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TESTING SUPERSYMMETRY AT THE NEXT LINEAR COLLIDER

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ABSTRACT

If new particles are discovered, it will be important to determine if they are the supersymmetric partners of standard model bosons and fermions. Supersymmetry predicts relations among the couplings and masses of these particles. We discuss the prospects for testing these relations at a future e^+e^- linear collider with measurements that exploit the availability of polarized beams.

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1. Introduction

The phenomenological predictions of supersymmetry (SUSY) may be divided into the following three categories: (I) predictions that would constitute indirect evidence for SUSY if verified, including, for example, the existence of a light Higgs boson; (II) the existence of particles with the correct spin and quantum numbers to be superpartners of standard model particles; and (III) well-defined quantitative relations among the couplings and masses of these new particles. While the predictions of (I) are of great interest, their verification is clearly no substitute for direct evidence. The discovery of a large number of particles in category (II) would be strong support for SUSY, but it is unlikely that future searches will immediately yield many sparticles. On the other hand, if only one or a few new particles are discovered, precise verification of the relations of category (III) could be taken as confirmation of SUSY. It is the prospects for such tests that we investigate in this study.

Studies have shown that the Next Linear Collider, a proposed linear e^+e^- collider with $\sqrt{s} = 500 \text{ GeV}$ and a luminosity of $10 - 100 \text{ fb}^{-1}/\text{year}$, is a powerful tool for studying the properties of new particles.¹ The clean environment and polarizable beams provided by such a machine make it well-suited to precision studies, and we will study the prospects for precision tests of SUSY in this setting. We will also limit the discussion to the case in which charginos are produced, but slepton and squark pair production is beyond reach. Remarks about other scenarios may be found in an extended version of this work done with H. Murayama, M. E. Peskin, and X. Tata.²

In Sec. 2 we assume SUSY and use it as a guide to selecting well-motivated case studies. We review the parameters that enter chargino production and decay, and we divide the SUSY parameter space into characteristic regions. In Sec. 3 we explore the first of these regions and test the form of the chargino mass matrix. In Sec. 4 we consider another region and test the chargino-fermion-sfermion coupling.

2. Regions of Parameter Space

This study will be conducted in the context of the minimal supersymmetric standard model (MSSM), the supersymmetric extension of the standard model with minimal field content. The charginos of the MSSM are mixtures of the charged Higgsinos

and electroweak gauginos and have mass terms $(\psi^-)^T M_{\tilde{\chi}^\pm} \psi^+ + h.c.$, where

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin \beta \\ \sqrt{2} M_W \cos \beta & \mu \end{pmatrix}, \quad (1)$$

and $(\psi^\pm)^T = (-i\tilde{W}^\pm, \tilde{H}^\pm)$. The chargino mass eigenstates are $\tilde{\chi}_i^\pm = V_{ij}\psi_j^\pm$ and $\tilde{\chi}_i^\mp = U_{ij}\psi_j^\mp$. The matrices V and U are effectively orthogonal rotation matrices parametrized by the angles ϕ_+ and ϕ_- , respectively.

We assume that R-parity is conserved, the LSP is the lightest neutralino $\tilde{\chi}_1^0$, there is no intergenerational mixing in the stermion sector, and sleptons and squarks are degenerate with masses m_i and $m_{\tilde{q}}$, respectively. (The last assumption may be partially relaxed.)³⁾ With these assumptions, the parameters that enter chargino events are μ , M_2 , $\tan \beta$, M_1 , m_t , and $m_{\tilde{q}}$. With an e_L^- beam, chargino production occurs through s -channel Z and γ diagrams and t -channel $\tilde{\nu}_e$ exchange, and so $d\sigma_L/d\cos \theta$ is governed by the first four parameters. In the case of an e_R^- beam, the $\tilde{\nu}_e$ diagram is absent, and so $d\sigma_R/d\cos \theta$ is dependent on only the first three parameters μ , M_2 , and $\tan \beta$. Charginos decay to the LSP either leptonically through W bosons or virtual sleptons, $\tilde{\chi}^+ \rightarrow (\tilde{\chi}_1^0 W^+ \rightarrow \tilde{\nu}_e \tilde{\nu}_e^*) \rightarrow \tilde{\chi}_1^0 \tilde{\nu}_e$, or hadronically through W bosons or virtual squarks, $\tilde{\chi}^+ \rightarrow (\tilde{\chi}_1^0 W^+ \rightarrow \tilde{q}^* q' \bar{q} q'') \rightarrow \tilde{\chi}_1^0 q \bar{q}'$. All six parameters enter the decay process.

