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Can minimal supersymmetry be ruled out at CERN LEP 200 from $e^+e^- \to Z\phi$ Higgs-boson searches?

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We show that if the CERN collider LEP 200 is capable of excluding a standard-model Higgs boson with $m_\phi = m_Z$ via the process $e^+e^- \to Z\phi \to \ell^+\ell^- q\bar{q}$, then the minimal supersymmetric model would also be excluded by similar searches for the light and heavy neutral Higgs scalars of minimal supersymmetry. We discuss how this might be achieved using the production rate and final-state particle distributions. An integrated luminosity of about 4 fb^{-1} should be sufficient to exclude at the 4σ level a standard-model Higgs boson with $m_\phi = m_Z$; with b tagging, 0.7 fb^{-1} may suffice. If a positive Higgs-boson signal is seen, minimal supersymmetry might not be distinguishable from the standard model in the $Z\phi$ mode alone.

The current lower bound on the standard-model Higgs-boson mass from $Z \to \phi f\bar{f}$ decays at the CERN e^+e^- collider at LEP is 44 GeV.[1] Standard-model Higgs-boson mass bounds have been used in conjunction with a search for Z decays to two Higgs bosons[2] to put constraints on the parameters in models with an extended Higgs sector;[2–4] for the minimal supersymmetric standard model[5] (MSSM) a Higgs boson with a mass below 26 GeV is now ruled out[6] by the Z decay data. It has been shown[7] that at LEP 200 the search limit for the standard-model Higgs boson can be pushed up to about 80 GeV via the process $e^+e^- \to Z\phi$. For Higgs-boson masses above 80 GeV, there is a significant background from $e^+e^- \to ZZ$, but recently it has also been shown[8] that, by examining the angular distribution of the final-state charged leptons in $e^+e^- \to \ell^+\ell^- q\bar{q}$, the standard-model Higgs-boson signal can be detected on top of the ZZ background if there is sufficient integrated luminosity. In this Rapid Communication we extend this analysis by also examining how the $Z\phi$ process affects the total rate and the angular distribution of the final-state bosons and quarks. We then show that if one is able to rule out a standard-model Higgs boson with $m_\phi = m_Z$ at LEP 200, then minimal supersymmetry can also be ruled out by searches for the two neutral Higgs scalars in the MSSM Higgs sector.

The main process for detecting a standard-model Higgs boson at LEP 200 is $e^+e^- \to Z\phi$, with the ϕ decaying mostly to $b\bar{b}$. The most background-free method of detecting the accompanying Z is to look for its decays to charged-lepton pairs. The Higgs-boson mass can be measured in two ways:[7] (i) direct measurement of the invariant mass of the two quark jets (suitably adjusted for undetected particles) and (ii) indirect measurement of the jet-jet invariant mass determined from the momenta of the charged-lepton pairs (the recoil mass). For $m_\phi \simeq m_Z$ there is substantial background from $e^+e^- \to ZZ \to \ell^+\ell^- q\bar{q}$, but as noted in Ref. 8 the charged-lepton angular distributions of the signal and background are significantly different. It was estimated

TABLE I. Angular distribution coefficient a for final-state charged leptons, quarks and bosons in the process $e^+e^- \to \ell^+\ell^- q\bar{q}$ via $Z\phi$, ZZ, and $Z\phi + ZZ$ (the sum of the two) when $m_\phi = m_Z$. All distributions are well described by $d\sigma/d\cos\theta \sim 1 + a\cos^2\theta$. The angles are measured with respect to the beam axis in the fermion-antifermion rest frame for fermions and in the laboratory frame for bosons. The quark distributions are averaged over two up-type and three down-type quarks.

Mechanism	$\ell^\pm$	Quark	Z
$Z\phi$	0.93	−0.01	−0.10
ZZ	−0.29	−0.29	0.75
$Z\phi + ZZ$	−0.08	−0.23	0.51

that an integrated luminosity of 10 fb^{-1} would be needed at LEP 200 to detect the $Z\phi$ signal on top of the ZZ background if $m_\phi = m_Z$.

