EXPERIMENTAL ASPECTS OF PRECISION SUSY MEASUREMENTS*

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Abstract

We studied search for SUSY particles and determination of SUSY breaking parameters at future e+e- linear colliders, using Monte Carlo simulations including initial state radiation, beamstrahlung and detector performance. The experimental methods to determine masses and cross sections are explained and a polarized electron beam is shown to be useful for the study. We concluded that we can get a lot of information about the SUSY parameters with a few SUSY particles. We also discuss the implication of determined parameters in relation to the GUT with a sample parameter set.

1. Introduction

SUSY model is one of the candidates which solve the naturalness problem and it becomes more attractive one as the LEP data shows that three couplings of $SU(3) \otimes SU(2) \otimes U(1)$ can be unified at high energy with SUSY contents[1]. Although there may be many SUSY models, the Minimal SUSY standard model (MSSM) with the framework of N=1 minimal supergravity(SUGRA) model is considered in our study. There are four parameters, which fix the considered SUSY model and so determine masses and interactions[2,3,4], as follows; μ: Higgsino mass, M_2: SU(2) gaugino mass, $tan\beta$: ratio of the two vacuum expectation values of Higgses and m_0: common scalar mass. Masses of sfermions are determined by m_0, M_2 and $tan\beta$, charginos and neutralinos are by μ, M_2 and $tan\beta$.

Squarks are heavier than sleptons in general, masses of sleptons are almost determined by m_0 with small dependence on M_2 in the case where m_0 is larger than a few hundreds GeV, and right-handed sleptons($\tilde{l}_R$) are lighter than left-handed($\tilde{l}_L$) ones (as shown in figures of ref.5 for an example). Charginos $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$ are the mixtures of charged wino $W^{\pm}$ and charged higgsino $H^{\pm}$ obtained from the diagonalization of the mass matrix and the lighter chargino $\tilde{\chi}_1^{\pm}$ is almost wino(higgsino) with mass of $\sim M_2(\mu)$ if $M_2 \ll (\gg)\mu$.

In order to avoid unnecessary complications we make the following assumptions in this study: i) R-parity is exactly conserved, ii) the lightest SUSY particle (LSP) is the lightest neutralino ($\tilde{\chi}_1^0$).

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Firstly, we performed the study of the lightest charged SUSY particle, where the methods for search and mass determination are discussed. There are two cases to be considered: (1) $\tilde{l}_R^{\pm}$ is the lightest charged SUSY particle and (2) $\tilde{\chi}_1^{\pm}$ is the one. Next, we proceed with the case study for SUSY hunting strategy in the case (1). We show that the discovered SUSY particles tell us the other SUSY particles to be discovered in the next higher energy region and we can know the SUSY parameters in detail. We used HELAS[6] to evaluate amplitudes of reactions and BASES25/SPRING25, an updated version of the BASES/SPRING[7] for integration and event generation, and assumed the detector described in JLC-1 report[8]. Initial state radiation and beamstrahlung[8] were taken into account.

2. Study of the lightest charged SUSY particles

1.1. Light slepton case

Smuon($\tilde{\mu}_{R/L}$)-pair productions take place through e^+e^- annihilation into a virtual γ/Z^0. Their differential cross sections behave as $sin^2\theta$ and the magnitudes are completely specified by their quantum numbers. The contours of the cross sections at $\sqrt{s}$=500GeV are plotted in Fig.1. Selectron($\tilde{e}_{R/L}$)-pair productions are

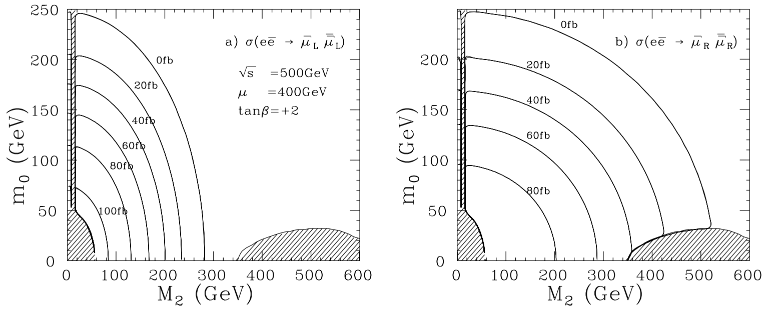

Figure 1: Contours of a) $\sigma(e\bar{e} \rightarrow \tilde{\mu}_L \bar{\tilde{\mu}}_L)$ and b) $\sigma(e\bar{e} \rightarrow \tilde{\mu}_R \bar{\tilde{\mu}}_R)$ in the $m_0 - M_2$ plane. The shaded regions are forbidden by the assumption that the LSP is the lightest neutralino.