We now divide the parameter space into characteristic regions. The chargino masses and $\sigma_R \equiv \sigma(e_R^- e_L^+ \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-)$ depend only on μ , M_2 , and $\tan \beta$. The dependence on $\tan \beta$ is weak; we set $\tan \beta = 4$ as a representative case. In Fig. 1, the cross-hatched region is excluded by present experiments, and chargino production is inaccessible for $\sqrt{s} = 500 \text{ GeV}$ in the hatched region. We divide the remaining bands of the (μ, M_2) plane into the three regions indicated. In region 1, $\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ production is possible, and so both chargino masses can be measured. Where $\tilde{\chi}_2^\pm$ is inaccessible, σ_R distinguishes regions 2 (shaded, $\sigma_R \approx 0$) and 3 (where, typically, $\sigma_R > 50 \text{ fb}$). We will consider case studies in which $m_{\tilde{\chi}_1^\pm} \approx 170 \text{ GeV}$; this contour is the dotted curve in Fig. 1. Region 3 presents difficulties even for the identification of a SUSY signal, since the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ become degenerate as M_2 increases. Although it may be possible to verify SUSY relations in certain parts of region 3, we will not consider this case further.

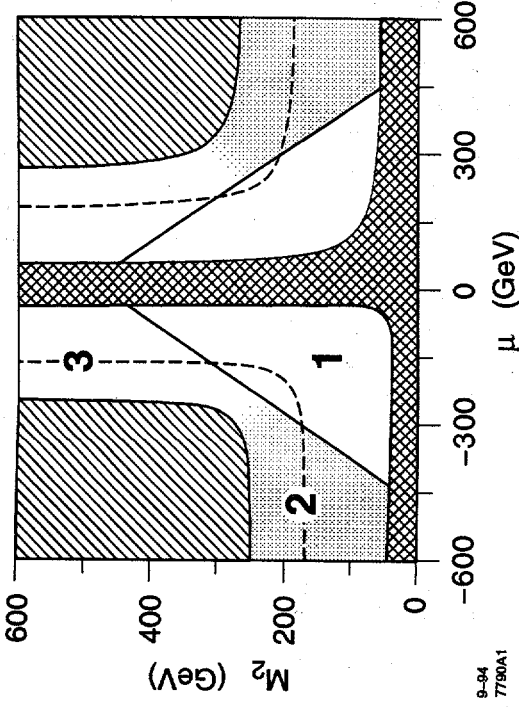


Fig. 1. The characteristic regions of parameter space.

3. Region 1

In region 1 we take the representative point in parameter space to be $(\mu, M_2, \tan \beta, M_1/M_2, m_t, m_{\tilde{q}}) = (-195, 210, 4, 0.5, 400, 700)$. For these parameters, $m_{\tilde{\chi}_1^\pm} = 172 \text{ GeV}$, $m_{\tilde{\chi}_2^\pm} = 105 \text{ GeV}$, and $m_{\tilde{Z}} = 255 \text{ GeV}$. The uncertainty in determining these masses is very small¹ and will be unimportant for this study. There are additional features that are typical of Region 1: σ_R is large enough to yield many events for study, and $\tilde{\chi}_1^\pm \approx \tilde{H}^\pm$, so the leptonic branching fraction B_l is $\frac{1}{3}$ to a very good approximation.