We propose that all available information from the final-state particles should be used: (i) the angular distributions of the final-state leptons and quarks, (ii) the angular distribution of the Z boson that decays to $\ell^+\ell^-$, and (iii) the total rate. In the analysis that follows we use the exact spin-averaged squared matrix elements for $e^+e^- \to \ell^+\ell^- q\bar{q}$ via the intermediate states $Z\phi$[8] and ZZ.[9] After examining the search possibilities for the standard-model Higgs boson, we then consider the search for Higgs bosons from minimal supersymmetry.

The angular distributions are well described by the functional form $d\sigma/d\cos\theta \sim 1 + a\cos^2\theta$, where θ is measured from the beam axis in an appropriate reference frame. Table I gives the coefficient a for charged leptons, quarks, and the Z boson (reconstructed from the charged-lepton momentum vectors) at $\sqrt{s} = 200$ GeV. For the lepton and quark distributions we have averaged over the fermion and antifermion, since in the quark case they cannot be experimentally distinguished and in the lepton case the smallness of the vector coupling to the Z makes the separate distributions nearly identical. We have used the fermion-antifermion rest frame for the quark and lepton distributions and the laboratory frame for the Z-boson distribution. Note that our choice of frame for the $\ell^\pm$ distribution differs from that of Ref. 8, where the laboratory frame was used.

We see from Table I that both the lepton and Z distributions are significantly different for $Z\phi$ and ZZ; the quark distribution is less sensitive to the production mechanism. Using the maximum log likelihood method of determining the expected uncertainty in measuring the angular distribution parameter a of the ZZ background (as in Ref. 8), we find $\Delta a = 2.6/\sqrt{N}$ for leptons and quarks and $\Delta a = 5.4/\sqrt{N}$ for the Z, where N is the total number of events. Detecting the presence of the $Z\phi$ signal on top of the ZZ background (i.e., distinguishing the $Z\phi + ZZ$ shape from the ZZ shape) at the 4σ level requires about 2400 events for the lepton distribution, 8000 events for the Z distribution and 30 000 events for the quark distribution. The tree-level cross section is $\sigma(e^+e^- \to ZZ \to \ell^+\ell^- q\bar{q}) \simeq 110$ fb.[10] Using the formulas of Ref. 11, we find that the QED radiative corrections, including initial-state radiation, reduce the cross sections by about 15% at $\sqrt{s} = 200$ GeV. After also factoring in an approximate 40% reduction in cross section due to acceptance cuts and detector efficiency,[7] we find that the integrated luminosity required for a 4σ $Z\phi$ exclusion using all of the angular distributions is about 32 fb^{-1}.

To use the total rate to search for the Higgs boson, one must take into account the uncertainty in the absolute luminosity, which is expected to be about $\Delta L/L \simeq 0.05$ at LEP 200.[12] If we assume that the statistical and luminosity errors are added in quadrature, then the integrated luminosity needed to exclude the signal at the $n\sigma$ level is

$$L = \frac{1}{\sigma_B} \frac{n^2}{(\sigma_S/\sigma_B)^2 - n^2(\Delta L/L)^2} , \tag{1}$$

where $\sigma_S \simeq 35$ fb^{-1} and $\sigma_B \simeq 110$ fb^{-1} are the signal and background $e^+e^- \to \ell^+\ell^- q\bar{q}$ cross sections, respectively, when $m_\phi = m_Z$. To establish the absence of the signal at the 4σ level (taking into account the acceptance cuts, detector efficiency, and radiative corrections) requires an integrated luminosity of about 4.8 fb^{-1}.

Using the rate and the angular distributions combined, an integrated luminosity of about 4 fb^{-1} should be sufficient to rule out at the 4σ level a standard-model Higgs boson that is degenerate with the Z. While this is greater than the canonical 0.5 fb^{-1} per detector, it is not beyond the realm of possibility.

