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What e^+e^- collider could make a "no-lose" search for minimal supersymmetric standard model Higgs bosons?

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(Received 19 November 1992; revised manuscript received 15 December 1992)

The lightest CP-even Higgs boson h in the minimal supersymmetric standard model (MSSM) has a mass upper bound depending on the top quark and squark masses. An e^+e^- collider with enough energy and luminosity to produce $h + Z$ at measurable rates up to the maximum h mass would cover the entire MSSM parameter space if $h + A$ production was also searched for. We explore the energy and/or luminosity needed for various top quark and squark masses. For $m_t = 150$ GeV and a 1 TeV supersymmetric mass scale, a 230 GeV collider with $10\,\text{fb}^{-1}$ luminosity would suffice, based on $e^+e^- \to hZ, hA \to \tau\tau jj$ signals. With future b tagging, other channels will contribute important additional signals and the luminosity requirements will be lowered by up to an order of magnitude.

PACS number(s): 13.10.+q, 12.15.Cc, 14.80.Gt

The theoretical appeal of supersymmetry (SUSY) is that it solves the problem of large radiative corrections in the scalar sector, associated with the grand unification scale. The minimal supersymmetric extension of the standard model (MSSM) [1] has five Higgs bosons, one of which (h) is necessarily relatively light; their discovery could contribute the first direct evidence both for SUSY and for the Higgs mechanism. These Higgs bosons are therefore the object of intense experimental investigation; a lower limit $m_h \gtrsim 40\,\text{GeV}$ has already been set by e^+e^- experiments at the CERN e^+e^- collider LEP I [2–5] and the range of search will be extended at LEP II with c.m. energy $\sqrt{s} = 190\,\text{GeV}$ to $240\,\text{GeV}$ possible [6]. In this Brief Report we address the question: what is the lowest-energy e^+e^- collider that could completely cover the MSSM parameter space [7–11] and thereby independently guarantee discovery or rejection of the MSSM? This question is relevant because LEP I, LEP II, the Superconducting Super Collider (SSC), and CERN Large Hadron Collider (LHC) will not fully cover all MSSM parameters [7, 10, 11], and the possibilities of higher-energy e^+e^- linear colliders are being examined [12].

The Higgs sector of the MSSM has three neutral and two charged Higgs bosons, h, H, A, $H^\pm$ of which h and H are CP even and $m_h < m_H$; a mixing angle α appears in the h and H couplings. At the tree level all their masses and couplings are controlled by two parameters that may be taken to be m_A and the ratio $\tan\beta = v_2/v_1$ of vacuum expectation values giving masses to up-type quarks (v_2) and down-type quarks (v_1), respectively. Renormalization group arguments in no-scale models and minimal supergravity models [13] suggest that $1 < \tan\beta < m_t/m_b$ but m_A is unconstrained. At the one-loop level, however, there are significant radiative corrections [14] that depend on several other parameters but especially on the top quark and squark masses; as a result the h mass has an upper bound

$$m_h^2 \lesssim M_Z^2 \cos^2\beta + \frac{6G_F}{\pi^2\sqrt{2}} m_t^4 \ln\left(\frac{\tilde{m}}{m_t}\right) , \qquad (1)$$

in an approximation where the usual SUSY parameters A_t, A_b, and μ are set to zero and $\tilde{m}$ is the common SUSY mass scale. The masses of H, A, and $H^\pm$ have no upper bounds. In our present discussion we shall use nonzero values of all SUSY parameters, following Ref. [8], with $\tilde{m} \simeq 1\,\text{TeV}$ and $1 < \tan\beta < 30$; the other supersymmetry breaking parameters are taken to be $A_{t,b} = 0.5\,\text{TeV}$ and $\mu = 0.25\,\text{TeV}$. The important parameter is the shift in the m_h upper bound; we note that large changes in the supersymmetry mass scale are effectively equivalent here to small changes in m_t.

