric Higgsino mass (μ), (iv) $\tan\beta = v/v'$ the ratio of the vacuum expectation values of the Higgs fields that couple to $T_3 = \frac{1}{2}$ and $T_3 = -\frac{1}{2}$ fermions, (v) m_{H_p} which fixes the tree level masses and couplings of the five Higgs bosons of the MSSM. As discussed by Pandita [9], radiative corrections due to top quark Yukawa interactions substantially alter these masses and mixing patterns so that these acquire a dependence on the top quark mass as well as on the other SUSY parameters. Together with the $A-$ parameter mentioned above, these parameters fix the properties of all the sparticles as well as the five physical Higgs bosons of the MSSM.

The MSSM thus provides a prototype framework for studying the Higgs sector of a supersymmetric theory in experiments at current and future colliders. The phenomenology of the Higgs sector of SUSY models differs from that of the SM Higgs sector [10] in a number of respects. The SUSY Higgs sector is more complex so that there are several physical Higgs bosons (five in the MSSM case) that can be searched for. The couplings of any of these is, however, different from the corresponding coupling of the SM Higgs boson (because of mixing angle factors) so that both production cross sections and decay patterns may be altered. Finally, in the context of SUSY models, Higgs bosons may decay into lighter Higgs bosons or even SUSY particles, or may be produced via the decays of heavier SUSY particles. The MSSM should be regarded as an effective low energy theory obtained under certain reasonable assumptions, that may in the future be derived from a deeper underlying theory. The predictions of the MSSM should primarily be used to guide our qualitative thinking. It should, however, be kept in mind that the actual signals discussed below may be somewhat different if there are additional light supermultiplets or if R-parity is violated.

2. Constraints on the MSSM Higgs sector from LEP experiments

The signals from the production of the Higgs bosons at LEP have been discussed by Gurtu [11] at this Symposium. The scalar H_l can be produced via the Bjorken process provided that they are kinematically accessible. These can thus be searched for in much the same way as the Higgs boson of the SM. In addition, MSSM Higgs bosons can also be produced via $Z \to H_l + H_p$ which proceeds via gauge interactions. The region of the m_{H_p} *vs.* $\tan\beta$ parameter plane of the MSSM Higgs sector excluded by the negative results [12] of the experiments at LEP is shown in Fig. 1. In our analysis, we have incorporated the effects of radiative corrections due to top quark Yukawa interactions [9,13] using the formulae in Ref. [14]. In Fig. 1, we have used the limit $m_{H_{SM}} > 57$ GeV on the mass of the SM Higgs boson [15] to infer an upper limit on the production of H_l via $Z \to Z^* + H_l$, taking into account the differences in the couplings of H_l and H_{SM}. We have assumed that the non-observation of the two-body decay $Z \to H_l + H_p$ in the total sample of about two million Z events at LEP can be used to infer that $m_{H_l} + m_{H_p} > M_Z$. We see that already the LEP experiments exclude $m_{H_p} < 40$ GeV, regardless of m_t or $\tan\beta$. Within our framework, this corresponds to $m_{H^+} > 90$ GeV, which essentially excludes the possibility of seeing H^+ signals at LEP 200. Finally, we have also shown the region of this plane that might be probed at LEP 200. We have made both optimistic and conservative projections of the reach during this second phase of LEP. For the

