The Hunting of the MR Model

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We consider experimental signatures of the standard model's minimal supersymmetric extension with a continuous $U(1)_R$ symmetry (MR model). We focus on the ability of existing and planned electron-positron colliders to probe this model and to distinguish it from both the standard model and the standard model's minimal supersymmetric extension with a discrete R-parity.

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1. Introduction

We consider experimental signatures of the standard model's minimal supersymmetric extension with a continuous $U(1)_R$ symmetry. When this class of models was first considered [1], LEP data on the non-observation of light Higgs bosons appeared to exclude the minimal such model (MR model). Once the large size of radiative corrections to Higgs masses from a very heavy top quark became apparent [2], the model was reexamined [3] and pronounced viable.

We focus here on the ability of existing and planned electron-positron colliders to test the Higgs boson and slepton sectors of the MR model. We also discuss the extent to which it is possible to experimentally distinguish the MR model from both the standard model (SM) and its minimal supersymmetric extension with a discrete R-parity (MSSM). As such, our work was partly inspired by and is complementary to recent papers on the prospects for studying the Higgs sector of the MSSM at various colliders [4]. Our results also complement previous work on MR model phenomenology. Experimental signatures involving gaugino production were considered in [1]; these are useful because they apply equally well to many non-minimal $U(1)_R$ symmetric models. The phenomenological implications of cosmological constraints on the lightest superpartner (the photino) were considered in [3]; those results will be revisited and applied in this work.

The second section of this paper introduces the model and indicates how cosmological constraints on the photino mass influence the model's phenomenology. Section 3 then discusses the masses and decay modes of the Higgs bosons for which we propose to search. In the next three sections, we discuss the extent to which current LEP I data and proposed LEP II and NLC searches for neutral Higgs bosons can and will constrain the MR model. Slepton searches are the subject of Section 7. Section 8 summarizes our results and compares the expectations for the MR, SM and MSSM models.

2. The MR Model

The model we study is the standard model's minimal supersymmetric extension with a continuous $U(1)_R$ symmetry. We define the continuous R symmetry by giving the coordinate of superspace, θ, and all matter superfields charge $+1$ while all Higgs superfields have charge 0. Expansions of the superfields in terms of the component fields then show that all ordinary particles are R neutral while all superpartners carry non-zero R charge. Since the $U(1)_R$ symmetry forbids Majorana gaugino masses, the model contains an additional

field to give a Dirac mass to the gluino. This field appears only in the soft supersymmetry-breaking sector and is irrelevant to the rest of this paper; we therefore omit it here and refer the reader to [1] for details.

The most general Lagrangian consistent with the above assumptions is described by the superpotential:

$$f \; = \; U^c \lambda_U \, Q \, H_2 \; + \; D^c \lambda_D \, Q \, H_1 \; + \; E^c \lambda_E \, L \, H_1 \tag{2.1}$$

where each term has $R = 2$ and the quark and lepton superfields Q, U^c, D^c, L, E^c have the usual $SU(3) \times SU(2) \times U(1)$ gauge interactions. The most general soft supersymmetry breaking potential consistent with our symmetries and a GIM-like mechanism to naturally suppress flavor-changing neutral currents is:

$$\begin{aligned}
\mathcal{L}_{soft} \; &= m_{H_1}^2 H_1^* H_1 + m_{H_2}^2 H_2^* H_2 + m_Q^2 \tilde{Q}^* \tilde{Q} + m_{U^c}^2 \tilde{U}^{c*} \tilde{U}^c + m_{D^c}^2 \tilde{D}^{c*} \tilde{D}^c + \\
&\quad m_L^2 \tilde{L}^* \tilde{L} \; + m_{E^c}^2 \tilde{E}^{c*} \tilde{E}^c + \; B H_1 H_2 + ...
\end{aligned} \tag{2.2}$$

where we neglect small Yukawa-suppressed corrections to superpartner masses. Notice that we do not assume that all superpartners have the same mass.