more complicated due to additional t-channel diagrams by exchange of neutralinos which depend strongly on masses and couplings of the neutralinos. The t-channel diagrams modify the differential cross sections and give larger cross sections than those of $\tilde{\mu}_{R/L}$-pair productions.

When the LSP has a sizable component of the bino state, there is a sizable branching fraction of direct slepton decay into the LSP + lepton. In addition to it, if the mass difference between sleptons and the LSP is large enough to detect leptons, detection of slepton pair production is easy. In this case, the event signature is an acoplanar lepton pair and the energy distribution of leptons is flat with two end-points giving the masses of sleptons and LSP. Fig.2 show the contours of decay branching fractions and mass differences, respectively. These show the direct mode dominates the $\tilde{l}_R$ decays and the mass differences are large enough for detection. Notice that the situation is also same for $\tilde{l}_L$ when m_0 is small (about less than 100 GeV).

It is required that m_0 is relatively lighter than M_2 and μ for the light slepton case($M_{\tilde{l}^{\pm}_R} < M_{\tilde{\chi}^{\pm}_1}$). For the study we took the model parameters; m_0=70 GeV, μ=400 GeV, M_2=250 GeV and $tan\beta$=2, resulting in $\tilde{l}_R$=141.9G eV, $\tilde{l}_L$=235.6 GeV, $\tilde{\chi}^{\pm}_1$=219.3 GeV and $\tilde{\chi}^0_1$=117.8 GeV. Selection cuts for acoplanar lepton pairs are as follows: 1) $e\bar{e}$ or $\mu\bar{\mu}$ with $5 < E_l < (\sqrt{s} - 100)/2$GeV, 2) $20 < E_{vis} < \sqrt{s} - 100$GeV, 3) $|M_{ll} - M_Z| > 10$GeV, 4) $|cos\theta_{l^{\pm}}| < 0.9$, 5) -$Q \cdot cos\theta_l < 0.75$ (Q:lepton charge), 6) $\theta_{acop} > 30°$.