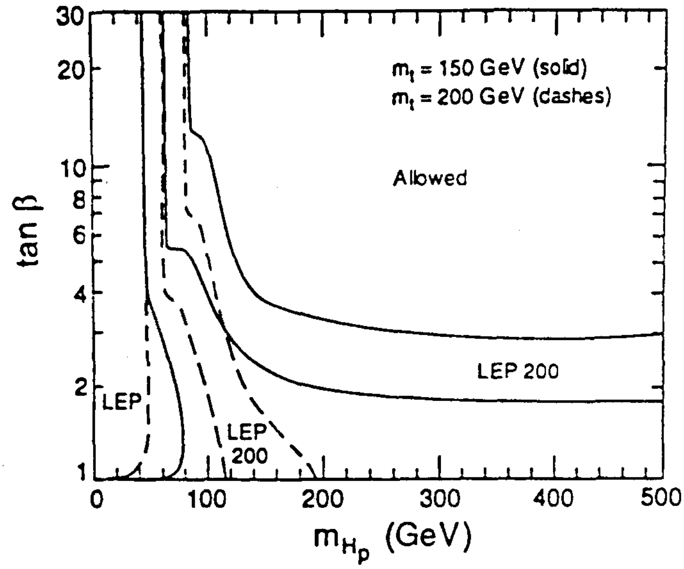

Figure 1. Regions in the $m_{H_p} - \tan\beta$ plane which are excluded by Higgs searches at LEP, for the decays $Z \to H_p H_l$ and $Z \to Z^* H_l$. We show excluded regions for $m_t = 150$ GeV (solid) and $m_t = 200$ GeV (dashed). We also show the conservative and optimistic contours for regions explorable at LEP 200. The LEP 200 criteria are as given in the text.

former, we have assumed $\sqrt{s} = 190$ GeV and taken 0.05 pb as the lower limit for an observable cross section for either the $e^+e^- \to ZH_l$ or the $e^+e^- \to H_l H_p$ processes. The conservative estimate assumes $\sqrt{s} = 175$ GeV and a lower limit of 0.2 pb on the cross sections. It is interesting to note that even at LEP 200 a non-observation of any Higgs boson signal cannot be used to infer any bound on $\tan\beta$, at least for the case that the top quark is very heavy.

3. Higgs boson searches at supercolliders

As discussed at this Symposium by Pandita [9], the radiative corrections (dominantly from the top quark Yukawa interactions) to the MSSM Higgs boson sector can substantially alter the masses and mixing patterns of the physical Higgs bosons [13]. In particular, the tree level mass bound, $m_{H_l} < Min\{M_Z, m_{H_p}\}$ is no longer valid. This obviously impacts on the searches for Higgs bosons at LEP and LEP 200. Most importantly, the discovery of H_l at LEP 200 is no longer guaranteed. This led several groups [14,16-18] to explore strategies for the detection of MSSM Higgs bosons in the case where H_l is too heavy for detection at LEP 200 [19]. These analyses are performed assuming that sparticles are too heavy to be produced via the decays of the Higgs bosons. Here, we review these strategies, and then discuss how these might be affected [7] if Higgs boson decays into charginos and neutralinos are kinematically accessible. We will see that these decays open up promising new modes for Higgs boson detection.

At hadron supercolliders, neutral MSSM Higgs bosons are dominantly produced by gluon fusion via diagrams involving third generation quark and squark loops. This is unlike as in the SM [10] where W-boson fusion becomes the dominant source if the Higgs boson is very heavy. The reason is that for large values of m_{H_h} for which the W fusion mechanism might be expected to be significant, the $H_h WW$ coupling becomes strongly suppressed, while H_p does not couple to vector boson pairs.

We first consider the detection of MSSM Higgs bosons, assuming as usual that their decays to supersymmetric particles are kinematically forbidden. In this case, H_l, whose mass is bounded above by about 150 GeV if $m_t < 200$ GeV and $m_{\tilde{q}} < 1$ TeV, dominantly decays via $H_l \rightarrow b\bar{b}$. Since the pseudoscalar H_p has no tree level couplings to vector boson pairs, it dominantly decays to $t\bar{t}$ or $b\bar{b}$ pairs. Large heavy flavour backgrounds from QCD preclude the possibility of the detection of either H_l or H_p via its dominant modes, so that their rare decay modes ($\gamma\gamma$, $\tau\tau$ and, for H_l, $ZZ^* \rightarrow 4l$) provide the only possibility for their detection. The heavier scalar H_h can indeed decay into W and Z pairs provided that it is heavy enough. However, as mentioned above, the $H_h WW$ and $H_h ZZ$ couplings rapidly decrease with increasing values of m_{H_h}, so that the WW and ZZ signals from the decays of H_h are significantly smaller than the corresponding signals from the SM Higgs boson [10]. The gold-plated $ZZ \rightarrow 4l$ mode offers an additional signal for H_h, but the WW mode will be more difficult to detect above SM background.