At e^+e^- colliders the signals for Higgs bosons are relatively clean and the opportunities for discovery and detailed study will be excellent. The principal production channels are

$$e^+e^- \to Z \to Zh, ZH, Ah, AH \ , \quad (2a)$$

$$e^+e^- \to \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}h, \nu\bar{\nu}H \ , \quad (2b)$$

$$e^+e^- \to t\bar{t}h, t\bar{t}H, t\bar{t}A, \ , \quad (2c)$$

$$e^+e^- \to Z, \gamma \to H^+H^- \ , \quad (2d)$$

$$e^+e^- \to t\bar{t} \to b\bar{b}\, H^+(W^+)\, H^-(W^-) \ . \quad (2e)$$

The s-channel processes (2a) offer the biggest contributions at the lower energies. In the limit $m_A \to \infty$ we have $m_H \simeq m_{H^+} \simeq m_A$ while m_h approaches the upper bound of Eq. (1) and only h can be produced at any given collider. Thus the channel $e^+e^- \to Zh$ and its kinematical limits are critical in any complete search of MSSM parameter space. The Zh production cross section contains an overall factor $\sin^2(\beta - \alpha)$ which suppresses it in certain parameter regions (with $m_A < 100\,\text{GeV}$ and $\tan\beta$ large); fortunately the Ah production cross section contains the complementary factor $\cos^2(\beta - \alpha)$. Hence the Zh and Ah channels together are well suited to cover all regions in the $(m_A, \tan\beta)$ plane, provided that the c.m. energy is high enough for Zh to be produced through the whole m_h mass range, and that an adequate event rate can be achieved. These conditions are already shown to be satisfied [12] for $\sqrt{s} = 500\,\text{GeV}$ with assumed luminosity 10 fb^{-1}. In the present work we study how well these conditions can be satisfied at lower energies with various luminosities.

Our discussion centers on the s-channel production channels $e^+e^- \to Zh, Ah, ZH, AH$, neglecting all others for simplicity (although other channels would obviously contribute to an eventual search and analysis). We also consider only the decays $Zh, Ah, ZH, AH \to \tau\tau jj$ (where j denotes a jet, here a b jet), that generally have substantial branching fractions at least in the Zh and Ah cases. We rely here on the possibility of recognizing and kinematically reconstructing τ decays experimentally [2–5, 12]; no b tagging of the other jets is assumed. This approach is conservative, since it implicitly ignores the $Z \to \ell^+\ell^-, \nu\bar{\nu}, jj$ decay modes that could enhance the detectability of Zh and ZH production. We note however that the $\ell^+\ell^- jj$ and $\nu\bar{\nu}jj$ channels have smaller signal/background ratios than the $\tau\tau jj$ channel, so that the net significance of the Zh or ZH signals would not be dramatically increased by including these channels. The $jjjj$ channel has large backgrounds from WW and ZZ production plus intrinsic combinatorial problems. However, these additional channels become more helpful if there is efficient b tagging, as we discuss at the end.

For any given energy and MSSM parameters, we calculate the Zh, Ah, ZH, and AH production cross sections and decay branching fractions from standard formulas [1] with one-loop corrections as described in Ref. [8]. We omit bremsstrahlung and beamstrahlung corrections that are not very large in currently favored collider designs. It is assumed that the Higgs bosons do not decay to light SUSY particles. The signals take the form of peaks in the distributions of invariant mass $m(\tau\tau)$ and $m(jj)$, centered at values m_h, m_H, and m_A, with an associated peak at M_Z also. These two $m(\tau\tau)$ and $m(jj)$ distributions are added to enhance the statistics, thus giving two counts per event. An irreducible background from $e^+e^- \to ZZ$ production and decay has a peak centered at M_Z; all other backgrounds can however be suppressed by suitable cuts at little cost to the signals [12]. For present purposes we estimate the background from the numerical simulation of Ref. [12], scaling the number of events according to the assumed luminosity and the energy dependence of the $e^+e^- \to ZZ \to \tau\tau jj$ cross section with $|\cos\theta| < 0.9$ for the τ's and jets. We assume that the acceptances of the $Zh\,(ZH)$ and $Ah\,(AH)$ signals remain 46% and 52%, respectively, as in Ref. [12] and that the Higgs boson peaks have the same mass resolution as the Z peak. This approach is approximate, but avoids lengthy Monte Carlo simulations for each of the many different energies and parameter settings that we have to consider.