In this region we generalize the chargino mass matrix to an arbitrary real 2×2 matrix, which we parametrize as

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin \beta \\ \sqrt{2} M_W \cos \beta & \mu \end{pmatrix}. \quad (2)$$

Our goal is to test the SUSY relation $M_W^\chi = M_W$, that is, the equality of the Higgs boson and Higgsino couplings. Formally, this is a simple task. The four parameters entering Eq. 2 may be exchanged for the parameters $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_2^\pm}$, ϕ_+ and ϕ_- . By measuring

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$m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_2^\pm}$, and two quantities derived from $d\sigma_R/d\cos\theta$, we may restrict the variables (ϕ_+, ϕ_-) and may therefore bound $M_{\tilde{W}}^\chi$. It is useful to work with the total cross section σ_R and a truncated forward-backward asymmetry $A_{FB}^{\chi'}$, defined below. Unfortunately, neither quantity is observed directly. We have performed Monte Carlo simulations at a large number of points obtained by varying the supersymmetry parameters and $M_{\tilde{W}}^\chi$ to determine the correlation of these quantities to experimental observables.

The Monte Carlo simulations for chargino events used the parton-level event generator of Feng and Strassler³ with detector parameters as chosen in the JLC study.¹ Chargino events were selected from mixed-mode events in which one chargino decays hadronically and the other leptonically, using the system of cuts presented by the JLC group. These cuts include the elimination of events with very forward leptons or hadron jets ($\cos\theta_{had}, \cos\theta_l < 0.75$), to remove the forward peak of WW events. With these cuts and a highly polarized e_R^- beam, the total background is negligible.

To find σ_R , we use the event rate in the mixed mode, the leptonic branching ratio $B_l = \frac{1}{3}$, and the efficiency of the cuts determined by Monte Carlo. The simulations also tell us that the theoretical quantity

$$A_{FB}^{\chi'} \equiv \frac{\sigma^X(0 < \cos\theta < 0.75) - \sigma^X(-1 < \cos\theta < 0)}{\sigma^X(-1 < \cos\theta < 0.75)} \quad (3)$$

is highly correlated with the forward-backward asymmetry of the hadronic system's direction. For an integrated luminosity of $50 fb^{-1}$, these two quantities should be determined to the level $\sigma_R = 48 \pm 2.4 fb$, $A_{FB}^{\chi'} = -37 \pm 6.9\%$, where the 1σ errors include uncertainty from the variation of parameters. The measurements of $A_{FB}^{\chi'}$ and σ_R constrain the (ϕ_+, ϕ_-) plane to the shaded region in Fig. 2. In this allowed region, $65 GeV < M_{\tilde{W}}^\chi < 100 GeV$, a significant quantitative confirmation of SUSY.

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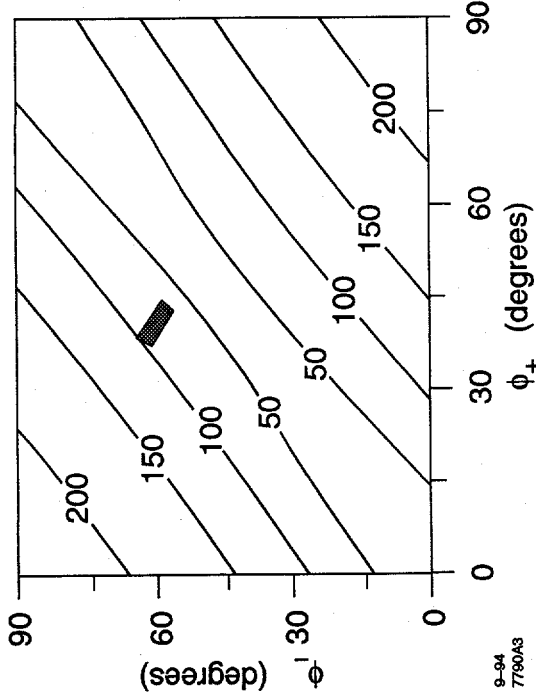


Fig. 2. The allowed region of the (ϕ_+, ϕ_-) plane. Contours of $M_{\tilde{W}}^\chi$ are plotted in GeV.