Since these signals have been just reviewed [10], and because there is already a considerable body of literature on this 14,16-18], we will not enter into a comprehensive discussion of these here but only present our results. We refer the reader to Ref. [14] and [7] for details of our calculation. The region of the $m_{H_p} - \tan\beta$ plane where each of the neutral Higgs bosons are observable at 99% CL above SM backgrounds after one year of running at the SSC is shown in Fig. 2 for $m_t = 150$ GeV. We have also required a minimum of ten signal events annually at the SSC. In this figure, we have taken $m_{\tilde{q}} = m_{\tilde{g}} = -\mu = 1$ TeV, and assumed a $\gamma\gamma$ mass resolution of $\pm 1\%$. The region already excluded by the LEP constraints is shown by the solid curve on the extreme left. The region where the cross sections for either ZH_l or $H_l H_p$ production by e^+e^- collisions at a centre of mass energy of 190 GeV exceeds 0.05 pb (which we optimistically take to be the limit of detectability at LEP 200) is shown by the dot-dashed curve. The regions denoted by the solid curves are where the $\gamma\gamma$ signal is observable while the dashed curve denotes the boundary of the region where the $4l$ signal is detectable above the background (the $H_l \rightarrow 4l$ signal becomes observable only if m_t is very large). The side on which the boundaries of the various curves are labelled is where the corresponding signal is observable.

We see from the figure that while at least one of the Higgs bosons is detectable over most of the parameter plane, there is the shaded region where none of the Higgs bosons are observable. We caution the reader that the size of this "hole" is very sensitive to the $\gamma\gamma$ mass resolution; *i.e.* the right hand boundary of the shaded region will move considerably to the right if a 1% resolution is not attained. On the positive side, recent calculations [20] show that QCD corrections tend to increase the cross section for H_h and H_l production by 50-70% from their values in Fig. 2. It may also be possible to probe these regions even without the 1% mass

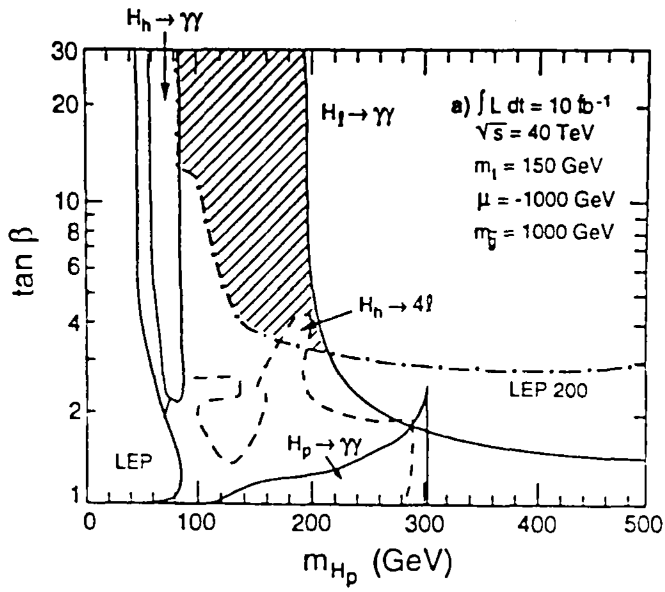

Figure 2. Regions of the m_{H_p} vs $\tan\beta$ plane where the various SUSY Higgs bosons are detectable at 99% CL, for 10^4 pb^{-1} of integrated luminosity at the SSC. Parameters are chosen so that SUSY decays of Higgs bosons are suppressed.

resolution by focussing on $l\gamma\gamma$ events from WH and $t\bar{t}H$ production [16-18]. In this case, however, the event rate is rather low, so that detector-dependent reducible backgrounds have to be carefully assessed. We have checked that even after five years of operation at the design luminosity, the region where there is no Higgs signal at the SSC (though it reduces to about half the area) remains. We have also studied the detectability of the signal from $t \to bH^+ \to b\tau\nu$ decays, and found that these are also unobservable in this region. For $m_t = 200$ GeV, this "hole" is considerably smaller, and essentially disappears for five years of operation of the SSC. We note, however, that there are large regions of parameter space where just one of the Higgs bosons is detectable. The direct detection of at least two Higgs bosons is particularly important since this would enable us to definitively infer the existence of a non-minimal Higgs sector. Although we have not shown this here, we note that the LHC operating at a luminosity of 100 fb^{-1} per year has roughly the same reach for Higgs search after two years of operation as the SSC operating at its design luminosity for five years [7].