The gaugino mass matrix has a simple form in the MR model because [1] there is neither a $H_1 H_2$ mass term in the superpotential (i.e. $\mu = 0$) nor any Majorana gaugino mass in the supersymmetry breaking potential (i.e. $M, M' = 0$). The only mass terms are the Dirac masses coupling the partners of the electroweak gauge bosons to the fermionic partners of the Higgs. As is conventional, we shall define a mixing angle β in terms of the ratio of the Higgs VEVs ($v_2/v_1 \equiv \tan\beta$) and shall denote the superpartner of the W gauge bosons as $\tilde{w}$ and that of the B gauge boson as $\tilde{b}$. Then the zino ($\tilde{z} \equiv -\sin\theta_W \tilde{b} + \cos\theta_W \tilde{w}_3$) and one of the higgsinos ($\tilde{H}_Z \equiv \cos\theta_W \tilde{b} + \sin\theta_W \tilde{w}^3$) combine to form a Dirac fermion which has the same mass as the Z gauge boson at tree level, while the photino and $\tilde{H}_\gamma$, the higgsino orthogonal to $\tilde{H}_Z$, are massless. The charginos have tree-level masses $m_+ = \sqrt{2} m_W \cos\beta$ and $m_- = \sqrt{2} m_W \sin\beta$. At one loop, the alteration of the mass structure most significant for our analysis is the generation of a Dirac mass for the photino and its associated higgsino, $\tilde{H}_\gamma$:

$$m_{\tilde{\gamma}} = 1.3 \text{GeV} \; \cot\beta \left(\frac{m_t}{200 \text{GeV}} \right)^2 \left| \frac{m_{\tilde{t}_L}^2}{m_{\tilde{t}_L}^2 - m_t^2} \ln \frac{m_{\tilde{t}_R}^2}{m_t^2} - \frac{m_{\tilde{t}_R}^2}{m_{\tilde{t}_R}^2 - m_t^2} \ln \frac{m_{\tilde{t}_R}^2}{m_t^2} \right|. \tag{2.3}$$

Note that the photino mass decreases as the top squarks $\tilde{t}_L$ and $\tilde{t}_R$ become more nearly degenerate.

Unlike the MSSM, the MR model is strongly constrained by photino phenomenology. To begin with, the small size of the photino mass (2.3) makes the decay $Z \rightarrow \tilde{\gamma} \tilde{H}_\gamma$ possible; this, in turn, renders the invisible Z width larger than the standard model value. The Z branching fraction into photino plus higgsino will be suppressed by a factor of $\cos^2 2\beta$ relative to the branching into one SM neutrino flavor. Therefore, the bound on the Z width [5] $\Delta\Gamma_Z/\Gamma_\nu < 0.11$ at 2σ translates into the constraint $|\cos 2\beta| < 0.33$. This implies that only the range $0.71 < \tan\beta < 1.41$ is allowed in the MR model. We will apply this constraint from here on.

In addition, the cosmological constraint ($\Omega_{\tilde{\gamma}} h^2 \leq 1$) on the present photino mass density must be satisfied. The upper bound on $\Omega_{\tilde{\gamma}}$ provides a lower bound on the cross-section for photino annihilation ($\sigma_{\tilde{\gamma}}$). Because $\sigma_{\tilde{\gamma}}$ grows as $m_{\tilde{\gamma}}^2$, very *light* photinos will yield too large a residual mass density. Further, since both s-channel Z exchange and t-channel slepton exchange are required to make $\sigma_{\tilde{\gamma}}$ large enough, the sleptons can weigh no more than about 140 GeV in the MR model (see fig. 7 and [3]); this point will be crucial to our discussion of slepton searches in Section 7. To determine the lightest allowed photino mass (the one giving $\Omega_{\tilde{\gamma}} h^2 = 1$), we maximize the slepton contribution to $\sigma_{\tilde{\gamma}}$ by making the sleptons degenerate at the lightest experimentally [6] allowed mass (65 GeV). Applying this lower bound on $m_{\tilde{\gamma}}$ to equation (2.3) has two important consequences for the MR model.

First, when the top quark is relatively light ($\lesssim 150$ GeV), producing a heavy enough photino requires $\tan\beta$ to be smaller than some maximum value, which is obtained when the top squark masses are as widely separated as possible (making one mass 1 TeV and the other, m_t) so as to maximize the top squark contribution to (2.3). This constraint is independent of m_A, and it further restricts the allowed range of $\tan\beta$. We find $\tan\beta < 0.95(1.2)$ for $m_t = 120(140)$ GeV.