We now turn to the problem of searching for Higgs bosons in the MSSM at LEP 200. We adopt the notation of Ref. 5. In the absence of CP violation there are two neutral Higgs bosons with scalar couplings to fermions, h and H, with $m_h < m_H$. There are two independent parameters in the Higgs sector, which we take to be m_h and

$$\tan\beta = v_2/v_1 , \tag{2}$$

where v_1 and v_2 are the vacuum expectation values of the real part of the neutral Higgs fields. The mass of the heavier neutral Higgs scalar is then given by

$$m_H = m_Z \left(\frac{(m_Z^2 - m_h^2)\cos^2 2\beta}{m_Z^2 \cos^2 2\beta - m_h^2} \right)^{1/2} , \tag{3}$$

from which it may be deduced that $m_h < m_Z|\cos 2\beta|$ and $m_H > m_Z$. The h and H couplings are

$$f_{ZZh}/f_{ZZ\phi} = \sin(\alpha - \beta) ,$$
$$f_{ZZH}/f_{ZZ\phi} = \cos(\alpha - \beta) , \tag{4}$$

where $f_{ZZ\phi}$ is the standard-model $ZZ\phi$ coupling, and

$$\sin^2(\alpha - \beta) = \frac{\sin^2 2\beta \cos^2 2\beta}{(\cos^2 2\beta - m_h^2/m_Z^2)^2 + \sin^2 2\beta \cos^2 2\beta} . \tag{5}$$

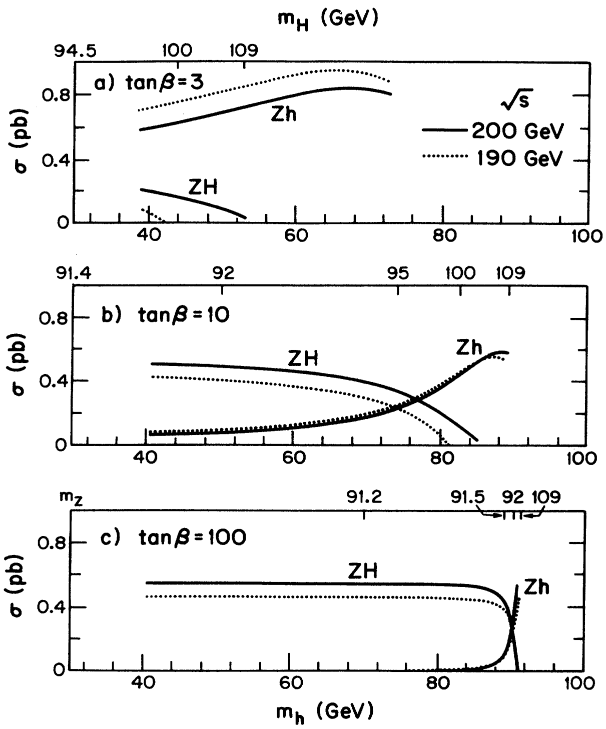

FIG. 1. Cross sections for $e^+e^- \to Zh$ and $e^+e^- \to ZH$ at $\sqrt{s}$ = 200 GeV (solid curves) and 190 GeV (dotted) in the MSSM. The value of m_H is shown on the top scale. The curves are shown only for values of m_h allowed by the current LEP data and the upper limit on m_h ($\le m_Z|\cos 2\beta|$) imposed by the theory.

The ZZh and ZZH couplings are complementary; at least one of them will be the same order of magnitude as the standard-model coupling. It is also true that m_H tends to be close to its minimum value of m_Z in the region of parameter space where f_{ZZH} is the largest (e.g., for $f_{ZZH} > 0.7$, $m_H < 100$ GeV). Thus when $f_{ZZh} < f_{ZZH}$ (and the rate for $e^+e^- \to Zh$ is suppressed), the process $e^+e^- \to ZH$ is kinematically accessible at LEP 200. Therefore by looking for both Zh and ZH production one can improve the limits on the MSSM over what could be obtained from Zh alone. Both h and H decay primarily to a quark-antiquark pair, so their signals are similar to that of the standard-model Higgs boson.

Figure 1 shows the $e^+e^- \to Zh$ and $e^+e^- \to ZH$ cross sections for different values of $\tan\beta$ (we show only examples with $\tan\beta > 1$ since the cross sections are the same when $\tan\beta$ is replaced by $\cot\beta$). At $\sqrt{s}$ = 200 GeV, a standard-model Higgs boson with $m_\phi = m_Z$ has a total $Z\phi$ production cross section of about 540 fb. From Fig. 1(a) we see that the Zh cross section for $\tan\beta = 3$ in the MSSM is larger than 540 fb for all allowed values of m_h. Therefore if a standard-model Higgs boson with $m_\phi = m_Z$ can be excluded, so will $\tan\beta = 3$ in the MSSM.