At this point it is worth remarking that the recent bound [21] $B < 8.4 \times 10^{-4}$, on the branching fraction B for $b \to s\gamma$ decays that has been obtained by the CLEO collaboration, can be translated to a bound on the charged Higgs boson mass. Assuming that H^+ is the only non-SM source of these flavour violating decays (this is true in the MSSM if all sparticles are heavy as has been assumed in Fig. 2 above), it has been shown that $m_{H_p} \gtrsim 80 - 100$ GeV [22] (for $m_t = 150$ GeV), so that these data begin to constrain the region of parameters in the "hole". It has been shown that even allowing for various uncertainties, an improvement of the bound on the branching ratio to about $(5-6)\times 10^{-4}$ would effectively probe the entire shaded region, assuming the absence of additional sources of flavour violation.

Up to now, we have assumed that the MSSM Higgs bosons cannot decay into supersymmetric particles. The philosophy behind this usual assumption is that if sparticles are light enough to be kinematically accessible in these decays, they can be directly searched for at either LEP 200, the Tevatron or ultimately, at the SSC. While this is certainly true of gluinos and squarks, the situation for charginos and neutralinos is not quite as clear. As shown in Ref. [7,23], there are significant regions of parameter space where H_p and H_h dominantly decay into charginos and neutralinos and where the chargino is too heavy to be detectable at LEP 200. Furthermore, there is some concern [24] as to whether charginos and neutralinos will be detectable at hadron supercolliders. We emphasize, however, that the discovery of Higgs bosons is a separate issue from the discovery of sparticles; since there are substantial regions of MSSM parameter space where H_p and H_h will dominantly decay into charginos and neutralinos (which may or may not be detectable at LEP 200), it is important to study the impact of these decays on the signals discussed above.

Towards this end, in Fig. 3 we have shown the regions of the $m_{H_p} - \tan\beta$ plane where the $\gamma\gamma$ and $4l$ signals (from the ZZ and ZZ^* decays of Higgs bosons) are observable after one year of operation of the SSC if the charginos and neutralinos are rather light. Here, we have taken $m_{\tilde{g}} = 400$ GeV and $\mu = -100$ GeV, and fixed

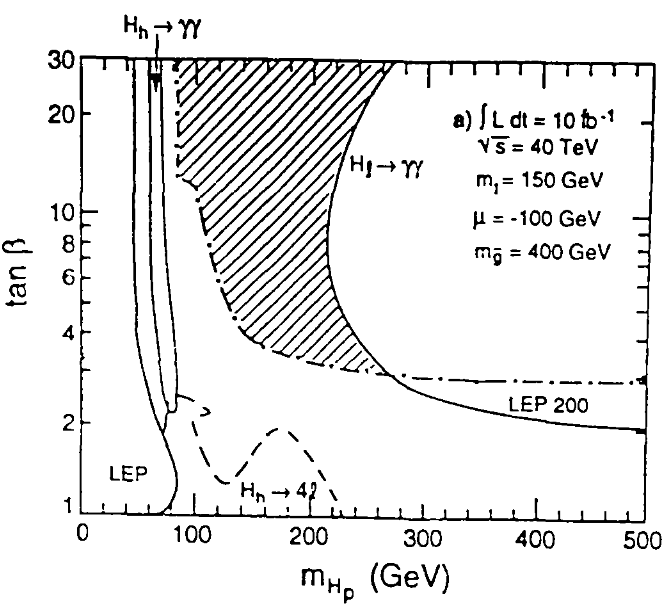

Figure 3. Regions of the m_{H_p} *vs.* $\tan\beta$ plane where the various SUSY Higgs bosons are detectable at 99% CL, for 10^4 pb^{-1} of integrated luminosity at the SSC. Here, decay modes to SUSY particles are allowed.