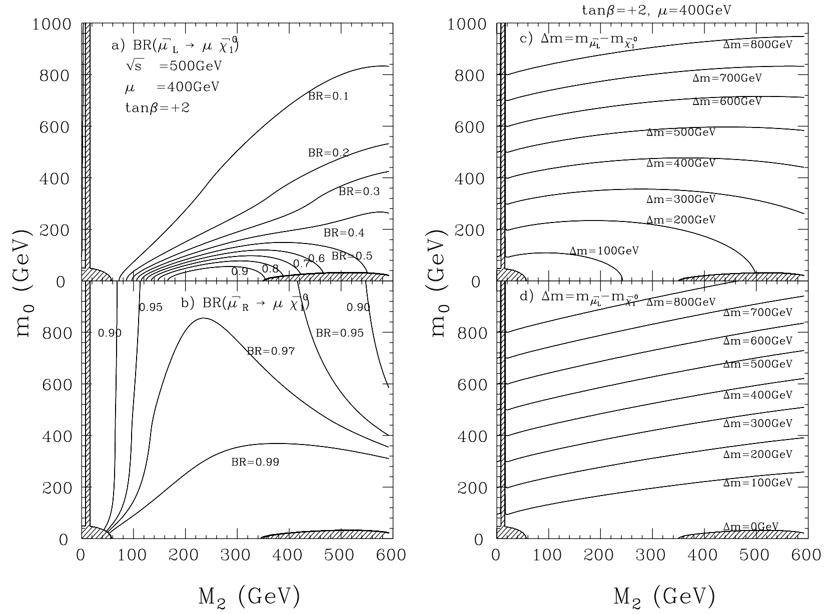

Figure 2: Contours of $\tilde{\mu}$ branching fraction in the $m_0 - M_2$ plane for $\tilde{\mu}_L$:(a) and $\tilde{\mu}_R$:(b), and contours of mass differences $\tilde{\mu} - m_{\tilde{\chi}^0_1}$ in the $m_0 - M_2$ plane for $\tilde{\mu}_L$:(c) and $\tilde{\mu}_R$:(d) The shaded regions are same as in Fig.1

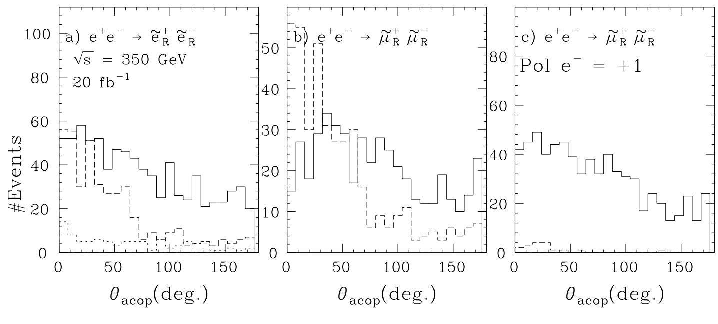

Figure 3: Acoplanarity angle distributions for (a) $\tilde{e}_R$ pair, (b) $\tilde{\mu}_R$ pair and (c) $\tilde{\mu}_R$ pair with a polarized right-handed electron beam, where solid:signal, dash:W-pair and dot:$e\nu W$.

Fig.3 shows lepton acoplanarity angle distributions. We can see that detection of slepton production is easy and the right-handed polarized electron beam improves the S/N ratio especially for $\tilde{\mu}_R$, since the production cross section for $\tilde{\mu}_R$ pairs almost doubles, while the W-pair cross section essentially vanishes and $e\nu W$ production in the central region is suppressed. Fig.4(a) is a plot of energy distribution of μ's. Though the distribution is a little bit different from the expected rectangular shape due to selection cuts, edges of lower and higher end-points are sharp enough for mass determination. Results of fit are shown as a solid curve in Fig.4(a) and $\Delta\chi^2$ contours in Fig.4(b). We can determine the masses of the slepton and the LSP with statistical errors of about 1.5GeV and 1.0GeV, respectively.

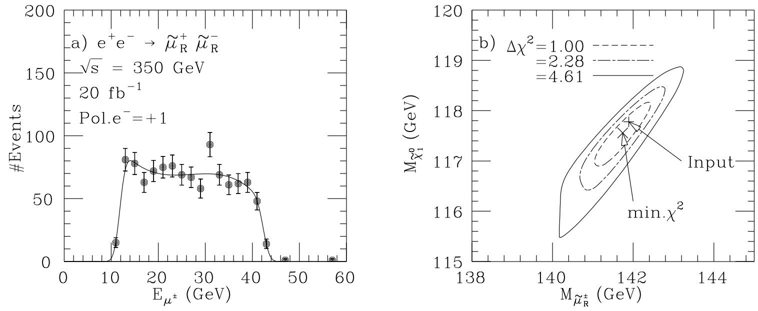

Figure 4: (a) The energy distribution of μ from $\tilde{\mu}_R$ decays with the fit result shown by a solid curve. (b) $\Delta\chi^2$ contours in the $M_{\tilde{\mu}_R}$-$M_{\tilde{\chi}_1^0}$ plane obtained from the fit.

1.2. Light chargino case

Charginos can be produced in a pair through s-channel γ/Z^0 annihilation diagram and t-channel $\tilde{\nu}$ exchange one. Fig.5(a) shows the the lighter chargino ($\chi_1^\pm$) pair production cross section in the M_2-μ plane and we can see that the cross section is large enough above the threshold.

