MINIMAL SUGRA MODEL AND COLLIDER SIGNALS

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The SUSY signals in the dominant stau-neutralino coannihilation region at a 500(800) GeV linear collider are investigated. The region is consistent with the WMAP measurement of the cold dark matter relic density as well as all other current experimental bounds within the mSUGRA framework. The signals are characterized by an existence of very low-energy tau leptons in the final state due to small mass difference between \( \tilde{\tau}_1 \) and \( \tilde{\chi}_1^0 \) (5-15 GeV). We study the accuracy of the mass difference measurement with a 1° active mask to reduce a huge SM two-photon background.

1 Introduction

The recent measurement of cold dark matter (CDM) relic density from WMAP\(^1\) along with the Higgs mass bound and the \( b \rightarrow s \gamma \) constraint have restricted the parameter space significantly\(^2\) within the framework of minimal supergravity (mSUGRA) model.\(^3,4\)

One prominent parameter space is the region where the mass difference (\( \Delta M \)) between the lighter stau (\( \tilde{\tau}_1 \)) and the lightest neutralino (\( \tilde{\chi}_1^0 \)) is about 5-15 GeV. This small mass difference allowed the \( \tilde{\tau}_1 \) to coannihilate in the early universe along with the \( \tilde{\chi}_1^0 \) in order to produce the current amount of the CDM (\( \tilde{\chi}_1^0 \)). The coannihilation region has a large extension for \( m_{1/2} \) up to 1-1.5 TeV, and can be explored at the LHC. The main difficulty, however, in probing this region is to detect very low-energy taus in the final state of the SUSY events due to the small \( \Delta M \) value.

In this paper, we report a feasibility study of measuring the small mass difference in this \( \tilde{\tau}_1-\tilde{\chi}_1^0 \) coannihilation region at a 500 GeV linear collider (LC).

2 mSUGRA Parameter Space

The mSUGRA model depends on only four parameters and one sign. These are \( m_0 \) (the universal soft breaking mass at the GUT scale \( M_G \)); \( m_{1/2} \) (the universal gaugino soft breaking mass at \( M_G \)); \( A_0 \) (the universal cubic soft breaking mass at \( M_G \)); \( \tan \beta = \langle H_2 \rangle / \langle H_1 \rangle \) at the electroweak scale; and the sign of \( \mu \), the Higgs mixing parameter in the superpotential (\( W_\mu = \mu H_1 H_2 \)).

Figure 1 is an example of the allowed region in the \( m_0-m_{1/2} \) plane from the relic density constraint for \( \tan \beta = 40, A_0 = 0 \) and \( \mu > 0 \). The details are provided in text.
Maxima, Dasi, etc.) and the 2σ bound of 0.095 < \Omega_{\chi_1^0} h^2 < 0.129 (blue band) from WMAP1; (4) The bound on the lightest chargino mass: \chi_{1}^\pm > 104 \text{GeV}; (5) Possible muon magnetic moment anomaly (light blue region to be excluded if \delta a_\mu > 11 \times 10^{-10}).

It is striking to learn that only two SUSY production processes can be studied at a 500 GeV LC: \tilde{\tau}_1^+ \tilde{\tau}_1^- and \chi_{2}^0 \chi_{1}^0. The kinematical reaches via the \tilde{\tau}_1^+ \tilde{\tau}_1^- and \chi_{2}^0 \chi_{1}^0 production are also shown in Fig. 1. The maximum reach in m_{1/2} along the coannihilation band can be expected via e^+ e^- \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^- \rightarrow (\tau^+ \chi_{1}^0) + (\tau^- \chi_{1}^0).

We use the hadronic final state of tau (\tau_h ) since it has larger branching ratios. Due to the small \Delta M value, the taus in the final states are low energy and hence harder to detect.

3 SUSY Signals at 500 GeV LC

In order to optimize the event selection cuts, we choose three points of m_0 = 205, 210 and 220 GeV for m_{1/2} = 360 GeV, tan\beta = 40, \mu > 0, and A_0 = 0. The SUSY masses given by ISAJET\(^9\) are summarized in Table 1. There are two major Standard Model (SM) background processes: (i) four-fermion final state \ell \nu \tau^+ \tau^- arising from processes such as diboson (WW, ZZ) production, and (ii) two-photon processes e^+ e^- \rightarrow \gamma^* \gamma^* + e^+ e^- \rightarrow \tau^+ \tau^- (or qq) + e^+ e^- where the final state e^+ e^- pair are at a small angle to the beam pipe and the qq jets fake a \tau^+ \tau^- pair.