For each input set of SUSY parameters, c.m. energy $\sqrt{s}$, and integrated luminosity $\mathcal{L}$, we define the signals, backgrounds, and discovery criteria of the MSSM mass peaks as follows. For an isolated peak, the signal strength S is taken to be the expected number of signal counts falling in a 10 GeV mass bin centered at the corresponding Higgs boson mass. When two Higgs peaks approach within 10 GeV we combine them; the signal strength S is then the total number of counts expected in a 10 GeV bin centered at the weighted mean mass. The background strength B is taken to be the total number of Z-decay counts (both from ZZ and from Zh, ZH production with the resolution of Ref. [12]) falling in the same mass bin. If the signal bin center is separated by more than 5 GeV from M_Z, our discovery criteria are $S/\sqrt{B} > 4$ with $S > 4$ counts. With such a separation, we expect that a distinct peak will be seen or that a recognizable distortion of the Z peak will be evident. But if the separation from M_Z is less than 5 GeV, we can only infer the presence of a new signal if the height of the supposed Z peak differs substantially from the expected ZZ background contribution. In this latter case we rely entirely on normalization and therefore require a higher degree of significance. Here the signal S is defined to be the sum of the MSSM (h, H, A, and Z) contributions falling in a 10 GeV bin centered at M_Z, and B is the expected ZZ background in the same bin; in this case we define a discoverable signal to have $S/\sqrt{B} > 6$ with $S > 5$ counts. In principle, b tagging of the quark jets offers another way to distinguish the presence of a Higgs boson contribution hiding under the Z peak; however, in the $Zh \to \tau\tau jj$ channel, tagging promises to suppress S more than $\sqrt{B}$ and hence actually to reduce the significance $S/\sqrt{B}$ (see below).

For full coverage of the $(m_A, \tan\beta)$ plane, the c.m. energy should be about 10 GeV or more above the maximum Zh threshold:

$$\sqrt{s}\,(\text{threshold}) = m_h\,(\text{max}) + M_Z \ , \quad (3)$$

where $m_h\,(\text{max})$ is the largest value of m_h in Eq. (1). For $\tilde{m} = 1\,\text{TeV}$ this threshold is 207 GeV for $m_t = 150$ GeV and 240 GeV for $m_t = 200$ GeV (the highest value of m_t

allowed by analyses of radiative corrections [15]). Apart from these threshold considerations, the principal factors that determine the discovery regions (where one or more MSSM signals are detectable) in the $(m_A, \tan\beta)$ plane are luminosity $\mathcal{L}$, top quark mass m_t, and c.m. energy $\sqrt{s}$. Figure 1 illustrates the effects of these factors separately, by means of four examples.

(i) Luminosity: In Figs. 1(a) and 1(b) we hold $m_t = 150$ GeV and $\sqrt{s} = 215$ GeV fixed (with all SUSY parameters fixed as in Ref. [8]), and compare discovery limits for $\mathcal{L} = 1\ \text{fb}^{-1}$ and $\mathcal{L} = 10\ \text{fb}^{-1}$. Here the $(m_A, \tan\beta)$ plane is fully accessible kinematically, but good luminosity is still needed to guarantee discovery; in fact $\mathcal{L} \gtrsim 20\ \text{fb}^{-1}$ would give full coverage.

(ii) Top quark mass: In Figs. 1(b) and 1(c) we hold $\mathcal{L} = 10\ \text{fb}^{-1}$ and $\sqrt{s} = 215$ GeV fixed and compare the discovery limits for $m_t = 150$ GeV and $m_t = 200$ GeV. Coverage becomes easier as m_t decreases; there would be complete coverage in this case with $m_t \lesssim 120$ GeV.

(iii) c.m. energy: In Figs. 1(c) and 1(d) we hold $\mathcal{L} = 10\ \text{fb}^{-1}$ and $m_t = 200$ GeV fixed and compare the discovery limits at $\sqrt{s} = 215$ and 270 GeV. We see that increasing s in this range generally widens the accessible region, although this is not uniformly true since the signals have different energy dependences in different parts of the plot. In fact, with our discovery criteria it appears that complete coverage is not achieved at any energy with this particular choice of $\mathcal{L}$ and m_t. We remark in passing that the small area lower left, inaccessible in Figs. 1(a) and 1(d), is not well served by $\tau\tau jj$ signals, since $h \to AA$ dominates the h decays here; however, this region is already excluded by LEP I data [2–5].