For larger values of $\tan\beta$, the situation becomes more complicated. The Zh mode is not always the largest, as indicated in Figs. 1(b) and 1(c). When ZH is domi-

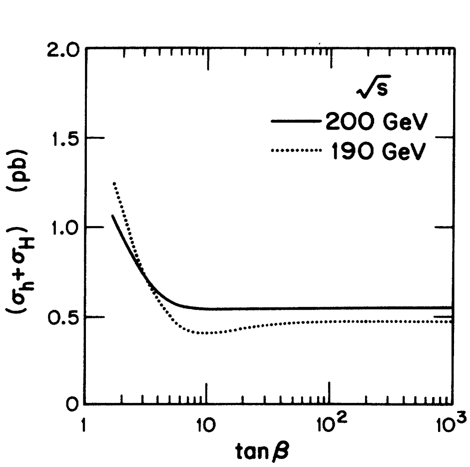

FIG. 2. Minimum value of $\sigma(e^+e^- \to Zh) + \sigma(e^+e^- \to ZH)$ vs $\tan\beta$ at $\sqrt{s}$ = 200 GeV (solid curve) and 190 GeV (dotted) in the MSSM. The parameter m_h has been varied over its allowed range for each value of $\tan\beta$.

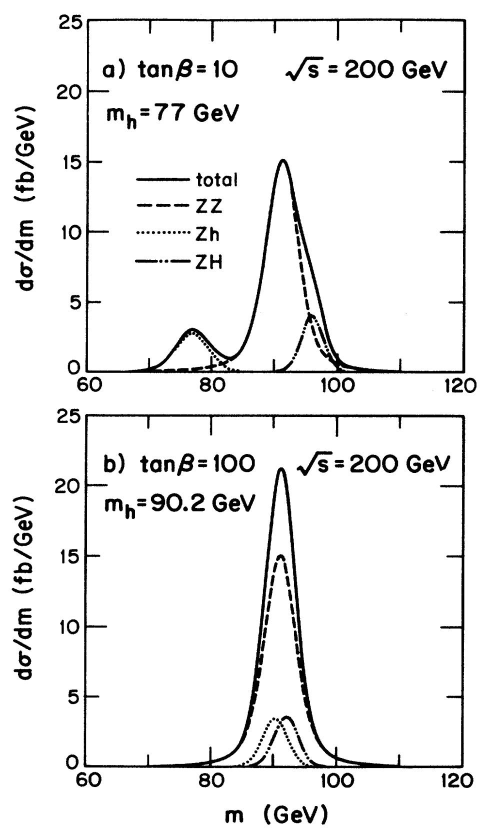

FIG. 3. Differential cross section for $e^+e^- \to \ell^+\ell^- q\bar{q}$ vs recoil mass at $\sqrt{s}$ = 200 GeV in the MSSM model for two sets of model parameters. Shown in each case are the total rate (solid curve), the signal from Zh (dotted) and ZH (dashed-dotted), and the ZZ background (dashed). A lepton momentum resolution of 2% has been included.

nant, m_H is close to m_Z and there will be a substantial background from ZZ, as discussed above. The minimum value of the sum of the Zh and ZH cross sections is shown in Fig. 2 versus $\tan\beta$; at $\sqrt{s} = 200$ GeV this sum is always greater than 540 fb. Therefore one can say that if sufficient statistics are obtained to exclude a standard-model Higgs boson with $m_\phi = m_Z$, then the MSSM would also be excluded for all values of $\tan\beta$. From the discussion above this would require an integrated luminosity of about 4 fb^{-1} for a 4σ limit. At $\sqrt{s} = 190$ GeV, the sum of the Zh and ZH cross sections can be as low as 400 fb^{-1}; hence about 5.4 fb^{-1} would be necessary at this energy to rule out minimal supersymmetry at the 4σ level.