The second effect arises more indirectly. Given the form of equation (2.3), the existence of a lower bound on $m_{\tilde{\gamma}}$ prevents the top squarks from being degenerate in the MR model. We will see in Section 3 that this reduces the maximum size of the radiative corrections to the Higgs masses relative to the the maximum size in the MSSM. As we will discuss in Section 5, the lighter CP-even neutral Higgs boson of the MR model is therefore accessible to LEP II in a wide region of the $\tan\beta$ vs m_A plane even if the top quark is very heavy.

3. Neutral Higgs Bosons in the MR Model

The relations among the tree-level masses of scalar (H_1^0, H_2^0), pseudoscalar (A^0) and charged (H^+, H^-) Higgs fields are identical to those in the MSSM. In terms of the variables m_A and β, the tree-level mass matrix for H_1^0 and H_2^0 is

$$\begin{pmatrix} M_Z^2 \cos^2\beta + m_A^2 \sin^2\beta & -\sin\beta\cos\beta(M_Z^2 + m_A^2) \\ -\sin\beta\cos\beta(M_Z^2 + m_A^2) & M_Z^2 \sin^2\beta + m_A^2 \cos^2\beta \end{pmatrix} . \tag{3.1}$$

At one loop, there are corrections due to loops involving the squarks and the top quark. In the MR model, the only [3] one-loop correction to the mass matrix (3.1) is a term added to the (2,2) entry (if we neglect the bottom squark contribution which is negligible in the allowed region of $\tan\beta$). If the renormalization point is chosen so as to maintain the tree level vacuum expectation of the Higgs fields, this term takes the form[1]

$$\frac{\epsilon}{\sin^2\beta} = \frac{3g^2}{16\pi^2\sin^2\beta}\frac{m_t^4}{M_W^2}\ln\left(\frac{m_{\tilde{t}_L}^2 m_{\tilde{t}_R}^2}{m_t^4}\right) . \tag{3.2}$$

As discussed in [3], this correction to the Higgs masses is quite significant; without it, LEP I would already have excluded the model entirely. Note that the non-degeneracy of the top squarks (Section 2) reduces the maximum size of this correction[2] relative to the maximum size in the MSSM (achieved with degenerate $\tilde{t}_L$ and $\tilde{t}_R$).

The dependence of the mass of the lighter CP-even neutral Higgs boson (h) on m_t and $\tan\beta$ is shown in fig. 1. Note that as the top quark gets lighter, m_h becomes more restricted. The mass of the heavier CP-even neutral Higgs (H) is at least twice the size of m_h throughout the parameter space of the MR model.

In order to discuss searches for the neutral Higgs bosons of the MR model, we need to understand the Higgs bosons' decay modes. The Higgses can potentially decay into fermion/anti-fermion pairs (at a rate proportional to the square of the fermion mass), chargino pairs, neutralino pairs, or other Higgs bosons. Due to the absence of the scalar trilinear terms in the soft supersymmetry breaking potential, the MR Higgs bosons do not

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[1] In the MSSM, there are also contributions involving the coefficient μ of the $H_1 H_2$ mass term in the superpotential and the coefficient A of the trilinear scalar operators in the supersymmetry breaking terms. Those two coefficients vanish in the MR model because of the continuous $U(1)_\mathrm{R}$ symmetry.

[2] The maximum is found for given m_t and $\tan\beta$ by setting one top squark mass to 1 TeV and the other to the largest value consistent with the lower bound on $m_{\tilde{\gamma}}$.

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decay to sleptons and squarks. It is important to note that the neutral Higgses of the MR model only couple to the neutralino pairs $\tilde{z}\tilde{H}_\gamma$ and $\tilde{z}\tilde{H}_Z$. This is because the vanishing of the parameters M, M' and μ (see Section 2) in the MR model greatly simplifies the matrix that diagonalizes the neutralino mass matrix. We will now discuss the dominant decay modes of each neutral Higgs as a function of its mass [3].

The light CP-even Higgs boson (h) decays dominantly to fermion pairs, except in the slice of parameter space where the decay $h \to AA$ is kinematically allowed. Therefore, the 'standard' searches used to look for h_{SM} are generally suitable for h, with slight modifications to take the AA channel into account as must be done in searching for h_{MSSM}.

In contrast, the heavy CP-even Higgs boson (H) is always sufficiently massive to decay to the Higgs boson pair hh or to the pair of neutralinos $\tilde{z}\tilde{H}_\gamma$. Decays to fermion pairs can dominate only when the H becomes heavy enough to open the $t\bar{t}$ decay channel. As a result, the kind of searches we are going to analyze in this paper are not suitable for H.