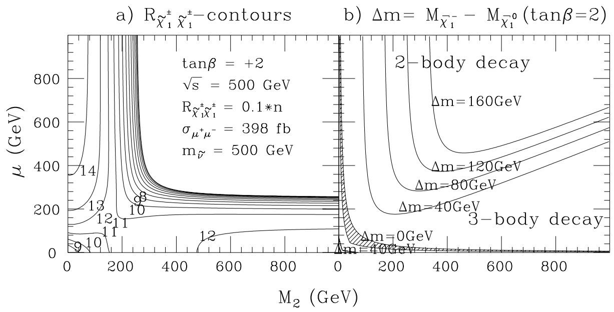

Figure 5: a) Cross section contours in the M_2-μ plane for $\tilde{\chi}_1^\pm$ pair production. b) Contours of the mass difference between $\tilde{\chi}_1^\pm$ and the LSP($\tilde{\chi}_1^0$) in the M_2-μ plane. The shaded region is forbidden by the assumption that the LSP is the lightest neutralino.

Here we note that, when $\Delta m \equiv M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0} > M_W$, the direct decay to $\chi_1^0 W$ dominates and when $\Delta m < M_W$, $\tilde{\chi}_1^\pm$ decays to $\tilde{\chi}_1^0 l \bar{\nu}_l$ and $\tilde{\chi}_1^0 q\bar{q}$, unless the higgsino component is negligible. Fig.5(b) shows this mass difference Δm in the $M_2 - \mu$ plane. $\tilde{\chi}_1^\pm$ pair production becomes an acoplanar W-pair event if $\Delta m > M_W$ or an acoplanar $l-l/l-2jets/2jets-2jets$ event if $\Delta m < M_W$. Acoplanar W-pairs are easy for detection since the potentially most serious background from $e^+e^- \rightarrow W^+W^-$ is absent and the remaining background from $e^+e^- \rightarrow W^+W^-Z$ has only a small cross section. In the latter case ($\Delta m < M_W$), both of leptonic and hadronic decays of $\tilde{\chi}_1{}^{\pm}$ are sizable and $l-2jets$ event signature is better since there are no ambiguity in jet combination and the W-mass cut can be applied on 2jets to reduce W-pair background.

If the lighter chargino $\tilde{\chi}_1^{\pm}$ is a almost pure wino $\tilde{W}^{\pm}$, its decay proceeds as $\tilde{\chi}_1^+ \rightarrow \nu_l \tilde{l}_L^{+*}/\tilde{\nu}_l^* l^+ \rightarrow \nu_l \tilde{\chi}_1{}^0 l^+$. The decay to $q\bar{q}\tilde{\chi}_1{}^0$ is suppressed by the heavy squark mass in the squark propagator and the smallness of the weak hypercharge relevant to the coupling to the LSP which is essentially a bino $\tilde{B}$, and the event becomes an acoplanar lepton pair.

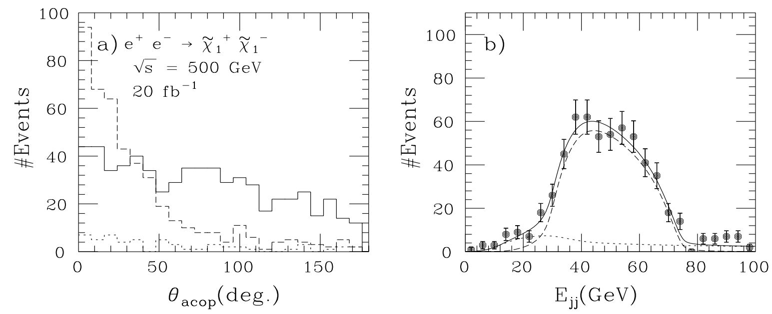

Figure 6: (a) Distribution of the acoplanarity angle between lepton and 2-jets with solid for $\tilde{\chi}_1^{\pm}$-pair, dash for W-pair and dot for $e\nu W$. (b) Energy distribution of the 2-jets system with the fit result,where solid:all, dash:$\tilde{\chi}_1^{\pm}$-pair and dot:W-pair.