The production cross-sections for SUSY (ISAJET) and SM four-fermion processes (WPHACT\(^10\)) are listed in Table 2 for a 500 GeV LC. We choose with right handed (RH) polarized electron beams to enhance the \tilde{\tau}_1^+ \tilde{\tau}_1^- events over the \chi_{2}^0 \chi_{1}^0 and SM four-fermion events.

In Table 3, we summarize the event selection criteria for the RH case. The Monte Carlo (MC) events are generated, simulated and analyzed using the following programs: ISAJET\(^9\) to generate SUSY events; WPHACT\(^10\) for SM backgrounds; TAUOLA\(^11\) for tau decay; a LC detector simulation\(^2\) to reconstruct jets with JADE algorithm.\(^12\) In our calculation, beamstrahlung and bremsstrahlung are included in both ISAJET and WPHACT.

The accepted number of signal and background events are summarized in Tables 4 and 5. It should be noted that the number of SM \gamma \gamma events with the forward electrons just below 3° are 11400. The acceptances for \tilde{\tau}_1^+ \tilde{\tau}_1^- events are 11.2%, 5.9%, and 0.86% for \Delta M = 19, 9.5, and 4.7 GeV, respectively with 1^\circ mask. The acceptance drops fast as \Delta M goes below 5 GeV. For example, 0.23% for \Delta M = 3.8 GeV (m_0 = 204 GeV). We see the robust discovery significance for the signal events for \Delta M \gtrsim 5 \text{GeV} with 1^\circ mask in Table 6. We conclude that the mask is essential to detect SUSY events in this region of parameter space.

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Table 1. Masses (in GeV) of SUSY particles in three representative scenarios of \Delta M for m_{1/2} = 360 GeV, tan\beta = 40, \mu > 0, and A_0 = 0.

| MC | m_0 | M_{\chi_0^0} | M_{\tilde{\tau}_1^+} | M_{\tilde{\tau}_1^-} | \Delta M |
|----|-----|-------------|----------------|----------------|---------|
| 1  | 205 | 274.2       | 147.2          | 142.5          | 4.7     |
| 2  | 210 | 274.2       | 152.0          | 142.5          | 9.5     |
| 3  | 220 | 274.3       | 161.6          | 142.6          | 19.0    |

Table 2. SUSY and SM production cross sections (\sigma \cdot B(\tau \rightarrow \tau_h)^2 in fb) for polarization for electron beams of P(e^-) = -0.90(RH).

| SUSY Pt. | \chi_{1}^0 \chi_{2}^0 | \tilde{\tau}_1^+ \tilde{\tau}_1^- | \tilde{\tau}_1^- \tilde{\tau}_1^- | \tilde{\tau}_1^+ \tilde{\tau}_1^- |
|----------|-----------------|-----------------|-----------------|-----------------|
| Pt. 1    | 0.43            | 28.25           | 22.95           | 0.39            |
| Pt. 2    | 0.39            | 25.85           | 22.95           | 0.38            |
| Pt. 3    | 0.38            | 22.95           | 22.95           | 0.38            |
| SM (four fermion process) | 7.84 |
Table 3. Event selection criteria for the RH ($P = -0.9$) case.

| Variable(s)          | Cuts                                      |
|----------------------|-------------------------------------------|
| $N_{\text{jet}}(E_{\text{jet}} > 3 \text{ GeV})$ | 2                                         |
| $\tau_{b}$ ID       | 1, 3 tracks                               |
| Jet acceptance      | $|\cos(\theta_{\text{jet}})| < 0.65$                                          |
|                     | $-0.6 < \cos(\theta(j_2, p_{\text{vis}})) < 0.6$ |
| Missing $p_T(p_T)$  | $> 5 \text{ GeV}$                         |
| Acoplanarity        | $> 40^\circ$                              |
| Veto on EM clusters | No EM cluster in $5.8^\circ < \theta < 28^\circ$ with $E > 2 \text{ GeV}$ |
| or electrons        | No electrons within $\theta > 28^\circ$ with $p_T > 1.5 \text{ GeV}$ |
| Beam mask $(1^\circ \text{ or } 2^\circ - 5.8^\circ)$ | No EM cluster with $E > 100 \text{ GeV}$ |

Table 4. Number of SUSY events expected with 500 fb$^{-1}$ for the RH case.

| Process | $\Delta M = 4.7$ | 9.5 | 19 |
|---------|------------------|-----|----|
| $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ | 15  | 26  | 29 |
| $\tilde{\tau}^+ \tilde{\tau}^-$ | 122 | 786 | 1283 |