other parameters as in Fig. 2. We see that the shaded region where none of the usually studied signals is detectable at the SSC, expands substantially. Furthermore, the region where H_h is detectable is considerably smaller while that where H_p is detectable essentially disappears. This is understandable if we recognize that, in the absence of SUSY decays, H_p dominantly decays via b-quark Yukawa couplings so that it is very narrow; once SUSY channels become kinematically allowed, they rapidly dominate the decays of H_p, leading to a large suppression of its rare decay modes. We also see that the region of parameters where the signal for more than one Higgs boson is observable either at LEP 200 or at the SSC is drastically reduced. Qualitatively similar conclusions obtain for the LHC and also for five years of operation of the SSC. We refer the reader to Ref. [7] for these details. We note that the CLEO data [21] on the $b \to s\gamma$ decays discussed above are on the verge of probing the region of the hole. We stress though that if the gauginos are indeed as light as assumed in this figure, there are additional SUSY contributions [25] to the amplitude for $b \to s\gamma$ decay which may interfere destructively with those from the W and H^+. A complete analysis that includes these effects is necessary to definitively exclude m_{H_p} values in the shaded region when sparticles are rather light.

While the SUSY decays of Higgs bosons reduce the rates for signals via which these are usually searched for, they also open up several new modes for their detection [7]. The most promising of these is the $4l$ signal which comes from the $\widetilde{Z}_2\widetilde{Z}_2$ decay of H_p or H_h, where both the neutralinos decay leptonically. As an illustration, we have shown the number of $4l$ events expected annually at the SSC from the decay, $H_p \to \widetilde{Z}_2\widetilde{Z}_2 \to 4l + \not{E}_T$ in Fig. 4. Here, we have fixed $m_{H_p} = 200$

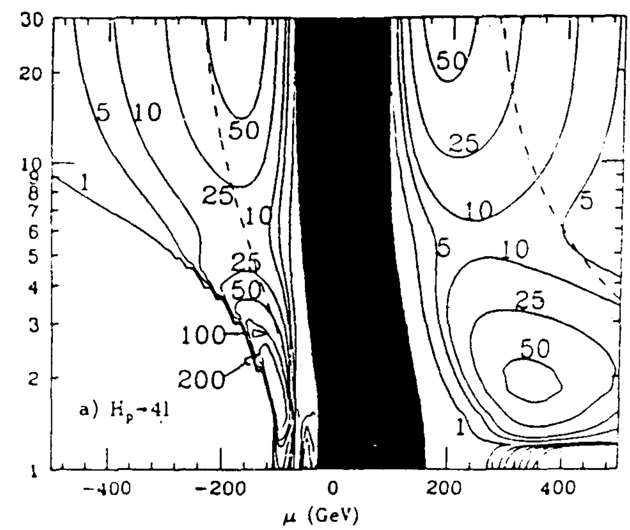

Figure 4. Number of events per 10^4 pb^{-1} of integrated luminosity at the SSC, for $H_p \to 4l + \not{E}_T$ in the μ vs. $\tan\beta$ plane, with parameters as fixed in the text.

GeV, $m_{\tilde{g}} = 400$ GeV and $m_t = 150$ GeV. The dark region is already excluded by constraints from LEP discussed in Sec. 2, while the area between the dashed lines roughly represents the region that will be probed at LEP 200. We see that as many as 200 $4l$ events may be expected annually at the SSC in a region not accessible at LEP 200. In this computation, we have assumed that $m_{\tilde{q}} = m_{\tilde{l}}$. As shown in Ref. [26], the rate shown may be significantly enhanced if sleptons are substantially lighter than squarks as is the case in supergravity models if squarks and gluinos have comparable masses. The dependence of the event rate on m_{H_p}, as well as the $4l$ event rate from the production and decay of H_h has been studied in Ref. [7]. For detection of the signal above background, it is necessary to be able to identify isolated leptons down to a momentum of just a few GeV in events triggered by one, or more, hard leptons. If this is indeed feasible, it has been noted that this process may provide the possibility of the measurement of $\tilde{Z}_1$ and $\tilde{Z}_2$ masses provided that the mass of the parent Higgs boson can be measured via its detection in, for instance, the $\gamma\gamma$ channel.