For the Monte Carlo study, we took the parameters; m_0=400 GeV, μ=250 GeV, M_2=400 GeV and $tan\beta$=2, resulting in $\tilde{l}_R$=444.1 GeV, $\tilde{\chi}_1^{\pm}$=219.3 GeV, $\tilde{\chi}_1^0$=169.2 GeV and $\triangle m < M_W$ with sizable higgsino component in $\tilde{\chi}_1{}^{\pm}$. Selection cuts are as follows: 1) #tracks ≥ 5 with isolated e/μ ($E_l > 5$GeV and E(around l within $30°$) $<$ 1GeV, 2) $20 < E_{vis} < \sqrt{s} - 100$GeV, 3) 2 jets for $y_{cut} > 5 \times 10^{-3}$ with $M_{jj} < M_W - 12$GeV and $E_{jj} < (\sqrt{s}-100)/2$GeV, 4) $|cos\theta_{j,l}| < 0.9$, -$Q \cdot cos\theta_{l,jj} < 0.75$ (Q:lepton charge), 5) $|M_{l\nu} - M_W| > 10$GeV with W-pair assumption, 6) $\theta_{acop} > 30°$. Fig.6(a) is the acoplanarity angle(θ_{acop}) distribution of selected events before θ_{acop}-cut showing that the detection of $\tilde{\chi}_1^{\pm}$ pair production is easy. The edge positions of lower and higher end-points in the energy distribution of 2-jets can be used to determine the masses of $\tilde{\chi}_1^{\pm}$ and LSP as done in the light slepton case, even though the distribution is not flat due to 3-bodies decay $\tilde{\chi}_1^{\pm} \rightarrow q\bar{q}\tilde{\chi}_1^0$. Fig.6(b) shows the energy distribution of 2-jets with the fit result. The masses of $\tilde{\chi}_1^{\pm}$ and the LSP are determined with statistical errors of about 3.0GeV and 2.0GeV, respectively.

3. Strategy for SUSY hunting in the light slepton case

In the previous section, we study the lightest charged SUSY particle in two cases where $M_{\tilde{l}_R} < M_{\tilde{\chi}_1^\pm}$ or $M_{\tilde{l}_R} > M_{\tilde{\chi}_1^\pm}$ and show that we can safely detect $\tilde{l}_R/\tilde{\chi}_1^\pm$ and measure $M_{\tilde{l}_R}/M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_1^0}$. Here we proceed the study for the subsequent heavier SUSY particles and test of SUSY by taking the light slepton case $M_{\tilde{l}_R} < M_{\tilde{\chi}_1^\pm}$ with the parameters as taken in the previous section.

With the masses of $\tilde{e}_R$, $\tilde{\mu}_R$ and LSP, we can do two things. Firstly we can check the one of the most important assumptions in th minimal SUGRA, that the scalar masses are degenerate among generations.

Secondly we can get the upper limit on masses of the lighter chargino $\tilde{\chi}_1^\pm$ and the second neutralino $\tilde{\chi}_2^0$ from the mass of LSP. Fig.7 is a plot of the upper limit on $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_2^0}$ showing that both of them never exceed twice the LSP mass in the region where the LSP mass is heavier than 30GeV for $\tilde{\chi}_1^\pm$ and 80GeV $\tilde{\chi}_2^0$. For a higgsino-like LSP ($\mu \ll M_2$) $\tilde{\chi}_1^\pm$ lies just above the LSP and for a bino-like LSP ($\mu \gg M_2$) $\tilde{\chi}_1^\pm$ is roughly twice as heavy as the LSP.

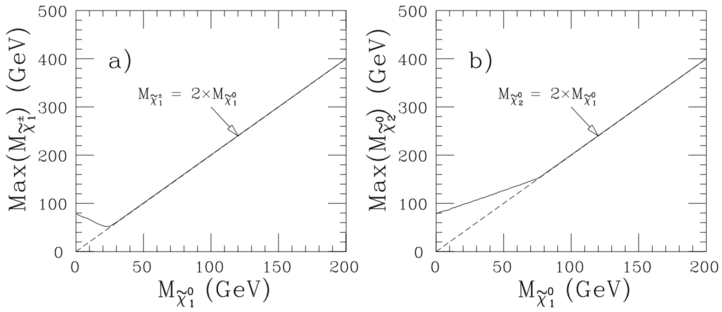

Figure 7: The upper limits on masses of (a)$\tilde{\chi}_1^\pm$ and (b)$\tilde{\chi}_2^0$ as a function the LSP mass.