The decays of the CP-odd Higgs boson (A) are shown in fig. 2 for $m_t = 160$ GeV and $\tan\beta = 0.71$; the qualitative features are independent of those particular values. An A boson lighter than roughly the Z mass will decay to the heaviest possible fermion pairs. When m_A rises a bit above m_Z, the channel $A \to \tilde{z}\tilde{H}_\gamma$ becomes kinematically accessible and it immediately dominates. Likewise, the $A \to \tilde{w}^+\tilde{w}^-$ and $A \to t\bar{t}$ channels each take over once they are allowed. The additional decay modes $A \to Zh$ and $A \to \tilde{z}\tilde{H}_Z$ also occur for sufficiently heavy A. The first is suppressed in the MR model by a ZAh coupling factor (see Section 4) whose value is minuscule for A bosons heavy enough to decay to Zh. The second is simply never large enough to dominate. Therefore 'standard' Higgs boson searches based on decays to fermions will be useful to probe the region of parameter space where $m_A \lesssim 90$ GeV.

4. 'Standard' Higgs Searches at LEP I

We now use the information we have gathered on the masses and decays of the Higgs bosons to discuss how electron-positron collider experiments can search for these particles. We begin by considering the implications of recent data from LEP experiments.

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[3] In evaluating the decay widths we have included the cosmological constraints discussed in Section 2.

At LEP I it is possible to search for the h and A Higgs bosons of the MR model; the H boson is too heavy to be produced. Specifically, the channels

$$e^+e^- \to Z \to Z^*h, Ah \tag{4.1}$$

are accessible if h and A are sufficiently light. We recall that any A boson light enough to be produced at LEP I decays only to fermions. The ZZh coupling is reduced relative to the standard model ZZh_{SM} coupling by a factor $\sin(\beta - \alpha)$, where α is the mixing angle in the CP-even sector, determined from the diagonalization of the mass matrix. At one loop, α is given by

$$\tan 2\alpha = \frac{(m_A^2 + M_Z^2)\sin 2\beta}{(m_A^2 - M_Z^2)\cos 2\beta + \frac{\epsilon}{\sin^2 \beta}}, \tag{4.2}$$

where ϵ was defined in eq. (3.2). The ZAh coupling is proportional to $\cos(\beta - \alpha)$, making the two channels complementary.

Recent ALEPH searches for Z^*h and Ah signals [7] have produced null results that may be translated into bounds on $\sin^2(\beta - \alpha)$ and $\cos^2(\beta - \alpha)$, respectively. Because the h mass depends on the top quark mass (cf. equations (3.1) and (3.2)), the bounds also depend on m_t. For a relatively light top quark, $\sin^2(\beta - \alpha)$ is almost identically 1, so that the bounds on the MR model come exclusively from the Z^*h channel. In this case, the h boson is not very heavy and the current data strongly constrain the $\tan \beta$ vs m_A plane. Specifically, we find that *a top quark lighter than 120 GeV is entirely excluded in the MR model*; for $m_t = 120$ GeV only the slice $0.71 < \tan \beta < 0.72$ is allowed, independent of m_A. The situation changes considerably as the top becomes heavier: the constraints from Z^*h searches get weaker (for $m_t = 200$ GeV the constraint has evaporated) while the constraint on $\cos^2(\beta - \alpha)$ from Ah production becomes stronger.

Our fig. 3 shows the excluded regions inferred from the ALEPH bounds on Z^*h production for several top quark masses. The bounds from Ah production are only relevant for $m_t \geq 160$ GeV and tend to exclude the small m_A, large $\tan \beta$ region of the plane; the bounds when $m_t = 180$ GeV and $m_t = 200$ GeV are shown in fig. 3 by way of illustration.

We conclude that if the top quark is discovered to be lighter than 120 GeV then the LEP I results just discussed will have excluded the MR model. If the top quark is heavier, input from future experiments will be necessary to reach any conclusions about the MR model.

5. 'Standard' Searches for Zh at LEP II

The lightness of the MR model's neutral Higgs boson h makes LEP II especially useful for testing this model. With a CM energy $\sqrt{s} \simeq 200$ GeV, the possible Higgs production channels will be

$$e^+ e^- \to Z^* \to Zh, Ah, AH, ZH \tag{5.1}$$

The cross-section for AH production is, like that for Zh, proportional to $\sin^2(\beta - \alpha)$. The complementary ZH production process is only kinematically allowed at LEP II when $m_t \leq 140 GeV$ - precisely the region of parameter space where $\cos^2(\beta - \alpha)$ is a drastic suppression factor. We will ignore H production since in the MR model it does not contribute substantially to the final states for which we propose to search.