It has been suggested [18] that Higgs bosons may also be identified via their decays to taus. One strategy [27] for the simultaneous detection of H_p (produced by gluon fusion) and H_l is provided by the process $H_p \to ZH_l$, where $Z \to l^+l^-$ and $H_l \to \tau^+\tau^-$. It is assumed that the taus can be identified via their single prong hadronic decays which have a branching fraction of 50%. The key point is that despite the neutrinos that escape detection, it is possible [28] to reconstruct the di-tau mass because H_l is produced with a substantial transverse momentum [29]. Thus, the signal is distinguished by the fact that the masses of the $\tau\tau$ and $l\bar{l}\tau\bar{\tau}$ systems exhibit peaks at m_{H_l} and m_{H_p}, respectively. The production of Z bosons in association with a pair of QCD jets can mimic the signal if each jet fragments into a single, hard track together with other neutral (or soft) debris. A preliminary study [27] shows that in order for the signal to be viable, a $\tau - jet$ discrimination at the level of a few percent is necessary. If m_{H_l} and M_Z are the same within the experimental resolution, the main physics background comes from ZZ production, when one of the Z decays to $l\bar{l}$ and the other to a τ pair. The region where the signal is observable at 99% CL above this background after one and five years of operation of the SSC, is shown in Fig. 5. Here, we have assumed a resolution of ± 15 GeV on the measurement of m_{H_l}. Other backgrounds have been shown to be small in Ref. [27] to which we refer the reader for further details. By comparing with Fig. 2, we see that this signal potentially expands the region over that where H_p is observable via its $\gamma\gamma$ decay. Qualitatively similar conclusions hold if $m_t = 200$ GeV. Of course, careful detector simulation including a realistic $\not{E}_T$ resolution (which has been ignored in this analysis) is necessary to assess the viability of the signal. It is worth noting that this process is complementary to the one considered by Unal *et. al.* [29] who find the signal is observable only for rather large values of $\tan\beta$. In view of the fact that direct detection of H_p appears to be possible only over a limited parameter range, we believe that all promising channels for its detection merit serious exploration.

4. Concluding remarks

Supersymmetry provides the only reasonable known framework if we assume that electroweak symmetry is indeed spontaneously broken by vacuum expectation values of elementary scalar fields. In this case, we have seen that the Higgs sector

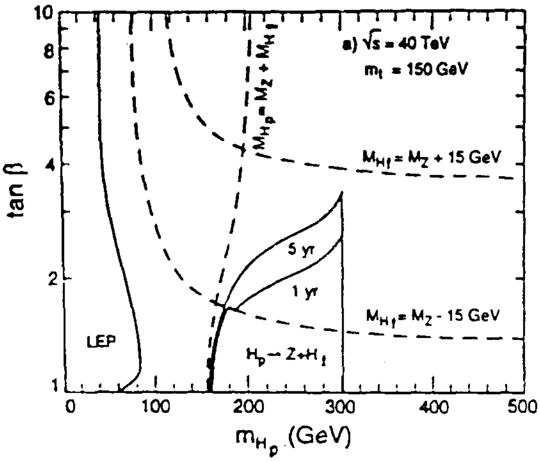

Figure 5. Regions of the $m_{H_p} vs. \tan\beta$ plane where the $H_p \to ZH_l$ signal may be seen above ZZ background at 99% CL, for 10^4 pb^{-1} of integrated luminosity at the SSC.

of even the simplest supersymmetric model contains five physical spin-zero bosons which may be searched for in experiments at colliders. In Sec. 2, we have reviewed the constraints on the parameters of the MSSM Higgs sector that may be deduced from the non-observations of any signals at LEP. These constraints, which were discussed in greater detail by Gurtu [11] at this Symposium, are shown in Fig. 1 where the region of the parameter space that might be probed at LEP 200 is also shown.