We can also get information about the bino components in the LSP. The t-channel $\tilde{\chi}_i^0$-exchange diagrams enhance the production cross section for $\tilde{e}_R$ pairs. Since only the bino component contributes to the enhancement, we can test whether the LSP is bino-like or higgsino-like by comparing the cross sections of $\tilde{e}_R$-pairs and $\tilde{\mu}_R$-pairs, namely bino-like for $\sigma(\tilde{e}_R - \mathrm{pairs}) \gg \sigma(\tilde{\mu}_\mathrm{R} - \mathrm{pairs})$ and higgsino-like for $\sigma(\tilde{e}_R - \mathrm{pairs}) \simeq \sigma(\tilde{\mu}_\mathrm{R} - \mathrm{pairs})$.

We will raise the beam energy for the production of $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ pair and $\tilde{\chi}_2^0$ pair with the upper bound of masses of them. If we don't find them less than the limit, we should discard the assumed model.

With the parameters we take for the case study, $\tilde{\chi}_1^0\tilde{\chi}_2^0$ associate production occurs at first. $\tilde{\chi}_2^0$ couples to $f\bar{\tilde{f}}(+cc.)$ and $Z^0\tilde{\chi}_1^0$, and the decay mode of $\tilde{\chi}_2^0 \to l\bar{\tilde{l}}+cc. \to l\bar{l}\tilde{\chi}_1^0$ is dominant in this case. Then the event signature is an acoplanar lepton pair with backgrounds from W-pair and sleptons-pair ($\tilde{e}_R\bar{\tilde{e}}_R$, $\tilde{e}_R\bar{\tilde{e}}_L + cc.$, $\tilde{\mu}_R\bar{\tilde{\mu}}_R$). Even though the background is large, $\tilde{\chi}_1^0\tilde{\chi}_2^0$ can be detected with polarized right-handed electron beam and lepton energy cut as shown in Fig.8. We should note that $\tilde{\chi}_2^0$ gives the same event rate of acoplanar $e\bar{e}$ and $\mu\bar{\mu}$. $\tilde{\chi}_2^0$-mass determination by the spectrum of lepton energy sum ($E_{l^-} + E_{l^+}$) is difficult due to backgrounds from slepton pairs which overlap the lower edge of the signal distribution. Once the $\tilde{\chi}_2^0$ is discovered, $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0$ is used to determine its mass. Signals can be detected as acoplanar $(e\bar{e})-(\mu\bar{\mu})$ events, where $e\bar{e}$ and $\mu\bar{\mu}$ are from $\tilde{\chi}_2^0$s and we can expect small backgrounds, and the mass is determined from $E_{l^-}+E_{l^+}$ spectrum.

With $\tilde{\chi}_1^\pm$ pair production, we can obtain $M_{\tilde{\chi}_1^\pm}$, M_{LSP} and a cross section. The t-channel diagram involves the $\tilde{\nu}_e$ exchange and, therefore the cross section with the polarized left-handed electron beam $\sigma_L(\tilde{\chi}_1^\pm)$ gives information of $m_{\tilde{\nu}_e}$ which is related to $m_{\tilde{l}_L}$ and so tells $m_{\tilde{l}_L}^2 = m_{\tilde{\nu}}^2 - (1-sin^2\theta_W)m_Z^2 cos2\beta \geq m_{\tilde{\nu}}^2 + (1-sin^2\theta_W)m_Z^2$.