Table 5. Number of SM events expected with 500 fb$^{-1}$.

| Process | 2-5.8$^\circ$ Mask | 1-5.8$^\circ$ Mask |
|---------|---------------------|---------------------|
| SM four-fermion | 129                 |                     |
| SM $\gamma \gamma$ | 248                 |                     |

Table 6. Significance ($N_S/\sqrt{N_B}$) with 500 fb$^{-1}$ for SUSY discovery using 1$^\circ$ mask.

| Process (RH) | $\Delta M = 4.7$ | 9.5 | 19 |
|--------------|------------------|-----|----|
| $\tilde{\tau}^+ \tilde{\tau}^-$ | 10  | 63  | 101 |

4 Measurement of Stau Neutralino Mass Difference

Since $\Delta M$ is small, it needs to be measured with a very good accuracy. We choose the invariant mass $M_{\text{eff}} = M(j_1, j_2, E)$ of two $\tau$-jets and missing energy as a key discriminator. We generate high statistics MC samples for the SM and various SUSY events (by changing the $m_0$ value) and prepare the templates of the $M_{\text{eff}}$ distributions for the SM, $\tilde{\chi}_2^0 \tilde{\chi}_1^0$, and $\tilde{\tau}^+_1 \tilde{\tau}^-_1$ events.

We then generate the MC samples equivalent to 500 fb$^{-1}$ of luminosity for particular $\Delta M$ values and fit them with the template functions. For example, in Fig. 2 we show the fitting of the 500 fb$^{-1}$ MC samples for Point 2 with the templates for $m_0 = 210$ GeV and calculate the $\chi^2$ of the fits. Here the $\chi^2$ value is calculated as $\chi^2 = \sum_i \left( \frac{N_i - \sum_j C_j F_j^i}{\sigma_i} \right)^2$ where $N_i$ is the number of events in $i$-th $M_{\text{eff}}$ bin of the 500 fb$^{-1}$ sample, $C_j F_j^i$ is the corresponding value for the template “j” where $j$ is for SM, $\tilde{\tau}^+_1 \tilde{\tau}^-_1$ or $\tilde{\tau}_0^0 \tilde{\tau}_1^0$ processes. $C_j$ is a normalization parameter and a free variable except for the SM process. This is because we should be able to measure the SM events very well before we discover SUSY events.

We scan the range of $m_0 = 203$-220 GeV and plot the $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ in Fig. 3. The $\Delta \chi^2$ value is minimum for the template for $m_0 = 210$ GeV. We find that $1\sigma$ in the $\Delta \chi^2$ corresponds to $9.5 \pm 1$ GeV, where the true value of $\Delta M$ for the Point 2 is 9.53 GeV.

We repeat the same study for different stau masses i.e. for different $\Delta M$ values and two different beam mask designs (1$^\circ$ and 2$^\circ$). For $\Delta M \sim 5$ GeV, a beam mask of 1$^\circ$ is crucial. The accuracy of mass determination for is summarized in Table 7, showing the uncertainties are at a level of 10%.
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Figure 2. $M_{\text{eff}}$ ($\equiv M(j_{1}, j_{2}, E)$) distributions for a 500 fb$^{-1}$ MC samples for SUSY ($m_{0} = 210$ GeV) and SM events, being fitted to the templates for $m_{0} = 210$ GeV.

Table 7. Accuracy of the $\Delta M$ determination for different beam mask designs. "-" means we cannot determine with 500 fb$^{-1}$.

| $\Delta M$ | $N_{\tilde{\tau}_{1}^{+} \tilde{\tau}_{1}^{-}}$ (500 fb$^{-1}$) | $\Delta M$ ("500 fb$^{-1}$" expt.) |
|------------|------------------------------------------------|-----------------------------------|
|            | $\tilde{\tau}_{1}^{+}$ mask $\tilde{\tau}_{1}^{-}$ mask | $\tilde{\tau}_{1}^{+}$ mask $\tilde{\tau}_{1}^{-}$ mask |
| 4.76       | 122                                      | $4.74^{+0.07}_{-0.03}$            |
| 9.53       | 787                                      | $9.5^{+1.0}_{-1.0}$               |
| 12.4       | 1027                                     | $12.5^{+1.4}_{-1.4}$              |
| 14.3       | 1138                                     | $14.5^{+1.1}_{-1.1}$              |

5 Conclusion

At 500 GeV LC, it is crucial to instrument an active mask to detect very forward electrons down to 1° for measurement of the small $\Delta M$. The expected accuracy is 10% (20% for $\Delta M \sim 5$ GeV) with 500 fb$^{-1}$.

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