In this section, we consider how well LEP II will be able to search for h in the $\nu\nu jj$, $lljj$ and $jjjj$ final states arising from production of Zh. Monte Carlo results on SM Higgs boson signals and backgrounds in these three channels have been presented for LEP II in ref. [9] . These show that h_{SM} weighing up to 80 GeV can be detected in $\nu\nu jj$ and $lljj$ channels, while one weighing up to 60 GeV can be seen in the $jjjj$ channel with integrated luminosity of 500pb^{-1} per detector. We follow Barger et al. [4] in scaling from the SM simulations to estimate the detectability of the MR model's Zh signals, which differ from the SM signals essentially by the cross-section factor $\sin^2(\beta - \alpha)$. To be considered 'detectable' we require a signal to satisfy

$$\frac{S}{\sqrt{B}} = \frac{\text{\# of signal events}}{\sqrt{\text{\# of background events}}} \geq 4 \tag{5.2}$$

for an integrated luminosity $\mathcal{L} = 500$pb^{-1}. We add the significance $\frac{S}{\sqrt{B}}$ of the three channels in quadrature, considering only channels with four or more events.

As usual, the bounds depend strongly on the top quark mass. For a light top quark, $\sin^2(\beta - \alpha) \approx 1$ and the limits are essentially the same as for h_{SM}. When the top quark is heavier ($\gtrsim 140$ GeV), $\sin^2(\beta - \alpha)$ drops significantly below 1 only in the region where m_h is substantially smaller than 80 GeV; even with the suppression factor the number of events is large. The net result is that where h decays dominantly to leptons or jets LEP II can do as good a job of looking for h in these channels as for h_{SM}

On the other hand, if a Higgs boson *is* found, the fact that $\sin^2(\beta - \alpha) \approx 1$ will make it difficult to tell whether h_{SM} or h has been seen. We have estimated the difference between the number of Zh and Zh_{SM} events, again using the simulations of SM Higgs

boson signals presented in ref. [9] . We observe that the difference is never statistically significant (i.e. is $< 3\sigma$) when the top is lighter than ≈ 160 GeV. For a heavier top, the difference is larger than 3σ typically in the small-m_A/large-$\tan\beta$ region of the parameter space (see fig. 4). However, even in the most favorable case ($m_t = 200$ GeV) the two models become indistinguishable when m_A is heavier than 100 GeV.

It is important to note that where kinematically allowed to do so, the MR h will decay dominantly to AA (except when there is an accidental suppression of the coupling). In this case, the final state topology and, hence, the efficiency of the standard searches depends on m_A. This issue has, naturally, arisen in the LEP I searches for h_{MSSM}. It was found [7] that the standard searches remain effective so long as $m_A > 2m_b$ and slightly modified searches for 'six-fermion' final states can cover the remaining region of parameter space. Hence our estimates based on the scaling of the SM simulations remain reliable for $m_A > 2m_b$. The remaining small slice of parameter space is either already excluded by LEP I or can be studied using the appropriate modified-standard searches.

Our fig. 4 shows the regions in the $(\tan\beta, m_A)$ plane accessible to LEP II, for different values of the top quark mass. Notice that if the top is lighter than 170 GeV, then h always weighs 80 GeV or less. In this case, if LEP II sees no sign of an h in the standard channels, the model's survival will depend entirely on the efficacy of the modified-standard channels' coverage of the light m_A region where $h \to AA$ dominates.

The above estimates do not assume b jet identification. However, b tagging will substantially improve the Higgs boson discovery limit, since the Z-boson's branching ratio into $b\bar{b}$ is only $\sim 15\%$ while the Higgs boson decays mainly into $b\bar{b}$. It has recently been shown [10] that by tagging b jets LEP II experiments will be able to detect a SM Higgs of mass $m_{h_{SM}} \sim \sqrt{s} - 100$ GeV [4]. Within the MR model, the regions of the $(\tan\beta, m_A)$ plane where h is heavier than 80 GeV correspond to $\sin^2(\beta - \alpha) \approx 1$, independent of the top mass, and therefore the mass limit set for the SM Higgs also applies for h. In fig. 5 we show the areas of the $(\tan\beta, m_A)$ which will be probed at LEP II assuming the b tagging performances stated in ref. [10] can be achieved. The improvement is enormous. Provided that the region where $h \to AA$ dominates can be excluded by modified-standard searches, LEP II with a beam energy of 95 (100) GeV will be able to rule out the MR model if the top is lighter than 180 (200) GeV.