The final question is what combinations of collider parameters $\sqrt{s}$ and $\mathcal{L}$ would just achieve complete coverage of the $(m_A, \tan\beta)$ plane for given m_t? Figure 2 shows the limiting curves in the $(\sqrt{s}, \mathcal{L})$ plane, for various values of m_t; we recall that changes in $\tilde{m}$ can be effectively absorbed into m_t, and that LEP I searches have already excluded small m_A values [2–5]. Pairs of values $(\sqrt{s}, \mathcal{L})$ that lie above the limiting curves have "no-lose" discovery potential in the MSSM, according to our approximations. For example, with $m_t = 150$ GeV and a 1 TeV SUSY mass scale, a 230 GeV e^+e^- collider with 10 fb^{-1} luminosity would suffice.

Our discussion thus far has conservatively neglected b tagging, but we recognize that it could bring substantial benefits eventually. Typical projections for 1995 at LEP 200 [16] suggest that $h, A, Z \to b\bar{b}$ decays could be tagged with 50% efficiency while rejecting 89% of $Z \to c\bar{c}$ decays and 95% of $WW \to jjjj$ events. We illustrate the effects of such tagging in Table I, for various Zh channels: the values of the Zh signal S, ZZ background B and significance $S/\sqrt{B}$ are shown as ratios to the corresponding $Zh \to \tau\tau jj$ no-tag case, assuming similar acceptances in all cases.