Our main results are contained in Sec. 3 where we have discussed several strategies by which the Higgs bosons of the MSSM might be detected at hadron supercolliders. We have seen that even with optimistic assumptions for the capabilities of the detector, there is a "hole" in parameter space where none of the Higgs bosons yields an observable signal even taking into account just the statistical uncertainties. The size of this region is detector-dependent, and could be considerably larger than that shown in Fig. 2 and Fig. 3, especially if the $\gamma\gamma$ mass resolution attainable is significantly worse than the assumed value of 1%. We should note, however, that we have ignored QCD corrections which enhance these signals by more than 50%.

We have also discussed the possibility that the heavier Higgs bosons can themselves decay into charginos and neutralinos. Within the MSSM framework, these branching fractions are sbstantial only if gluinos are rather light so that the signal from gluino pair production should readily be observable. This, of course, assumes the validity of the relation between gaugino masses which is sensitive to assumptions of physics at the Planck scale. These SUSY decays, which can be significant even for parameter values such that charginos are inaccessible even at LEP 200, lead to a reduction of the conventional signals for Higgs boson detection. As a result, the "hole" becomes larger, and further, the region where the signal for two or more Higgs bosons are detectable is greatly reduced. These decays may, however, open up new signals for Higgs detection. The most promising of these appears to be the $4l$ signal from the decays, H_p or $H_h \to \widetilde{Z}_2\widetilde{Z}_2 \to 4l + \not{E}_T$. For some ranges of SUSY parameters, these signals are potentially detectable in the "hole" in Fig. 3. A systematic study of this merits further investigation.

It appears that the pseudoscalar Higgs boson is the most difficult to detect – the two-photon signal is observable only if $\tan\beta$ is rather close to unity. This led us the possibility of detecting H_p via its decay, $H_p \to ZH_l$, where $Z \to l^+l^-$ and $H_l \to \tau^+\tau^-$. Our results which are summarized in Fig. 5 suggest that this signal substantially increases the parameter space where H_p might be detectable, but careful simulations are needed before a definitive conclusion can be made.

It should by now be clear that the detection of the MSSM Higgs bosons at hadron supercolliders is not easy. In view of its importance, however, it is essential that all reasonable strategies be explored. A novel approach [8] is to study the production of Higgs bosons produced via the cascade decays of squarks and gluinos. Neutral Higgs boson production may be signalled by an anomalously high multiplicity of bottom mesons in the SUSY event sample characterized by a large value of $\not{E}_T$ or by a pair of hard, isolated like-sign dileptons. Charged Higgs boson production via these cascade decays may be signalled by an excess of τ leptons (relative to e or μ) in the SUSY sample. Except to mention that the observability of these signals crucially depend on the efficiencies with which bottom mesons and τ leptons can be identified, we will not discuss these signals any further for want of time.

To summarize, we have seen that the detection of the various Higgs bosons of even the simplest SUSY model offers a considerable challenge. Although various very promising strategies for the detection of these particles have been devised, it should be kept in mind that the signals are often on the edge of observability even for detectors with excellent capabilities. We should continue to explore new strategies whereby the different Higgs bosons might be detectable. The importance of detecting (and identifying) two or more of these particles cannot be overstressed as this would be conclusive evidence of a non-SM Higgs sector. Finally, we should not forget that charged Higgs bosons with masses in the "hole" may be excluded if the CLEO collaboration is able to further strengthen the bound on the branching fraction for $b \to s\gamma$ decays unless there is yet more new physics that conspires to give a null result.

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Discussion

D.P. Roy : Could you comment on the associated production of intermediate mass Higgs with a $t\bar{t}$ pair as a Higgs signal?

X. Tata : The signal to irreducible background ratio is clearly better for the $\ell\gamma\gamma$ signal (the decaying W may or may not be produced from the decay of a top). But because of the tiny event rates, I would worry about the reducible backgrounds. In my view, the $\gamma\gamma$ signal I talked about, though it has a large background, has the advantage that the background can be normalized by the experimental observation of $\gamma\gamma$ events outside the Higgs peak. You do not have to rely on the theorists' ability to compute this.

M. Drees: Regarding $b \to s\gamma$: when extracting bounds on non-SM contributions, the QCD uncertainties of the SM prediction have to be included.