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[4] We thank J.J. Gómez-Cadenas for pointing out to us this upgrade of the LEP detectors.

To conclude, standard Zh searches in the MR model are strongly affected by the fact that $\sin^2(\beta - \alpha) \approx 1$ in most of the MR model's parameter space. On the one hand, a large (i.e. visible) number of Zh events is guaranteed, so that failure to find a neutral CP-even Higgs boson at LEP II would eliminate much of the $\tan \beta$ vs m_A plane. On the other hand, the MR and SM Higgs bosons will look very similar unless the top quark is quite heavy, so that further searches may well be required to disentangle the two models.

6. Searches for A and H in $\tau\tau jj$ at LEP II and beyond

To distinguish the MR model from the SM with neutral Higgs searches, one must seek evidence of the A and H bosons in addition to the h. Studies of the Higgs sector of the MSSM [9][11] suggest exploiting the bosons' potentially large branching fraction to tau leptons by looking for the processes

$$e^+ e^- \to Zh, Ah, ZH, AH \to \tau\tau jj. \tag{6.1}$$

The scalars' masses could be deduced from the shape of the $M_{\tau\tau}$ and M_{jj} invariant mass spectra of these events. In the MR model, we have already noted that the H dominantly decays to hh or to $\tilde{z}\tilde{H}_\gamma$; thus production of H bosons will not contribute appreciably to $\tau\tau jj$ final states. The A boson on the other hand, decays primarily to fermion pairs if its mass is below the Z mass; decays to $\tau^+\tau^-$, $b\bar{b}$ and $c\bar{c}$ pairs dominate since the scalar-fermion coupling grows with the fermion mass. We therefore focus on the reactions

$$e^+ e^- \to Zh, Ah \to \tau\tau jj \tag{6.2}$$

in the remainder of this section. We shall consider whether a distinct peak due to the A boson will be directly visible and also whether slight alterations in the Z and h peaks due to the non-standard-ness of the model would be visible.

We note that the irreducible background for the proposed signal comes from $e^+ e^- \to ZZ$ events, which cluster at $M_{\tau\tau}, M_{jj} = M_Z$. As shown in [11] the background would be noticeable only when the scalar masses are close enough to M_Z for the invariant mass peaks to overlap.

The cross-section for Ah production depends on the scalars' masses and on the suppression factor of $\cos^2(\beta - \alpha)$. Even for the largest attainable cross-section (essentially meaning for the smallest value of $\sin^2(\beta - \alpha)$), we predict only about five $\tau\tau jj$ signal

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events for 500pb^{-1} of integrated LEP II luminosity. Folding in the expected 50% detection efficiency [11] makes the signal essentially unobservable even before worrying about the precise size of the background. Hence LEP II does not appear capable of directly detecting the A scalar of the MR model in $\tau\tau jj$ final states.

One might also wonder whether the slight alterations in the rate of Zh production in the MR model as compared with the SM would be visible in $\tau\tau jj$. We find that, for a heavy top quark, the number of $e^+e^- \to Zh \to \tau\tau jj$ events predicted by the two models can differ by of order 2σ for small m_A and large $\tan\beta$. For example, with $m_t = 200$ GeV, the region with a deviation of at least 2σ is roughly that above the curve labeled A in fig. 4. When combined with the 'standard channel' signals, this could aid differentiation of the SM and the MR model in the appropriate region of parameter space.

Moving the search to a hypothetical NLC with a beam energy of 250 GeV and an integrated luminosity of 10 fb^{-1} changes the picture enormously. The luminosity compensates for the cross-section's reduction due to the increased CM energy. In the most favorable regions of parameter space (small m_A and large $\tan\beta$) , one might now expect of order 100 events (after including the detection efficiency); contours of number of events are shown in fig. 6. This should make the A boson directly visible if $m_A \lesssim M_Z$. In addition, one can more usefully exploit the difference between the predicted number of Zh and Zh_{SM} events at the higher event rates of the NLC. For the $\tau\tau jj$ channel, we find that for heavy m_t the significance of this difference is now quite high: for $m_t > 180$ GeV (160 GeV) it is *less* than 3σ only for $m_A \gtrsim$ 100 GeV (70 GeV). Including the 'standard' Zh decay channels in that comparison will naturally improve the strength of the signal.