4. Region 2

In region 2 we take the representative point to be $(\mu, M_2, \tan\beta, M_1/M_2, m_t, m_b) = (-500, 170, 4, 0.5, 400, 700)$. For these parameters, $m_{\tilde{\chi}_1^\pm} = 172 GeV$, $m_{\tilde{\chi}_2^\pm} = 86 GeV$, $m_{\tilde{\chi}_3^\pm} = 512 GeV$, and $\sigma_R \approx 0$. Here we must rely on measurement of $d\sigma_L/d\cos\theta$, which introduces dependence on $m_{\tilde{\nu}}$. Fortunately, there is a compensating simplification: in region 2, $\phi_+, \phi_- \approx 0$, i.e., charginos and neutralinos are very nearly pure gauginos. In addition, as is typical in region 2, on-shell W decays are allowed, and so again $B_l = \frac{1}{3}$.

We will generalize the $\tilde{\chi}_1^\pm f \tilde{f}$ coupling to $g^X V_{11}$ and test the SUSY relation $g^X = g$, that is the equality of the W boson and wino couplings. The differential cross section $d\sigma_L/d\cos\theta$ is a function of $(m_{\tilde{\chi}_1^\pm}, \phi_+, \phi_-, m_{\tilde{\nu}}, g^X)$, but because we can measure $m_{\tilde{\chi}_1^\pm}$, and $\phi_+, \phi_- \approx 0$, we have only two unknowns. These may be constrained with two quantities formed from $d\sigma_L/d\cos\theta$, in particular, σ_L and $A_{FB}^{\chi'}$.

We follow the procedure of the previous section, with the exception of using cuts appropriate to on-shell W decays.⁴ Including all errors, we find that $A_{FB}^{\chi'} = 20 \pm 5.3\%$

and $\Delta\sigma_L/\sigma_L = 6.4\%$ for an integrated luminosity of 50 fb^{-1} . These measurements constrain the allowed region of the $(m_{\tilde{\nu}}, g^X)$ plane to the three shaded areas shown in Fig. 3. If $m_{\tilde{\nu}} < 250\text{ GeV}$ can be excluded, the allowed region is only the largest of these shaded regions, in which $0.75g \leq g^X \leq 1.3g$. In addition to confirming the prediction of SUSY, it is clear from Fig. 3 that we have simultaneously bounded $m_{\tilde{\nu}}$, a useful result for future particle searches.

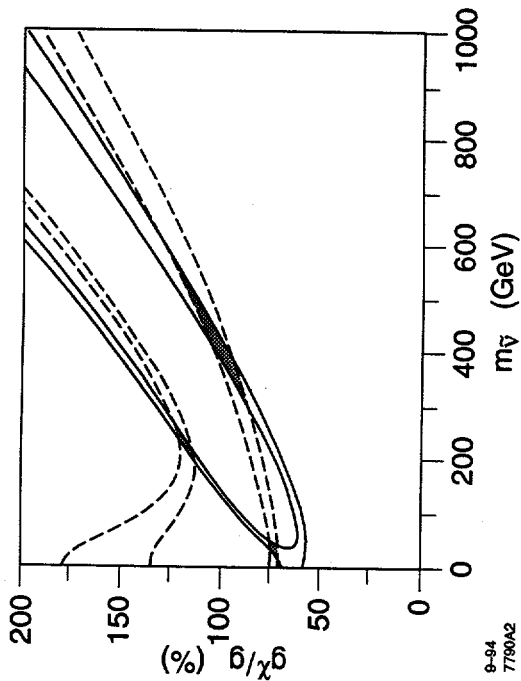


Fig. 3. Allowed regions of the $(m_{\tilde{\nu}}, g^X)$ plane. Solid (dotted) curves are σ_L (A'_{FB}) constraints.

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