If an excess of events is seen, the integrated luminosity that may be needed to actually claim discovery of a standard Higgs boson degenerate with the Z from the cross-section measurement is given by Eq. (1) with σ_B replaced by $\sigma_B + \sigma_S$. We find that at the 4σ level, the integrated luminosity needed to detect a Higgs boson is about 12 fb^{-1}, much more than the value needed to exclude it. Therefore an ambiguous result is possible; the presence of a Higgs boson might be neither confirmed nor ruled out.

If there is a positive Higgs-boson signal, it may still be difficult to distinguish the MSSM Higgs bosons from the standard-model Higgs boson. A bimodal recoil mass distribution (after subtracting the ZZ background) could reveal that there are actually two Higgs bosons contributing to the signal. For instance, for $\tan\beta = 10$ and $m_h = 77$ GeV, the Zh and ZH cross sections are equal ($\simeq 280$ fb) and $m_H = 96$ GeV; with an integrated luminosity of 4 fb^{-1} there would be (after considering cuts, efficiencies, and QED corrections) about 40 $\ell^+\ell^- b\bar{b}$ events centered at $m = 77$ GeV, 40 events at $m = 96$ GeV, plus 220 background events at $m = m_Z$ [see Fig. 3(a)]. The jet-jet invariant-mass distribution should be similar, although the resolution would not be as good. The rates for Zh and ZH are also comparable for $\tan\beta = 100$ and $m_h = 90.2$ GeV (implying $m_H = 92$ GeV); in this case both the Zh and ZH signals lie under the ZZ background [see Fig. 3(b)]. There are also regions in MSSM parameter space where one Higgs boson is nearly degenerate with the Z and has essentially the standard-model coupling to the Z, while the other has very small couplings to the Z. In situations where most of the Higgs-boson signal is under the ZZ background, the MSSM would not be distinguishable from the standard model by this mode alone.

One can also make a Higgs-boson-mass search using the modes $e^+e^- \to \nu\bar{\nu}q\bar{q}$ and $e^+e^- \to q\bar{q}q\bar{q}$. Both of these modes are subject to severe backgrounds,[7] but any additional information that could be obtained would reduce the integrated luminosity necessary to detect the Higgs boson. In the MSSM, one can also look for $e^+e^- \to hA$ or HA,[5] where A is the pseudoscalar boson; the primary signal is $q\bar{q}q\bar{q}$, with a significant ZZ background if the Higgs-boson masses are near m_Z.

For the standard model and the MSSM with $\tan\beta > 1$ (for which the Higgs bosons decay dominantly to $b\bar{b}$), tagging of b quarks would considerably enhance the signal-to-noise ratio by eliminating the background from Z decays to non-b quarks. In the MSSM with $\tan\beta < 1$ Higgs bosons decay primarily to $c\bar{c}$; the charm signal would clearly indicate a nonstandard Higgs sector. Charm quarks could also be tagged via $D^* \to D\pi$.[13] Using a combination of vertex chambers and neural triggers, a heavy-quark tagging efficiency of 50% could perhaps be achieved;[14] the integrated luminosity needed to exclude a standard-model Higgs boson with $m_\phi = m_Z$ or the MSSM would then be reduced by approximately a factor of 6 from the value needed without heavy-quark tagging. Heavy-quark tagging would also enhance search possibilities in the $\nu\bar{\nu}q\bar{q}$ and $q\bar{q}q\bar{q}$ modes.

In summary, we have shown that an integrated luminosity of about 4 fb^{-1} at LEP 200 should be sufficient to rule out at the 4σ level a standard-model Higgs boson with $m_\phi = m_Z$ via the process $e^+e^- \to \ell^+\ell^- q\bar{q}$. It should also be sufficient to rule out the minimal supersymmetric standard model since the combined cross section for producing the two neutral scalars in the MSSM is greater than that of the standard-model Higgs boson with $m_\phi = m_Z$. With heavy-quark tagging 0.7 fb^{-1} may suffice to test these scenarios.

During the preparation of this manuscript we received[15] a paper by N. Brown on detecting a standard Higgs boson degenerate with the Z at LEP 200 and learned of a paper by J.F. Gunion and L. Roszkowski on detecting the Higgs bosons from minimal supersymmetry at LEP 200.

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