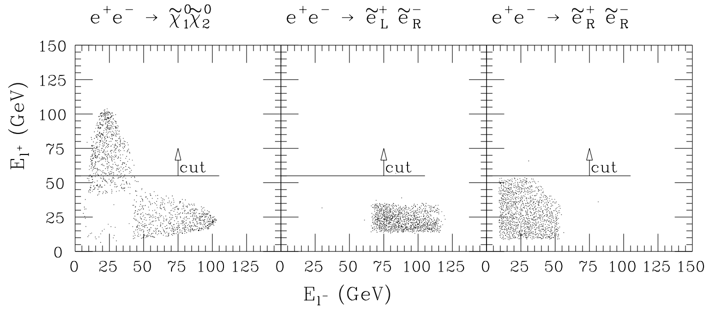

Figure 8: Scatter plots for energy of l^+ and l^- after event selection of acoplanar lepton pairs with a polarized right-handed electron beam for $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and backgrounds of $\tilde{e}_R$-pair and $\tilde{e}_R^-\tilde{e}_L^+$. 5k events are simulated for each process. A cut on E_{l^+} shown in the figures can eliminate the backgrounds.

We can also study the SUSY parameters. If the gaugino-higgsino mixing is large ($M_2 \simeq \mu$), the measurements of $M_{\tilde{\chi}^\pm}$, M_{LSP} and $\tilde{\chi}_1^\pm$ pair production cross sections with polarized right- and left-handed beams $\sigma_{R/L}(\tilde{\chi}_1^\pm)$ fix the three parameters of (M_2, μ, $tan\beta$) which determine the neutralino-chargino sector under the assumption of the GUT condition $M_1/M_2 = \alpha_1/\alpha_2$. In our present case, $\tilde{\chi}_1^\pm$ is almost a pure charged wino and the measurements are not very sensitive to μ and $tan\beta$. Even in this case, we can test the M_1-M_2 relation as shown in Fig.9.

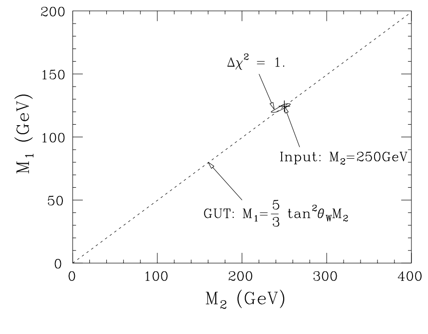

Figure 9: The $\Delta\chi^2$-contour by the fit to $m_{\tilde{e}_R}$, $M_{\tilde{\chi}_1^0}$, $M_{\tilde{\chi}_1^\pm}$, $\sigma_R(\tilde{\chi}_1^\pm)$ and $\sigma_R(\tilde{e}_R)$ with ($m_{\tilde{e}_R}$, μ, M_1, M_2, $tan\beta$). The dotted line shows the SUSY-GUT condition

With information of $m_{\tilde{l}_L}$ we can set the energy to study $\tilde{l}_L$ with $\tilde{e}_R\bar{\tilde{e}}_L + cc.$ associate production and $\tilde{l}_L$ pair. We should note that $\tilde{l}_L$ decays to $l\tilde{\chi}_1^0$ dominantly in the light slepton case and the event signature is acoplanar $l\bar{l}$. With a polarized right-handed electron beam, we can produce only $\tilde{e}_R\bar{\tilde{e}}_L$ in the associate production and obtain different spectrum of E_{l^-} and E_{l^+} which are from $\tilde{e}_R$ and $\bar{\tilde{e}}_L$, respectively, and can separate the background from $\tilde{e}_R$ pair as shown in Fig.8. $m_{\tilde{l}_L}$ determination can be carried out with $\tilde{l}_L$ pair as done with $\tilde{l}_R$ pair.

4. Summary and conclusion

SUSY particles can be easily discovered at the future e^+e^- linear colliders such as the JLC if they are kinematically accessible. With the polarized electron beam, we can suppress the background such as W-pair and enhance the signals such as $\tilde{l}_R$ pair and get clean SUSY events. Using these clean events, we can determine mass of SUSY particles with a statistical error of a few GeV with a luminosity of 20fb^{-1}. With only the lightest charged SUSY particle, we can get information about the subsequent heavier SUSY particles in addition to itself and the LSP. The mass and cross section measurement of them allow us to determine SUSY parameters in the model and to test the assumptions such as GUT-condition and universal scaler mass before detecting all the SUSY particles.

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