7. Searching for Sleptons

We have found that LEP II is not likely to be able to distinguish the MR model from the SM by studying the Higgs sector alone. Therefore, one should consider other searches LEP II could make to fulfill this mission. What immediately suggests itself is searching for superpartners. Since photino cosmology (Section 2) tells us that MR model sleptons weigh no more than 140 GeV (while squarks could all have masses of a TeV), it is most logical to search for these.

As the sleptons in the MR model are not appreciably different from those of the MSSM (except, perhaps in their masses), we can adapt some results obtained for the MSSM to predict how one might search for the MR sleptons. Detailed Monte Carlo studies of slepton

searches at electron-positron machines [13] have shown that sleptons are generically visible if their masses are no more than 80% to 90% of the beam energy.

As fig. 7 shows, the slepton mass is less than 80 GeV in the MR model so long as the top quark mass is less than about 140 GeV. And the maximum slepton mass for any top quark mass is about 140 GeV. Therefore, if the top quark is known to weigh less than 140 GeV and LEP II finds no sleptons below a mass of 80 GeV, then the MR model will be ruled out. Even if the top quark mass is unknown or is greater than 140 GeV, the allowed range of $\tan\beta$ in the MR model will be strongly constrained if sleptons are not found at LEP II. Only an e^+e^- collider with a beam energy of at least 175 GeV could search the entire allowed mass range of the sleptons; the NLC's discussed in [11] meet the energy requirement easily.

It is instructive to briefly consider how useful hadron colliders are likely to be in searching for MR model superpartners. Judging from the cross-sections plotted in ref [12], the 4pb^{-1} of CDF's current integrated luminosity would be expected to have produced only 4 (1) pairs of low-rapidity 50 GeV (100 GeV) sleptons [5]. Hence the only sleptons light enough to be visible at the Tevatron are already excluded by other experiments [6]. While squarks would be more readily produced than sleptons (due to their color), they can also be nearly ten times as heavy; the first consideration pales before the second. It is only at the higher energies and luminosities of the SSC or LHC that the full range of either slepton or squark masses of the MR model will be open to study.

8. Discussion/Conclusions

Because the Higgs and slepton sectors of the MR model are strongly constrained by photino cosmology, they provide interesting search candidates for experiments at both existing and planned electron-positron colliders. We have seen that studying the Higgses and sleptons provides opportunities both for excluding the model and for distinguishing it from the SM and the MSSM.

No matter what mass the top quark is found to have, at least one e^+e^- collider will be able to use such searches to try to rule out the MR model entirely. Current LEP I data on Zh searches will immediately exclude the MR model if the top quark is found to

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[5] The numbers of events given include a rapidity cut of $|y| < 1.5$ to ensure that only 'detectable' sleptons are included.

weigh less than 120 GeV. LEP II will have two opportunities (slepton and higgs searches) to exclude the model. For $m_t < 140$ GeV, LEP II would rule out the MR model if it found no sleptons weighing less than 80 GeV. For $m_t < 180$ GeV, LEP II would rule out the model if it did not find a neutral CP-even Higgs boson using 'standard' Zh search channels. Finally, even if the top quark is as heavy as 200 GeV, combined searches for sleptons and neutral Higgs bosons at an NLC with a beam energy of at least 175 GeV will have the potential to exclude the MR model.

Assuming that the MR model is not directly excluded, one would naturally wish to experimentally distinguish between it and the SM. Two possible approaches are (1) finding a light CP-even Higgs boson and demonstrating that it is not h_{SM} (2) finding a particle such as A or $\tilde{l}$ that exists in the MR model and not the SM. We have seen that the first approach is most useful when the top quark is very heavy. If a neutral CP-even Higgs boson is found at LEP II, it will be difficult to directly tell whether h or h_{SM} has been found simply because $\sin(\beta - \alpha) \approx 1$ through much of the MR parameter space. A deviation of the observed number of Zh events from the number predicted in the SM would only be detectable at LEP II if $m_t \gtrsim 180$ GeV (fig. 4); the services of an NLC would be required to make this signal useful if the top quark is lighter. The second approach is more broadly applicable. While the A boson of the MR model will not be detectable in $\tau\tau jj$ searches at LEP II, that collider can find sleptons weighing up to 80 GeV. An NLC could both polish off the allowed slepton mass range and search a respectable fraction of the parameter space in which the A decays appreciably to ordinary fermions.