This example of b tagging reduces significance in the

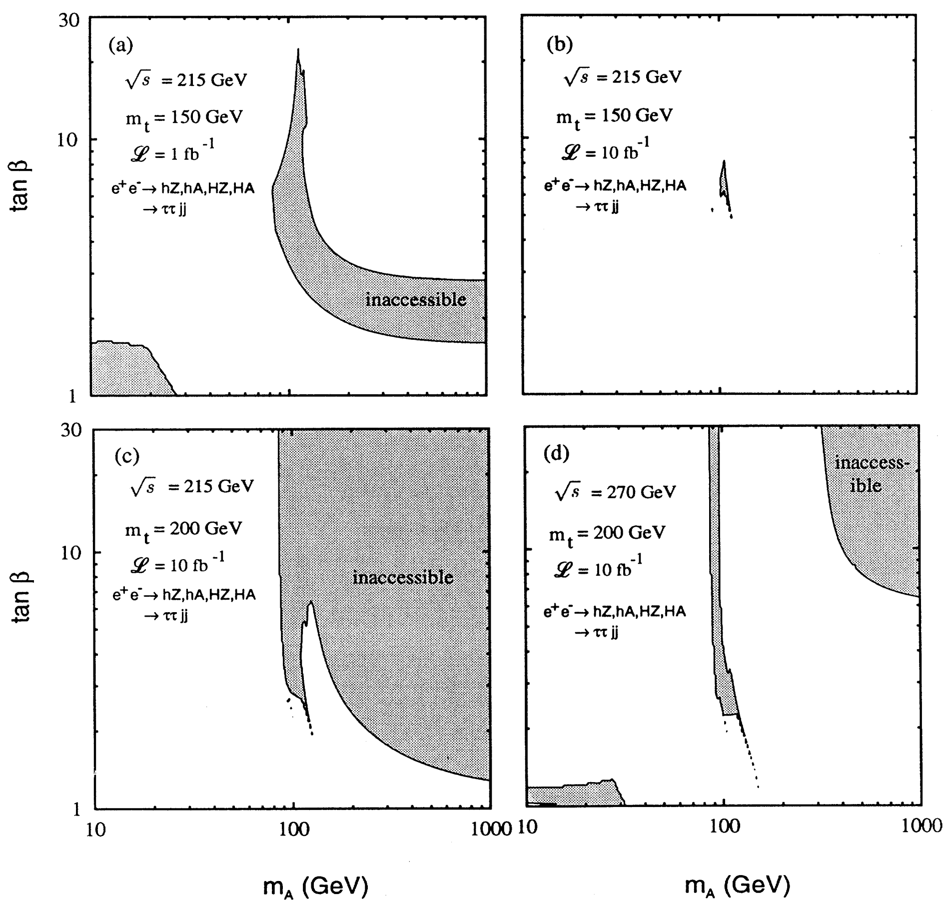

FIG. 1. Discovery limits in the $(m_A, \tan\beta)$ plane for $e^+e^- \to Zh, Ah, ZH, AH$ signals in the $\tau\tau jj$ channel, for various illustrative cases: (a) $\sqrt{s} = 215$ GeV, $m_t = 150$ GeV, $\mathcal{L} = 1\ \text{fb}^{-1}$; (b) $\sqrt{s} = 215$ GeV, $m_t = 150$ GeV, $\mathcal{L} = 10\ \text{fb}^{-1}$; (c) $\sqrt{s} = 215$ GeV, $m_t = 200$ GeV, $\mathcal{L} = 10\ \text{fb}^{-1}$; (d) $\sqrt{s} = 270$ GeV, $m_t = 200$ GeV, $\mathcal{L} = 10\ \text{fb}^{-1}$.

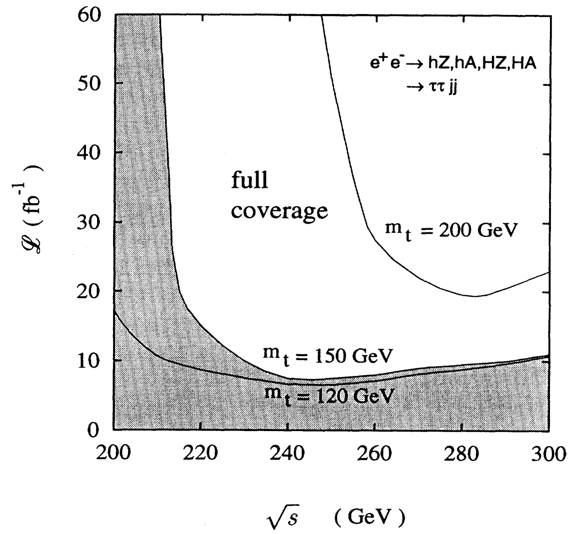

FIG. 2. Conditions for covering the whole MSSM $(m_A, \tan\beta)$ plane with $\tan\beta > 1$, using $\tau\tau jj$ signals. Limiting curves are shown in the $(\sqrt{s}, \mathcal{L})$ plane, for various values of m_t. The region that does not give complete coverage for $m_t = 150$ GeV is shaded.

$\tau\tau jj$ channel, but improves it in the $\ell^+\ell^- jj$ and $\nu\bar{\nu}jj$ channels and rescues the $jjjj$ channel (hopeless without tagging). If we take the best signals in each channel and add significances in quadrature, the net significance exceeds that of the no-tag $\tau\tau jj$ case alone by a factor 3, equivalent to an order of magnitude increase in luminosity. This illustrates the potential power of tagging, especially for the $Zh \to jjjj$ channel (with $Z \to jj$ identified by its mass). The complementary $Ah \to jjjj$ signals still have combinatorial background problems, however.

TABLE I. Effects of tagging $h, A, Z \to b\bar{b}$ decays for various Zh channels.

Channel	$S(Zh)$	$B(ZZ)$	$S/\sqrt{B}$
$\tau\tau jj$ (no tag)	1	1	1
(tagged)	0.26	0.13	0.7
$\ell^+\ell^- jj$ (no tag)	0.70	2.0	0.5
(tagged)	0.35	0.26	0.7
$\nu\bar{\nu}jj$ (no tag)	2.1	6.1	0.9
(tagged)	1.1	0.78	1.2
$jjjj$ (tagged)	4.2	2.6	2.6

We thank Peter Norton for conversations about experimental issues and Wilbur Venus for information about b tagging efficiencies. This work was supported in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881, in part by the Texas National Research Laboratory Commission under Grant No. RGFY9273, and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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