X. Tata : I agree.

M. Drees : How would you measure $H\tilde{g}\tilde{g}$ couplings ?

X. Tata : I do not see why we should worry about this. If gluinos are light enough to be produced via (loop) decays of Higgs, surely the continuum strong production of gluinos will swamp the gluinos produced by rare decays of Higgs. Furthermore, since we already know that $m_{\tilde{g}} > 150$ GeV or so, the Higgs has to be very heavy for this decay to do. But in this case, the branching fraction for the decay may be tiny as the $t\bar{t}$ mode may be open. Of course, the cross section for Higgs production will also be kinematically suppressed. Finally, I think the coupling will be extremely tough to measure if gluino pairs are not accessible in thses decays. But, once again, I reiterate that I do not see the significance of the question.

B. Ananthanarayan : If the CLEO result on $b \to s\gamma$ is improved what is the new limit on m_{H_p}?

X. Tata : For $m_t = 150$ GeV, Hewett concludes that H_p will be heavier than 200 GeV if the bound be improved to 6×10^{-4}.

B. Ananthanarayan : Can one be more definite about which way the bound will go if charginos are present at low mass scales?

X. Tata : The SUSY contributions can certainly be computed within the MSSM framework. There is a paper in Nuclear Physics **B** by Borzumatti et al. where detailed formulae are given. I do not know how much light charginos will affect the rate, but I guess it may be significant. Anyway, the effects of all light sparticles should be included in the calculation since there could be significant interference between various amplitudes.

Probir Roy : Would a closer agreement of $b \to s\gamma$ with SM in a B-factory shift the charged Higgs mass to very high values?

X. Tata : If $b \to s\gamma$ is indeed observed at the rate expected in the SM, then the sum total of all non-SM contributions will, of course, be bounded. If H^+ is assumed to be the sole new source of $b \to s\gamma$, the mass bound that can be obtained will be limited by the precision with which the branching fraction is measured (and also by the precision with which it is calculated). Of course, not observing the decay at the expected rate will also suggest some new physics that destructively interferes with the SM amplitude.

Probir Roy : What about the Gunion-Haber-Wudka $H \to \Upsilon\gamma$ proposal for SUSY intermediate Higgs?

X. Tata : Gunion, Kane and Wudka [Nucl. Phys. **B299** (1988) 231] have shown that the $H \to \Theta_t\gamma$ signal is an order of magnitude below the continuum $\Theta_t\gamma$ background (in a 2% mass bin about the Higgs mass) over the whole intermediate mass range. I would then guess that the signal from the $\psi\gamma$ or $\Upsilon\gamma$ decays of the Higgs would be even harder to observe. I say this because the charm (or bottom) quarks produced via the decay of an intermediate mass H would be relativistic. In order to form a bound state, however, it is reasonable to suppose that the $q\bar{q}$ pair should be produced with a small relative momentum between them. Since this is a kinematically unlikely configuration, it seems to me that the branching fraction for $H \to \psi\gamma$ and $H \to \Upsilon\gamma$ decays should be suppressed by a form factor, making these decays even more difficult to see than the $\Theta_t\gamma$ decays.

N.G. Deshpande : How big an effect on $b \to s\gamma$ do you expect from other SUSY contributions in the loop?

X. Tata : I do not really know as I have never done this computation myself. The relevant formulae may be found in Borzumatti et al. Nucl. Phys. **B353** (1991) 591. These authors work within the MSSM framework and assume supergravity mass relations for the masses. They find that neutralino contributions are always small while those from the flavour violating contributions to the $b \to s\gamma$ amplitude can be as large as 10% of the SM amplitude. As might be expected, the largest contributions come from chargino-top squark loops. These contributions can have either sign, and may be as large as half the magnitude of the SM contribution for $m_t = 130$ GeV. It should, however, be kept in mind that in their analysis $\tilde{W}$ ($\tilde{t}$) masses as low as 35 (25) GeV are allowed. I think that a new analysis which incorporates today's experimental constraints is certainly warranted. Phenomelogically, it may also be interesting to see just how large the contribution of flavour violating gluino and neutralino interactions can be, without restricting these to be radiatively generated as in SUGRA models.