One would also wish to distinguish the MR model from the MSSM. The difficulty of this will depend on the masses of the sleptons and Higgs bosons. If the sleptons are heavier than the MR model allows for given top quark mass or if the values of m_h and m_A correspond to a value of $\tan\beta$ outside the MR model range, then the choice is clear. However if those masses are such that either model is possible, one can still make progress by studying the neutral Higgs bosons' decay modes. For example, the discovery in $\tau\tau jj$ final states of any A boson at LEP II or of an A with $m_A \gtrsim M_Z$ at an NLC would provide strong evidence for the MSSM as opposed to the MR model. Searching for decay modes of the neutral Higgs bosons that are allowed in the MSSM but forbidden in the MR model (such as decays to sleptons, squarks, and certain combinations of neutralinos) would also be useful in disentangling the two models.

Acknowledgements

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Figure Captions

Fig. 1. Mass of the CP-even neutral Higgs boson as a function of $\tan\beta$, including one loop radiative corrections with the photino cosmological constraint incorporated, for $m_t = 140$ GeV (solid), 160 GeV (dashed), 180 GeV (dashed-dotted) and 200 GeV (dotted). For each value of the top mass, the lower curve corresponds to $m_A = 10$ GeV and the upper curve to $m_A = 1$ TeV.

Fig. 2. CP-odd Higgs boson partial decay widths for $m_t = 160$ GeV and $\tan\beta = 0.71$. The decay modes are $f\bar{f}$ (A), $\tilde{H}_\gamma\tilde{z}$ (B), $\tilde{w}^+\tilde{w}^-$ (C), hZ (D) and $\tilde{H}_Z\tilde{z}$ (E).

Fig. 3. Excluded regions of the $(m_A, \tan\beta)$ plane inferred from the ALEPH results at LEP I. Solid curves correspond to $Z \to Z^*h$ searches for $m_t =130$ GeV (A), 140 GeV (B), 160 GeV (C) and 180 GeV (D). Discontinuous curves correspond to $Z \to Ah$ searches for $m_t = 180$ GeV (dashed) and 200 GeV (dashed-dotted). Areas above or to the left of the curves are excluded.

Fig. 4. Regions in the $(m_A, \tan\beta)$ plane accessible to LEP II, for $m_t = 170$ GeV (dashed), 180 GeV (dashed-dotted) and 200 GeV (solid). Areas to the right of the curves are inaccessible. The dotted curves on the left side of the plot show the region of the $(m_A, \tan\beta)$ plane where the difference between the number of Zh and Zh_{SM} events is larger than 3σ for $m_t = 180$ GeV (A) and 200 GeV (B). In the areas above or to the left of the dotted curves it should be possible to disentangle the MR h boson from h_{SM}.

Fig. 5. Same as fig. 4 with b quark tagging, assuming $\sqrt{s} = 190$ GeV, for $m_t = 180$ GeV (dashed-dotted) and 200 GeV (solid); and assuming $\sqrt{s} = 200$ GeV for $m_t = 200$ GeV (dashed).

Fig. 6. Contours showing how number of $Ah \to \tau\tau jj$ events at NLC depends on m_A and $\tan\beta$. Curves shown are for $m_t = 160$ GeV; numbers of events for each curve are: A=90, B=80, C=70, D=60, E=50, F=40, G=30. As m_t is varied, the upper curves simply correspond to an altered number of events. For $m_t = 180$ GeV, one has A=120, B=110, C=100, D=90, E=80, F=70. For $m_t = 140$ GeV, one has C=40, D=30; in this case, the plane extends only up to $\tan\beta = 1.2$, as discussed in Section 3.

Fig. 7. Maximum slepton mass (assuming all the sleptons are degenerate) as a function of $\tan\beta$, for different values of m_t: 140 GeV (solid), 160 GeV (dashed), 180 GeV (dashed-dotted) and 200 GeV (dotted). The constraint $m_h \geq 44$ GeV has been incorporated.